Search for long-lived scenarios of dark matter and supersymmetry in final states with jets and missing energy in the CMS detector

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A thesis submitted to Imperial College London
for the degree of Doctor of Philosophy

Abstract

LHCb is a b-physics detector experiment which will take data at the 14 TeV LHC accelerator at CERN from 2007 onward…

Declaration

This dissertation is the result of my own work, except where explicit reference is made to the work of others, and has not been submitted for another qualification to this or any other university. This dissertation does not exceed the word limit for the respective Degree Committee. Say what I worked on.

Christian Laner

Acknowledgements

Of the many people who deserve thanks, some are particularly prominent, such as my supervisor…

Contents

Chapter 1.

Introduction

Fancy introduction to particle physics, DM, SUSY, LLPs.

Dark matter is a hypothetical form of matter which constitutes about 27% of the total energy content of the universe [1]. Its nature is unknown and its presence has so far only been inferred indirectly through its gravitational effects. Large efforts by the astrophysical and particle physics communities are being made on searches for the elusive dark matter.

Chapter 2 will describe the theoretical foundations and motivations for this search. Chapter 3 will do bla, etc.

Chapter 2.

Theory and motivation

Some introductory paragraph. We will begin by looking at the SM. Then bla and finally bla. I wouldnâĂŹt have so much SM math - brief intro to SM (each term in Lagrangian) and then move on to BSM (DM, SUSY, LL, simplified models, current limits). Theory and motivation (15%) (15 pages âĂŞ 2 pages per bullet below)

2.1. The standard model of particle physics

3 pages. Brief intro to SM - see Marco-Andrea two pages. If have time/space/botheredness, mention SM Lagrangian and SU3xSU2xU1. QED and QCD.

The Standard Model (SM) is a quantum field theory which describes the fundamental particles (quarks, leptons, gauge bosons and Higgs boson) and their interactions (electromagnetic, weak nuclear and strong nuclear). Fermions (half-integer spin, matter) and bosons (integer spin, force carriers).

SM particles summarised in Table. We will describe in the following subsections. Table summarising all SM particles with their mass and charge (Marco-Andrea, Adam, Nick).

2.1.1. Fundamental fermions

Quarks (6) and leptons (6), generations, charges, interactions.

2.1.2. Fundamental bosons

Quanta of gauge fields. Mediators of em, weak, strong interactions. Describe each interaction in turn. Gravity not included in SM. Ranges. Which particles feel each force.

Electroweak symmetry breaking. Higgs boson (scalar, spin 0). Discovered in 2012 (final piece of SM).

2.2. Beyond the standard model

1.5 pages. Problems with the standard model. Tapper slides. MA and AE.

The SM has been well tested experimentally and has been found to describe very accurately a wide range of physical phenomena. However, it does not incorporate the gravitational force, account for neutrino oscillations or explain the matter-antimatter asymmetry in the universe. There are also theoretical concerns about the lack of unification of forces at the Grand Unified Theory (GUT) scale as well as the hierarchy problem, whereby higher order loop corrections to the mass of the Higgs boson lead to a divergence in its mass unless a large amount of 'un-natural' fine tuning is introduced. Finally, and most relevant to this discussion, no particle in the SM is a viable candidate for dark matter. The SM is therefore thought to be an effective theory which is only valid at low energies and a more complete model at larger energy scales must exist. Gravitational force, Planck scale

Neutrino masses

Dark matter. Makes up large proportion of universe. Lots of evidence. No particle in SM is DM candidate. Discussed in more detail in Sec. 2.3. Or if chapter ends up being too long summarise and merge that section into here (maybe make a subsection)

Higgs mass/hierarchy problem

Gauge coupling unification

Matter-antimatter asymmetry

2.3. Dark matter

1-1.5 pages. More details on DM (evidence, WIMP miracle, cosmology) (borrow from my reports)

Evidence – see my report.

The most favoured DM candidate is a non-baryonic, weakly interacting massive particle (WIMP) which is stable and electrically neutral [8]. WIMPs fall into the category of cold dark matter, meaning that they were non-relativistic at the time of freeze-out and hence lead to the large scale structures observed in the universe today. Their weak interaction cross section also results in the correct relic abundance required to explain the present dark matter content of the universe (the "WIMP miracle").

Searching for DM (report): DD, ID, collider (complimentary).

2.4. Supersymmetry

1.5-2 pages. SUSY theory (borrow from RA1/kostas theses and RA1 papers). MA and AE.

Poincare group, additional symmetry between bosons and fermions. Broken symmetry. Solves hierarchy problem, unification, DM.

MSSM is simplest version of SUSY (minimal particles). 105 parameters. Table of MSSM particles (MA). R-parity. Relationship with DM âĂŞ LSP/neutralino is DM candidate. stop naturalness?

A theoretically well motivated extension to the Standard Model is supersymmetry (SUSY) [6, 7], which introduces a new spacetime symmetry between fermions and bosons. Essentially, for every fundamental particle there exists a supersymmetric partner with spin differing by 12. Fermions and bosons enter the mass correction calculation of the Higgs boson with opposite signs, so if the mass difference between SM particles and their superpartners is not too large (ab 1 TeV), an incomplete cancellation between the two leads to the naturally small Higgs boson mass. Thus, supersymmetry can provide a solution to the hierarchy problem of the Standard Model. Furthermore, the strong, weak and electromagnetic couplings are found to converge at the GUT scale, thus providing a solution to the unification problem as well. Finally, most supersymmetric theories predict a particle candidate for dark matter, as explained in the next section.

R-parity is a quantity defined such that Standard Model and supersymmetric particles are assigned PR = +1 and PR = -1, respectively. If R-parity is conserved, the lightest supersymmetric particle (LSP) cannot decay and thus is stable. If it is neutral, this LSP satisfies the WIMP criteria. The LSP is usually assumed to be the neutralino, a superposition of the superpartners of the Higgs boson and gauge bosons. Other dark matter candidates include the axion and the lightest Kaluza-Klein particle (LKP) arising from solutions to the strong CP problem and theories of extra spatial dimensions, respectively.

2.5. Exotic long-lived particles

1 page.

Many BSM theories predict long-lived particles. There are examples in the SM (give examples). They travel some distance before decaying. Could be within or outside the detector. Decay length follows an exponential distribution (give pdf). Width is inverse of lifetime.

Briefly describe MSSM (NLSP), GMSB, hidden valleys, RPV SUSY.

2.5.1. Split supersymmetry

LLP thesis 4.2.4 and paper. SUSY borken near unification scale. Squarks decoupled to very high scale. Gluinos are long-lived. Coloured. Must decay via highly virtual squarks. Lifetime larger than hadronisation scale (ps?). Gluinos form R-hadrons (so-called because of non-trivial R-parity) (can be mesons, baryons or gluinoballs). Can change charge through nuclear interactions.

2.6. Simplified models

1.5 pages. Motivation for simplified models (see 3 reasons in OB LLDM, too many parameters in MSSM. CMSSM not model-independent).

These are the simplified models that are used in this thesis to interpret the results in this thesis.

The long-lived particle's lifetime is a parameter of the model. Consider life distances (lifetimes) from ctau = 1 um (tau = x ns) to 100 m (tau = y ns), plus prompt and stable.

2.6.1. Simplified models of supersymmetry

General SUSY signature at LHC: Pair production, strong interaction dominant at LHC (squarks and gluinos), decay to SM particles and LSP, large mass hence large MET (briefly describe MET - momentum imbalance due to LSP not being detected).

Only one decay considered, other particles at much higher scale.

T1qqqq and T1qqqqLL (split SUSY): here consider (long-lived) gluino pair production, each decays to two quarks and an LSP. As gluino lifetime goes to 0 recover prompt model. Interaction of R-hadron with detector material not simulated (won't have an effect on our analysis/not the purpose of our analysis – see paper). If necessary, describe cloud model, and percentages of gluinoball etc (and/or describe in simulation section).

Feynman diagram of T1qqqqLL (a) and dDM (need to make it myself?) (b) together.

2.6.2. Simplified models of dark matter

Buch. DMF, DMSimp?, dDM vector/axial

Run 2 DM searches interpreted using simplified "mono-X" models with V/A/S/P s-channel mediator pair decaying to Dirac fermion DM, with 4 parameters (two masses and couplings). (Lagrangians probably not necessary)

Extend these models to incorporate long-lived neutral particles. Kevin/me: instead of mediator decaying to stable DM, it decays intermediate chi2 that is long-lived and then chi2 decays to SM particles and stable DM. As chi2 lifetime goes to infinity recover stable model.

EFT description of chi2 decay. Lambda parameter can be swapped for lifetime parameter.

In this thesis consider model with vector mediator, couplings X and Y, and various masses and lifetimes.

2.7. Status of searches for dark matter, supersymmetry and long-lived particles

Current DM/SUSY limits (CMS/ATLAS and briefly compare to DD, mention X GeV limits on mediator/DM/gluino/LSP), very constrained hence look for LL signatures, we think weâĂŹve excluded X GeV gluinos but thatâĂŹs not true if theyâĂŹre LL. Mono-X but monojet strongest constraints.

Current LL limits (CMS/ATLAS). Many possible types of striking signatures – displaced leptons/photons/jets, disappearing/kinked tracks, stopped particles, etc. Not many with MET, first LL interpretation of prompt analysis (as long as decays within tracker can still reconstruct with standard algorithms, plus ISR), briefly mention complementarity (sensitive to whole range of lifetime, sub-cm and all mass splittings).

Chapter 3.

Experimental setup

20-25 pages. Intro to chapter.

3.1. The Large Hadron Collider

CERN and LHC. Franco-Swiss border. 26 km. x km underground. Largest and most powerful. Collider physics. Luminosity (instantaneous/integrated) and cross section formulas (Marco-Andrea/Pesaresi). Used to search for new physics and discover Higgs boson. Need very high energy to produce high mass particles and search for new physics (cf xs vs com). (Compare to ep collider and fixed target). Proton-proton (and ion) collisions. Bunch spacing, number of bunches, number of protons per bunch (Marco-Andrea table). ATLAS, CMS, LHCb, ALICE. Accelerator complex: hydrogen, LINAC, PS, SPS, etc (show diagram). Centre of mass energy. Pileup (formula/estimate using inelastic xs?).

Diagram of accelerator complex.

History of Run1, shutdown, Run 2. Amount of data delivered.

3.2. The Compact Muon Solenoid

One of two multipurpose detectors. Used to search for new physics and discover Higgs boson.

Hermetic coverage. Overview of subdetectors. Magnet strength.

Diagram.

Coordinate system. Pseudorapidity.

3.2.1. Tracker

How tracker works, ie electron-hole pairs (see Adam and MSci report). High radiation environment. Little material.

Pixel tracker.

Silicon strip tracker.

TOB, TEC, etc. Their positions/extents.

Diagram of layout.

Momentum resolution, tracking efficiency, spatial resolution.

3.2.2. Electromagnetic calorimeter

Designed to detect electrons and photons. Lead tungstate crystals.

EB. EE. Preshower.

Diagram of layout.

How ECAL works (ECAL shower, bremmstrahlung and pair production - see Adam and APP MSci course.)

Resolution formula (a+b+c).

3.2.3. Hadronic calorimeter

Designed to detect hadrons/jets. Brass and scintillating plastic. Photodiodes. HF. Fibres.

HB. HE. HO. HF

Diagram of layout.

How HCAL works (hadronic showers produce scintillation light - see Adam and APP MSci course.)

Resolution formula.

3.2.4. Muon system

Adam: As muons are heavier than electrons, they are minimally ionising and lose little energy through bremsstrahlung. They therefore mostly pass through the ECAL and HCAL. As muons are a key component of many electroweak decays, CMS has a dedicated muon system interleaved with the iron return yoke surrounding the solenoid.

DT (MB), CSC (ME), RPC.

Diagram of layout.

Momentum resolution 1%.

3.2.5. Magnet

Just one or two short paragraphs. See Marco-Andrea, Citron, Baber.

3.2.6. Trigger and data acquisition

40 MHz.

L1 trigger.

HLT.

Computing tiers.

L1 trigger upgrade and my service work?

Not sure yet. Look at Adam, Matt, Jad.

3.3. Event reconstruction

Intro: need to put together the things observed in the detector to reconstruct the objects.

Object reconstruction/identification (requires revision). Tag and probe. vertexing/tracking, btagging, PF, antikt. PU subtraction, isolation, cross-cleaning. MC corrections (JECs, PU, btagging, lepton ID, etc.).

Mention objects/working points used in analysis as you go along. Maybe summary table like Matt. Actually maybe include this in analysis chapter (see Adam).

3.3.1. Tracks and vertices

Combinatorial track finder (CTF), Kalman filter.

Primary vertex. PU vertices. Secondary/displaced vertices (b quarks) found in subsequent levels of reconstruction.

Efficiencies.

Isolated tracks? (when talking about analysis objects).

3.3.2. Electrons and photons

3.3.3. Muons

3.3.4. Particle flow algorithm

Need to decide where to put this. Not clear on the connection between object reconstruction and particle flow. Resources: Particle Flow paper, Particle Flow summary.

The tracks are extrapolated through the calorimeters, if they fall within the boundaries of one or several clusters, the clusters are associated to the track. The set of track and cluster(s) constitute a charged hadron and the building bricks are not considered anymore in the rest of the algorithm. The muons are identified beforehand so that their track does not give rise to a charged hadron. The electrons are more difficult to deal with. Indeed, due to the frequent Bremsstrahlung photon emission, a specific track reconstruction [3] is needed as well as a dedicated treatment to properly attach the photon clusters to the electron and avoid energy double counting. Once all the tracks are treated, the remaining clusters result in photons in case of the electromagnetic calorimeter (ECAL) and neutral hadrons in the hadron calorimeter (HCAL). Once all the deposits

3.3.5. Jets

Briefly describe what a jet is (hadronisation, tight cone of particles [MA]). antikt algorithm. Infrared and collinear safe. Inputs are PF candidates. Pileup subtraction (not just here but for all objects).

Correcting the energy of jets

b-tagging

Identification of jets originating from bottom quarks.

3.3.6. Energy sums and missing energy

Define HT, MHT and MET. At some point (maybe near the beginning) explain why we use the transverse plane (initial momentum is zero, whereas it isn't in the longitudinal plane).

Neutrinos do not interact in particle detectors, and therefore escape undetected. Their presence can be inferred by the momentum imbalance of the visible particles in an event. (this should be mentioned in overview of analysis in intro chapter).

Type-1 corrections.

3.4. Data sets

See Nick. MA has this in the analysis chapter. We use data collected by the CMS during certain runs, plus simulated data of background and signal processes.

3.4.1. Collected data

35.9 fb-1. 2016. (This would be mentioned in the intro anyway). Show lumi delivered/collected vs time. Triggers/Primary Datasets. SR and Muon CRs.

Maybe keep this chapter general, just have section on MC simulation, and mention which specific data and MC samples elsewhere.

3.4.2. Monte Carlo simulation

Description of madgraph, pythia, GEANT.

MC simulation data sets. (Grid of masses and ctau, couplings used) - no need to specify grid, couplings mentioned in simplified models section. See paper.

Describe weights and xs/lumi normalisation?

Chapter 4.

Search strategy

This chapter describes the analysis strategy of a search for physics beyond the standard model in proton-proton collisions at a centre of mass energy of 13 TeV. The search is performed in final states containing missing transverse momentum and at least one jet.

The search is designed to have sensitivity to a wide range of new physics models that involve the production of a weakly interacting particle (WIMP), such as dark matter or the lightest supersymmetric particle. The search has been optimised for signatures in which the WIMP is produced from prompt decays at the primary collision vertex. However, as will be discussed in Chap. 5, the search is also sensitive to signatures in which the WIMP is produced at a displaced vertex following the decay of a long-lived particle.

In the proton-proton collisions, the net momentum of the colliding partons in the plane transverse to the beam direction is effectively zero, whereas the longitudinal momentum is not necessarily so. In order to conserve momentum, the outgoing particles produced in the collision must therefore have an overall transverse momentum of zero. As WIMPs do not interact with the detector material, the measured net transverse momentum in the event will be non-zero. This non-zero "missing transverse momentum" is the key signature of such particles. In addition, at a hadron collider such as the LHC, the dominant production is via the strong interaction, and hence jets are readily produced either in association with the WIMP, or as initial or final state radiation (ISR, FSR). For these two reasons the search is performed in final states containing jets and missing energy. At least one jet is required in order for the missing momentum to be defined and for the event to be triggered.

A missing energy signature is not unique to WIMPs, however, and is also present in certain standard model processes. Neutrinos (produced in the decays of Z and W bosons, for example) are also weakly interacting and undetectable at CMS. It is also possible for particles to be over or under-measured, thereby introducing a "fake" momentum imbalance. This type of background arising from energy mismeasurements is suppressed as much as possible (to lt1% of the total background) using the variables described in Sec. X. The remaining standard model background (that involving neutrinos) must be estimated as precisely as possible, using a combination of theory calculations, simulation, and calibrations in data. This is described in Sec. X. One can then look for a statistically significant excess in the data above the expected amount of standard model background that would be an indication of the observation of physics beyond the standard model. The statistical analysis is covered in Chap. 5.

inclusiveness The ways in which a WIMP/BSM signature can manifest are numerous SR CRs binning in four variables

Similar searches for supersymmetry have been performed in Runs 1 and 2 of the LHC, at centre of mass energies of both 8 and 13 TeV, and for a range of integrated luminosities. These can be found in Refs. [1,2,3,4,5]. These searches are used as a basis for the analysis described in this thesis. A series of developments and optimisations have been made in order to adapt the analysis for the higher centre of mass energy and larger amount of data collected. In addition, the interpretations in dark matter and long-lived particles described in Chap. X are a novelty to this search.

This chapter is organised as follows: Section bla describes bla etc.

Dataset used is 36.9 pm x fb-1 and corresponds to the p-p run of 2016.

4.1. Physics objects

2-3 pages

Using reconstruction algorithms described in Detector Chapter. Additional requirements are imposed in the analysis. Jets and energy sums form key component in the search. Electrons and photons are vetoed in the SR. Muons are vetoed in the SR and selected in the CRs. Isolated tracks are vetoed in both SR and CRs. See AN section 6.

Jets

antikt 0.4. pt 40 eta 2.4 CHS. loose ID (chf, nhf, etc). b-tagging medium working point CSVv2IVF.

Photons

Vetoed in SR. Tight working point. Isolation. Pileup correction. Some other requirements. pt 25 eta 2.5

Electrons

Vetoed in SR. Loose working point. Isolation. Pileup correction. Some other requirements. pt 10 eta 2.5

Muons

Vetoed in SR, selected in CRs. Loose, tight. Bunch of requirements. mini-isolation.

Isolated tracks

Vetoed in SR and CRs. pt 10, dz, isolation.

Energy sums

HT and MHT computed using jets as described above. MET computed using all PF candidates in the event, with type 1 corrections. Used in MT and MHT/MET cuts.

4.2. Baseline selections

1 page

Summary table of selections at some point.

Events collected by triggers as described later in Section X.

Wants jets and missing energy. Veto photons and leptons and SITs. Jet pt and eta requirements. MET filters (bullet list). Beam halo CHF cuts. Primary vertex selection. HT and MHT. Forward jet veto here or QCD rejection?

Beam halo plots - jet phi data/MC with and without cut (and jet CHF?).

4.3. Standard model backgrounds

2-3 pages

After these requirements, still left with significant SM backgrounds from electroweak and QCD processes.

4.3.1. Electroweak processes

Dominant are Z and W.

Z is irreducible. Neutrinos.

W/ttbar is when lepton lost - not reconstructed or out of acceptance.

Plus minor/residual backgrounds - single top, diboson, Higgs, etc.

4.3.2. QCD processes

Different QCD mechanisms (bullet list plus my studies) - detector effects, fake MET, mismeasurement, below threshold, heavy flavour.

4.4. QCD background rejection

2-3 pages.

Various ways of killing it: alphat, bdphi, mht/met. Propaganda plots.

4.4.1. alphaT

4.4.2. bdphi

4.4.3. missing energy ratio MHT/MET

4.5. Event selection

2-3 pages

Now define the cuts to suppress the QCD, the definition of the signal region where we expect the signal, and the definition of the control regions that are used to estimate the SM backgrounds.

Big summary table of all selections/regions.

4.5.1. Signal region

alphat (summarise HT-dependent cuts in table), bdphi, mht/met cuts. Anything else?

4.5.2. Control regions

Enriched in background they want to estimate. No overlap with SR events. Ignored lepton in sums to mimic/proxy the SR. Exactly the same cuts as SR except for inversion of muon veto to selection, plus some other differences described in the following.

Background estimation described in Sec X (EWK) and Y (QCD).

mujets

Exactly one muon that passes requirements mentioned before. DeltaR. MT. No alphat or bdphi.

mumujets

Exactly two muons opposite charge. DeltaR. Mll.

QCD sidebands

bdphi and MHT/MET sidebands. Enriched in QCD.

4.6. Event categorisation

2 pages.

See AN.

Signal region binning in njet, nb, ht, mht. Jet pt (mono sym asym).

Same bins in single mu as SR. Slightly different in double mu - only two nb bins. Explain why? Higher stats. Show nb extrapolation validation (AN) or just summarise briefly in couple of sentences (similar to MHT validation).

Table of bins.

4.7. Triggers

5 pages.

See Mark. List of SR and CR triggers. Efficiencies.

4.8. Simulation samples

0.5 pages. Maybe put here the "datasets" section of data and MC samples (see Matt).

4.9. Corrections to simulation

3-5 pages

Simulation modelling is not perfect. Need to correct it using scale factors by comparing data and MC. These corrections introduce systematic uncertainties in the background estimation, that will be described later in Sec X.

4.9.1. Pileup

4.9.2. b-tagging efficiency

Reweighting formula.

4.9.3. Trigger efficiency

4.9.4. Lepton and photon reconstruction, identification, isolation and triggering efficiency

Tag and probe.

4.9.5. Top quark pT

4.9.6. Cross-sections

Sideband corrections. Summarise in table.

4.9.7. Plus more?

NLO, pdf/scale Signal (maybe later): nISR, gen met

4.10. b-tag formula method

1-2 pages.

See Burton. AN Sec 4.4. Relevant but be brief. How much improves limits? Just refer to T1bbbb as T1qqqqLL 1 mm is very similar.

Purpose: reduce stat uncertainty of simulation in higher nb bins (where signal can lie).

Method: show the formula and explain it.

Summarise in table/plot or one-two sentences how much the stat unc is reduced. Maybe also how much the limits are improved (Lucien did this).

Formula systematics.

4.11. Estimation of electroweak background processes

Predict normalisation using CRs (data-driven to reduce reliance on MC). Use MHT templates from MC.

4.11.1. nj, nb, ht dimensions

1 page

Transfer factor method.

4.11.2. MHT dimension

2 pages

Take templates because don't want to bin CRs too finely (lose statistical power - curse of dimensionality).

Validation: Check data MC ratio is flat in CRs. Assign syst as described later in Sec X.

4.12. Estimation of QCD background processes

2 pages

Method.

Validation.

Plot of estimated yields per bin.

4.13. Systematic uncertainties on background estimation

These are explained below and also summarised, with representative magnitudes, in the big summary table of systs.

4.13.1. MC-based

3-4 pages (maybe 2 pages just of plots).

Known theoretical and experimental uncertainties. Largely cancel out in the TF ratio.

Refer to Section of corrections to simulation. These are the associated uncertainties.

Pileup, JEC, b-tagging, lepton, photon, trigger, top pt, W/tt, NLO, ttbar nISR.

Example 2D plots of variations in the bins.

4.13.2. Closure tests

2-3 pages.

Probe additional sources of systematics.

Define method.

Go through each test (there's not many now) and describe what it's probing: extrapolation in alphat and bdphi, W polarisation, SITV.

Closure plots.

4.13.3. MHT templates

2 pages. See Matt and old ANs.

Derivation of uncertainties. Vs njet and ht.

Plot illustrating size of uncertainty in each bin.

Chapter 5.

Results and interpretation

All signal model studies and systematics go first.

First LL interpretation of prompt analysis. say why this is interesting/important (benchmark for future LL searches, see where sensitivity to LL currently lies - surprisingly already quite sensitive)

5.1. Systematic uncertainties on signal model simulation

1-2 pages.

Similar to backgrounds. Luminosity, trigger, MC stat, pileup, b-tagging, JEC, ISR, genmet.

Additional systs for LL. b-tagging, odd jet (chf, jet id), trigger.

Summarise in table or words typical size of systs for relevant models.

5.2. Statistical model

2-3 pages.

Model the bins and number of events and uncertainties and correlations between bins as a likelihood function (probability of observing the observed data given some model parameters). This will then be fitted/maximised/used to make the background estimations and perform statistical tests to determine limits.

Maybe describe how minimisation is done (gradient descent bla migrad bla).

5.3. Results under background-only hypothesis

3-5 pages.

CR fit ("predictions") and full fit (background-only).

Mountain range plots (2 pages).

Distributions of pulls.

Pulls on nuisances.

No excess observed hence set limits.

5.4. title

2-3 pages. Hypothesis testing, setting limits, asymptotic CLs See Nick.

5.5. Limits

Exclusion

Acceptance times efficiency. Most sensitive bins. Some LL studies - in results section?

DMLL: my presentations, raffaele, oliver exo workshop (future prospects). Take home message: (see presentation - lack of coverage for models with compressed (N2,N1) and small ctau). Prompt search retains some sensitivity for long (short) gluino (DM) lifetimes (and is the most sensitive sub-cm and lifetimes beyond the detector, hence continue with prompt search in future), although clearly could be improved with a dedicated search/tagger as shown by the b-tag effects. Also compressed DM can be much improved by removing dphi cut.

Chapter 6.

Conclusion

This is the conclusion.

Appendix A.

Transfer factors

Appendixes (or should that be "appendices"?) make you look really clever, 'cos it's like you had more clever stuff to say than could be fitted into the main bit of your thesis. Yeah. So everyone should have at least three of them…

A.1. Like, duh

Padding? What do you mean?

A.2. $y = \alpha x^2$

See, maths in titles automatically goes bold where it should (and check the table of contents: it *isn't* bold there!) Check the source: nothing needs to be specified to make this work. Thanks to Donald Arsenau for the teeny hack that makes this work.

Appendix B.

Systematics

Hi.

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List of figures

List of tables