The Search for Dark Matter at Large Hadron Collider

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27 March 2014

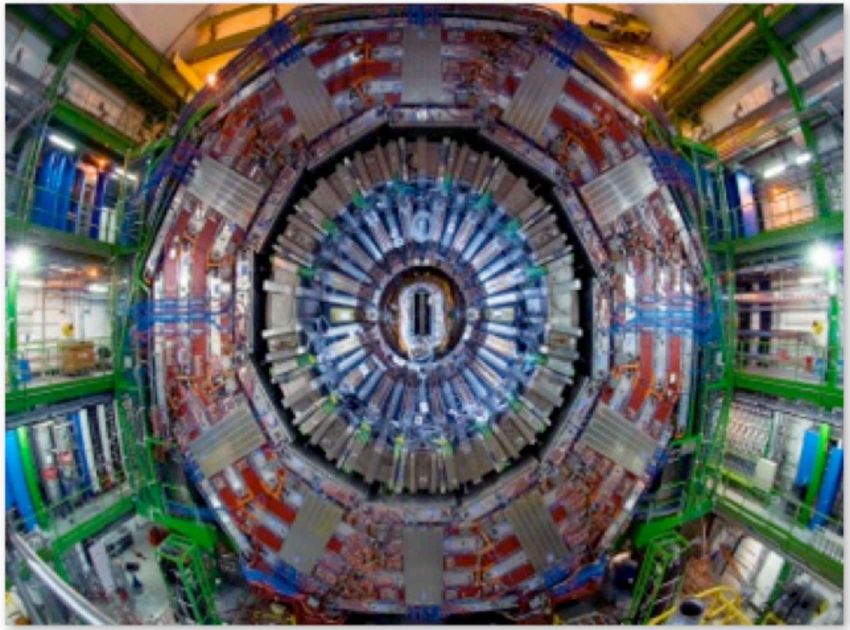
Dark Matter: complementary searches?

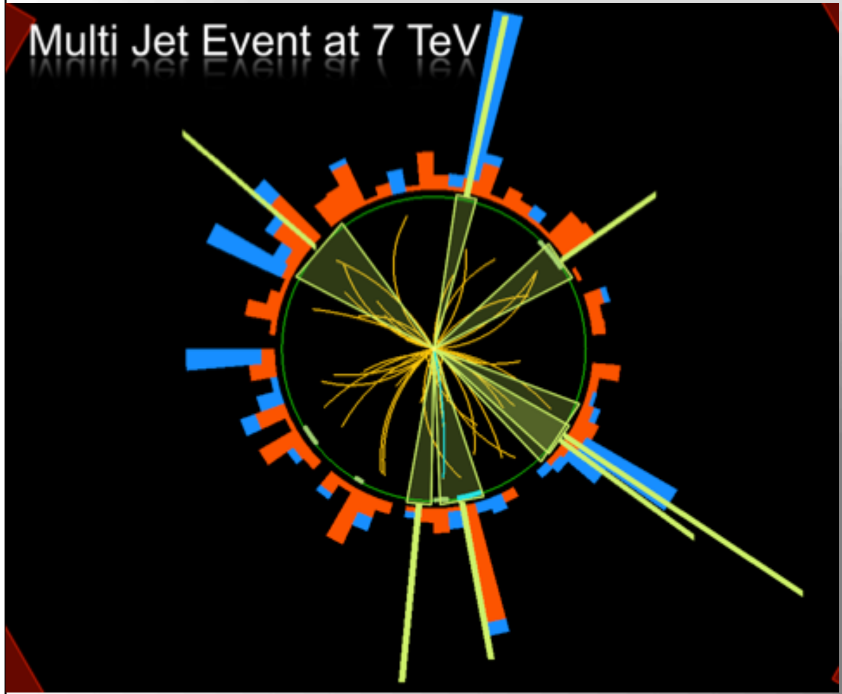
This seminar:

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.



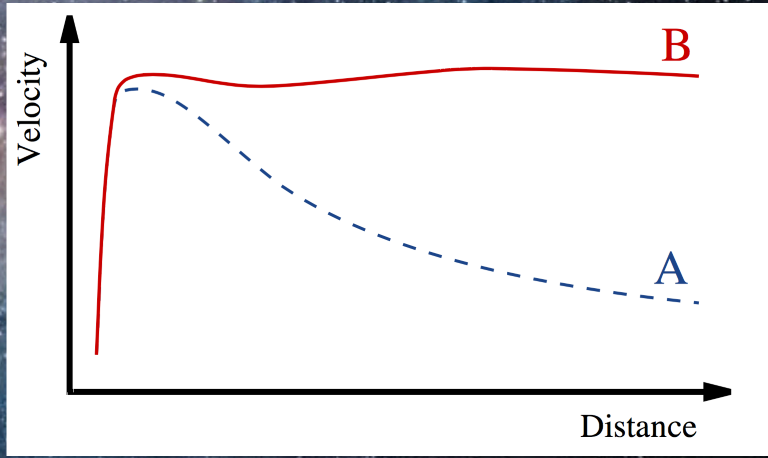


Outline

- 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: The Next Challenge

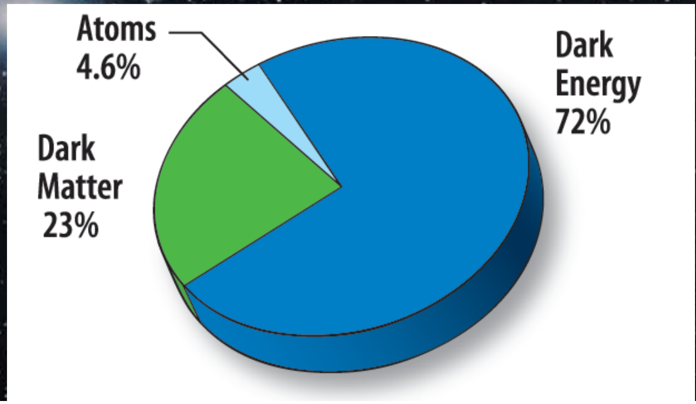
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



'Supersymmetric' particles ?

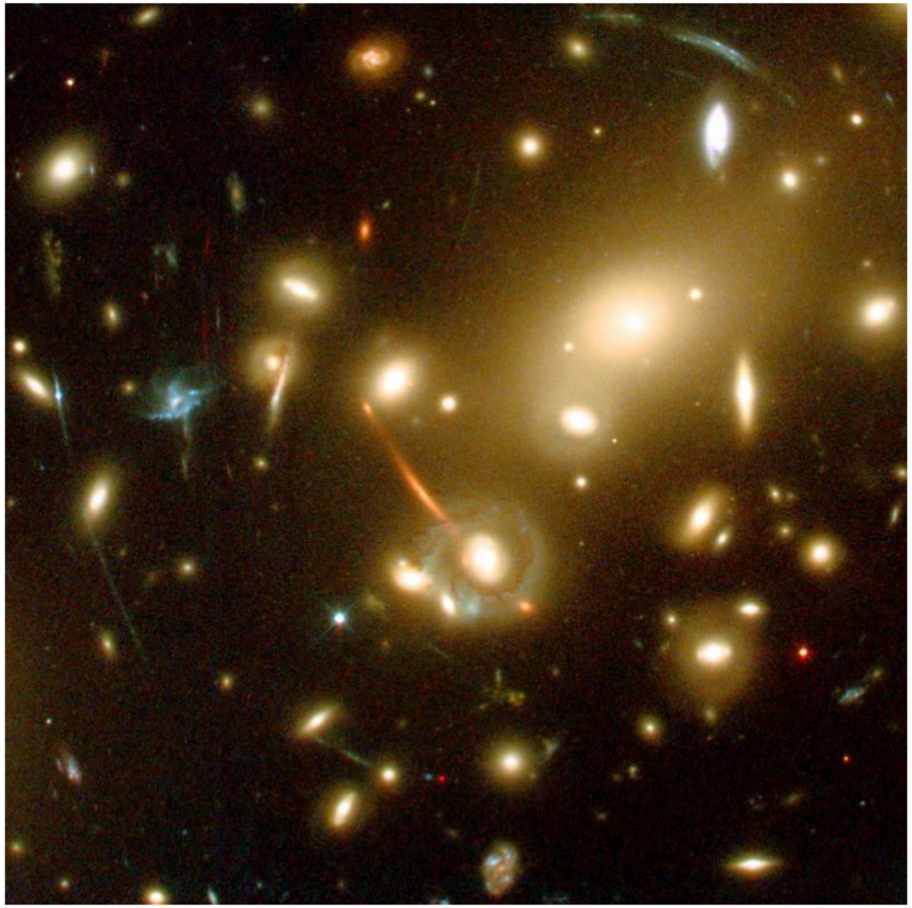
F. Zwicky 1898-1974

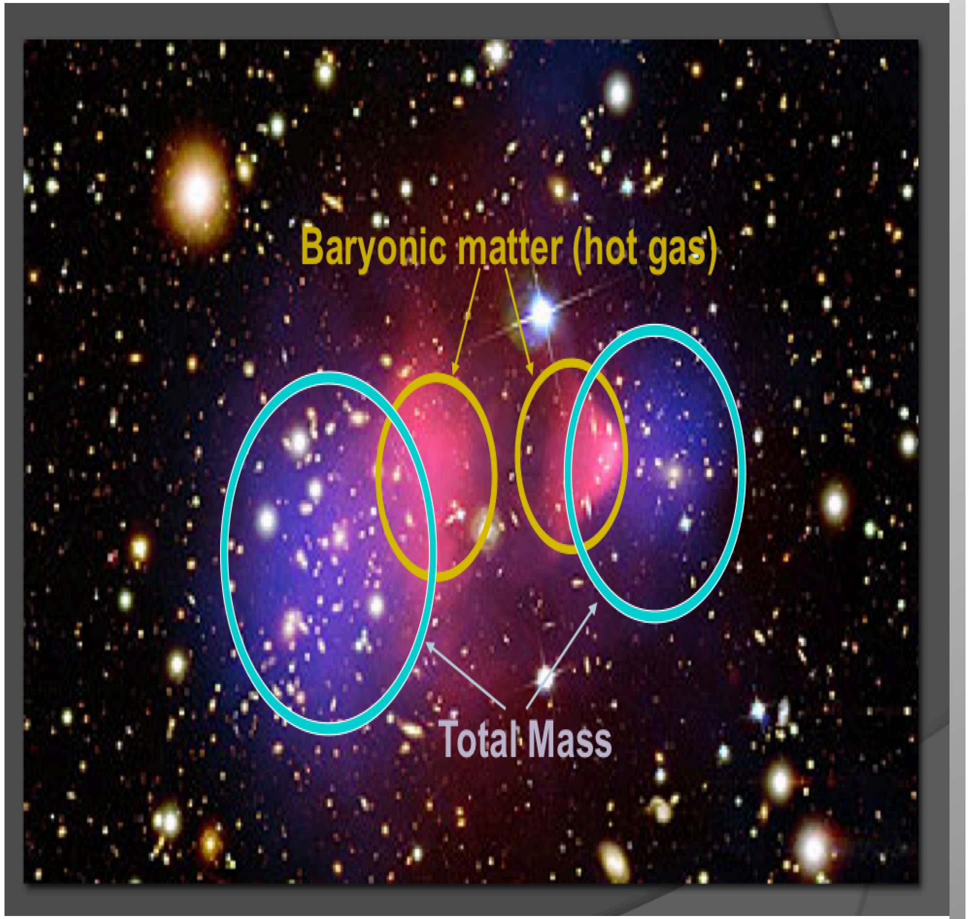
Vera Rubin ~ 1970



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
  - Does not really match modified gravity

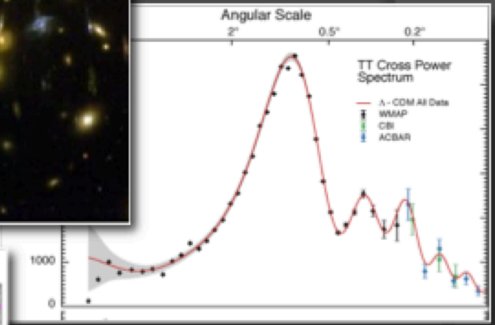


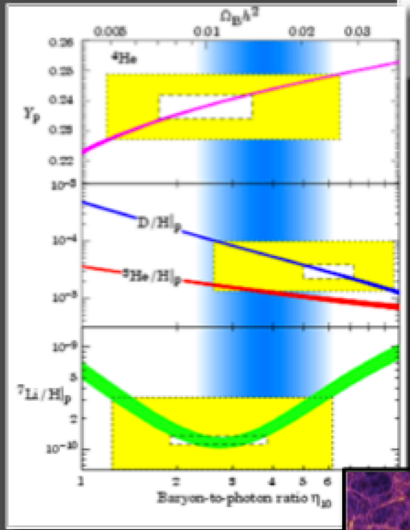


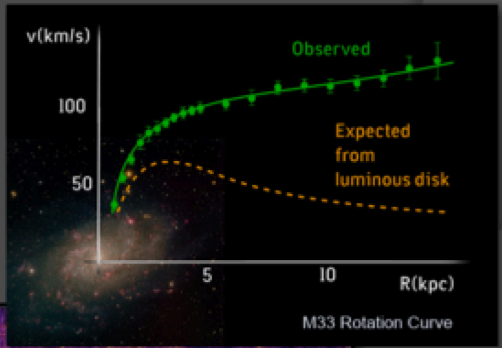
Evidence Piling-up

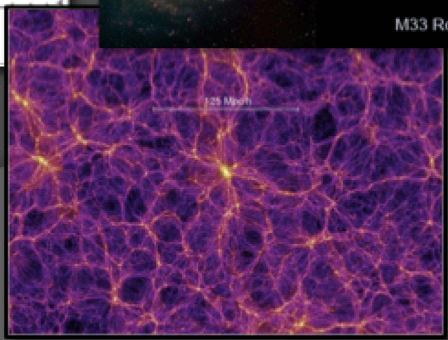
- There is a wide variety of evidence indicating that dark matter exists
- Each of these observations infer dark matter's presence uniquely through its gravitational influence
- To-date, no (non-controversial) observations have been made of dark matter's electroweak or other non-gravitational interactions

Instead of dark matter, might we not understand gravity?

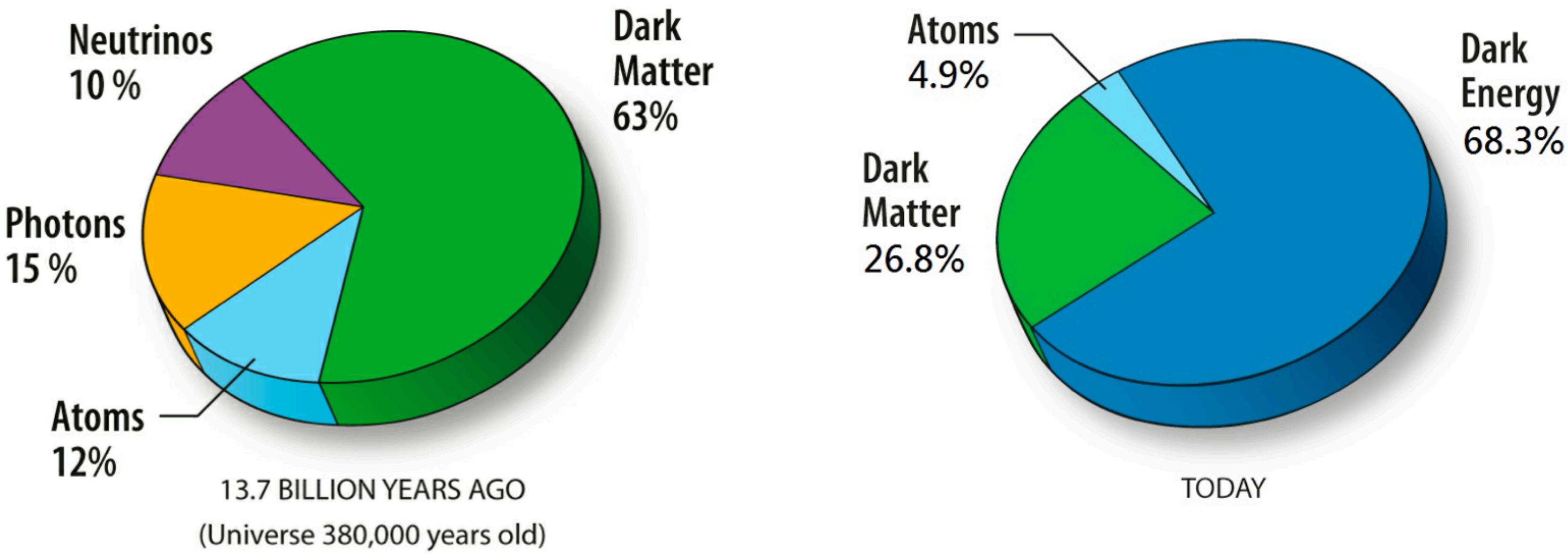








The Universe, Then and Now



- 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 (~10-100 GeV) particle (WIMP).

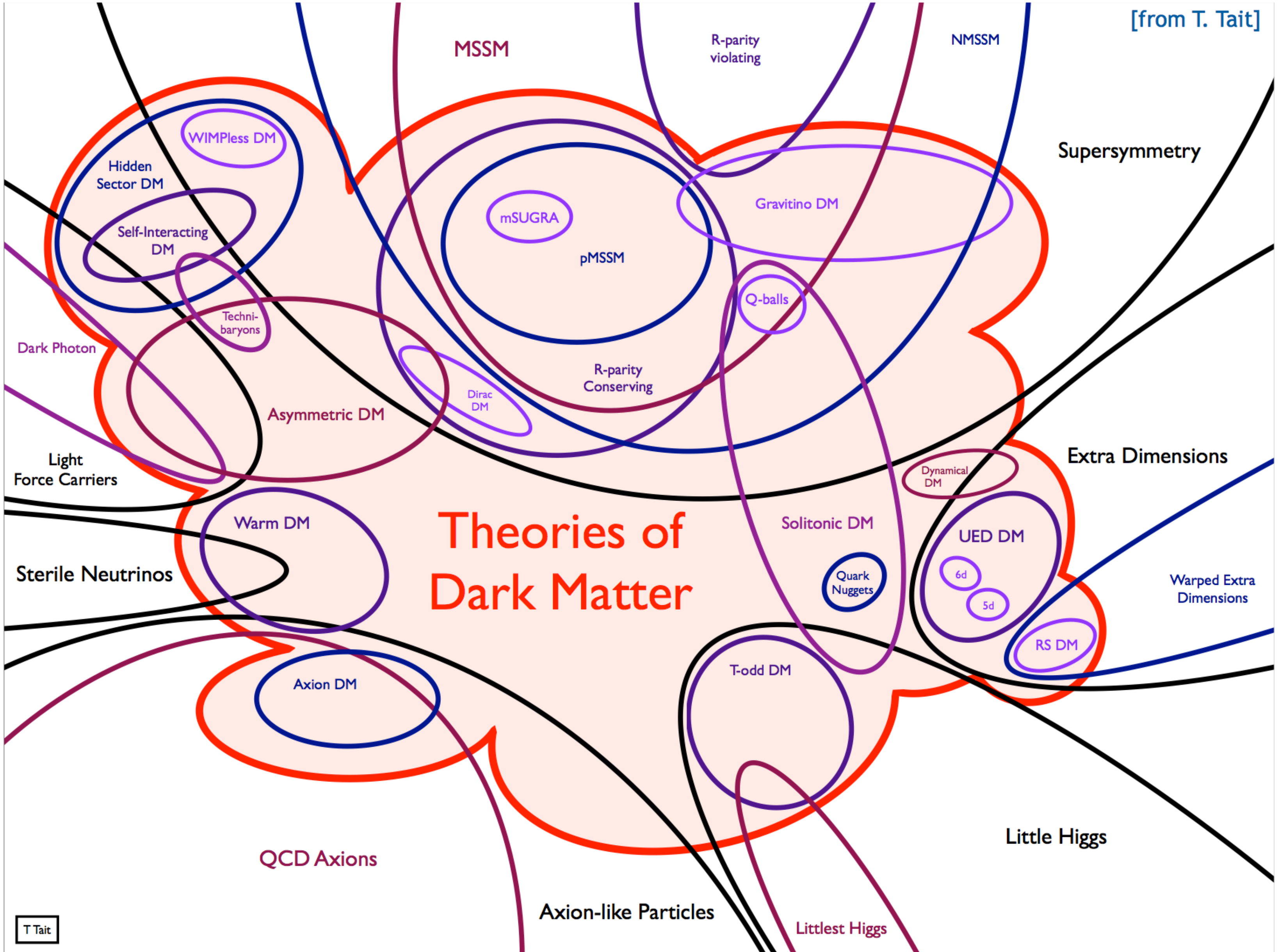
Particle Dark Matter?

The Dark Matter Candidate Zoo

- 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…

From D. Hooper

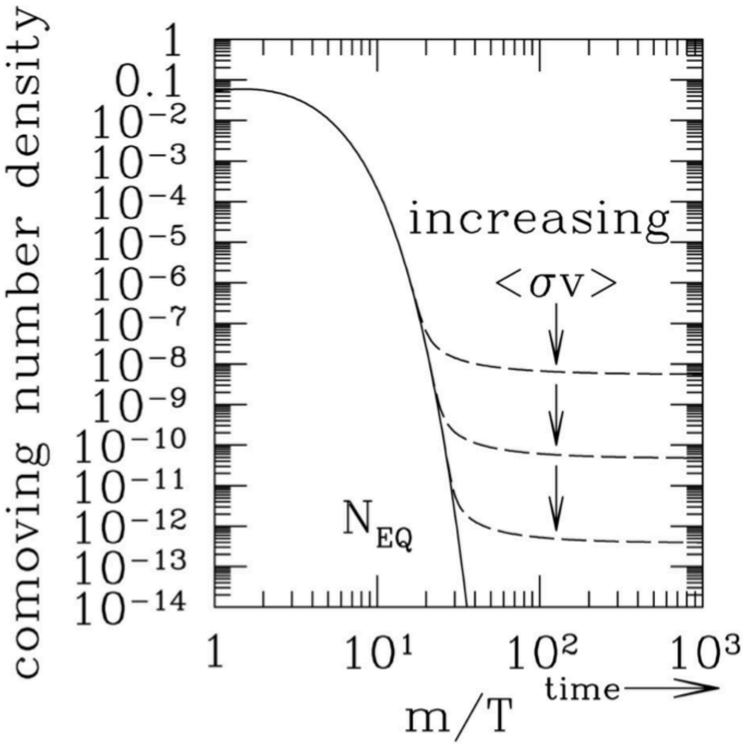
No Lack of Theoretical Ideas…



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

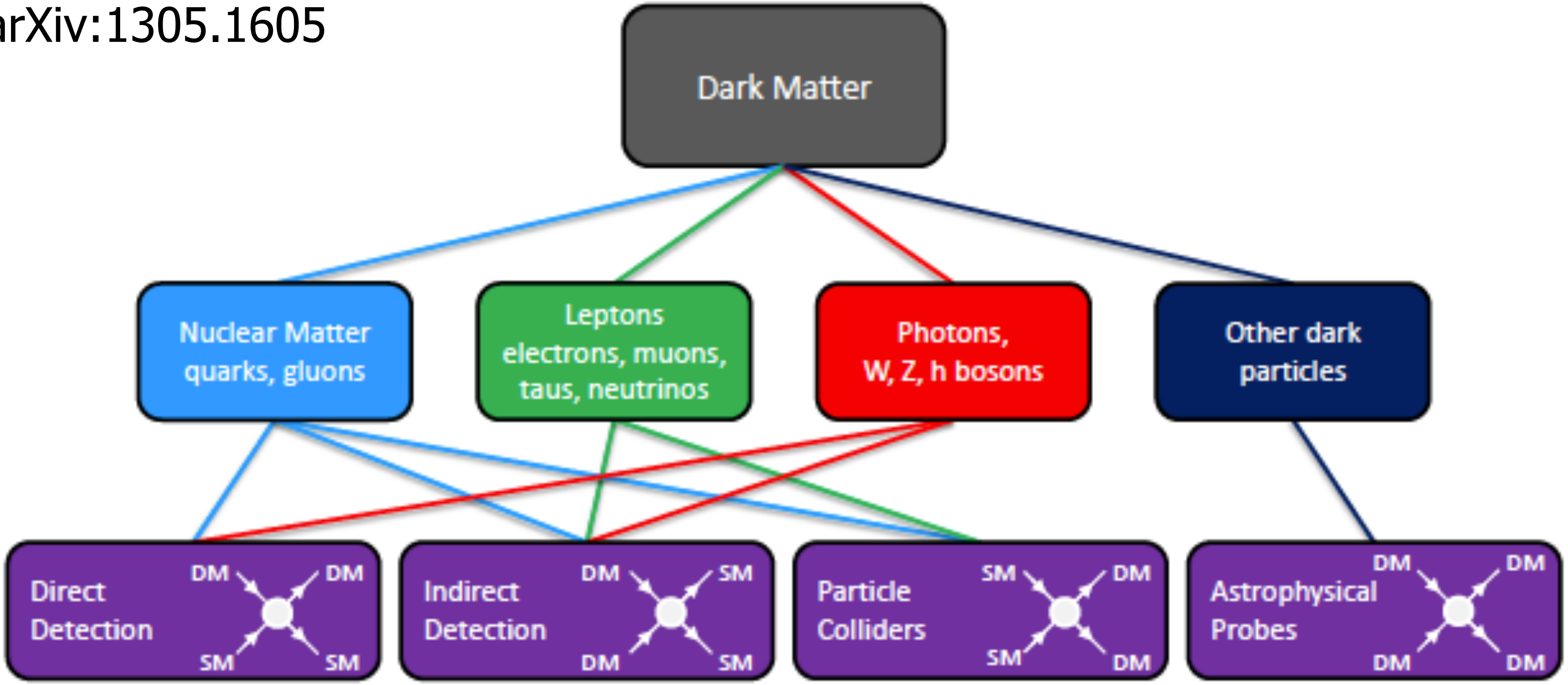


Weakly-interacting massive particles naturally provide the right relic abundance - "WIMP miracle"

Dark Matter @ LHC?

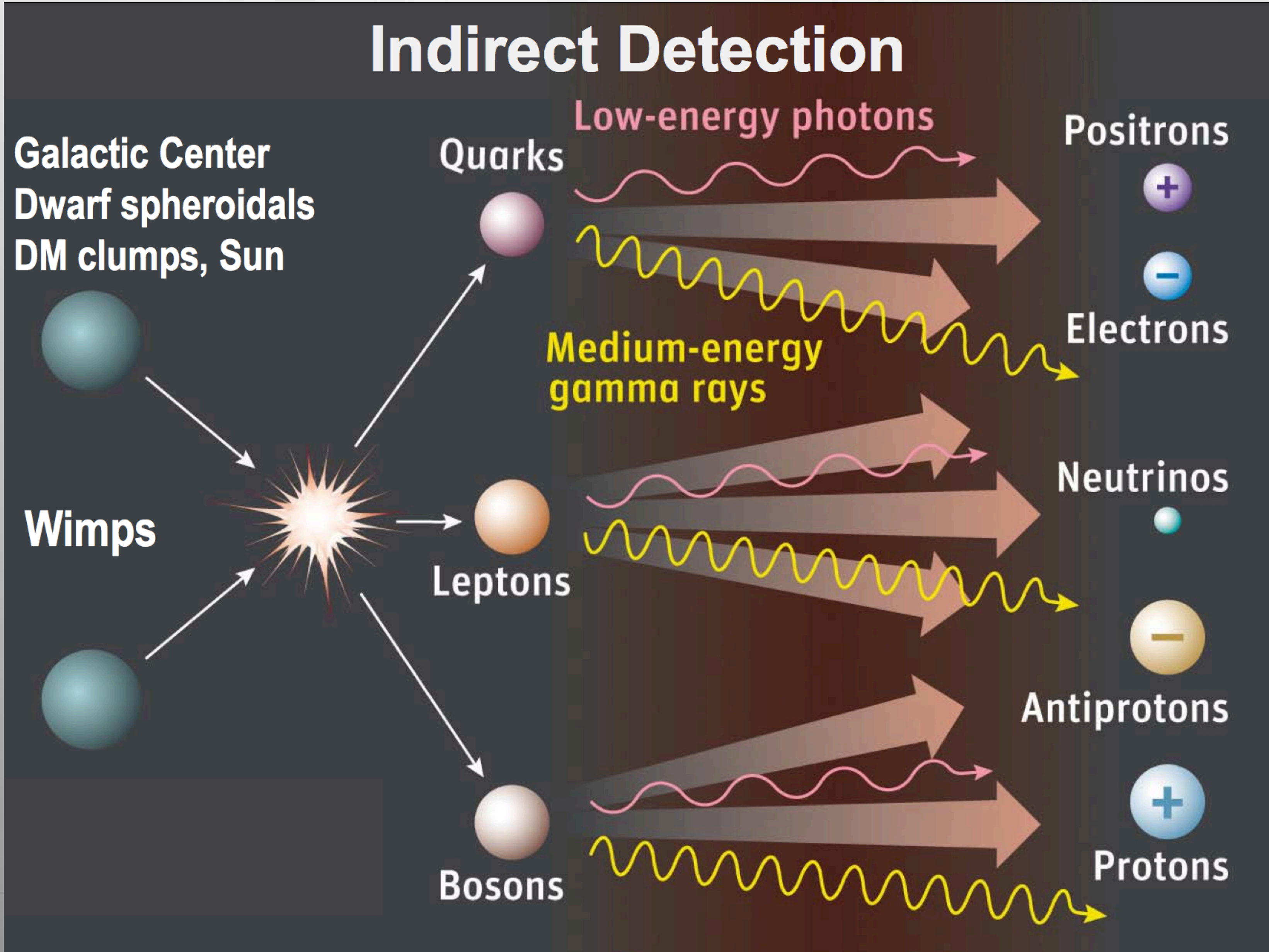
Search for WIMP candidates in events with Missing Transverse Momentum
EG: SUSY searches, monojet and mono-photon Searches, W' searches…

arXiv:1305.1605

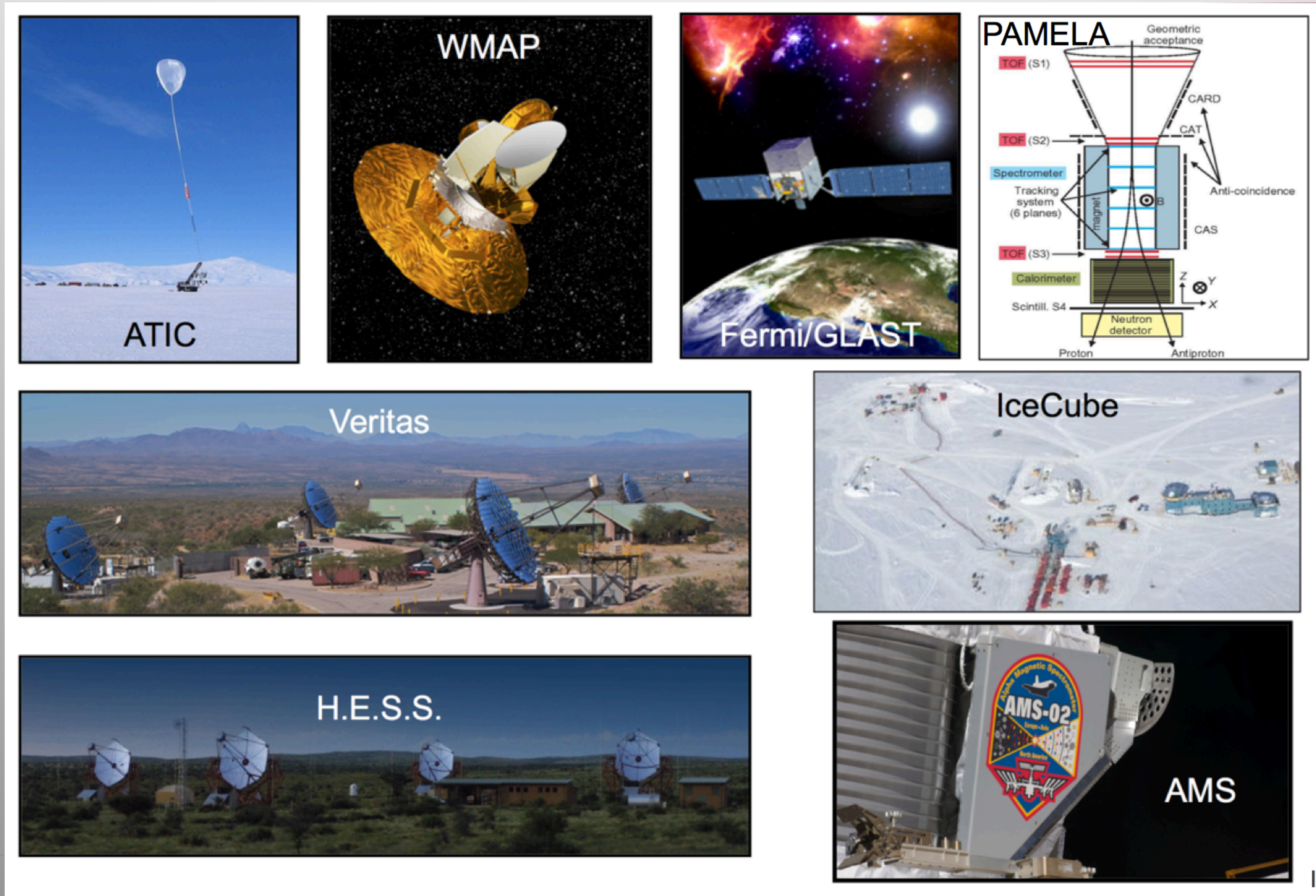


+ CAST experiment, searching for axion DM

Dark Matter: Indirect Detection



Indirect Detection Experiments



Indirect Detection

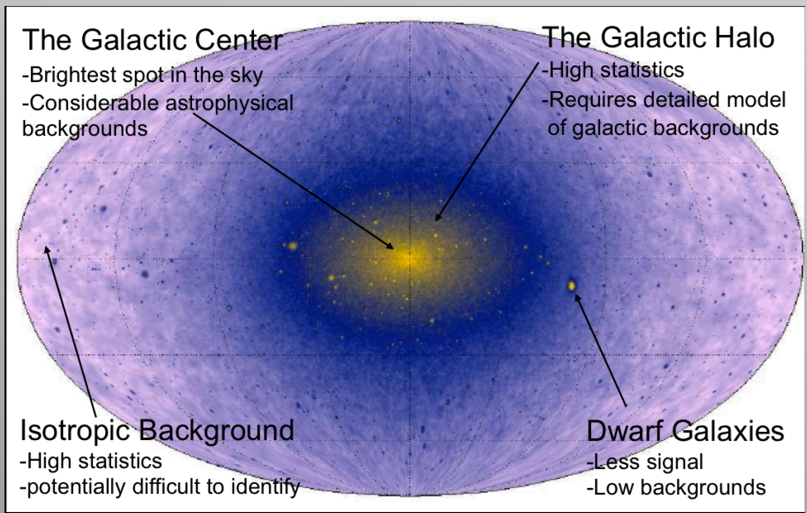
Some scientists are believers!!

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]

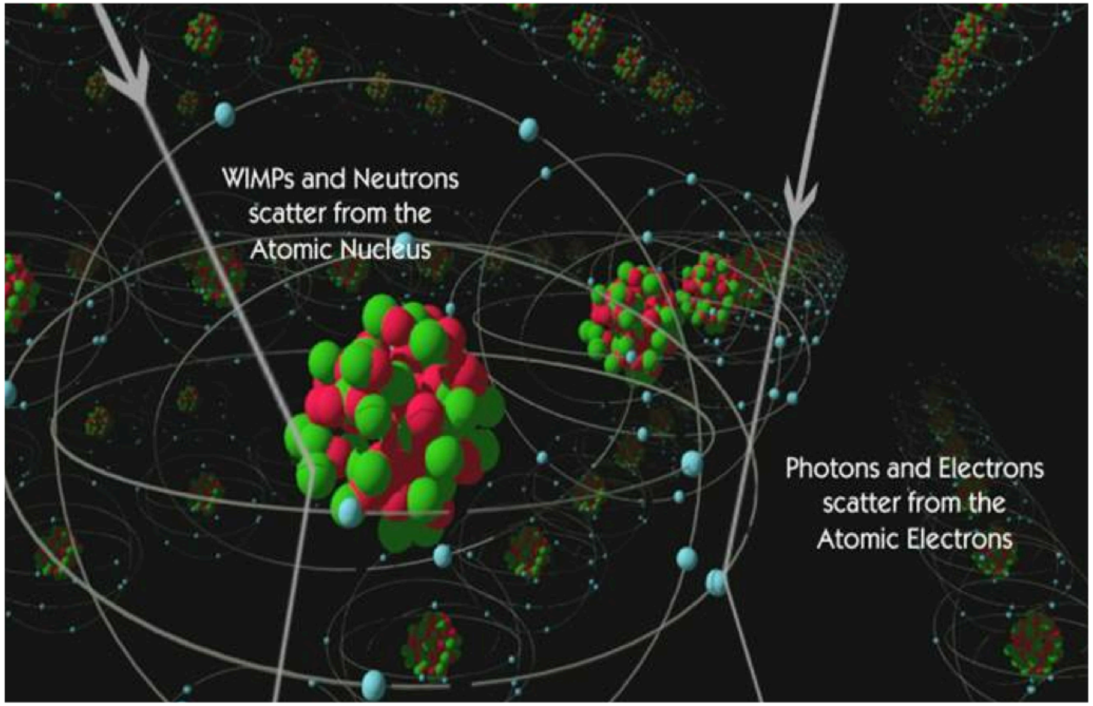
Using gamma-ray data from the FERMI satellite
DM annihilation into b anti-b quarks?



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

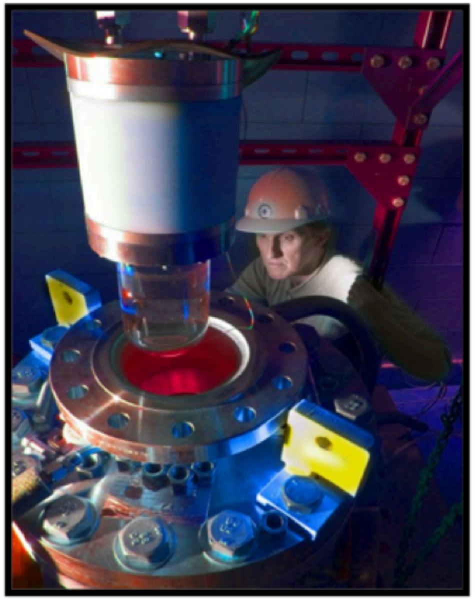
Dark Matter: Direct Detection

- 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...

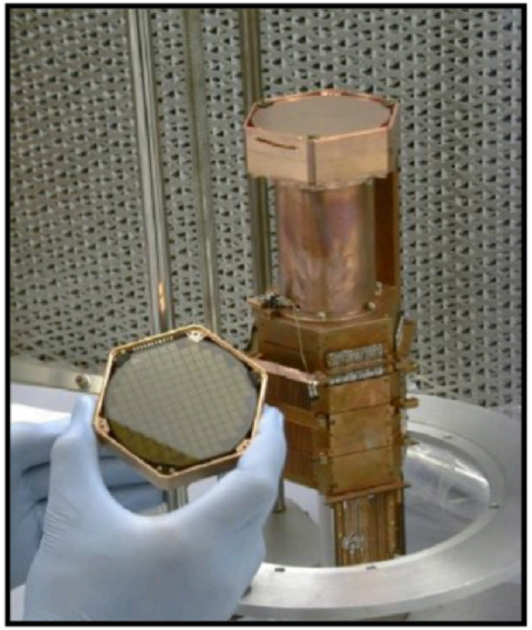


Direct Detection: Examples

COUPP

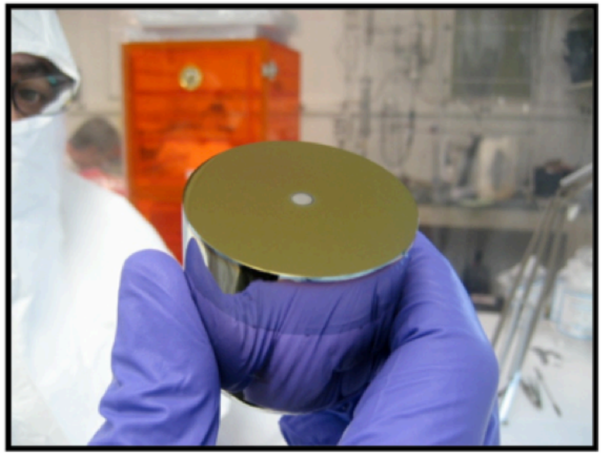


CDMS



CRESST

CoGeNT

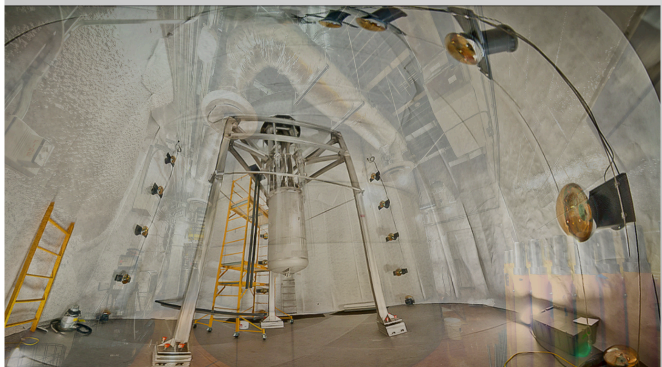


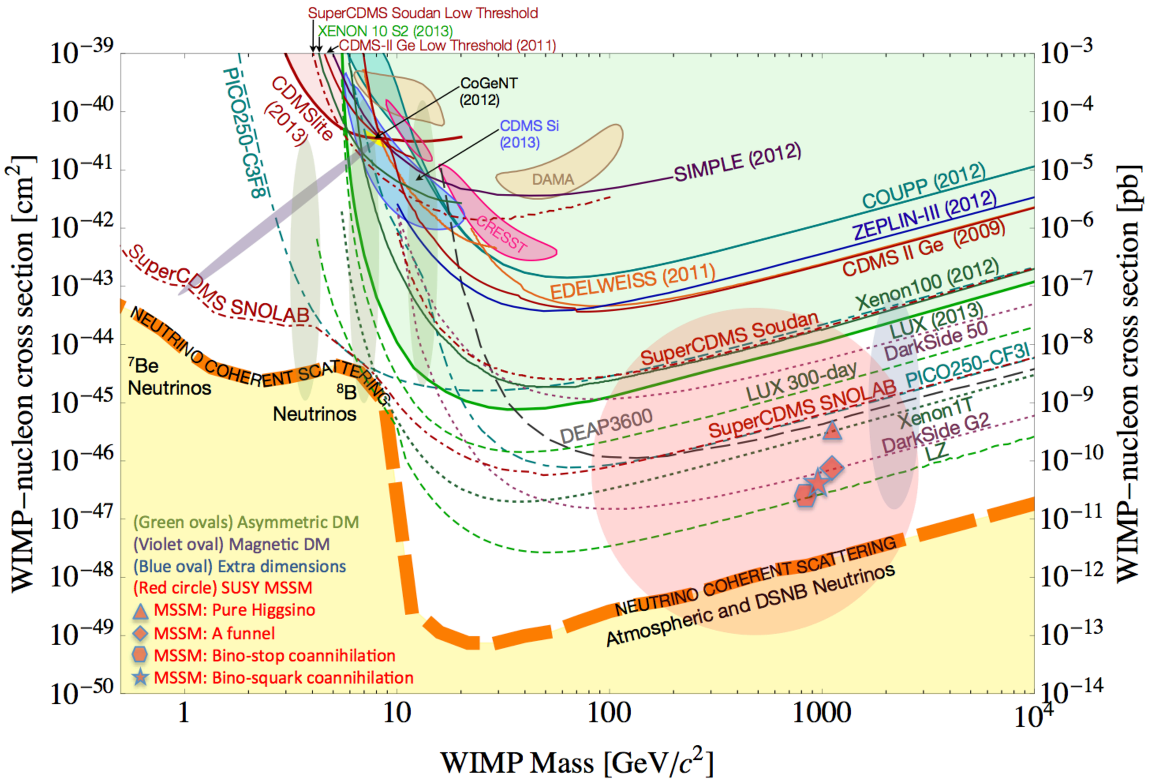
(+ EDELWEISS, DAMA, EURECA, ZEPLIN, DEAP, ArDM, WARP, LUX, SIMPLE, PICASSO, DMTPC, DRIFT, KIMS, …)

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…

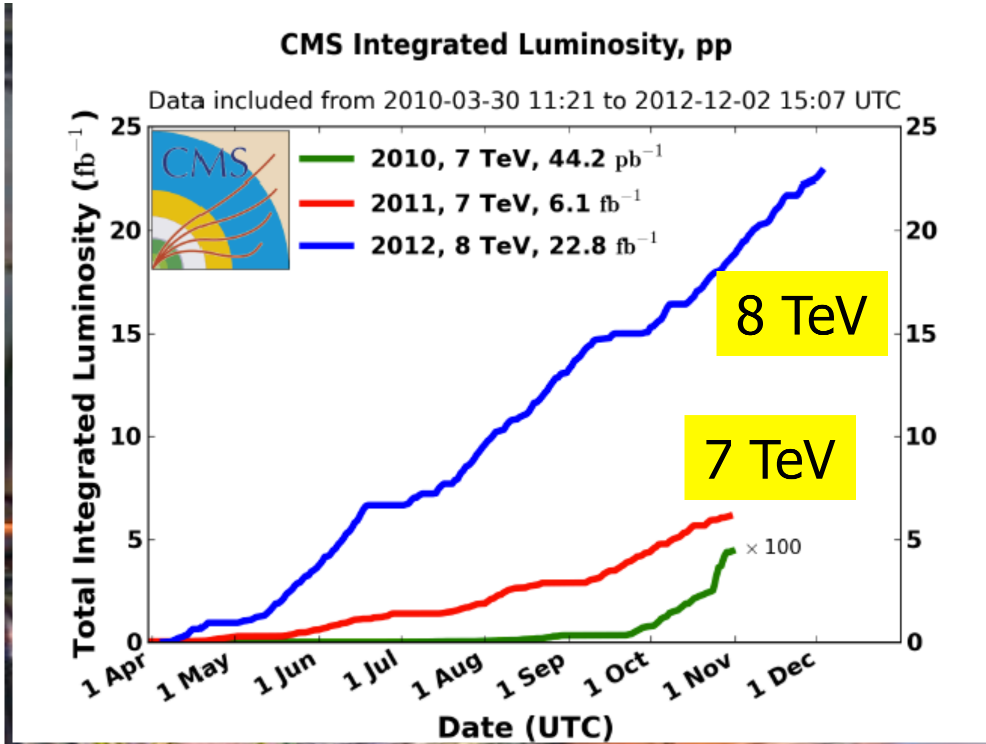
The LUX Experiment

One has always to be careful with the press…

Search for dark matter by UC Davis researchers comes up empty

☺

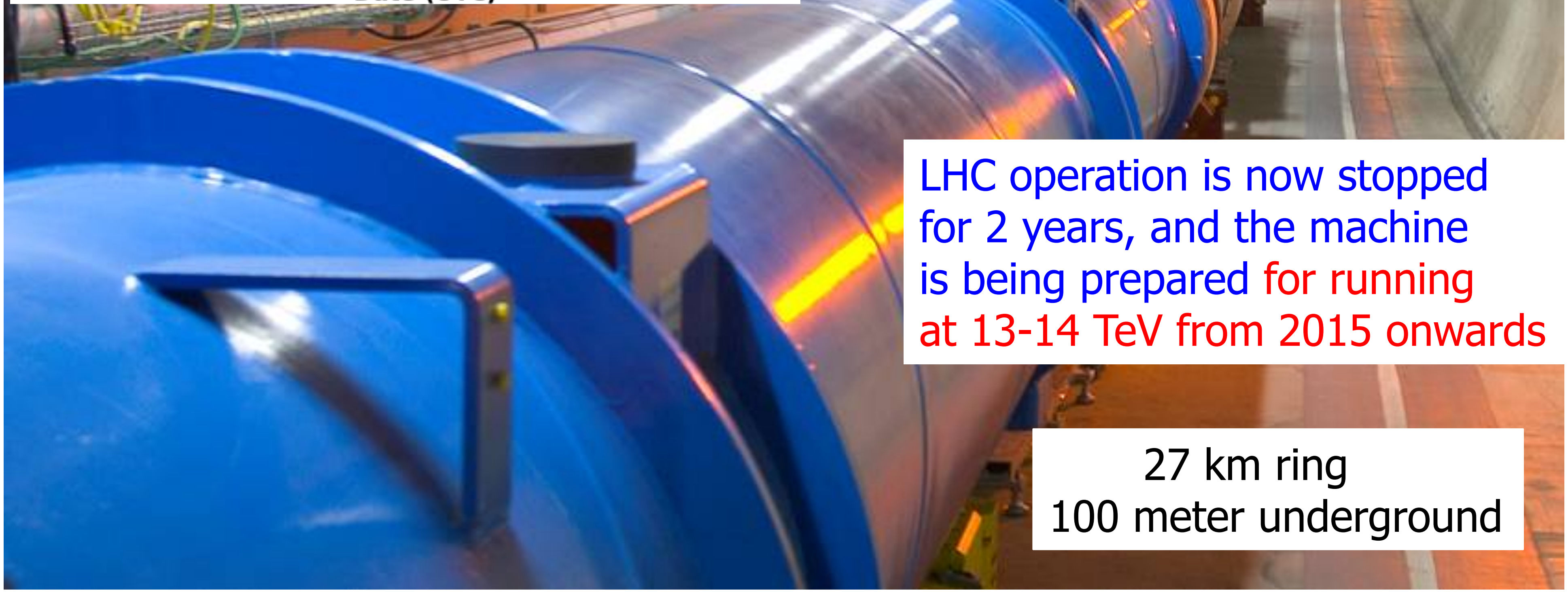
The LHC



Primary physics targets

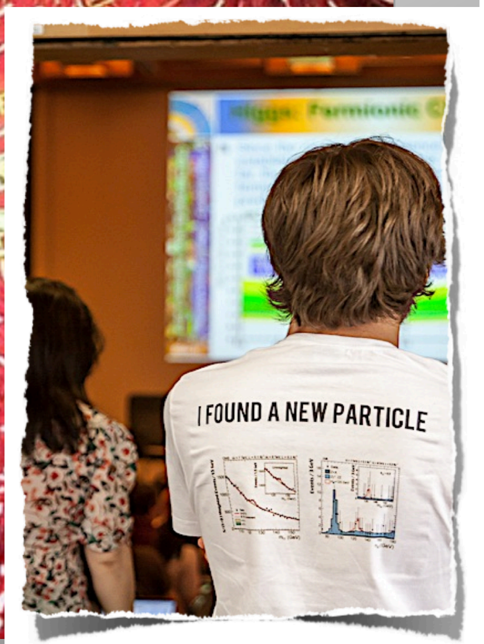
- Origin of mass
- Nature of Dark Matter
- Understanding space time
- Matter versus antimatter
- Primordial plasma (PbPb)

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

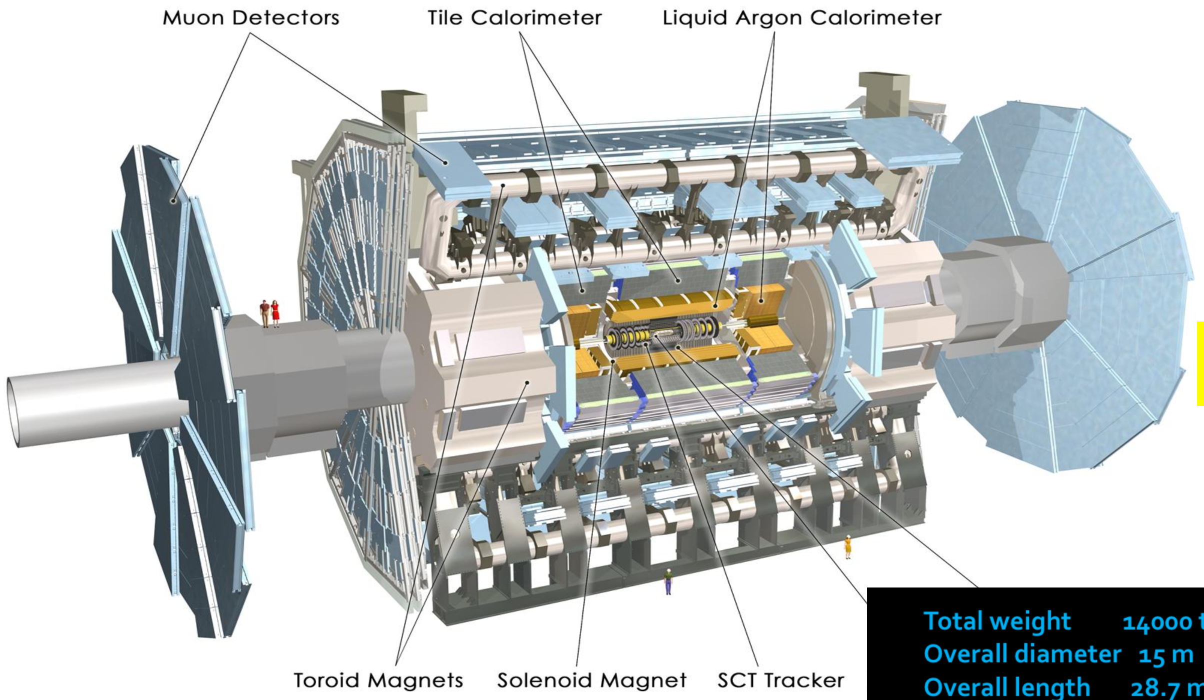


27 km ring
100 meter underground

4th of July 2012…



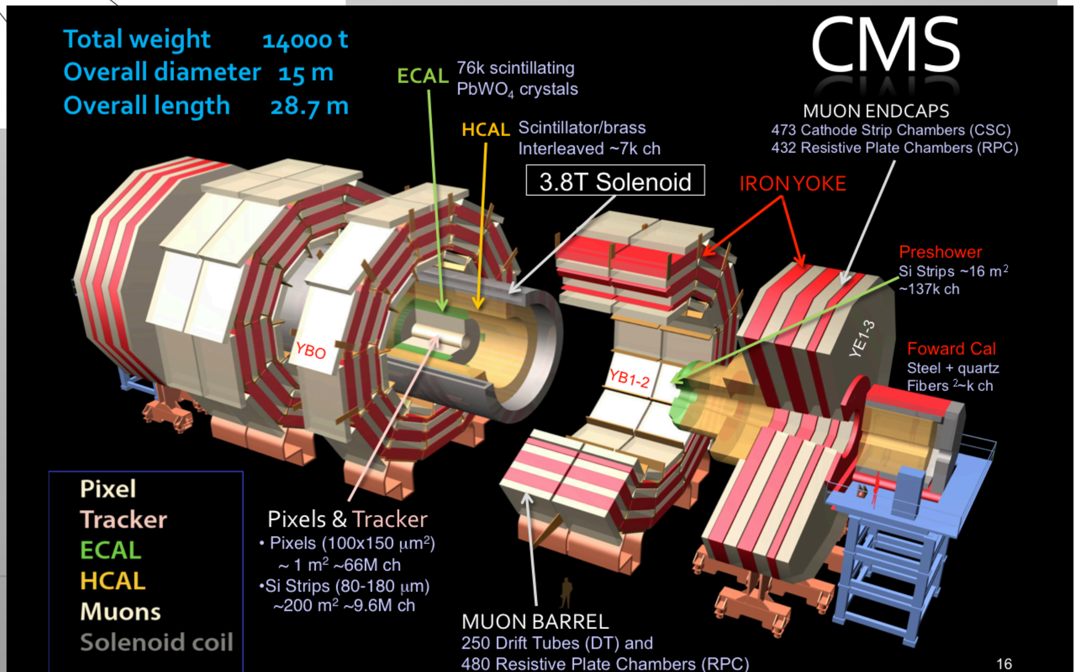
The Higgs Hunters @ the LHC



LHC: pp collisions at 7/8 TeV

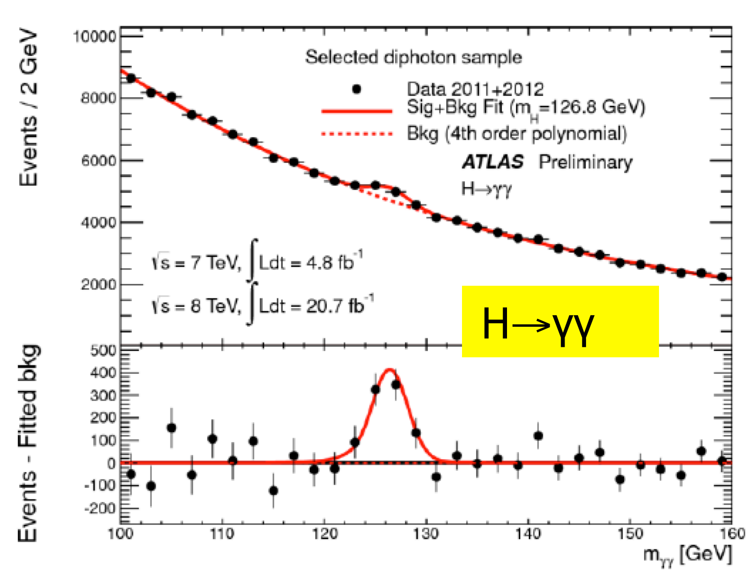
The ATLAS experiment

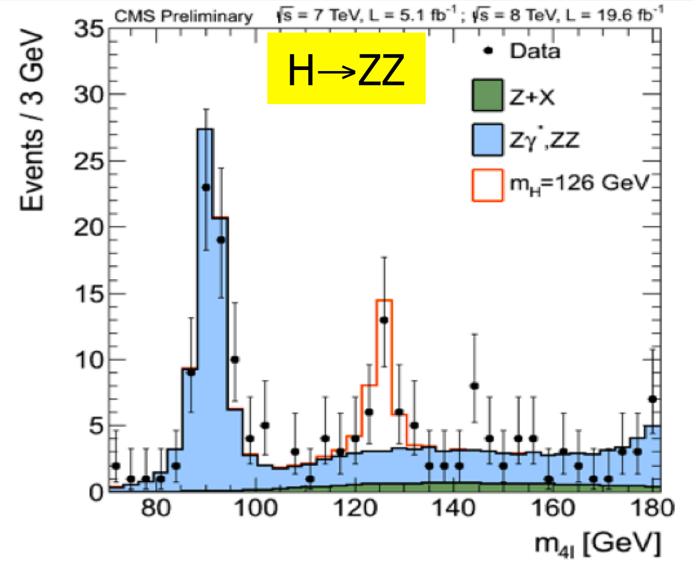
The CMS experiment

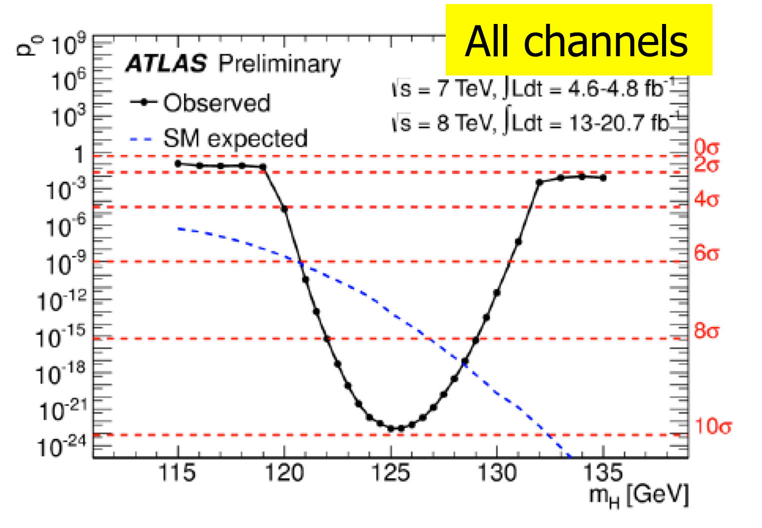


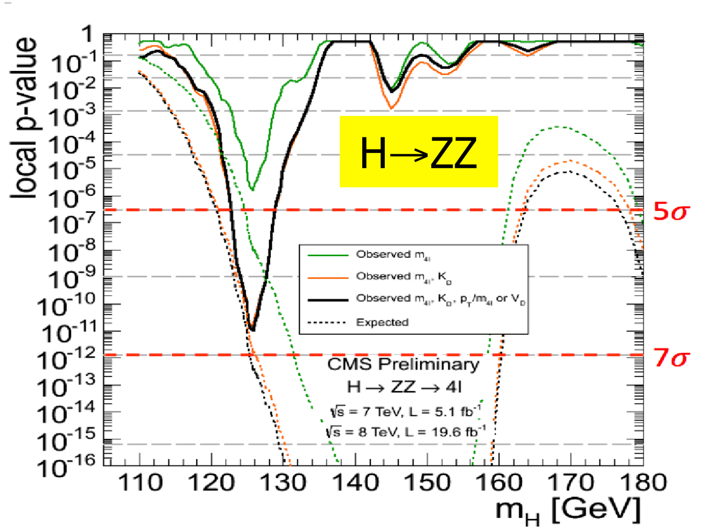
These experiments are likely to become DARK MATTER HUNTERS in 2015 and beyond…

Evidence for a Higgs (2013)









The particle is clearly still with us, now with a significance of >10σ !! in both CMS and ATLAS

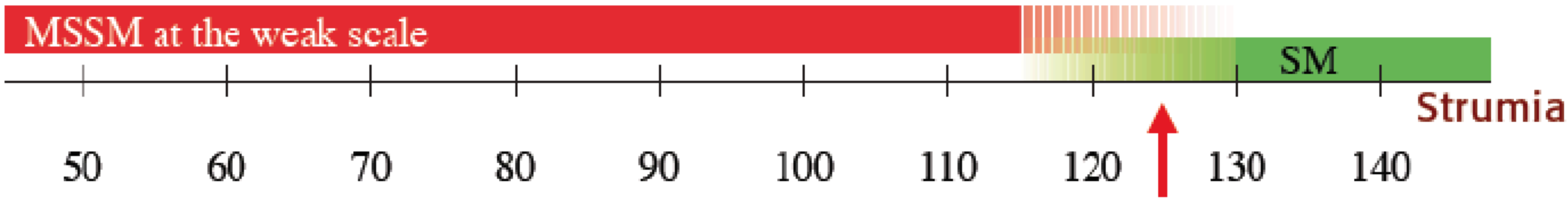
It has a mass of about 126 GeV

We now enter the phase of measuring the properties of the new particle

A Higgs…

A malicious choice!

$m_H = 125.6 \pm 0.4$ GeV



The Higgs:
so simple yet so unnatural

Guido Altarelli

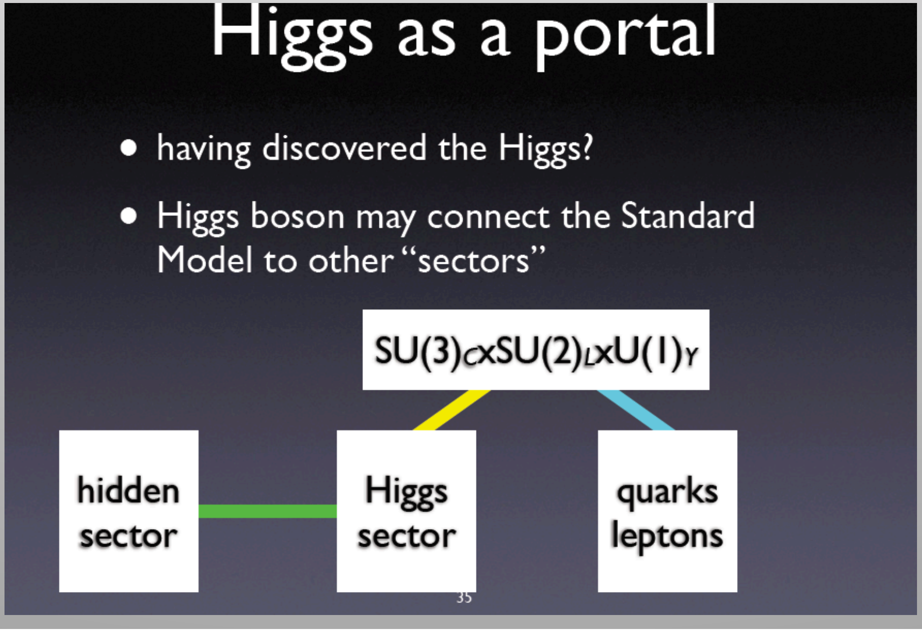
Stockholm Nobel Symposium
May 2013

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

What is Next?

The work is not over yet: Many questions still remain unanswered:

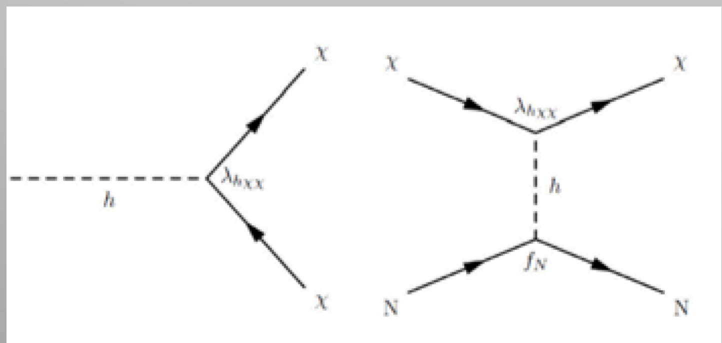
- Is it THE Standard Model Higgs boson or a messenger of New Physics ?
- How can we explain a Higgs mass ~ 126 GeV? What stabelizes the mass?
- What explains the mass pattern of the particles that we observe?
- What is Dark Matter and Dark energy? Supersymmetry at higher masses??
- Where is the antimatter in the Universe? How did it disappear??



Need for precision measurements with ~100x the present statistics

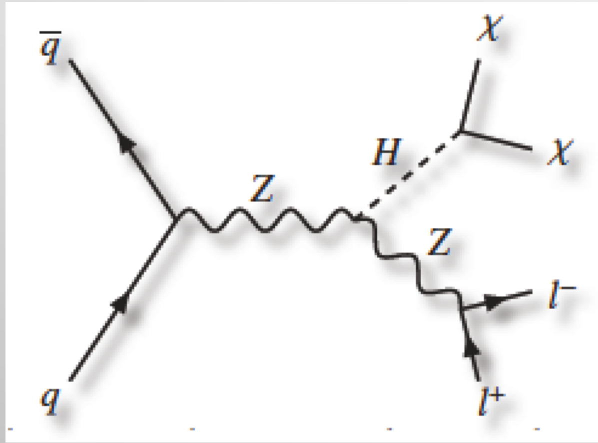
LHC upgrade ! Experiment upgrades!! (Other machines?)

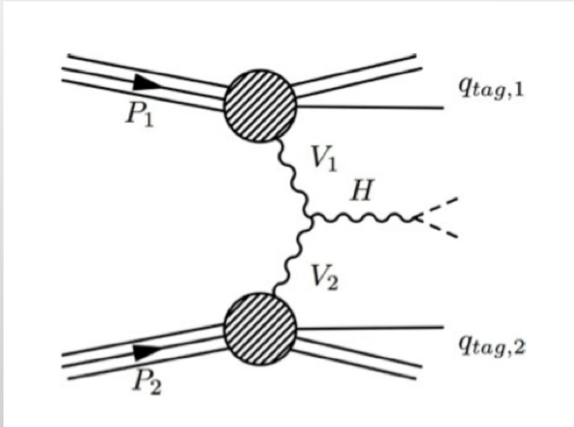
Dark Matter and the Higgs



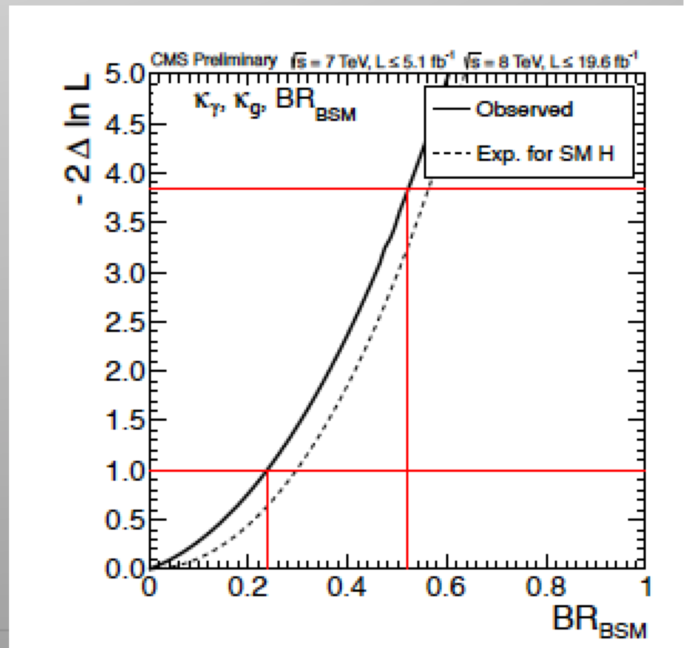
"higgs portal models"
Eg: arXiv:1205.3169

Invisible Higgs Decay Channel





- 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)



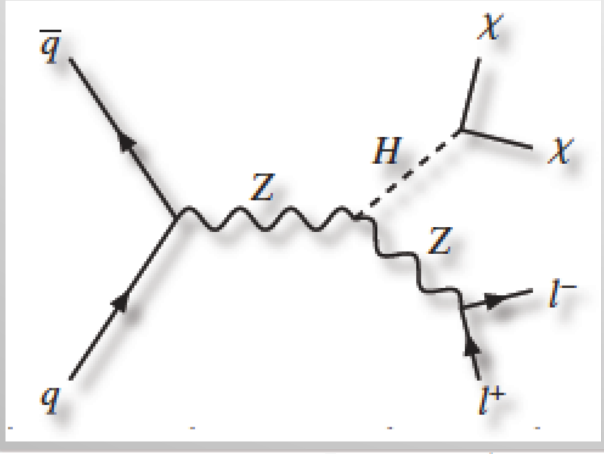
Invisible Higgs Decay Channel

CMS-PAS-HIG-13-018

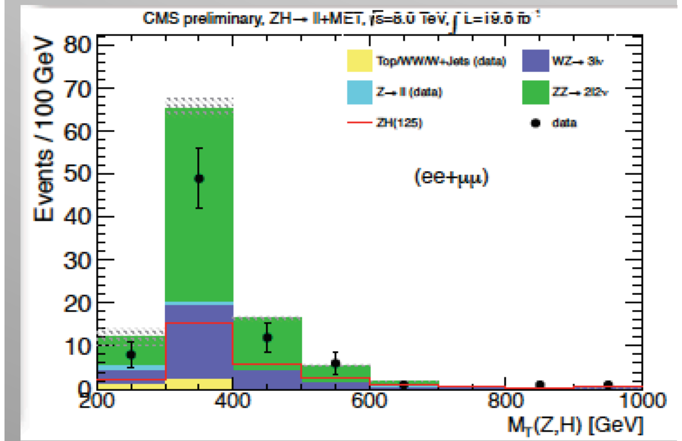
Search for Invisible Higgs decays in the ZH process

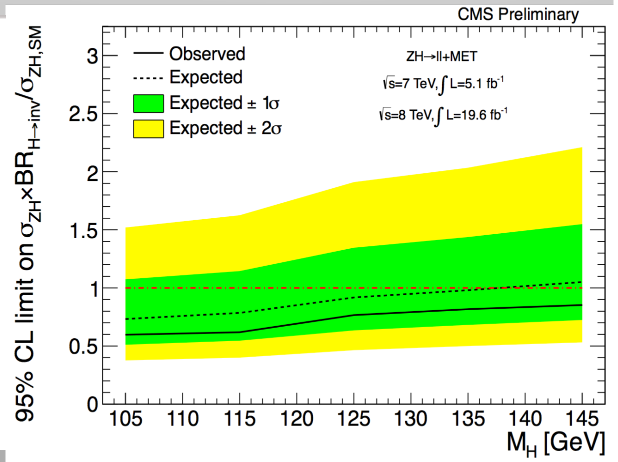
Z+H → 2 leptons + missing E_T

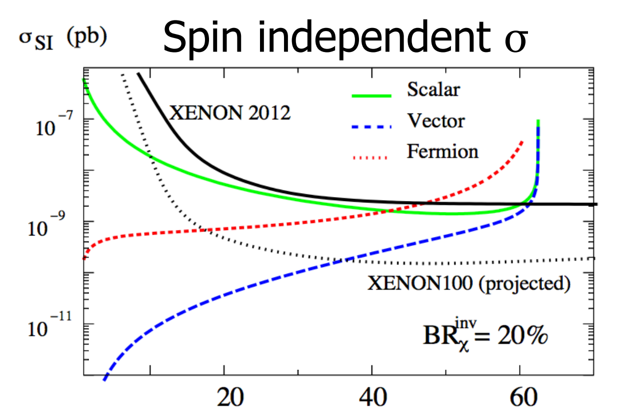
Possible decay in Dark Matter particles (if $M<M_H/2$)



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







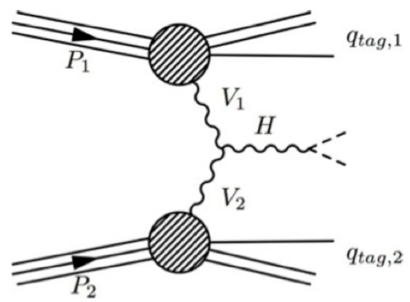
arXiv:1205.3169

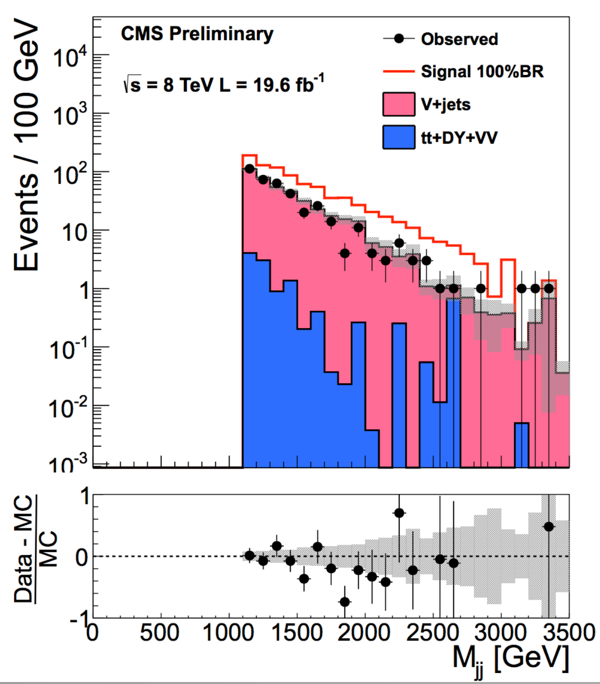
- No evidence for invisible decays found so far

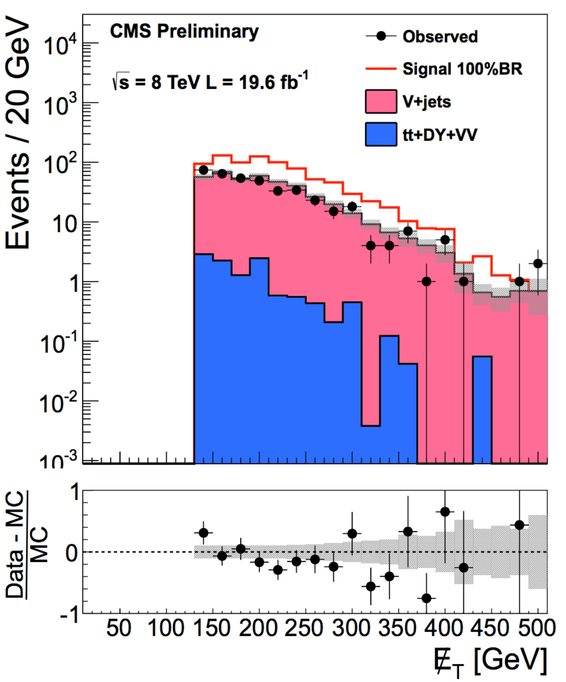
Invisible Higgs Decay Channel

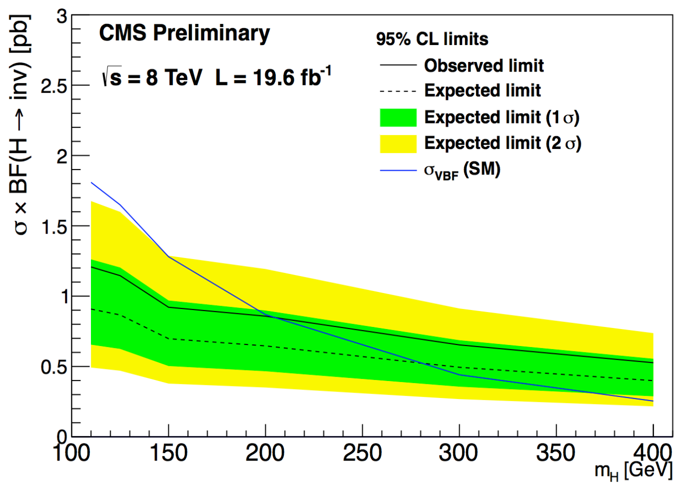
CMS-HIG-13-013

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



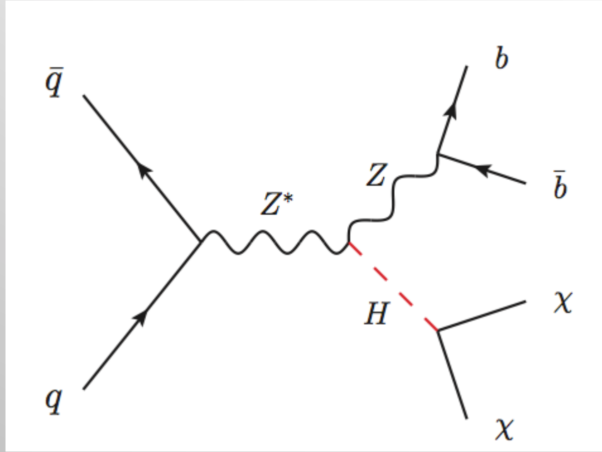






95% CL upper limit on BF(invisible) = 69% (53% expected)

Invisible Higgs Decay Channel



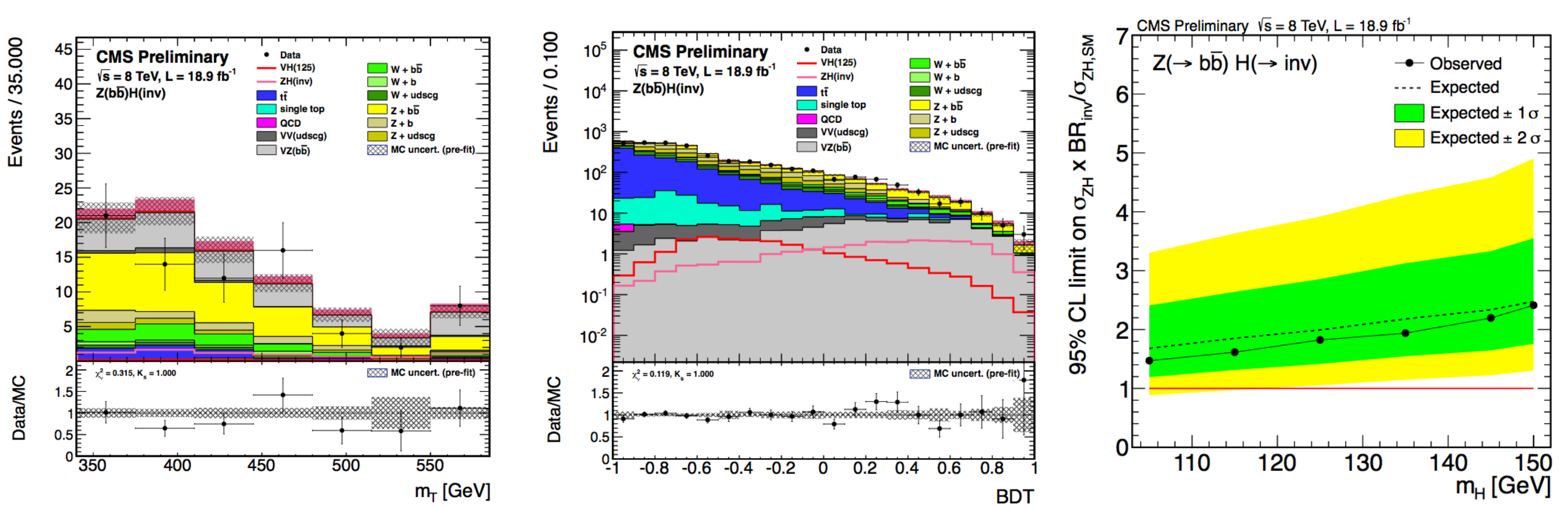
Search for Invisible Higgs decays in the ZH process

Z+H → 2 b quarks + missing E_T

Similar to the process Z+H with H →bb and Z→νν

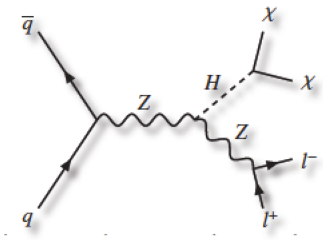
CMS-PAS-HIG-13-028

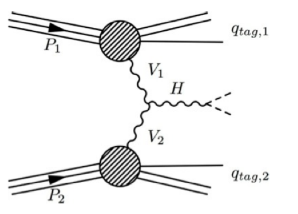
95% CL upper limit on BF(invisible) = 1.82 (1.99 expected)



•No evidence for invisible decays found so far

Invisible Higgs Decay Channel





Search for invisible Higgs decays in the processes

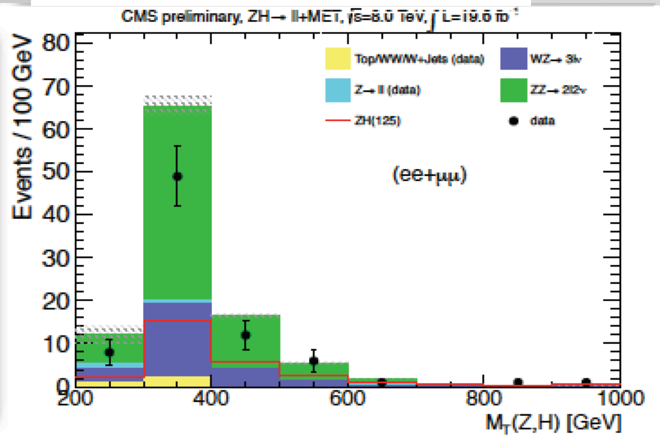
Z+H → 2 leptons + missing E_T

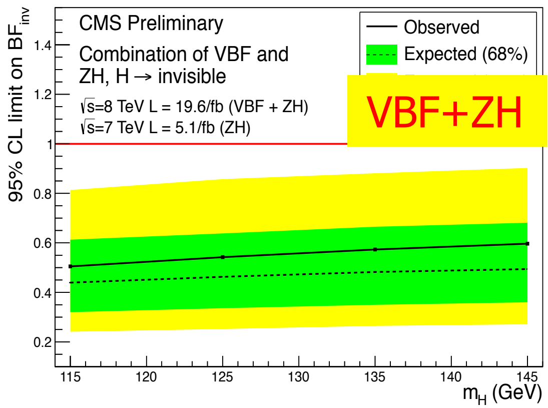
VBF H → 2 jets + missing E_T

Possible decay in Dark Matter particles (if $M<M_H/2$)

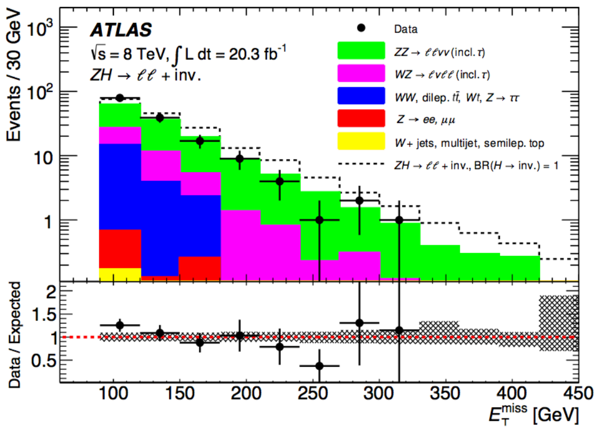
ATLAS :arXiv:1402.3244

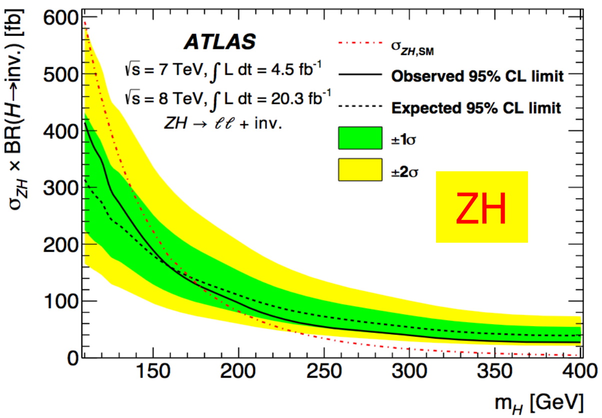
CMS-PAS-HIG-13-013/018





- 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

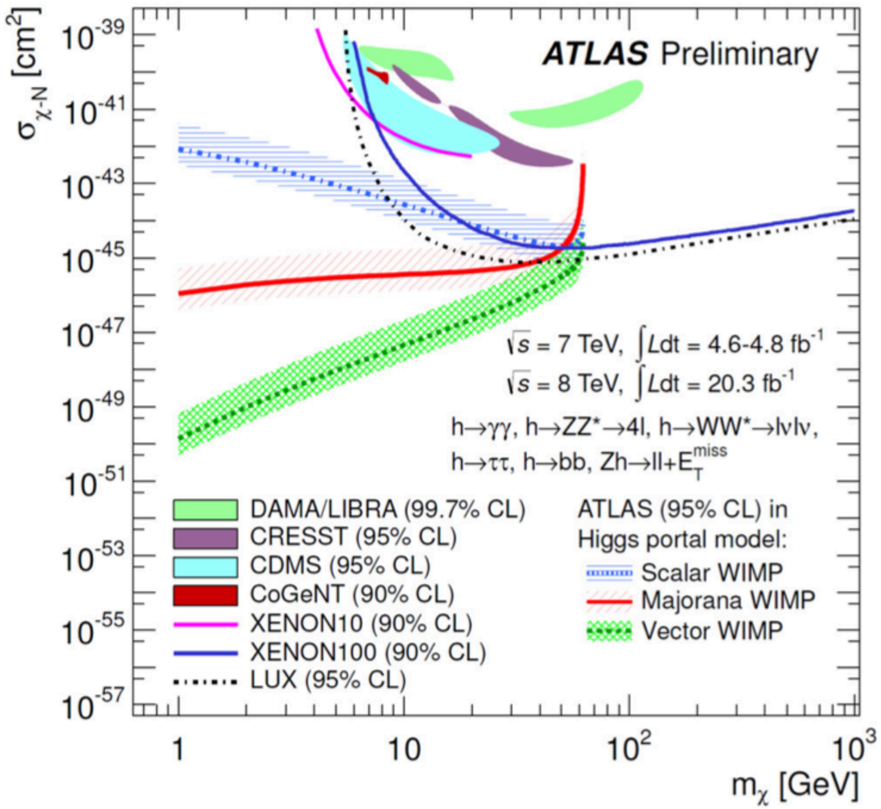


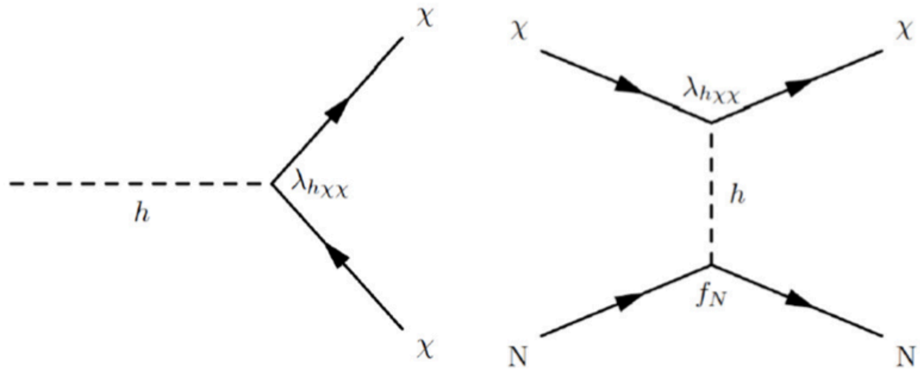


- No evidence for invisible decays found so far
- More channels & data coming up…

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)





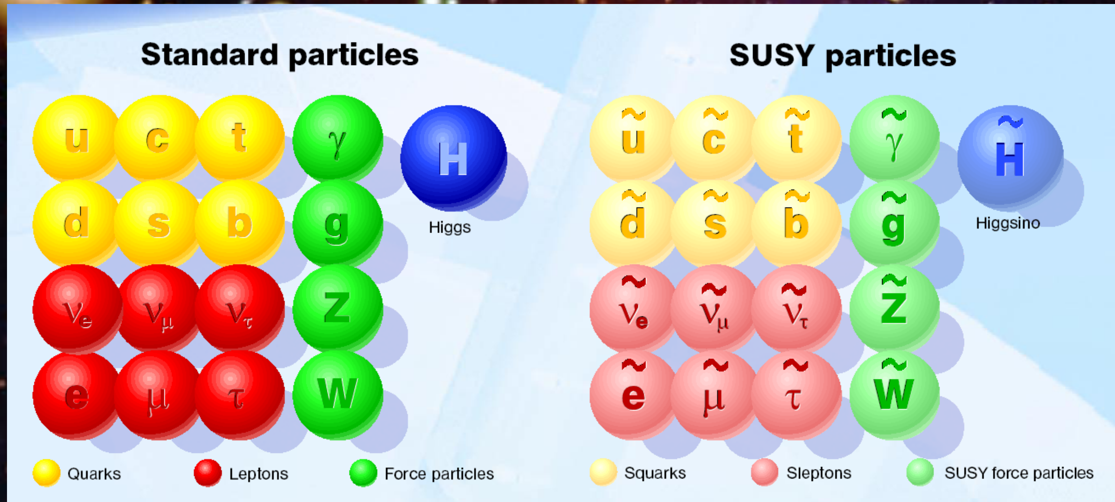
- Significantly more sensitive at low mass for vector WIMP than direct detection experiments *assuming Higgs Portal model*
- Sensitivity dominated by 5-channel coupling combination

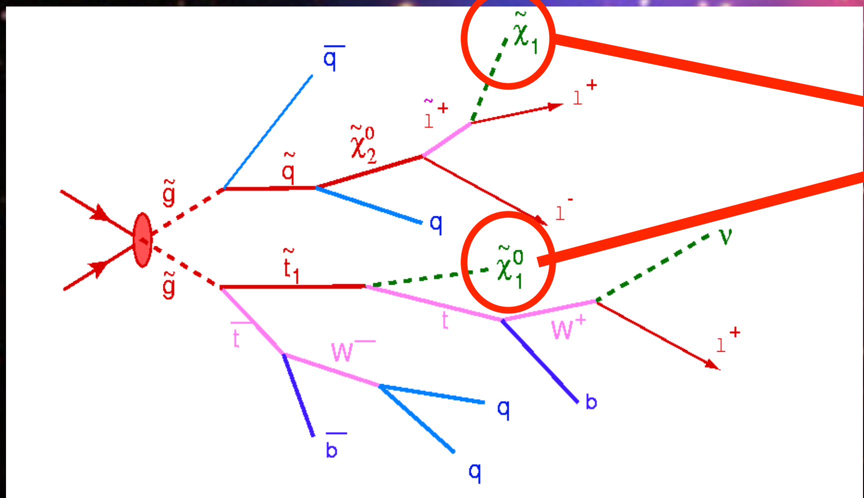
Includes results from a fit of the visible+invisible cross sections results

Searches for Supersymmetry

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

Supersymmetry: a new symmetry in Nature?





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

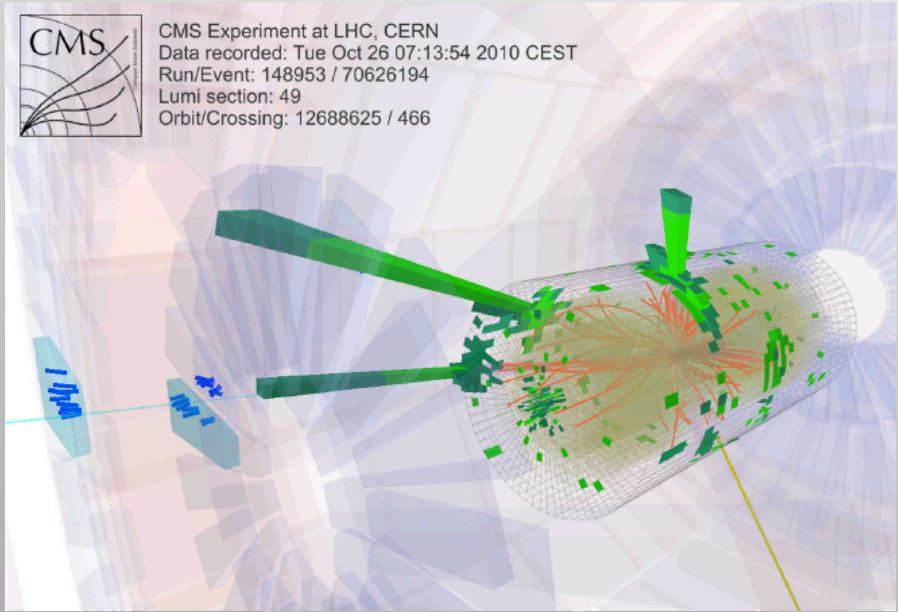
SUSY particle production at the LHC

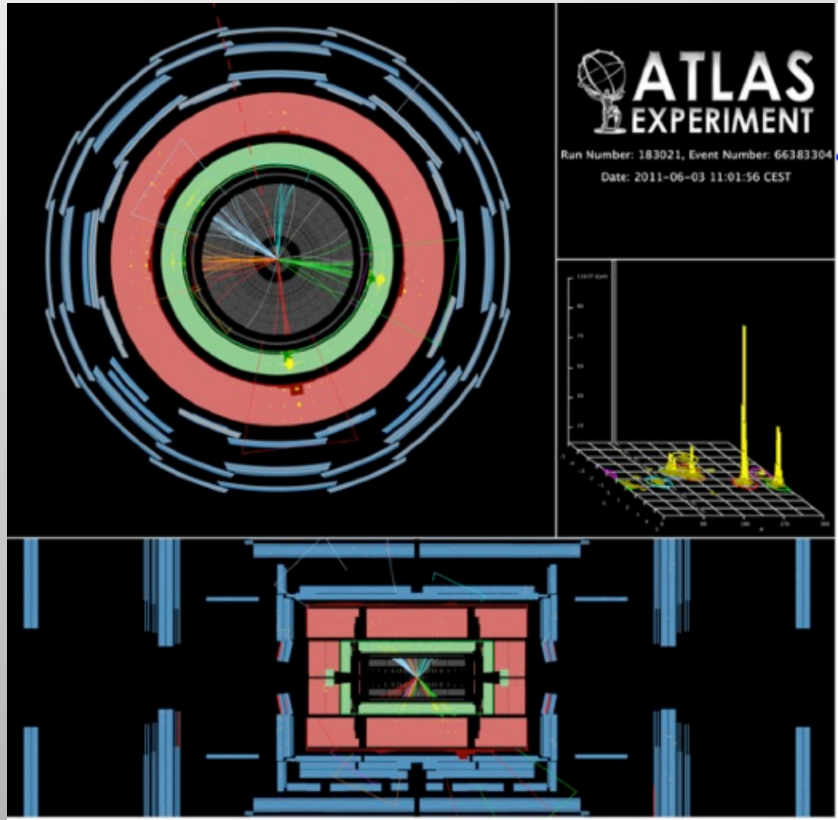
Picture from Marusa Bradac

+ 2 b-jets
+ 4 jets

…Some Interesting Collisions…

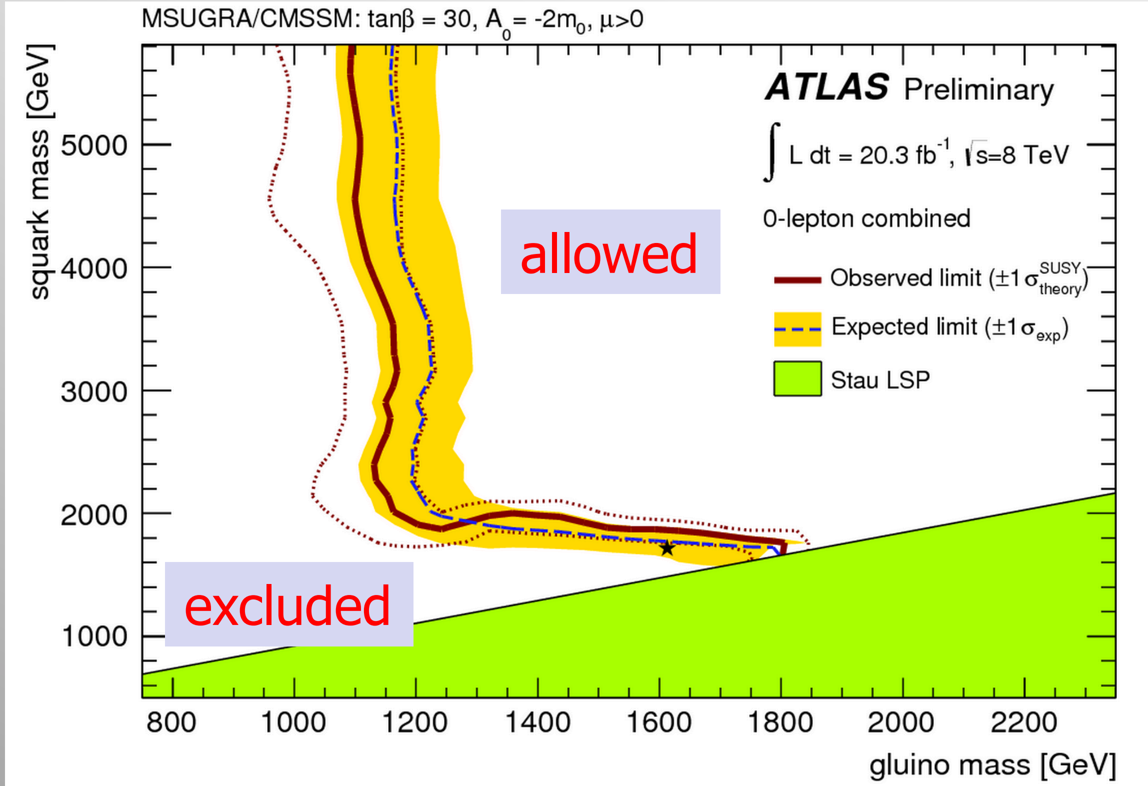
…already in 2010…





- 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: No signal yet to date…

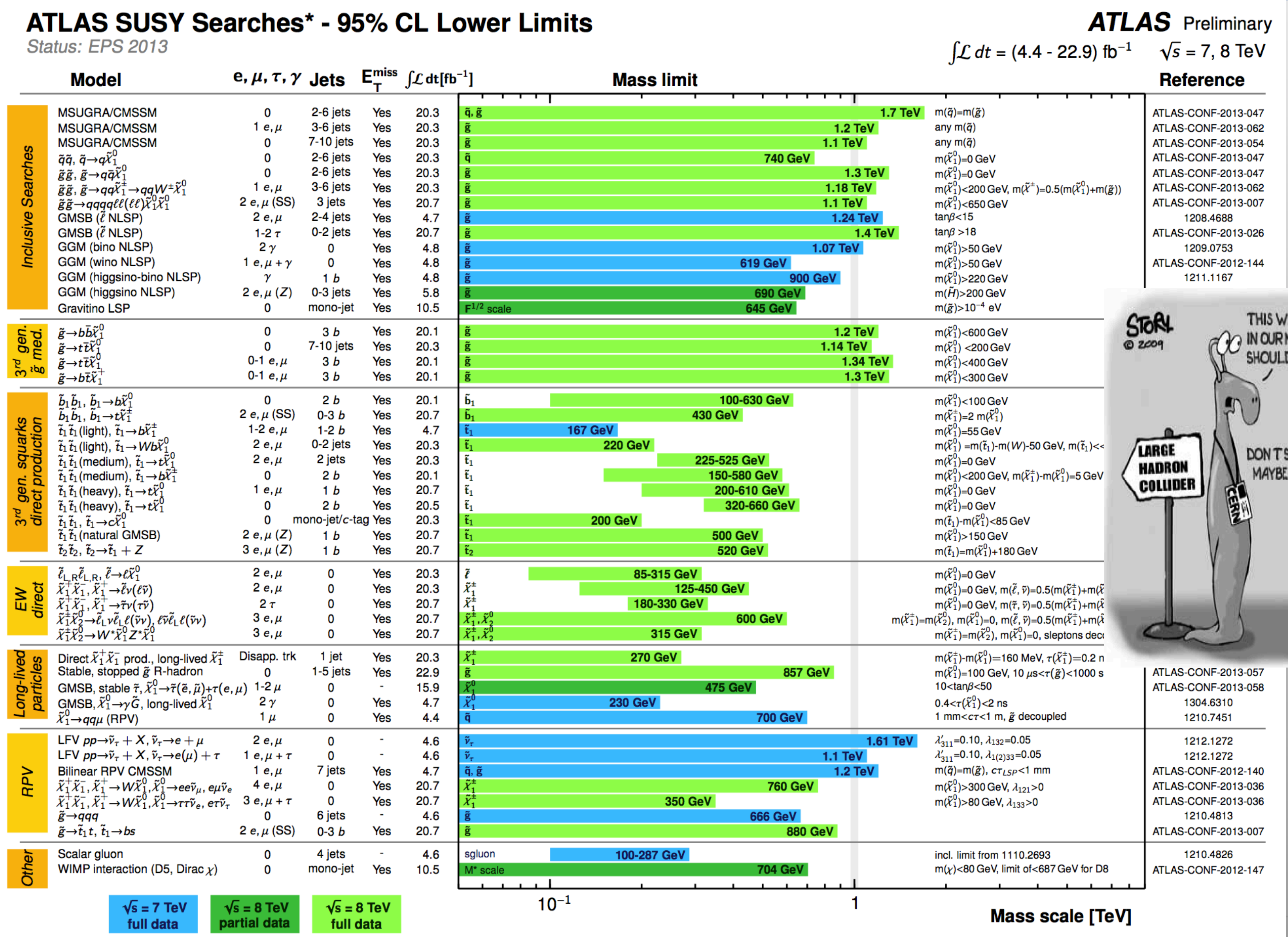


- So far NO clear signal of supersymmetric particles has been found
- We can exclude regions where the new particles could exist.
- Searches will continue for the higher energy in 2015

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

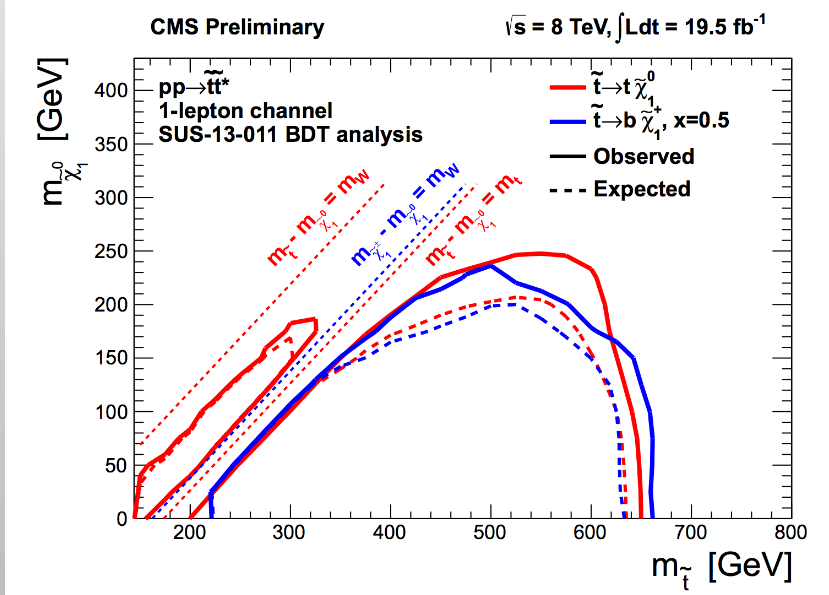
Also special searches for contrived model regions

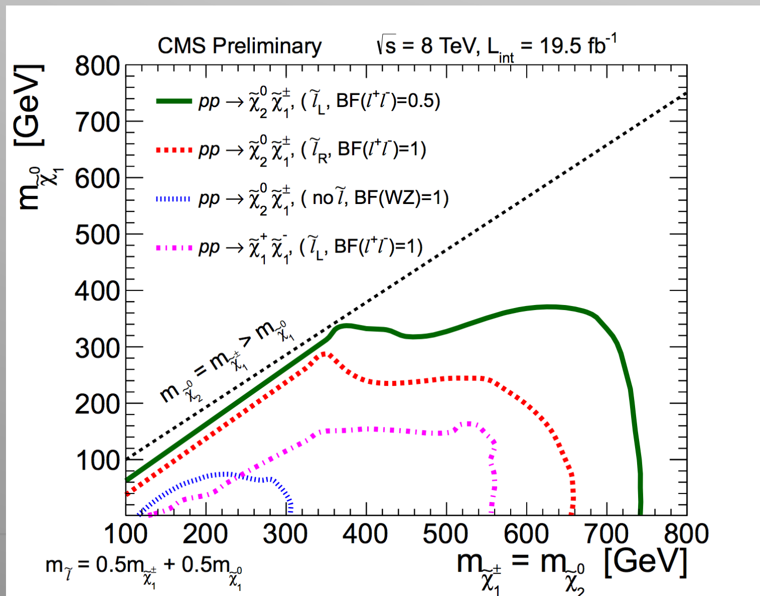
Searches for SUSY



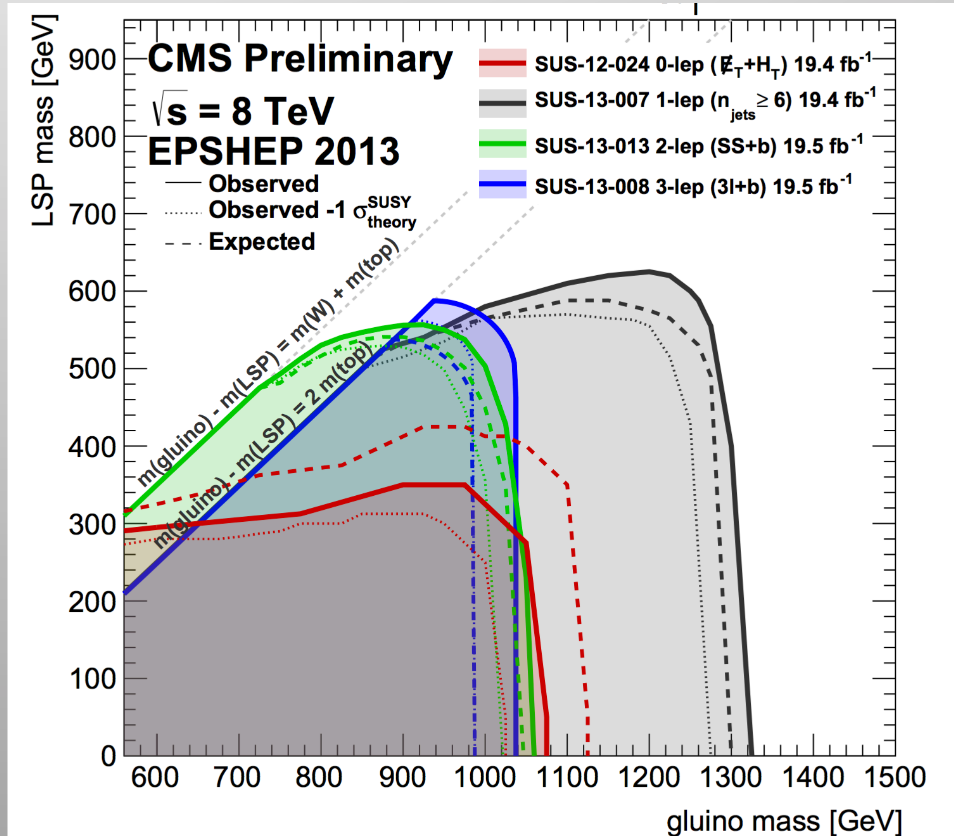
*similar results obtained by CMS

Typical Lightest SUSY particle limits…





Various limits on sparticles:
No 'light' Lightest SUSY Particle (LSP) so far



But could hide in contrived scenarios

…Theory interpretation…

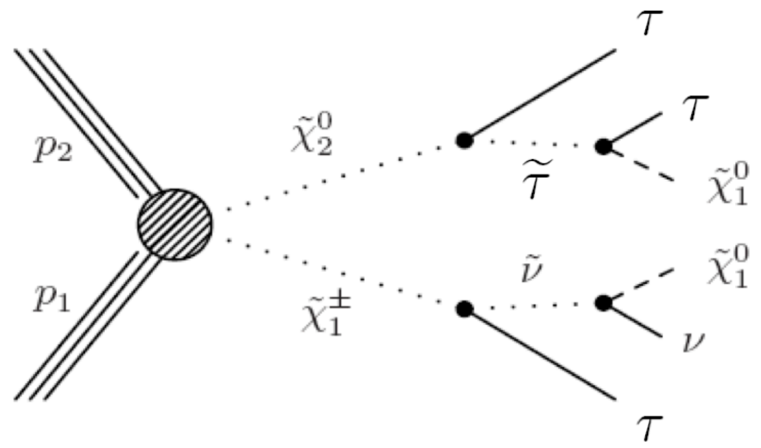
How light the neutralino is allowed to be after LHC searches at 8 TeV?

Problem: the SUSY space is vast
Simplifying assuptions are always needed
Example from Moriond EWK (last week):

Lorenzo Calibbi (ULB)

Assumptions:

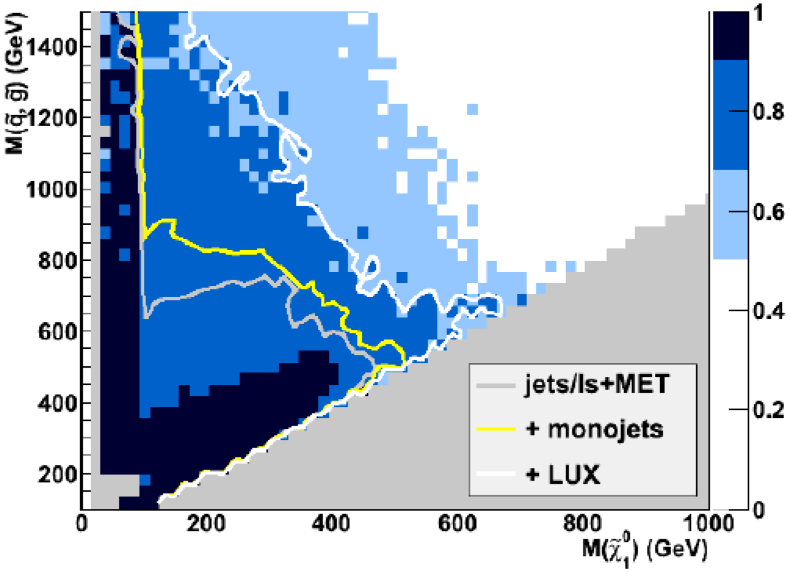
- Only MSSM superfields
- R-parity
- Dark Matter thermal relic, standard history of the universe
- Neutralino DM candidate, $\Omega_{\rm DM} h^2 \leq 0.124$



$$m_{\tilde{\chi}_1^0} > 24 \div 25 \text{ GeV}$$

Dark Matter SUSY space Left?

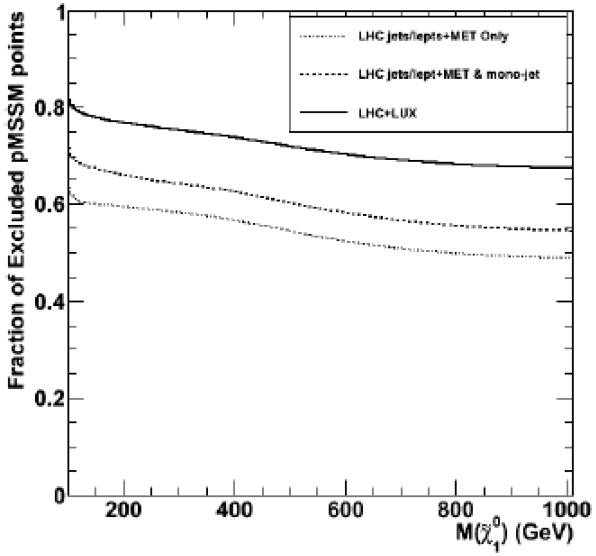
arXiv:1311.7641

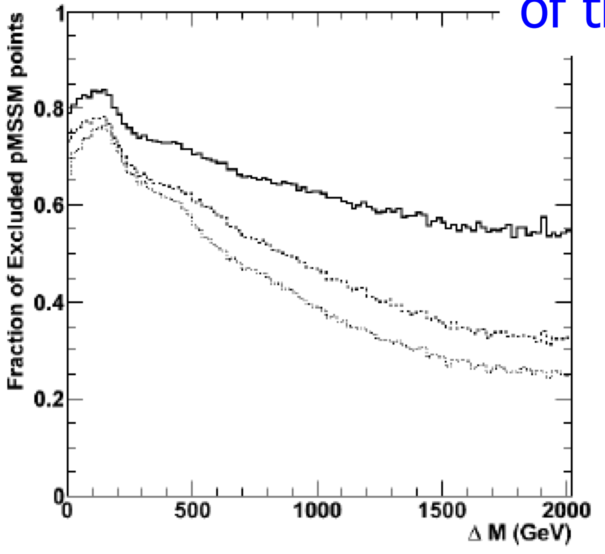


- Use the pMSSM SUSY model (19 parameters)
- Use all the ATLAS SUSY Data + mono-jet searches + LUX DM results

- Check what fraction of pMSSM solutions that is excluded.

No real full systematic study of the SUSY space yet



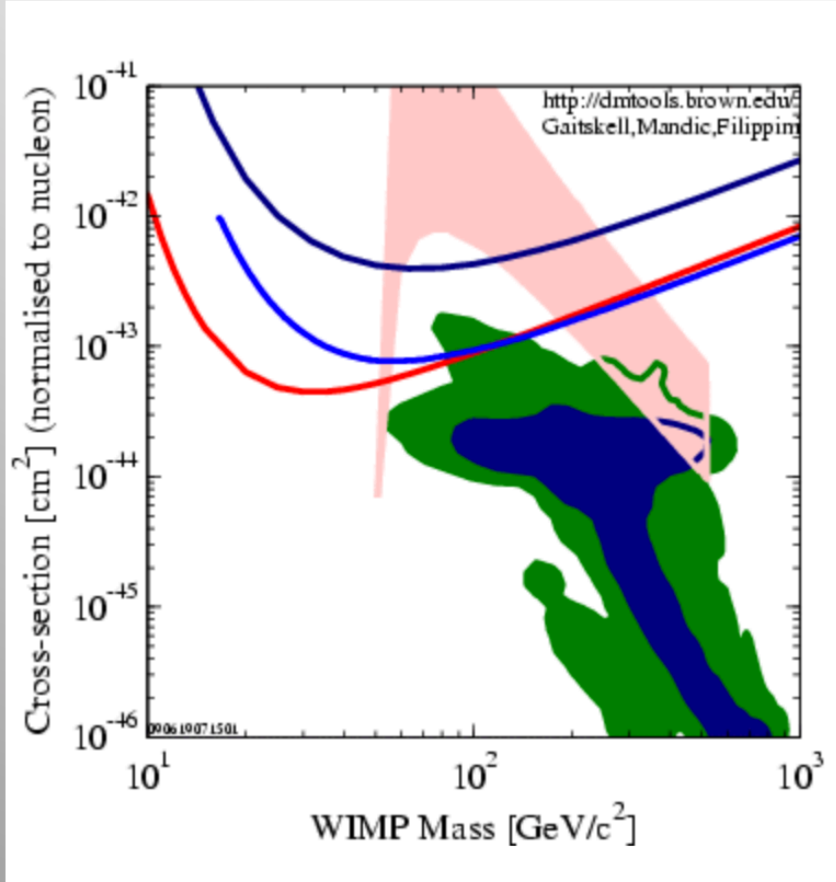


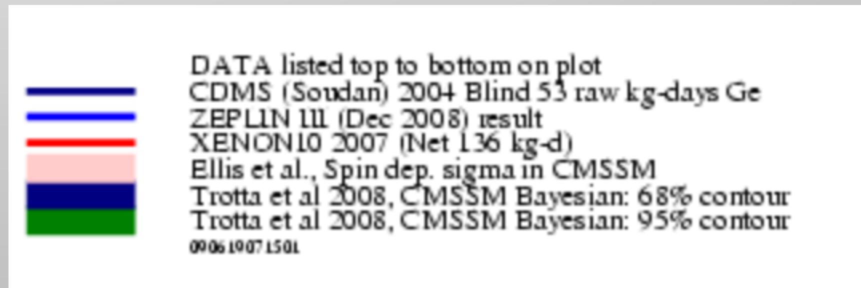
60-80% of the solutions excluded as function of the neutralino mass

Constrained SUSY Models

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

Study of the allowed DM space in CMSSM model



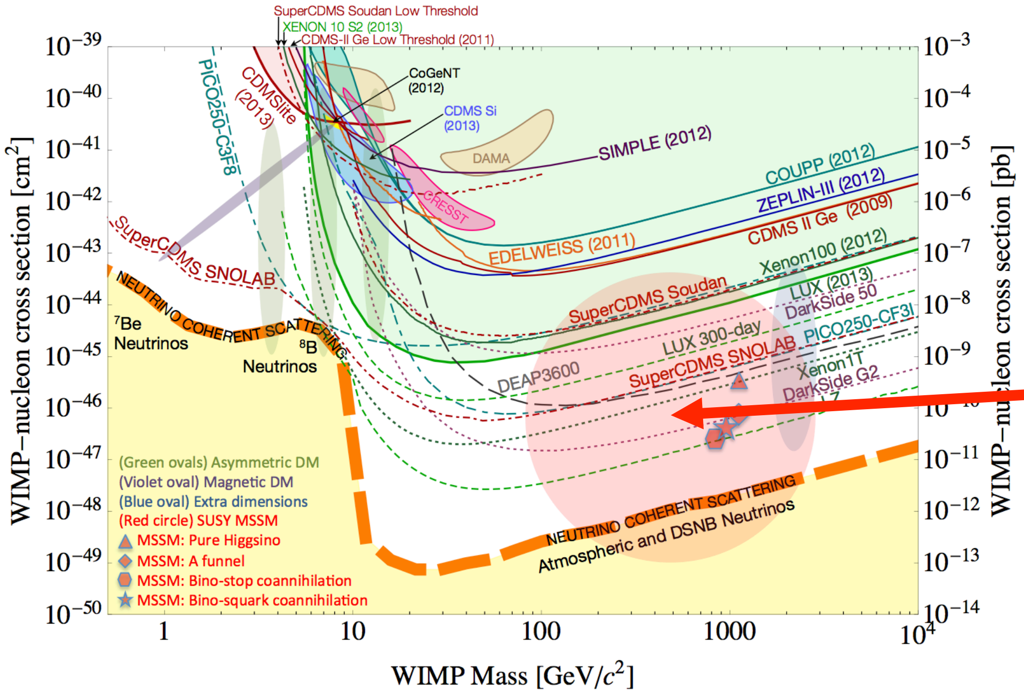


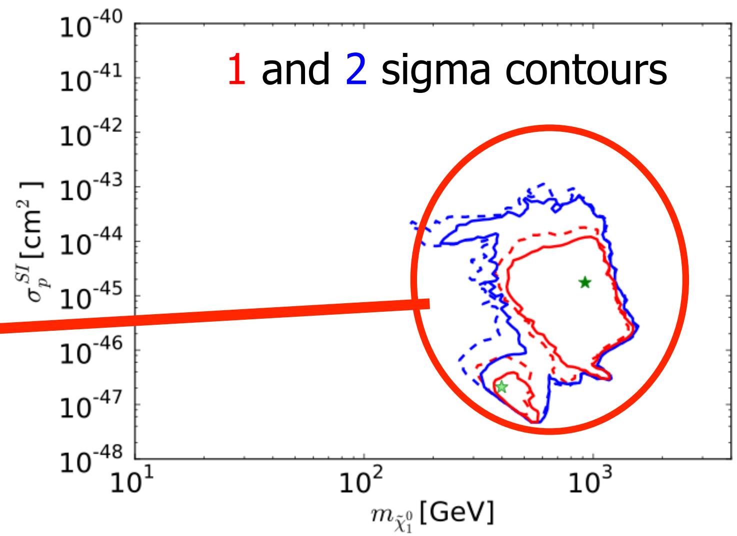
Region allowed in the CMSSM
includes constraints of the Run-I LHC searches (SUSY) and precision data, g-2, cold dark matter constraints…

Constrained SUSY Models

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

Study of the allowed DM space in CMSSM model



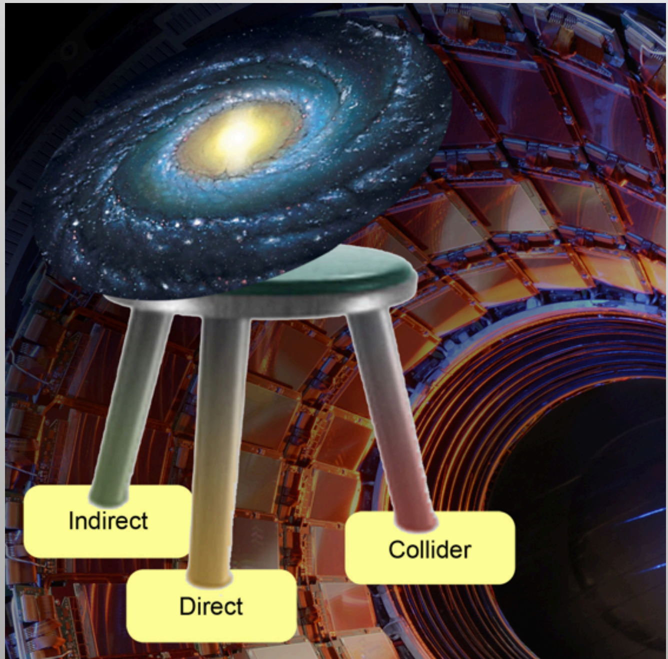


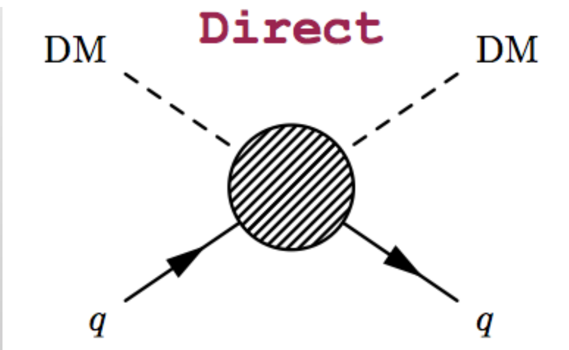
Region allowed in the CMSSM
includes constraints of the Run-I LHC searches (SUSY) and precision data, g-2, cold dark matter constraints…

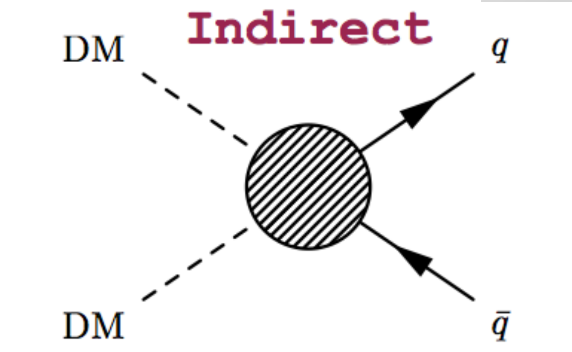
General Searches for Dark Matter

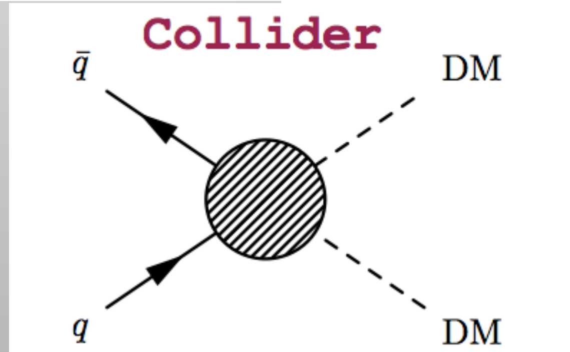
The Other Dark Matter Connection

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

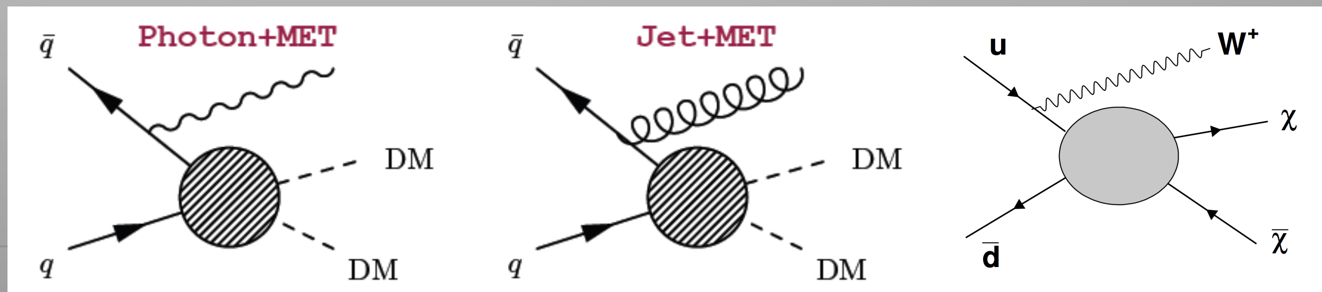






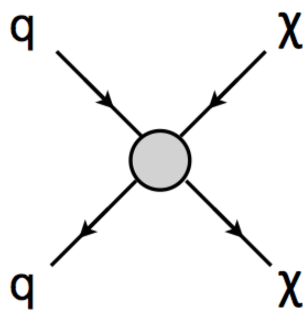


Use effective theory to relate measurements to Dark Matter studies



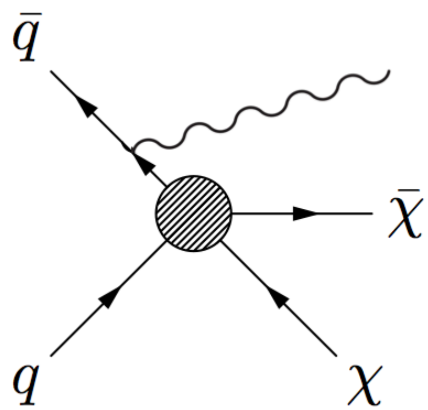
Dark Matter Production at the LHC

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

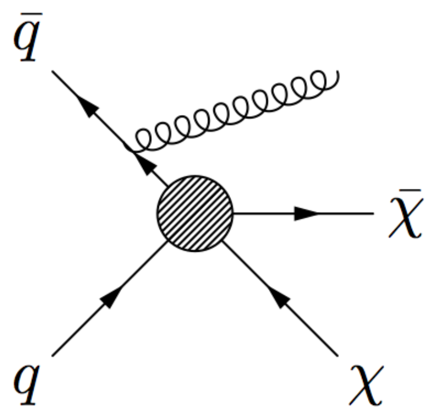


Production at Colliders (s-channel)

- 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

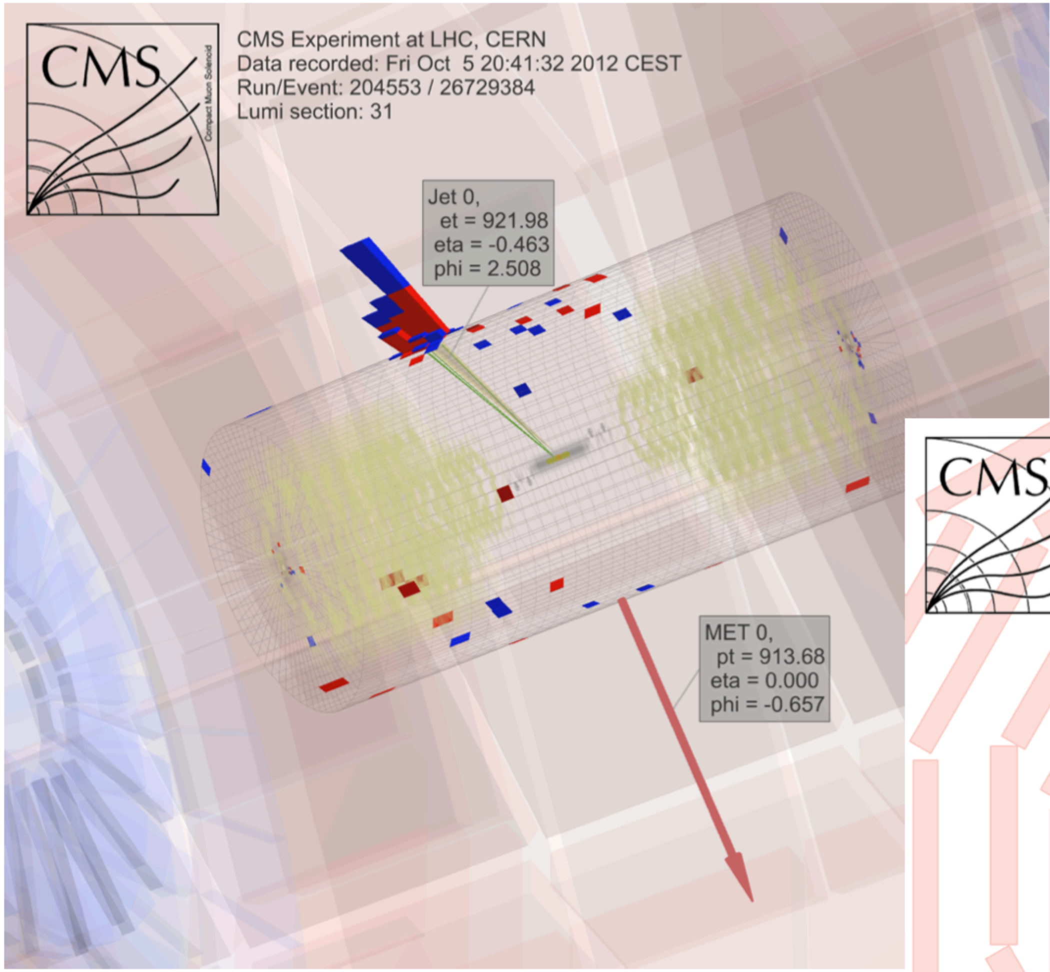


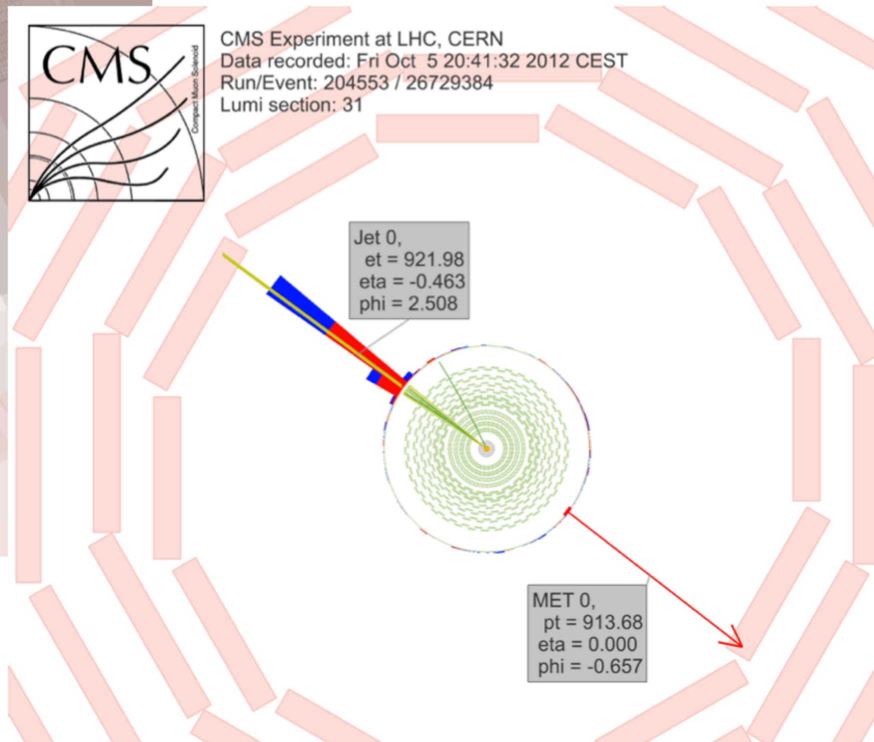
Monophoton + MET



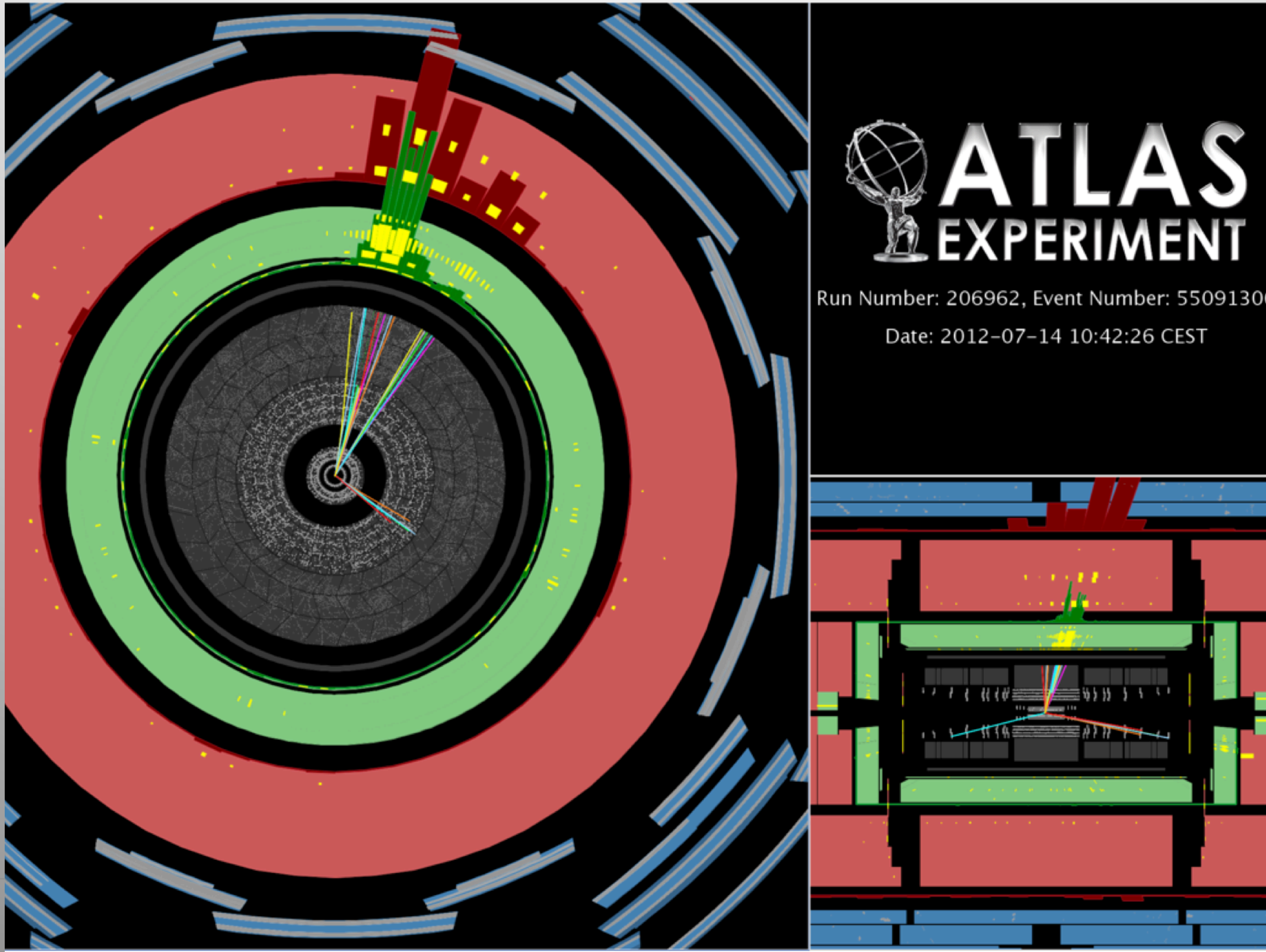
Monojet + MET

Mono-Jet Event





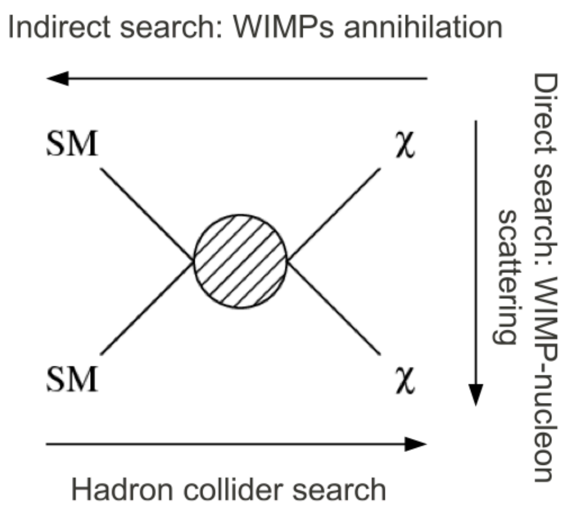
Mono-Jet Event



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

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

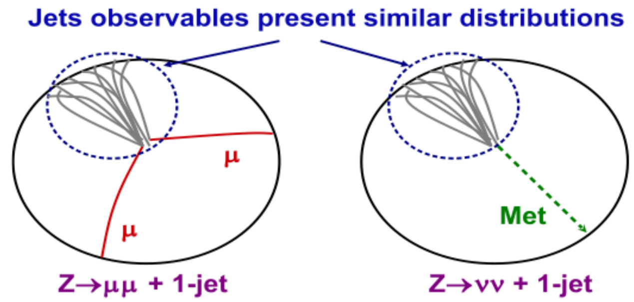
[Bai, Fox and Harnik, JHEP 1012:048 (2010), Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, Phys.Rev.D82:116010 (2010), Beltran, Hooper, Kolb, Krusberg, Tait, JHEP 1009:037 (2010)]

The Search for Mono-jets

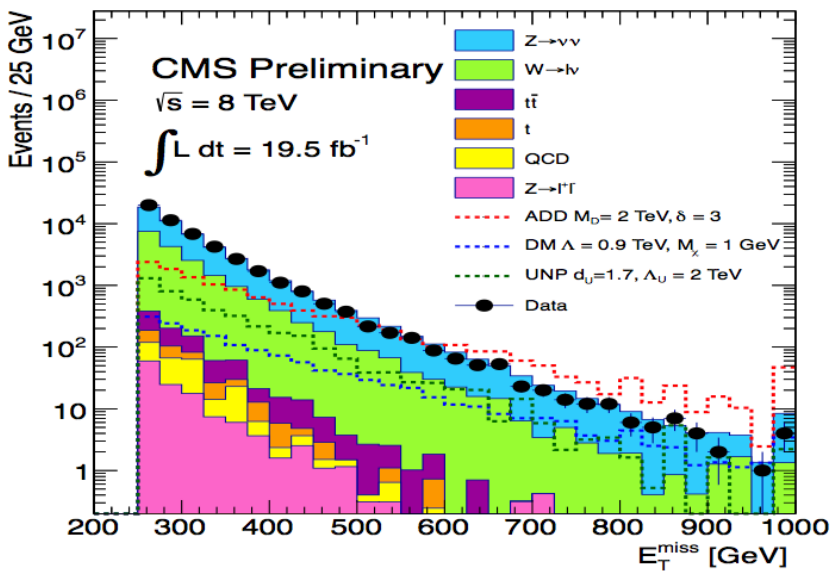
- Preliminary results at $\sqrt{s} = 8\,\mathrm{TeV}$:
  CMS-PAS-EXO-12048 $\mathcal{L} = 20\,\mathrm{fb}^{-1}$
  ATLAS-CONF-2012-147 $\mathcal{L} = 10.5\,\mathrm{fb}^{-1}$
  ATLAS $7\,\mathrm{TeV}$, $5\,\mathrm{fb}^{-1}$: JHEP 04 (2013) 075
  CMS $7\,\mathrm{TeV}$, $5\,\mathrm{fb}^{-1}$: JHEP 09 (2012) 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)



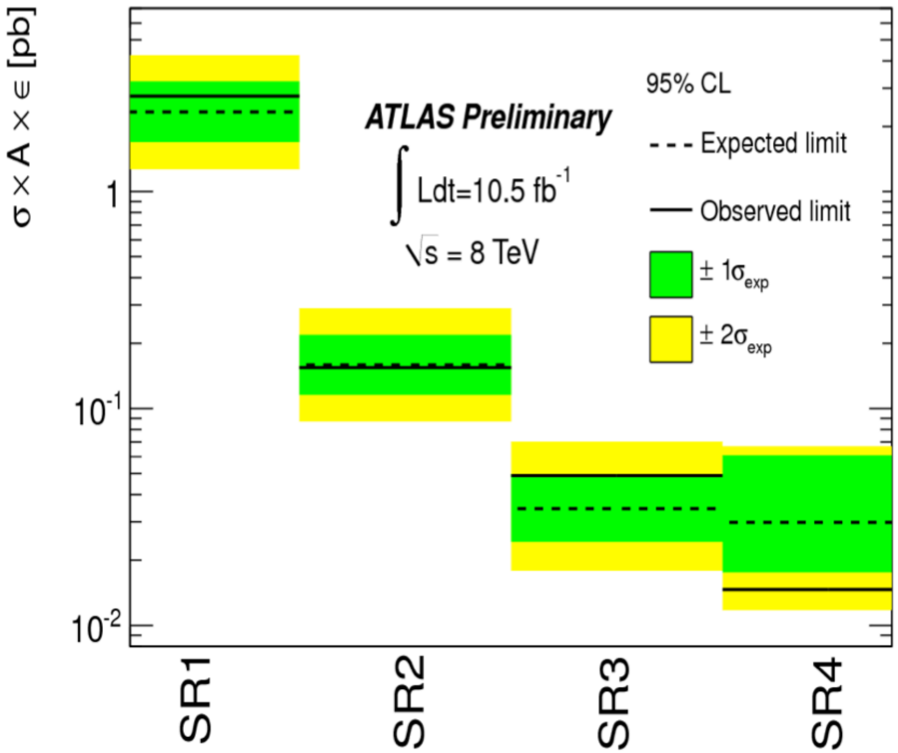
  - Transfer CR to SR via simulation

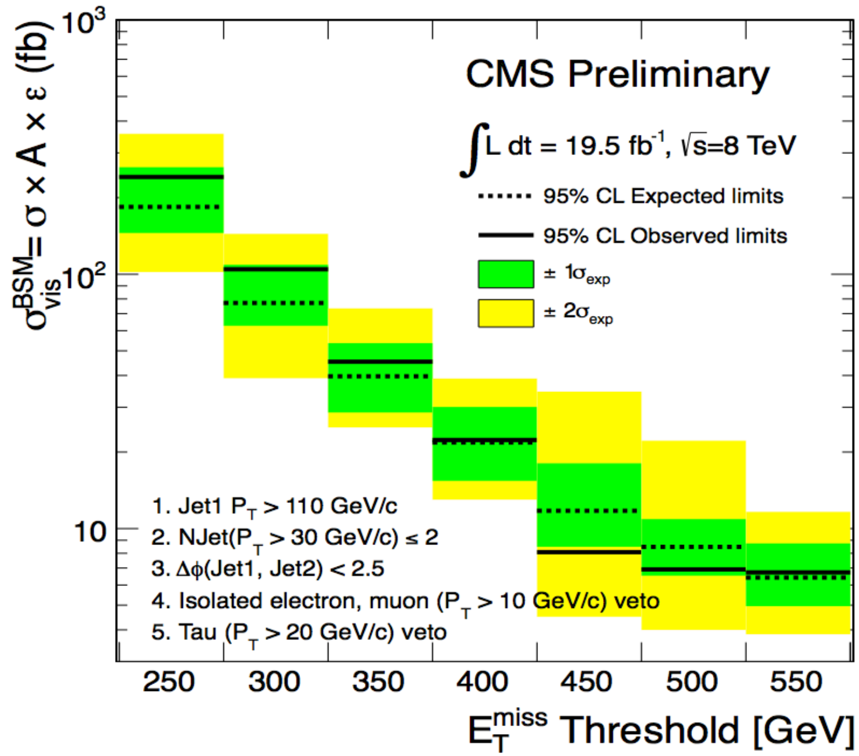


Search for Mono-jets

[ATLAS-CONF-12-147, CMS EXO-12-048]

- Both experiments quote model-independent limits for generic applicability to SUSY compressed spectra, invisible Higgs, or any other "monojet" signature



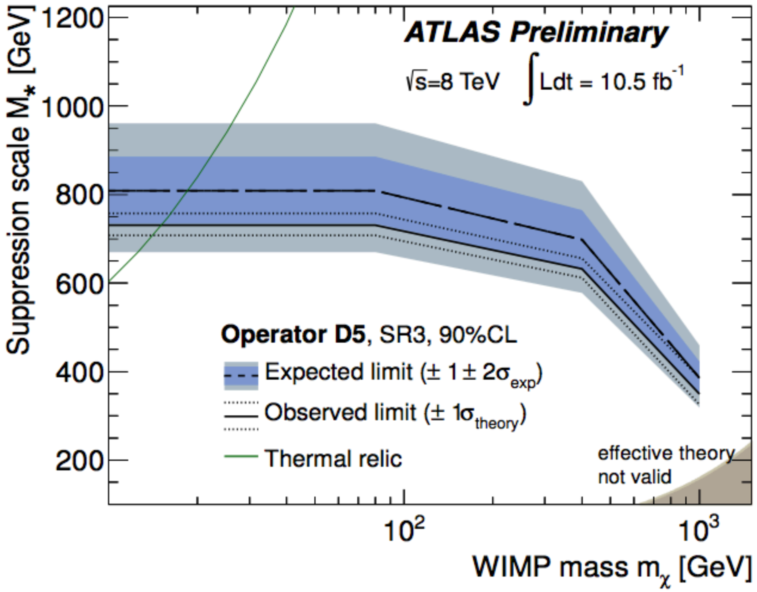


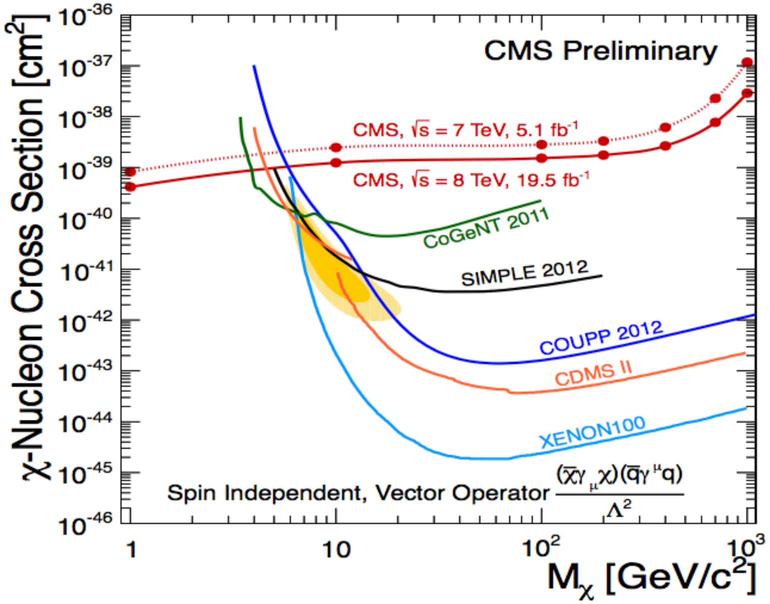
The Search for Mono-jets

- 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 $\sigma(\chi\text{-nucleon})$ upper limits
  -

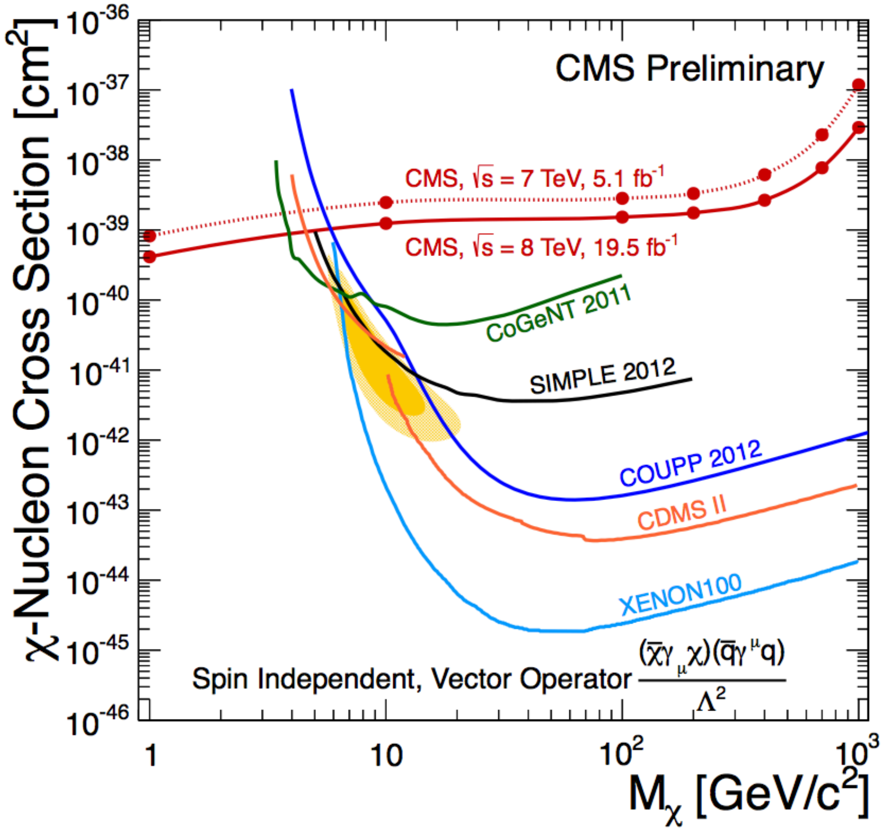


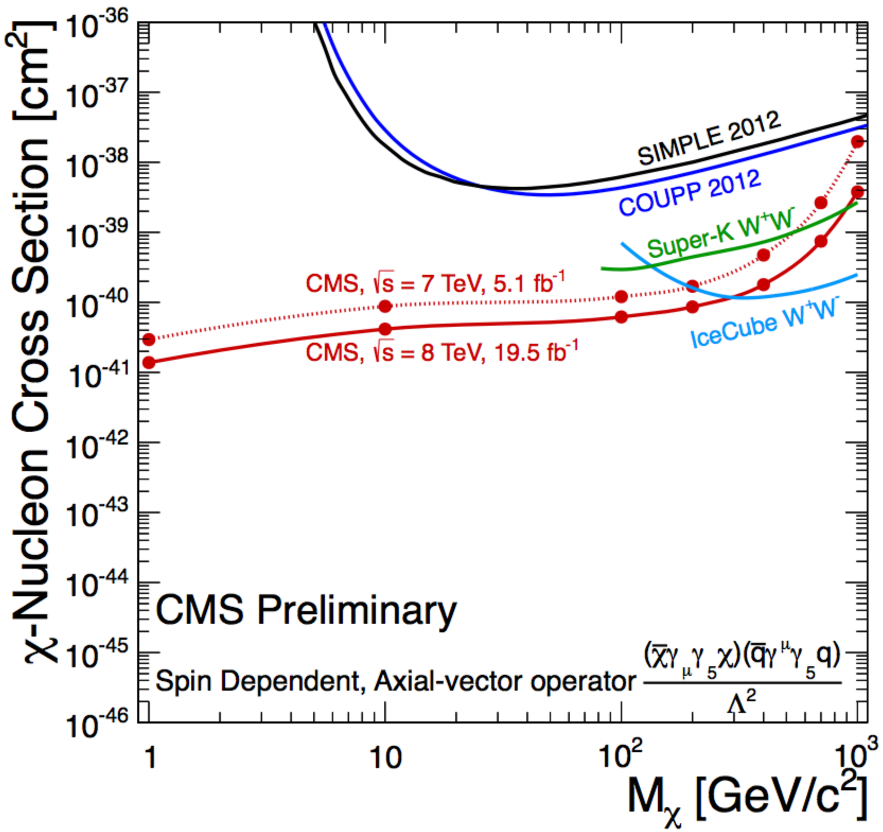


Results from Monojets

[CMS EXO-12-048]

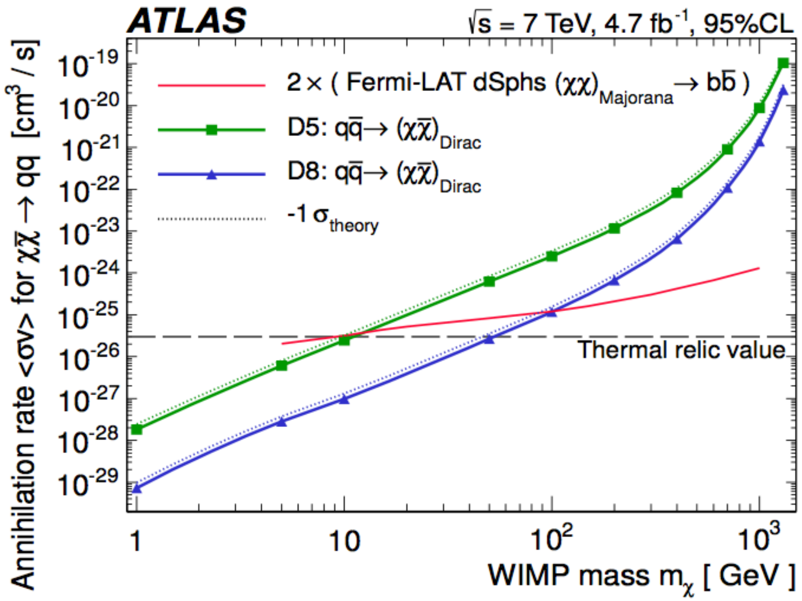
- Derived EFT limits then compared to direct-detection experiments
- CMS results improved with 8 TeV (higher E, more data)



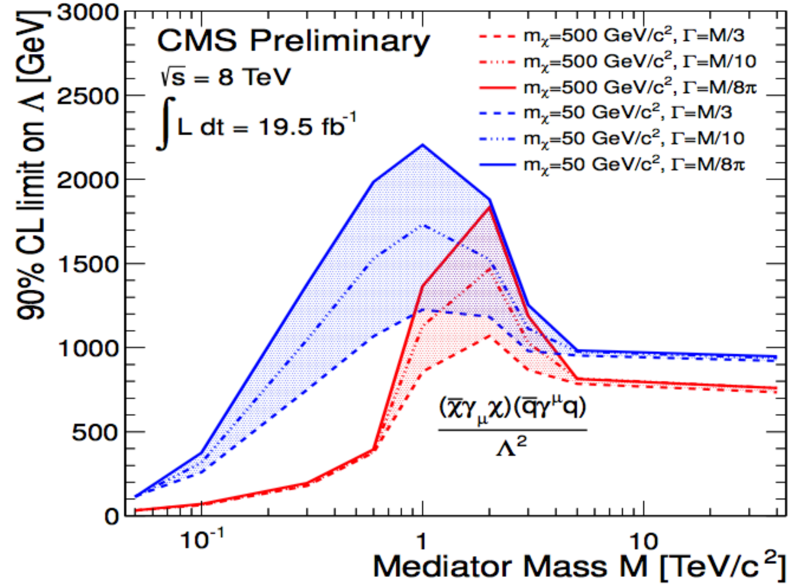


The Search for Mono-jets

- 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



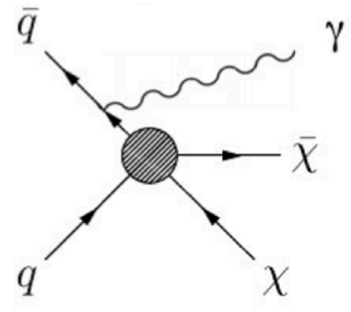
- Lower bound on scale (Λ) of UV-complete simplified model:
  - Interactions via massive vector mediator (of mass M)
  - At high M, limits converge to those obtained assuming EFT
  - Width constrained from $M/8\pi$ to $M/3$



The Search for Mono-Photons

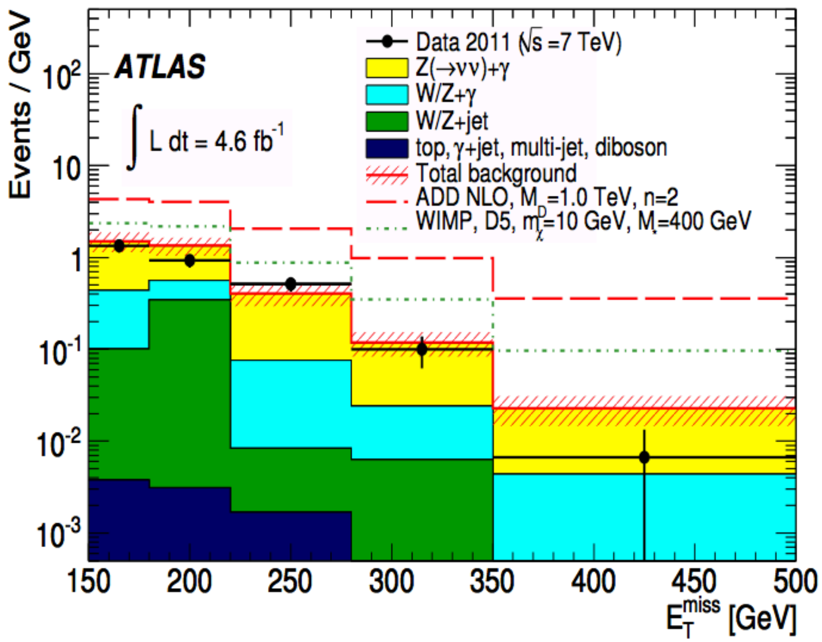
First “Mono-study” to be interpreted DM limits at the LHC
UC-Davis strongly involved

- 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]



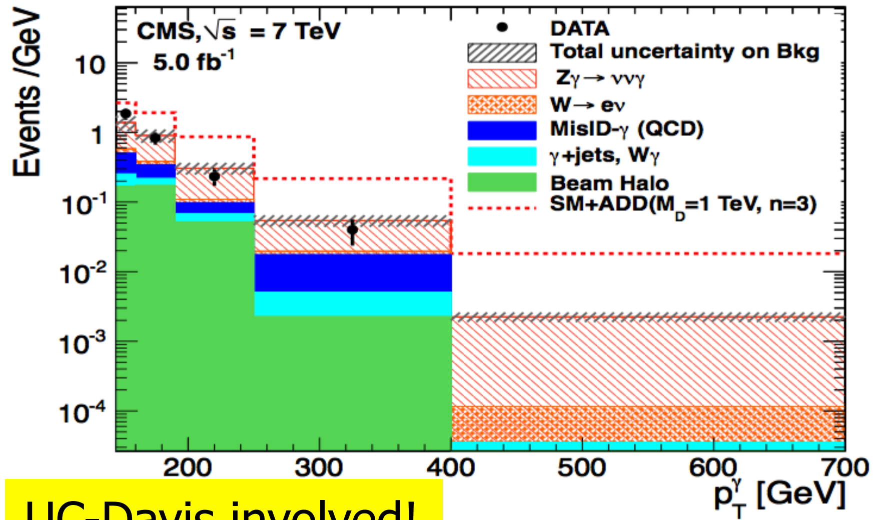
- Main background: $Z(\to \nu\nu) + \gamma$
  - ATLAS: extrapolated from $\gamma + \mu + \not{E}_T$ CR
  - CMS: estimation from simulation (NLO)

- 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

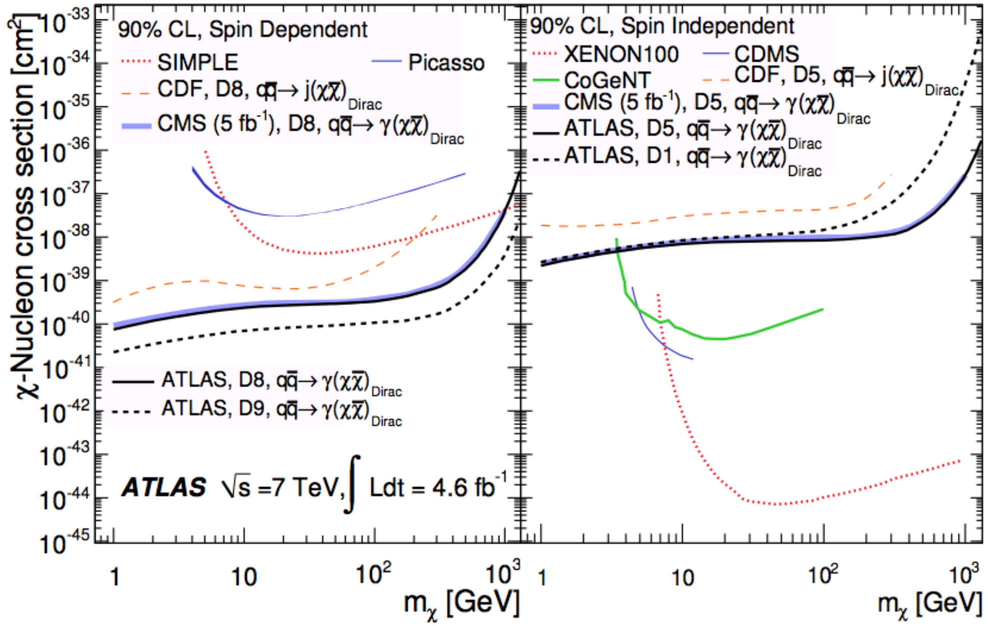


The Search for Mono-Photons

- 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
- D11 is not available (gg interaction)



UC-Davis involved!



The Search for Mono-W's

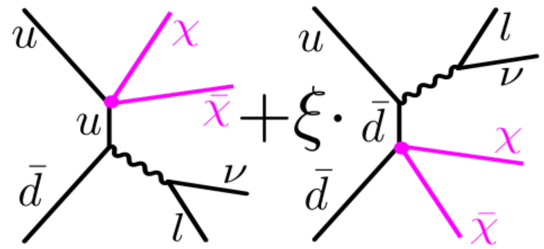
Leptonic channel

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

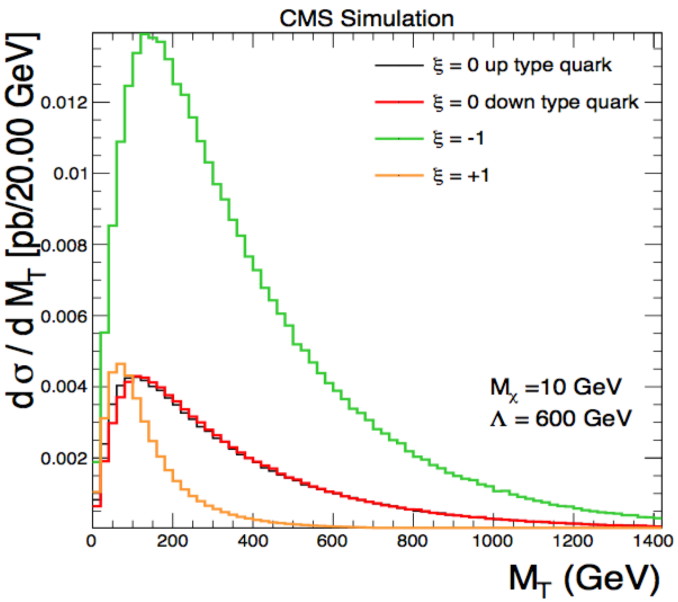
$$M_T = \sqrt{2.p_T^{\ell}.\not\!\!E_T.(1 - \cos\Delta\Phi_{\ell,\not\!\!E_T})}$$

- 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:



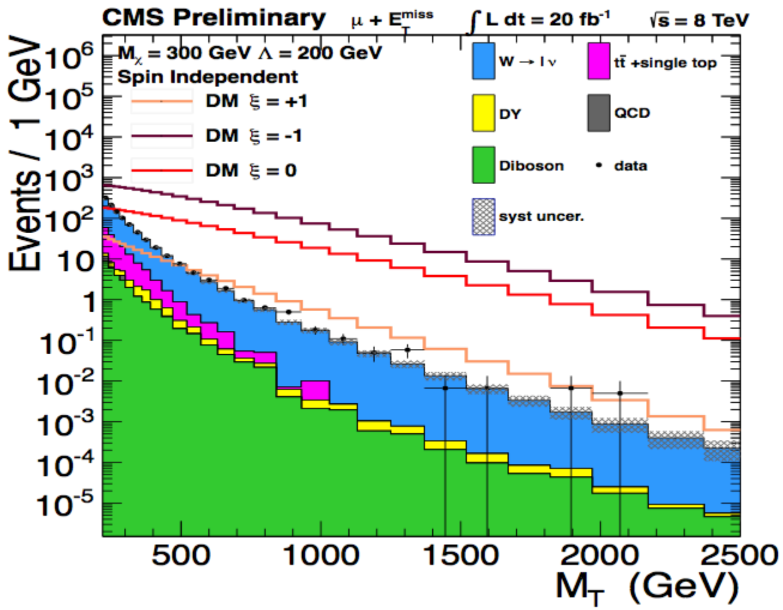
  - Interference ξ between 2 processes
  - $\xi = 1\ (-1)$: destructive (constructive)

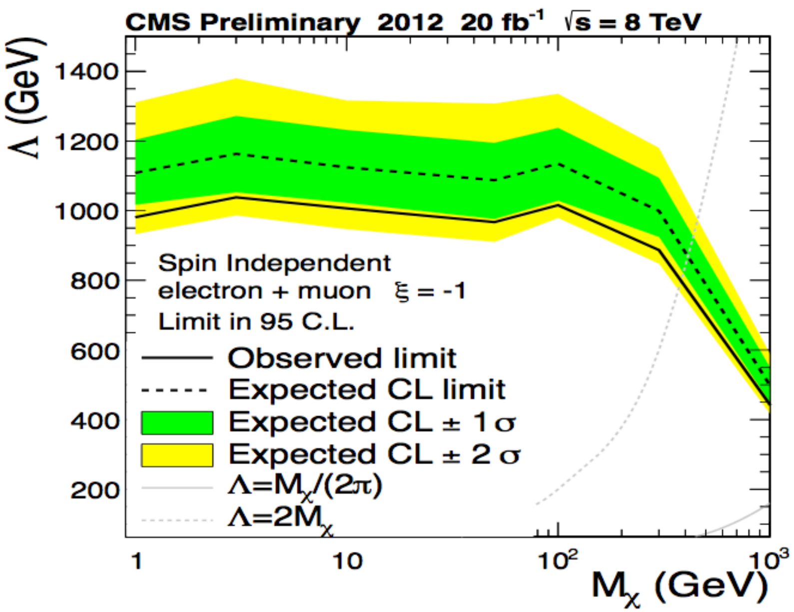


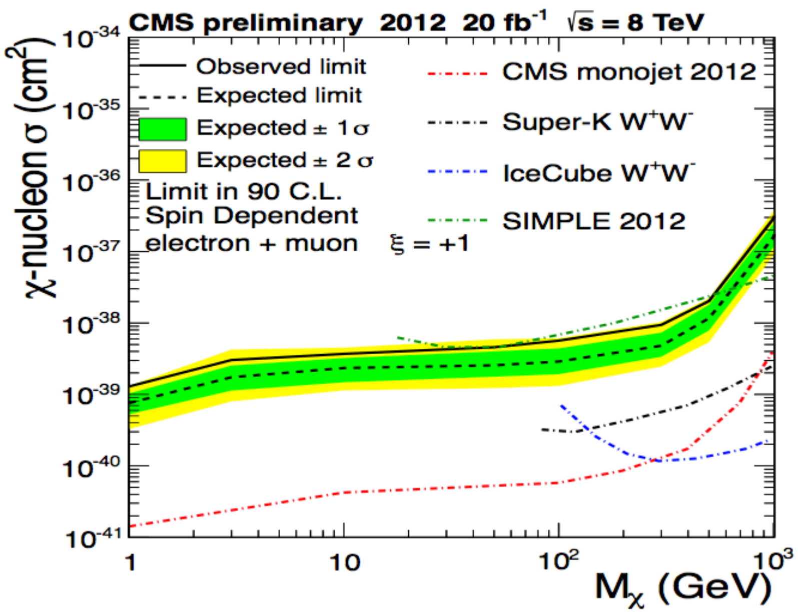
Allows to test if DM couplings to down type and up type quarks is the same

The Search for Mono-W's

- Main background: $W \rightarrow \ell\nu$ (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)







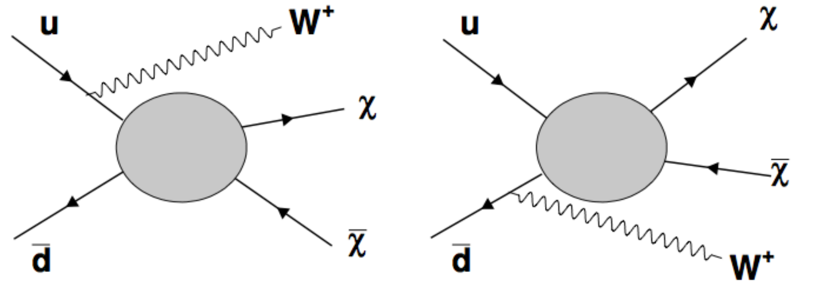
The Search for Mono-W/Z's

Hadronic channel

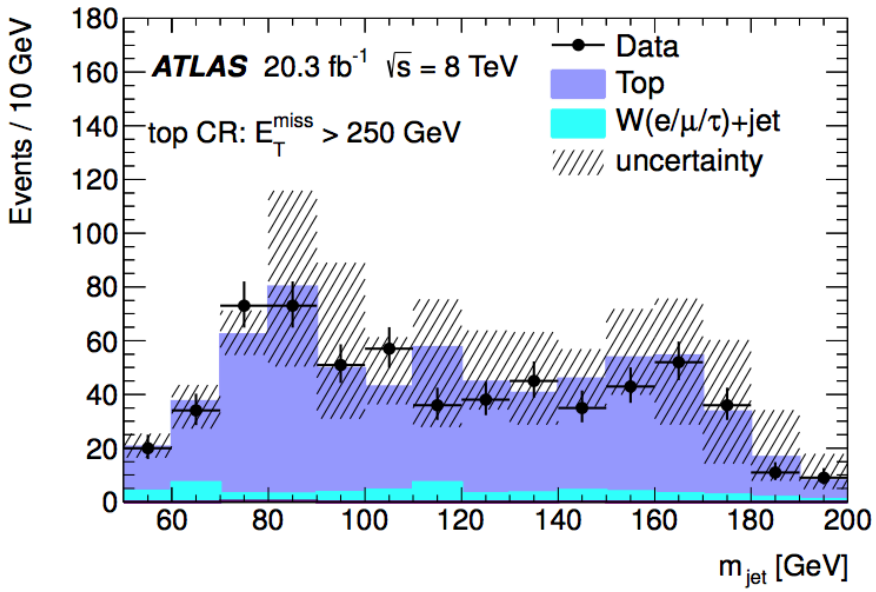
- Published: PRL 112, 041802 (2014)
  $\sqrt{s} = 8\,\text{TeV} \quad \mathcal{L} = 20\,\text{fb}^{-1}$

- 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 $500\,\text{GeV}$

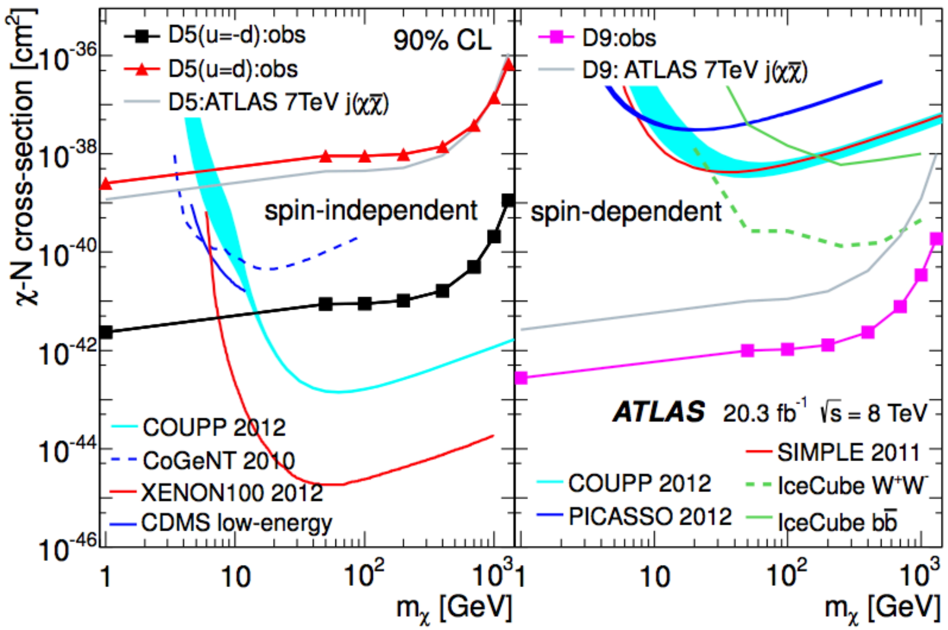


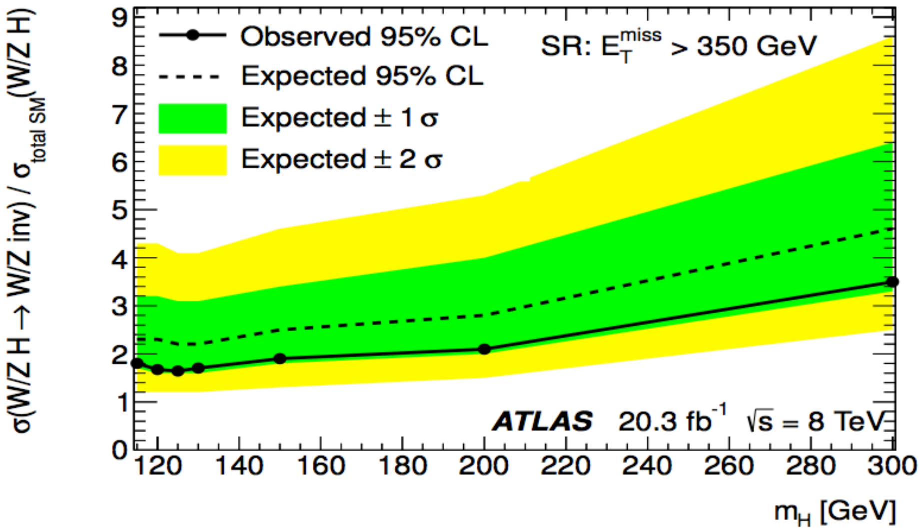
- Main backgrounds:
  - $Z(\rightarrow \nu\nu)$+jets and $W(\rightarrow \ell\nu)$+jets
  - Determined by extrapolating a data muon CR using simulation



The Search for Mono-W/Z's

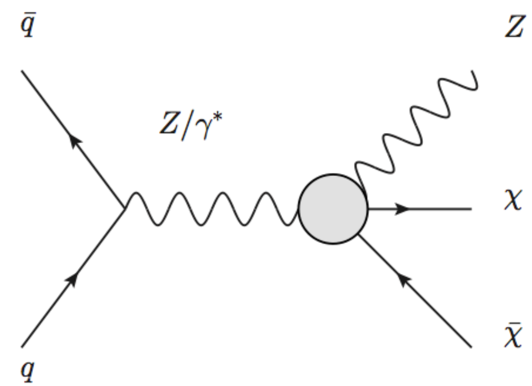
- Total background systematics:
  - Main: data CR statistics, fat jet and $\not{E}_T$ calibration, theory
  - 5 to 13% (low to high $\not{E}_T$)
- EFT limits:
  - Upper limits on $\sigma(\chi\text{-nucleon})$ in D5 case with opposite sign u and d-quark couplings are improved by 3 orders of magnitude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

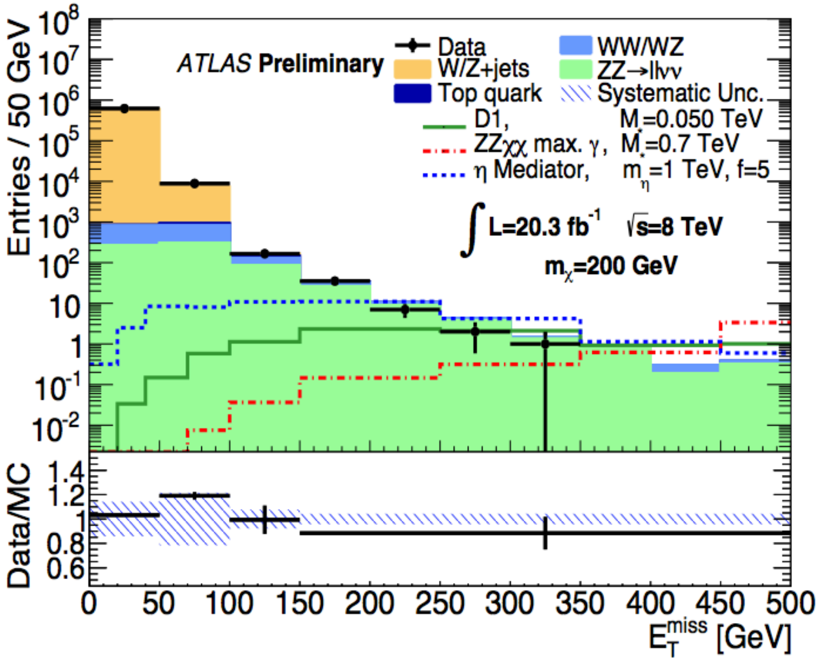




The Search for Mono-Z's

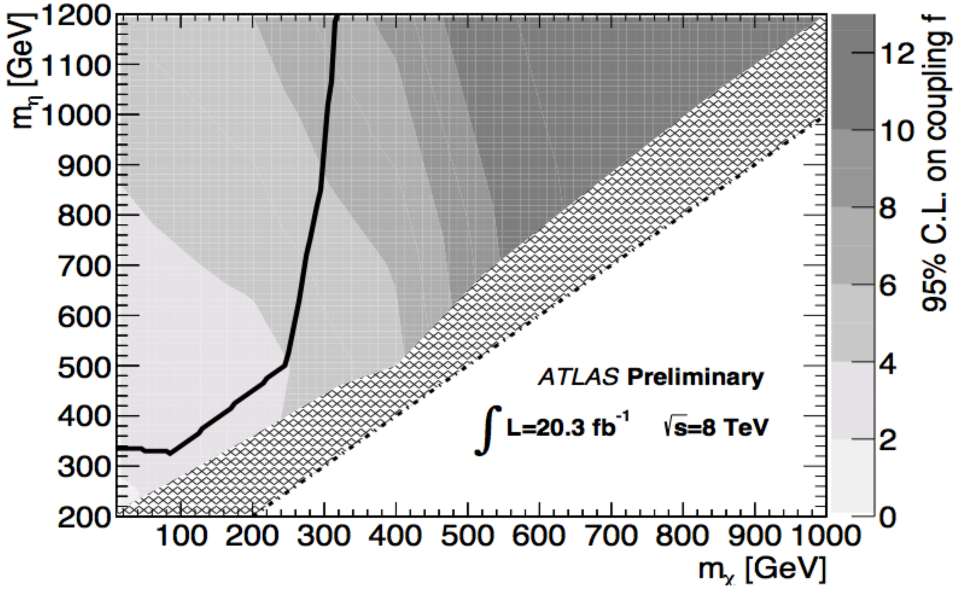
- Preliminary result: $\sqrt{s} = 8\,\mathrm{TeV}$, $\mathcal{L} = 20\,\mathrm{fb}^{-1}$
- 2 scenarios for DM pair production:
  - Z radiated from ISR
  - Z interacts directly with DM
    Z/γ^* mixing is a theory parameter
- e and μ channels combined
- Main background: $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ (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 3^{rd} lepton and no jets
  - SR defined by $\not{E}_T > 150, 250, 350, 450\,\mathrm{GeV}$

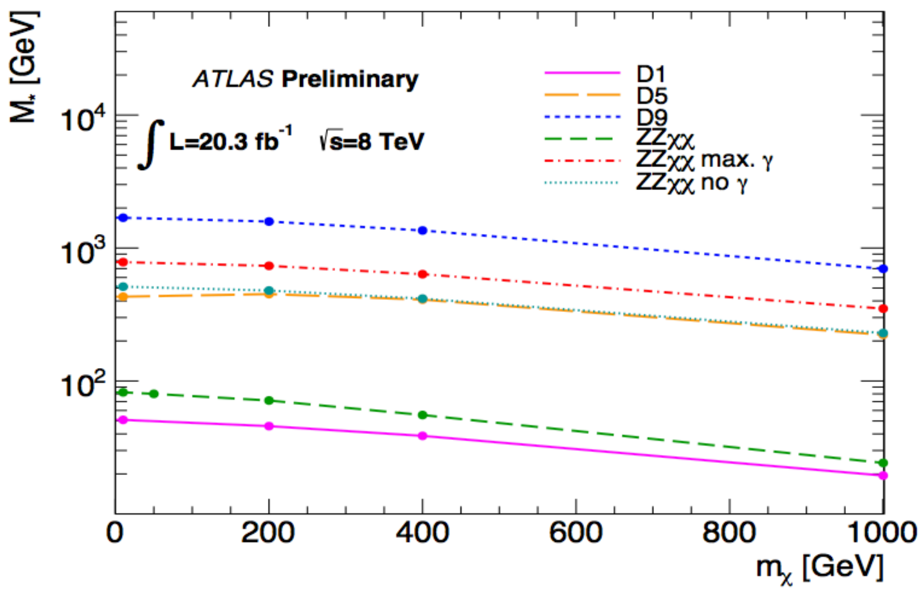


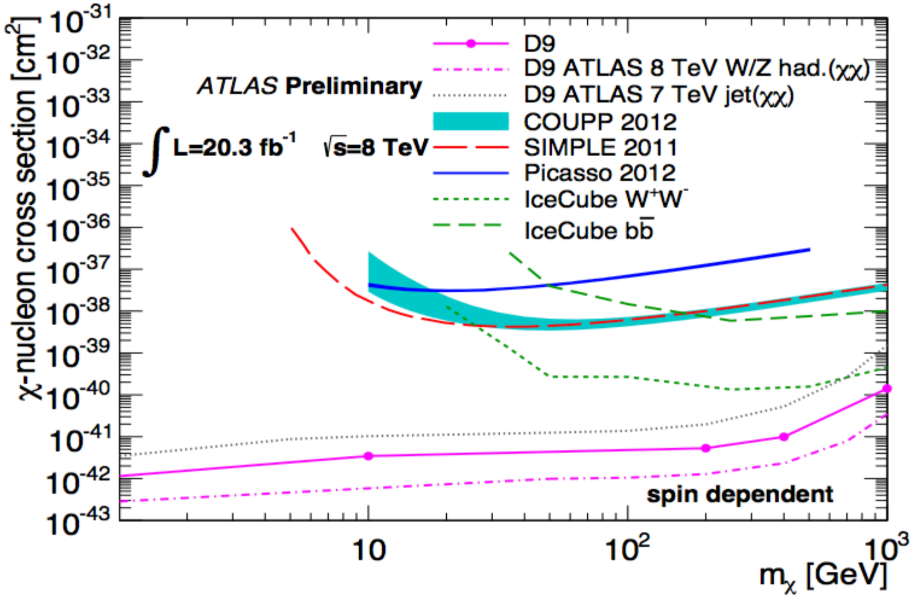


The Search for Mono-Z's

- 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 $\sigma(\chi\text{-N})$

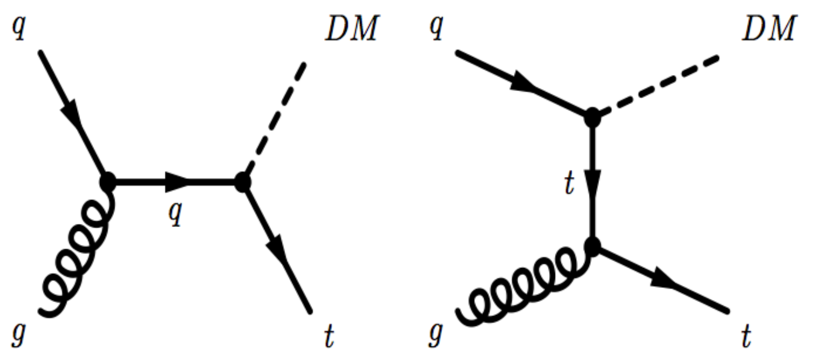


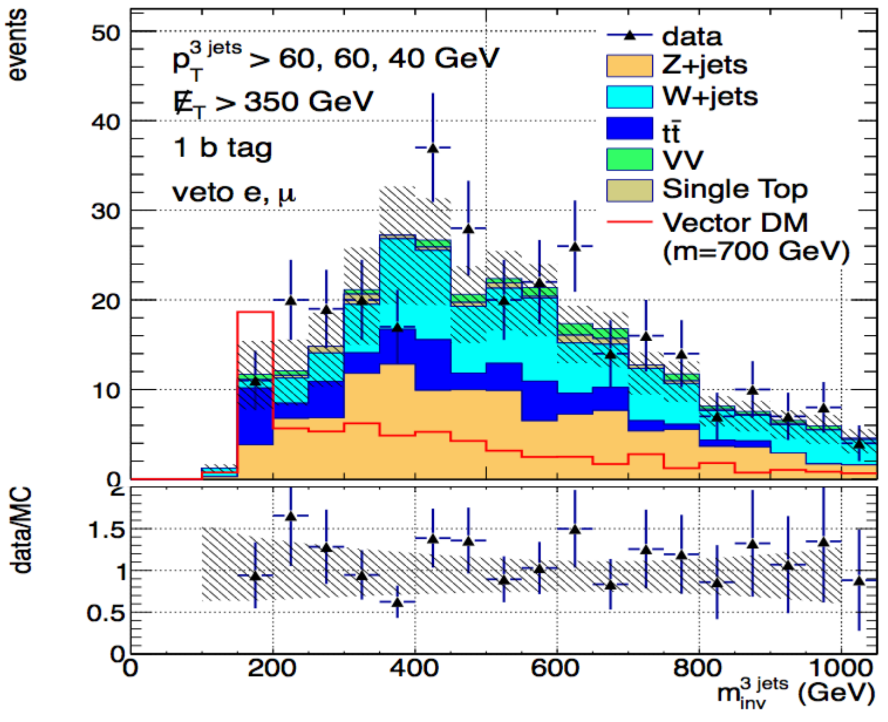




The Search for Mono-Top Quarks

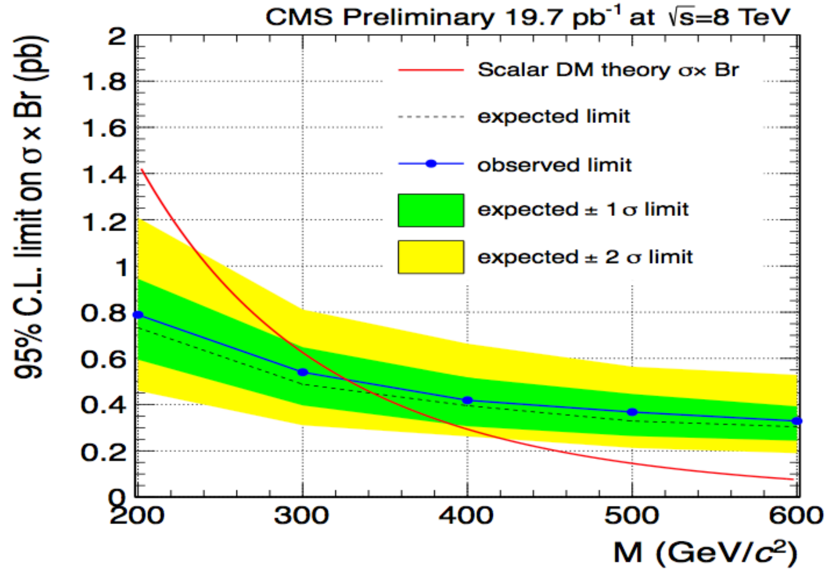
- Preliminary result at $\sqrt{s} = 8\,\mathrm{TeV}$:
  CMS-PAS-B2G-12-022, $\mathcal{L} \sim 20\,\mathrm{fb}^{-1}$
- Scenario:
  - top produced in association with DM (not from ISR)
  - top decays hadronically
  - FCNC considered
- Main backgrounds:
  - $\mathrm{Z}(\rightarrow \nu\nu)$+jets (from data 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
  - $\not{E}_T > 350\,\mathrm{GeV}$

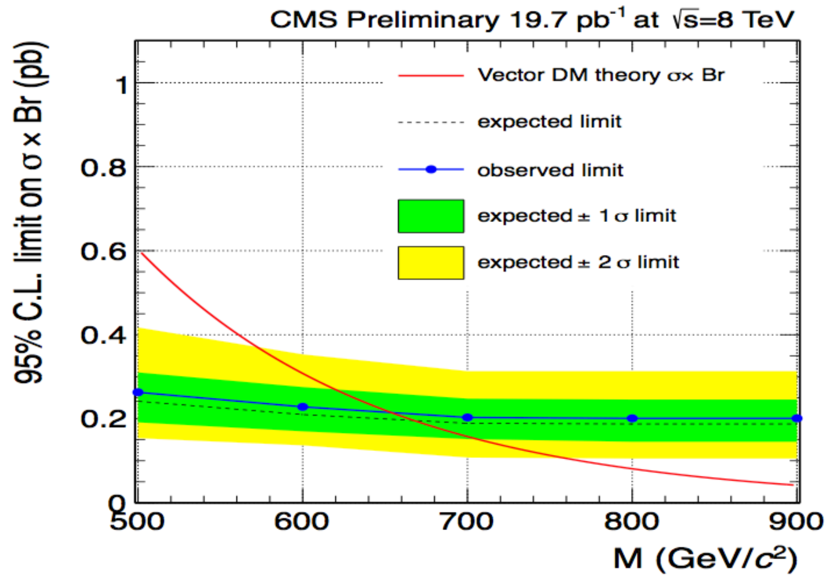




The Search for Mono-Top Quarks

- 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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[2] *Department of Physics and Astronomy, University of California, Irvine, CA 92697*
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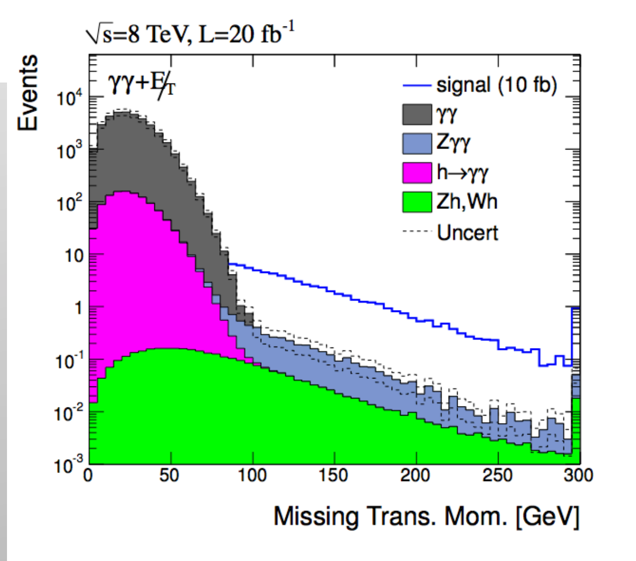
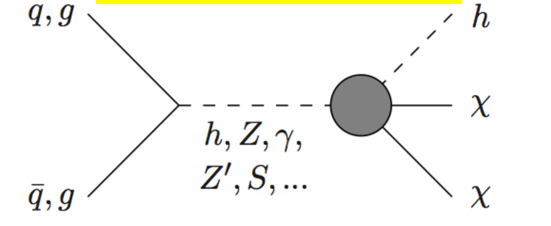
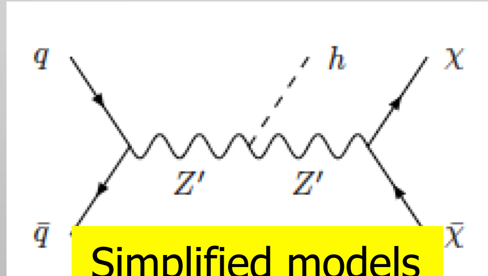


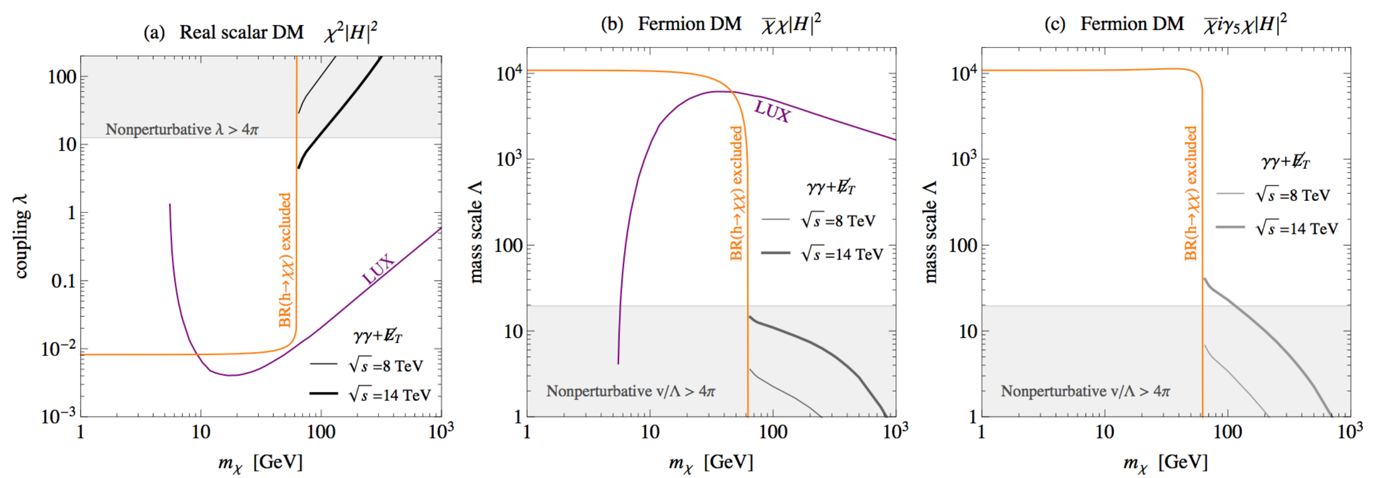
The next mono-object to study?
No ISR, but coupling to the DM directly

Effective theories





Simplified models



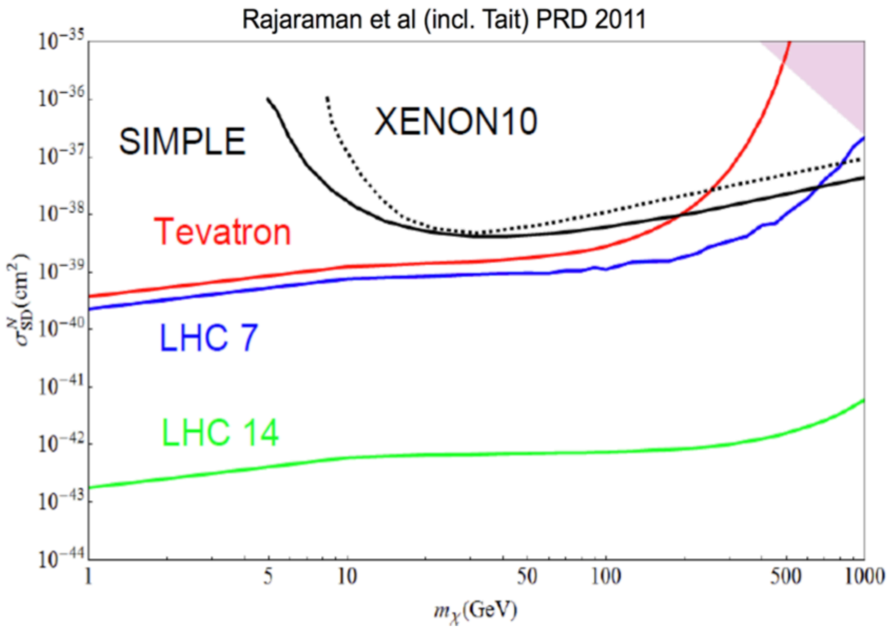
Result:
For 14 TeV?

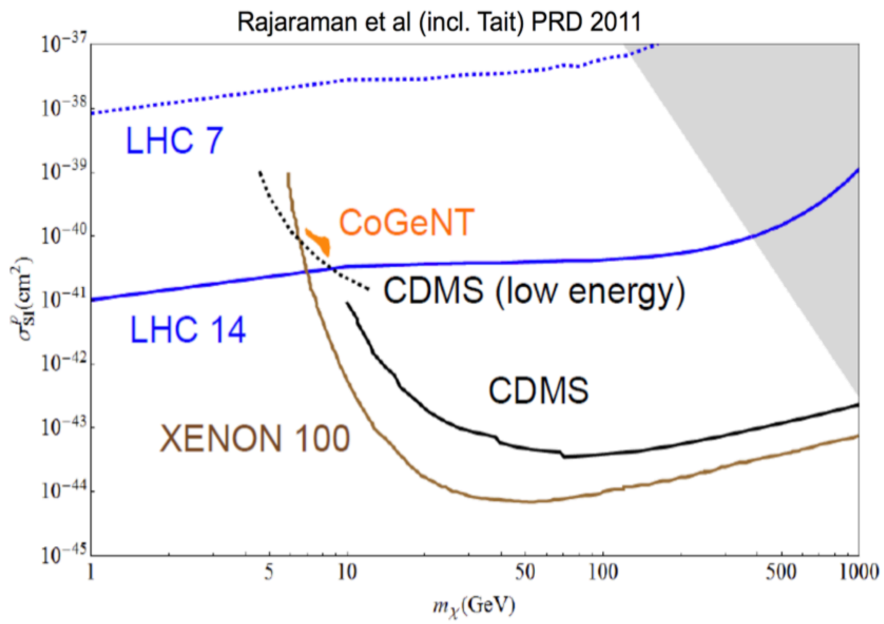
Summary

- 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 RP-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:

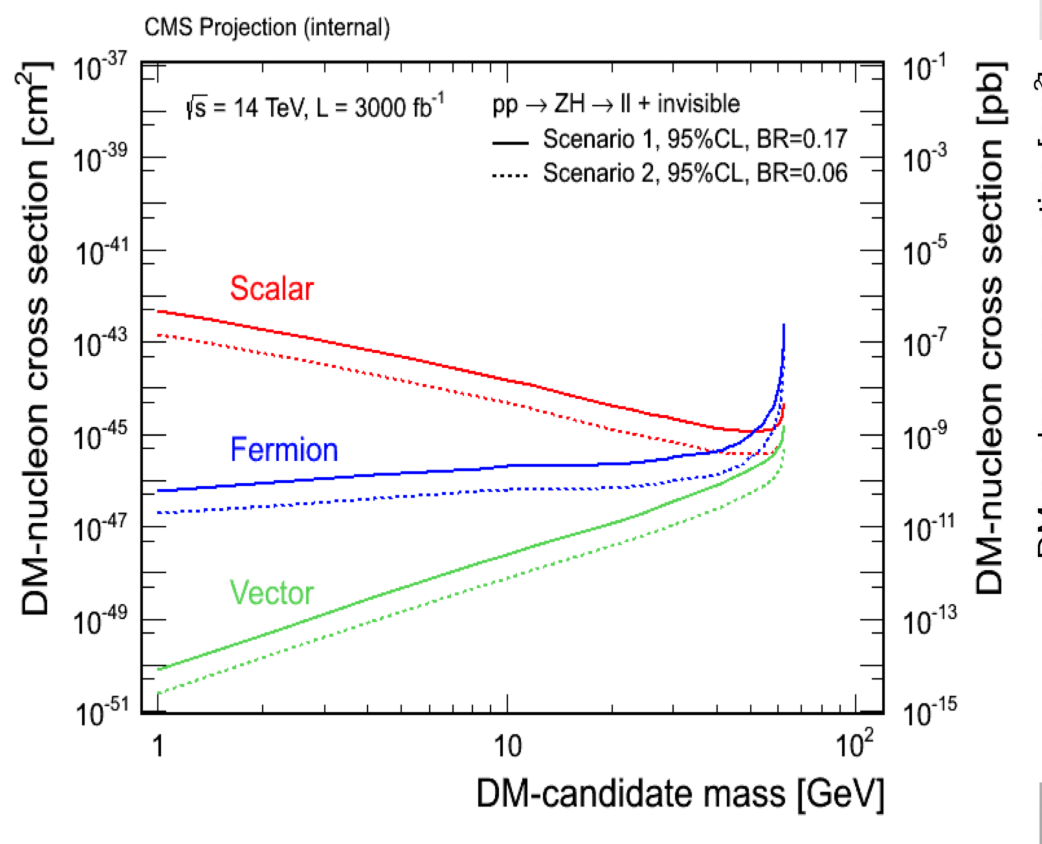
Higher LHC Energies

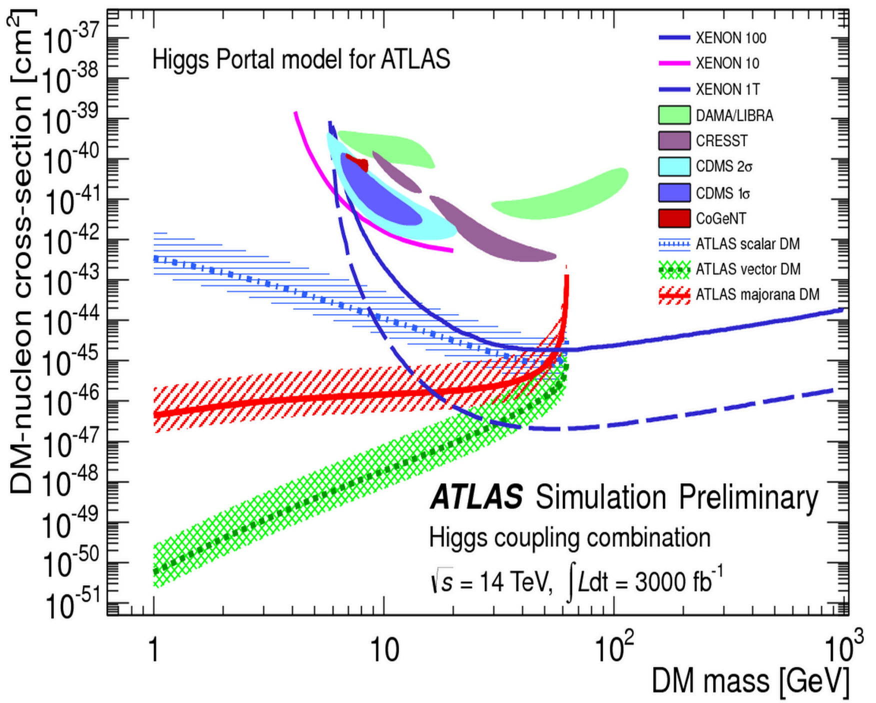
- The theorists think we will do much better at 14 TeV!





Higher LHC Energies





Data Interpretation

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{X}\gamma^\mu\partial_\mu X - M_X\bar{X}X + \sum_q \sum_{i,j} \frac{G_{qij}}{\sqrt{2}} \; [\bar{X}\Gamma_i^X X]\,[\bar{q}\Gamma_q^j q]$$

Name	Type	G_X	Γ^X	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
M8	GG	$i\alpha_s/8M_*^3$	γ_5	-
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	-
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$	γ_5	-

Majorana WIMP

R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$

Spin zero WIMPs

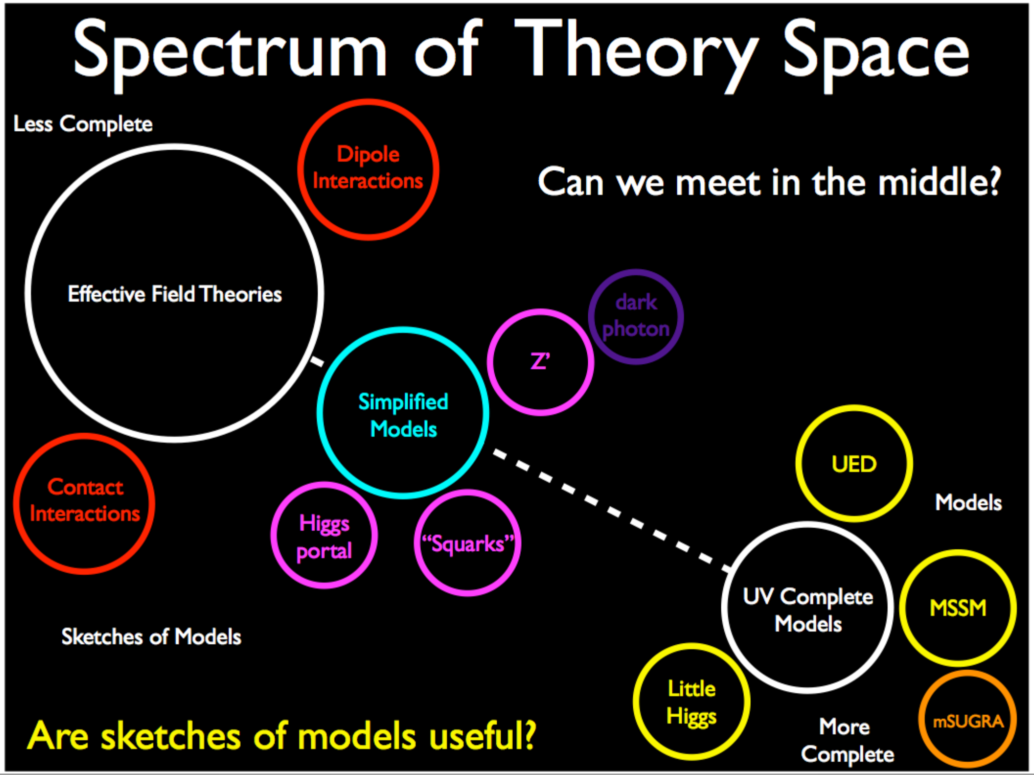
Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
D15	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	M
D16	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$	D

Dirac WIMPs

- Many operators/interactions can contribute
  - Typically pick a few expected to be dominant
  - Gradually expanding to look at more

Data Interpretation

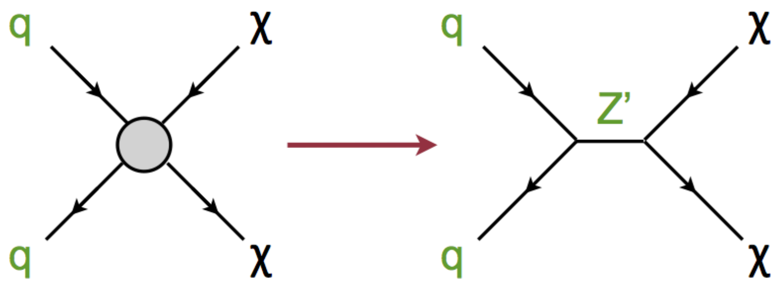
- EFTs: a simple description for searches and interpretation… too simple?
  - EFT useful to characterise and compare, but some model dependence and limitations
  - Next steps widely discussed in the community…

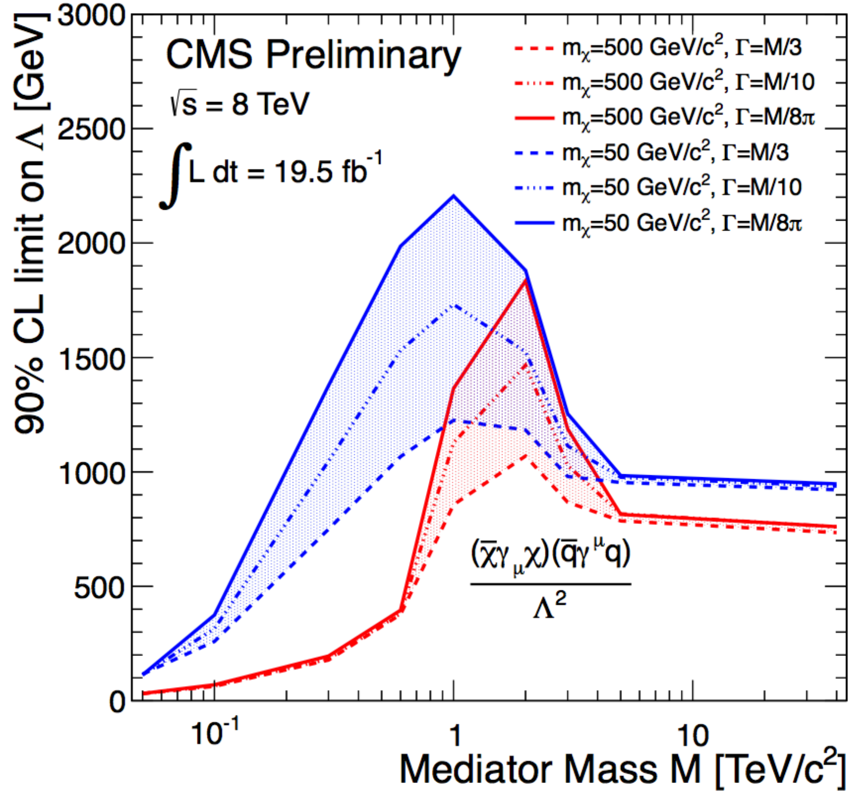


Tim Tait, LeptonPhoton 2013

Data Interpretation

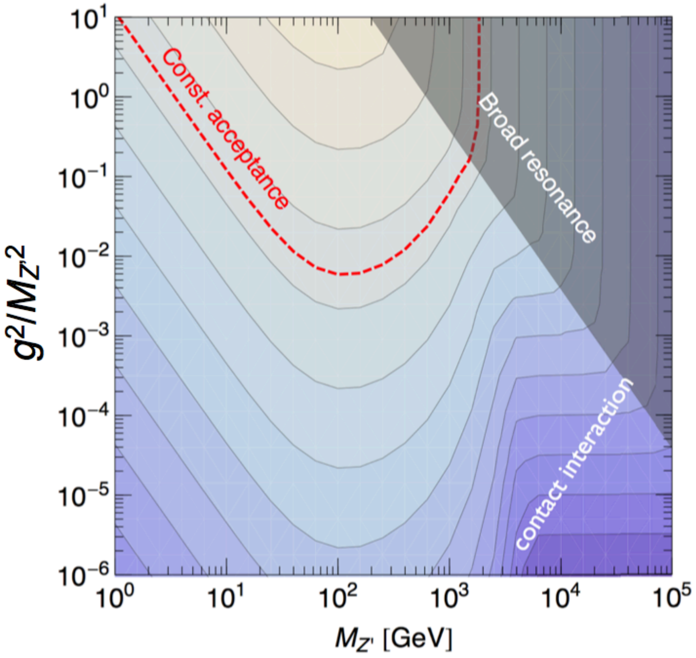
- First step: put in a mediating particle (e.g. s-channel Z') and look at limits vs $m_{Z'}$
- EFT gives good/conservative results above a few hundred GeV (high M)

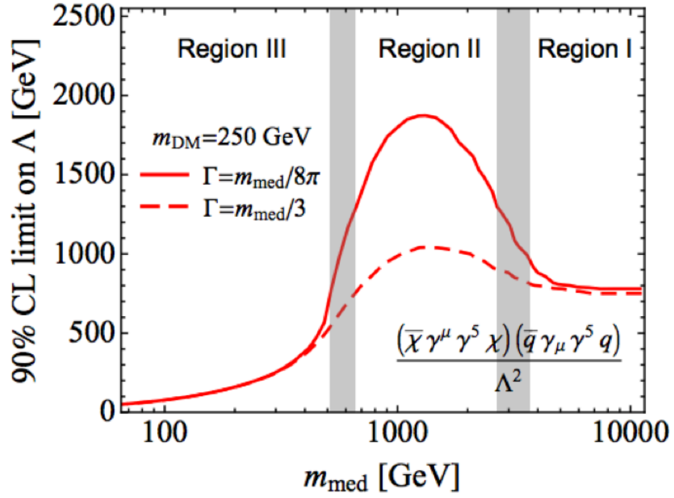


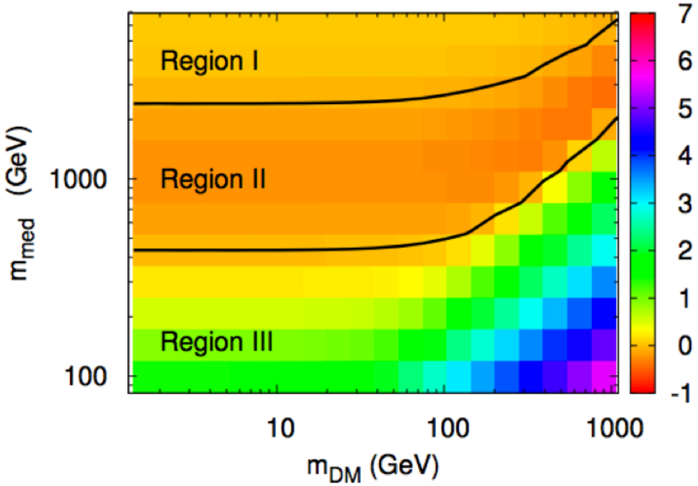


[arXiv:1204.3839, arXiv:1109.4398, I. Shoemaker]

- Z' mediator: Should look carefully at coupling vs. mass, mediator mass vs. DM mass
- Results vary with beam energy



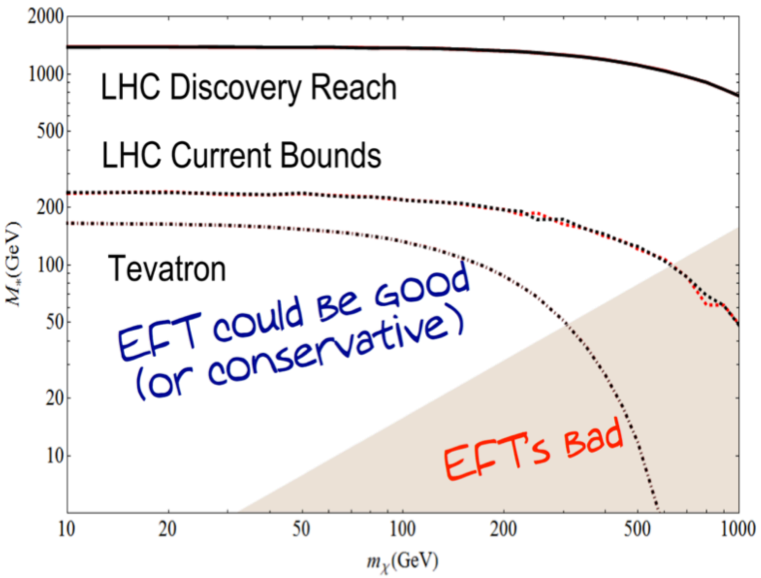




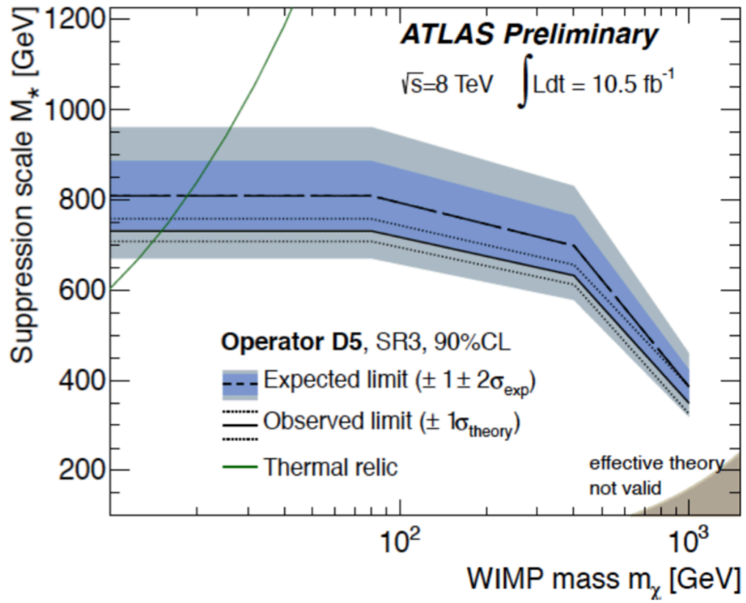
Data interpretation

[arXiv:1112.5457, arXiv:1308.6799, arXiv:1307.2253]

- LHC limits: bottom corner requires large couplings given small phase space
  - Limit from perturbative bound: $\Lambda \simeq M/\sqrt{gg_\chi} \gtrsim M_\chi/4\pi$ (original papers)
  - Unitarity limit: $gg_\chi > 4\pi/\sqrt{3}$
  - Recent papers: $\Lambda > m_M/4\pi > Q_{TR}/4\pi$, or even $\Lambda > Q_{TR}/4\pi > 2m_{DM}/4\pi$
- Starting to include these bounds in results



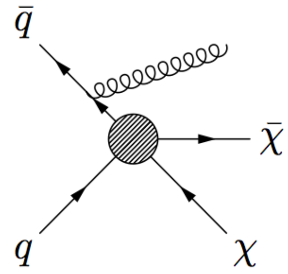
[from R. Harnik, Dark Matter in Collision, UC Davis, 2012]



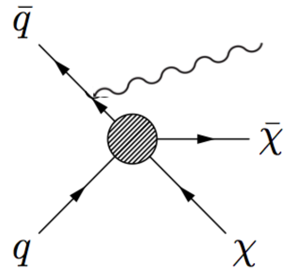
[from Gramling et. al., DM@LHC 2013]

Data Interpretation

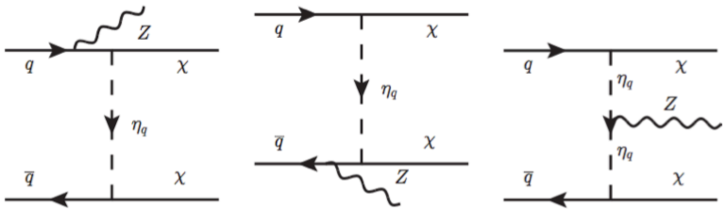
- In last two years:
  - *Hundreds* of citations for collider DM
  - *Hundreds* of phenomenology papers
  - "ISR tagging" now established technique for all searches (not just DM)



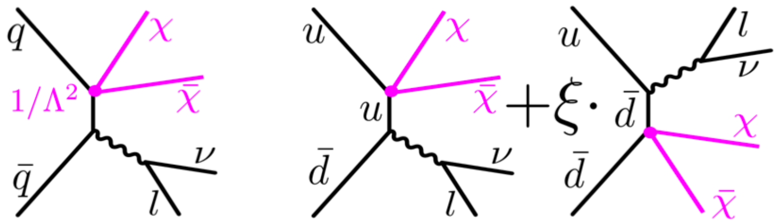
Monojet



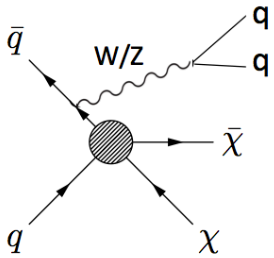
Monophoton



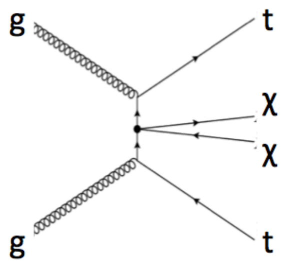
MonoZ



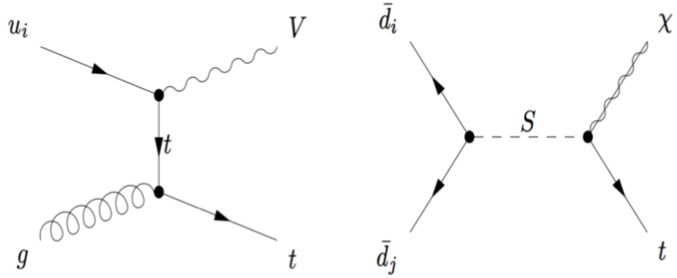
MonoW (Monolepton)



MonoW/Z (hadronic)



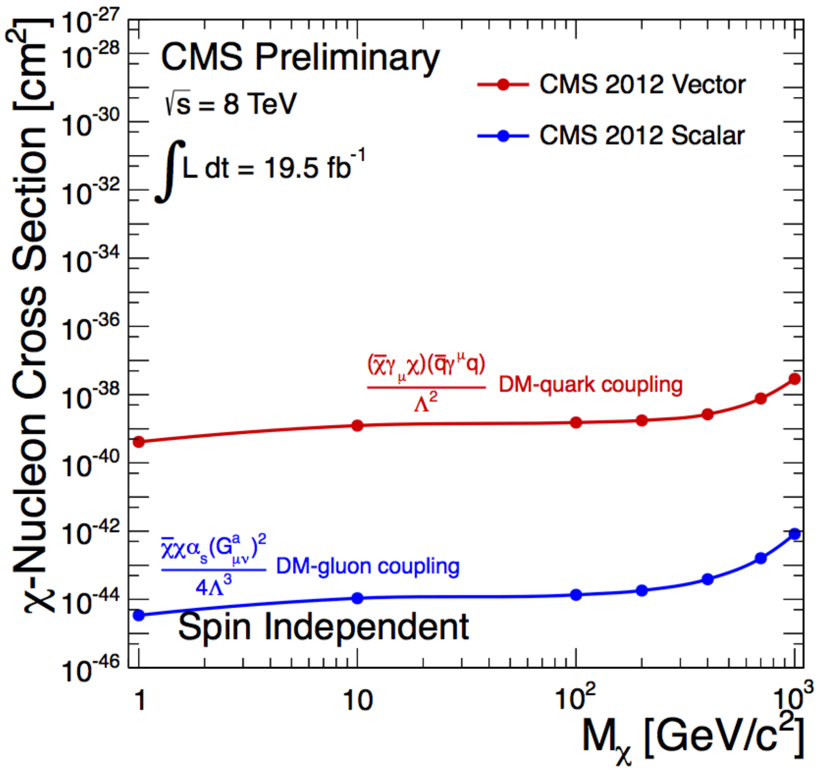
ttbar DM

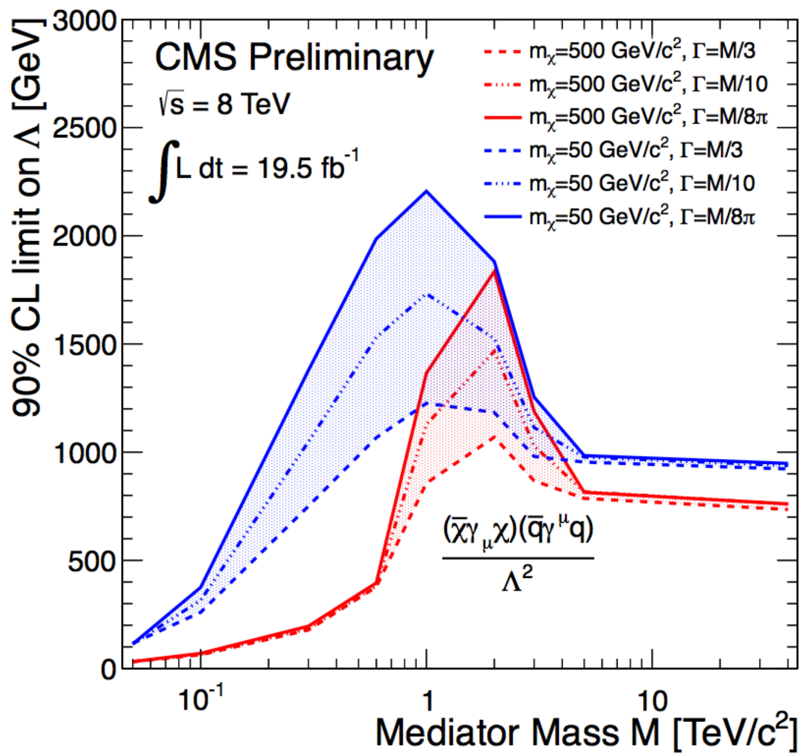


MonoTop

[CMS EXO-12-048]

- Starting to extend simple contact interaction scenario with new operators and a scan over mediator mass

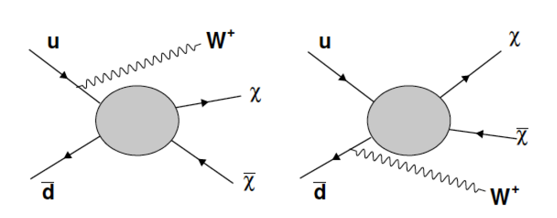


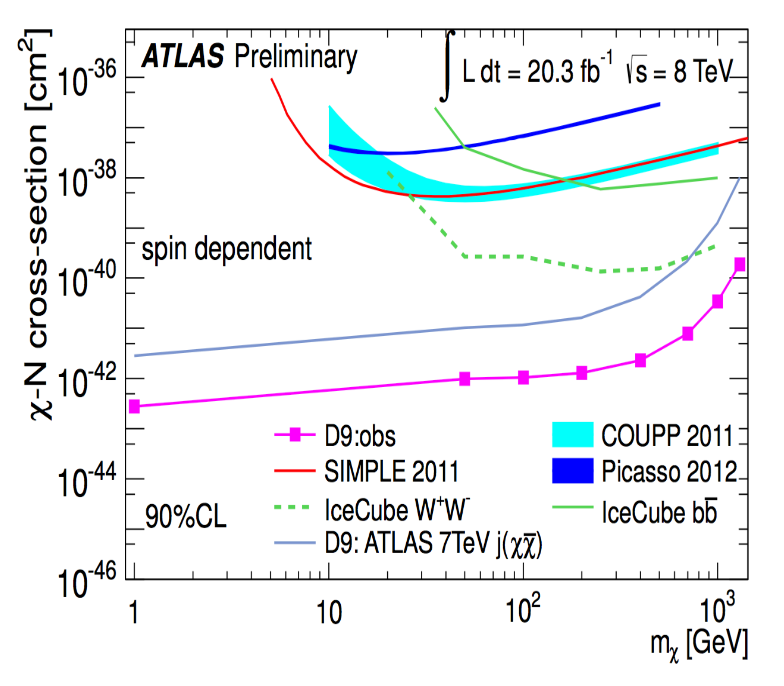


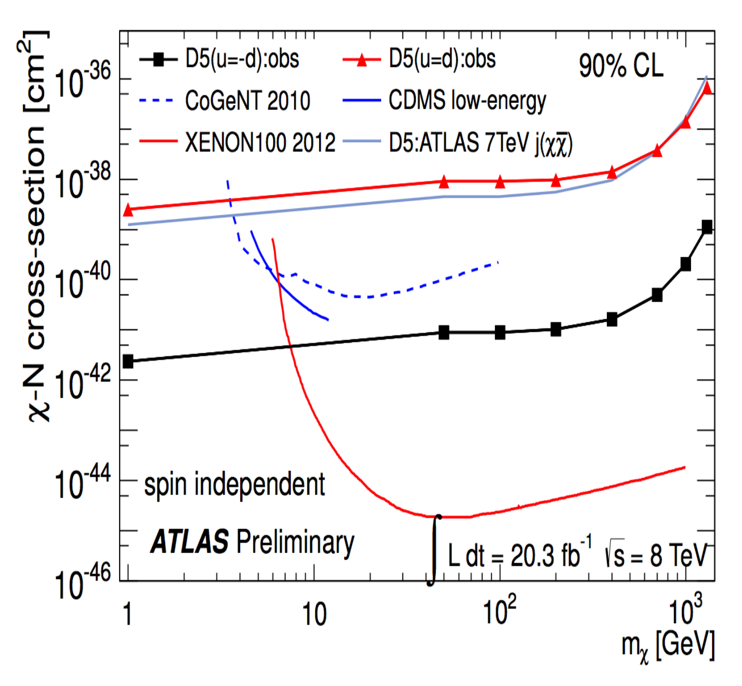
The Dark Matter Connection

Results for direct searches and collider searches for Dark Matter

-> Spin dependent and spin independent cross sections of Dark Matter with ordinary matter (W/Z + MET searches)



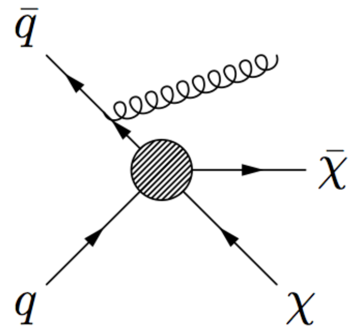




Competitive if DM-u quark coupling different from DM-d quark coupling

Data interpretation

- Effective Field Theory (EFT)
  - Assume heavy particle mediating interaction: contact interaction (integrate out mediator)
  - For M → ~40 TeV, where $\Lambda \equiv M/\sqrt{g_\chi g_q}$

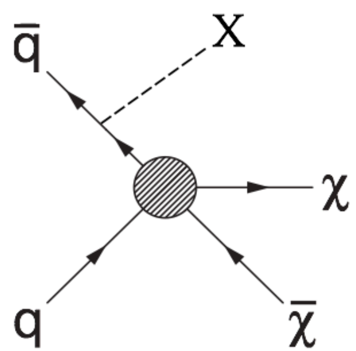


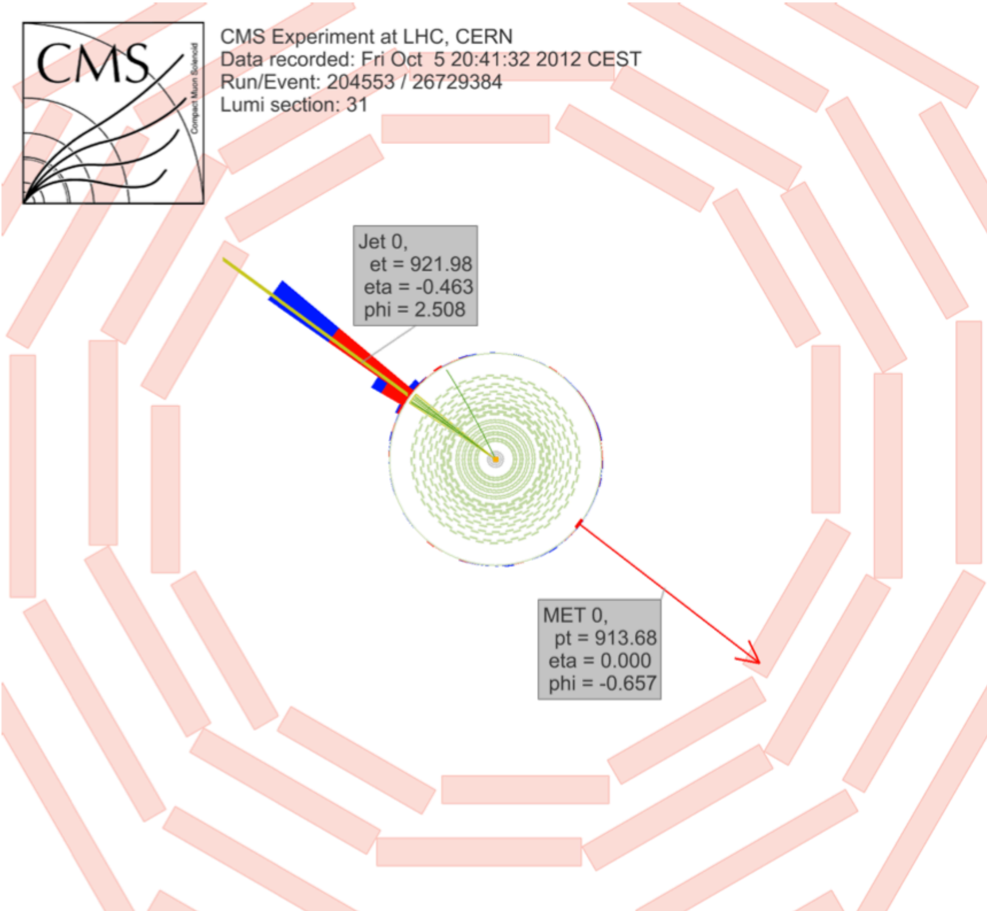
$$\sigma(pp \to \bar{\chi}\chi + X) \sim \frac{g_q^2 g_\chi^2}{(q^2 - M^2)^2 + \Gamma^2/4} E^2 \approx \Lambda^{-4} E^2$$

- Simple model for comparison
  - ✓ Only a few parameters; dark matter mass m_χ and cut-off scale Λ
  - ✓ Much easier than e.g. a full SUSY model
  - ✓ Easy comparison to direct or indirect DM experiments
  - ✓ DM can be fermion (Dirac or Majorana) or scalar (complex or real)
  - ✗ Limitations on model validity
  - ✗ Probe only one interaction at a time

The Mono-x Signature

- Particle X can be radiated from the initial state (ISR), or be produced in association with invisible particle(s)



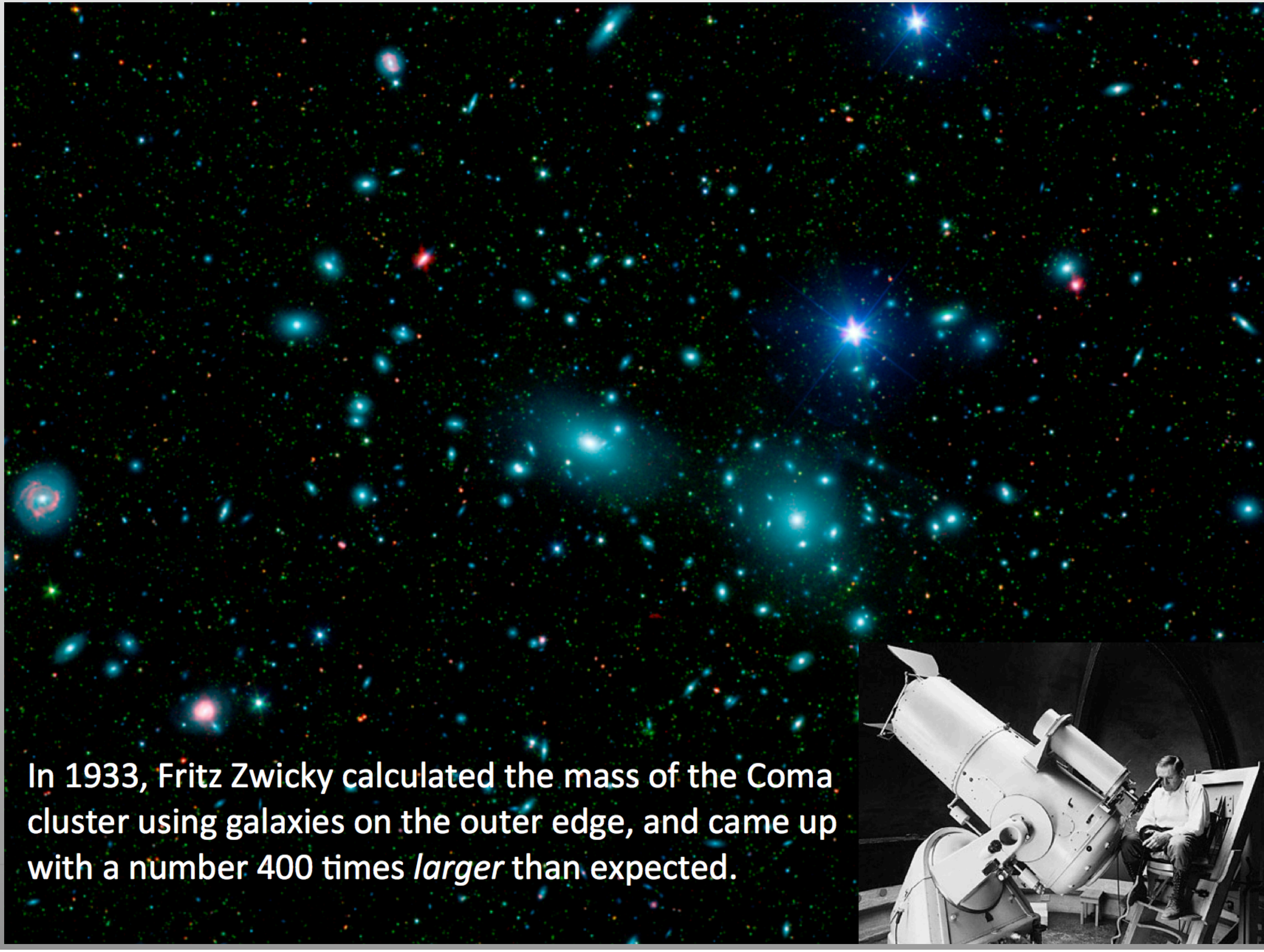


- X balances "missing energy" in transverse plane ($\not{E}_T$)
- X particles considered:

jet, W, Z, photon, top

- Mono-X topology allows for tagging production of new undetected particles

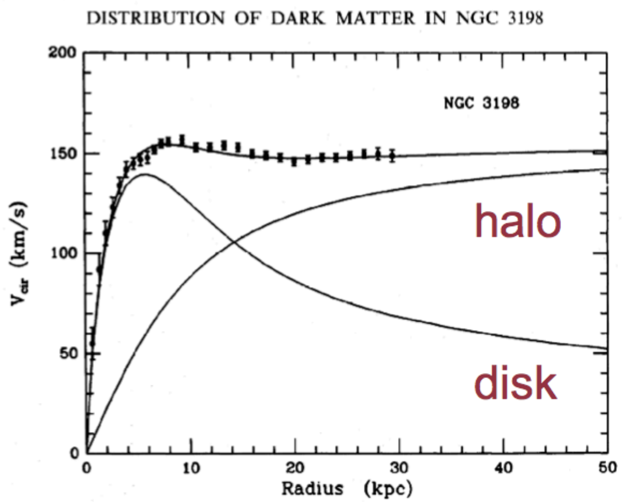
Dark Matter: Started a Long Time Ago

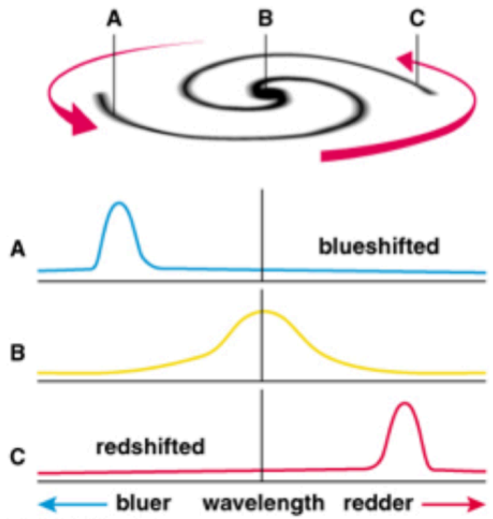


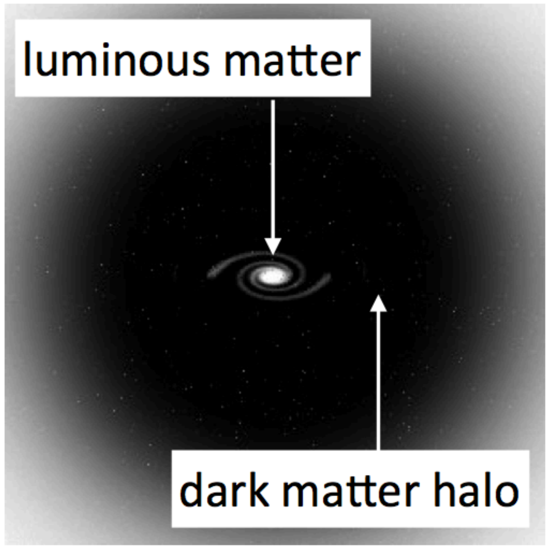
Galactic Rotation

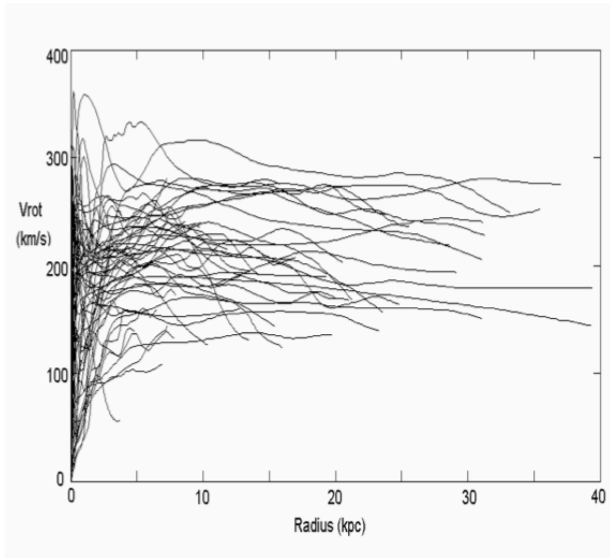
- Starting in the 1970’s, measured velocity vs. radius of edge-on spiral galaxies
- They found them to be flat, consistent with ~10x as much “dark” mass…

…and not just one galaxy









Particle Dark Matter?

- Properties of Dark Matter
  - old (long lived)
  - slow (non-relativistic)
  - not charged (electric or colour)
  - interacts very weakly with SM
  - feels the effects of gravity

- Many candidates for Dark Matter
  - *Warm:* sterile neutrinos, gravitinos
  - *Cold:* Lightest SUSY particle (neutralino, gravitino), Lightest Kaluza-Klein particle
  - *Nonthermal relics:* Bose-Einstein Condensate, axions, axion clusters, solitons, supermassive wimpzillas

WIMP= Weakly Interacting Dark Matter (M. Turner)

The observed density of dark matter is of the magnitude expected for a thermal relic weakly-interacting massive (~100 GeV) particle (WIMP).

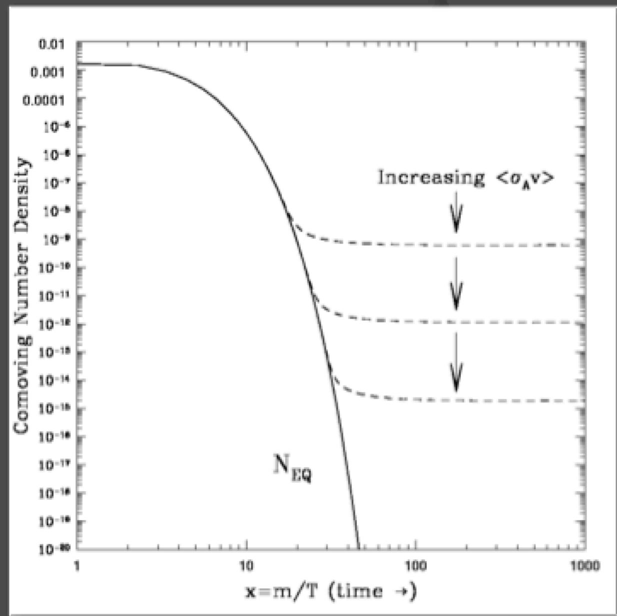
WIMPs

- T>>M_X, WIMPs are in thermal equilibrium
- T<M_X, number density becomes exponentially suppressed
- Including the effects of expansion pulls the density away from its equilibrium value:

$$\frac{dn_X}{dt} + 3Hn_X = - < \sigma_{X\bar{X}}|v| > (n_X^2 - n_{X,\,\mathrm{eq}}^2)$$

- Numerically, this yields an abundance of:

$$\Omega_X h^2 \approx 0.1 \left(\frac{x_{\mathrm{FO}}}{20}\right)\left(\frac{g_\star}{80}\right)^{-1/2}\left(\frac{< \sigma_{X\bar{X}}|v| >}{3 \times 10^{-26}\mathrm{cm}^3/\mathrm{s}}\right)^{-1}$$



Effective Field Operators

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta} q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

TABLE I: Operators coupling WIMPs to SM particles. The operator names beginning with D, C, R apply to WIMPS that are Dirac fermions, complex scalars or real scalars respectively.

Supersymmetry? New Physics?

H. Murayama

no sign of new physics