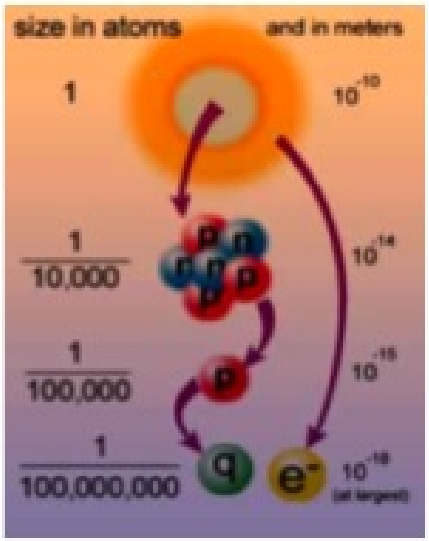
Title: Discovery of the Higgs Boson: Sweet Dream or Nightmare

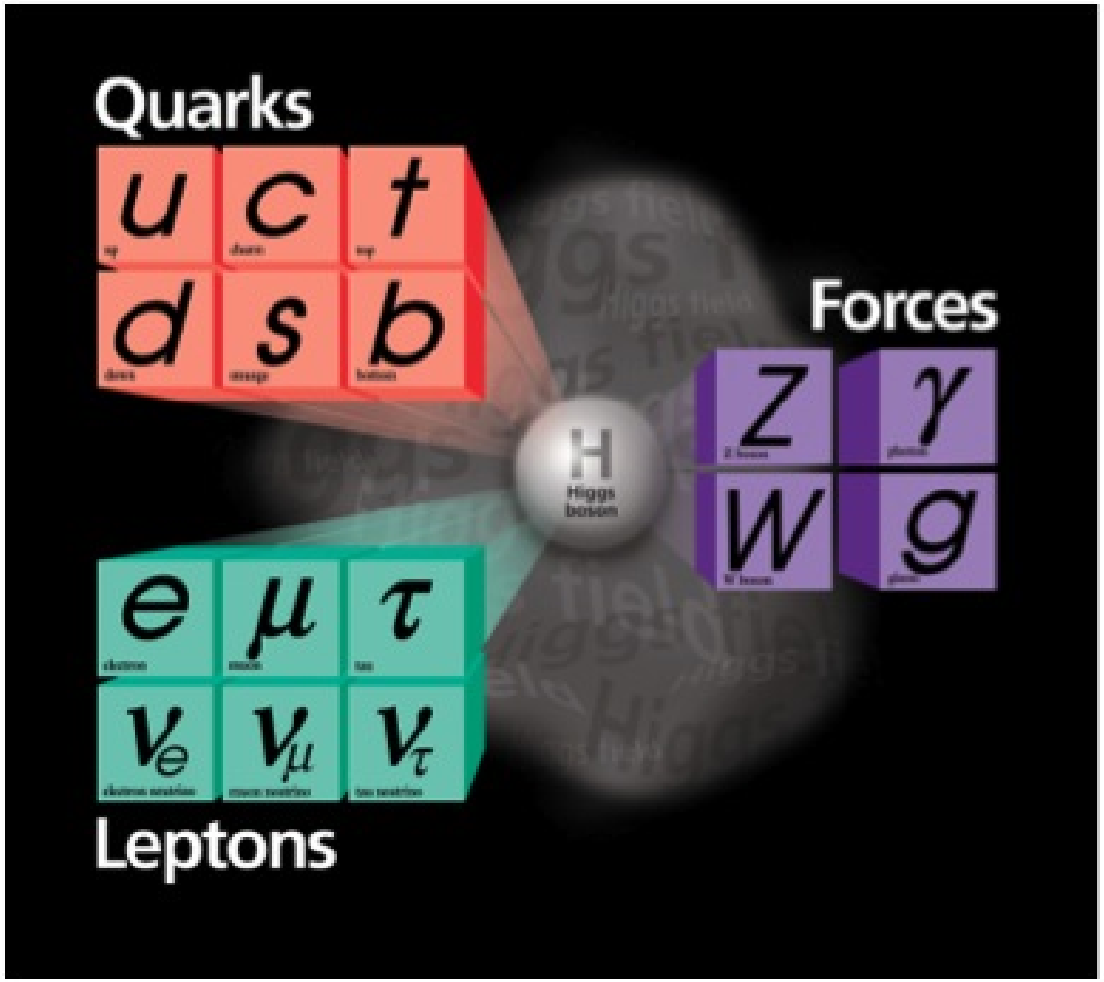
Date: Nov 07, 2012 07:00 PM

URL: http://pirsa.org/12110055

Abstract:

WE FOUND A NEW PARTICLE !





BOSON WOMAN

Now
When I walk down the street
I am thinking about the Higgs
field I am walking through
It feels weird.
Theorists have been
feeling like this since
1982 when the W, Z
were discovered
or possibly before

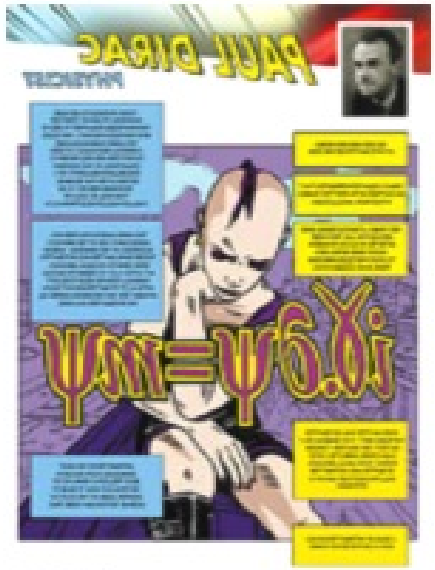
'Quantum Cloud XX' by Antony Gromely

THEORISTS AND EXPERIMENTALISTS
THE RELATIONSHIP

Theorists study exact symmetries of an approximate world

Experimentalists measure the world wrapped in fog

Georgi



Me

EXPERIMENTALISTS

CANADIAN PHILOSOPHER OF SCIENCE

IAN HACKING WROTE ABOUT SCIENTIFIC REALITY

"IF YOU CAN SPRAY IT, ITS REAL"

Electrons ✔

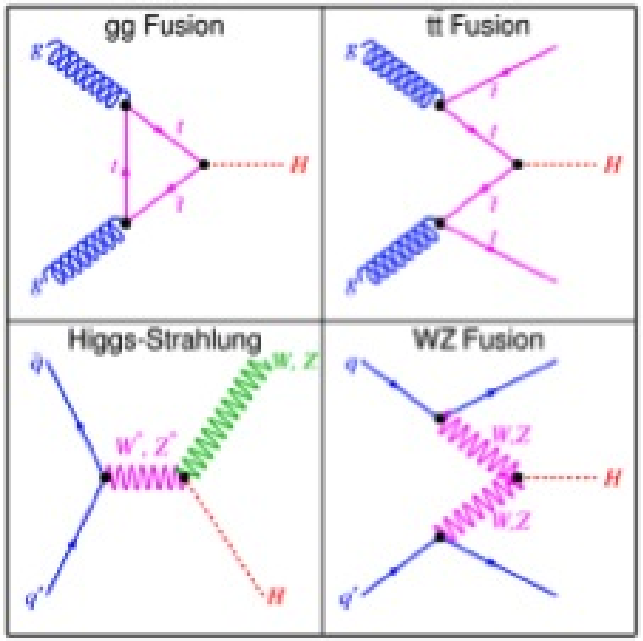
Quarks ✔

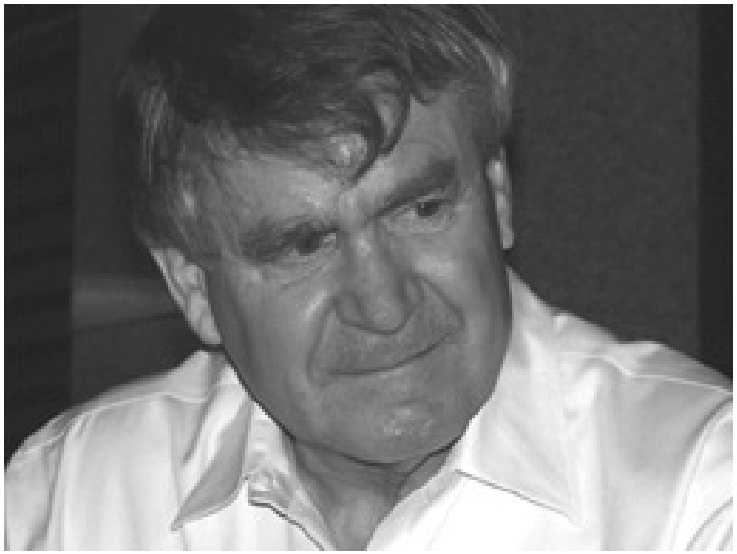
Gluons ✔

W's (almost)

Top quarks ✔

Higgs????





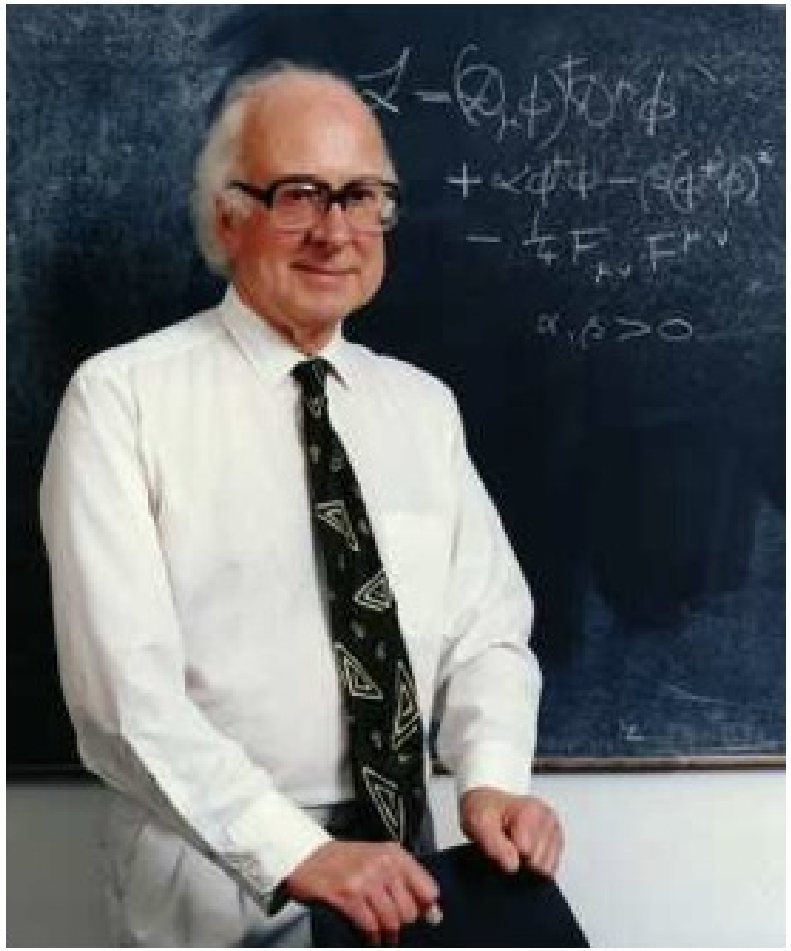
HIGGS AMONG OTHER THEORISTS SOLVED THE THEORETICAL PROBLEM AND PREDICTED THE HIGGS PARTICLE

WE DIDN'T BELIEVE IT

WE WERE ALL

"HIGGS SCHMIGGS"

BUT WE LOOKED FOR IT IN OUR SPARE TIME



Peter HIGGS

WAKING UP TO THE HIGGS BOSON : SWEET DREAM OR NIGHTMARE

MELISSA FRANKLIN

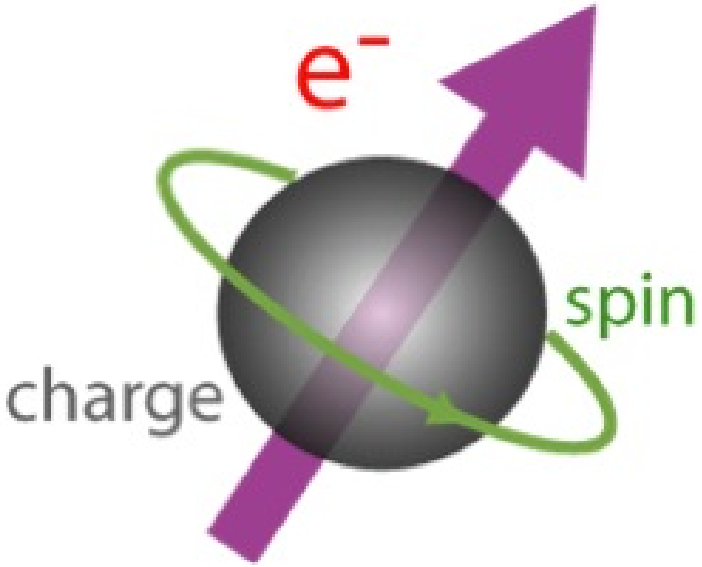
PERIMETER NOVEMBER 2012

THIS TALK IS ABOUT FINDING THE HIGGS & WHAT HAPPENS TO US NEXT

BOSON
SPIN
PARTICLE
COUPLING
QUARKS
LEPTONS
FORCE CARRIERS
W, Z, GLUON
PHOTONS
MASS
FIELD?

WHAT

WHAT'S A BOSON?



SPIN is QUANTISED

BOSONS: spin $0, 1, 2, \ldots$

FERMIONS: spin $\frac{1}{2}, \frac{3}{2}, \ldots$

Higgs should have spin 0

WHAT IS A PARTICLE?

TWO KINDS: STABLE AND UNSTABLE:
ELECTRON OR TOP QUARK

AN UNSTABLE PARTICLE DECAYS RANDOMLY

TOP QUARK-> W BOSON + BOTTOM QUARK

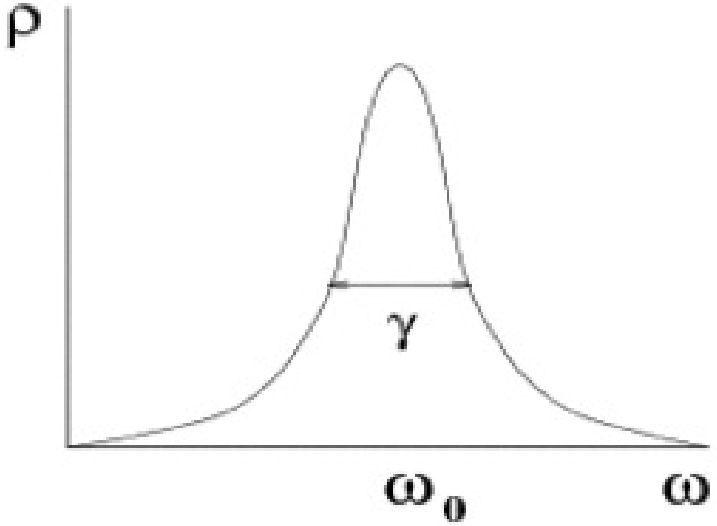
INVARIANT MASS (W+B) = MASS TOP

WE RECONSTRUCT THE MASS OF UNSTABLE PARTICLES FROM THEIR DECAY PRODUCTS

CLASSICAL RESONANCE

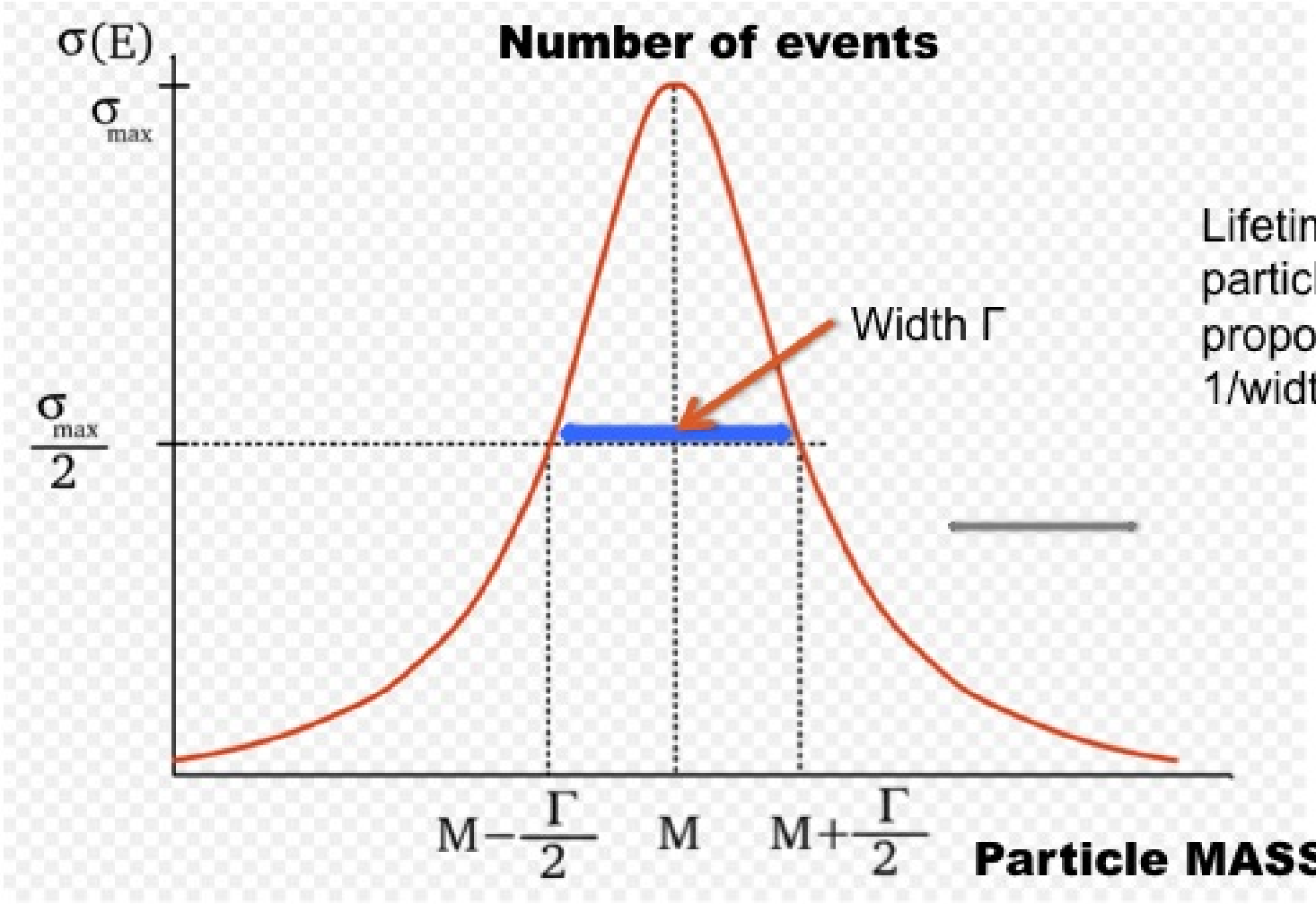
HOW DO WE IDENTIFY A PARTICLE/RESONANCE?

Power absorbed vs frequency



ω_0 is the resonant frequency, Y is called the width, P is the power absorbed

PARTICLE RESONANCE



Particle has characteristic Mass and lifetime, just like a wine glass!

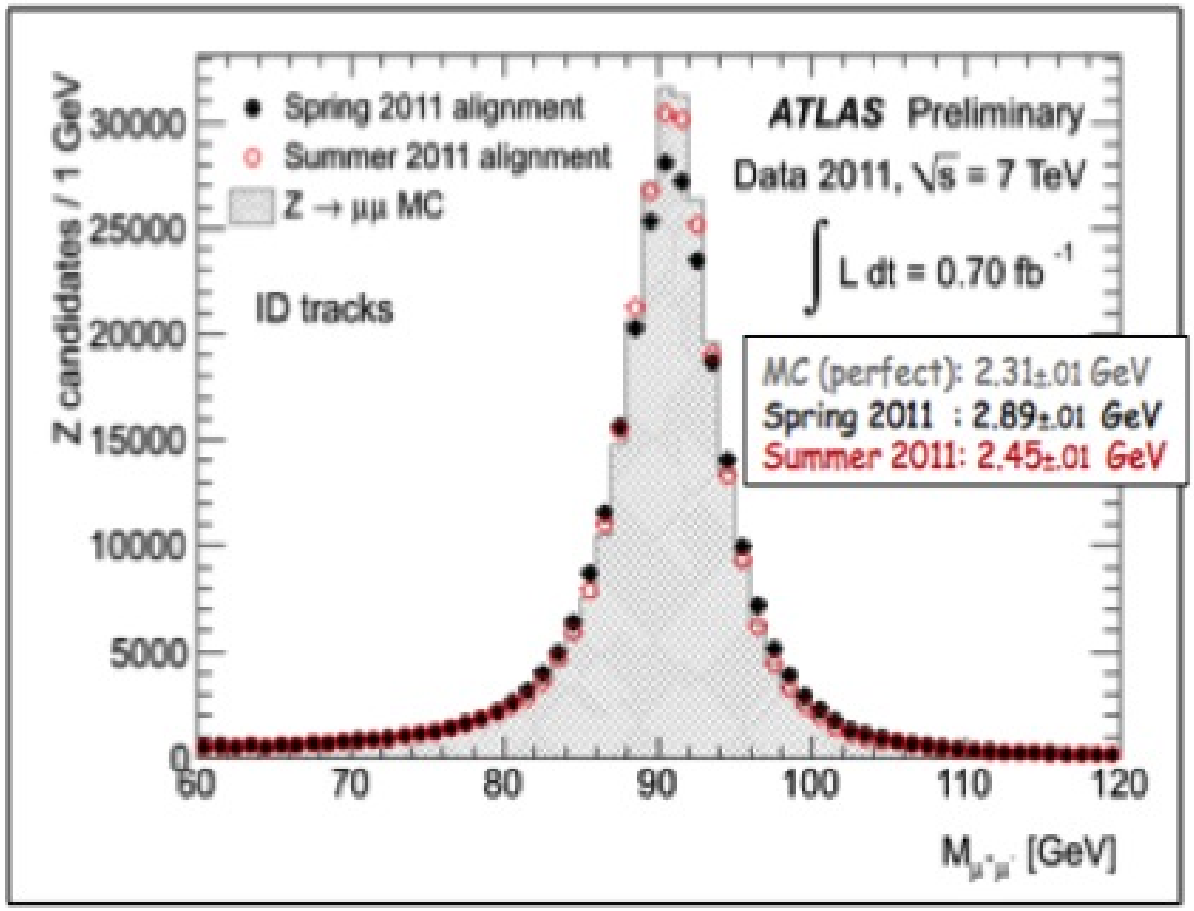
FOR INSTANCE: THE Z BOSON MASS

$Z > \mu^+ \mu^-$

MASS ~ 91 GeV

Characteristic WIDTH smaller than detector resolution.

LIFETIME ~ 10^{-22} s



INVARIANT MASS OF MUON MUON

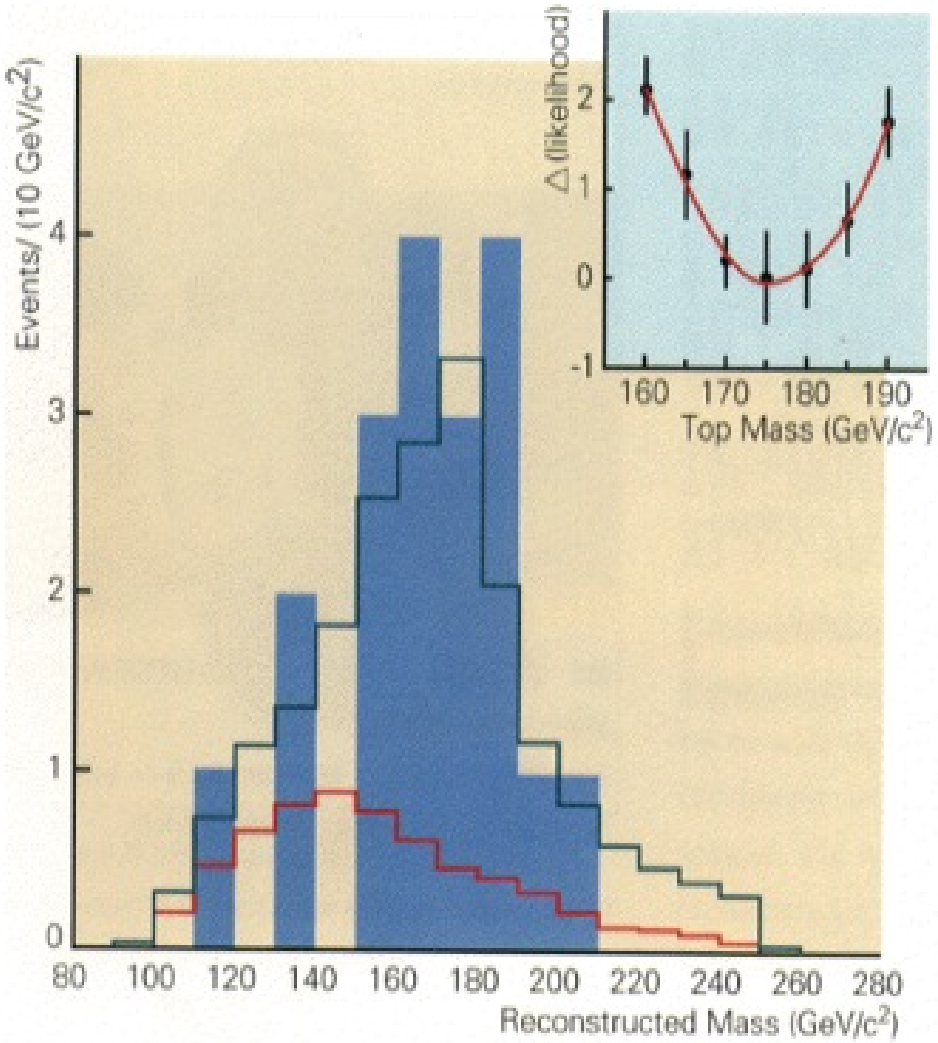
DISCOVERY OF TOP QUARK:

WE CONVINCE OURSELVES WE HAVE DISCOVERED A PARTICLE IF WE SEE A BELL SHAPE MASS DISTRIBUTION

THIS IS THE TOP QUARK DISCOVERY INVARIANT MASS IN 1995.

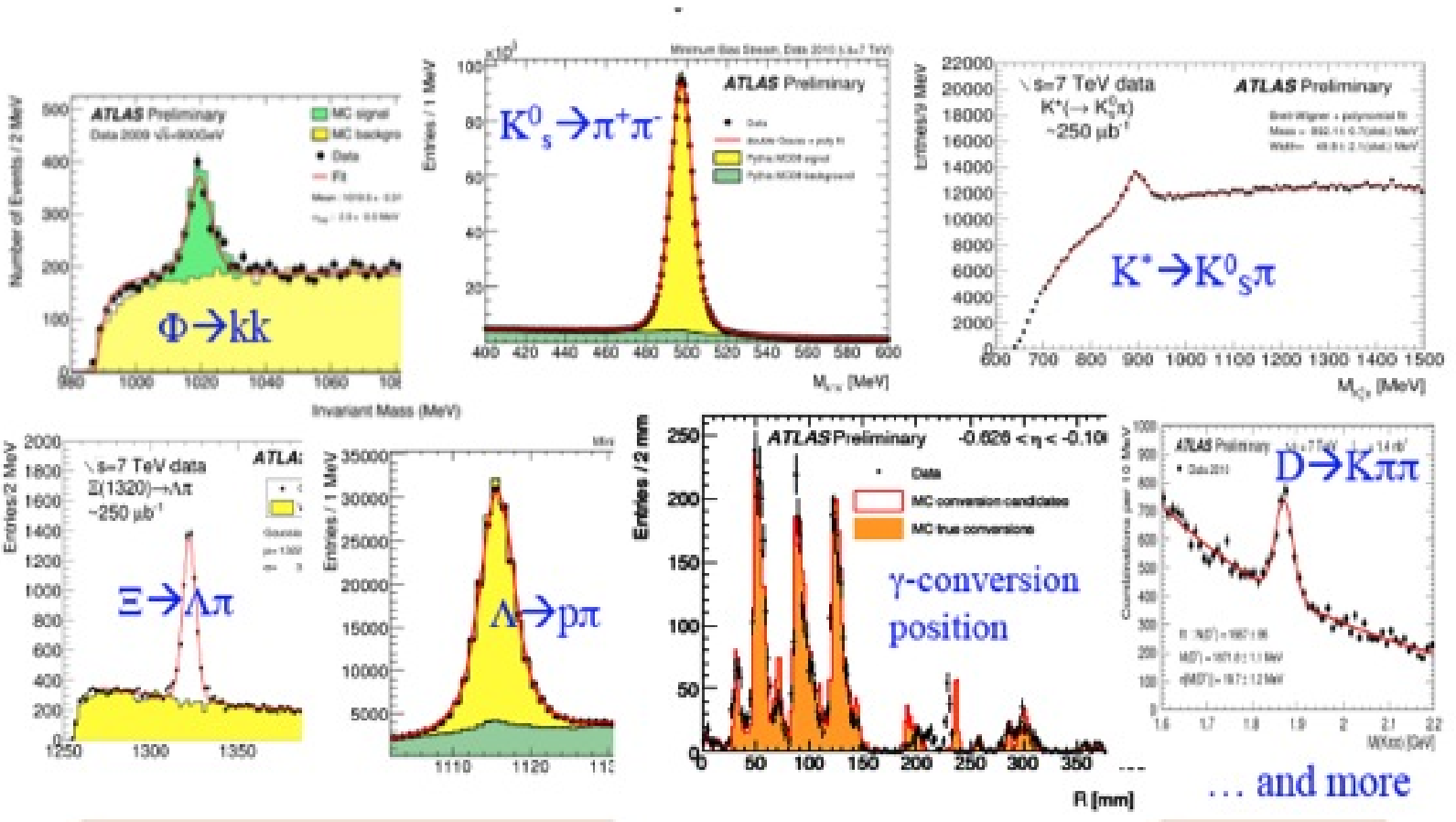
Lifetime of top quark ~ 10^{-24}seconds

#

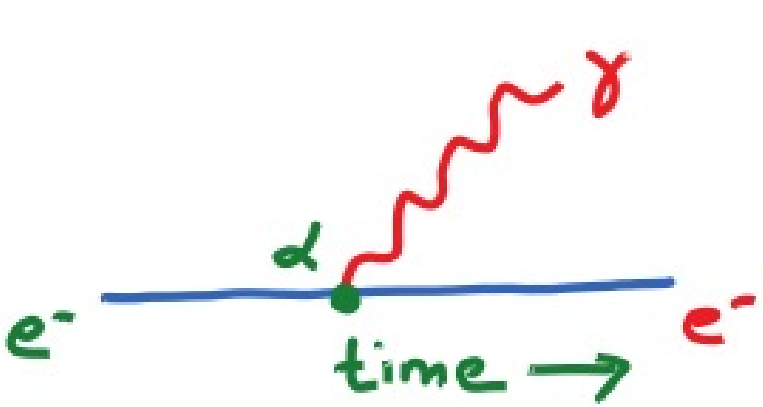


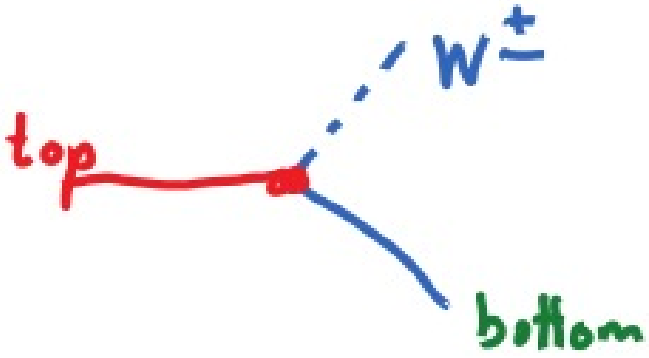
MASS

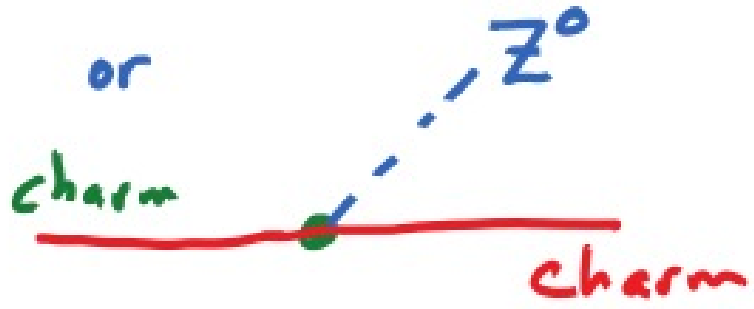
WE FIND ALL THE STUFF WE ALREADY KNOW

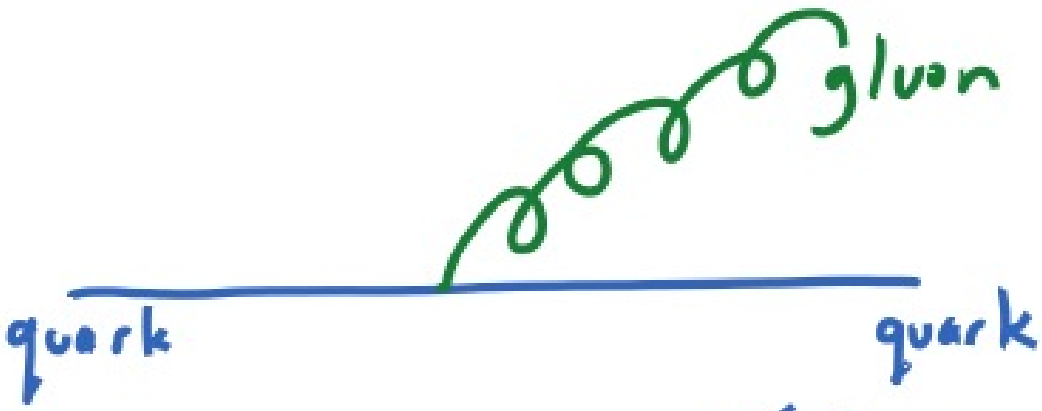


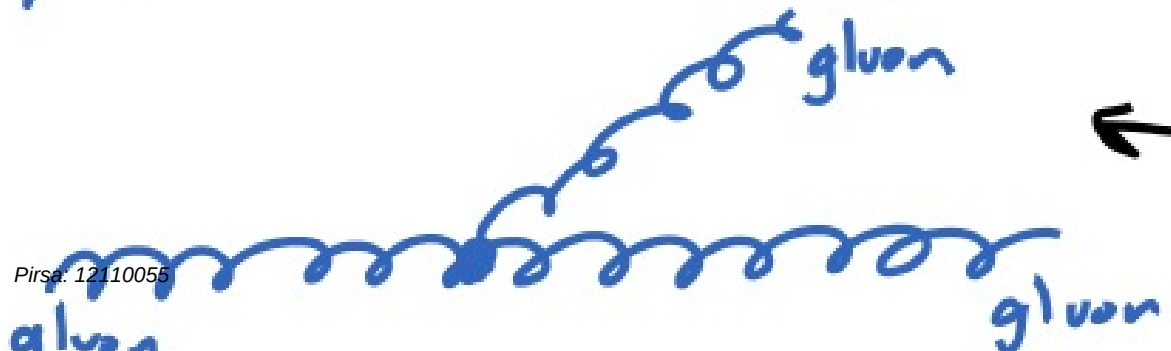
COUPLINGS







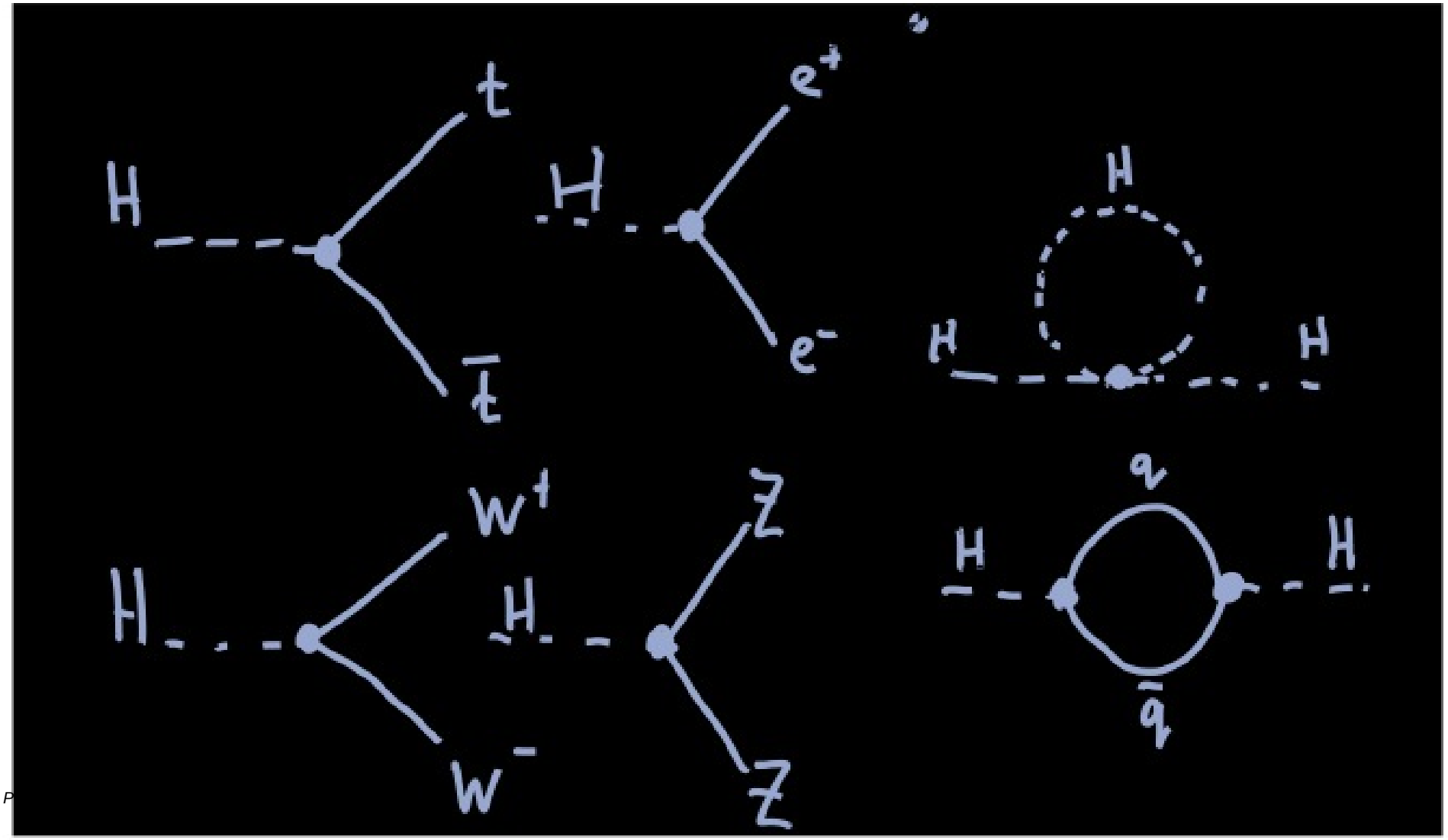




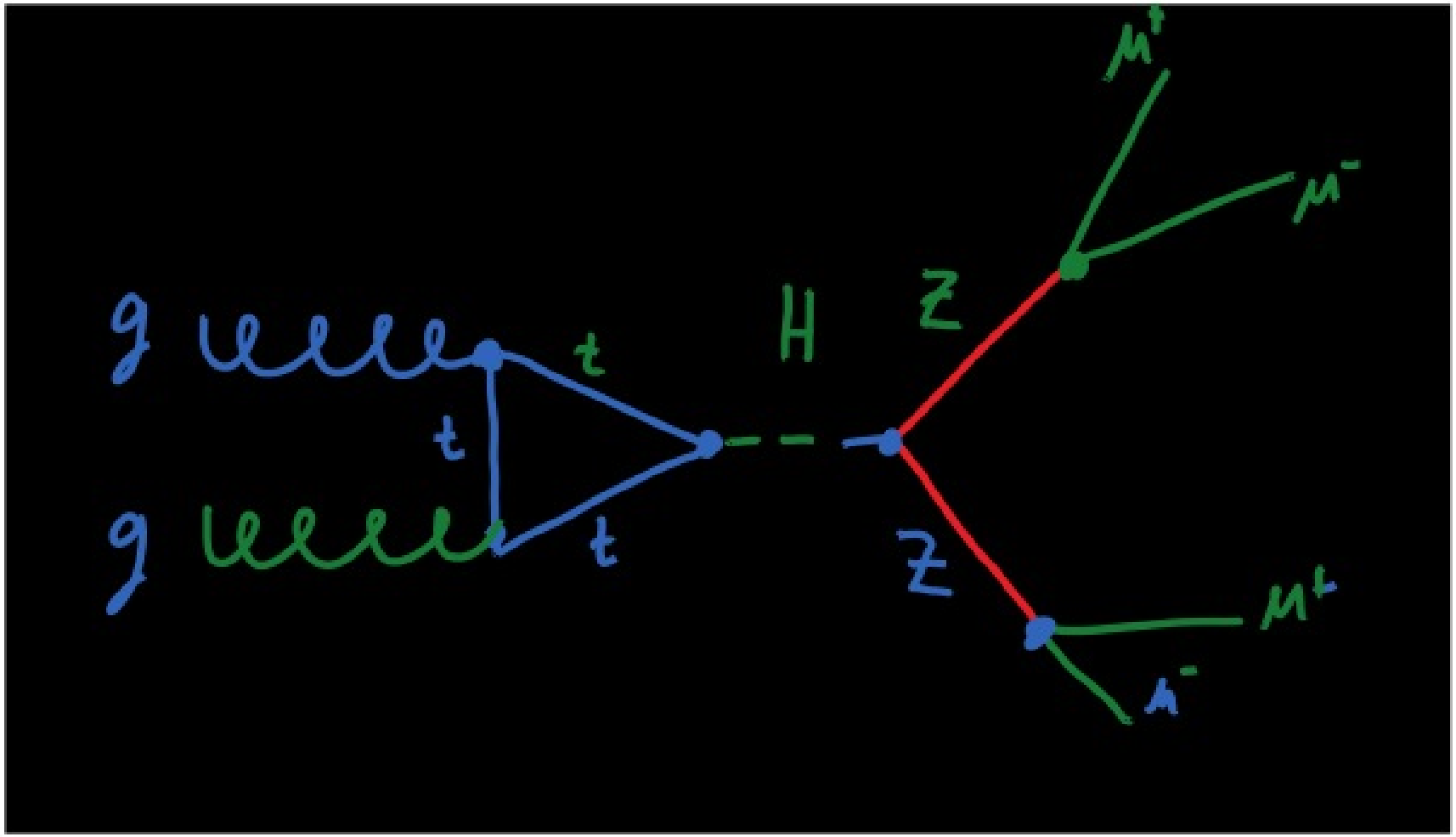
← STRONG INTERACTION

HIGGS COUPLINGS DEPEND ON MASS OF PARTICLES

HIGGS GET MASS TOO!



THIS CAN HAPPEN



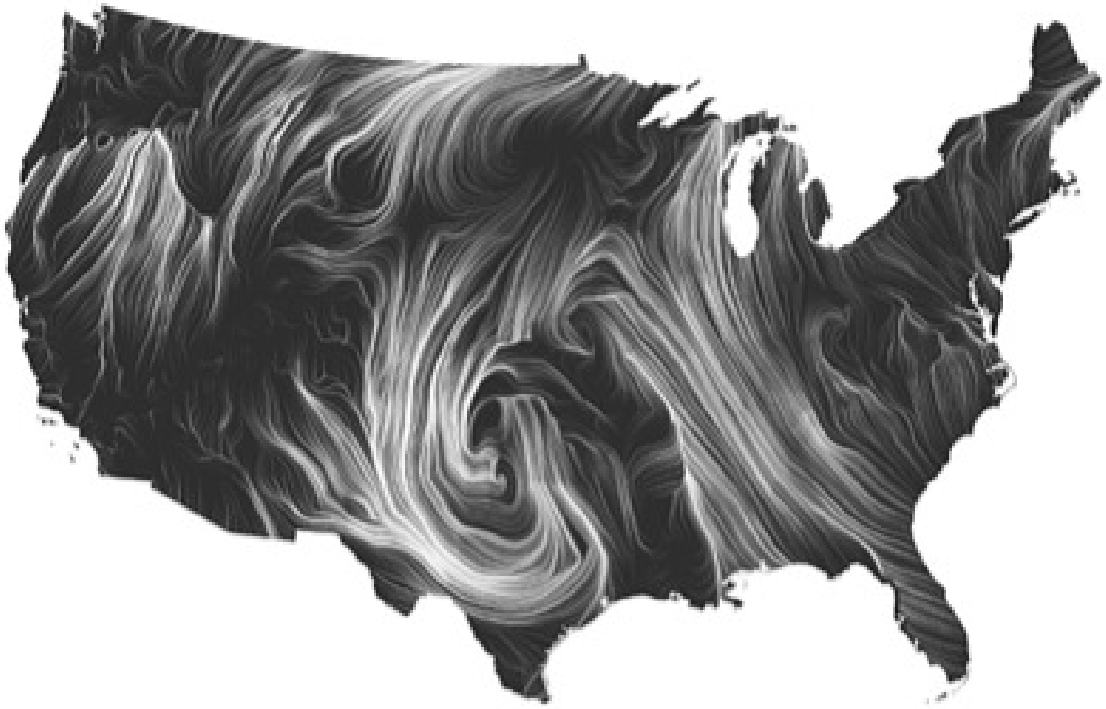
HOW OFTEN?

WHAT IS A FIELD?

Some quantity defined at every point in space
A magnitude and a direction for example.

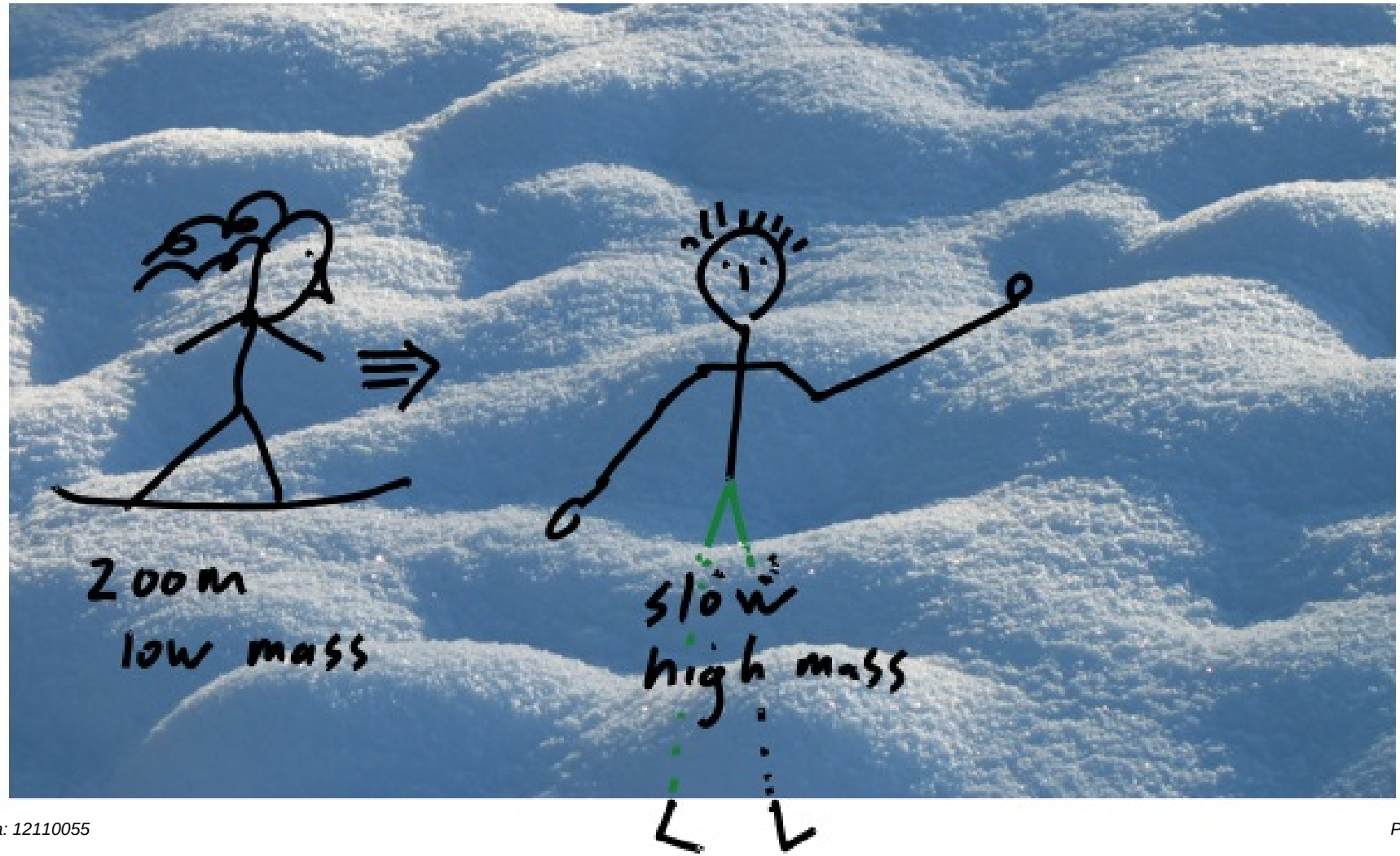
Magnetic field strength and direction,
gravitational field strength and direction

wind as a field

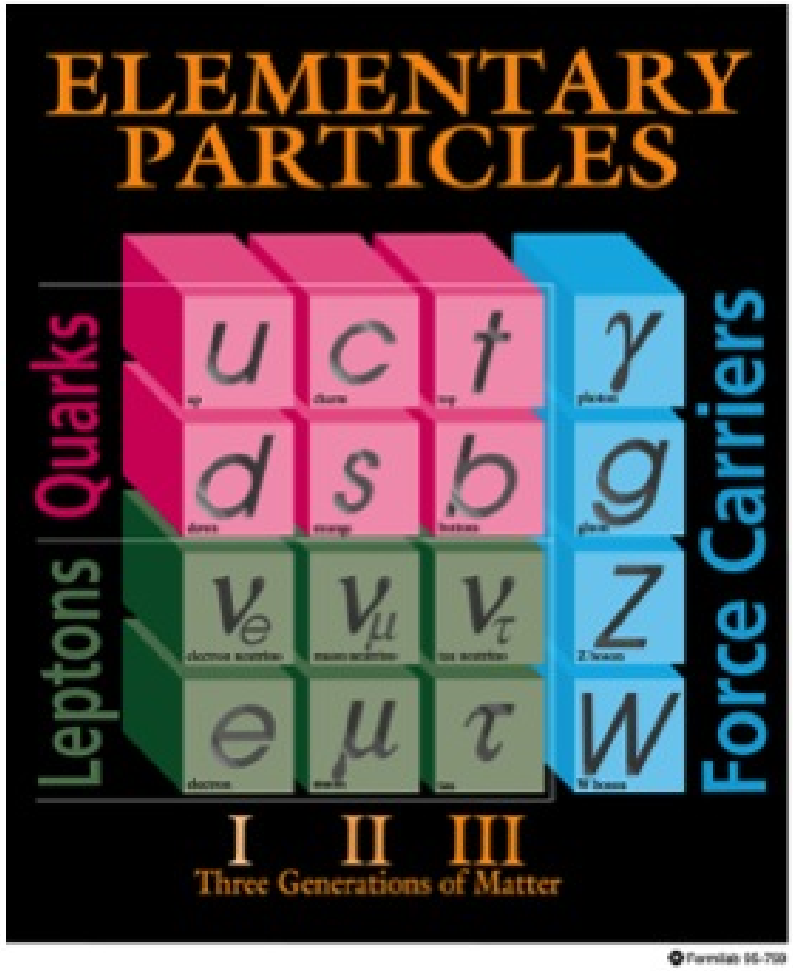


Wind speed and
direction at every point
in the US

SNOW FIELD – HIGGS FIELD



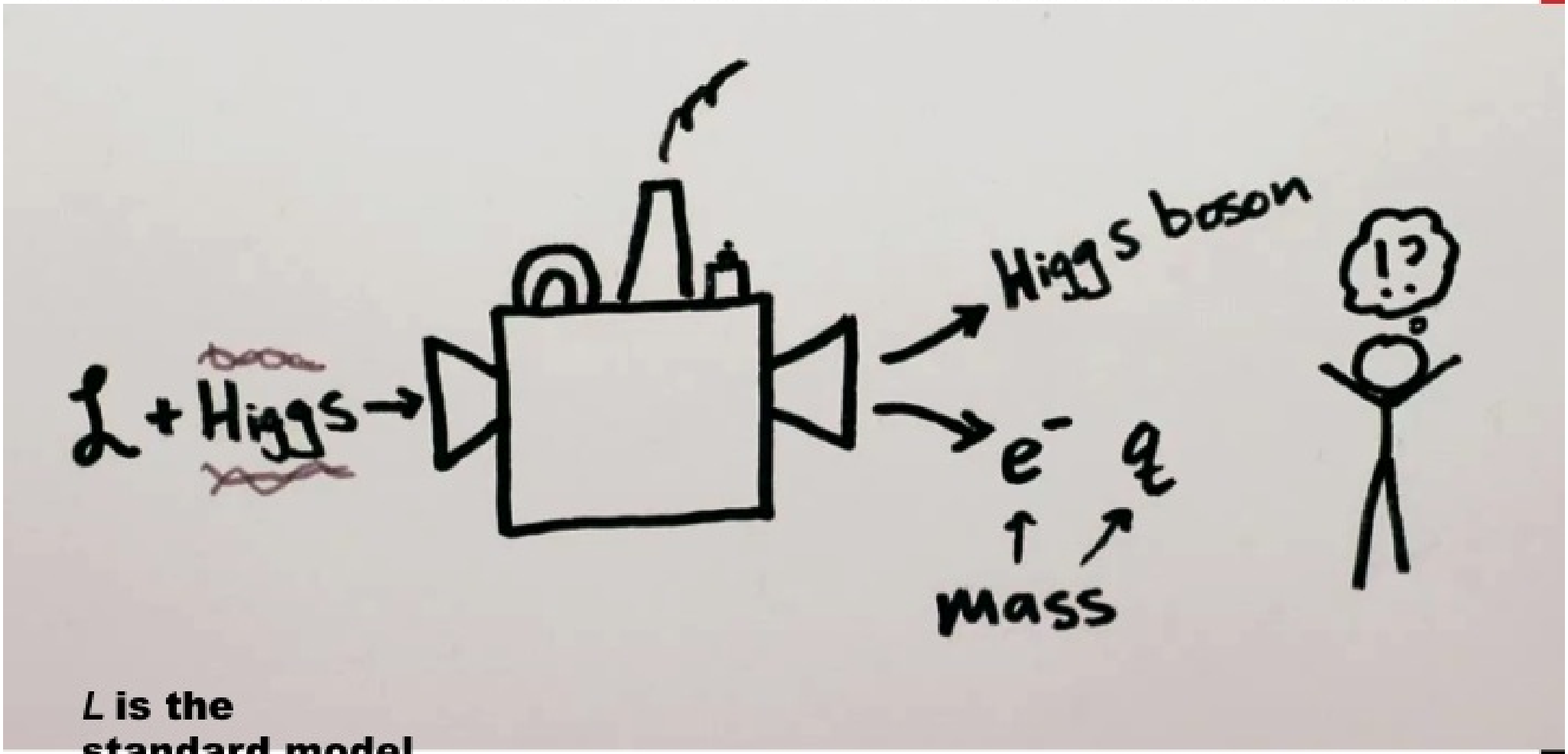
THE STANDARD MODEL AND ME:



Without the Higgs the W,Z, and fermions would be massless!

MY ONE THEORY SLIDE

THE HIGGS FIELD AS INPUT INTO THE STANDARD MODEL MACHINE



***L* is the standard model theory**

From Minutephysics by Perimeter's Henry Reich

WITH AN ACCELERATOR WE CAN DO TWO THINGS

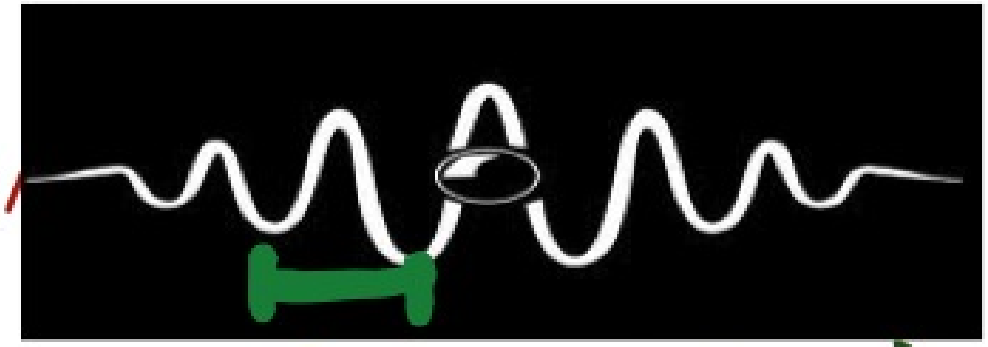
- LOOK AT VERY SMALL THINGS VERY CAREFULLY
  WITH HIGH RESOLUTION USING PARTICLE BEAMS

- TAKE ADVANTAGE OF EINSTEIN ENERGY MASS RELATION
  USE HIGH ENERGY PARTICLES TO MAKE HIGH MASS PARTICLES

THE ENERGY FRONTIER!

WE KNOW QUANTUM MECHANICS

⇒ PARTICLES BEHAVE LIKE WAVES



$$\text{MOMENTUM } P = \frac{h}{\lambda}$$

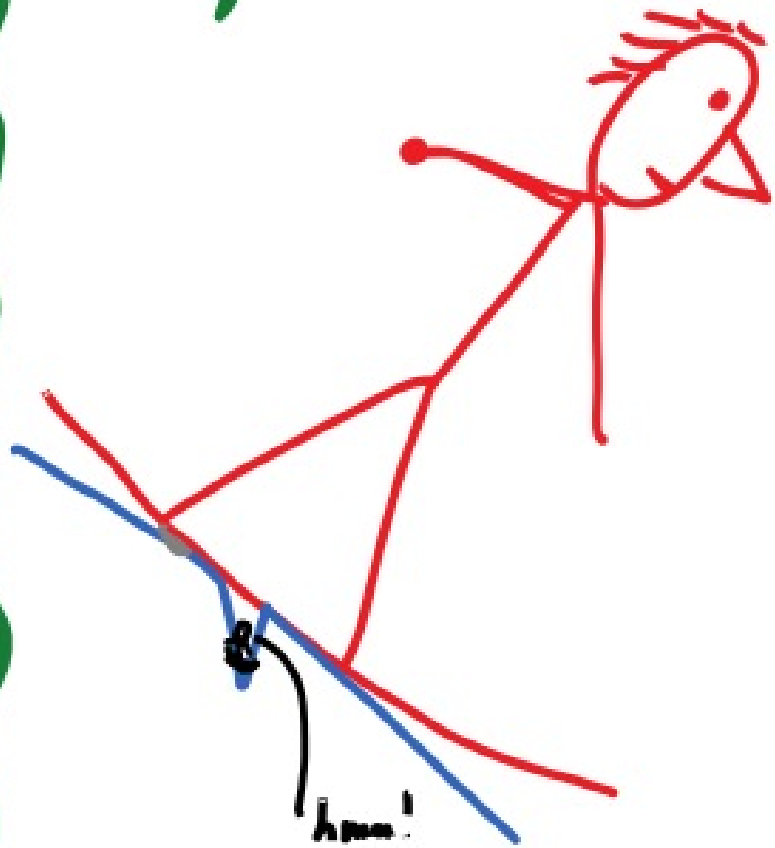
h ← Plancks constant

P ← particle

λ ← wave

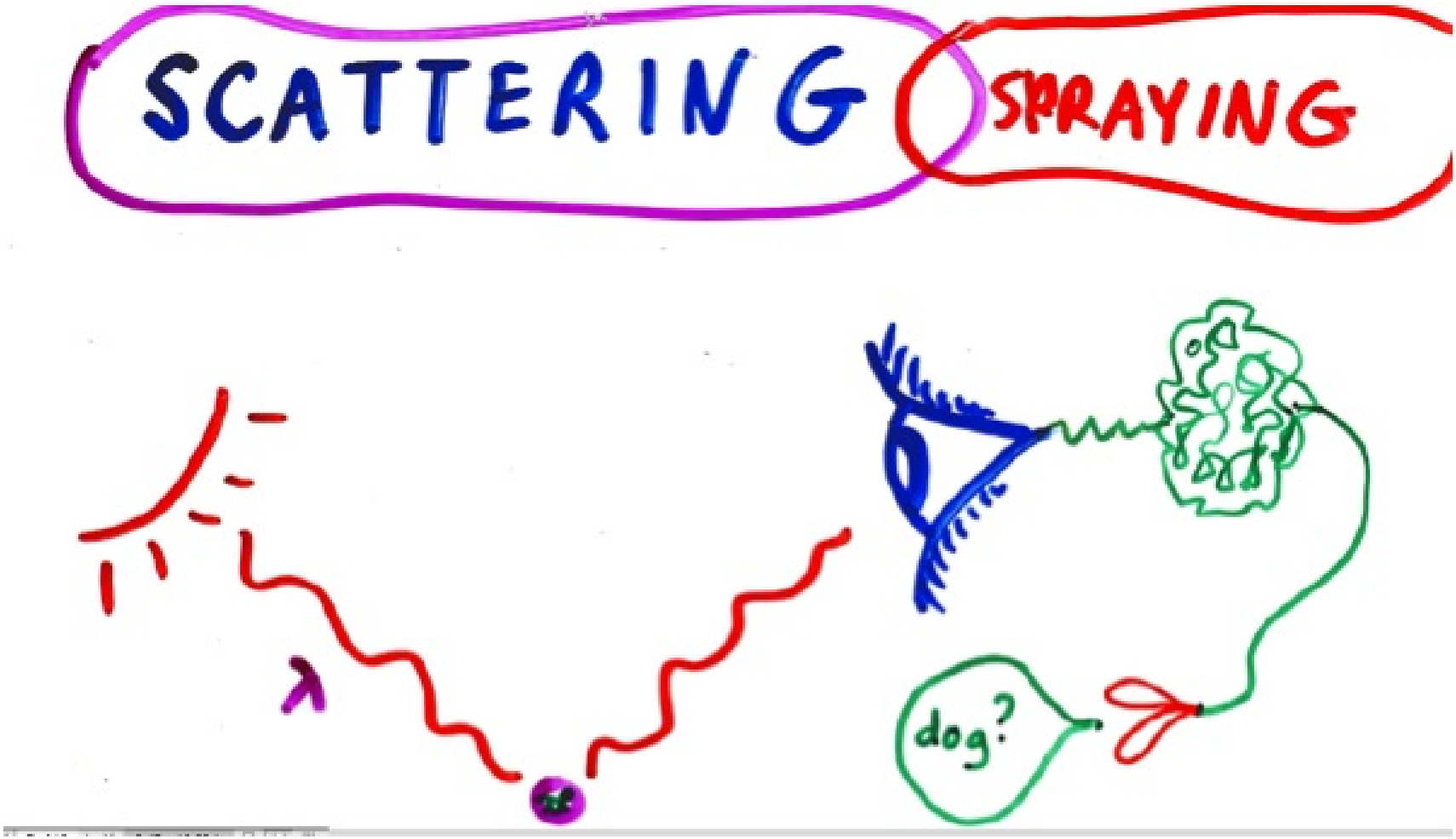
Small λ

⇒ good resolution



⇒ accelerators

WE DO THE FIRST EVERY DAY

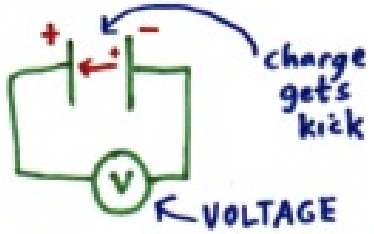


MAKE ANY WAVELENGTH

NEED SMALL λ

⇒ LARGE MOMENTUM P

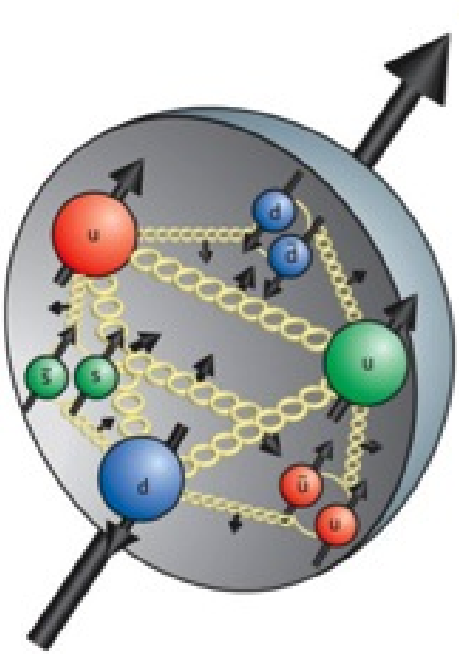
⇒ NEED TO ACCELERATE



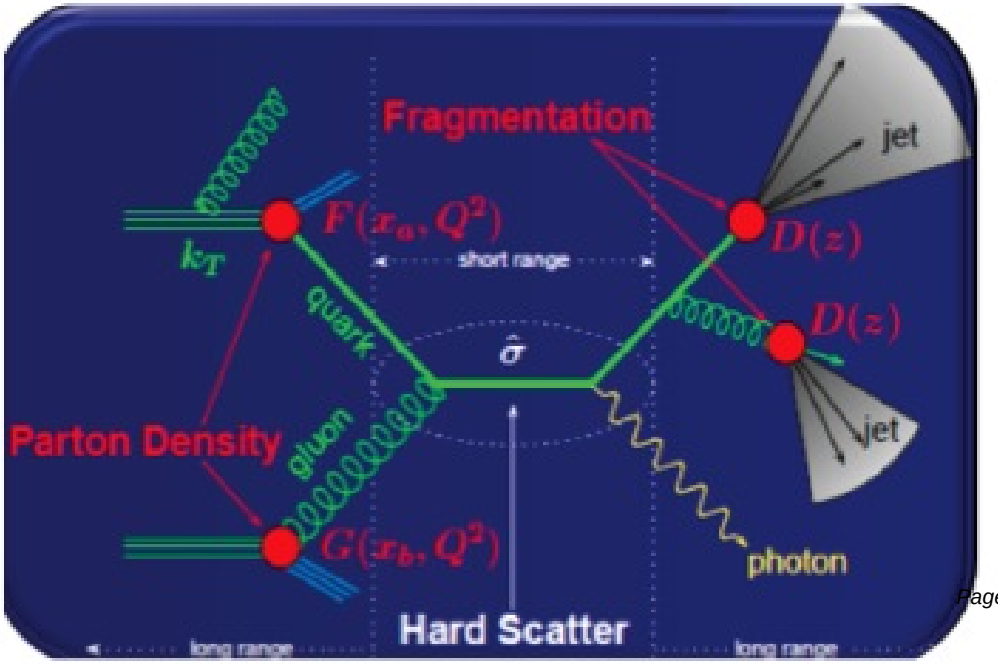
DO THIS MULTIPLE TIMES

Bend particles with magnets

WHAT SHOULD WE ACCELERATE?



PROTONS! WE COLLIDE PROTONS. THAT"S REALLY COLLIDING QUARKS AND GLUONS AND ANTI-QUARKS

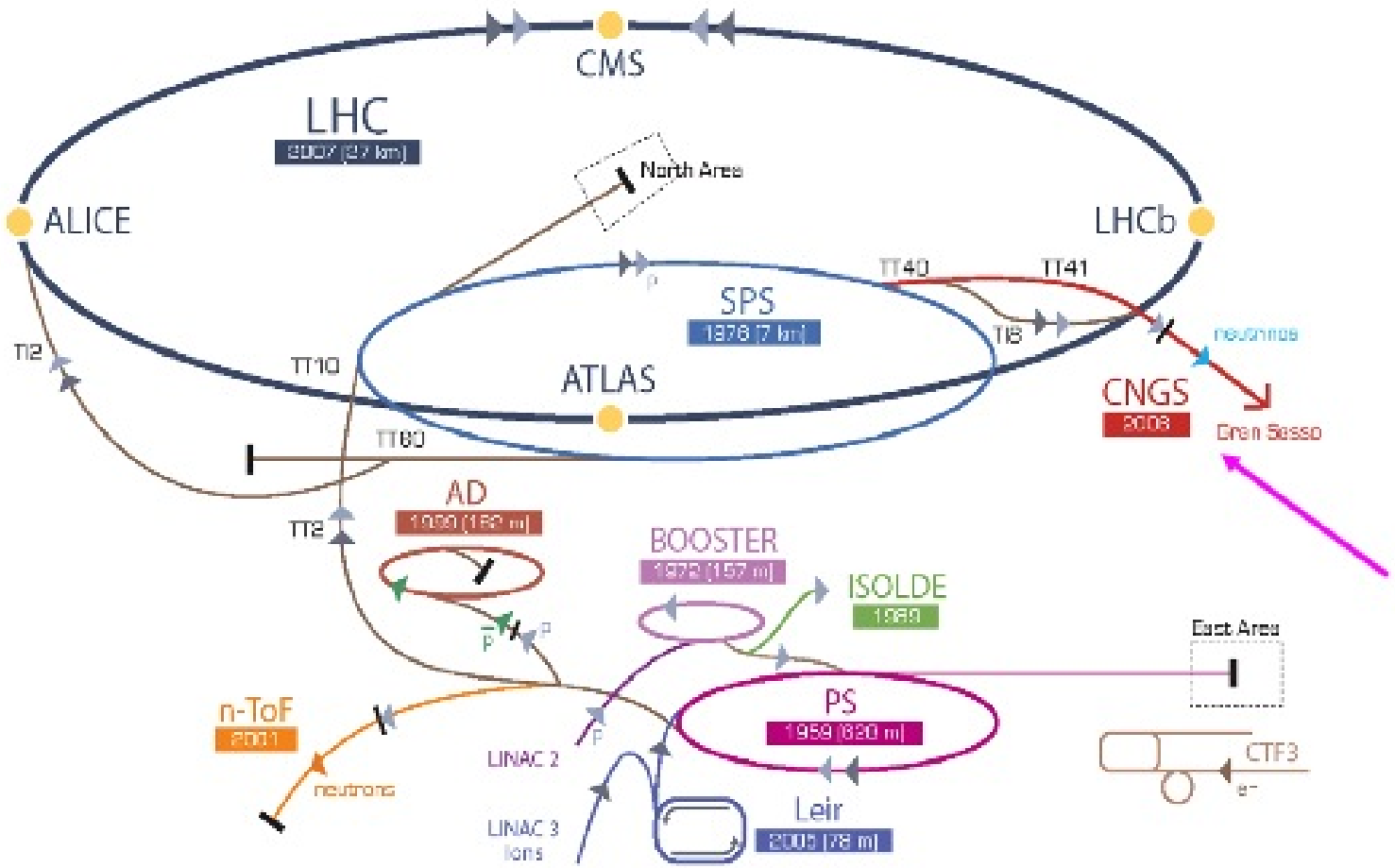


NB. This is the only part that's complicated

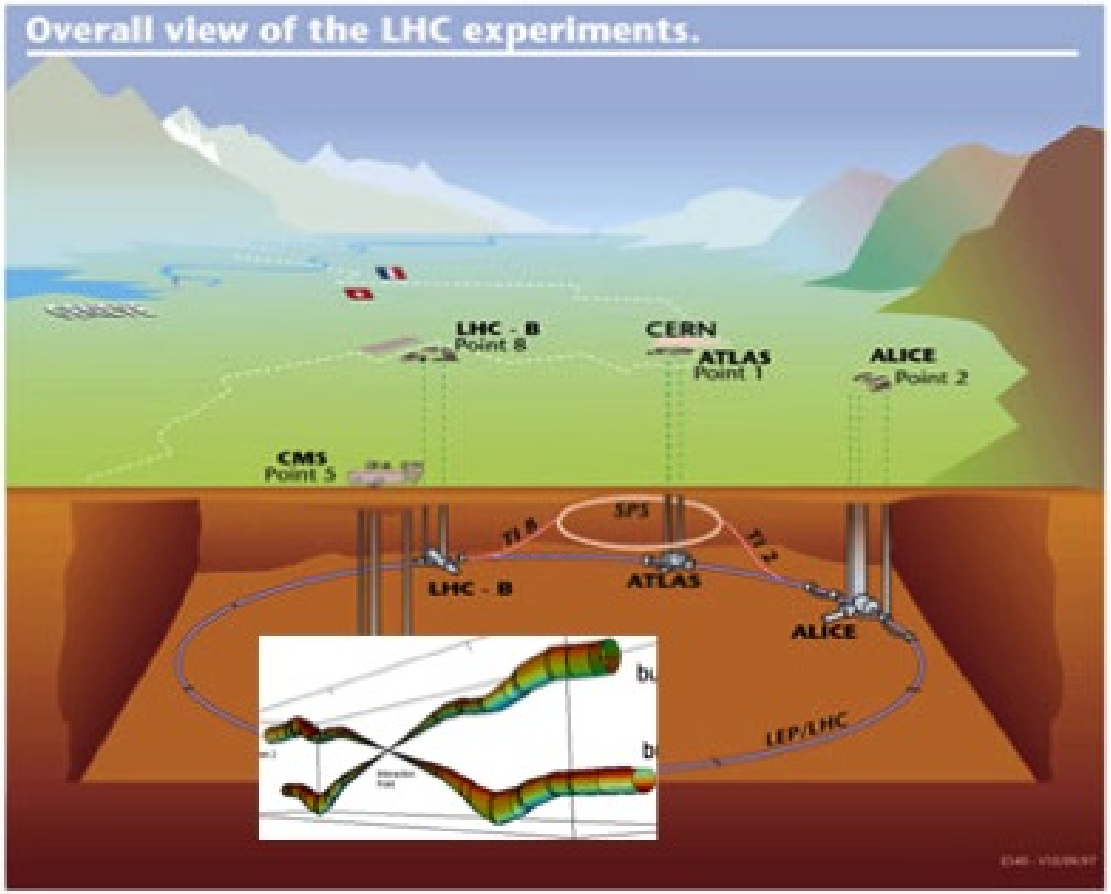
OK WE USE QUARKS TO LOOK INSIDE OTHER QUARKS AND WE CAN CREATE NEW PARTICLES!

TURN ENERGY INTO MASS

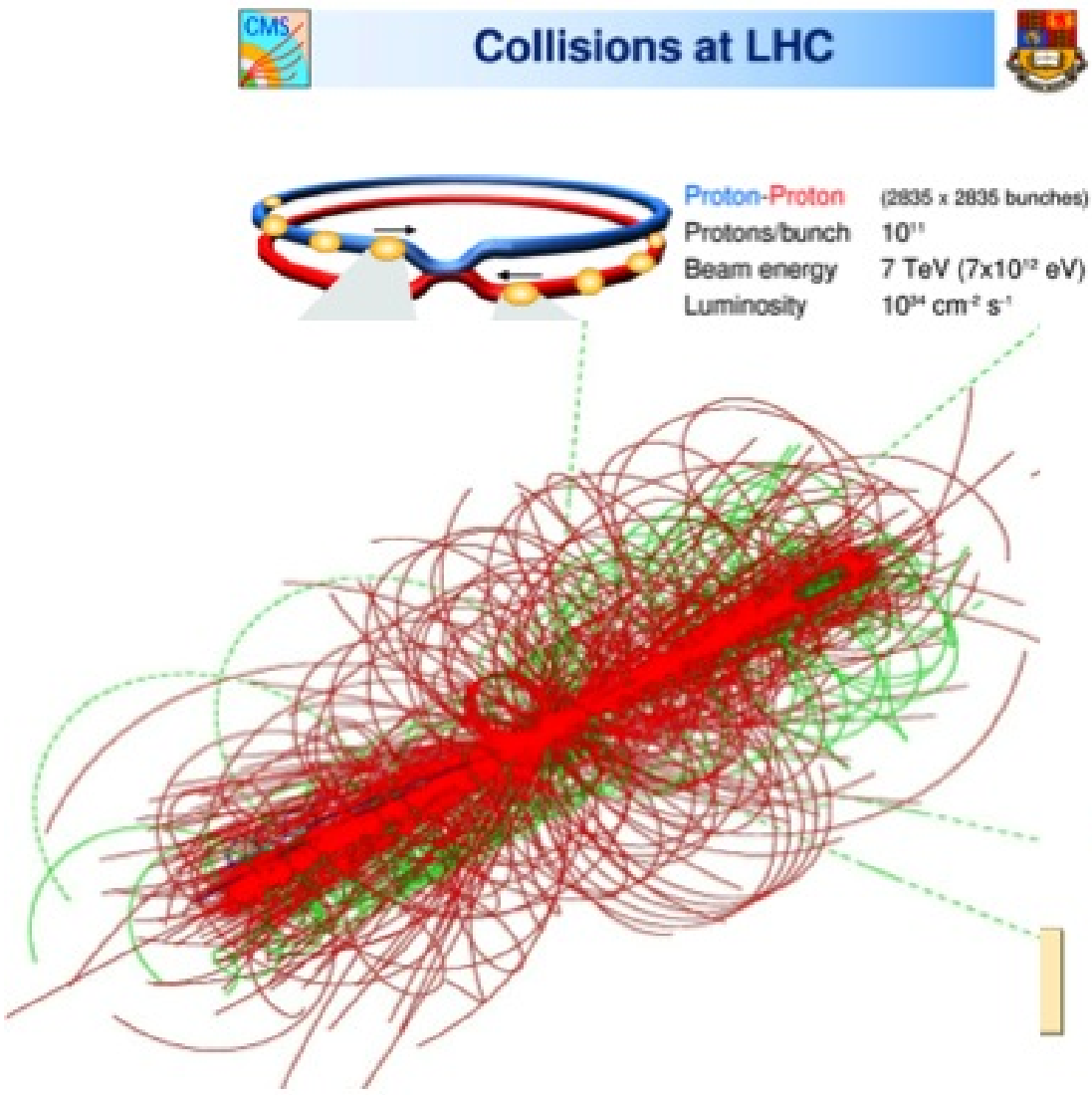
CERN Accelerator Complex



THE LARGE HADRON COLLIDER



PROTON PROTON COLLISIONS AT THE LHC



proton – proton:

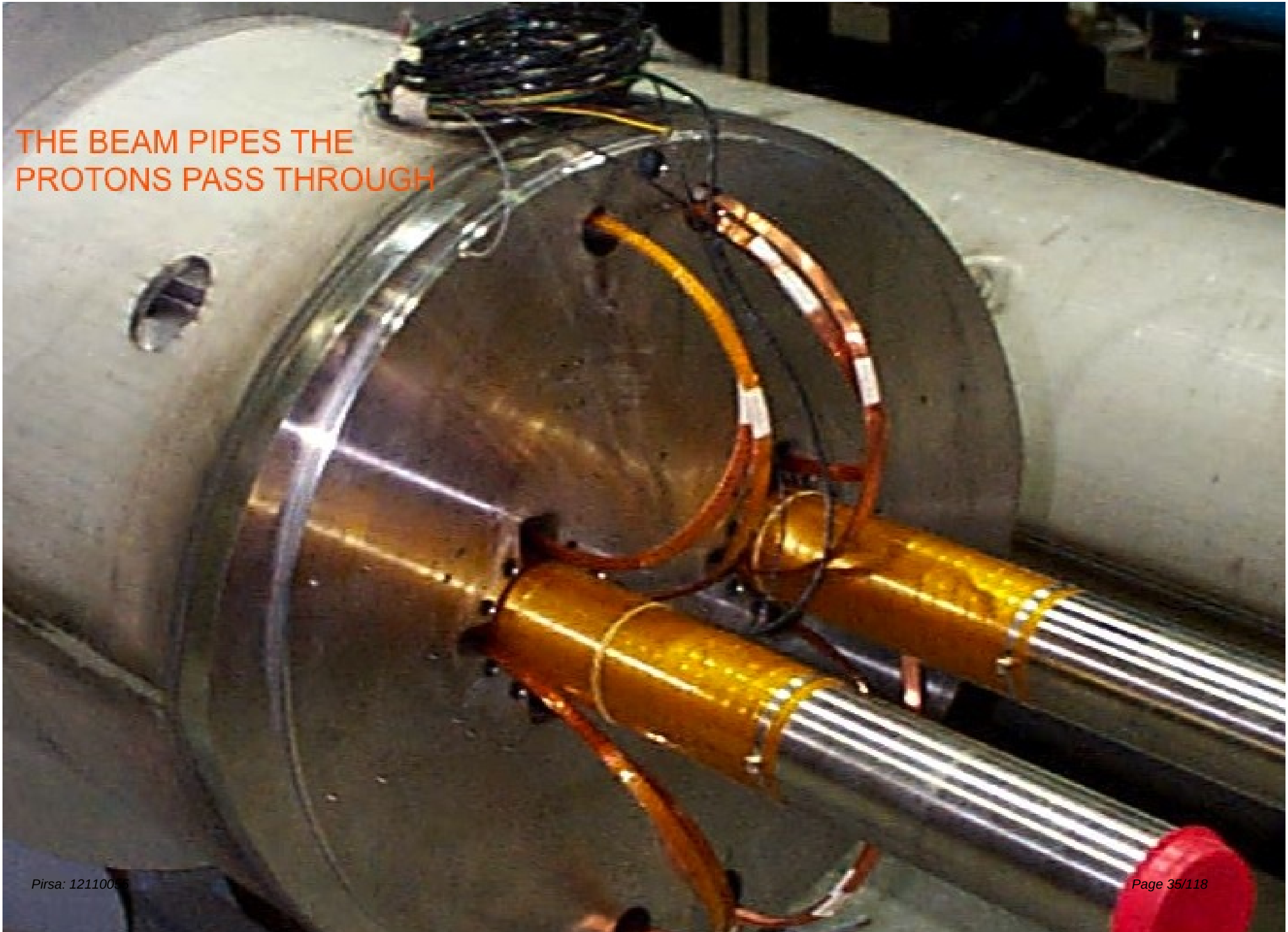
2835 x 2835 bunches
Separation: 7.5 m (25 ns)
10^{11} protons / bunch
Crossing rate of p-bunches: 40 Million/ sec
Luminosity: $L = 10^{34}$ cm^{-2} s^{-1}
An event is when protons collide
~10^{9} pp collisions / second
~1600 charges particles in the detector

(superposition of 23 pp-interactions per bunch crossing: **pile-up**)

Trigger reduces data rate 40,000 events/sec to 3000 events /sec
RAW data – 3200 Terabytes/year
Equivalent to 3 billion books.

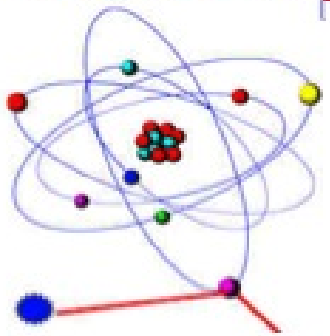
Like a 100MPixel camera taking pictures
At a rate of 40,000 pictures per second

27 KILOMETRES OF SUPERCONDUCTING MAGIC

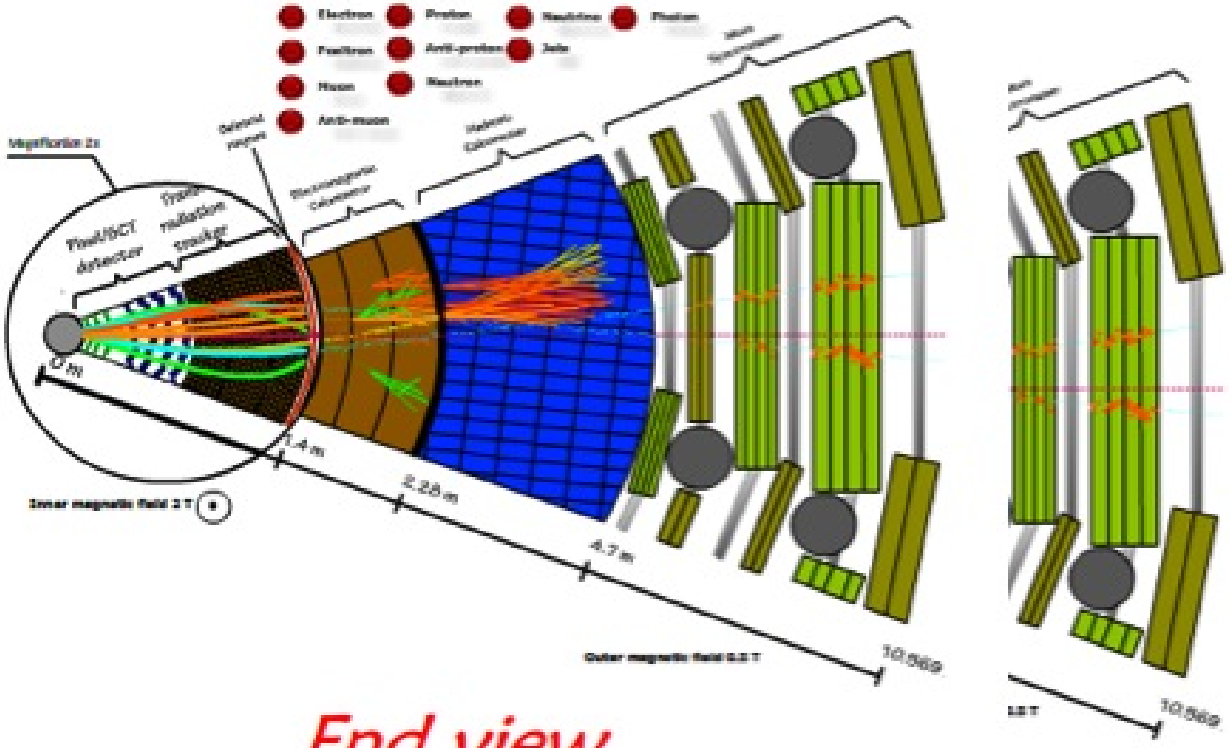

THE BEAM PIPES THE
PROTONS PASS THROUGH

LIQUID HELIUM CAN BE DANGEROUS

DESIGN A DETECTOR: EVERYTHING IS IONIZATION

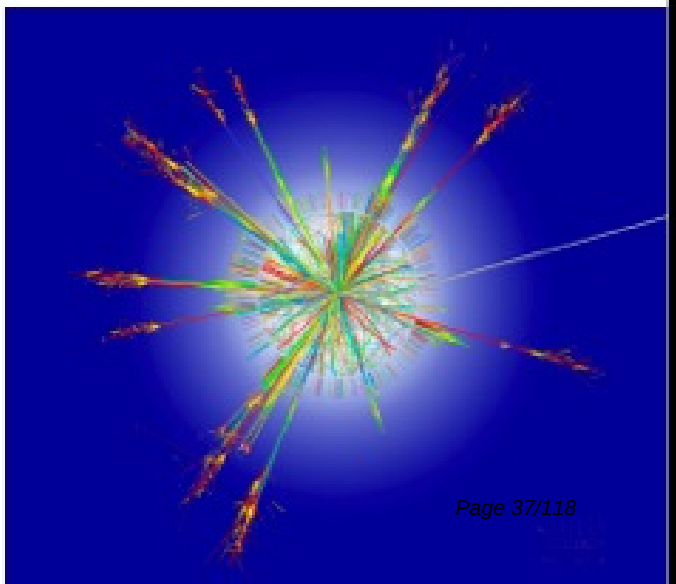


This is a charged particle track bending in a magnetic field

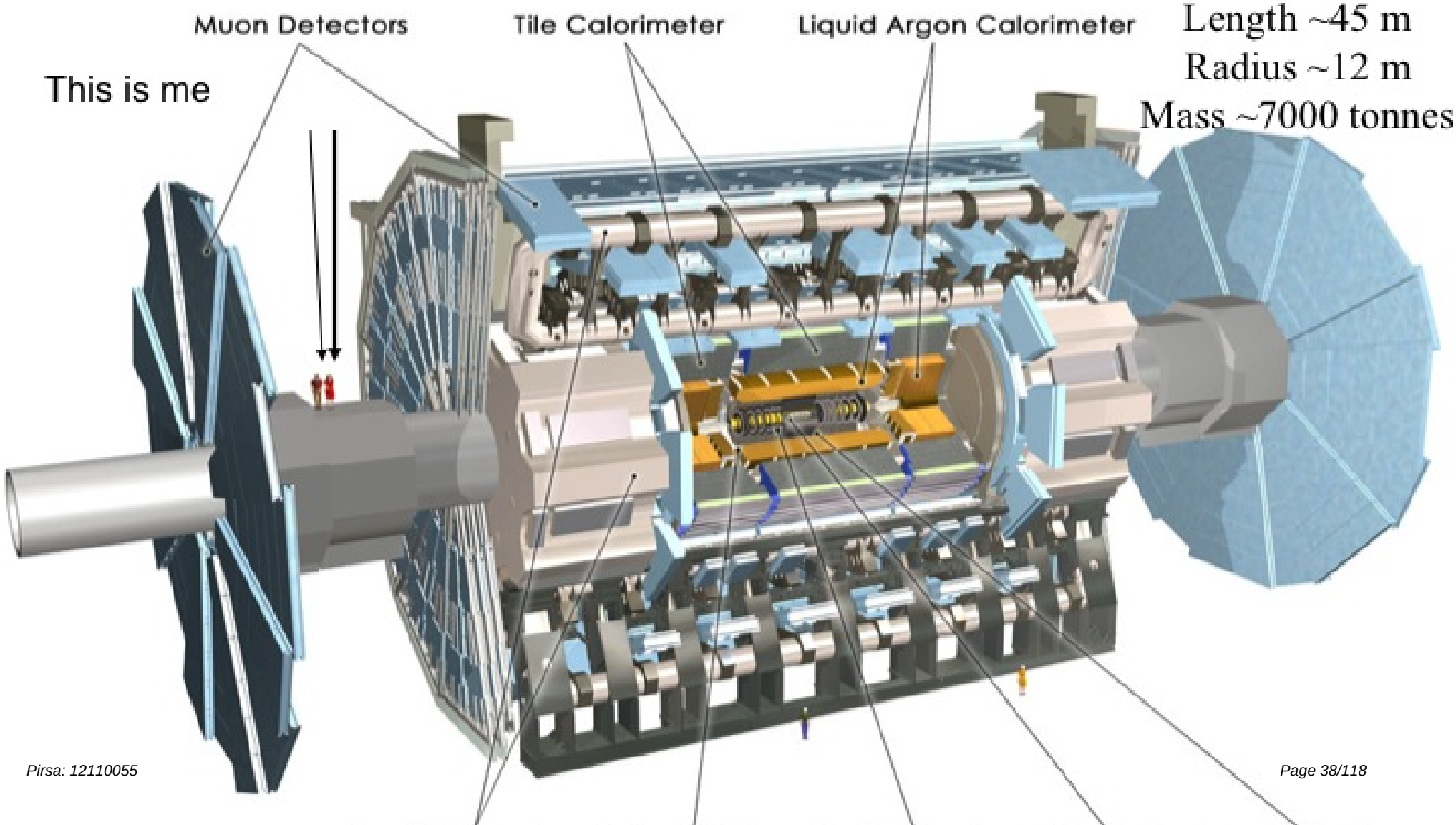


End view

Black hole looks like this?



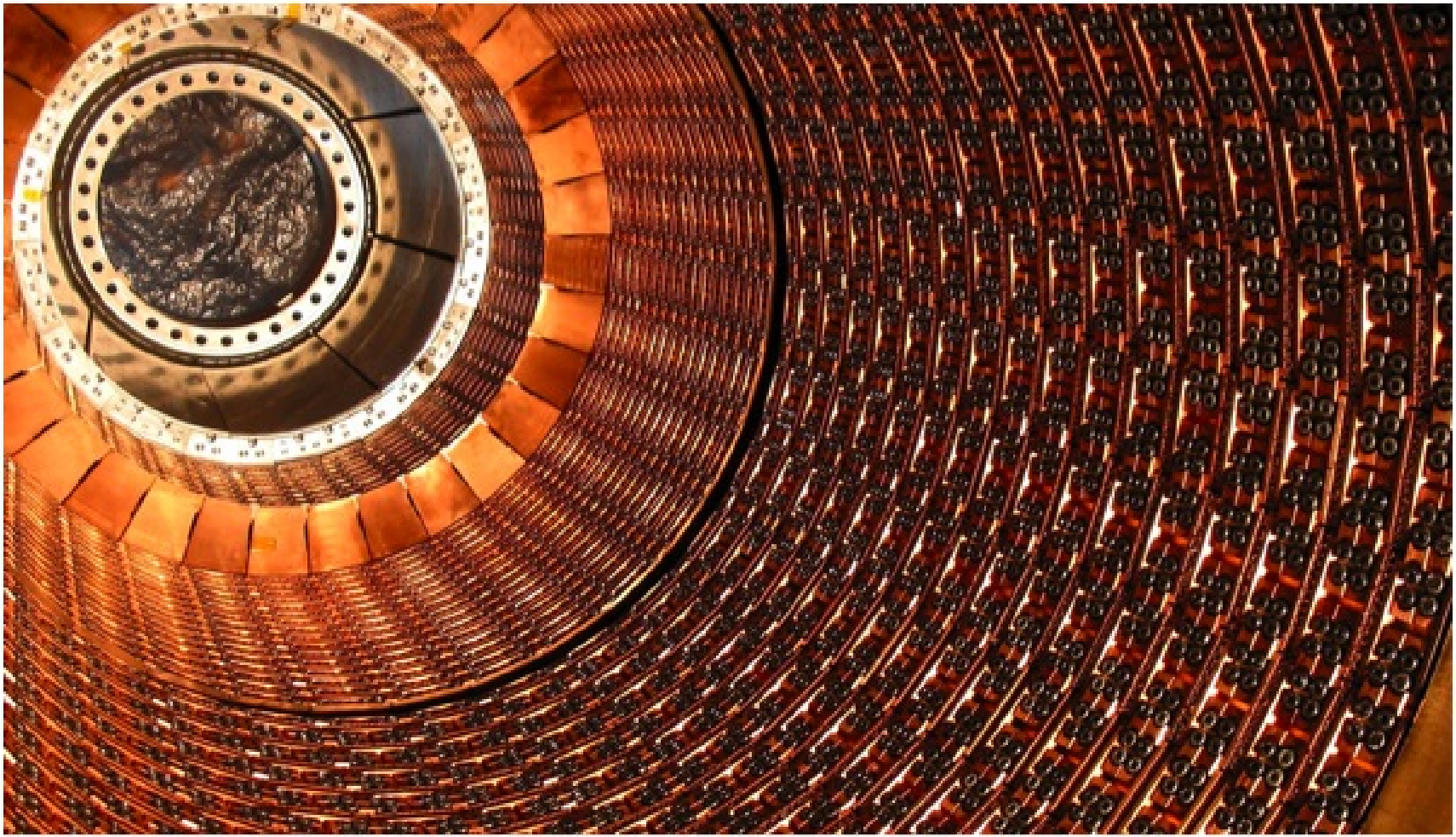
THE ATLAS DETECTOR – WE BUILD BIG DETECTORS TO STUDY COLLISIONS

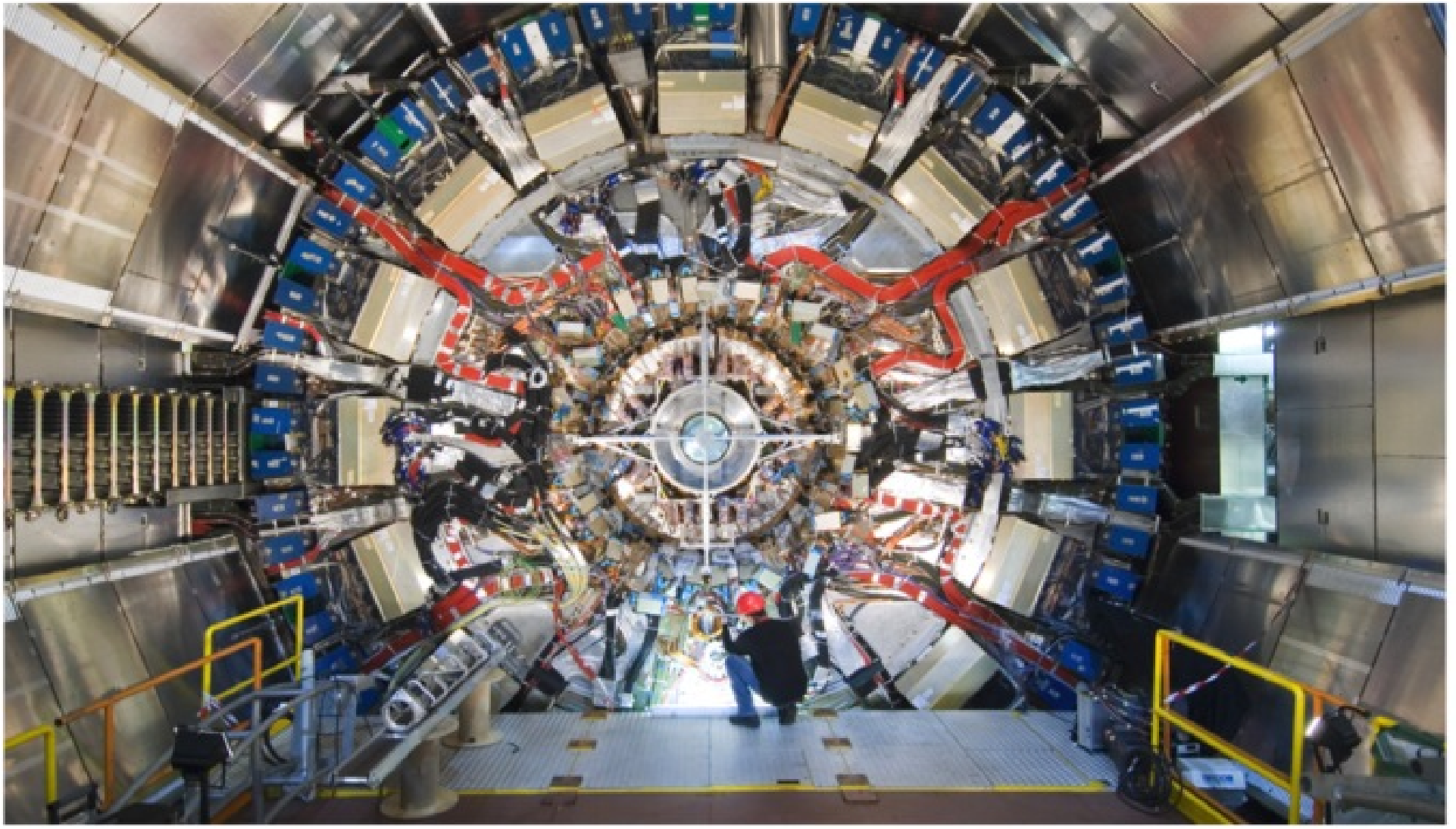


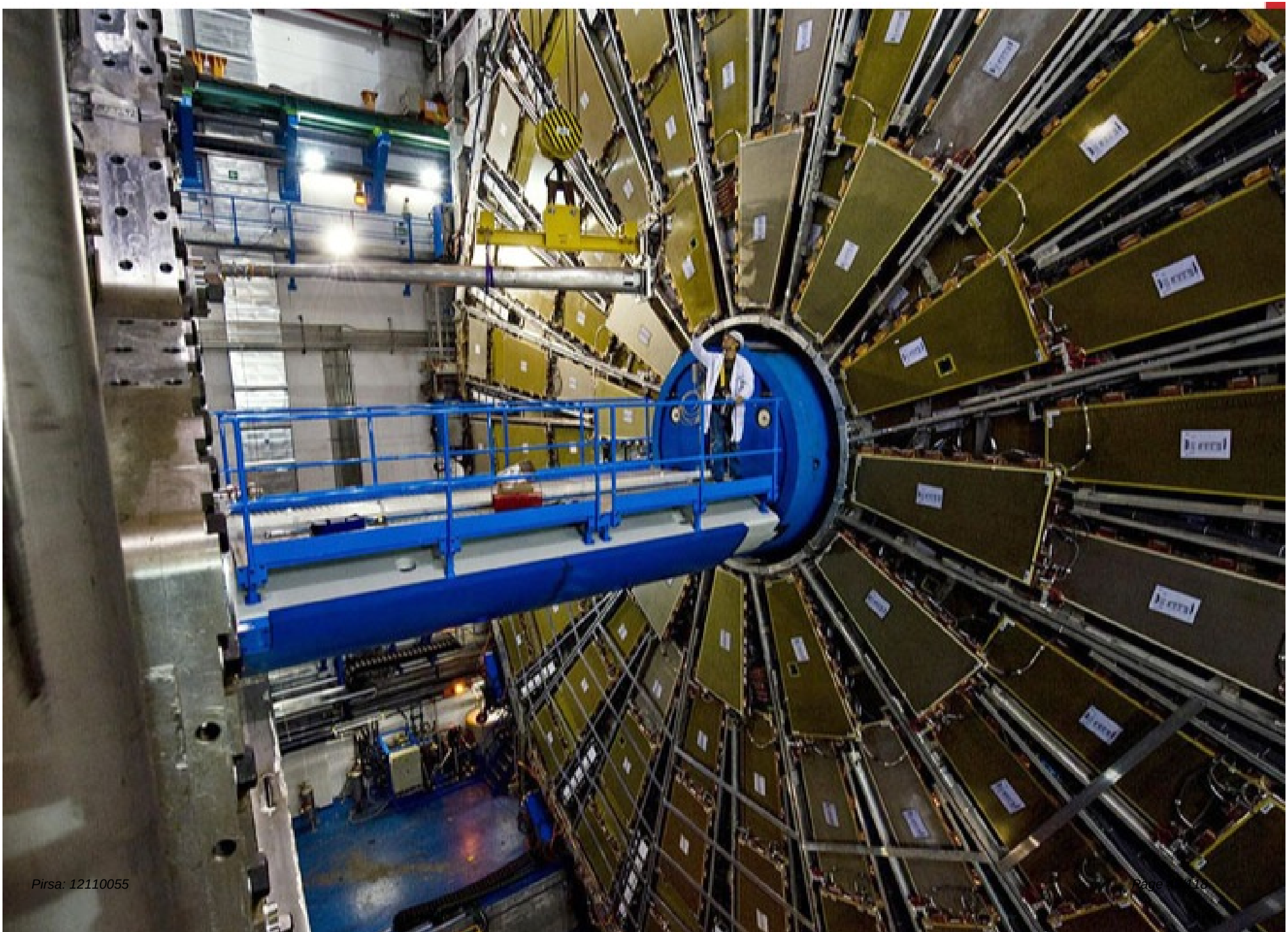
MUON TOROID STRUCTURE

MUON DETECTOR BEING LOWERED INTO THE EXPERIMENTAL HALL

INSIDE OF THE LIQUID ARGON CALORIMETER







ATLAS Collaboration

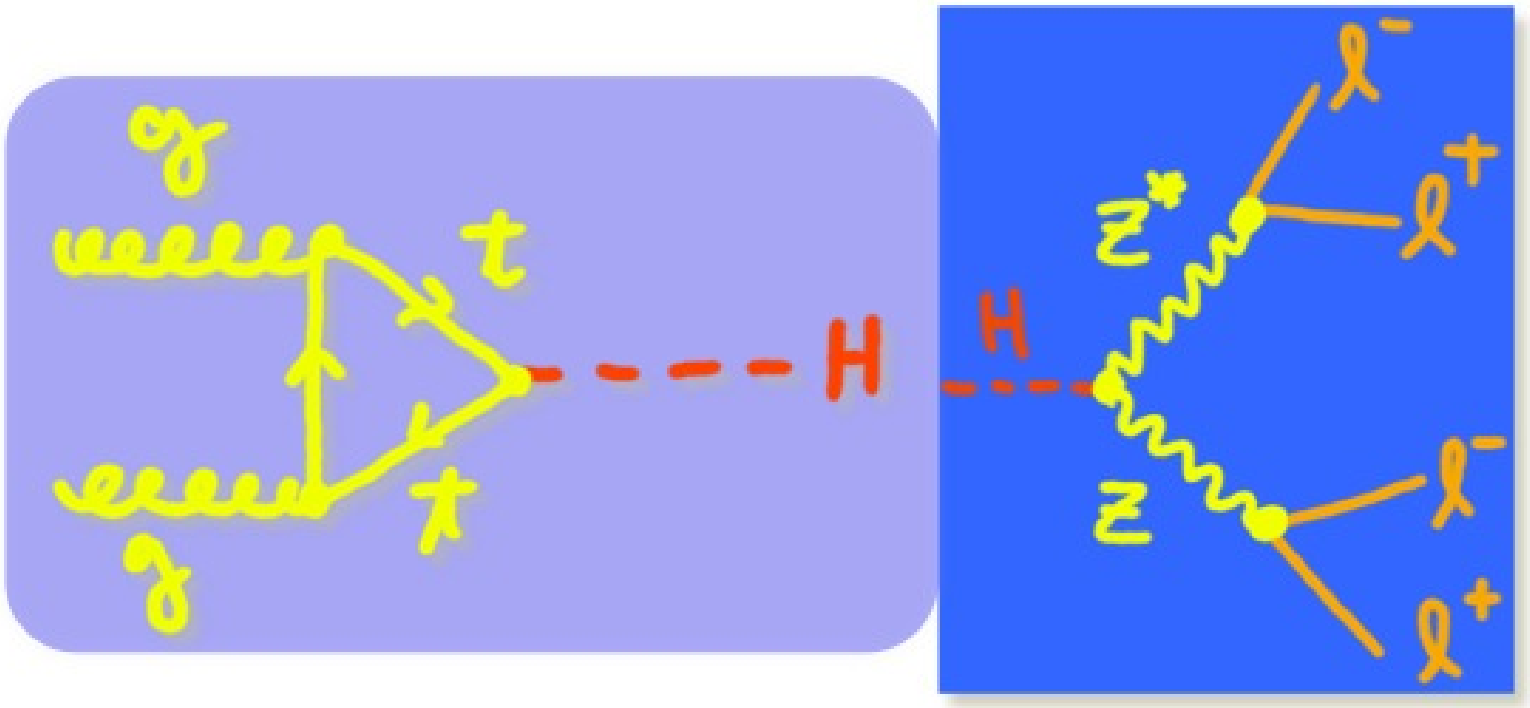
~ 3000 scientists from 174 institutions and 38 Countries

4 experiments

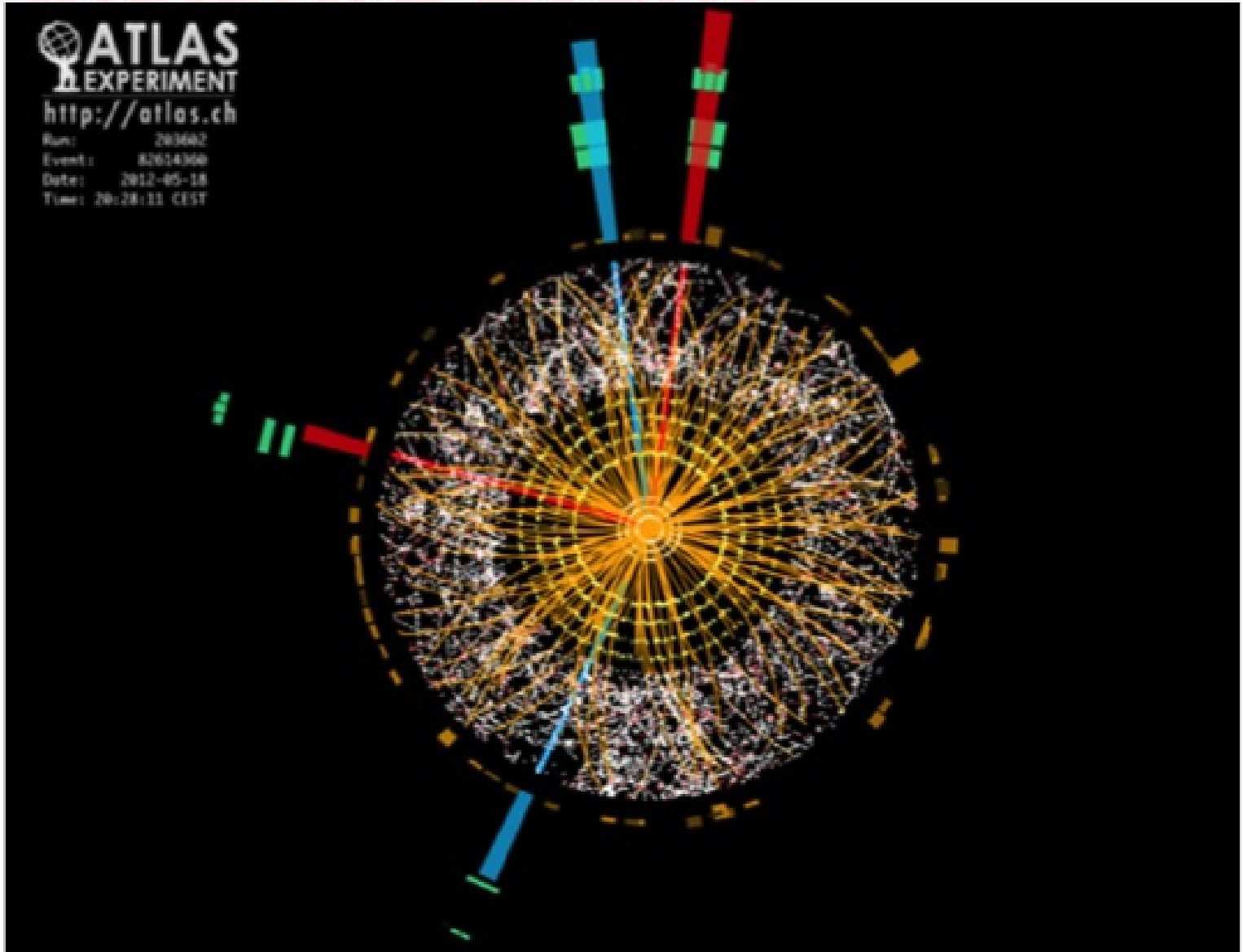
Each democratically run

Multipurpose experiments

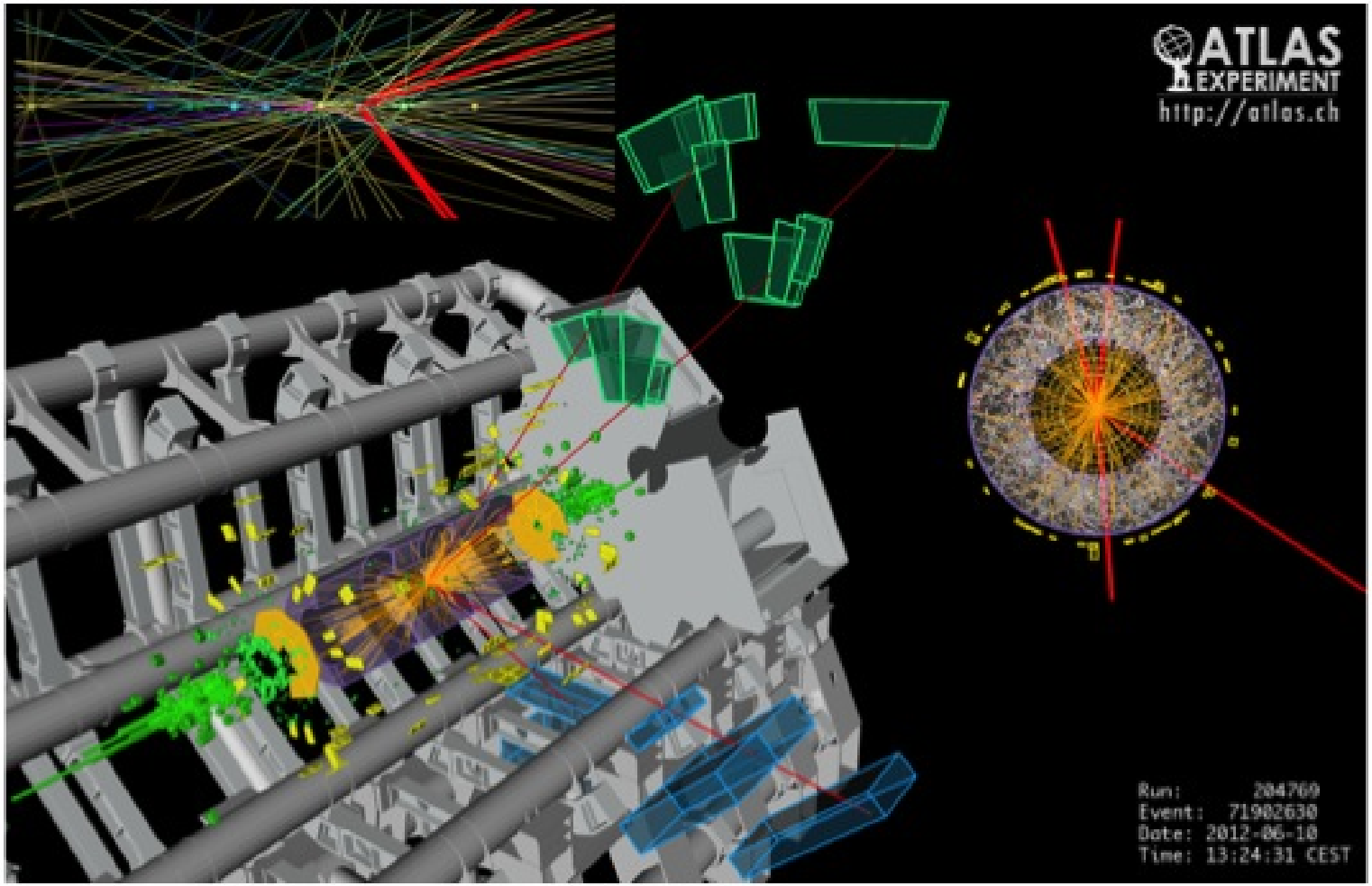
SO EVERYTHING NOT FORBIDDEN IS COMPUSLORY

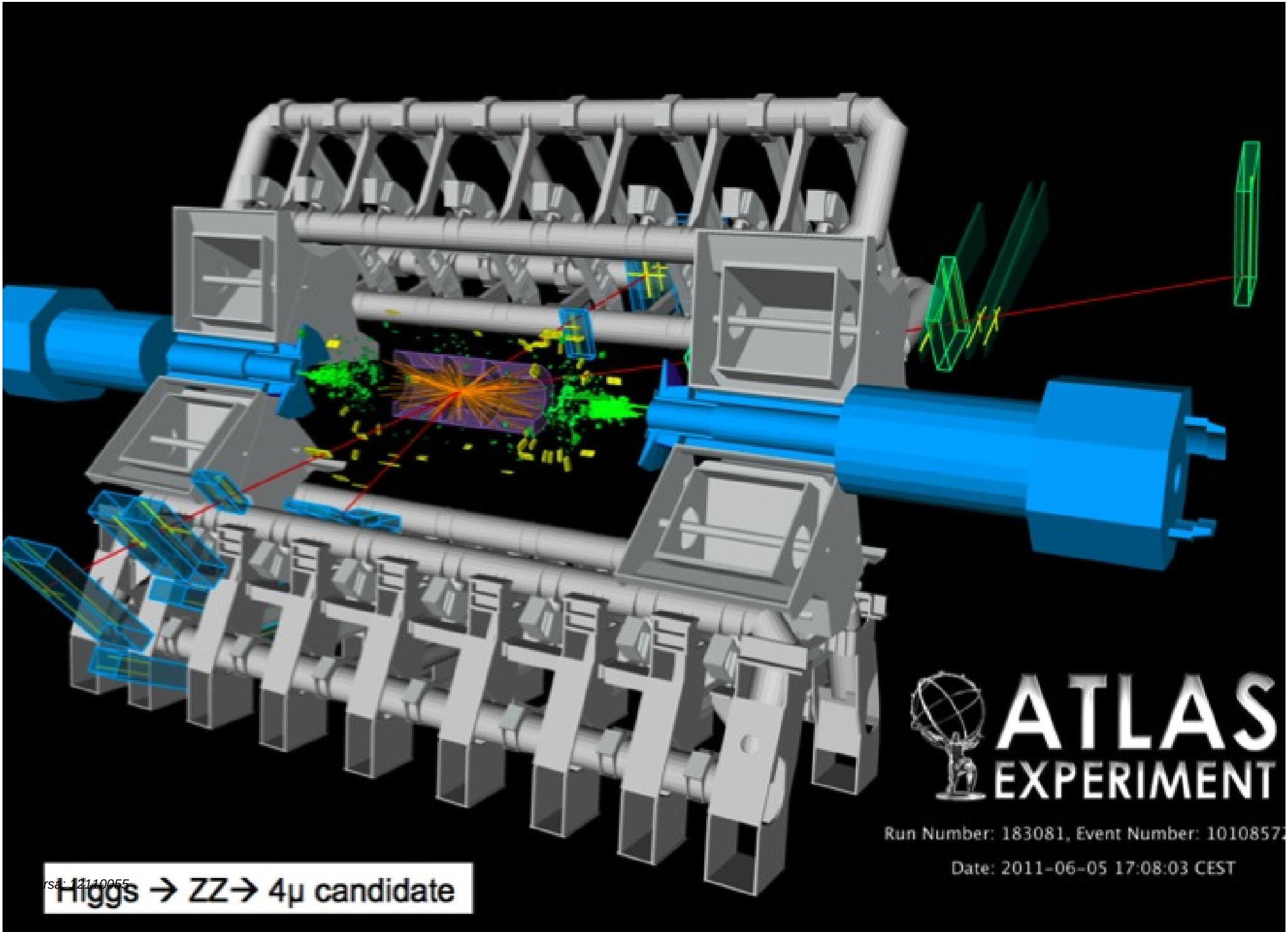


ATLAS HIGGS TO 4 LEPTON CANDIDATE EVENT

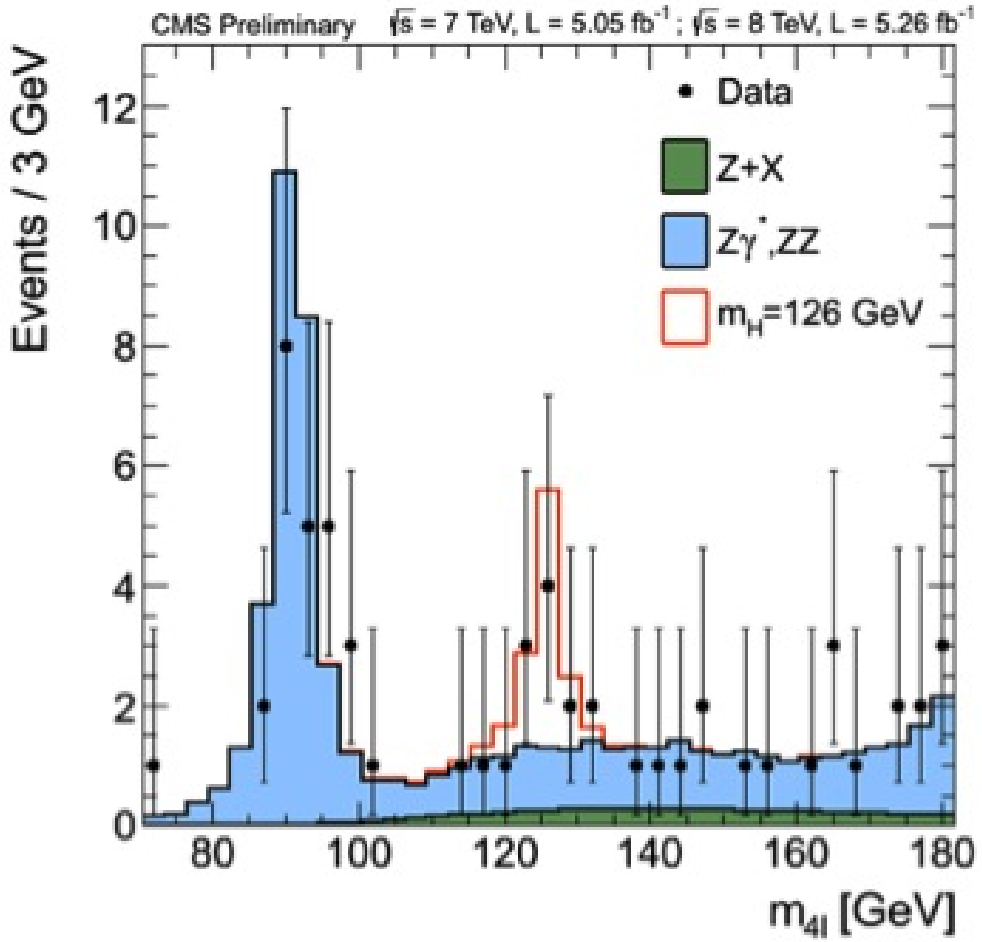


HIGGS TO 4 MUONS CANDIDATE



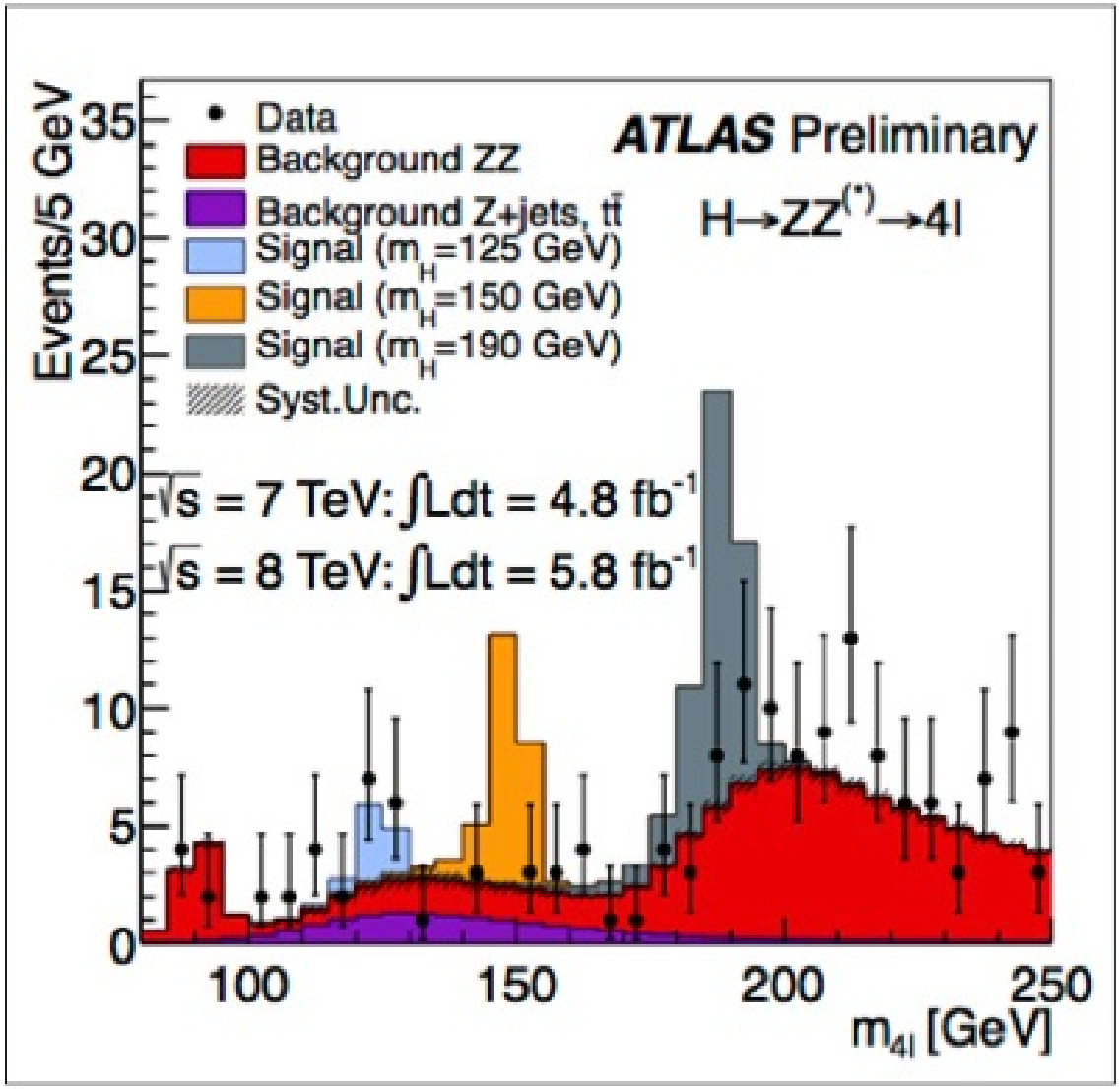

ATLAS
EXPERIMENT
Run Number: 183081, Event Number: 10108572
Date: 2011-06-05 17:08:03 CEST
Higgs → ZZ→ 4μ candidate

MASS OF ZZ DATA CMS



MASS OF ZZ* GeV

HIGGS TO ZZ* DATA ATLAS



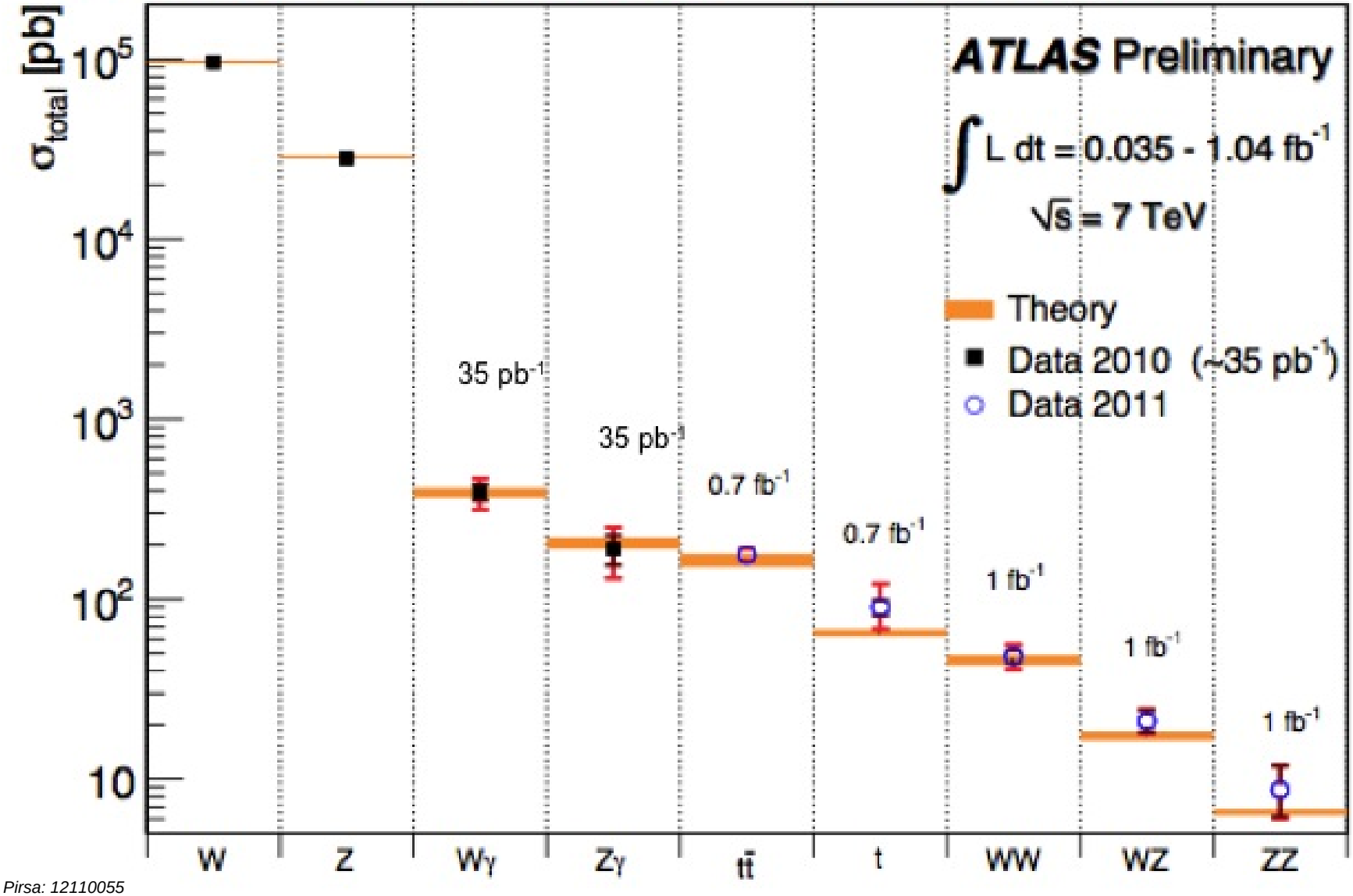
MASS OF ZZ

WHY IS IT SO HARD? BACKGROUNDS

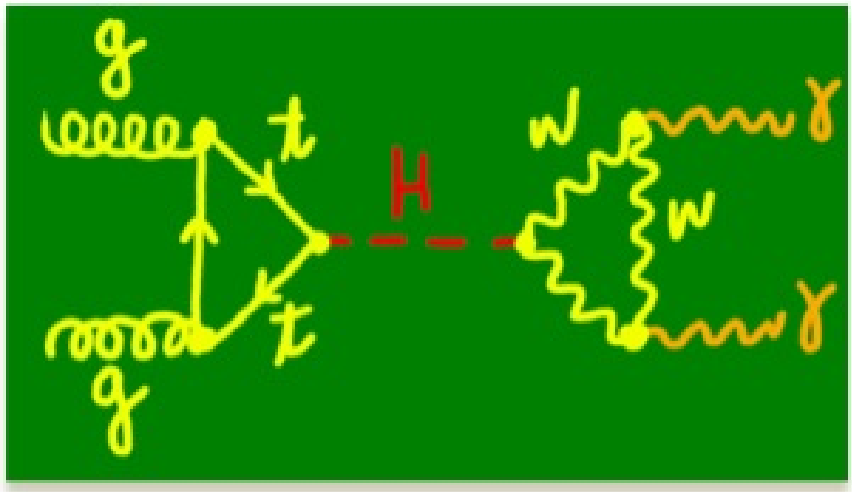
Since everything that can happen does, and most of it much more than Higgs production, if it has the same final state, it is a background.

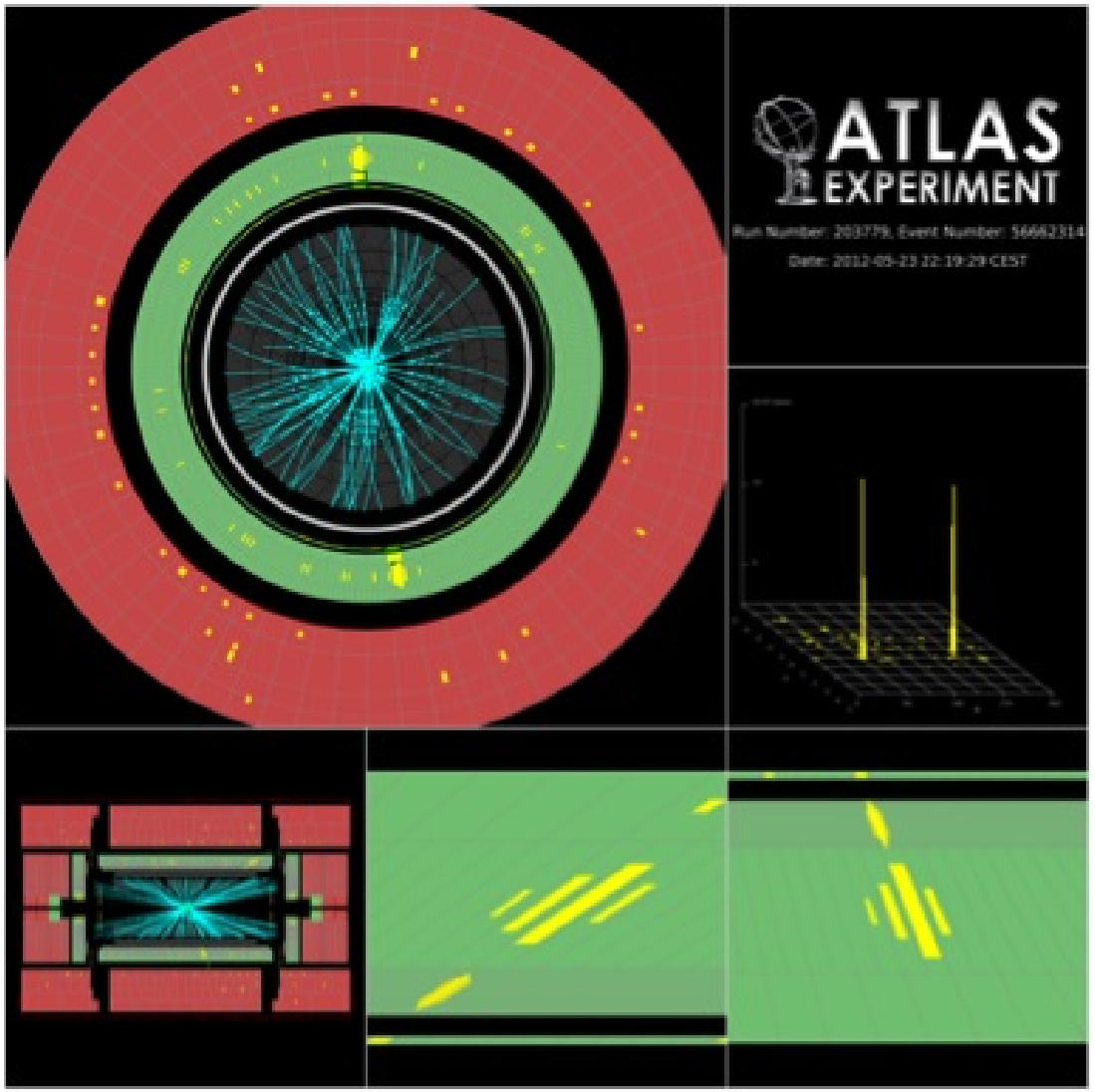
wineglass

SM CROSS SECTIONS MEASURED BY ATLAS - ALL "SPOT ON"

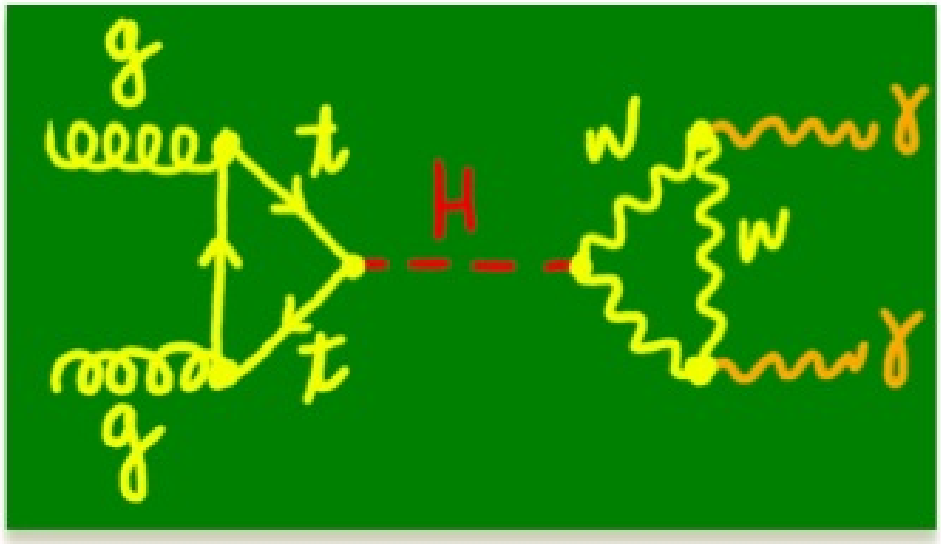


ANOTHER DECAY CHANNEL CANDIDATE HIGGS→PHOTON PHOTON

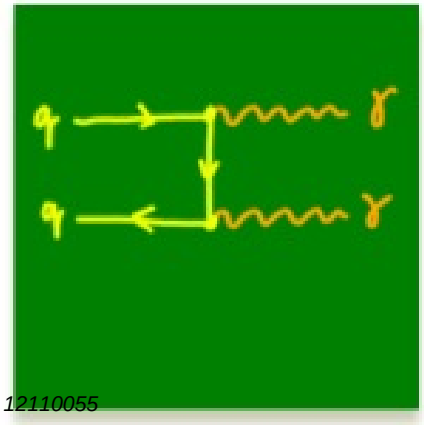


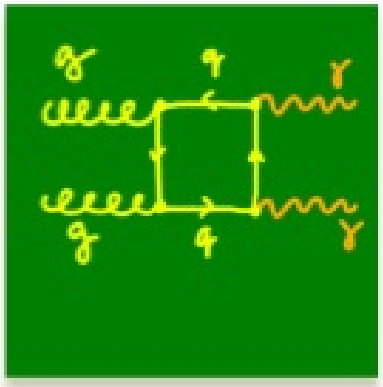


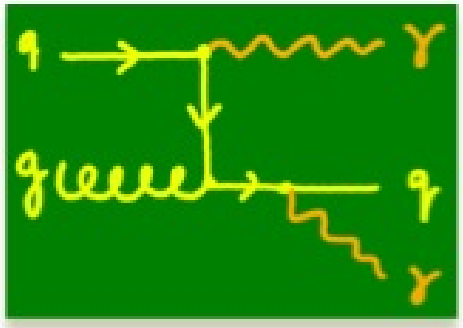
H → γγ



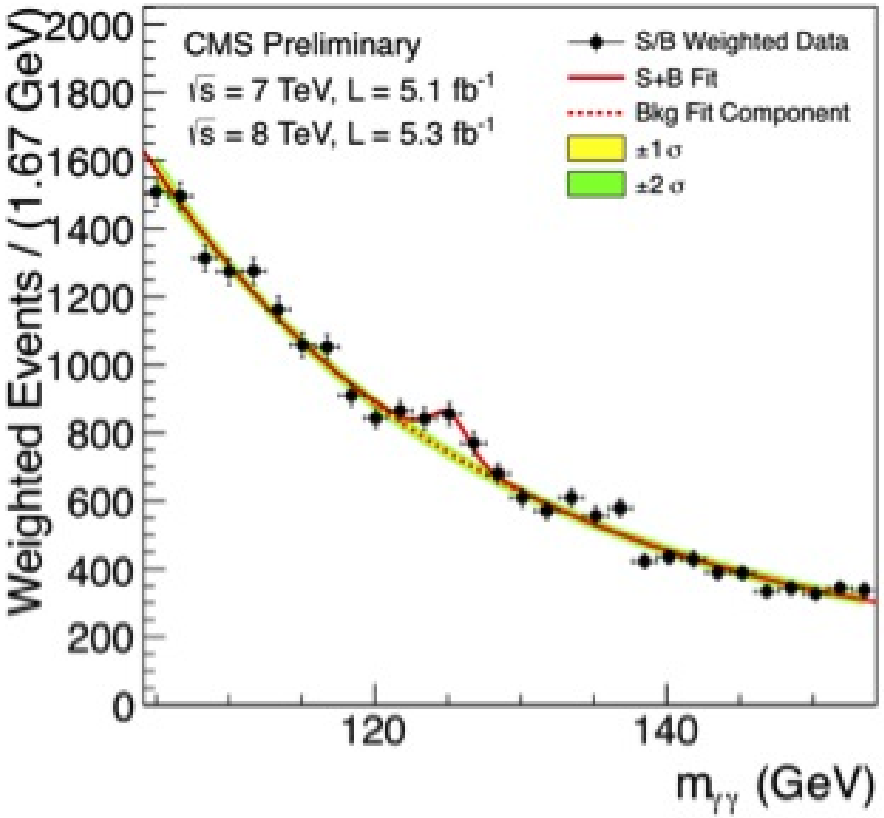
BACKGROUNDS



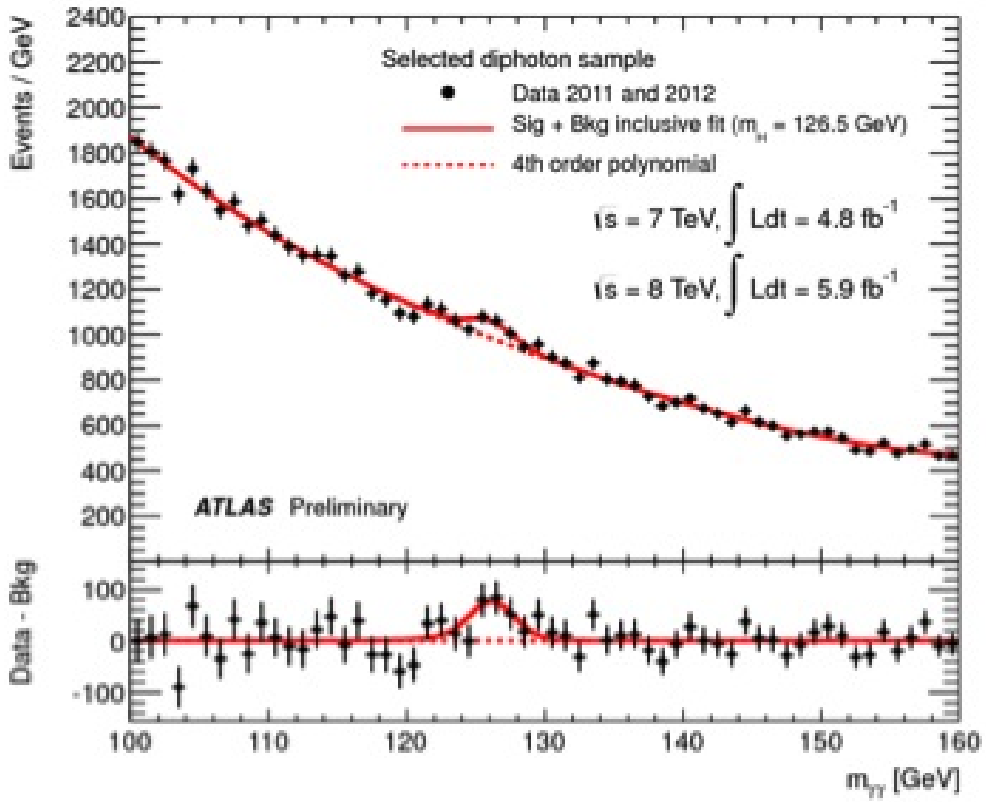




H→PHOTON +PHOTON (CMS+ATLAS)

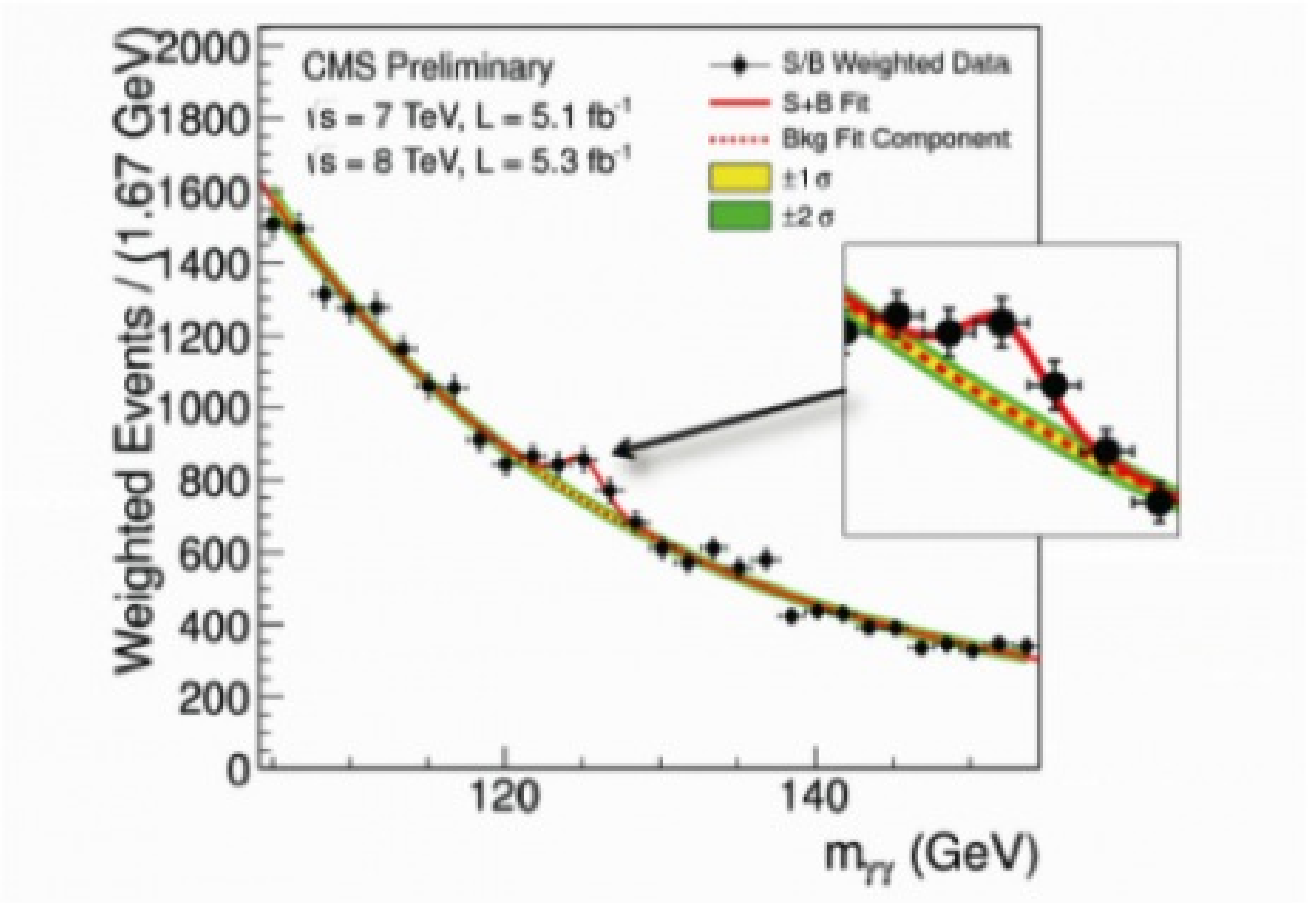


CMS MASS



ATLAS MASS

DATA CMS H ->γγ



MASS of γγ

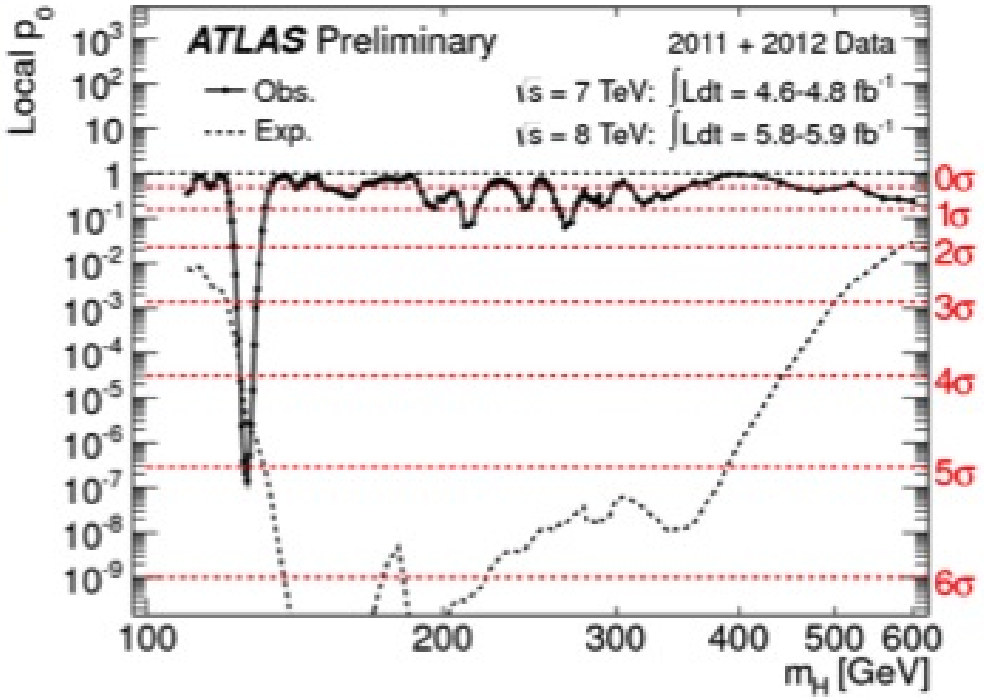
HOW WE QUANTIFY THE EXCESS

What is the probability to see what we see if the Higgs does not exist?

For a given number of events, the p-value is:

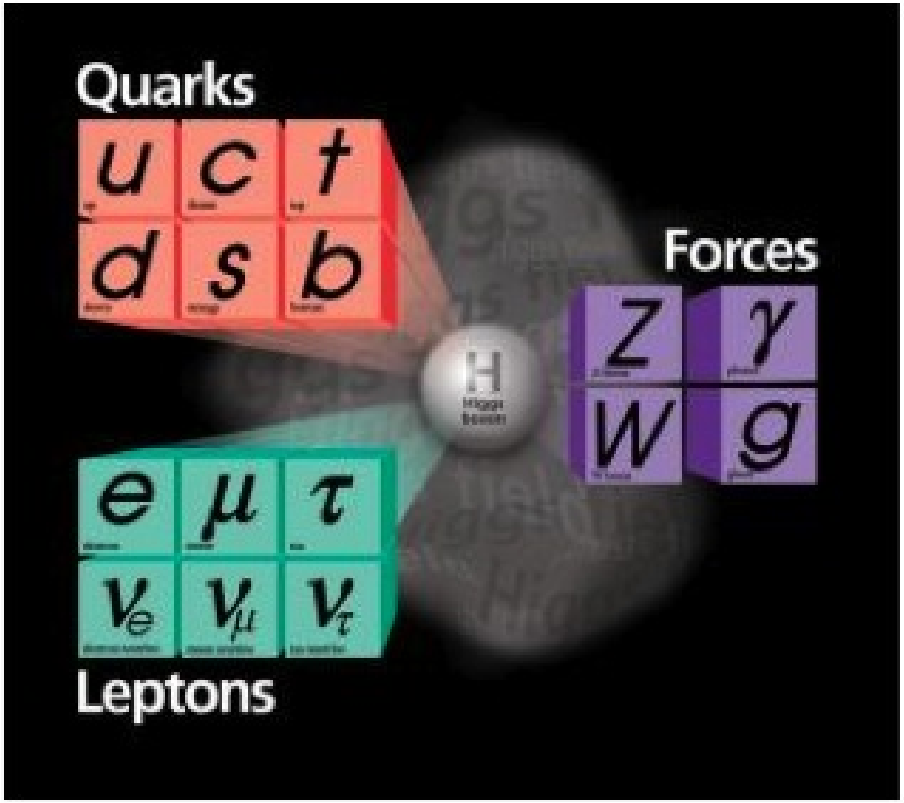
*"The probability to observe as many events as this number (or even more) under the assumption that the Higgs does **not** exists"*

→ Can be translated into a (gaussian) significance

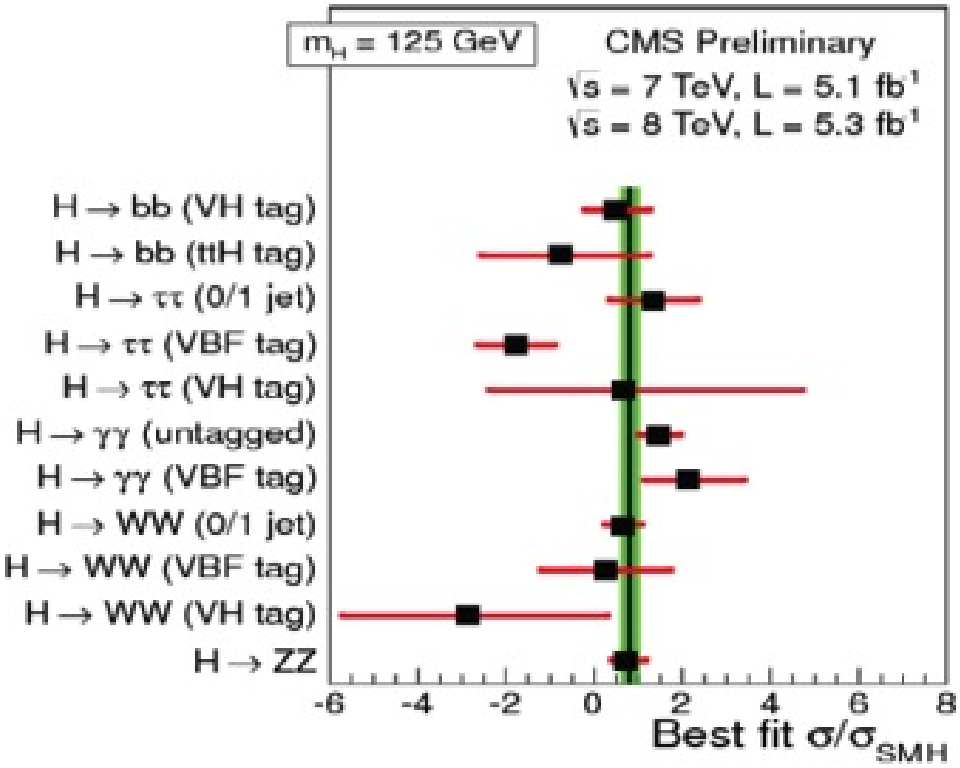


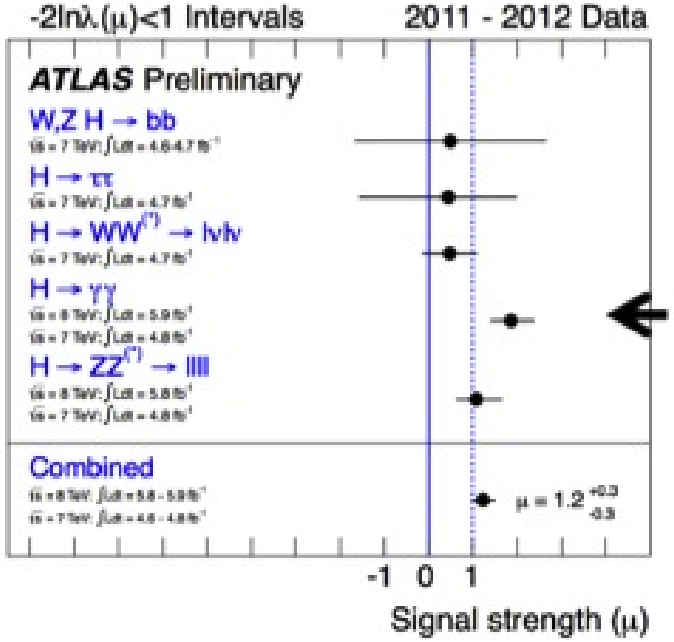
At 125 GeV probability is < 10^{-7}

WE FOUND A PARTICLE: IS IT THE HIGGS? IF SO WHICH HIGGS IS IT? → MORE DATA, MORE WORK, MORE FUN



DOES THE SHOE FIT?





WHAT CAN WE MEASURE ABOUT THE HIGGS WITH MORE DATA AT LHC AT HIGHER ENERGY (14 TEV) AND 2X HIGHER LUMINOSITY?

HIGGS MASS TO 2%

HIGGS WIDTH TO 50%

HIGGS TO FERMION COUPLINGS TO 30%

HIGGS COUPLINGS TO WW, ZZ TO 30%

HIGGS COUPLING TO HIGGS???

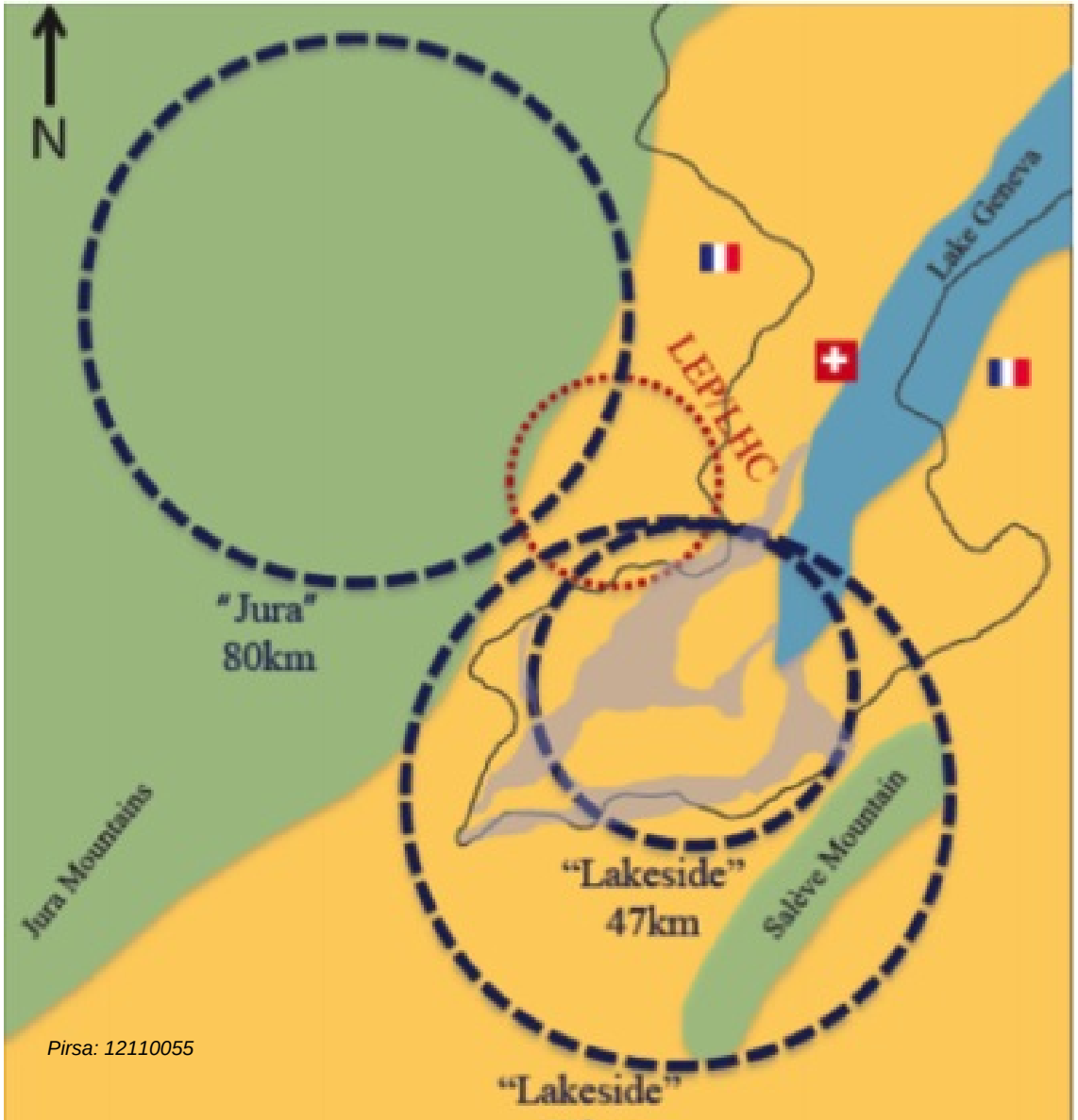
SPIN: RULE OUT SPIN 1, 2

WE NEED TO STUDY HIGGS – XX (X IS DARK MATTER)

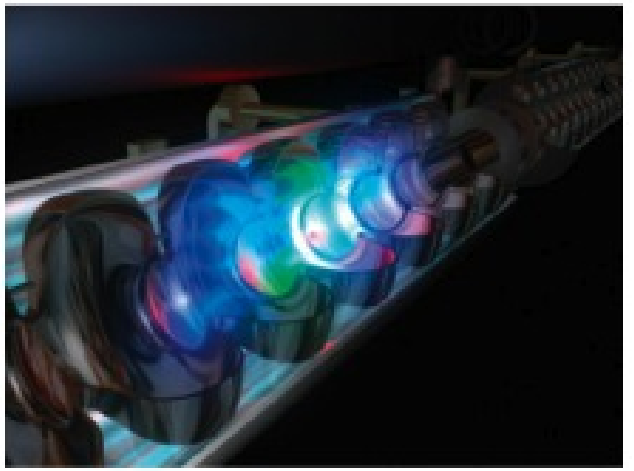
LOOK FOR NEW RESONANCES

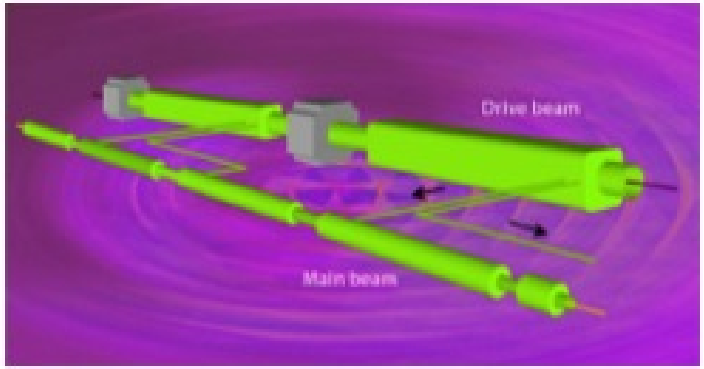
POSSIBLE FUTURE ACCELERATORS

BIG LHC

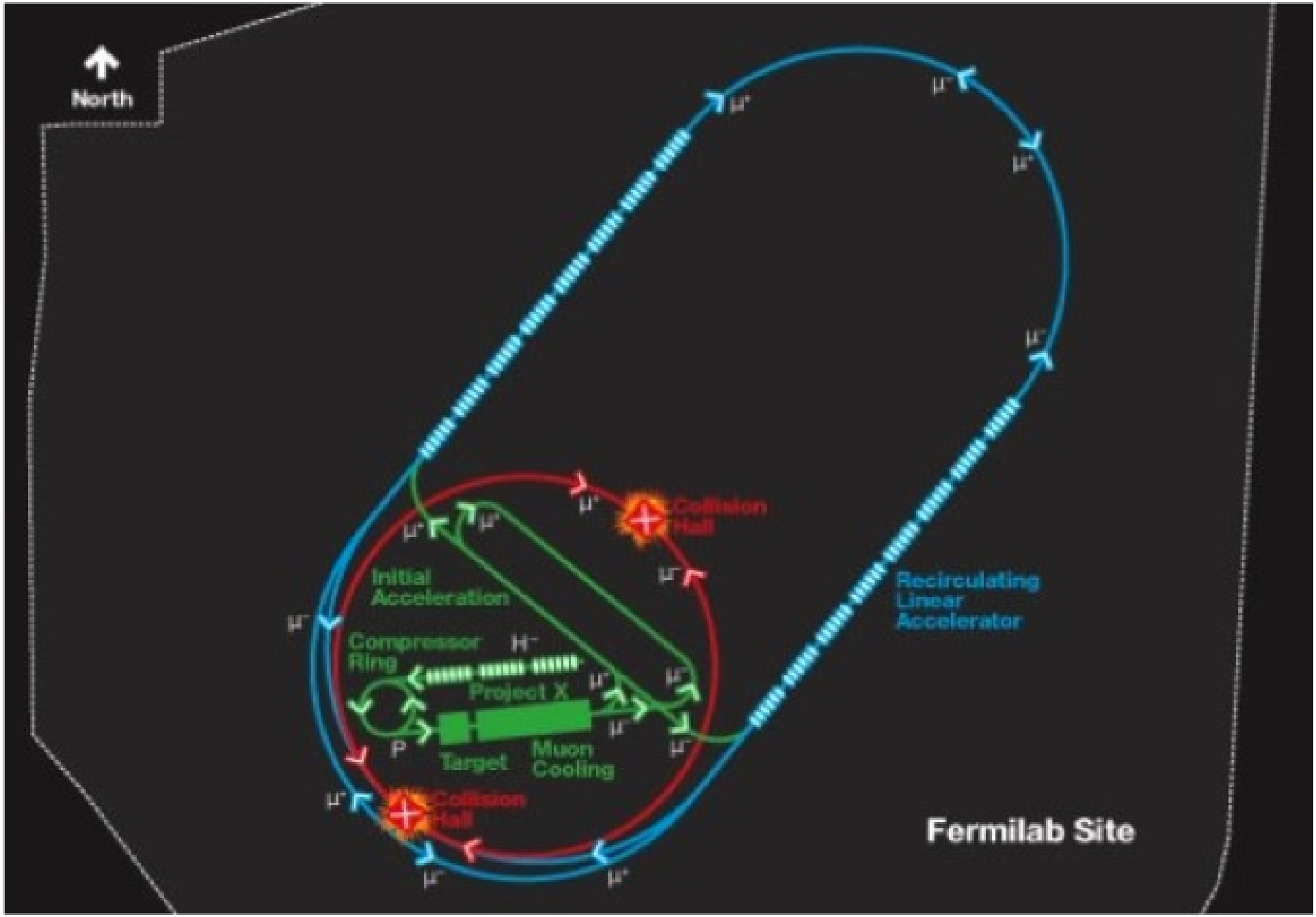


ILC





CLIC



MUON COLLIDER

DREAM OR NIGHTMARE?

We found something at 125 GeV

And it is probably the Higgs –> it is a dream for people of all ages

We can have total fun measuring everything we can at the LHC

Rule out infinitely many Beyond the Standard Model theories or NOT (extra dimensions, supersymmetry, etc)

Make up new BSM theories

Then build a new collider just to look at Higgs***

Then spend another 20 years measuring detailed aspects of the Higgs to see if there is hidden physics in the electroweak sector

It's lovely!

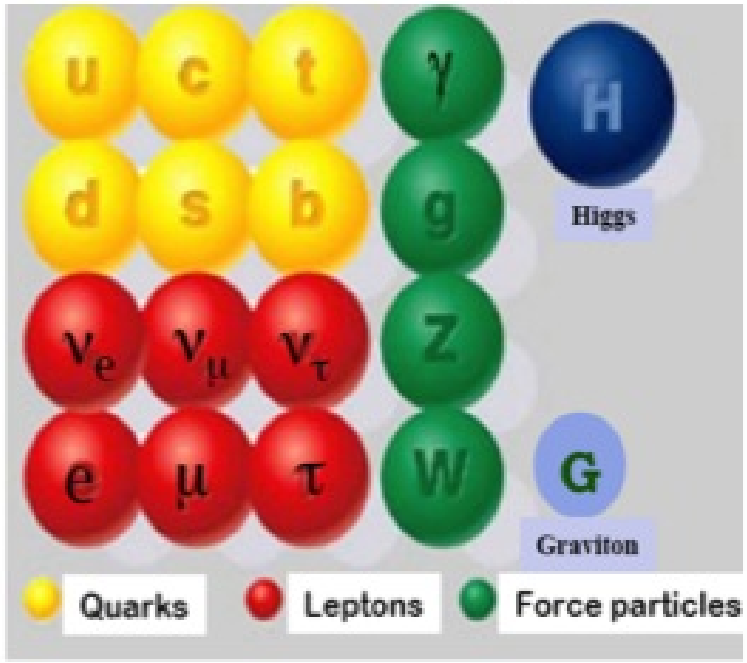
***If nothing else, no Supersymmetry, no other new stuff, no new collider?**

OR NO NEW ACCELERATOR – and then what.....

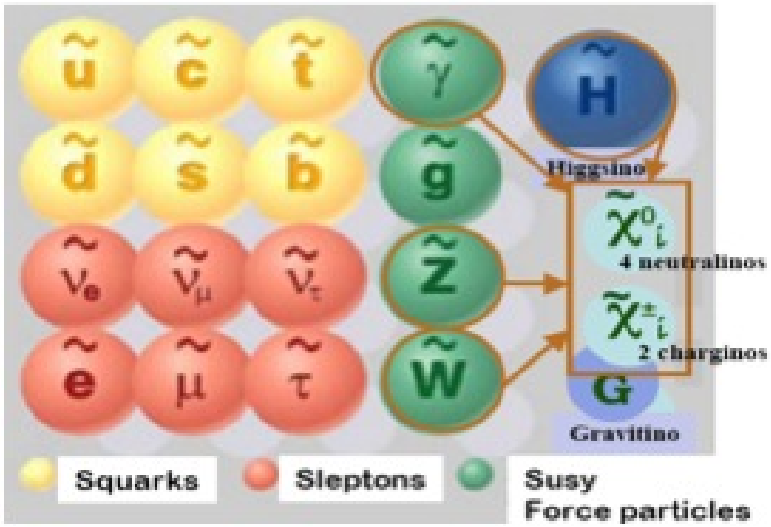
Extends the Standard Model by predicting a new symmetry
Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

SUPERSYMMETRY

Standard Model particles

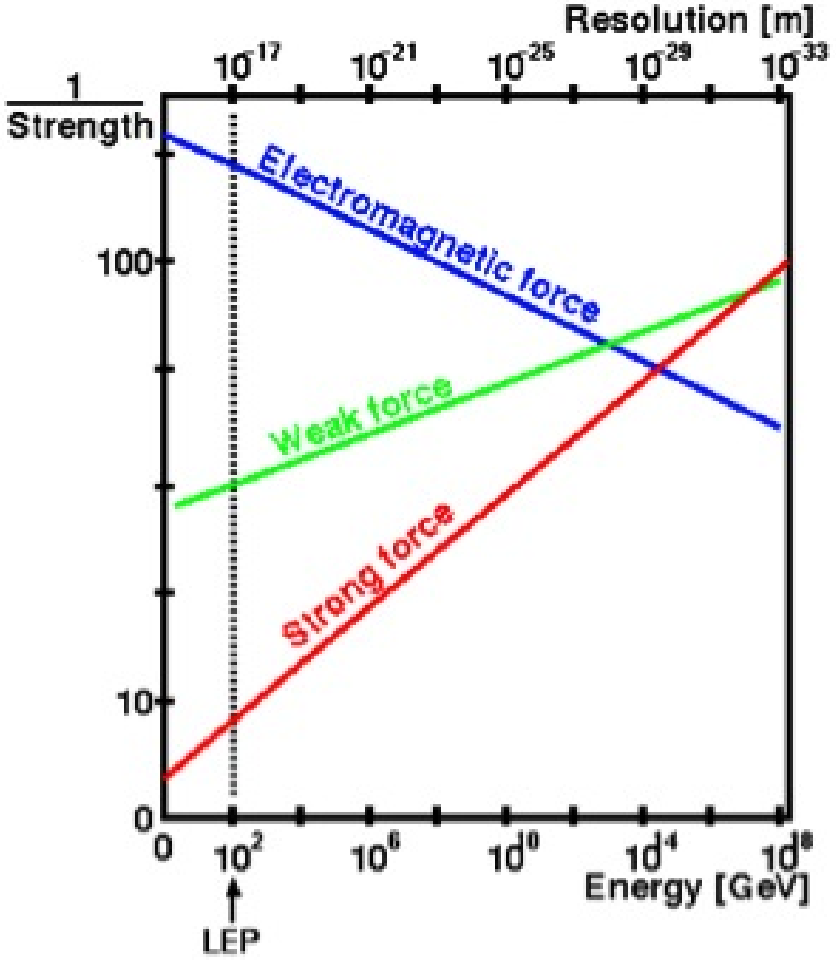


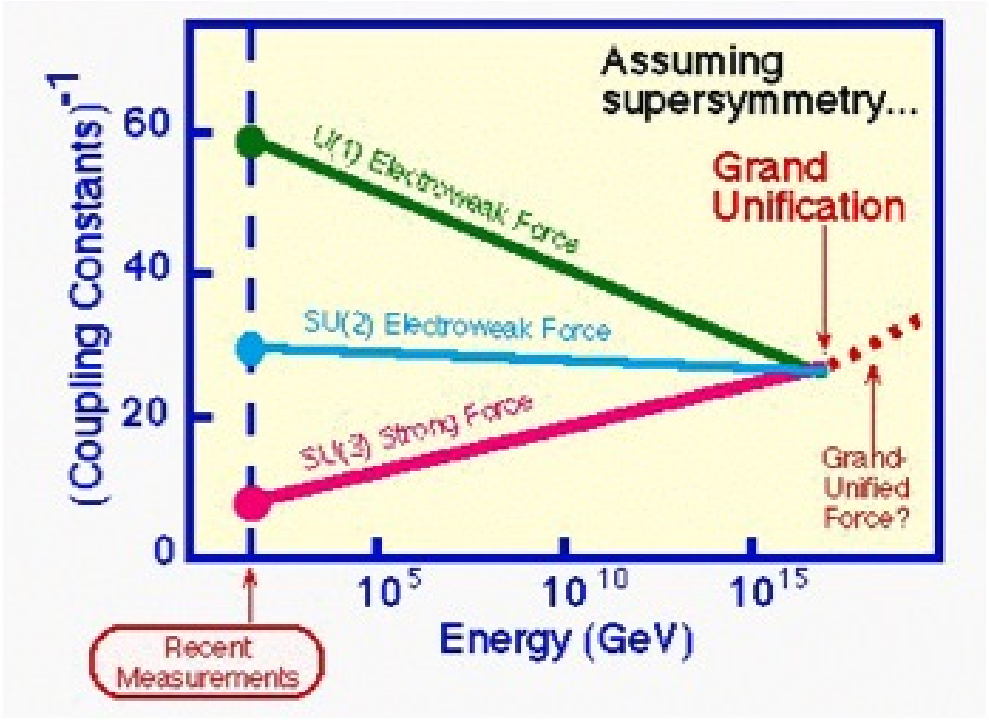
SUSY particles



New Quantum number: R-parity: $R_p = (-1)^{B+L+2s}$ = +1 SM particles
- 1 SUSY particles

SUPERSYMMETRY BRINGS US CLOSER TO GRAND UNIFICATION





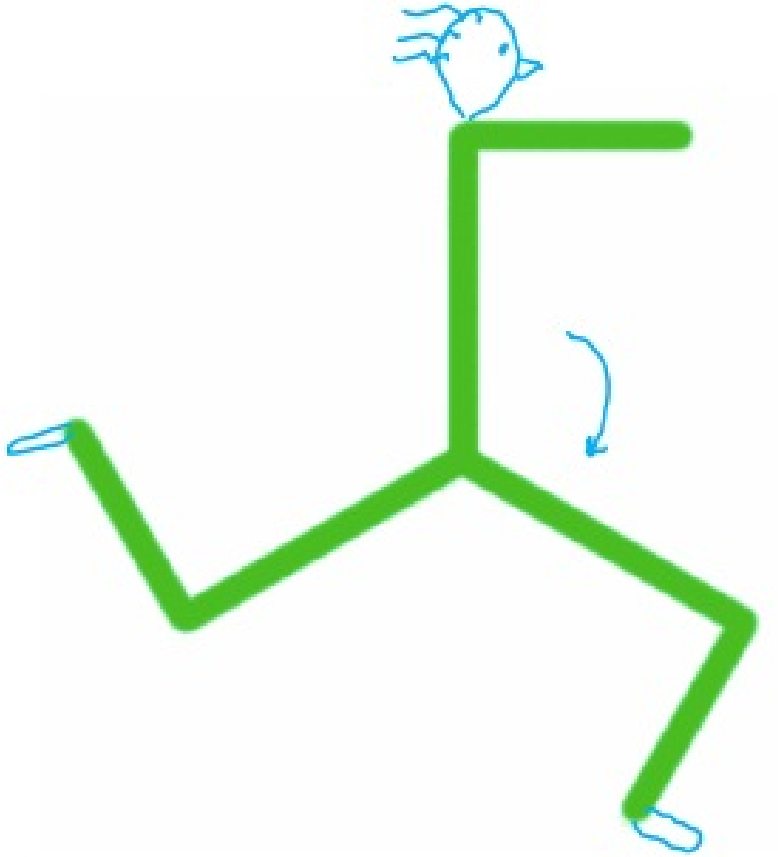
Coupling strengths of the three forces are the same at high energies

WHY DO WE DO IT

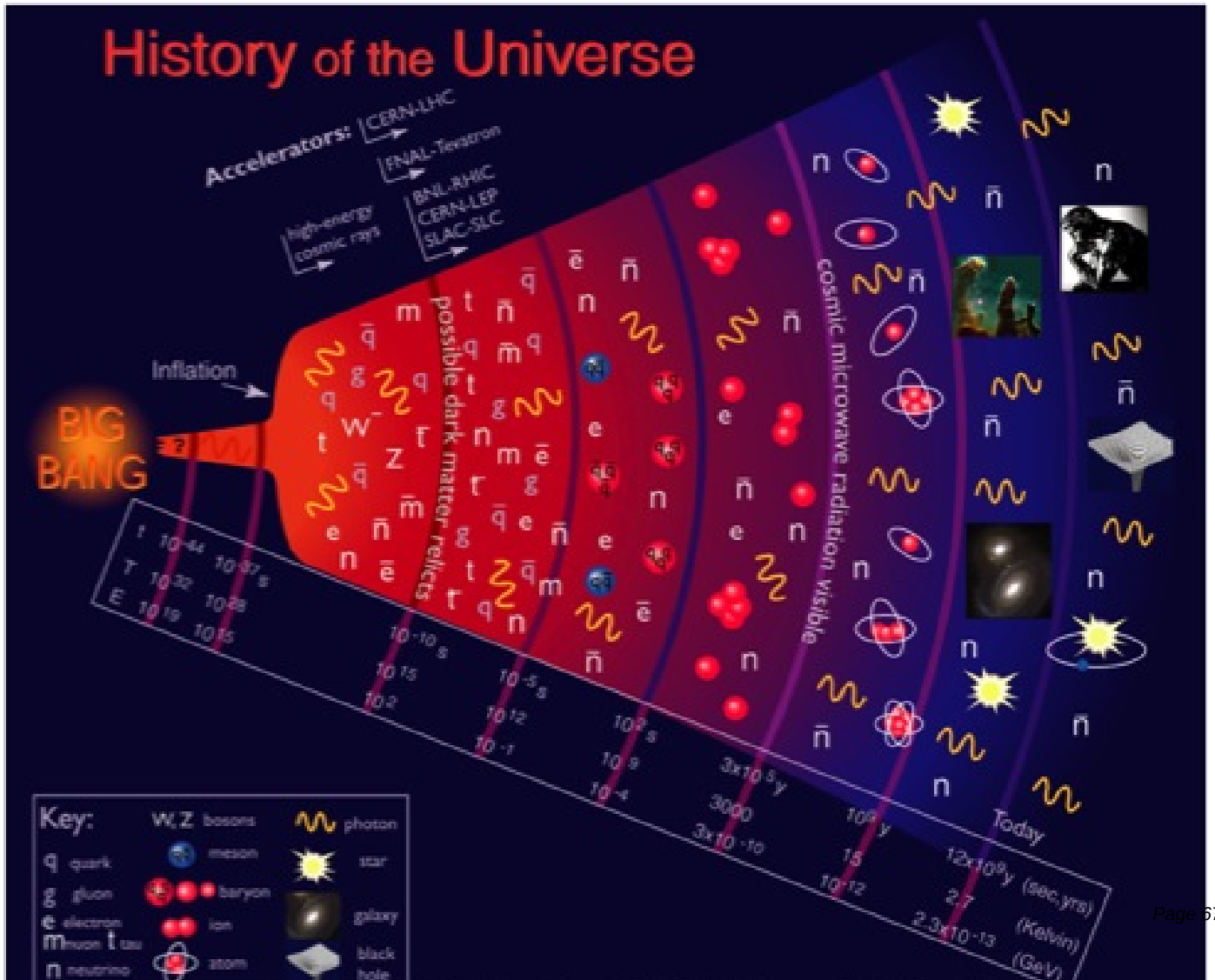
Understand interactions at small distance scales

Know the forces and the underlying symmetries

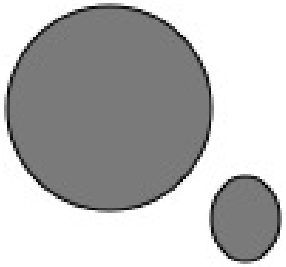
Understand structure of space- time (this includes understanding the big bang)



LOCATING OURSELVES IN HISTORY

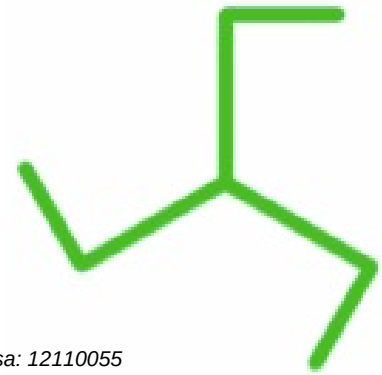


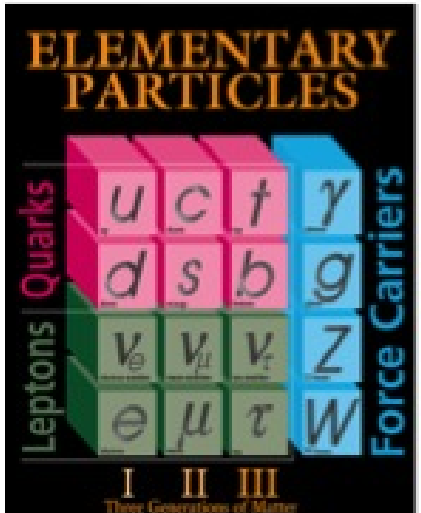
STUDY FORCES AT SMALL DISTANCES BETWEEN SMALL THINGS



Use Energy to create massive particles

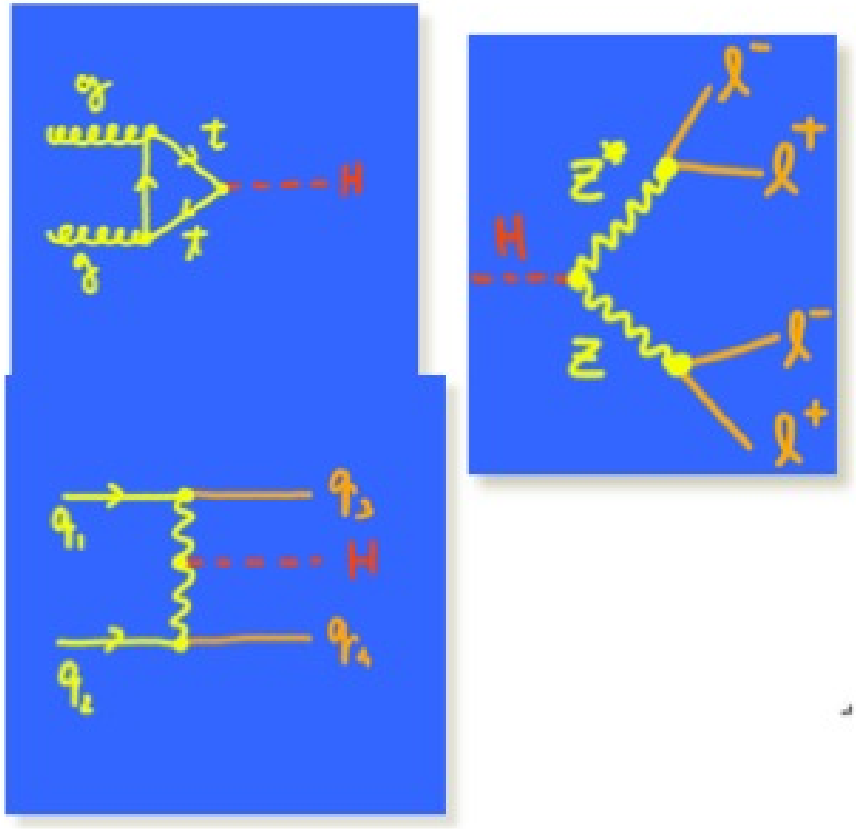
Study symmetries (mostly broken) of particles/anti-particles and of space-time





$H \rightarrow ZZ^{(*)} \rightarrow llll$

(eeee, μμμμ, eeμμ)



The Golden Channel

$110 < m_H < 600$ GeV

$\sigma \times BR \sim 2\text{-}5$ fb

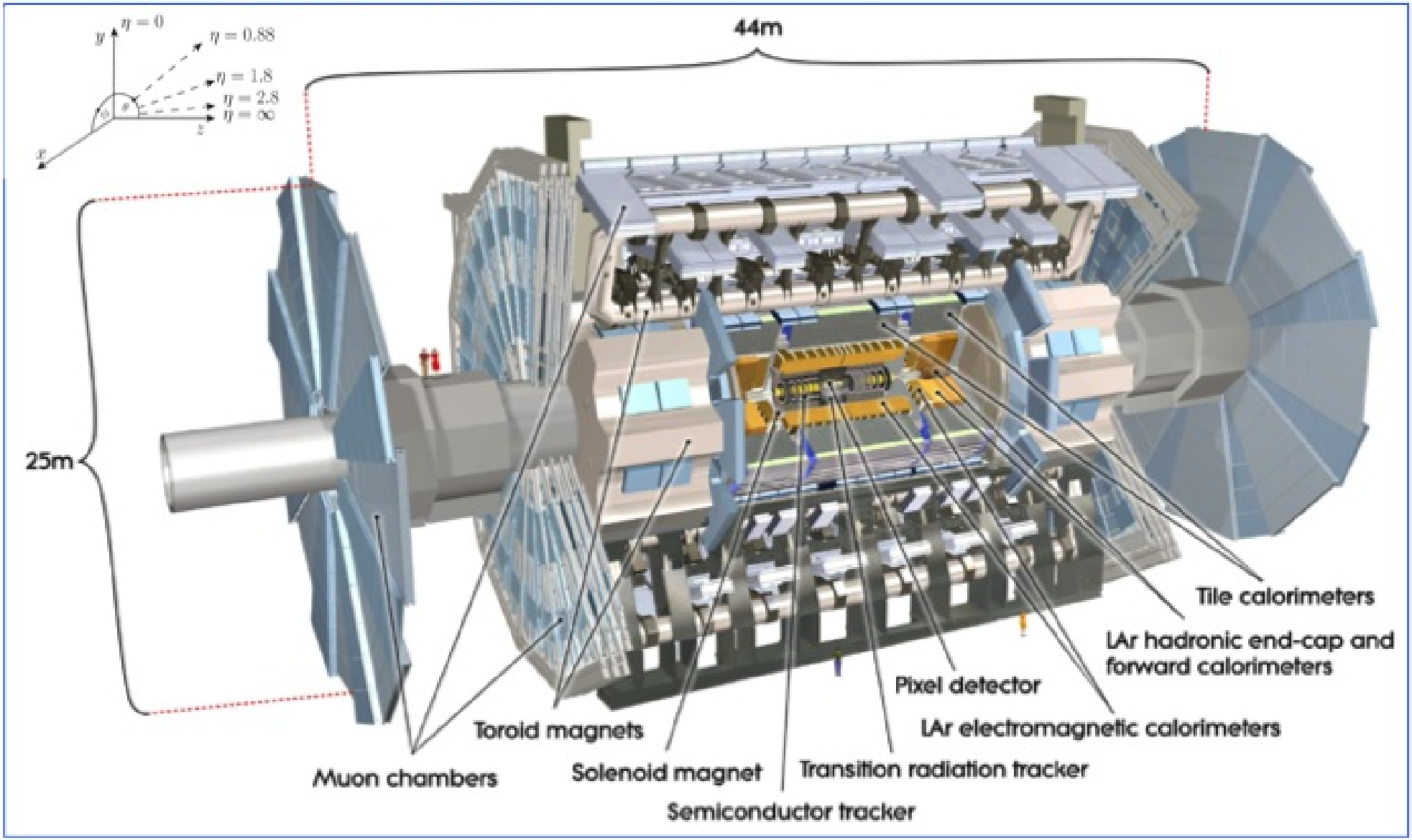
Mass can be fully reconstructed

- Events must cluster in a narrow peak

Low backgrounds: S/B ~ 1

- SM ZZ: irreducible background
- Analysis similar to SM ZZ

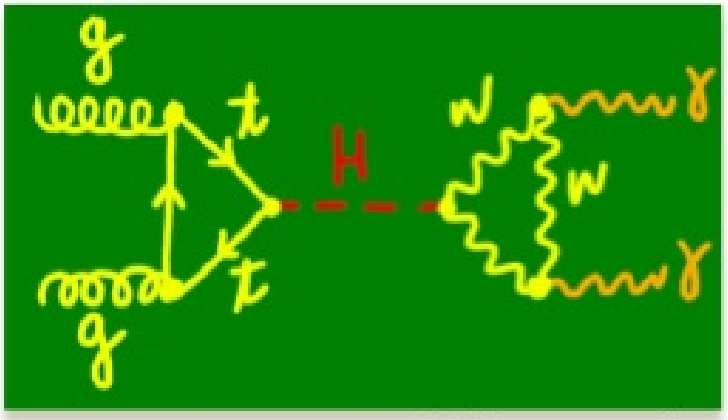
THE ATLAS

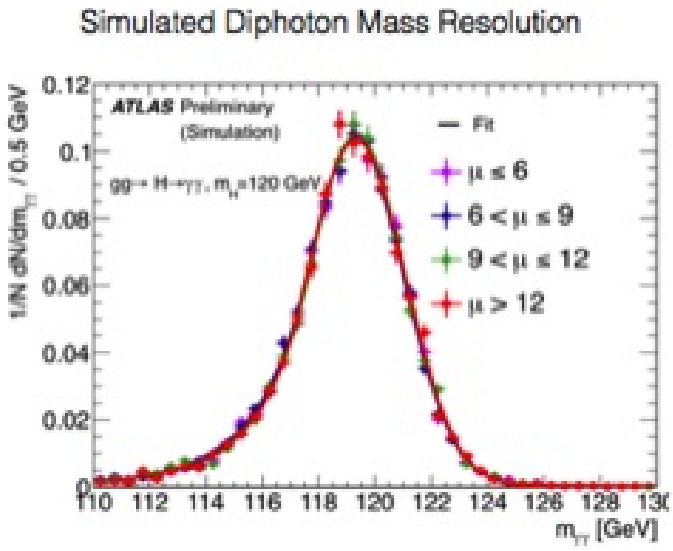

44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

Key channel for the low-mass Higgs

$H \rightarrow \gamma\gamma$

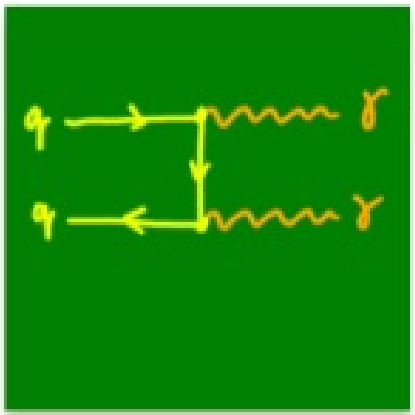
$110 < m_H < 150$ GeV

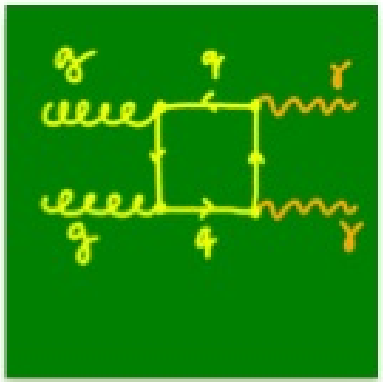


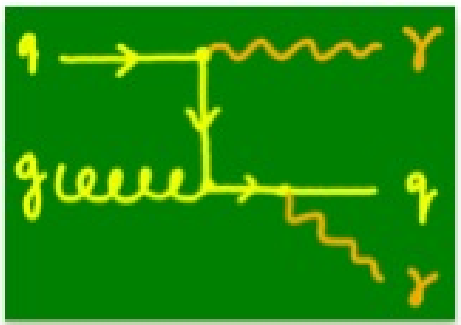


SM $\gamma\gamma$ production:

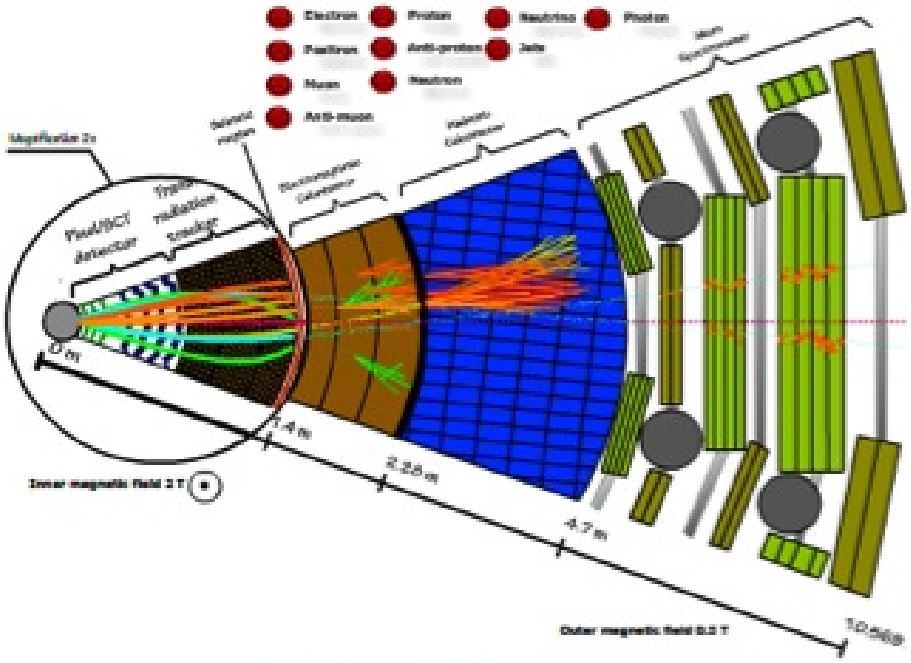
Irreducible, smooth background





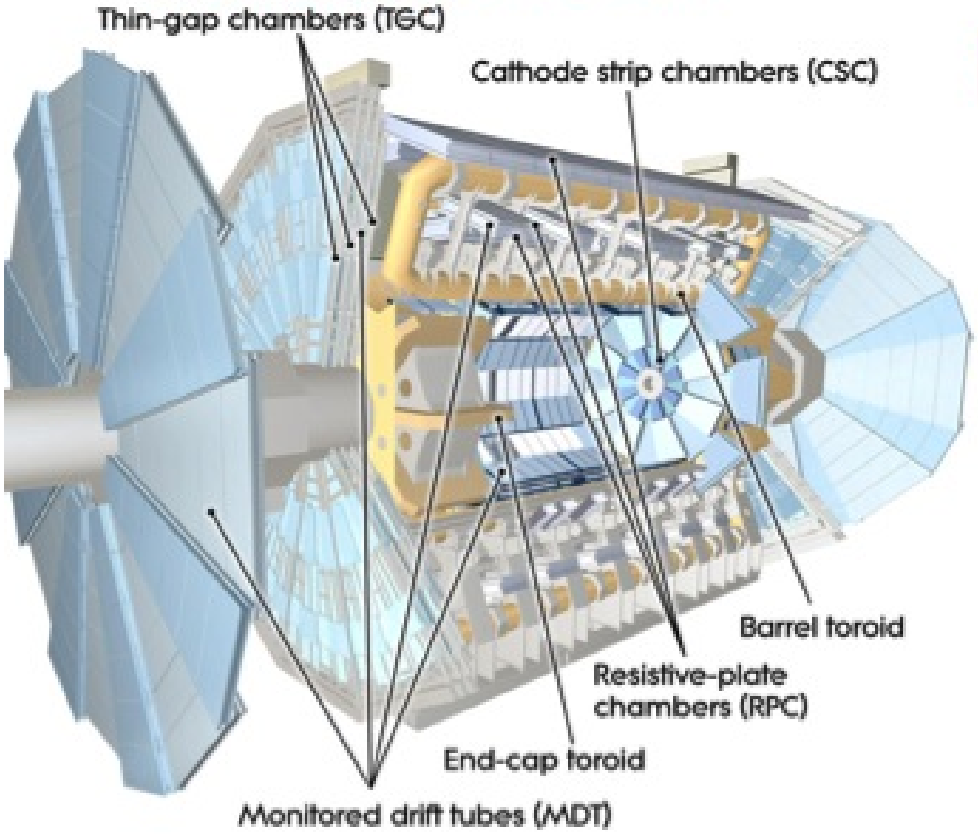


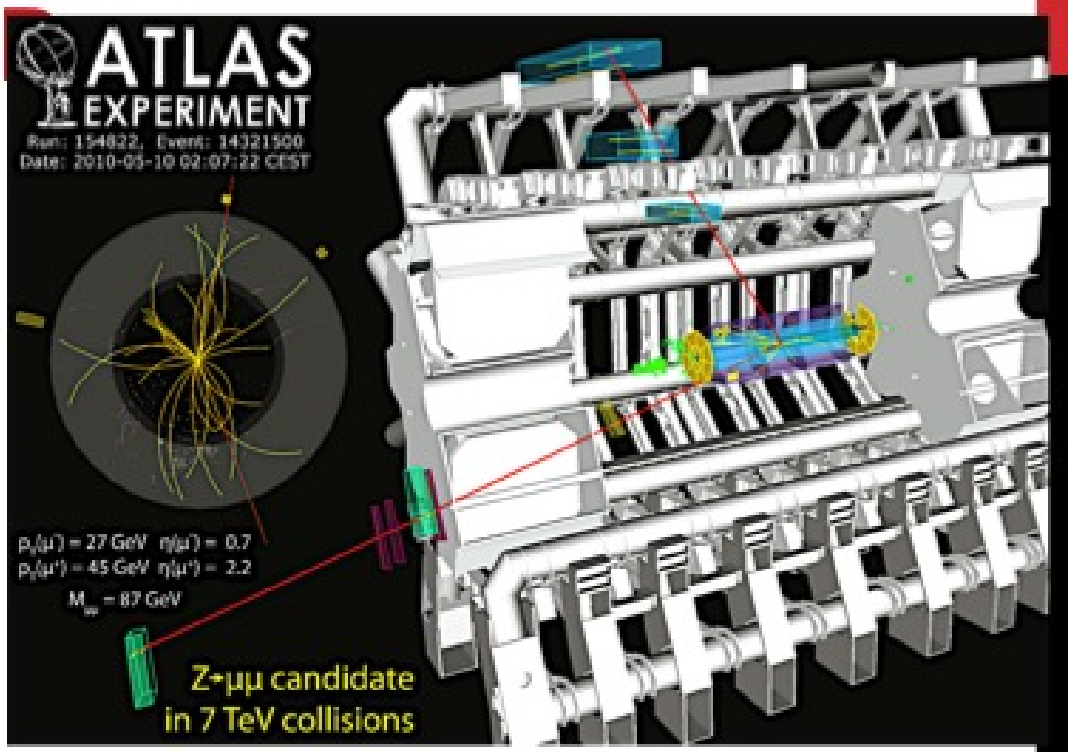
EVERYTHING IS IONIZATION



End view

THE MUON





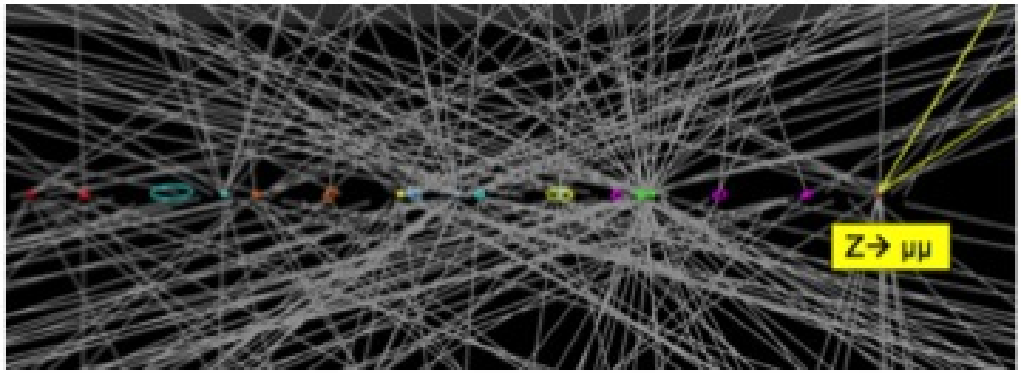
Muon Detectors

Precision tracking: Drift tubes (MDT) and Cathode Strip Chambers (CSC)

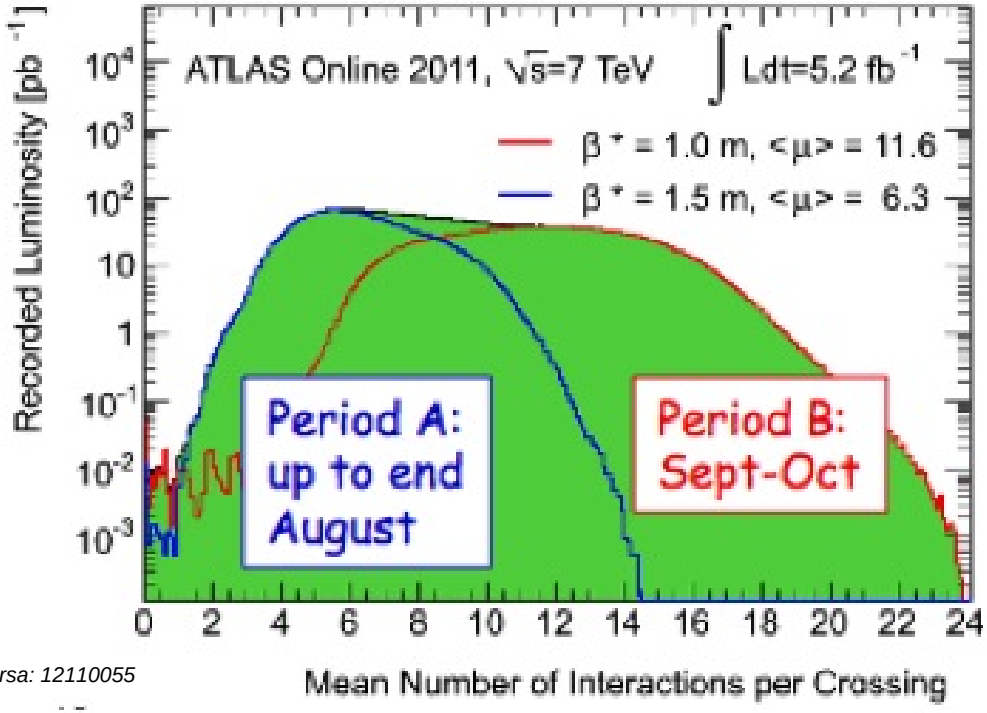
Trigger: Resistive Plate Chambers (RPC) and Thin Gap Chambers (TGC)

Toroidal Magnet

DOING PHYSICS WITH MULTIPLE INTERACTIONS PER CROSSING



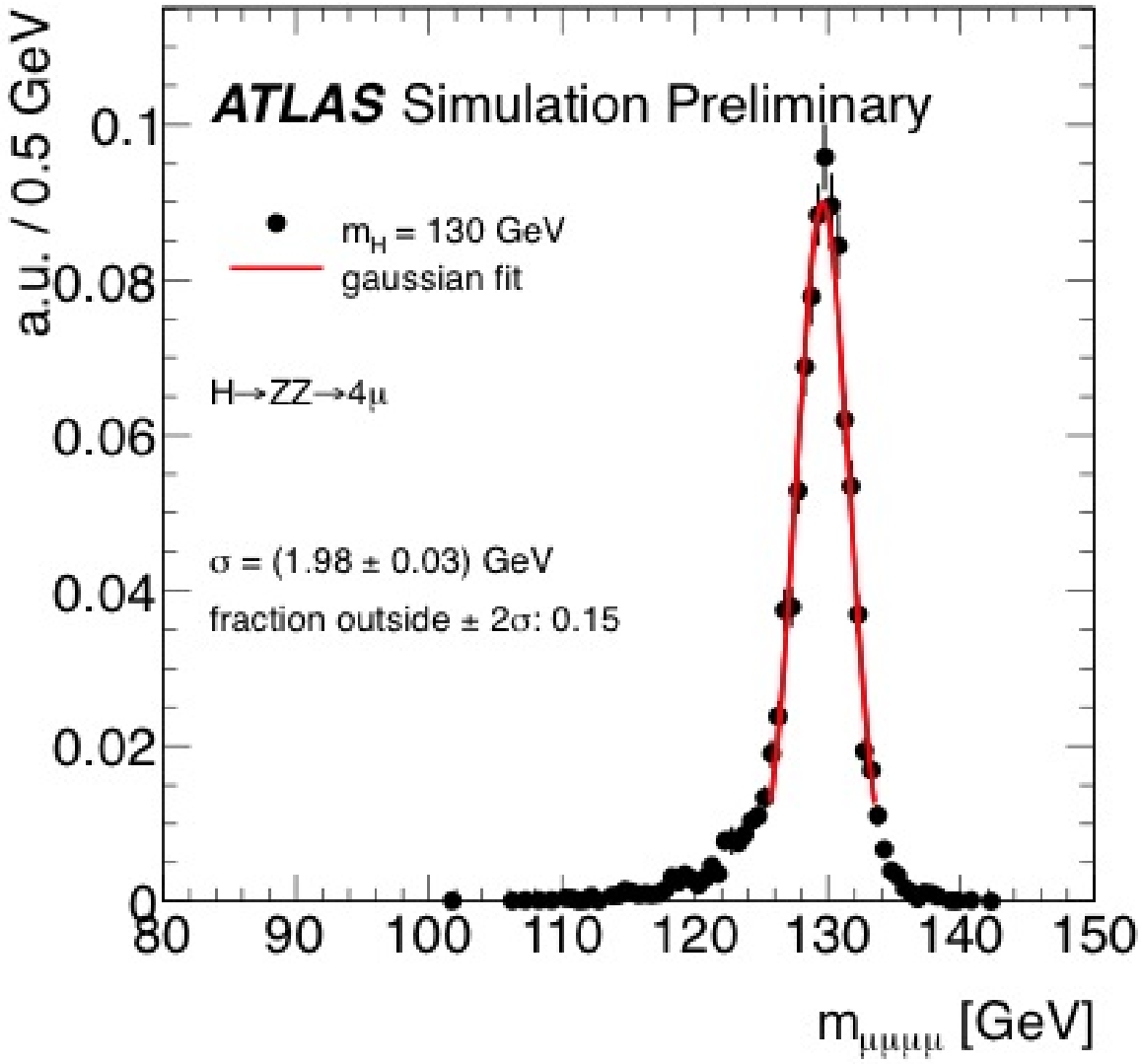
Event with 20 vertices



Use track information to improve calorimeter measurement

Require energy to come from primary vertex of interest

4 MUON MASS RESOLUTION



IF WE RULE OUT THE HIGGS 0-700TEV?

And don't find anything else to replace its function

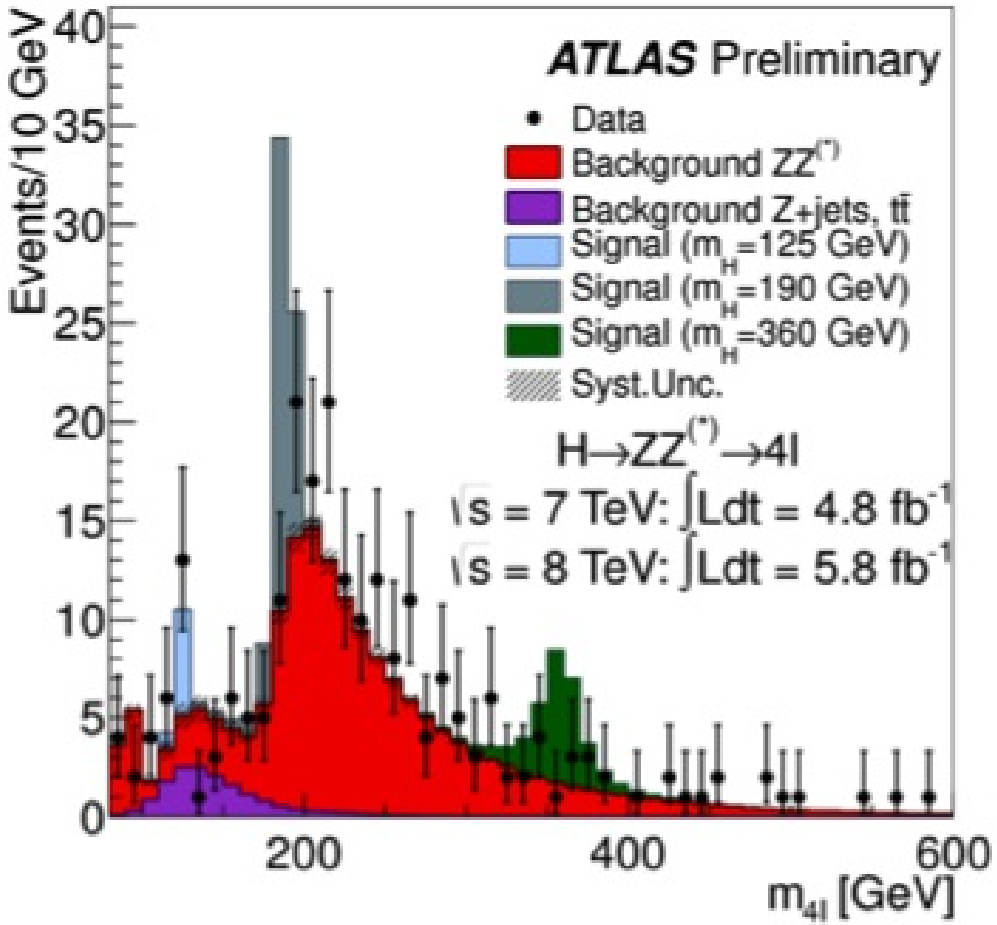
It is a nightmare, but one which is completely riveting

We don't get to build a new accelerator unless we can make one really small and really cheap. Crystals? Plasmas?shock waves?

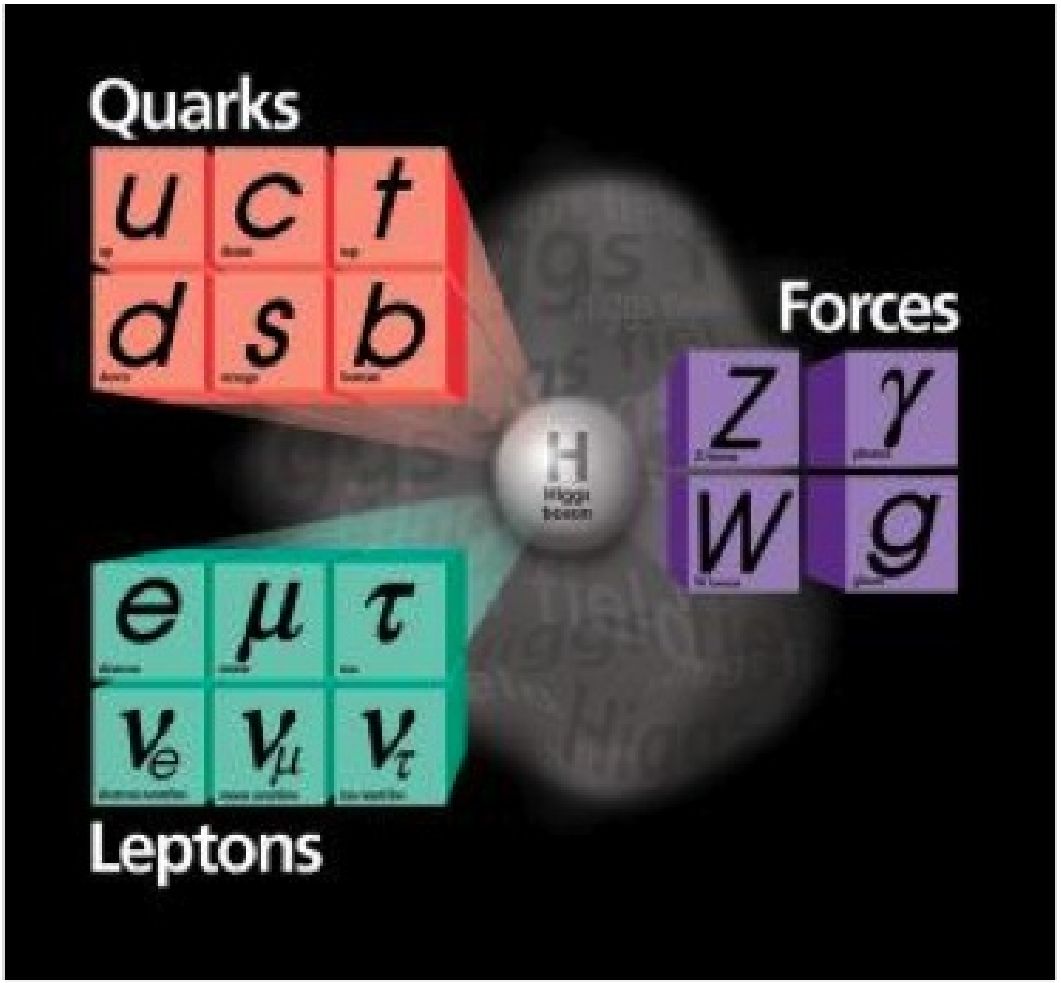
String theorists get replaced by accelerator physicists or we learn so many new things about field theory that we are no longer interested in how EW symmetry is broken

or we get to be experts on calculating how many angels sit on the head of a pin.

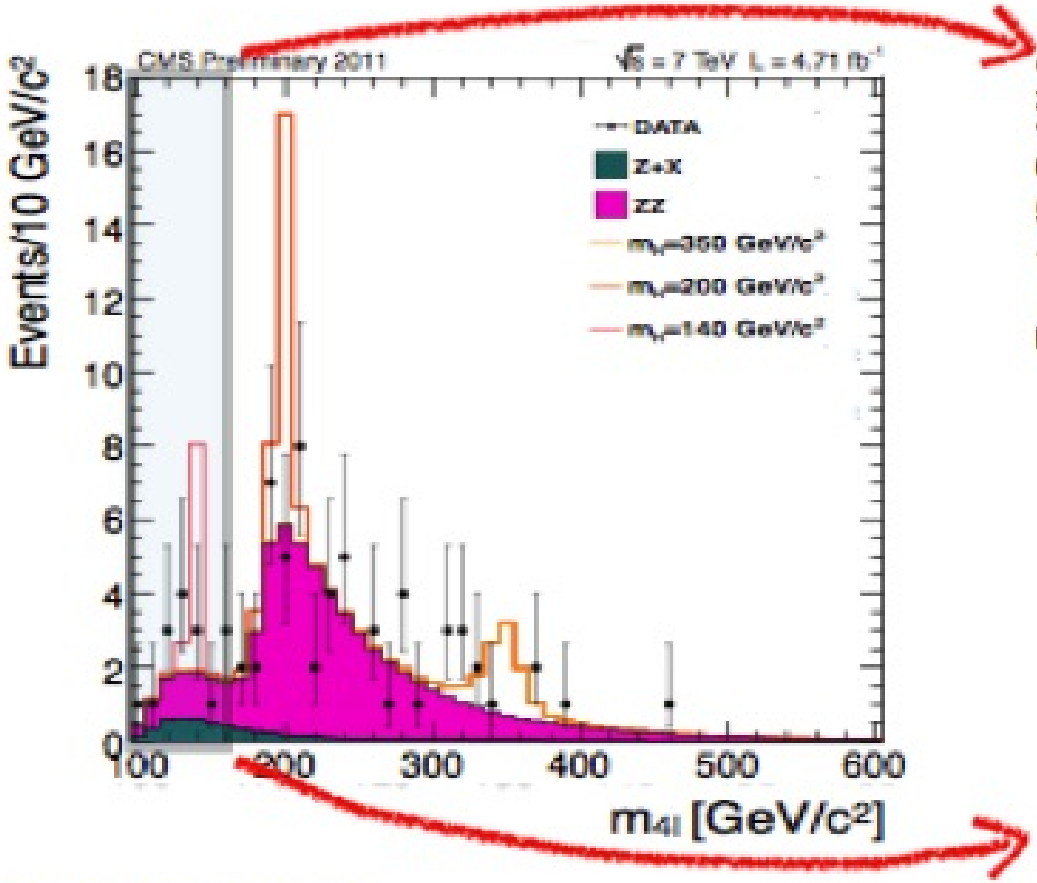
THE DATA: THE FINAL STATE
4 LEPTONS

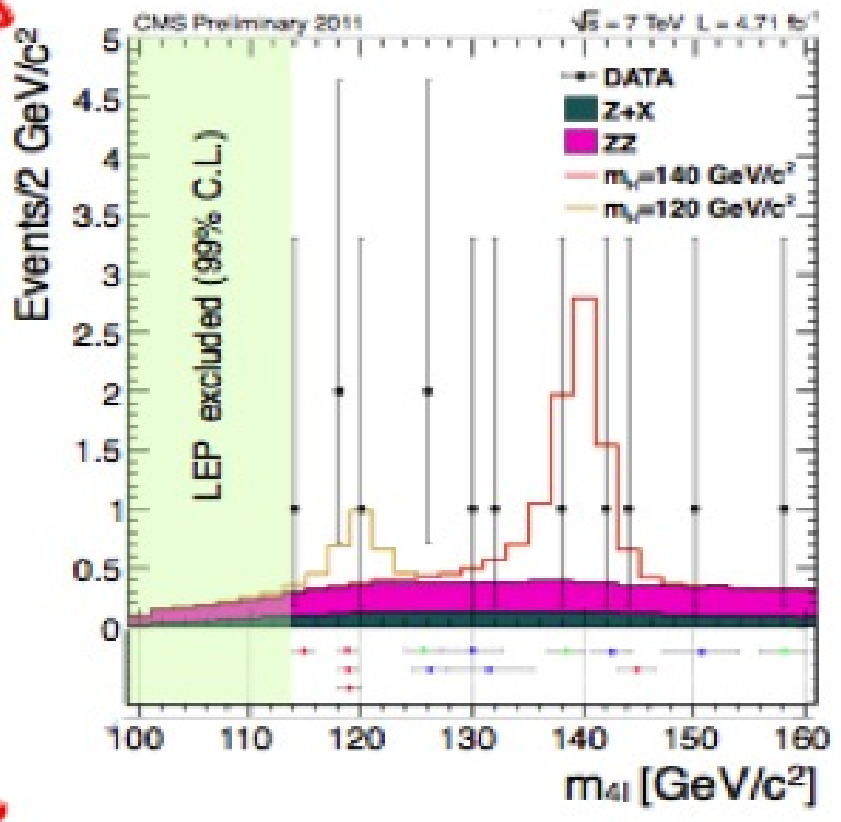


THE MISSING PIECE – THE HIGGS BOSON



CMS H → ZZ(*) → llll: Results





Full Mass Range:

72 events observed

(23 μμμμ, 12 eeee, 37 eeμμ)

M_H < 160 GeV :

Observed: 13 events

Expected: 9.5 ± 1.3

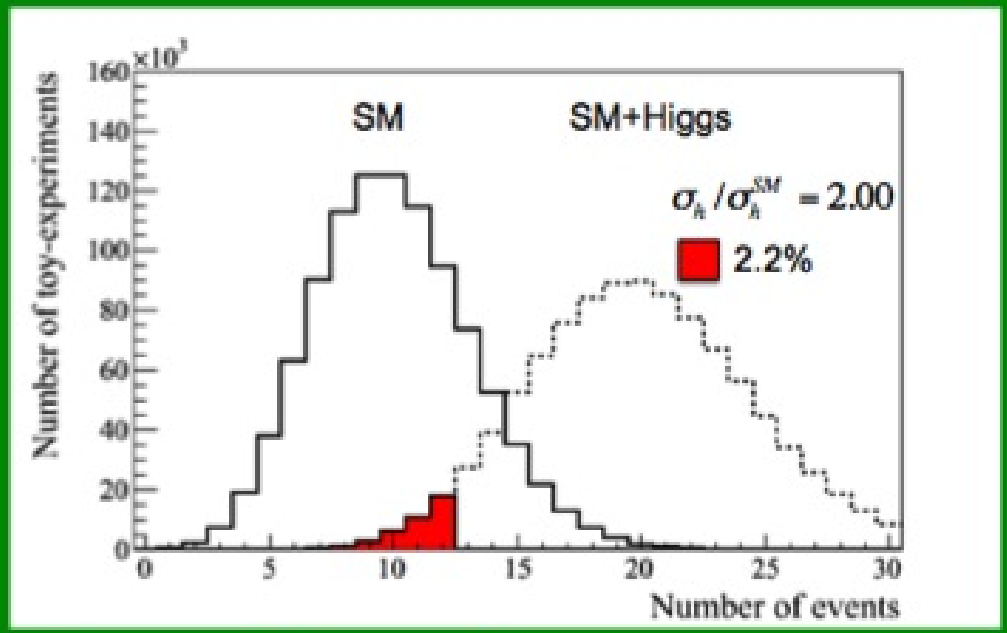
When / how do you exclude a signal

Standard Model

SM	10
Higgs	5
Data	12

1) Can we exclude the SM+Higgs hypothesis ?

*2) If not, what σ_H/σ_h^{SM} **can** we exclude ?*



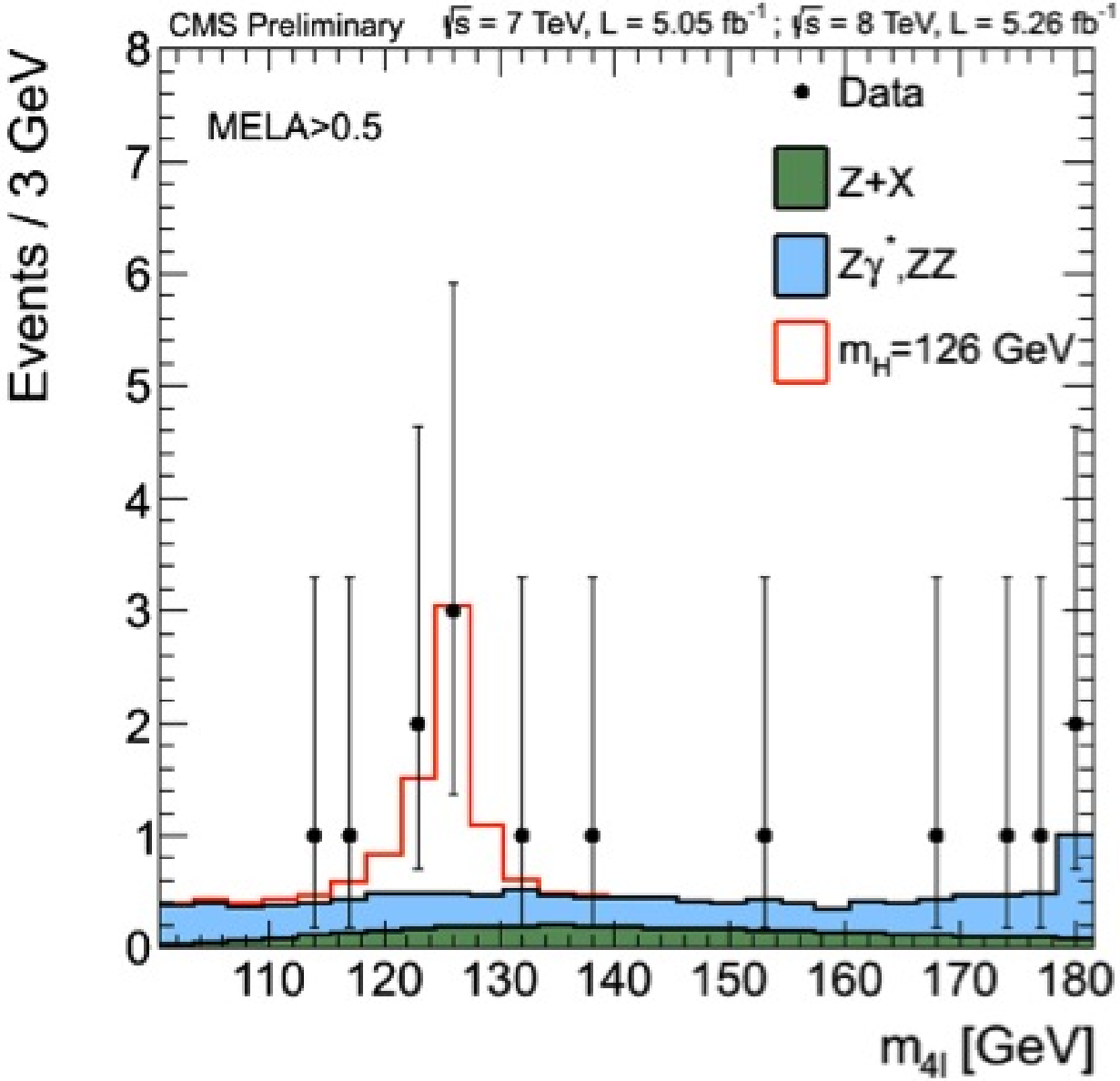
σ/σ_{SM}	SM	# data	SM+Higgs	
1.0	10	12	15.0	18.5 %
1.5	10	12	17.5	6.8%
2.0	10	12	20.0	2.2%

< 5%? Exclude at 95% CL

Expected exclusion ? Use mean SM instead of Ndata

Observed excluded cross-section, $\sigma_H/\sigma_h^{SM} = 1.64$

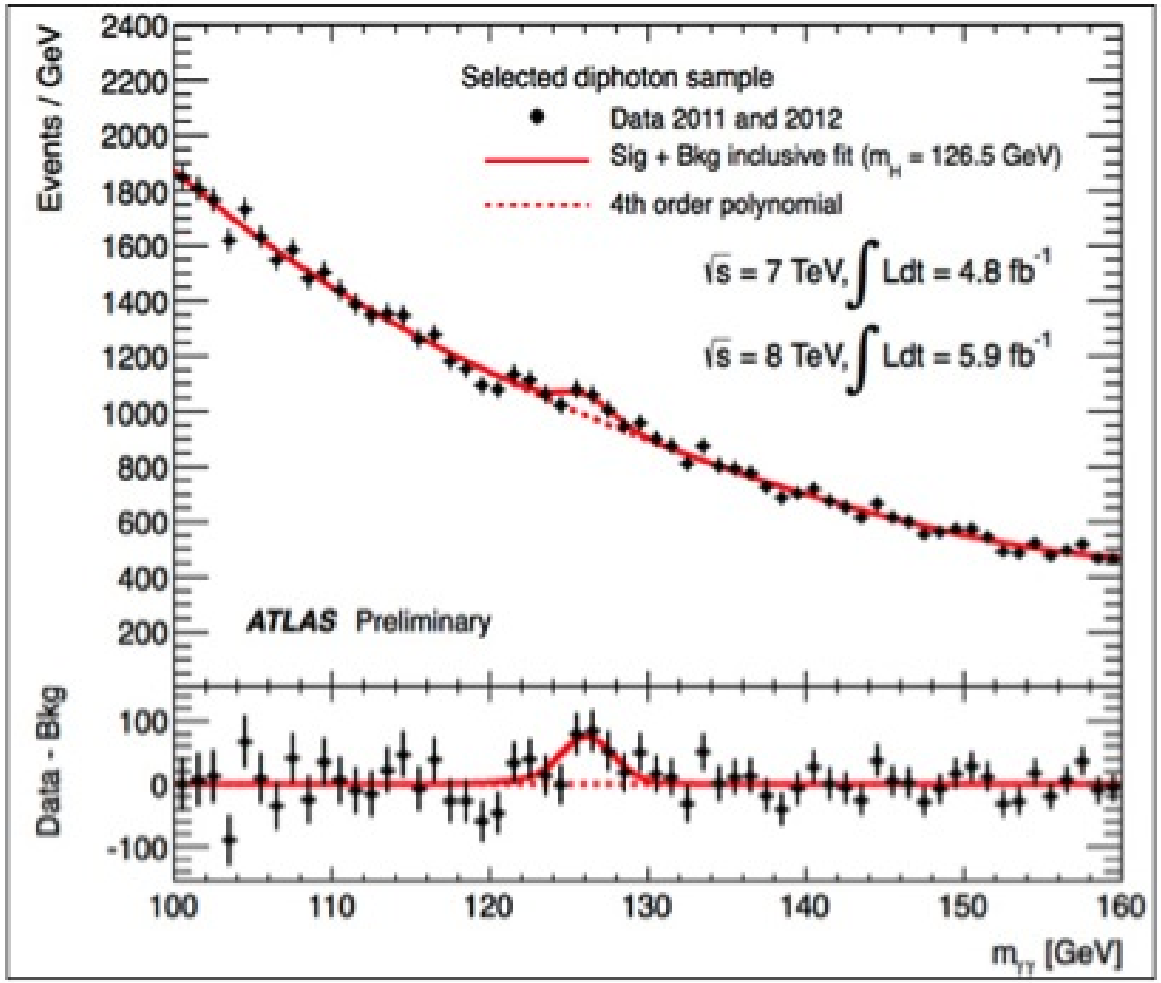
CMS H→ZZ*



Invariant mass of 4 leptons/new particle

ATLAS DATA H - γγ

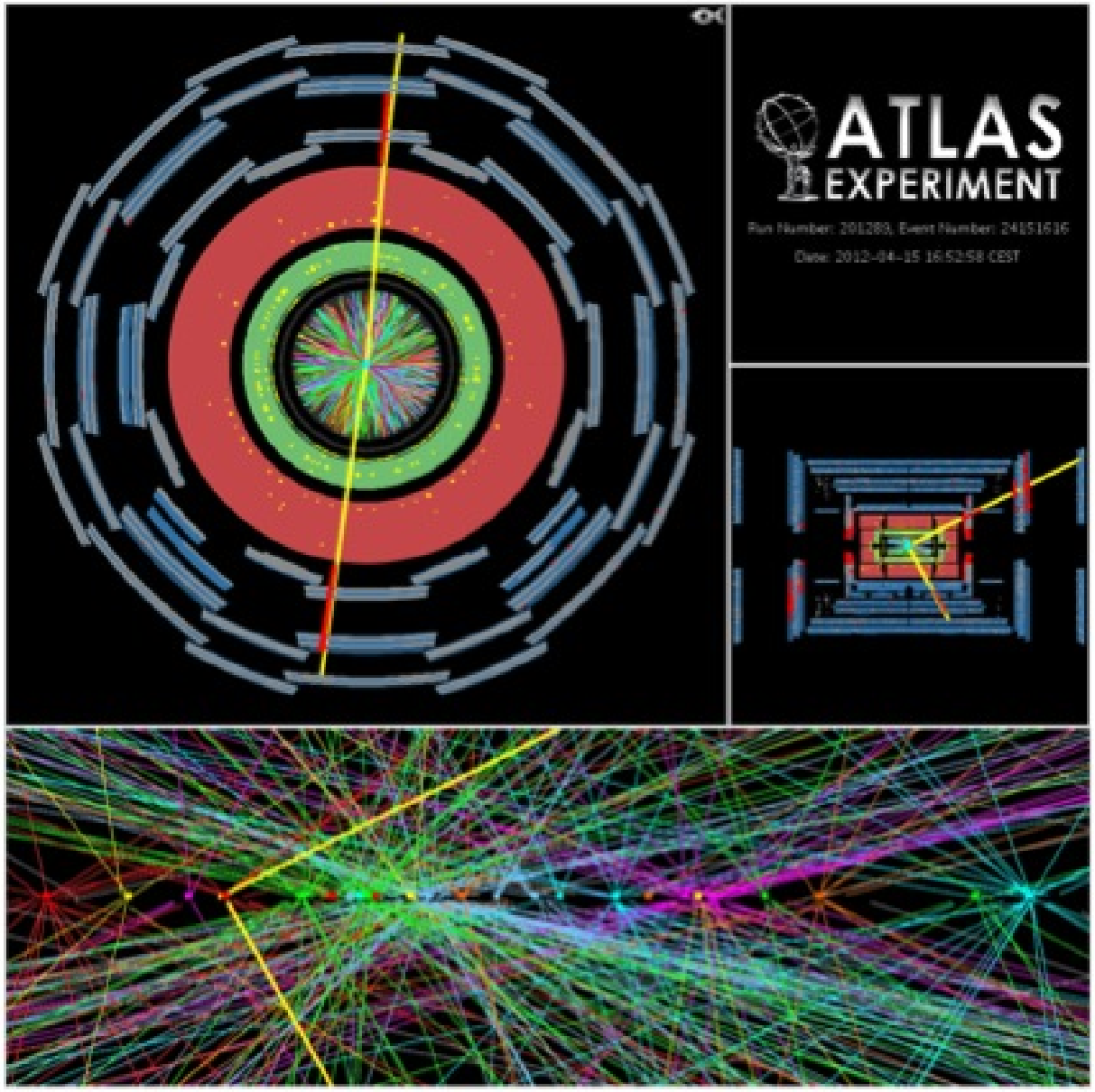
♯ of events



MASS OF γγ

PP –> Z → MUON MUON WITH MULTIPLE VERTICIES FROM PP COLLISIONS

Yikes! How can we reconstruct that?



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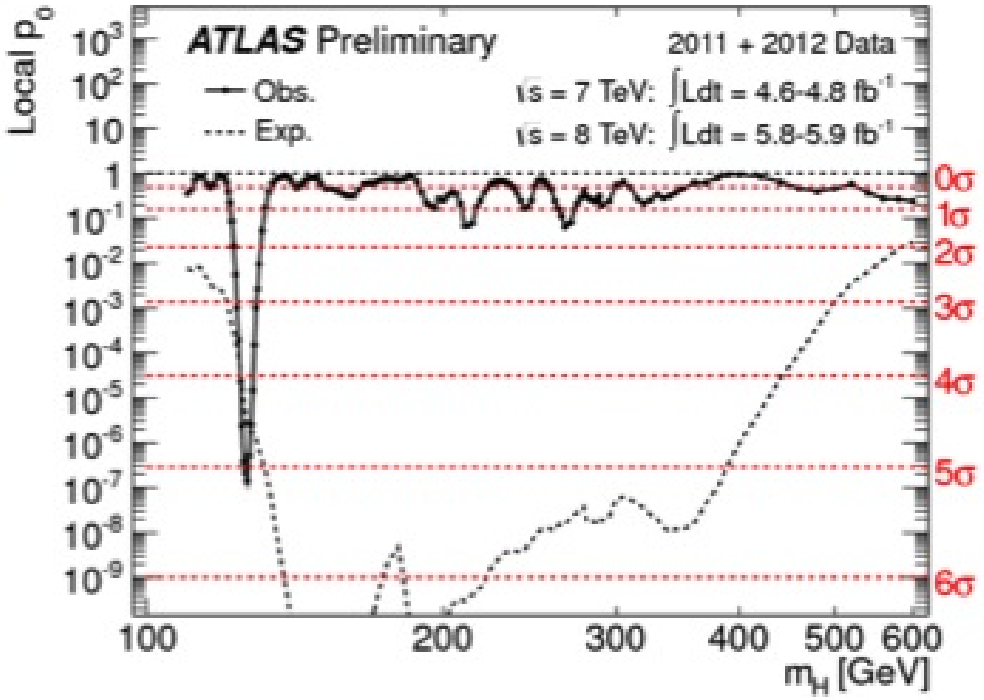
For a given number of events, the p-value is:

*"The probability to observe as many events as this number (or even more) under the assumption that the Higgs does **not** exists"*

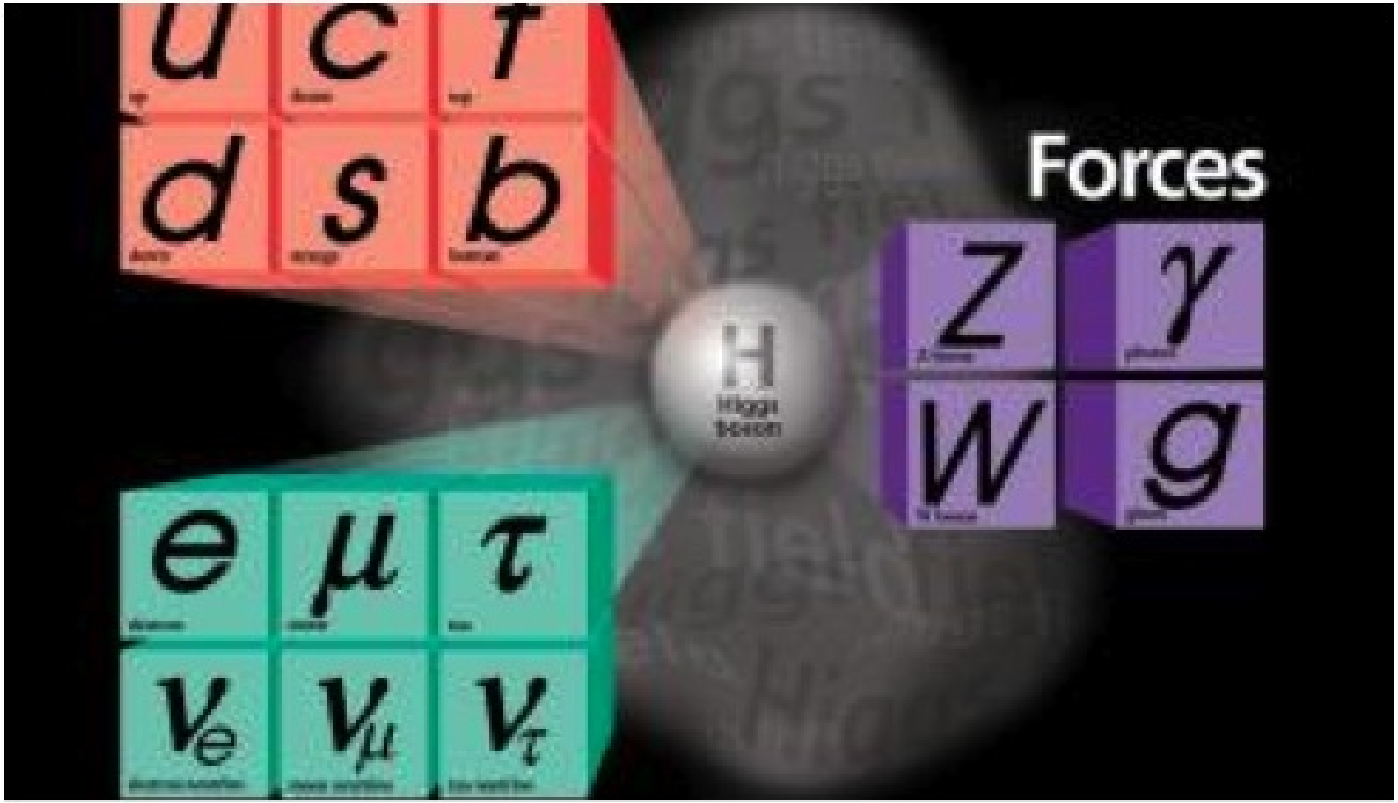
→ *Can be translated into a (gaussian) significance*



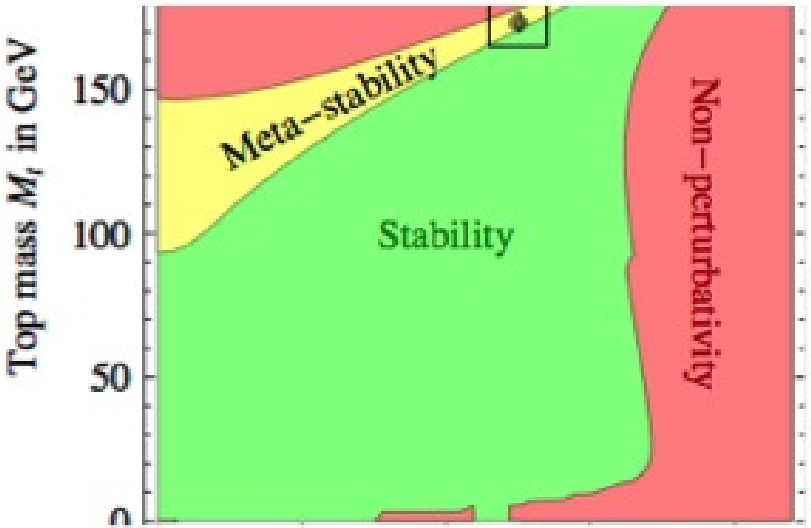
Good motivation to take STAT 110.

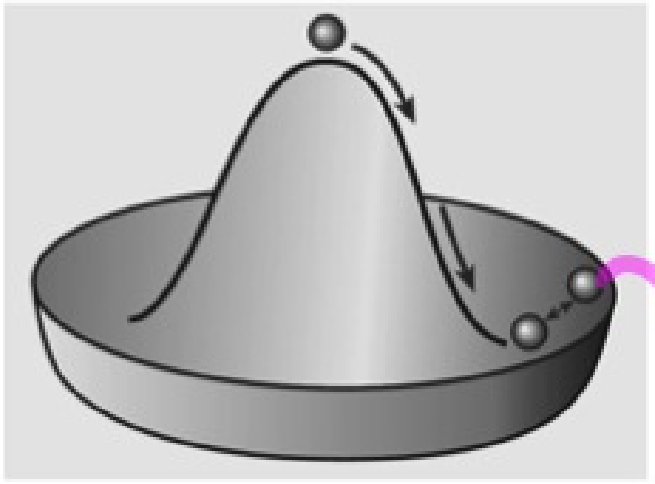
At 125 GeV probability is < 10^{-7}

WE FOUND A PARTICLE: IS IT THE HIGGS? IF SO WHICH HIGGS IS IT? → MORE DATA, MORE WORK, MORE FUN



STABILITY OF THE VACUUM





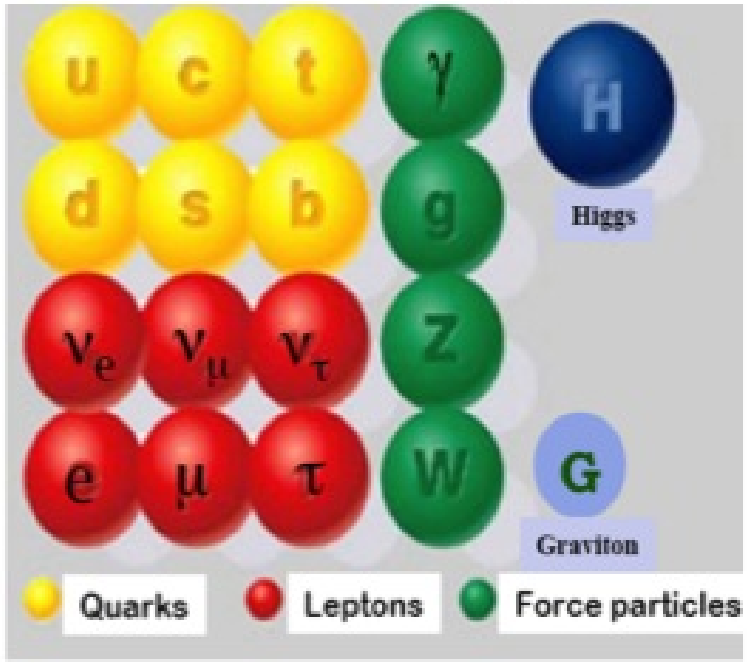
Higgs Potential

Angle

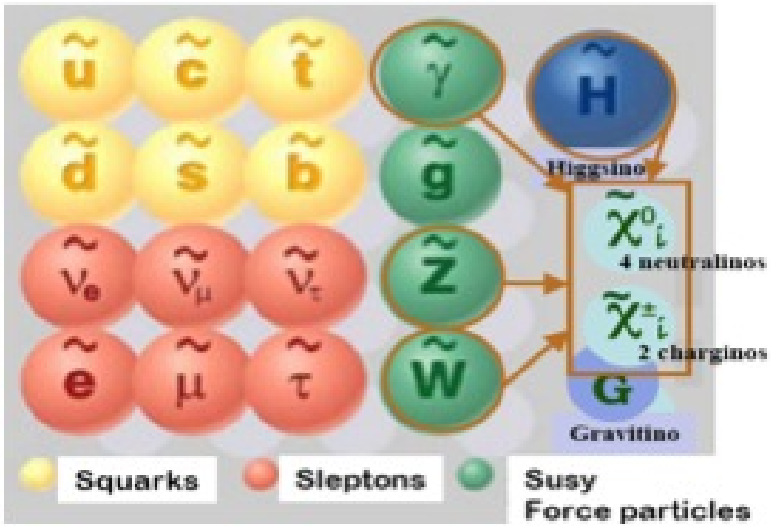
Extends the Standard Model by predicting a new symmetry
Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

SUPERSYMMETRY

Standard Model particles



SUSY particles



New Quantum number: R-parity: $R_p = (-1)^{B+L+2s}$ = +1 SM particles
- 1 SUSY particles

WHAT CAN WE MEASURE WITH MORE DATA AT LHC

MASS TO 1%

WIDTH 50%

FERMION COUPLINGS 30%

COUPLINGS TO WW, ZZ 30%

SPIN: RULE OUT SPIN 1

WE NEED TO STUDY HIGGS – XX (X IS DARK MATTER)

LOOK FOR NEW RESONANCES

Z DISCOVERED IN $P^+ P^-$ STUDIED SERIOUSLY AT LEP IN E^+E^-

LINEAR COLLIDER, STORAGE RING, MUON COLLIDER?

DREAM OR NIGHTMARE?

We found something at 125 GeV

And it is probably the Higgs –> it is a dream for people of all ages

We can have total fun measuring everything we can at the LHC

Rule out infinitely many Beyond the Standard Model theories or NOT (extra dimensions, supersymmetry, etc)

Make up new BSM theories

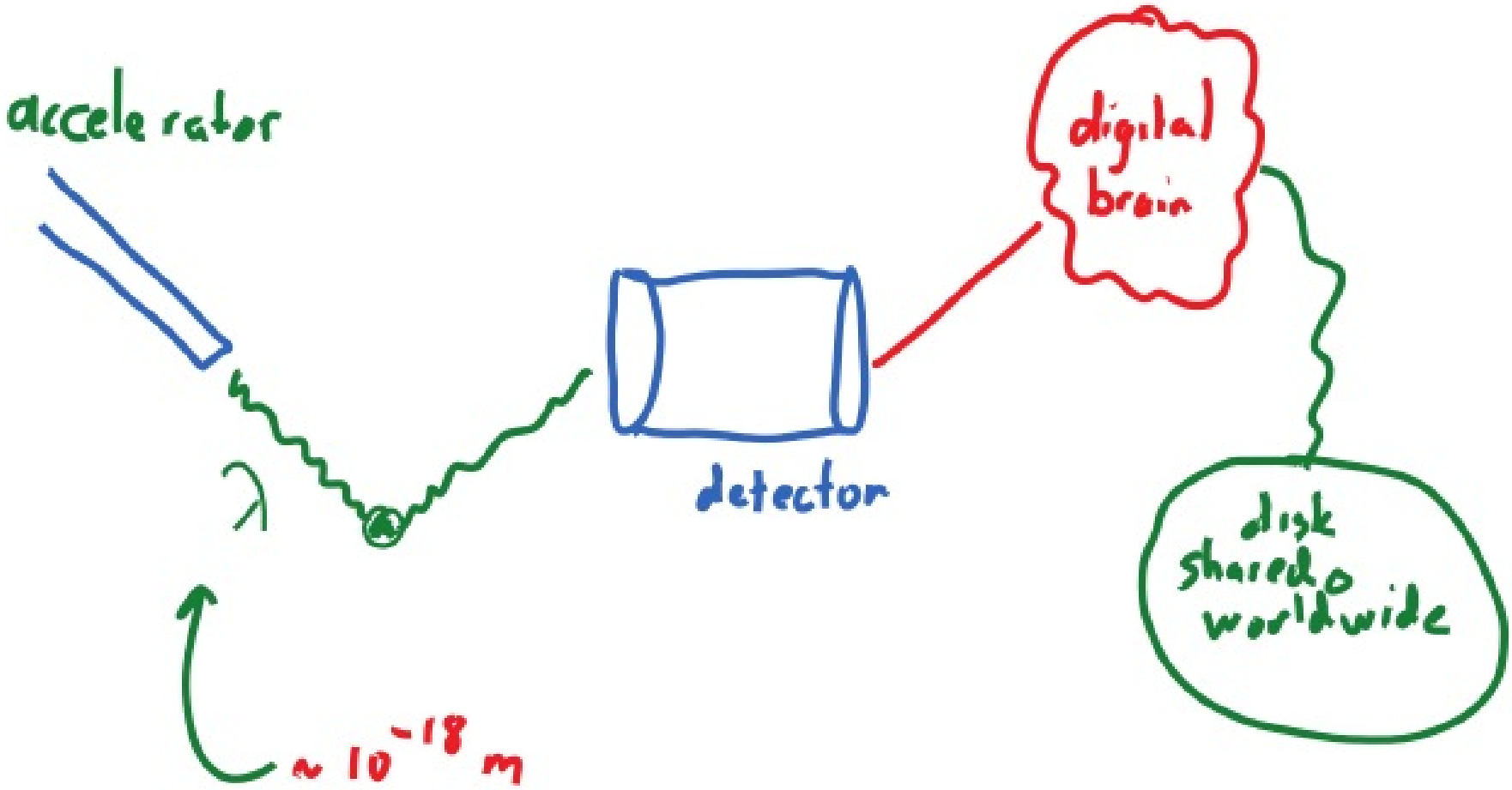
Then build a new collider just to look at Higgs

Then spend another 20 years measuring detailed aspects of the Higgs to see if there is hidden physics in the electroweak sector

It's lovely!

WE CAN MAKE ANY WAVELENGTH WITH AN ACCELERATOR

(Wavelengths down to $10^{(-18)}$m)

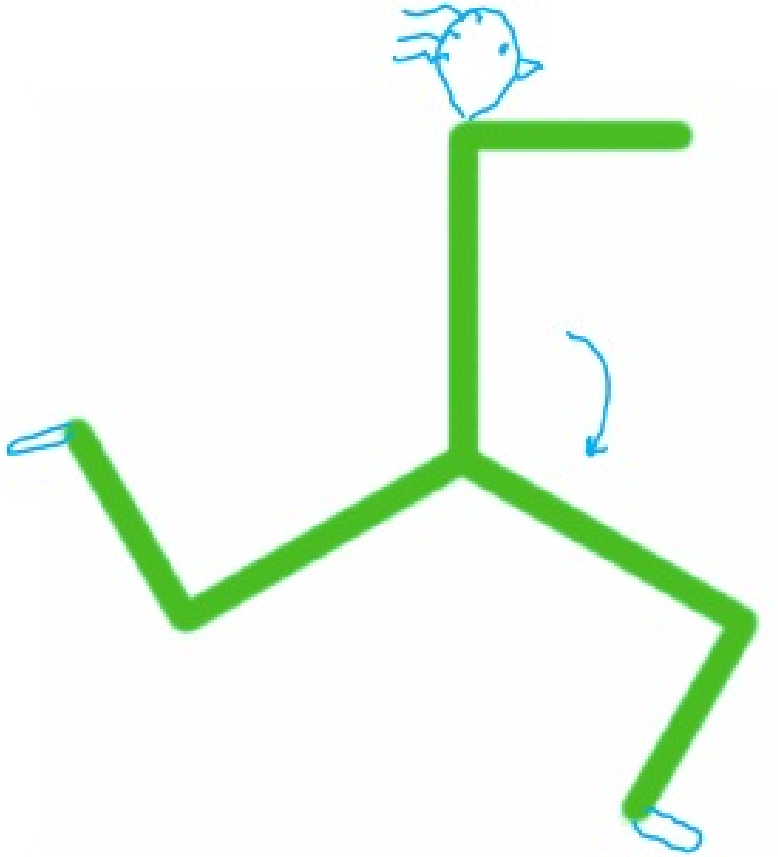


WHY DO WE DO IT

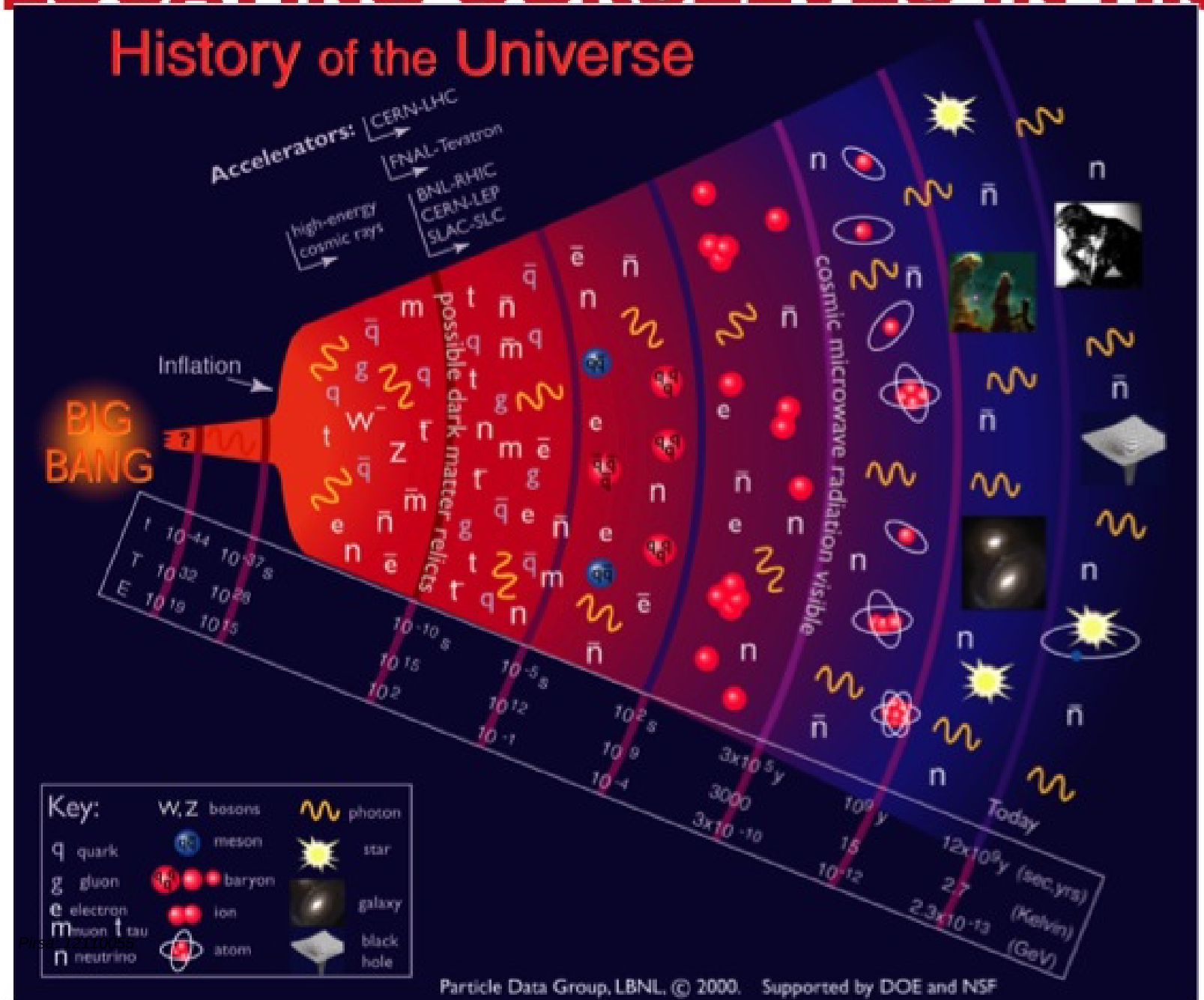
Understand interactions at small distance scales

Know the forces and the underlying symmetries

Understand structure of space- time (this includes understanding the big bang)



LOCATING OURSELVES IN HISTORY



WHEN WE WILL KNOW

And what comes after that

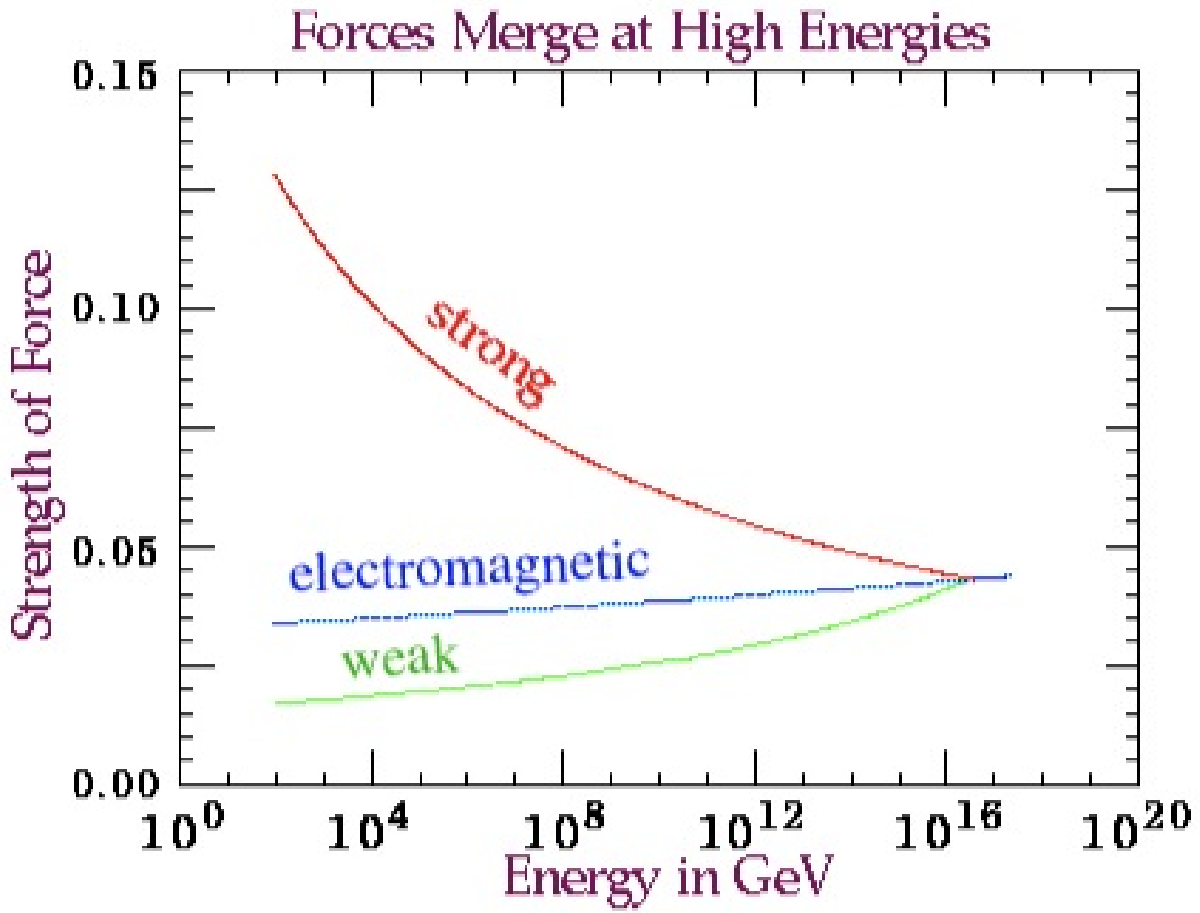
SUSY

Extra dimensions

New weird stuff we can’t even imagine

Get out of the groove

MAYBE ALL THREE FORCES ARE REALLY ONE? WE TRY TO UNIFY.



HIGGS MECHANISM WHAT IT IS AND WHY WE WANT IT

Breaks electroweak symmetry ✓

Vector bosons and fermions become massive ✓

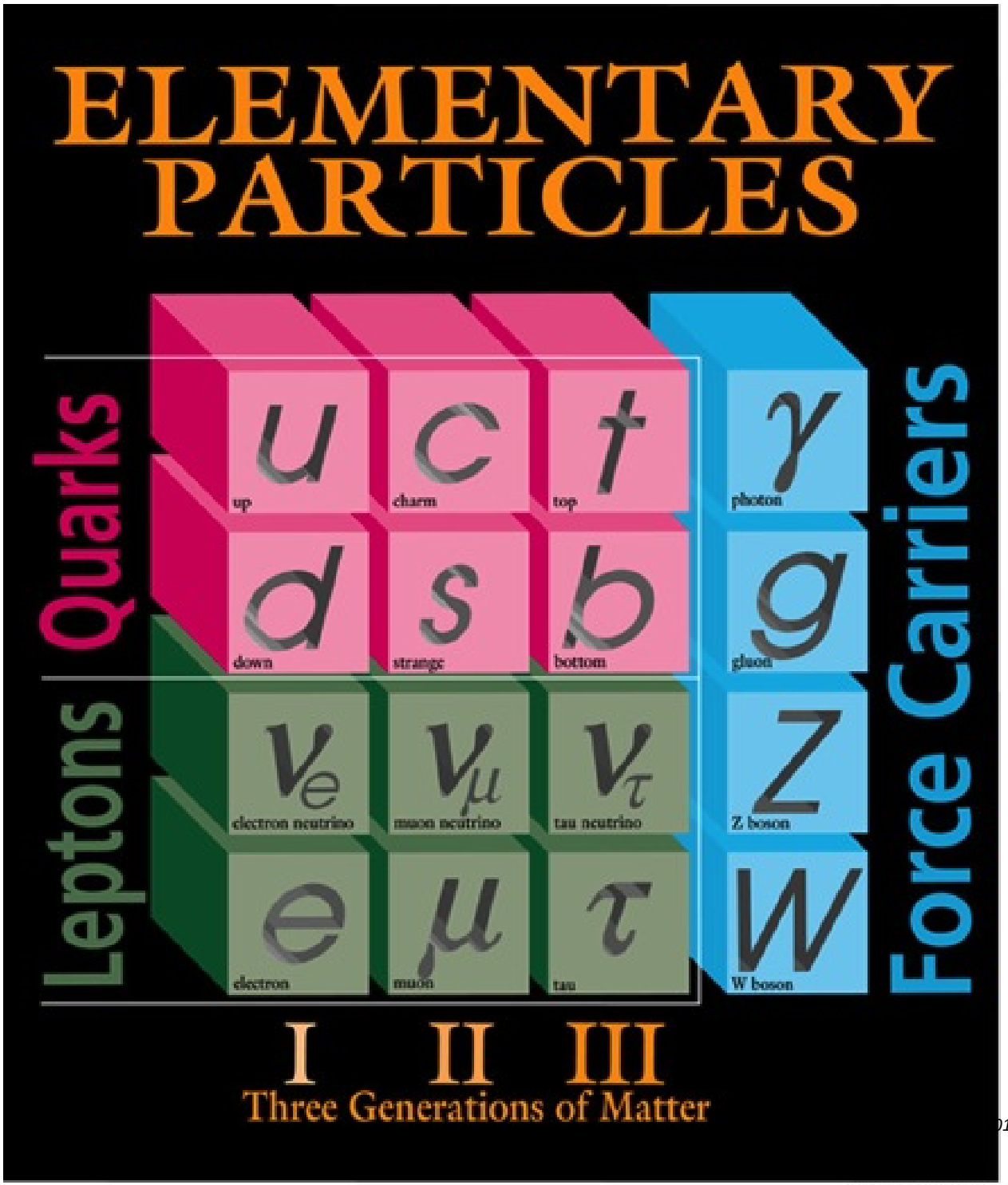
Completes our Standard Model (maybe) ✓

Problems with present SM without Higgs:

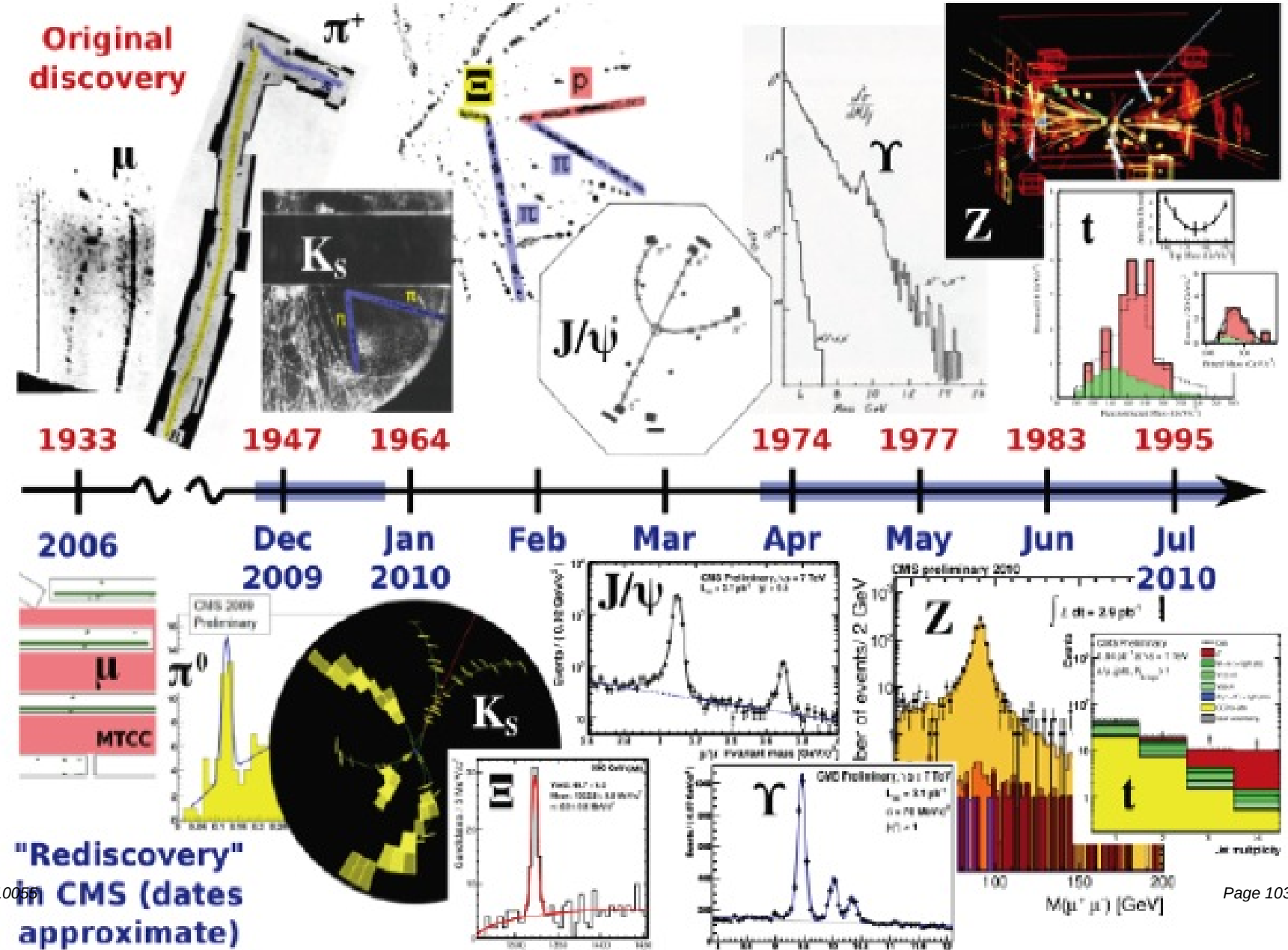
Gauge bosons would not be massive

Fermions would not have mass

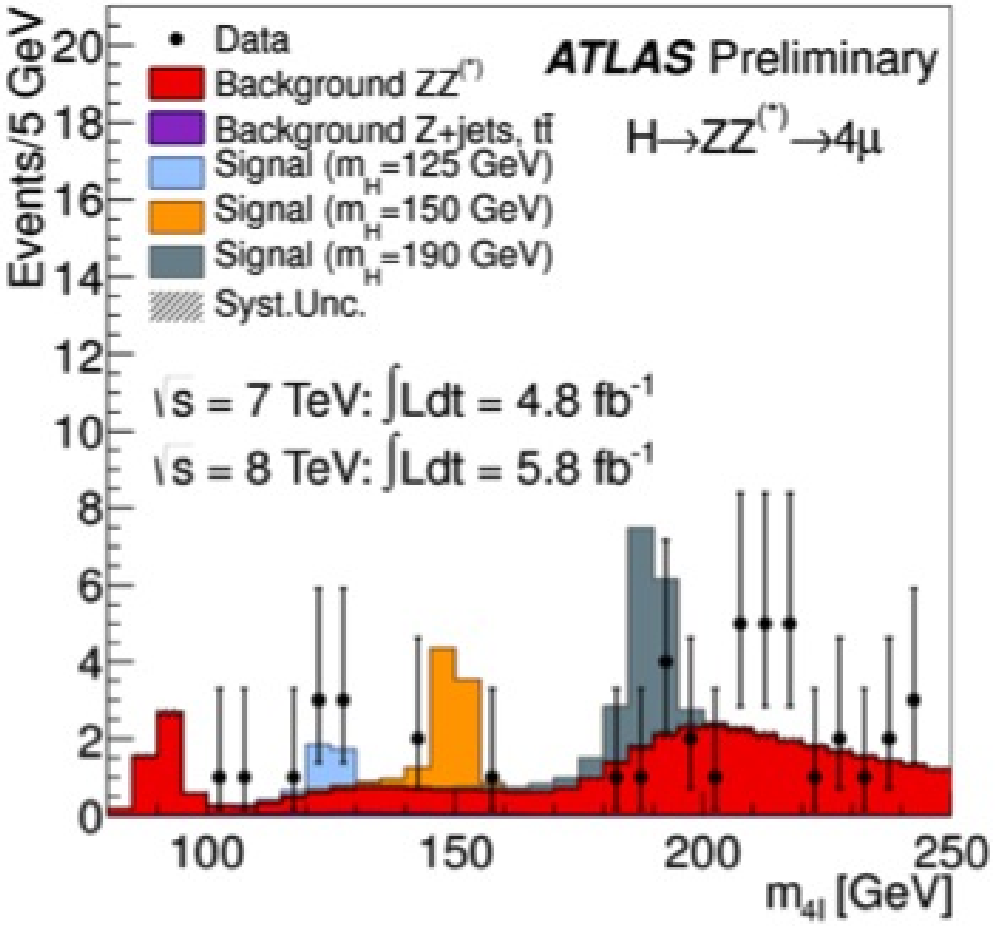
WW scattering diverges


ELEMENTARY PARTICLES
Quarks
Leptons
Force Carriers
u
up
c
charm
t
top
γ
photon
d
down
s
strange
b
bottom
g
gluon
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Z
Z boson
e
electron
μ
muon
τ
tau
W
W boson
I
II
III
Three Generations of Matter

Brief History of the Standard Model



HIGGS EVIDENCE – LIGHT BLUE IS 125 GEV HIGGS



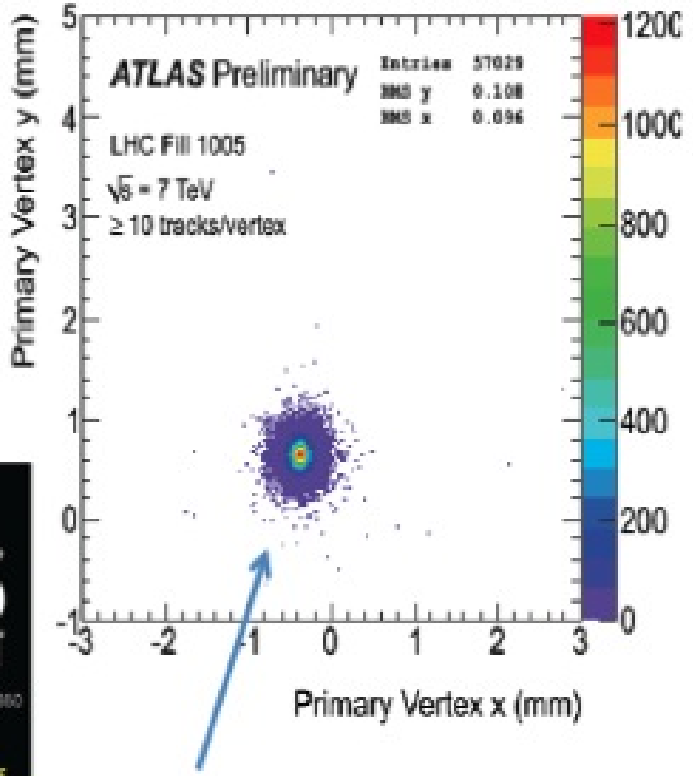
Primary vertex

Thinner than a hair on your head

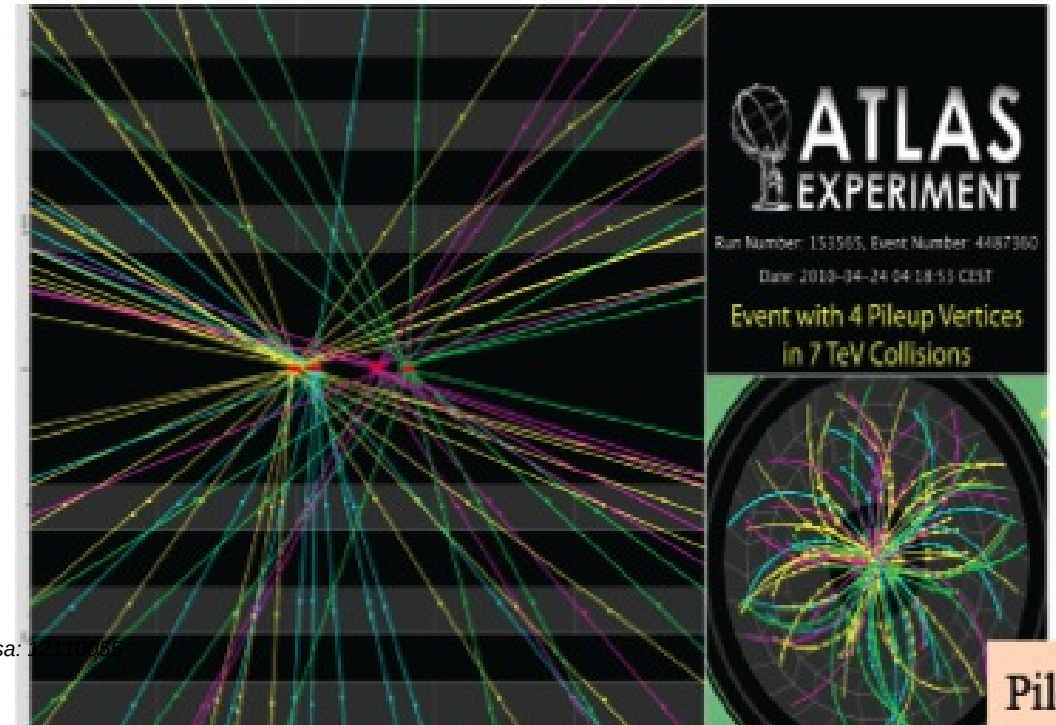
$\sigma_{x,y} \approx 30\ \mu m$ with beam spot constraint

$\sigma_z \approx 50\ \mu m$

Good separation within interaction region (~28mm in the longitudinal plane)



Distribution of primary vertices in transverse plane



Pile-up event: 4 primary vertices

I DON'T CARE ABOUT HIERARCHY, STILL THE EVIL GENIUS ENGINEERING COLLISIONS

NOT THE

PASSIVE VIEWER

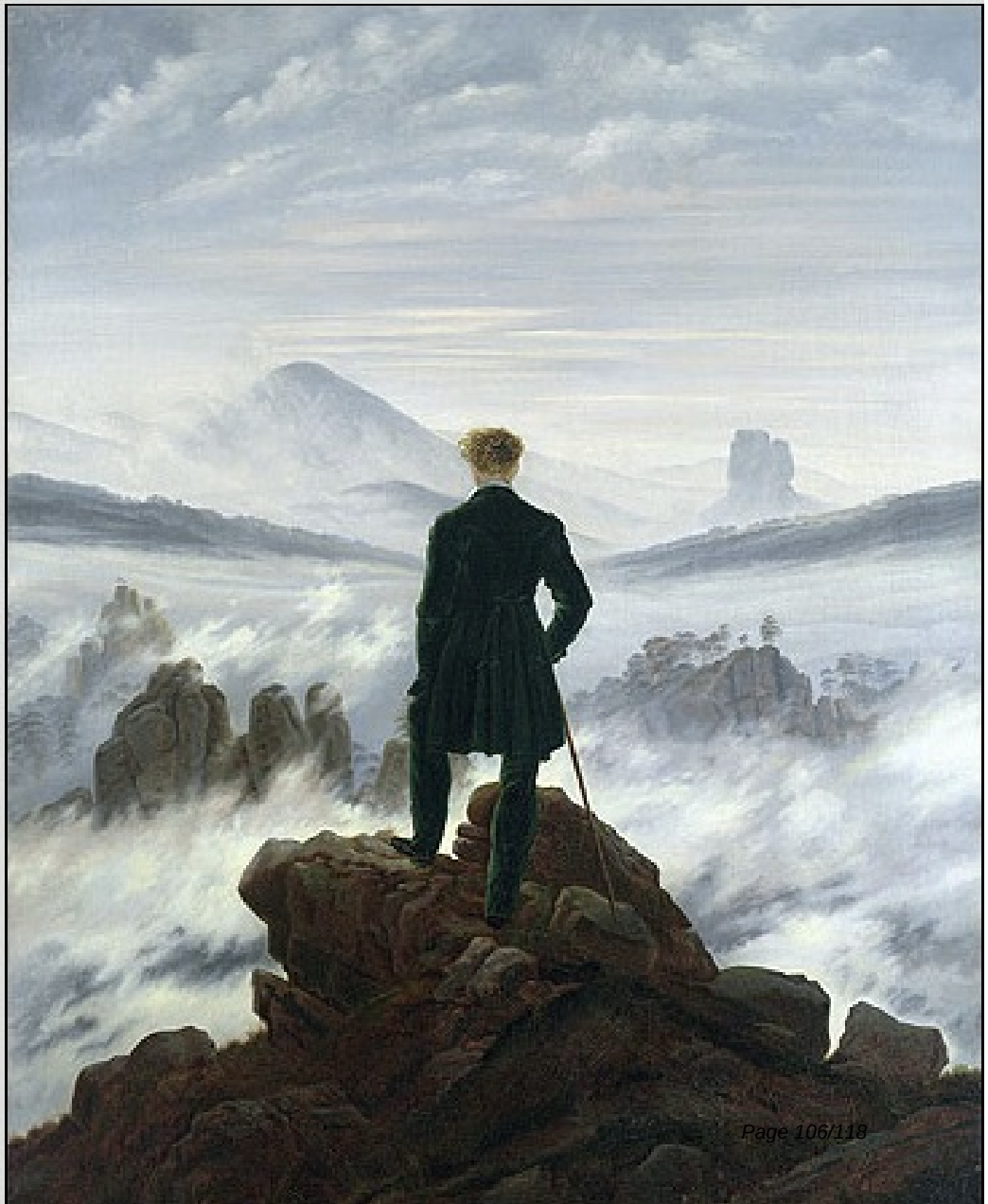
CAREFUL NOT TO

LOOK AT THE

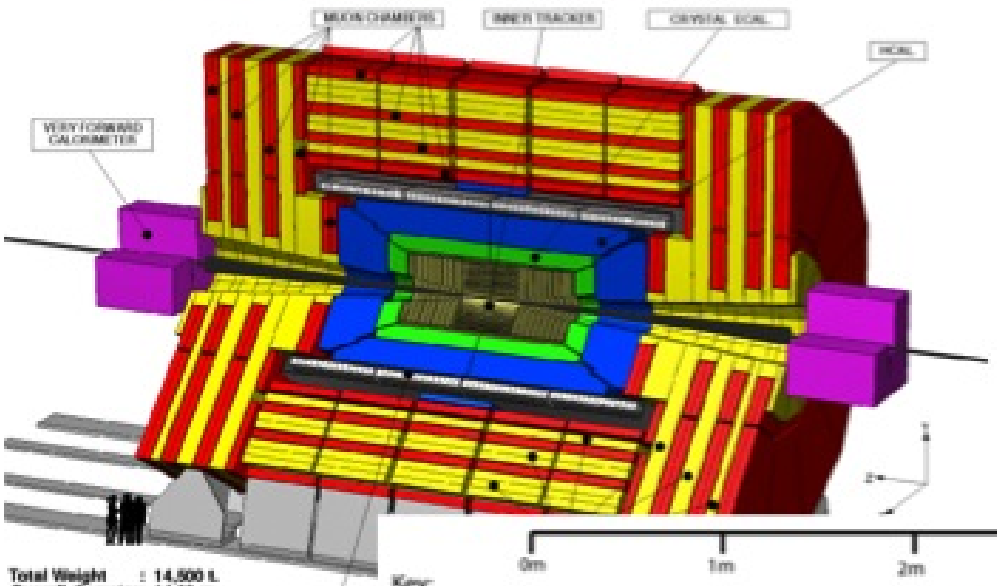
BACK OF HER

OWN HEAD

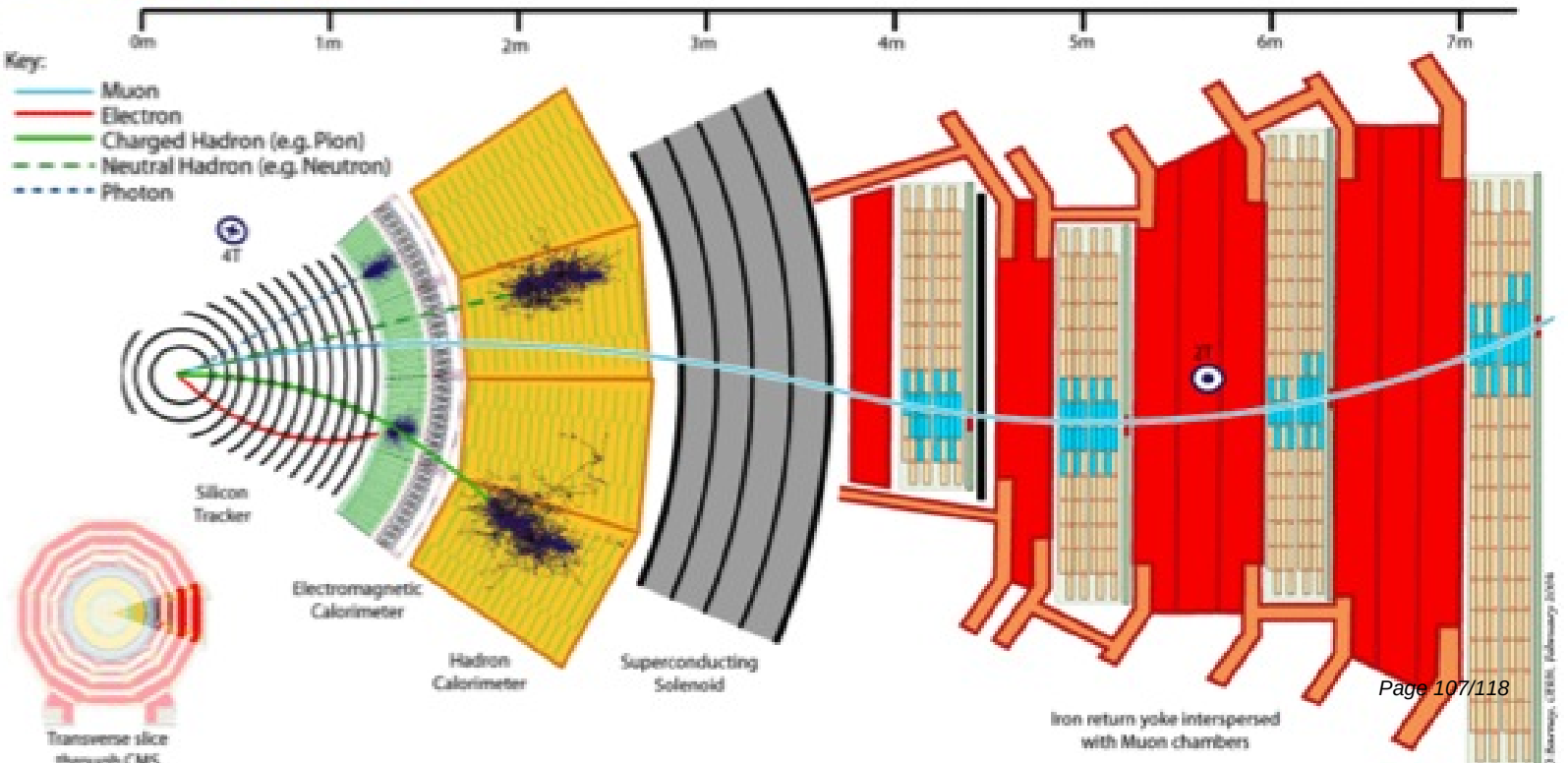
Caspar David Friedrich Art Reproductions
The Wanderer Above a Sea of Mist, c.1818
Hamburger Kunsthalle, Hamburg, Germany



THE CMS



Total Weight : 14,500 t.
Overall diameter : 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla



OTHER QUARKS AND WE CAN CREATE

E=MC2 -> CONVERT ENERGY INTO MASS

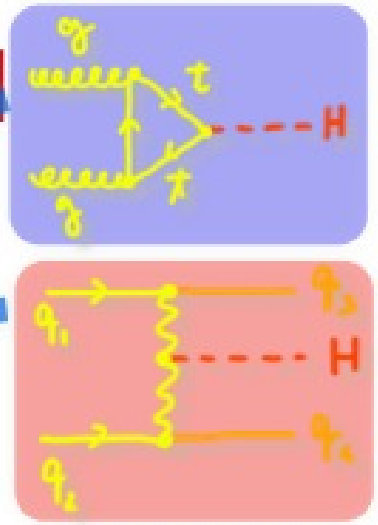
At high energy frontier we can create particles never seen since big bang -trade momentum of protons for mass of new particle

$110 < m_H < 300$ GeV

H → WW → LNLN

σ x BR ~ 200 fb

(EN,MNMN,ENMN)



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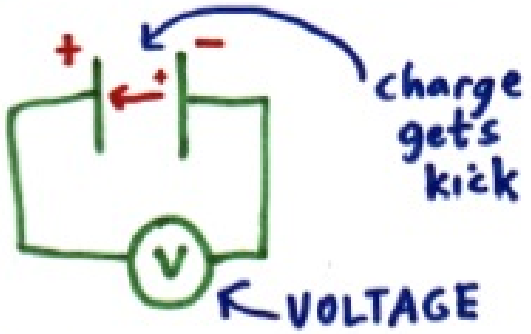
The most sensitive at intermediate Higgs masses

- **SM WW: Large irreducible background**
- **Analysis similar to SM WW + topological cuts**
- **Reconstruction of invariant mass not possible**

NEED SMALL λ

$\Rightarrow$ LARGE MOMENTUM P

$\Rightarrow$ NEED TO ACCELERATE



DO THIS MULTIPLE TIMES

Bend particles with magnets

bend with dipoles, focus with quadrupoles!

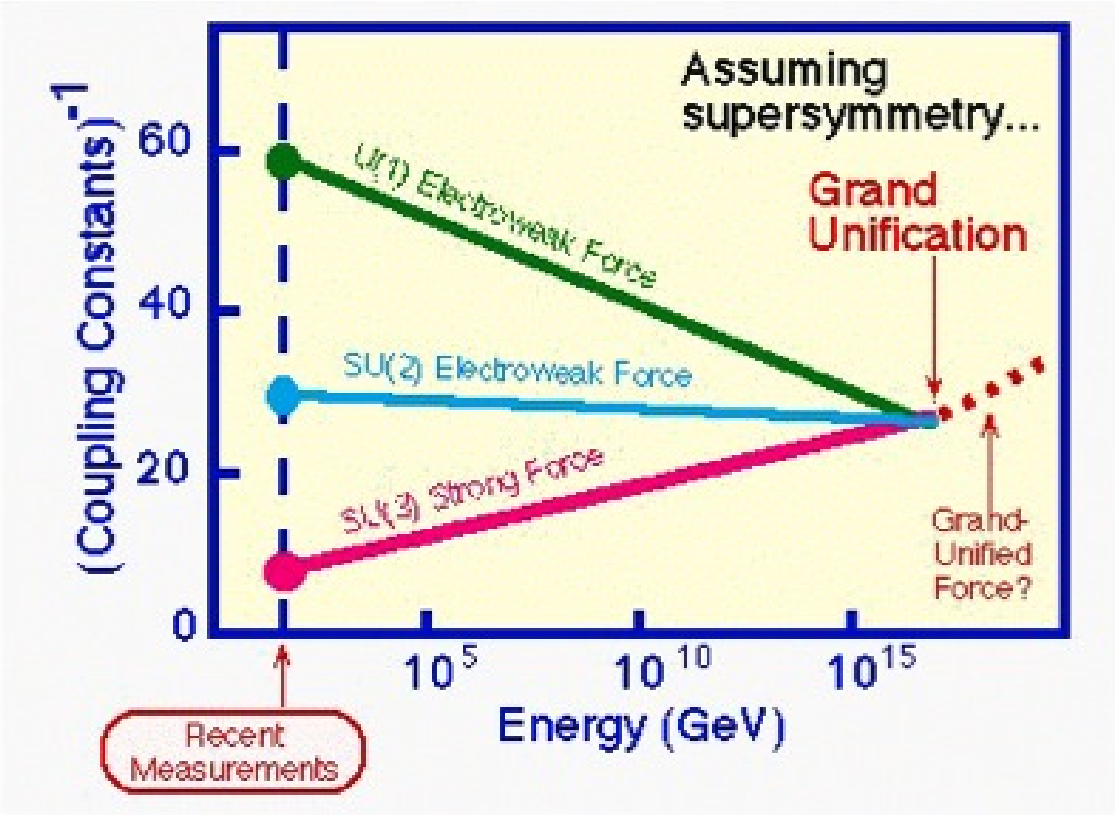
WHAT'S NEXT?
STUDY THE HIGGS HOW

Linear electron collider

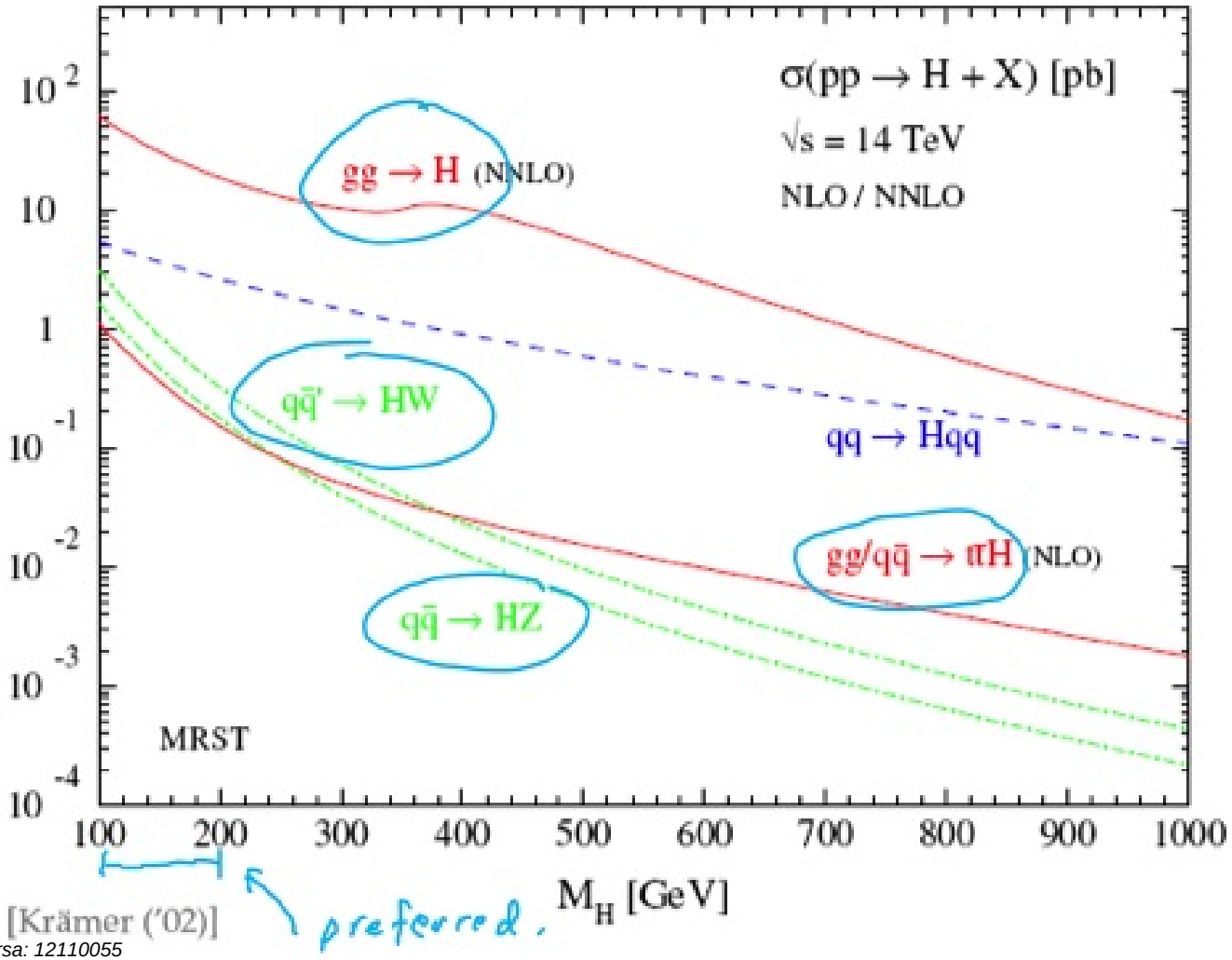
LEP but bigger and better

Just more LHC

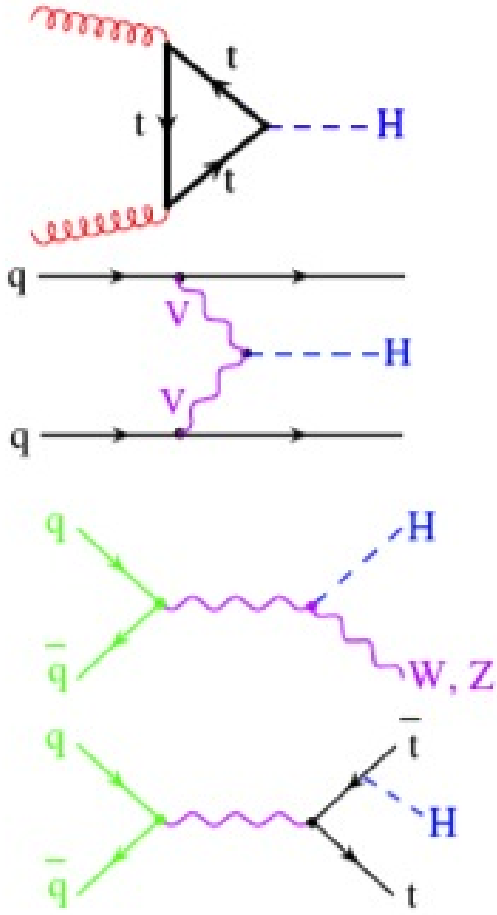
Muon Collider


Assuming
supersymmetry...
Grand
Unification
U(1) Electroweak Force
SU(2) Electroweak Force
SU(3) Strong Force
Grand-
Unified
Force?
(Coupling Constants)$^{-1}$
60
40
20
0
10^5
10^{10}
10^{15}
Energy (GeV)
Recent
Measurements

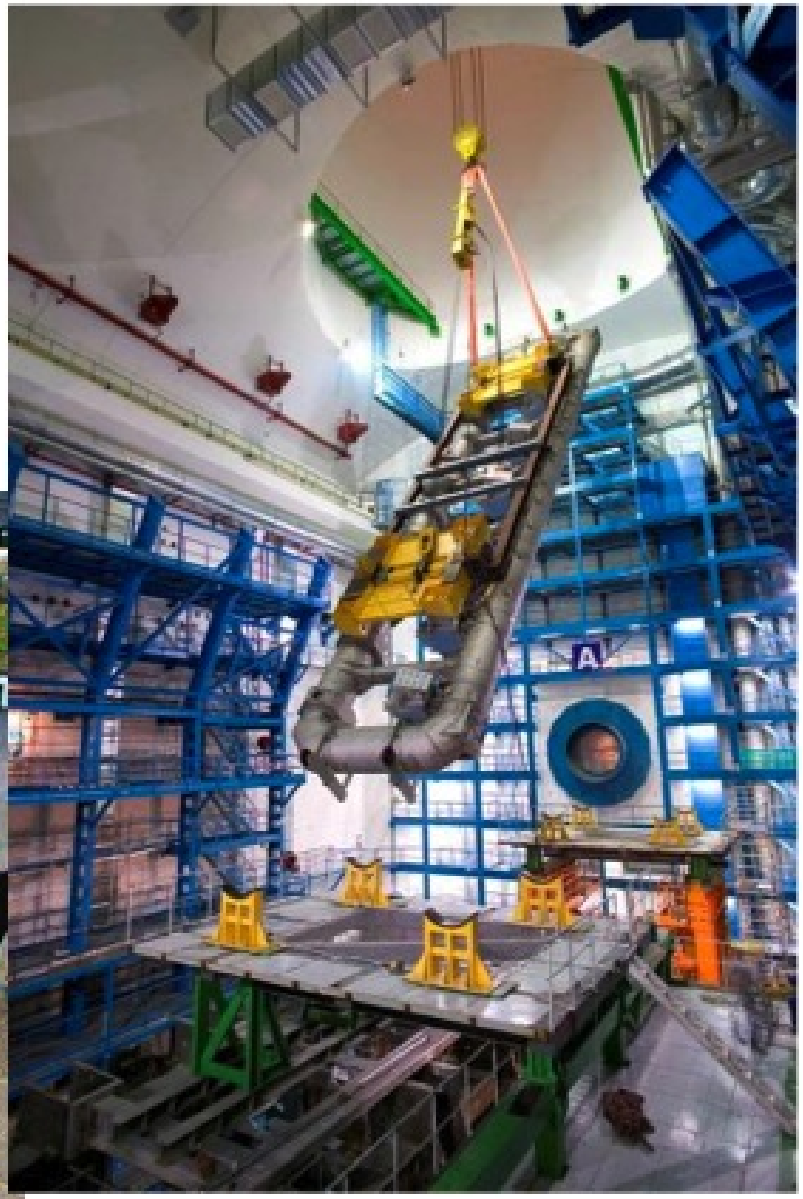
PRODUCTION CROSS-SECTIONS



[Krämer ('02)]



ATLAS TOROID CONSTRUCTION AND INSTALLATION

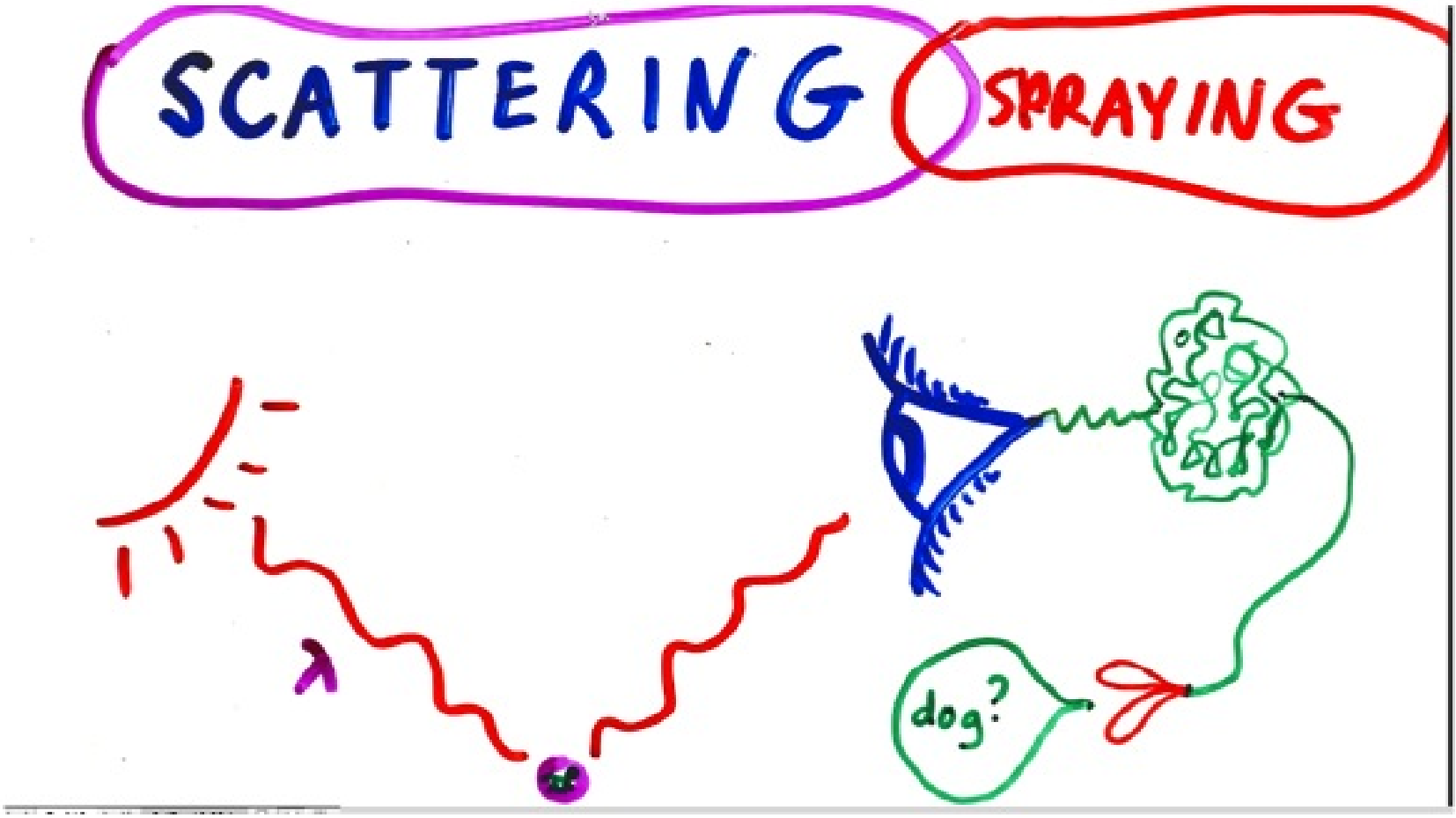


WHAT COMES OUT AND HOW FAST

RESULTS FROM CDF AND DO AND CMS

COMBINED RESULTS 2012

YOU NEED PROBES OF SMALL WAVELENGTH AND HIGH PARTICLE/WAVE MOMENTA : P=H/Λ



Use accelerators to get to high momentum