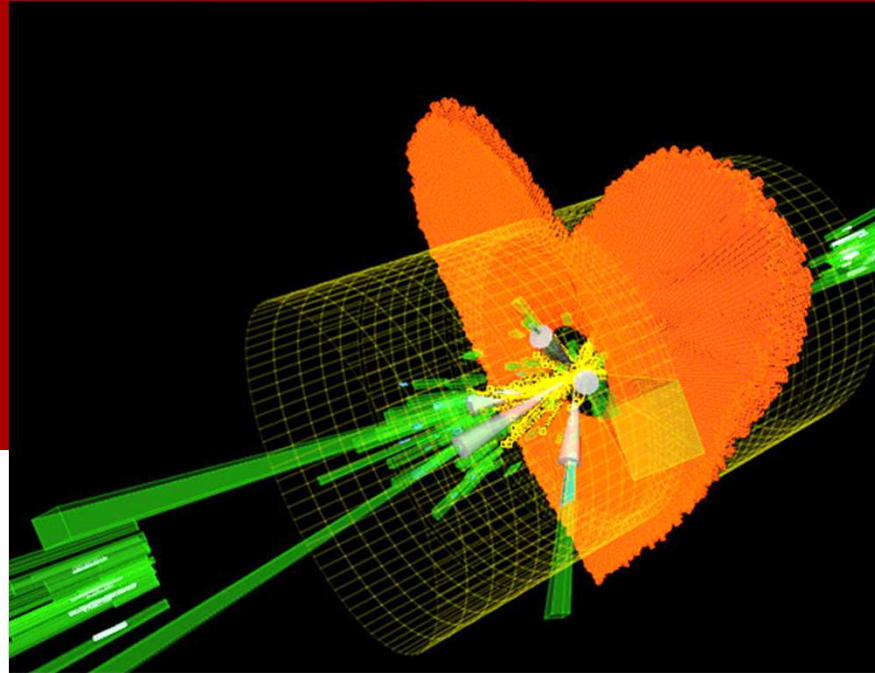
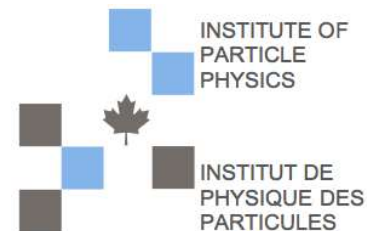


FROM QUARKS TO NEUTRINOS



Nikolina Ilic
Institute of Particle Physics &
University of Toronto
WNPPC 2020, Banff, Alberta



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

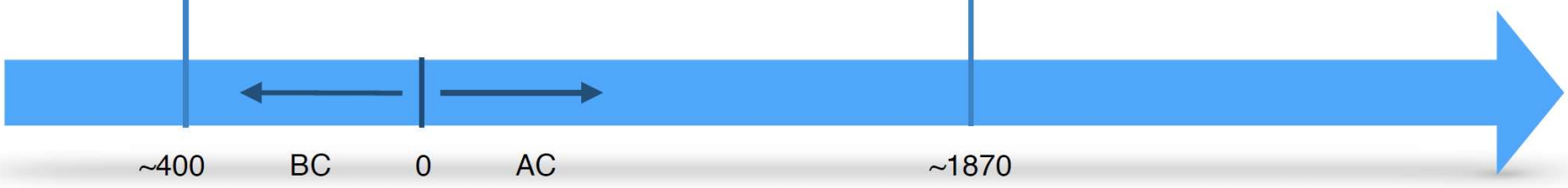
Matter



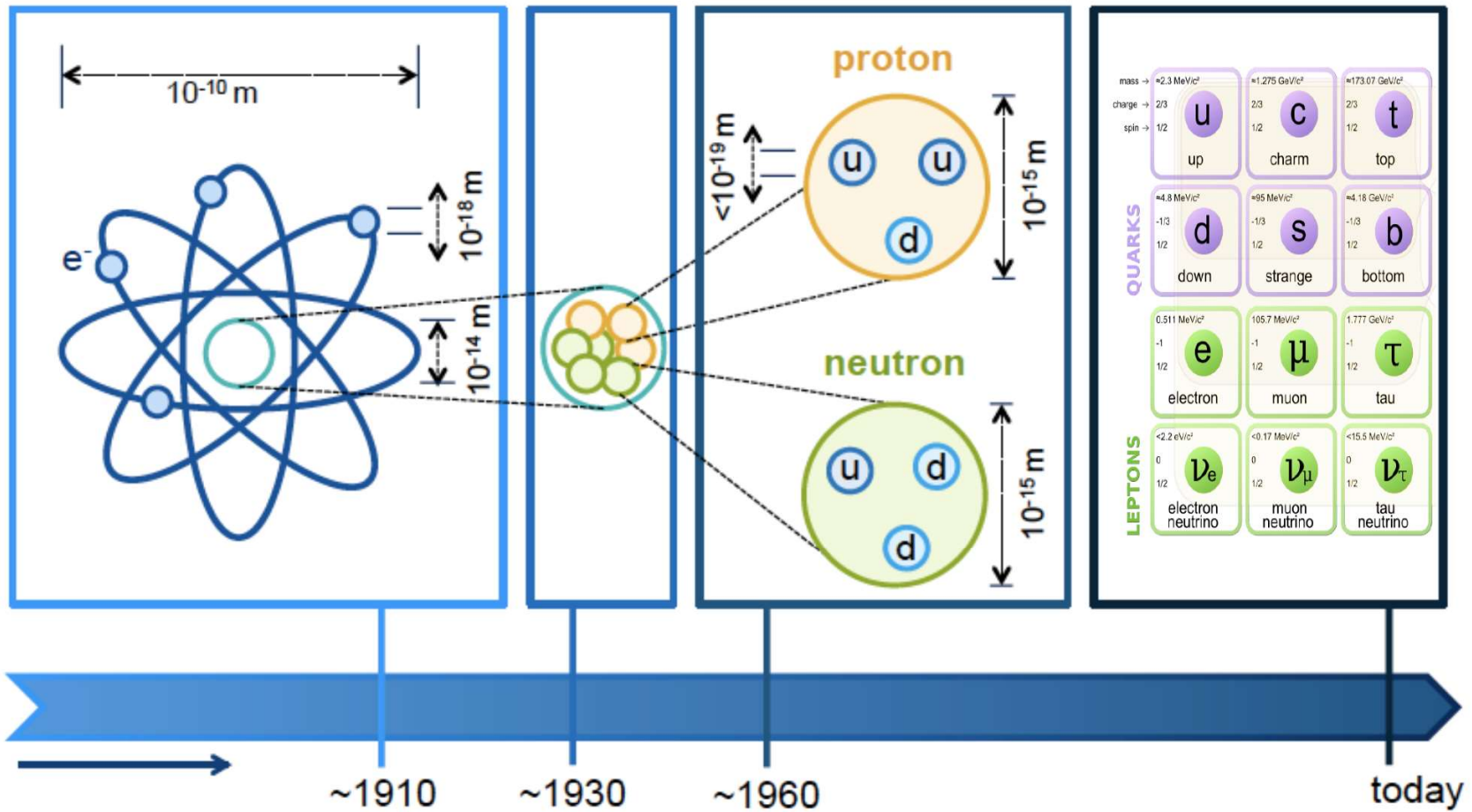
Periodic Table of the Elements

1 IA 11A	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A								
1 H Hydrogen 1.008												5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180								
3 Li Lithium 6.941	4 Be Beryllium 9.012											11 Na Sodium 22.990	12 Mg Magnesium 24.305											17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 83.80								
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 101.07	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.905	54 Xe Xenon 131.29								
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium 209	85 At Astatine 210	86 Rn Radon 222								
87 Fr Francium 223	88 Ra Radium 226	89-103 Actinide Series	104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 263	107 Bh Bohrium 264	108 Hs Hassium 265	109 Mt Meitnerium 266	110 Ds Darmstadtium 269	111 Rg Roentgenium 272	112 Cn Copernicium 277	113 Uut Ununtrium unknown	114 Fl Flerovium 289	115 Uup Ununpentium unknown	116 Lv Livermorium 293	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown								
57 La Lanthanum 138.905	58 Ce Cerium 140.12	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.965	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.967											
89 Ac Actinium 227	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium 252	100 Fm Fermium 257.103	101 Md Mendelevium 258	102 No Nobelium 259	103 Lr Lawrencium 262											
Alkali Metal	Alkaline Earth	Transition Metal	Semimetal	Nonmetal	Basic Metal	Halogen	Noble Gas	Lanthanide	Actinide																

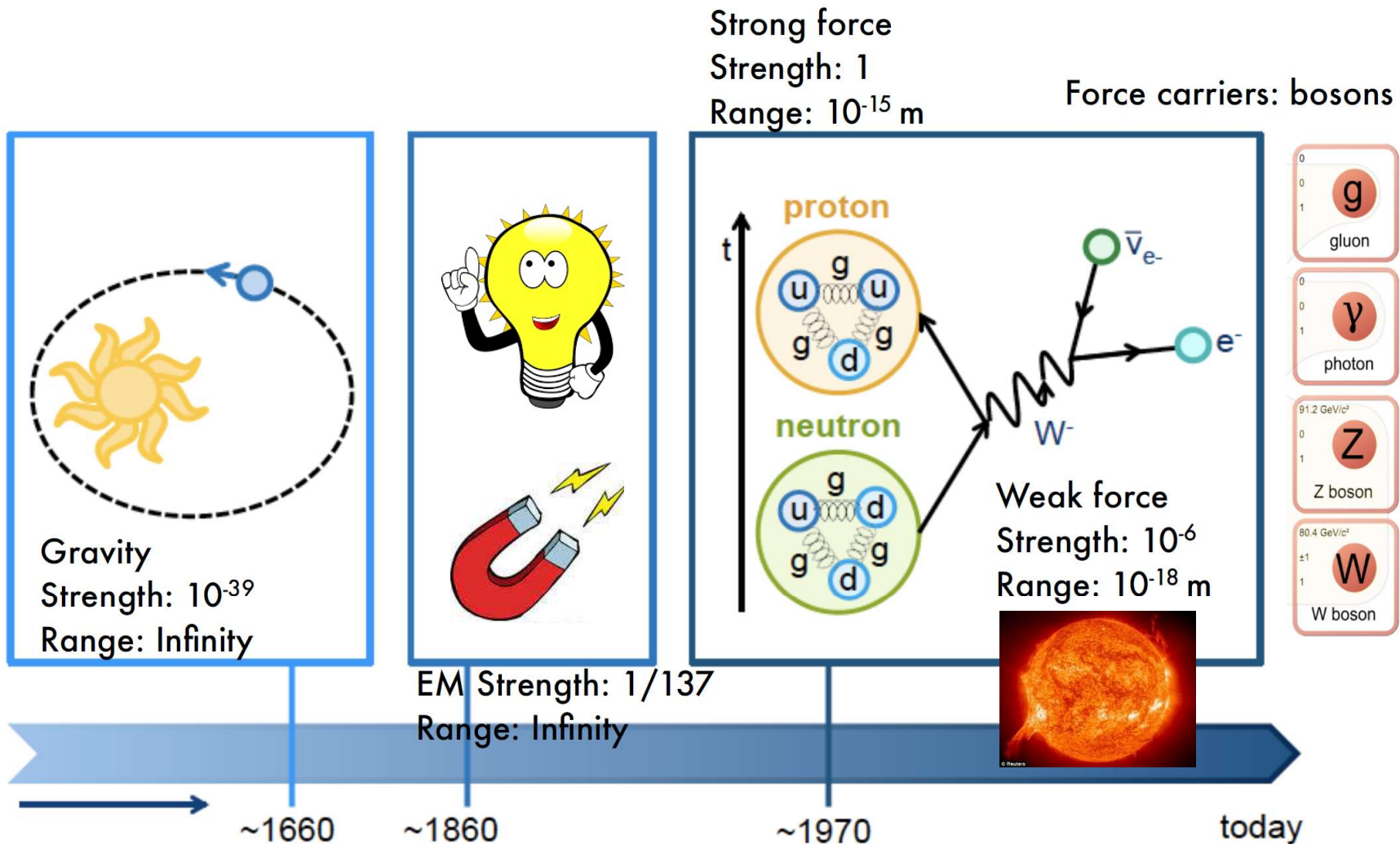
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Matter



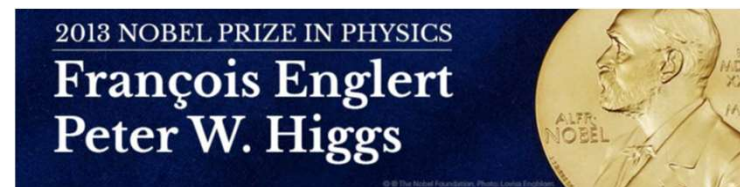
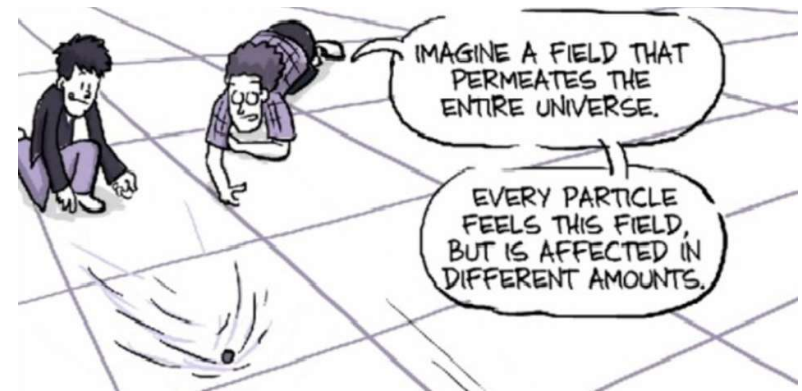
Forces



The Standard Model

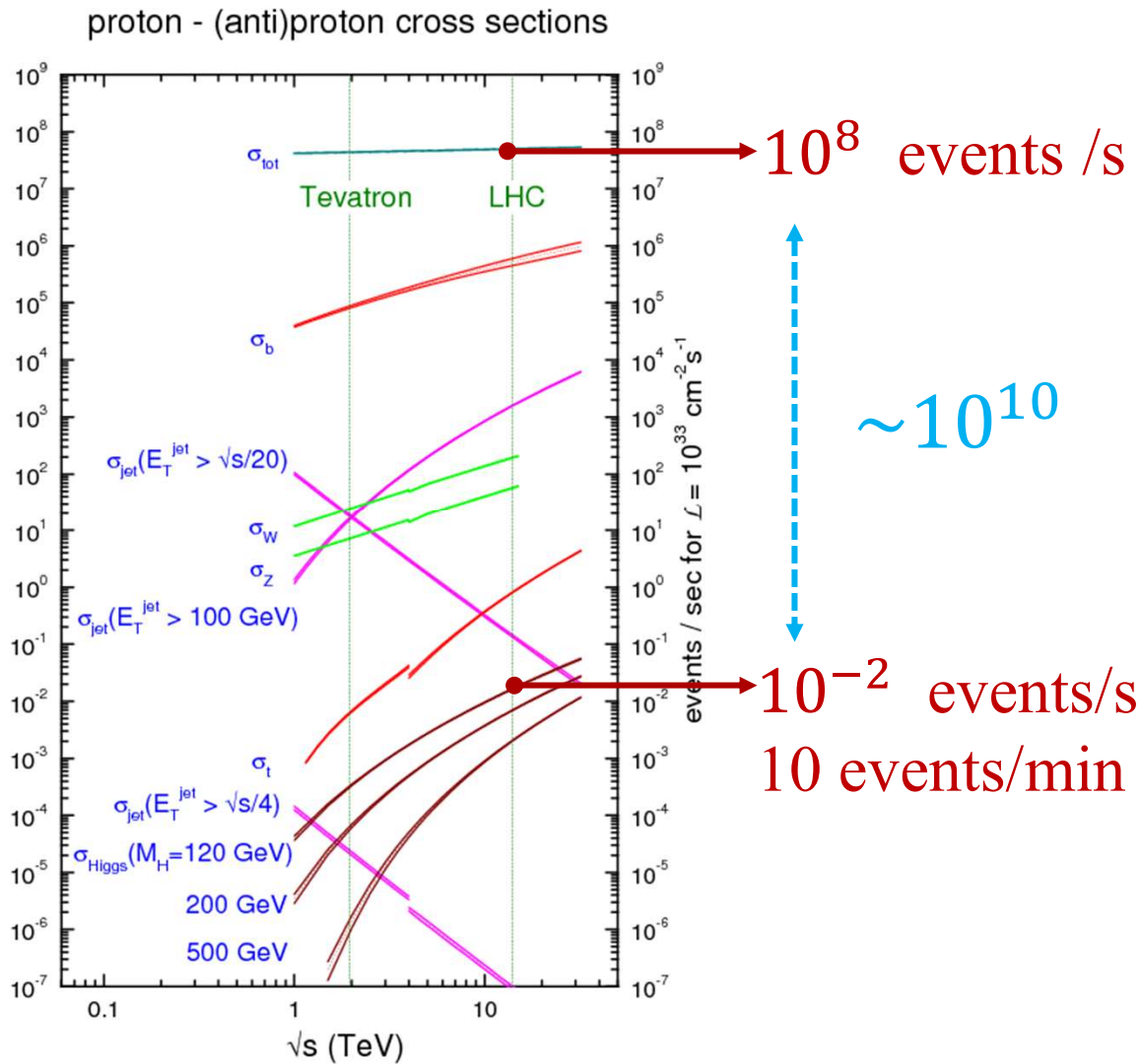
- In 2012 Higgs Boson found!
- Gravity is not in Standard Model (SM)

mass	$\approx 2.4 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 172.44 \text{ GeV}/c^2$	0	$\approx 125.09 \text{ GeV}/c^2$
charge	2/3	2/3	2/3	0	0
spin	1/2	1/2	1/2	1	0
	u up	c charm	t top	g gluon	H Higgs
QUARKS	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	d down	s strange	b bottom	γ photon	
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.67 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS	$< 2.2 \text{ eV}/c^2$	$< 1.7 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	± 1	
	1/2	1/2	1/2	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
				GAUGE BOSONS	
				SCALAR BOSONS	



The Standard Model

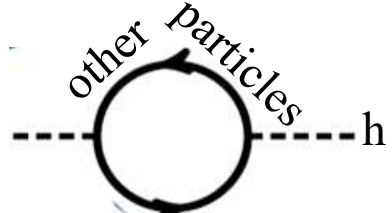
- Finding the Higgs was hard work! Looking needle in haystack!



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

– Albert Einstein

So What Don't We Know? Hierarchy Problem

$$m_h^2 \sim m_0^2 + \left(\text{h} \text{---} \text{other particles} \text{---} \text{h} \right)^2 = 125^2 \text{ GeV}$$
A Feynman diagram representing a loop correction to the Higgs mass. It consists of a central circle with a clockwise arrow, labeled "other particles" above it. Two dashed lines, each labeled "h", extend horizontally from the left and right sides of the circle, representing the external Higgs bosons.

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

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

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 at the gravitational scale: $M_{Planck} \sim 10^{18} \text{ GeV}$

So What Don't We Know? Hierarchy Problem

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

68027489174732987197032748931274927856 -

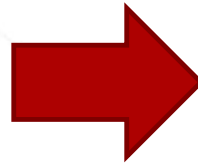
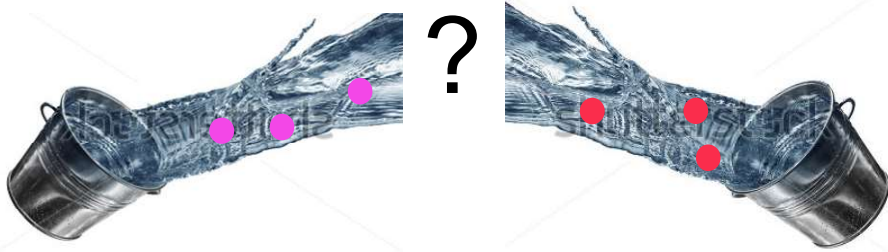
68027489174732987197032748931274912231 = 125² GeV²



“The Higgs has a snowball’s chance in hell of having a mass in that ballpark”

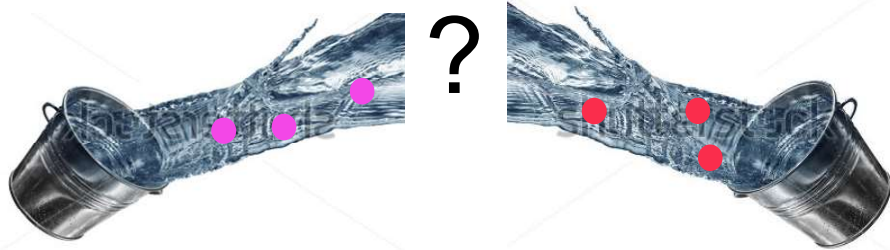
So What Don't We Know? Dark Matter

- What's so different about it?

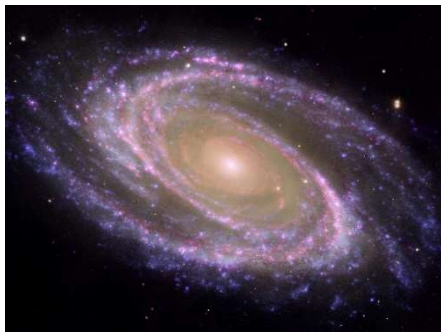


So What Don't We Know? Dark Matter

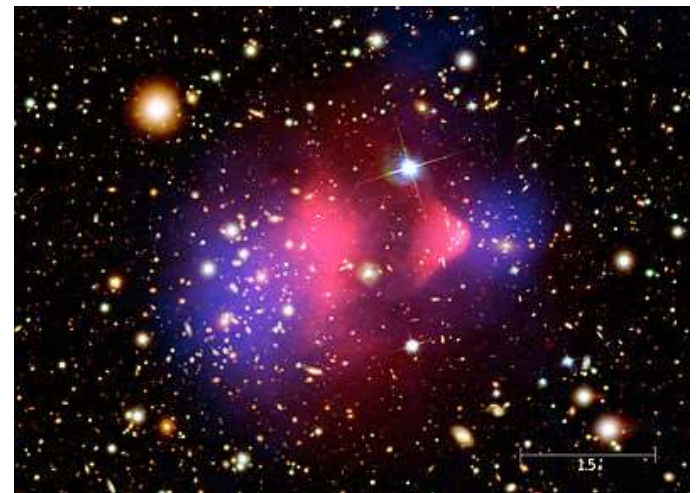
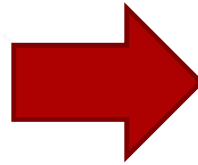
- What's so different about it?



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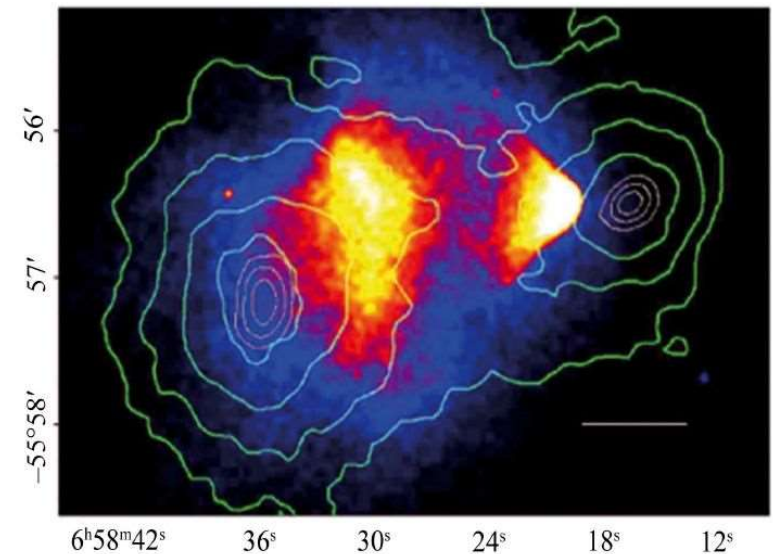
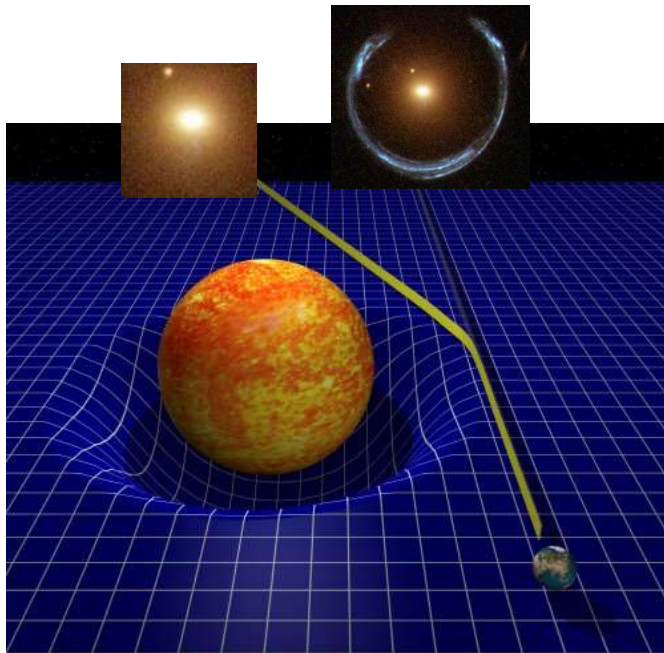
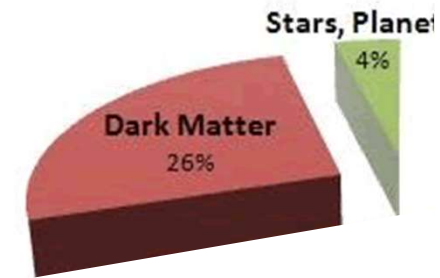
?



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?

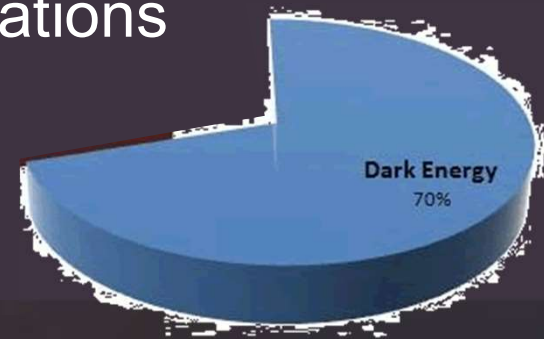


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So What Don't We Know?



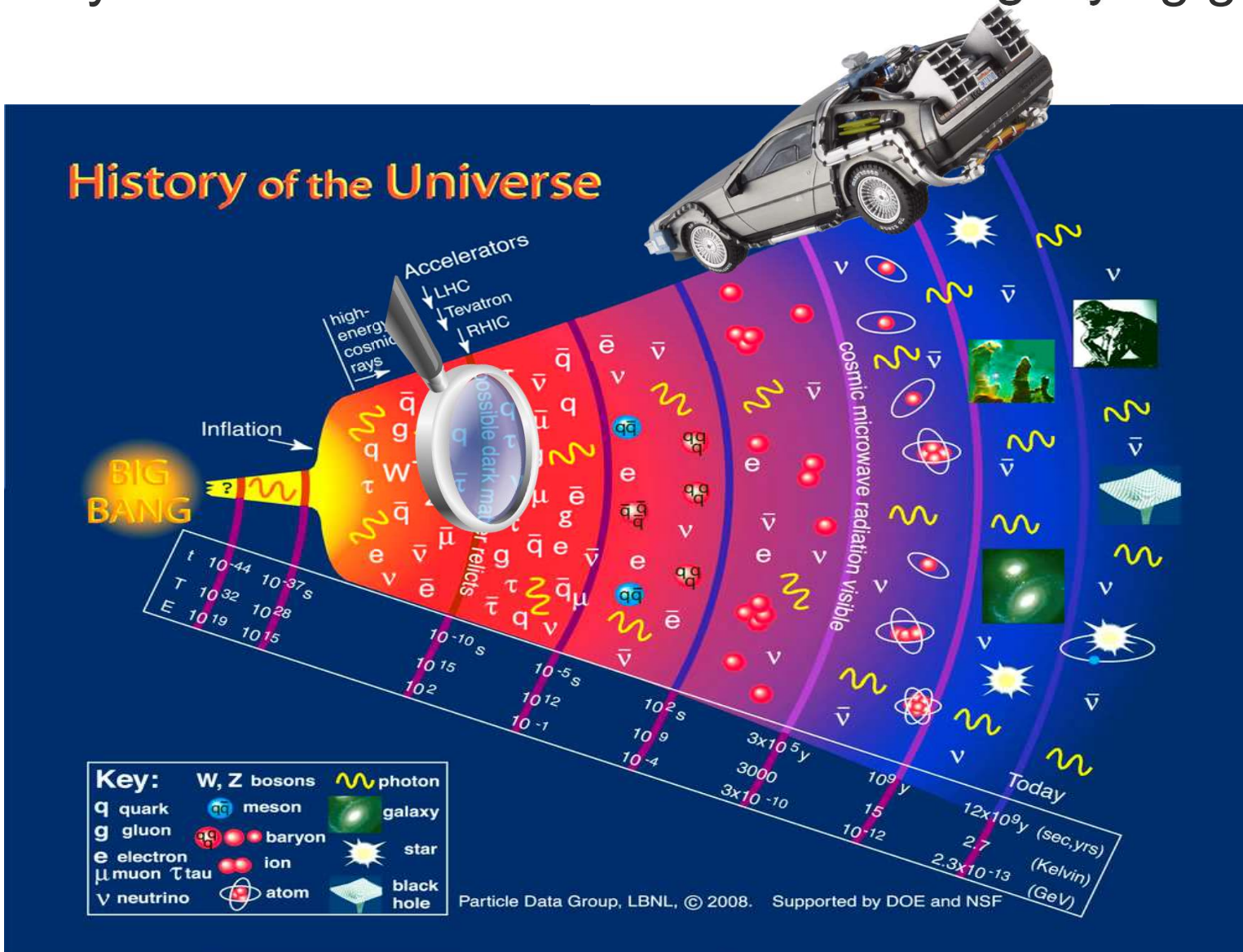
- How does gravity fit with the SM?
- Why do neutrinos have mass?
- Why is there more matter than anti-matter?
- What is Dark Energy?
-
- Look for SM deviations by measuring SM & Higgs properties
- Search for beyond SM theories with explanations



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

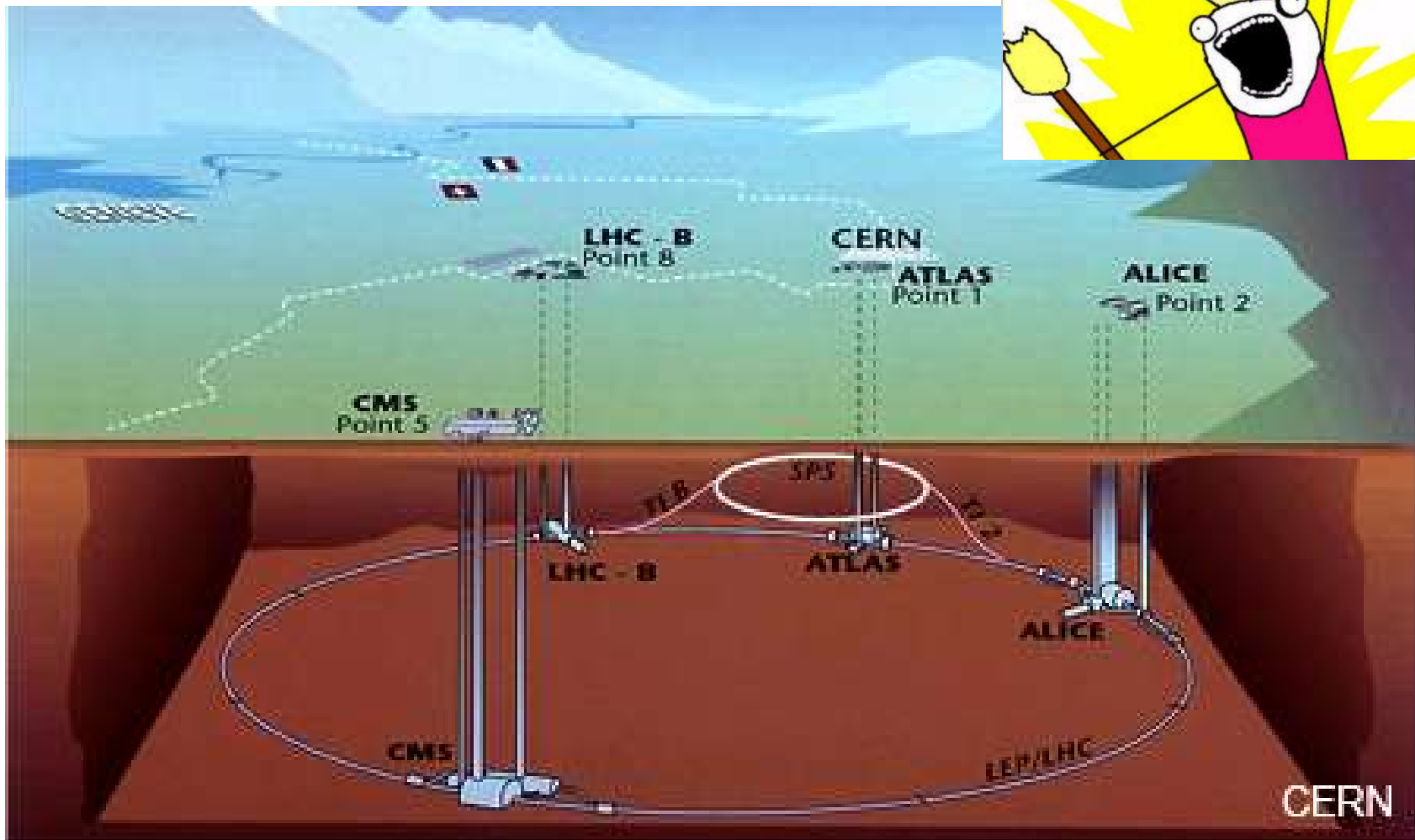
How Do We Get Data?

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

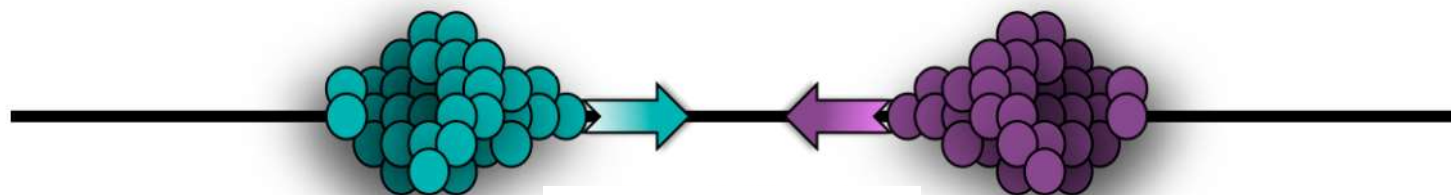


The LHC and ATLAS

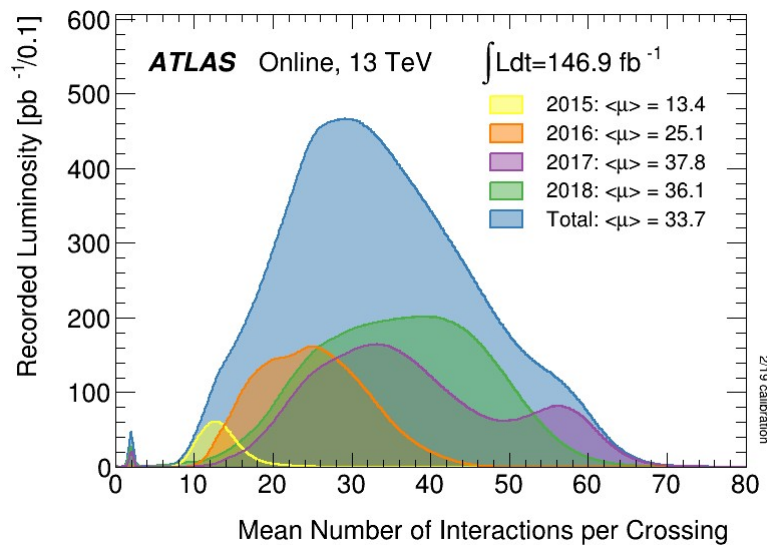
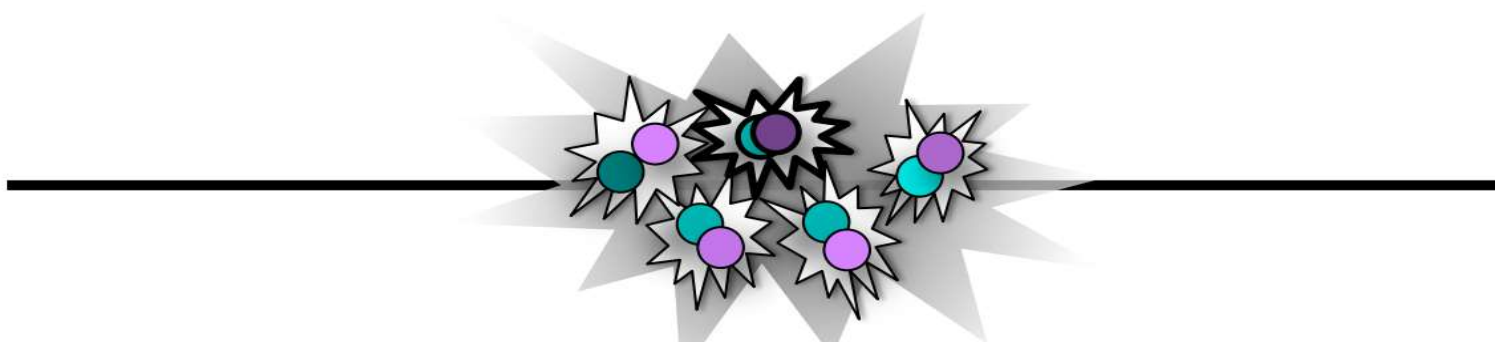
Large Hadron Collider



Large Hadron Collider

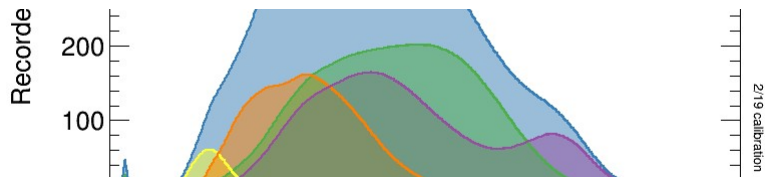
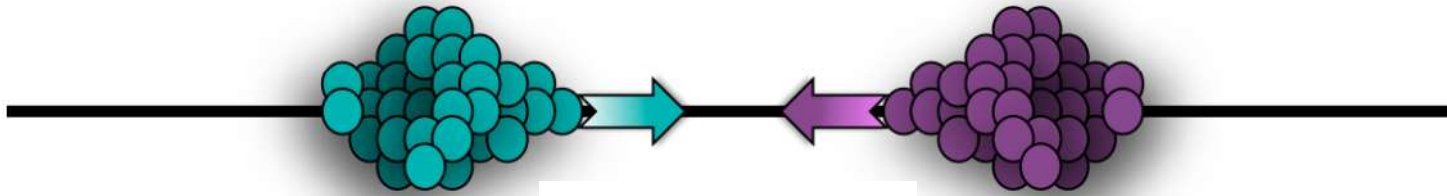


10^{11} protons per bunch, colliding at 40 MHz (every 25 ns)



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

Large Hadron Collider



- Selecting interesting events a challenge!

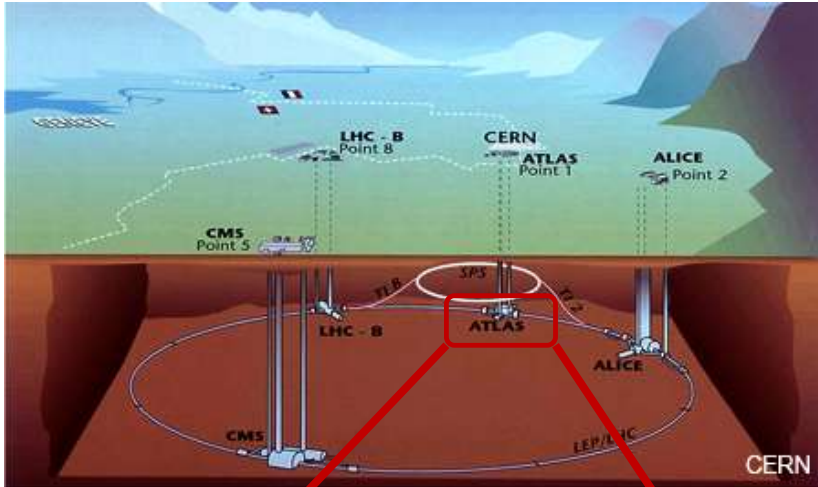
Large Hadron Collider

Find needle in haystack in battlefield!

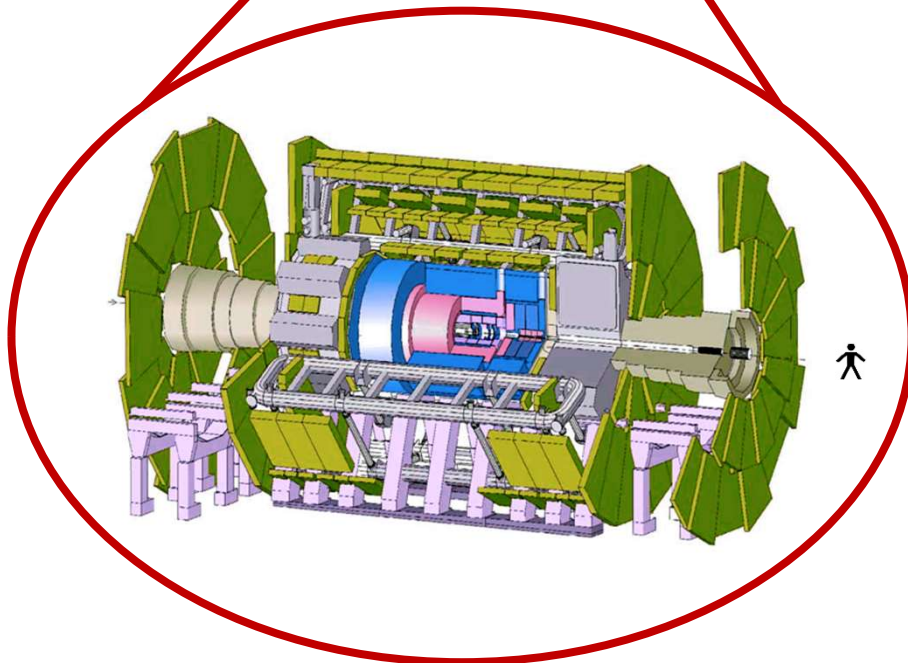


- LHC gives us 40 MHz, but we can only save 1kHz!
- Our interesting physics events are rare!

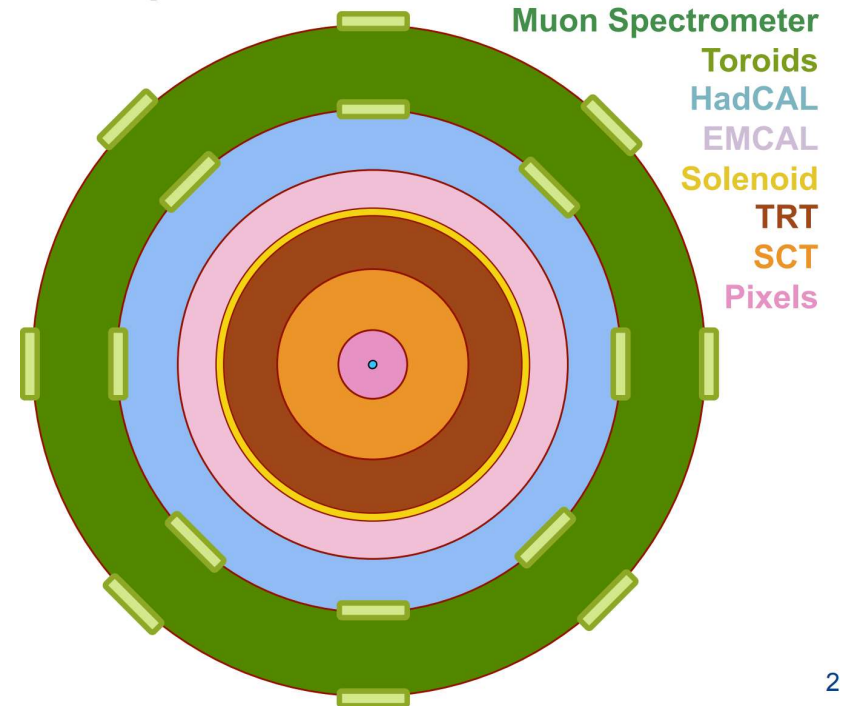
ATLAS Detector



- 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

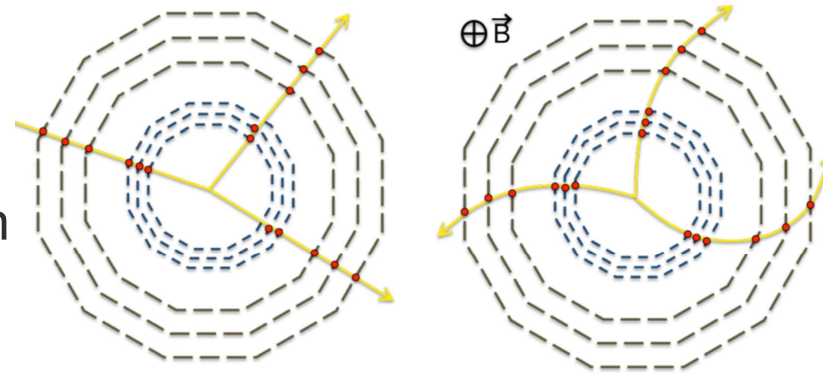


Simplified Detector Transverse View

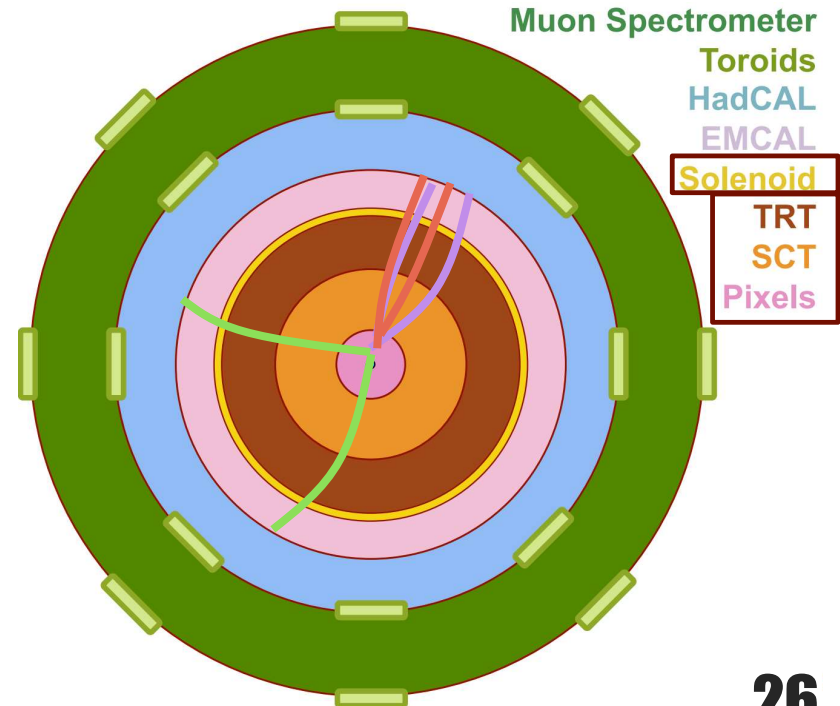


ATLAS Detector

- 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

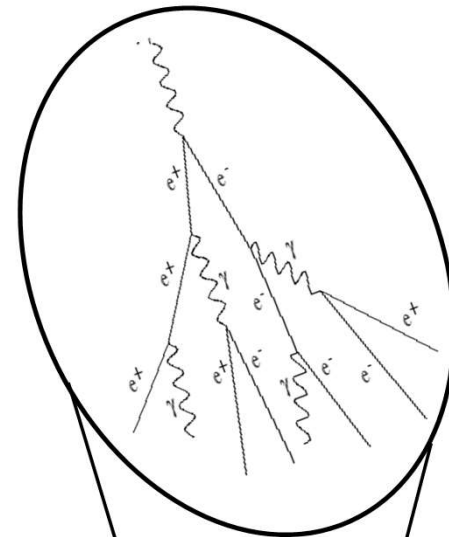


	mass $\approx 2.4 \text{ MeV}/c^2$ charge $2/3$ spin $1/2$ u up	mass $\approx 1.275 \text{ GeV}/c^2$ charge $2/3$ spin $1/2$ c charm	mass $\approx 172.44 \text{ GeV}/c^2$ charge $2/3$ spin $1/2$ t top	mass 0 charge 0 spin 1 g gluon	mass $\approx 125.09 \text{ GeV}/c^2$ charge 0 spin 0 H Higgs
QUARKS	mass $\approx 4.8 \text{ MeV}/c^2$ charge $-1/3$ spin $1/2$ d down	mass $\approx 95 \text{ MeV}/c^2$ charge $-1/3$ spin $1/2$ s strange	mass $\approx 4.18 \text{ GeV}/c^2$ charge $-1/3$ spin $1/2$ b bottom	mass 0 charge 0 spin 1 γ photon	SCALAR BOSONS
	mass $\approx 0.511 \text{ MeV}/c^2$ charge -1 spin $1/2$ e electron	mass $\approx 105.67 \text{ MeV}/c^2$ charge -1 spin $1/2$ μ muon	mass $\approx 1.7768 \text{ GeV}/c^2$ charge -1 spin $1/2$ τ tau	mass $\approx 91.19 \text{ GeV}/c^2$ charge 0 spin 1 Z Z boson	
	mass $< 2.2 \text{ eV}/c^2$ charge 0 spin $1/2$ ν_e electron neutrino	mass $< 1.7 \text{ MeV}/c^2$ charge 0 spin $1/2$ ν_μ muon neutrino	mass $< 15.5 \text{ MeV}/c^2$ charge 0 spin $1/2$ ν_τ tau neutrino	mass $\approx 80.39 \text{ GeV}/c^2$ charge ± 1 spin 1 W W boson	
LEPTONS				Gauge Bosons	

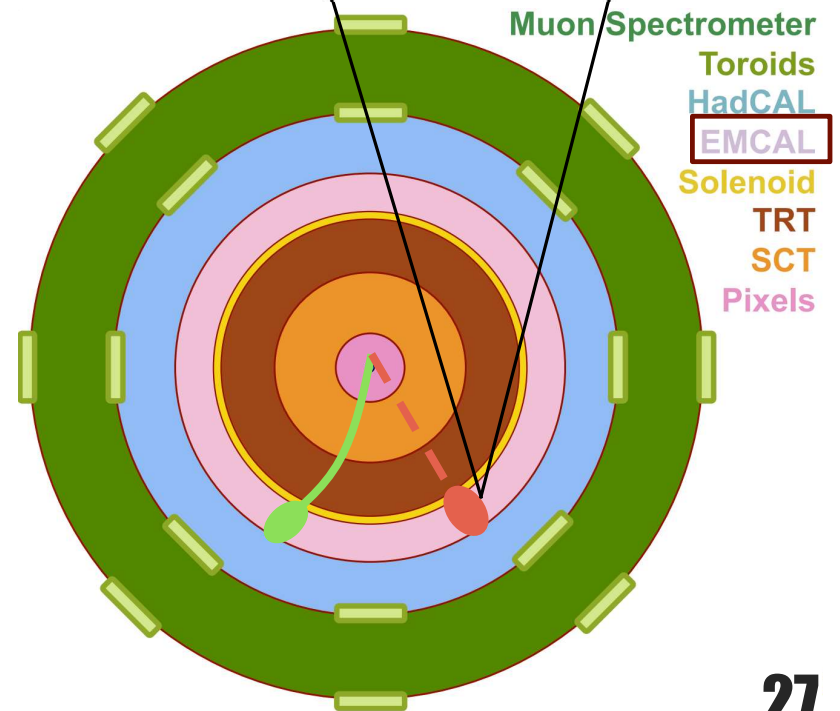


ATLAS Detector

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

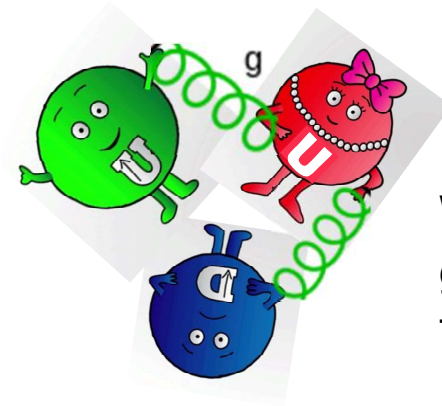


mass	$\approx 2.4 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 172.44 \text{ GeV}/c^2$	0	$\approx 125.09 \text{ GeV}/c^2$
charge	2/3	2/3	2/3	0	0
spin	1/2	1/2	1/2	1	0
	u up	c charm	t top	g gluon	H Higgs
	d down	s strange	b bottom	γ photon	
	e electron	μ muon	τ tau	Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	



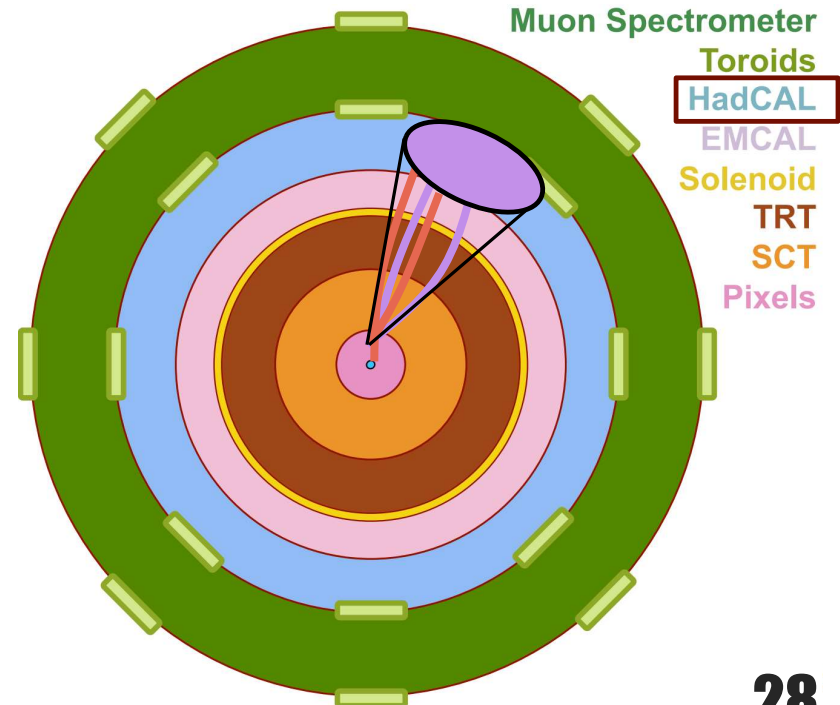
ATLAS Detector

- 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)



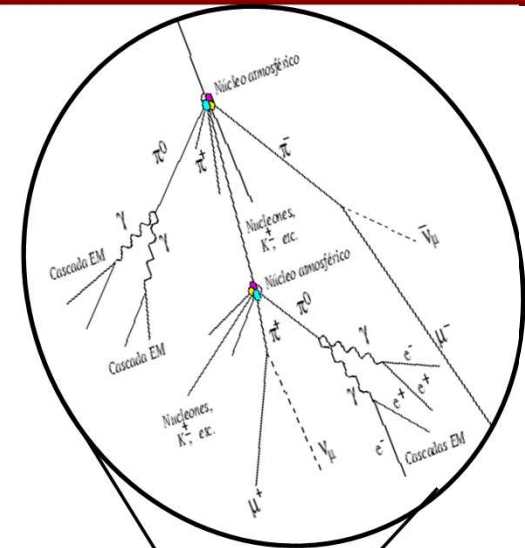
We're glued together!

	mass $\approx 2.4 \text{ MeV}/c^2$ charge $2/3$ spin $1/2$ u up	mass $\approx 1.275 \text{ GeV}/c^2$ charge $2/3$ spin $1/2$ c charm	mass $\approx 172.44 \text{ GeV}/c^2$ charge $2/3$ spin $1/2$ t top	mass 0 charge 0 spin 1 g gluon	mass $\approx 125.09 \text{ GeV}/c^2$ charge 0 spin 0 H Higgs	
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	mass $< 2.2 \text{ eV}/c^2$ charge 0 spin $1/2$ ν_e electron neutrino	mass $< 1.7 \text{ MeV}/c^2$ charge 0 spin $1/2$ ν_μ muon neutrino	mass $< 15.5 \text{ MeV}/c^2$ charge 0 spin $1/2$ ν_τ tau neutrino	mass $\approx 80.39 \text{ GeV}/c^2$ charge ± 1 spin 1 W W boson		

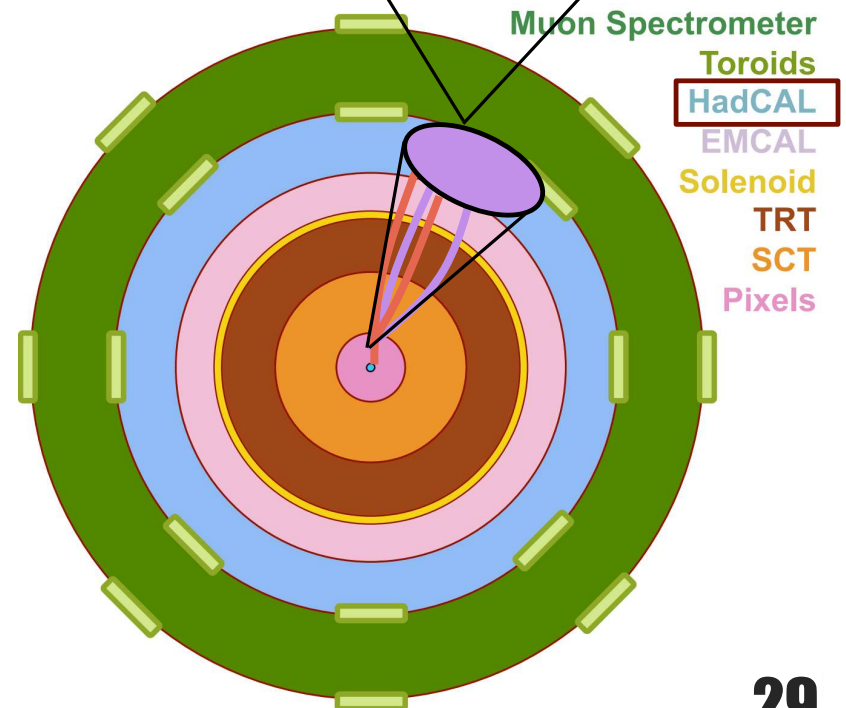


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













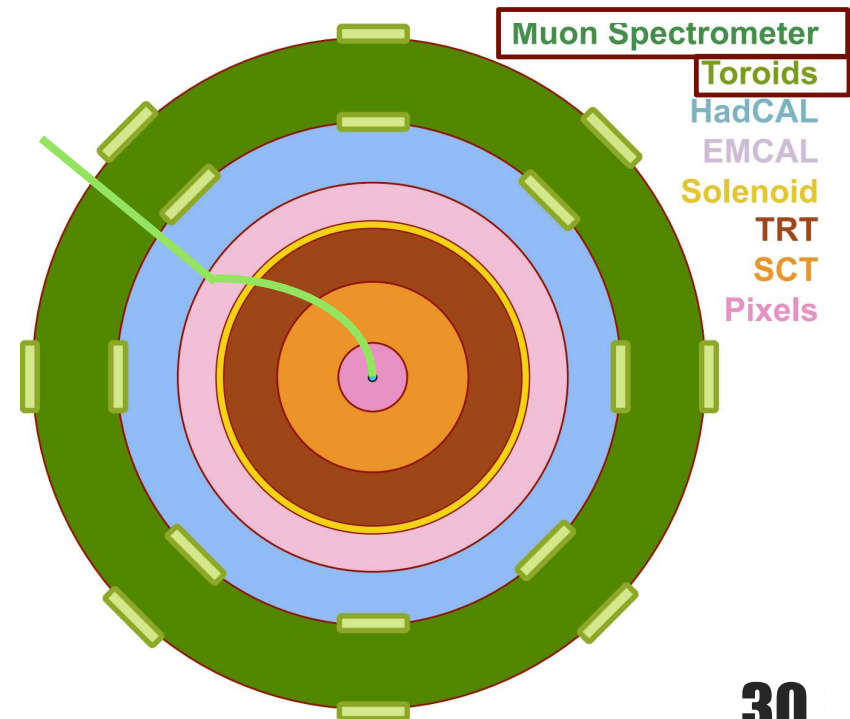
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	u up	c charm	t top	g gluon	H Higgs
QUARKS					SCALAR BOSONS
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	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	d down	s strange	b bottom	γ photon	
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.67 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS					GAUGE BOSONS
	$< 2.2 \text{ eV}/c^2$	$< 1.7 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	±1	
	1/2	1/2	1/2	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	



ATLAS Detector

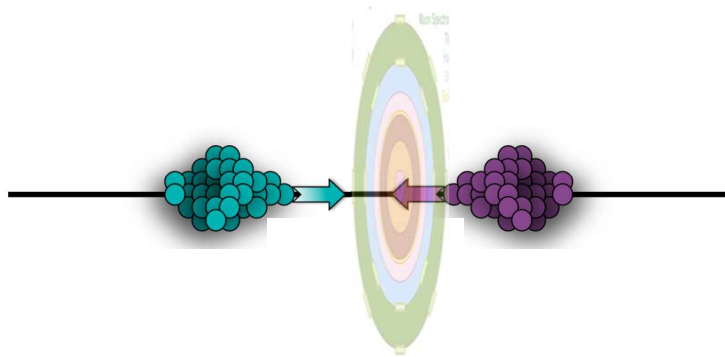
- Muons escape the detector, but leave tracks in the muon spectrometers, which are also surrounded by magnetic field

	mass $\approx 2.4 \text{ MeV}/c^2$ charge $2/3$ spin $1/2$  up	mass $\approx 1.275 \text{ GeV}/c^2$ charge $2/3$ spin $1/2$  charm	mass $\approx 172.44 \text{ GeV}/c^2$ charge $2/3$ spin $1/2$  top	mass 0 charge 0 spin 1  gluon	mass $\approx 125.09 \text{ GeV}/c^2$ charge 0 spin 0  Higgs	
QUARKS	mass $\approx 4.8 \text{ MeV}/c^2$ charge $-1/3$ spin $1/2$  down	mass $\approx 95 \text{ MeV}/c^2$ charge $-1/3$ spin $1/2$  strange	mass $\approx 4.18 \text{ GeV}/c^2$ charge $-1/3$ spin $1/2$  bottom	mass 0 charge 0 spin 1  photon	SCALAR BOSONS	
	mass $\approx 0.511 \text{ MeV}/c^2$ charge -1 spin $1/2$  electron	mass $\approx 105.67 \text{ MeV}/c^2$ charge -1 spin $1/2$  muon	mass $\approx 1.7768 \text{ GeV}/c^2$ charge -1 spin $1/2$  tau	mass $\approx 91.19 \text{ GeV}/c^2$ charge 0 spin 1  Z boson		GAUGE BOSONS
	mass $< 2.2 \text{ eV}/c^2$ charge 0 spin $1/2$  electron neutrino	mass $< 1.7 \text{ MeV}/c^2$ charge 0 spin $1/2$  muon neutrino	mass $< 15.5 \text{ MeV}/c^2$ charge 0 spin $1/2$  tau neutrino	mass $\approx 80.39 \text{ GeV}/c^2$ charge ± 1 spin 1  W boson		



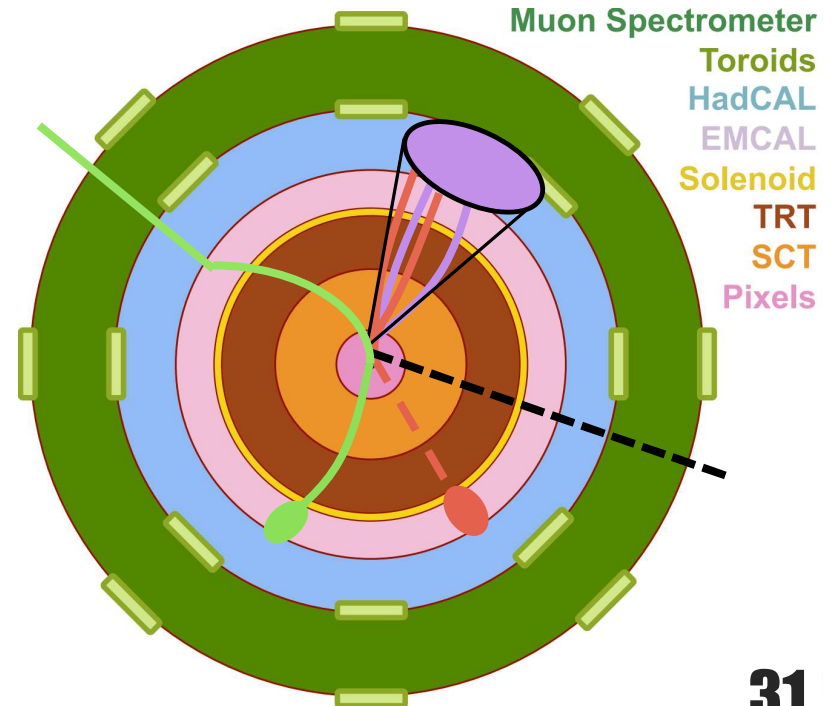
ATLAS Detector

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



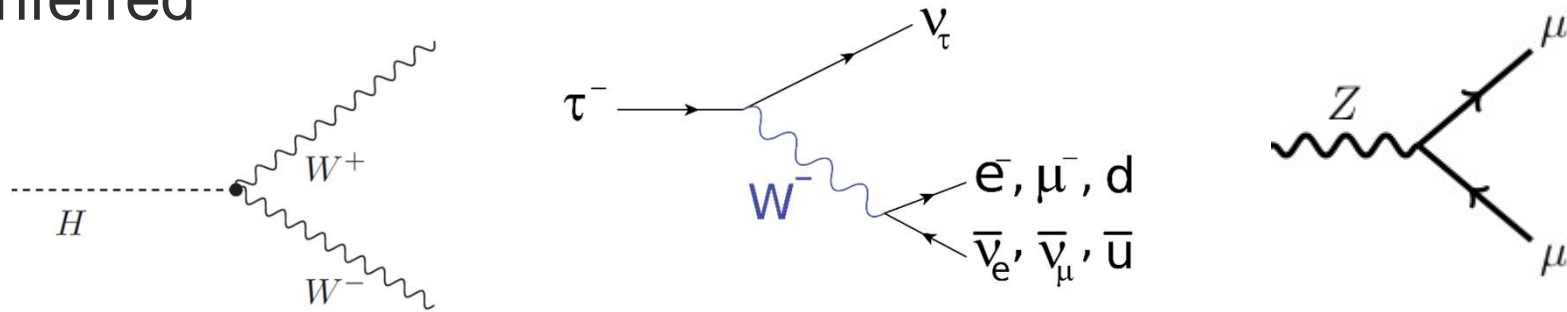
Before collision sum of momenta in transverse plane is 0. Must be true after collision as well

	mass $\approx 2.4 \text{ MeV}/c^2$ charge $2/3$ spin $1/2$ u up	mass $\approx 1.275 \text{ GeV}/c^2$ charge $2/3$ spin $1/2$ c charm	mass $\approx 172.44 \text{ GeV}/c^2$ charge $2/3$ spin $1/2$ t top	mass 0 charge 0 spin 1 g gluon	mass $\approx 125.09 \text{ GeV}/c^2$ charge 0 spin 0 H Higgs
QUARKS	mass $\approx 4.8 \text{ MeV}/c^2$ charge $-1/3$ spin $1/2$ d down	mass $\approx 95 \text{ MeV}/c^2$ charge $-1/3$ spin $1/2$ s strange	mass $\approx 4.18 \text{ GeV}/c^2$ charge $-1/3$ spin $1/2$ b bottom	mass 0 charge 0 spin 1 γ photon	SCALAR BOSONS
	mass $\approx 0.511 \text{ MeV}/c^2$ charge -1 spin $1/2$ e electron	mass $\approx 105.67 \text{ MeV}/c^2$ charge -1 spin $1/2$ μ muon	mass $\approx 1.7768 \text{ GeV}/c^2$ charge -1 spin $1/2$ τ tau	mass $\approx 91.19 \text{ GeV}/c^2$ charge 0 spin 1 Z Z boson	
	mass $< 2.2 \text{ eV}/c^2$ charge 0 spin $1/2$ ν_e electron neutrino	mass $< 1.7 \text{ MeV}/c^2$ charge 0 spin $1/2$ ν_μ muon neutrino	mass $< 15.5 \text{ MeV}/c^2$ charge 0 spin $1/2$ ν_τ tau neutrino	mass $\approx 80.39 \text{ GeV}/c^2$ charge ± 1 spin 1 W W boson	
LEPTONS				Gauge bosons	



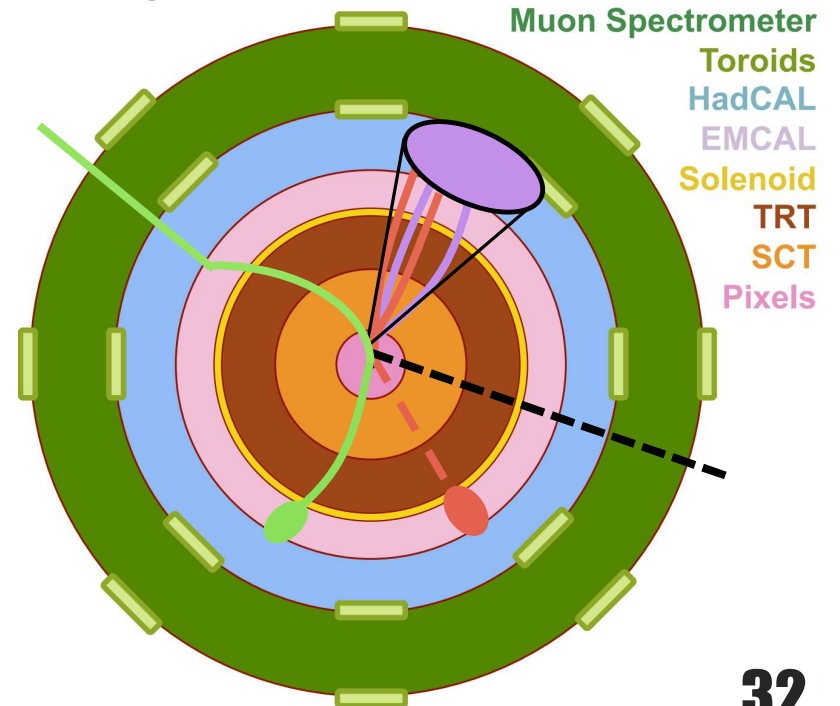
ATLAS Detector

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



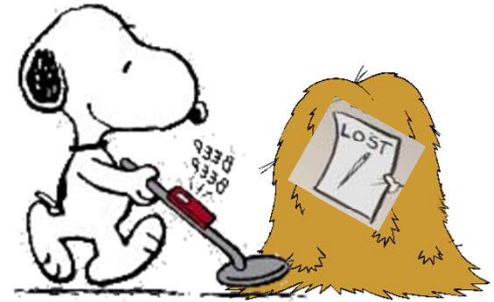
	mass $\approx 2.4 \text{ MeV}/c^2$ charge $2/3$ spin $1/2$ u up	mass $\approx 1.275 \text{ GeV}/c^2$ charge $2/3$ spin $1/2$ c charm	mass $\approx 172.44 \text{ GeV}/c^2$ charge $2/3$ spin $1/2$ t top	mass 0 charge 0 spin 1 g gluon	mass $\approx 125.09 \text{ GeV}/c^2$ charge 0 spin 0 H Higgs
QUARKS	mass $\approx 4.8 \text{ MeV}/c^2$ charge $-1/3$ spin $1/2$ d down	mass $\approx 95 \text{ MeV}/c^2$ charge $-1/3$ spin $1/2$ s strange	mass $\approx 4.18 \text{ GeV}/c^2$ charge $-1/3$ spin $1/2$ b bottom	mass 0 charge 0 spin 1 γ photon	SCALAR BOSONS
	mass $\approx 0.511 \text{ MeV}/c^2$ charge -1 spin $1/2$ e electron	mass $\approx 105.67 \text{ MeV}/c^2$ charge -1 spin $1/2$ μ muon	mass $\approx 1.7768 \text{ GeV}/c^2$ charge -1 spin $1/2$ τ tau	mass $\approx 91.19 \text{ GeV}/c^2$ charge 0 spin 1 Z Z boson	
	mass $< 2.2 \text{ eV}/c^2$ charge 0 spin $1/2$ ν_e electron neutrino	mass $< 1.7 \text{ MeV}/c^2$ charge 0 spin $1/2$ ν_μ muon neutrino	mass $< 15.5 \text{ MeV}/c^2$ charge 0 spin $1/2$ ν_τ tau neutrino	mass $\approx 80.39 \text{ GeV}/c^2$ charge ± 1 spin 1 W W boson	
LEPTONS	GAUGE BOSONS				

Simplified Detector Transverse View



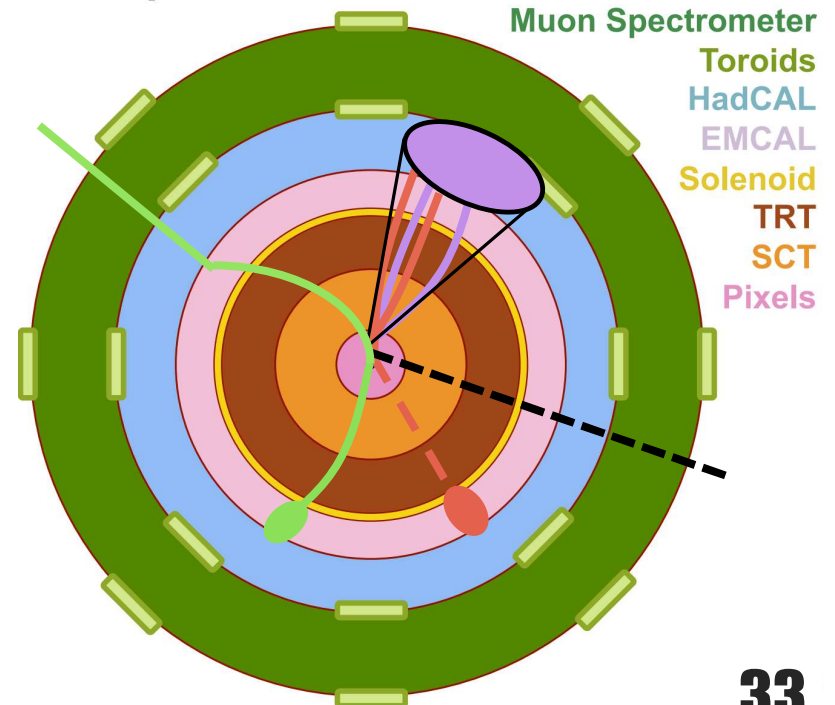
ATLAS Detector

- 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?



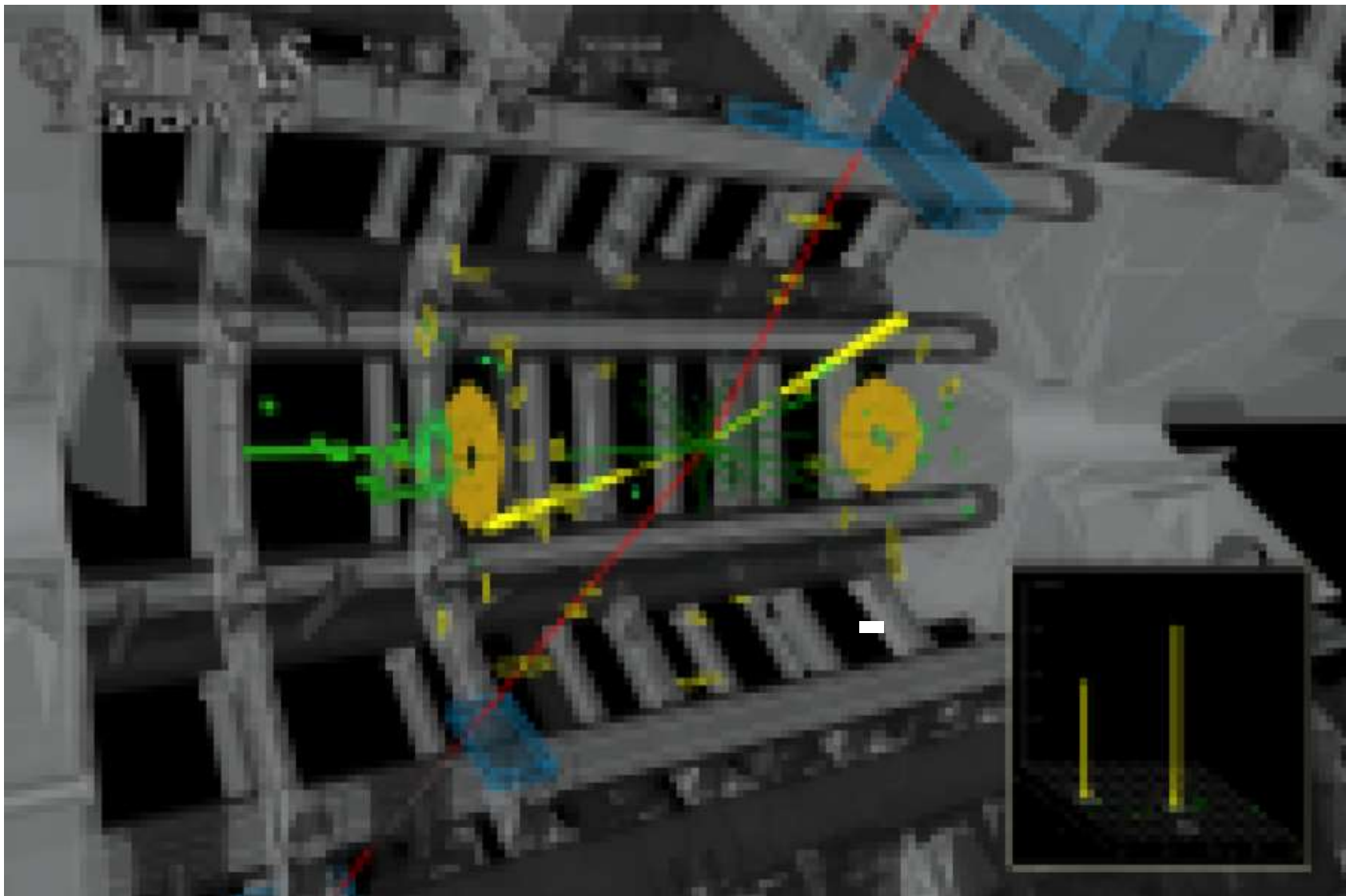
mass	$\approx 2.4 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 172.44 \text{ GeV}/c^2$	0	$\approx 125.09 \text{ GeV}/c^2$
charge	$2/3$	$2/3$	$2/3$	0	0
spin	$1/2$	$1/2$	$1/2$	1	0
	u up	c charm	t top	g gluon	H Higgs
QUARKS	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-1/3$	$-1/3$	$-1/3$	0	
	$1/2$	$1/2$	$1/2$	1	
	d down	s strange	b bottom	γ photon	
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.67 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$1/2$	$1/2$	$1/2$	1	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS	$< 2.2 \text{ eV}/c^2$	$< 1.7 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	± 1	
	$1/2$	$1/2$	$1/2$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
					GAUGE BOSONS

Simplified Detector Transverse View



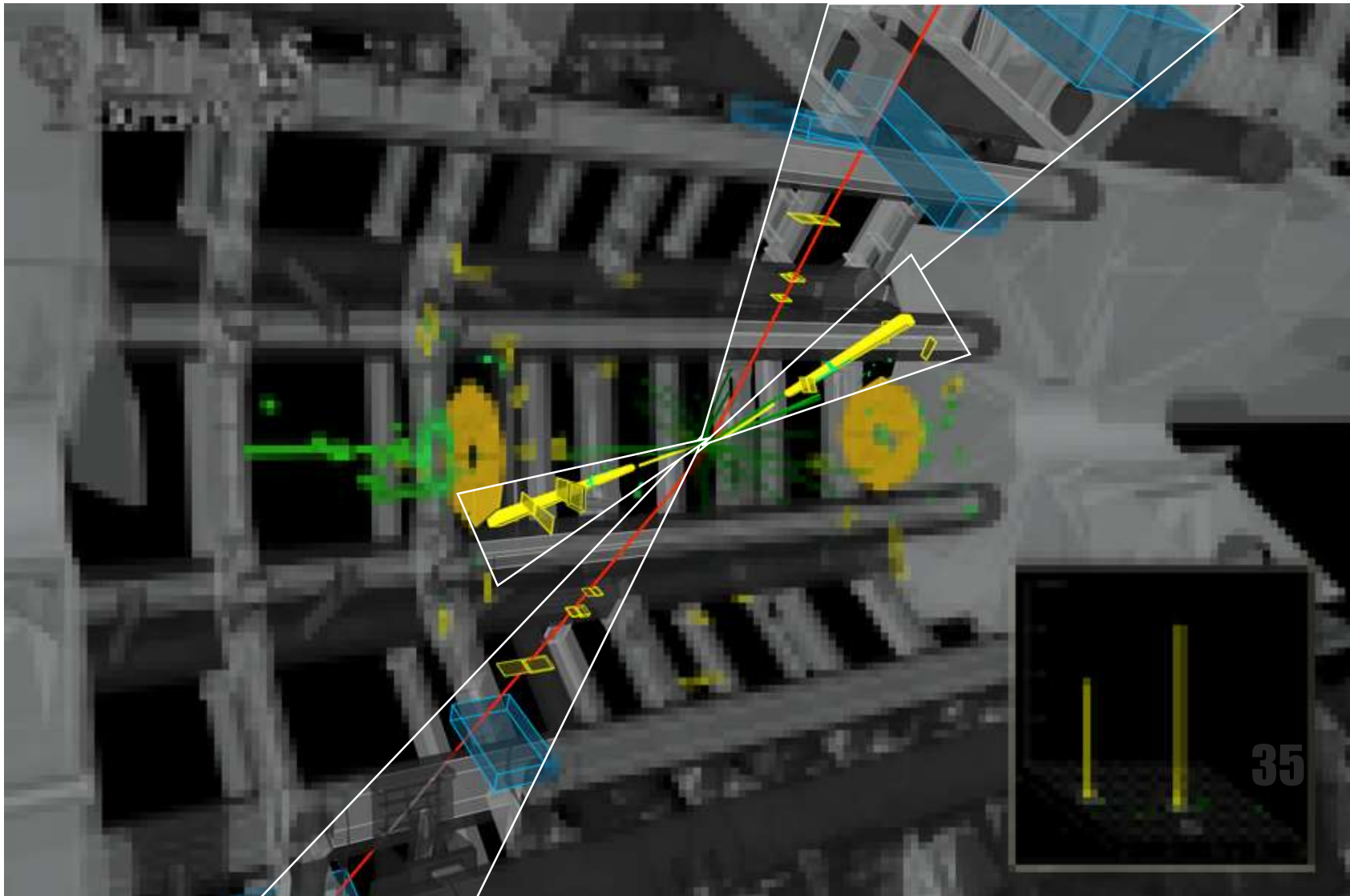
ATLAS Detector : Trigger – STEP 1 L1

- Reduce 40 MHz to 100 kHz in $2.5 \mu\text{s}$
- Level 1 (L1) Trigger: electronics on calorimeters and muon detector



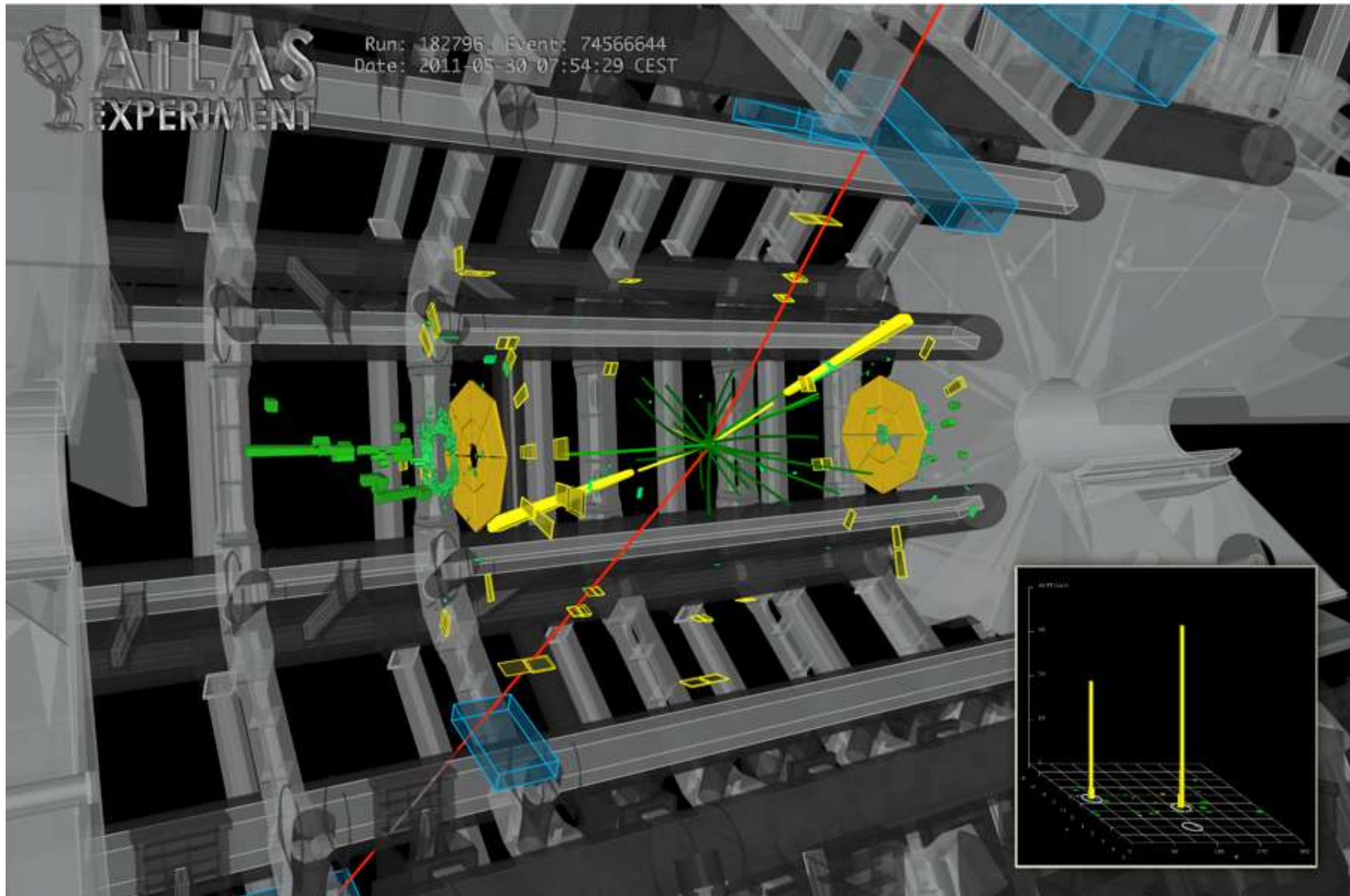
ATLAS Detector : Trigger – STEP 2 HLT

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



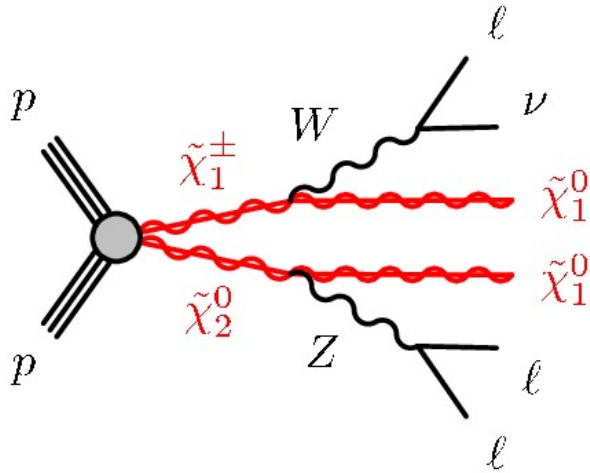
ATLAS Detector : Trigger – STEP 3 HLT

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

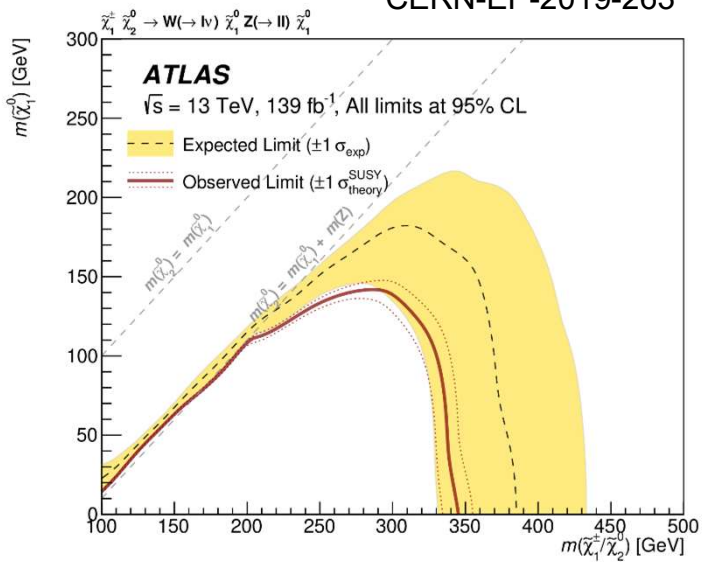


ATLAS Physics

Mass Hierarchy solution: SUSY

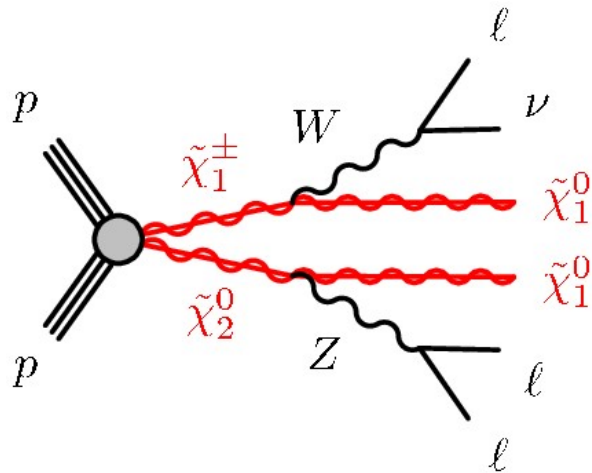


CERN-EP-2019-263

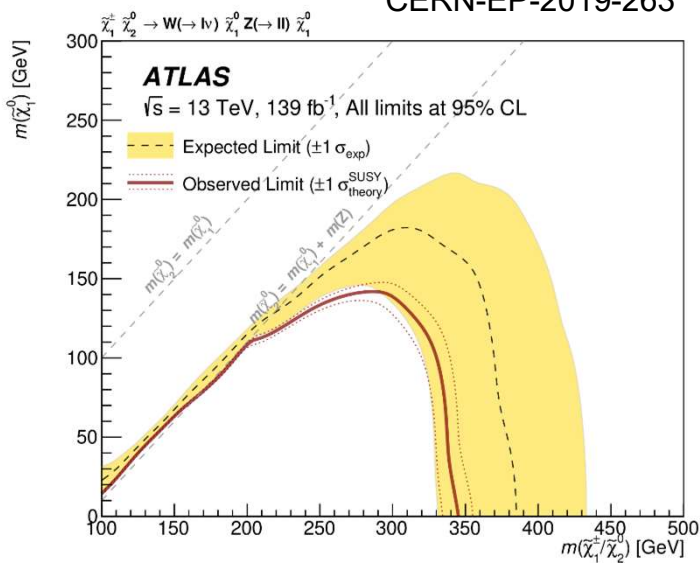


ATLAS Physics

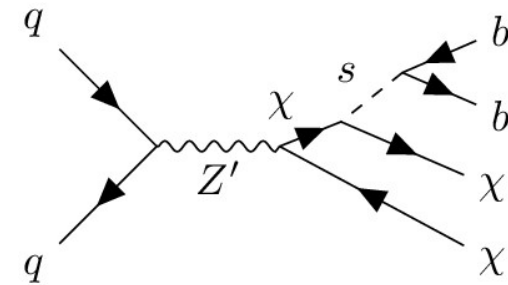
Mass Hierarchy solution: SUSY



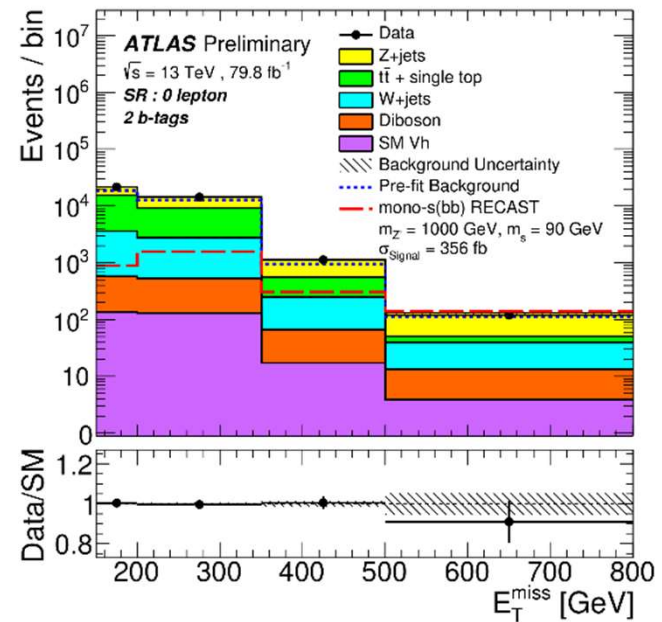
CERN-EP-2019-263



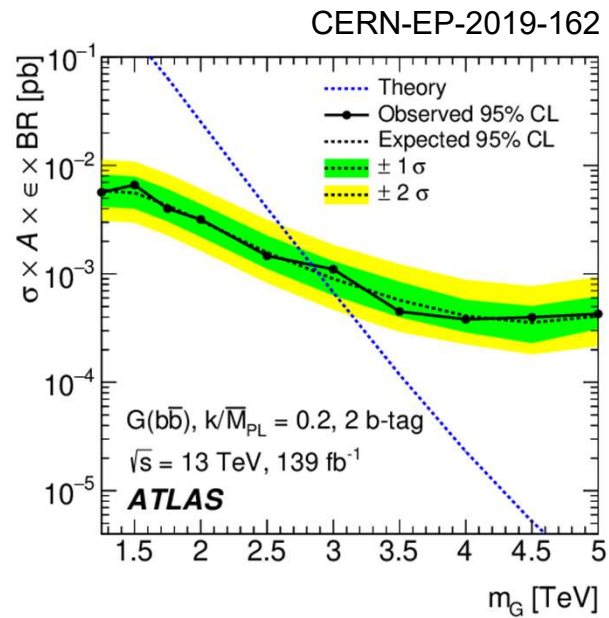
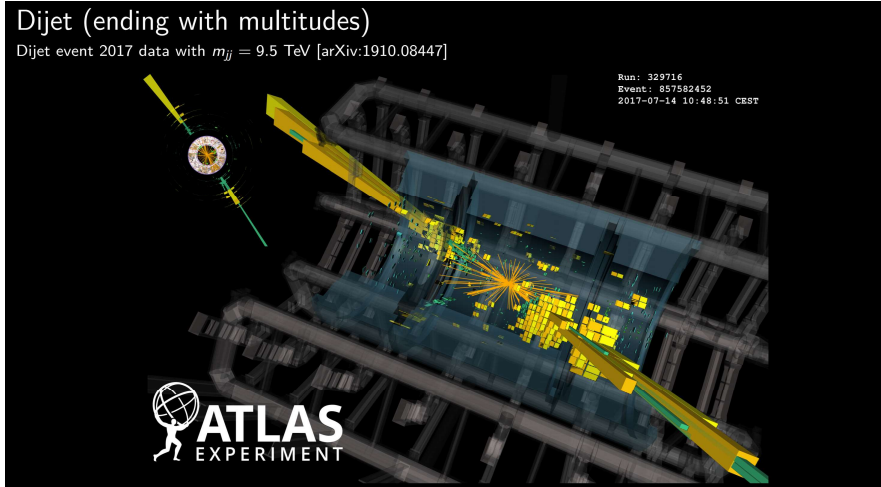
Dark Matter Candidates



ATL-PHYS-PUB-2019-032

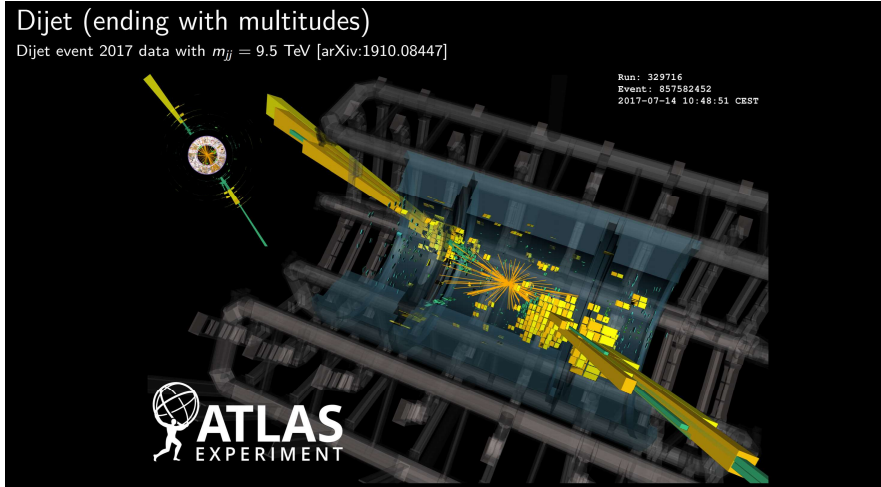


Gravitons

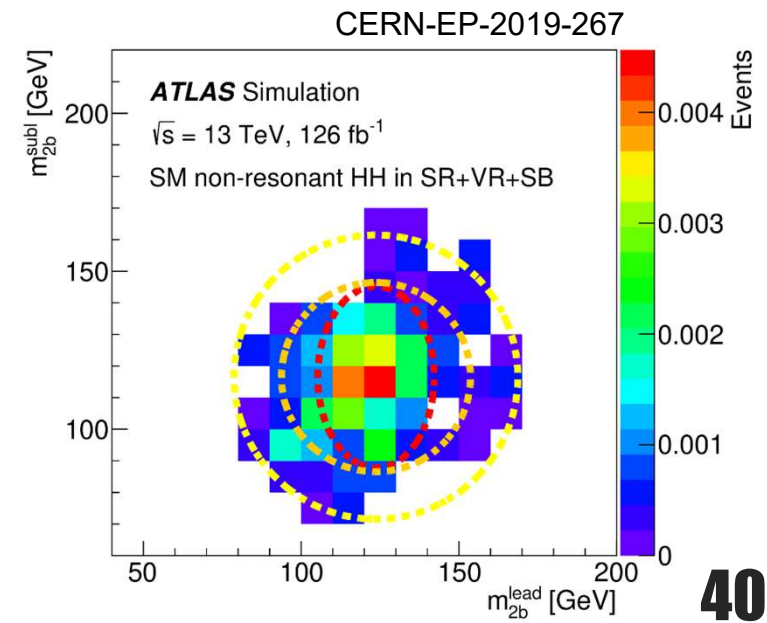
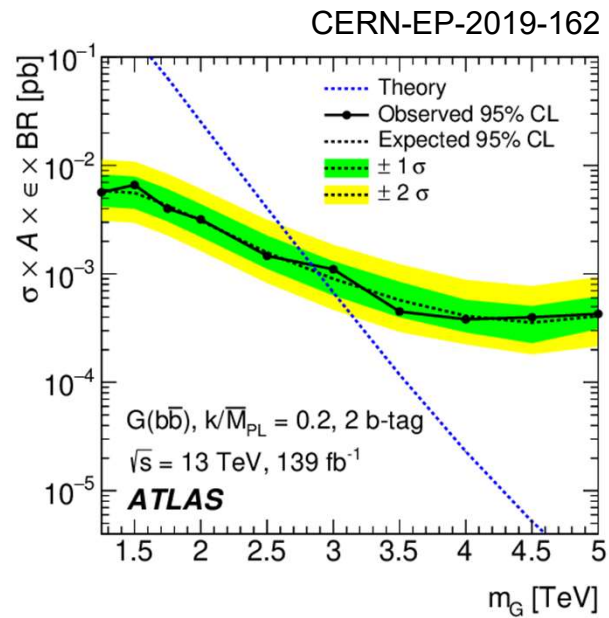
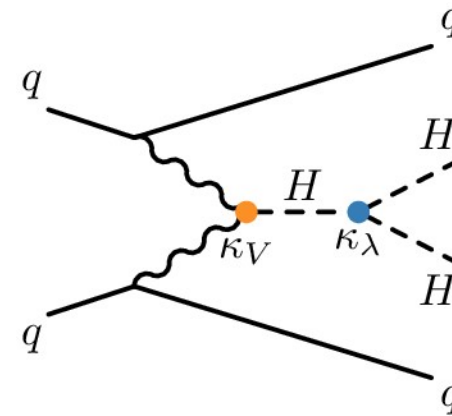


ATLAS Physics

Gravitons



Higgses



LBNF and DUNE

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

– Wolfgang Pauli

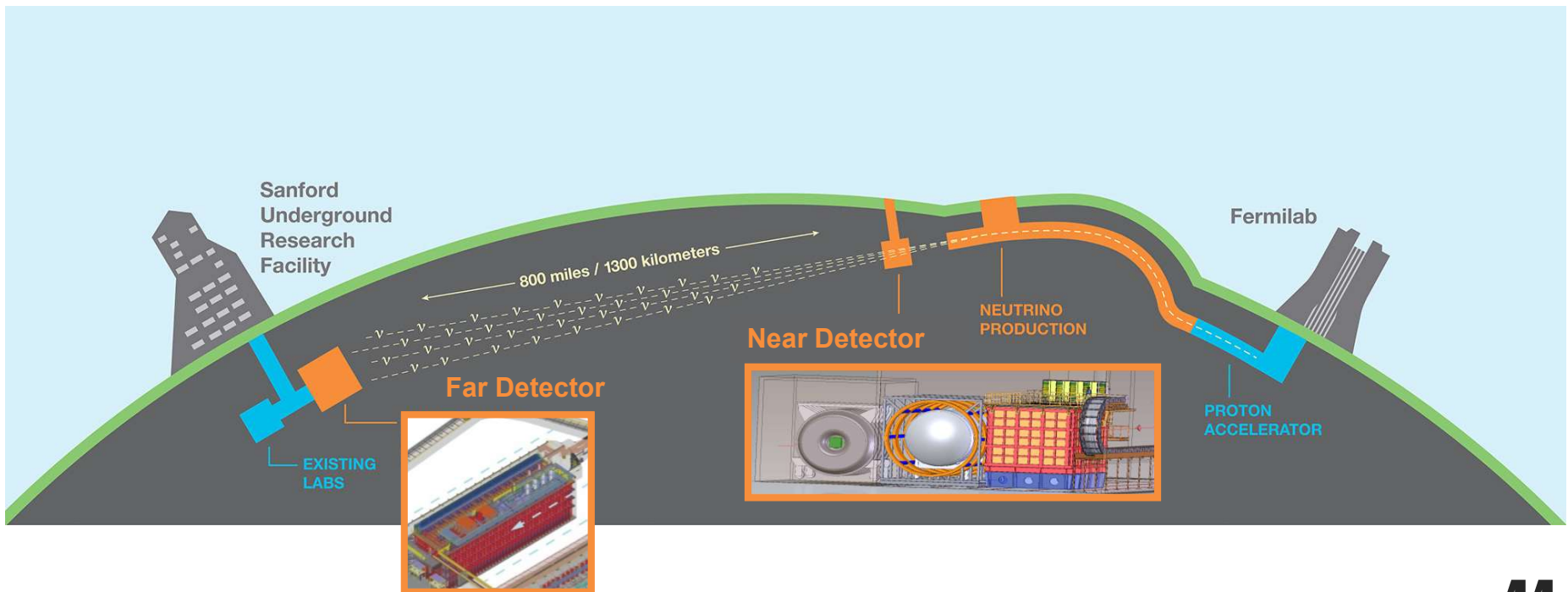
So What Don't We Know?



- 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?

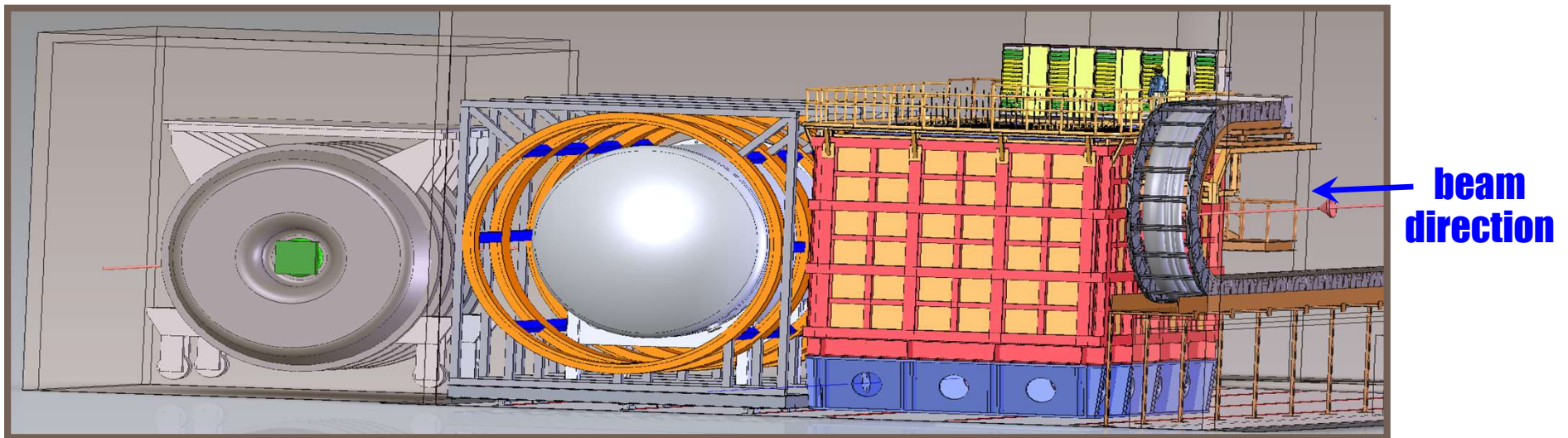
LBNF DUNE Facility

- 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

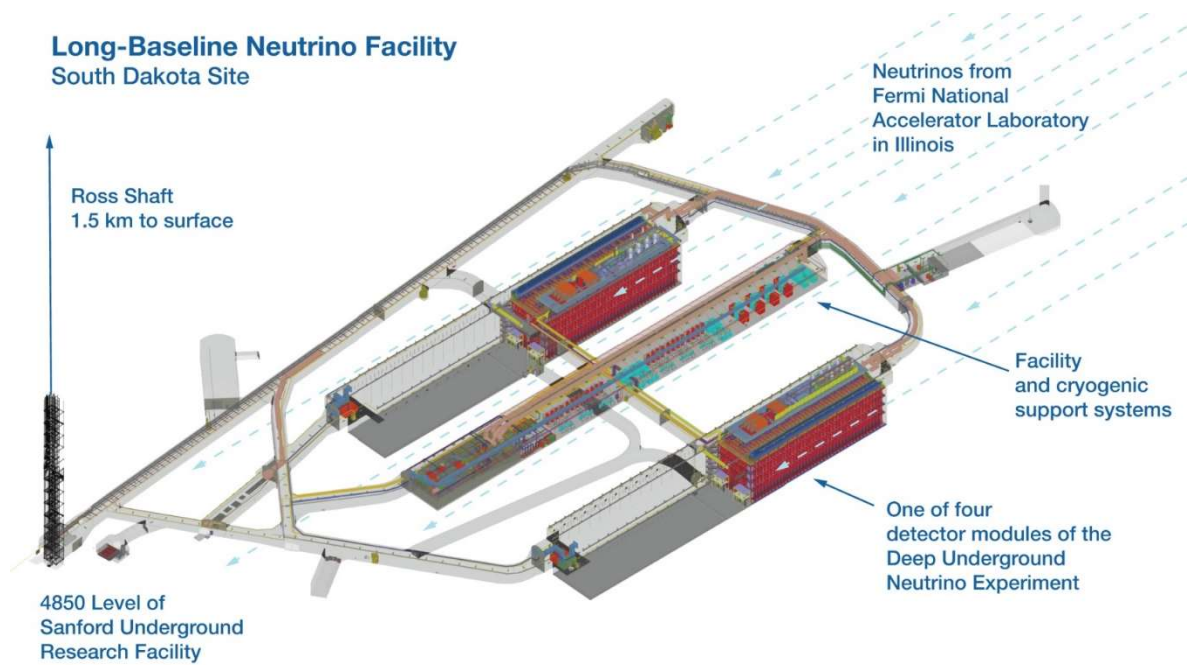


Scintillator cubes
for beam monitor

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

Liquid Argon TPC:
Most like Far Detector

DUNE Far Detector

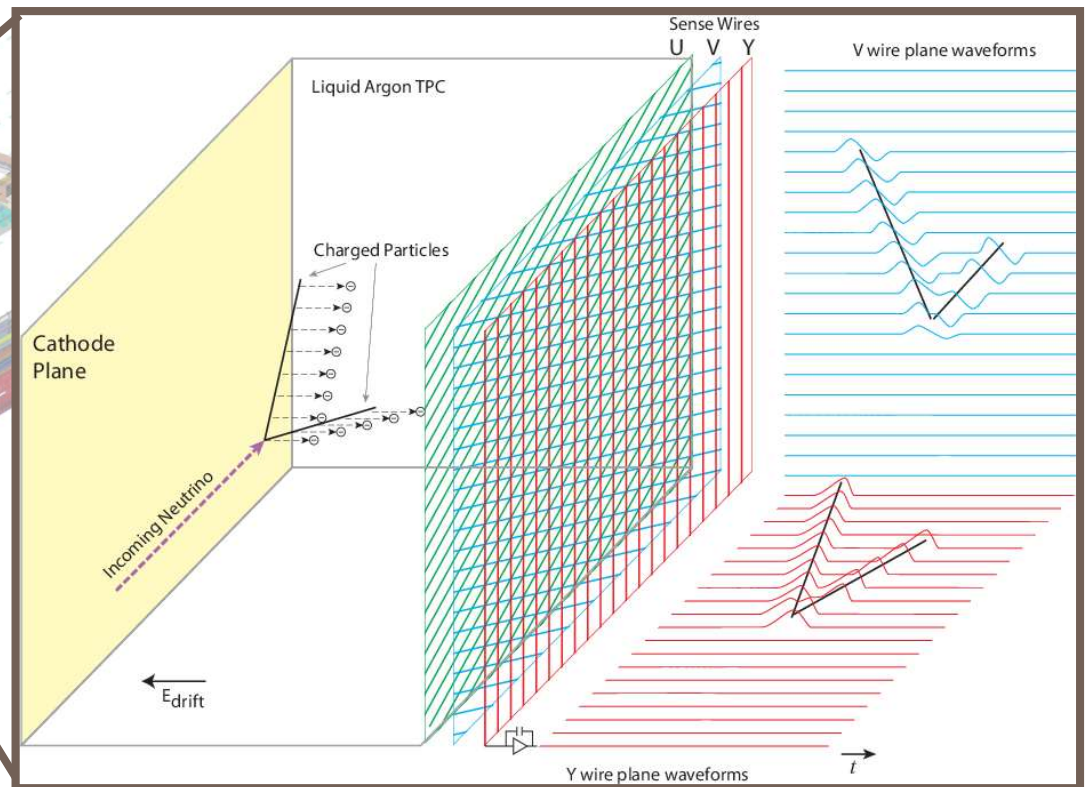
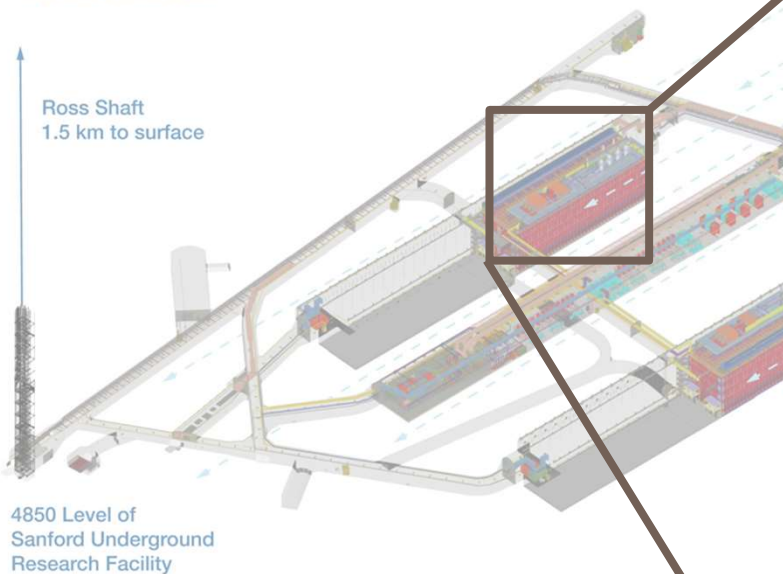


4 chambers, 17 kton total mass each

DUNE Far Detector

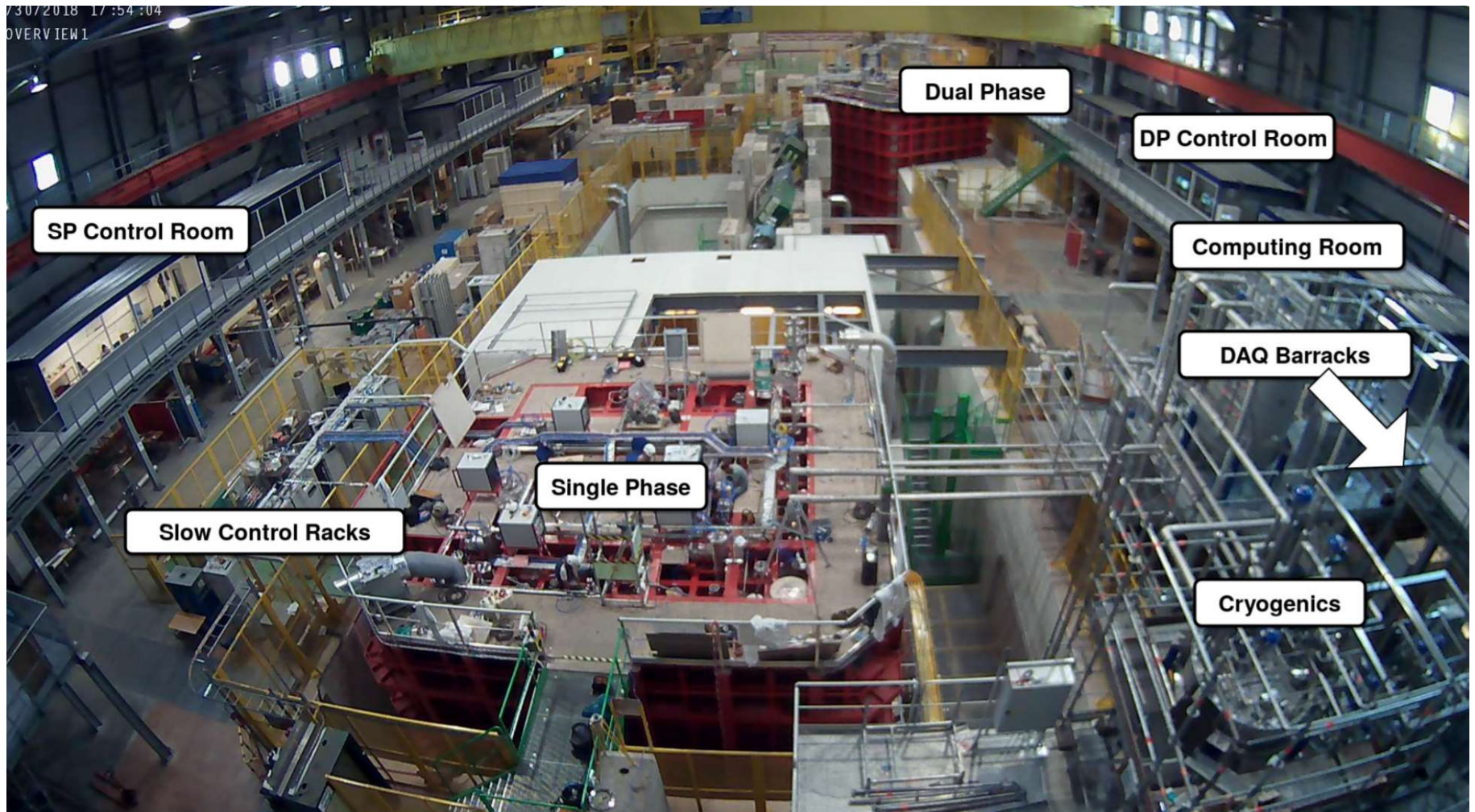
LAr TPC: few mm resolution, 3D image

Long-Baseline Neutrino Facility
South Dakota Site



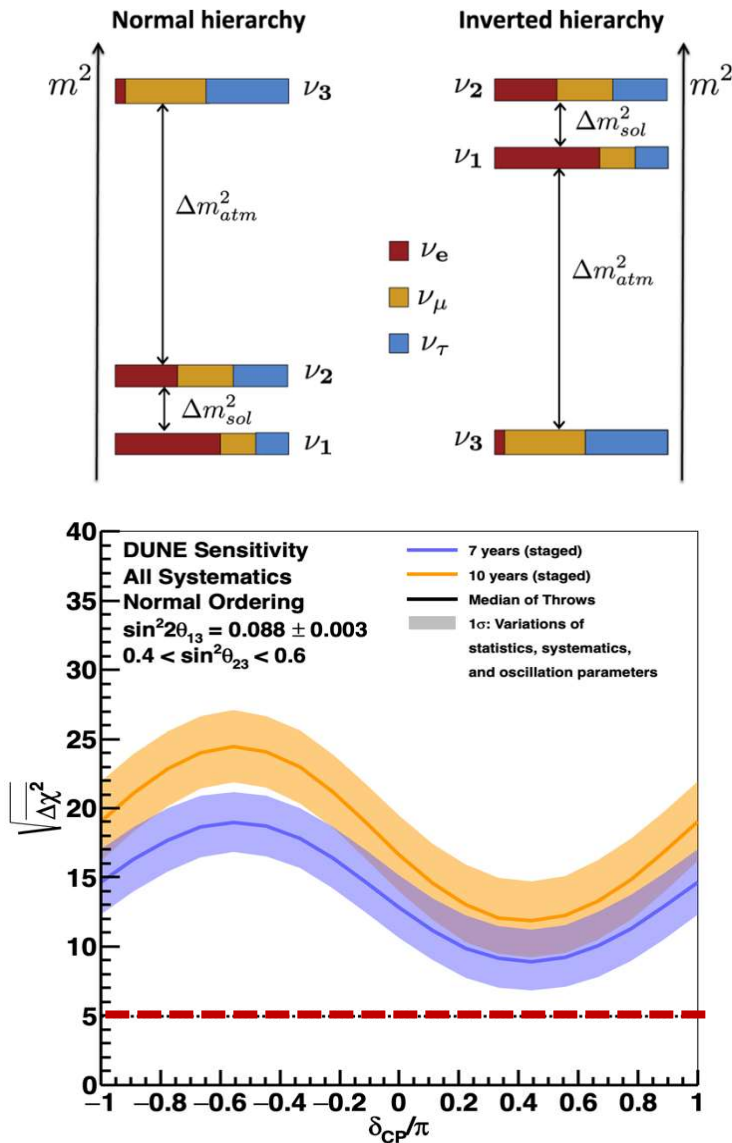
Installation of first module in 2024

DUNE Prototype

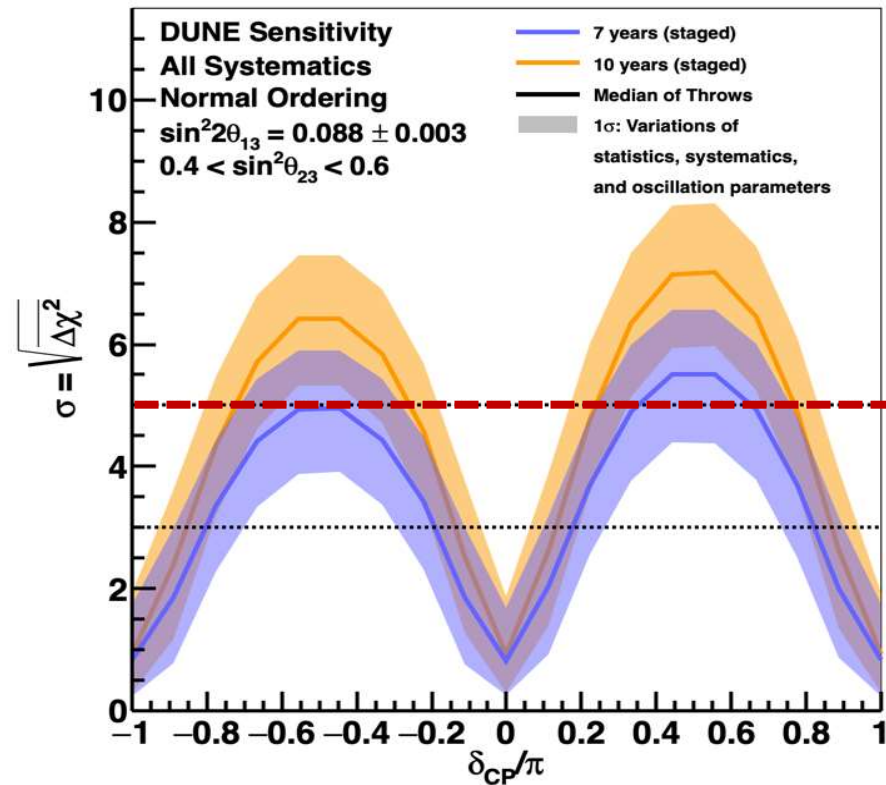


DUNE Physics

Mass Ordering Sensitivity



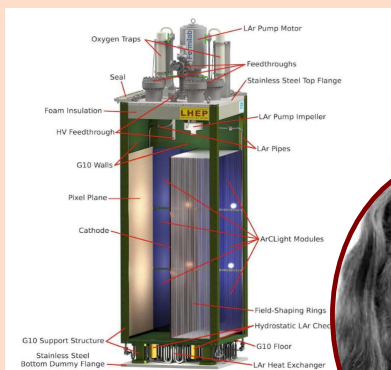
CP violation Sensitivity



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

Planned Canadian Contributions

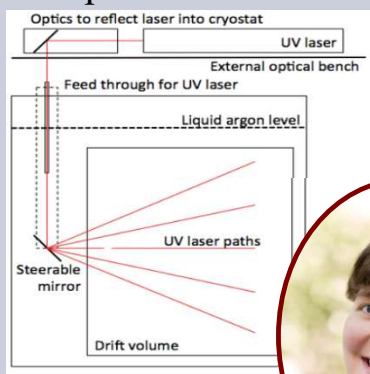
Near Detector Prototype & Neutrino Interaction model



Deborah Harris
Dharris@fnal.gov



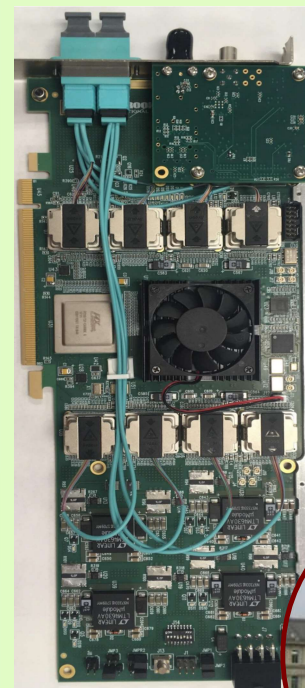
Computing, Calibration & Supernova neutrinos



Claire David
Claire.David@cern.ch



FELIX readout system & Extra neutrino & NSI searches



Nikolina Ilic
Nikolina.Ilic@cern.ch



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

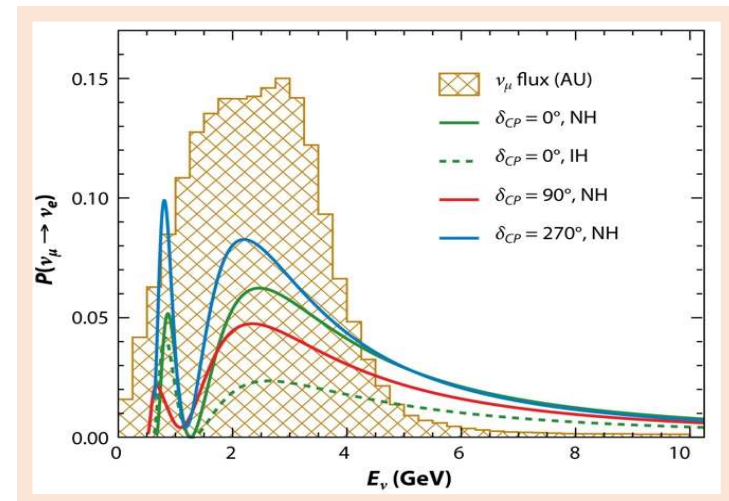
Summary & Outlook

- 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

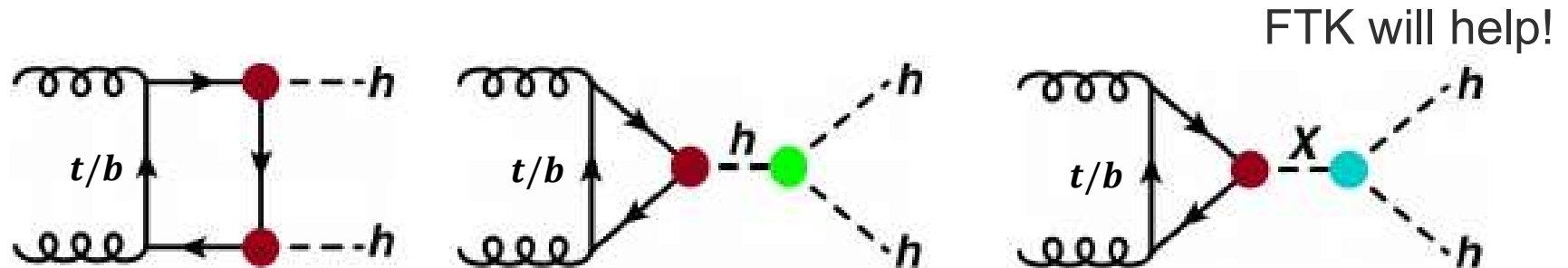
Large oscillations length (~1000 km) = significant matter effects

On axis beam gives wide range of neutrino energy – differentiate CPV effects from matter effects through energy dependence

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

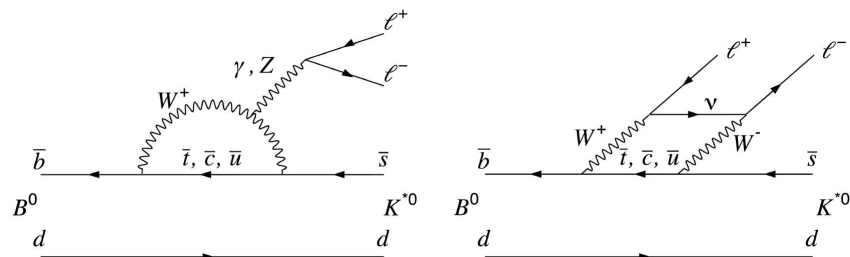


Di-Higgs production enhanced in many BSM models

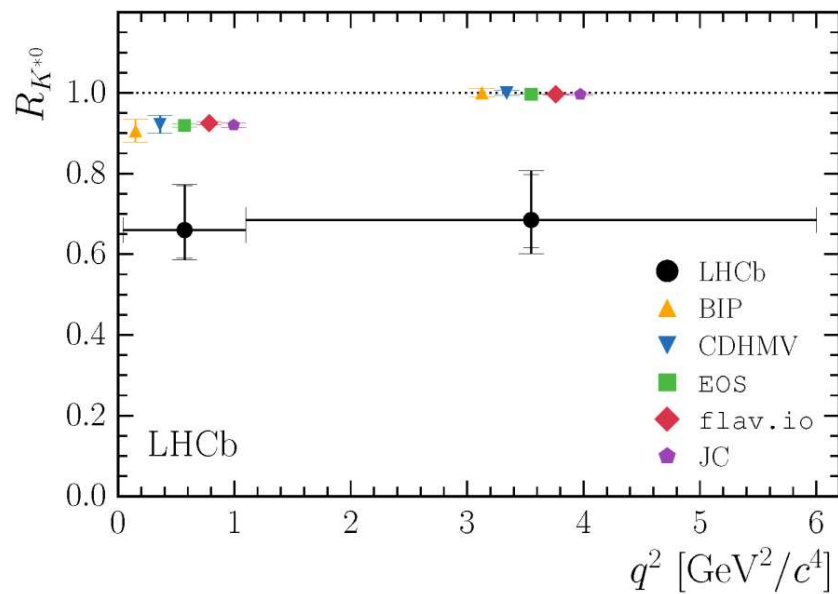
- Non resonant production: Higgs coupling to t, b, h modified wrt SM values
- Resonant production: Replacing virtual Higgs boson with an intermediate heavy resonance (2HDM, G_{kk^*})

*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%



$$R(K^*) = \frac{BR(B^0 \rightarrow K^* \mu\mu)}{BR(B^0 \rightarrow D^* ee)}$$



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