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

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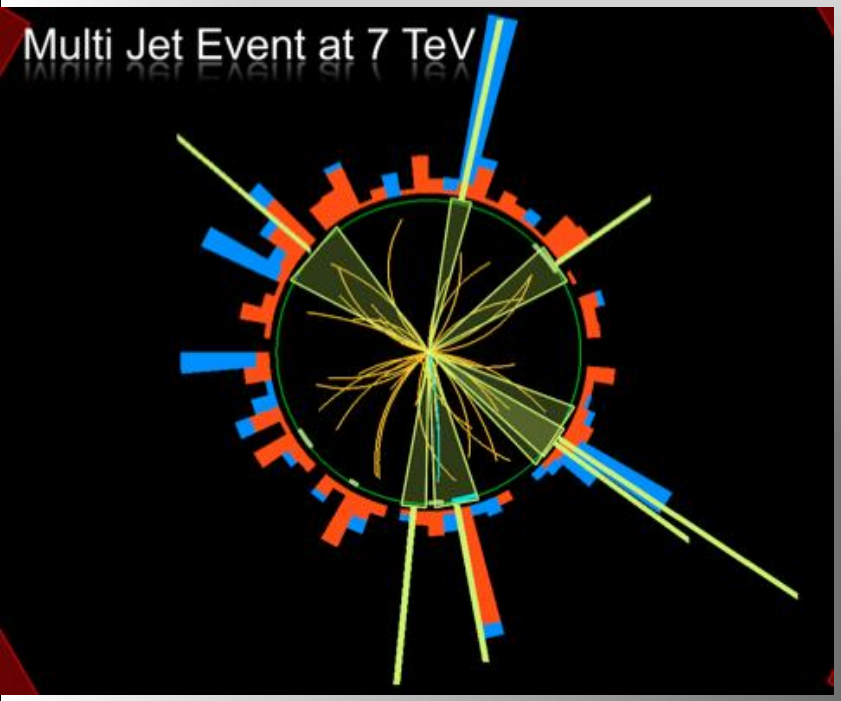
The first CERN Philippines School 2014

Lecture Plan

Overview of the 3 lectures in the next days

- Lecture 1: The study of standard model processes at the LHC
- Lecture 2: Searching for Beyond the Standard Model at the highest energies
- Lecture 3: The next ultimate challenge: identifying Dark Matter in the Universe, and its connection to Supersymmetry



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

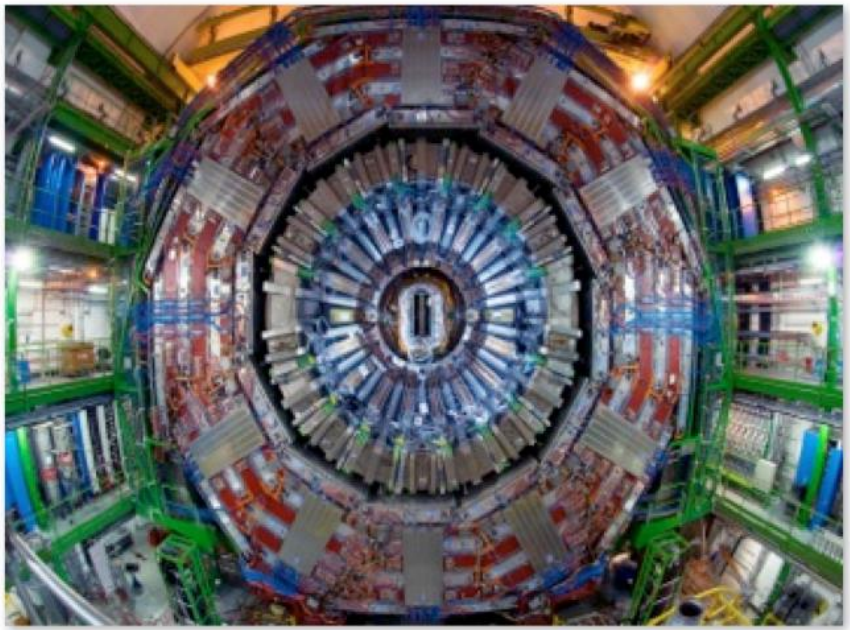
Dark Matter: Complementary Searches?

This Lecture:

After the discovery of the Higgs particle @ the LHC:

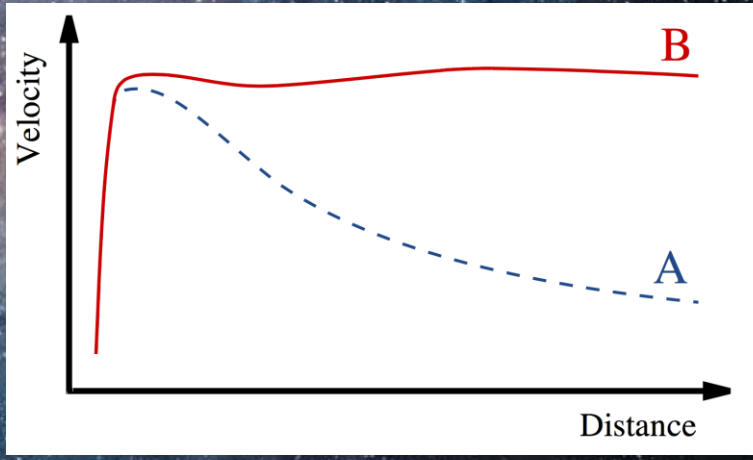
Dark matter is the next important physics problems to tackle for the LHC

The search is complementary to other experimental techniques used.



Dark Matter: The Next Challenge

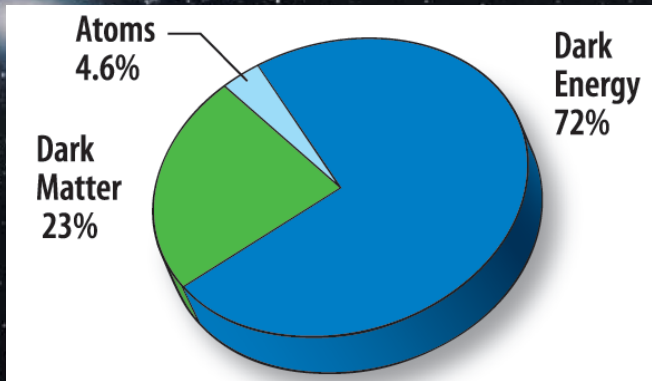
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



'Supersymmetric' particles ?

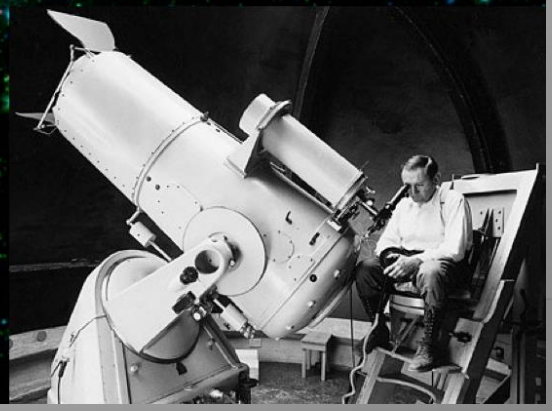
F. Zwicky 1898-1974

Vera Rubin ~ 1970



Dark Matter: Started a Long Time Ago

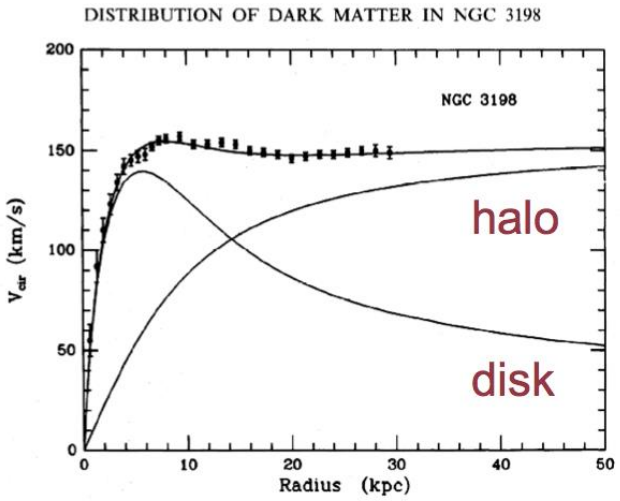
In 1933, Fritz Zwicky calculated the mass of the Coma cluster using galaxies on the outer edge, and came up with a number 400 times *larger* than expected.

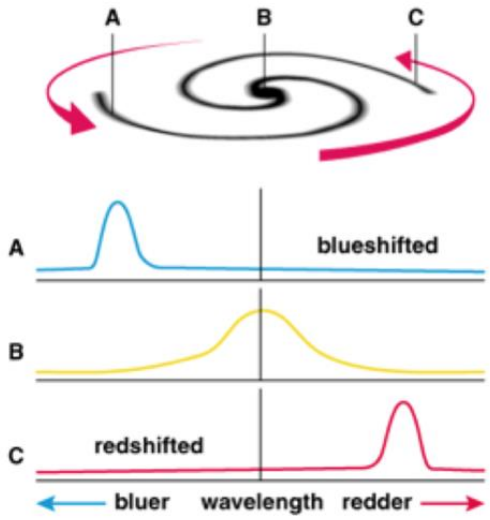


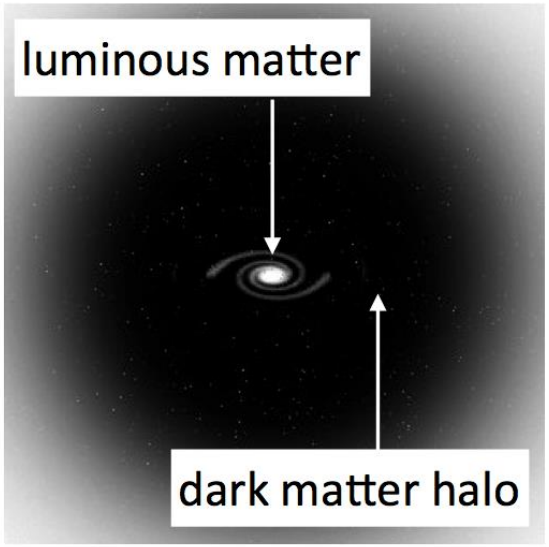
Galactic Rotation

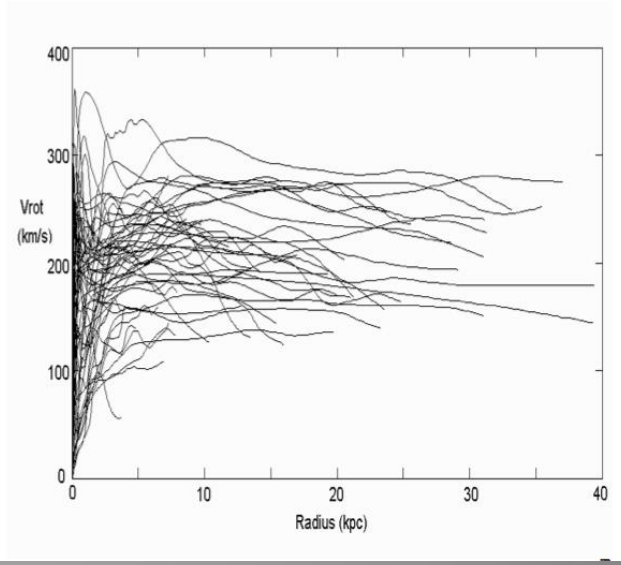
- Starting in the 1970's, measured velocity vs. radius of edge-on spiral galaxies
- They found them to be flat, consistent with ~10x as much "dark" mass...

...and not just one galaxy



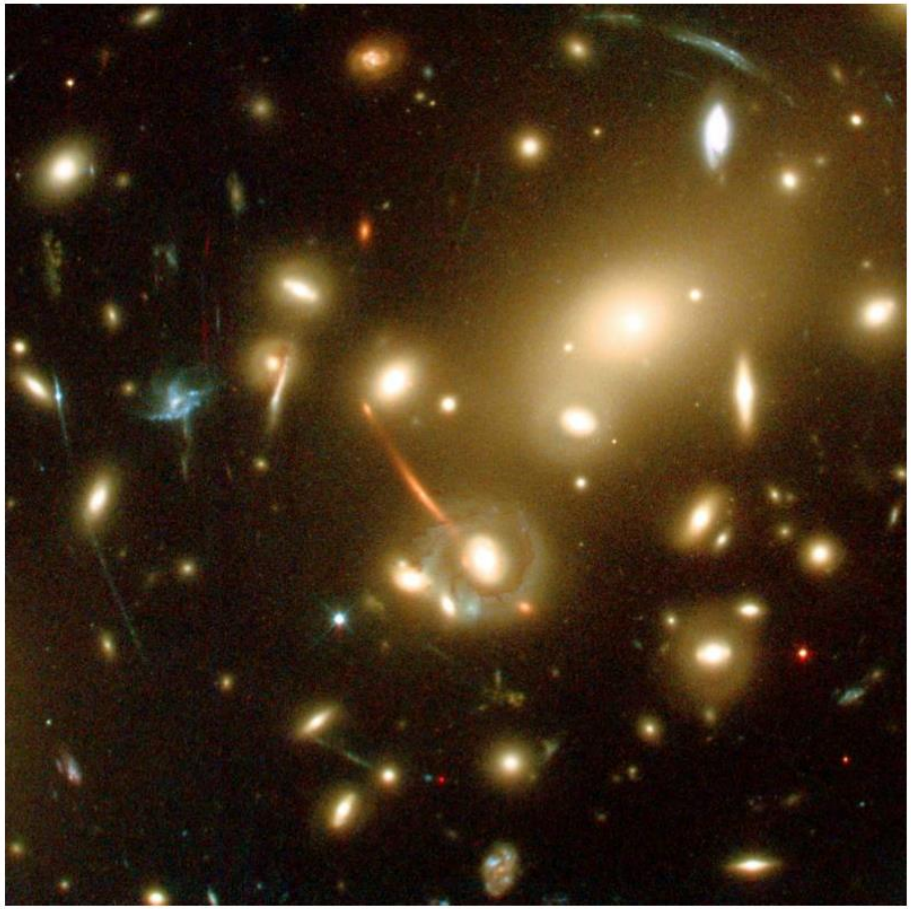




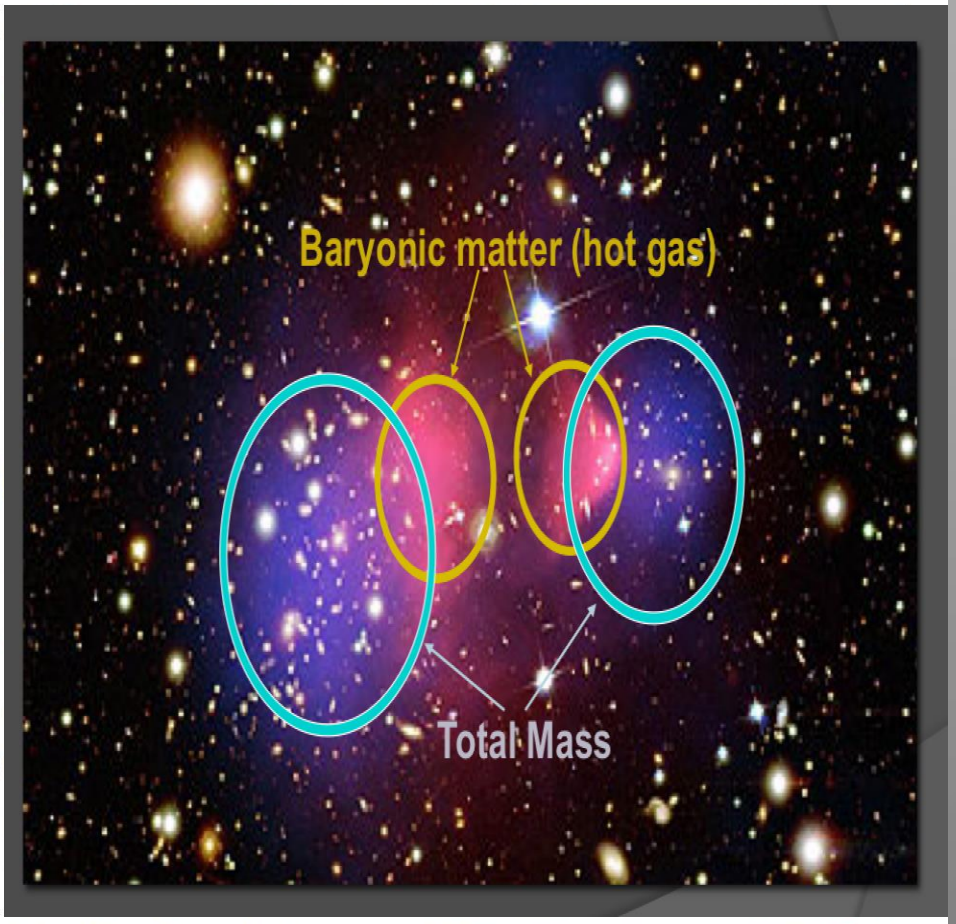


Evidence Piling-up

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

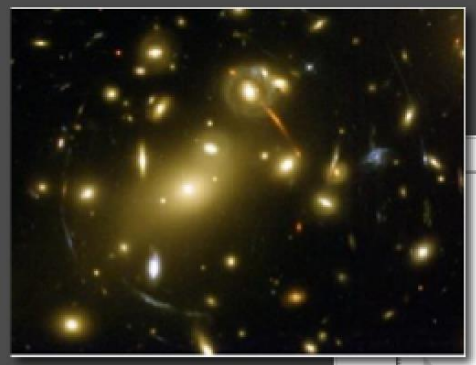


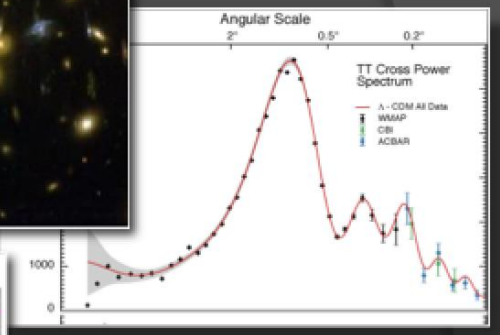
- Bullet Cluster; colliding galaxies
  - Composite x-ray, visible image, 10x DM

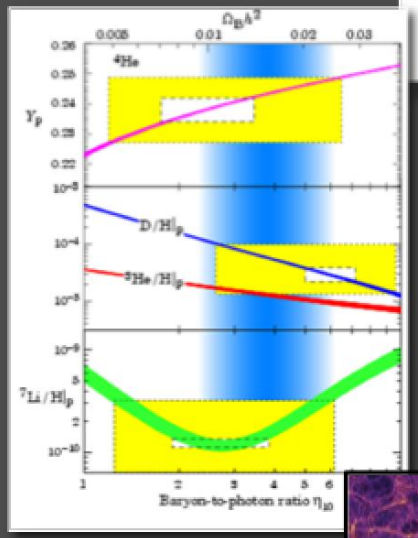


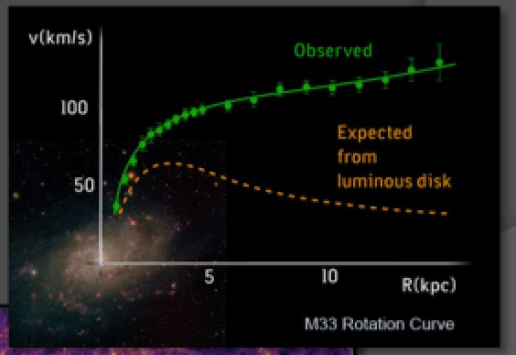
Evidence Piling-up

- 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



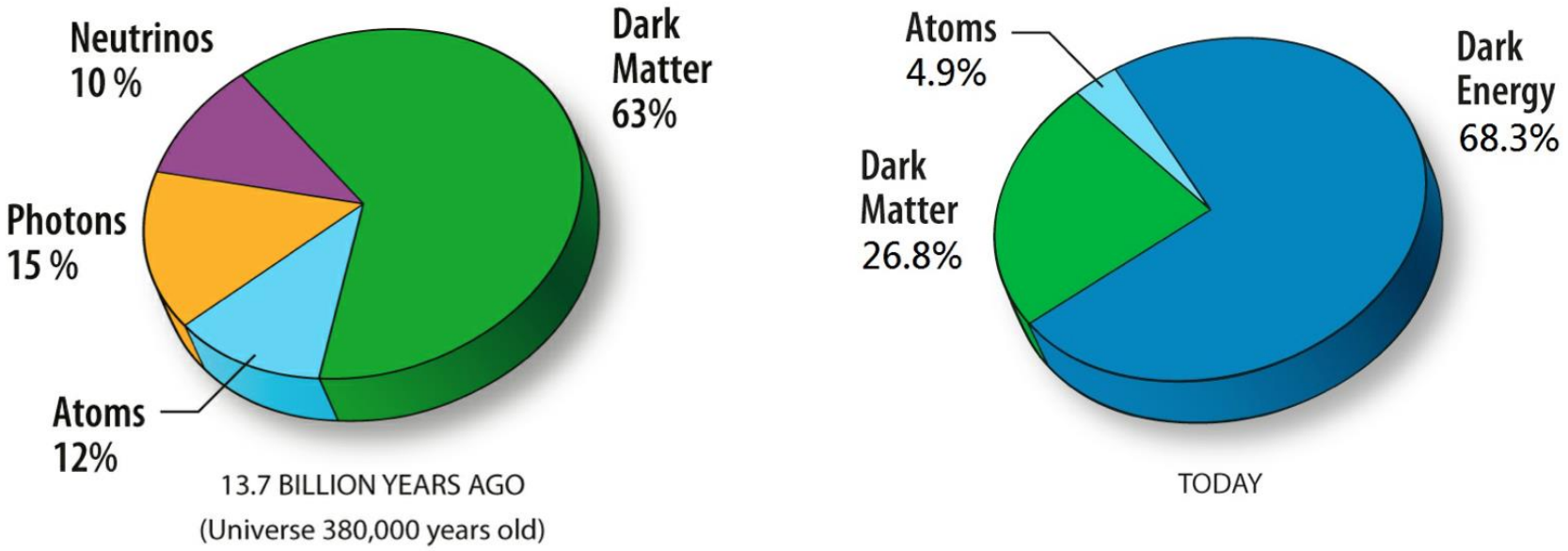






Instead of dark matter, might we not understand gravity?

The Universe, Then and Now



- Strong astrophysical evidence for the existence of dark matter
  - Evidence from bullet cluster, gravitational lensing, rotation curves
  - DM is six times more abundant than baryons
  - Contributes ~1/4 of the total energy budget!

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).

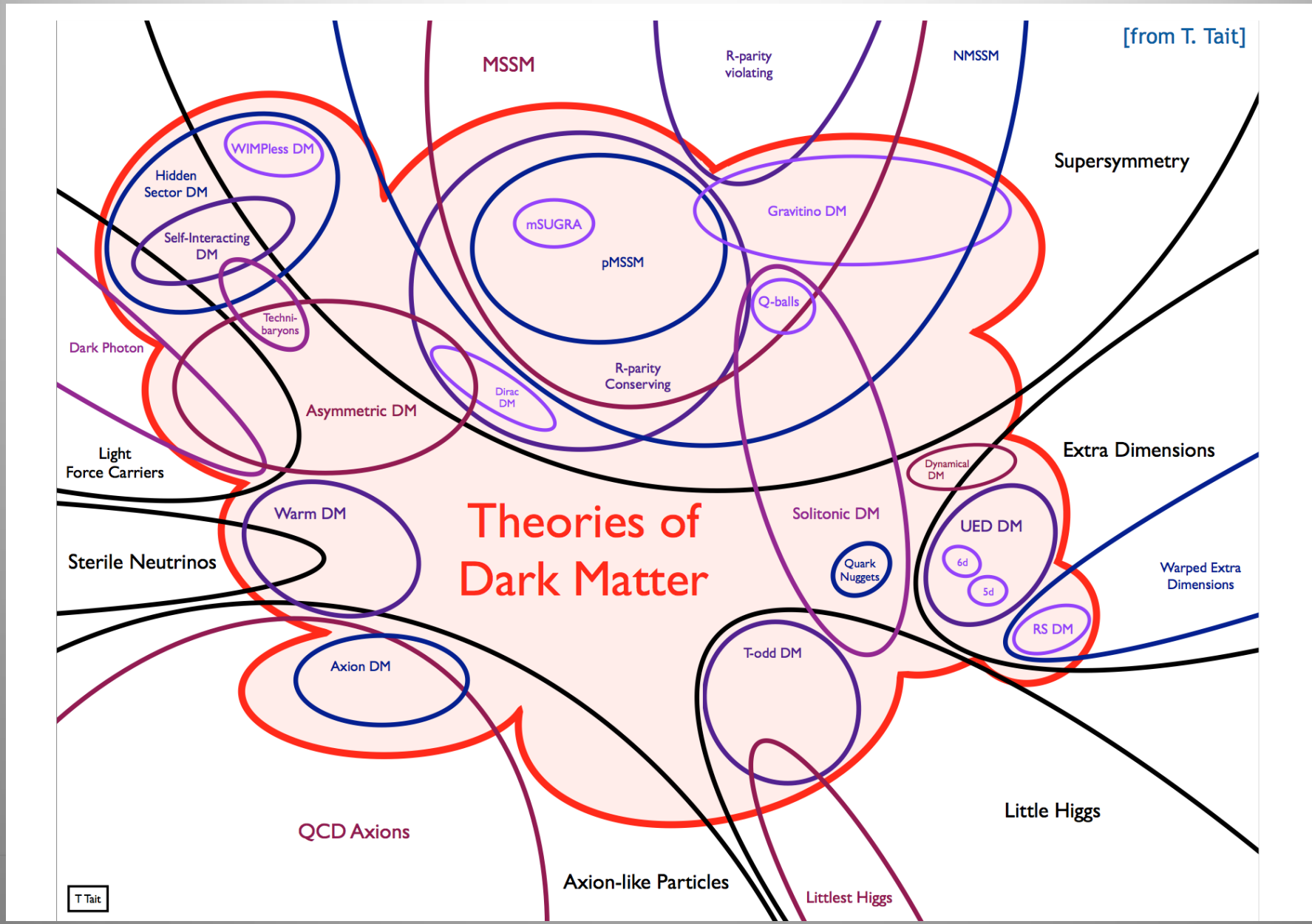
Particle Dark Matter?

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…

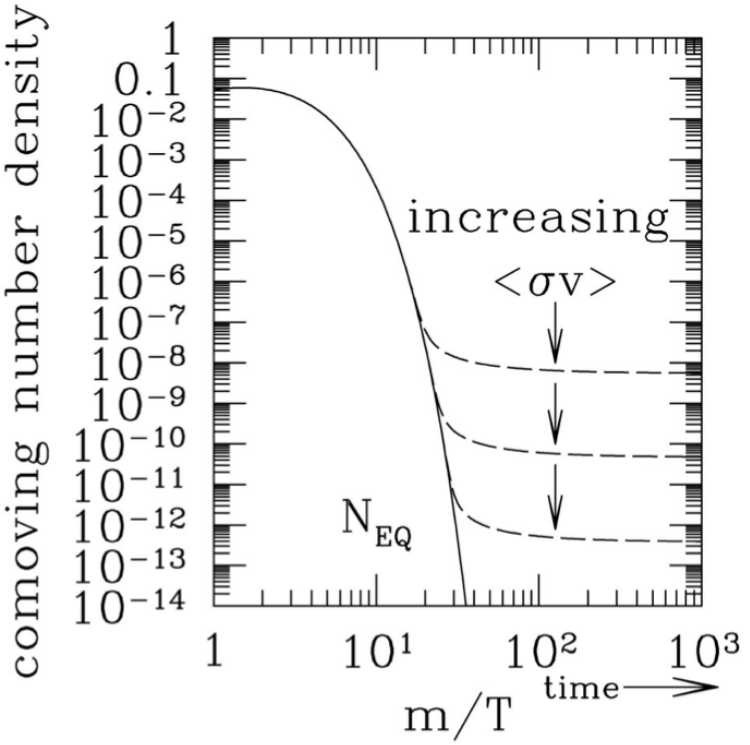
No Lack of Theoretical Ideas…



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

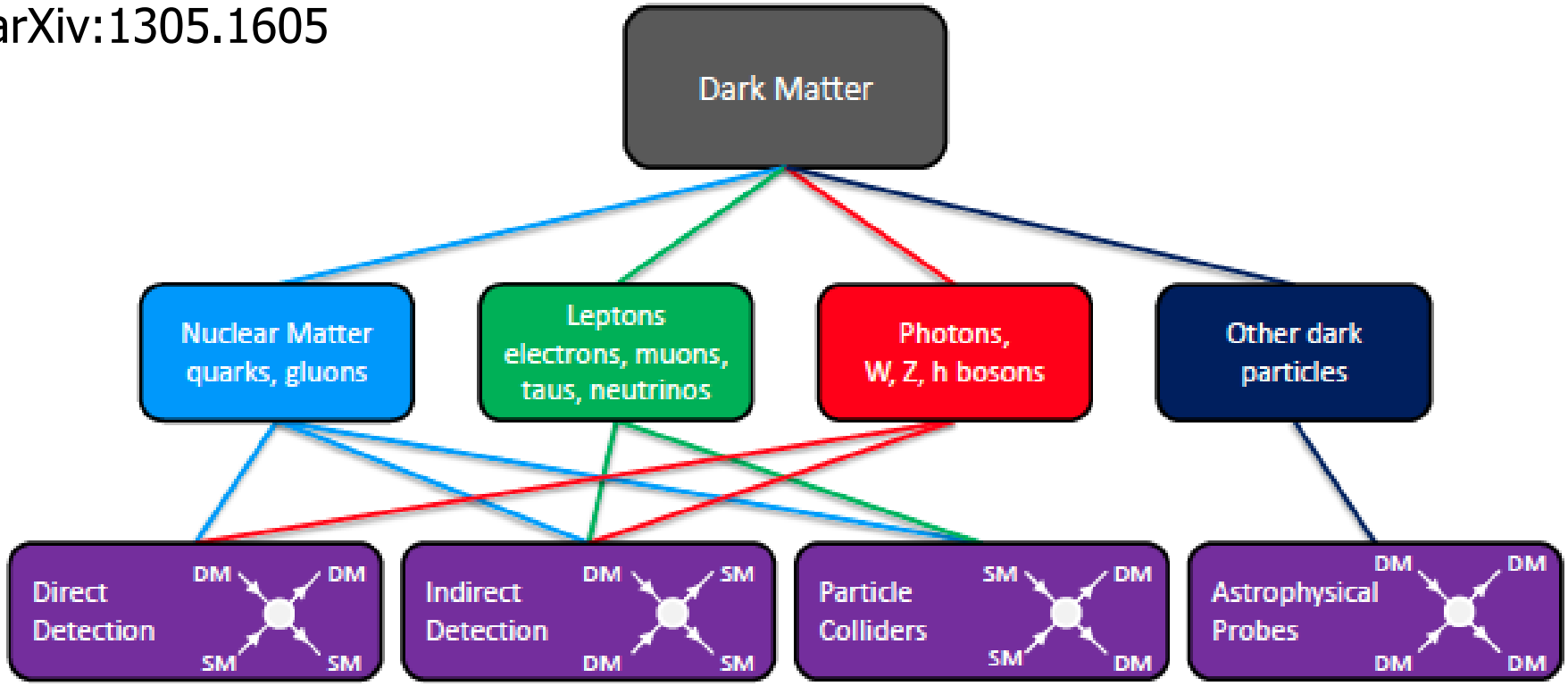


Weakly-interacting massive particles naturally provide the right relic abundance - "WIMP miracle"

Dark Matter @ LHC?

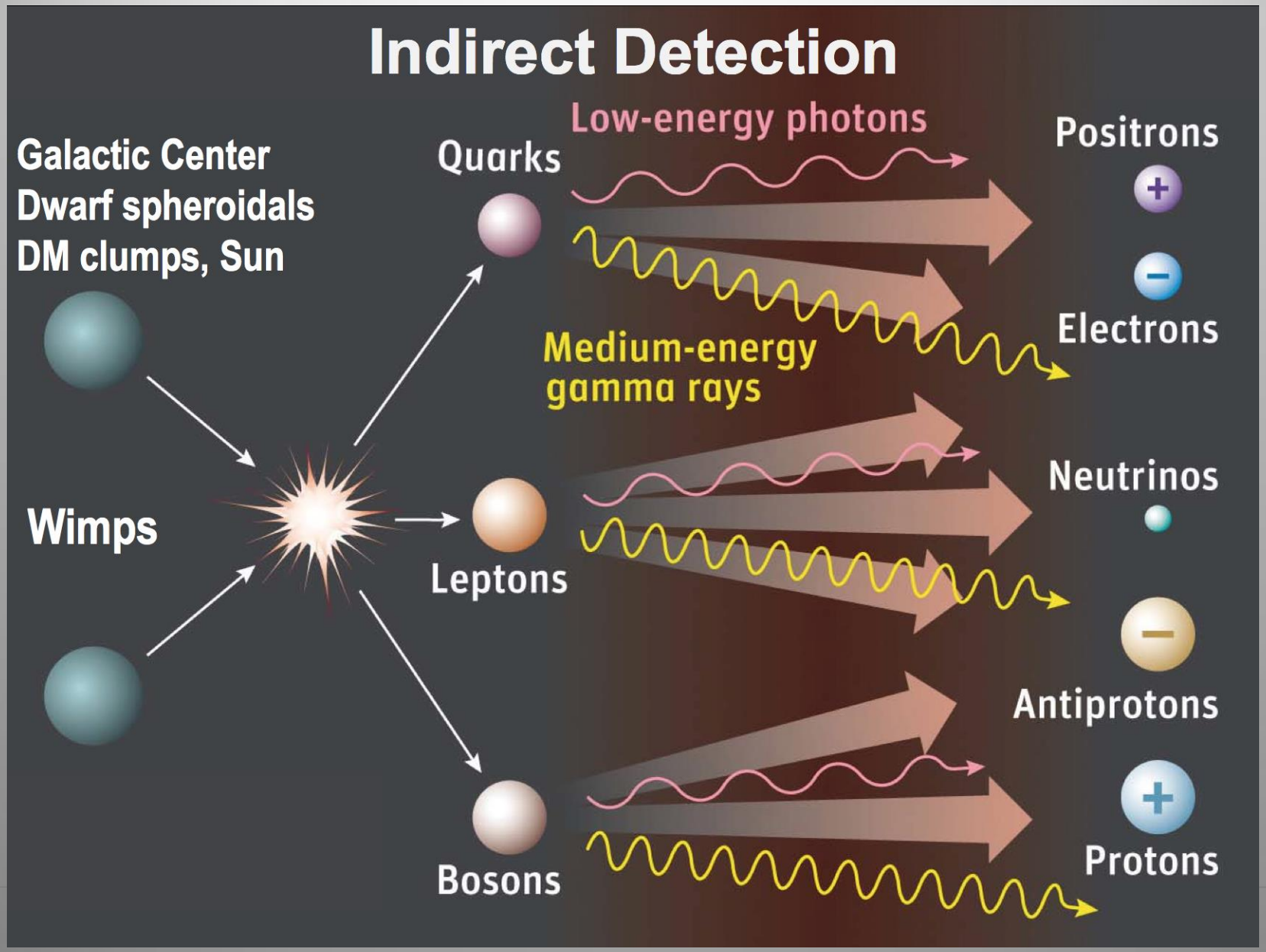
Search for WIMP candidates in events with Missing Transverse Momentum
EG: SUSY searches, monojet and mono-photon Searches, W' searches...

arXiv:1305.1605

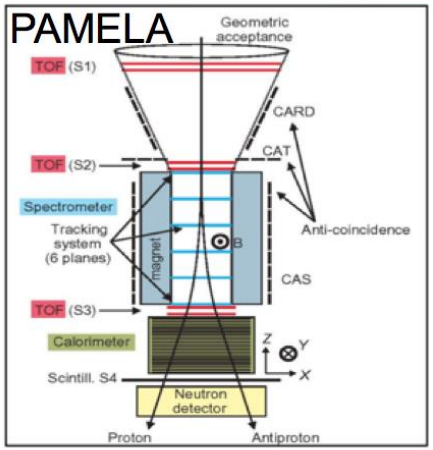


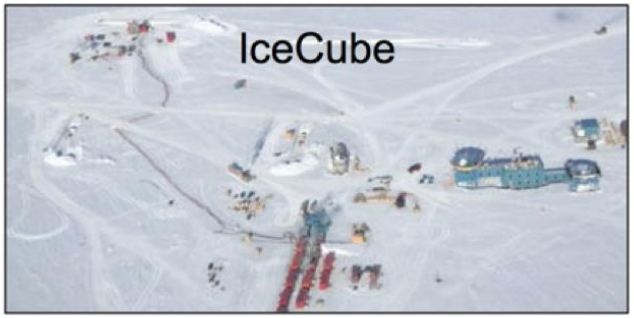
+ CAST experiment, searching for axion DM

Dark Matter: Indirect Detection



Indirect Detection Experiments





Indirect Detection

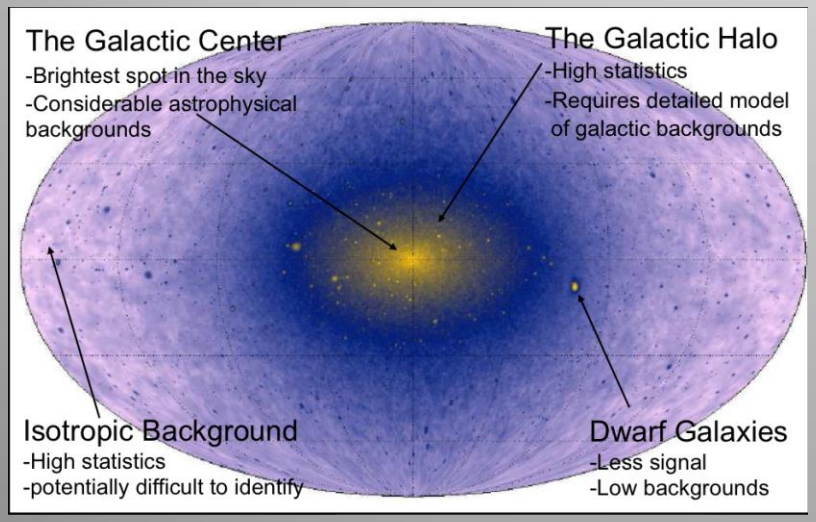
Some scientists are believers!!

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]

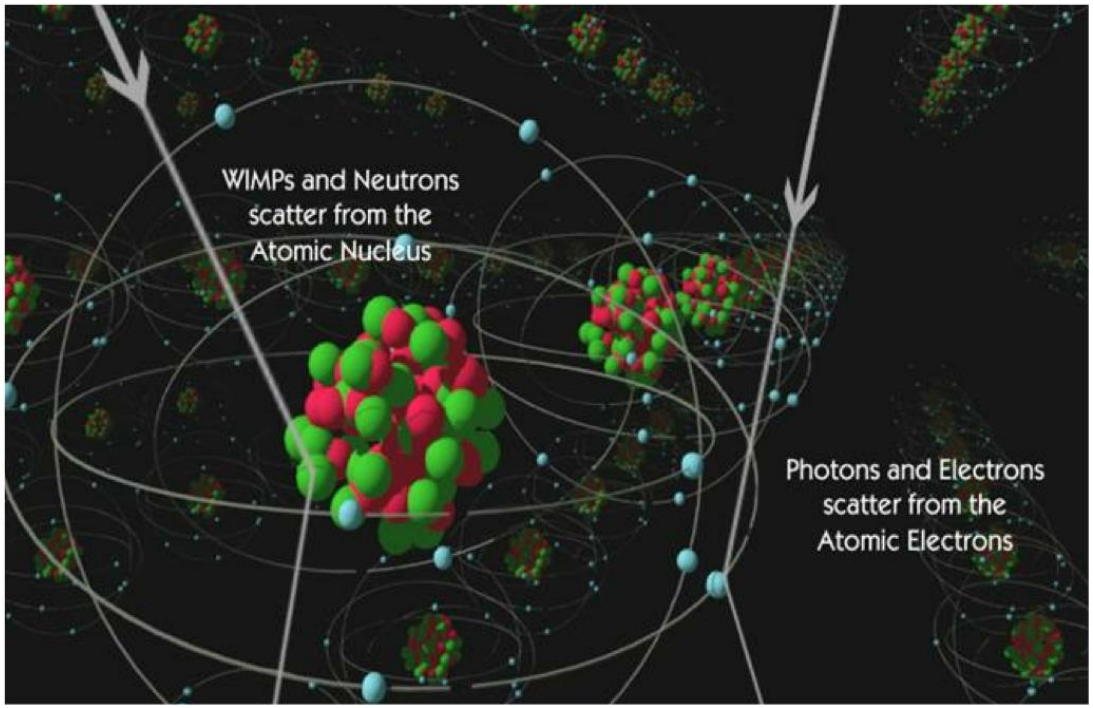
Using gamma-ray data from the FERMI satellite
DM annihilation into b anti-b quarks?



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

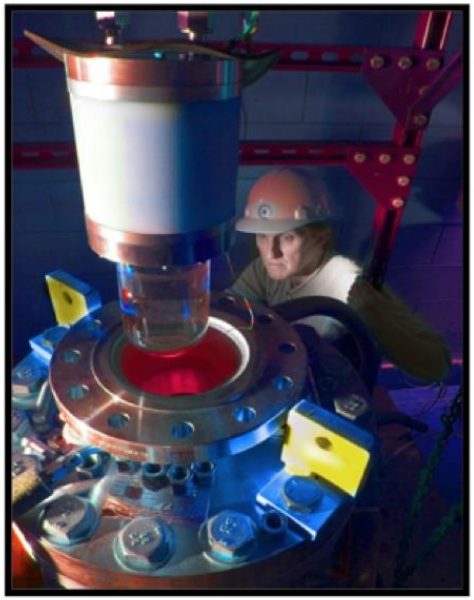
Dark Matter: Direct Detection

- 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...

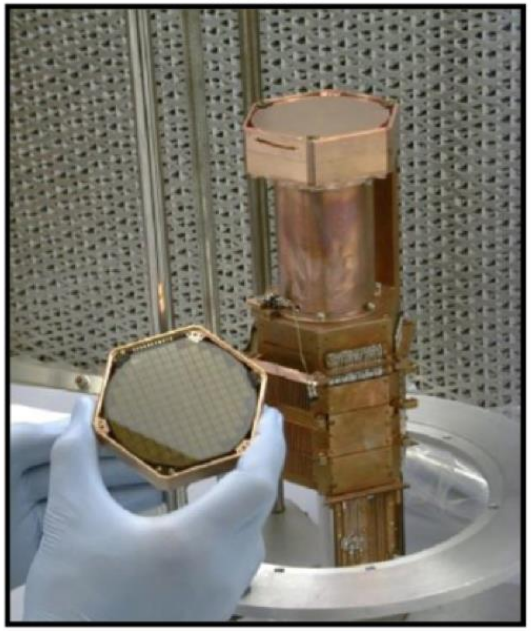


Direct Detection: Examples

COUPP

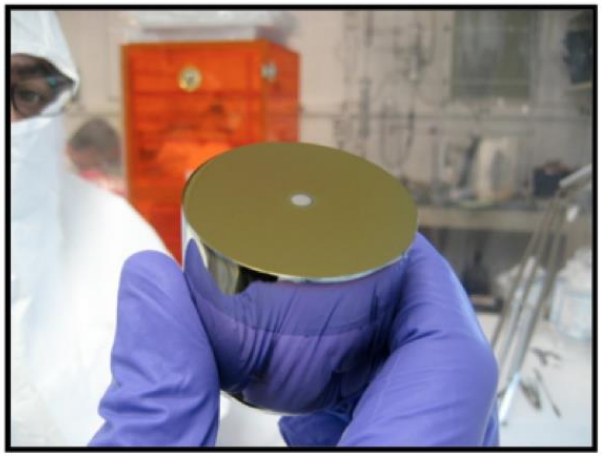


CDMS



CRESST

CoGeNT

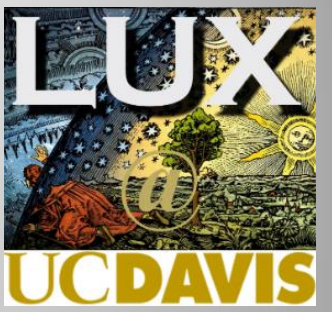


(+ EDELWEISS, DAMA, EURECA, ZEPLIN, DEAP, ArDM, WARP, LUX, SIMPLE, PICASSO, DMTPC, DRIFT, KIMS, …)

Xenon

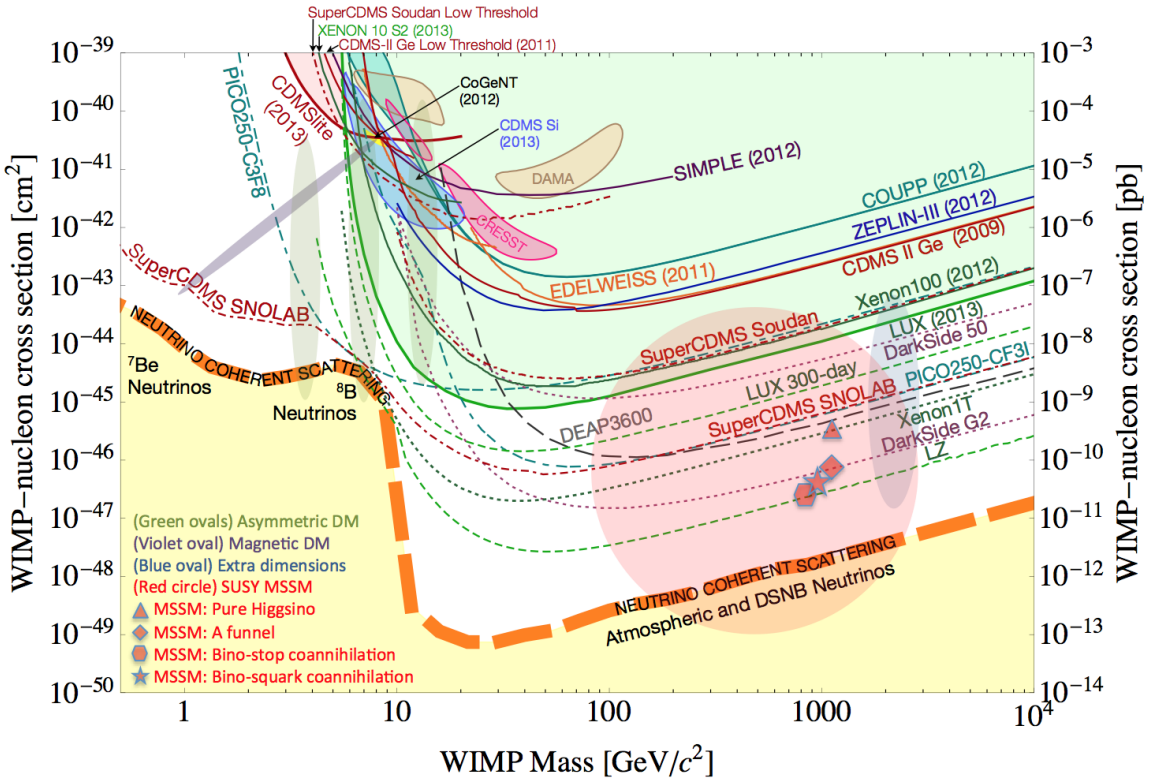
Direct Searches for Dark Matter

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

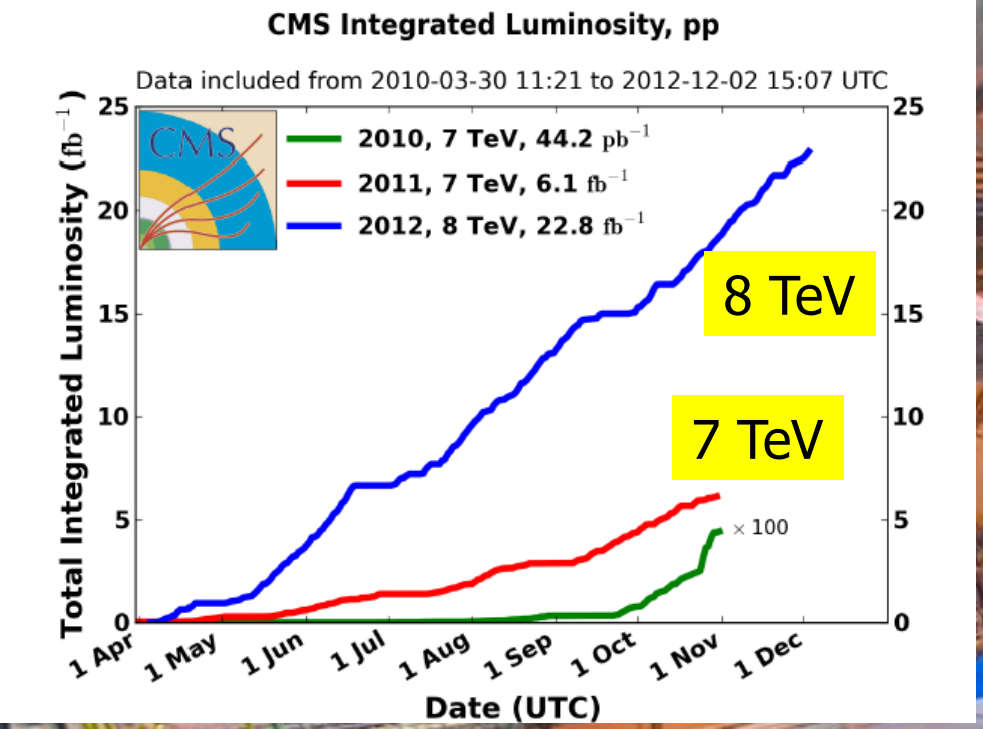


Intensive campaign of direct detection experiments since more than ~20 years

No (real) sign so far...



The LHC



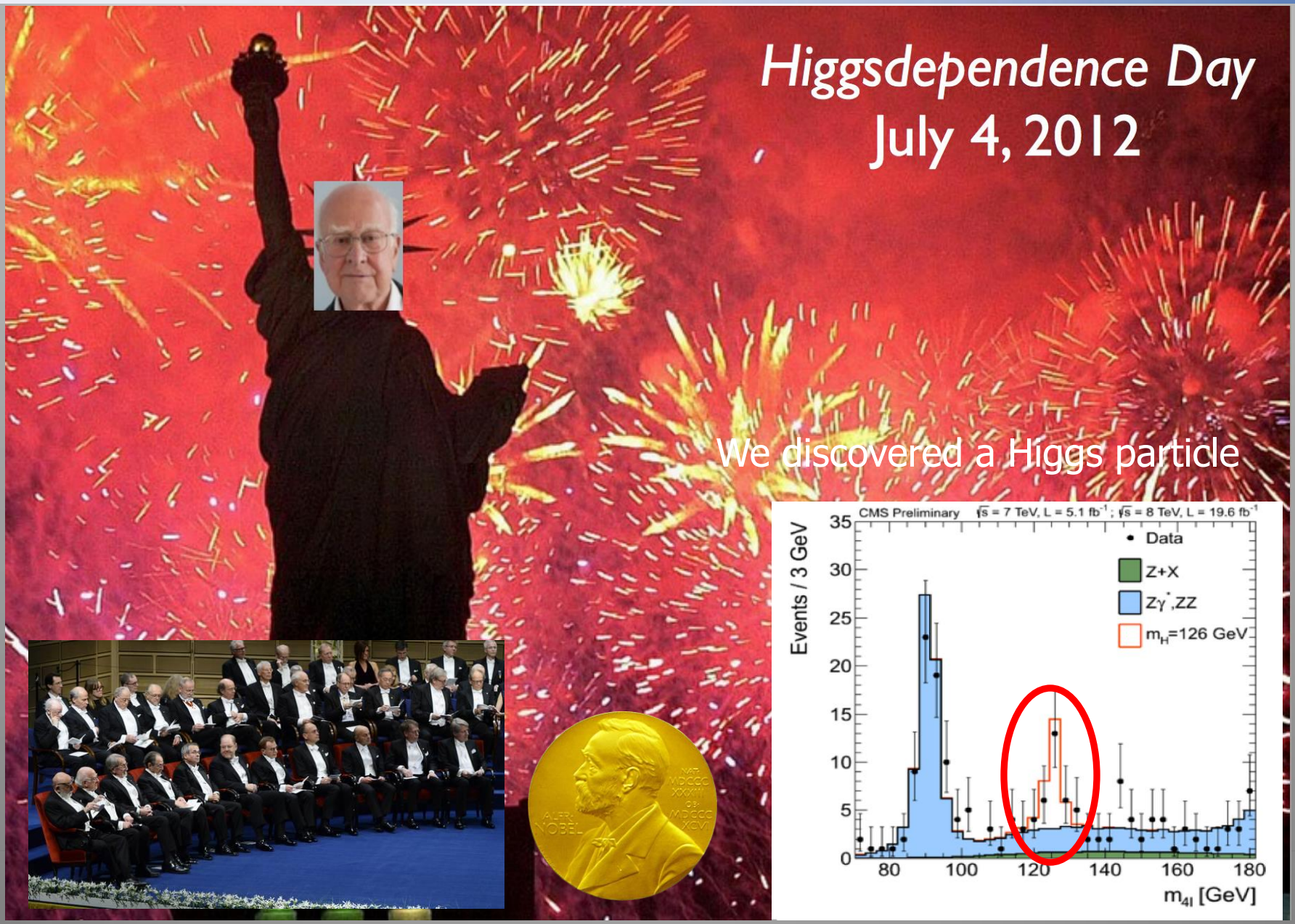
Primary physics targets

- 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

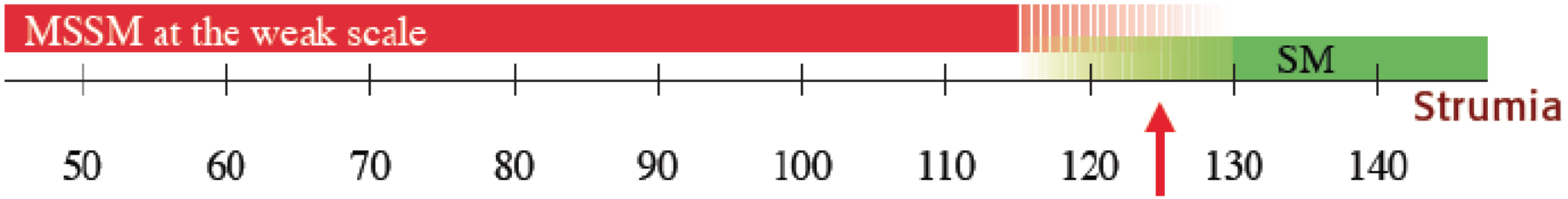
4th of July 2012…



A Higgs…

A malicious choice!

$m_H = 125.6 \pm 0.4$ GeV



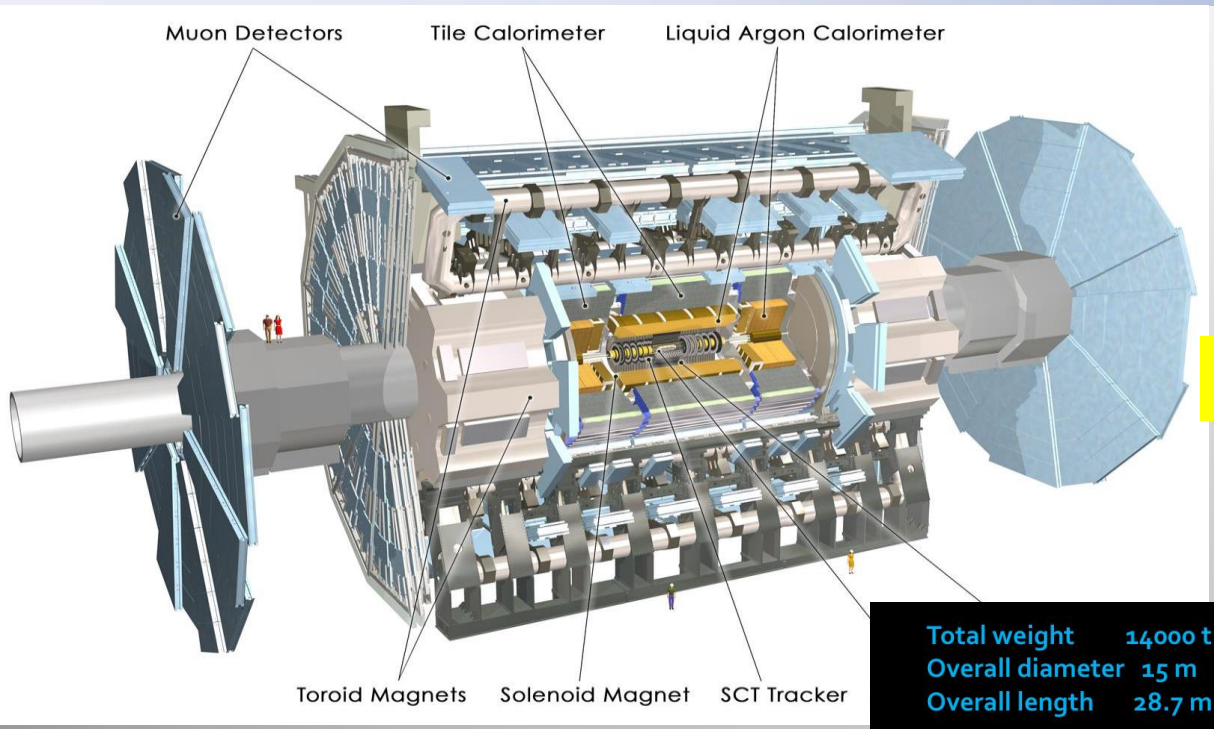
The Higgs:
so simple yet so unnatural

Guido Altarelli

Stockholm Nobel Symposium
May 2013

Note: the LHC is a Higgs Factory: 1 Million Higgses already produced
15 Higgses/second with present lumi.

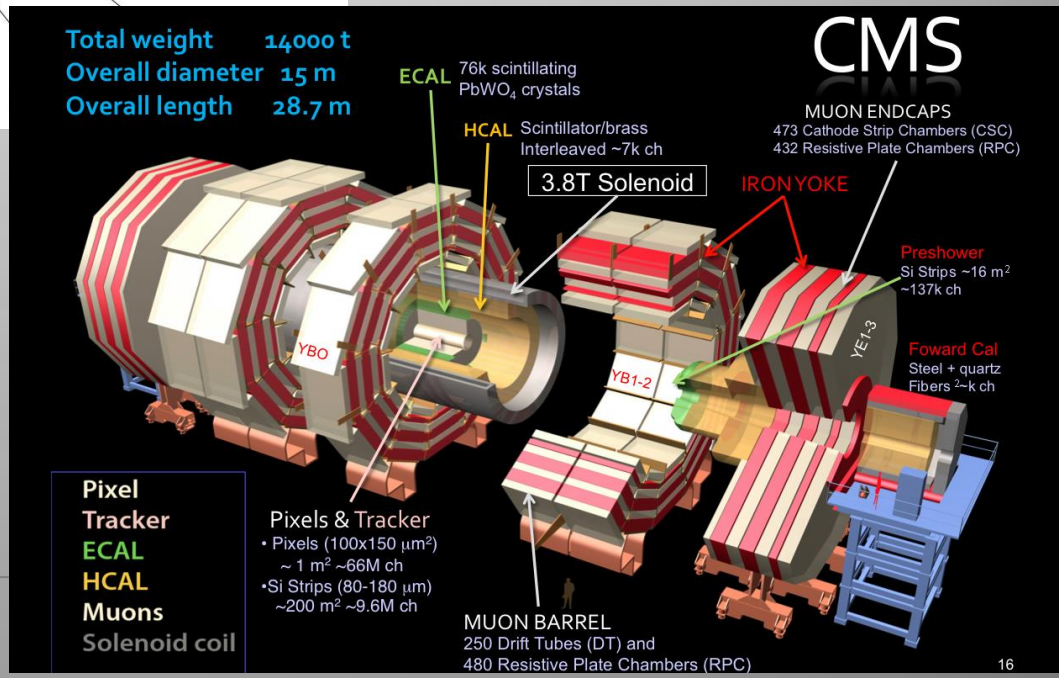
The Higgs Hunters @ the LHC



LHC: pp collisions at 7/8 TeV

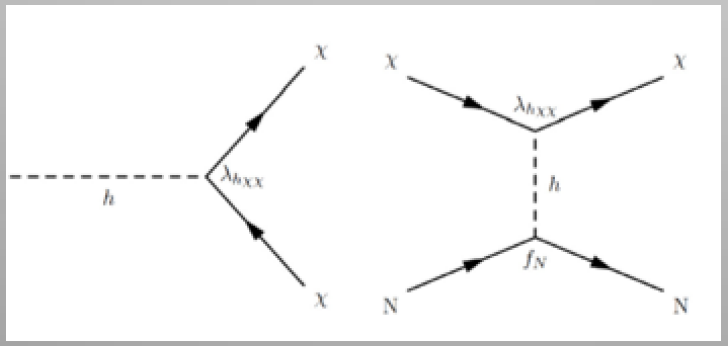
The ATLAS experiment

The CMS experiment



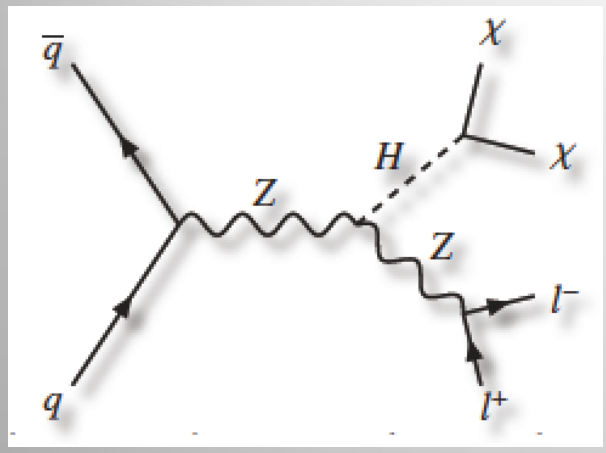
These experiments are likely to become DARK MATTER HUNTERS in 2015 and beyond…

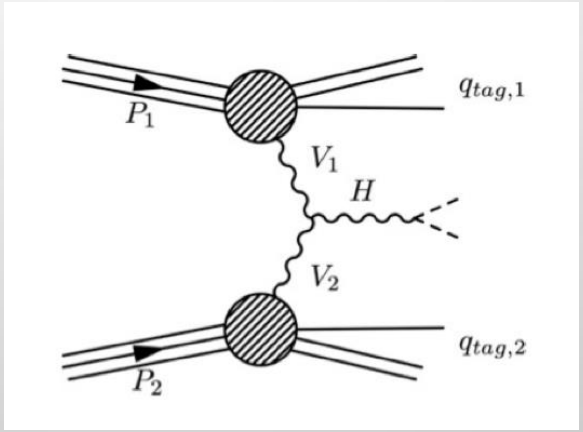
Dark Matter and the Higgs



"higgs portal models"
Eg: arXiv:1205.3169

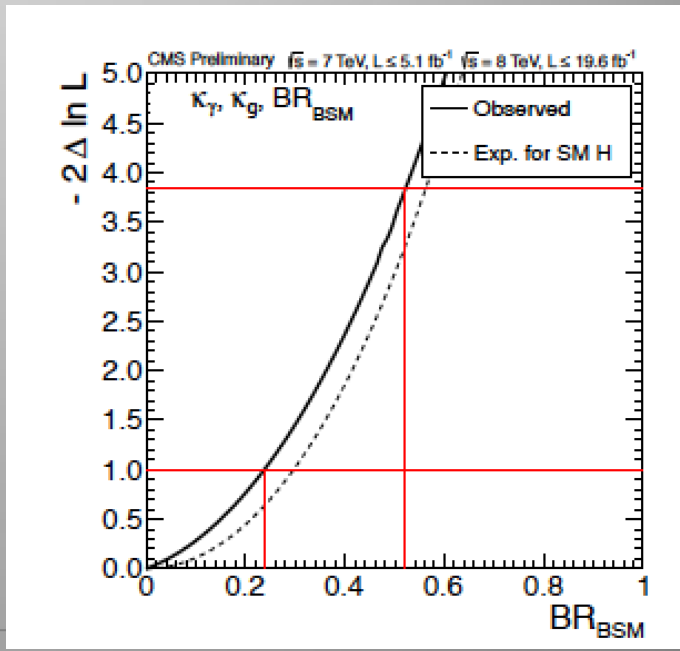
Invisible Higgs Decay Channel





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)

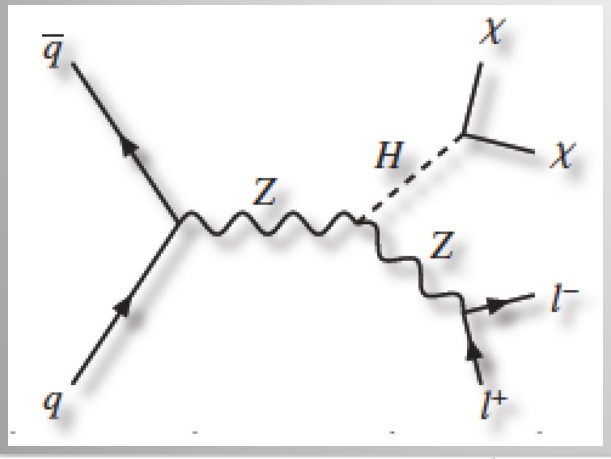


See lectures of Andre next week

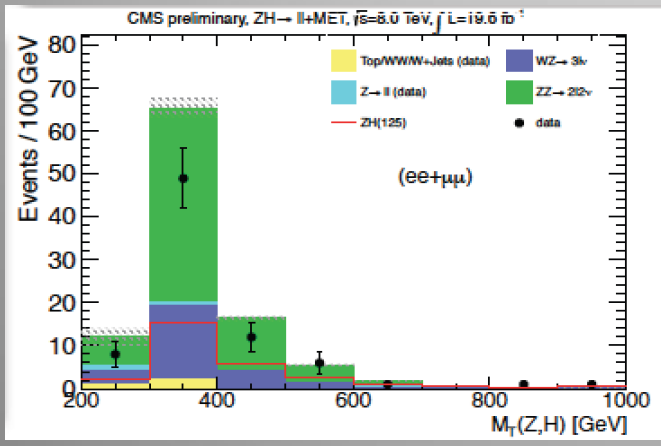
Invisible Higgs Decay Channel

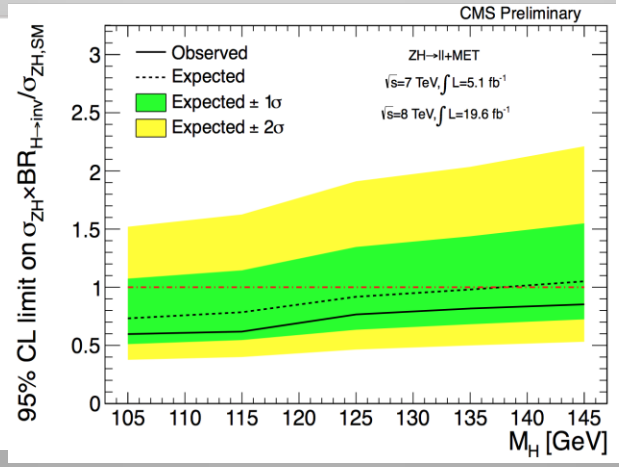
CMS-PAS-HIG-13-018

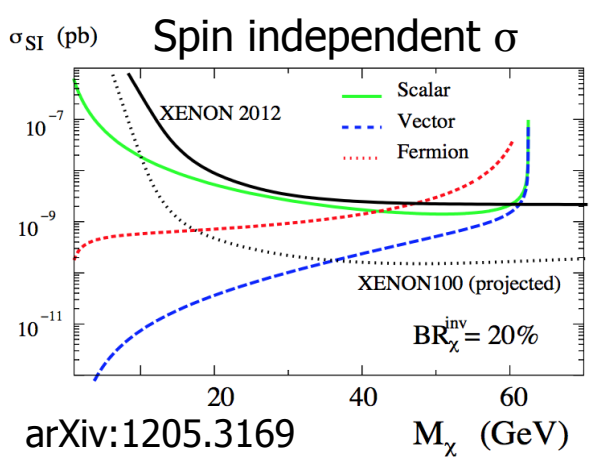
Search for Invisible Higgs decays in the ZH process
Z+H → 2 leptons + missing E_T
Possible decay in Dark Matter particles (if $M<M_H/2$)



- CMS (5+20 fb^{-1}):
  - Br(H→χχ) < 75% (91% exp.) @ 95% CL, m_H = 125 GeV





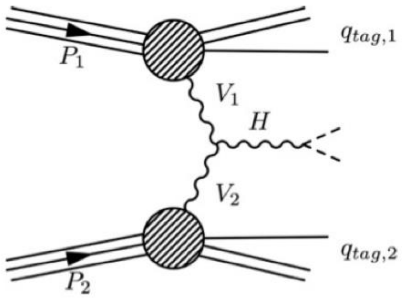


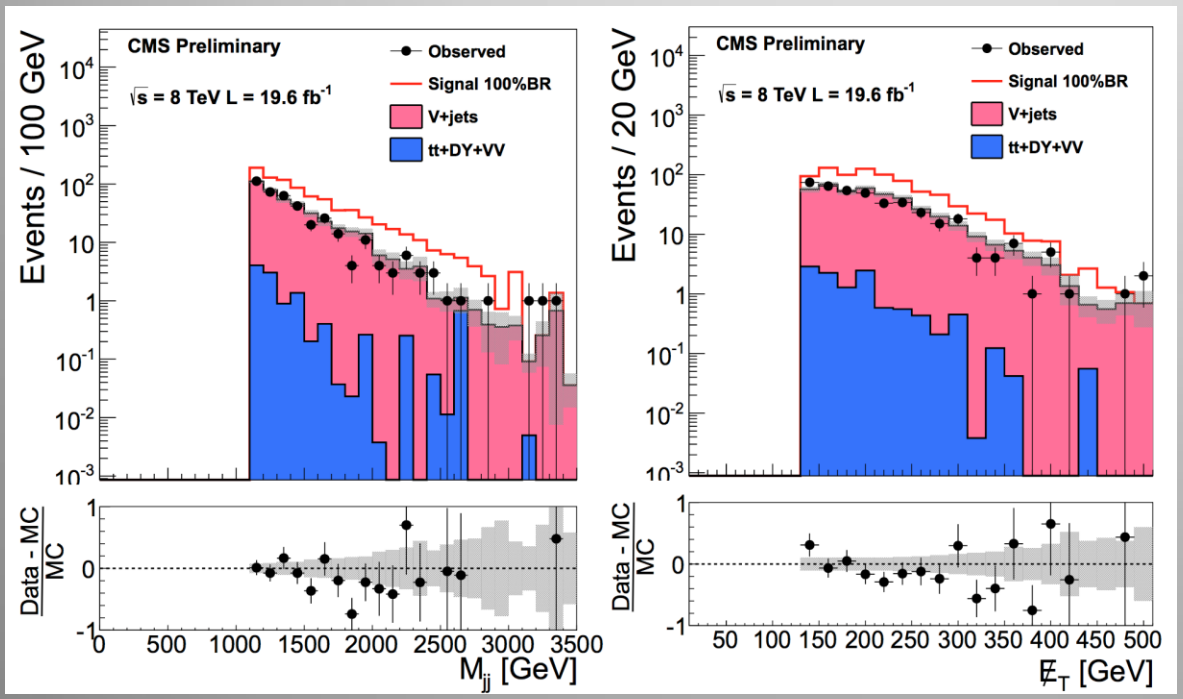
- No evidence for invisible decays in this channel

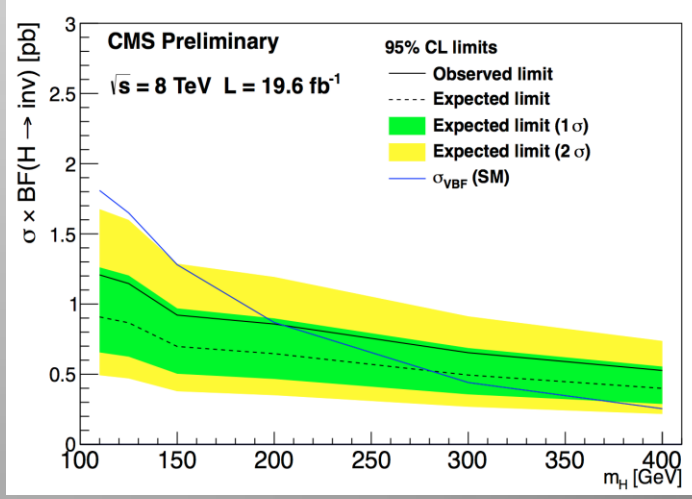
Invisible Higgs Decay Channel

CMS-HIG-13-013

- VBF associated Higgs production
- Special VBF+MET L1&HL triggers & big effort to reduce QCD BG
- Z(νν)+Jets background predicted using Z(μμ)

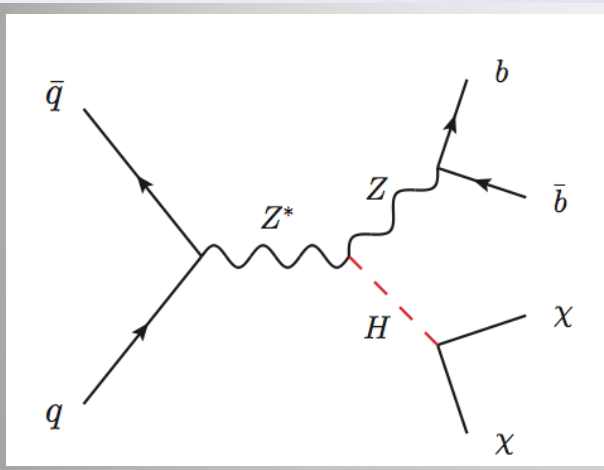






95% CL upper limit on BF(invisible) = 69% (53% expected)

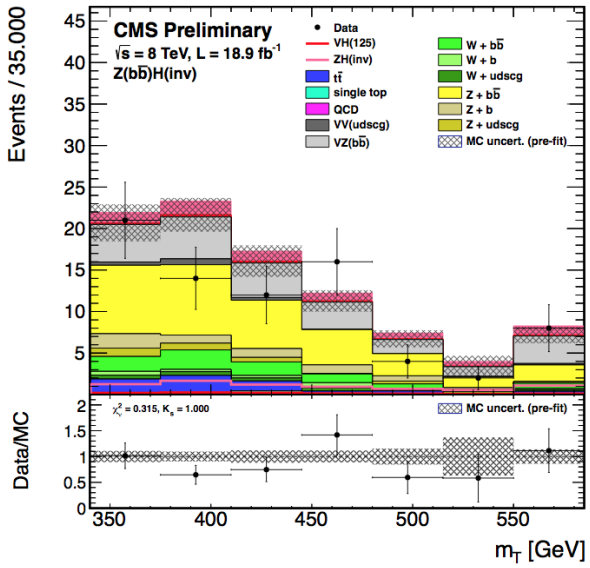
Invisible Higgs Decay Channel

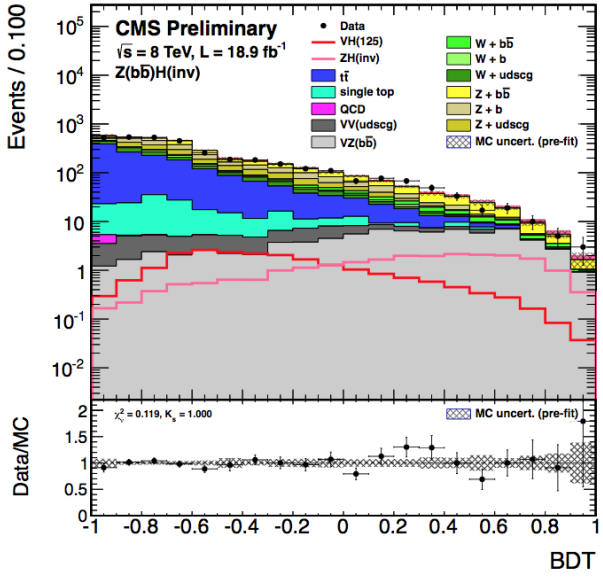


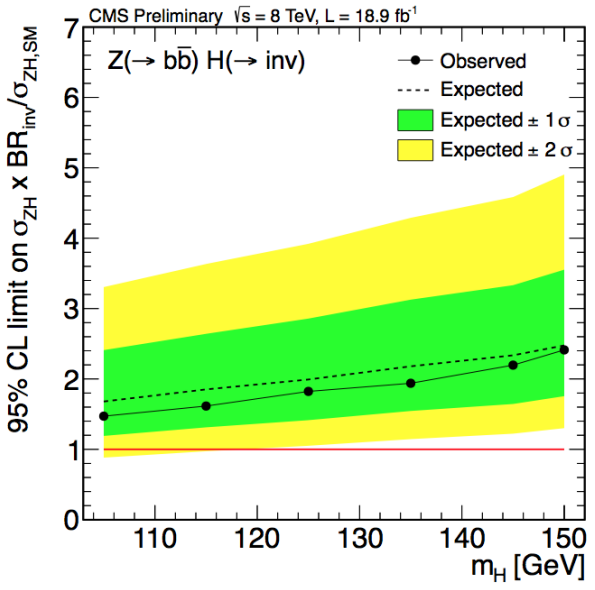
Search for Invisible Higgs decays in the ZH process
Z+H → 2 b quarks + missing E_T
Similar to the process Z+H with H →bb and Z→νν

CMS-PAS-HIG-13-028

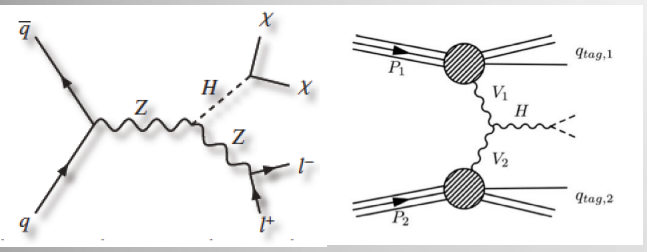
95% CL upper limit on BF(invisible)
= 1.82 (1.99 expected)





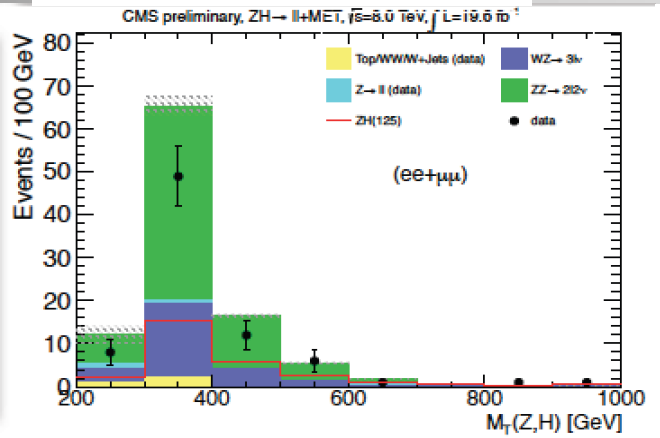


Invisible Higgs Decay Channel

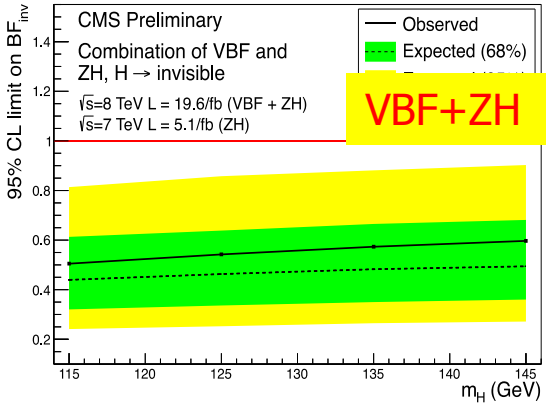


Search for invisible Higgs decays in the processes
Z+H → 2 leptons + missing E_T
VBF H → 2 jets + missing E_T
Possible decay in Dark Matter particles (if $M<M_H/2$)

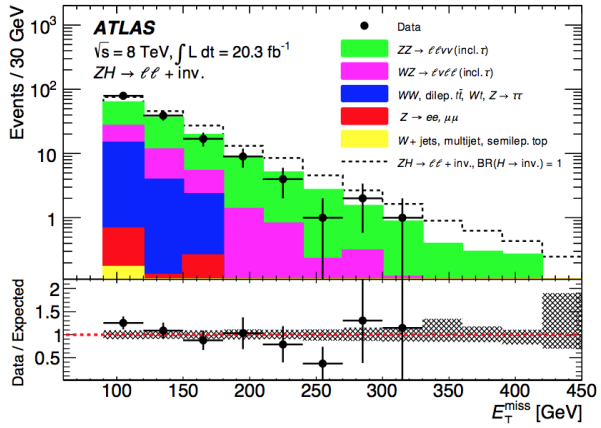
ATLAS :arXiv:1402.3244

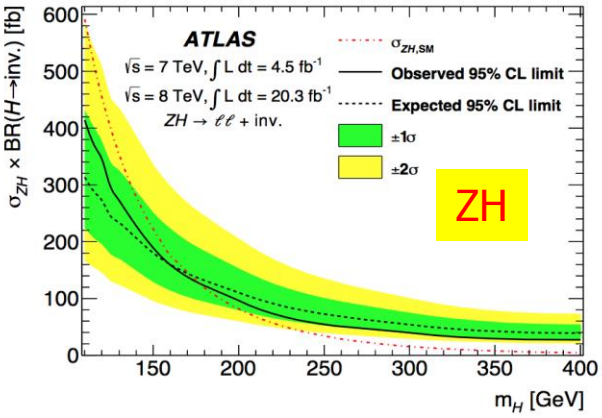


CMS-PAS-HIG-13-013/018



- ATLAS (4.7+13.0 fb^{-1}):
  - Br(H→χχ) <75%(62% exp) at 95% CL. m_H = 125 GeV
- CMS (5+20 fb^{-1}):
  - Br(H→χχ) <54%(46% exp) at 95% CL. m_H = 125 GeV

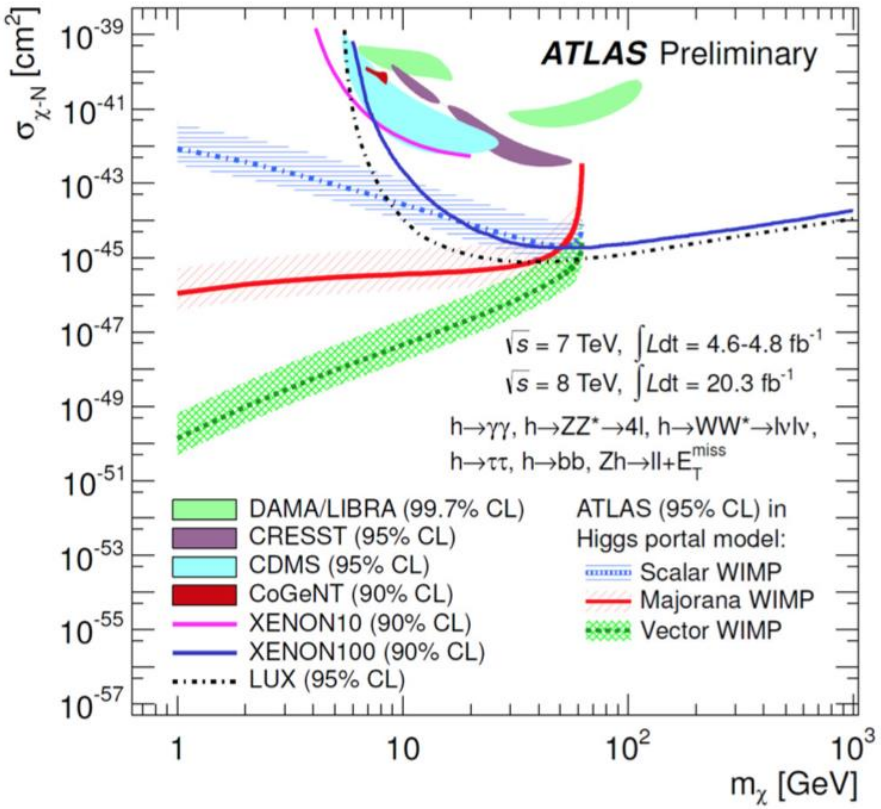


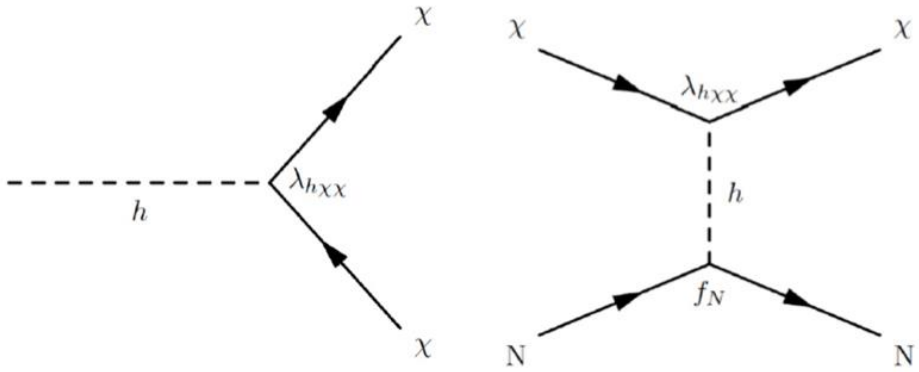


- No evidence for invisible decays found so far
- More channels & data coming up...

Higgs Portal to Dark Matter

- "Higgs Portal" model extends SM to include weakly interacting massive particles (WIMPs) coupling to Higgs boson
- Dark matter-nucleon scattering as well as decay rate inferred from Higgs invisible decays
- Translate $BR_{i,u} < 0.37$ (0.39) obs. (exp.) at 95% CL (5-channel + Zh) into limits on DM rate (depends on WIMP spin)





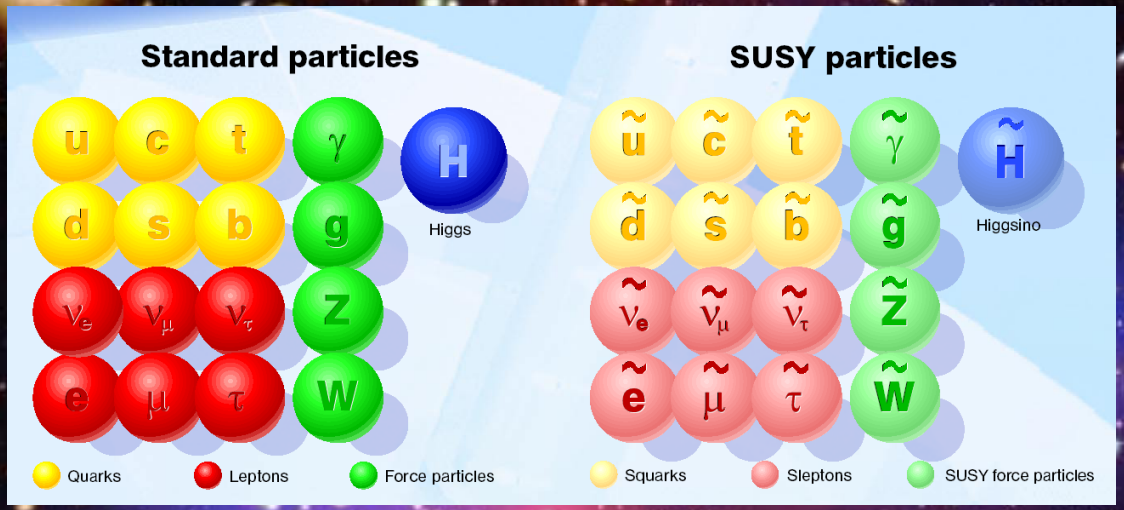
- Significantly more sensitive at low mass for vector WIMP than direct detection experiments *assuming Higgs Portal model*
- Sensitivity dominated by 5-channel coupling combination

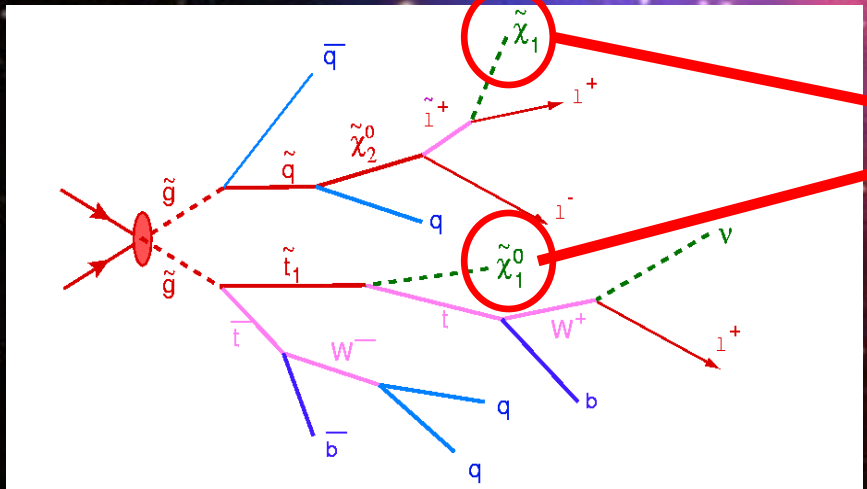
Includes results from a fit of the visible+invisible cross sections results

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?





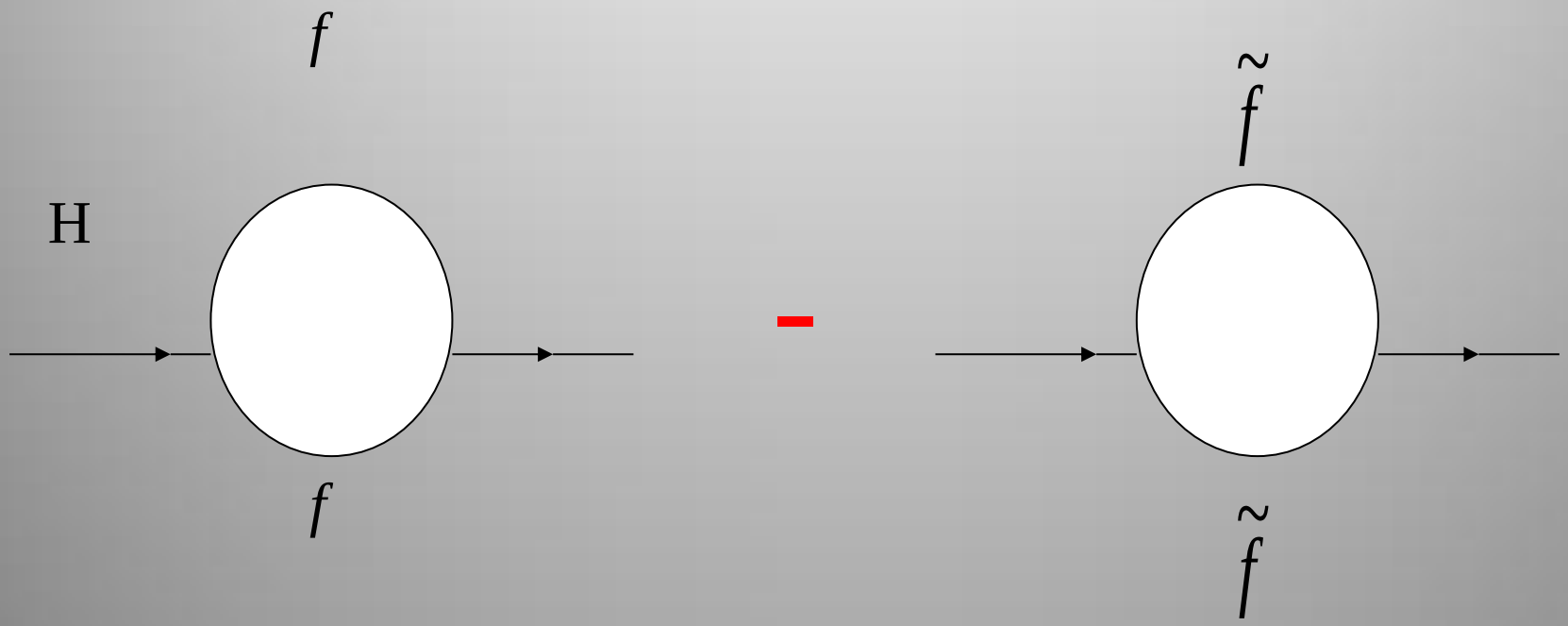
SUSY particle production at the LHC

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

Picture from Marusa Bradac

Supersymmetry

Supersymmetry (SUSY) → assumes a new hidden symmetry between the bosons (particles with integer spin) and fermions (particles with half integer spin). Stabelize the Higgs mass up to the Planck scale



Fermion and boson loops cancel, provided $m_{\tilde{f}} \leq$ TeV.

Why weak-scale SUSY ?

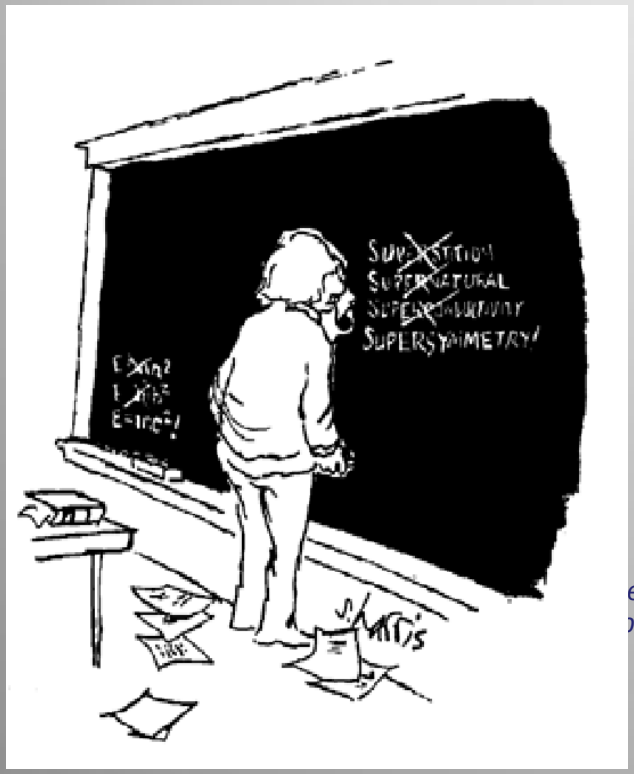
- stabilises the EW scale: $|m_F - m_B| < O(1\ \text{TeV})$
- predicts a light Higgs $m_h < 130$ GeV
- predicts gauge unification
- accomodates heavy top quark
- dark matter candidate: neutralino, sneutrino, gravitino, ...
- consistent with EW precision tests (discussed yesterday)

Discovering SUSY – A revolution in particle physics!!

Supersymmetry

A VERY popular benchmark…

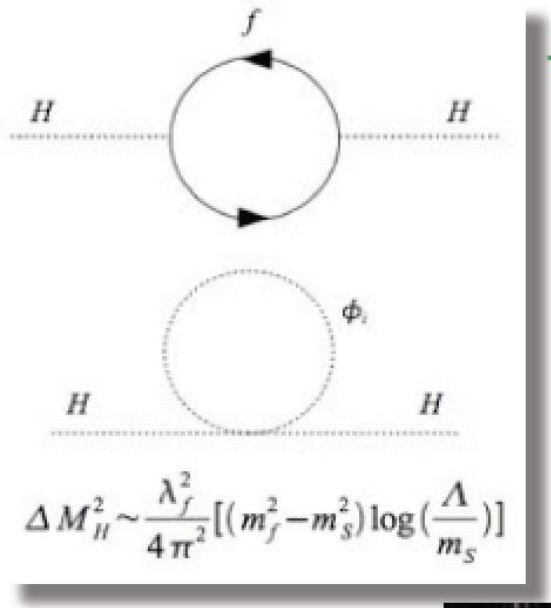
More than 10000 papers since 1990



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

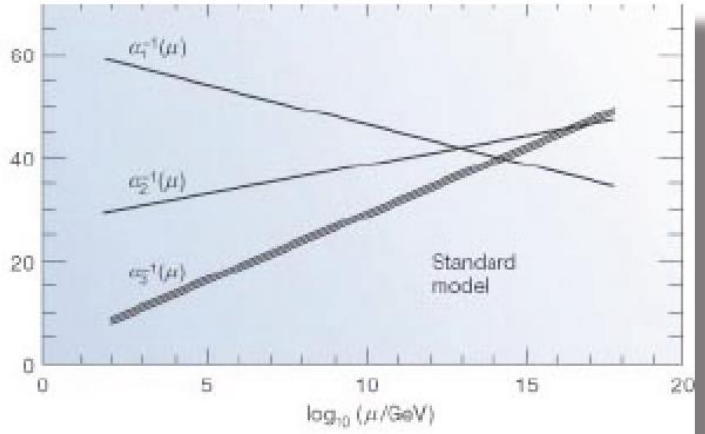
Considered as a benchmark for a large class of new physics models

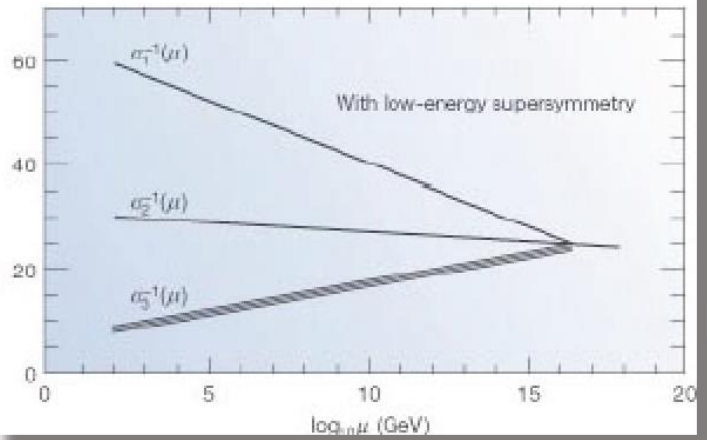
Summary: Why SUSY is good for you!!



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

- Gauge unification

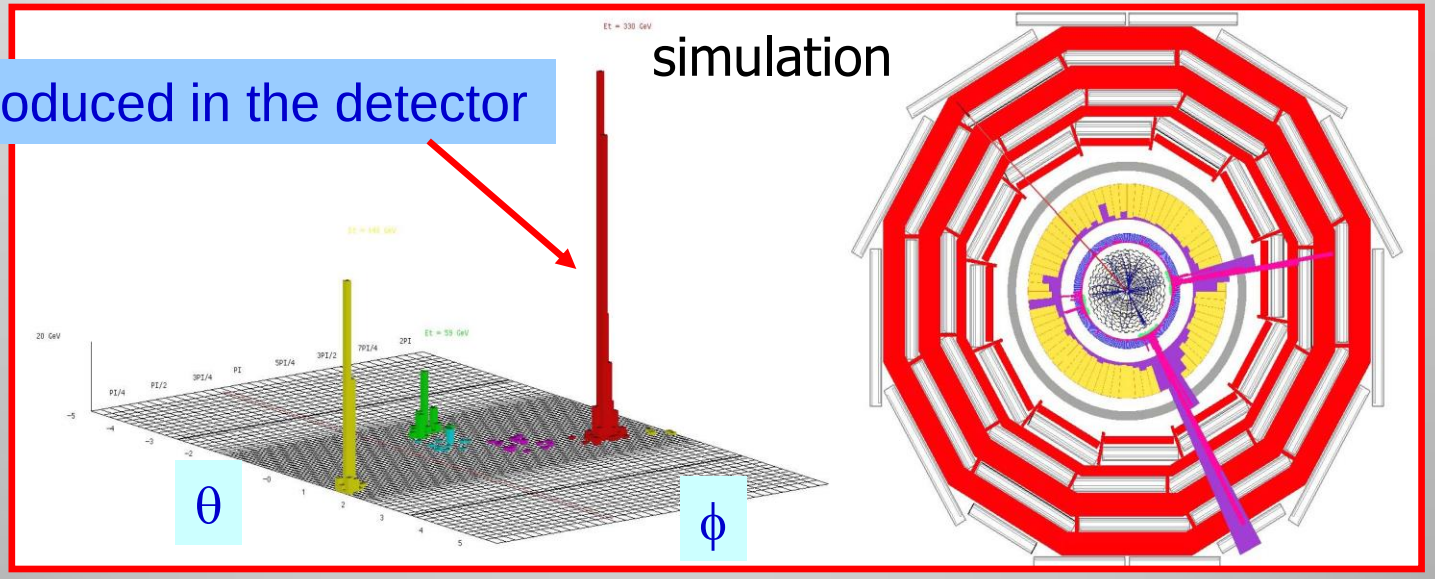


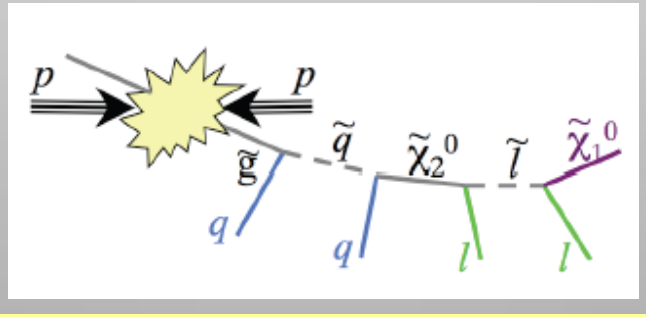


- Dark matter candidate with the right abundance

Detecting Supersymmetric Particles

Energy produced in the detector





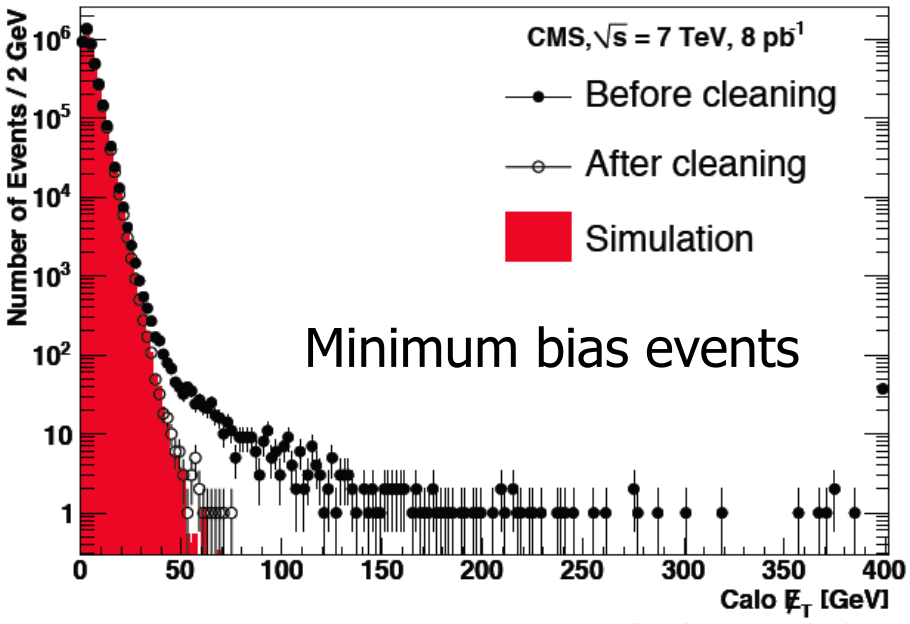
Supersymmetric particles decay and produce a cascade of jets, leptons and missing transverse energy (MET) due to escaping ‘dark matter’ particle candidates

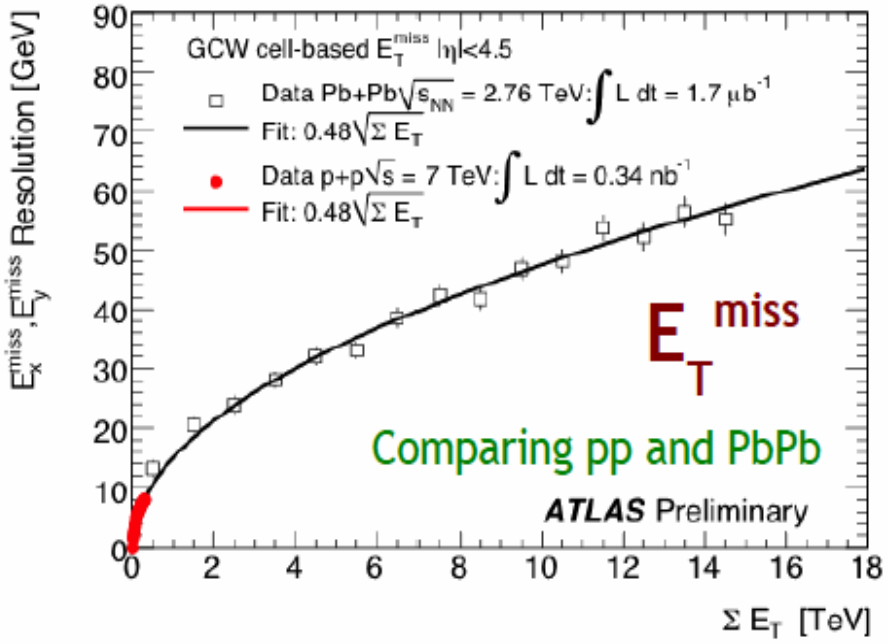
→ Very prominent signatures in CMS and ATLAS

Missing Transverse Energy

Total transverse momentum imbalance

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



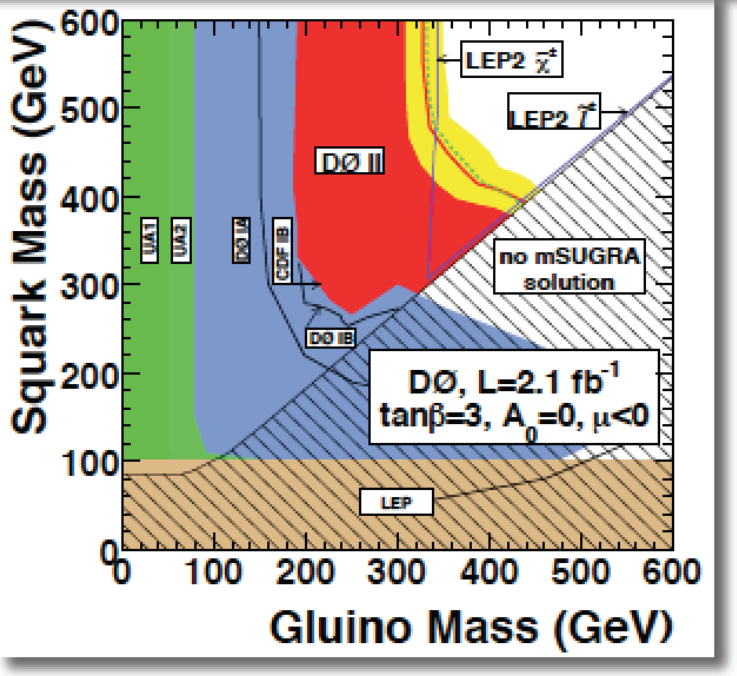


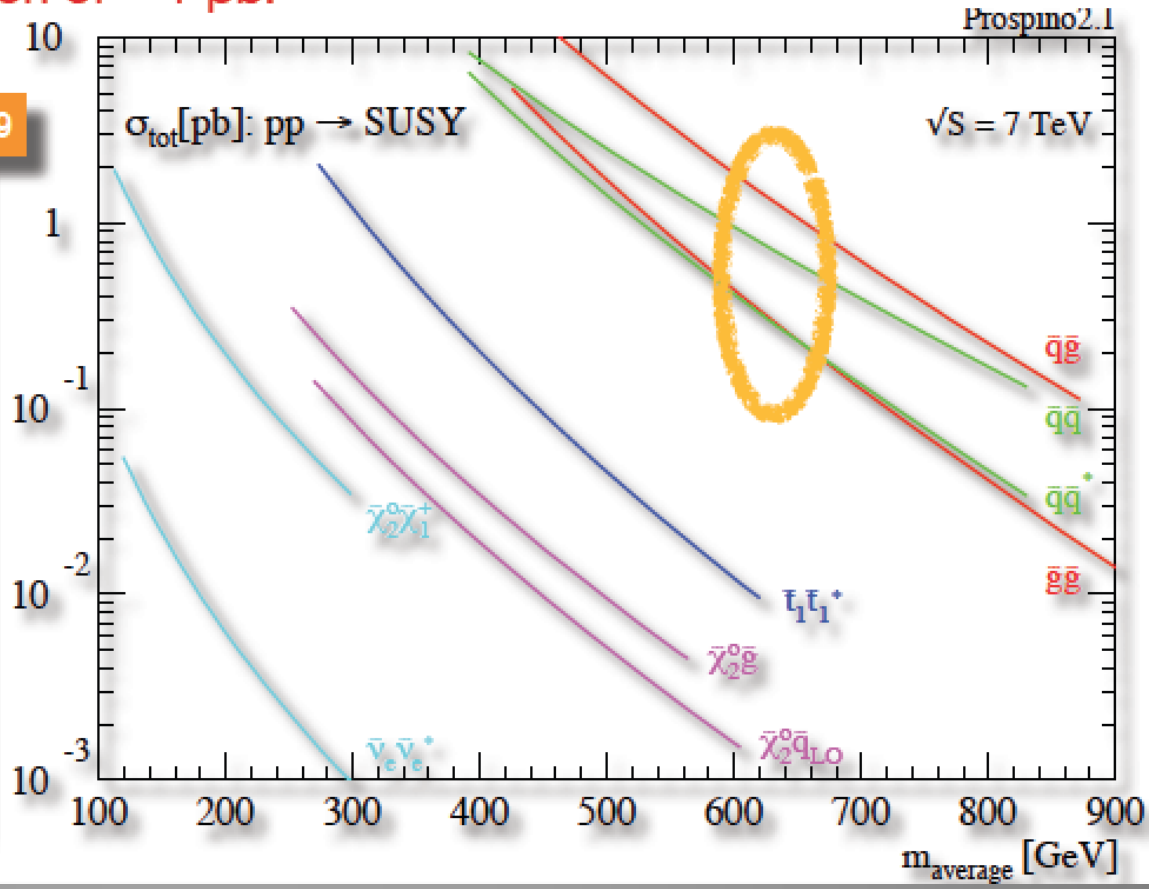
- In practice, rather well under control, from the start
- Good resolution using 'particle flow' ie maximally identifying particles
- More Pile-up in future will NOT make this simpler

SUSY 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 ~ 1 pb!

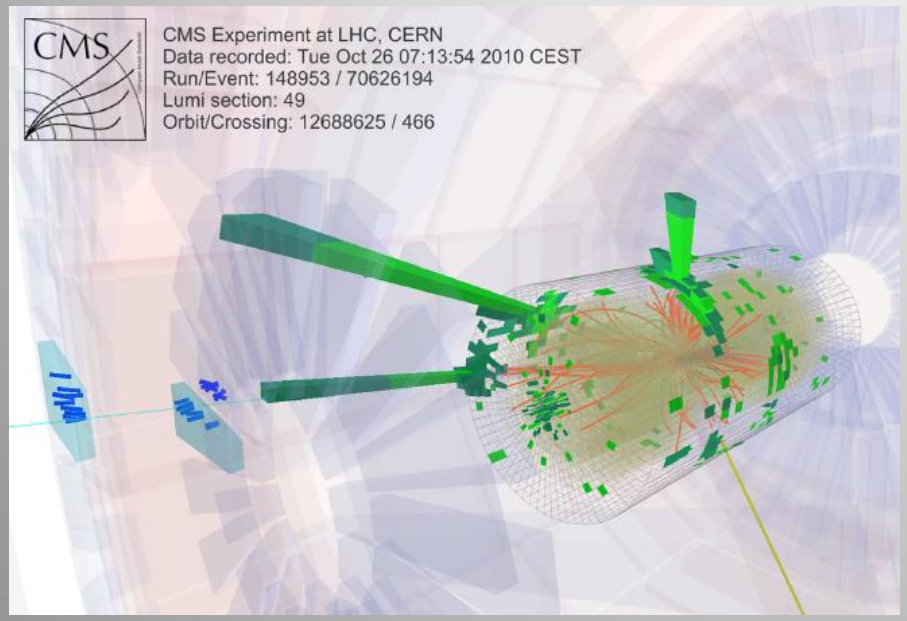
D0 Collaboration, Phys. Lett. B660 (2008) 449

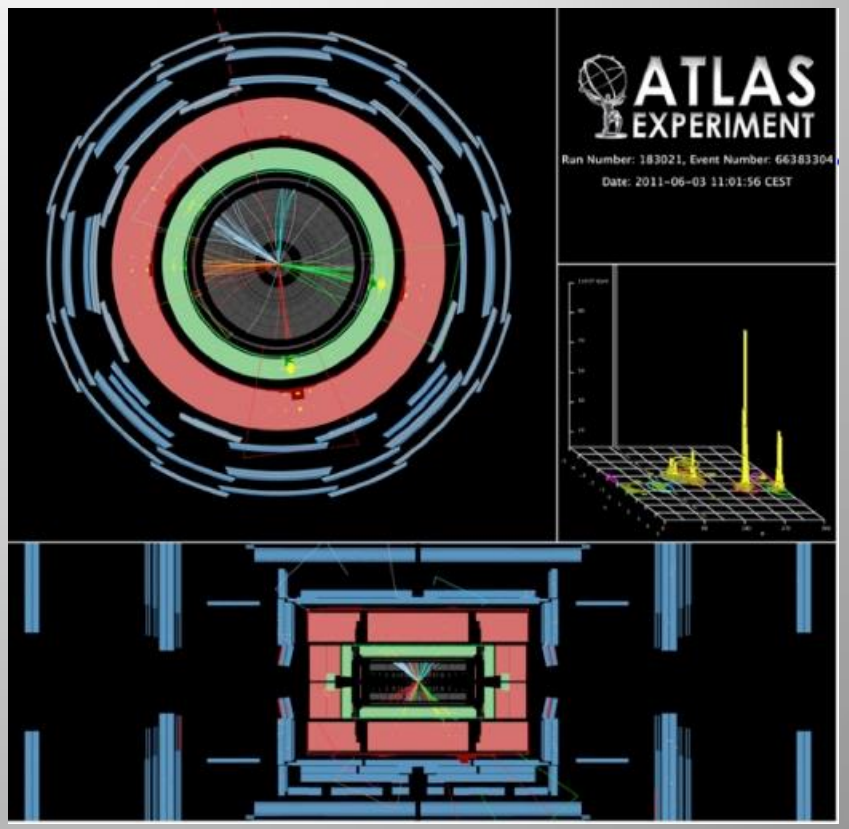




…Some Interesting Collisions…

…already in 2010…



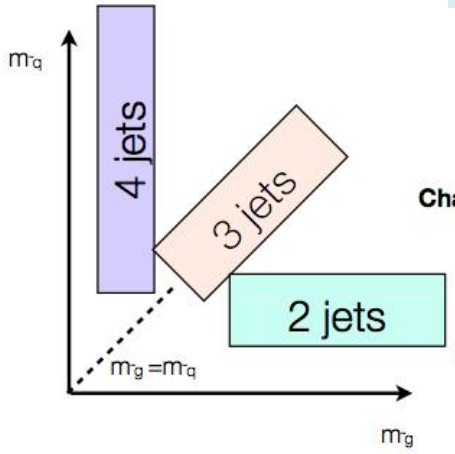


- Events with five jets of particles and large missing energy which could come from a possible dark matter particle
- But a few events is not enough too prove we have something new
  No visible excess has been building up with time…

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

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

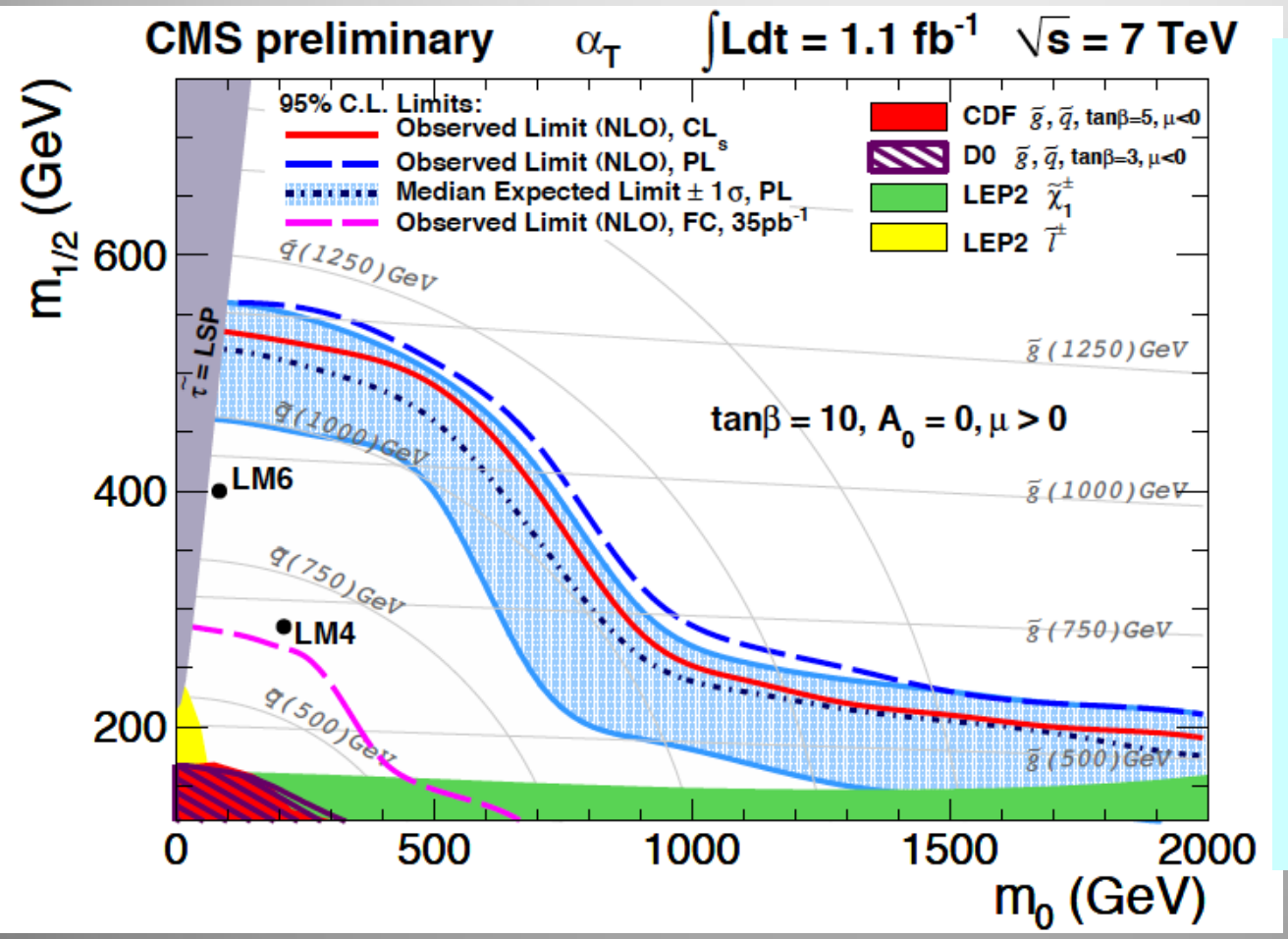
Take one example to show steps involved:

- 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 Search: Jets + Missing E_T Channel

CMS-SUS-11-003

Using 1 fb^{-1}



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

-tanβ: vev ratio for 2 Higgs doublets

-A_0: trilinear coupling

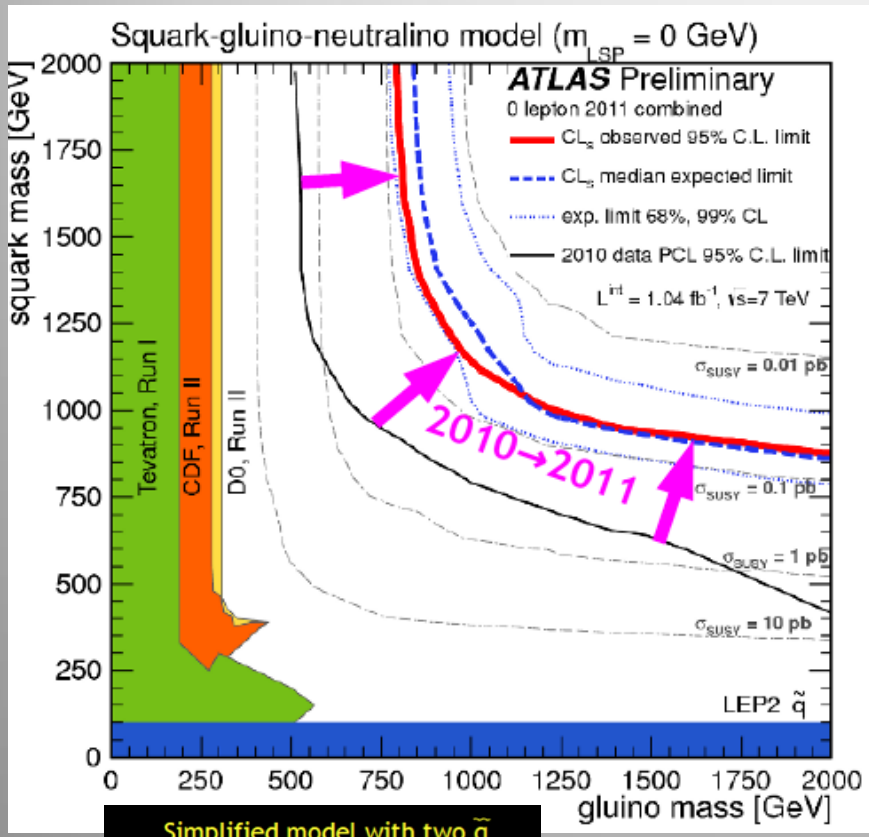
and the sign of Higgs mixing parameter μ

SUSY Search: Jets + Missing E_T Channel

Limits in a simplified model

Using 1 fb^{-1}

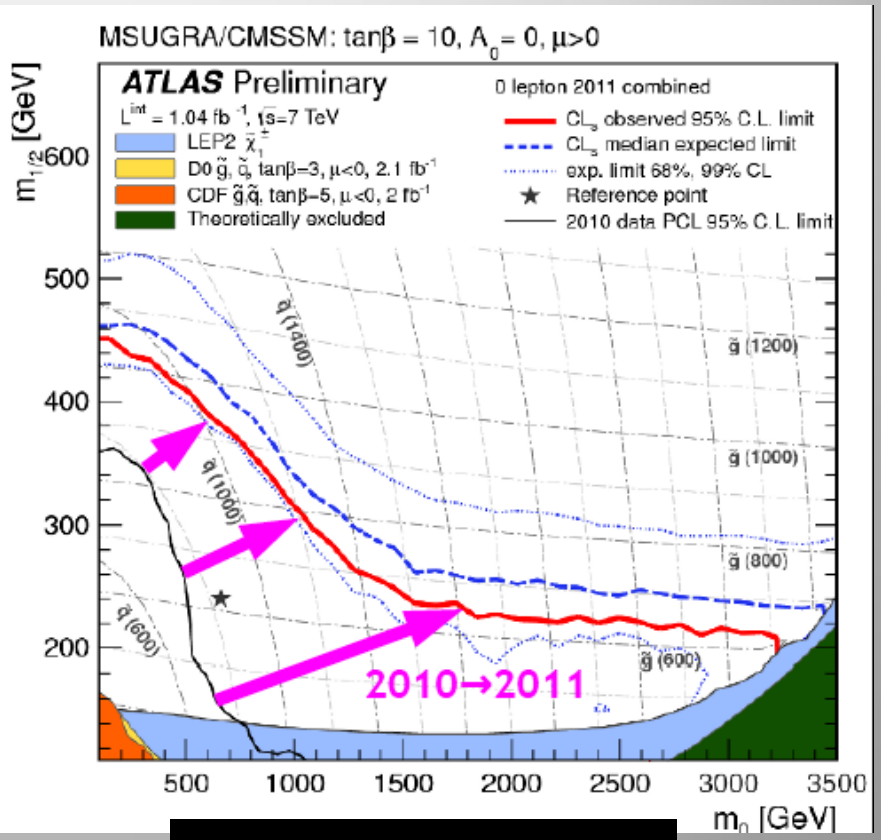
Limits in CMSSM



Simplified model with two $\tilde{q}$ generations, $m(\tilde{\chi}_1^0)$~0

$m_{\tilde{g}}$>800 GeV $m_{\tilde{q}}$>850 GeV

Equal mass case: $m_{\tilde{g}}=m_{\tilde{q}}$>1.075 TeV



MSUGRA/CMSSM: tanβ=10, A_0=0, μ>0

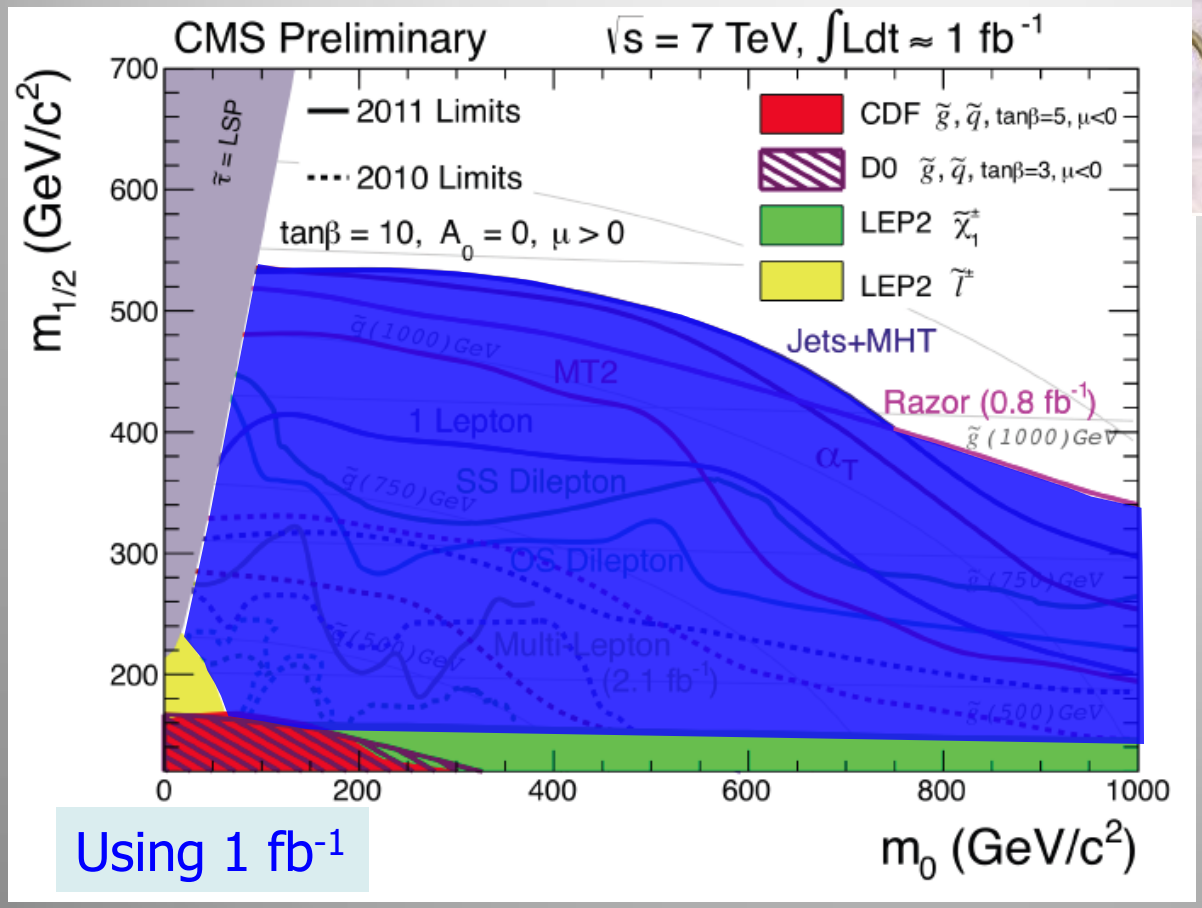
Equal mass case: $m_{\tilde{q}}=m_{\tilde{g}}$ > 980 GeV

Up to masses of 1 TeV excluded for equal gluino-squark masses

Extends the 2010 data limits by ~ 250 GeV

SUSY Summary:lepton and hadronic channels

Many different analysis



Using 1 fb^{-1}

The spaghetti monster plot

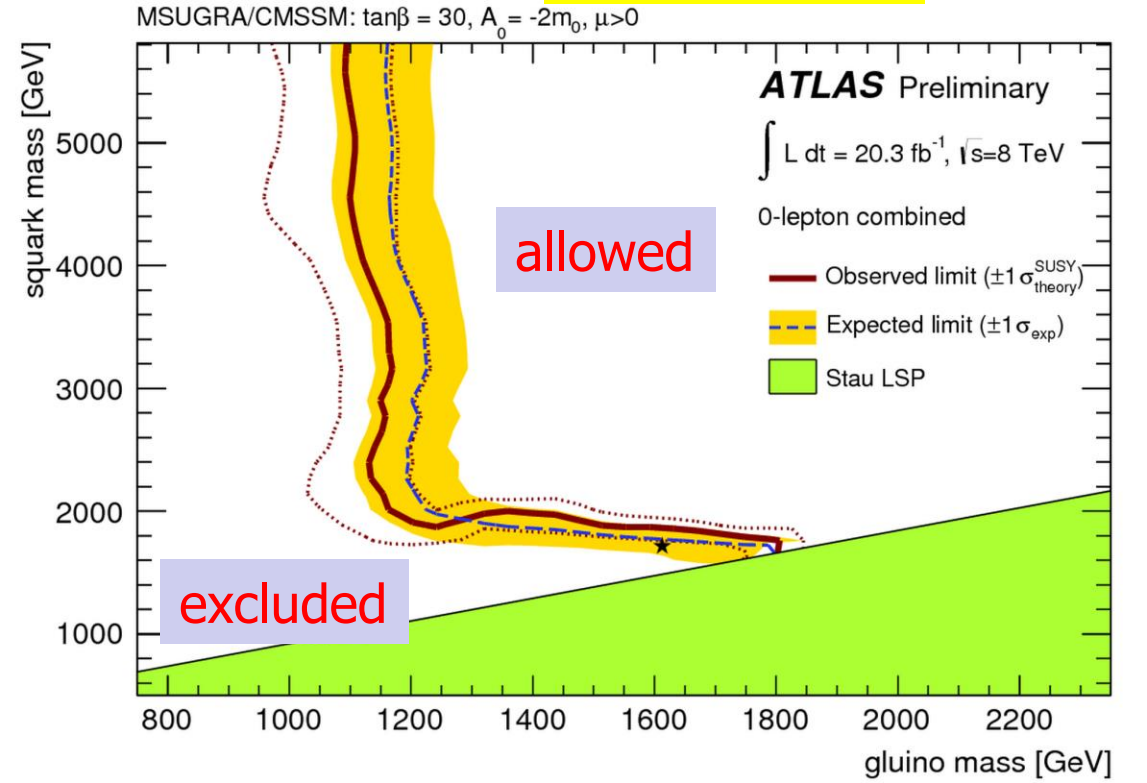
Results of SUSY analyses with 1 fb^{-1}
α_T , MHT, MT2, Razor, Same Sign and Opposite Sign dileptons…

The CMSSM has 4 parameters
-$m_{1/2}$: universal gaugino mass at GUT scale
- m_0: universal scalar mass at GUT scale
-tanβ 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

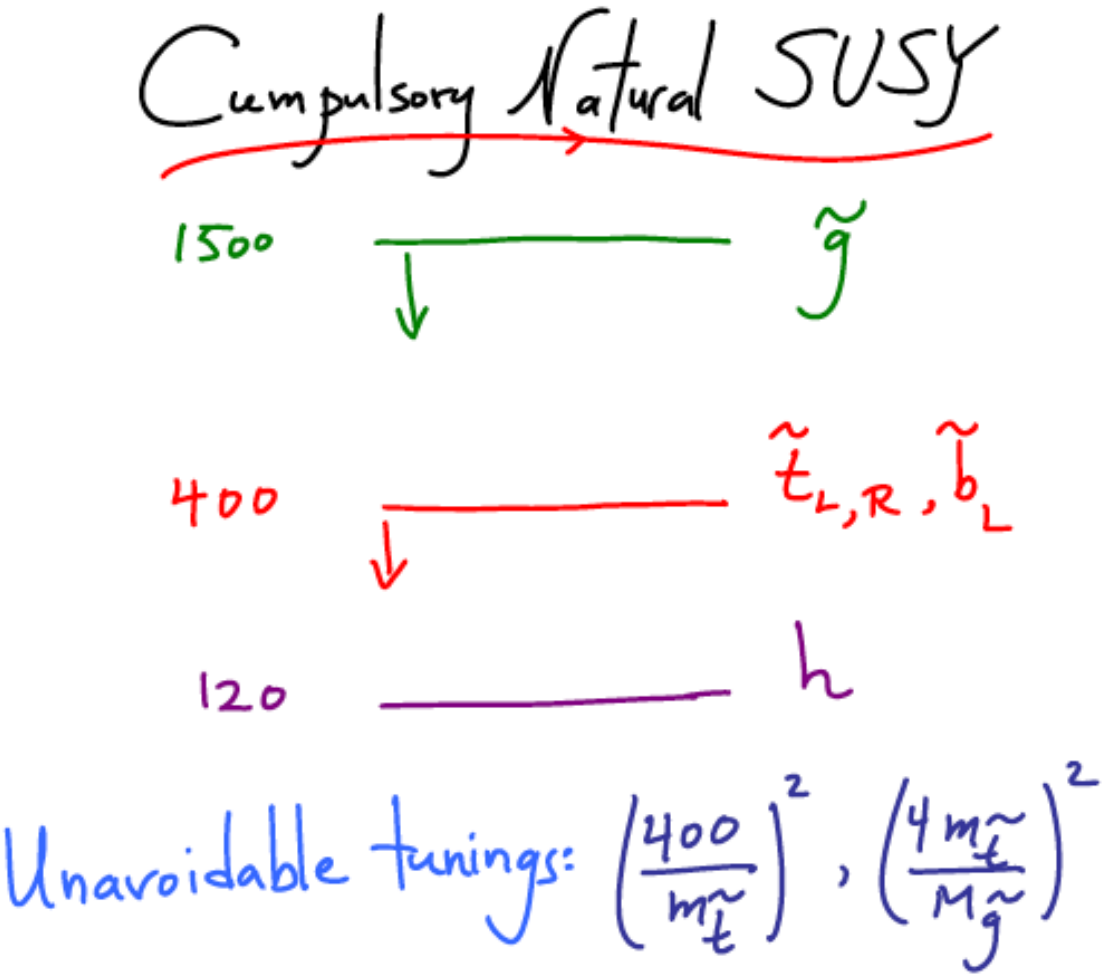
What is really needed from SUSY?

N. Arkani-Ahmed
CERN Nov 2011

Papucci, Ruderman, Weiler arXiv:1110.6926

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

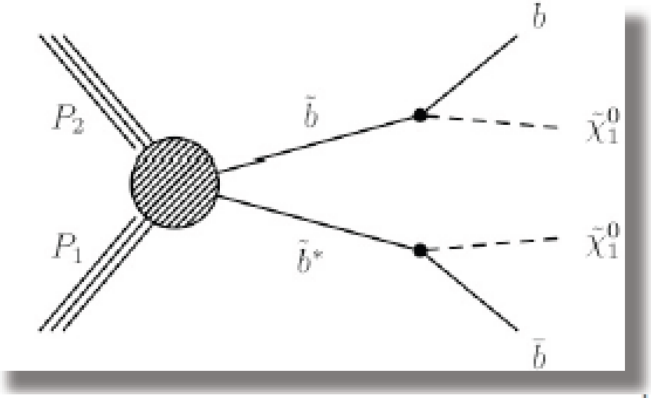
Natural SUSY survived LHC so far, but we are getting close to push it at its limits!

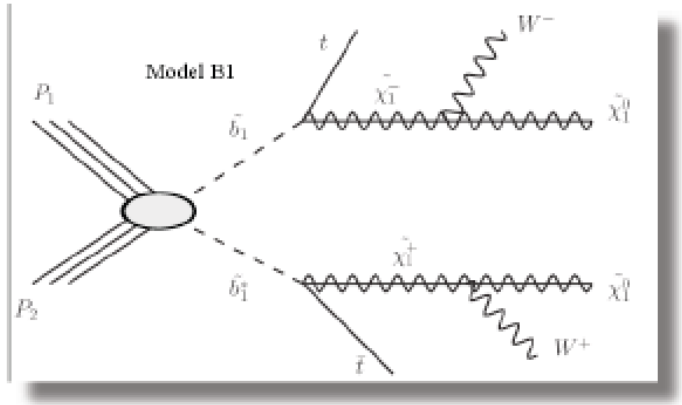


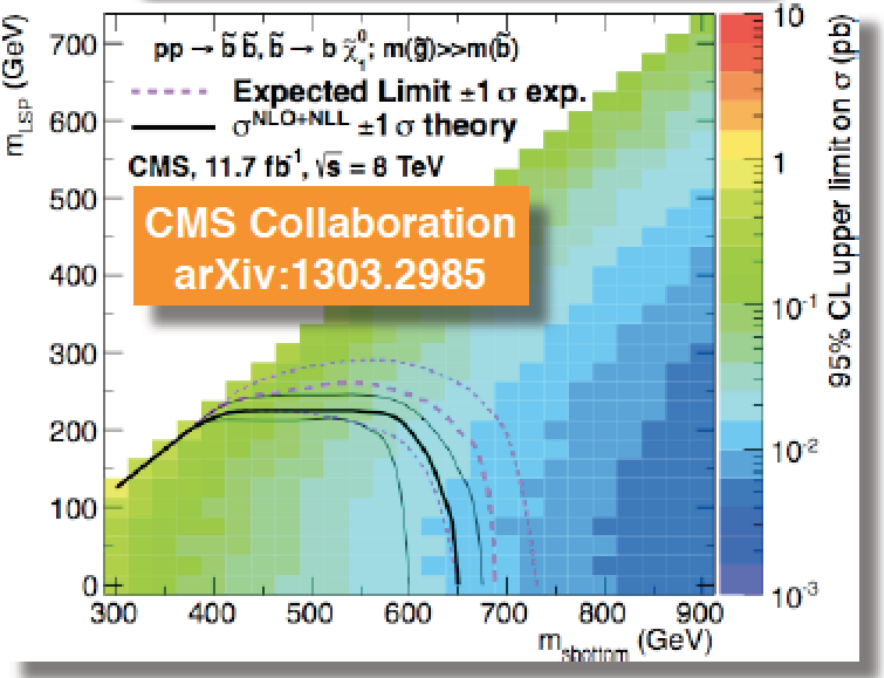
...Lawrence Hall 2011 Berkeley Workshop

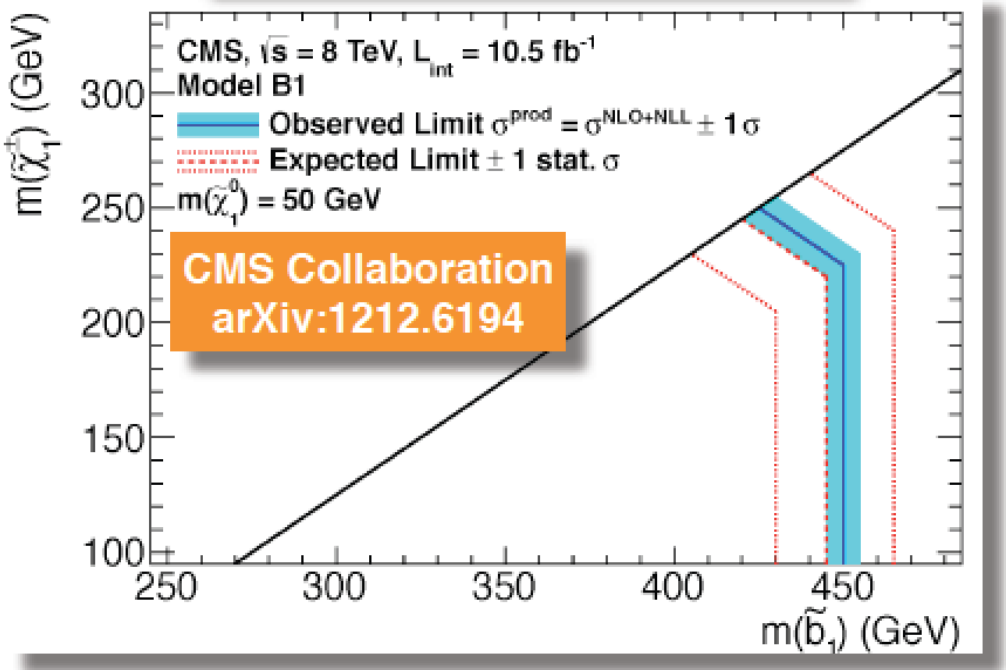
SUSY: Search for Third Generation Squarks

- Direct sbottom pair production was looked at in the all-hadronic α_T + b-jets and same-sign dilepton + b-jets channels:



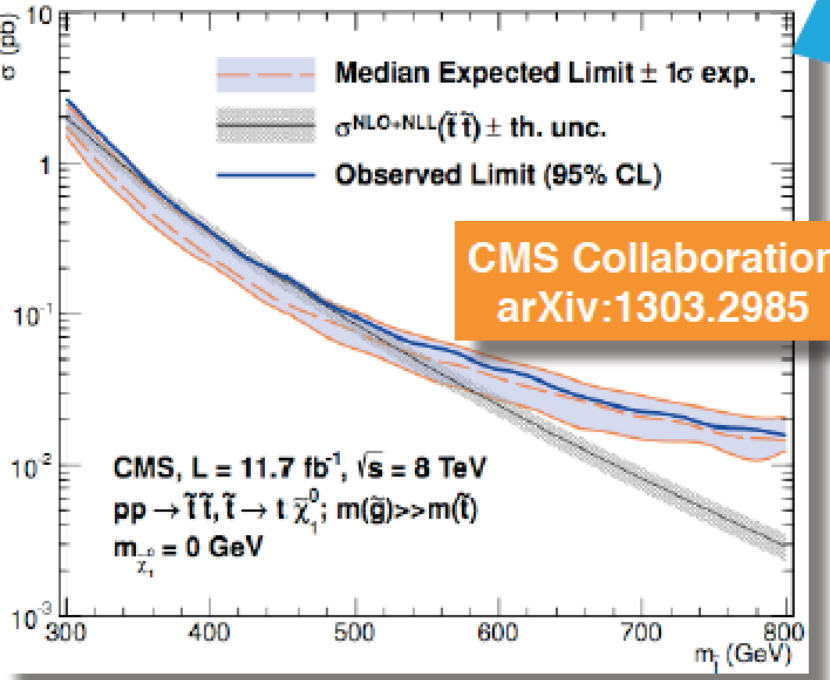




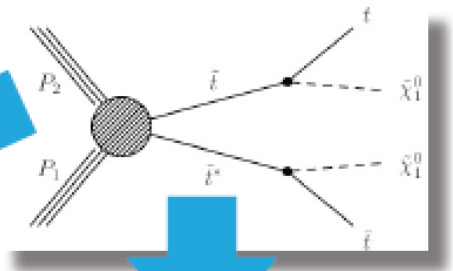


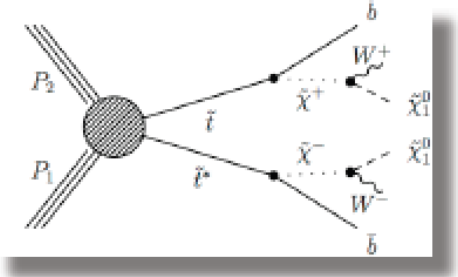
SUSY: Search for Third Generation Squarks

- This is the most hopeful, and yet the toughest channel at the LHC
- Simple reinterpretation of the existing analyses is not sensitive enough
- Requires a dedicated optimized tour-de-force analysis:
  - W+jets and tt with τ_h and lost leptons (from W(μν)+jets with embedded τ_h), invisible Z decays (from Z(μμ)), and multijets (reweighted MC with kinematics and resolutions reweighted to match multijet data)

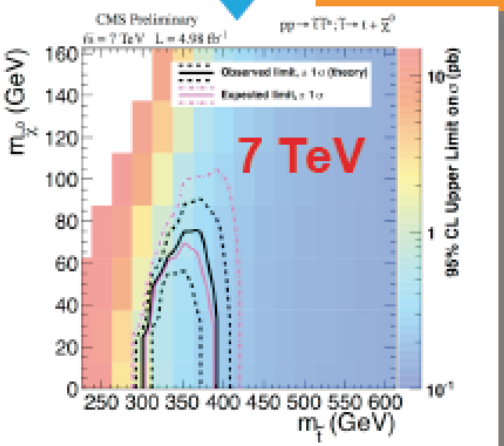


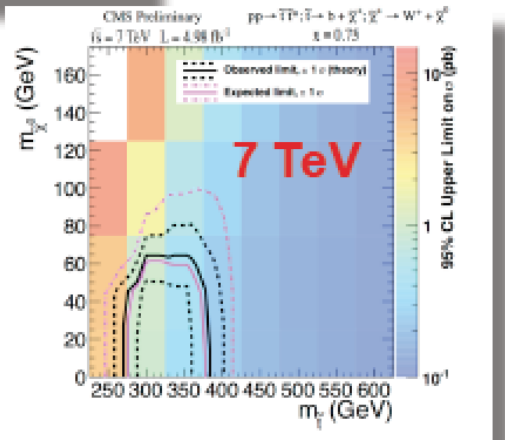
CMS Collaboration
arXiv:1303.2985



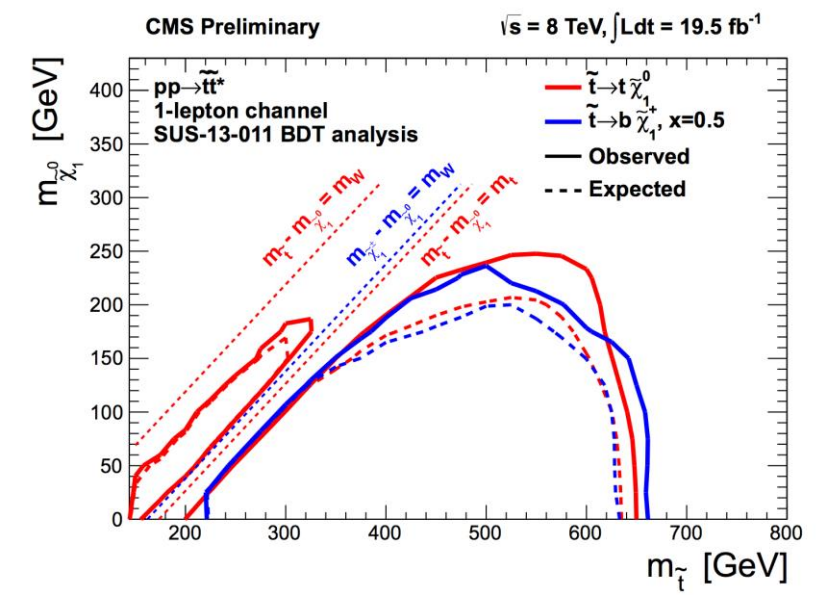


CMS SUS-11-030

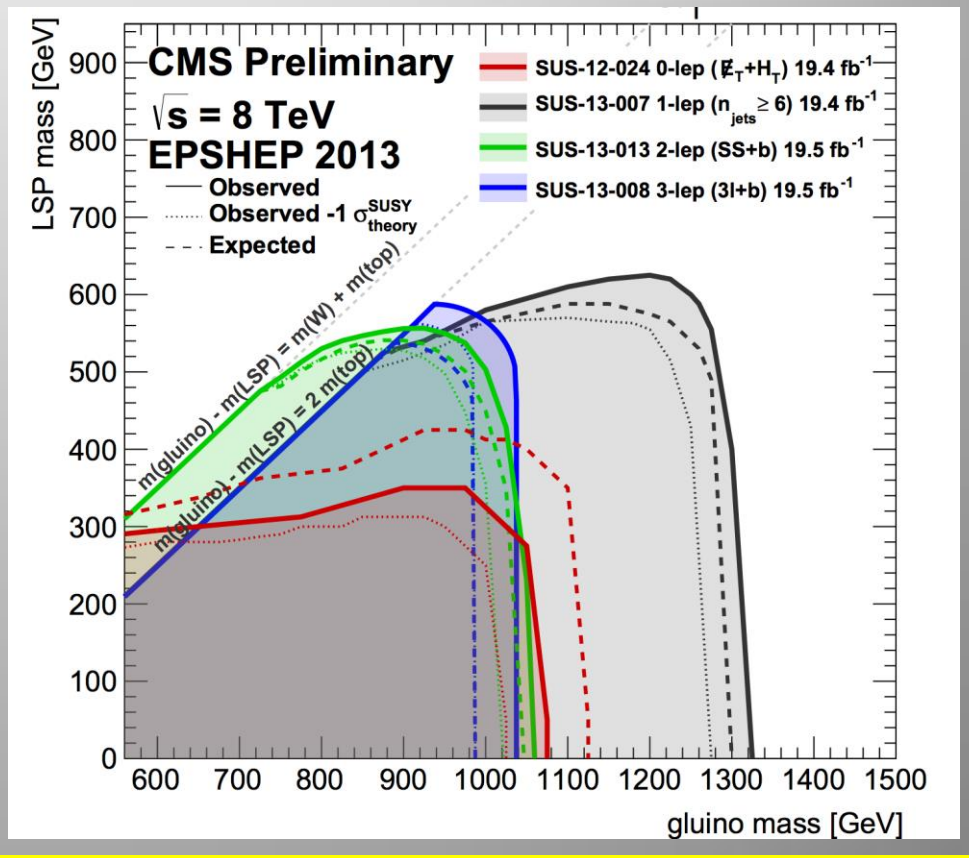


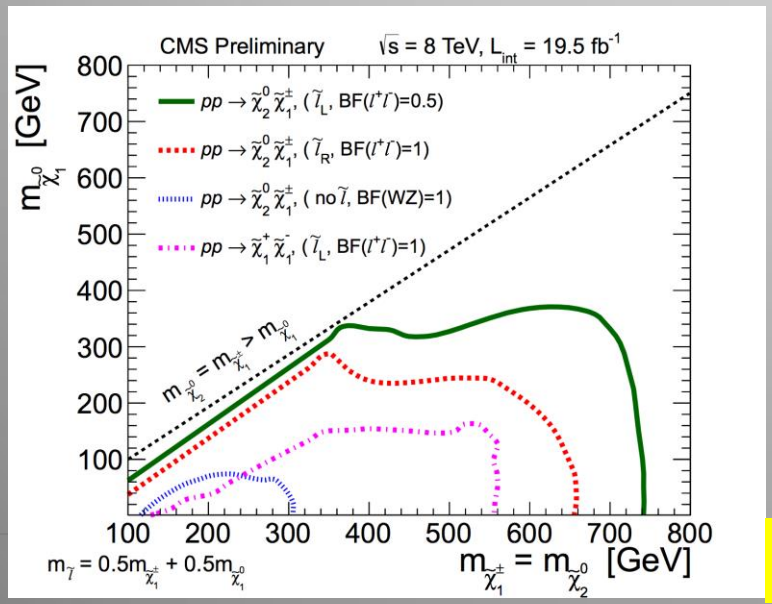


Typical Lightest SUSY particle limits…



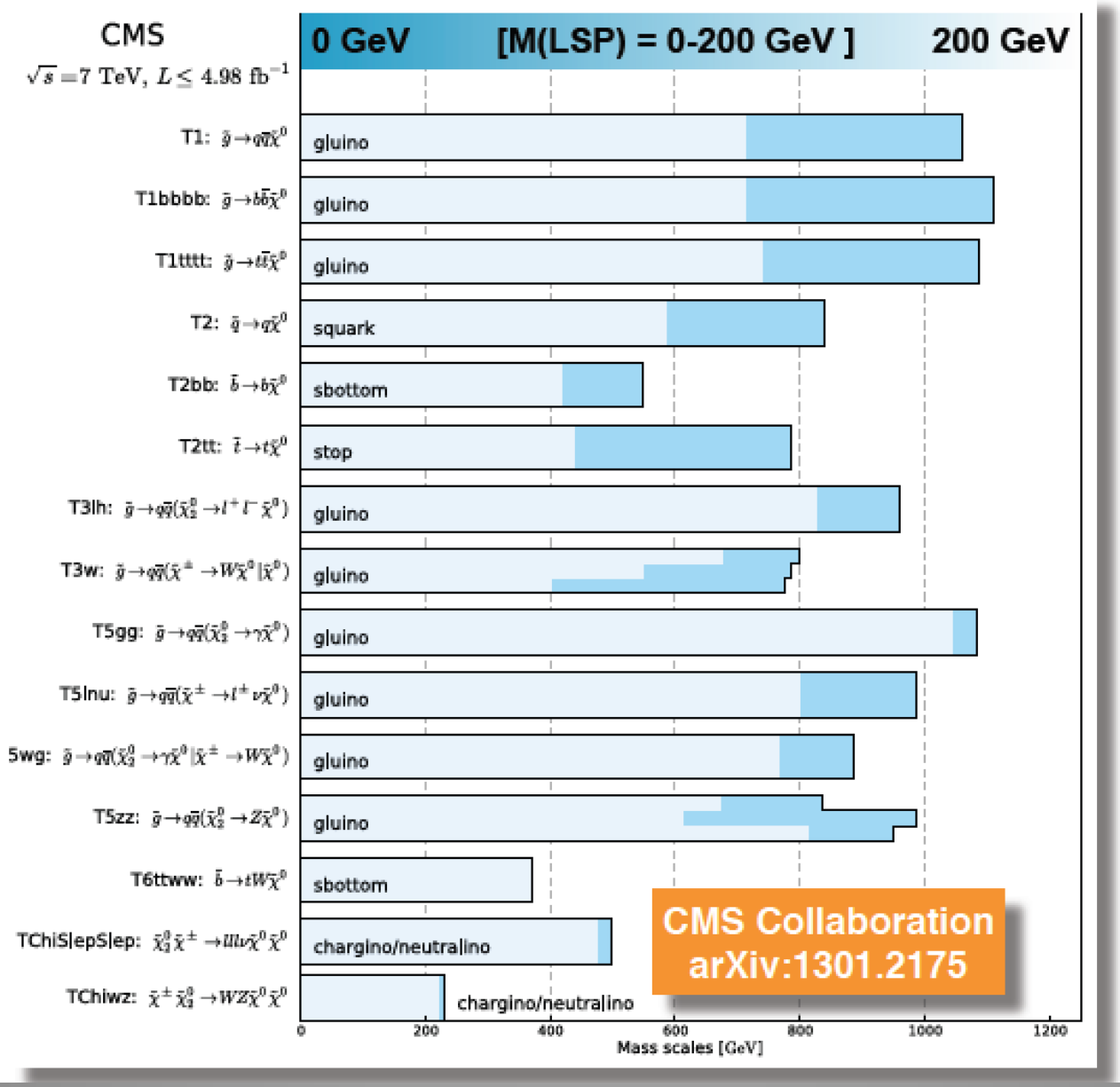
Various limits on sparticles:
No 'light' Lightest SUSY Particle (LSP) so far. No full mass region proxy.upd.ed



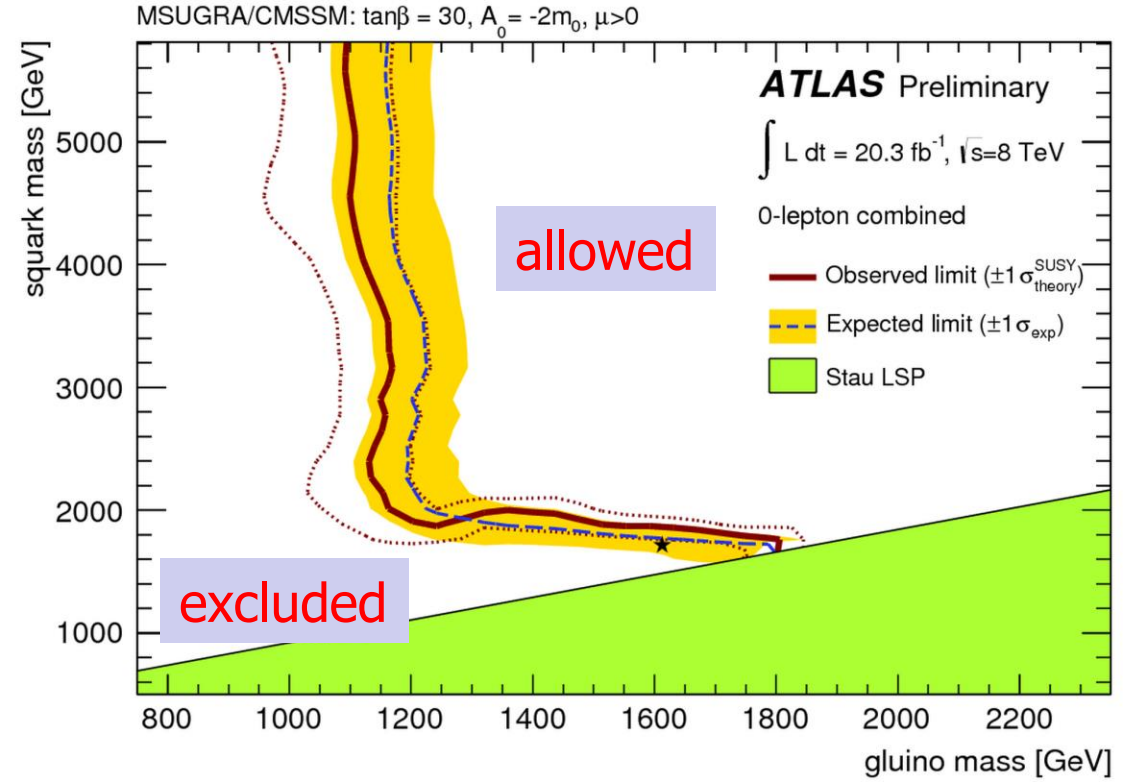


But SUSY could hide in contrived scenarios

SUSY Sparticle Mass Limits



SUSY Searches: No signal yet to date…

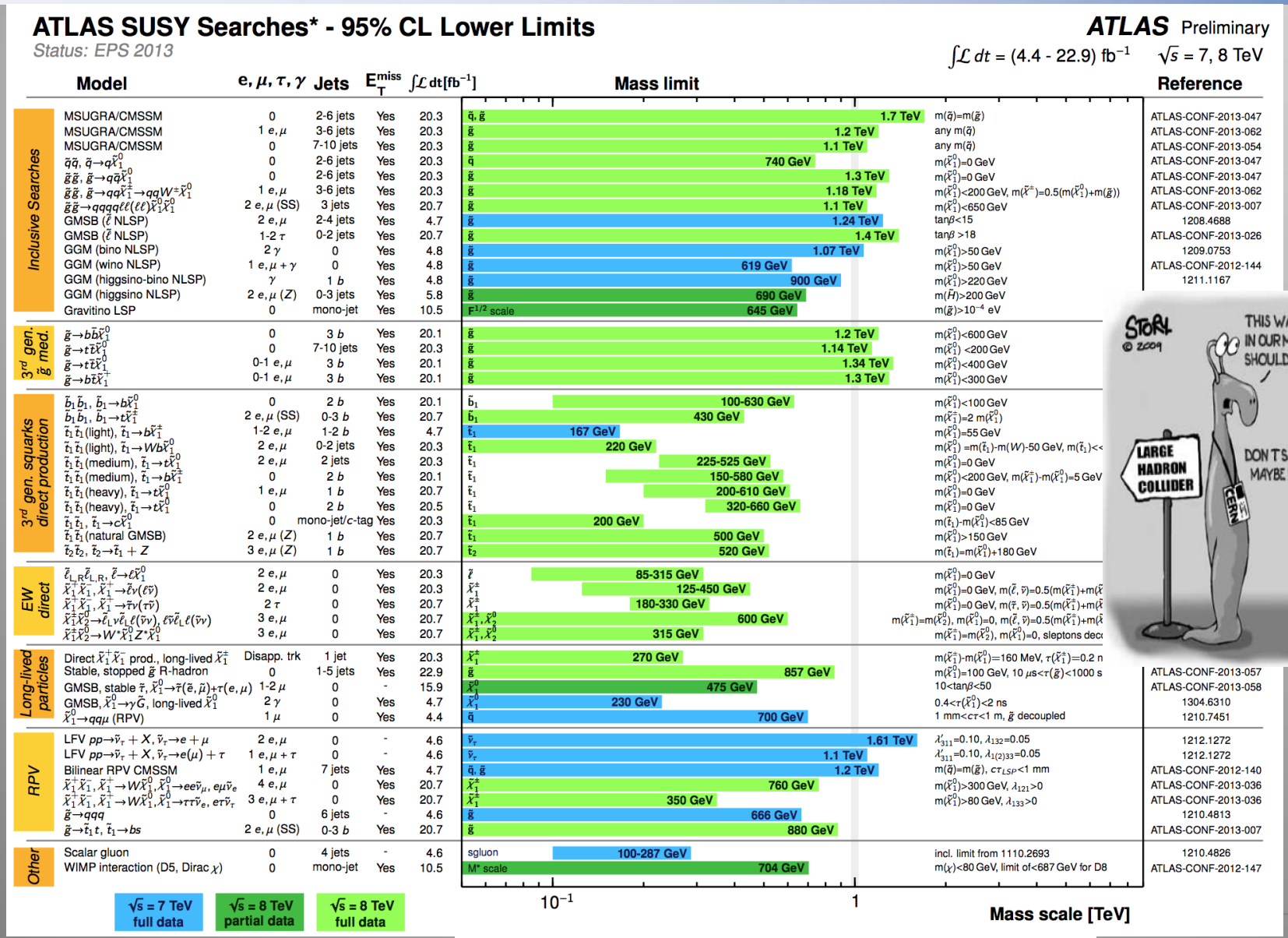


- So far NO clear signal of supersymmetric particles has been found
- We can exclude regions where the new particles could exist.
- Searches will continue for the higher energy in 2015

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

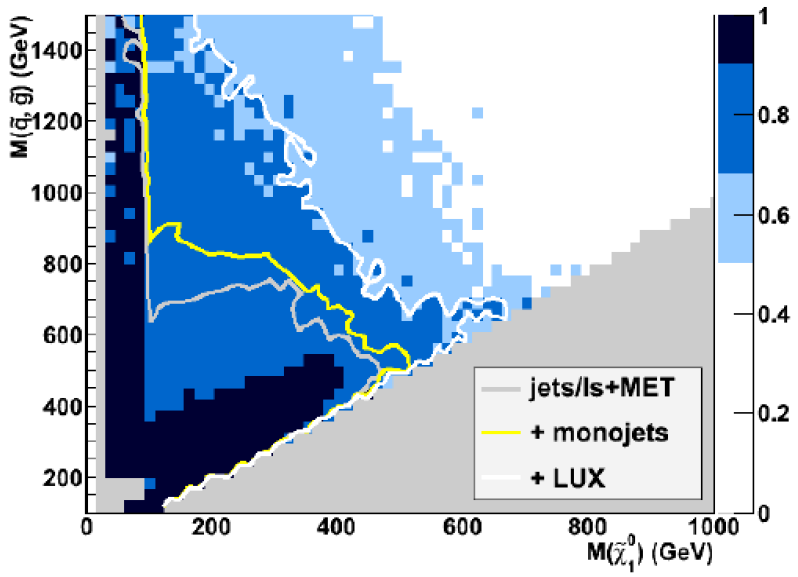
Searches for SUSY



*similar results obtained by CMS

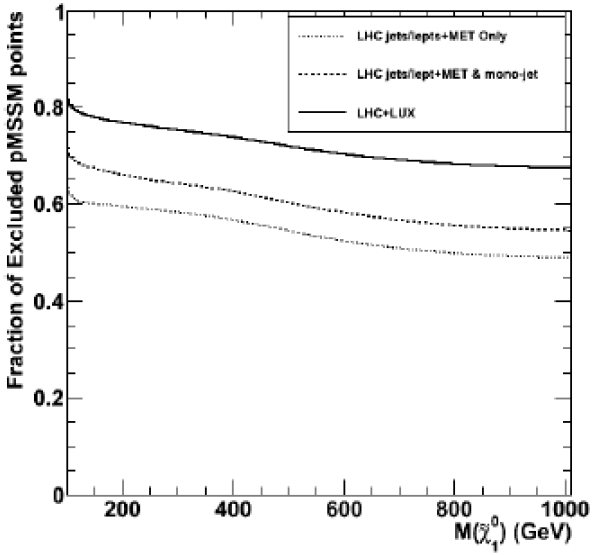
Dark Matter SUSY Space Left?

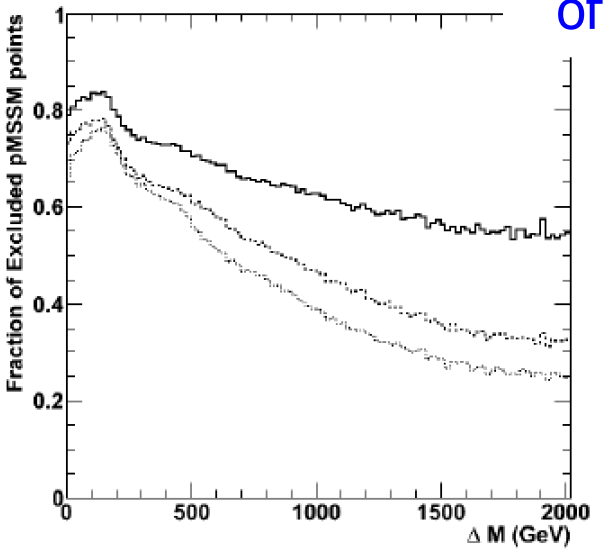
arXiv:1311.7641



- 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



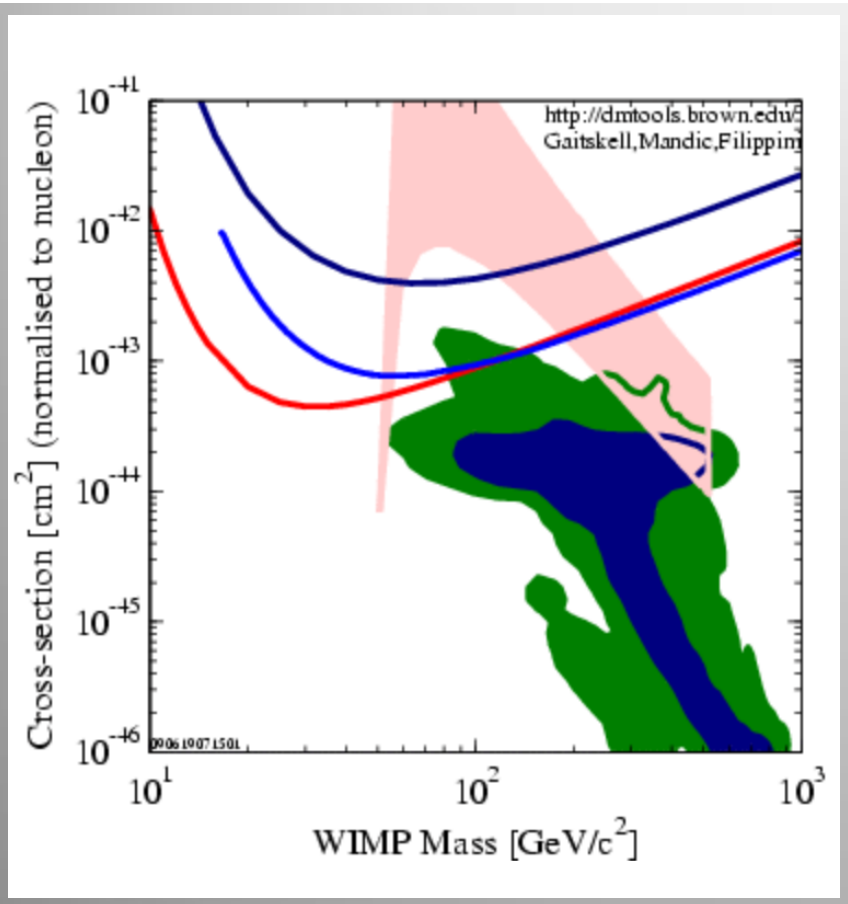


60-80% of the solutions excluded as function of the neutralino mass

Constrained SUSY Models

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

Study of the allowed DM space in CMSSM model



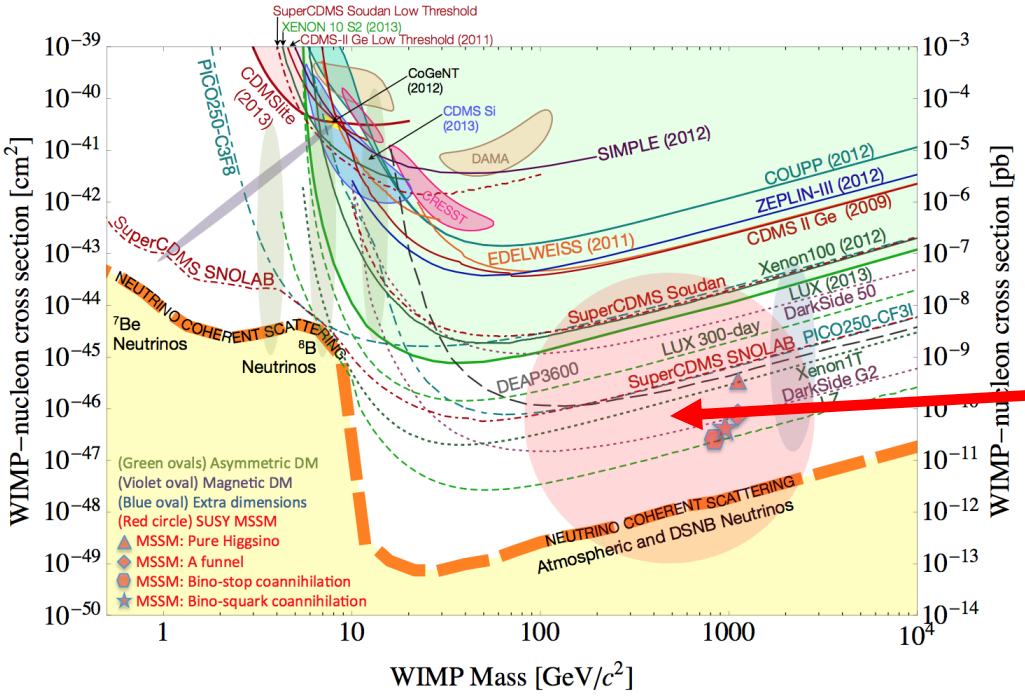
DATA listed top to bottom on plot
CDMS (Soudan) 2004 Blind 53 raw kg-days Ge
ZEPLIN III (Dec 2008) result
XENON10 2007 (Net 136 kg-d)
Ellis et al., Spin dep. sigma in CMSSM
Trotta et al 2008, CMSSM Bayesian: 68% contour
Trotta et al 2008, CMSSM Bayesian: 95% contour
0906.1907 1501

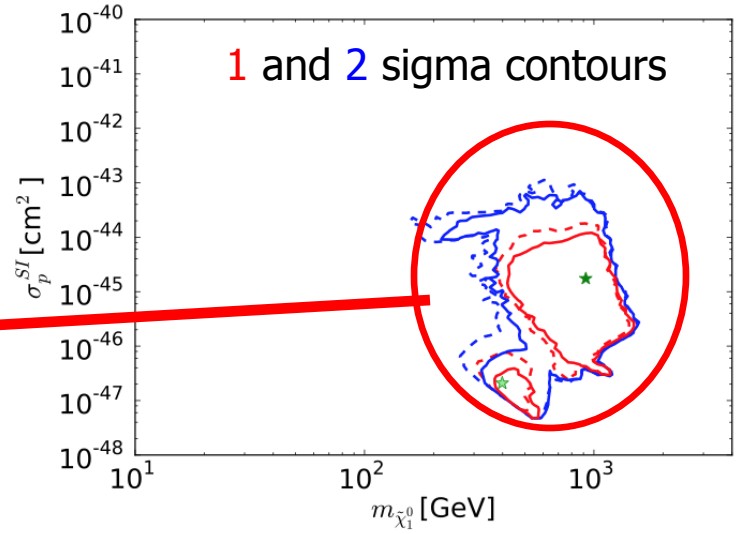
Region allowed in the CMSSM
includes constraints of the Run-I LHC searches (SUSY) and precision data, g-2, cold dark matter constraints…

Constrained SUSY Models

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

Study of the allowed DM space in CMSSM model



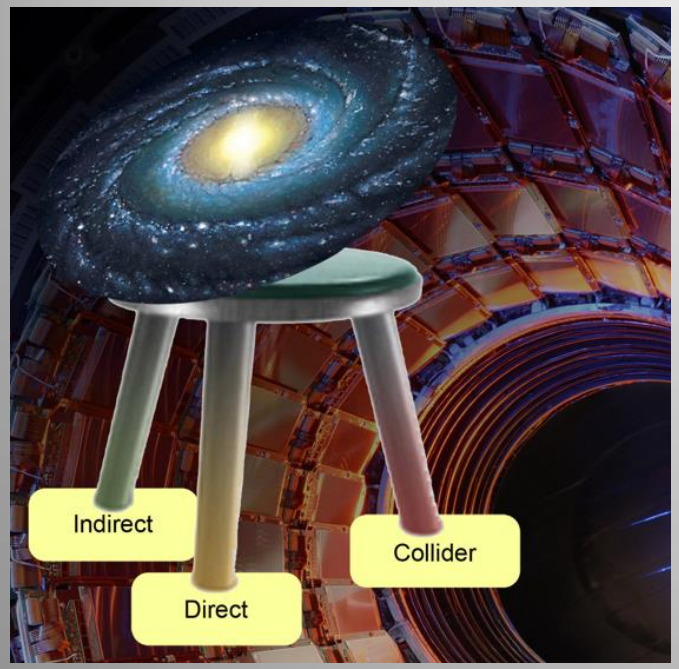


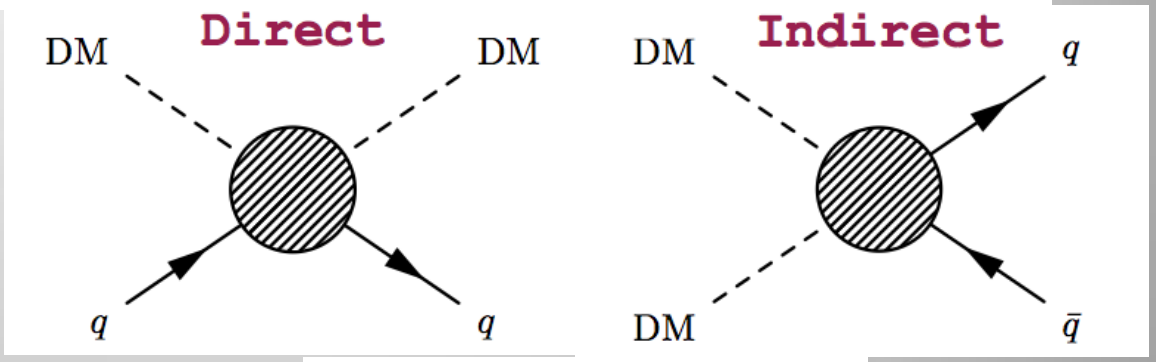
Region allowed in the CMSSM
includes constraints of the Run-I LHC searches (SUSY) and precision data, g-2, cold dark matter constraints…

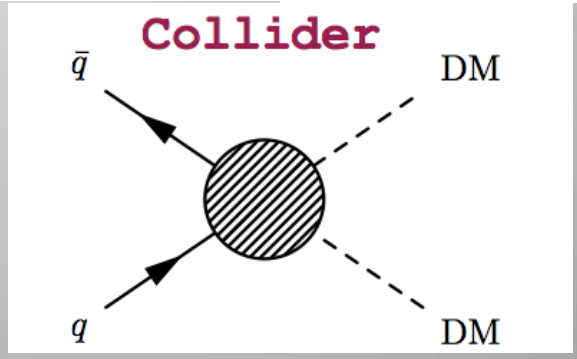
General Searches for Dark Matter

The Generic Dark Matter Connection

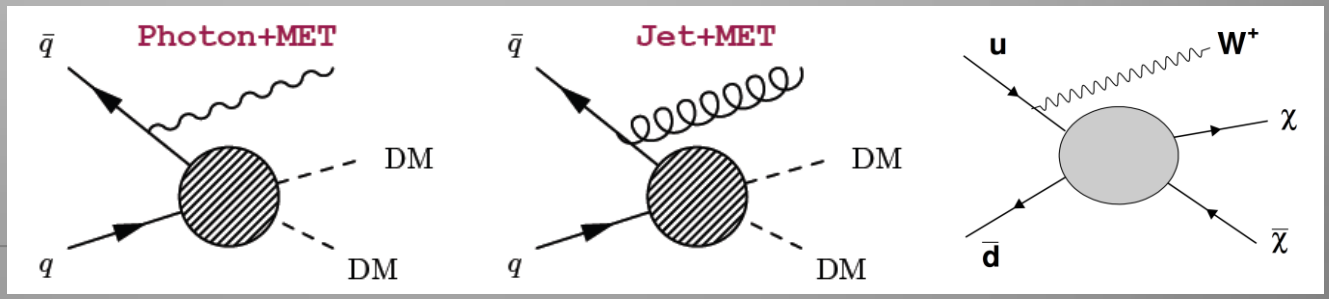
Searches for mono-jets and mono-photons can be used to search for Dark Matter (DM)





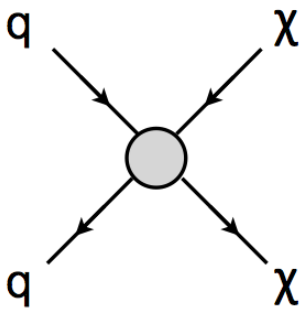


Use effective theory or simplified models to relate measurements to Dark Matter studies



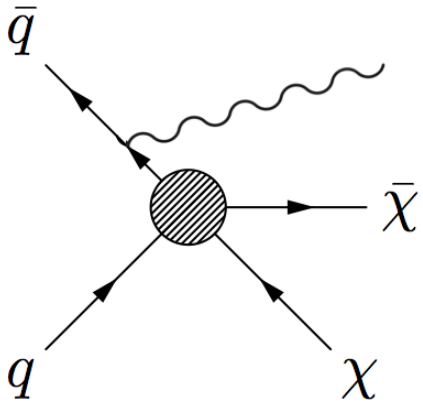
Dark Matter Production at the LHC

- Search for evidence of pair-production of Dark Matter particles (χ)

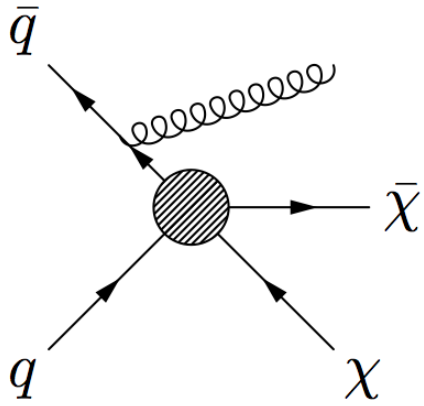


Production at Colliders (s-channel)

- Dark Matter production gives *missing transverse energy (MET)*
- Photons (or jets from a gluon) can be radiated from quarks, giving monophoton (or monojet) plus MET

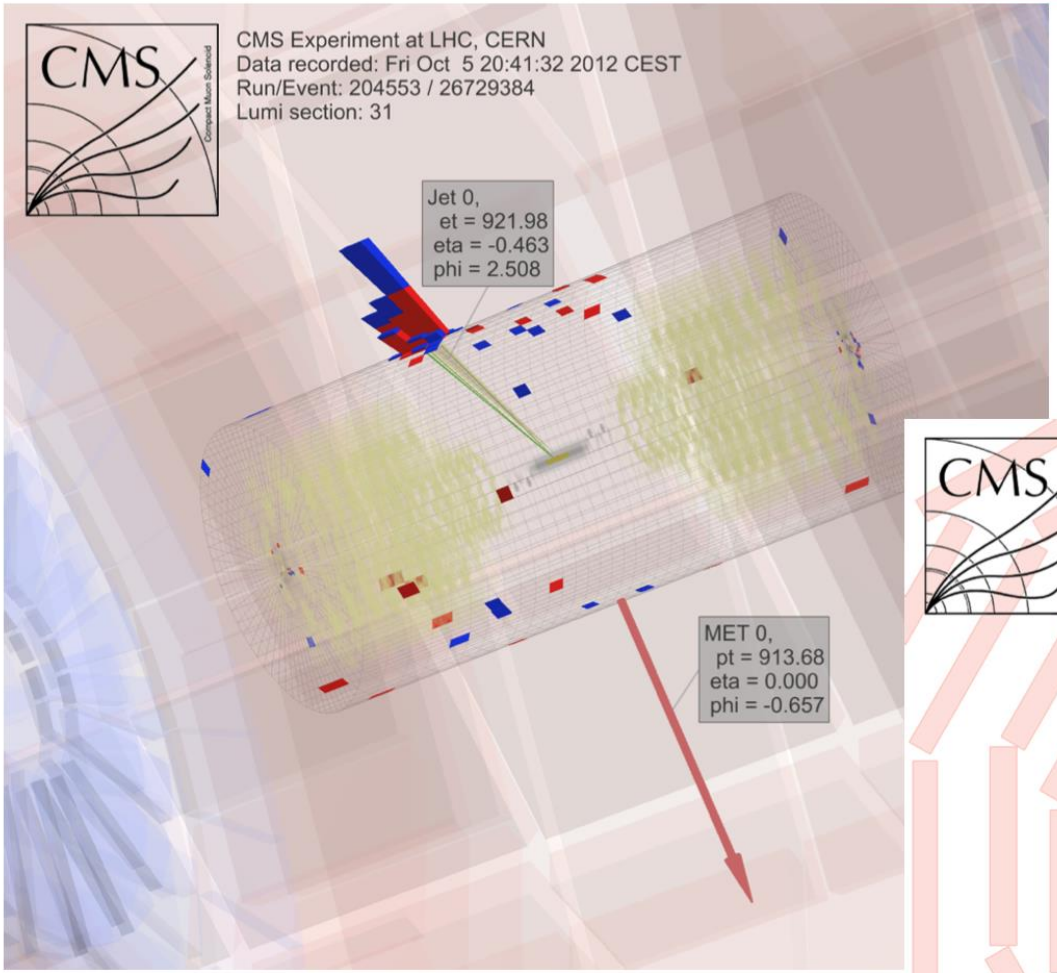


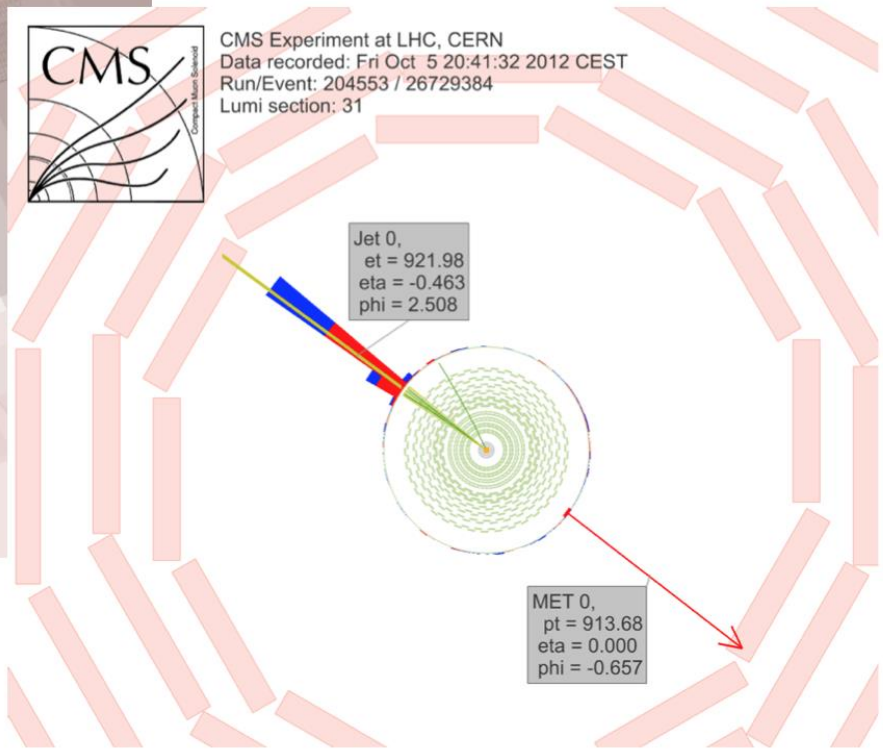
Monophoton + MET



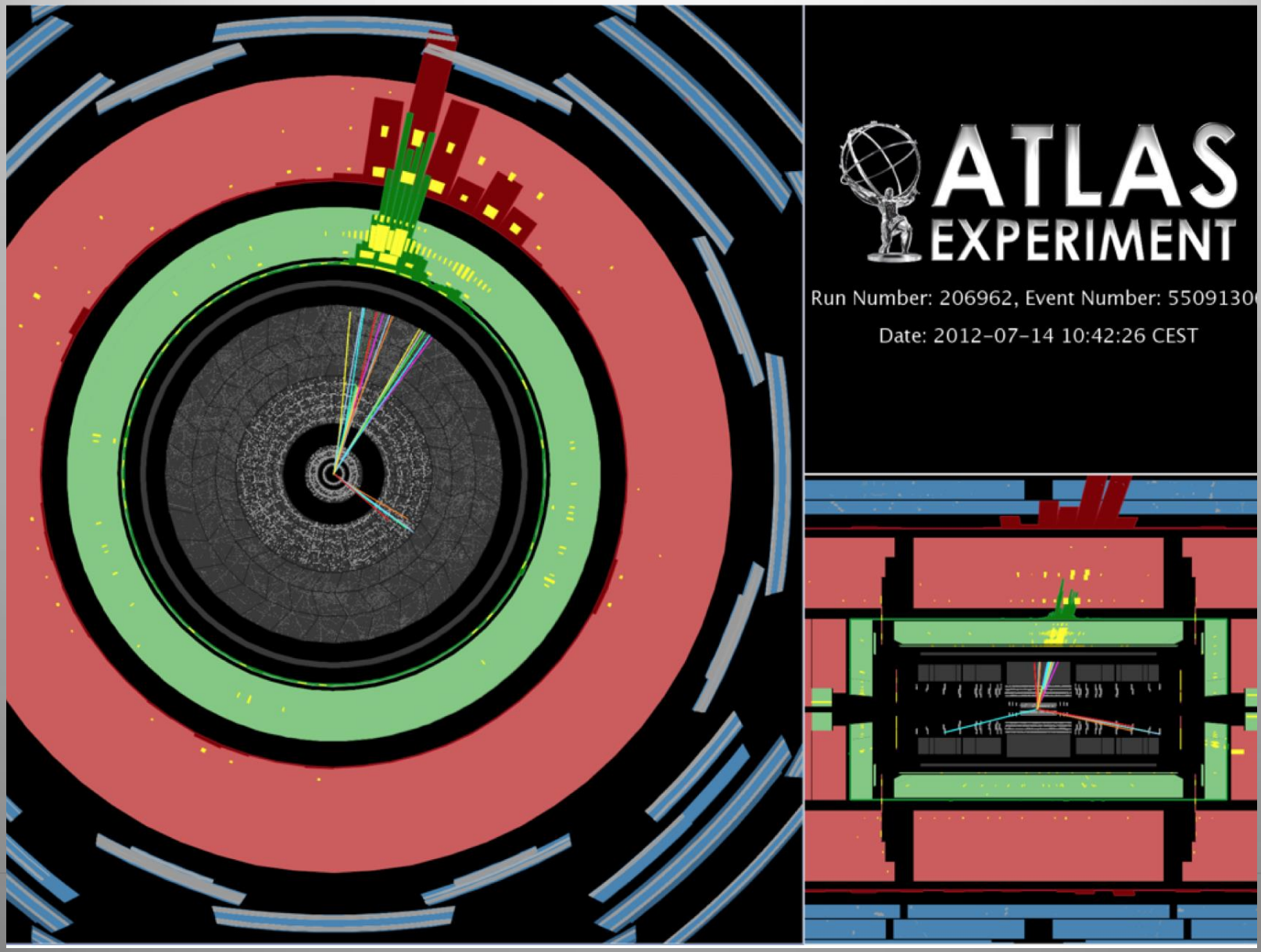
Monojet + MET

Mono-Jet Event





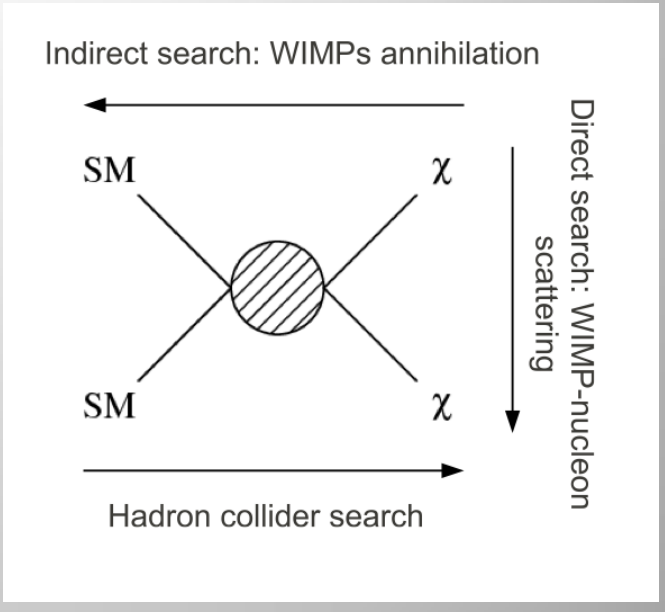
Mono-Jet Event



Dark Matter Searches

Convert experimental search results into limits on DM quantities
Two ways:

- Effective field theory (EFT):
  - Mediator too heavy to be generated directly
  - Contact interation with suppression scale $M_\star \sim \frac{M}{\sqrt{g_\chi g_{SM}}}$, with g_χ and g_{SM} the couplings to Standard Model (SM) and DM, and M the mediator mass
- Simplified models: Popular in SUSY
  - Specified massive mediator
  - UV-complete (no validity issue)



Name	Initial state	Type	Operator
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	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

Types of interactions chosen in the studies by ATLAS

Discussions on the region of validity ongoing...

Data Interpretation

- Pair-production of χ characterised by a contact interaction with operators

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

vector --> spin independent (SI)

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

axial-vector --> spin-dependent (SD)

- Cross section depends on the mass (m_χ) and the scale Λ (for couplings g_χ, g_q)

$$\sigma_{SI} = 9\frac{\mu^2}{\pi\Lambda^4}$$

$$\sigma_{SD} = 0.33\frac{\mu^2}{\pi\Lambda^4}$$

spin-independent and spin-dependent cross sections

$$\Lambda = M/\sqrt{g_\chi g_q} \qquad \mu = \frac{m_\chi m_p}{m_\chi + m_p}$$

[Bai, Fox and Harnik, JHEP 1012:048 (2010), Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, Phys.Rev.D82:116010 (2010), Beltran, Hooper, Kolb, Krusberg, Tait, JHEP 1009:037 (2010)]

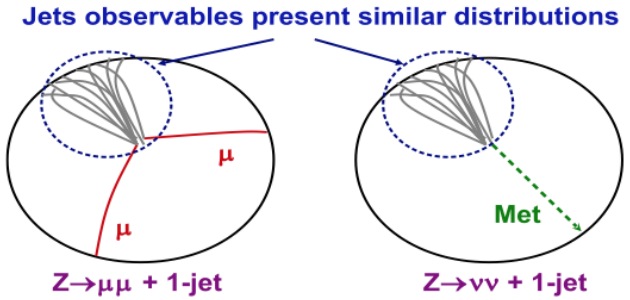
Mono-object Searches

- 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

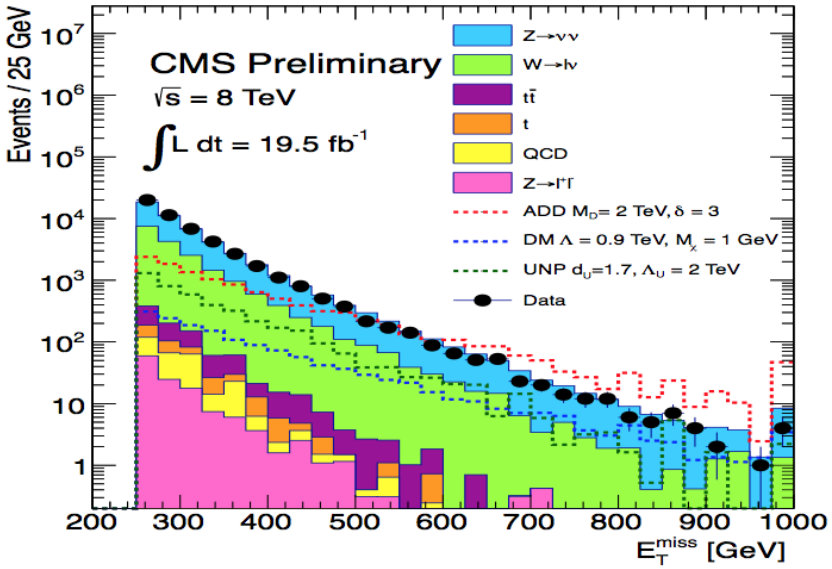
The Search for Mono-jets

- Preliminary results at $\sqrt{s} = 8\,\mathrm{TeV}$:
  CMS-PAS-EXO-12048 $\mathcal{L} = 20\,\mathrm{fb}^{-1}$
  ATLAS-CONF-2012-147 $\mathcal{L} = 10.5\,\mathrm{fb}^{-1}$
  ATLAS $7\,\mathrm{TeV}$, $5\,\mathrm{fb}^{-1}$: JHEP 04 (2013) 075
  CMS $7\,\mathrm{TeV}$, $5\,\mathrm{fb}^{-1}$: JHEP 09 (2012) 094
- Event selection:
  - Trigger: $\not{E}_T$ [ATLAS] or $\not{E}_T$+jet [CMS]
  - Central leading jet, at most 2 good jets
  - To suppress QCD multi-jet events:
    - ATLAS: $\Delta\phi(\not{E}_T, jet_2) > 0.5$
    - CMS: $\Delta\phi(jet_1, jet_2) < 2.5$
  - Veto on e and μ [ATLAS, CMS]
    Explicit τ veto [CMS]
  - Inclusive signal regions (SR):
    - ATLAS: both lead jet p_T and $\not{E}_T > 120, 220, 350, 500\,\mathrm{GeV}$
    - CMS: lead jet $p_T > 110\,\mathrm{GeV}$ and $\not{E}_T > 250$ to $550\,\mathrm{GeV}$ (step $50\,\mathrm{GeV}$)

- Main background: $Z \to \nu\nu$
  - Estimate with W/Z [ATLAS] or Z [CMS] lepton data control regions (CR)



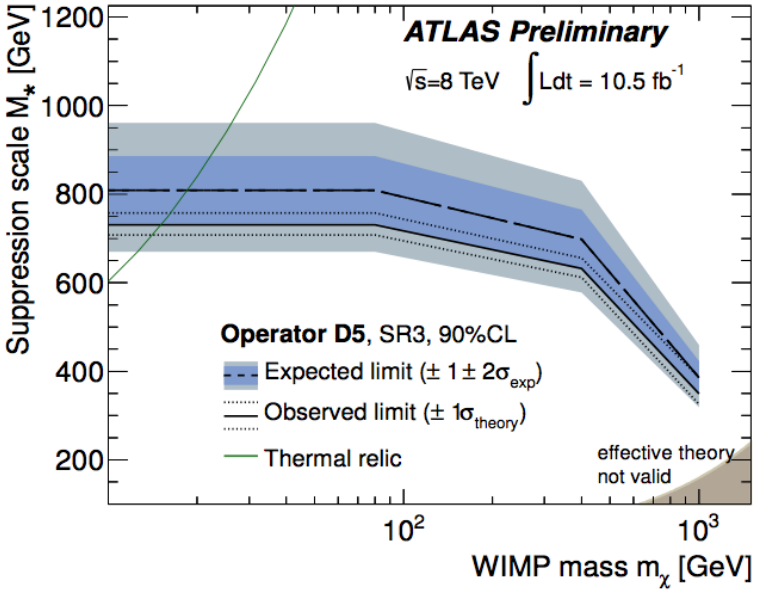
  - Transfer CR to SR via simulation

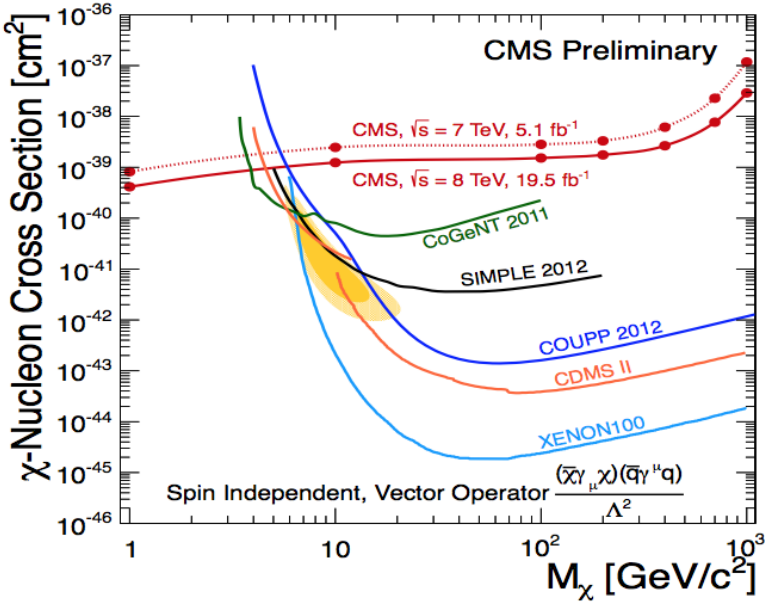


The Search for Mono-jets

- Total uncertainties on $Z \to \nu\nu$:
  - CMS: 4.5-15.6%
  - ATLAS: 3.3-20%
  - Main: low CR statistics at high $\not{E}_T$
- Limits:
  - Lower bound on EFT scale $M_\star$ (Λ) extracted from limit on signal rate
  - Thermal relic density from WMAP compared to $M_\star$ bounds

    (If $M_\star$ above relic line, results not consistent with WMAP, assuming one WIMP species produced via one given operator)
  - EFT scale bounds translated into $\sigma(\chi$-nucleon) upper limits

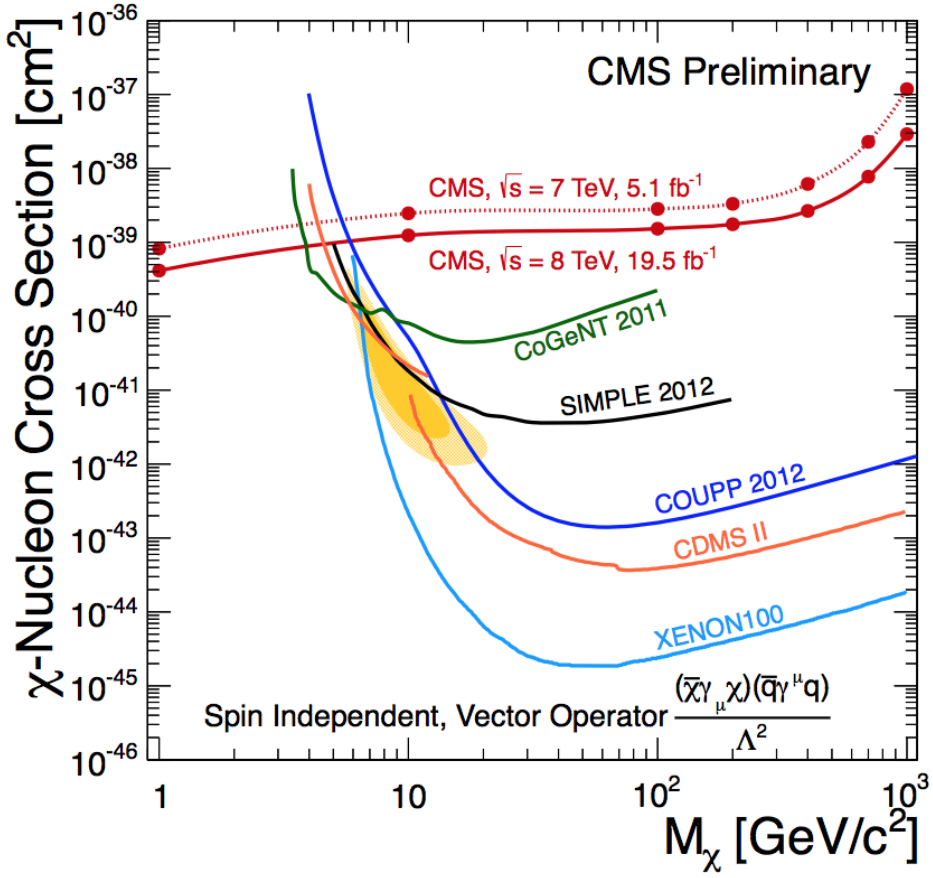


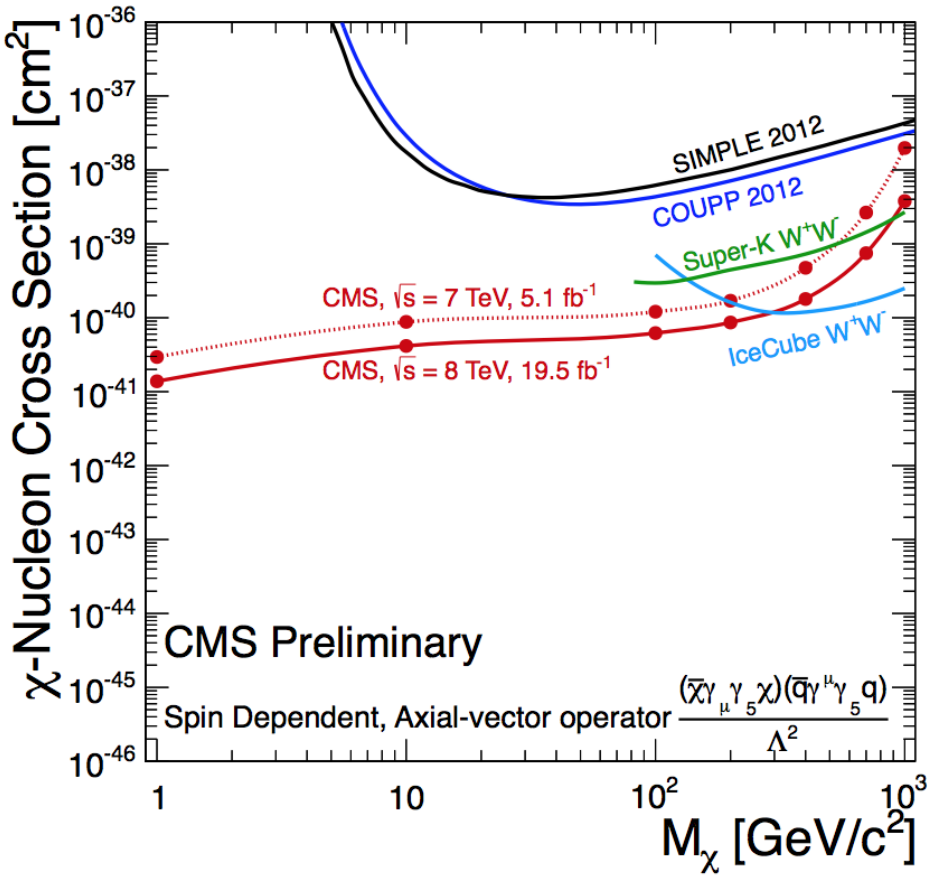


Results for Mono-jets

[CMS EXO-12-048]

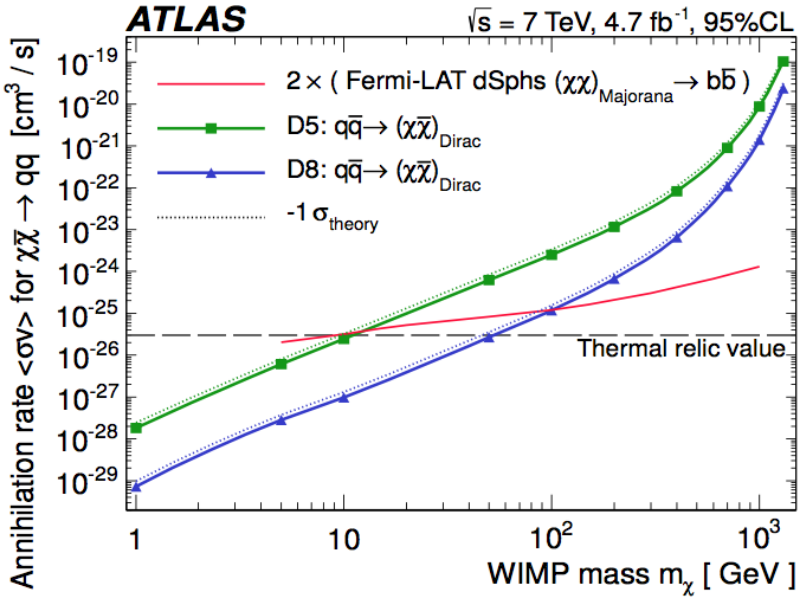
- Derived EFT limits then compared to direct-detection experiments
- CMS results improved with 8 TeV (higher E, more data)



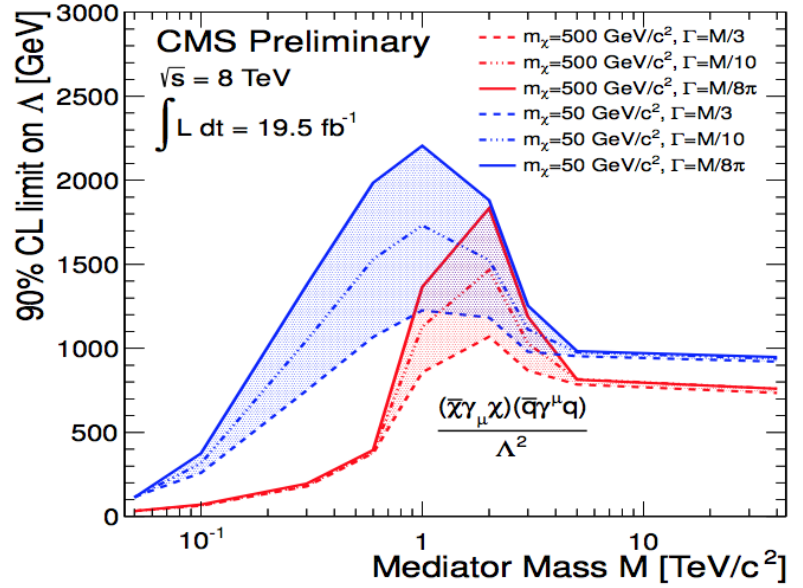


Results for Mono-jets

- Upper limit on DM annihilation:
  - Bounds on vector and axial-vector interactions translated into upper limits on $\sigma(\chi\chi \to qq)$ (light q)
  - Results compared to the annihilations to bb from Fermi LAT
  - Limits below relic value are not consistent with WMAP



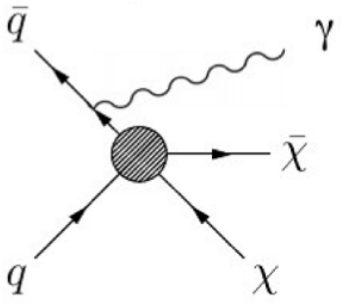
- Lower bound on scale (Λ) of UV-complete simplified model:
  - Interactions via massive vector mediator (of mass M)
  - At high M, limits converge to those obtained assuming EFT
  - Width constrained from $M/8\pi$ to $M/3$



The Search for Mono-Photons

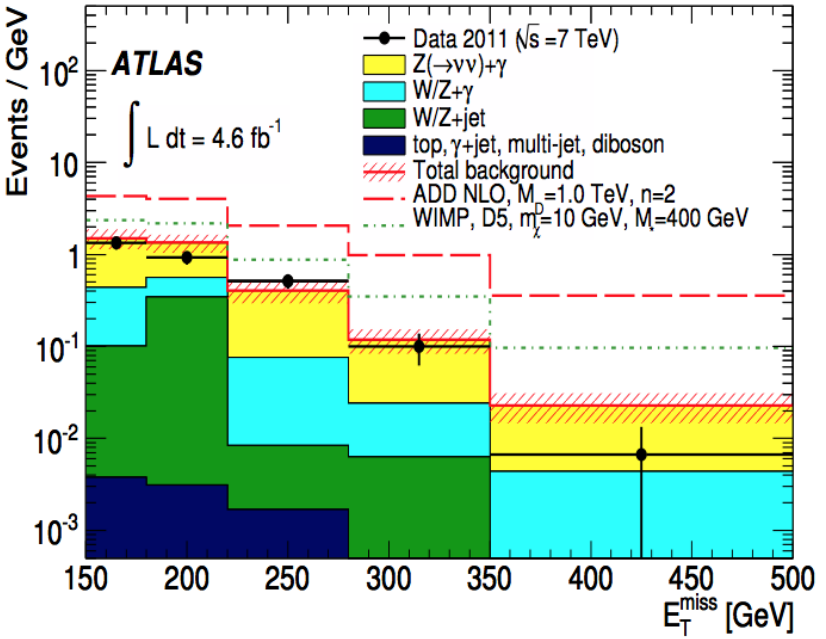
First "Mono-study" to be interpreted DM limits at the LHC

- Published with $\mathcal{L} \sim 5\,\mathrm{fb}^{-1}$ and $\sqrt{s} = 7\,\mathrm{TeV}$:
  PRL 110, 011802 (2013) [ATLAS]
  PRL 108, 261803 (2012) [CMS]



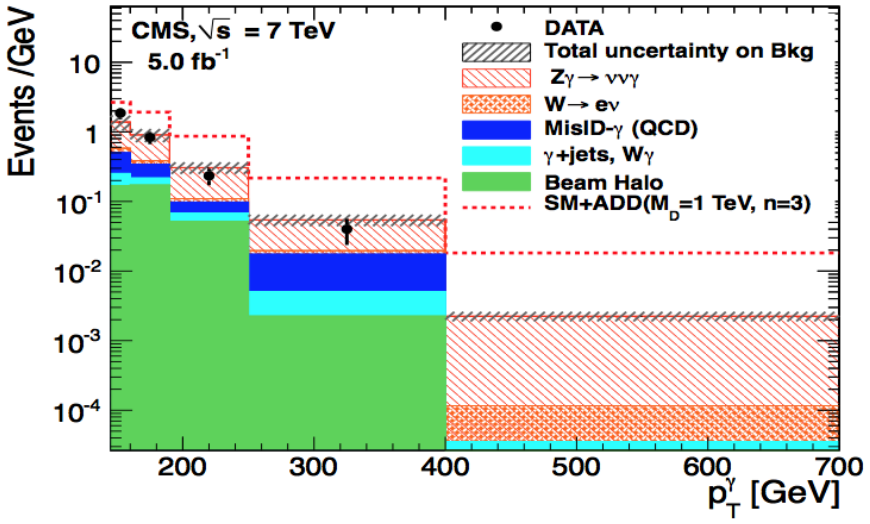
- Main background: $\mathrm{Z}(\rightarrow \nu\nu) + \gamma$
  - ATLAS: extrapolated from $\gamma + \mu + \not{E}_T$ CR
  - CMS: estimation from simulation (NLO)

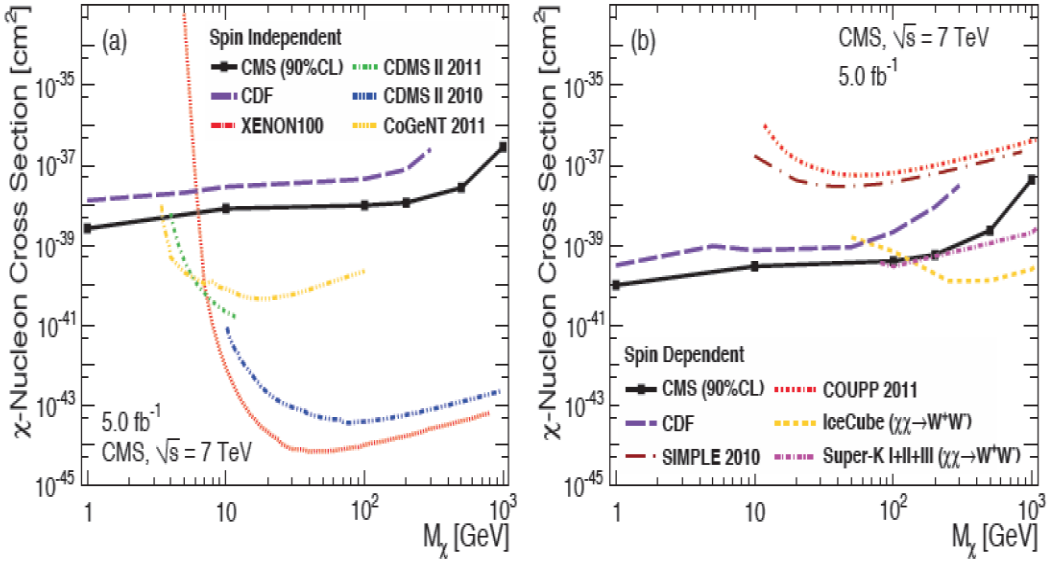
- Event selection
  - Trigger: $\not{E}_T$ [ATLAS], photon [CMS]
  - Central photon, $p_T > 150\,\mathrm{GeV}$ [ATLAS]
    $p_T > 145\,\mathrm{GeV}$ [CMS]
  - $\not{E}_T > 150\,\mathrm{GeV}$ [ATLAS], $130\,\mathrm{GeV}$ [CMS]
  - Veto on electron and muons
  - ATLAS: allow up to one jet. Photon, jet and $\not{E}_T$ well separated.
  - CMS: veto significant hadronic activity



The Search for Mono-Photons

- Systematics on background:
  - Total amounts to 15% [ATLAS] and 13% [CMS]
  - Main sources: $\not{E}_T$, jet and photon modelling, theory [CMS], and muon CR statistics [ATLAS]
- Limits on EFT scale obtained from simple counting experiment and translated into upper bounds on $\sigma(\chi\text{-N})$
- ATLAS and CMS limits are similar





The Search for Mono-W's

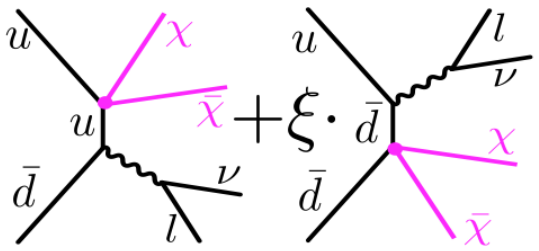
Leptonic channel

- Preliminary result at $\sqrt{s} = 8\,\text{TeV}$: CMS-PAS-EXO-13-004 $\mathcal{L} = 20\,\text{fb}^{-1}$
- Scenario:
  - W radiated from u or d quark
  - W leptonic decays
- e and μ channels combined
- Main observable: mass of $(\ell, \not{E}_T)$

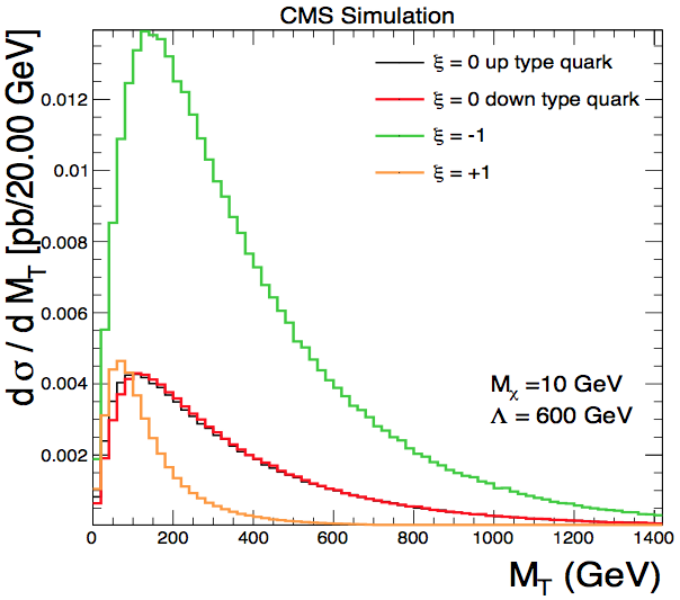
$$M_T = \sqrt{2.p_T^{\ell}.\not{E}_T.(1 - \cos\Delta\Phi_{\ell,\not{E}_T})}$$

- Event selection:
  - Based on CMS W' search [CMS-PAS-EXO-12-060]
  - Trigger: single electron and single muon
  - $\not{E}_T$ balanced by lepton: $0.4 < p_T^{\ell}/\not{E}_T < 1.5$ and $\Delta\Phi(\ell, \not{E}_T) > 0.8\pi$

- DM production mode:



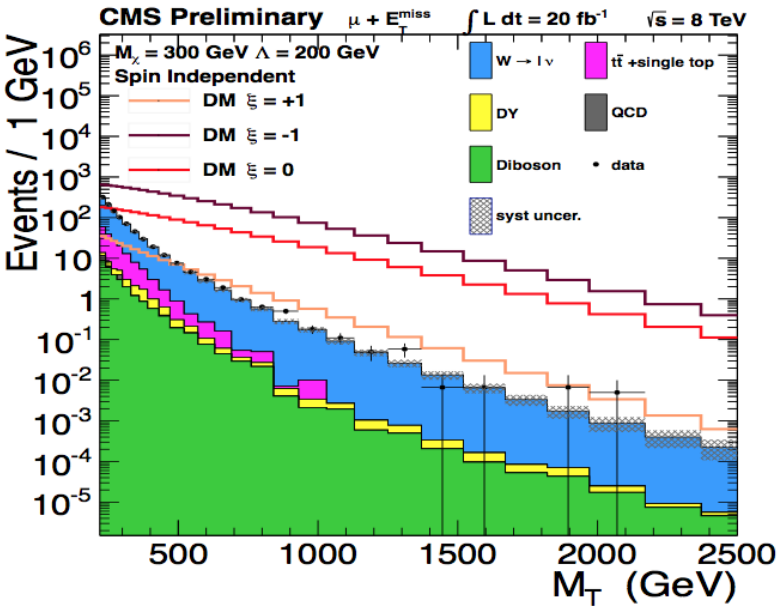
  - Interference ξ between 2 processes
  - $\xi = 1\ (-1)$: destructive (constructive)

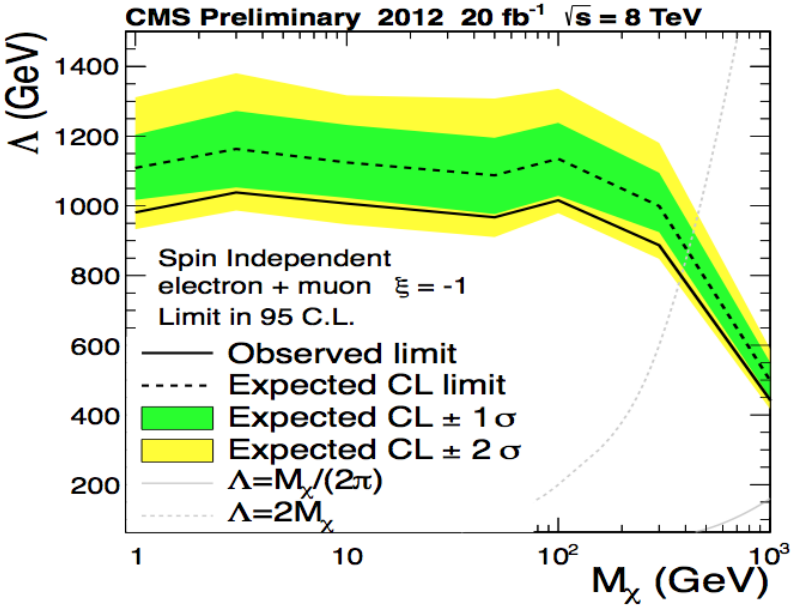


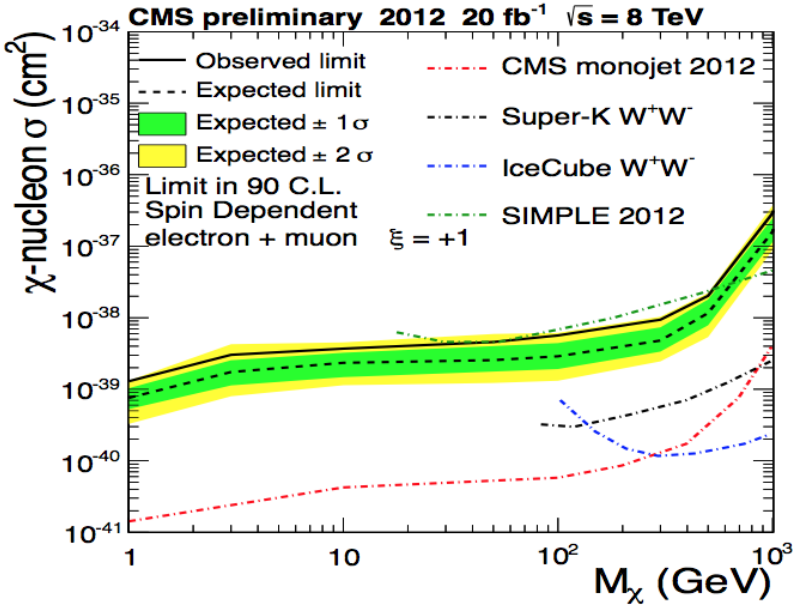
Allows to test if DM couplings to down type and up type quarks is the same

The Search for Mono-W's

- Main background: $W \to \ell\nu$ (simulation, M_T-dependent NLO k-factors)
- Main uncertainty on background: lepton energy scale/resolution (1-10%)
- Lower bounds on EFT scale Λ derived using full M_T shape, and translated into $\sigma(\chi$-nucleon) upper limits (more in backup)



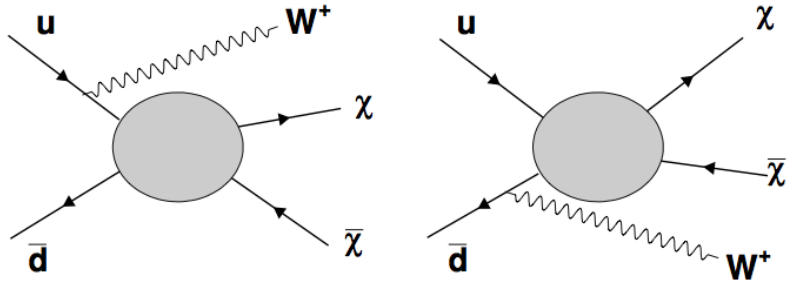




The Search for Mono-W/Z's

Hadronic channel

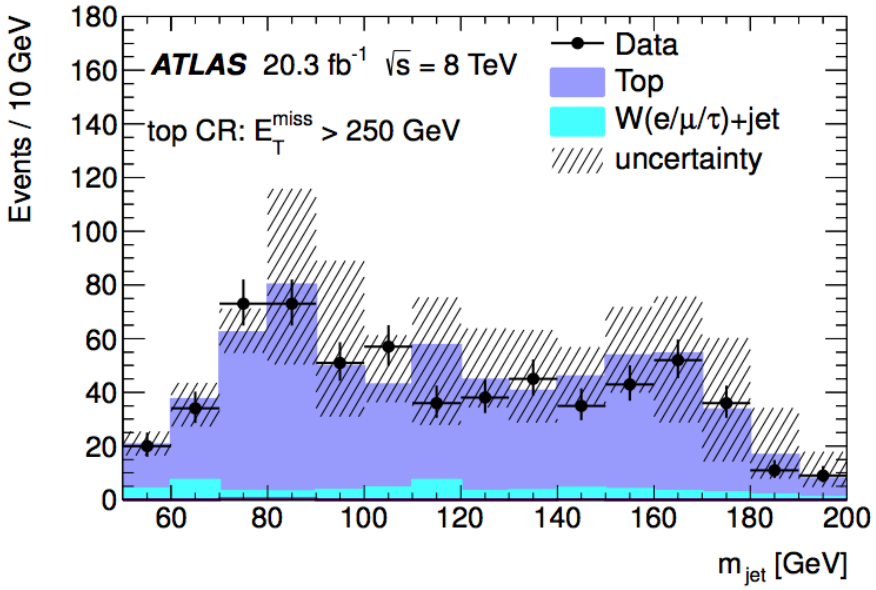
- Published: PRL 112, 041802 (2014)
  $\sqrt{s} = 8\,\text{TeV}$ $\mathcal{L} = 20\,\text{fb}^{-1}$



- Scenario:
  - W/Z radiated from u or d quark
  - W and Z hadronic decays
- W/Z decay reconstructed as single massive "fat" jet of mass m_{jet} (Cambridge-Aachen, $R = 1.2$)

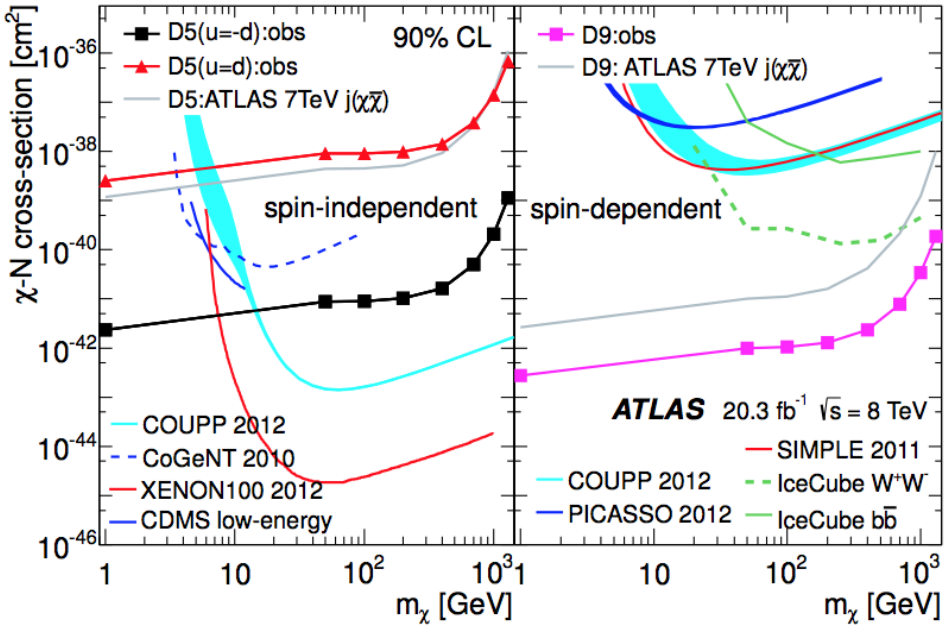
  Validation in top CR: includes W peak and tail due to b jet from top decay
- Event selection:
  - $\not{E}_T$ trigger
  - ≥ 1 central fat jet with $p_T > 250\,\text{GeV}$ and $50\,\text{GeV} < m_{jet} < 120\,\text{GeV}$
  - ≤ 1 jet ($R = 0.4$) away from lead fat jet
  - Veto on electron, muon and photon
  - 2 SR: $\not{E}_T > 350\,\text{GeV}$ or $500\,\text{GeV}$

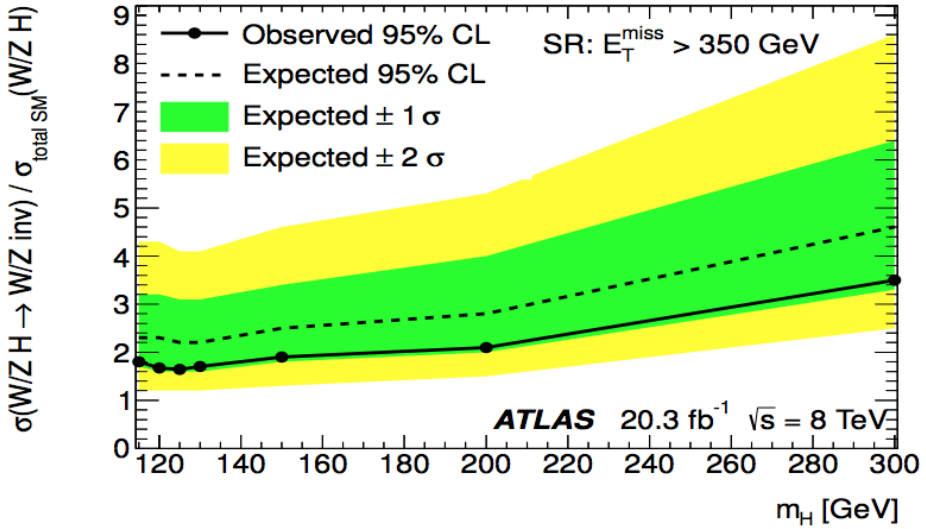
- Main backgrounds:
  - $\text{Z}(\rightarrow \nu\nu)$+jets and $\text{W}(\rightarrow \ell\nu)$+jets
  - Determined by extrapolating a data muon CR using simulation



The Search for Mono-W/Z's

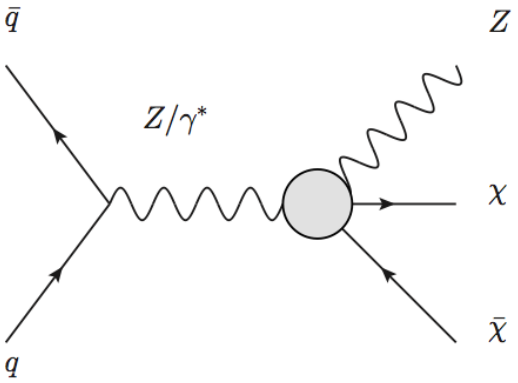
- Total background systematics:
  - Main: data CR statistics, fat jet and $\not{E}_T$ calibration, theory
  - 5 to 13% (low to high $\not{E}_T$)
- EFT limits:
  - Upper limits on $\sigma(\chi$-nucleon) in D5 case with opposite sign u and d-quark couplings are improved by 3 orders of magnitude due to constructive interference ($\xi = -1$)
  - Lower bounds on scale in backup
- DM-SM interaction with Higgs:
  - Simple low mass mediator
  - σ(W/ZH)× Br(H→ $\chi\chi$) normalized to σ_{SM}(W/ZH) lower than 1.6 for $m_H = 125\,\mathrm{GeV}$

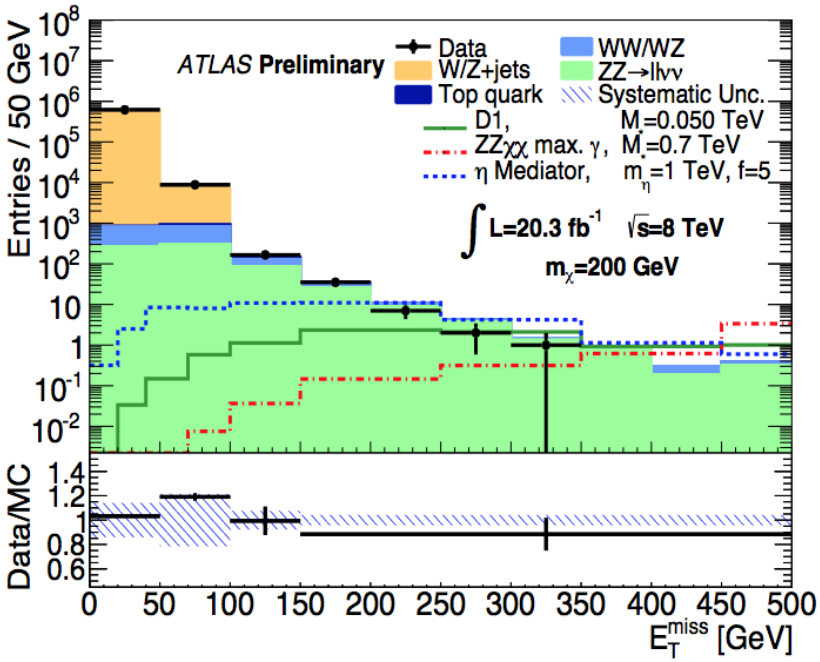




The Search for Mono-Z's

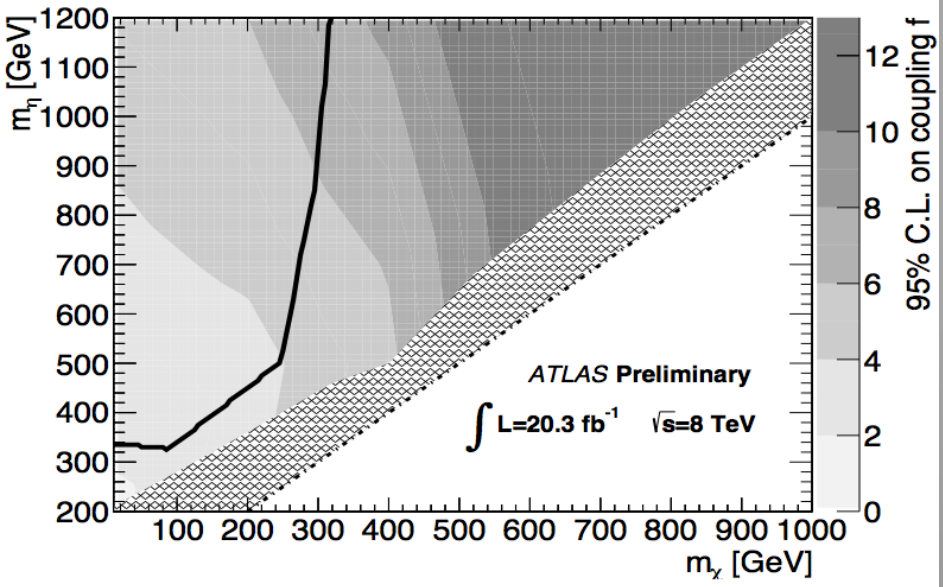
- Preliminary result: $\sqrt{s} = 8\,\text{TeV}$, $\mathcal{L} = 20\,\text{fb}^{-1}$
- 2 scenarios for DM pair production:
  - Z radiated from ISR
  - Z interacts directly with DM
    Z/γ^* mixing is a theory parameter
- e and μ channels combined
- Main background: $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ (NLO simulation)
- Event selection:
  - Trigger: di-lepton or single lepton
  - 2 good leptons, $M_{\ell\ell}$ under Z-mass peak
  - No $\not{E}_T$ from mismeasured jets:
    $\Delta\Phi(\not{E}_T, p_T^{\ell\ell}) > 2.5$, $|\eta^{\ell\ell}| < 2.5$, and $|p_T^{\ell\ell} - \not{E}_T|/p_T^{\ell\ell} < 0.5$
  - No 3rd lepton and no jets
  - SR defined by $\not{E}_T > 150, 250, 350, 450\,\text{GeV}$

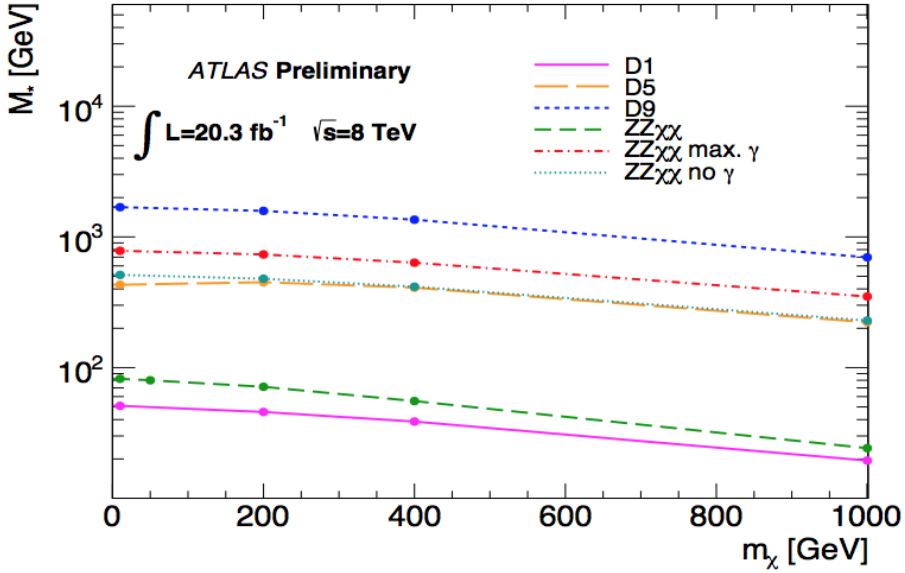


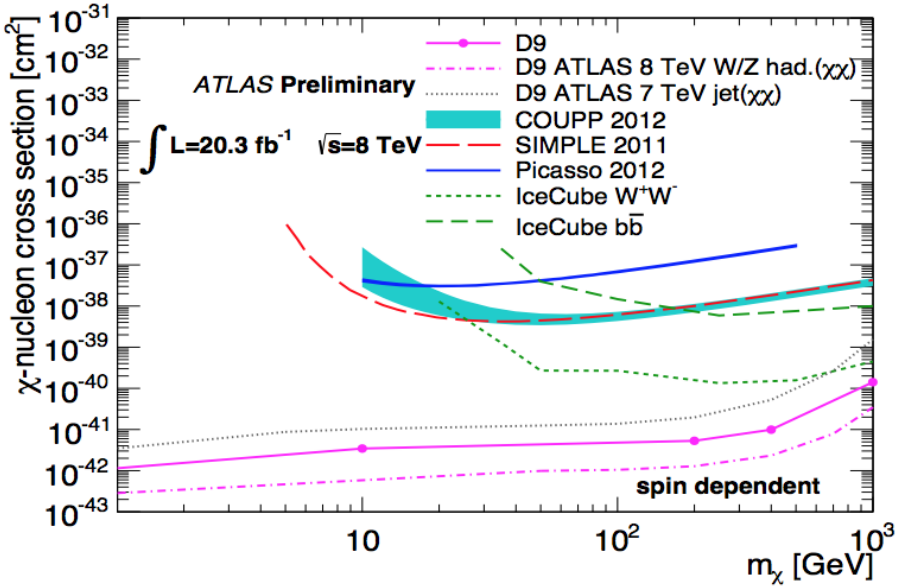


The Search for Mono-Z's

- Main background uncertainty: 17-99% (depending on SR, mainly due to theory)
- Case of scalar massive mediator (η) in UV-complete model:
  - Upper bounds on χ-η coupling (f)
  - Above black line, these are smaller than lower limit from relic abundance
- Below: limits on EFT scale and upper bounds on $\sigma(\chi$-N)

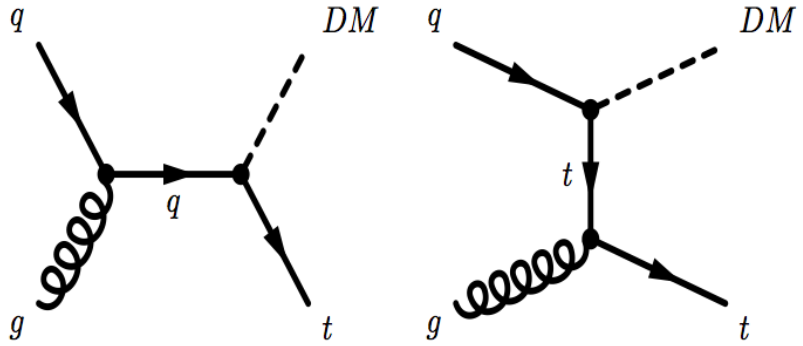


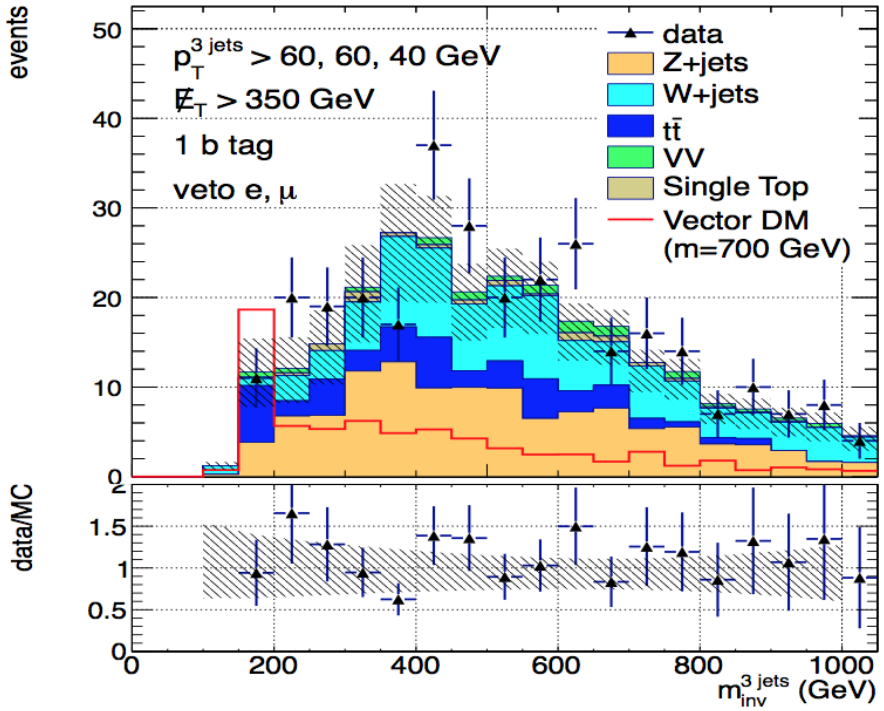




The Search for Mono-Top Quarks

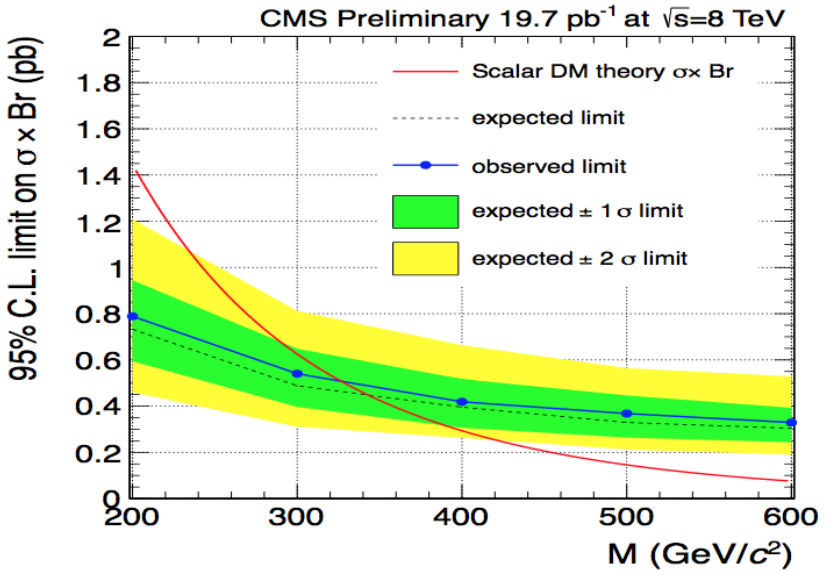
- Preliminary result at $\sqrt{s} = 8\,\mathrm{TeV}$: CMS-PAS-B2G-12-022, $\mathcal{L} \sim 20\,\mathrm{fb}^{-1}$
- Scenario:
  - top produced in association with DM (not from ISR)
  - top decays hadronically
  - FCNC considered
- Main backgrounds:
  - $\mathrm{Z}(\rightarrow \nu\nu)$+jets (from data CR)
  - $\mathrm{W}(\rightarrow \ell\nu)$+jets (from data CR)
  - $\mathrm{t\bar{t}}$ (NNLO, top p_T reweighting)
- Event selection
  - SR trigger: $\not{E}_T$
  - Exactly 3 jets: $p_T > 60, 60, 40\,\mathrm{GeV}$, 1 b-tag, $m_{inv}^{3\,jets} < 250\,\mathrm{GeV}$
  - Veto on electron and muon
  - $\not{E}_T > 350\,\mathrm{GeV}$

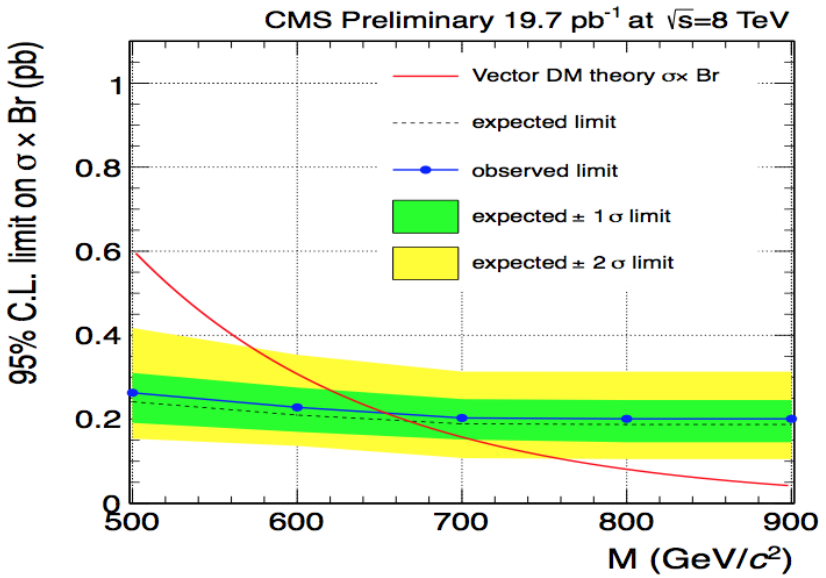




The Search for Mono-Top Quarks

- Systematics on background
  - Total: 57%
  - Main sources: $t\bar{t}$ theory and top p_T modeling, Z/W data CR statistics
- Limits:
  - Effective field theory for DM-SM interaction
  - Upper limits on $\sigma\times$ BR interpreted as lower bounds on DM candidate mass:
    - Scalar DM: $327\,\mathrm{GeV}$
    - Vector DM: $655\,\mathrm{GeV}$





The Search for Mono-Higgs Next?

Mono-Higgs: a new collider probe of dark matter

Linda Carpenter,[1] Anthony DiFranzo,[2] Michael Mulhearn,[3] Chase Shimmin,[2] Sean Tulin,[4] and Daniel Whiteson[2]

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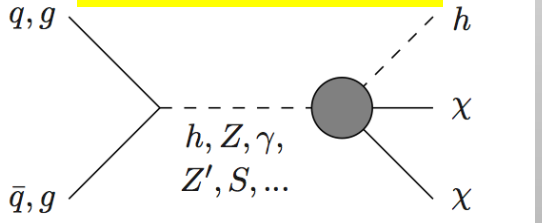
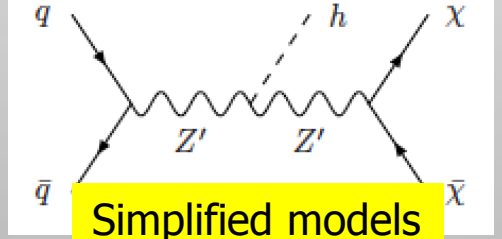
[4] *Department of Physics and Astronomy, University of Michigan, MI*

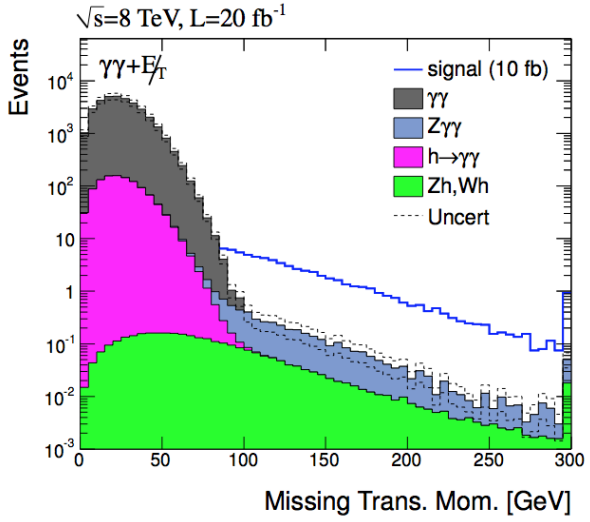
The next mono-object to study?
No ISR, but coupling to the DM directly

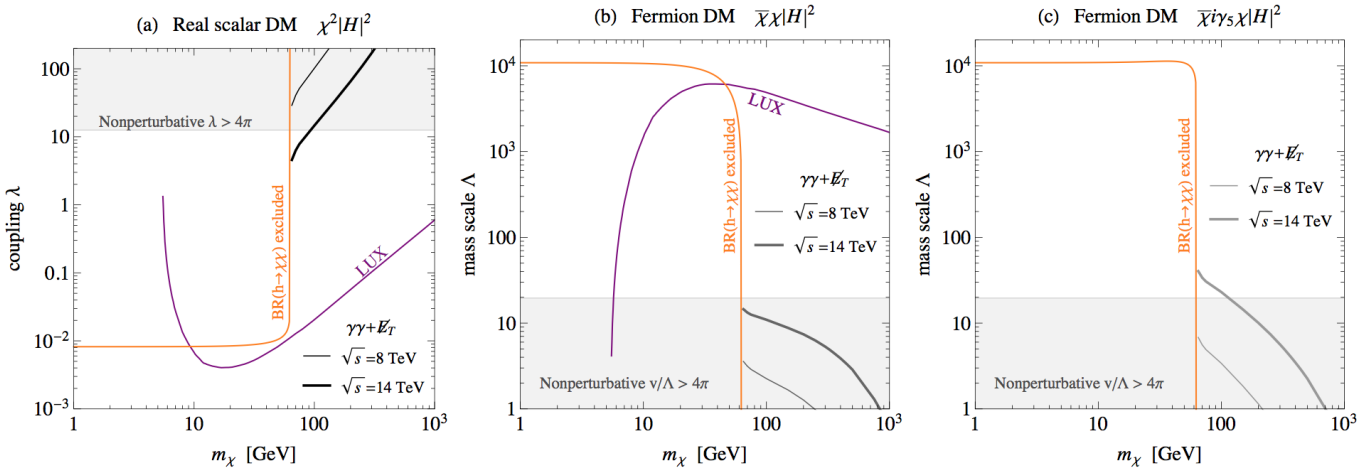
Effective theories





Simplified models





Result:
Promising for
14 TeV?

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: