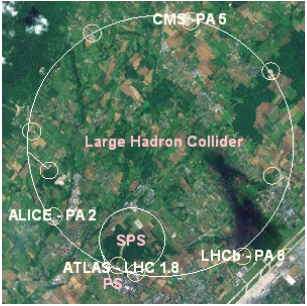
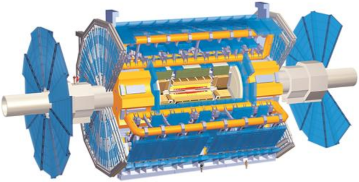
Searching for Dark Matter at the LHC

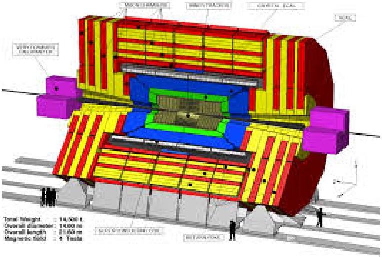
M. Shapiro

September 23, 2015

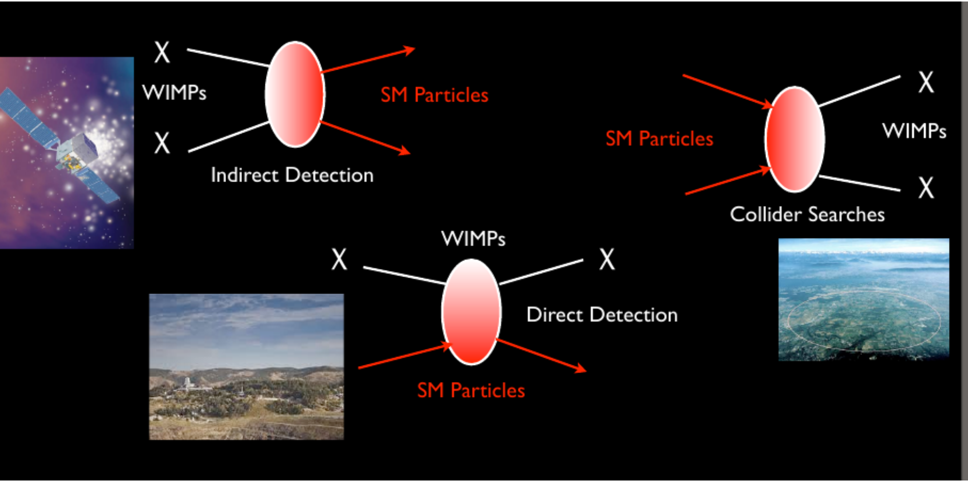
The LHC and its experiments







Complementarity of DM Search Strategies



Tim Tait: DarkMatter LHC 2013

Hopes for LHC Dark Matter Searches

In an ideal world (for us), the LHC would:

- Produce DM candidates in LHC collisions
- Produce heavier exotic particles that are relatives of the DM candidate
- Allowing us to:
  - Determine quantum numbers of the DM particles
  - Determine how DM candidates interact with SM particles
  - Relate observations to direct and indirect searches

Making Dark Matter at the LHC: the possibilities

- Create from decay of SM particle
  - Some possibilites are
    - $Z \to \chi\chi$
    - $h \to \chi\chi$
    - $t \to c\chi\chi$
  - Constraints on Z decays to DM severe
- Produce DM directly with SM particles
  - Initial State Radiation of SM particle (γ, g, etc)
  - Associated Production of DM with $t\bar{t}$, W/Z, etc
- Create BSM particles that decay to SM candidate
  - SUSY has many such possibilities
  - Exotic resonance $E \to \chi\chi$

Dark Matter Interactions with SM Particles

- We know DM particles feel gravity
- We don't know what other interactions they have with SM particles
- Only SM mediators possible are Z and Higgs
- Also possible that exotic BSM particles mediate SM-DM interactions
  - If these mediators light, could be produced at LHC
  - If they are heavy need to parameterize the interaction phenomenologically
  - Possible approaches:
    - Effective field theory (high mass mediator)
    - Simplified model (defined by interaction and exchanged mass)
    - A full theoretical model (eg SUSY)
  - All 3 approaches used
- Will be very important if DM is seen
  - Required to compare LHC limits with direct and indirect detection

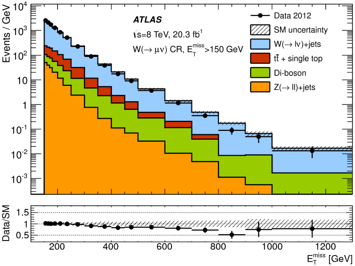
Experimental Issues (I): Seeing the invisible

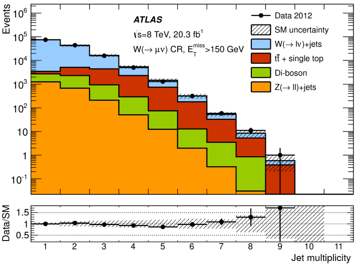
- DM particles will escape detector without being seen
- Signature is momentum imbalance
- Can only use transverse components of momentum (stuff always goes down the beampipe)
- Often call missing-E_t:

$$\not{E}_T = -\sum_i (\vec{p_T})_i$$

- Major sources of missing E_T in SM are:
  - Neutrinos
  - Mismeasurement of hadronic jets

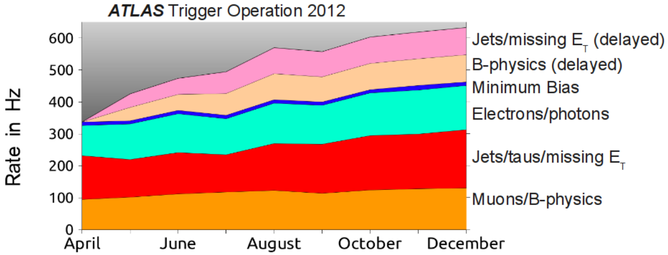
Experimental Issues (II): It's the background, stupid

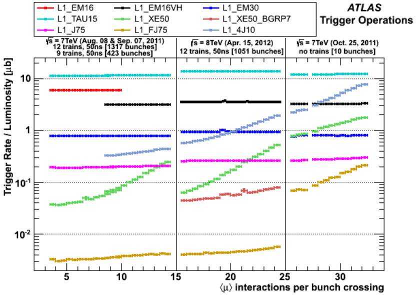


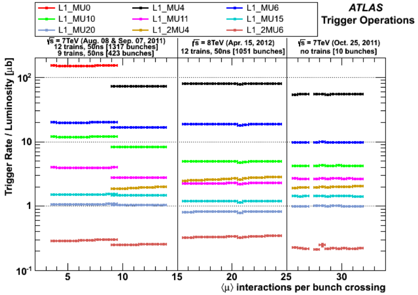


- Looking for small rate processes in environment where overall rate huge
- Must indentify signatures where signal stands out
- Must demonstrate that any potential signal is real
- Requires validation of background

Experimental Issues (III): You have to trigger first!







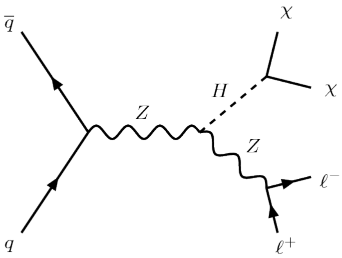
Searches we will review today

- Higgs decays to DM
- DM pairs in association with SM particles
- SUSY

Dark Matter and the Higgs

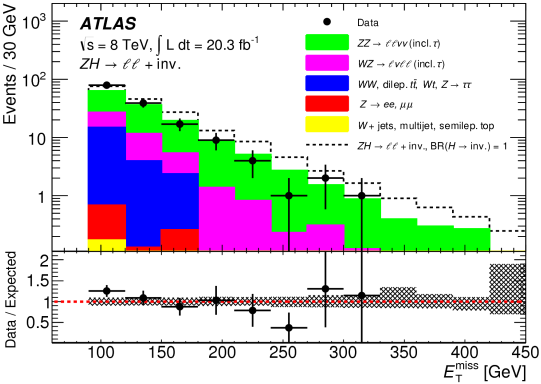
- A simple, well defined model
  - Higgs decays to pair of DM particles
  - DM only couples to SM particles via Higgs
    - "Higgs portal"
    - Probes models relevant for current and next generation direct detection experiments (see comments by Kathryn Zurek from Sept 2)
- Measurements of Higgs properties can contrain this:
  - DM contributes to "invisible Higgs decays"
  - Requires $M_{DM} < M_h/2$
  - Bound depends on DM spin
  - Powerful for low M_{DM}

Higgs to "Invisible"



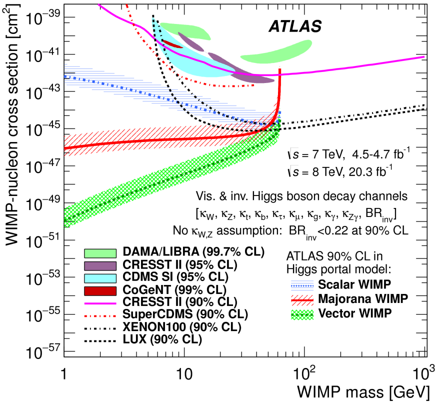
- Associated production of Higgs with a Z
- Signature is Z with nothing balancing p_T
- Background dominated by ZZ with one $Z \to \nu\nu$
  - All backgrounds well studied for Higgs search
- Additional analyses look for Higgs plus hadronically decaying Z or Higgs produced with tagged jets from vector boson fusion

Invisible Higgs Results: Associated Production Search



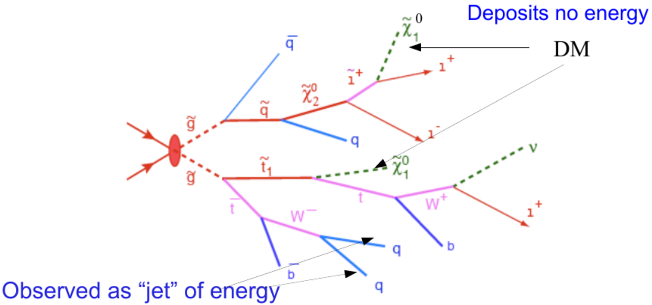
- Search only sensitive if Higgs to invisible BR large
- Current limits on BR combining all channels $\sim 22\%$
- But, this is still good enough to constrain Higgs portal models!

Invisible Higgs: Global Fit



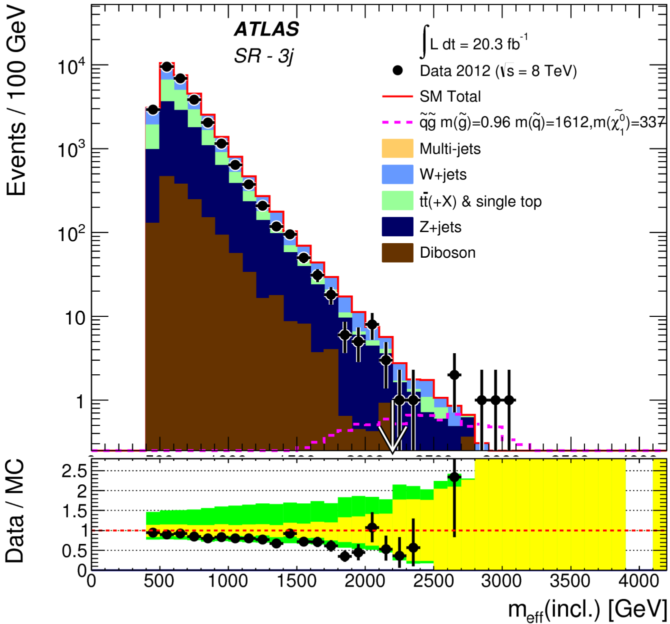
- Translate limit to coupling of Higgs to DM
- Three options: scalar, majorana fermion or vector
- Can compare to direct detection experiments
- LHC results very powerful for low mass WIMP

SUSY and Dark Matter



- SUSY models can provide DM candidates
  - R-parity: Lighest SUSY particle (LSP) stable
  - In most models LSP is weakly interacting
  - Must be neutral to be DM candidate
- Strongly interacting SUSY particles heavier than LSP
  - Large production cross sections
  - Decay chains with LSP at the bottom
- Classic signature: missing momentum + many jets

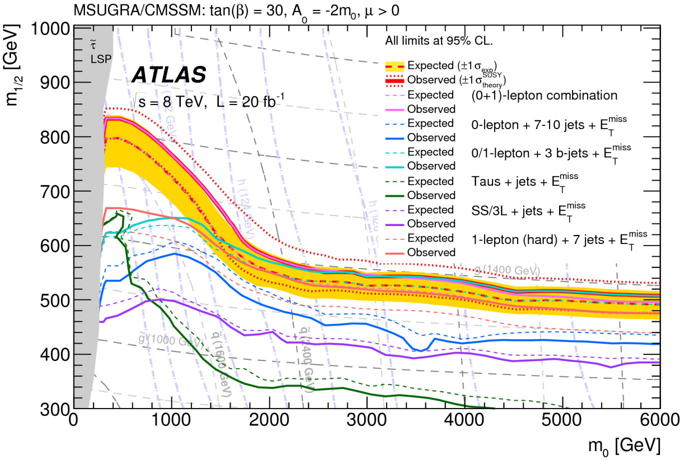
Example: Jets and Missing Et



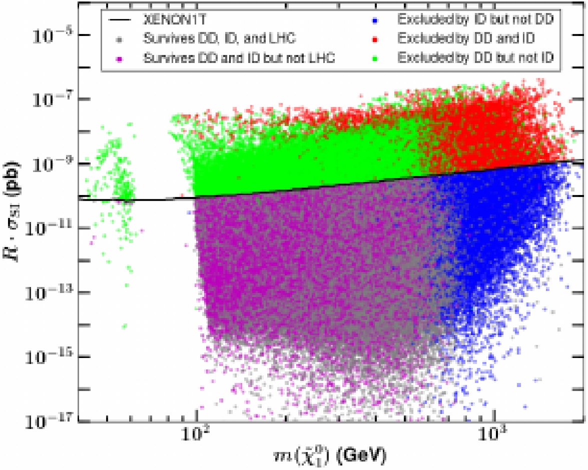
SUSY Limits and DM Constraints

- Tranlating limits on SUSY parameters into a form where we can compare with direct and indirect DM searchs requires a model
- Most general SUSY model has 100 parameters: impossible to turn into constraints
- Simplest model (CMSSM) with 5 parameters largely ruled out
- Next simplest model (PMSSM): 19 parameters
  - Difficult to characterize using a 2D plot
  - Favored space to favor large DM mass

CMSSM Limits



PSSM Constraints



Cahill-Rowley et al, arXiv:1305.6921

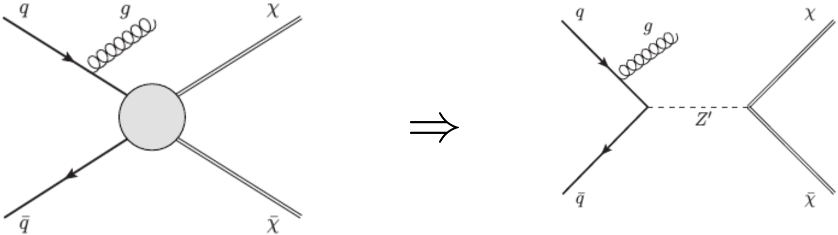
Effective Operators: Parameterization of the new physics

- Parameterize production by
  - DM mass
  - Interaction Strength M^*
- Assumptions
  - Only SM and DM producted
    - No other new particles
  - Interaction is treated as a point
    - $M^* >$ kinematics of production

Characterizing DM production: Effective Operators

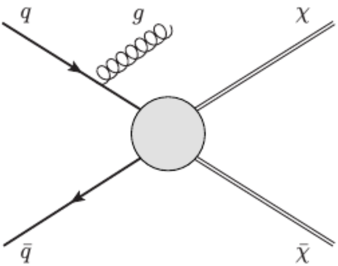
Name	Initial state	Type	Operator
C1	qq	scalar	$\frac{m_q}{M_\star^2}\chi^\dagger\chi\bar{q}q$
C5	gg	scalar	$\frac{1}{4M_\star^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

Beyond Effective Operators: Simpified Models



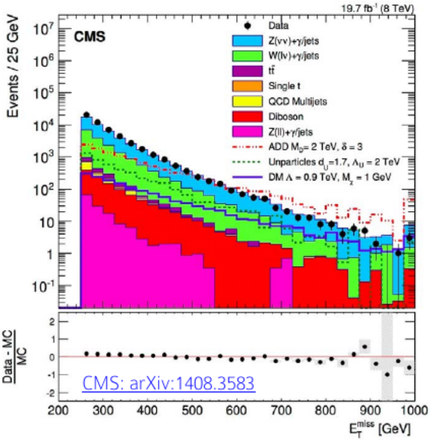
- Effective operators assume mass of mediator high
- Assumption not necessarily true at LHC where momentum transfer can be large
  - For direct detection, this is not an issue
- While form of allow operators won't change, cross sections will if mediator mass comparable to momentum transfer
- Can be important if when comparing limits from LHC to direct detection limits
- Will be important if something is found in either place

Associated Production (ISR)



- Partons in proton can radiate before interacting
- Radiation can be g, γ, W, Z, etc
- If interaction produces DM pair, this pair recoils against the ISR particle
- DM exits detector unobserved
  - Mono-X
- Depending on couplings of DM interaction, relative rates for different ISR particles will change

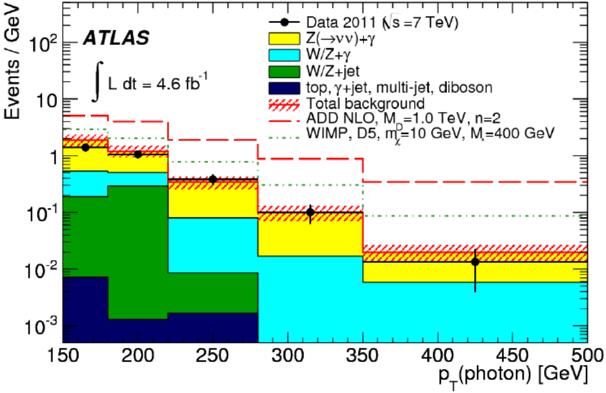
Example I: Monojets



CMS:arXiv1408.3583

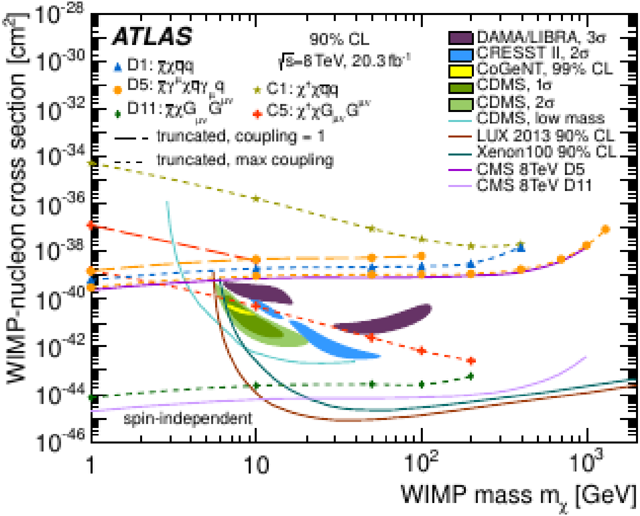
- Search for high p_T jet recoiling against nothing
- Background dominated by decays with ν (eg W/Z+jets and $t\bar{t}$)

Example II: Mono-photon

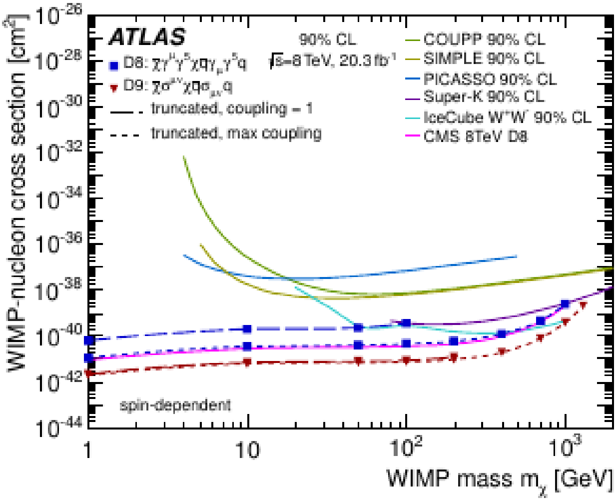


- Search for high p_T photon recoiling against nothing
- Background dominated by decays with ν (eg W/Z+jets and $t\bar{t}$)

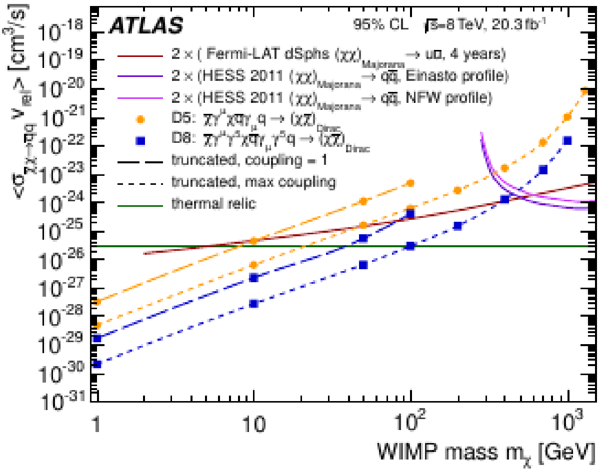
Limits: Spin Independent Operators



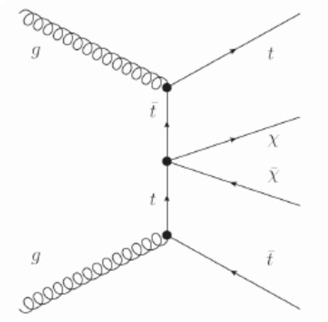
Limits: Spin Dependent Operators



Comparisons with Indirect Detection



DM in Top-Pair events

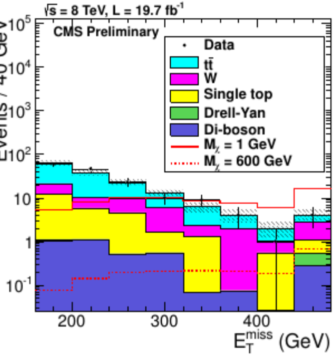


- Sensitive to C1 operator:

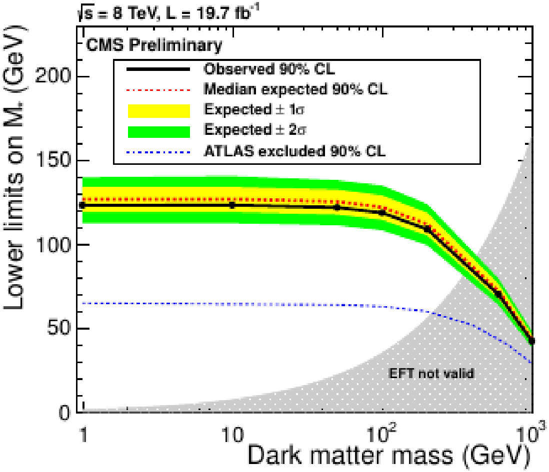
$$\frac{m_q}{M^{*3}}\overline{q}q\overline{\chi}\chi$$

DM with $t\bar{t}$: Search Strategy

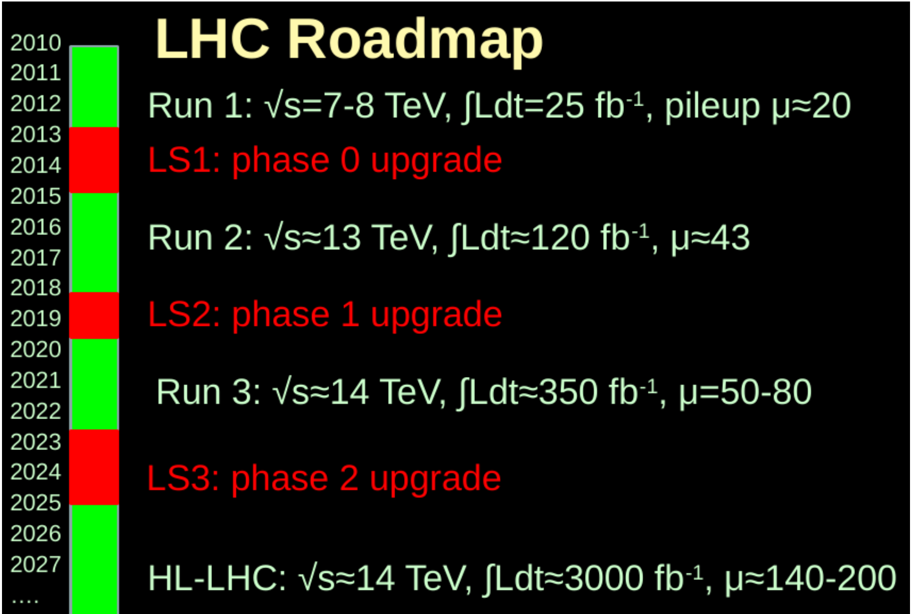
- Search for $t\bar{t}$ events where one or both t's decay to leptons
- Require missing momentum recoiling agains top pair
- Look for excess at large missing momentum



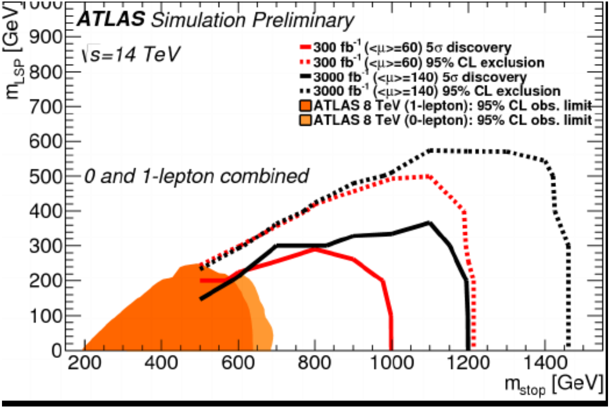
Top-Pair Results



The Future


LHC Roadmap
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
....
Run 1: √s=7-8 TeV, ∫Ldt=25 fb-1, pileup μ≈20
LS1: phase 0 upgrade
Run 2: √s≈13 TeV, ∫Ldt≈120 fb-1, μ≈43
LS2: phase 1 upgrade
Run 3: √s≈14 TeV, ∫Ldt≈350 fb-1, μ=50-80
LS3: phase 2 upgrade
HL-LHC: √s≈14 TeV, ∫Ldt≈3000 fb-1, μ≈140-200

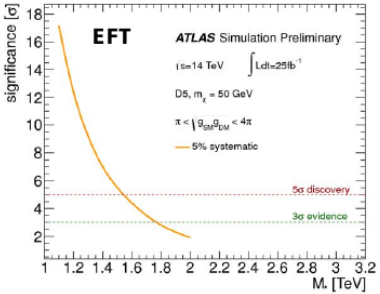
Future Prospects for SUSY Discovery

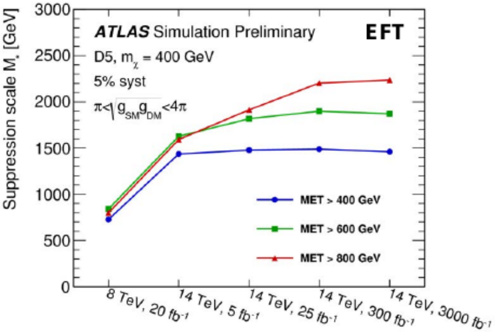


- Run 2 LHC will approximately double mass reach with respect to Run 1
- Significant further increases in Runs 3 and 4

Adopting similar **search strategy** as **8 TeV**
Generator-level backgrounds **+ smearing** for pile-up and detector conditions

	$\sqrt{s}$ [TeV]	μ	L [fb^{-1}]
	8	20	20
Phase 0 upgrade (2014-2015)	14	60	25
Phase 1 upgrade (2018)	14	60	300
Phase 2 upgrade (2022)	14	140	3000



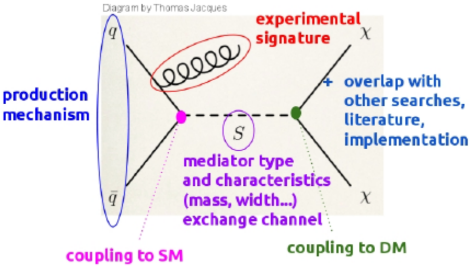


Surpassing previous limits within **1st year of data taking**

ATLAS/CMS Dark Matter Forum:

experiment/theory discussion towards Run-2 DM searches

Many possibilities to be used as building blocks:



https://twiki.cern.ch/twiki/bin/view/LHCDMF/WebHome
Mailing list: lhc-dmf@cern.ch

This Forum will agree upon:

- Prioritized **set of simplified models**
- Common **model implementation and details** (e.g. matching, scales) towards MC generation of benchmarks
- **EFT validity** assessment procedure

This Forum will document:

models and choices (arXiv write-up + SVN repository)

Conclusions

- LHC provides complementary approach to DM searchs
- Many possible models, including but not limited to SUSY
- Broad range of searches
  - Nothing found to date
- Use effective operators or simplified models to compare sensitivity to direct and indirect detection
- Run 2 will have significant increase in reach for both SUSY and non-SUSY Wimp DM

Exciting Times Ahead!