ABSTRACT

RNTUPLE FOR ATLAS ANALYSIS WORKFLOWS

Fatima Rodriguez, M.A.
Department of Physics
Northern Illinois University, 2025
Hector de la Torre, Director

RNTuple is the new data storage format set to replace TTree at the start of the High Luminosity LHC. An investigation was conducted on how analysis workflows for ATLAS researchers will change with RNTuple. Additionally, performance studies have been conducted that demonstrate an improvement in speed and memory usage at the analysis front. Finally, different compression algorithms were tested and it was found that blah blah remains to best work with RNTuple.

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RNTUPLE FOR ATLAS ANALYSIS WORKFLOWS

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FATIMA RODRIGUEZ

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ACKNOWLEDGEMENTS

Thanks thanks

DEDICATION

To my mum.

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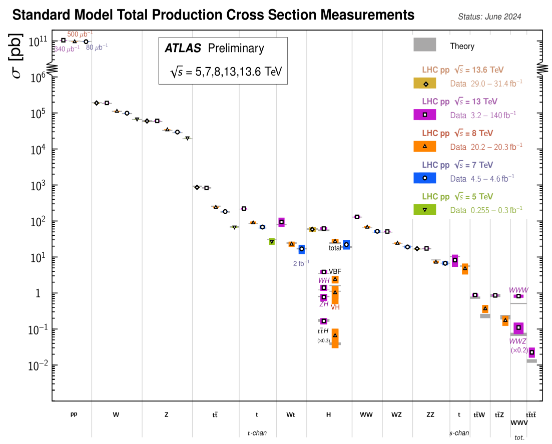
CHAPTER 1

INTRODUCTION

Our current understanding of the building blocks of our universe is summarized with one model, called the Standard Model (SM). From the way we power our cities, to the particles that hold them together, the SM explains how the basic building blocks of matter interact, governed by the four fundamental forces: gravity, electromagnetism, the strong force and the weak force. Yet, questions remain about the SM, such as why are there only three generations of fundamental particles? What is the nature of dark matter and dark energy, and how does it fit within the SM? What about the origin of the matter-antimatter asymmetry? Is there a unification theory for the fundamental forces? Is the SM complete or do other exotic particles exists? Over the years, experimental particle physicists and engineers have built technology to test the SM, either by performing precision measurements of particles and their behaviors, or by colliding particles and measuring their outputs. As a result, we have increased our confidence in the SM theory, but continue to search for answers for these remaining questions through experimental discovery.

A Toroidal LHC Apparatus (ATLAS) is a particle physics experiment designed to detect the high-energy particle collisions from the Large Hadron Collider (LHC). At the LHC, collisions take place at a rate of more than a billion interactions per second, which is a combined data volume of about 60 million megabytes per second. However, in order to study rare processes, as shown in Figure 1.1, the LHC will have a major upgrade to increase the number of collisions by a factor of 5 to 7.5. This upgrade, called the High-Luminosity LHC, will require a new data storage format that can handle this increase in data.



Standard Model Production Cross Section Measurements

Status: June 2024

ATLAS Preliminary
$\sqrt{s}$ = 5, 7, 8, 13, 13.6 TeV

Model	E_{CM} [TeV]	$\int\mathcal{L}\,dt$ [fb^{-1}]	Measurement	Theory	Reference
pp	13	34×10^{-8}	$\sigma = 104.7 \pm 0.22 \pm 1.07$ mb	$\sigma = 100.3 \pm 0.12$ mb (COMPETE HPR1R2)	EPJC 83 (2023) 441
pp	8	50×10^{-8}	$\sigma = 96.07 \pm 0.18 \pm 0.91$ mb	$\sigma = 99.55 \pm 2.14$ mb (COMPETE HPR1R2)	PLB 761 (2016) 158
pp	7	8×10^{-8}	$\sigma = 95.35 \pm 0.38 \pm 1.3$ mb	$\sigma = 97.26 \pm 2.12$ mb (COMPETE HPR1R2)	Nucl. Phys. B (2014) 486
W	13.6	29.0	$\sigma = 187 \pm 0.1 \pm 6.5$ nb	$\sigma = 193.2 + 3.8 - 5.9$ nb (DYTURBO+CT18 (NNLO+NNLL))	PLB 854 (2024) 138725
W	13	0.3	$\sigma = 190.1 \pm 0.4 \pm 4.2$ nb	$\sigma = 185.3 + 3.8 - 5.5$ nb (DYTURBO + CT18 (NNLO+NNLL))	arXiv:2404.06204
W	8	20.2	$\sigma = 112.69 \pm 3.1$ nb	$\sigma = 110.919889503 \pm 3.7$ nb (DYNNLO + CT14NNLO)	EPJC 79 (2019) 760
W	7	4.6	$\sigma = 98.71 \pm 0.028 \pm 2.191$ nb	$\sigma = 95.9 \pm 2.9$ nb (DYNNLO + CT14NNLO)	EPJC 77 (2017) 367
W	5	0.3	$\sigma = 67.334 \pm 0.06 \pm 0.74$ nb	$\sigma = 66.36 + 1.3 - 2.1$ nb (DYTURBO+CT18 (NNLO+NNLL))	arXiv:2404.06204
Z	13.6	29.0	$\sigma = 59.12 \pm 0.029 \pm 1.6$ nb	$\sigma = 59.12 \pm 3.56$ nb (DYTURBO+CT18 (NNLO+NNLL))	PLB 854 (2024) 138725
Z	13	0.3	$\sigma = 60.18 \pm 0.2 \pm 1.78$ nb	$\sigma = 57.67 + 1.4 - 1.9$ nb (DYTURBO + CT18 (NNLO+NNLL))	arXiv:2404.06204
Z	8	20.2	$\sigma = 34.24 \pm 0.03 \pm 0.92$ nb	$\sigma = 32.94 + 0.8 - 0.92$ nb (DYNNLO+CT14 NNLO)	JHEP 02 (2017) 117
Z	7	4.6	$\sigma = 29.53 \pm 0.03 \pm 0.77$ nb	$\sigma = 28.31 + 0.68 - 0.8$ nb (DYNNLO+CT14 NNLO)	JHEP 02 (2017) 117
Z	5	0.3	$\sigma = 20.11 \pm 0.04 \pm 0.35$ nb	$\sigma = 19.32 + 0.31 - 0.55$ nb (DYTURBO+CT18 (NNLO+NNLL))	arXiv:2404.06204
$t\bar{t}$	13.6	29.0	$\sigma = 850 \pm 3 \pm 27$ pb	$\sigma = 924 + 32 - 40$ pb (LHC TOP WG)	PLB 848 (2024) 138376
$t\bar{t}$	13	140	$\sigma = 829 \pm 1 \pm 15.4$ pb	$\sigma = 834 + 29 - 37$ pb (LHC TOP WG)	JHEP 07 (2023) 141
$t\bar{t}$	8	20.2	$\sigma = 242.9 \pm 1.7 \pm 8.6$ pb	$\sigma = 256 + 10.4 - 12$ pb (LHC TOP WG)	EPJC 74 (2014) 3109
$t\bar{t}$	7	4.6	$\sigma = 182.9 \pm 3.1 \pm 6.4$ pb	$\sigma = 179.6 + 7.8 - 8.7$ pb (LHC TOP WG)	EPJC 74 (2014) 3109
$t\bar{t}$	5	0.3	$\sigma = 67.5 \pm 0.9 \pm 2.6$ pb	$\sigma = 69.5 + 3.5 - 3.7$ pb (LHC TOP WG)	JHEP 06 (2023) 138
t_{t-chan}	13	140	$\sigma = 221 \pm 1 \pm 13$ pb	$\sigma = 214.2 + 4.1 - 2.6$ pb (MCFM (NNLO))	JHEP 05 (2024) 305
t_{t-chan}	8	20.3	$\sigma = 89.6 \pm 1.7 + 7.2 - 6.4$ pb	$\sigma = 84.3 + 1.7 - 1.2$ pb (MCFM (NNLO))	EPJC 77 (2017) 531
t_{t-chan}	7	4.6	$\sigma = 68 \pm 2 \pm 8$ pb	$\sigma = 63.7 + 1.4 - 0.8$ pb (MCFM (NNLO))	PRD 90, 112006 (2014)
t_{t-chan}	5	0.3	$\sigma = 27.1 + 4.4 - 4.1 + 4.4 - 3.7$ pb	$\sigma = 30.3 + 0.7 - 0.5$ pb (MCFM (NNLO))	PLB 854 (2024) 138726
Wt	13	3.2	$\sigma = 94 \pm 10 + 28 - 23$ pb	$\sigma = 79.3 + 2.9 - 2.8$ pb (NLO+NNLL)	JHEP 01 (2018) 63
Wt	8	20.3	$\sigma = 23 \pm 1.3 + 3.4 - 3.7$ pb	$\sigma = 24.4 + 1.1 - 1$ pb (NLO+NLL)	JHEP 01, 064 (2016)
Wt	7	2.0	$\sigma = 16.8 \pm 2.9 \pm 3.9$ pb	$\sigma = 17.1 \pm 0.8$ pb (NLO+NLL)	PLB 716, 142-159 (2012)
H	13.6	31.4	$\sigma = 58.2 \pm 7.5 \pm 4.5$ pb	$\sigma = 59.9 \pm 2.6$ pb (LHC-HXSWG YR4)	EPJC 84 (2024) 78
H	13	139	$\sigma = 55.5 \pm 3.2 + 2.4 - 2.2$ pb	$\sigma = 55.6 \pm 2.5$ pb (LHC-HXSWG YR4)	JHEP 05 (2023) 028
H	8	20.3	$\sigma = 27.7 \pm 3 + 2.3 - 1.9$ pb	$\sigma = 24.5 + 1.3 - 1.8$ pb (LHC-HXSWG YR4)	EPJC 76 (2016) 6
H	7	4.5	$\sigma = 22.1 + 6.7 - 5.3 + 3.3 - 2.7$ pb	$\sigma = 19.2 + 1 - 1.4$ pb (LHC-HXSWG YR4)	EPJC 76 (2016) 6
H VBF, $\lvert y_H \rvert < 2.5$	13	139	$\sigma = 3.86 + 0.29 - 0.28 + 0.37 - 0.33$ pb	$\sigma = 3.5 \pm 0.07$ pb (LHC-HXSWG)	Nature 607, pages 52-59 (2022)
H VBF	8	20.3	$\sigma = 2.43 + 0.5 - 0.49 + 0.29 - 0.31$ pb	$\sigma = 1.6 \pm 0.04$ pb (LHC-HXSWG YR4)	EPJC 76 (2016) 6
VH	8	20.3	$\sigma = 1.03 + 0.37 - 0.36 \pm 0.4$ pb	$\sigma = 1.12 \pm 0.03$ pb (NNLO QCD + NLO EW)	EPJC 76 (2016) 6
WH, $\lvert y_H \rvert < 2.5$	13	139	$\sigma = 1.41 + 0.21 - 0.2 + 0.18 - 0.17$ pb	$\sigma = 1.22 \pm 0.024$ pb (Powheg Box NLO QCD)	Nature 607, pages 52-59 (2022)
ZH, $\lvert y_H \rvert < 2.5$	13	139	$\sigma = 0.77 \pm 0.13 + 0.12 - 0.1$ pb	$\sigma = 0.8 \pm 0.03$ pb (Powheg Box NLO QCD)	Nature 607, pages 52-59 (2022)
$t\bar{t}H$	13	139	$\sigma = 560 \pm 80 + 70 - 80$ fb	$\sigma = 580 \pm 50$ fb (LHCHXSWG NLO QCD + NLO EW)	Nature 607, pages 52-59 (2022)
$t\bar{t}H$	8	20.3	$\sigma = 220 \pm 100 \pm 70$ fb	$\sigma = 133 + 8 - 13$ fb (LHCHXSWG NLO QCD + NLO EW)	PLB 784 (2018) 173
WW	13	36.1	$\sigma = 130.04 \pm 1.7 \pm 10.6$ pb	$\sigma = 128.4 + 3.2 - 2.9$ pb (NNLO)	EPJC 79 (2019) 884
WW	8	20.3	$\sigma = 68.2 \pm 1.2 \pm 4.6$ pb	$\sigma = 65 + 1.2 - 1.1$ pb (NNLO)	PLB 763, 114 (2016)
WW	7	4.6	$\sigma = 51.9 \pm 2 \pm 4.4$ pb	$\sigma = 49.04 + 1.03 - 0.88$ pb (NNLO)	PRD 87 (2013) 112001, PRL 113 (2014) 212001
WZ	13	36.1	$\sigma = 51 \pm 0.8 \pm 2.3$ pb	$\sigma = 49.1 + 1.1 - 1$ pb (MATRIX (NNLO))	EPJC 79 (2019) 535
WZ	8	20.3	$\sigma = 24.3 \pm 0.6 \pm 0.9$ pb	$\sigma = 23.92 \pm 0.4$ pb (MATRIX (NNLO))	PRD 93, 092004 (2016)
WZ	7	4.6	$\sigma = 19 + 1.4 - 1.3 \pm 1$ pb	$\sigma = 19.34 + 0.3 - 0.4$ pb (MATRIX (NNLO))	EPJC 72 (2012) 2173
ZZ	13.6	29.0	$\sigma = 16.9 \pm 0.7 \pm 0.7$ pb	$\sigma = 16.7 \pm 0.4$ pb (Matrix (NNLO) & Sherpa (NLO))	PLB 855 (2024) 138764
ZZ	13	36.1	$\sigma = 17.3 \pm 0.6 \pm 0.8$ pb	$\sigma = 16.9 + 0.6 - 0.5$ pb (Matrix (NNLO) & Sherpa (NLO))	PRD 97 (2018) 032005
ZZ	8	20.3	$\sigma = 7.3 \pm 0.4 + 0.4 - 0.3$ pb	$\sigma = 8.284 + 0.249 - 0.191$ pb (NNLO)	JHEP 01 (2017) 099
ZZ	7	4.6	$\sigma = 6.7 \pm 0.7 + 0.5 - 0.4$ pb	$\sigma = 6.735 + 0.195 - 0.155$ pb (NNLO)	JHEP 03 (2013) 128 , PLB 735 (2014) 311
t_{s-chan}	13	140	$\sigma = 8.2 \pm 0.6 + 3.4 - 2.8$ pb	$\sigma = 10.32 + 0.4 - 0.36$ pb (NLO+NNL)	JHEP 06 (2023) 191
t_{s-chan}	8	20.3	$\sigma = 4.8 \pm 0.8 + 1.6 - 1.3$ pb	$\sigma = 5.61 \pm 0.22$ pb (NLO+NNL)	PLB 756 (2016) 228-246
$t\bar{t}W$	13	140	$\sigma = 880 \pm 50 \pm 70$ fb	$\sigma = 745 \pm 52$ fb (NNLO QCD + NLO EW)	JHEP 05 (2024) 131
$t\bar{t}W$	8	20.3	$\sigma = 369 + 86 - 79 \pm 44$ fb	$\sigma = 232 \pm 32$ fb (MCFM)	JHEP 11 (2015) 172
$t\bar{t}Z$	13	140	$\sigma = 860 \pm 40 \pm 40$ fb	$\sigma = 860 + 80 - 90$ fb (NLO + NNLL)	arXiv:2312.04450
$t\bar{t}Z$	8	20.3	$\sigma = 176 + 52 - 48 \pm 24$ fb	$\sigma = 215 \pm 30$ fb (HELAC-NLO)	JHEP 11, 172 (2015)
WWW	13	139	$\sigma = 0.82 \pm 0.01 \pm 0.08$ pb	$\sigma = 0.511 \pm 0.018$ pb (NLO QCD)	PRL 129 (2022) 061803
WWZ	13	79.8	$\sigma = 0.55 \pm 0.14 + 0.15 - 0.13$ pb	$\sigma = 0.358 \pm 0.036$ pb (Sherpa 2.2.2)	PLB 798 (2019) 134913
$t\bar{t}t\bar{t}$	13	140	$\sigma = 22.5 + 4.7 - 3.4 + 6.6 - 5.5$ fb	$\sigma = 13.4 + 1 - 1.8$ fb (NLO QCD + EW)	EPJC 83 (2023) 496

Figure 1.1: Summary of several Standard Model cross-section measurements (a) with associated references (b) [1]. Cross-sections can be thought of as probabilities that a process occurs. This means that the processes with smaller cross-sections are considered rare-processes because it has a lower probability of being observed. Increasing the probability of these rare-processes would require an increase of luminosity or collisions. The measurements are corrected for branching fractions, compared to the corresponding theoretical expectations.

RNTuple is the new ROOT data storage format that will be in use at the start of the HL-LHC. Due to its design, which takes advantage of modern C++ techniques, it is set to improve read speedability and memory usage compared to its predecessor, TTree, and other data storage formats such as HDF5 and Parquet. At the start of this work, performance studies on RNTuple were conducted at the production level, and RNTuple was still at an experimental stage.

This thesis investigates the performance of RNTuple for ATLAS analysis workflows. This chapter will provide a more detail introduction of the SM, followed by an introduction to the ATLAS experiment and its detector technology in Chapter 2. In Chapter 3, the ATLAS software and computing system, and data contents are introduced. In Chapter 4, an introduction to RNTuple and TTree is provided along with examples of how RNTuple is applied in comparison to TTree. Performance studies conducted for RNTuple and how they compare with TTree will be presented in Chapter 5. In Chapter 6, the Analysis Grand

Challenge (AGC) is introduced along with its RNTuple implementation. A final discussion and conclusions are given in Chapter 7.

1.0.1 Standard model of particle physics

The SM is a quantum field theory that explains and catagorizes all observed fundamental particles by their properties and interactions. Quantum field theory (QFT) is the main theoretical tool for describing particle interactions by combining special relativity and quantum mechanics. Due to this combination, QFT is a probabilistic theory where each particle has an associated field that permeates all of space; therefore, forces are simply the interactions between these different fields. For example, the electromagnetic force is just the interaction between the electromagnetic field and charged matter fields, which fall under quantum electrodynamics (QED). In sum, the SM encompasses all known elementary particle interactions, except for gravity, through a collection of quantum field theories, each dictated by gauge symmetries: QED ($U(1)$), the Glashow-Weinberg-Salam theory of electroweak processes ($SU(3)$), and quantum chromodynamics ($SU(2)xU(1)$).

1.0.1.1 Symmetries and Particle Content

In physics, symmetries are fundamental because they lead to conservation laws through Noether's Theorem. Symmetries can manifest in two notions: invariance and covariance. Properties of a system are described as invariant if they do not change under a symmetry transformation. For example, rotating a sphere and without altering gravitational force would indicate a conservation of angular momentum. In contrast, covariance is used to describe a system that changes in accordance to changes induced by symmetry transformations.

The SM is a gauge theory based on the symmetry group $SU(3)_C x SU(2)_L x U(1)_Y$. Gauge theory is a QFT that requires invariance under continous transformations, and a symmetry group is a set objects that obey the four properties listed in Table 1.1. $SU(3)_c$ is called the color symmetry group describing the strong nuclear force, which is the intraction between quarks and gluons. $SU(2)_L x U(1)_Y$ describes the electromagnetic and weak nuclear forces, which is the interactions between leptons, photons and WZ bosons.

Table 1.1: Properties of a Group [4].

CLOSURE	If $g_1, g_2 \in G \rightarrow g_1 \diamond g_2 \in G$	(combinations remain i
IDENTITY	There exists $I \in G \rightarrow I \diamond g_i = g_i$ for every $g_i \in G$	(one element does no
INVERSE	Every $g_i \in G$ has a $g_i^{-1} \in G$ such that $g_1 \diamond g_i^{-1} = I$	(combinations can be
ASSOCIATIVITY	If $g_1, g_2, g_3 \in G \rightarrow (g_1 \diamond g_2) \diamond g_3 = g_1 \diamond (g_2 \diamond g_3)$	(combinational groupings can

Furthermore, the four groups of particles shown in Figure 1.2: quarks, leptons, gauge bosons, and scalar bosons, can be further categorized as *bosons* or *fermions* because of a fundamental property called spin. Similar to the Earth, particles carry orbital angular momentum and spin angular momentum; however, for particles, spin is an intrinsic property. All bosons carry an integer spin; meanwhile, fermions carry half-integer spin. As a result from QFT, each fermion has an antiparticle with the same mass and lifetime as the particle itself, but oppositely charged. The three charged leptons (e, μ, τ) are massive, while their corresponding nuetrinos (ν_e,ν_μ,ν_τ), are massless with nuetral charge. Due to QCD, there are 8 types of gluons. The Higgs boson has its own section as a scalar boson because unlike the vector bosons with spin 1, the Higgs boson has spin 0. In sum, there are a total of 12 leptons including their antiparticles, 36 quarks including all the flavors and their antiparticles, 12 vector bosons, and 1 scalar boson, which makes a total of 61 fundamental particles.

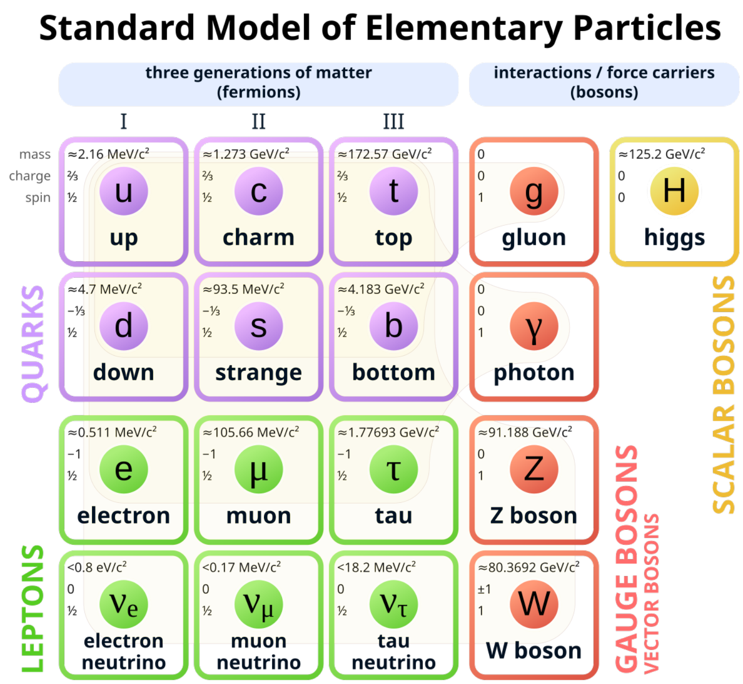


Figure 1.2: Particle content of the Standard Model [?].

1.0.2 Standard Model Limitations

1.0.3 Phenomenology of Large Hadron Colliders

CHAPTER 2

THE ATLAS EXPERIMENT

In October 1992, the ATLAS collaboration, then composed of about 800 members, submited a letter of intent to the LHC Experiment Committee highlighting the design of what came to be today's ATLAS Experiment **??**. From the start, ATLAS was designed to be a general-purpose experiment, optimized to search for the Higgs boson, top quark decays, and supersymmetry. In July 1997, the ATLAS Experiment was approved and by November 2008, ATLAS was the largest detector ever constructed at 44 meters long and 25 meters in diameter. By November 2009, ATLAS recorded its first proton-proton collision and by December 2010, ATLAS was first to observed the production of top quark pairs, which are the heaviest known elementary particle with a strong coupling to the Higgs boson. By July 2012, both ATLAS and the CMS Experiment successfully observed the infamous Higgs boson. ATLAS is projected to continue operation until 2035 to continue searching for standing questions from the SM.

In par with other particle experiments, the ATLAS detector has two general components: calorimeters and magnets. Calorimteter

: calorimeters and magnets. Calorimeters are devices that measures the energy a particle loses when passing through. Through

2.1 Detector Technology

To do this, ATLAS has six different detecting subsystems wrapped concentrically in layers around the collision point to record the trajectory, momentum, and energy of particles. Apart, a hurge magnet system bends the paths of the charged particles so that their momenta can be measured as precisely as possible. Overall, the detector tracks and identifies particles to investigate a wide range of physics.

2.1.1 Inner Detector

what is its main functions

2.1.1.1 Pixel Detector

2.1.1.2 Semiconductor Tracker

2.1.1.3 Transition Radiation Tracker

2.1.2 Calorimeter

2.1.2.1 Liquid Argon Calorimeter

2.1.3 Tile Hadronic Calorimeter

2.1.4 Muon Spectrometer

2.1.4.1 Thin Gap Chambers

2.1.4.2 Resistive Plate Chambers

2.1.4.3 Monitored Drift Tubes

2.1.4.4 Small-Strip Thin-Gap

2.1.4.5 Micromegas

2.1.5 Magnet System

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APPENDIX

OBJECTIVE SYMPTOMS

Appendices follow the same page-numbering rules as regular chapters. The first page of a multi-page appendix is not numbered. But the page of a single-page appendix *is* numbered.

Are they slow learners or is it a *REAL* problem? These are classic findings in the hopelessly computer challenged.

1. Can't copy from hard drive to disk.
2. Can't eject disks.
3. The word "disk" has thousands of meanings to them. None are correct.
4. Saving a document in any form is a concept totally unexplainable to them.
5. Desktop covered with Untitled Folders - look again, untitled folders are everywhere.
6. "Lost" documents found often in the Apple Menu.
7. Trash always full. Claim they don't know how to place things in trash.
8. Mysterious things happen to their documents or computer when they are not present. AKA "computer victims".
9. Highlighting = deleting. Dragging = Oblivion.
10. Selecting, double-clicking a problem? They will always say their mouse is broken.
11. Their double- click mechanics wants you to send them to a neurologist.
12. Computer always on due to fear of having to restart it.
13. Have never read their QuickMail - will say "I prefer a phone call".
14. Have magical beliefs about what computers do.
15. Describes some flaky way computers could REALLY help them, but is not yet available.

16. Constantly saying they need more “memory”.

17. Requests gizmos and gadgets, i.e., “mouse leash” or “disk cozy”.

18. Avoids eye contact when talking about computers.