

# Search for Dark Matter @ the LHC: SUSY and other Searches

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IPPP, Durham UK

29 april 2014

## The 4<sup>th</sup> School on High Energy Physics

26 April – 2 May 2014

Ain Shams University (ASU) & The British University in Egypt (BUE)

Organized by

Egyptian Network of High Energy Physics (ENHEP)

European Network for Particle Physics (ENPP)

Goal of the School:

The goal of this series of schools is to give graduate courses on the basic topics of theoretical, computational and experimental particle physics for the Egyptian as well as regional graduate students. The prospective outcome of the school is to have qualified students capable to join the Egyptian national project related to CMS experiment of the Large Hadron Collider (LHC) at CERN.

Topics Taught in the School:

1. Foundations of Particle Physics and Standard Model
2. Latest Results of LHC Experiments
3. Discoveries in Supercollider
4. Beyond the Standard Model at LHC

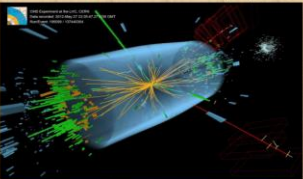
A. Grid Computing

B. Computational and Analysis Tools

C. Medical Physics

D. Mathematical Theory for Colliders

E. CMS Stream System Upgrade During LHC



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(President of The British University in Egypt)

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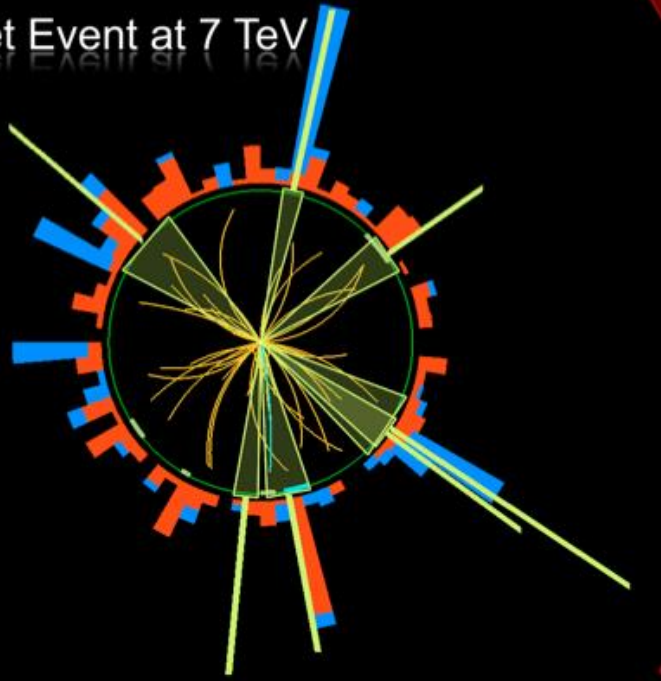


# Lecture Plan

Overview of the 3 lectures in the next days

- **Lecture 1:** Searching for Physics Beyond the Standard Model: exotic signatures
- **Lecture 2:** The next ultimate challenge: identifying Dark Matter in the Universe, and its connection to Supersymmetry
- **Lecture 3:** The future program at the LHC and the studies/ideas for 'beyond the LHC'

Multi Jet Event at 7 TeV



# Outline

- Introduction: Dark Matter and the WIMP miracle
- The LHC & Experiments
- The Higgs and dark matter
- **Supersymmetry searches**
- Generic searches via missing  $E_T$ , including mono-jets, top, photons, leptons...
- New: mono-Higgs production
- Summary

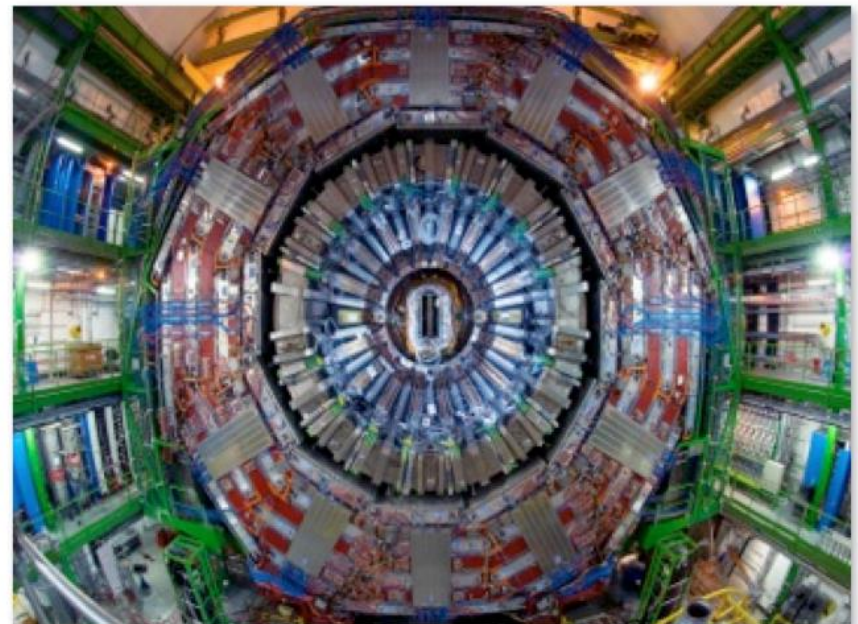
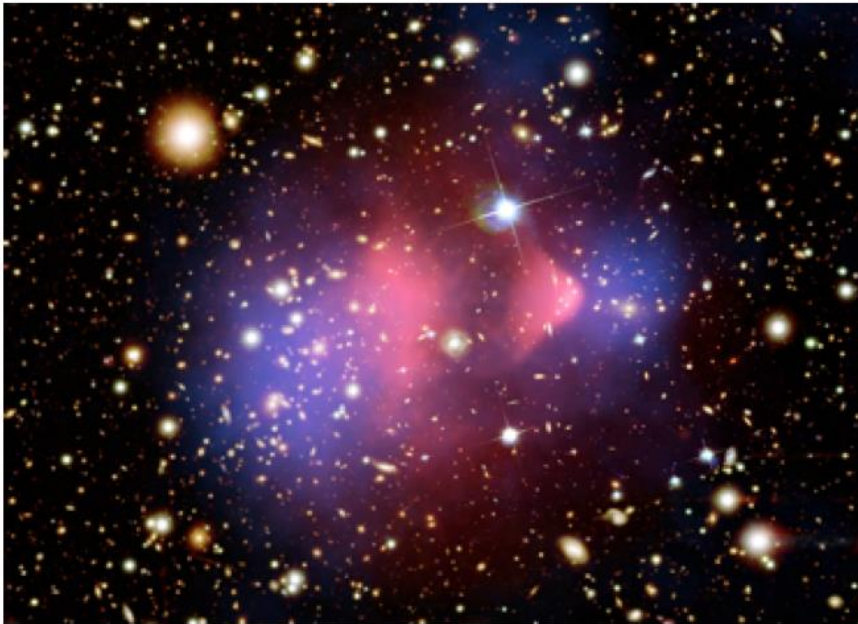
# Dark Matter: Complementary Searches?

## This Lecture:

After the discovery of the Higgs particle @ the LHC:

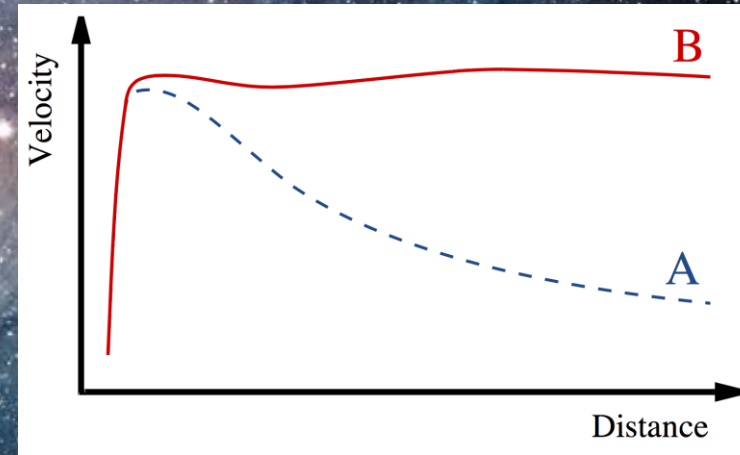
Dark matter is the next important physics problems to tackle for the LHC

The search is complementary to other experimental techniques used.



# Dark Matter: The Next Challenge

Astronomers found that most of the matter in the Universe must be invisible Dark Matter



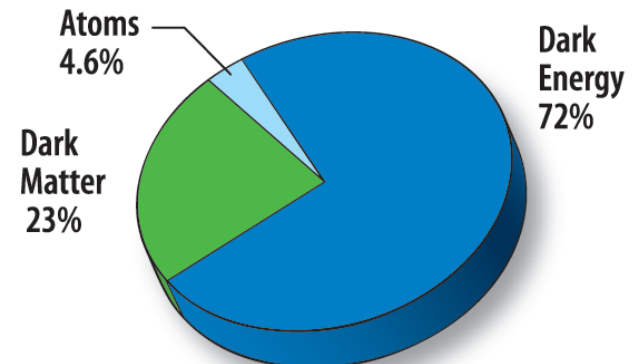
**'Supersymmetric' particles ?**



F. Zwicky 1898-1974

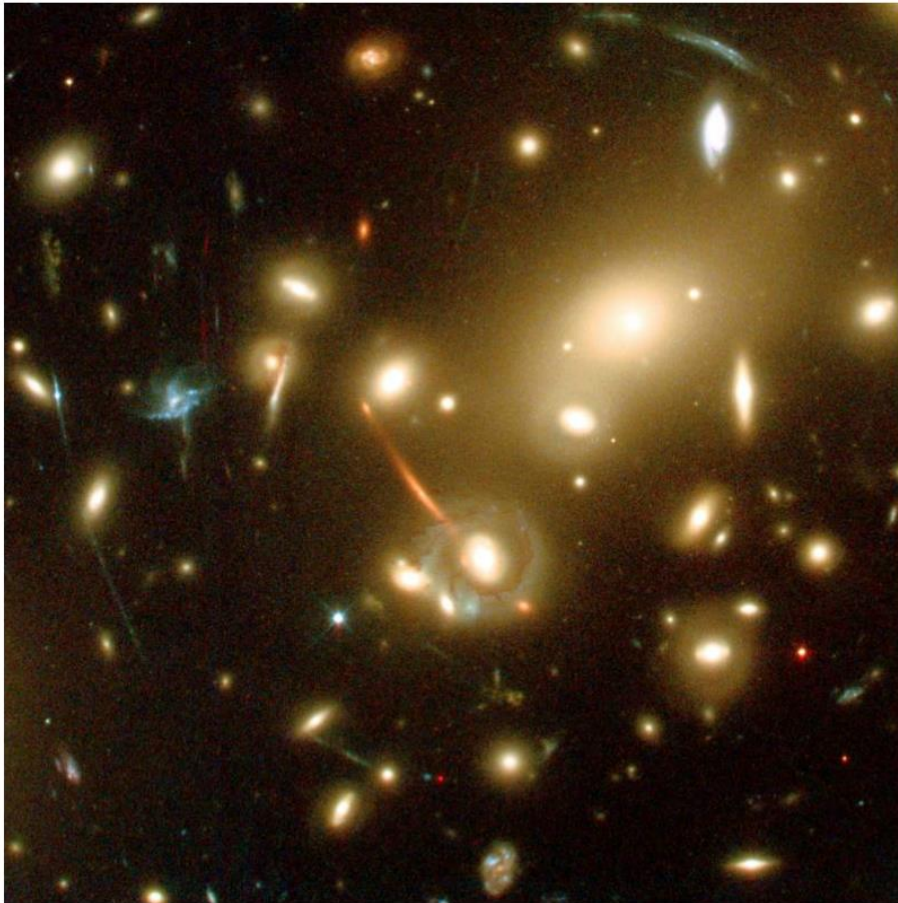


Vera Rubin ~ 1970

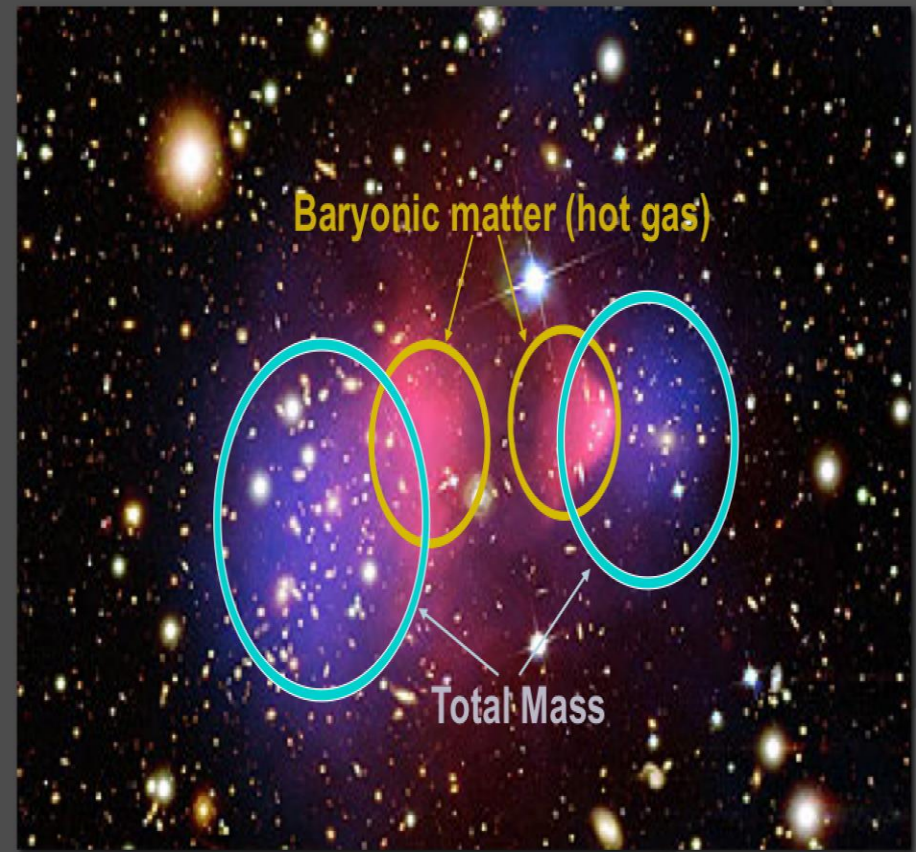


# Evidence Piling-up

- Gravitational Lensing
  - much more lensing than can be explained by visible mass

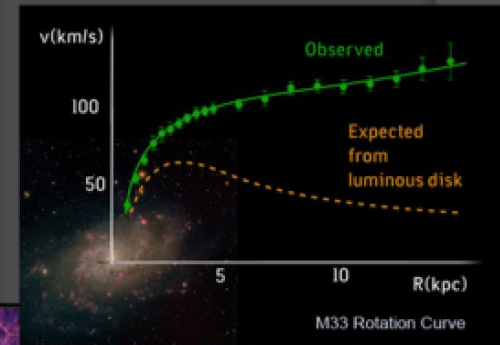
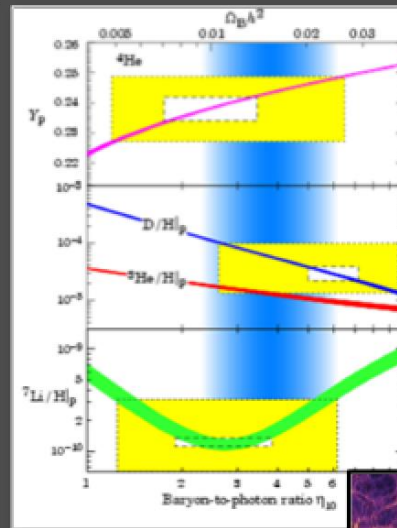
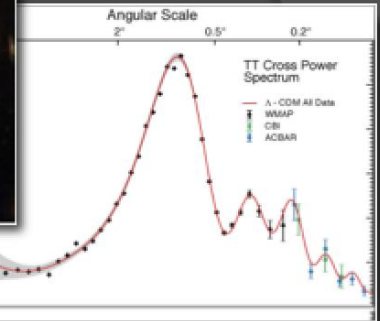


- Bullet Cluster; colliding galaxies
  - Composite x-ray, visible image, 10x DM

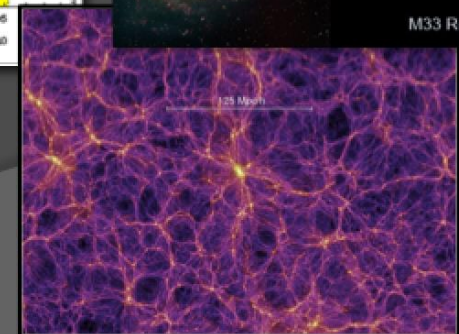


# Evidence Piling-up

- There is a wide variety of evidence indicating that dark matter exists
- Each of these observations infer dark matter's presence uniquely through its gravitational influence
- To-date, no (non-controversial) observations have been made of dark matter's electroweak or other non-gravitational interactions



*Instead of dark matter, might we not understand gravity?*



# Particle Dark Matter?

- We know only little about the nature of dark matter:
  - Cold (non-relativistic)
  - Stable
  - Dark and collisionless (no electric charge or QCD color)
- No particle contained in the Standard Model fulfills these criteria
- This leaves us with a vast range of possibilities from Planck/GUT scale “WIMPzillas” to ultra-light axions
- Dark matter candidates in the form of weakly interacting particles with masses in the GeV-TeV range (WIMPs) stand out for their
  - Testability
  - Theoretical motivation (solution to electroweak hierarchy problem)
  - The “WIMP Miracle”

The observed density of dark matter is of the magnitude expected for a thermal relic weakly-interacting massive ( $\sim 10$ - $1000$  GeV) particle (WIMP).

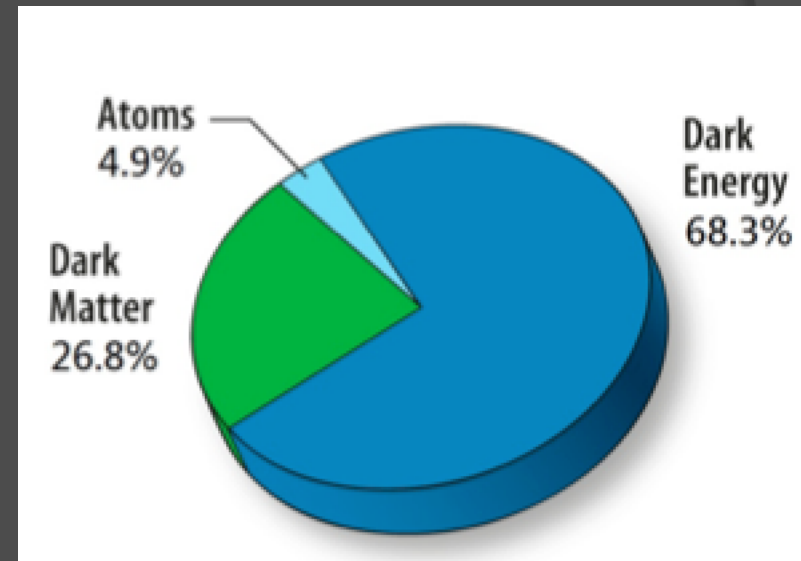


# Particle Dark Matter?

## The Dark Matter Candidate Zoo

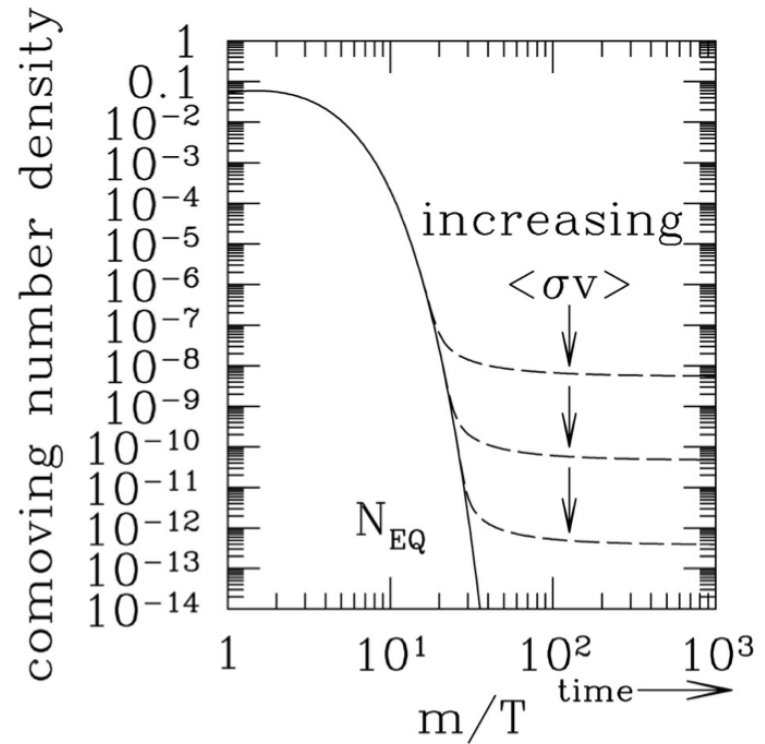
From D. Hooper

- Neutralinos (higgsino, bino, wino, singlino)
- Axinos
- Gravitinos
- Sneutrinos
- Axions
- Sterile neutrinos
- 4<sup>th</sup> generation neutrinos
- Kaluza-Klein photons
- Kaluza-Klein gravitons
- Brane world dark matter/D-matter
- Little higgs dark matter
- Light scalars
- Superheavy states (*ie.* “WIMPzillas”)
- Self-interacting dark matter
- Super-WIMPs
- Asymmetric dark matter
- Q-balls (and other topological states)
- CHAMPs (charged massive particles)
- Cryptons, mirror matter, and many, many, many others...



# Weakly Interaction Massive Particles (WIMPs)

- Perhaps Dark Matter is a particle with weak-scale mass?
  - *Weakly Interacting Massive Particles (WIMPs)*
  - Produced in the Big Bang, interact via  $\chi + \chi \rightarrow q + q$
- As the universe expands and the temperature drops...
  - WIMPs become diluted, interact less often and ‘freeze out’.
  - Higher cross-section ( $\langle\sigma v\rangle$ ) yields lower relic density

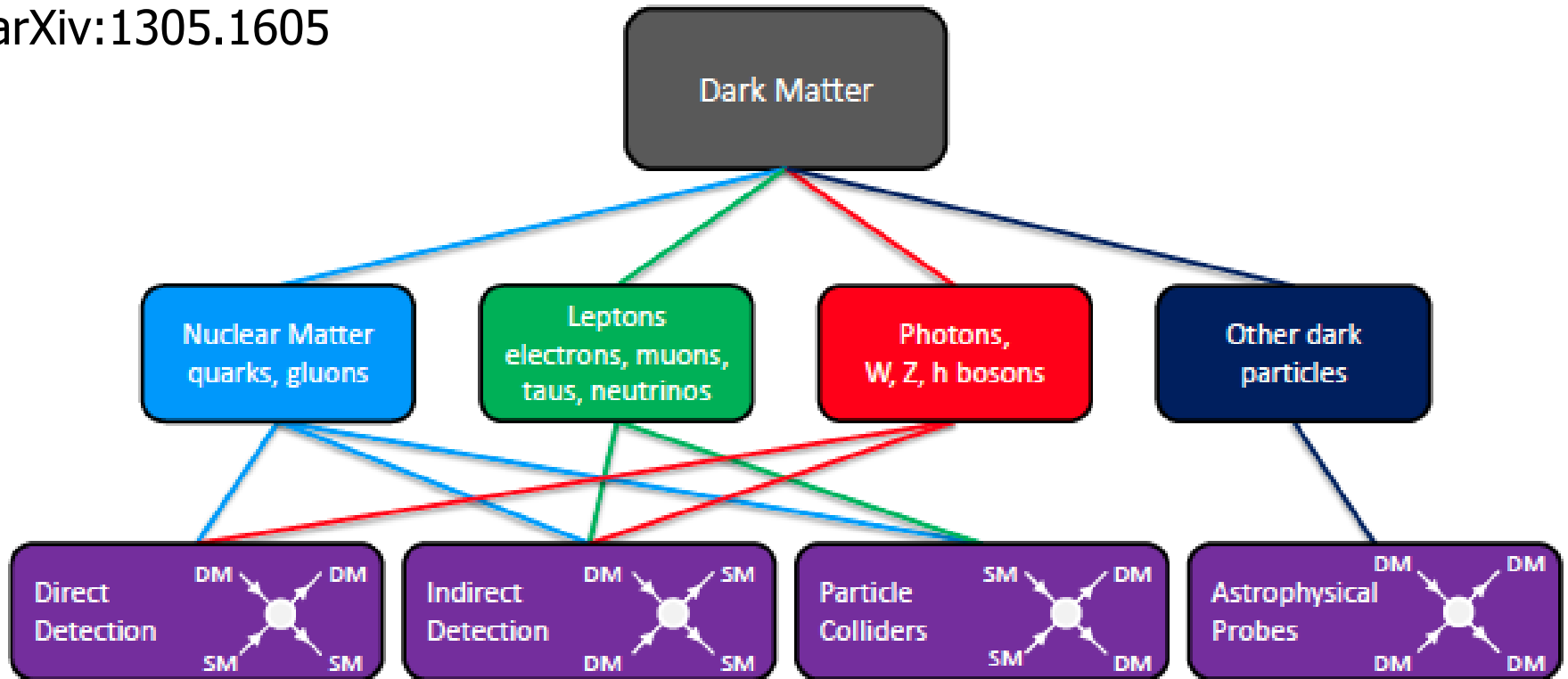


*Weakly-interacting massive particles naturally provide the right relic abundance - "WIMP miracle"*

# Dark Matter @ LHC?

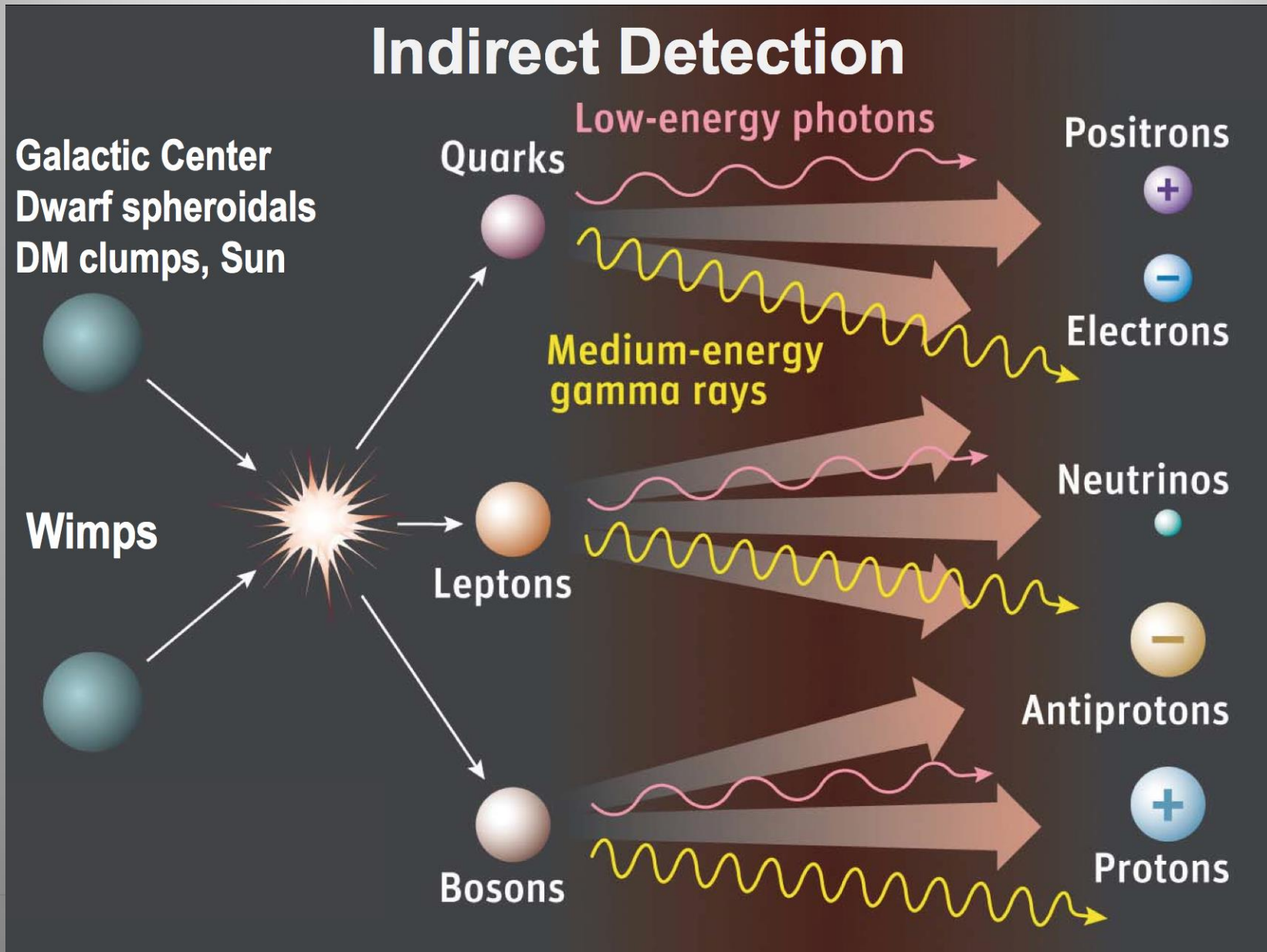
Search for WIMP candidates in events with Missing Transverse Momentum  
EG: SUSY searches, monojet and mono-photon Searches,  $W'$  searches...

arXiv:1305.1605

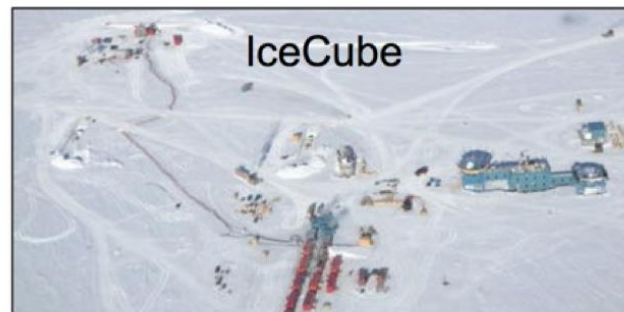
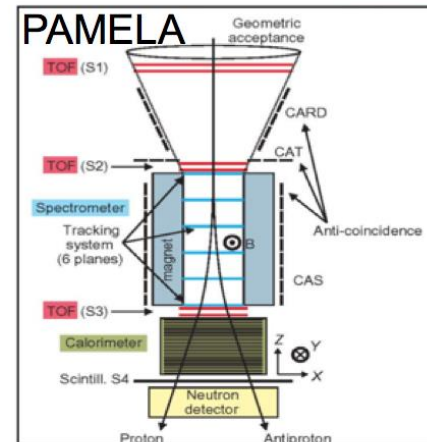
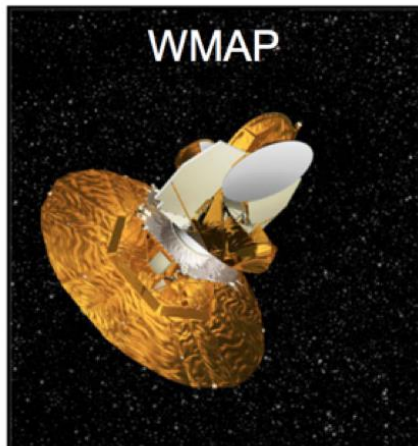


+ CAST experiment, searching for axion DM

# Dark Matter: Indirect Detection



# Indirect Detection Experiments



# Indirect Detection

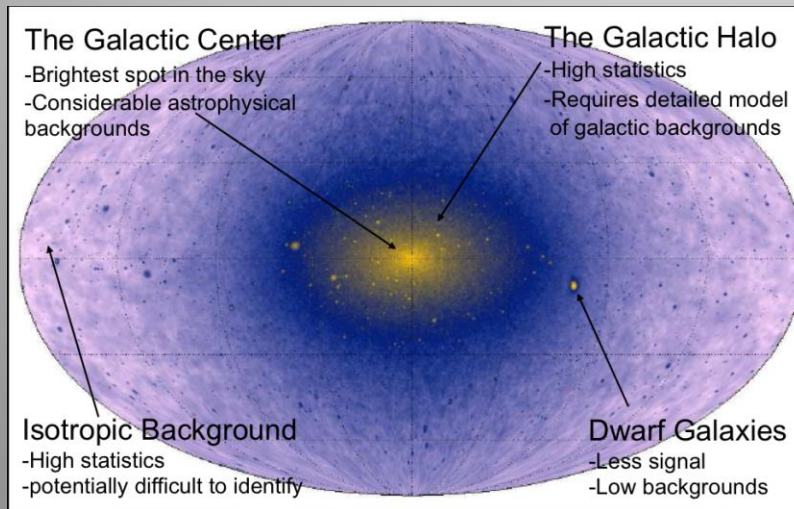
Some scientists are believers!!

arXiv:1402.6703v1

## The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter

Tansu Daylan,<sup>1</sup> Douglas P. Finkbeiner,<sup>1,2</sup> Dan Hooper,<sup>3,4</sup> Tim Linden,<sup>5</sup>  
Stephen K. N. Portillo,<sup>2</sup> Nicholas L. Rodd,<sup>6</sup> and Tracy R. Slatyer<sup>6,7</sup>

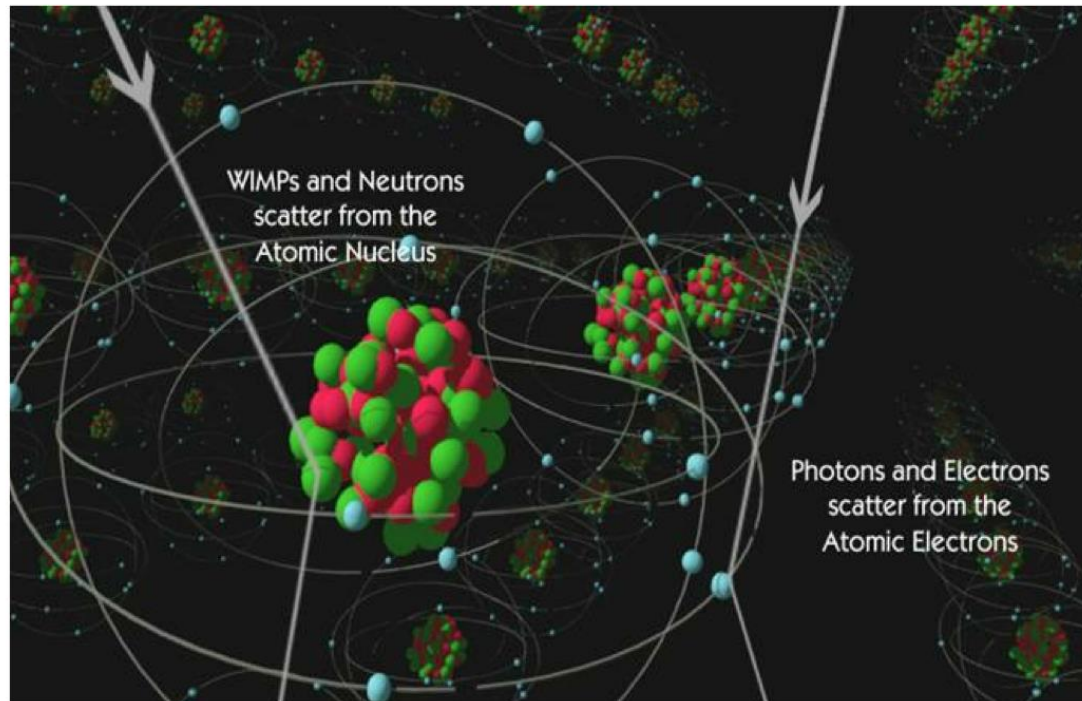
Using gamma-ray data from the FERMI satellite  
DM annihilation into  $b$  anti- $b$  quarks?



Also the 3.5 KeV line: light axion-like particle annihilation?

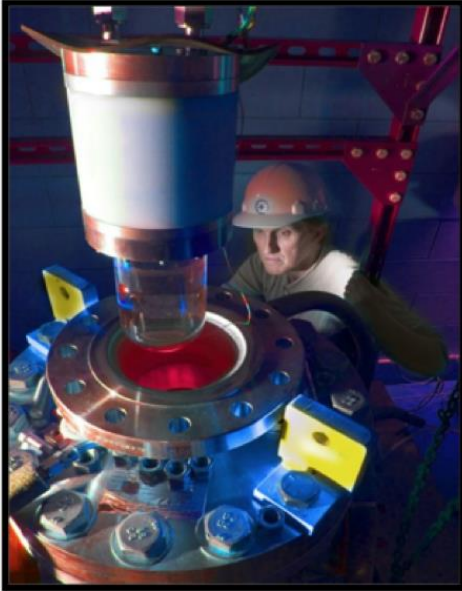
# Dark Matter: Direct Detection

- Direct detection experiments: nuclear recoil from DM collision
  - Extremely sensitive, extremely difficult... extremely successful!
  - Excesses observed but not confirmed (10 GeV DM candidate?)
- Need for independent verification from non-astrophysical experiments
  - Low mass region not accessible to direct detection experiments
  - Limited by threshold effects, energy scale, bkgnds; spin-dependent couplings difficult...

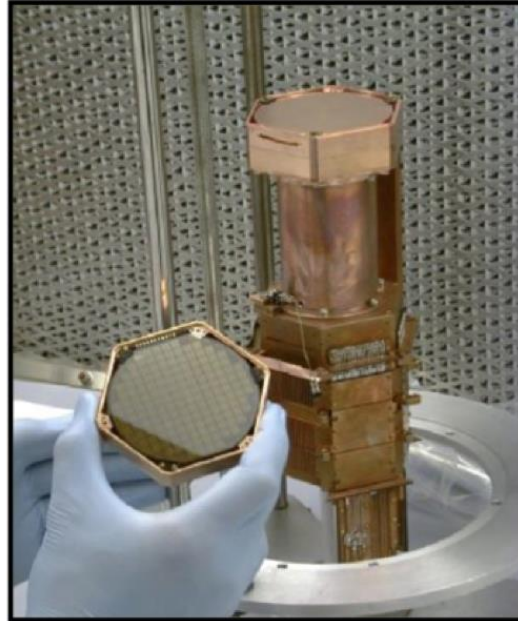


# Direct Detection: Examples

COUPP



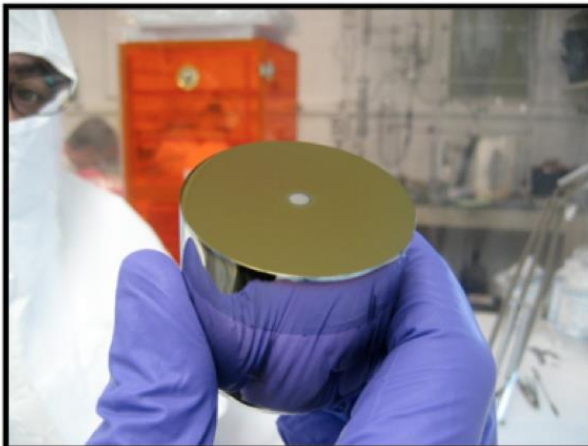
CDMS



CRESST



CoGeNT



Xenon



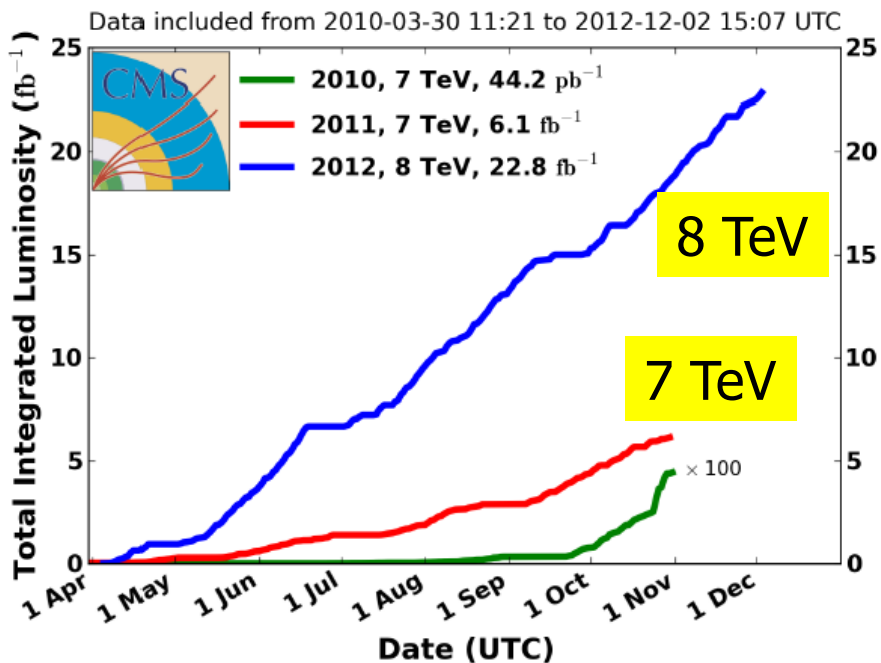
( + EDELWEISS,  
DAMA, EURECA,  
ZEPLIN, DEAP, ArDM,  
WARP, LUX, SIMPLE,  
PICASSO, DMTPC,  
DRIFT, KIMS, ...)





# The LHC

## CMS Integrated Luminosity, pp



## Primary physics targets

- Origin of mass
- Nature of Dark Matter
- Understanding space time
- Matter versus antimatter
- Primordial plasma (PbPb)

LHC operation is now stopped for 2 years, and the machine is being prepared for running at 13-14 TeV from 2015 onwards

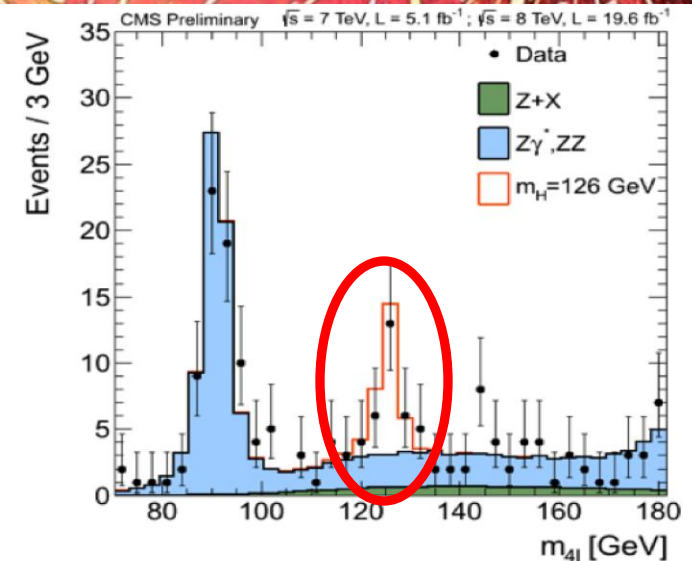
27 km ring  
100 meter underground

# 4<sup>th</sup> of July 2012...

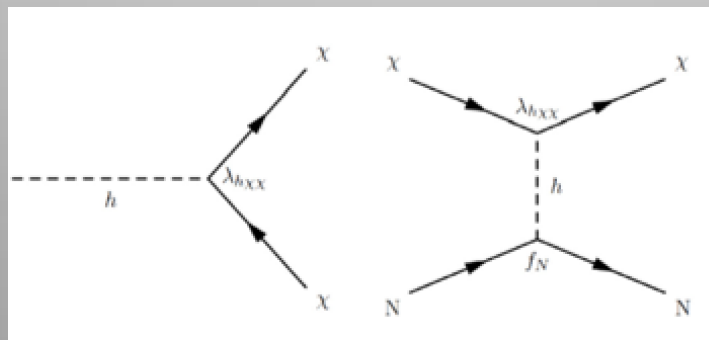
## Higgsdependence Day July 4, 2012



We discovered a Higgs particle

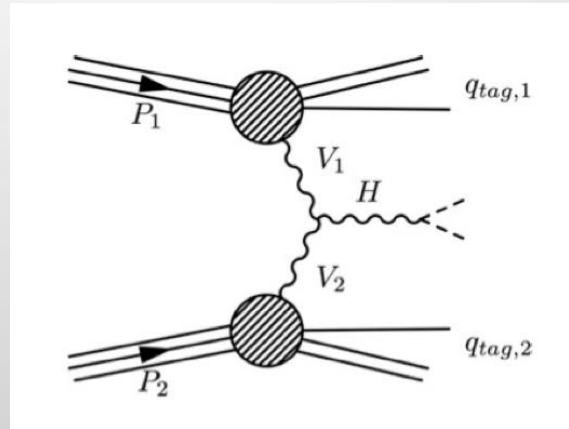
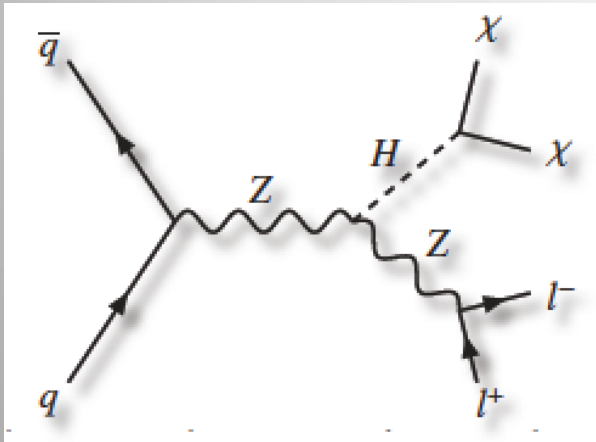


# Dark Matter and the Higgs



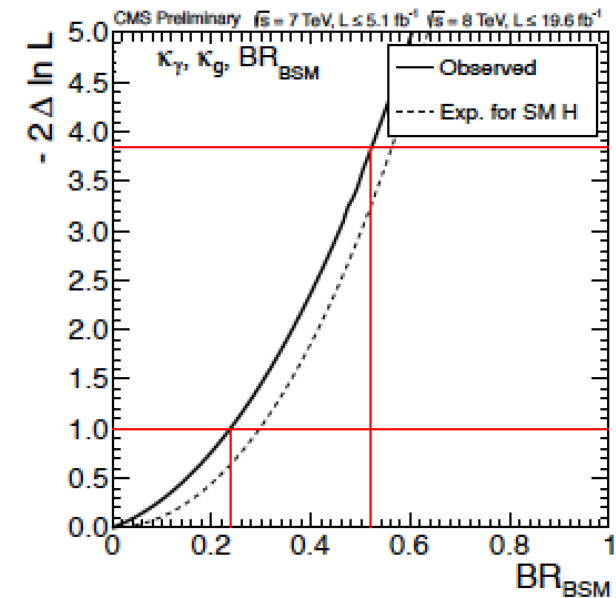
“higgs portal models”  
Eg: arXiv:1205.3169

# Invisible Higgs Decay Channel

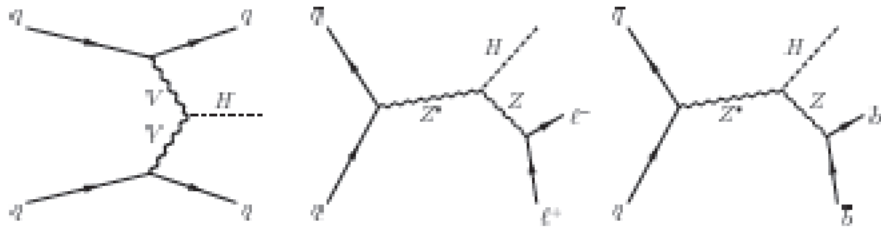


CMS-PAS-HIG-13-005

- Possible decay of the Higgs in Dark Matter particles (if  $M < M_H/2$ )
- Different searches:
  - Direct search
    - Look for the invisible decay channels
  - Indirect search
    - Make a global fit of all production and decays (and some modest assumptions)

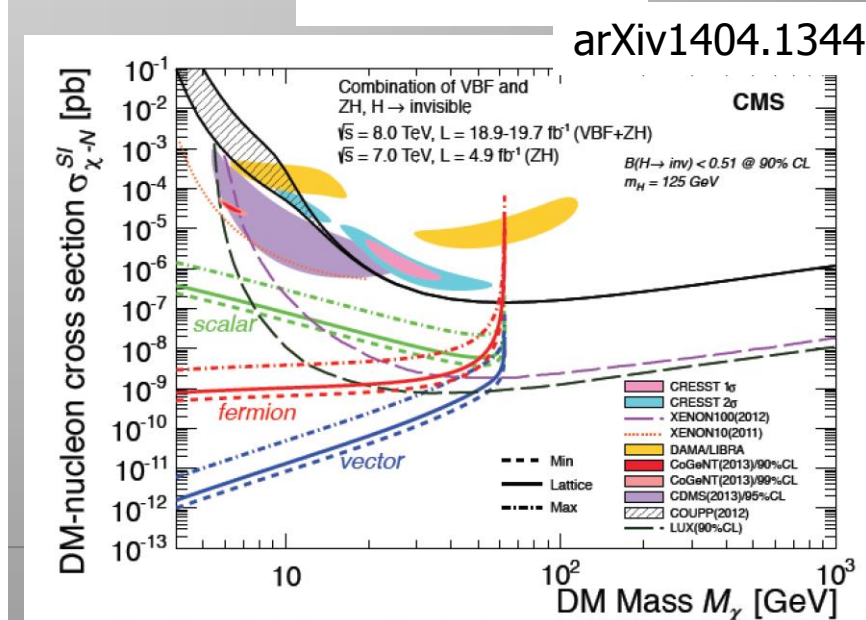
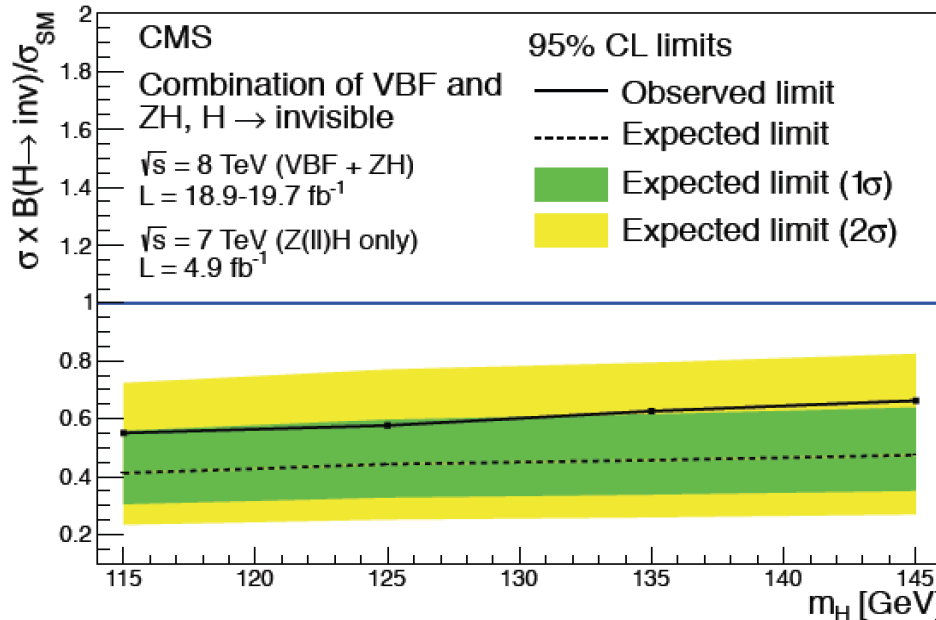
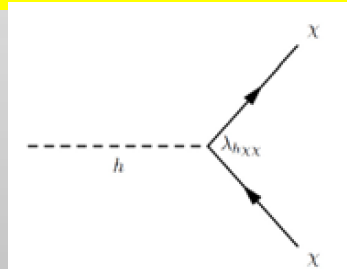


# Invisible Higgs Decay Channel



Search for invisible Higgs decays using  
 $Z+H \rightarrow 2 \text{ leptons} + \text{missing } E_T$   
 $VBF H \rightarrow 2 \text{ jets} + \text{missing } E_T$   
 Possible decay in Dark Matter particles  
 (if  $M < M_H/2$ ): Higgs Portal Models

Combined result from the three channels  
 $BR(H \rightarrow \text{invisible}) < 58\% (44\% \text{ exp})$  at 95% CL.  
 for a Higgs with a mass of 125 GeV



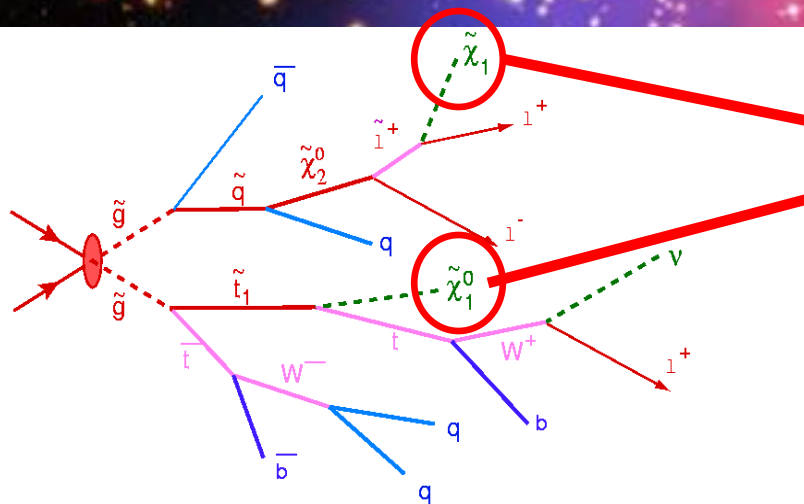
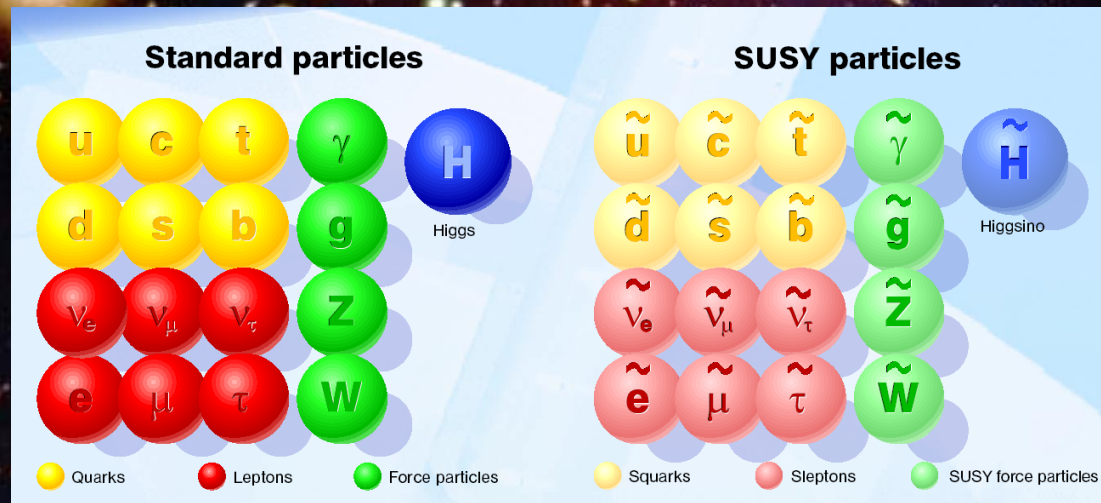
# Searches for Supersymmetry

Supersymmetry was not “invented” to solve the dark matter problem, but can provide a great solution!

**WIMP Dark Matter candidate comes for free**



# Supersymmetry: a new symmetry in Nature?



Candidate particles for Dark Matter  
 $\Rightarrow$  Produce Dark Matter in the lab

SUSY particle production at the LHC

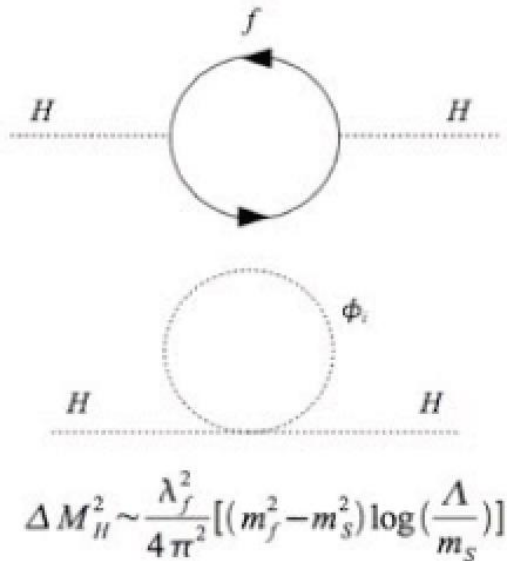
Picture from Marusa Bradac

# Why weak-scale SUSY ?

- stabilises the EW scale:  $|m_F - m_B| < O(1 \text{ TeV})$
- predicts a light Higgs  $m_h < 130 \text{ GeV}$
- predicts gauge unification
- accomodates heavy top quark
- dark matter candidate: neutralino, sneutrino, gravitino, ...
- consistent with EW precision tests (discussed yesterday)

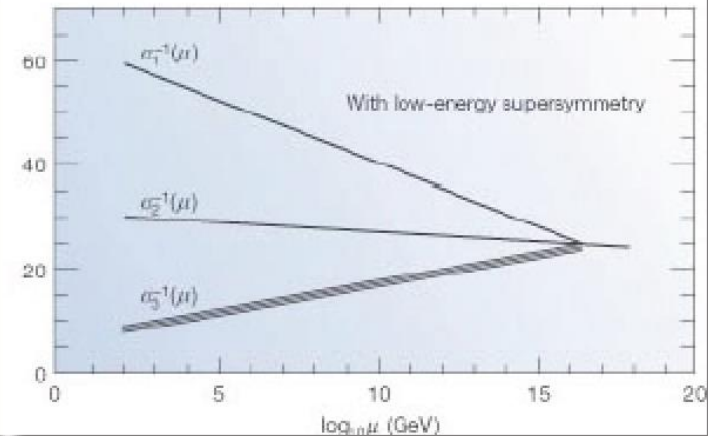
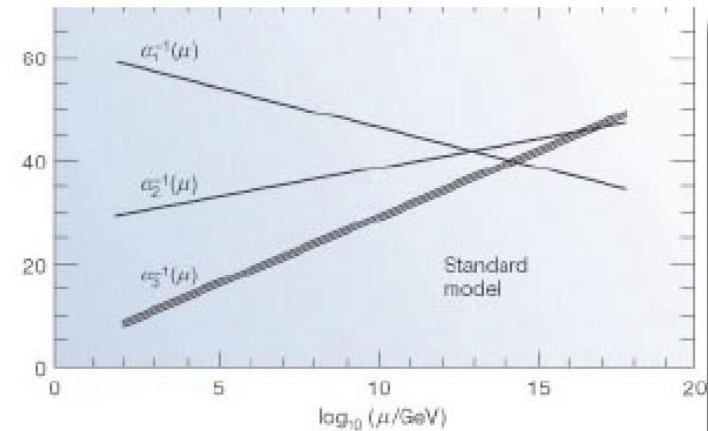
**Discovering SUSY – A revolution in particle physics!!**

# Summary: Why SUSY is good for you!!



◆ Elegant solution to the hierarchy problem (i.e., why the Higgs mass is not at the Planck scale)

◆ Gauge unification

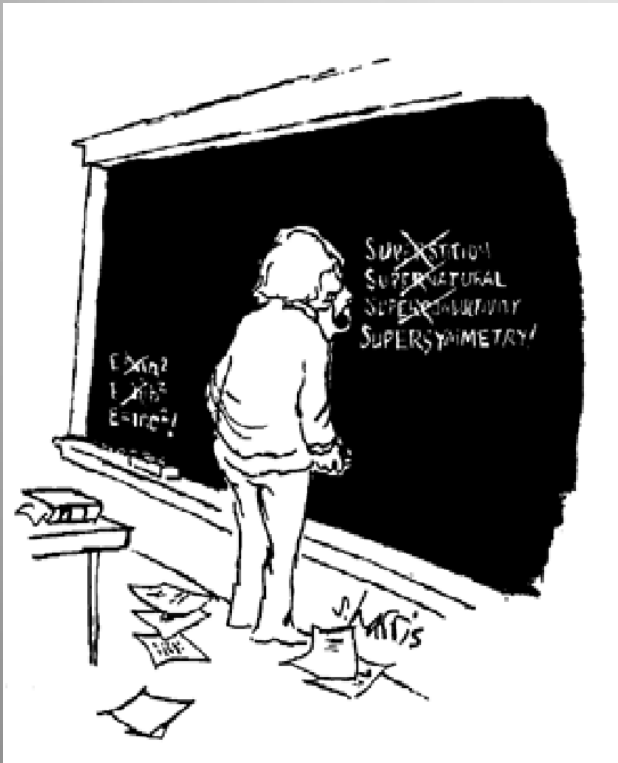


◆ Dark matter candidate with the right abundance

# Supersymmetry

A VERY popular benchmark...

More than 10000 papers since 1990



These will  
be papers."

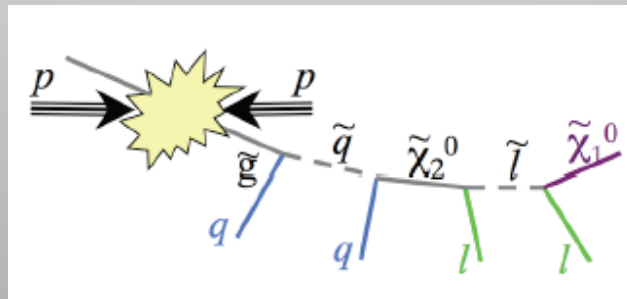
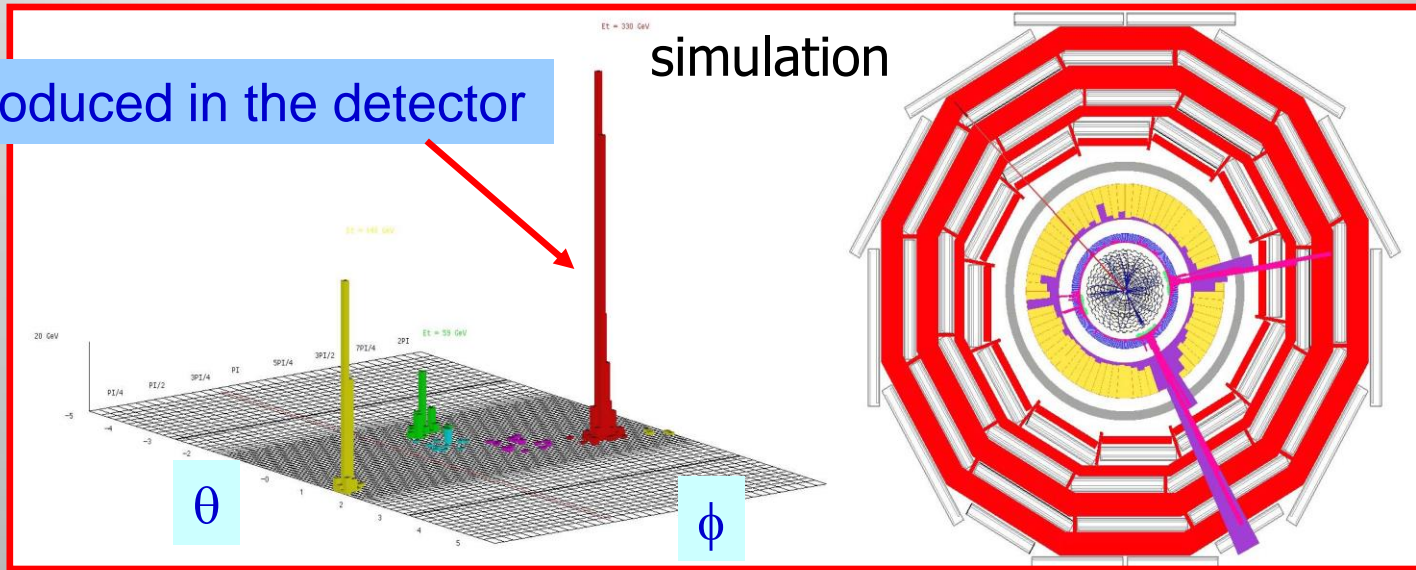


"One day all these trees will be SUSY phenomenology papers"

Considered as a benchmark for a large class of new physics models

# Detecting Supersymmetric Particles

Energy produced in the detector



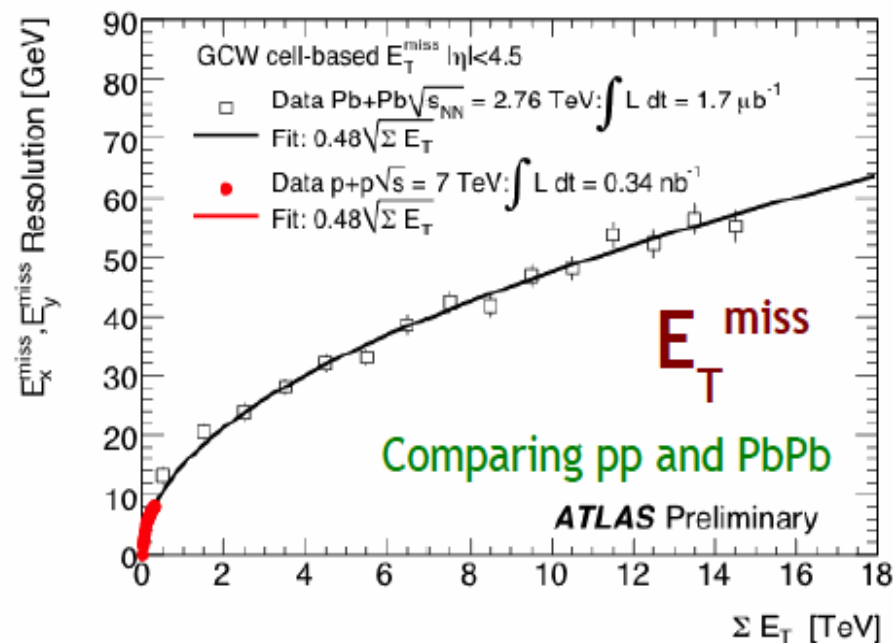
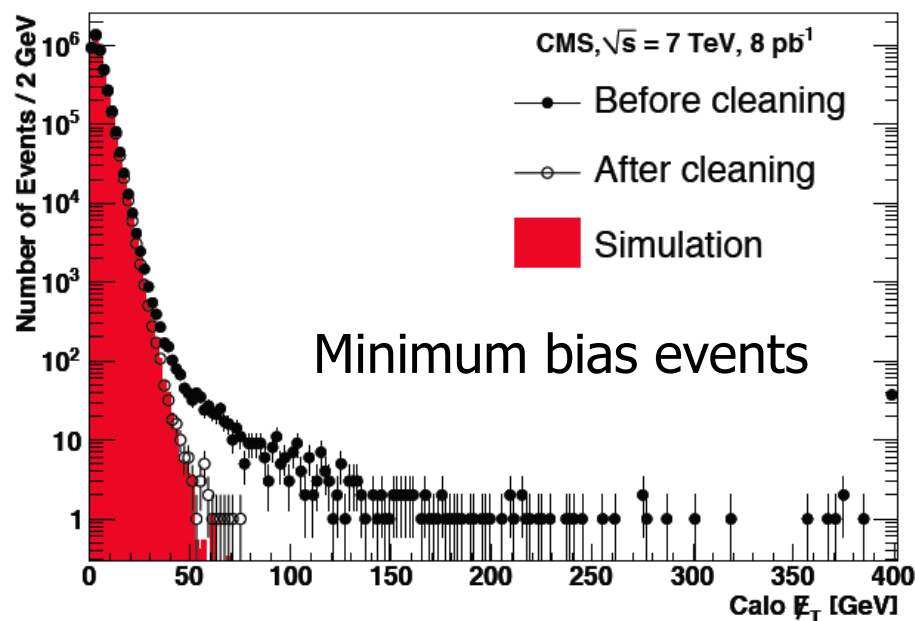
Supersymmetric particles decay and produce a cascade of jets, leptons and missing transverse energy (MET) due to escaping 'dark matter' particle candidates

**Very prominent signatures in CMS and ATLAS**

# Missing Transverse Energy

## Total transverse momentum imbalance

Generally appreciated to be a difficult quantity to measure  
Very sensitive to fluctuations, miss-measurements, noise, backgrounds



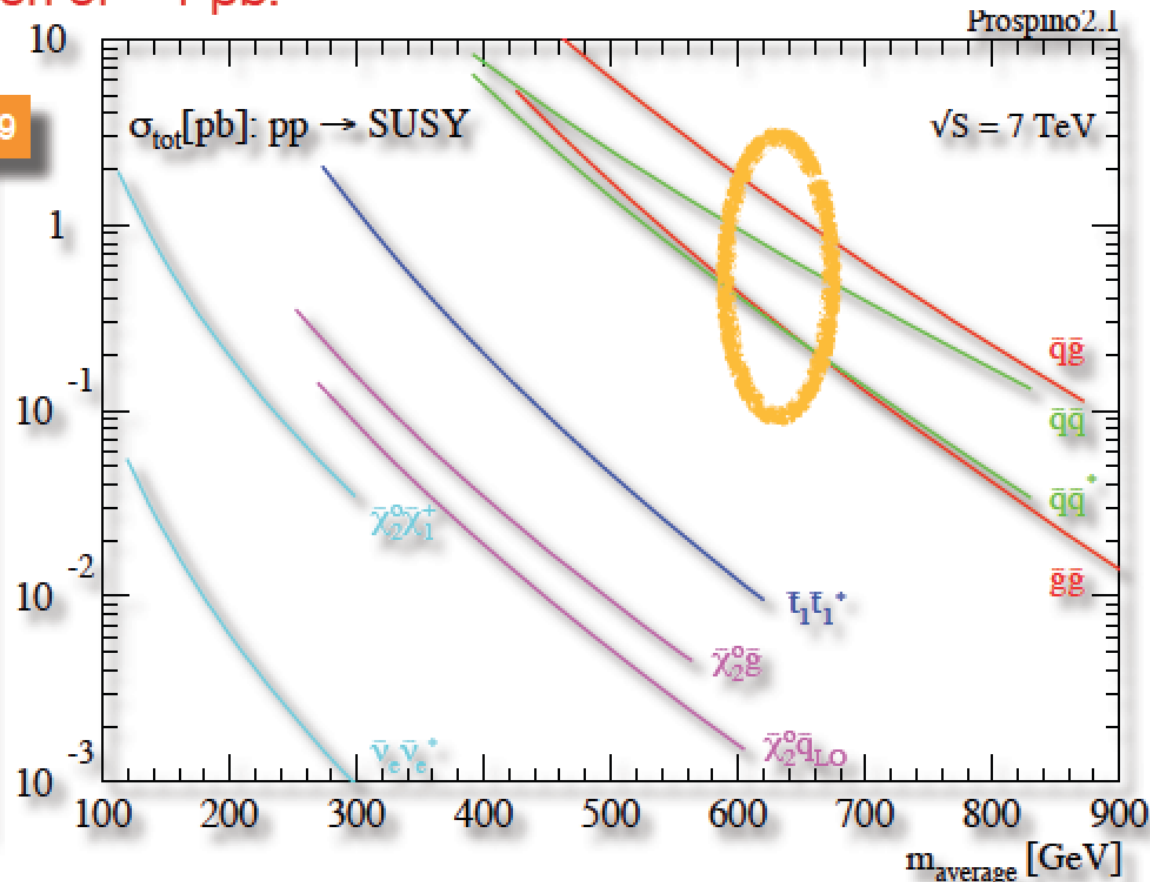
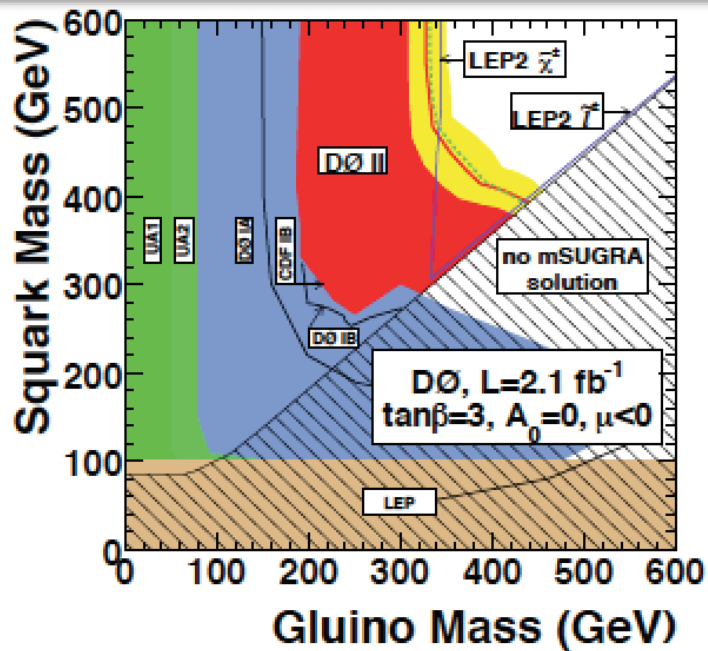
- In practice, rather well under control, from the start
- Good resolution using 'particle flow' ie maximally identifying particles
- More Pile-up in future will NOT make this simpler

# SUSY before LHC

When the LHC turned on at 7 TeV in 2010, the hopes to find SUSY almost immediately were high

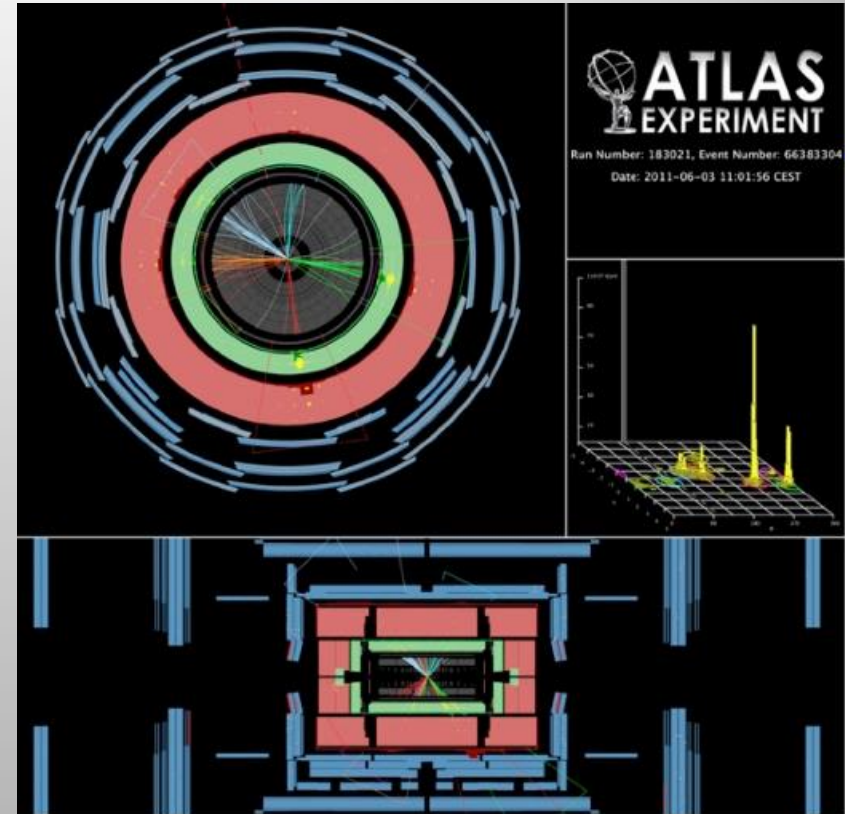
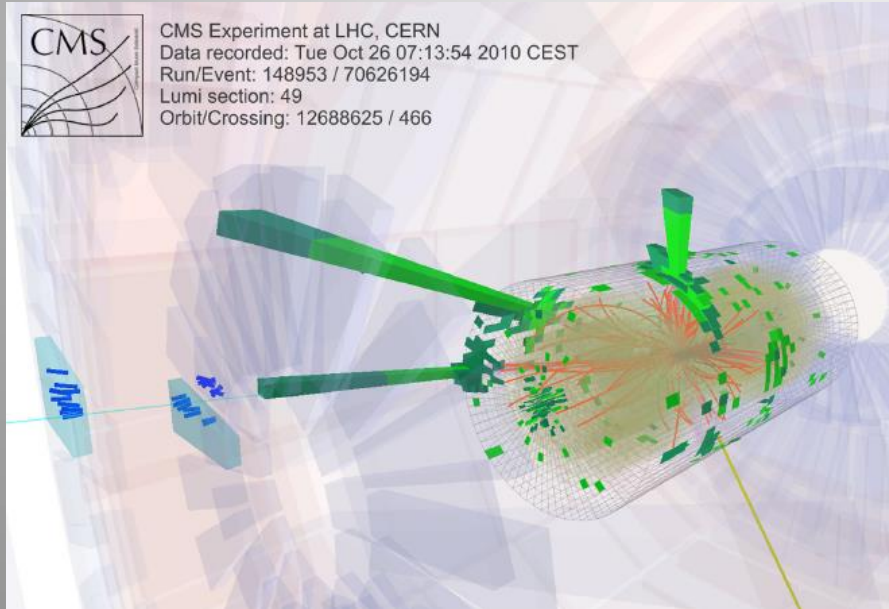
- 650 GeV squarks/gluinos (quite beyond the Tevatron reach) are pair produced at the LHC with cross section of  $\sim 1$  pb!

D0 Collaboration, Phys. Lett. B660 (2008) 449



# ...Some Interesting Collisions...

...already in 2010...



- Events with five jets of particles **and large missing energy** which could come from a possible dark matter particle
- But a few events is not enough to prove we have something new  
No visible excess has been building up with time...



# SUSY Searches

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

Large

SM backgrounds

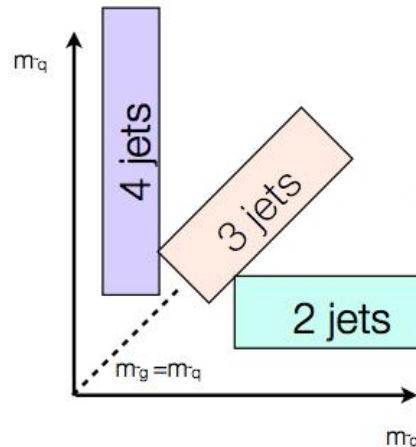
Low

sensitivity to strongly produced SUSY

sensitivity to gauge-mediated SUSY

All Analyses (CMS)

JET+MET (ATLAS)



Channel definition

Reduce QCD

Enhance signal

Signal Region	≥ 2 jets	≥ 3 jets	≥ 4 jets	High mass
$E_T^{miss}$	> 130	> 130	> 130	> 130
Leading jet $p_T$	> 130	> 130	> 130	> 130
Second jet $p_T$	> 40	> 40	> 40	> 80
Third jet $p_T$	-	> 40	> 40	> 80
Fourth jet $p_T$	-	-	> 40	> 80
$\Delta\phi(\text{jet}, E_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
$E_T^{miss}/m_{eff}$	> 0.3	> 0.25	> 0.25	> 0.2
$m_{eff}$ [GeV]	> 1000	> 1000	> 500/1000	> 1100

$$m_{eff} = \sum_{i=1}^n |\vec{p}_T^{jet\ i}| + E_T^{miss}$$

Note: Strong effort to get background (tail) estimates from data itself

# Example: Search for SUSY

Take one example to show steps involved:

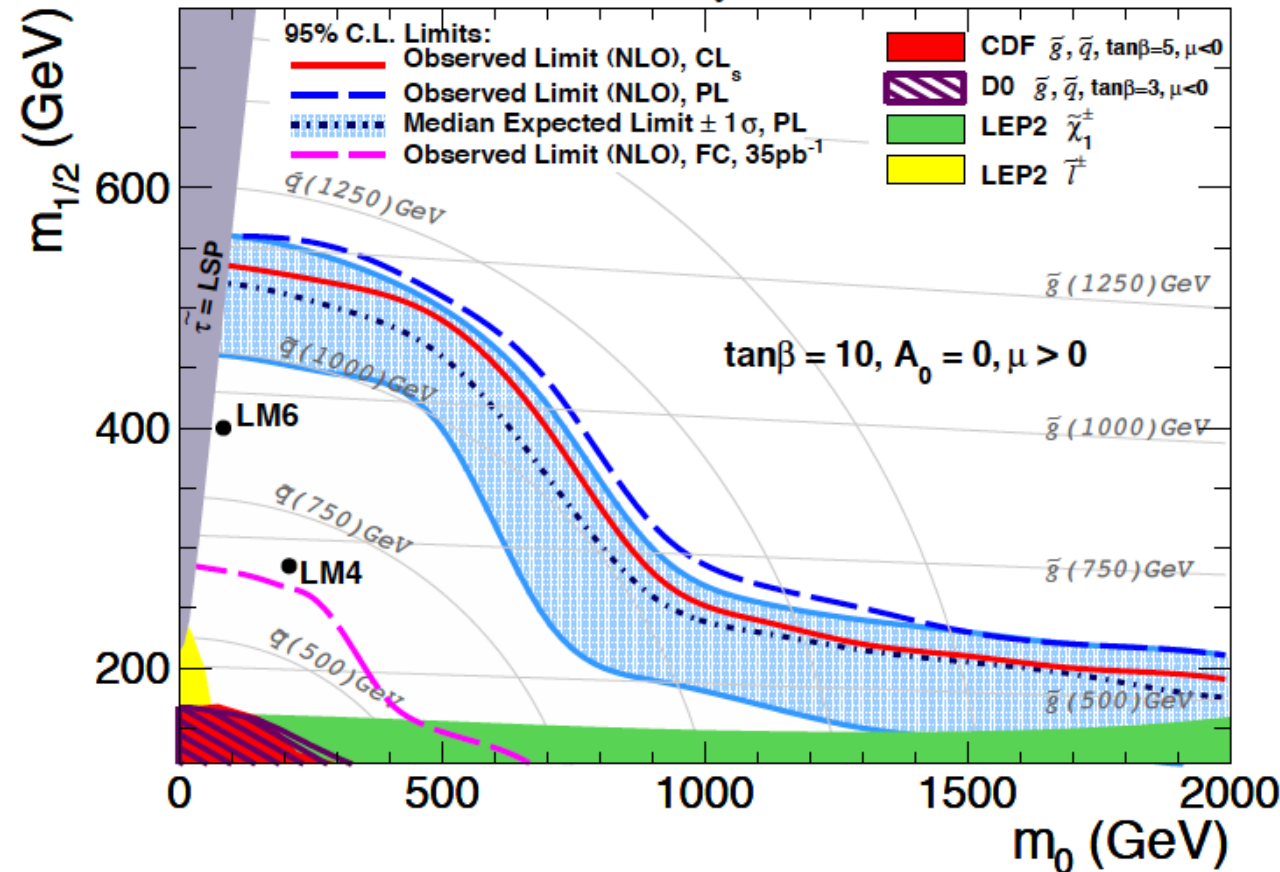
- Define event selection criteria
- Go through  $\sim 2.000.000.000$  events triggered and stored on-line, to select candidates
- Use eg kinematical cuts to suppress background
- “Predict” backgrounds in signal region
- Determine efficiencies and systematics
- Open the data box: Excess or no excess?

# SUSY Search: Jets + Missing $E_T$ Channel

CMS-SUS-11-003

Using  $1 \text{ fb}^{-1}$

CMS preliminary  $\alpha_T \int \mathcal{L} dt = 1.1 \text{ fb}^{-1} \sqrt{s} = 7 \text{ TeV}$



So far Constrained Minimal Supersymmetric Standard Model **CMSSM** is often used as a benchmark model for presenting the search results...

The CMSSM has 4 parameters

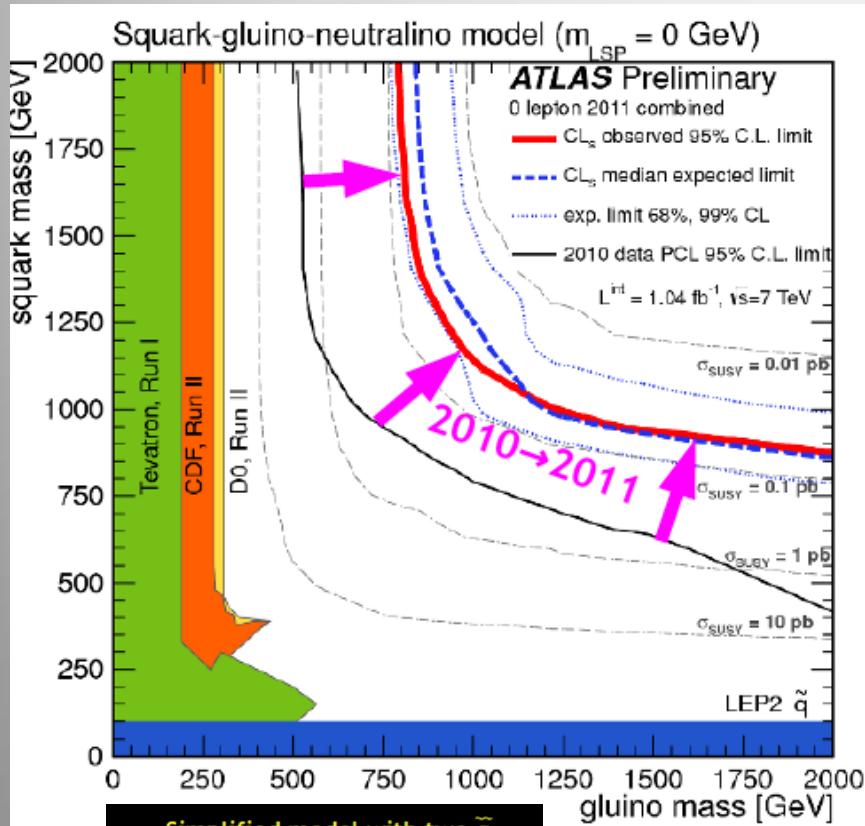
- $m_{1/2}$ : universal gaugino mass at GUT scale
- $m_0$ : universal scalar mass at GUT scale
- $\tan\beta$ : vev ratio for 2 Higgs doublets
- $A_0$ : trilinear coupling and the sign of Higgs mixing parameter  $\mu$

# SUSY Search: Jets + Missing $E_T$ Channel

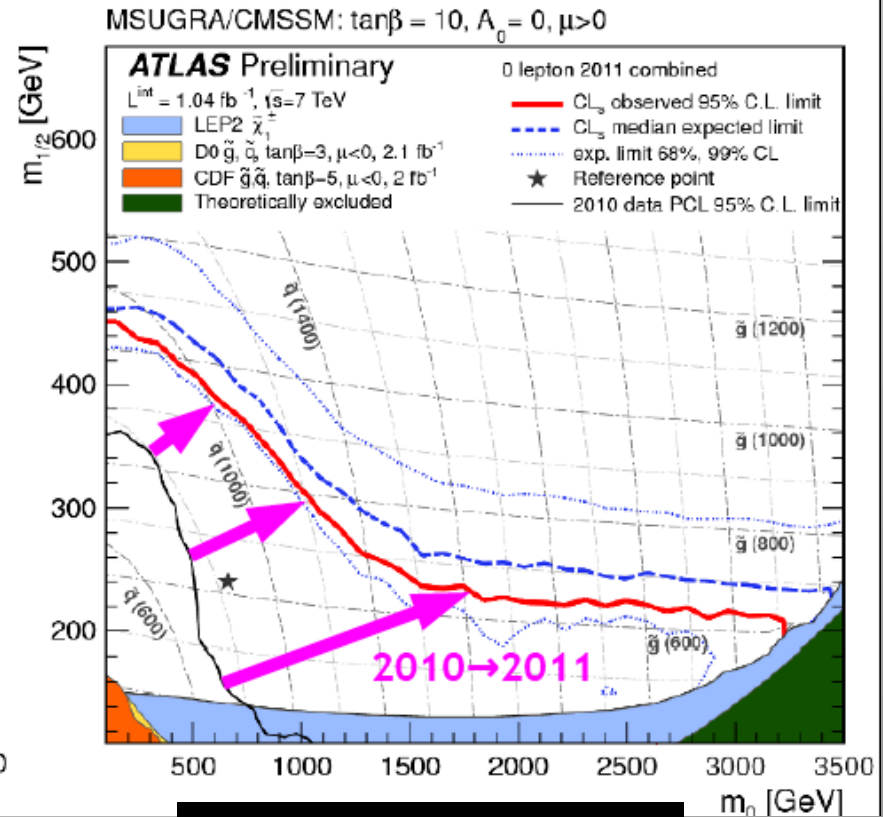
Limits in a simplified model

Using  $1 \text{ fb}^{-1}$

Limits in CMSSM



Simplified model with two  $\tilde{q}$  generations,  $m(\tilde{\chi}_1^0) = 0$   
 $m_{\tilde{g}} > 800 \text{ GeV}$   $m_{\tilde{q}} > 850 \text{ GeV}$   
 Equal mass case:  $m_{\tilde{g}} = m_{\tilde{q}} > 1.075 \text{ TeV}$

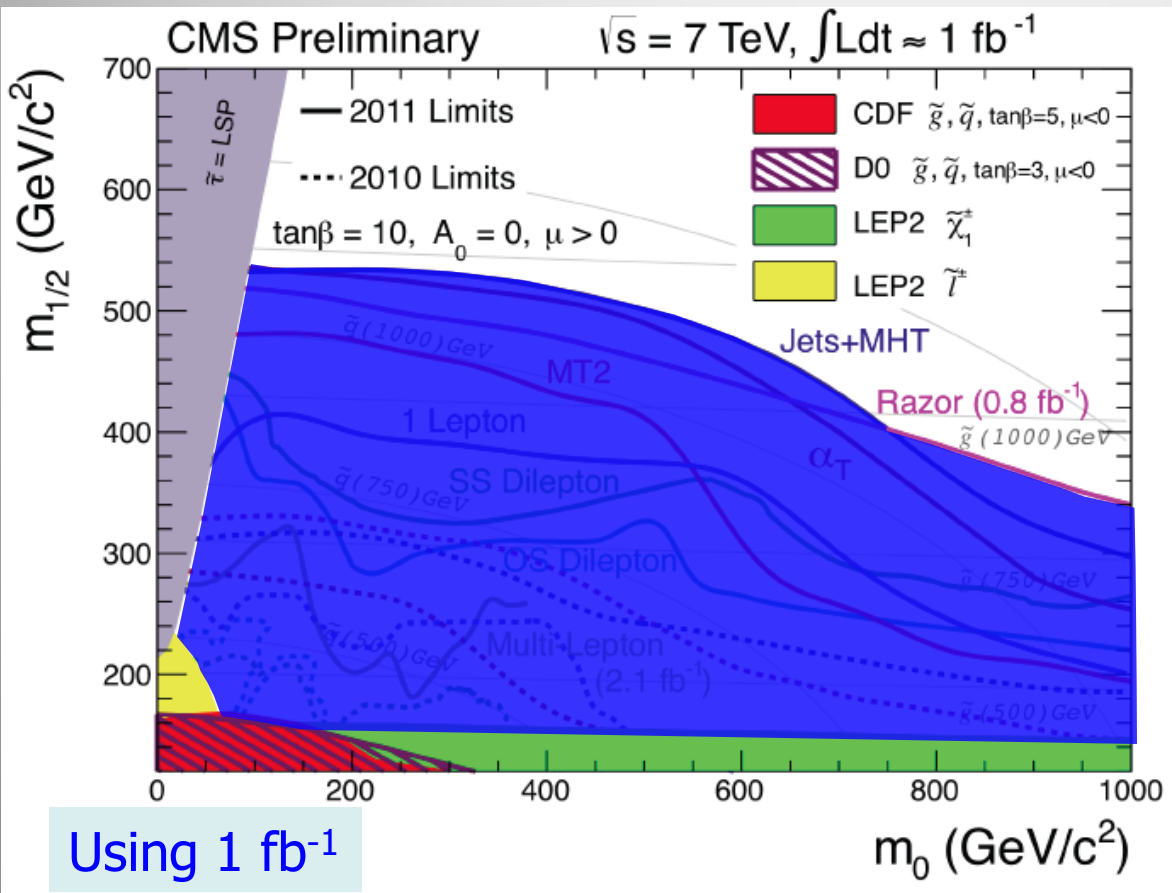


MSUGRA/CMSSM:  $\tan\beta=10$ ,  $A_0=0$ ,  $\mu>0$   
 Equal mass case:  $m_{\tilde{q}} = m_{\tilde{g}} > 980 \text{ GeV}$

Up to masses of 1 TeV excluded for equal gluino-squark masses  
 Extends the 2010 data limits by  $\sim 250 \text{ GeV}$

# SUSY Summary: lepton and hadronic channels

Many different analysis



The spaghetti monster plot

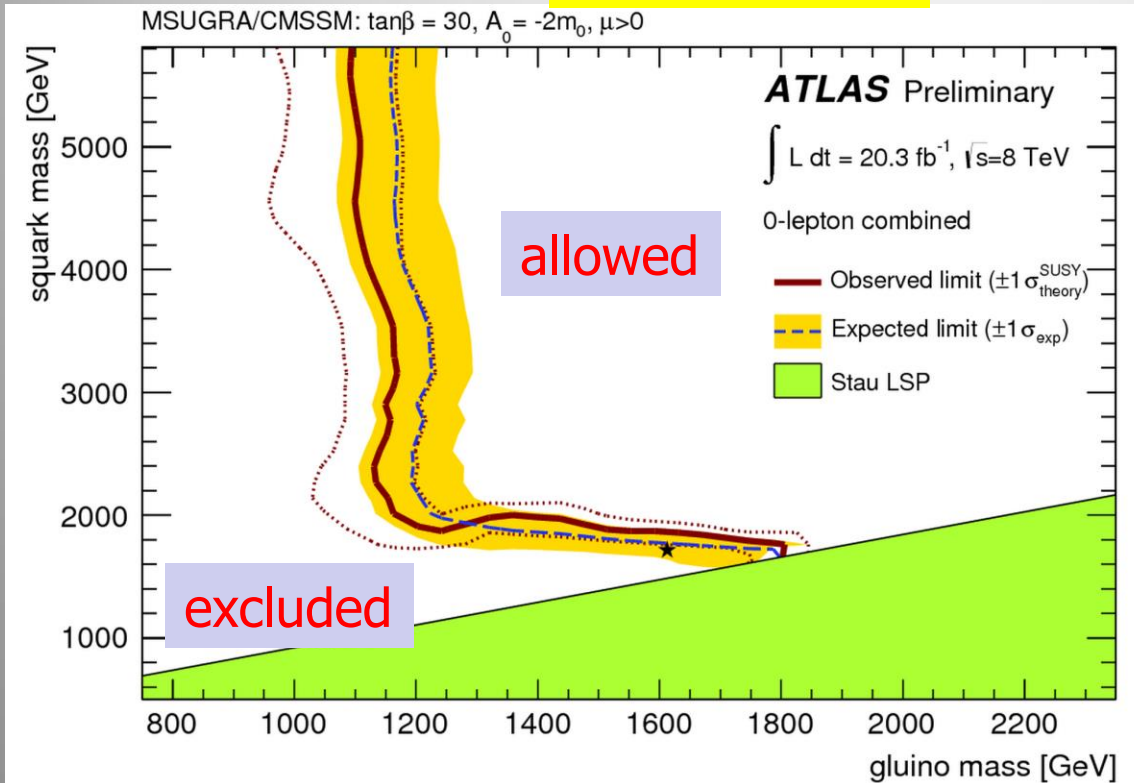
Results of SUSY analyses with 1 fb<sup>-1</sup>  
 $\alpha_T$ , MHT, MT2, Razor,  
 Same Sign and Opposite Sign dileptons...

The CMSSM has 4 parameters  
 -  $m_{1/2}$ : universal gaugino mass at GUT scale  
 -  $m_0$ : universal scalar mass at GUT scale  
 -  $\tan\beta$  and  $A_0$

Within the Constrained MSSM model we are crossing the border of excluding gluinos up to 1 TeV and squarks up to 1.25 TeV

# SUSY Searches: No signal yet to date...

## Status in 2013



- So far **NO** clear signal of supersymmetric particles has been found

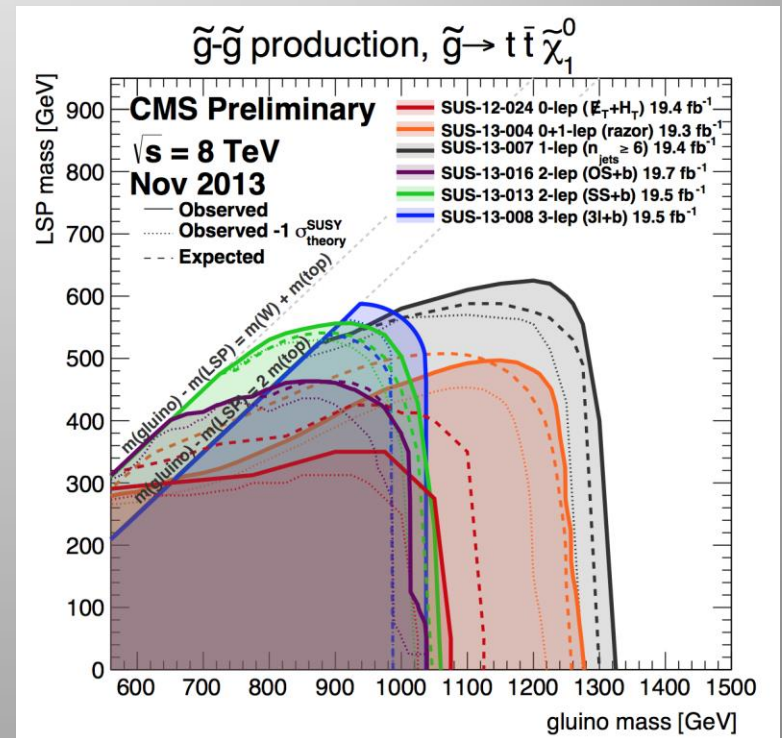
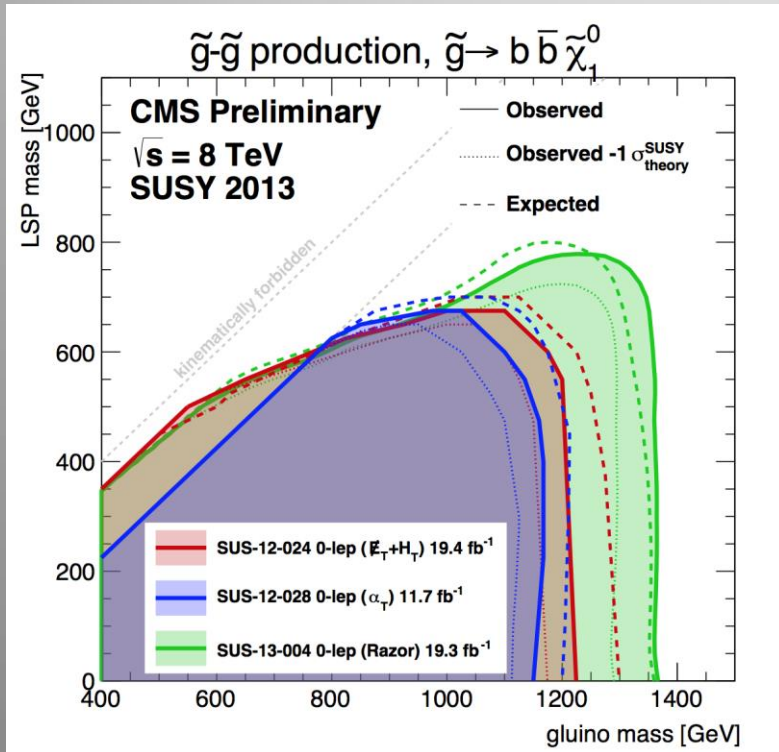
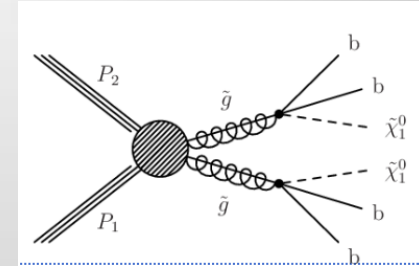
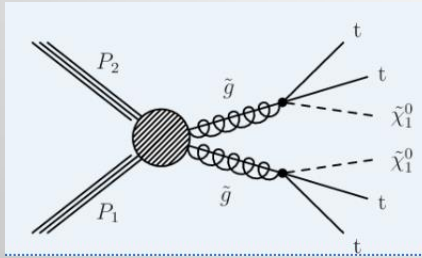
- We can exclude regions where the new particles could exist.

- Searches will continue for the higher energy in 2015

Plenty of searches ongoing: with jets, leptons, photons, W/Z, top, Higgs, with and without large missing transverse energy  
Also special searches for contrived model regions

# Limits on Squarks and Gluinos

Examples using b and t quarks

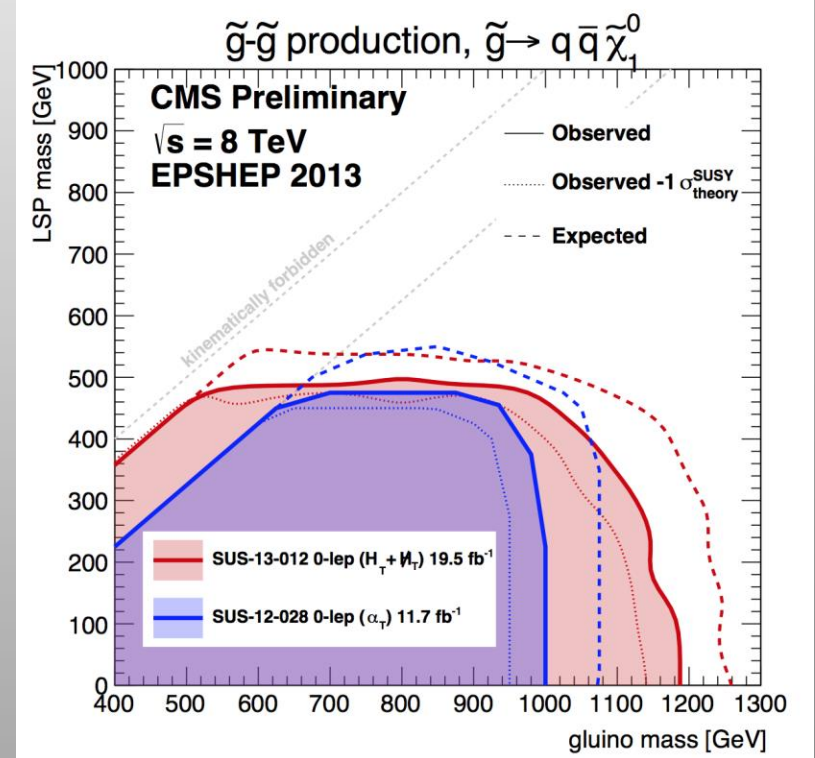
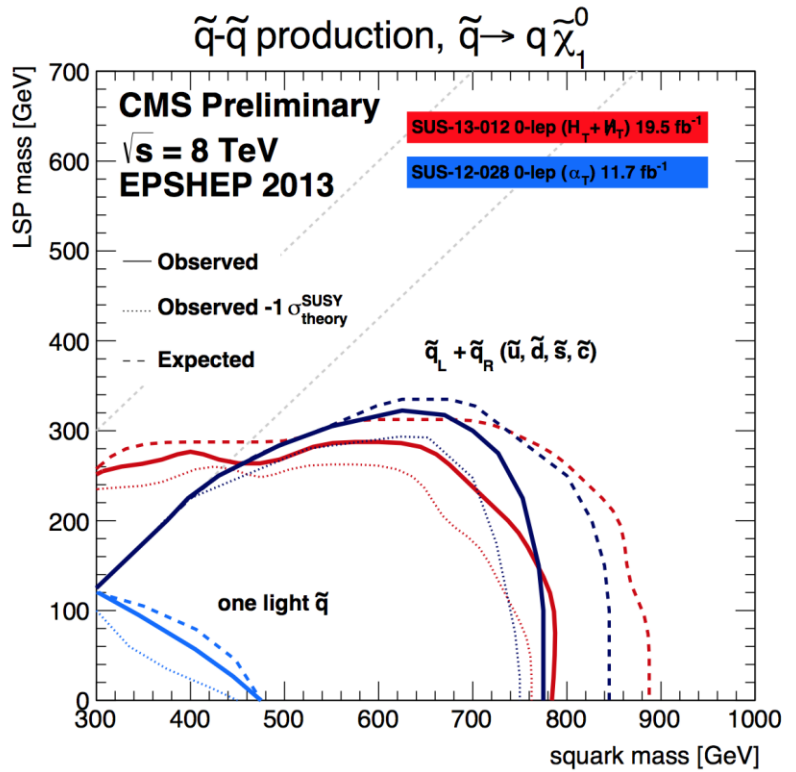
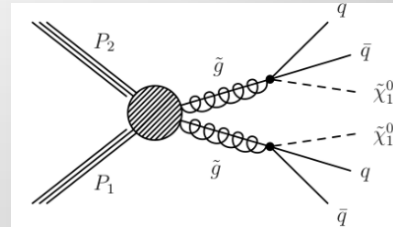
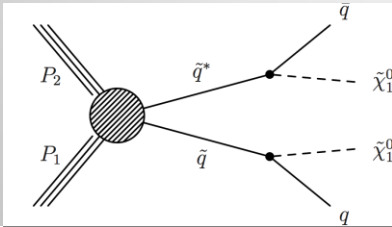


Combined limits typically  $> 1\text{-}1.5 \text{ TeV}$  on sparticle masses

# Limits on Squarks and Gluinos

Results depend on the topologies studies, assumed mass of the LSP etc.

Examples



Combined limits typically  $> 1\text{-}1.5 \text{ TeV}$  on sparticle masses



# What is really needed from SUSY?

End 2011: Revision!

N. Arkani-Ahmed  
CERN Nov 2011

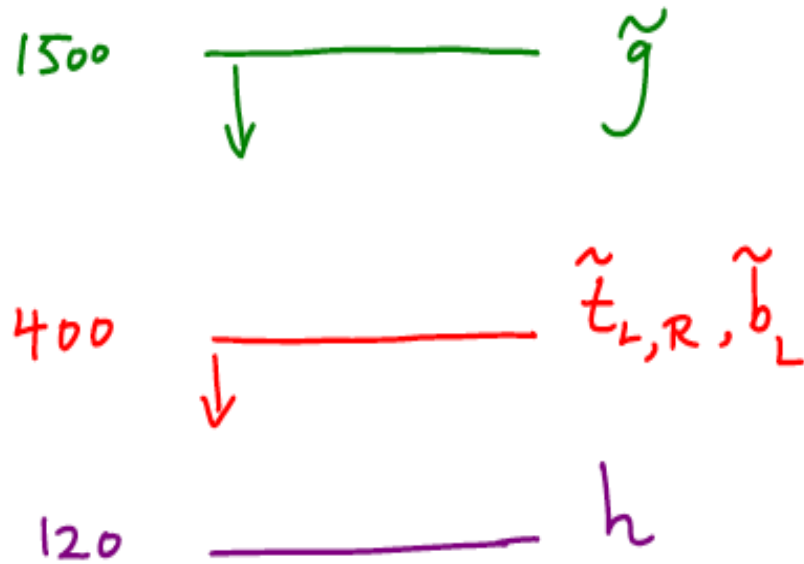
Papucci, Ruderman,  
Weiler arXiv:1110.6926

LHC data end 2011  
Stops > 200-300 GeV  
Glino > 600-800 GeV

Moving away from  
constrained SUSY models  
to 'natural' models

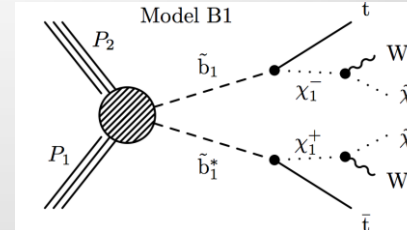
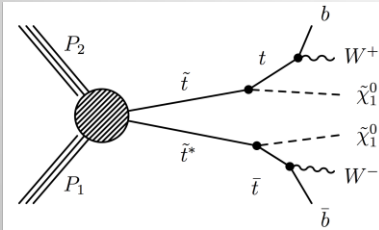
Natural SUSY survived  
LHC so far, but we  
are getting close to  
push it to its limits!

Compulsory Natural SUSY

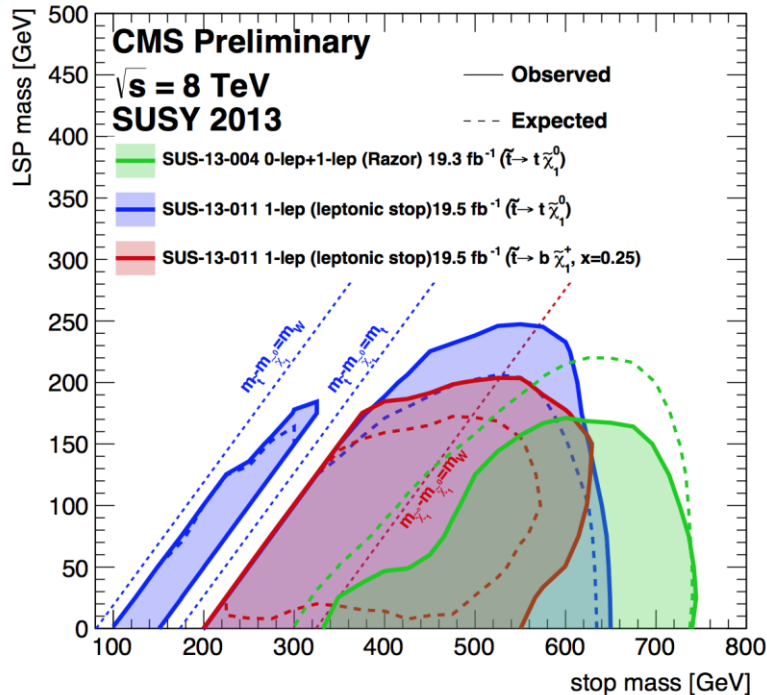


Unavoidable tunings:  $\left(\frac{400}{m_{\tilde{t}}}\right)^2$ ,  $\left(\frac{4m_{\tilde{t}}}{M_{\tilde{g}}}\right)^2$

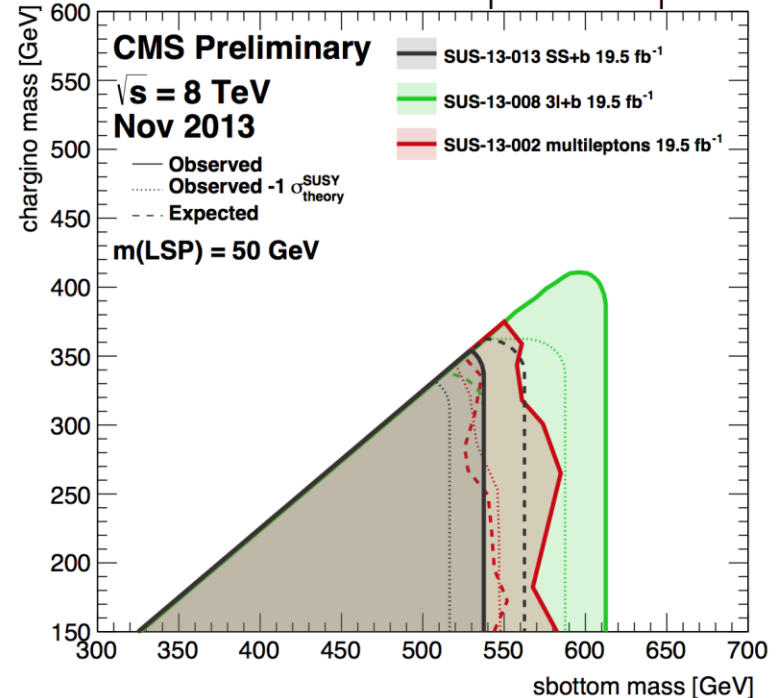
# Natural SUSY?



$\tilde{t}\text{-}\tilde{t}^*$  production



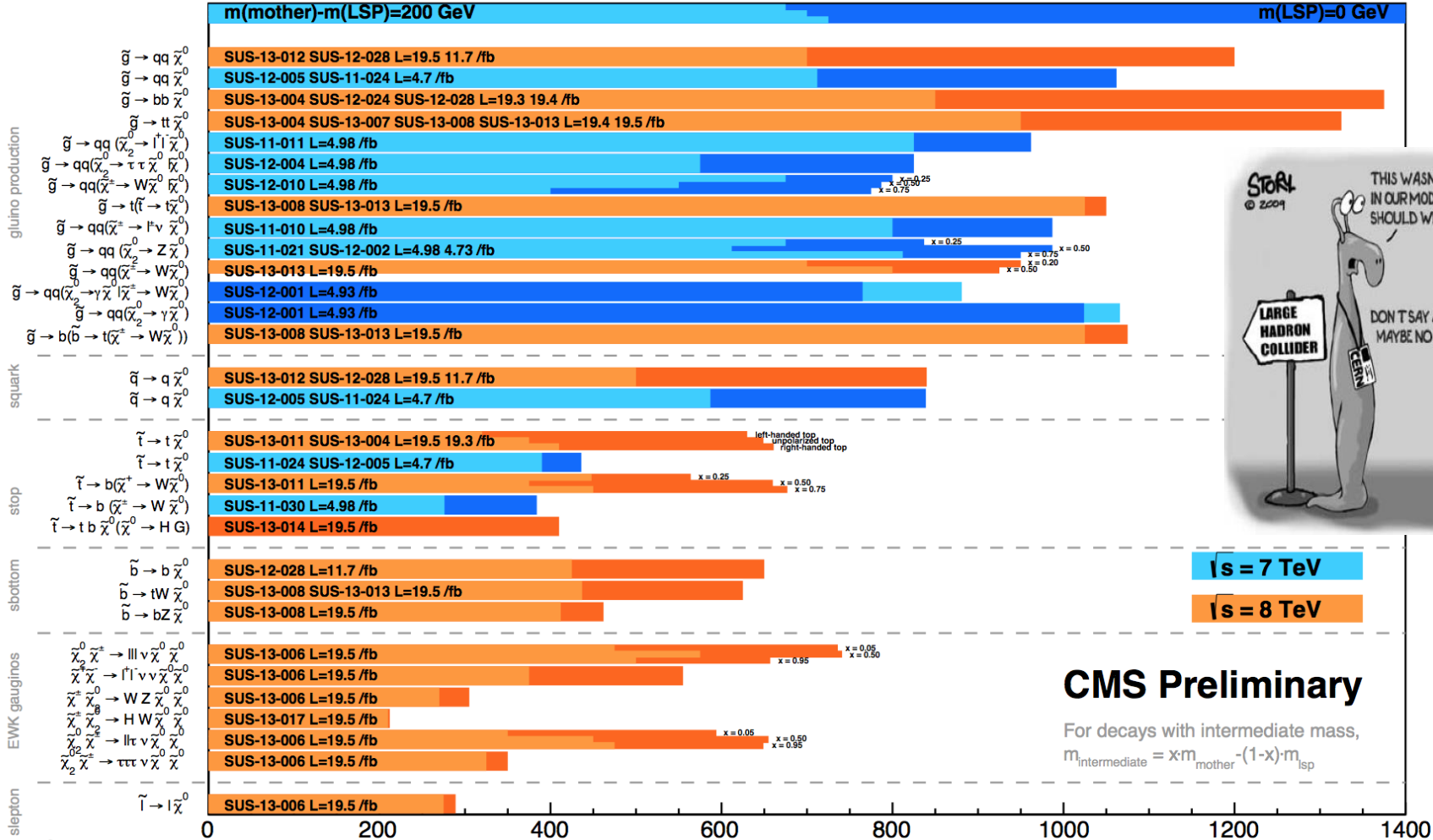
$\tilde{b}\text{-}\tilde{b}^*$  production,  $\tilde{b} \rightarrow t \tilde{\chi}_1^\pm \rightarrow t W^\pm \tilde{\chi}_1^0$



Limits now typically > 600-750 TeV for sbottom and stop  
 Natural models are getting under pressure!

# Summary of SUSY Searches

## Summary of CMS SUSY Results\* in SMS framework SUSY 2013



**CMS Preliminary**

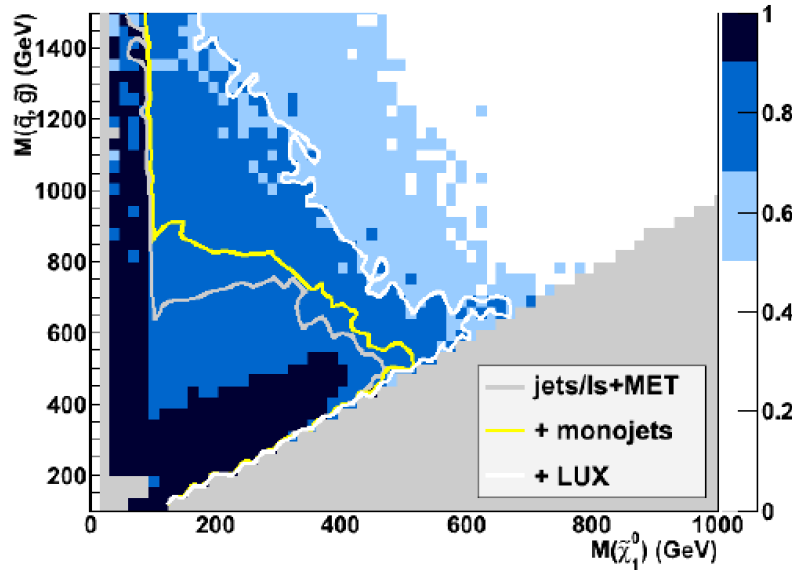
For decays with intermediate mass,  
 $m_{\text{intermediate}} = x m_{\text{mother}} - (1-x) m_{\text{LSP}}$

\*Observed limits, theory uncertainties not included  
 Only a selection of available mass limits  
 Probe \*up to\* the quoted mass limit

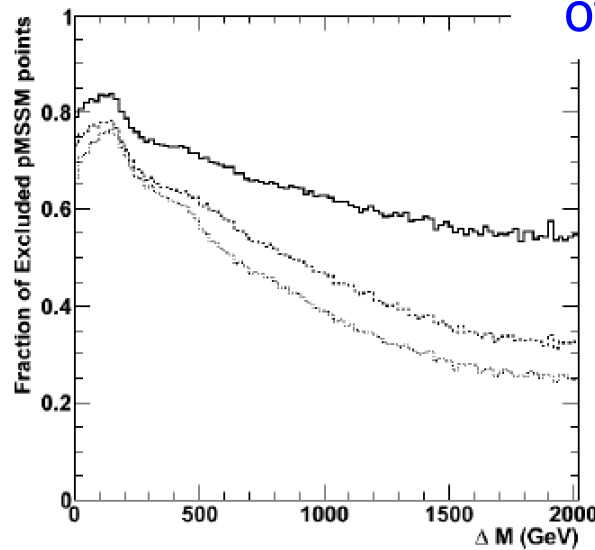
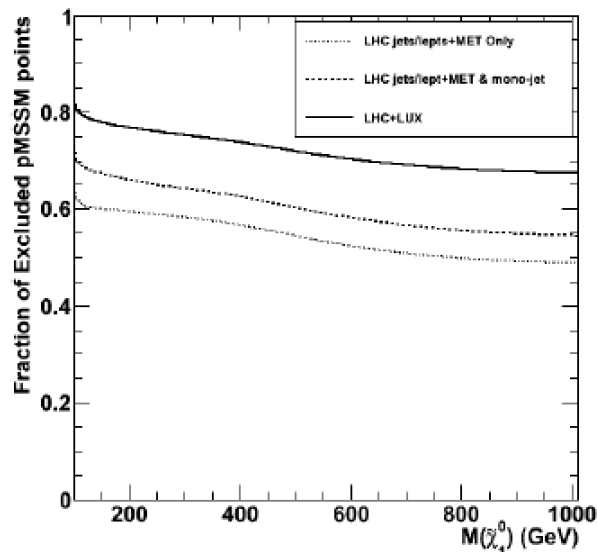
Mass scales [GeV]

# Dark Matter SUSY Space Left?

arXiv:1311.7641



- Use the pMSSM SUSY model (19 parameters)
- Use all the ATLAS SUSY Data + mono-jet searches + LUX DM results
- Check what fraction of pMSSM solutions that is excluded.
- No real full systematic study of the SUSY space yet

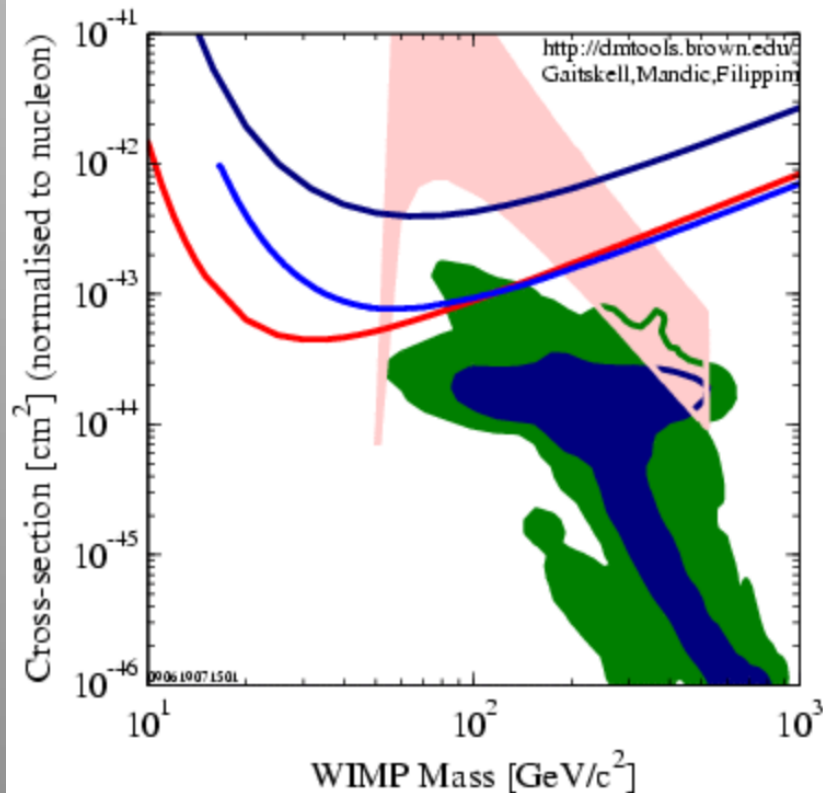


60-80% of the solutions excluded as function of the neutralino mass

# Constrained SUSY Models

O Buchmuller, ... ADR, Ellis... et al: arXiv:08084128

Study of the allowed DM space in CMSSM model



DATA listed top to bottom on plot  
CDMS (Soudan) 2004 Blind 53 raw kg-days Ge  
ZEPLIN III (Dec 2008) result  
XENON10 2007 (Net 136 kg-d)  
Ellis et al., Spin dep. sigma in CMSSM  
Trota et al 2008, CMSSM Bayesian: 68% contour  
Trota et al 2008, CMSSM Bayesian: 95% contour  
09061907150L

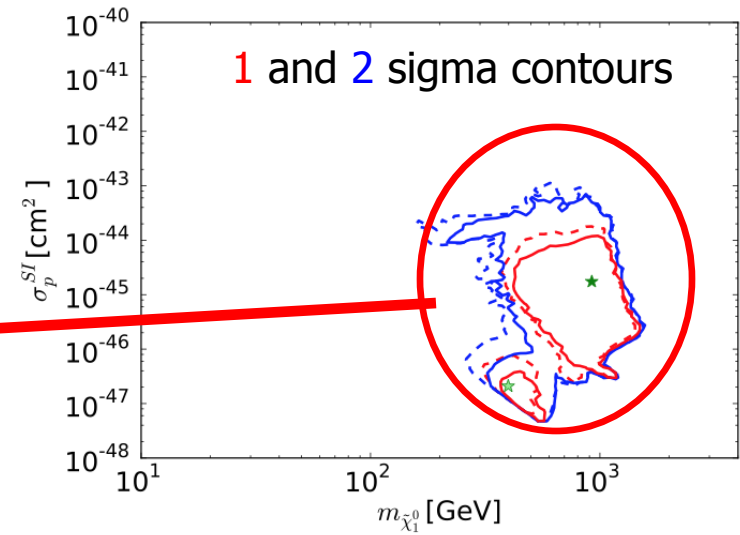
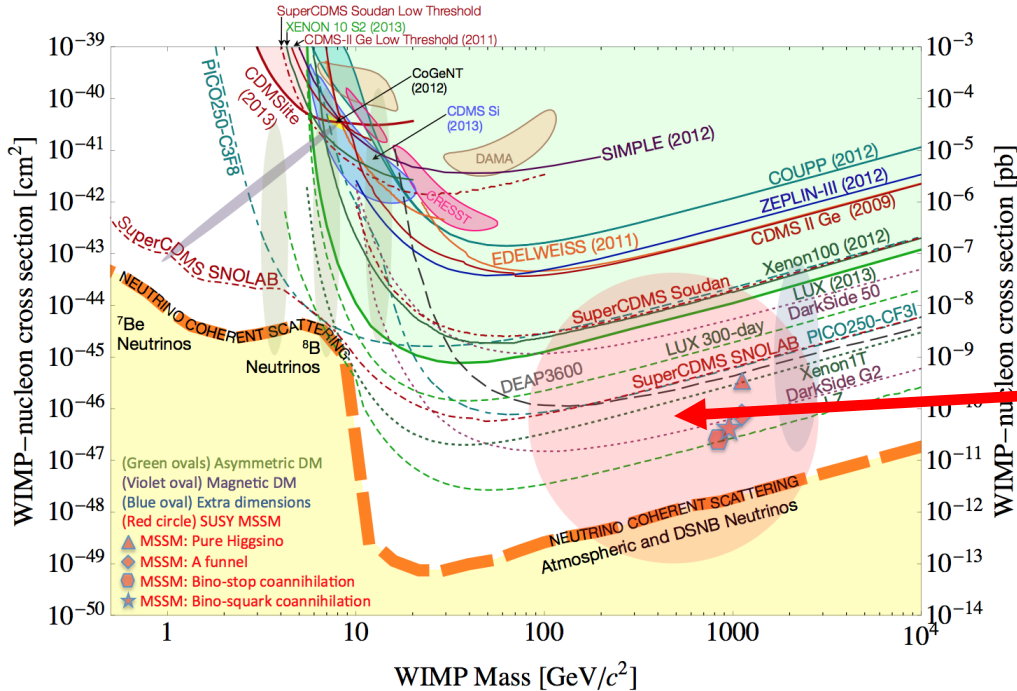
Region allowed in the CMSSM

includes constraints of the Run-I LHC searches (SUSY) and precision data, g-2, cold dark matter constraints...

# Constrained SUSY Models

O Buchmuller, ... ADR, Ellis... et al: arXiv:13125250

Study of the allowed DM space in CMSSM model

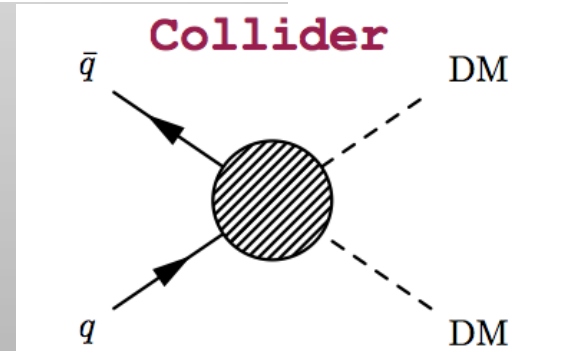
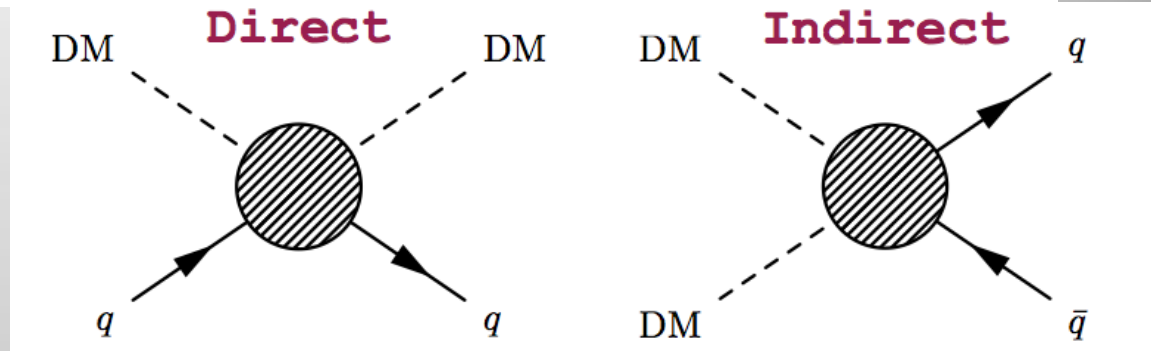
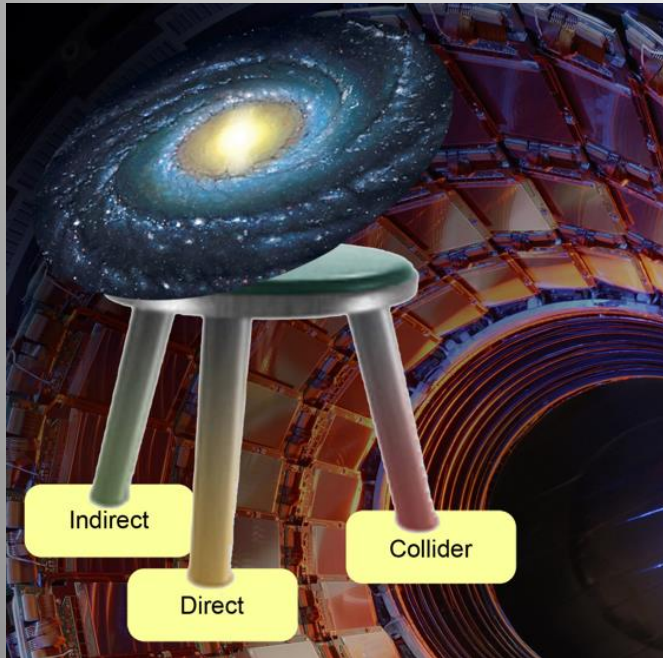


Region allowed in the CMSSM includes constraints of the Run-I LHC searches (SUSY) and precision data, g-2, cold dark matter constraints...

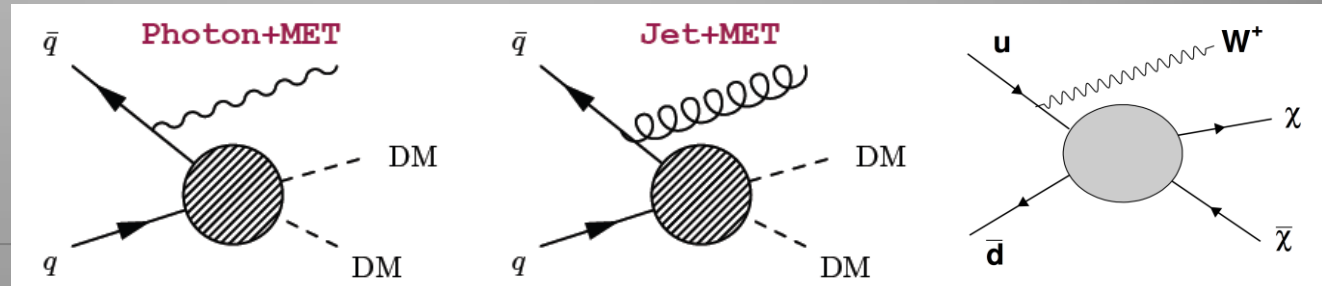
# General Searches for Dark Matter

# The Generic Dark Matter Connection

Searches for mono-jets and mono-photons can be used to search for Dark Matter (DM)



Use effective theory or simplified models to relate measurements to Dark Matter studies

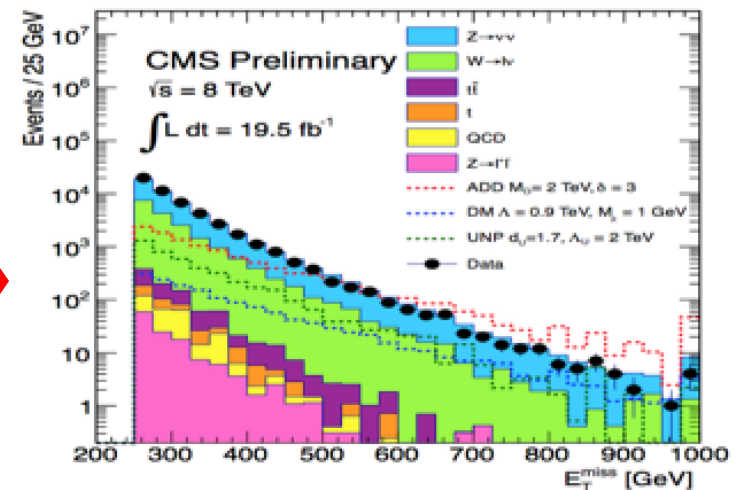
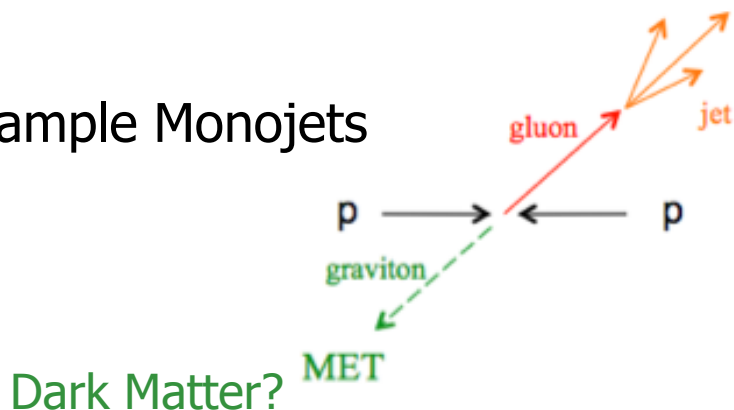




# Mono-object Searches in CMS

- **Mono-jets:** Generally the most powerful
- **Monophotons:** First used for dark matter Searches
- **Mono-Ws:** Distinguish dark matter couplings to u- and d-type of quarks
- **Mono-Zs:** Clean signature
- **Mono-Tops:** Couplings to tops
- **Mono-Higgs:** Higgs portal of dark matter

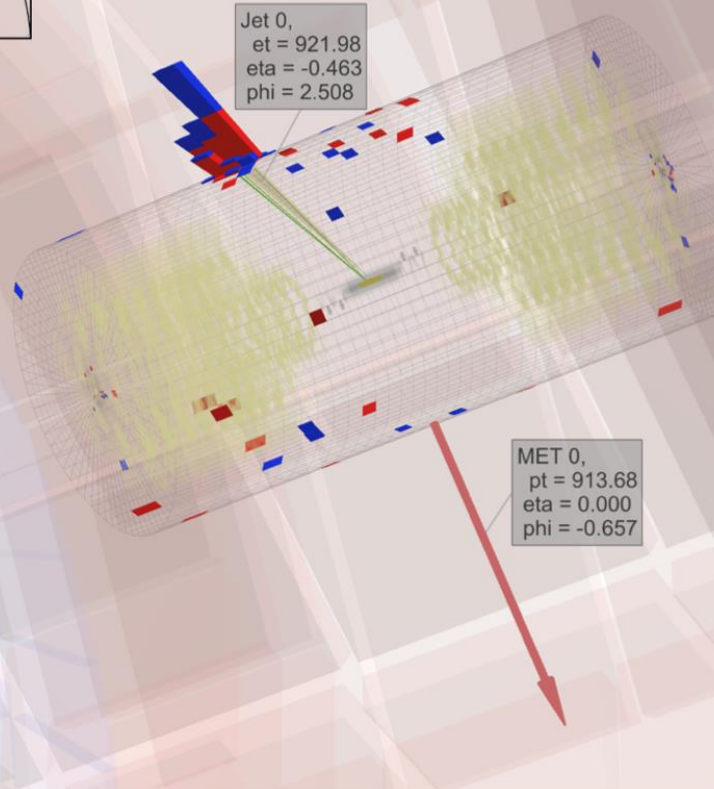
## Example Monojets



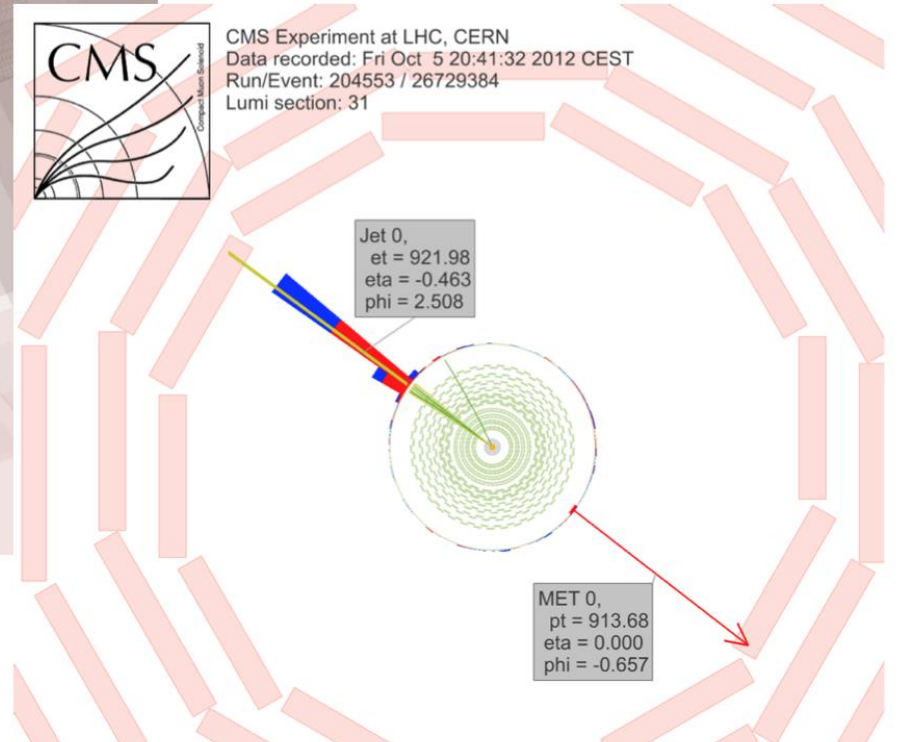
# Mono-Jet Event



CMS Experiment at LHC, CERN  
Data recorded: Fri Oct 5 20:41:32 2012 CEST  
Run/Event: 204553 / 26729384  
Lumi section: 31



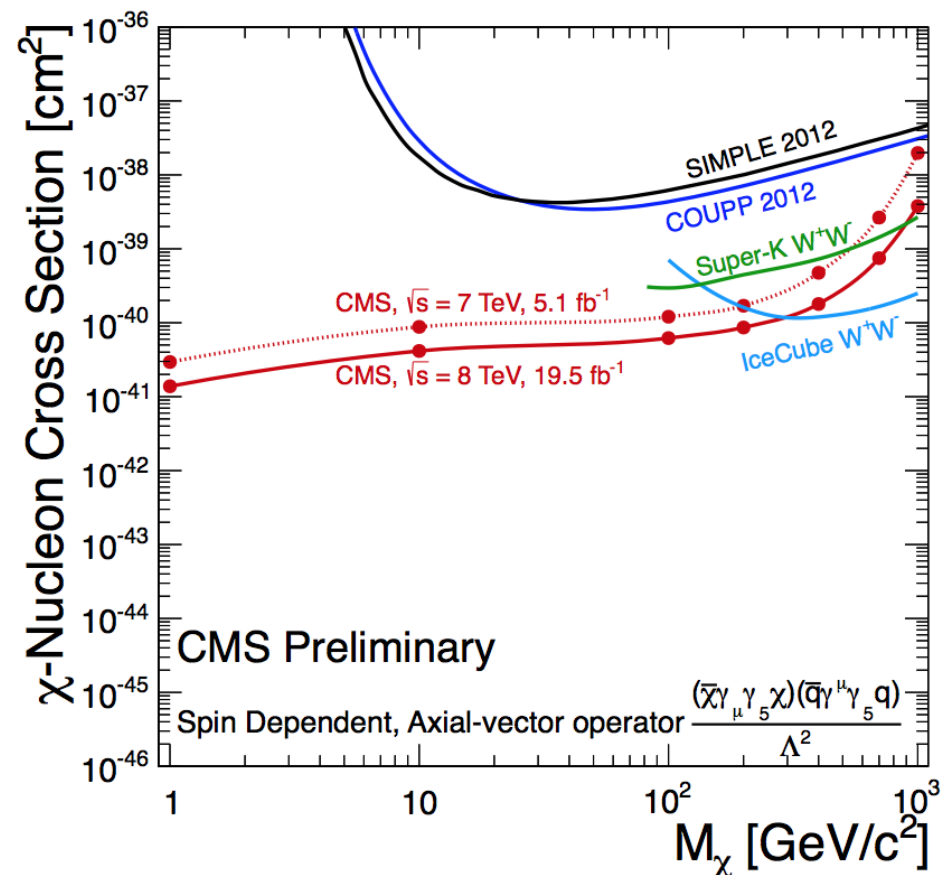
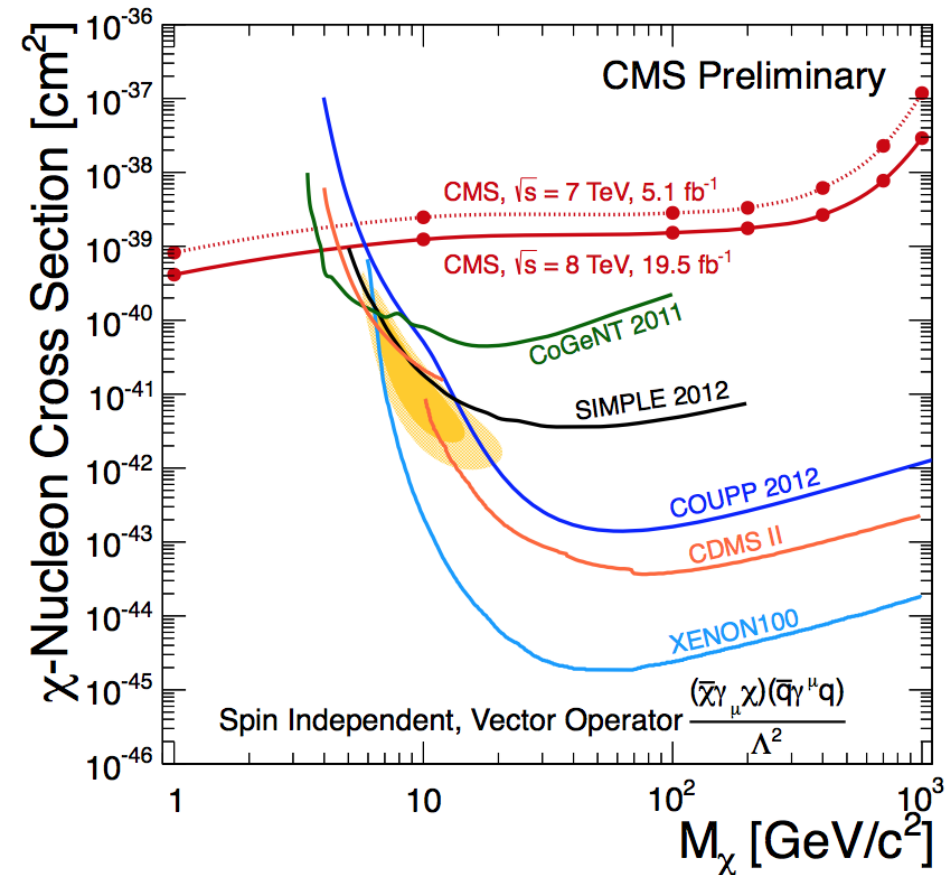
CMS Experiment at LHC, CERN  
Data recorded: Fri Oct 5 20:41:32 2012 CEST  
Run/Event: 204553 / 26729384  
Lumi section: 31



# Results for Mono-jets

[CMS EXO-12-048]

- Derived EFT limits then compared to direct-detection experiments
- CMS results improved with 8 TeV (higher E, more data)



# Summary

- Dark Matter is an important open point in fundamental physics right now and the LHC data can contribute to the quest.
- The Higgs particle may couple to DM or may even decay into it. Invisible decays and deviations from SM Higgs couplings are explored
- Supersymmetry scenarios with  $R_p$ -conservation can have a natural DM candidate. Discovery of supersymmetry will have important impact on DM
- Generic searches for DM in analyses dealing with missing  $E_T$ : typically mono-object searches
- So far exclusion limits only, but maybe soon:

