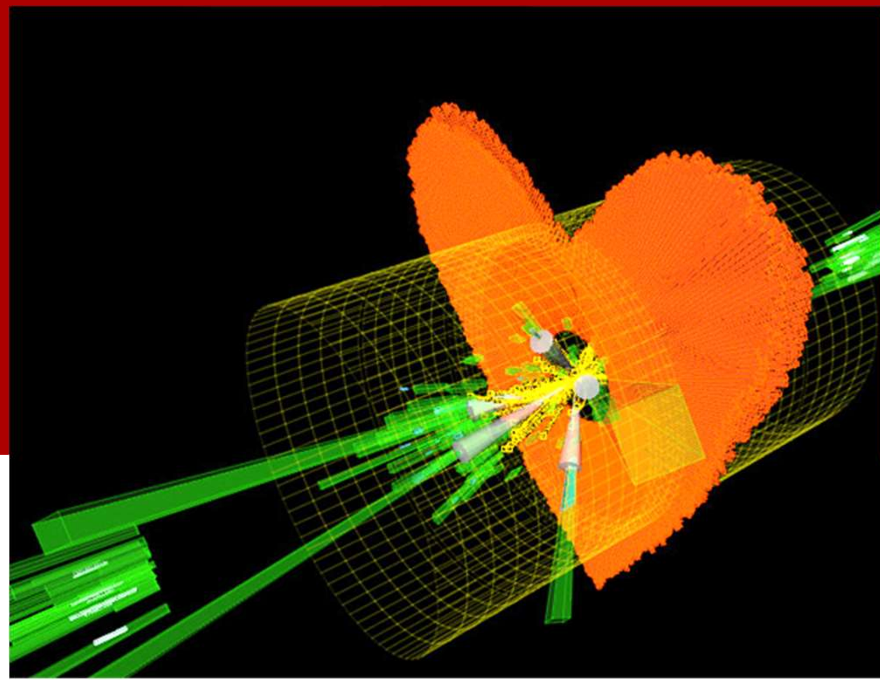
FROM QUARKS TO NEUTRINOS



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WNPPC 2020, Banff, Alberta

INSTITUTE OF PARTICLE PHYSICS

INSTITUT DE PHYSIQUE DES PARTICULES

VELUT ÆVO ARBOR

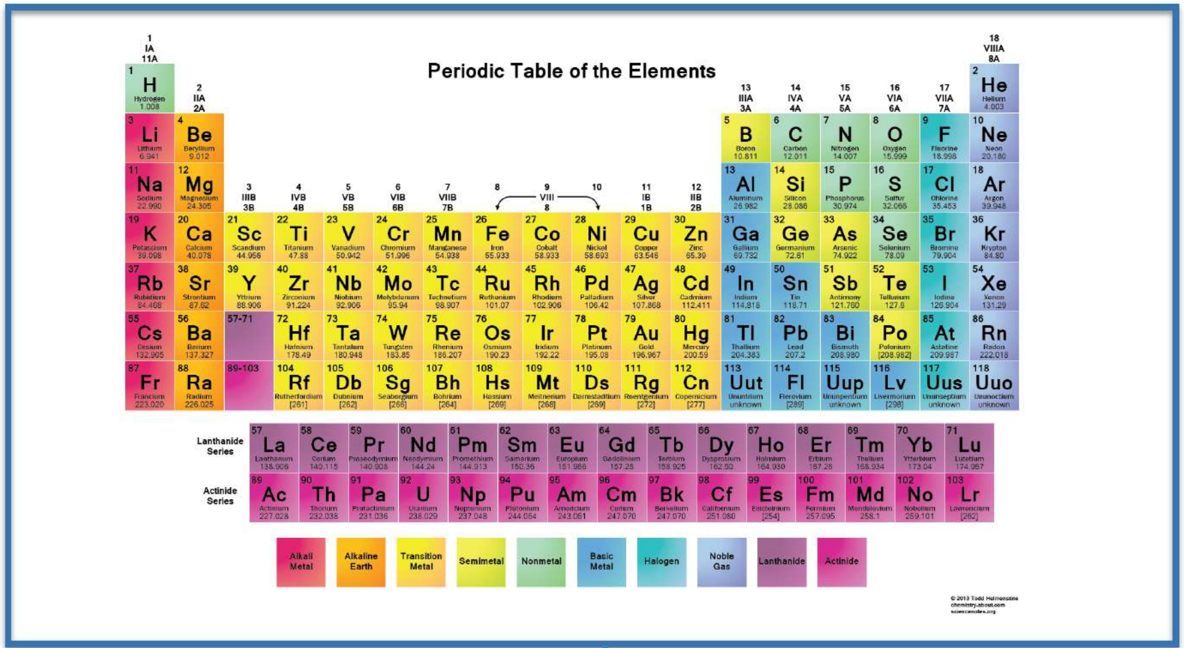
Outline

- The Standard Model and Outstanding Problems
- The LHC and ATLAS
  - ATLAS Physics
- LBNF and DUNE
  - DUNE Physics
- Conclusions

The Standard Model and Outstanding Problems

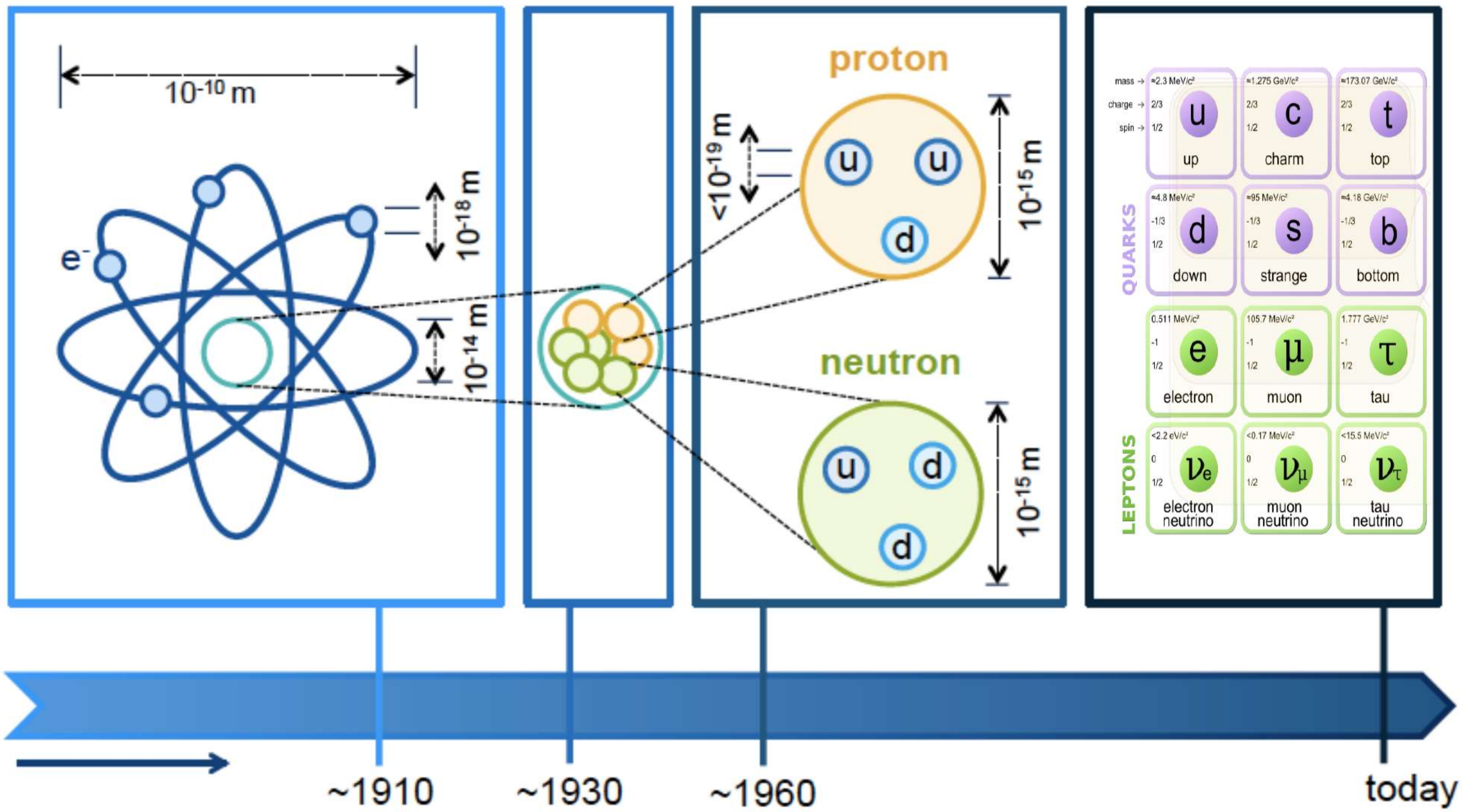
"The more important fundamental laws and facts of physical science have all been discovered" – Michelson in 1903

Matter



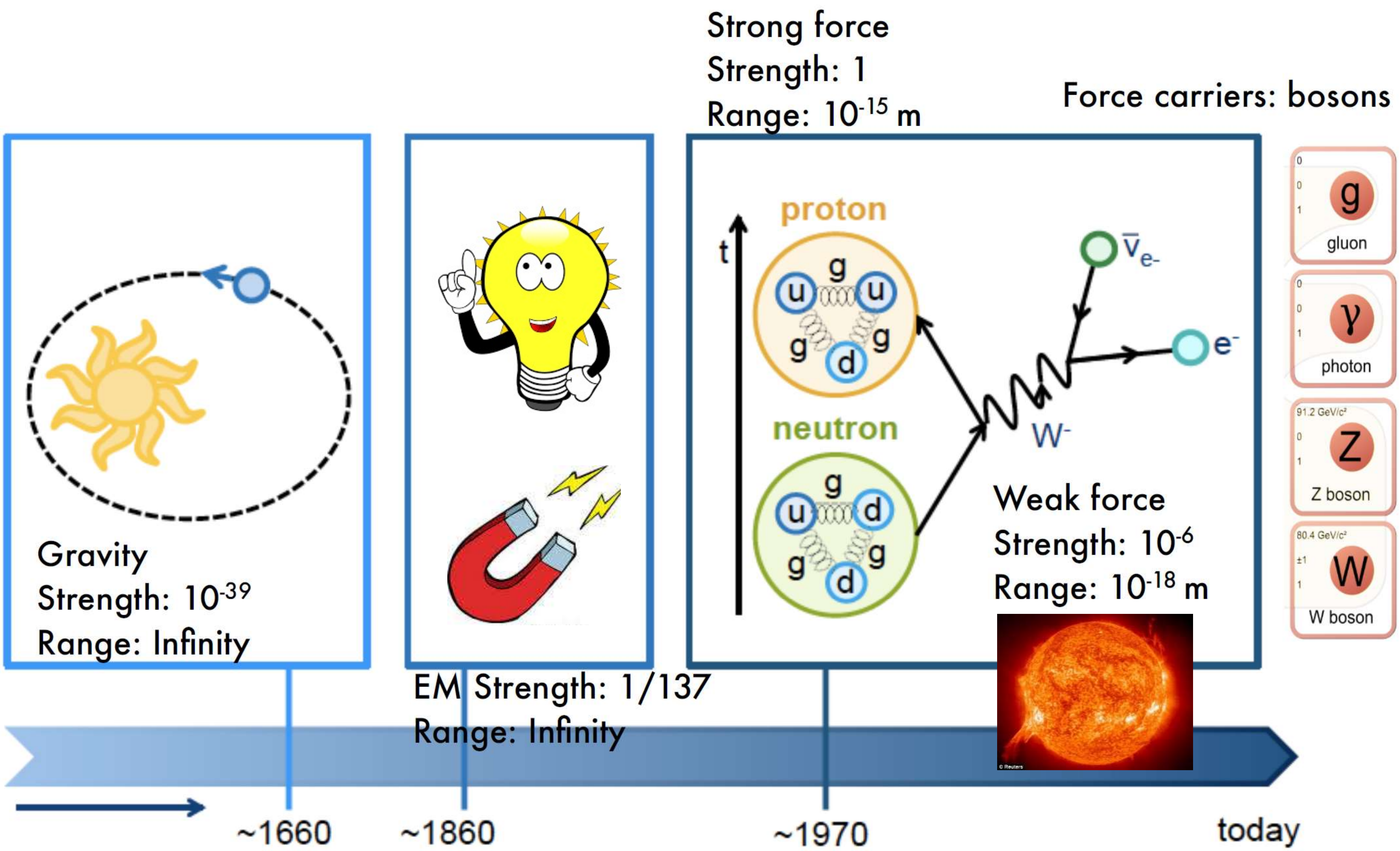
~400 BC 0 AC ~1870

Matter



10-10 m
e-
10-18 m
10-14 m
<10-19 m
proton
u
u
d
10-15 m
neutron
u
d
d
10-15 m
QUARKS
u
up
c
charm
t
top
d
down
s
strange
b
bottom
LEPTONS
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
~1910
~1930
~1960
today

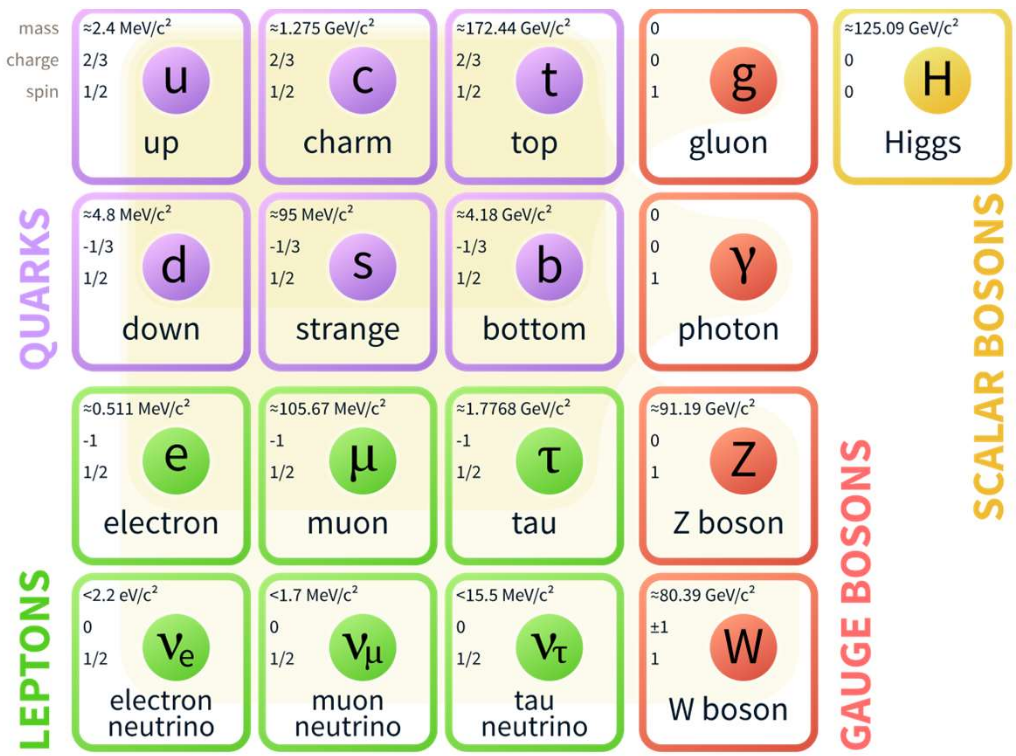
Forces

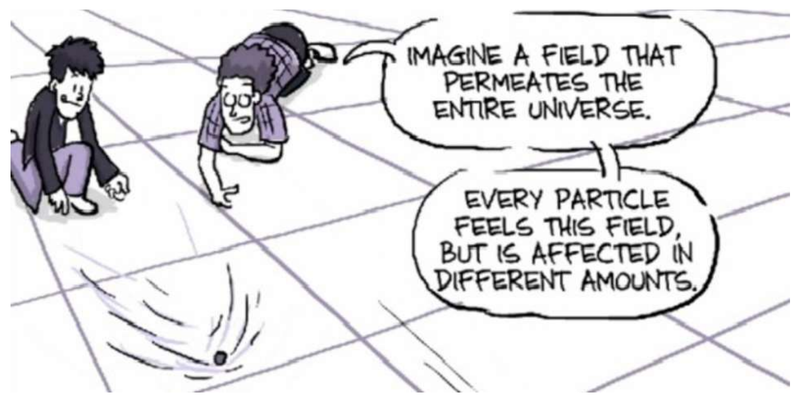


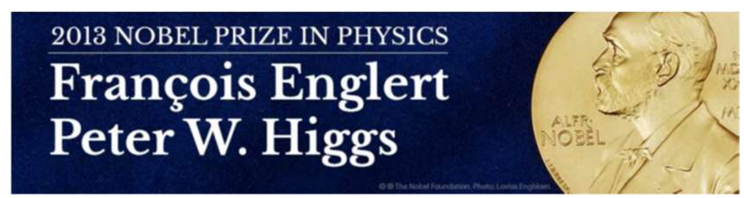
Strong force
Strength: 1
Range: 10-15 m
Force carriers: bosons
proton
neutron
u u d g
u d d g
t
νe-
e-
W-
Weak force
Strength: 10-6
Range: 10-18 m
Gravity
Strength: 10-39
Range: Infinity
EM Strength: 1/137
Range: Infinity
g
gluon
γ
photon
91.2 GeV/c²
Z
Z boson
80.4 GeV/c²
W
W boson
~1660
~1860
~1970
today

The Standard Model

- In 2012 Higgs Boson found!
- Gravity is not in Standard Model (SM)

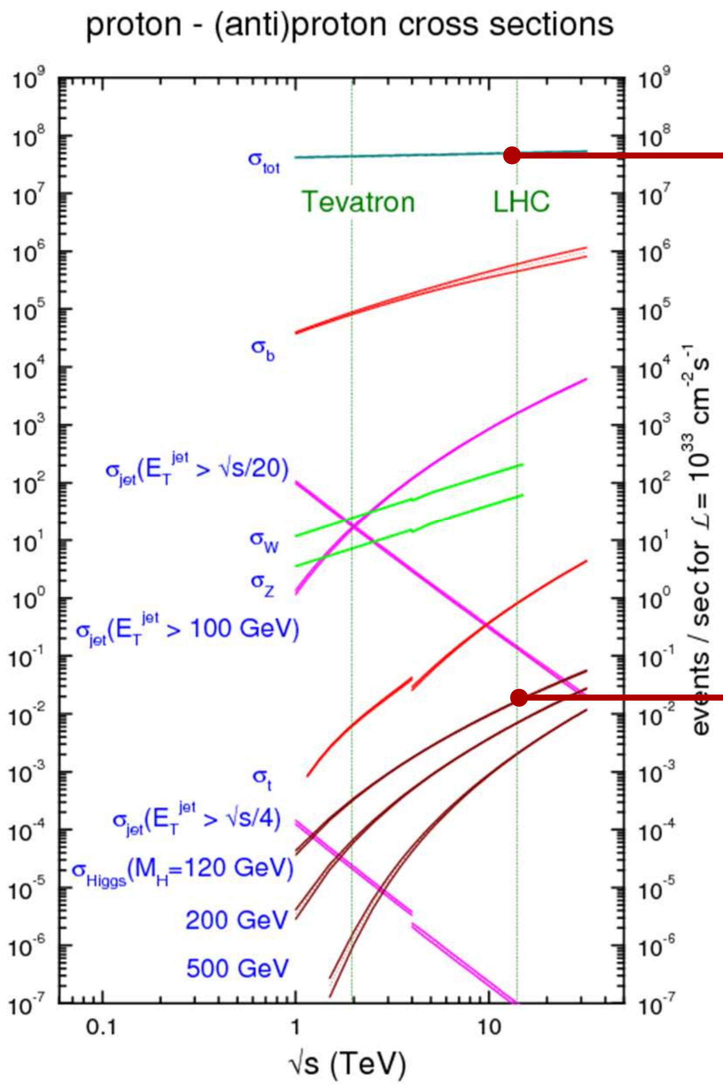






The Standard Model

- Finding the Higgs was hard work! Looking needle in haystack!



10^8 events /s

$\sim 10^{10}$

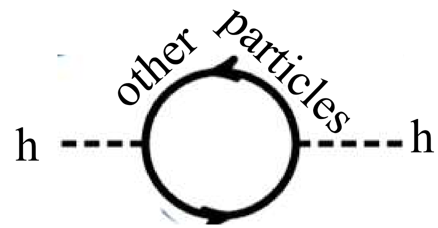
10^{-2} events/s

10 events/min

“The more I learn, the more I realize how much I don't know”

– Albert Einstein

So What Don't We Know? Hierarchy Problem

$m_h^2 \sim m_0^2 + ($  $)^2 = 125^2\ GeV$

Mass of Higgs in vacuum

Quantum Mechanics: Higgs can turn into other particles and back. At higher energy, these contributions approach infinity!

So What Don't We Know? Hierarchy Problem

$$m_h^2 \sim m_0^2 + O\left(10^{18} GeV\right)^2 = 125^2\ GeV$$

Mass of Higgs in vacuum

Quantum Mechanics: Higgs can turn into other particles and back. At higher energy, these contributions approach infinity!

If no new physics, SM breaks down is the gravitational scale: M_{Planck} ~10^{18} GeV

So What Don't We Know? Hierarchy Problem

$$m_h^2 \sim m_0^2 + O\left(10^{18} GeV\right)^2 = 125^2\ GeV$$

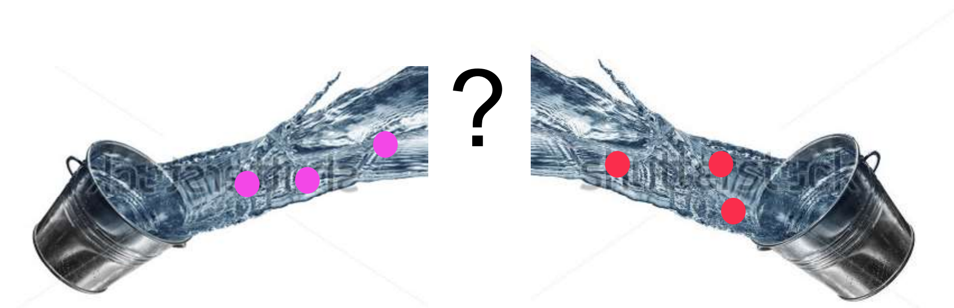
680274891747329871970327489312749 27856 -

680274891747329871970327489312749 12231 $= 125^2\ GeV$

"The Higgs has a snowball's chance in hell of having a mass in that ballpark"

So What Don’t We Know? Dark Matter

- What’s so different about it?



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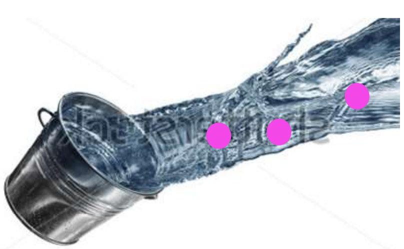

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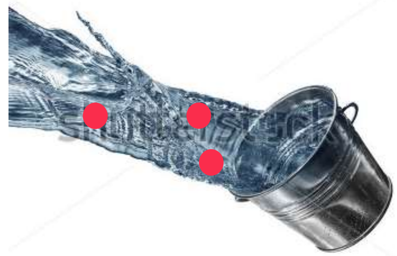
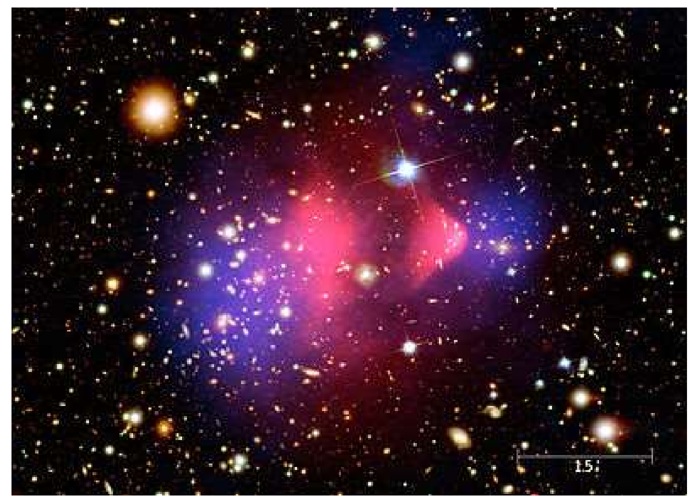


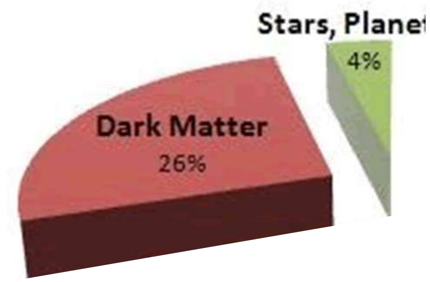
?

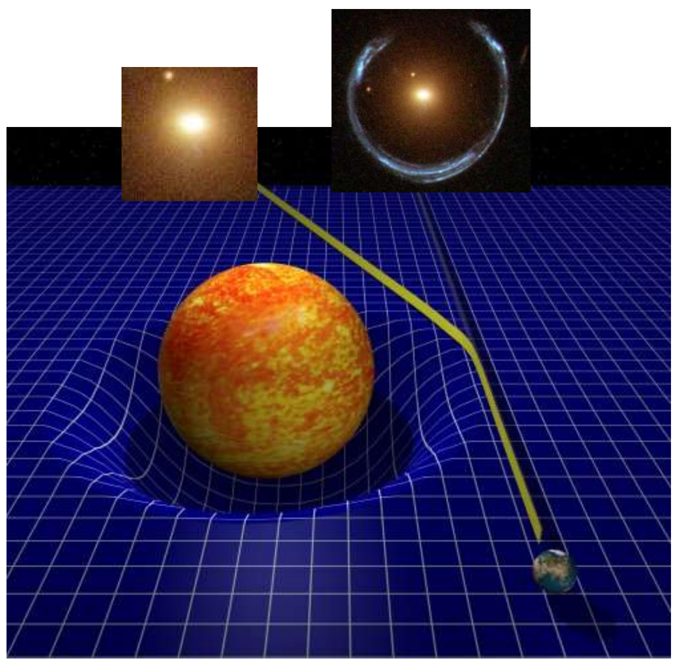


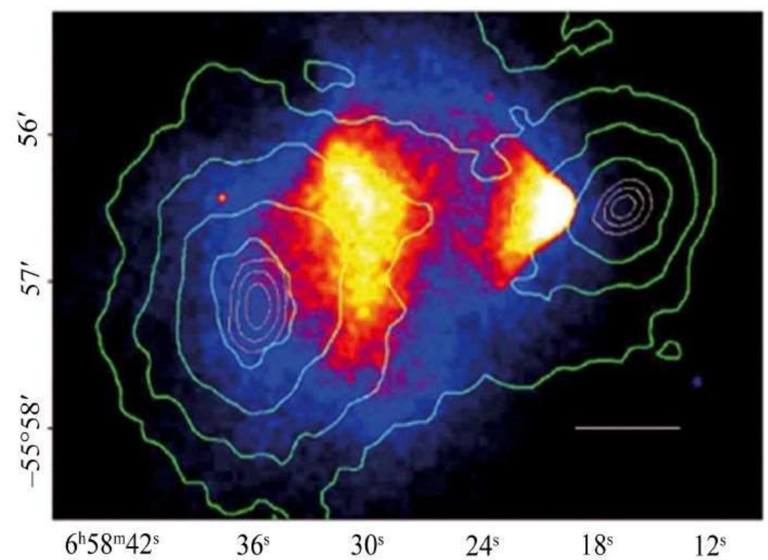
Galaxies made of stars (seen by optical telescope)
and gas+plasma (seen by X-ray telescope)

So What Don’t We Know? Dark Matter

- By looking at gravitational lensing we can calculate where most of mass is. Not where plasma located!
- It seems dark matter passed right through, how did it interact?

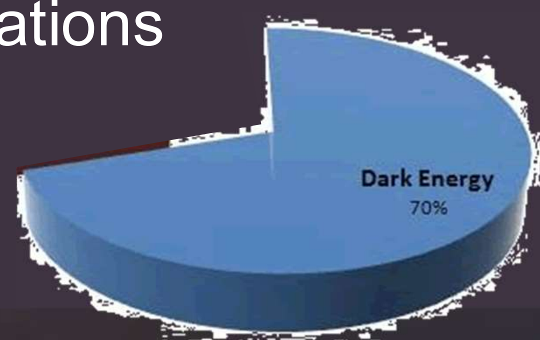






So What Don't We Know?

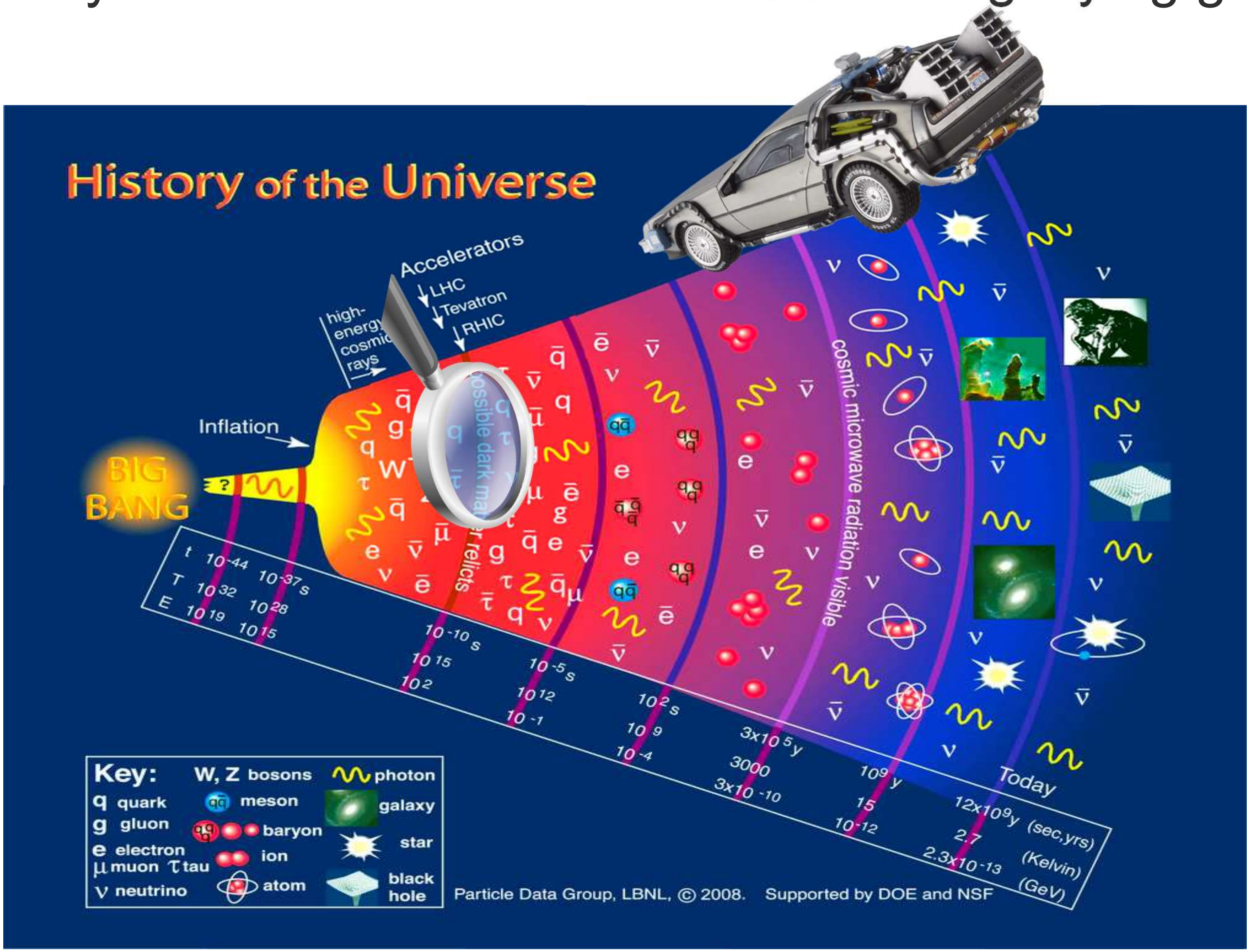
- How does gravity fit with the SM?
- Why do neutrinos have mass?
- Why is there more matter than anti-matter?
- What is Dark Energy?
- ……..
- Look for SM deviations by measuring SM & Higgs properties
- Search for beyond SM theories with explanations



"In god we trust, all others must bring data" – William Deming?

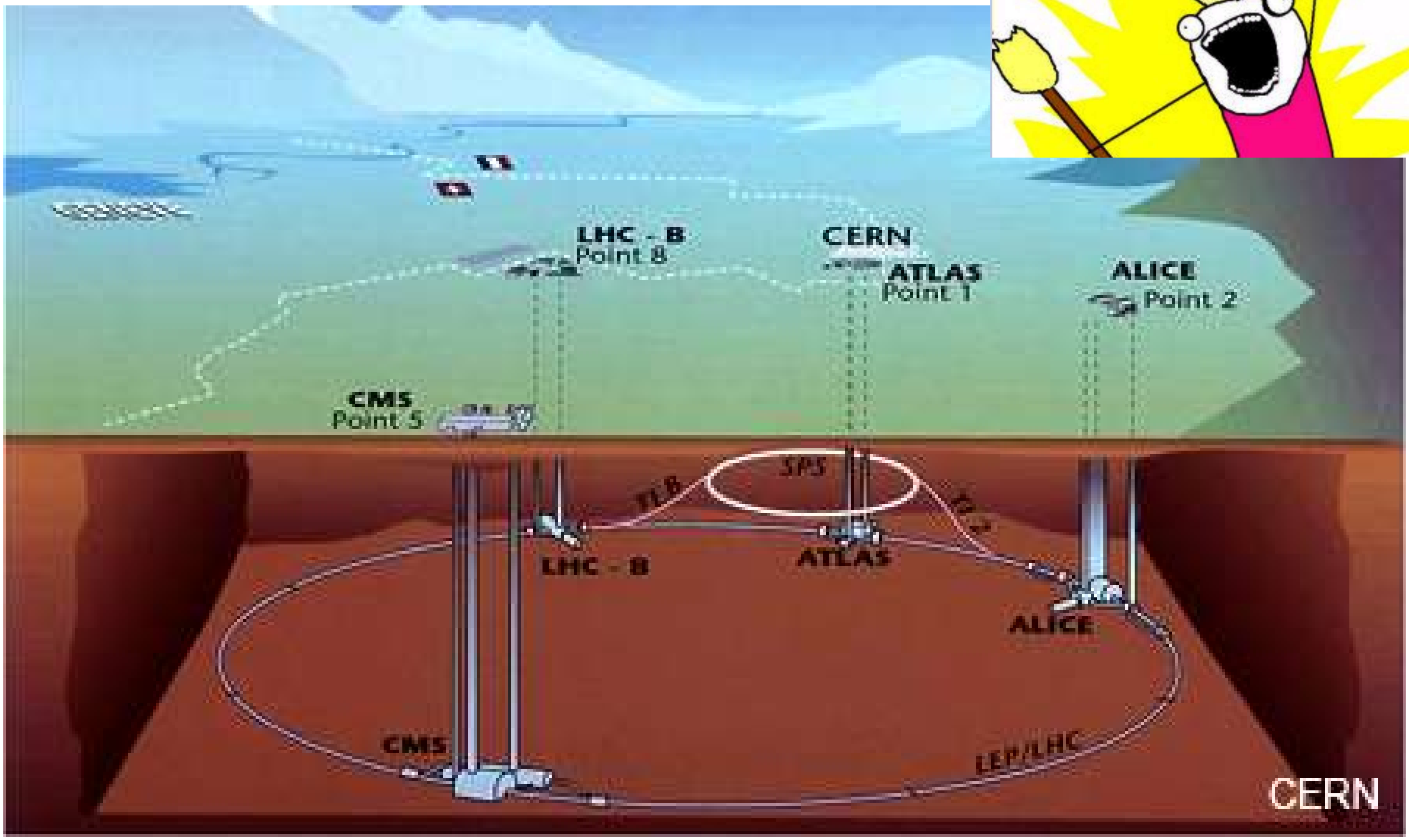
How Do We Get Data?

- Easy! Just need a time machine and magnifying glass!

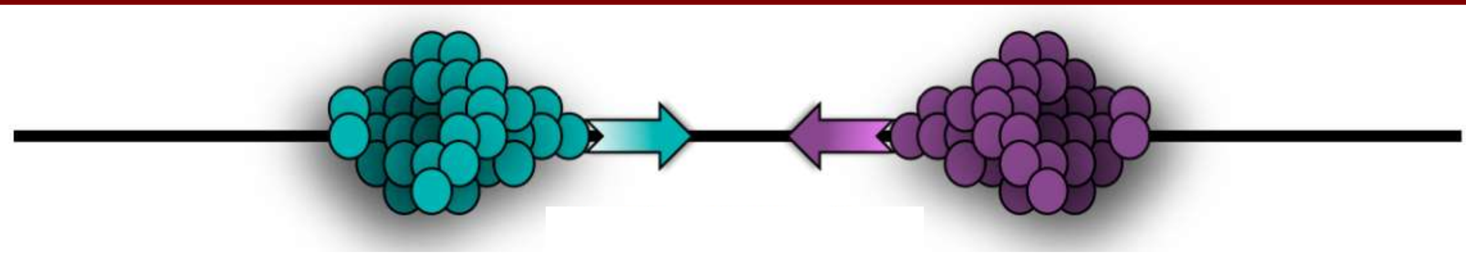


The LHC and ATLAS

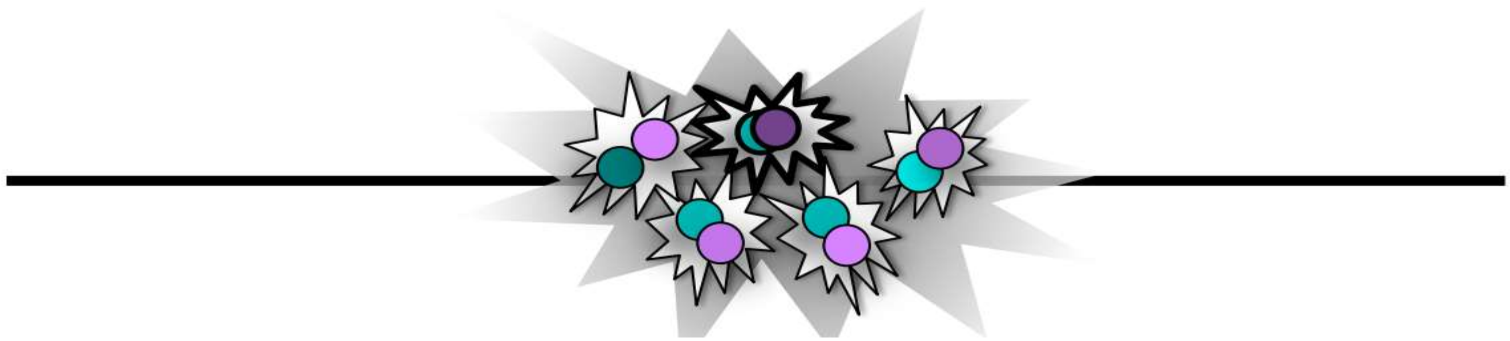
Large Hadron Collider

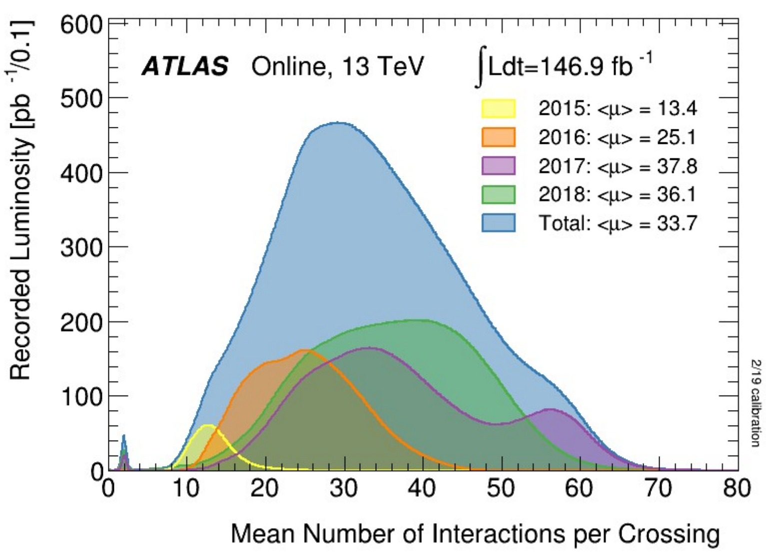


Large Hadron Collider



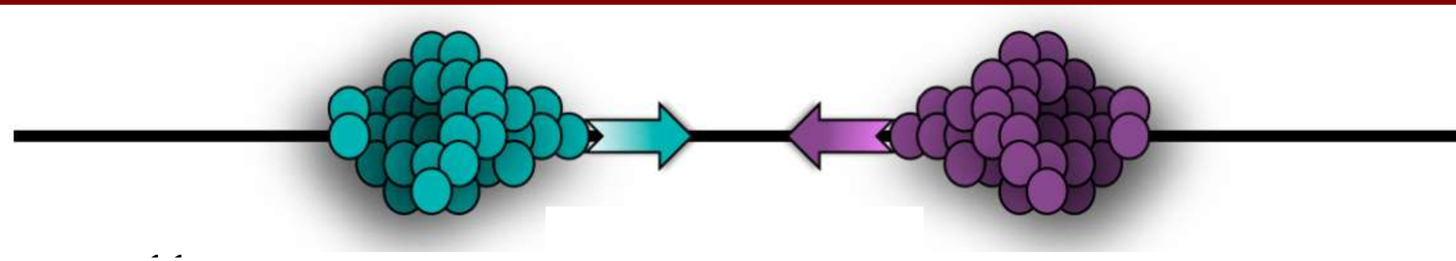
10^{11} **protons per bunch, colliding at 40 MHz (every 25 ns)**

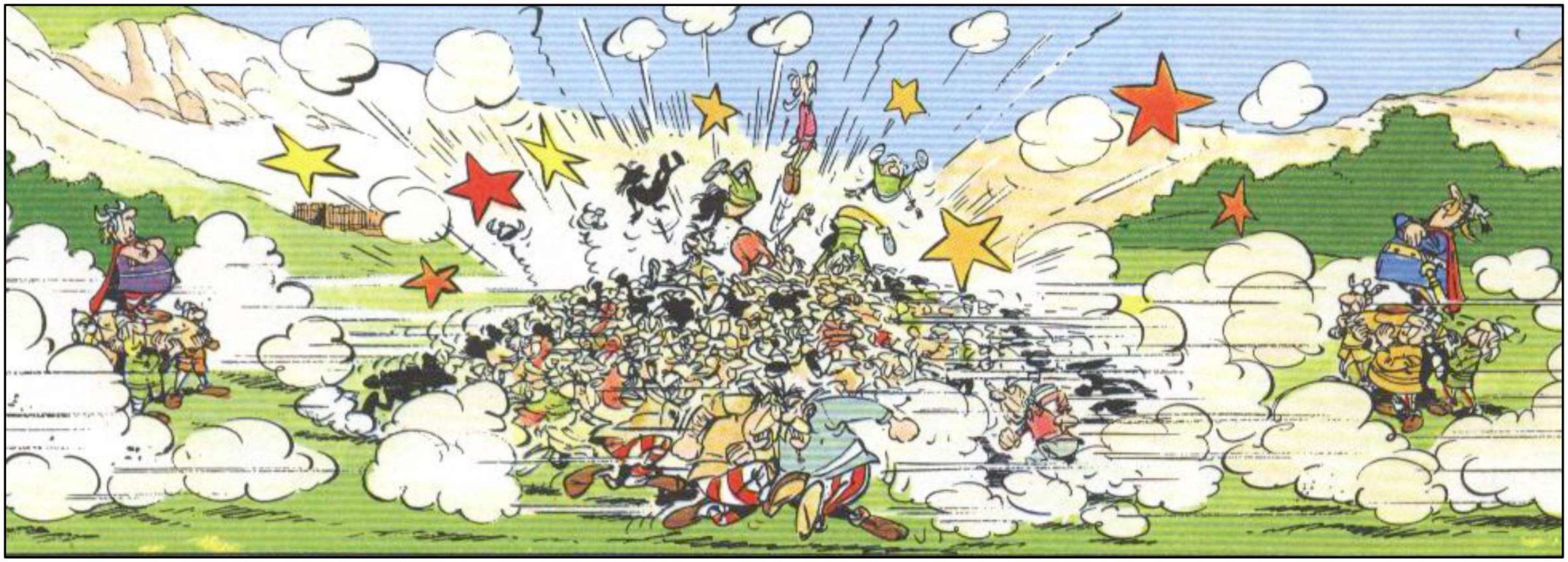


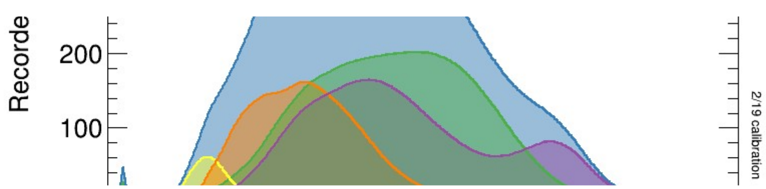


- **Number of interactions per bunch crossing goes up to 70**
- Selecting interesting events a challenge!

Large Hadron Collider



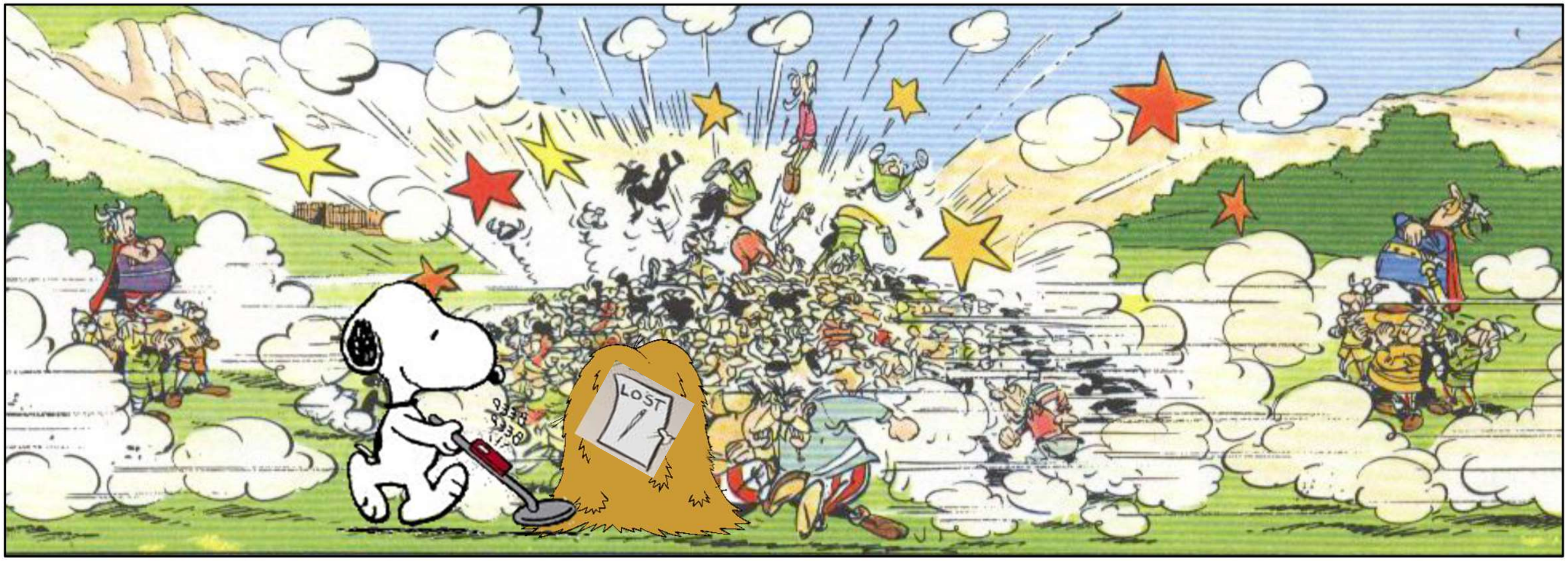




- Selecting interesting events a challenge!

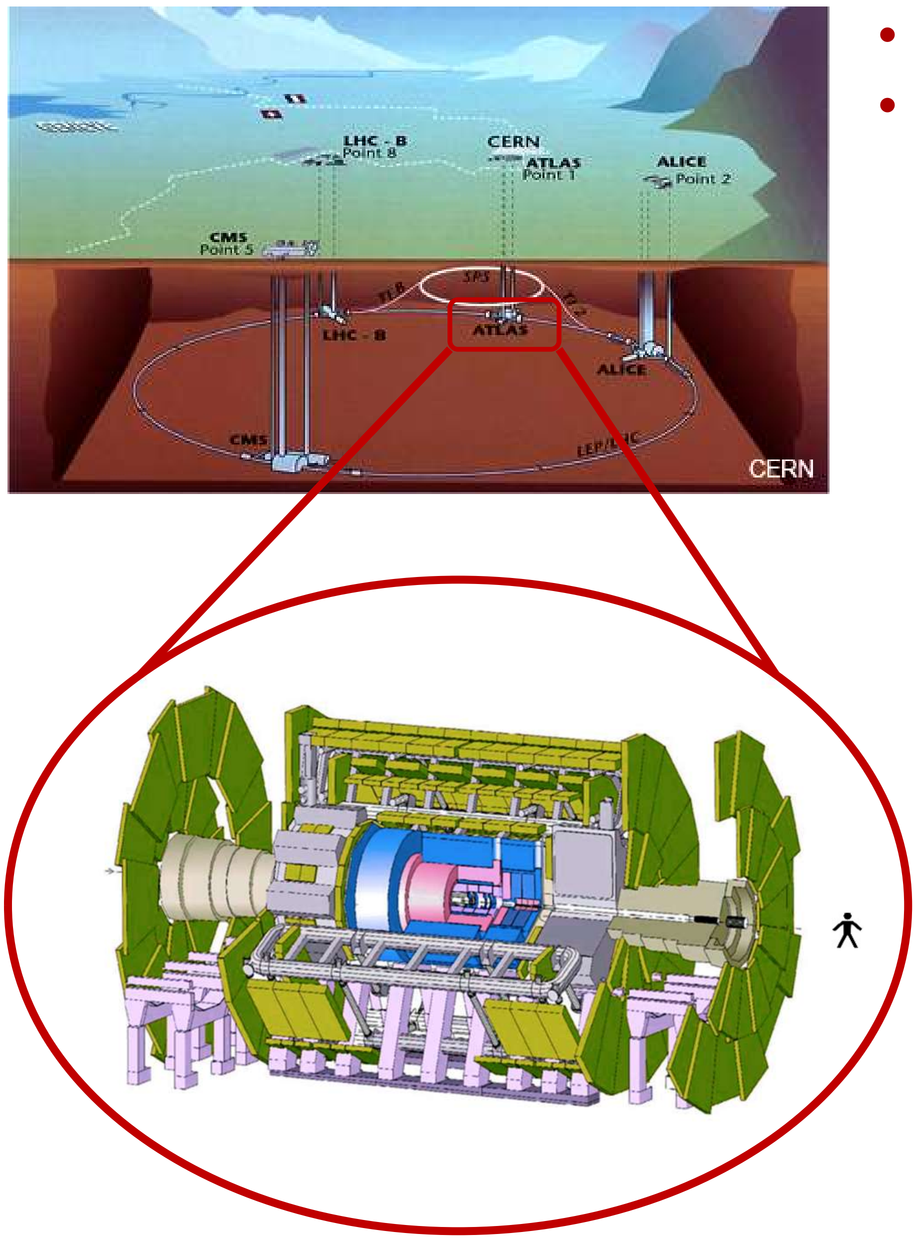
Large Hadron Collider

Find needle in haystack in battlefield!



- LHC gives us 40 MHz, but we can only save 1kHz!
- Our interesting physics events are rare!

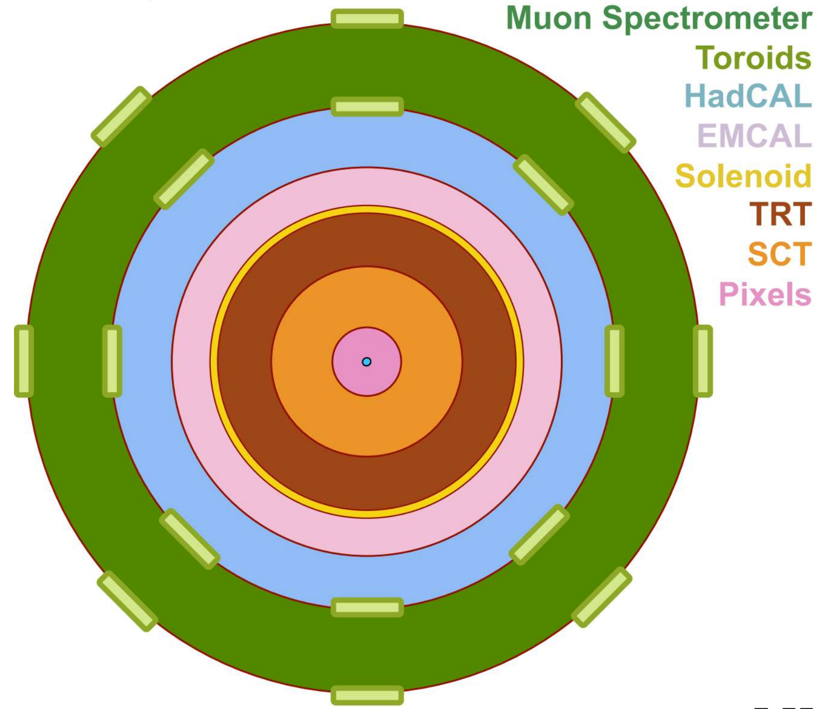
ATLAS Detector



- A big fancy camera!
- ATLAS is a multi purpose detector, 46 m in length, 25 m in diameter with a weight of

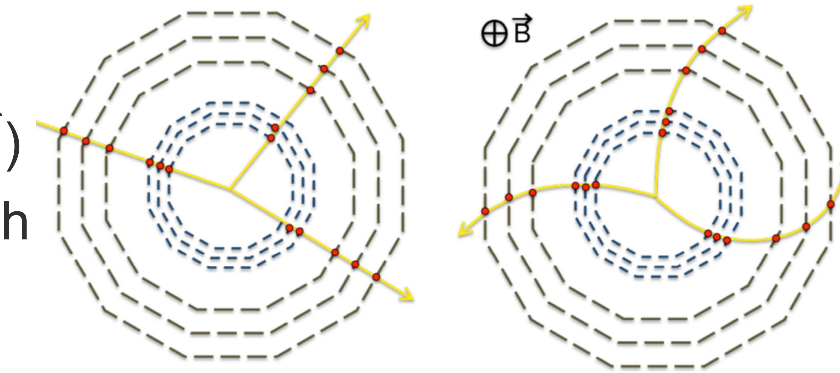
  7 000 tonnes

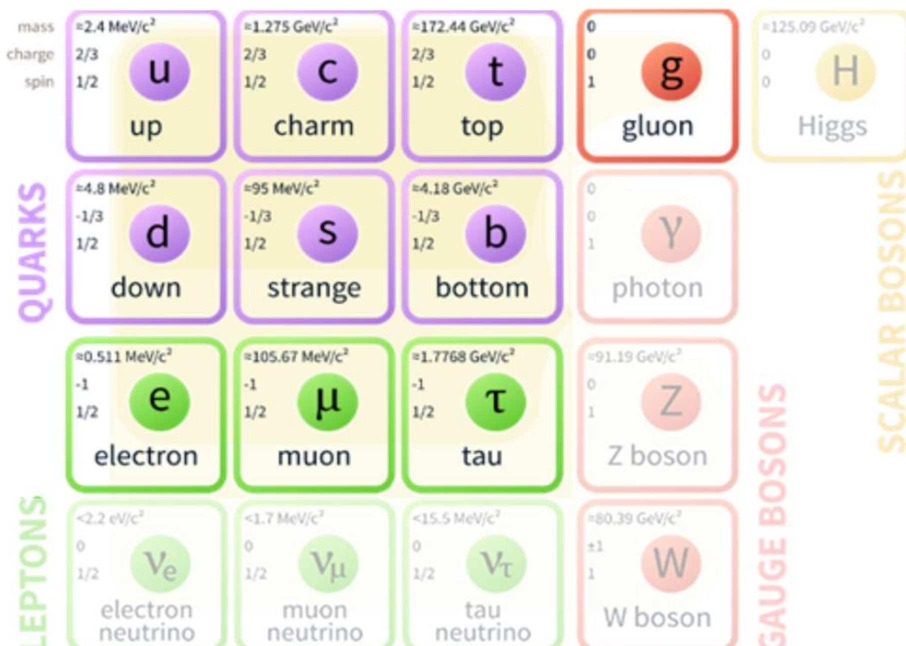
Simplified Detector Transverse View

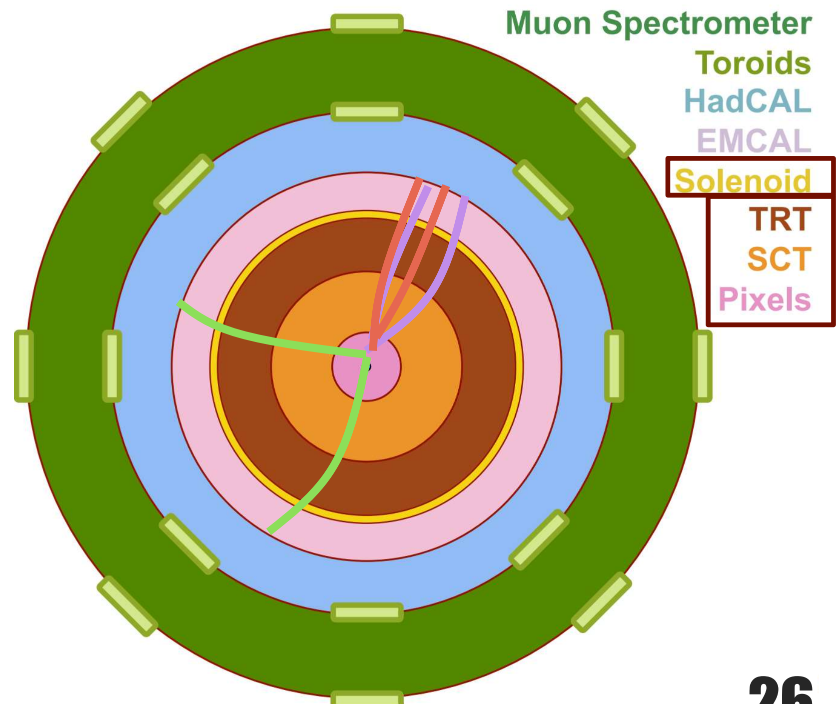


ATLAS Detector

- The ATLAS Inner Detector consists of Pixel, SCT and TRT in magnetic field ($\vec{B}$)
- By knowing strength of $\vec{B}$ and how much track curves, can calculate momentum
- Provides measurement of momentum, direction, charge for all charged particles

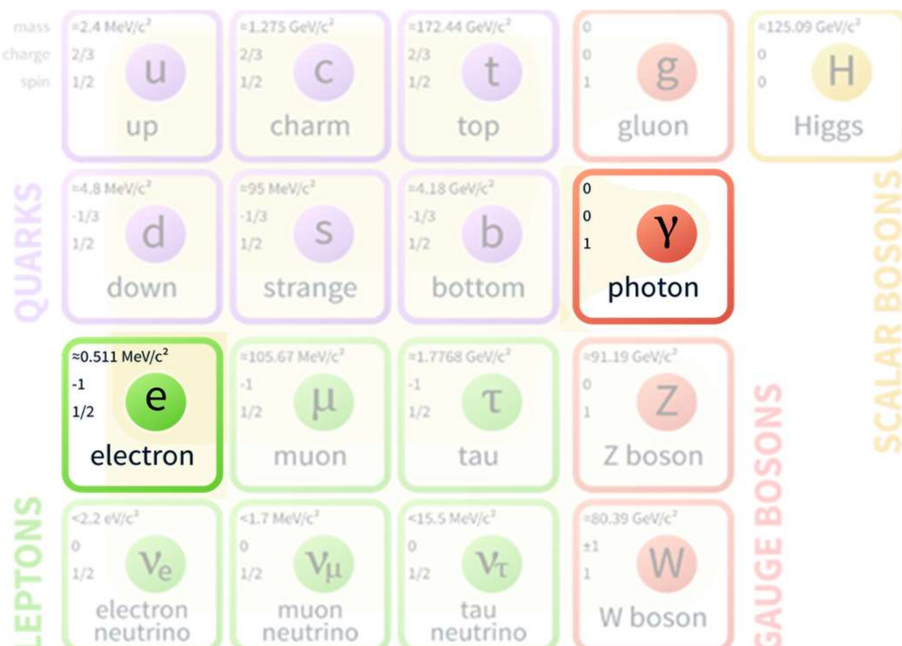


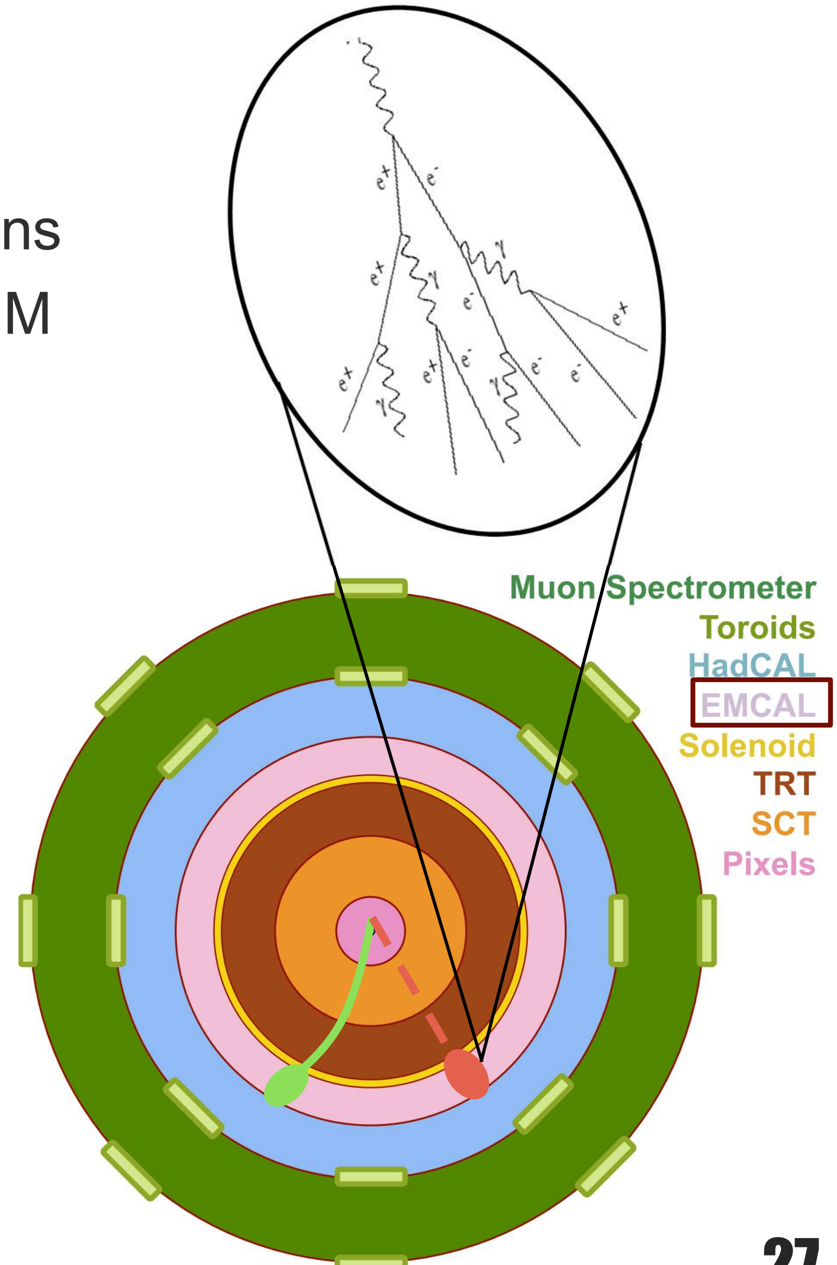




ATLAS Detector

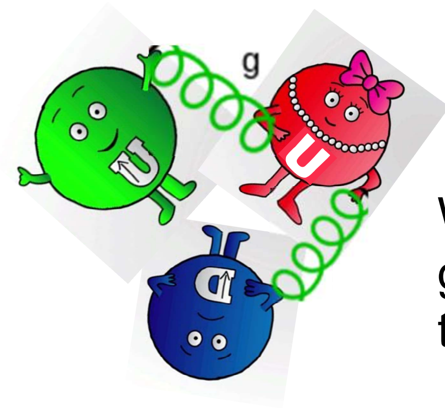
- Electromagnetic calorimeter (Liquid Argon) absorbs electrons and photons
- Provides energy measurement of EM showers



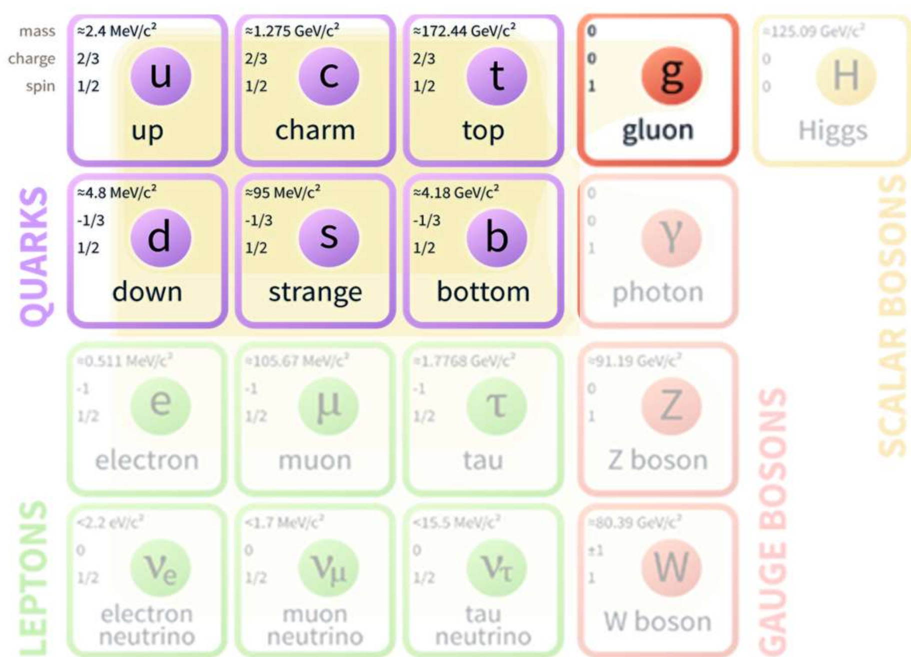


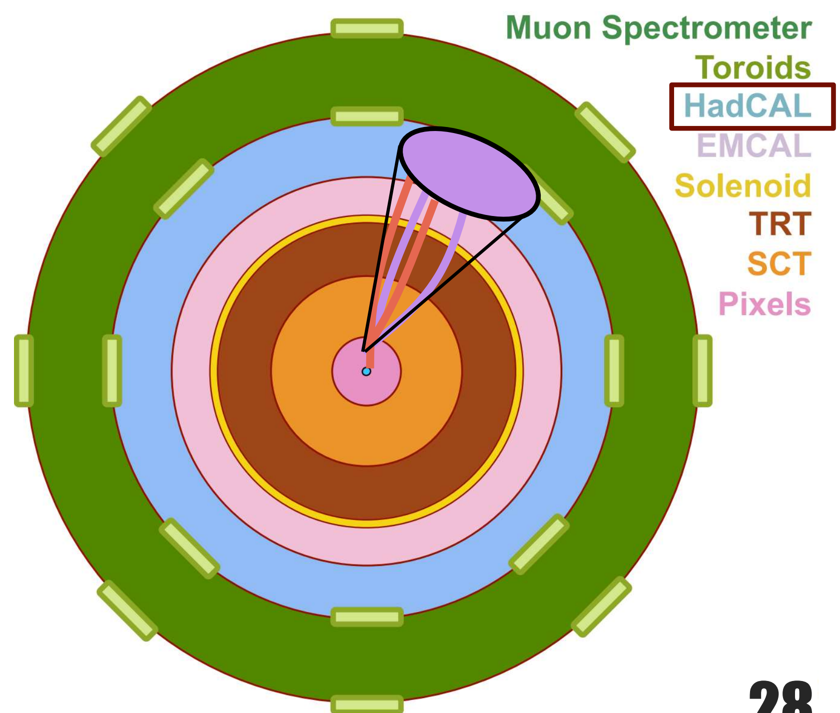
ATLAS Detector

- Quarks hate loneliness, they always team up to make hadrons
- Hadronic calorimeter (TileCal) absorbs hadrons (protons, neutrons etc.)
- Provides energy measurement of jet hadronic showers (jets)



We're glued together!





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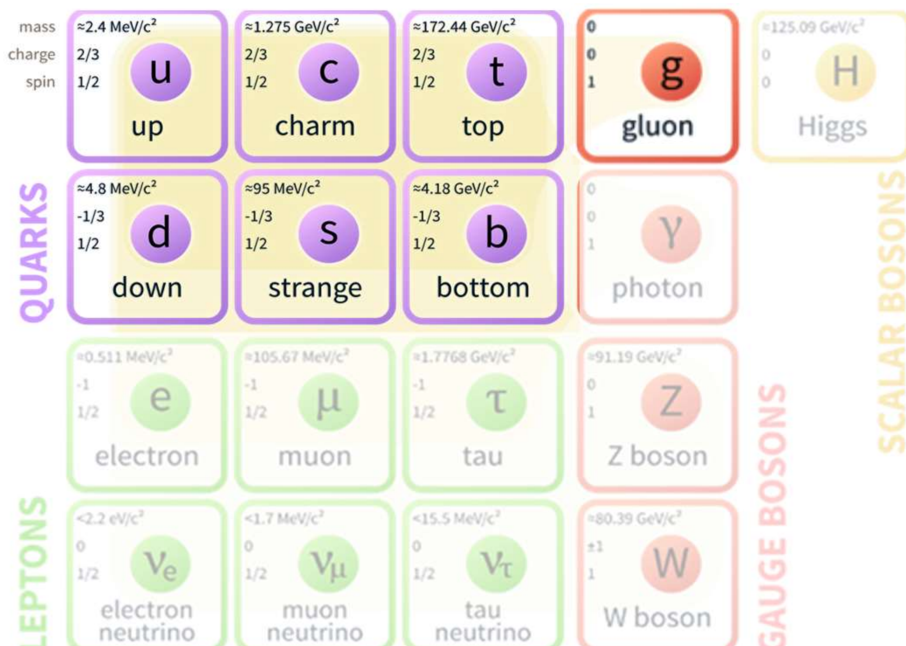
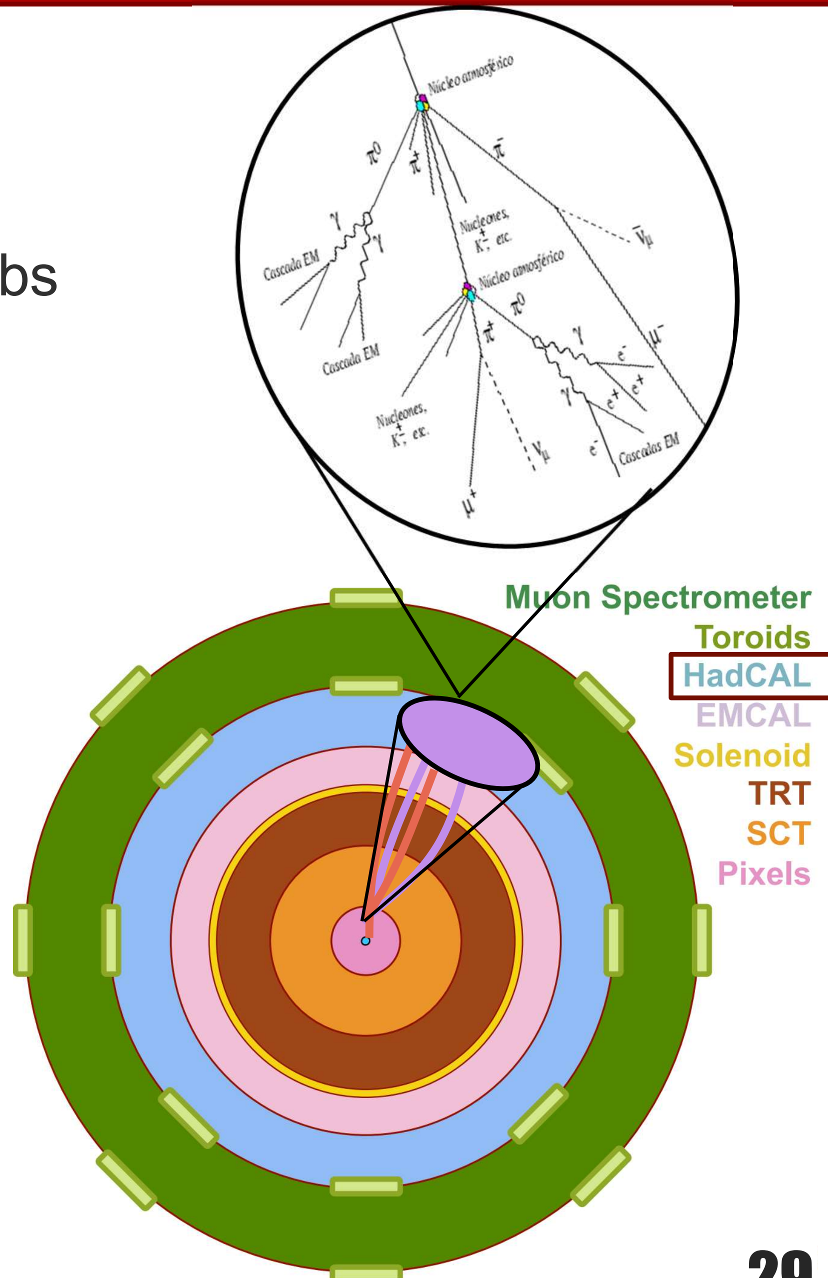
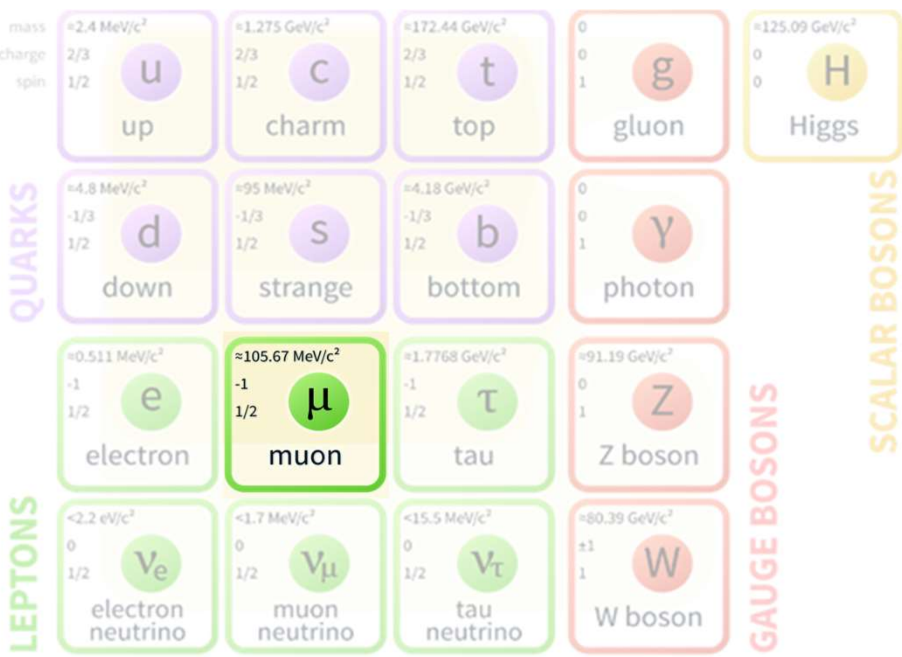
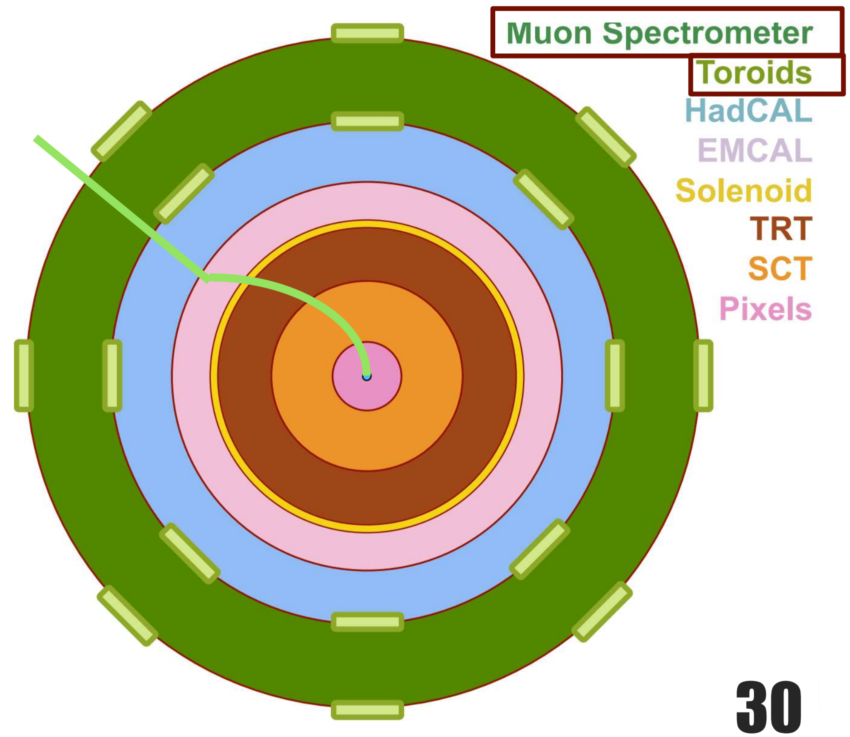




ATLAS Detector

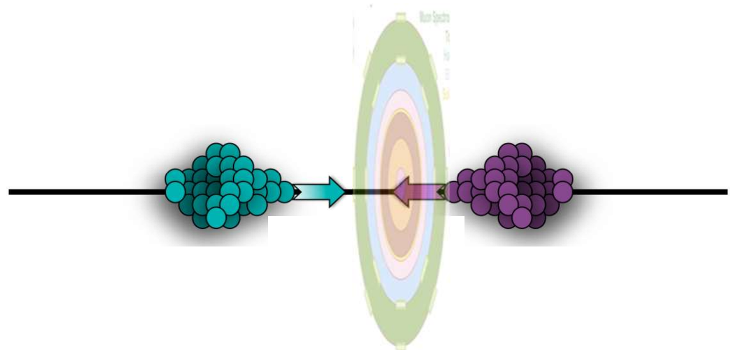
- Muons escape the detector, but leave tracks in the muon spectrometers, which are also surrounded by magnetic field



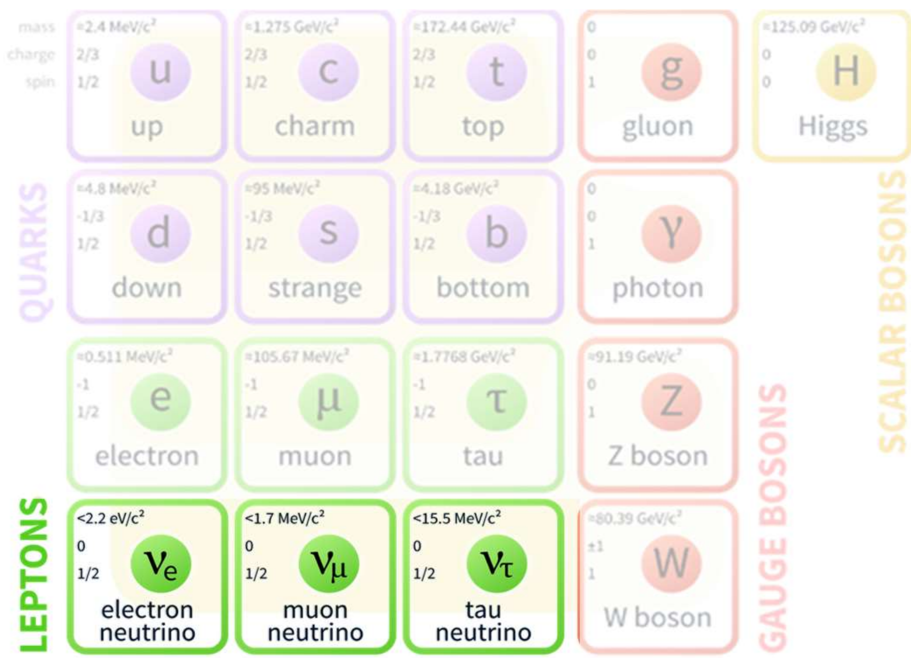


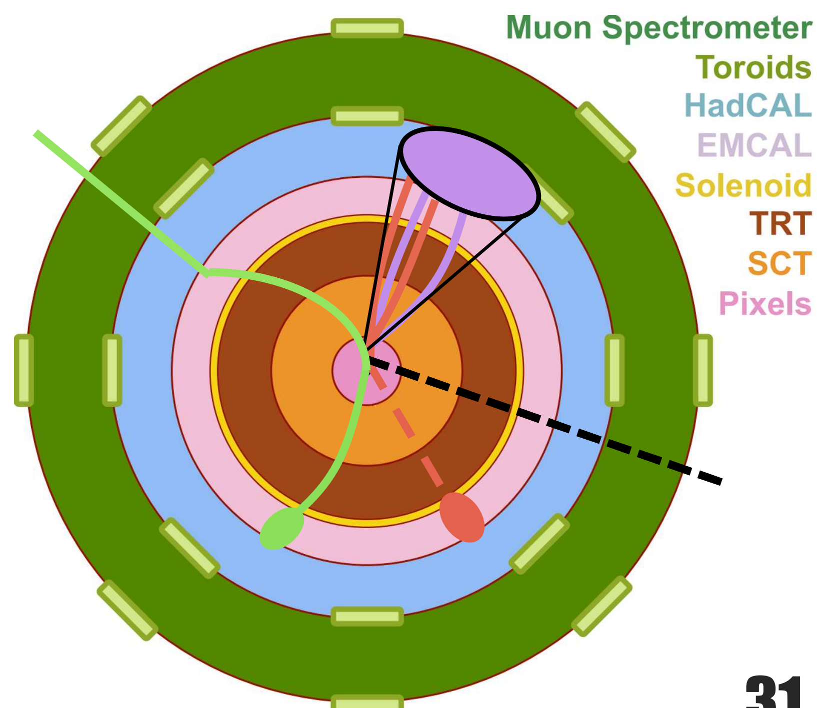
ATLAS Detector

- Neutrinos escape the detector, but their presence inferred from missing transverse energy



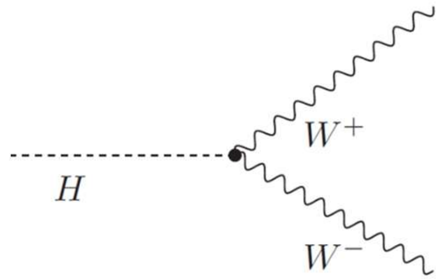
Before collision sum of momenta in transverse plane is 0. Must be true after collision as well

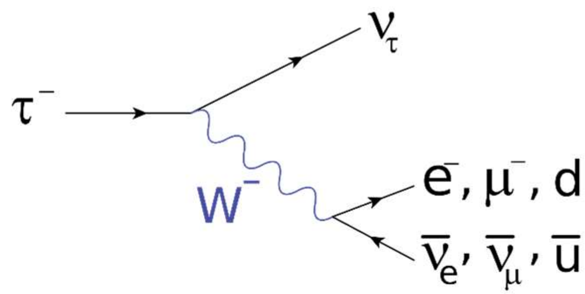


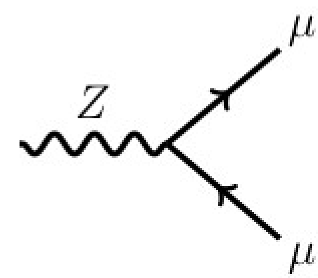


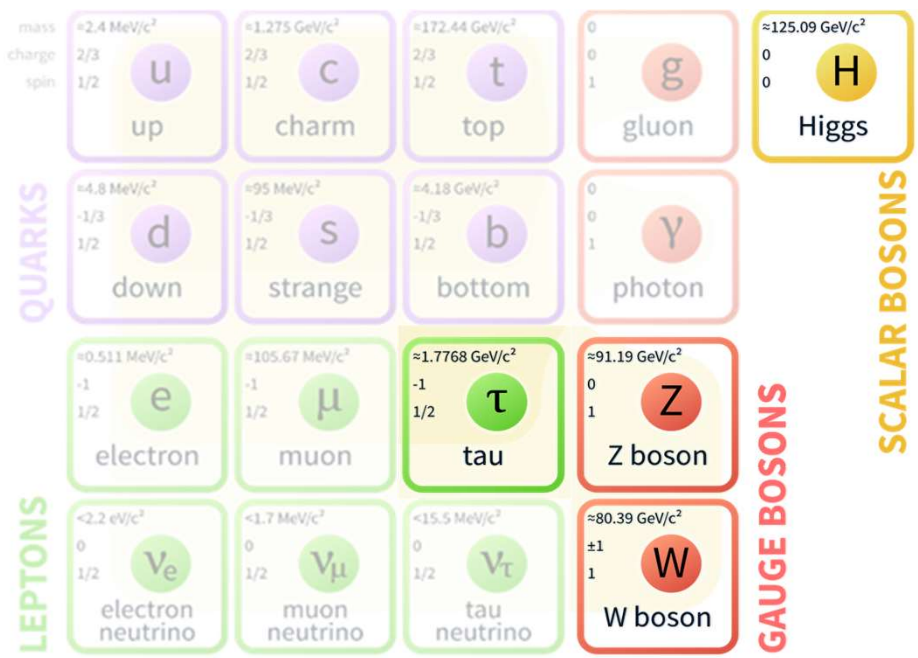
ATLAS Detector

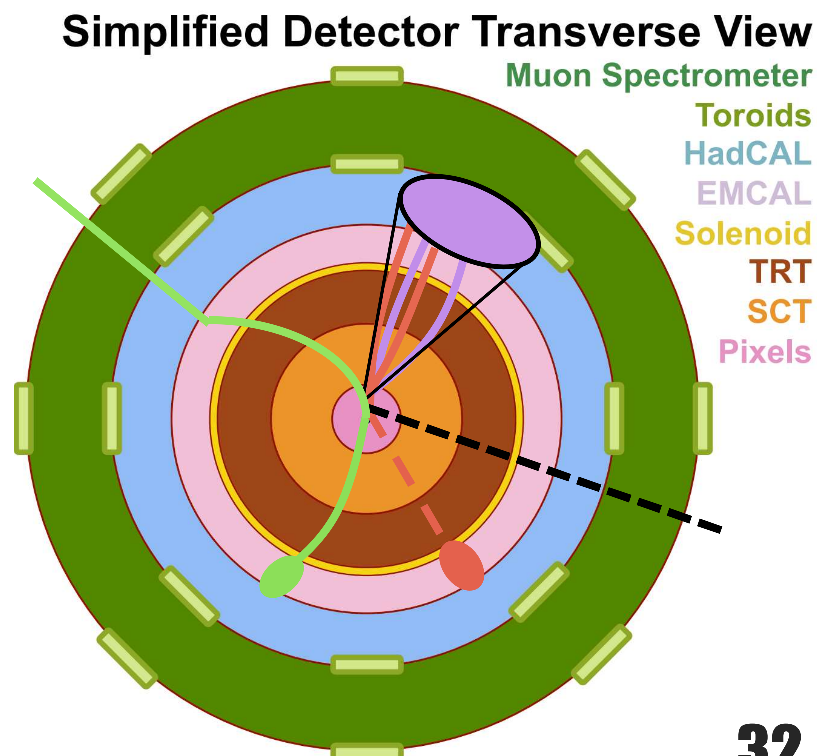
- Some particles decay quickly to others and their presence is inferred





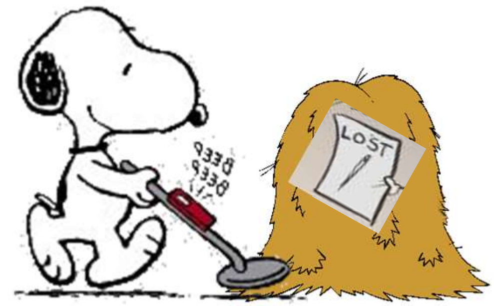


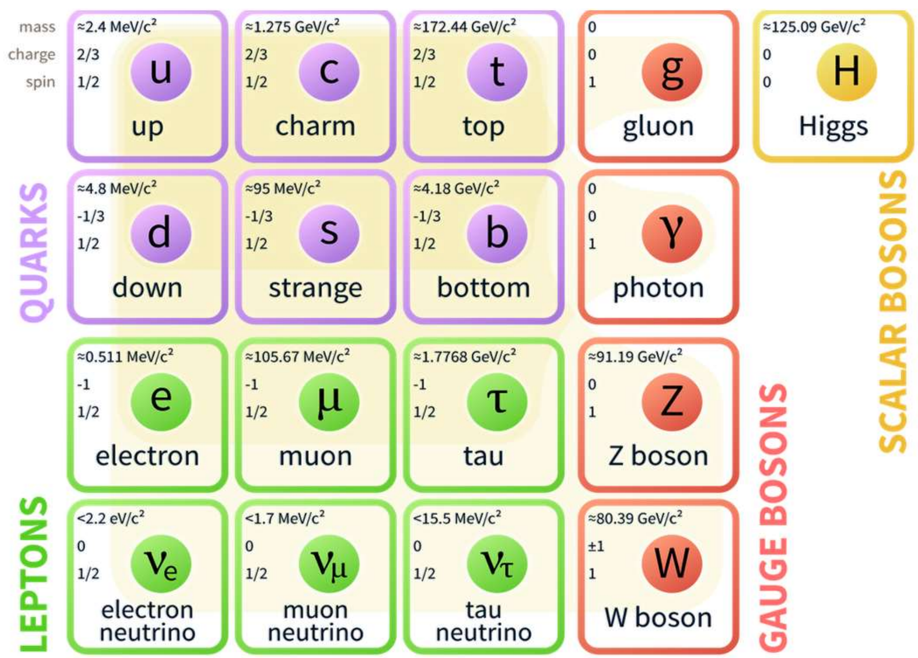




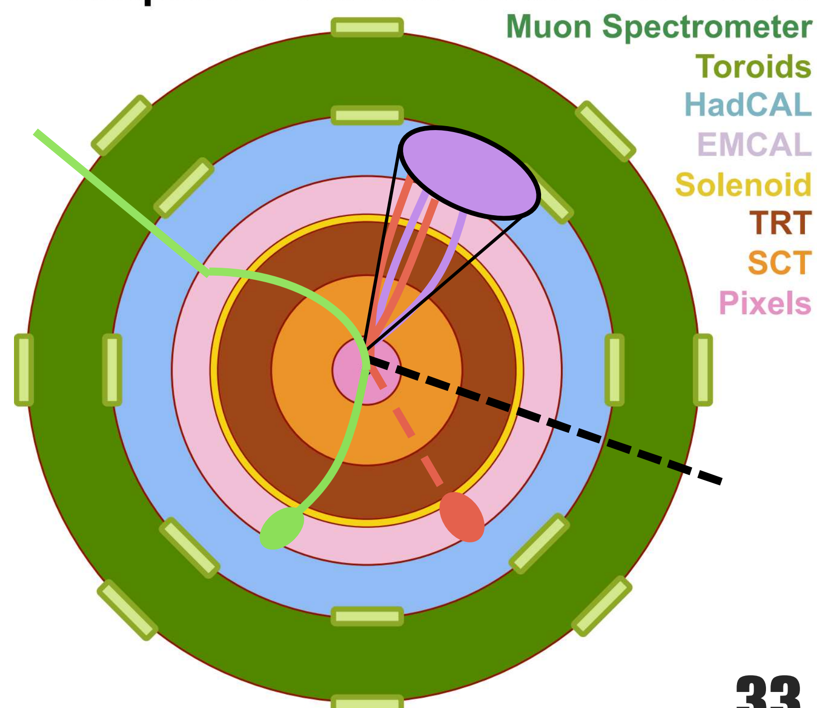
ATLAS Detector

- That's how our camera builds a picture of all particles in each event
- But, how does it sort through junk to find important events?



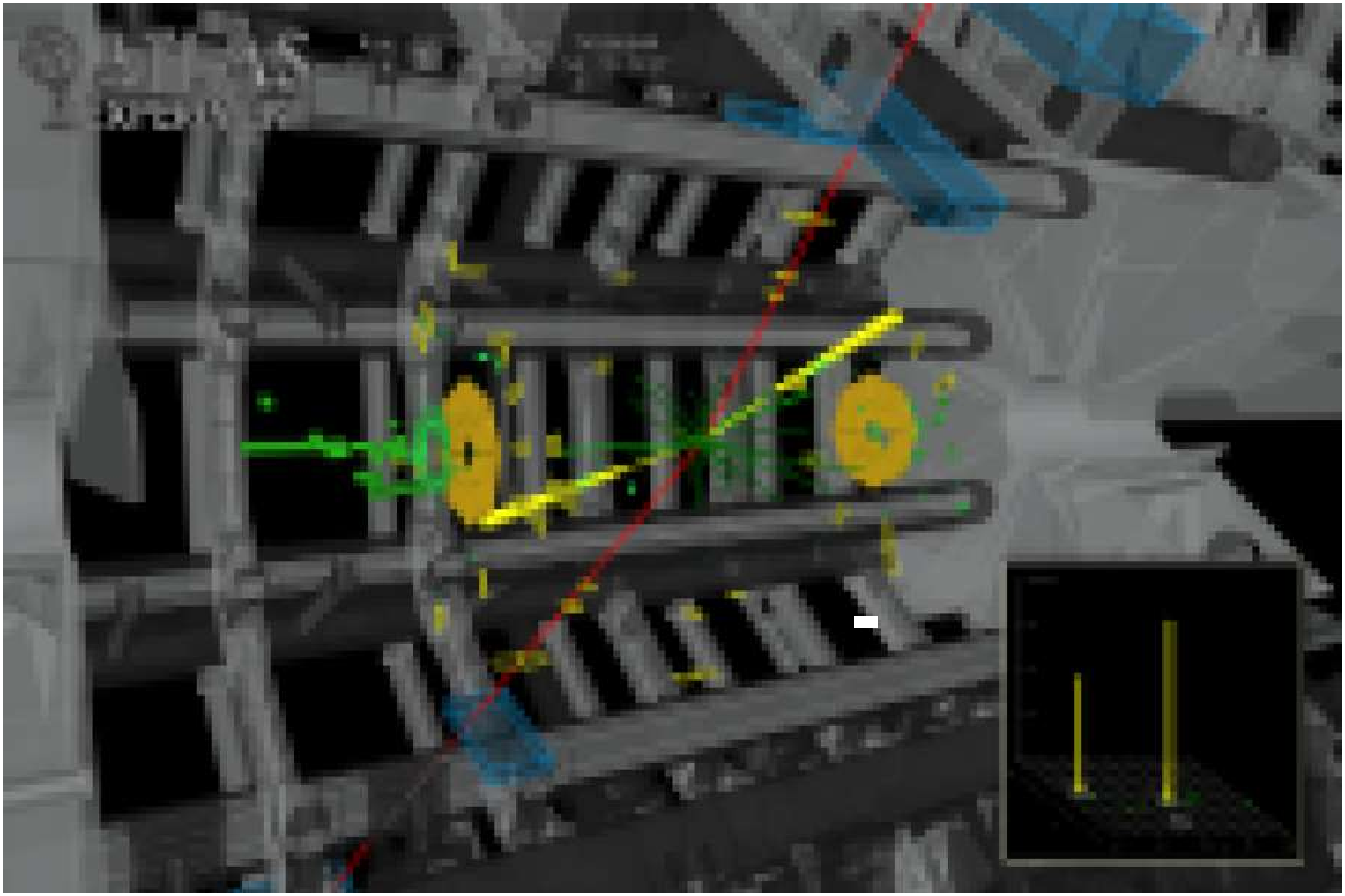


Simplified Detector Transverse View



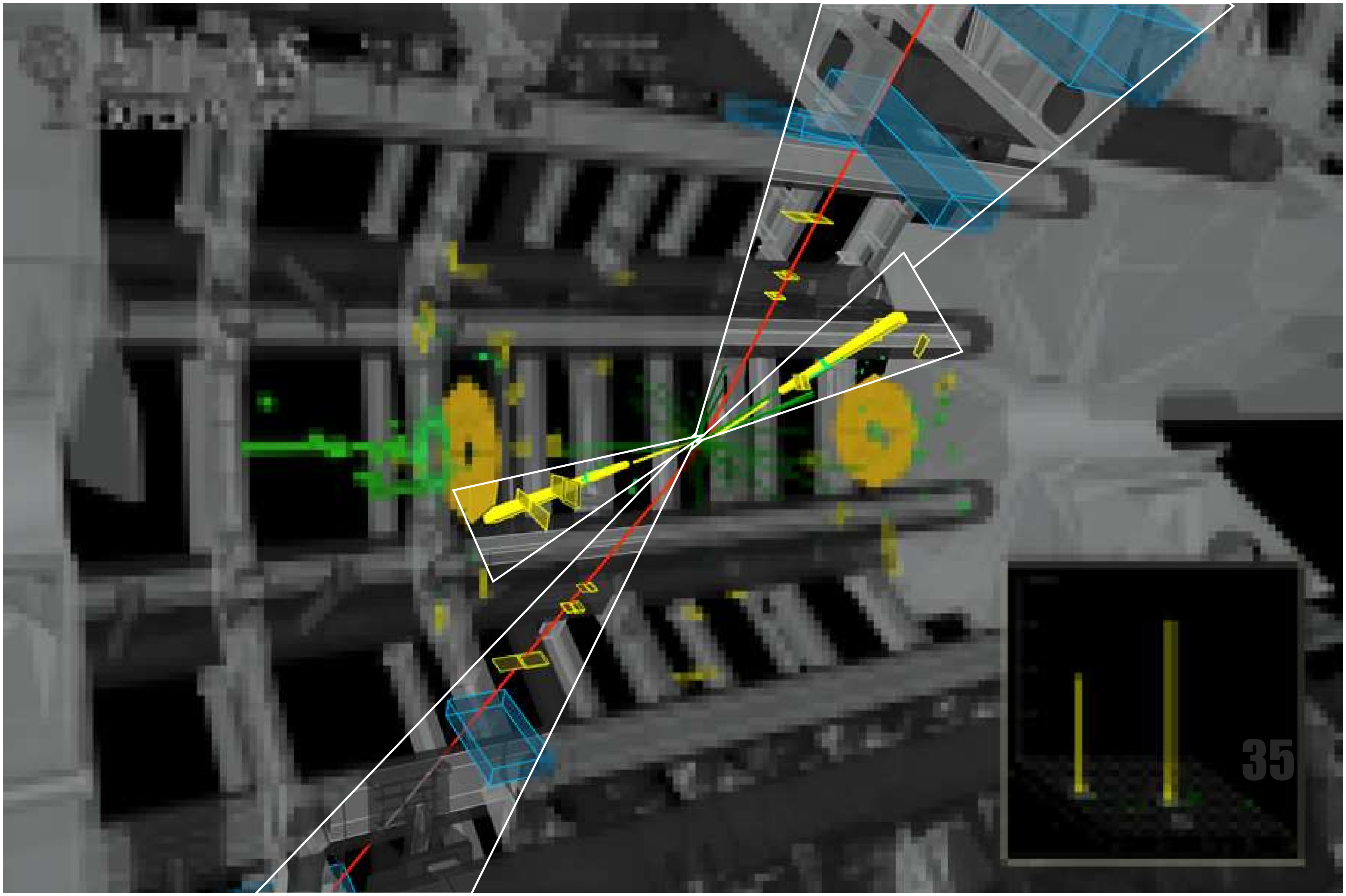
ATLAS Detector : Trigger – STEP 1 L1

- Reduce 40 MHz to 100 kHz in 2.5 μs
- Level 1 (L1) Trigger: electronics on calorimeters and muon detector



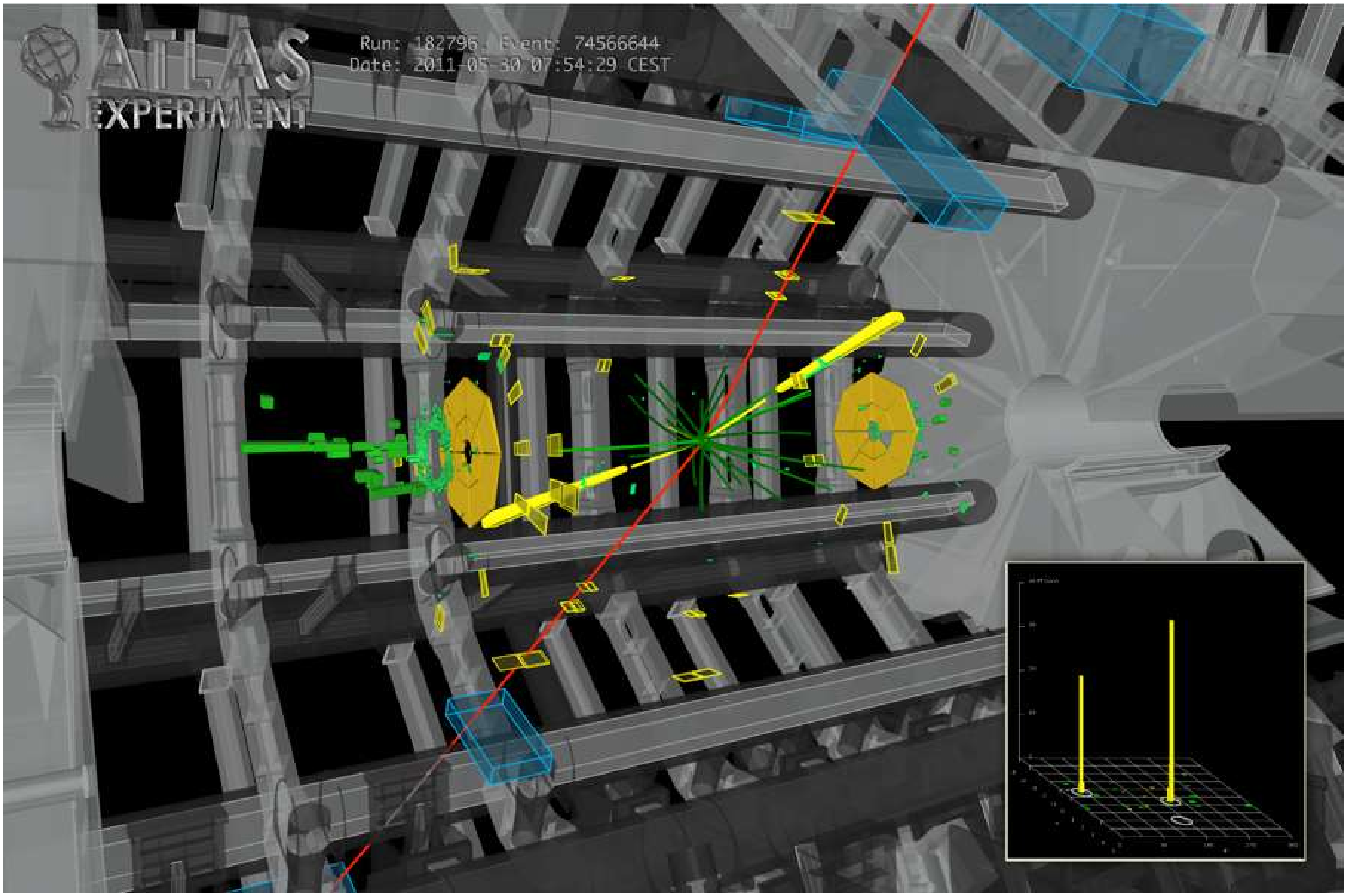
ATLAS Detector : Trigger – STEP 2 HLT

- Reduce 100 kHz to 1kHz in ~ 0.2 s
- Higher Lever Trigger (HLT): software



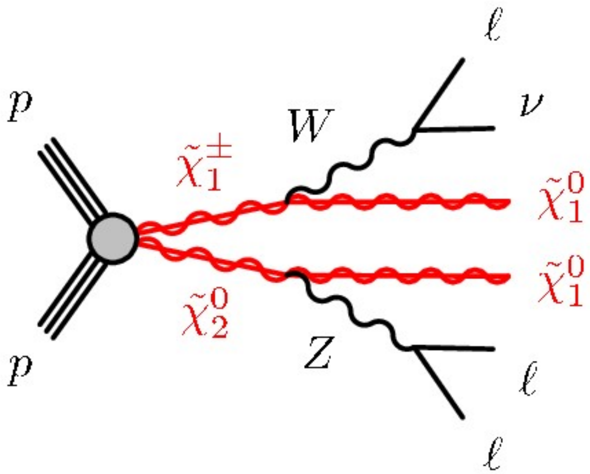
ATLAS Detector : Trigger – STEP 3 HLT

- Reduce 100 kHz to 1kHz in ~ 0.2 s
- Higher Lever Trigger (HLT): software

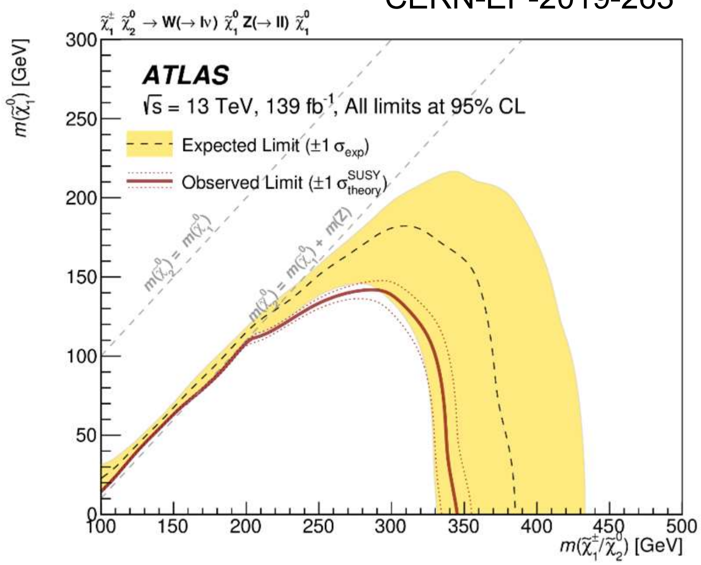


ATLAS Physics

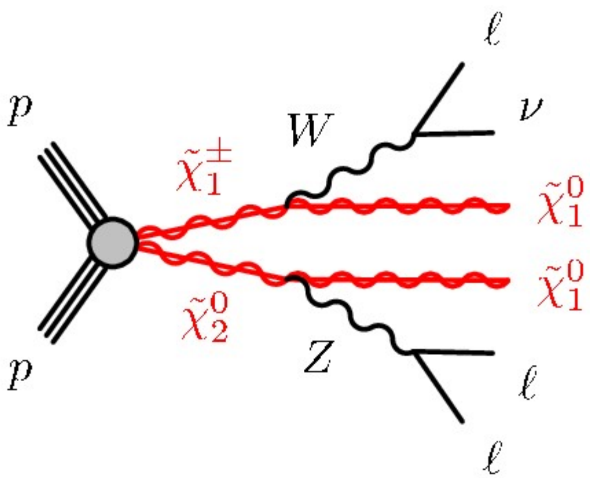
Mass Hierarchy solution: SUSY



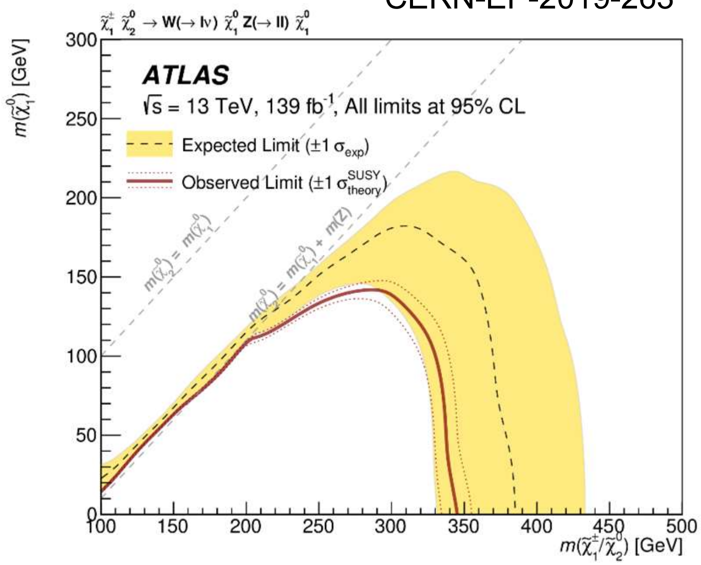
CERN-EP-2019-263



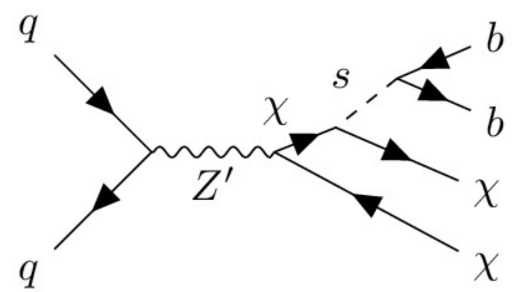
Mass Hierarchy solution: SUSY



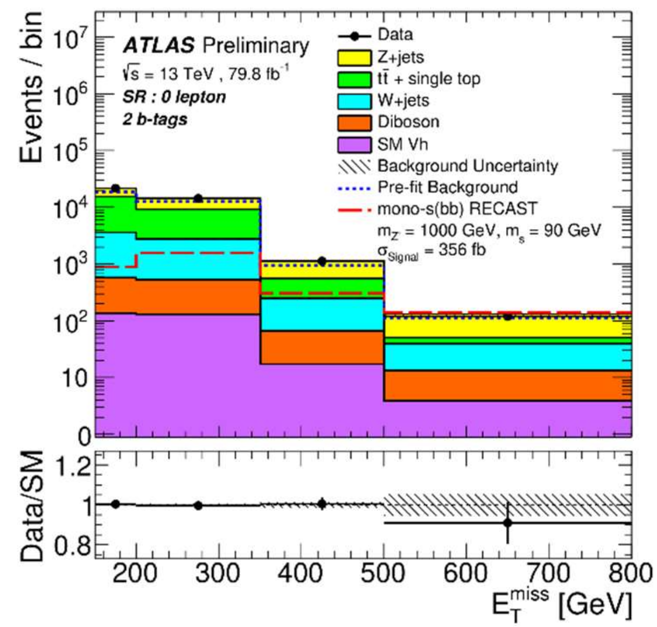
CERN-EP-2019-263



Dark Matter Candidates

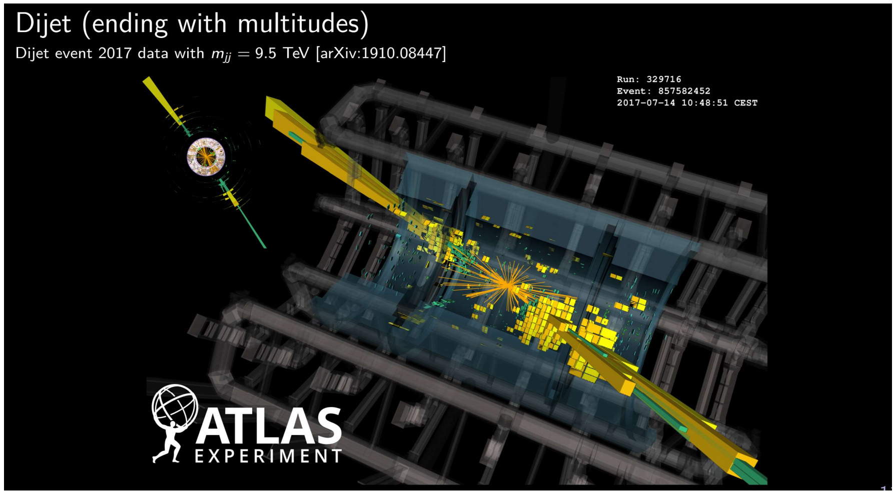


ATL-PHYS-PUB-2019-032

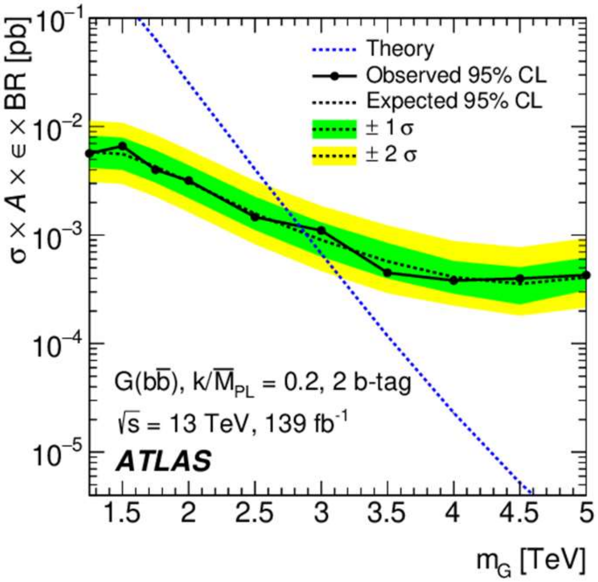


ATLAS Physics

Gravitons

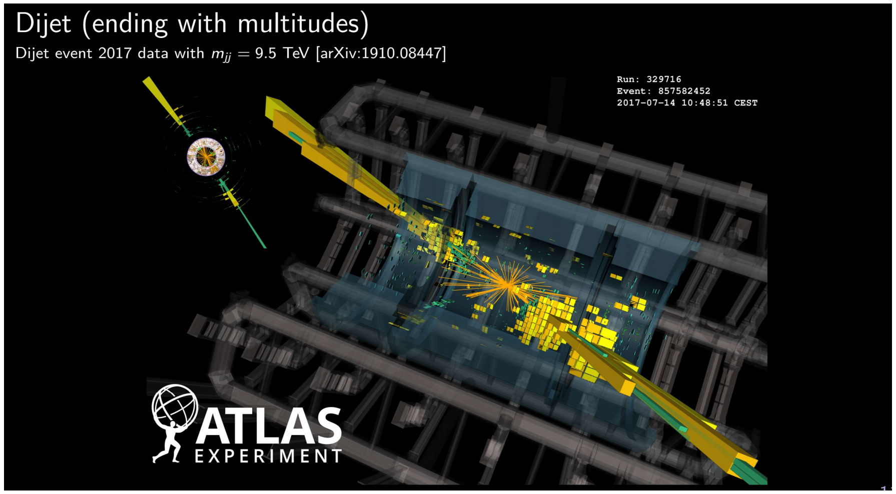


CERN-EP-2019-162

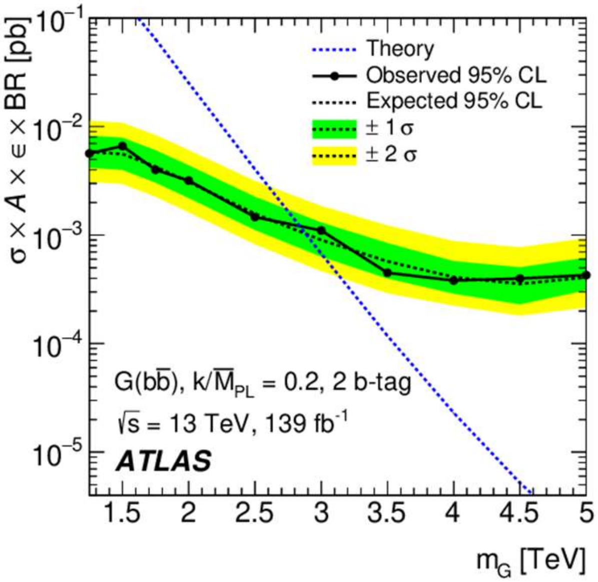


ATLAS Physics

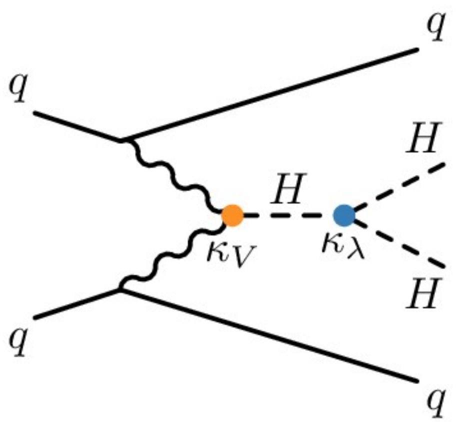
Gravitons



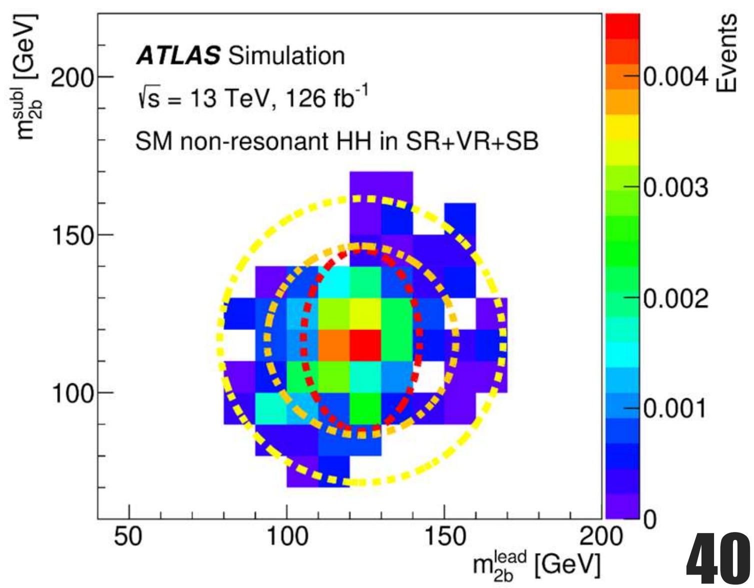
CERN-EP-2019-162



Higgses



CERN-EP-2019-267



LBNF and DUNE

"I have done a terrible thing: I have postulated a particle that cannot be detected."

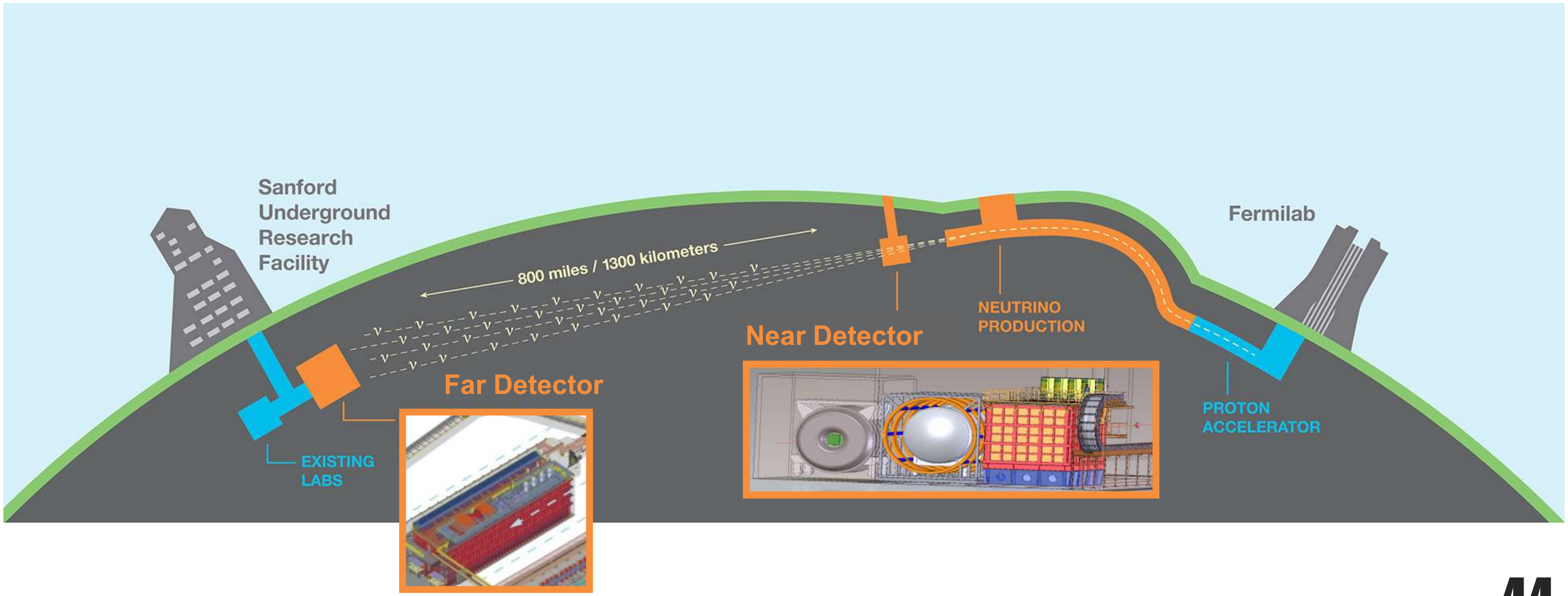
– Wolfgang Pauli

So What Don't We Know?

- Why do neutrinos have mass?
- What are the relative masses of neutrinos?
- Is there CP violation in the neutrino sector? Could it be responsible for matter-anti-matter asymmetry?
- Why are the neutrino and quark mixing matrix elements so different?
- Can we detect neutrinos from Supernova events?

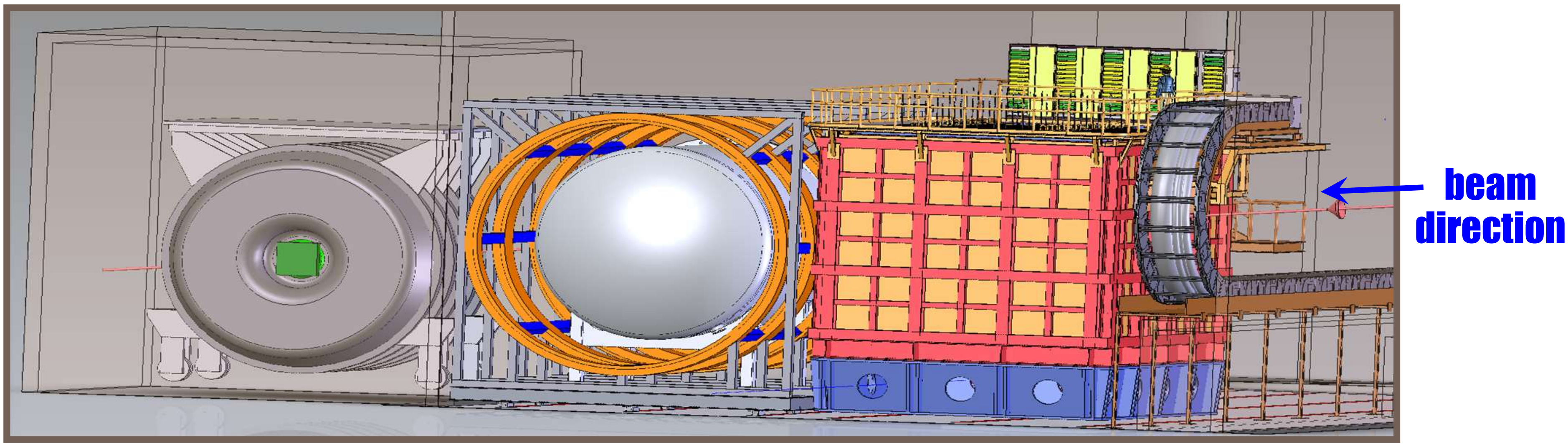
LBNF DUNE Facility

- 1-6 GeV muon neutrinos/antineutrinos obtained from high-power proton beam (1.2 MW)
- Near detector will characterize the beam (100s of millions of neutrino interactions)
- Far Detector is >40 kton Liquid Argon Time Projection Chambers (LAr TPC) – fine granularity



DUNE Near Detector

measure precisely neutrino fluxes & constrain systematic uncertainty

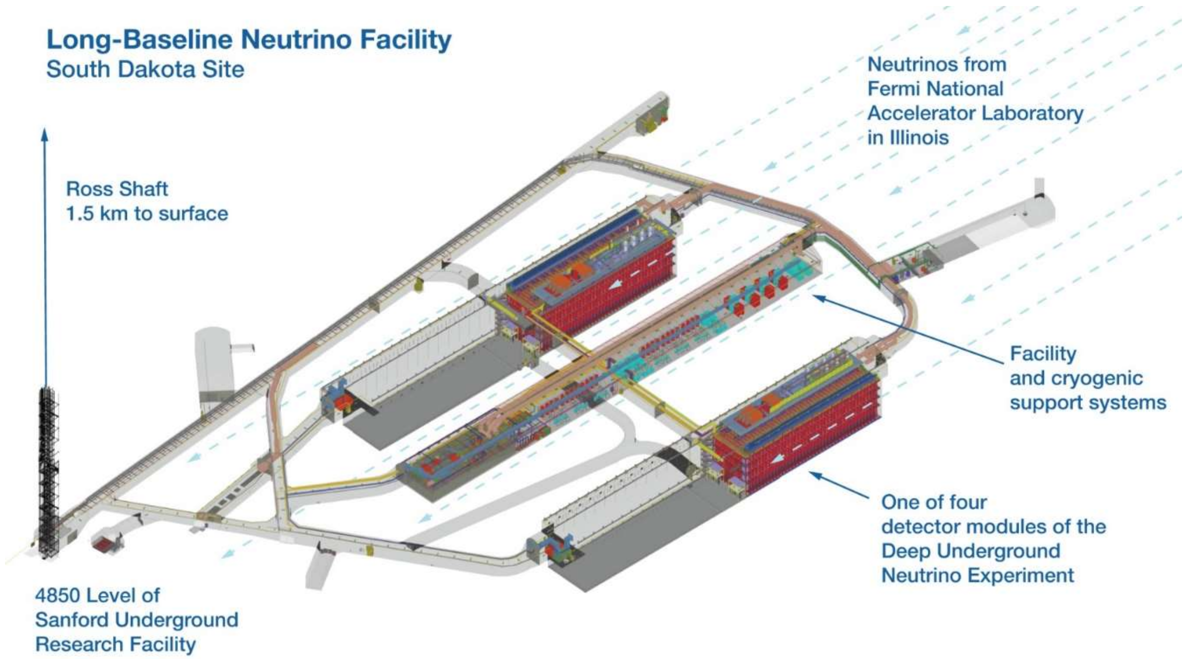


Scintillator cubes for beam monitor

Gaseous Argon TPC: Study $\nu - Ar$ interactions in detail

Liquid Argon TPC: Most like Far Datector

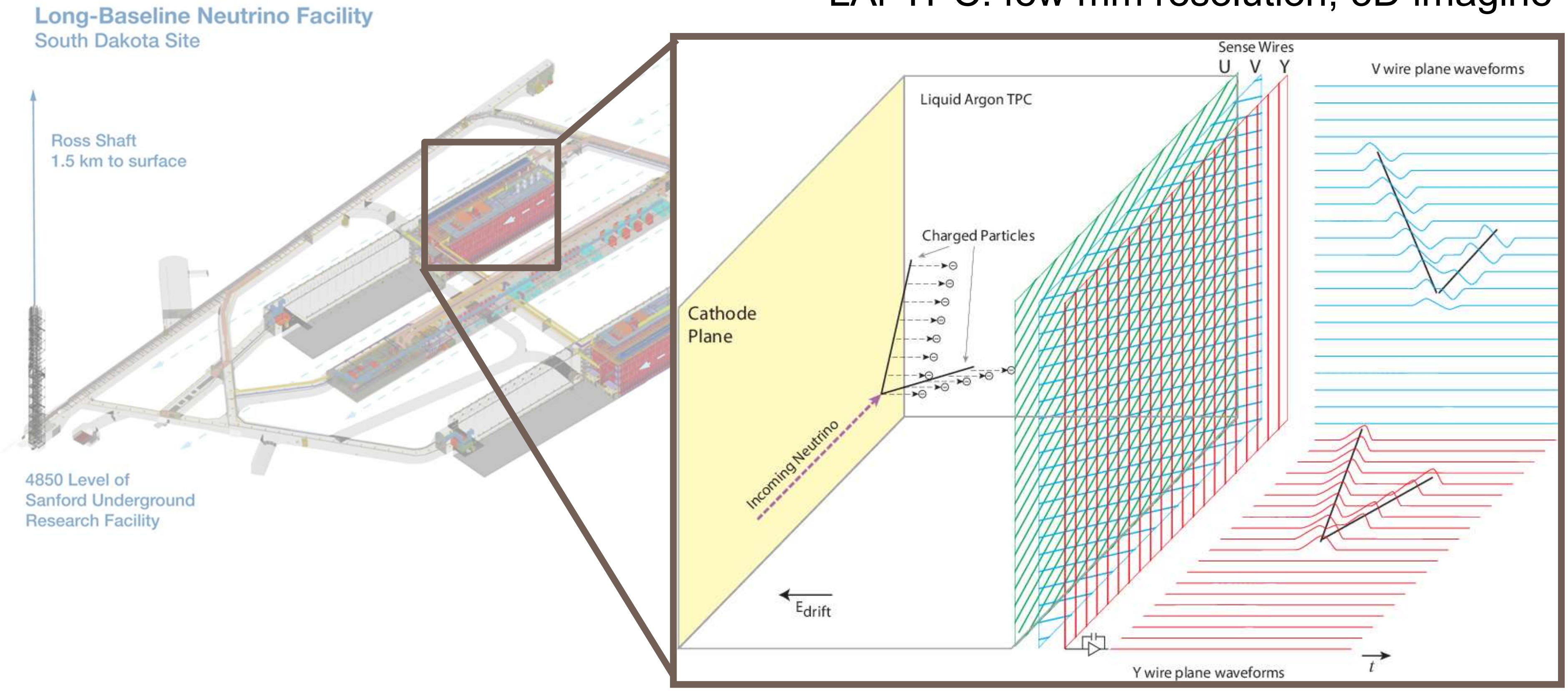
DUNE Far Detector



4 chambers, 17 kton total mass each

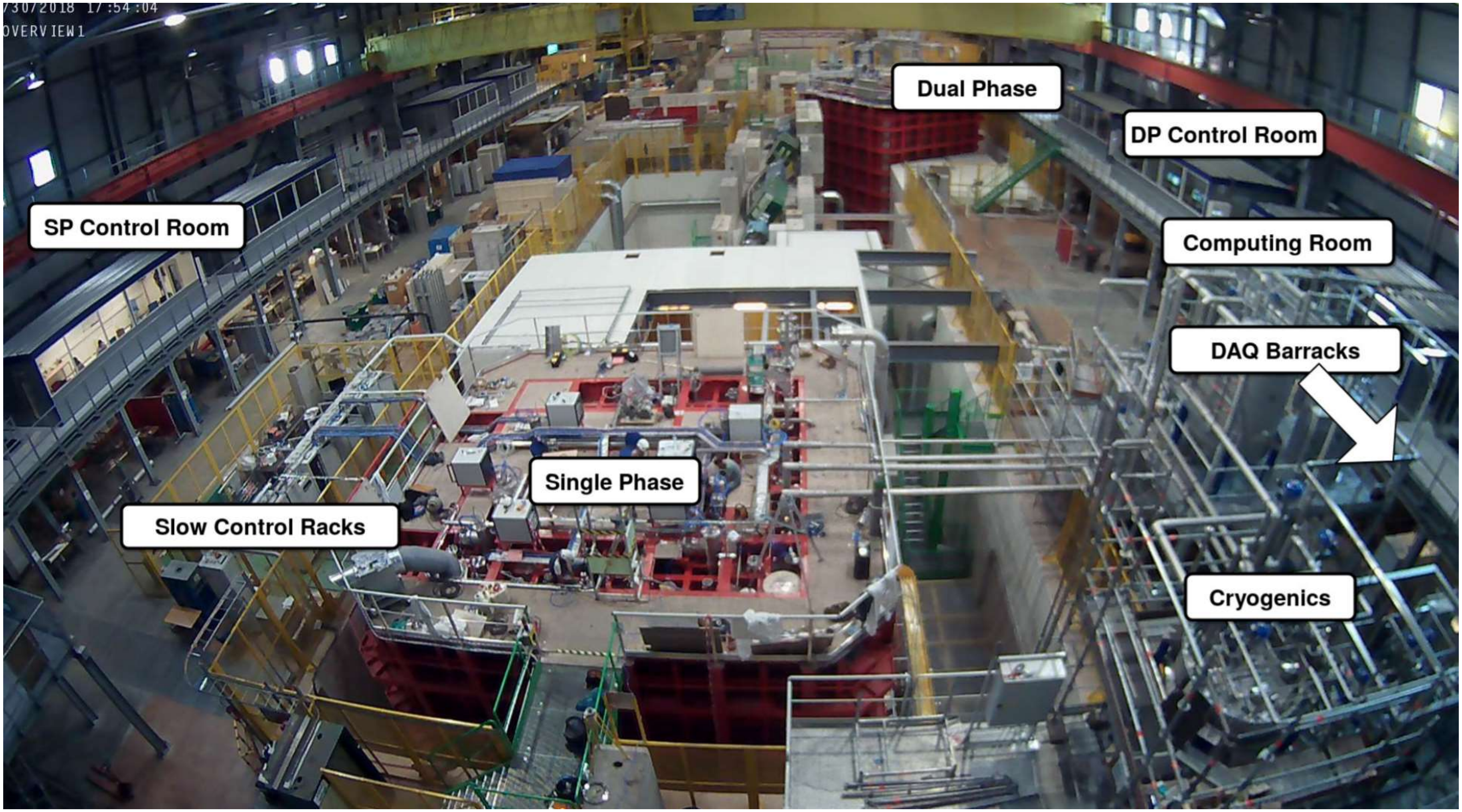
DUNE Far Detector

LAr TPC: few mm resolution, 3D imagine



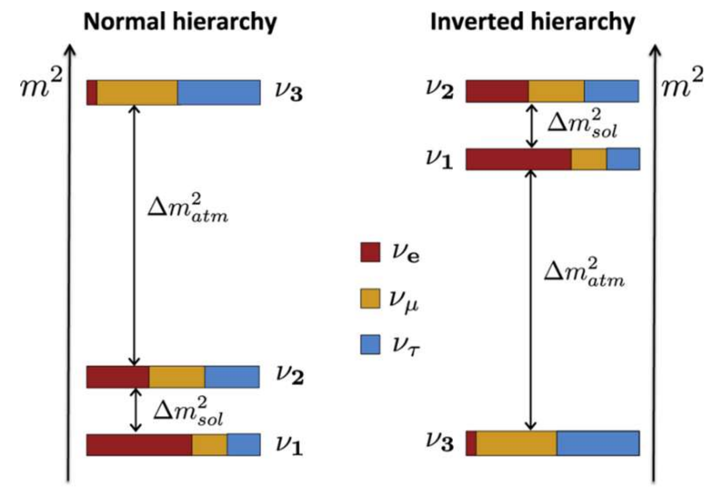
Installation of first module in 2024

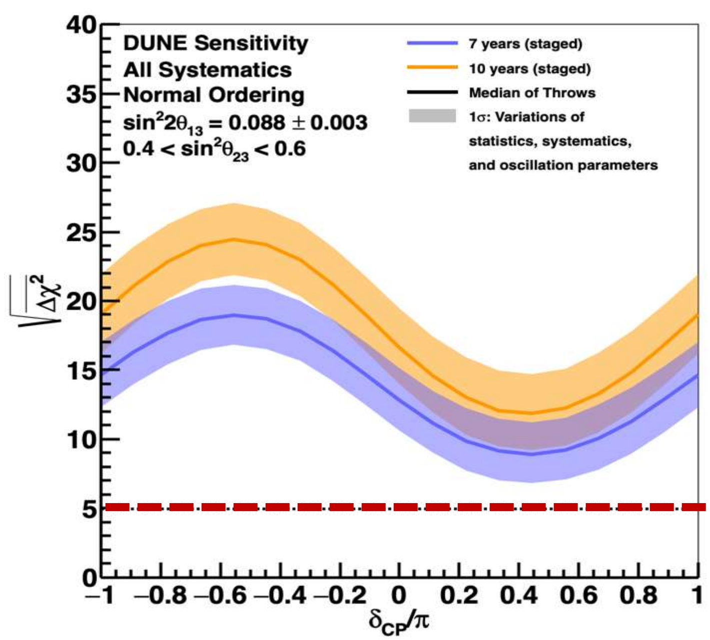
DUNE Prototype



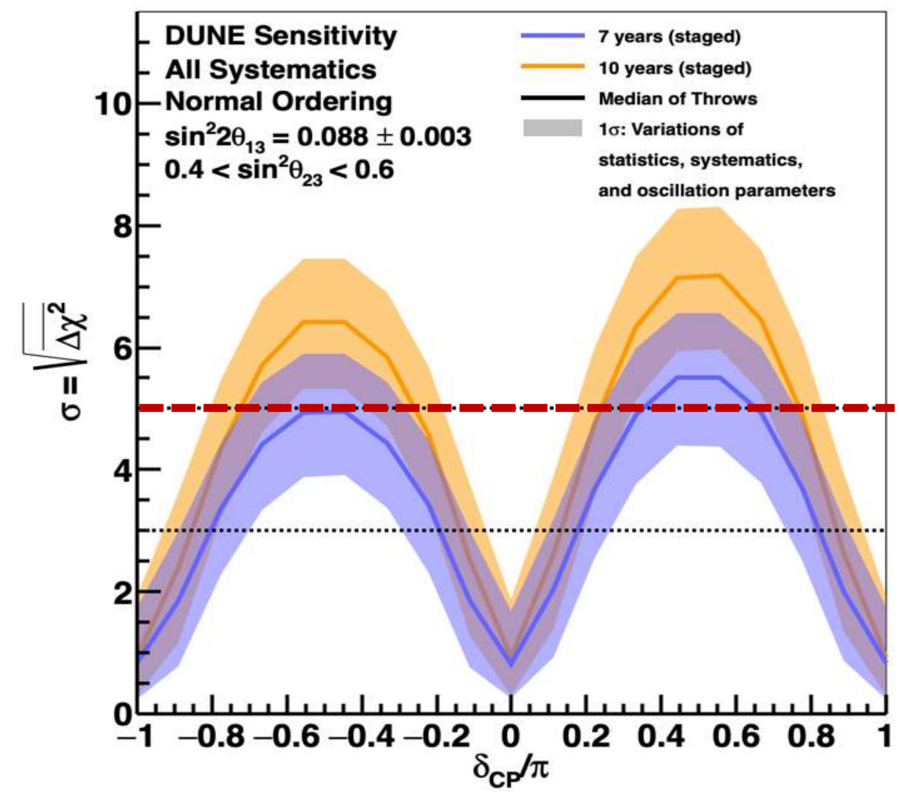
DUNE Physics

Mass Ordering Sensitivity





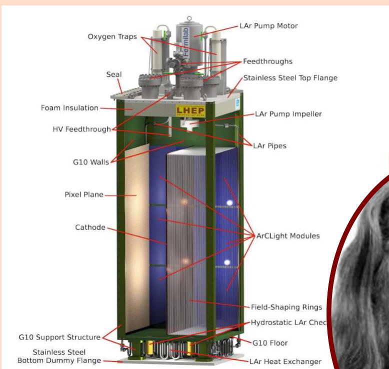
CP violation Sensitivity



+ Expect thousands of electron neutrinos from super nova bursts
+ Sensitivity to possible additional neutrinos

Planned Canadian Contributions

Near Detector Prototype &
Neutrino Interaction model



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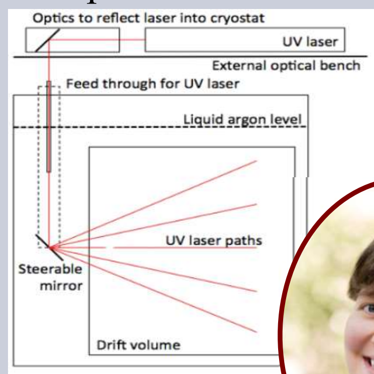
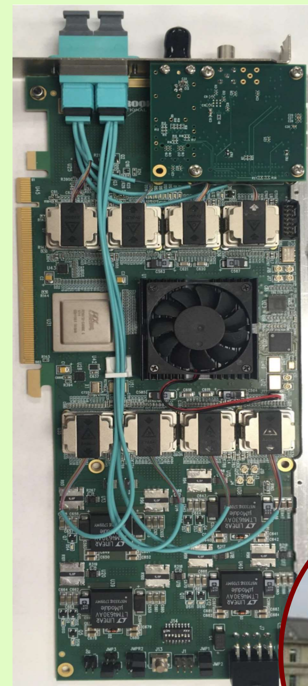
Computing, Calibration
& Supernova neutrinos



Claire David
Claire.David@cern.ch

FELIX readout system &
Extra neutrino & NSI searches



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More manpower is very welcome!
Please contact us to join!

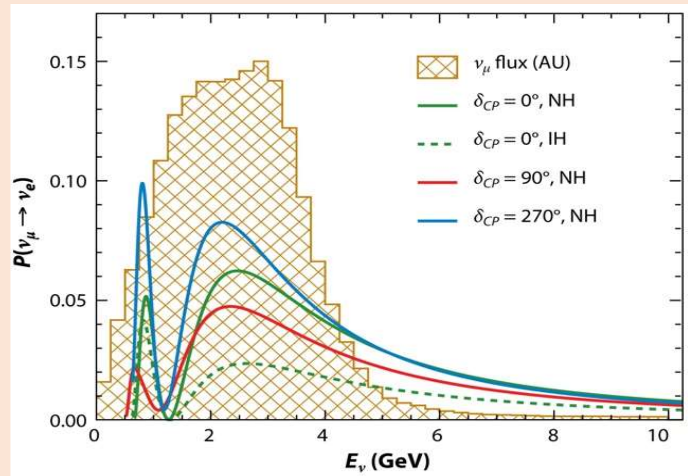
Summary & Outlook

- Overview of ATLAS and DUNE experiments presented
- ATLAS is analyzing its full dataset and hopes to answer many outstanding questions related to the SM
- With the first DUNE module installation set to begin in 2024, DUNE hopes to answer many neutrino-related questions soon!

BACKUP

Neutrinos: Experimental setups

- Effect on matter on neutrino oscillations complicates some measurements
- Matter does not have same effect on neutrino and anti-neutrino oscillations – complicates CPV measurement
- Possible strategies:



Small oscillations length (~300 km) = insignificant matter effects
Off axis beam gives high flux at oscillation maximum, narrow energy range

Hyper-Kamiokande

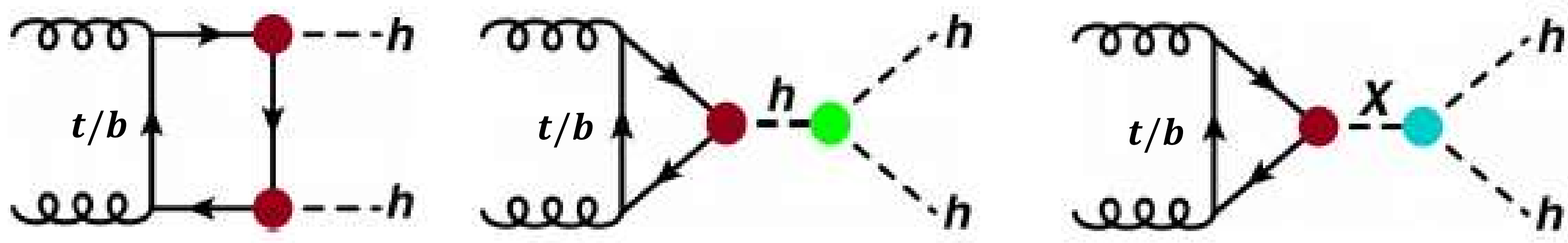
Large oscillations length (~1000 km) = significant matter effects
On axis beam gives wide range of neutrino energy – differentiate CPV effects from matter effects through energy dependence
v

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Physics with b and τ

SM Di-Higgs production several orders of magnitude lower than single Higgs production AND destructive interference among diagrams makes it smaller

FTK will help!

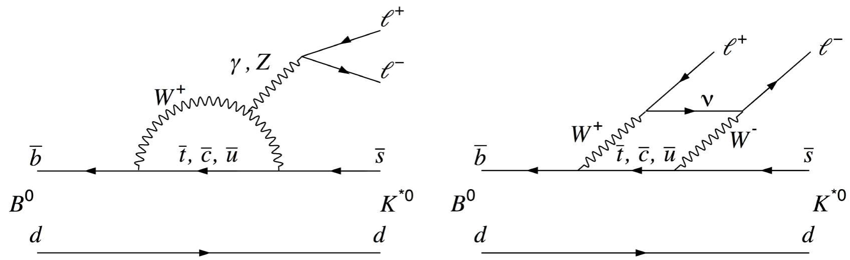


Di-Higgs production enhanced in many BSM models

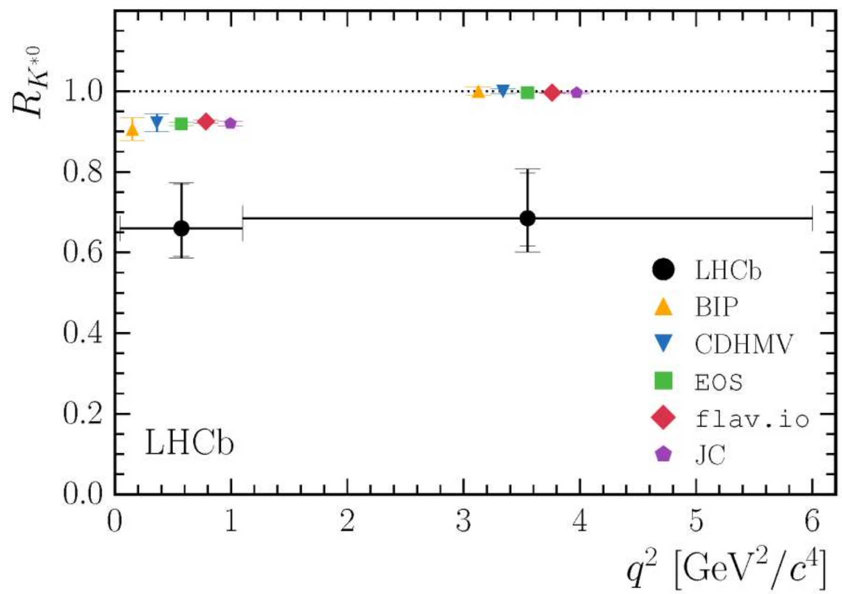
- Non resonant production: Higgs coupling to t , b , h modified wrt SM values
- Resonant production: Replacing virtual Higgs boson with an intermediate heavy resonance (2HDM, G_{kk^*})

Analysis I am working on… paper out soon

BR	bb	WW
bb	33%	
WW	25%	4.6%
$\tau\tau$	7.4%	2.5%
ZZ	3.1%	1.2%
$\gamma\gamma$	0.26%	0.10%



$$\mathrm{R}(K^*)\,\frac{BR(B^0 \to K^*\,\mu\mu\,)}{BR(B^0 \to D^*\,ee)}$$



[S. Bifani LHC seminar, 18/04/2017]