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

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19th November 2014

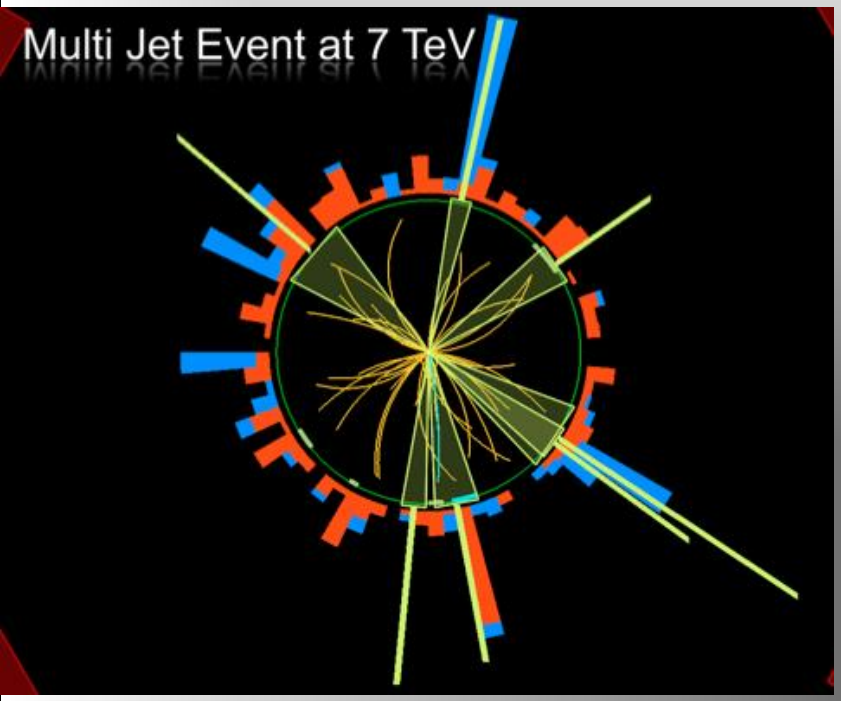
The Abdus Salam International Centre for Theoretical Physics
50th Anniversary 1964–2014

ICTP-NCP School on LHC Physics
17 – 28 November 2014
(Islamabad, Pakistan)

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’



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

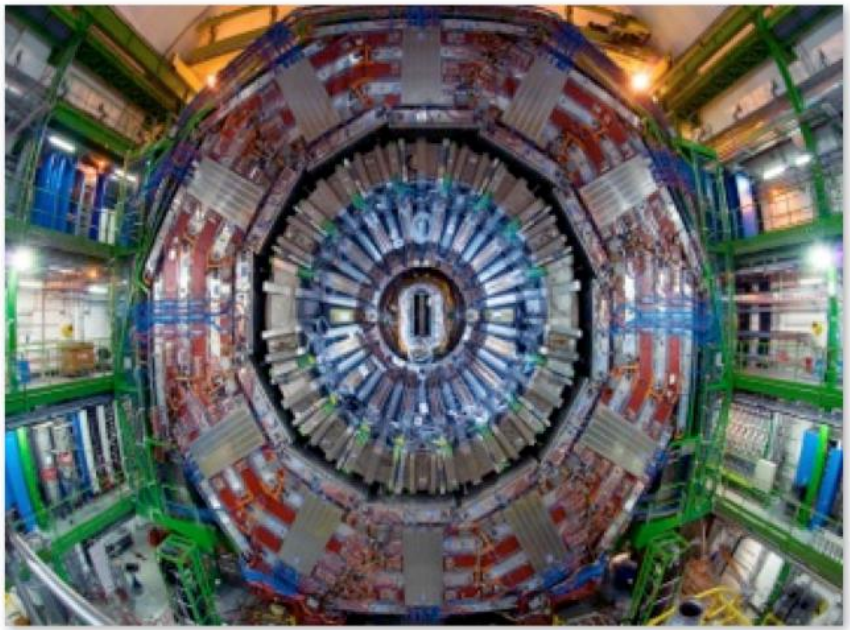
Dark Matter: Complementary Searches?

This Lecture:

After the discovery of the Higgs particle @ the LHC:

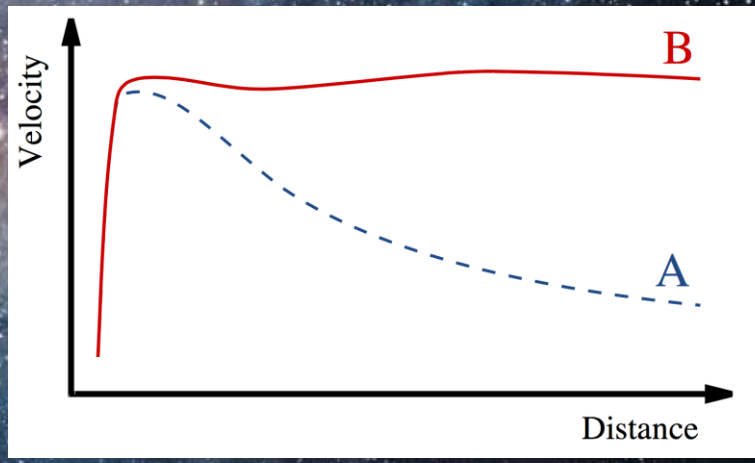
Dark matter is the next important physics problems to tackle for the LHC

The search is complementary to other experimental techniques used.



Dark Matter: The Next Challenge

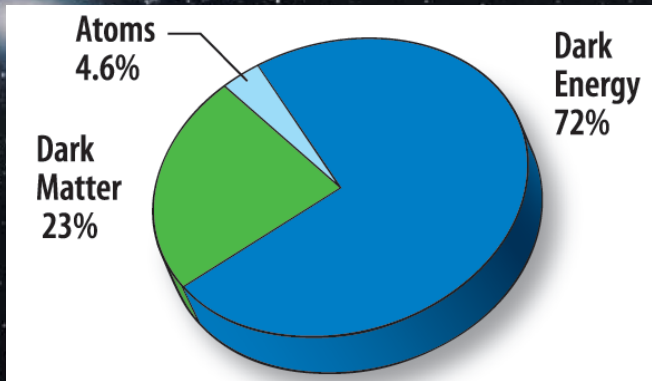
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



'Supersymmetric' particles ?

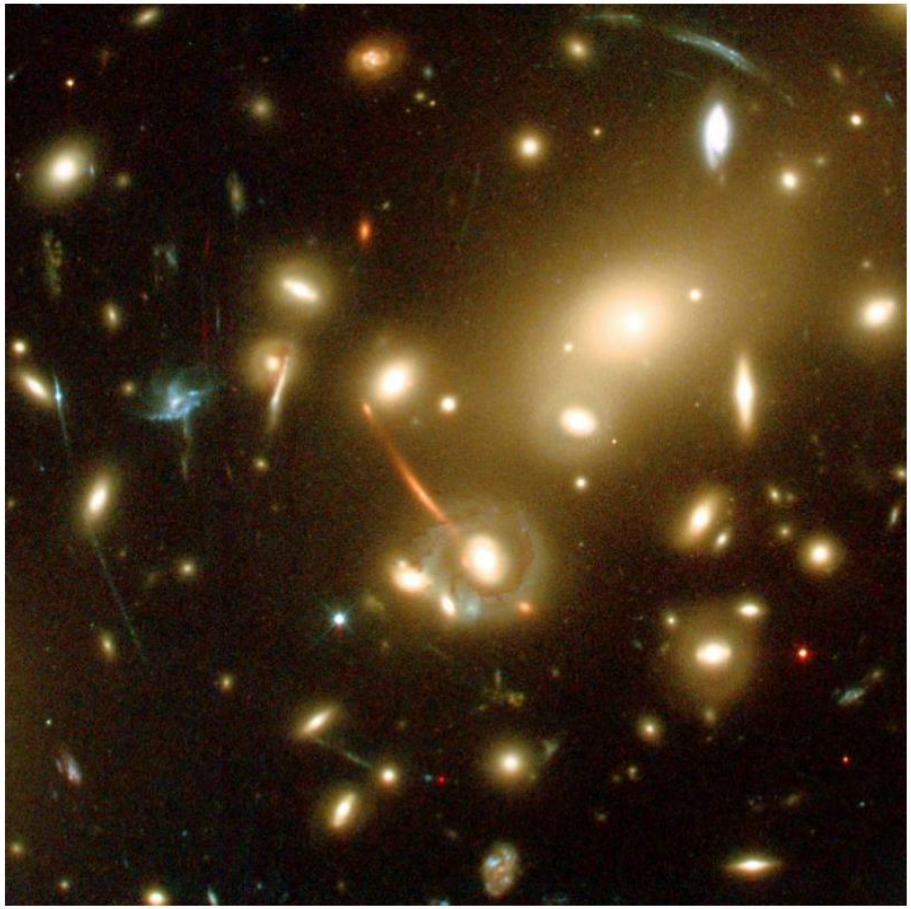

F. Zwicky 1898-1974


Vera Rubin ~ 1970

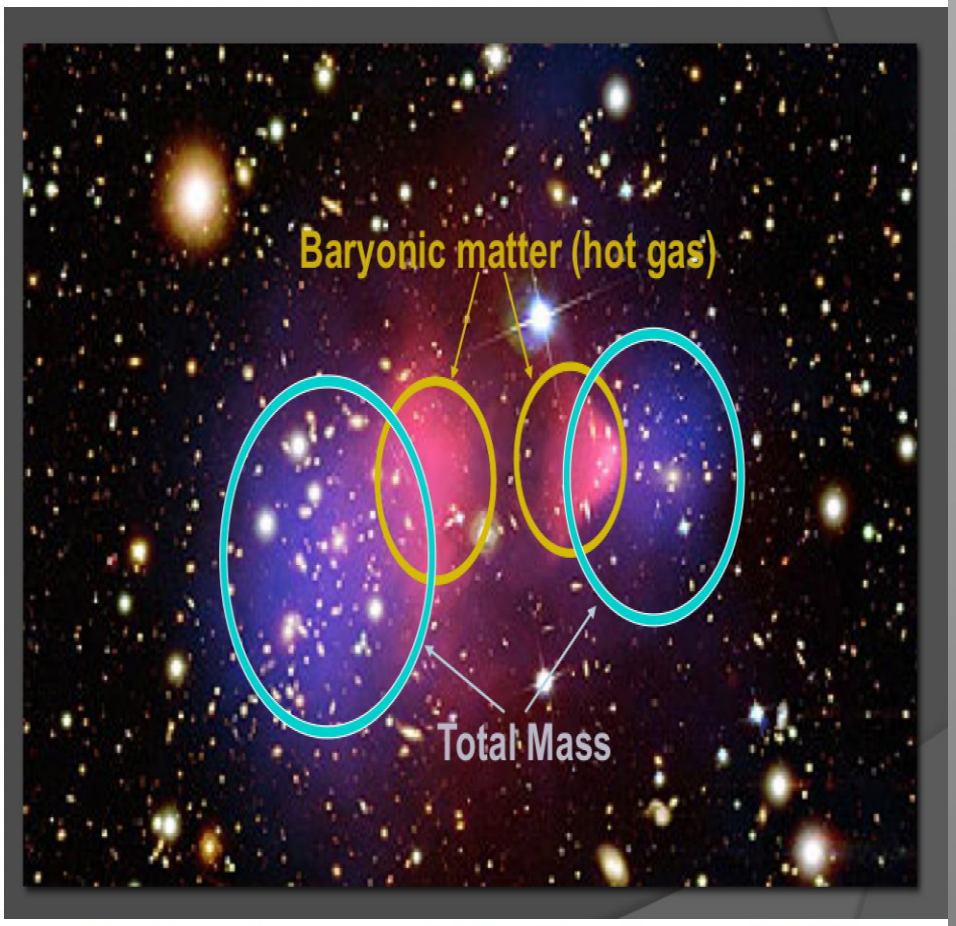


Evidence Piling-up

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

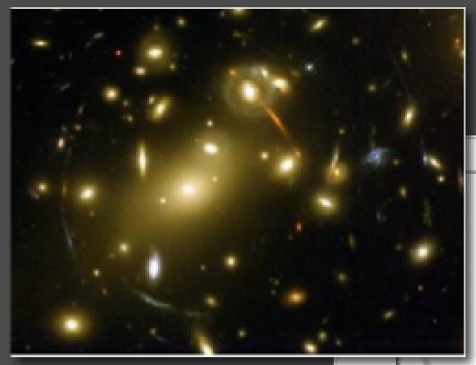


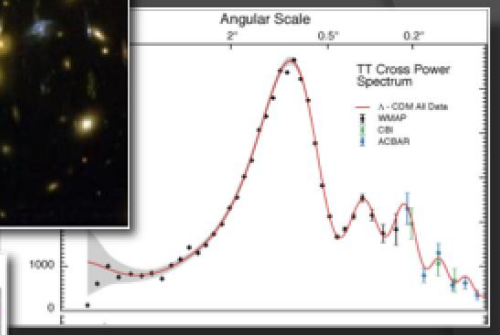
- Bullet Cluster; colliding galaxies
  - Composite x-ray, visible image, 10x DM

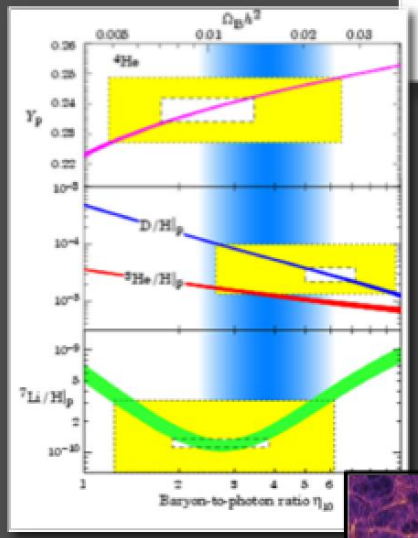


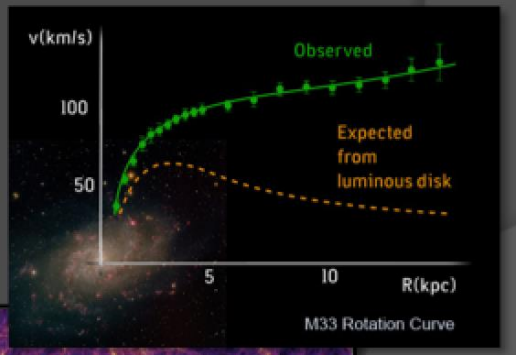
Evidence Piling-up

- 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”

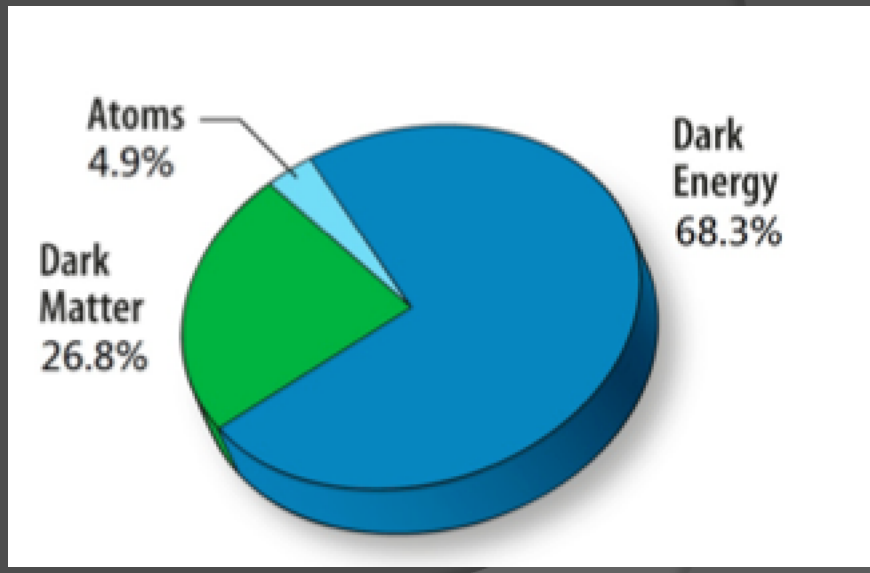
The observed density of dark matter is of the magnitude expected for a thermal relic weakly-interacting massive (~10-1000 GeV) particle (WIMP).

Particle Dark Matter?

The Dark Matter Candidate Zoo

From D. Hooper

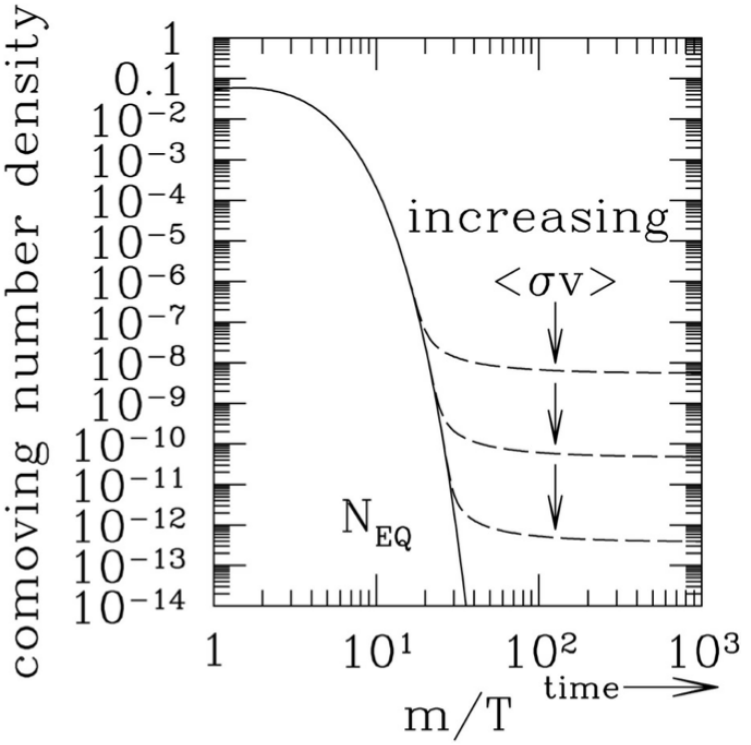
- Neutralinos (higgsino, bins, winos, singlinos)
- Axinos
- Gravitinos
- Sneutrinos
- Axions
- Sterile neutrinos
- 4th generation neutrinos
- Kaluza-Klein photons
- Kaluza-Klein gravitons
- Brane world dark matter/D-matter
- Little higgs dark matter
- Light scalars
- Superheavy states (*ie*. "WIMPzillas")
- 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 (<σv>) yields lower relic density

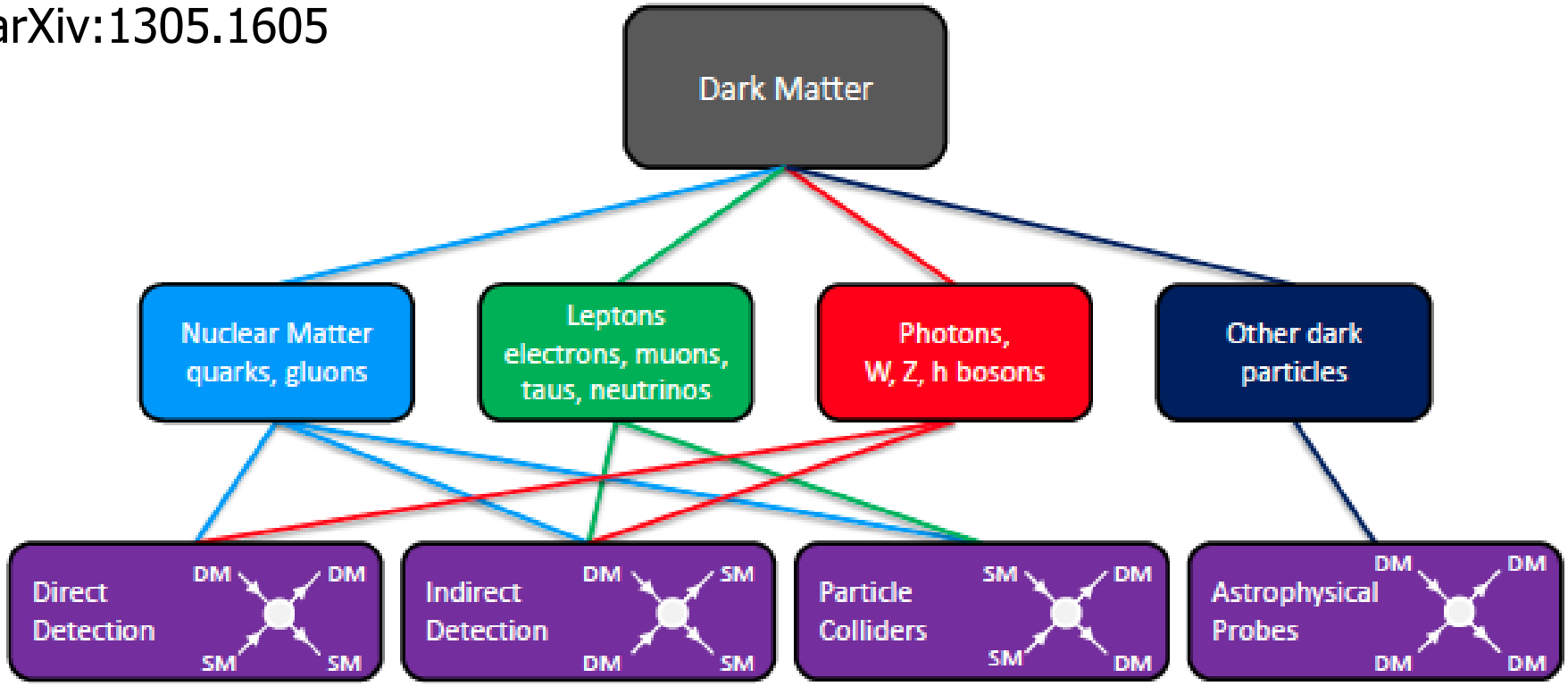


Weakly-interacting massive particles naturally provide the right relic abundance - "WIMP miracle"

Dark Matter @ LHC?

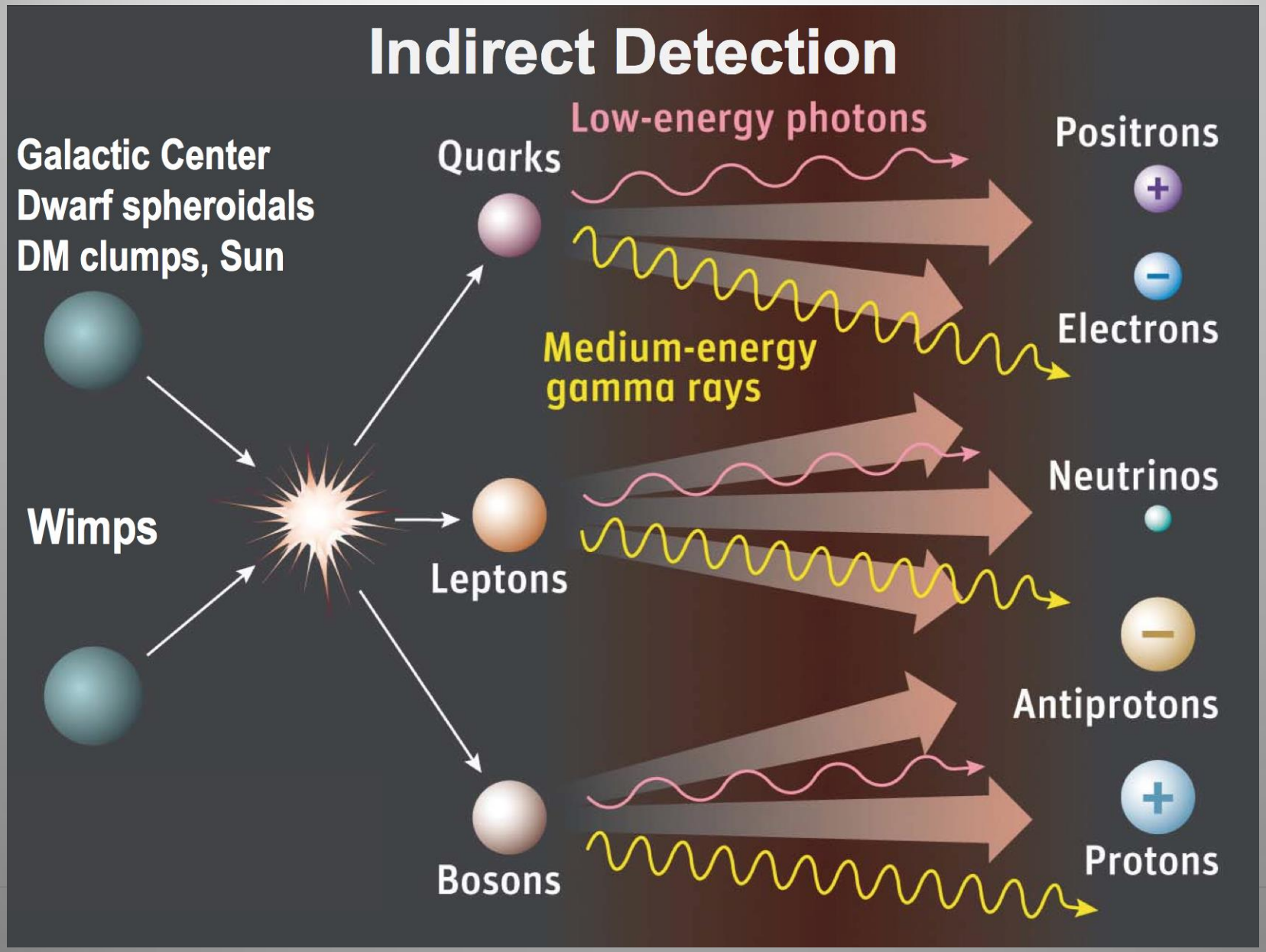
Search for WIMP candidates in events with Missing Transverse Momentum
EG: SUSY searches, monojet and mono-photon searches, W' searches…

arXiv:1305.1605

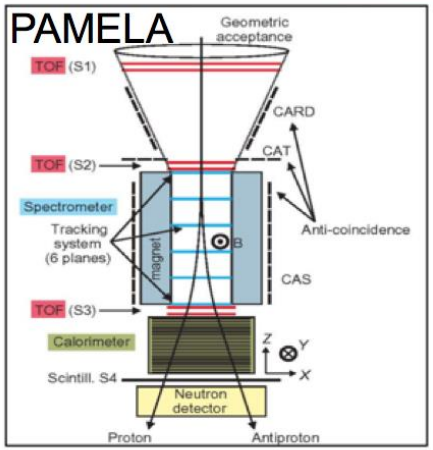


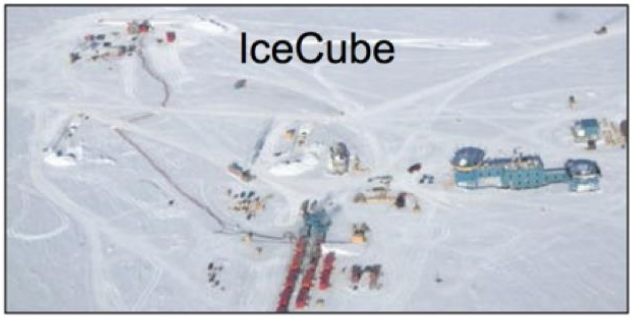
+ CAST experiment, searching for axion DM

Dark Matter: Indirect Detection



Indirect Detection Experiments





Indirect Detection

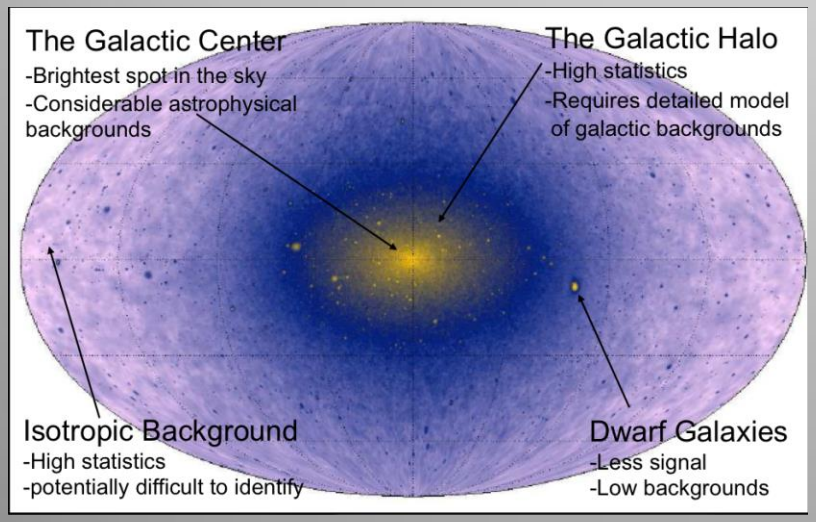
Some scientists are believers!!

arXiv:1402.6703v1

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

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

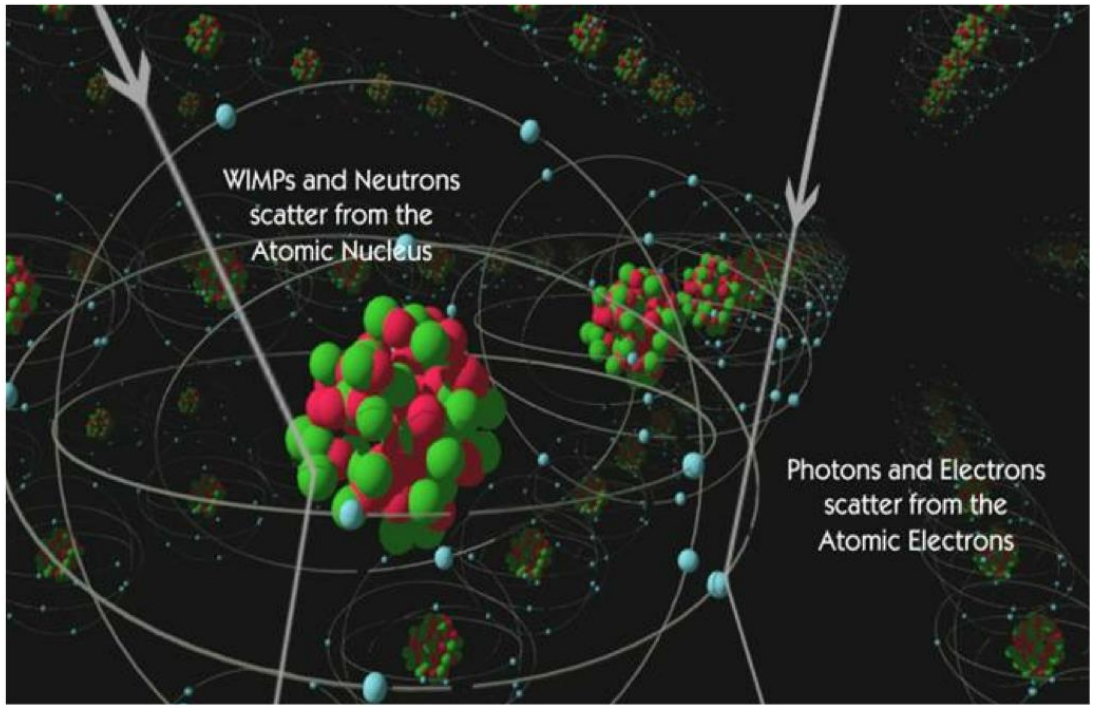
Using gamma-ray data from the FERMI satellite
DM annihilation into b anti-b quarks?



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

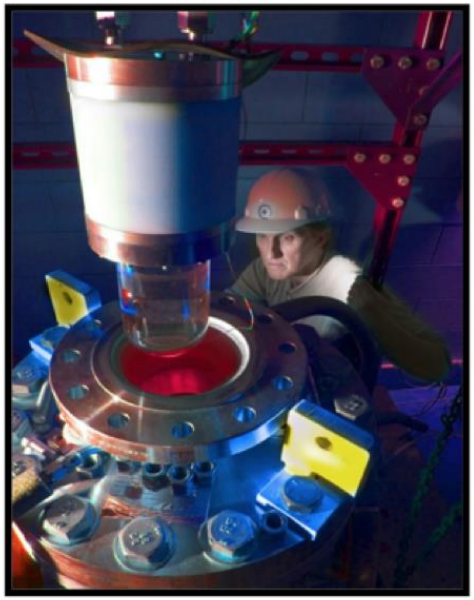
Dark Matter: Direct Detection

- 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...

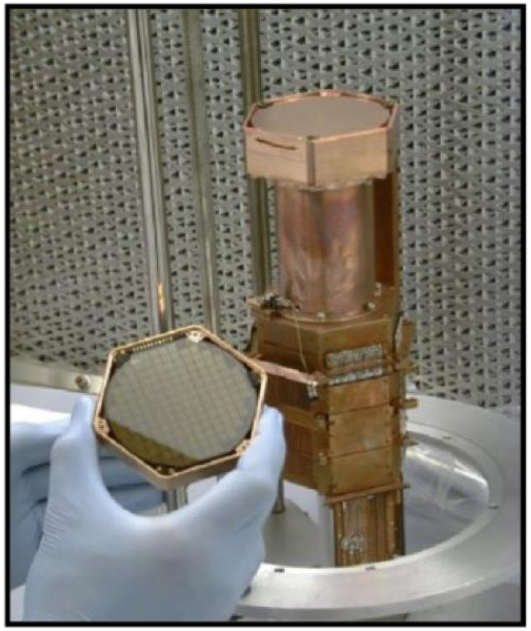


Direct Detection: Examples

COUPP

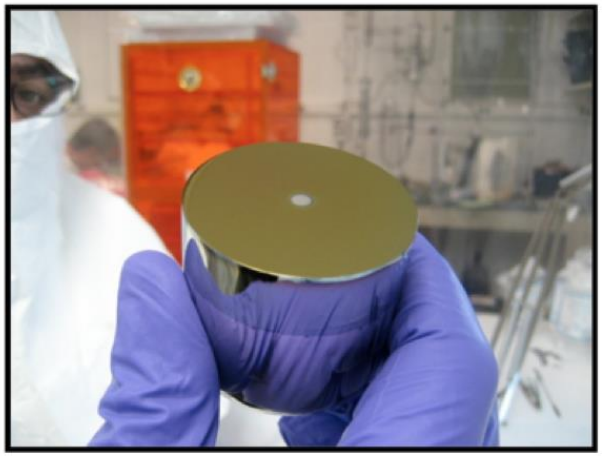


CDMS



CRESST

CoGeNT

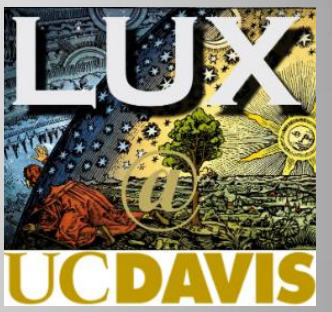


(+ EDELWEISS, DAMA, EURECA, ZEPLIN, DEAP, ArDM, WARP, LUX, SIMPLE, PICASSO, DMTPC, DRIFT, KIMS, …)

Xenon

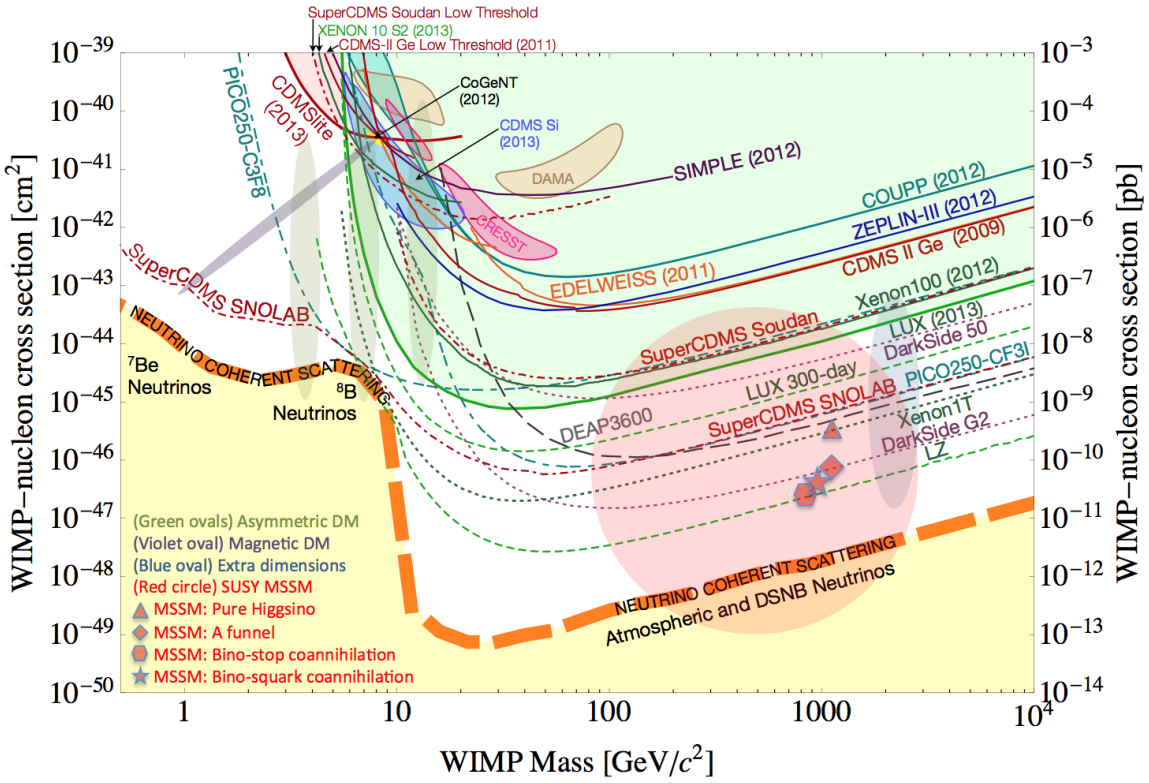
Direct Searches for Dark Matter

State of the art today:
Driven by the results of the LUX experiment



Intensive campaign of direct detection experiments since more than ~20 years

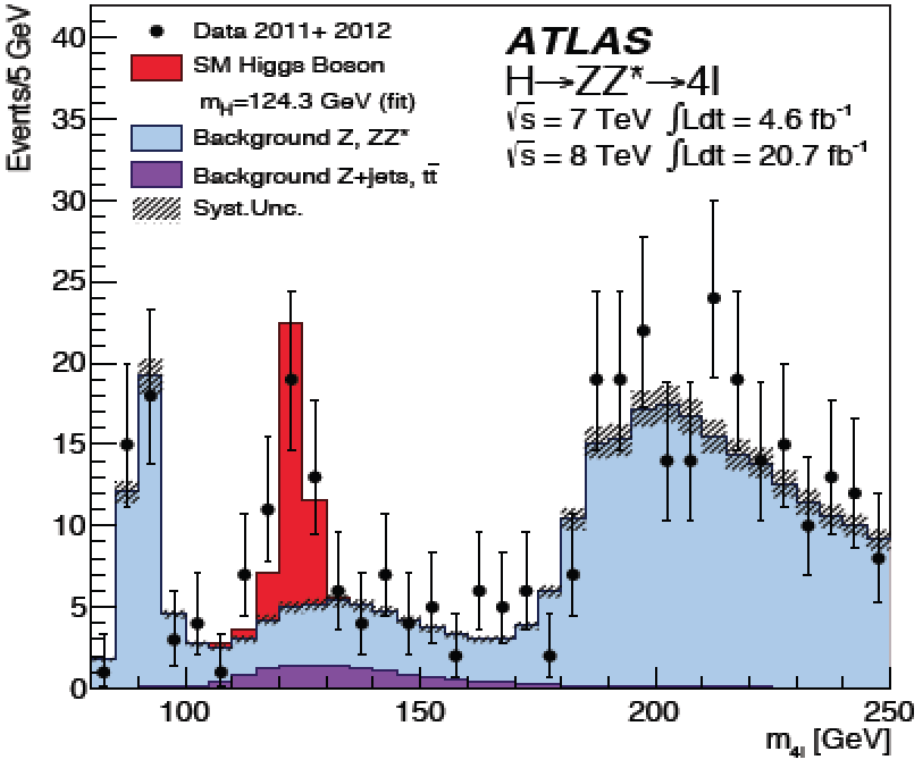
No (real) sign so far...

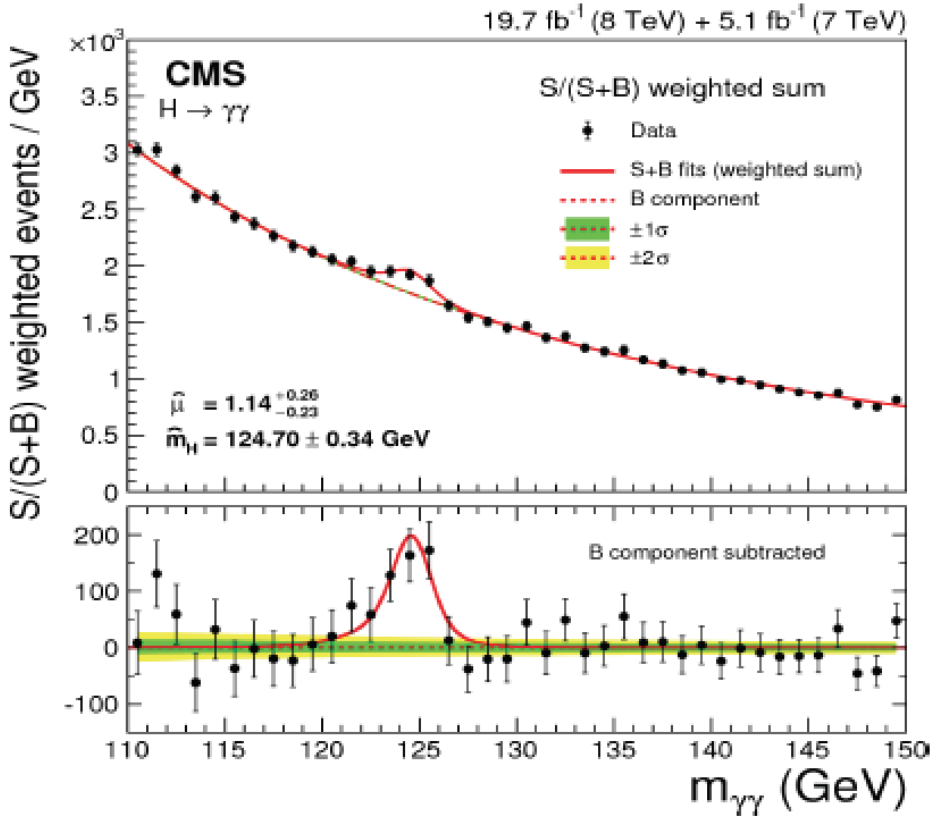


The LHC

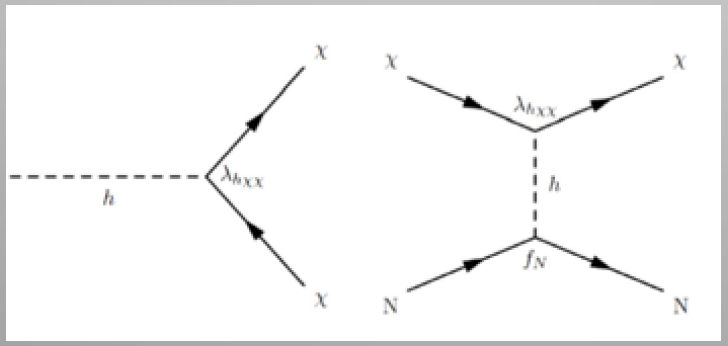
The Higgs Discovery

- Our shiny new Boson!



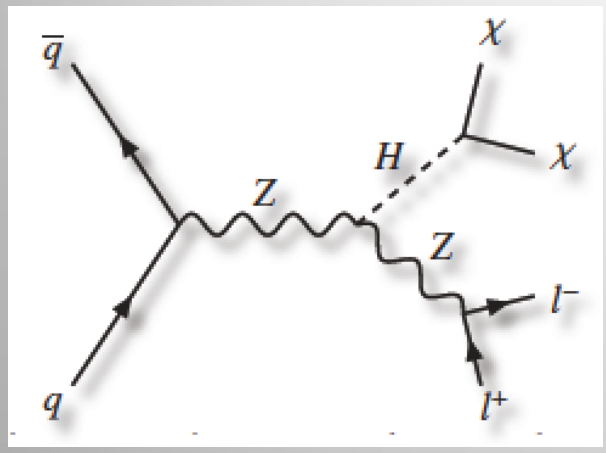


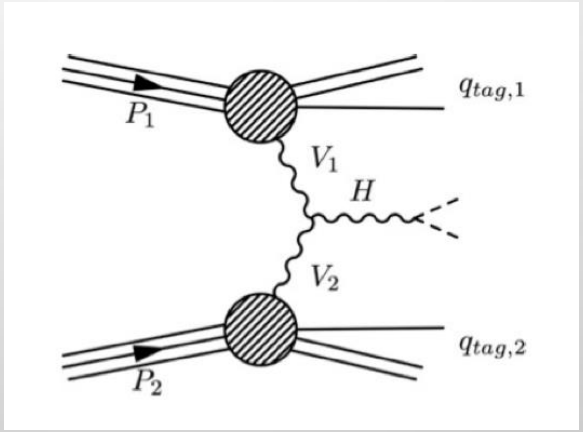
Dark Matter and the Higgs



"higgs portal models"
Eg: arXiv:1205.3169

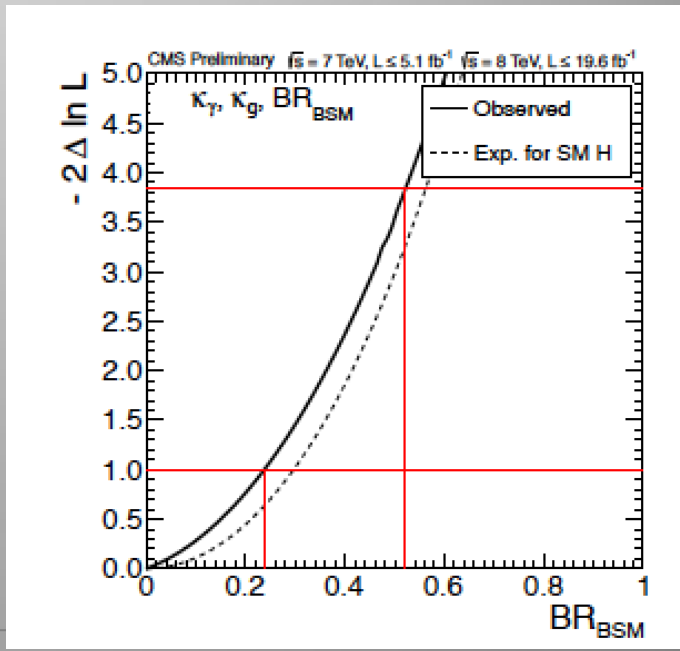
Invisible Higgs Decay Channel



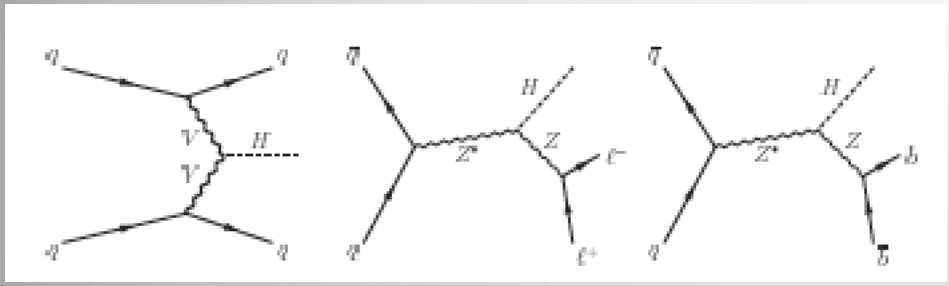


CMS-PAS-HIG-13-005

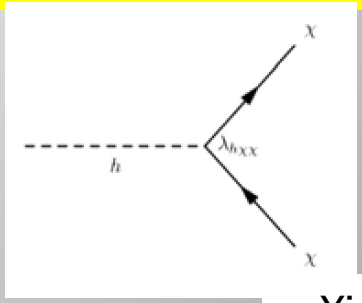
- Possible decay of the Higgs in Dark Matter particles (if $M<M_H/2$)
- Different searches:
  - -Direct search
    Look for the invisible decay channels
  - -Indirect search
    Make a global fit of all production and decays (and some modest assumptions)



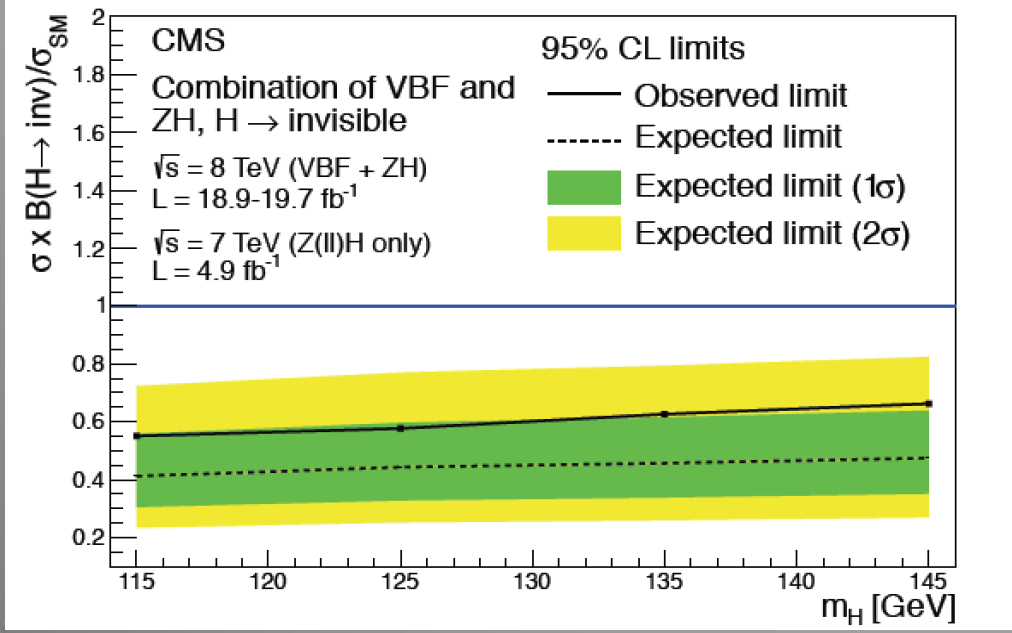
Invisible Higgs Decay Channel



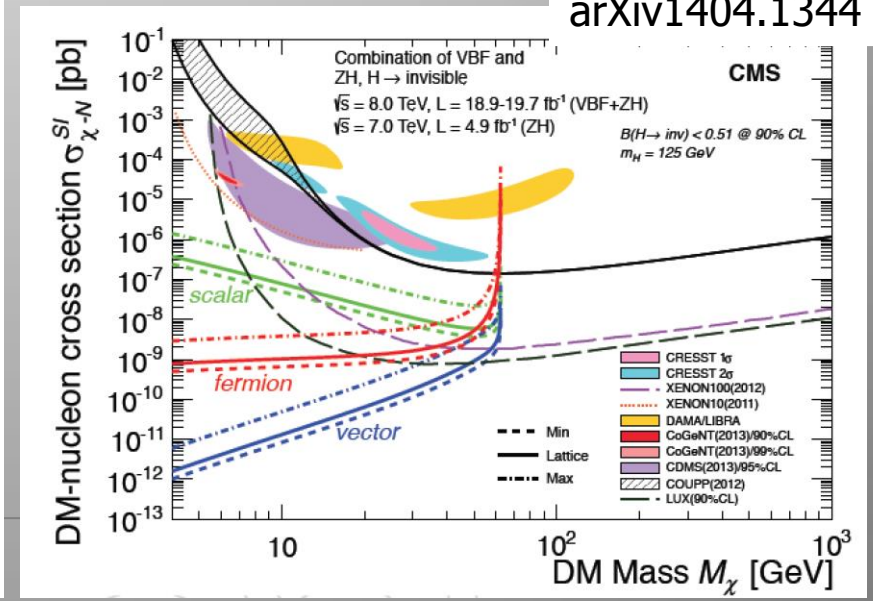
Search for invisible Higgs decays using
Z+H → 2 leptons + missing E_T
VBF H → 2 jets + missing E_T
Possible decay in Dark Matter particles
(if $M<M_H/2$): Higgs Portal Models



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



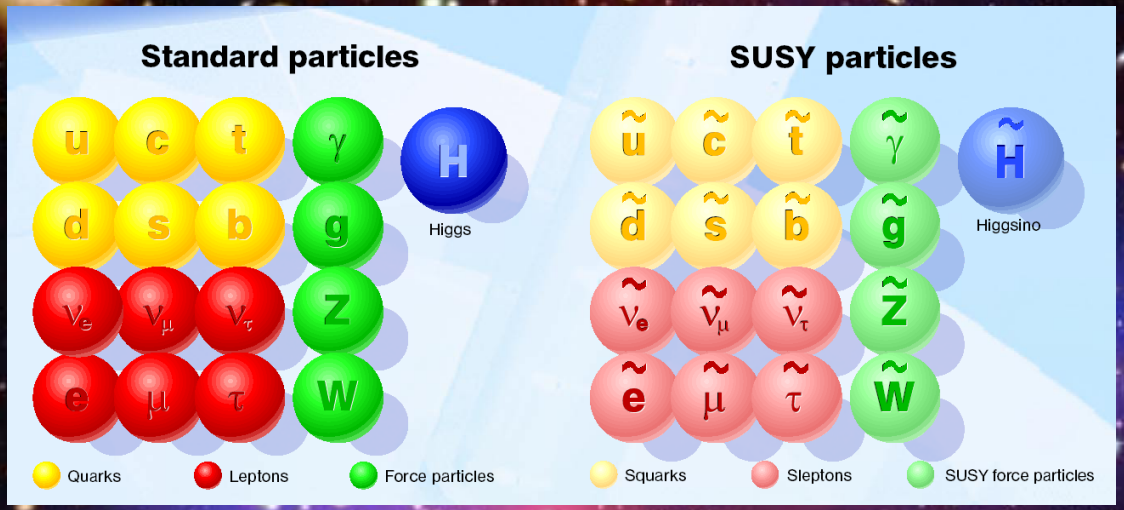
arXiv1404.1344

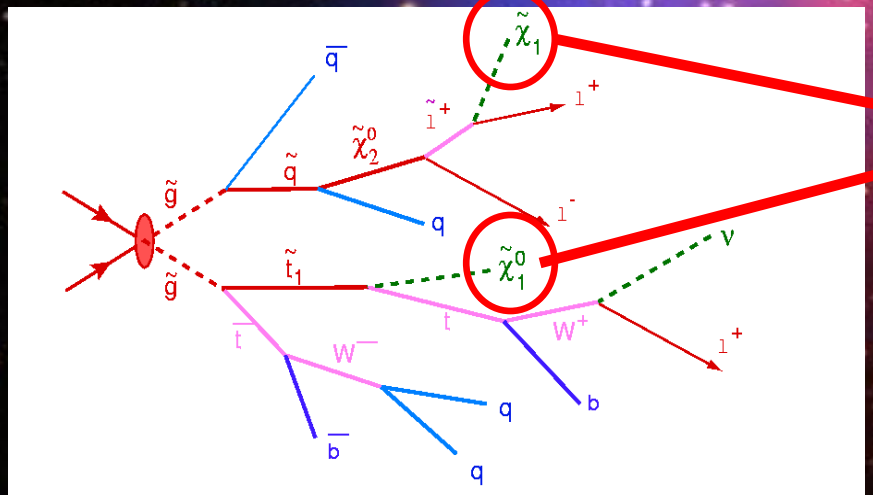


Searches for Supersymmetry

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?



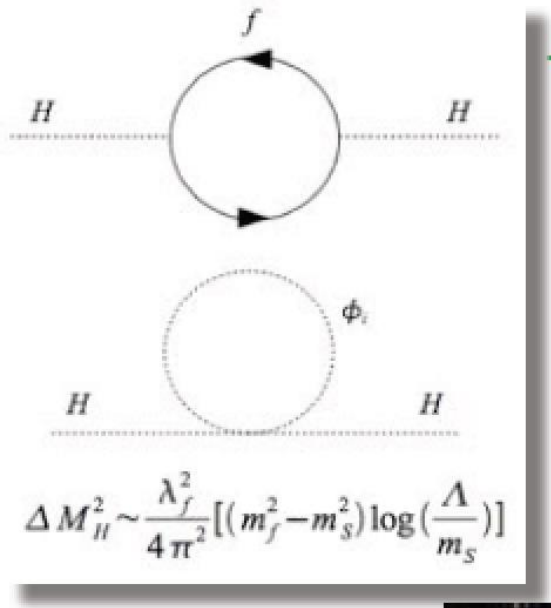


SUSY particle production at the LHC

Candidate particles for Dark Matter
⇒ Produce Dark Matter in the lab

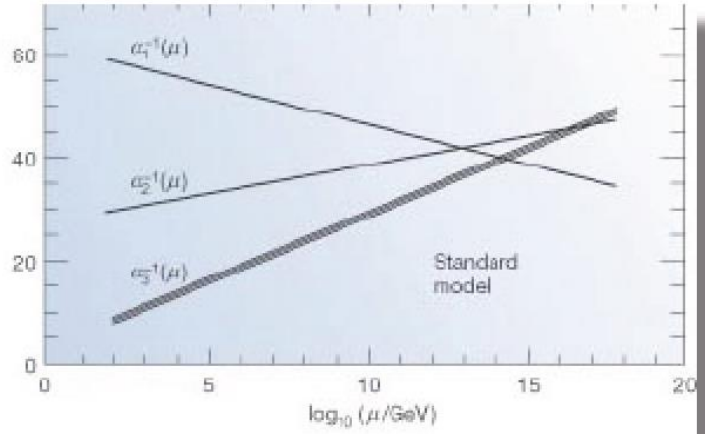
Picture from Marusa Bradac

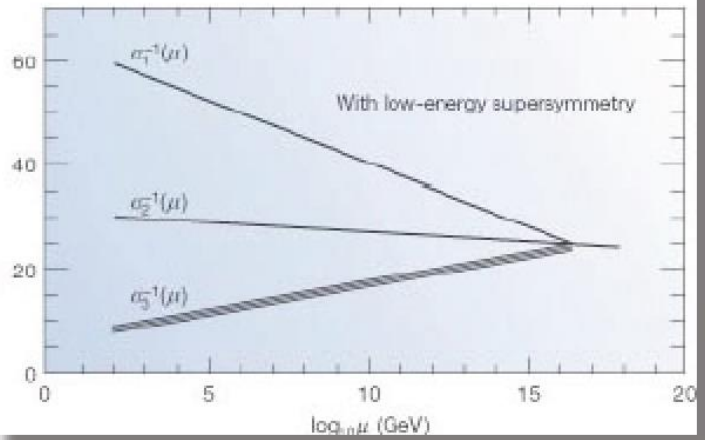
Summary: Why SUSY is good for you!!



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

- Gauge unification

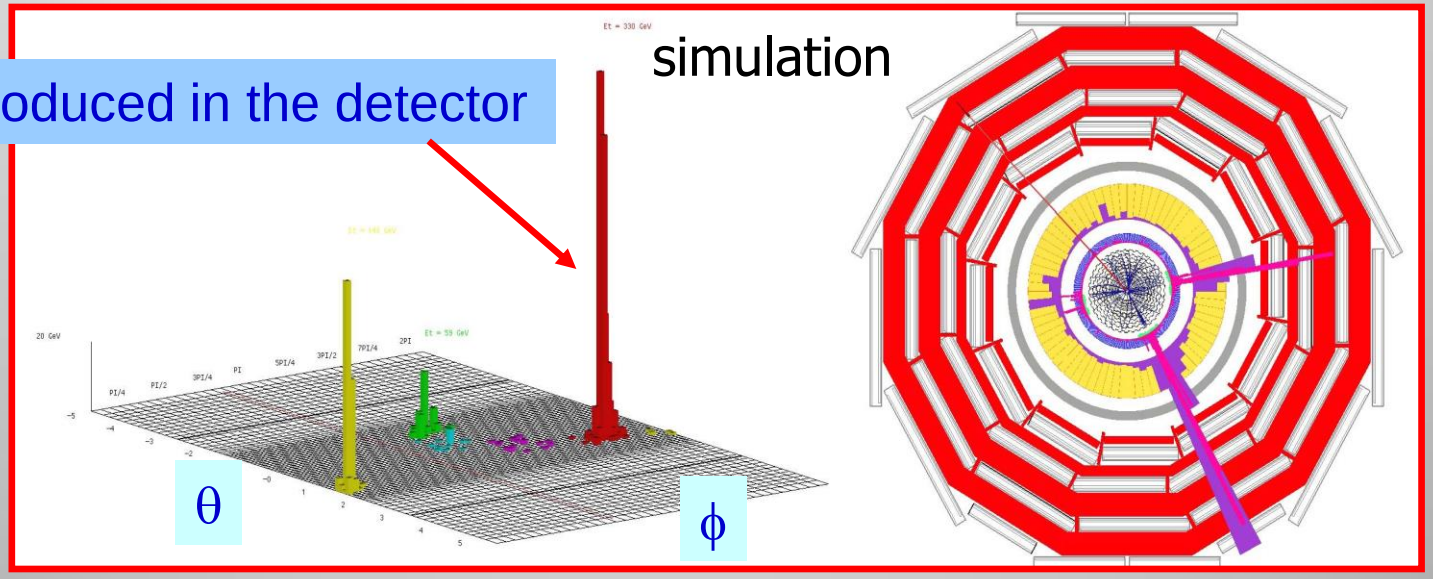


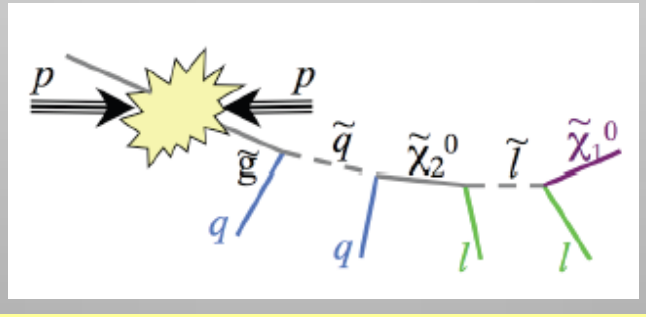


- Dark matter candidate with the right abundance

Detecting Supersymmetric Particles

Energy produced in the detector





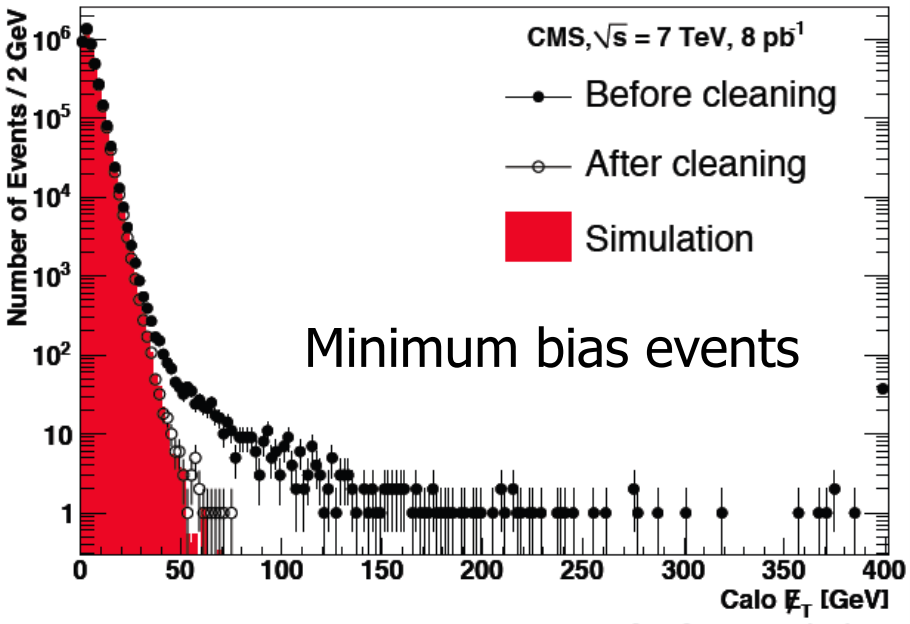
Supersymmetric particles decay and produce a cascade of jets, leptons and missing transverse energy (MET) due to escaping ‘dark matter’ particle candidates

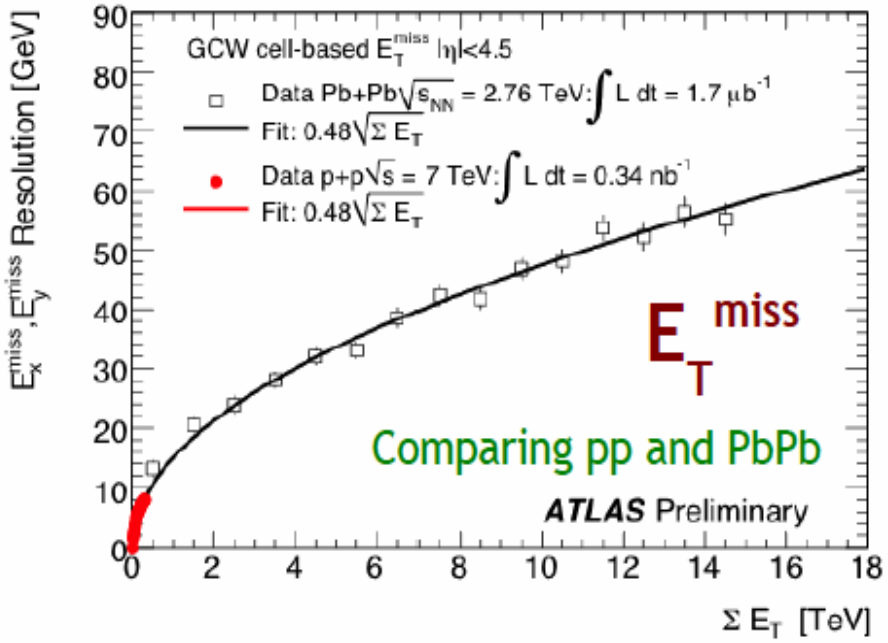
Very prominent signatures in CMS and ATLAS

Missing Transverse Energy

Total transverse momentum imbalance

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



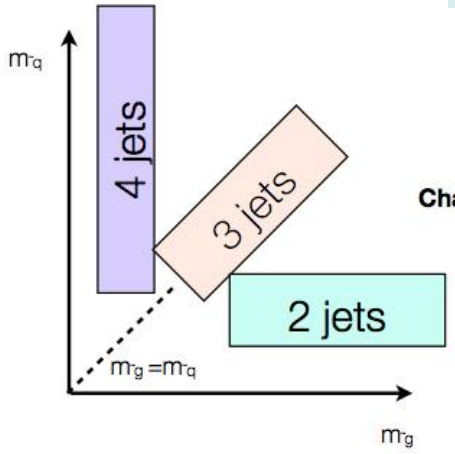


- In practice, rather well under control, from the start
- Good resolution using 'particle flow' ie maximally identifying particles
- More pile-up in future will NOT make this simpler

SUSY 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

All Analyses (CMS)



JET+MET (ATLAS)

	Signal Region	≥ 2 jets	≥ 3 jets	≥ 4 jets	High mass
Trigger requirements	E_T^{miss}	> 130	> 130	> 130	> 130
	Leading jet p_T	> 130	> 130	> 130	> 130
Channel definition	Second jet p_T	> 40	> 40	> 40	> 80
	Third jet p_T	–	> 40	> 40	> 80
	Fourth jet p_T	–	–	> 40	> 80
Reduce QCD	$\Delta\phi(\text{jet}, E_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
	E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25	> 0.2
Enhance signal	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

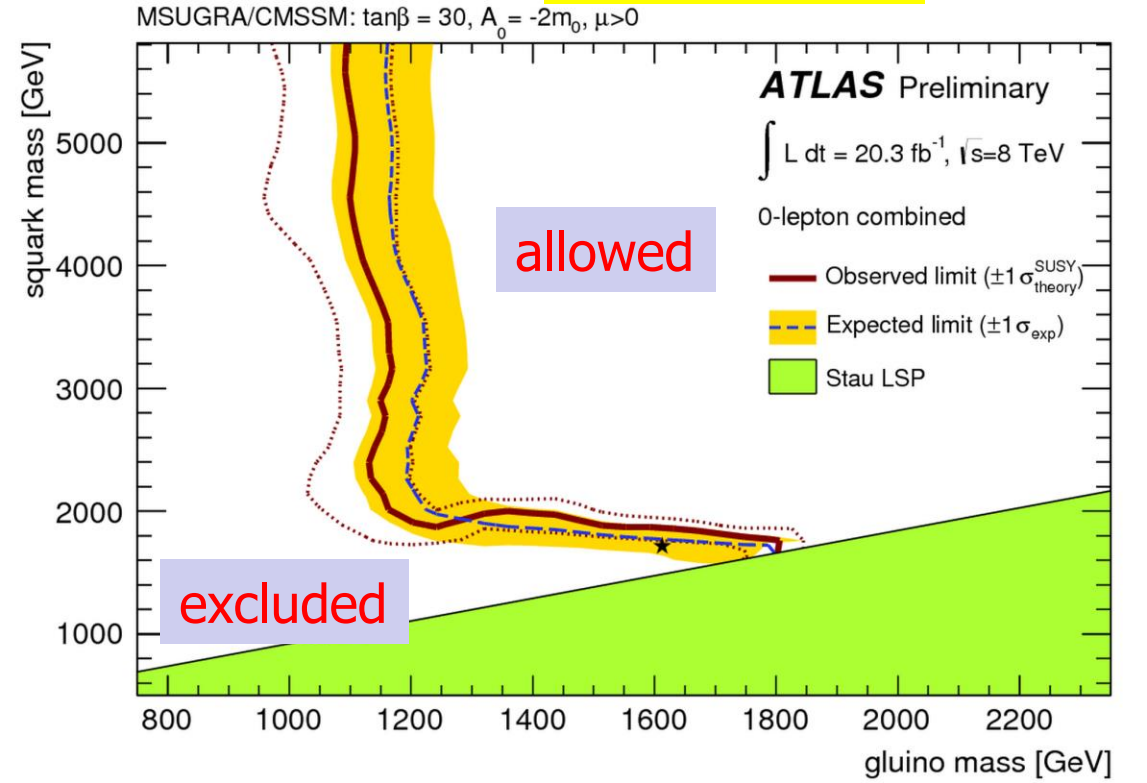
Example: Search for SUSY

Take one example to show steps involved:

- Define event selection criteria
- Go through ~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 Searches: No signal yet to date…

Status in 2013



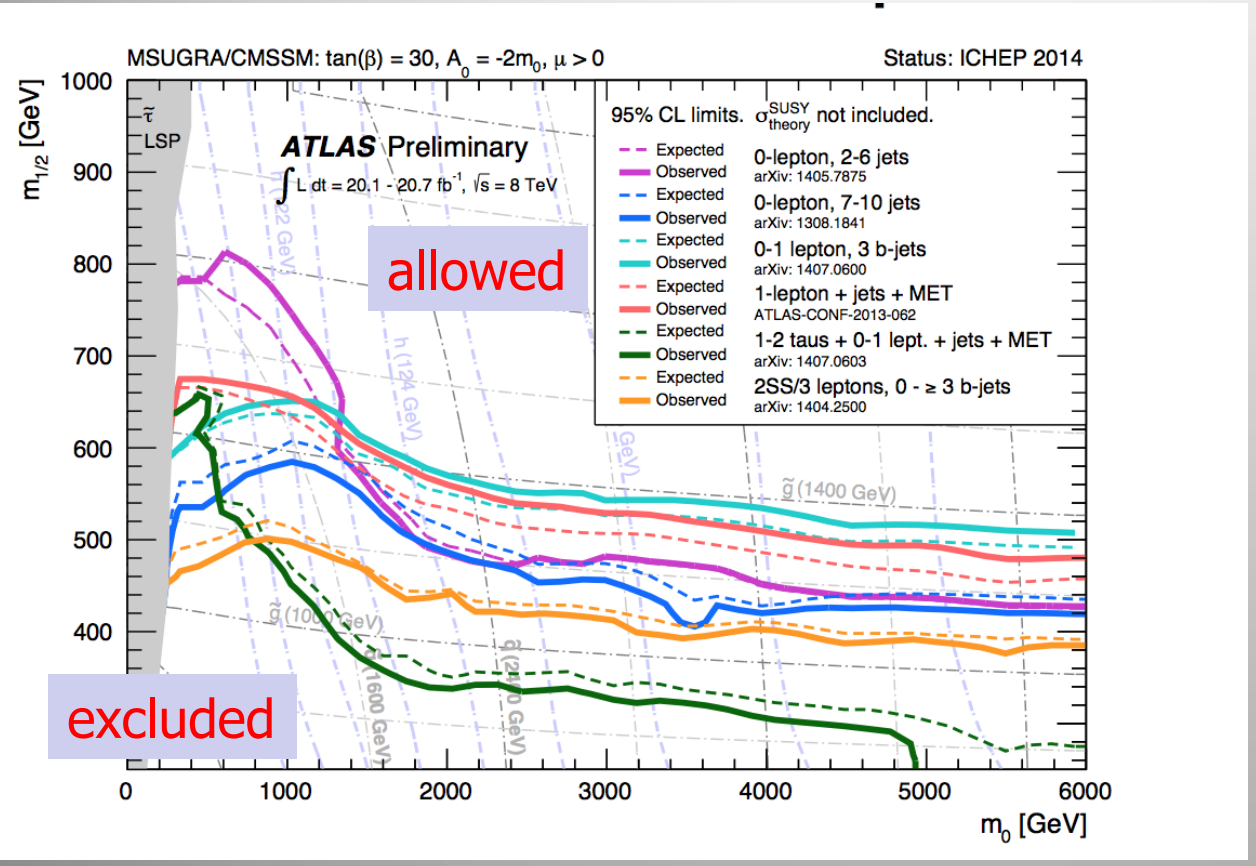
- So far NO clear signal of supersymmetric particles has been found
- We can exclude regions where the new particles could exist.
- Searches will continue for the higher energy in 2015

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

Constrained MSSM: Various Studies

Status in 2014



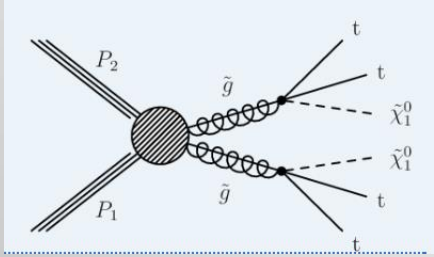
- So far NO clear signal of supersymmetric particles has been found
- We can exclude regions where the new particles could exist.
- $m_{1/2}$: universal gaugino mass at GUT scale
- m_0: universal scalar mass at GUT scale

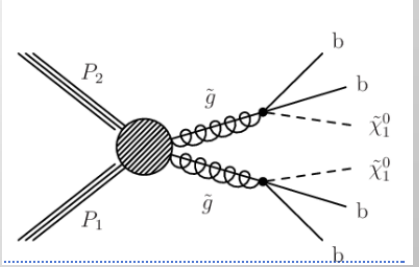
Plenty of searches ongoing: with jets, leptons, photons, W/Z, top, Higgs, with and without large missing transverse energy

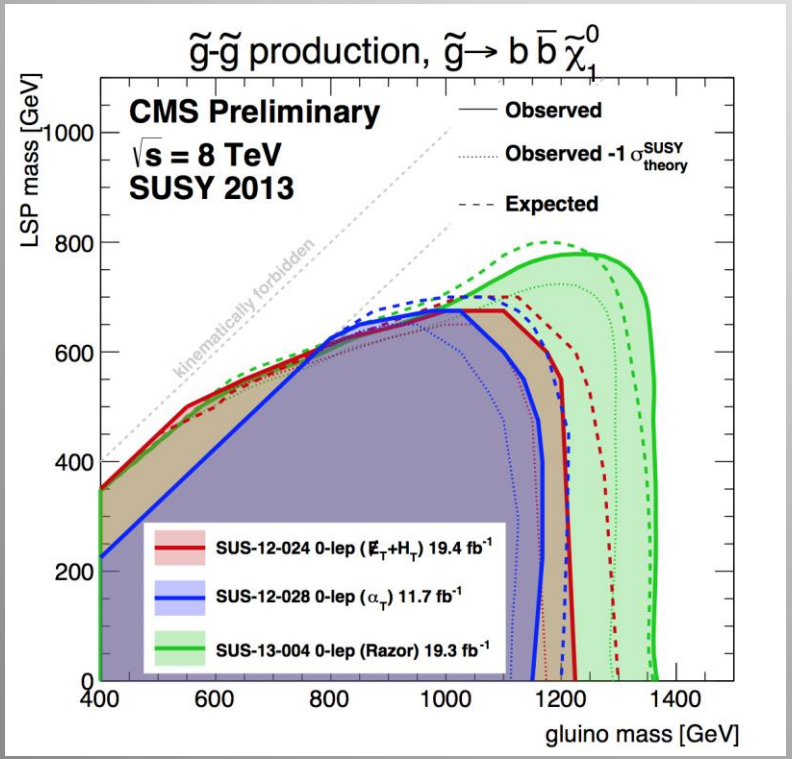
Also special searches for contrived model regions

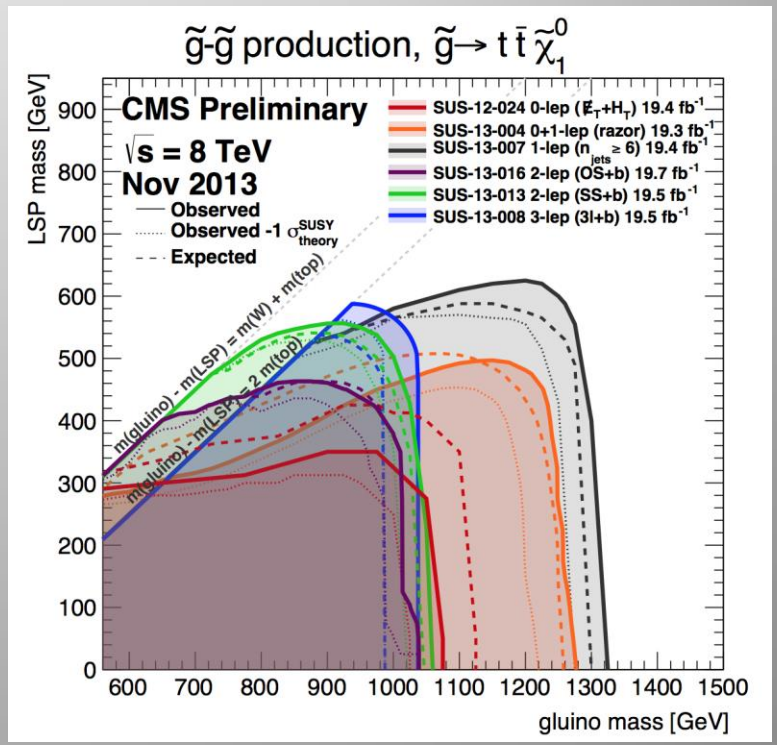
Limits on Squarks and Gluinos

Examples using b and t quarks







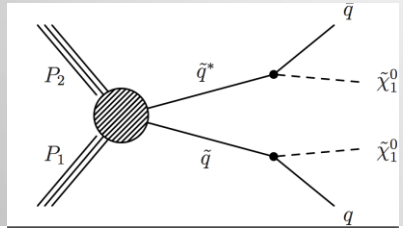


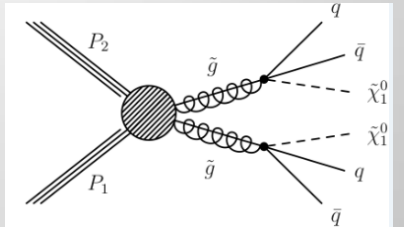
Combined limits typically > 1-1.5 TeV on sparticle masses

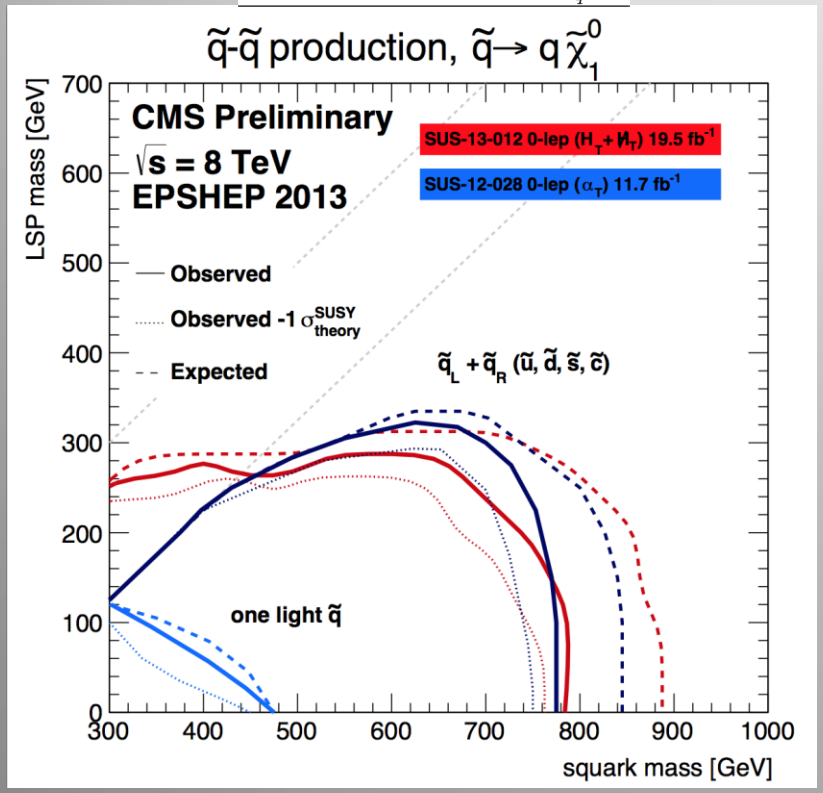
Limits on Squarks and Gluinos

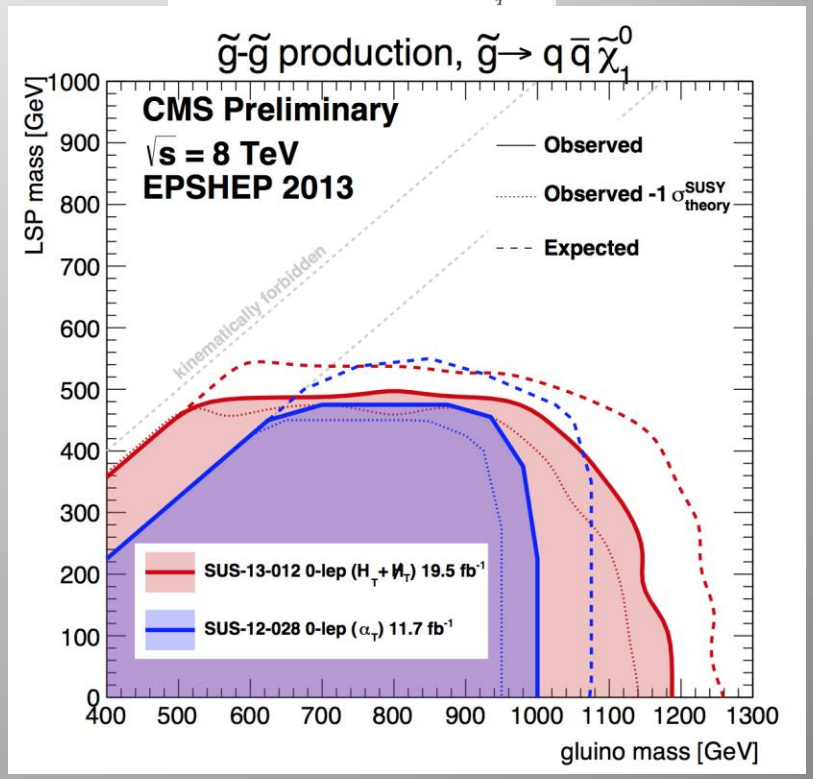
Results depend on the topologies studies, assumed mass of the LSP etc.

Examples









Combined limits typically > 1-1.5 TeV on sparticle masses

What is really needed from SUSY?

End 2011: Revision!

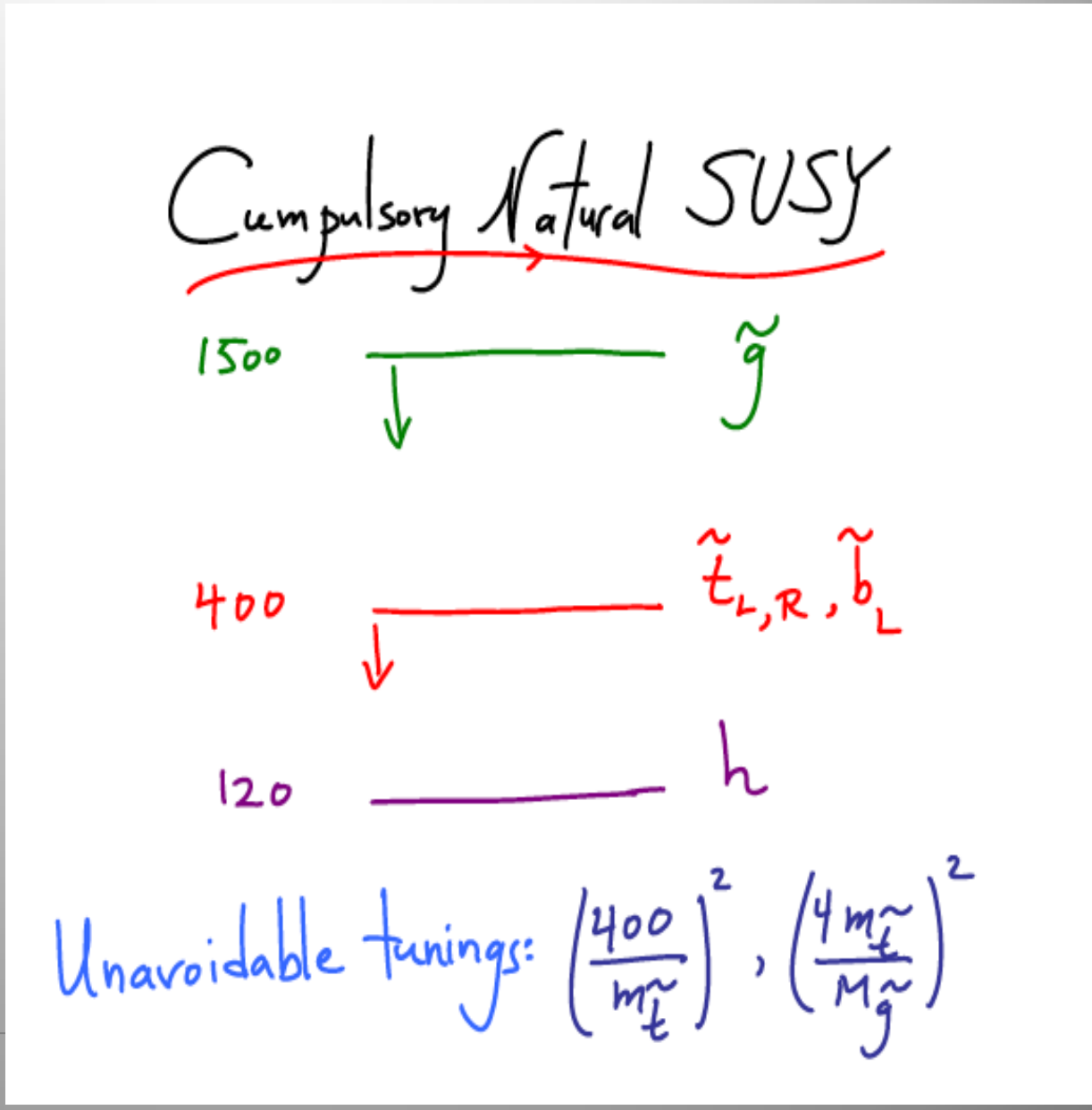
N. Arkani-Ahmed
CERN Nov 2011

Papucci, Ruderman, Weiler arXiv:1110.6926

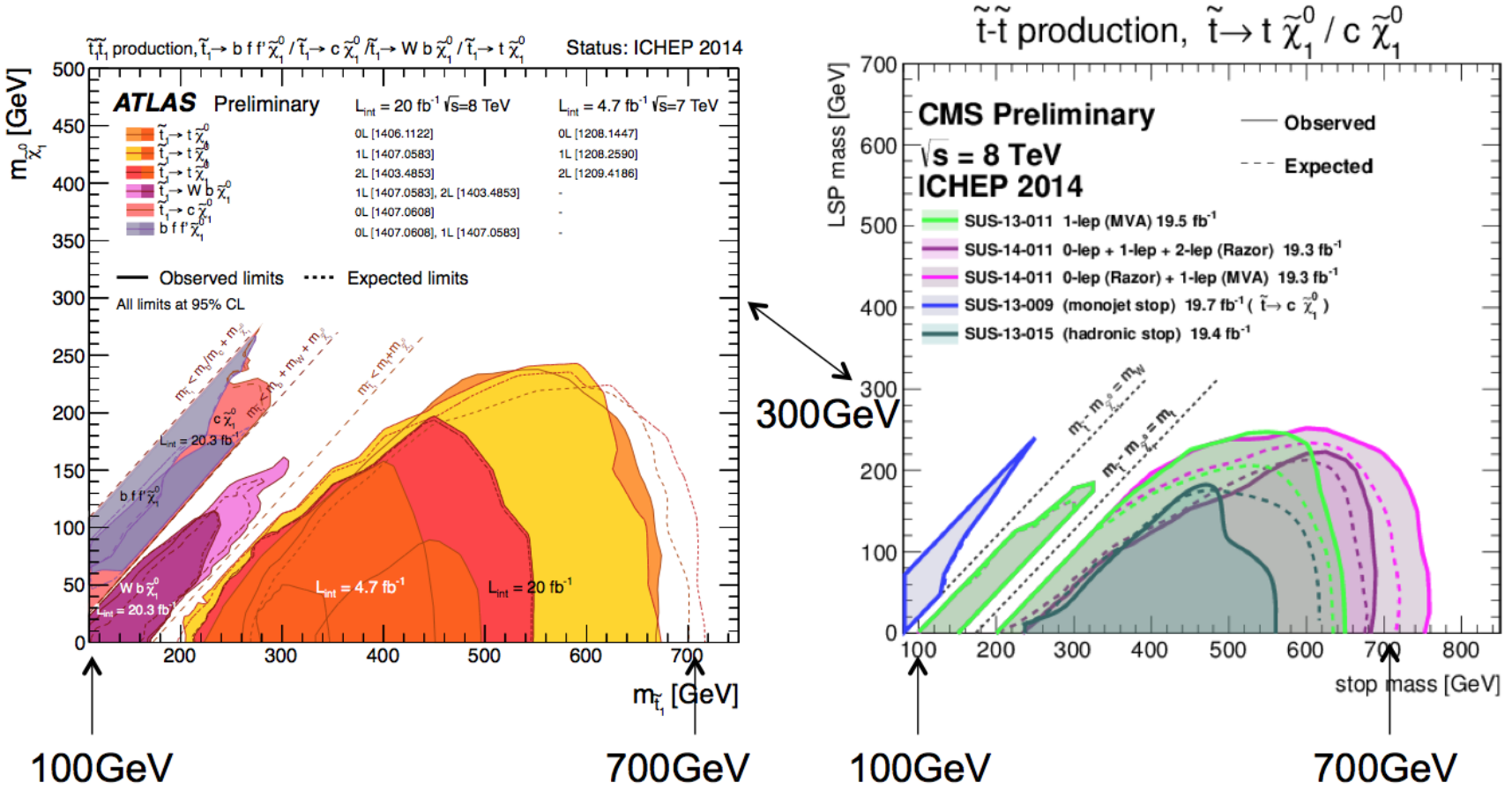
LHC data end 2011
Stops > 200-300 GeV
Gluino > 600-800 GeV

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!

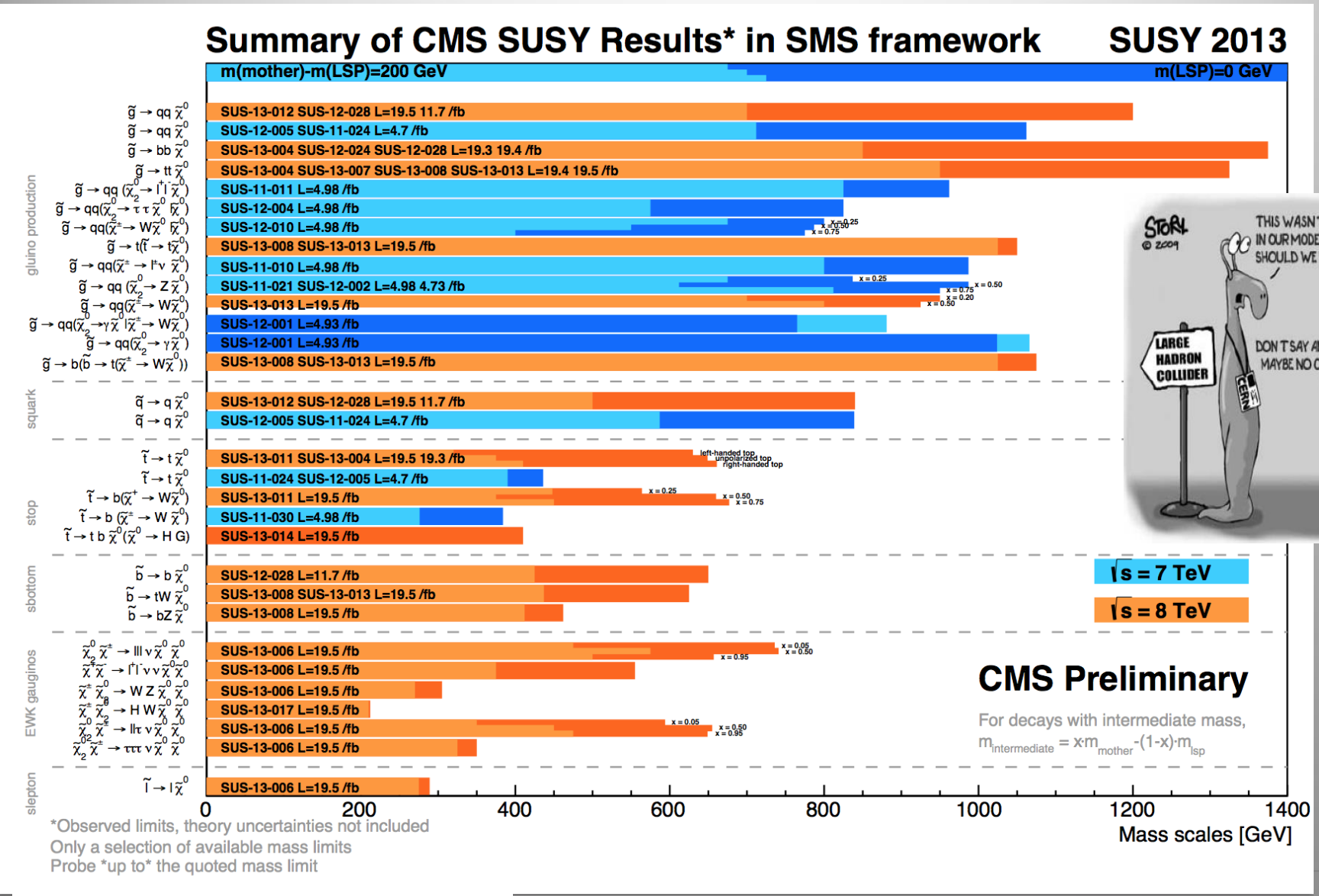


Natural SUSY?



Searches for stop quarks are pushing limits now to 700 GeV

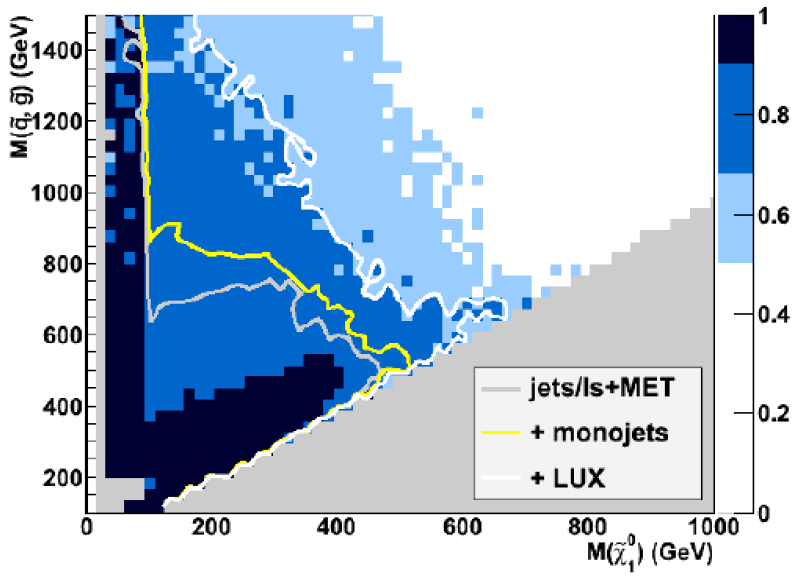
Summary of SUSY Searches



Similar table for ATLAS

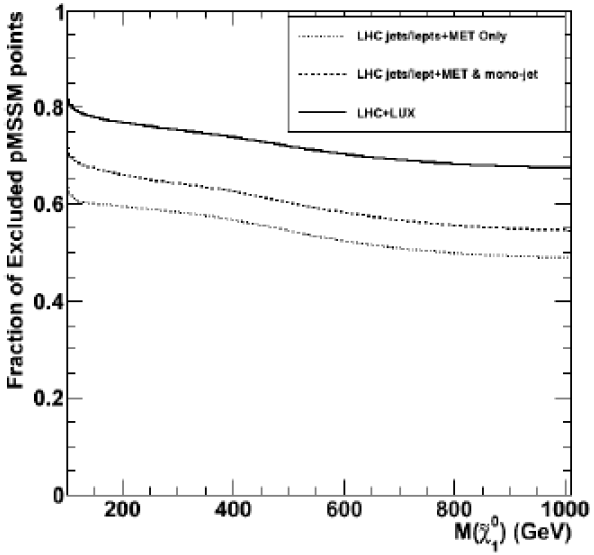
Dark Matter SUSY Space Left?

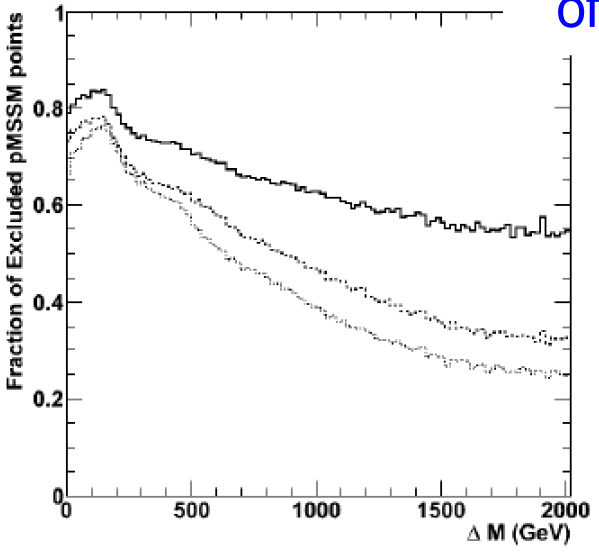
arXiv:1311.7641



- 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



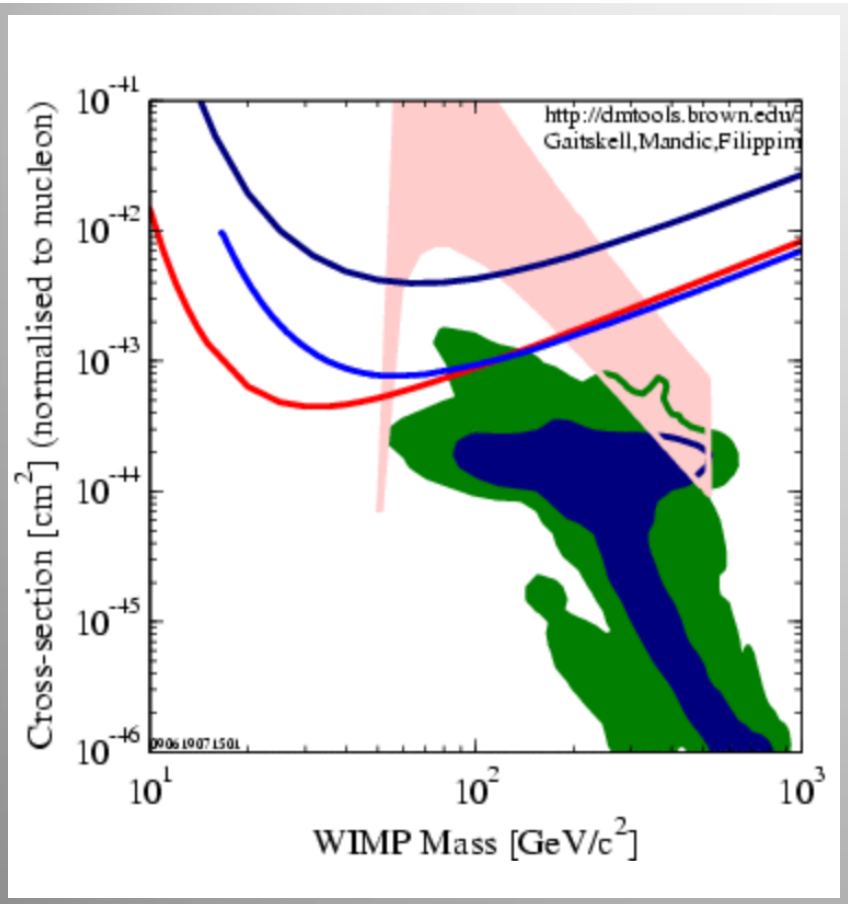


60-80% of the solutions excluded as function of the neutralino mass

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
Trotta et al 2008, CMSSM Bayesian: 68% contour
Trotta et al 2008, CMSSM Bayesian: 95% contour
0906.1907 1501

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

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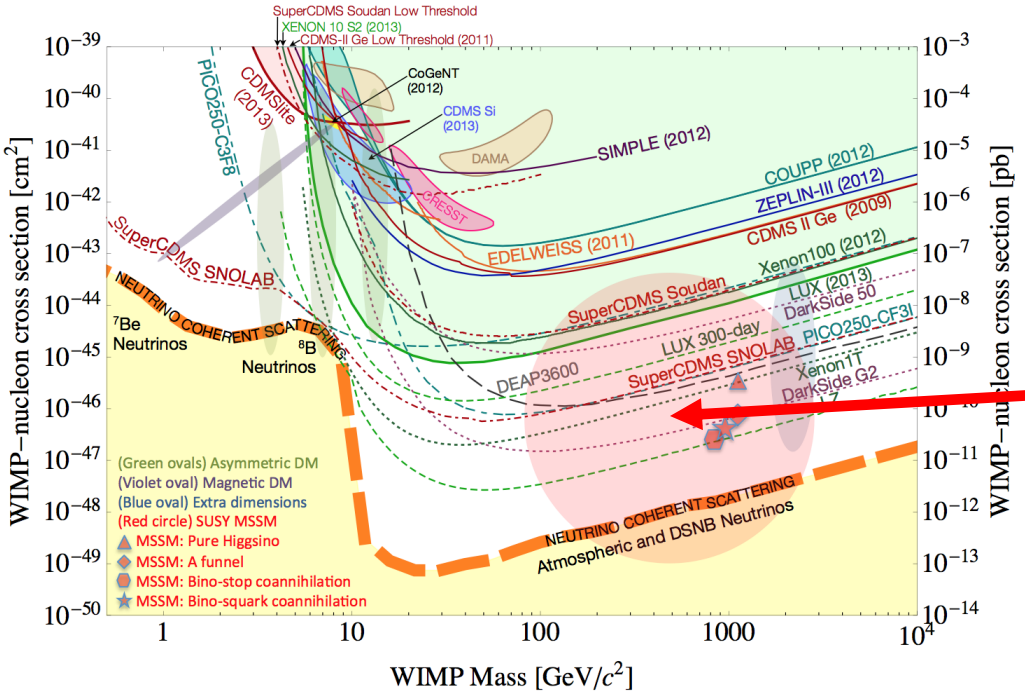
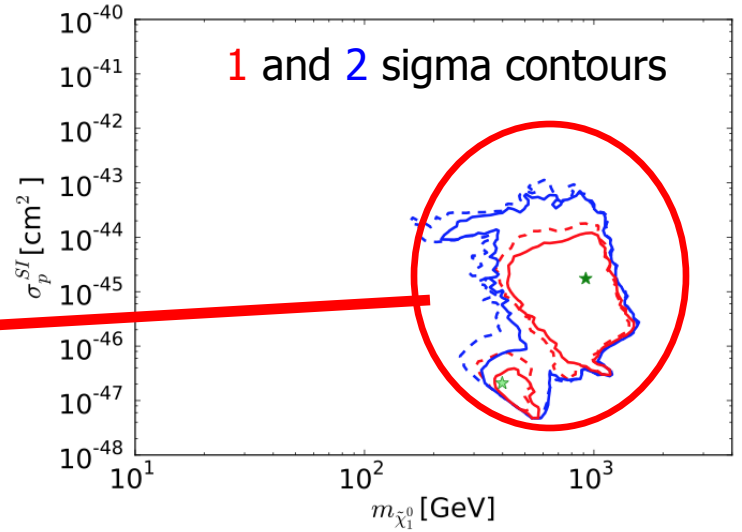


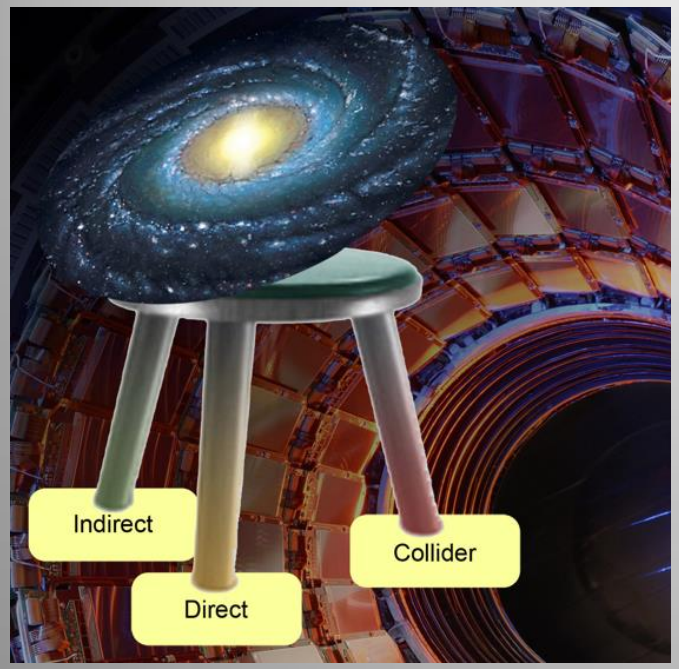


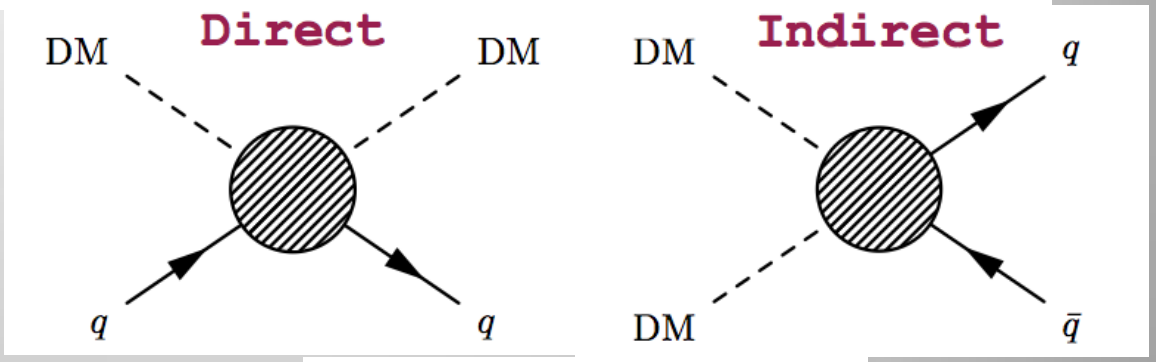
Region allowed in the CMSSM
includes constraints of the Run-I LHC searches (SUSY) and precision data, g-2, cold dark matter constraints…

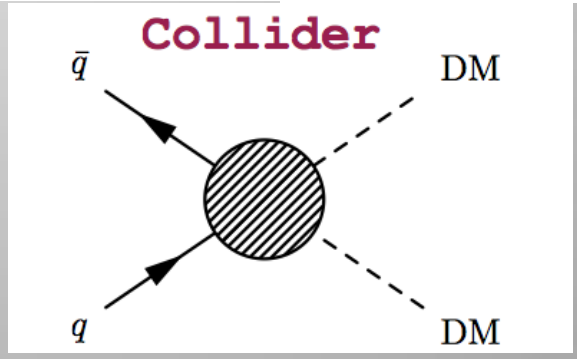
General Searches for Dark Matter

The Generic Dark Matter Connection

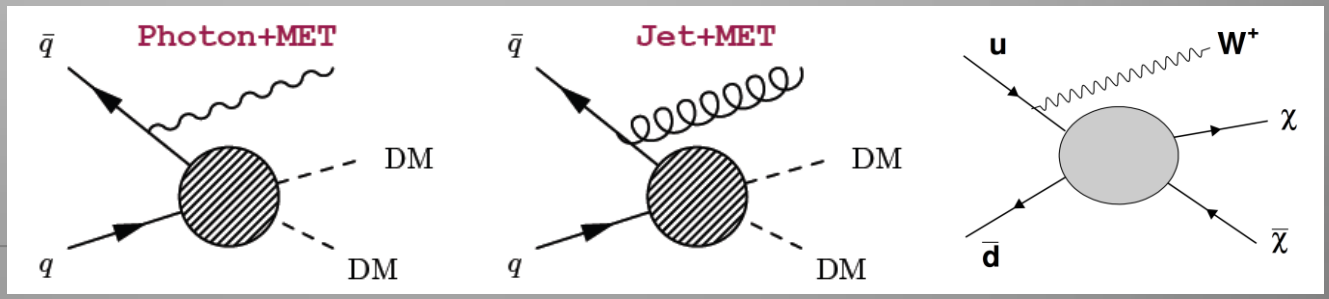
Searches for mono-jets and mono-photons can be used to search for Dark Matter (DM)







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

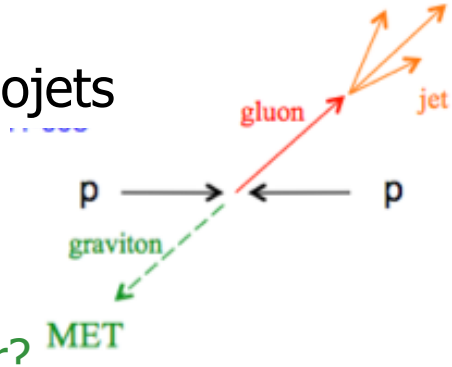


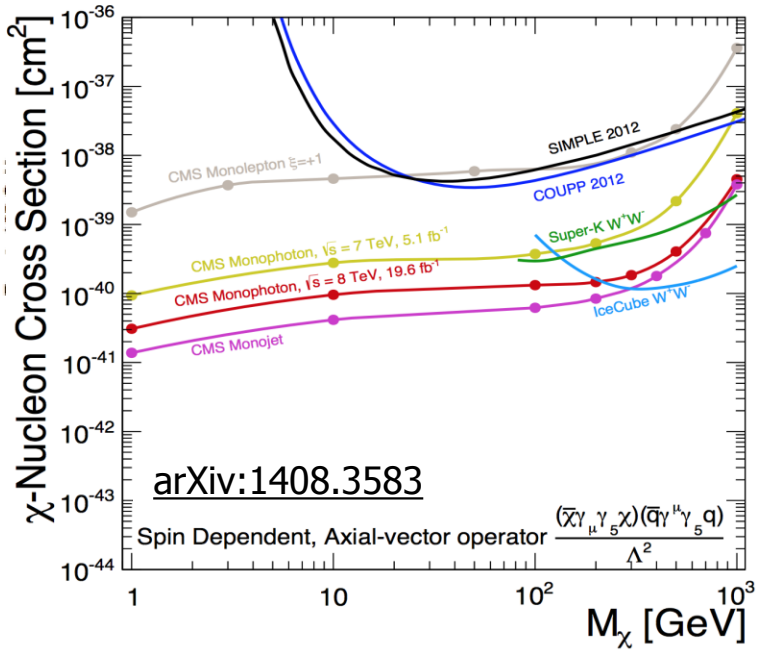
Mono-object Searches in CMS

- Mono-jets: Generally the most powerful
- Mono-photons: 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-portals
- Higgs Decays?

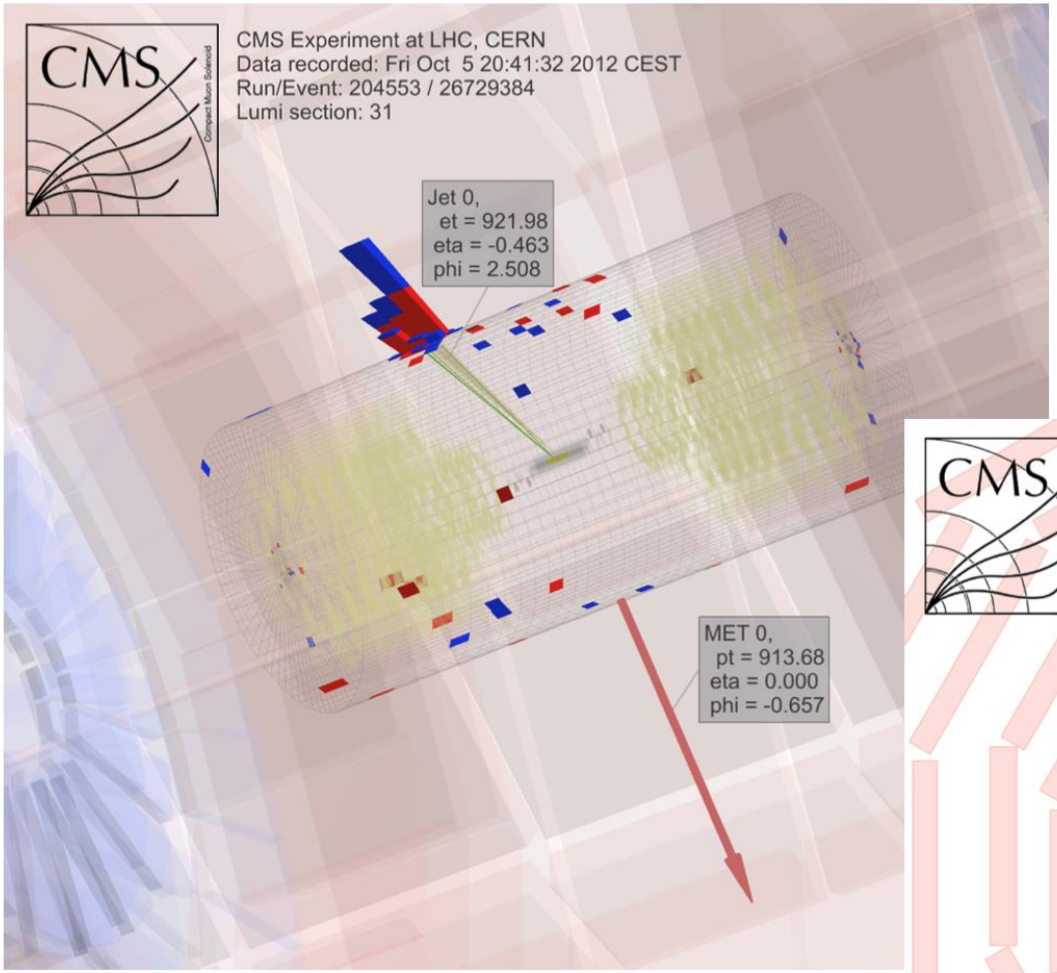
Effective Field Theories for DM interpretation are under attack! Alternatives like SMS proposed…

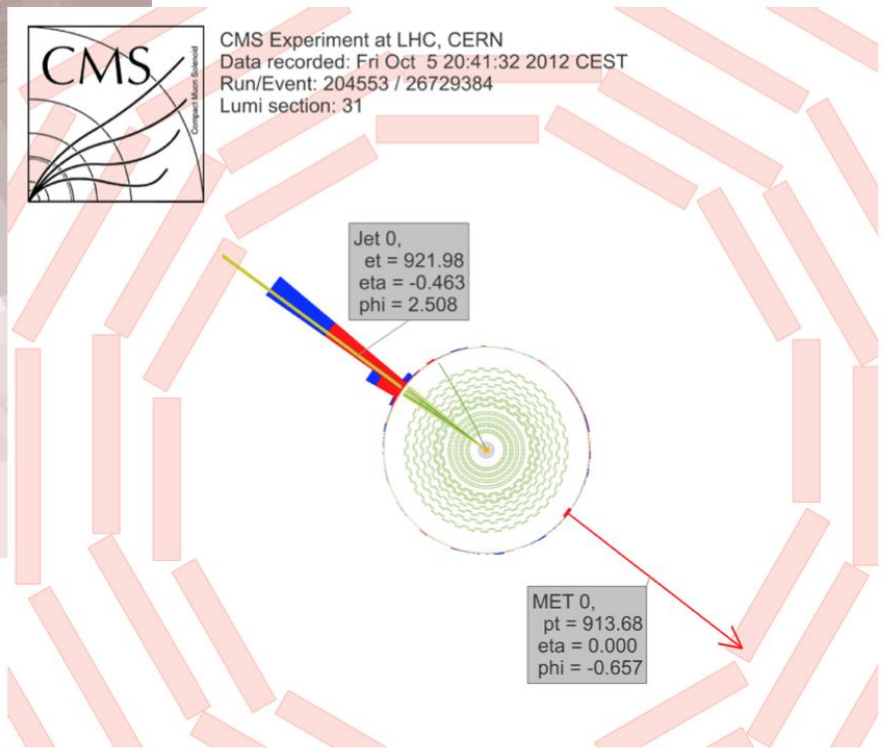
Example Monojets





Mono-Jet Event

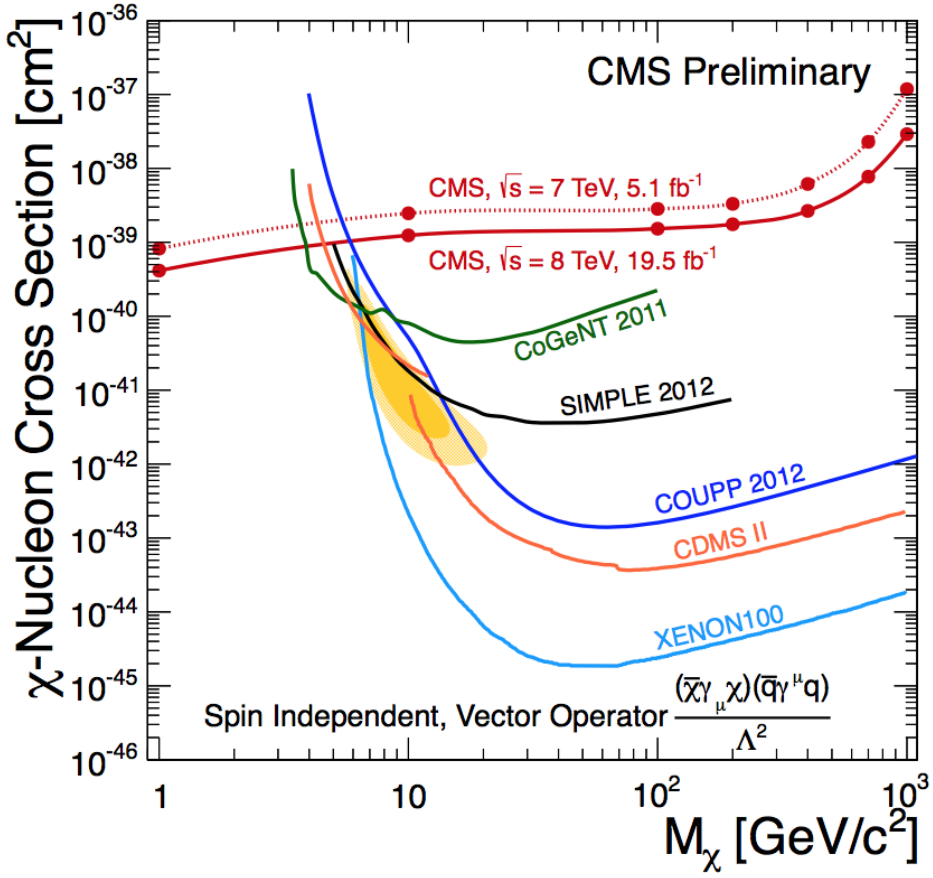


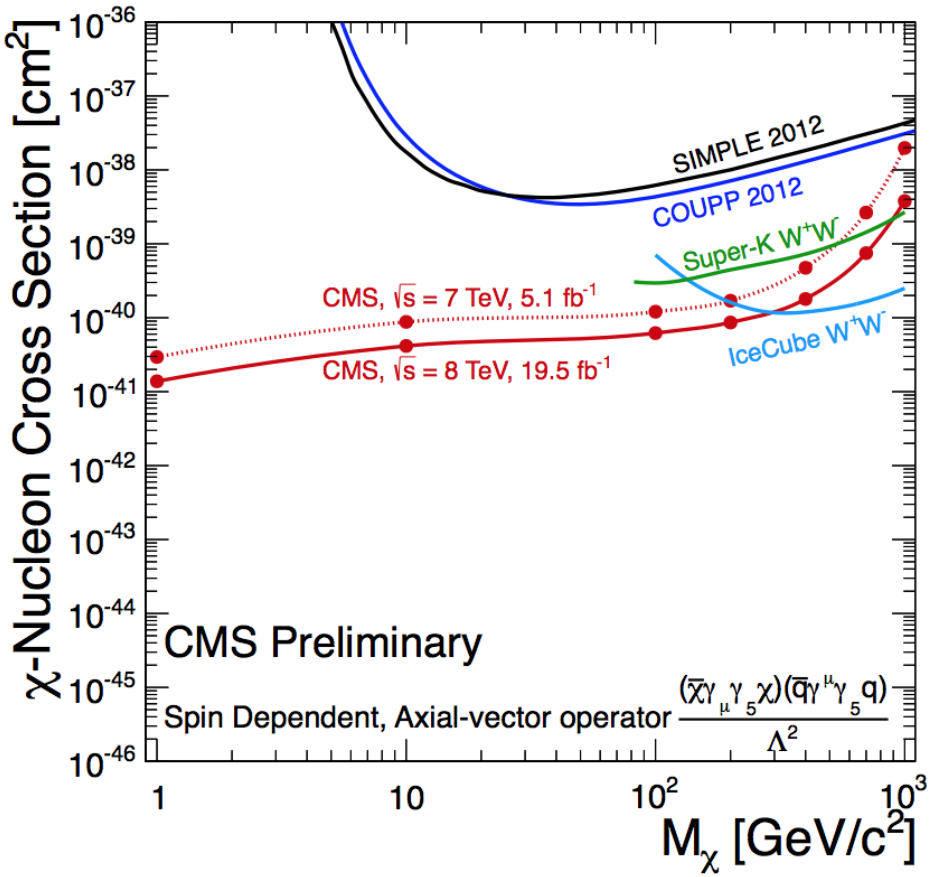


Results for Mono-jets

[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: