“News from the Dark” Workshop, Montpellier, December 4-6, 2013

Current and Future Collider Searches/Constraints on Dark Matter

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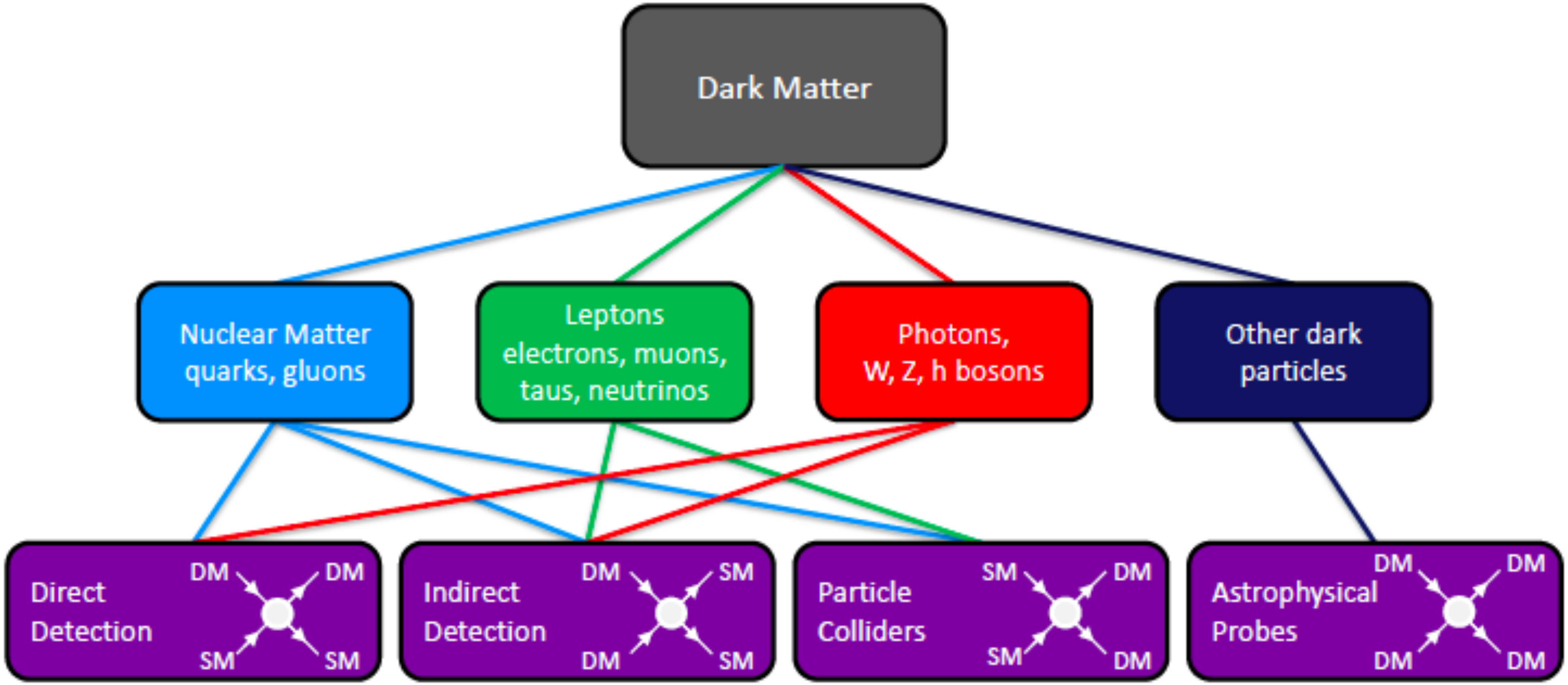
Searching for Dark Matter



arXiv:1305.1605

- A broad program of complementary searches is underway.
- Particle colliders are critical to elucidate the particle properties of dark matter (DM), but they will only contribute a fraction of the pieces needed to complete the puzzle.

Today's Presentation

- Introduction to DM searches at colliders
- SUSY-like DM
- Direct DM production
- Extended models
- Conclusions

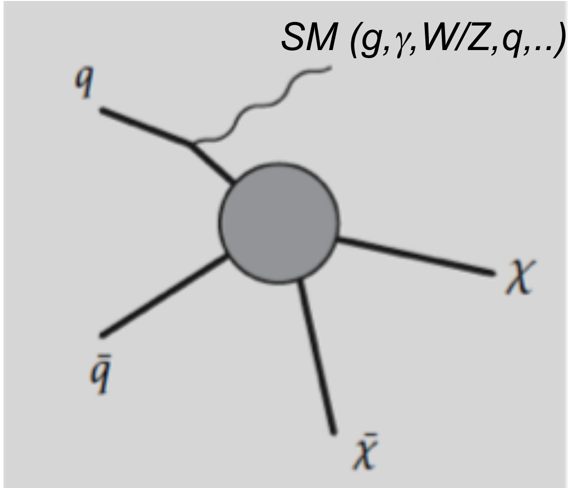
Disclaimers:

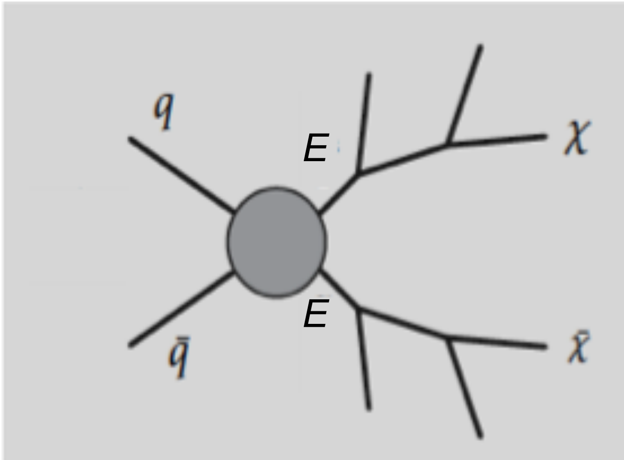
- There is plenty of material that could not be included.
- This is not my main area of expertise.

Searches for Dark Matter at Colliders

How to make DM particles at colliders:

- SM decays to χ: Z→χχ, h→χχ, t→cχχ
- Direct production: χχ+SM particles
- Associated production with a heavier exotic: χ+E, then E→χ+SM
- Pair of heavier exotics:
  E+E, then both E→χ+SM
- Exotic resonance decays: E→χχ
- Heavier metastable exotic decay of E→χ not seen in the detector





Searches for Dark Matter at Colliders

How to describe DM particles at colliders:

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Effective operators

SUSY

Extra dimensions

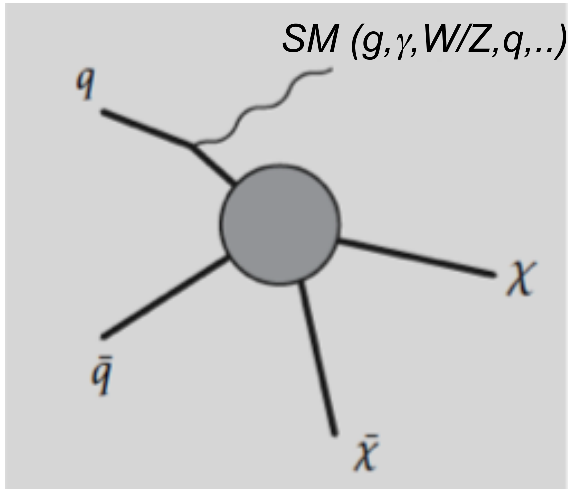
Little Higgs

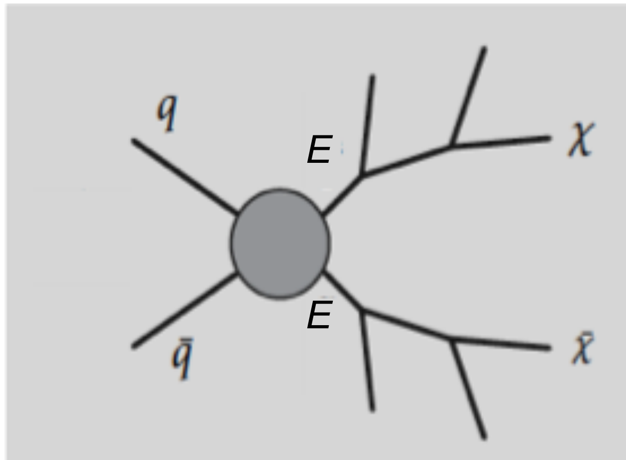
...

Dark sectors

More model independent

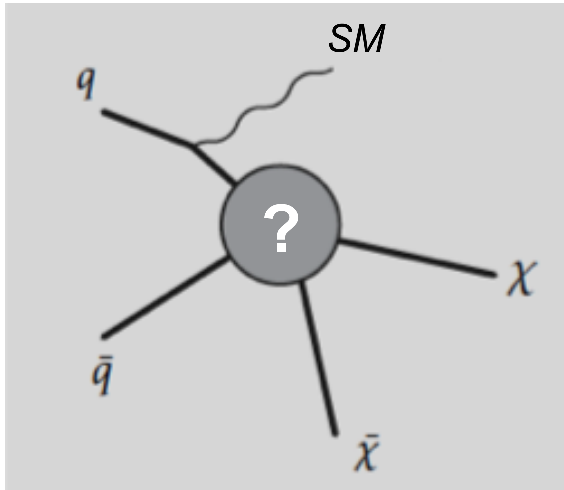
More model dependent

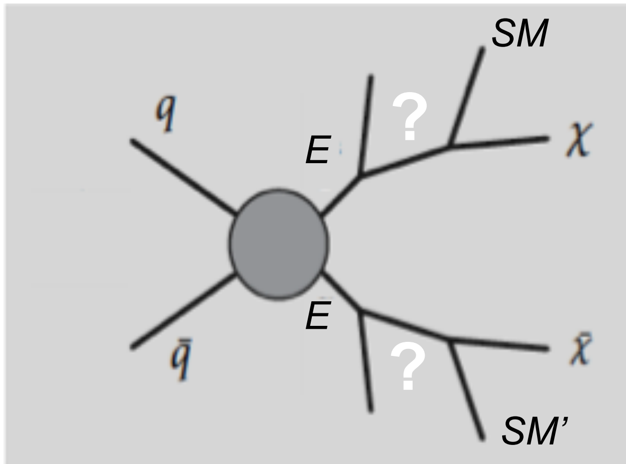




Searches for Mediators at Colliders

- We are also interested in the particles that mediate the non-gravitational interactions between DM and SM particles.
- Depending on the DM-SM interaction, different mediators could be at play!
- In the SM the only possible mediators are the Z and Higgs bosons.
- Very heavy mediators ➔ describe DM-SM interactions in terms of effective operators.
- If mediators are light enough, they can be produced and identified at the LHC, not necessarily in association with DM (e.g. Z'→qq, heavy SUSY Higgs,…).
- If mediators are very light, they can be produced and identified at lower energy experiments (e.g. dark photons).



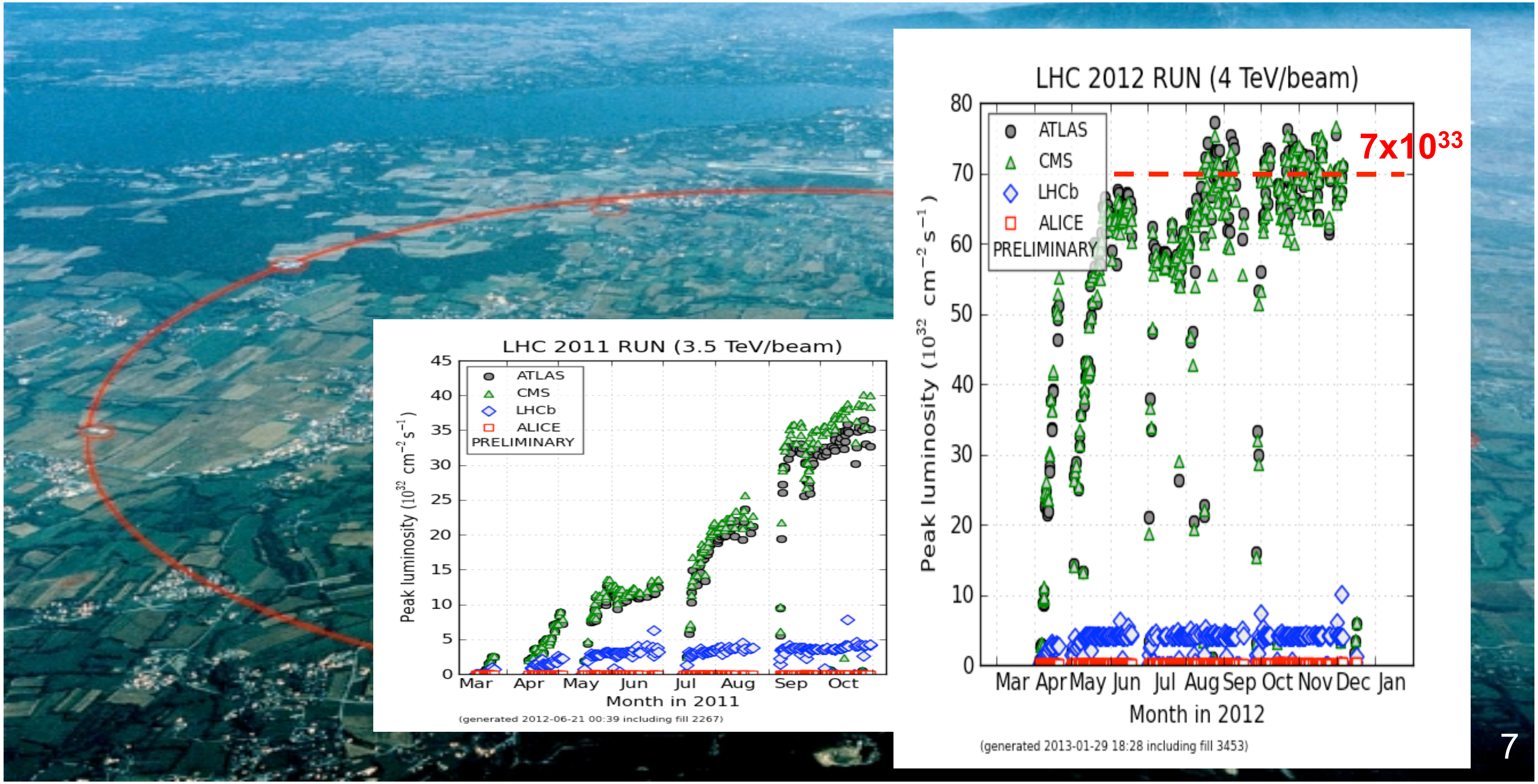


Large Hadron Collider

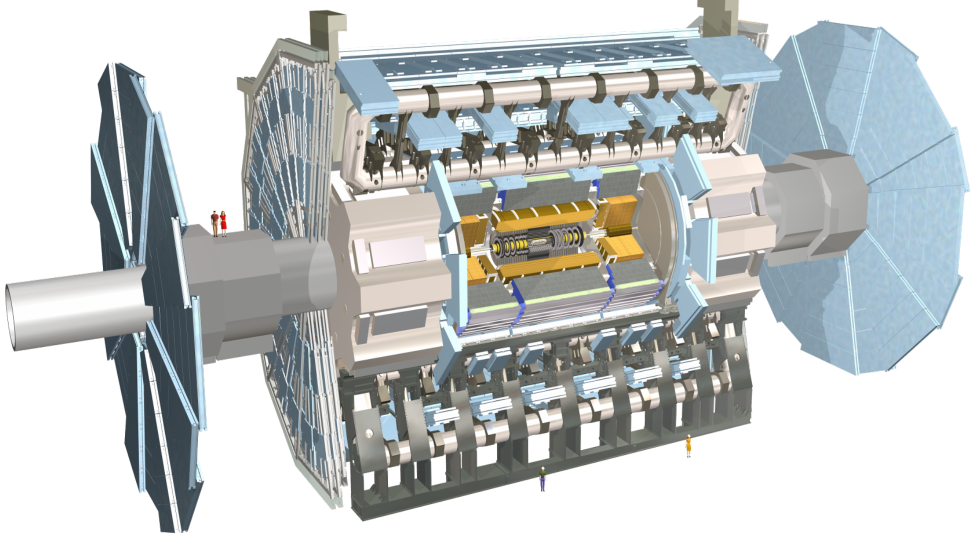
- Outstanding performance of the LHC over the last two years:
  - 2011: pp collisions at $\sqrt{s}$=7 TeV, ~5.8 fb^{-1}
  - 2012: pp collisions at $\sqrt{s}$=8 TeV, ~23.3 fb^{-1}

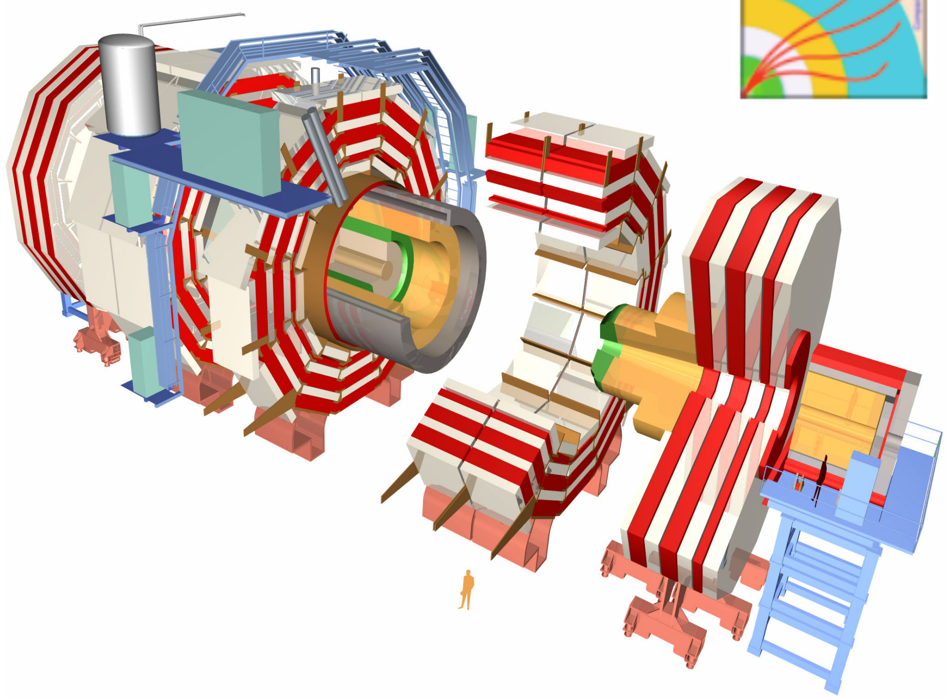
  (delivered to ATLAS and CMS)
- Collisions to resume in 2015 at $\sqrt{s}\geq$13 TeV and $L\geq10^{34}$ $cm^{-2}s^{-1}$

  ➔ projecting ~25-45 fb^{-1}/year!



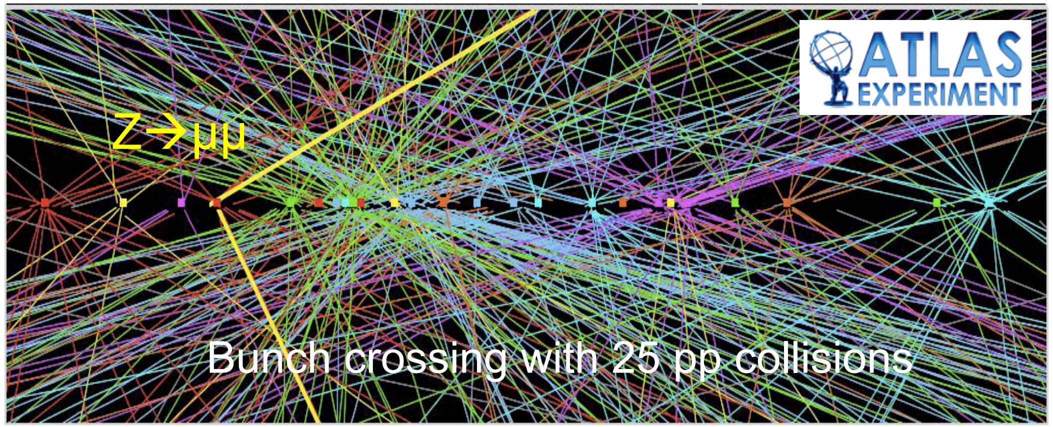
ATLAS and CMS Experiments





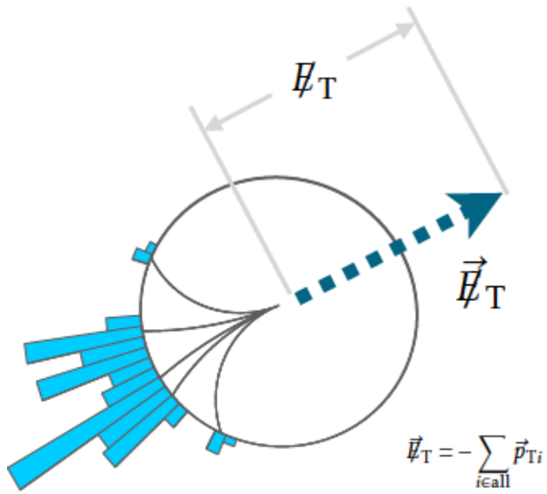
- Excellent performance up to the highest instantaneous luminosities delivered by the LHC.
  ~93% data-taking efficiency

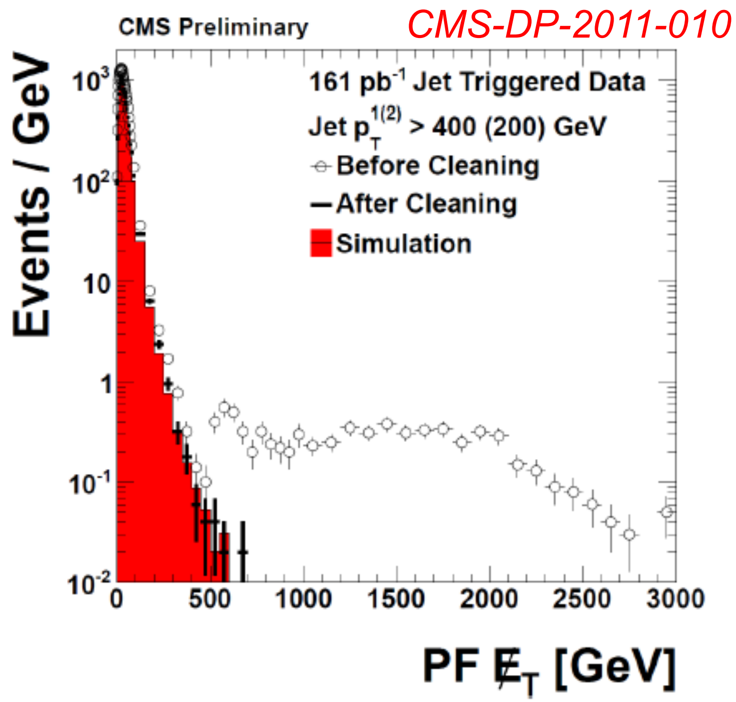
- Most results shown use the full 2011 dataset (~ 5 fb^{-1} at $\sqrt{s}$=7 TeV) and some results use the full 2012 dataset (~20 fb^{-1} at $\sqrt{s}$=8 TeV).



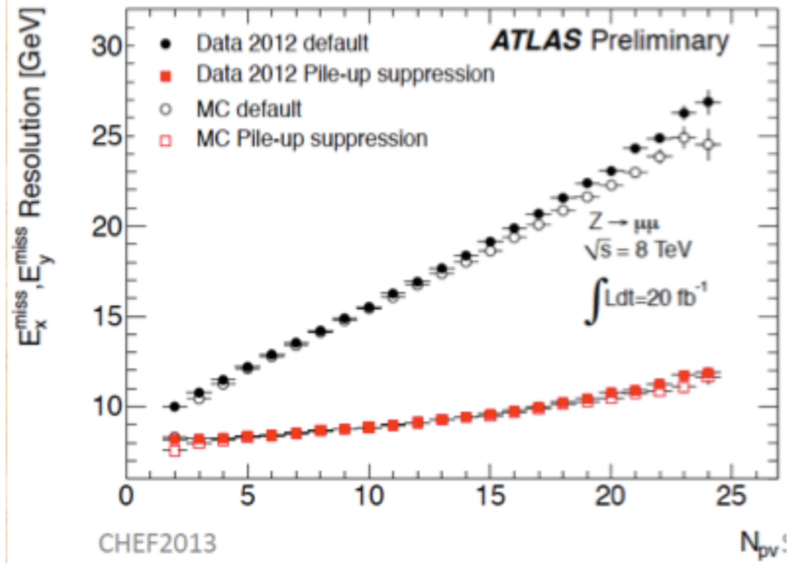
E_{Tmiss} and DM Particles

- DM particles will manifest themselves as an imbalance in the visible vector sum p_T (E_{Tmiss}).





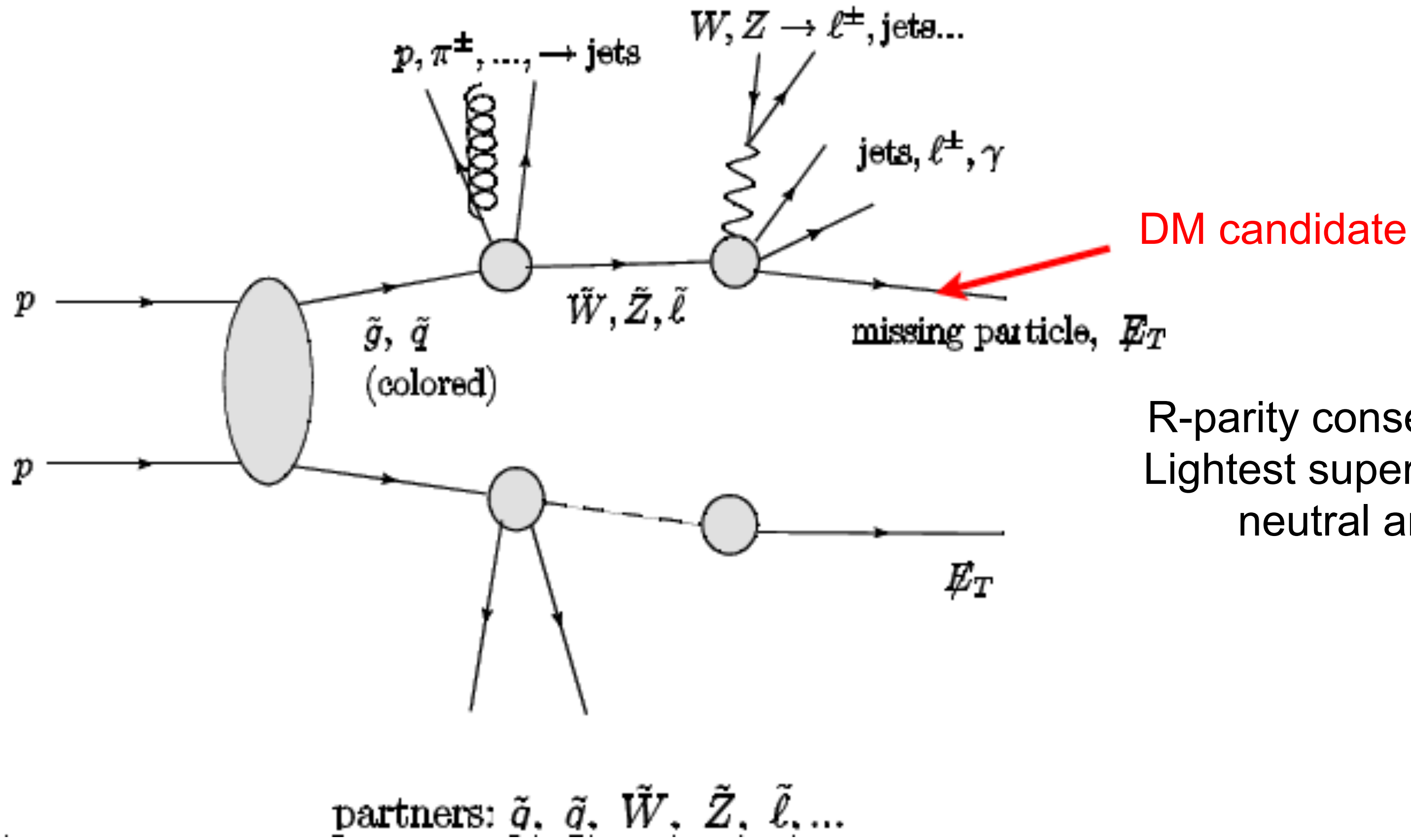
- E_{Tmiss} reconstruction:
    - requires hermetic detectors;
    - requires precise measurement of energies of particles with EM and hadronic interactions;
    - affected by many types of imperfections (hot calorimeter cells, detector noise, beam-halo particles,..).
- E_{Tmiss} resolution significantly affected at the LHC by to pileup effects. Several pileup suppression techniques successfully deployed to mitigate impact.



SUSY-Like DM

SUSY-Like Scenarios

- DM candidate embedded in an extended TeV-scale new physics scenario.



R-parity conserving SUSY:
Lightest superpartner (LSP)
neutral and stable

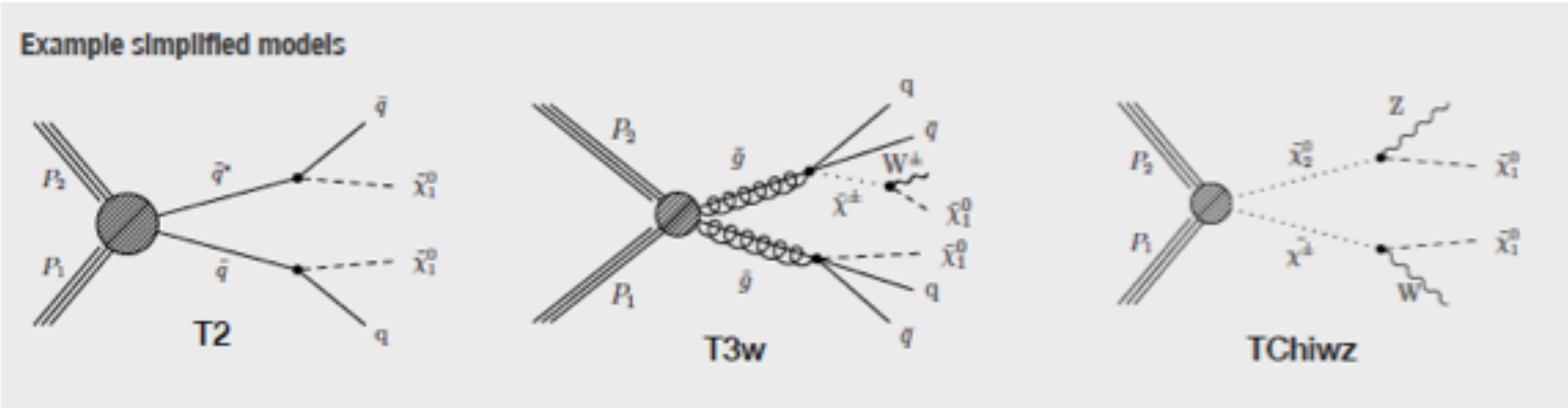
- SUSY-like signatures are common in other BSM scenarios.
- Discovery could be “straightforward” (depending on mass of heavier exotics).
- Measuring the properties (mass, spin,…) will be hard….

SUSY Searches at LHC Run 1

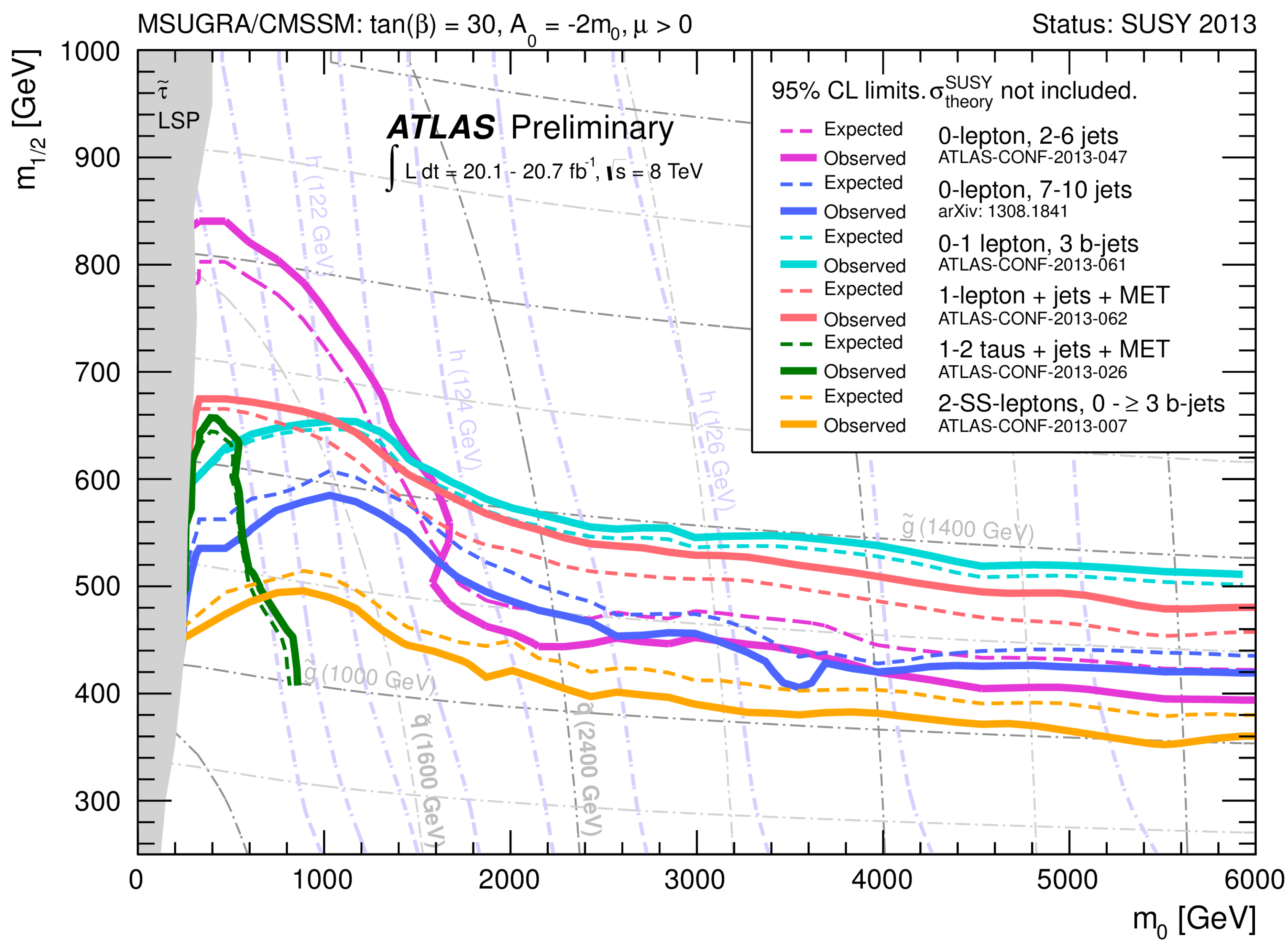
- A broad program of SUSY searches is underway in many topologies:
  - **MET + jets (ie, quarks/gluons)**
  - **MET + b-quarks**
  - **MET + jets + 1 lepton (e or μ)**
  - **MET + jets + 2 leptons (same sign)**
  - **MET + jets + 2 leptons (opposite sign)**
  - **MET + single jet**
  - **MET + jets + 1 lepton + b-quarks**
  - **MET + jets + 2 leptons + b-quarks**
  - **MET + jets + Z-boson**
  - **MET + 3 or 4 leptons**
  - **MET + jets + 1 photon**
  - **MET + jets + 2 photons**
  - **MET + leptons and no jets**
  - **etc etc etc**

  No significant excess found so far.

- Results interpreted in the CMSSM, other SUSY models, and Simplified Models (SMS):
  - CMSSM: adds five parameters to the SM: m_0, $m_{1/2}$, $\tan\beta$, A_0, $\sin(\mu)$
    - Over most of the parameter space the neutralino is the LSP (DM candidate).
  - SMS: consider just a few particles and pair production. Set limits on σxBR.
    - Allows to explore wider kinematic phase space than particular models predict.



Summary Results: CMSSM

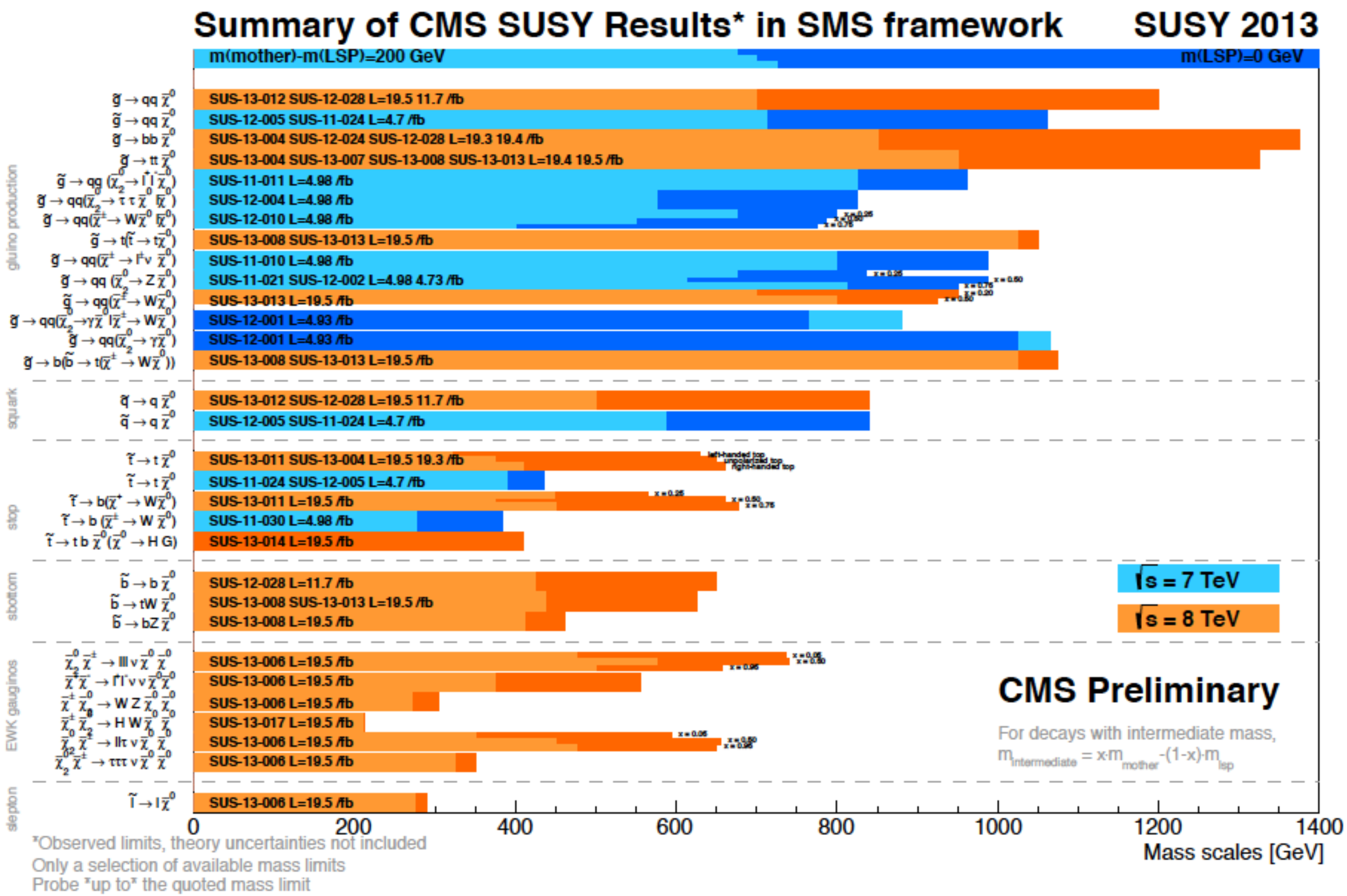


For more details:

ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Summary Results: SMS

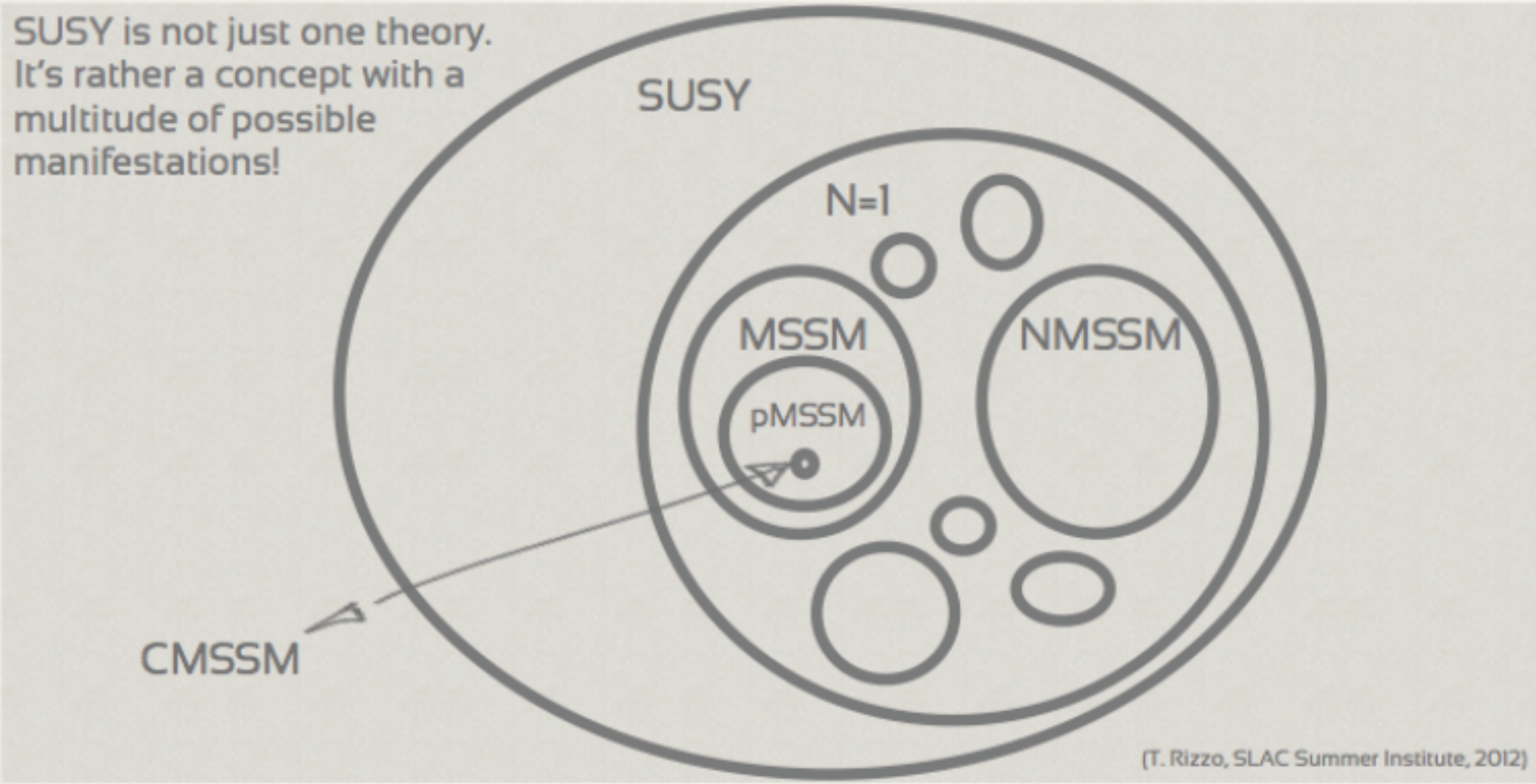


For more details:

ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

What Did We Learn So Far?

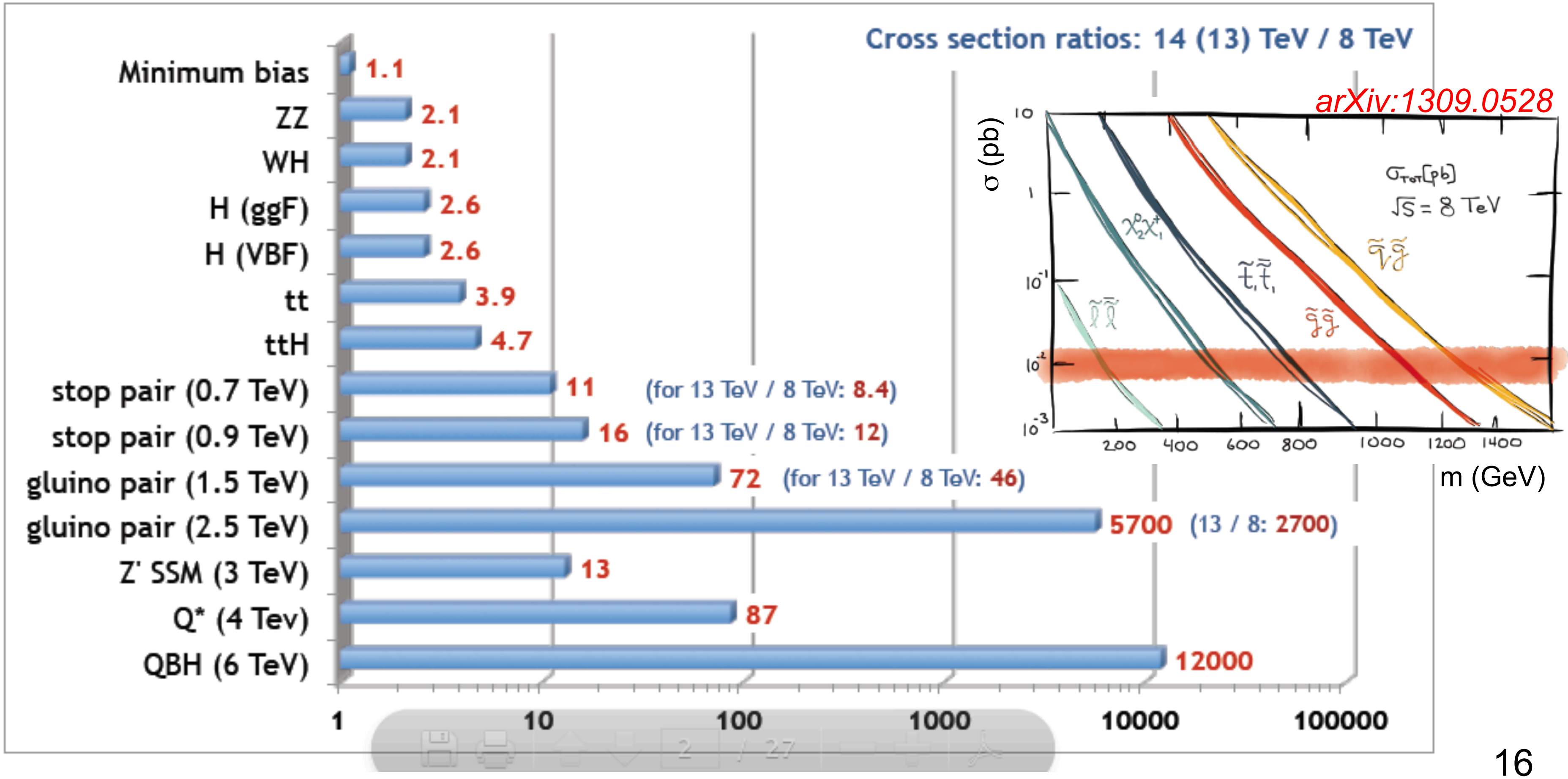


LHC searches at 7 and 8 TeV have so far excluded about 1/3 of the parameter space of the pMSSM

- Too soon to tell from LHC exclusions if SUSY is related to the EW scale and DM.

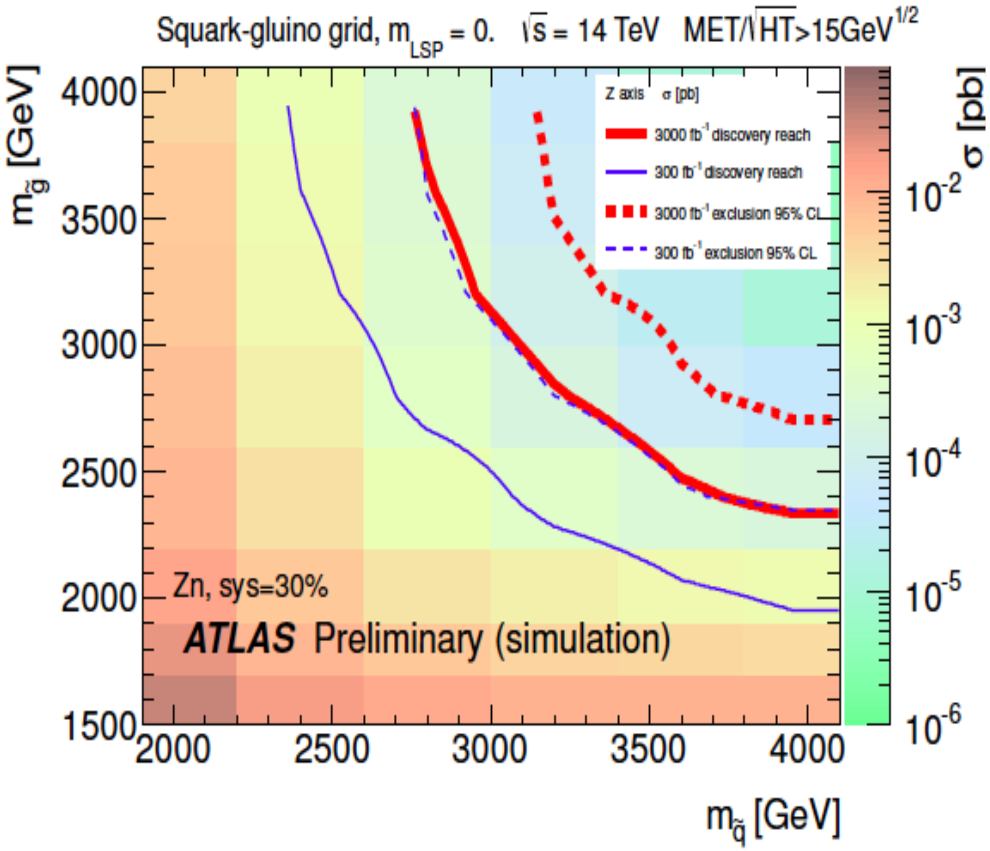
Prospects for LHC SUSY Searches

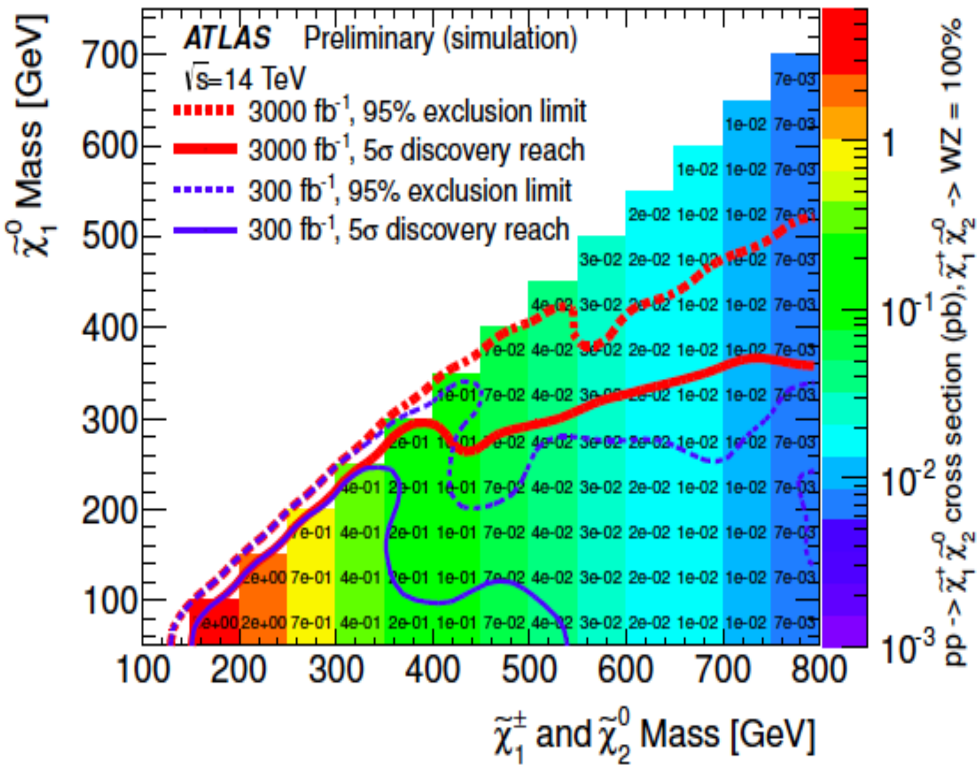
- Huge improvement in sensitivity expected at the edge of phase space during Run 2.
- For gluinos/stop searches an achieve sensitivity of full Run1 dataset with just 1-4 fb^{-1} at 13 TeV.
  - Preliminary estimates are ~15-30 fb^{-1} by the end of 2015.



Ultimate LHC Reach for SUSY?

ATL-PHYS-PUB-2013-002





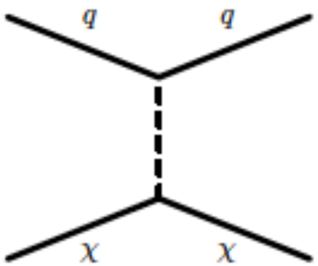
- It's hard to make predictions, especially about the future.
- Run 1 results have already exceed expectations in many respects…

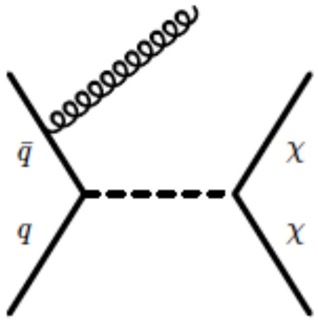
DM Direct Production

Collider Production

- Assuming dark matter (DM) couples to the SM (quarks and gluons), we can relate direct detection searches to production of dark matter at hadron colliders:

Scattering off a nucleus



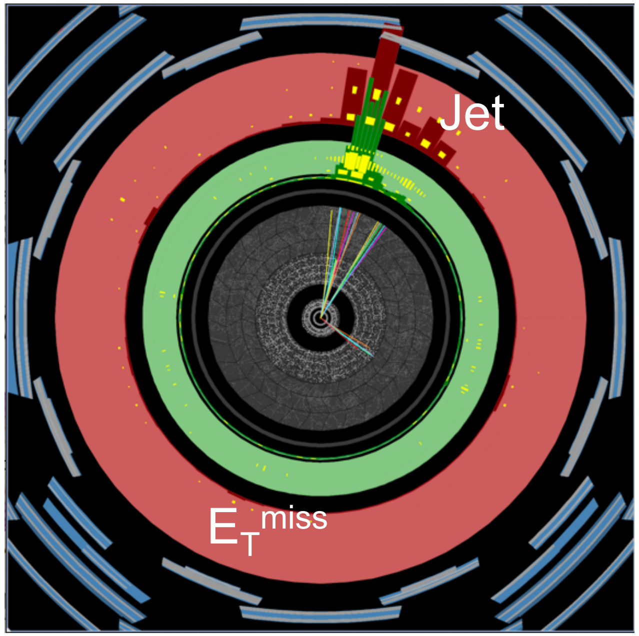


jet+E_T^{miss} signature

$$\sigma \sim g_q^2 g_\chi^2 \frac{\mu^2}{M^4},\ \mu \sim 1 \text{ GeV}$$

$$\sigma \sim \alpha_s g_q^2 g_\chi^2 \frac{p_T^2}{M^4}$$ (Heavy mediator)

- Advantages of collider searches:
  1) No detection threshold
     (for light DM the nucleus recoil can fall below threshold in direct detection searches)
  2) Independent of type of interaction
     (spin-independent vs spin-dependent)
     and of astrophysics assumptions
     (e.g. direct detection searches assume a DM local abundance of ρ_{DM}~0.3 GeV/cm^3)
- Interpretation under a number of assumptions.



Theoretical Framework

- Main assumptions:
  - DM particles are Dirac fermions.
  - DM particles are pair-produced via a mediator particle that couples to quarks and/or gluons. Interactions must be flavor-universal for the four light quarks.
  - Mediators are too heavy to be produced directly ➔ contact interaction
- DM-SM interactions described by only two parameters: M_* and m_χ.
  $M_* \sim M/g_1g_2$ [$M>2m_\chi$, $g_1g_2<(4\pi)^2$]
- 90% CL upper limits on $\sigma(pp\rightarrow\chi\chi+X)$ used to set limits on M_* for the different operators.
- Upper limits on M_* translated to limits on DM-nucleon scattering cross section.

PRD 82, 116010 (2010)

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

Spin independent

Spin dependent

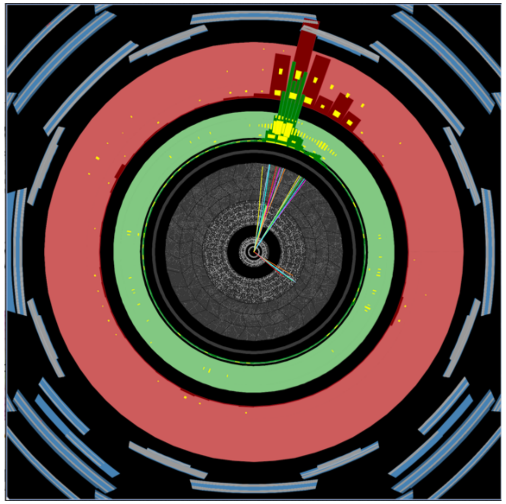
$$\sigma_0^{D1} = 1.60\times10^{-37}\mathrm{cm}^2\left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2\left(\frac{20\mathrm{GeV}}{M_*}\right)^6,$$

$$\sigma_0^{D5,C3} = 1.38\times10^{-37}\mathrm{cm}^2\left(\frac{\mu_\chi}{1\mathrm{GeV}}\right)^2\left(\frac{300\mathrm{GeV}}{M_*}\right)^4,$$

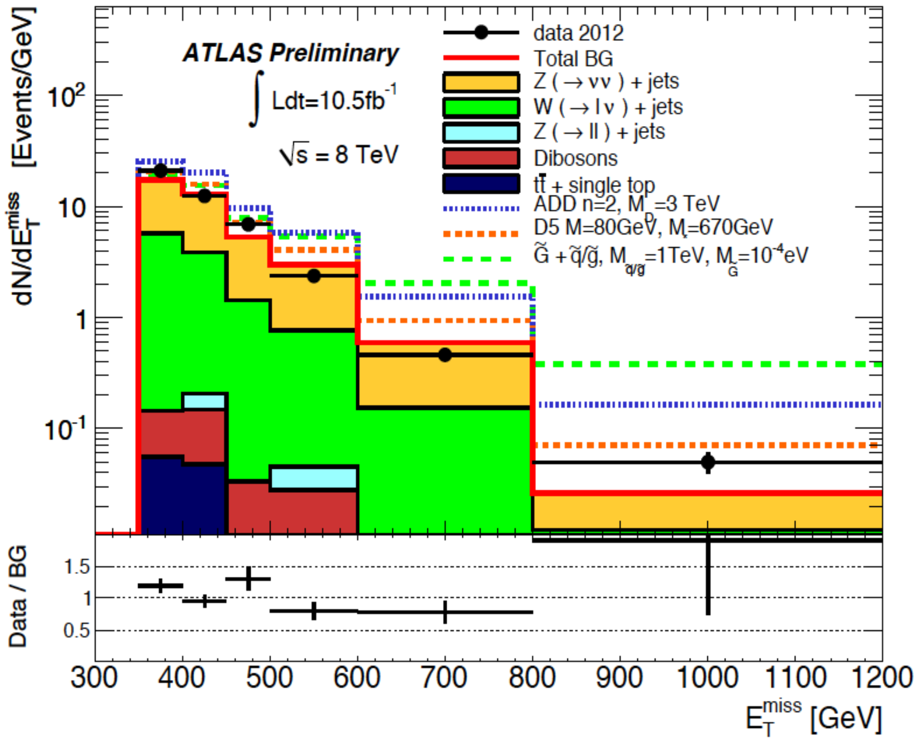
However EFT only valid when $Q^2 \ll M^2$ [$Q^2 \ll (4\pi M_*)^2$, $m_\chi<2\pi M_*$]

Mono-Jet

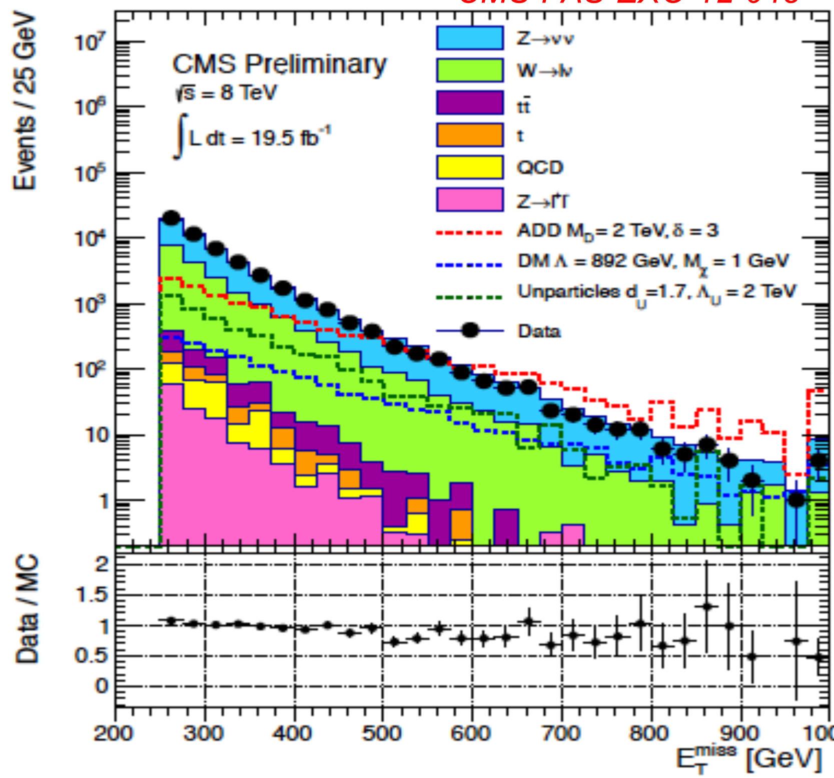
- Basic requirements:
  - High p_T jet and large E_{Tmiss}
  - Low jet multiplicity
- Main backgrounds estimated using data-driven techniques:
  - $Z(\rightarrow\nu\nu)$+jets
  - $W(\rightarrow l\nu)$+jets



ATLAS-CONF-2012-147

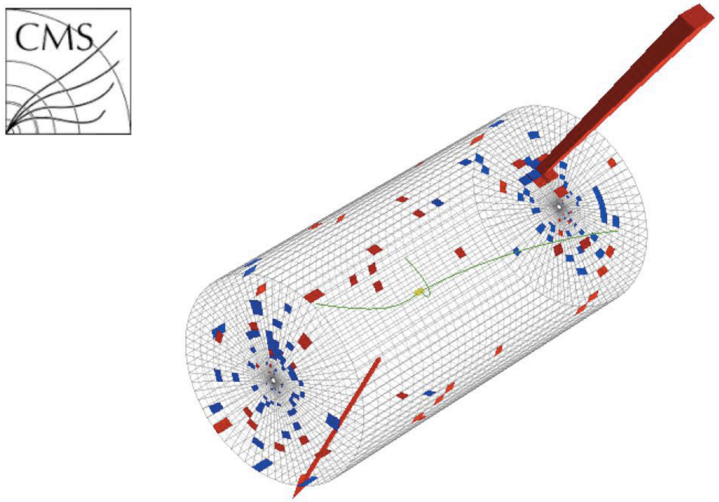


CMS-PAS-EXO-12-048



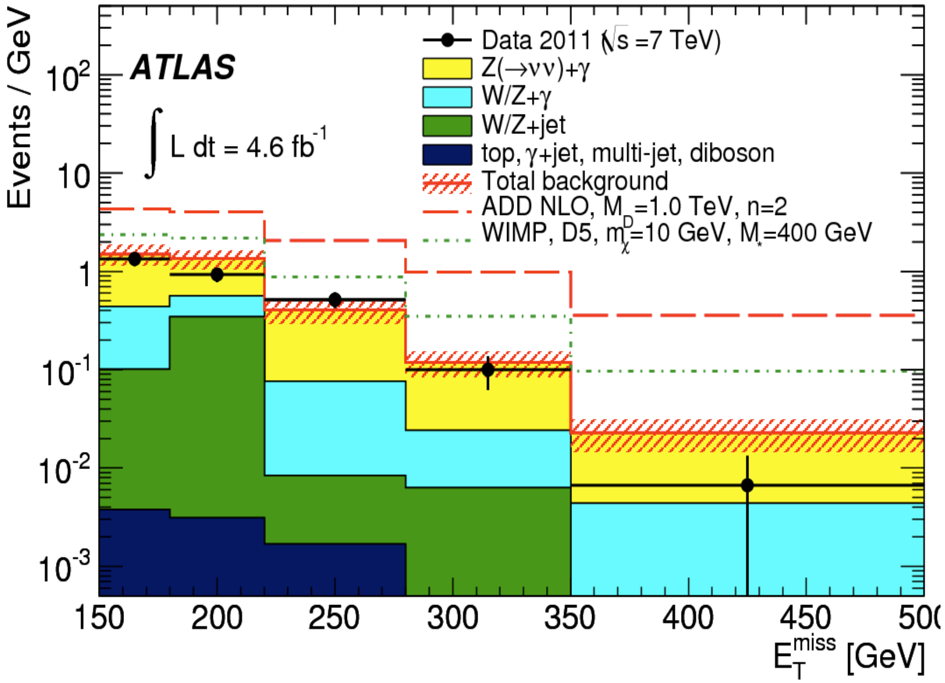
Mono-Photon

- Basic requirements:
  - High p_T photon and large E_{tmiss}
  - Low jet multiplicity, veto leptons
- Main backgrounds:
  - W/Z+γ (from simulation)
  - W/Z+jet, with misID jet (data-driven)
- Complementary to monojet, but the former dominates in rate so most sensitivity comes from monojet.

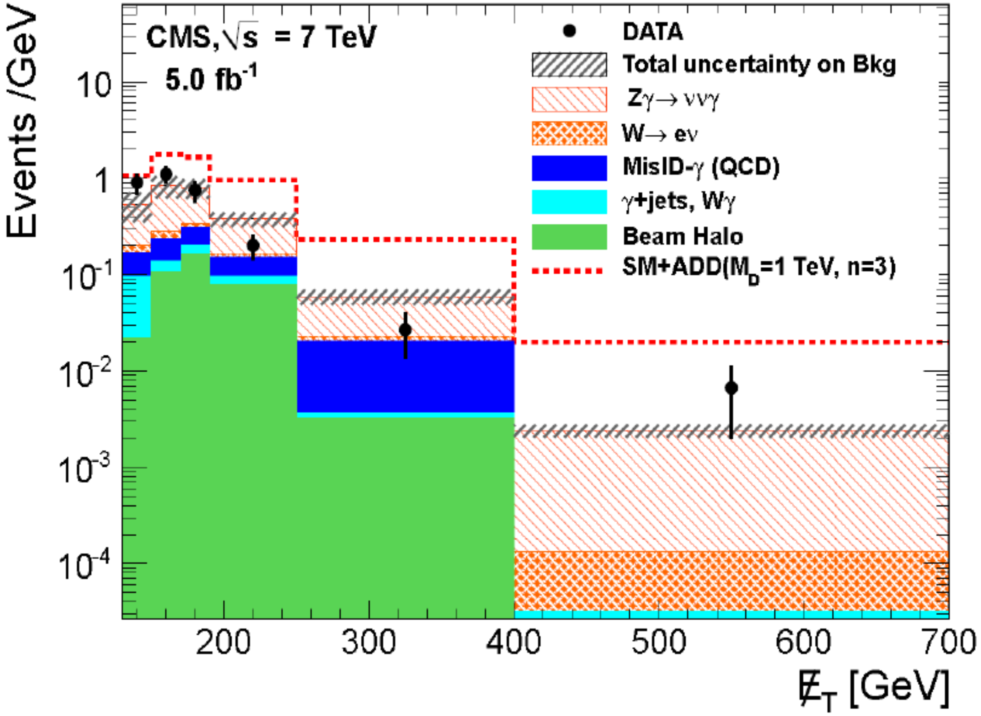


CMS Experiment at LHC, CERN
Data recorded: Sun Apr 24 22:57:52 2011 CDT
Run/Event: 163374 / 314736281
Lumi section: 604

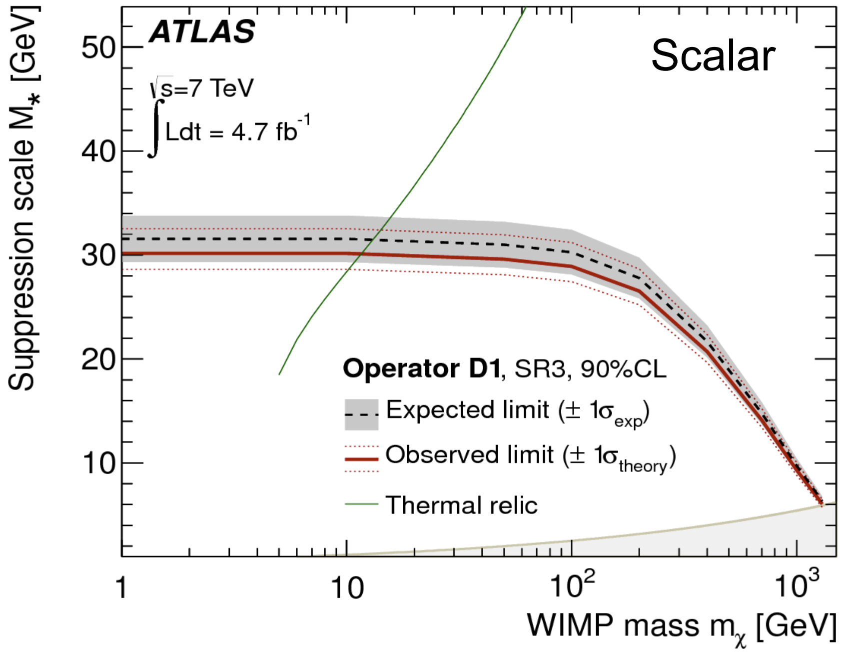
PRL 110, 011802 (2013)

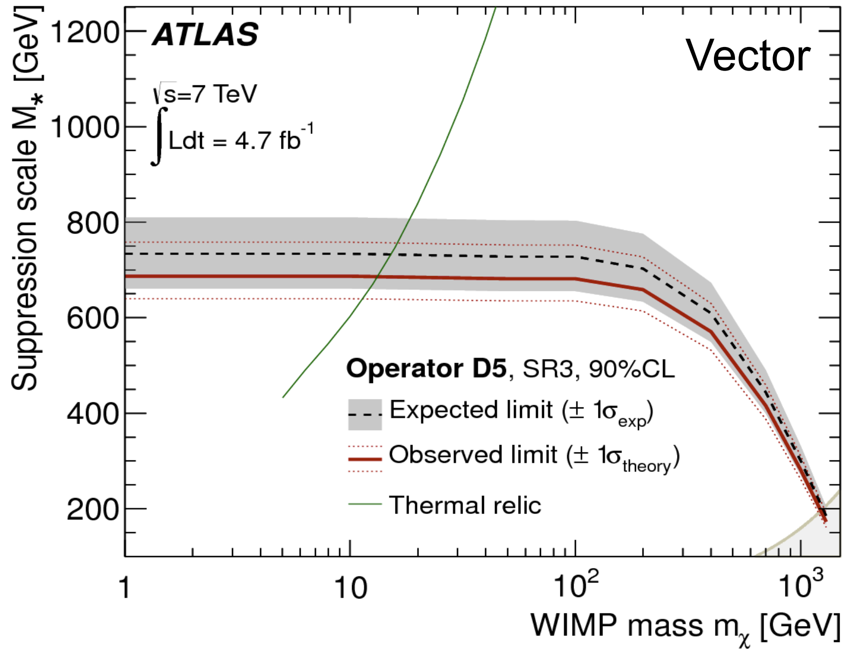


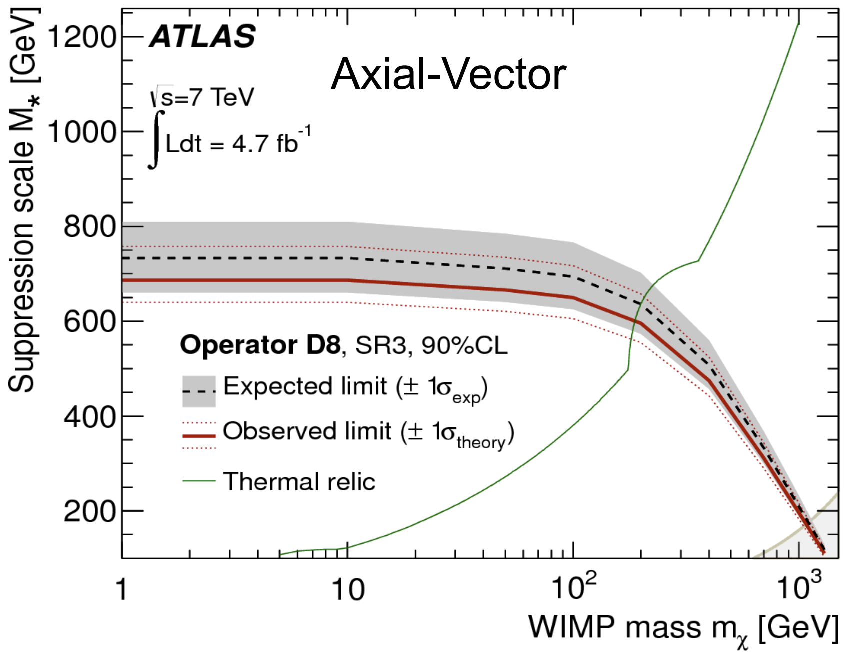
PRL 108, 261803 (2012)



Limits on Suppression Scale



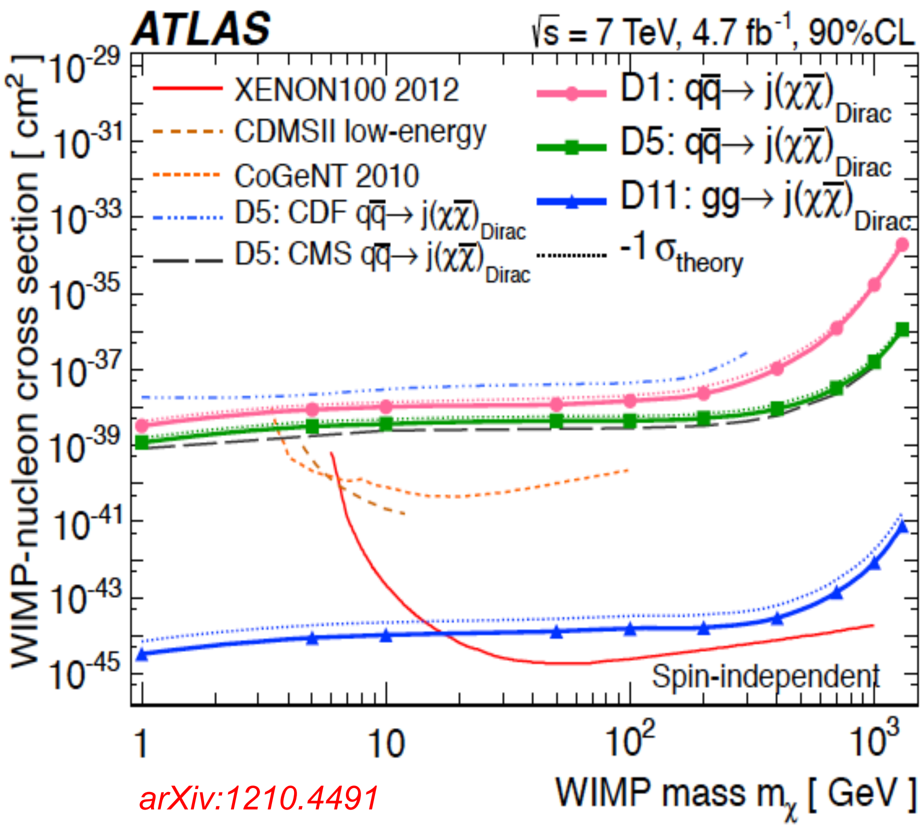




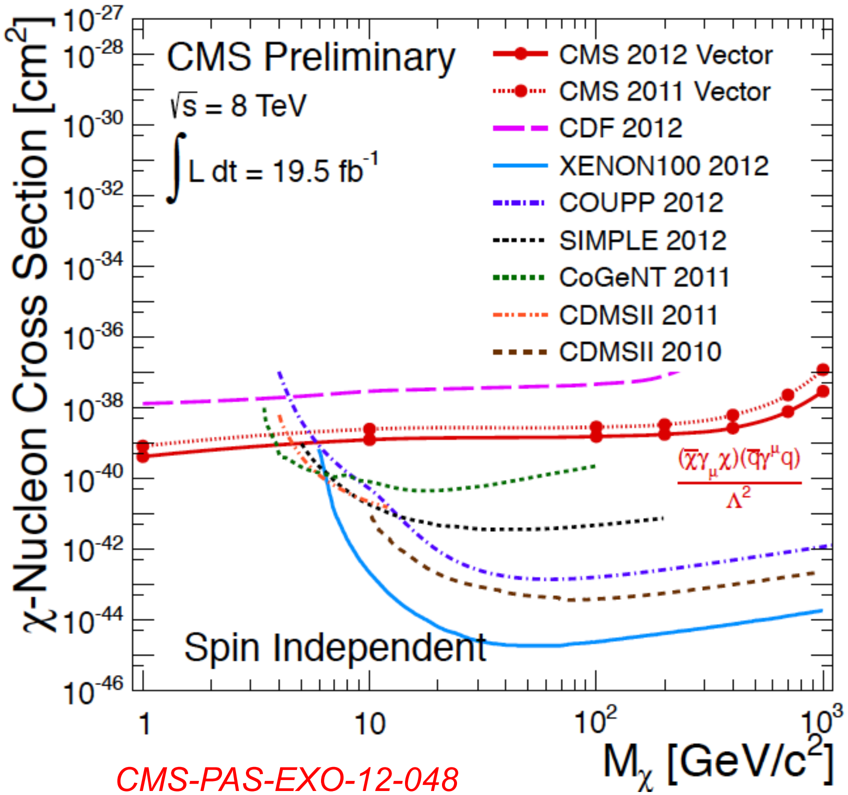
- 90% upper limits on the visible cross section for NP are translated into limits on M_* as a function of WIMP mass for the different operators.
- Note poor sensitivity to scalar coupling (proportional to mass of light quarks).

Limits on WIMP-Nucleon Scattering Cross Section

- Translation to spin-independent bounds on WIMP-nucleon scattering cross section:



arXiv:1210.4491

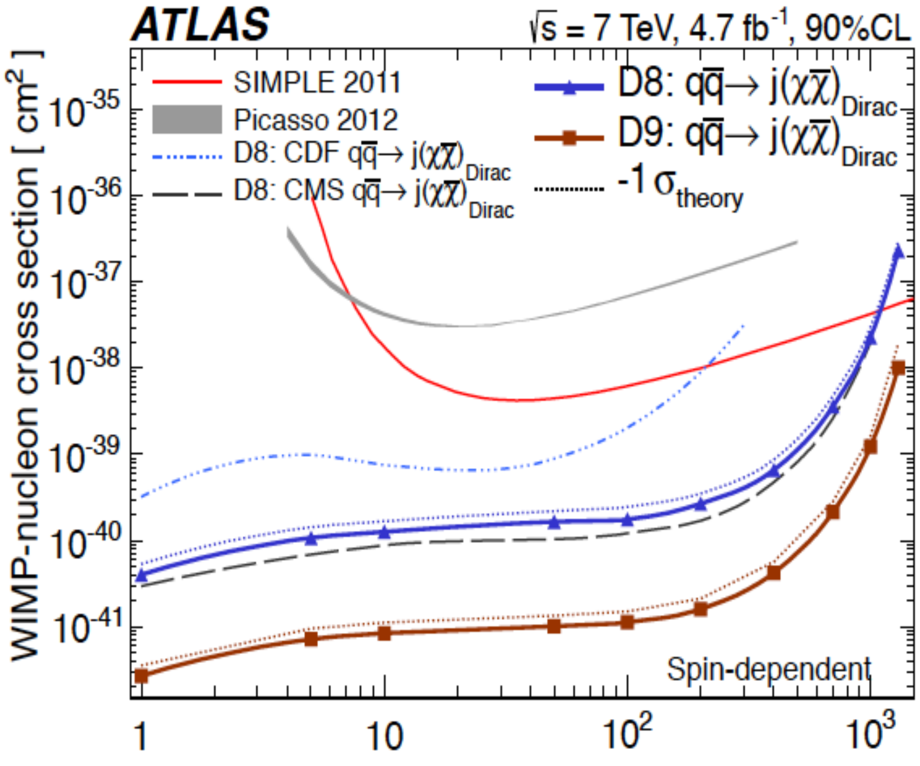


CMS-PAS-EXO-12-048

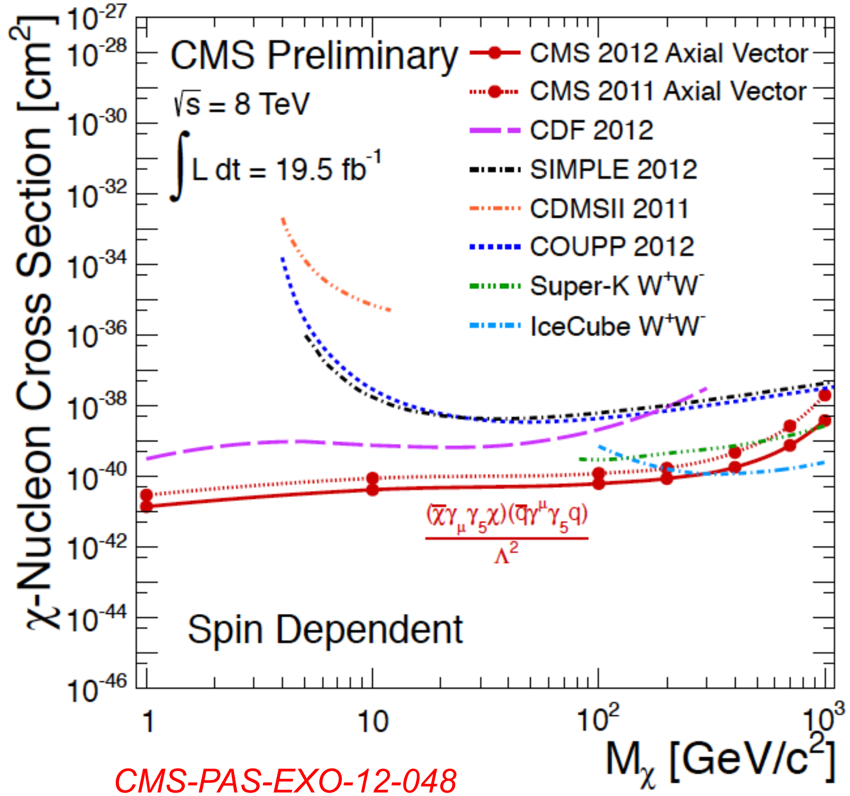
Most sensitive bounds for m_χ~1-6 GeV (in the case of $q\bar{q}$)
and for m_χ~1-17 GeV (in the case of gg)

Limits on WIMP-Nucleon Scattering Cross Section

- Translation to spin-dependent bounds on WIMP-nucleon scattering cross section:



arXiv:1210.4491

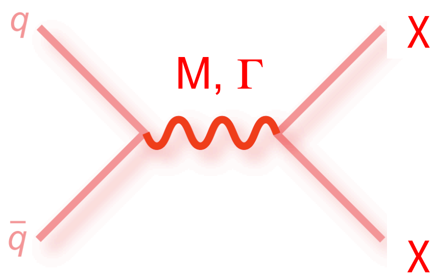


CMS-PAS-EXO-12-048

Most sensitive bounds for m_χ~1-200 GeV

Assuming a Light Mediator

- Exploring the scenario of a vector coupling and a light mediator with mass M and with Γ:

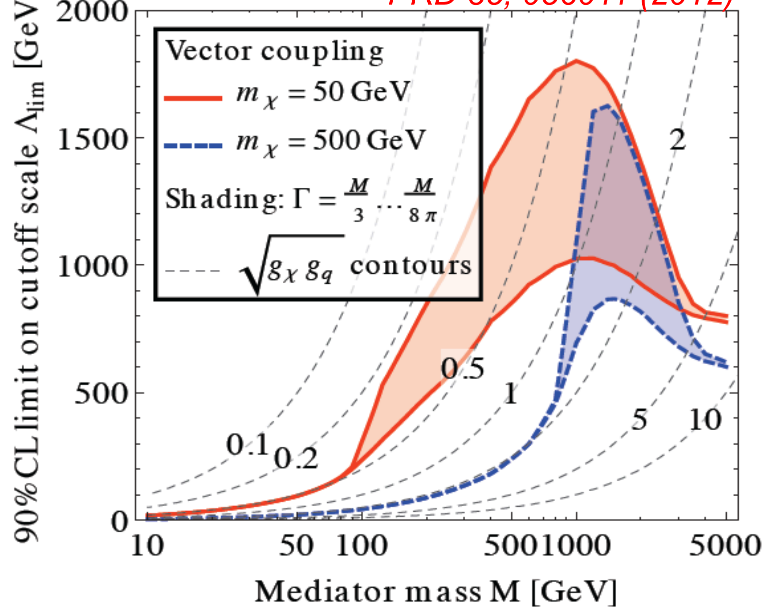


$$\sigma(pp \to \bar{\chi}\chi + X) \sim \frac{g_q^2 g_\chi^2}{(q^2 - M^2)^2 + \Gamma^2/4} E^2$$

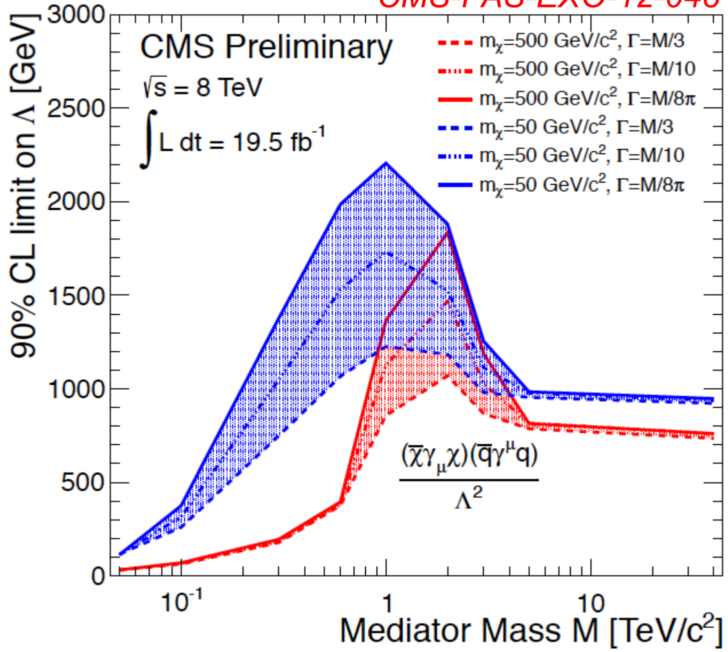
- For M>few x 100 GeV the EFT is adequate and somewhat conservative in the bounds on Λ* (however, note the effective couplings become large).

- For M<100 GeV the actual bounds are much weaker than claimed by the EFT approach.

PRD 85, 056011 (2012)



CMS-PAS-EXO-12-048

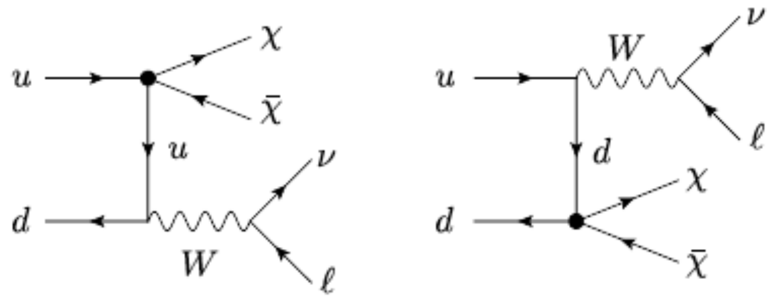


Mono-W/Z

- Motivation: CoGent and DAMA favored regions can be made to overlap assuming isospin-violating dark matter: -0.72<fn/fp<-0.66

  f_n/f_p = ratio of neutron and proton couplings

  In addition, constraint from XENON sufficiently reduced that it can be consistent with these signals.
- Mono-W/Z production at the LHC provides information on the couplings to u- and d-quarks, as well as on their relative sign.

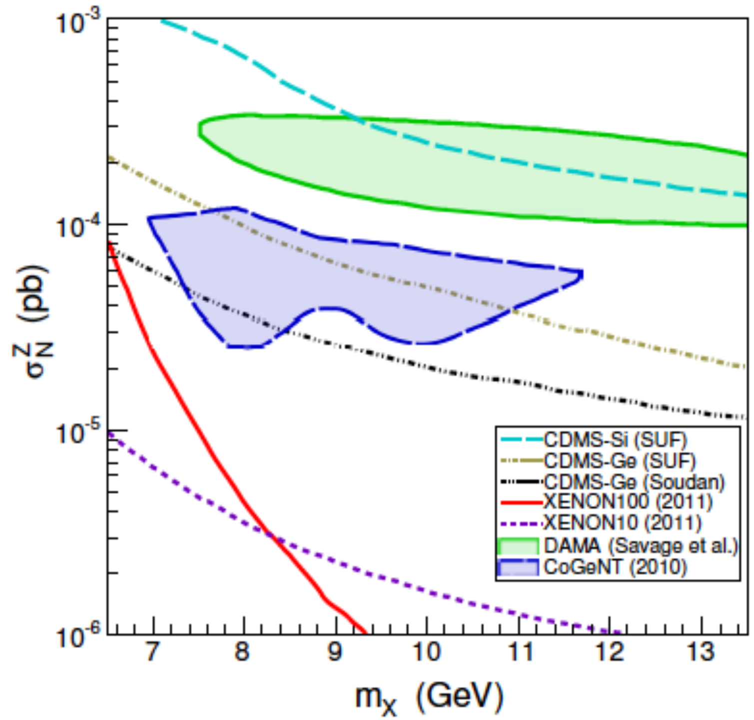


V: $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi \quad (\bar{u}\gamma^\mu u + \xi \bar{d}\gamma_\mu d)$

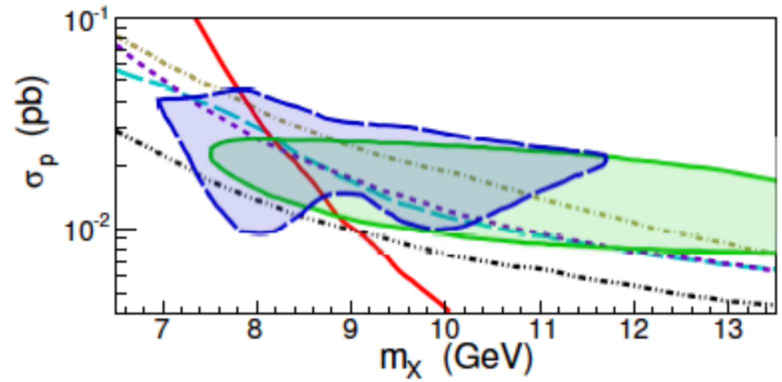
AV: $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi \quad (\bar{u}\gamma^\mu\gamma_5 u + \xi \bar{d}\gamma^\mu\gamma_5 d)$

- Large enhancement in production cross section for ξ=-1 (constructive interference).
- Signatures probed: mono-lepton, mono-hadronic W/Z

arXiv:1102.4331



$f_n/f_p = -0.7$

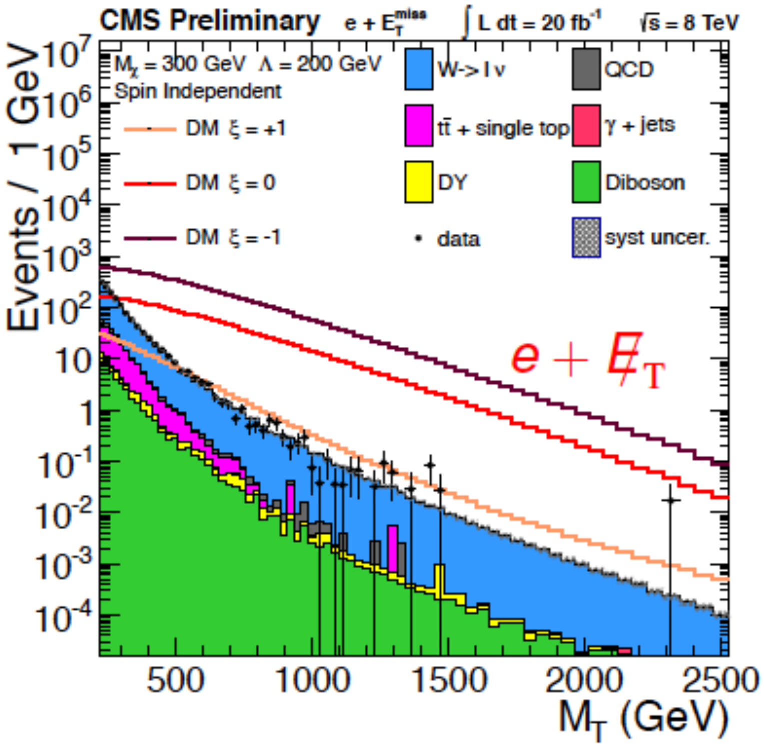


Mono-W/Z

Mono-lepton

- Signature:
  - High p_T e or μ and
  - High E_{Tmiss} (back-to-back with lepton)
- Main backgrounds: W+jets, tt, diboson
- Analyze tail of transverse mass distribution

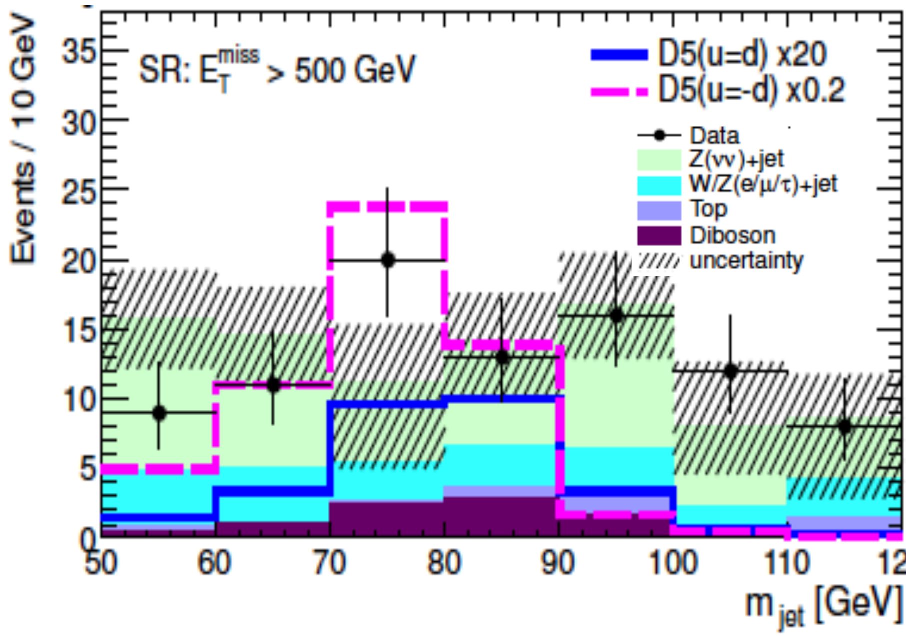
CMS-PAS-EXO-13-004



Mono-hadronic W/Z

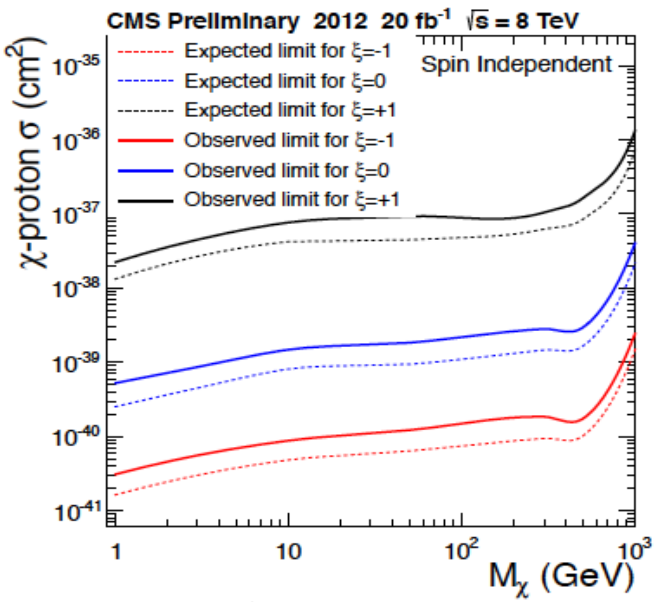
- Signature:
  - High p_T fat jet (Cambridge-Aachen) encompassing W decay products
  - Balanced leading subjets
- Main backgrounds: W/Z+jets
- Analyze jet mass distribution in range 50-120 GeV.

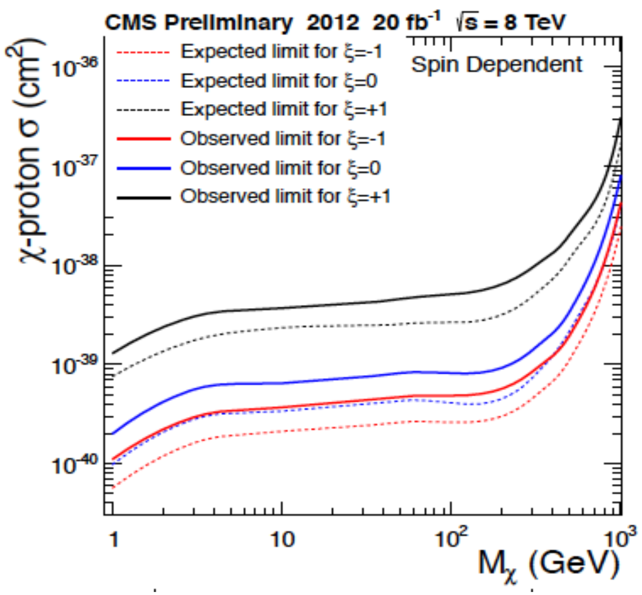
arXiv:1309.4017



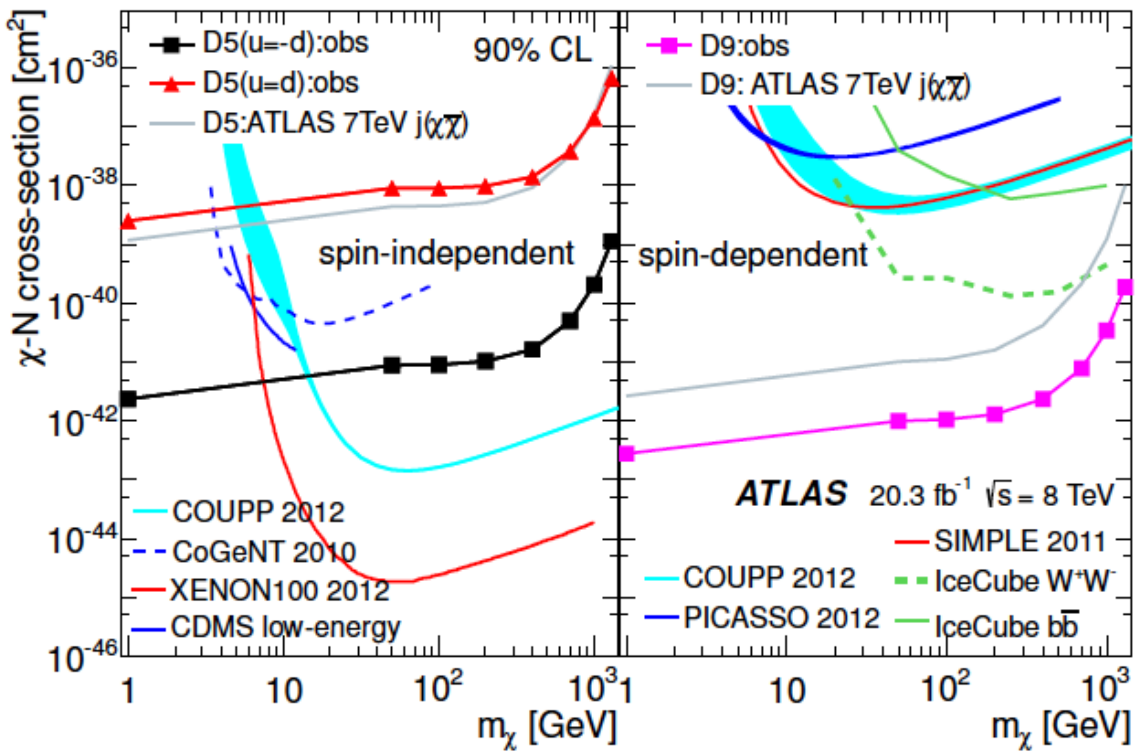
Mono-W/Z: Results

Mono-lepton



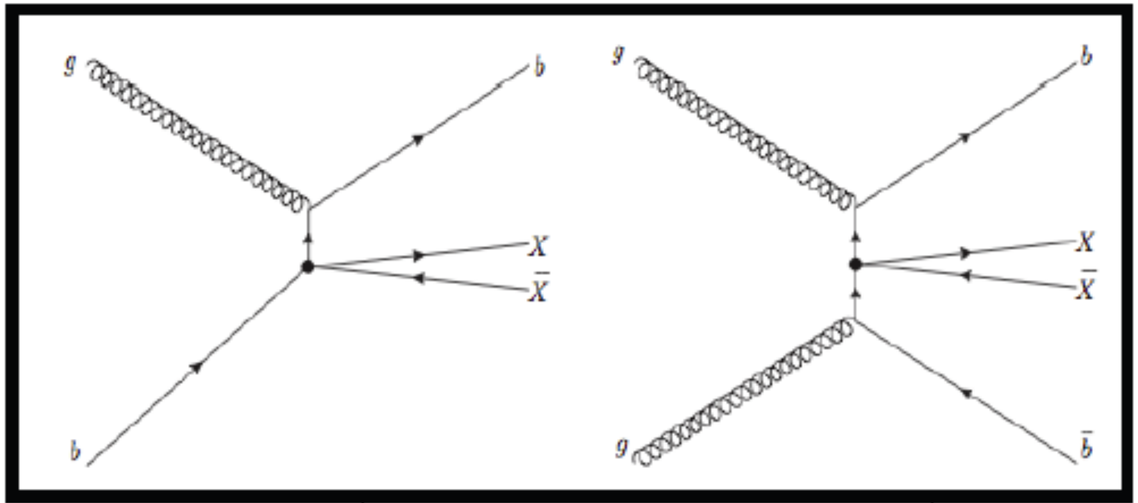


Mono-hadronic W/Z

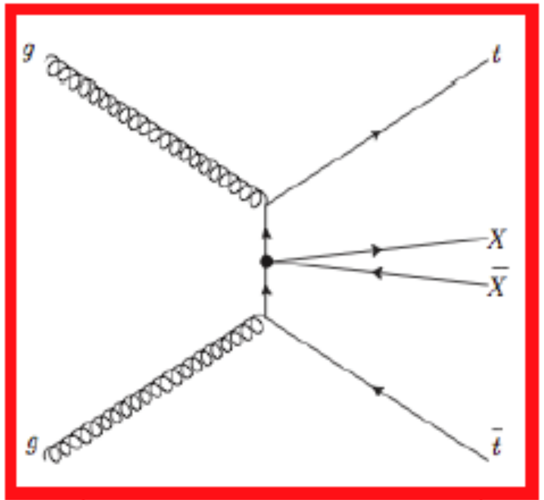


- Mono-hadronic W/Z has ~x10 better sensitivity than mono-lepton.
- Large increase in sensitivity in the case of constructive interference makes mono-hadronic W/Z to exceed monojet sensitivity.

Couplings to Heavy-Flavor



Direct b production:
Smaller contribution to x-section



$t\bar{t}$ channel:
dominant contribution

- Sensitivity to scalar interaction between DM and quarks can be boosted by focusing on final states with a heavy quark produced at the LHC.

$$\mathcal{O} = \frac{m_q}{M_*^3}\bar{q}q\bar{X}X$$

- Requirement of b-tagged jet also helps to reduce background.

arXiv:1303.6638

	Process	Monojet	b-tag on j_1
Background	Z+jets(fake)	406 fb	7 fb
	Z+b+jet	6.7 fb	3 fb
	W+jets,W+b	95 fb	2 fb
	$t\bar{t}$+jets	16 fb	6 fb
Signal	$\bar{X}X$+jets	11 fb	0.7 fb
	$\bar{X}X+b$+jets	65 fb	33 fb
	$\bar{X}X+t\bar{t}$	244 fb	113 fb

$\varepsilon_{\text{back}} \sim 2\%$

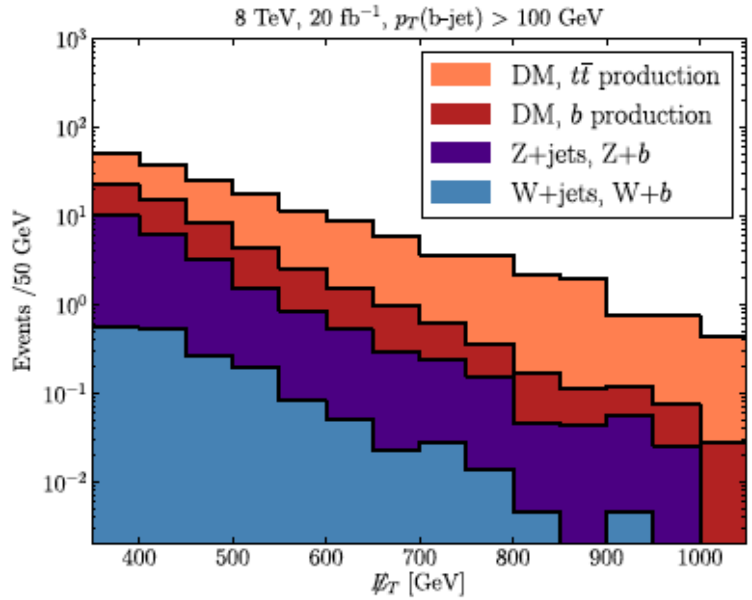
$\varepsilon_{\text{signal}} \sim 50\%$

Expected signal (M_*=50GeV, m_χ =10GeV) and background at 8 TeV
Basic cuts applied: E_T^{miss}>350 GeV, p_T^{lead}>100 GeV

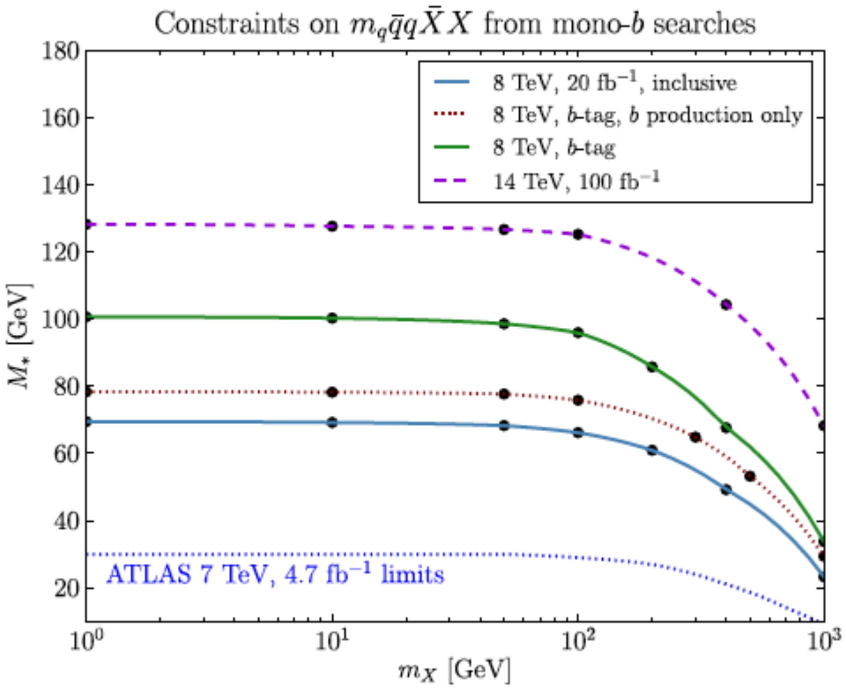
Example: Mono-B

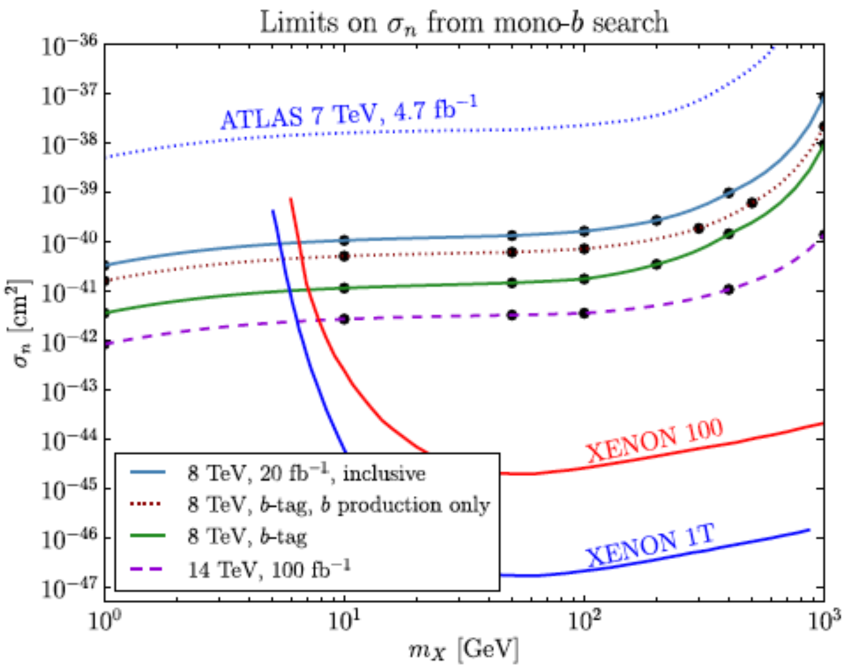
- Signature:
  Large E_{Tmiss} recoiling against energetic b jet(s)
  Lepton veto to suppress W+jet and Z+jet, SM tt backgrounds
- Signal contribution dominated by tt channel.
- Constraints on WIMP-nucleon cross section:

$$\sigma_n = \frac{(0.38 m_n)^2 \mu_{\chi n}^2}{\pi M_*^6} \approx 2 \times 10^{-38} \mathrm{cm}^2 \left(\frac{30\ \mathrm{GeV}}{M_*} \right)^6$$



arXiv:1303.6638

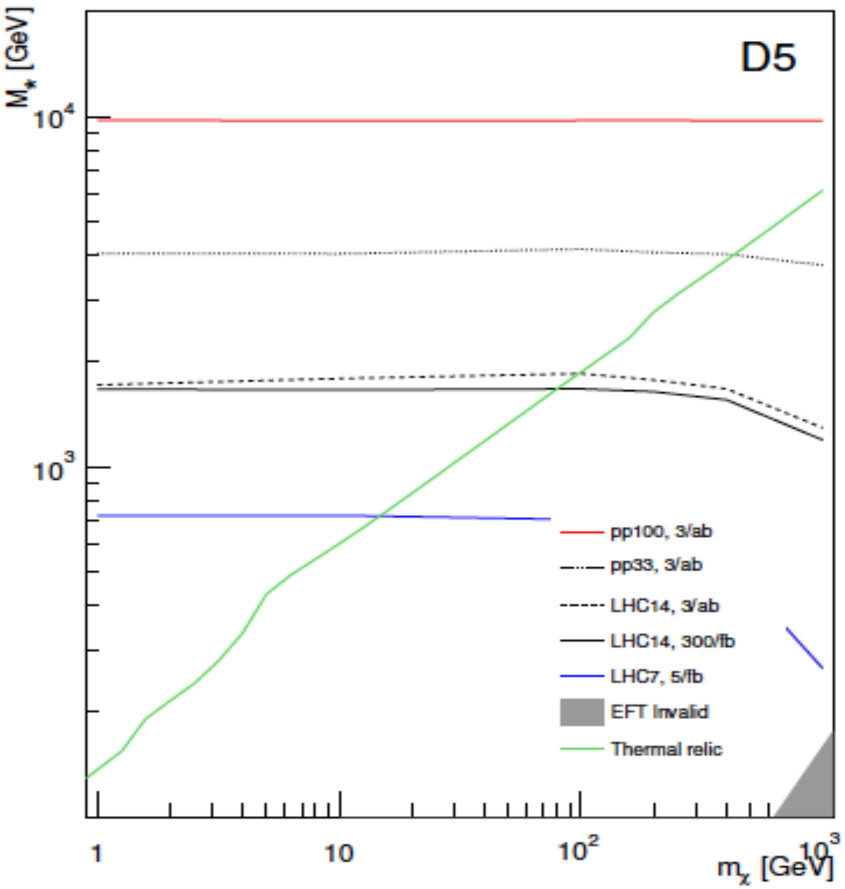


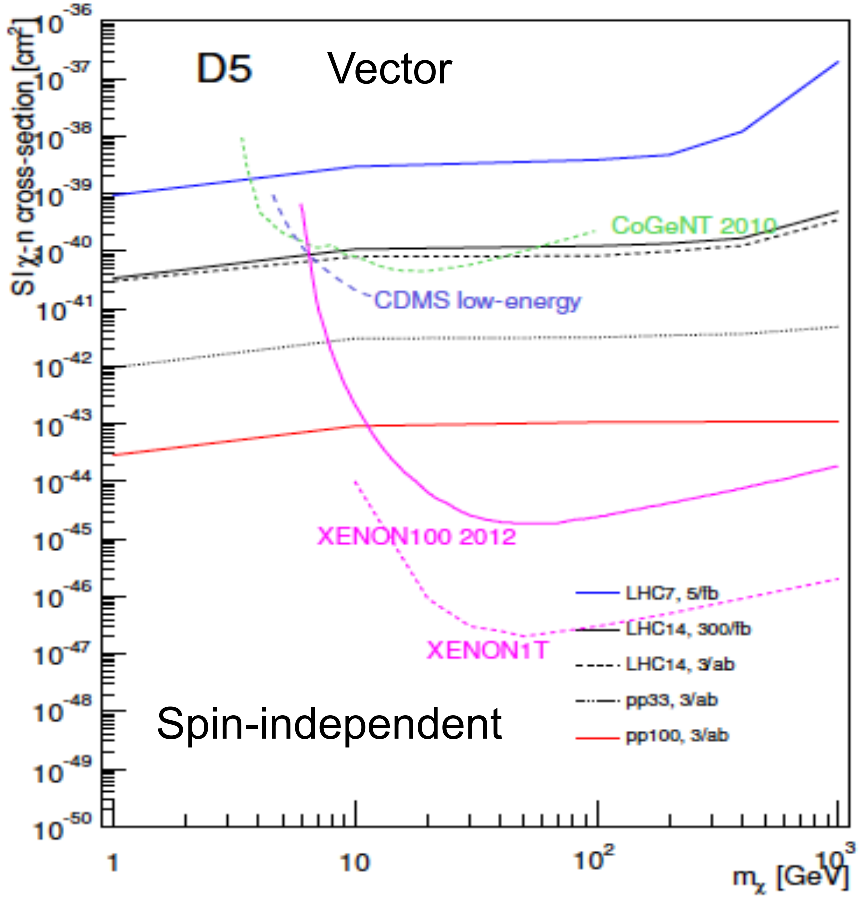


LHC Projections

- Projections performed for monojet and mono-b searches under the assumption that the EFT is valid (heavy mediator).

arXiv:1307.5327





- Significant improvement from LHC 7 TeV. 5 fb^{-1} to LHC 14 TeV. 300 fb^{-1}.
  No real improvement from HL-LHC. Much better to go to higher energy.

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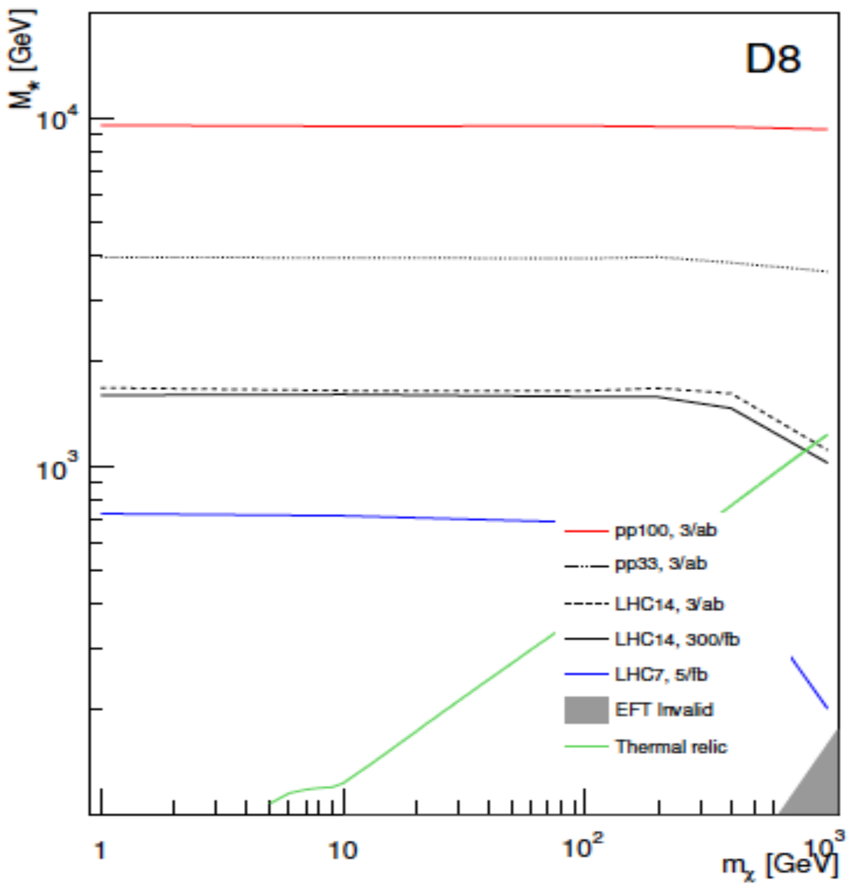

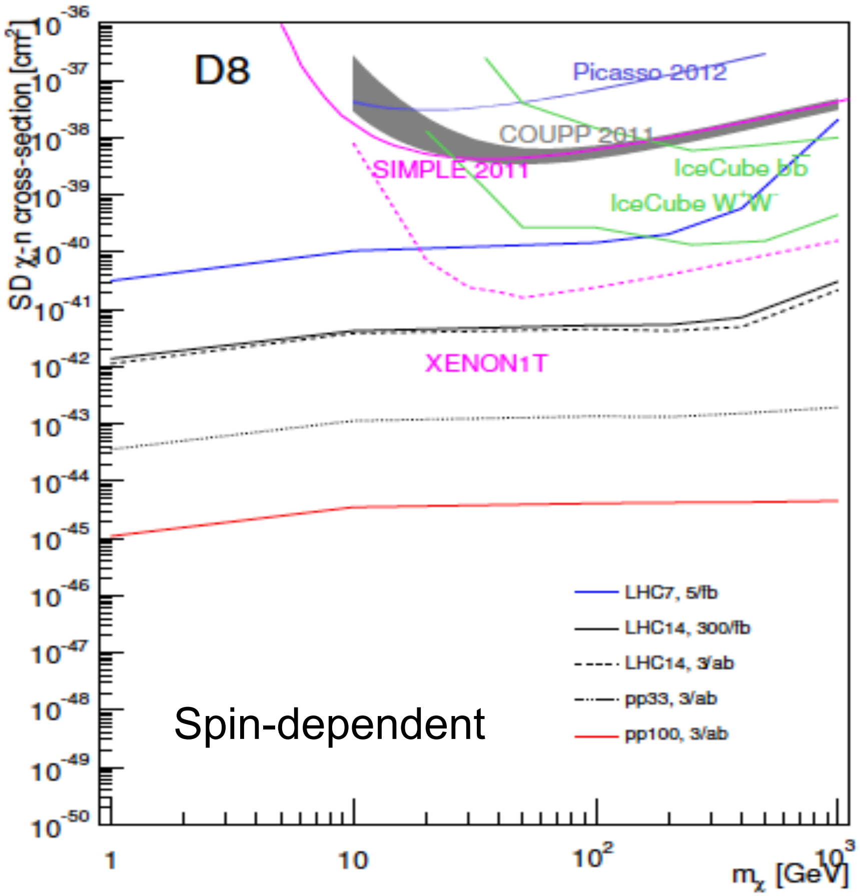

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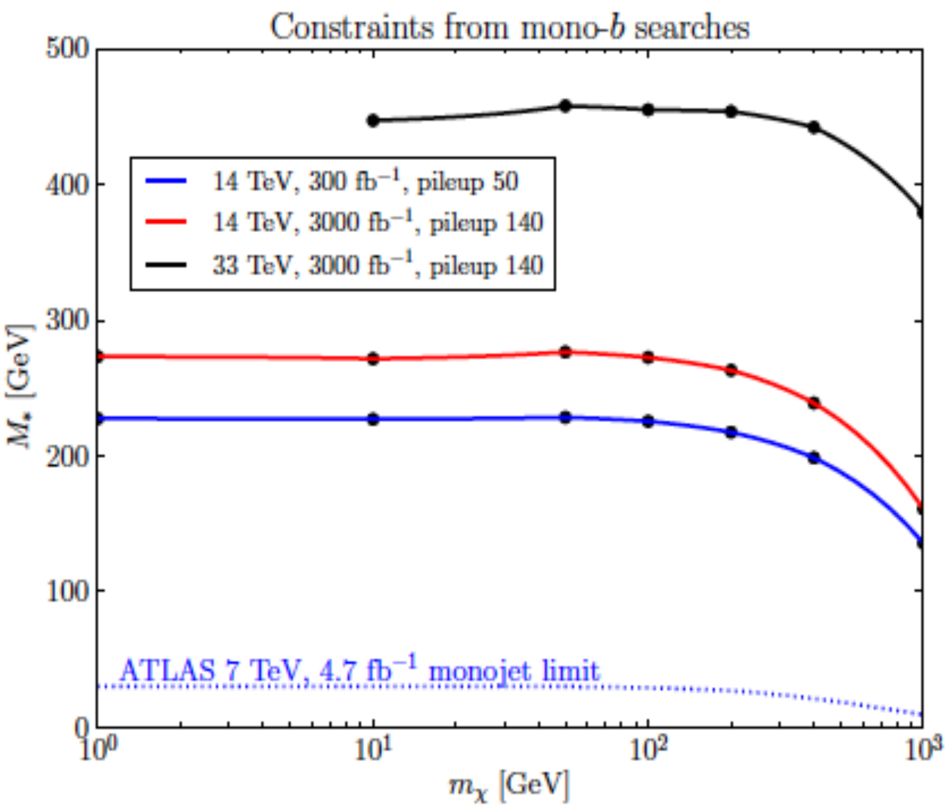
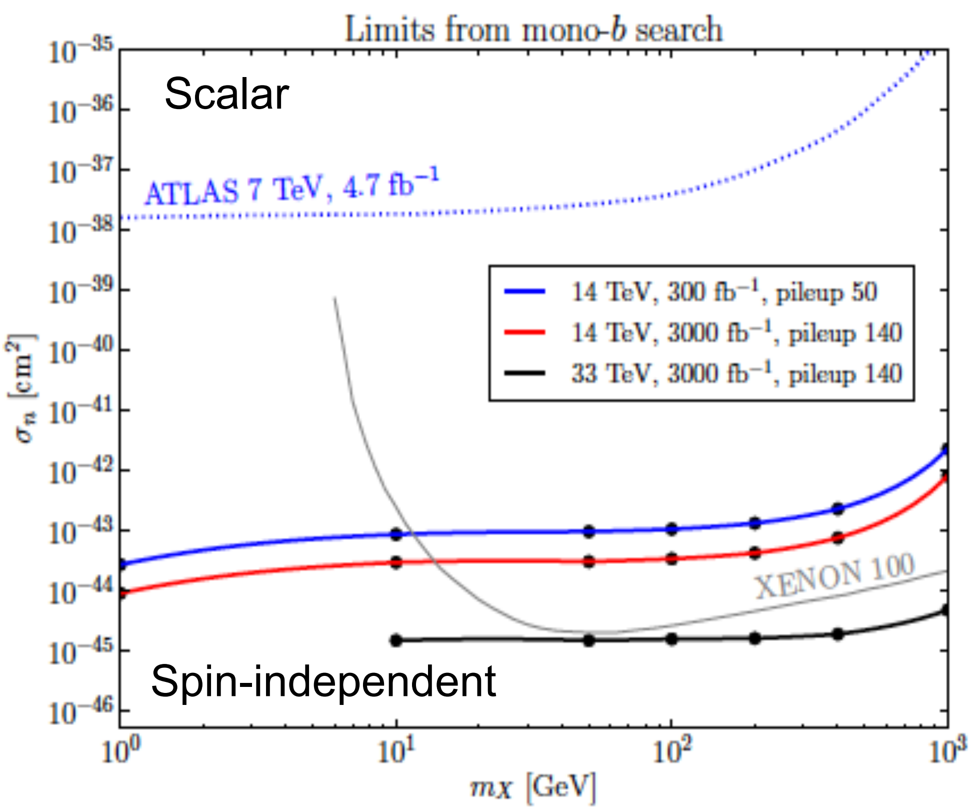
arXiv:1307.7834

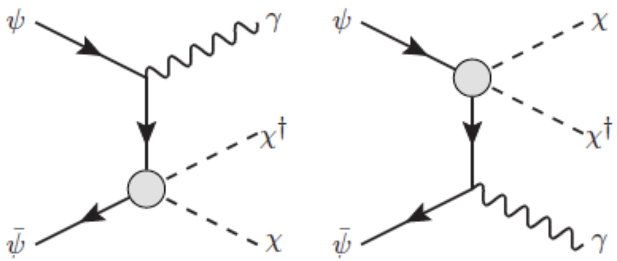




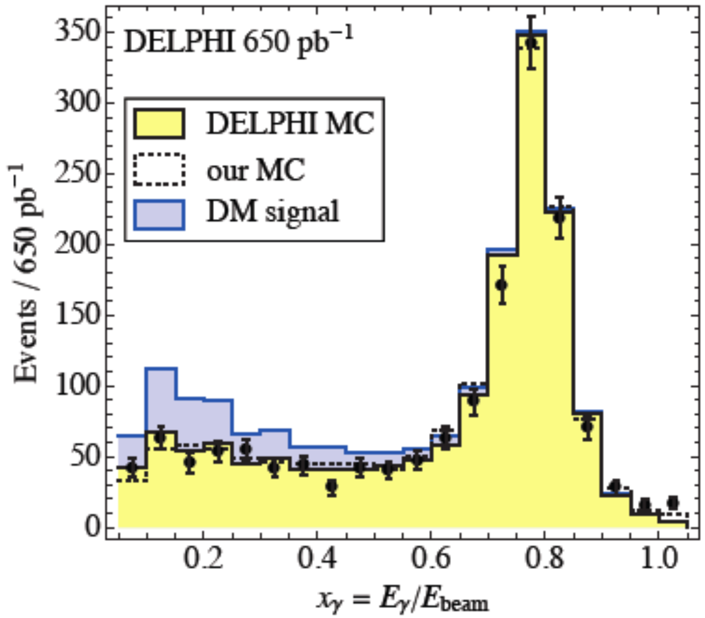
- Significant improvement from LHC 7 TeV. 5 fb^{-1} to LHC 14 TeV. 300 fb^{-1}.
  No real improvement from HL-LHC. Much better to go to higher energy.

Searches at e^+e^- Colliders

- Searches for dark matter in monophoton final state.

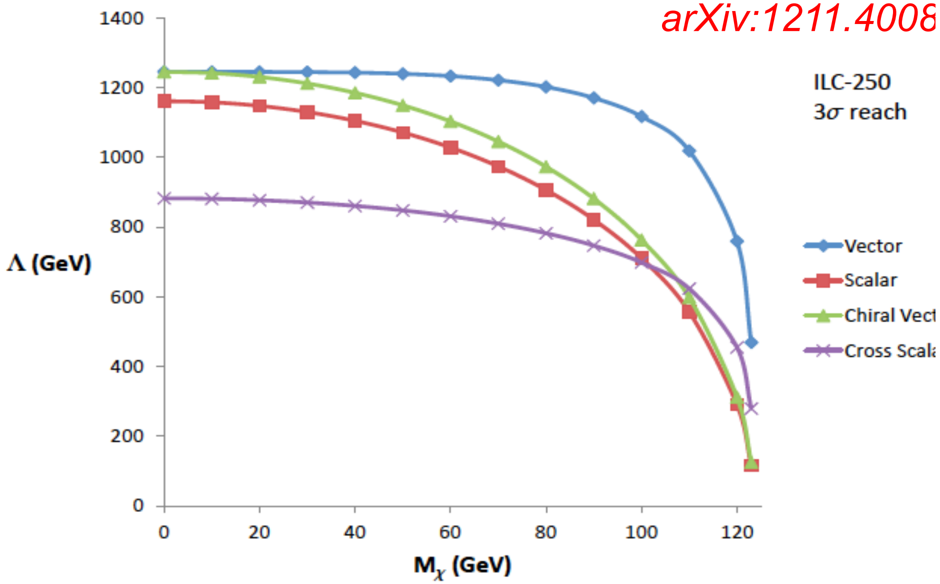


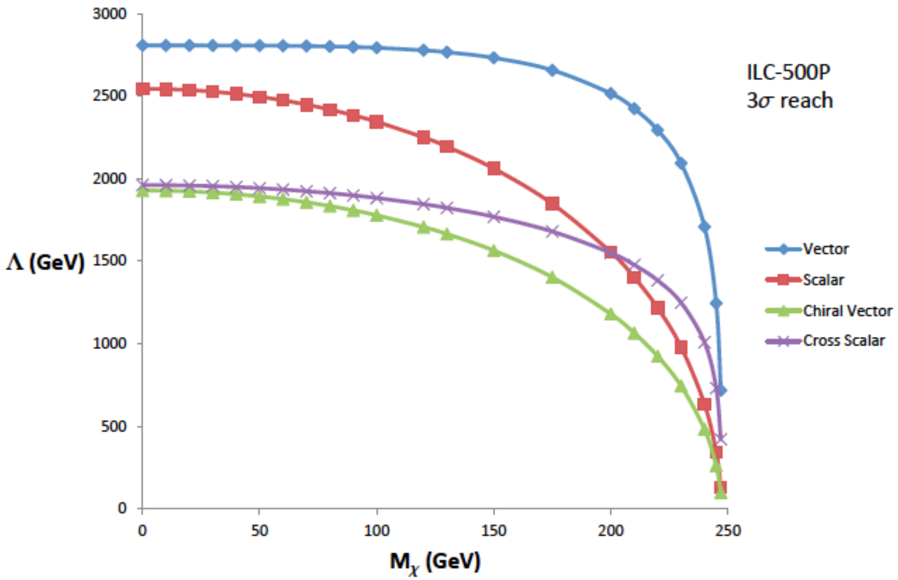
Vector, m_χ=10 GeV, Λ^*= 300 GeV



- In terms of the scale, the accessible regions are approximately independent of the M_χ, until the kinematic reach of the collider ($M_\chi \sim \sqrt{s}/2$) is reached.
- Higher energies and beam polarization important.

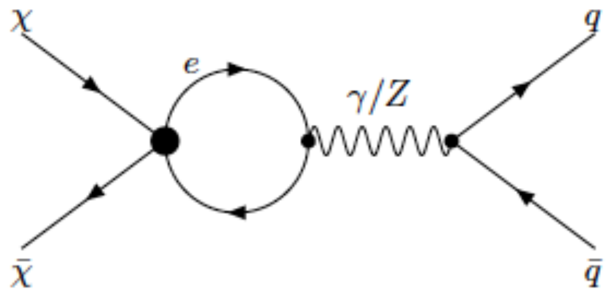
arXiv:1211.4008



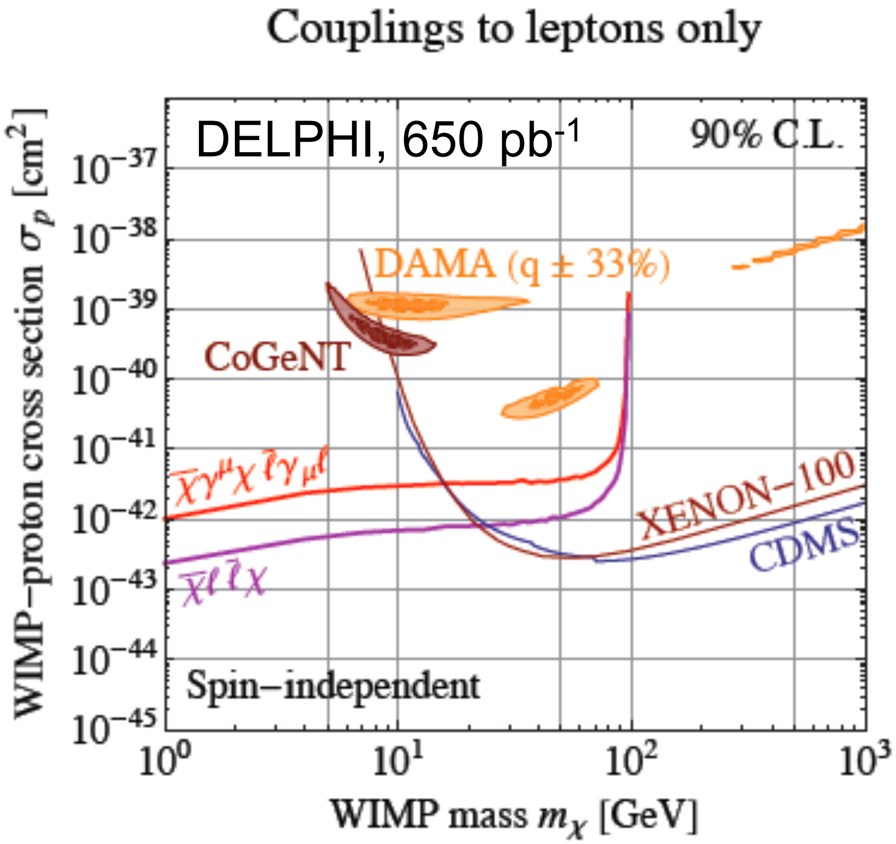


Searches at e⁺e⁻ Colliders

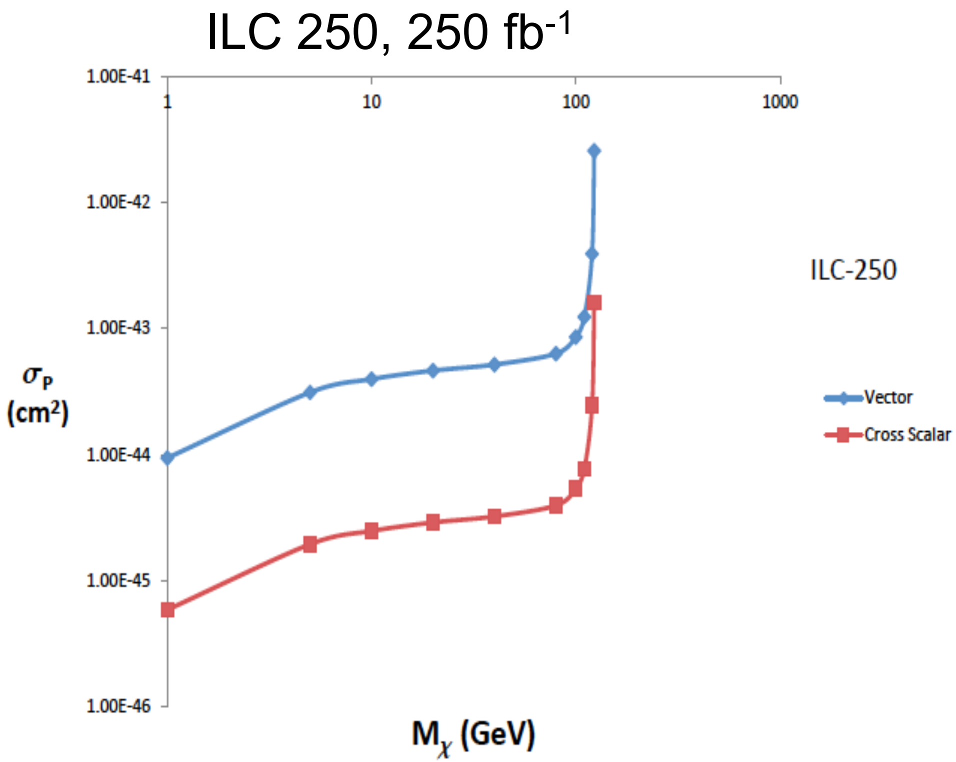
- Dramatic increase in sensitivity compared to direct searches in case of leptophilic DM couplings
  ➔ loop-induced couplings to quarks.



arXiv:1103.0240



arXiv:1211.4008



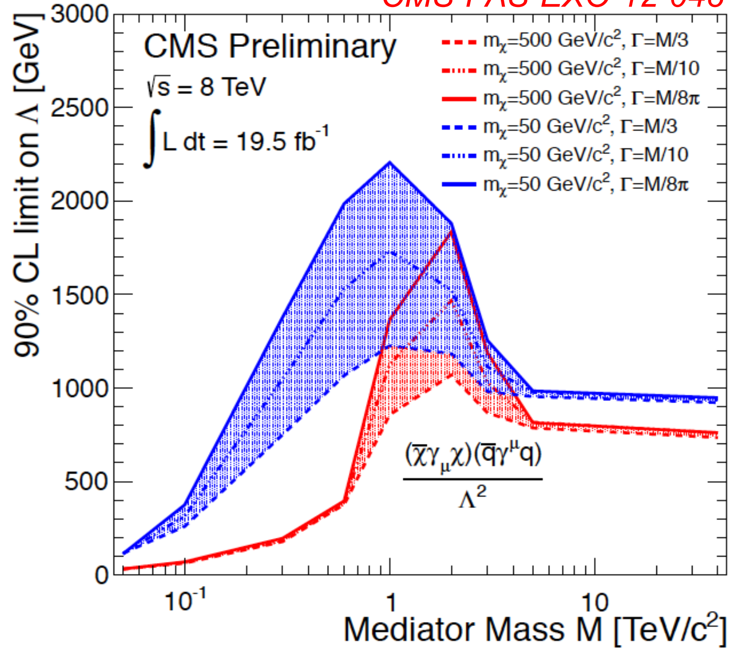
Searching for the Mediator

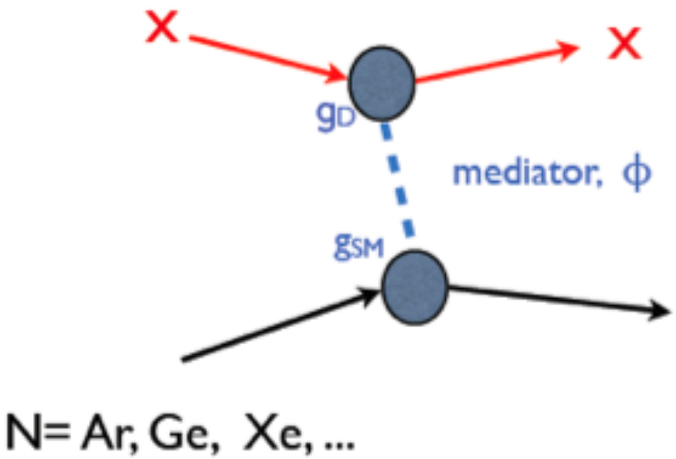
Searching for the Mediator

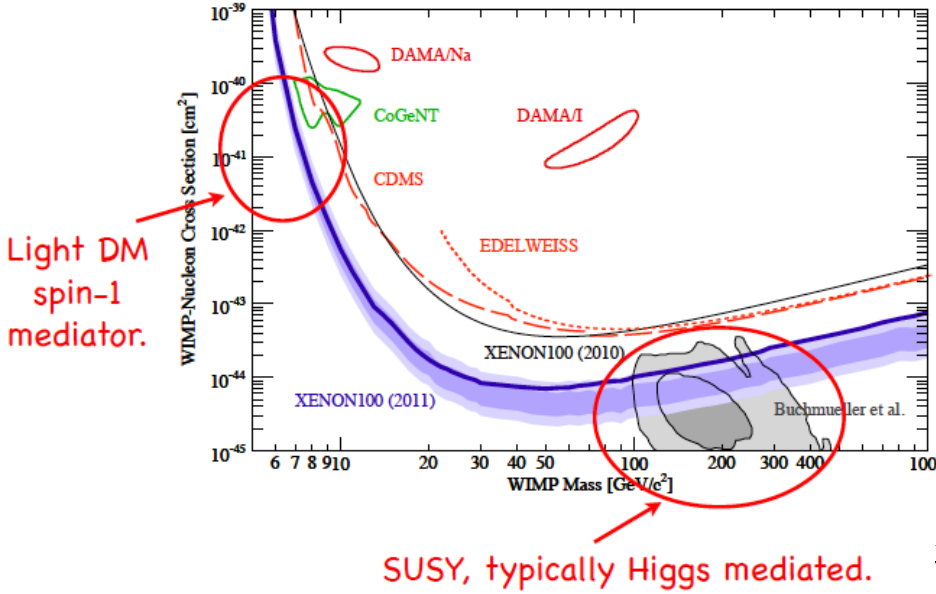
- For energies larger than the mediator mass, probing more structure of the s-matrix
  - ➔ Depending on more details of the mediator.
  - ➔ However, in that case the mediator itself can be searched directly!

- Two typical examples of mediator Φ:
  - Φ = Higgs (spin 0)
    - $M_\Phi \sim 100$ GeV
    - $g_{SM} \sim (100\ \mathrm{MeV})/(100\ \mathrm{GeV})$
    - $\sigma_n \sim 10^{-43}\text{-}10^{-45}\ \mathrm{cm}^{-2}$
  - Φ = Z' (spin 1)
    - $\sigma_n \sim 10^{-36}\text{-}10^{-39}\ \mathrm{cm}^{-2}$

CMS-PAS-EXO-12-048







Higgs Mediator

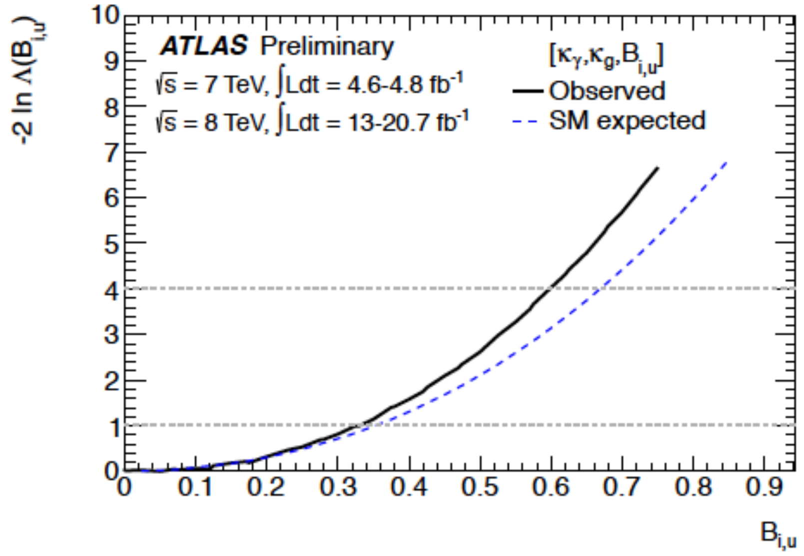
- Constraints on the invisible Higgs rate at the LHC can be translated into limits in the WIMP-nucleon cross section and compared with direct-detection experiments.

$$\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2 \,,$$
$$\Delta\mathcal{L}_V = \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu,$$
$$\Delta\mathcal{L}_f = -\frac{1}{2}m_f f f - \frac{1}{4}\frac{\lambda_{hff}}{\Lambda} H^\dagger H f f + \text{h.c.}\,. \qquad (5)$$

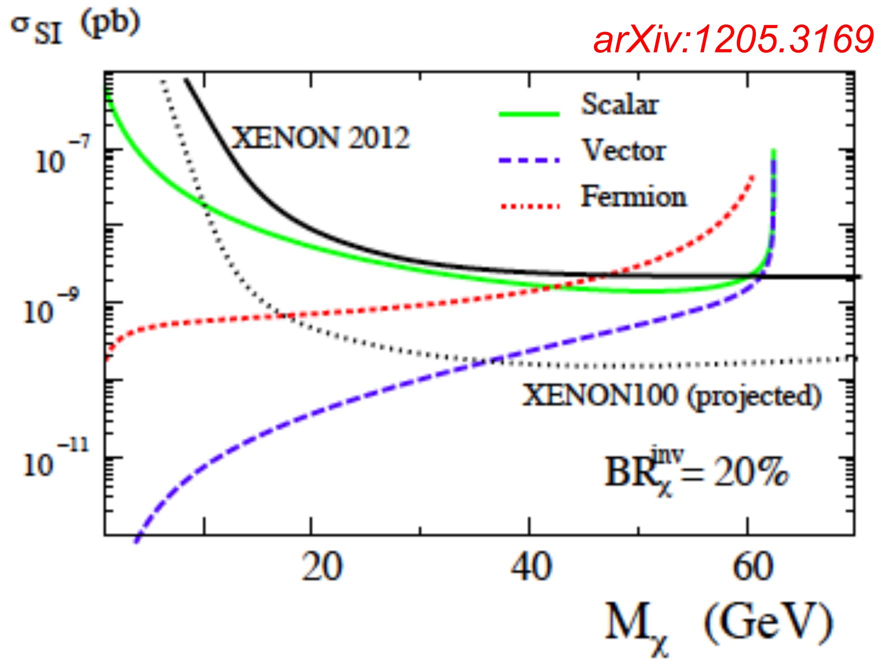
$$\mathrm{BR}_\chi^{\mathrm{inv}} \equiv \frac{\Gamma(H\to\chi\chi)}{\Gamma_H^{\mathrm{SM}} + \Gamma(H\to\chi\chi)} = \frac{\sigma_{\chi p}^{\mathrm{SI}}}{\Gamma_H^{\mathrm{SM}}/r_\chi + \sigma_{\chi p}^{\mathrm{SI}}}$$

r_χ=function of M_χ and known masses and couplings (assuming M_H=125 GeV)

ATLAS-CONF-2013-034

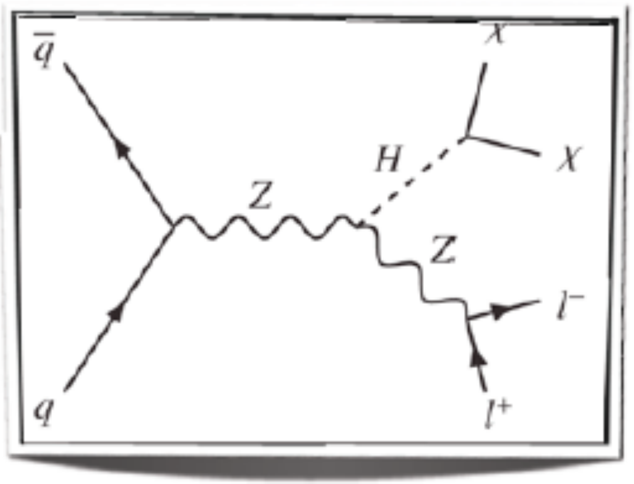


arXiv:1205.3169

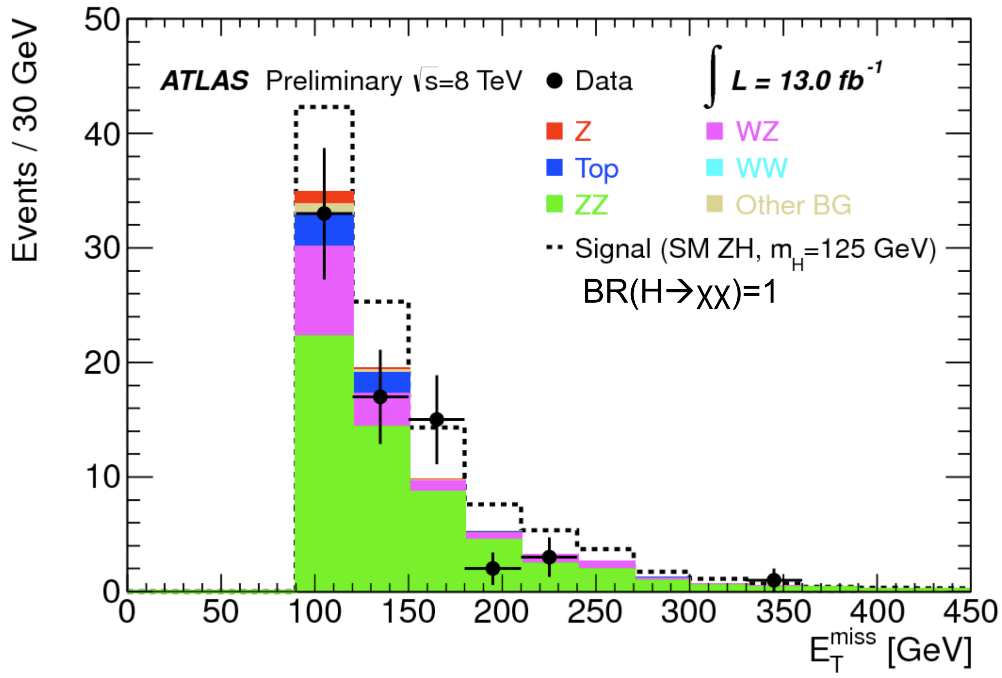


Direct Searches for H→invisible

- LEP excluded invisibly decaying Higgs boson for m_H < 114.4 GeV assuming it is produced in association with Z and that it decays predominantly to invisible particles.
- At the LHC can search for a narrow scalar boson decaying to invisible particles over a mass range between 115 and 300 GeV.



ATLAS-CONF-2013-011



Signature:

- Z→ee/μμ candidate
- Large E_{tmiss} back-to-back

Main backgrounds:

- WZ, ZZ production

Direct Searches for H→invisible

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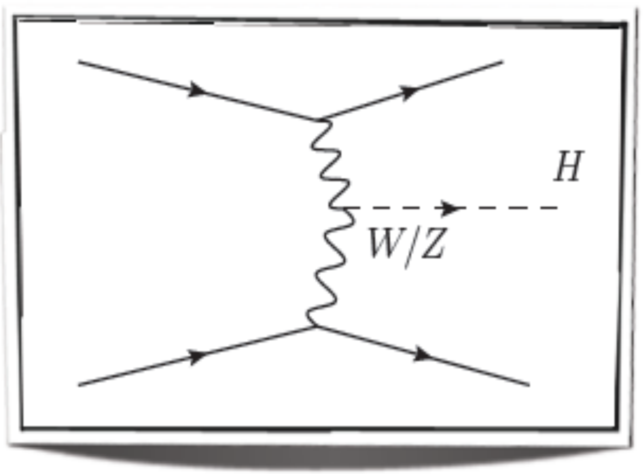
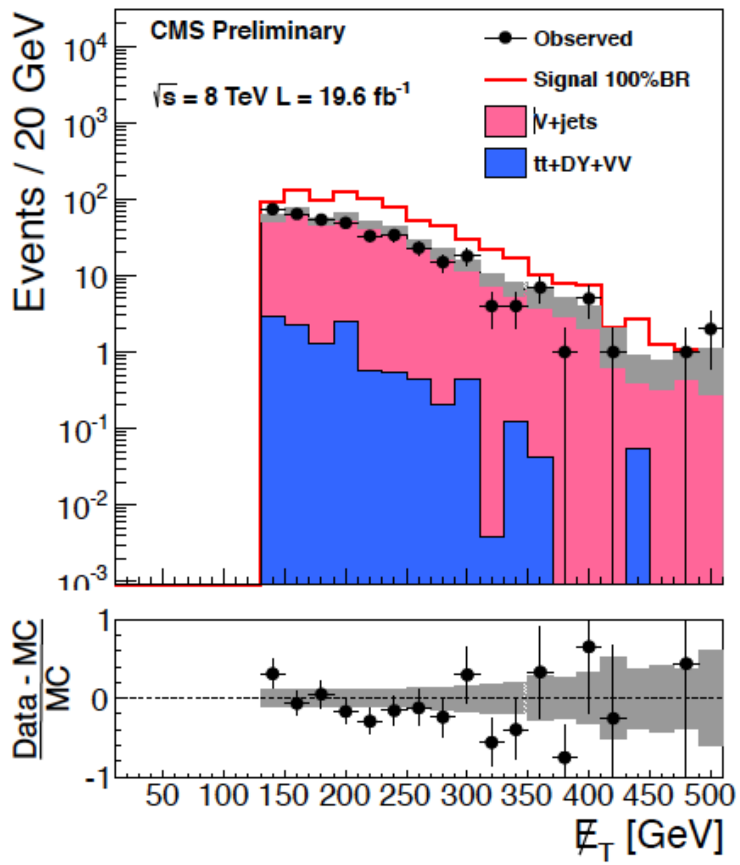


CMS-PAS-HIG-13-013



Signature:

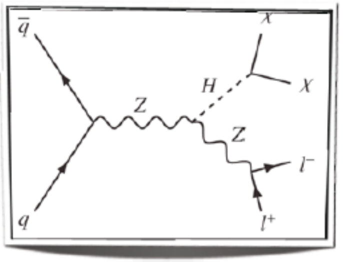
- Two jets separated by larger rapidity gap and high dijet mass.
- Large E_{Tmiss}

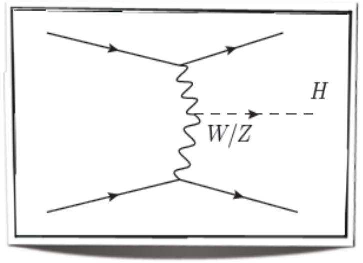
Main backgrounds:

- WZ, ZZ production

Direct Searches for H→invisible

- Upper limits on production cross section times BR(H→inv) are set as a function of M_H.
- Assuming the SM cross section prediction for M_H=125 GeV, upper limits on BR(H→inv) are obtained.





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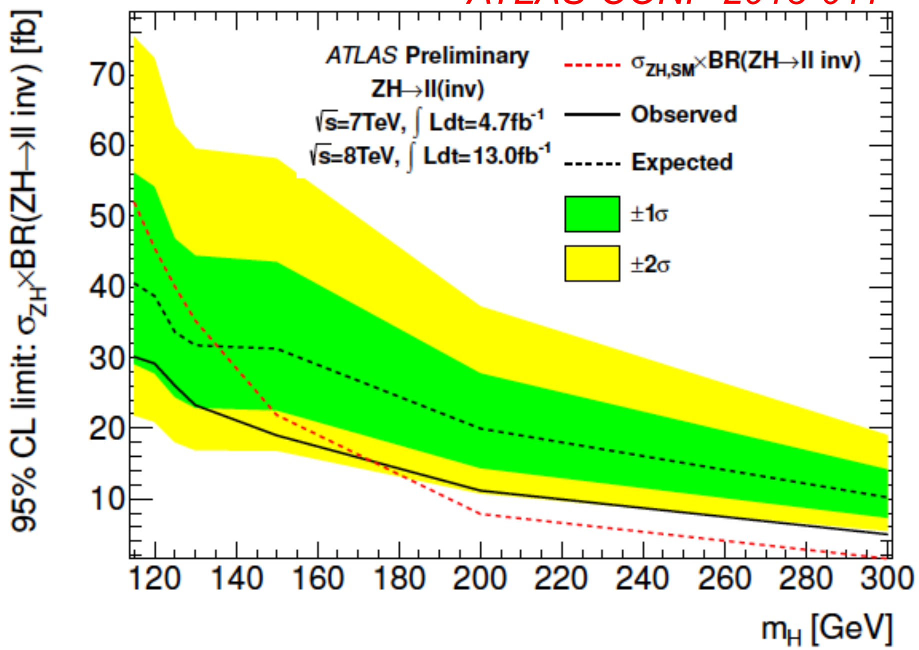
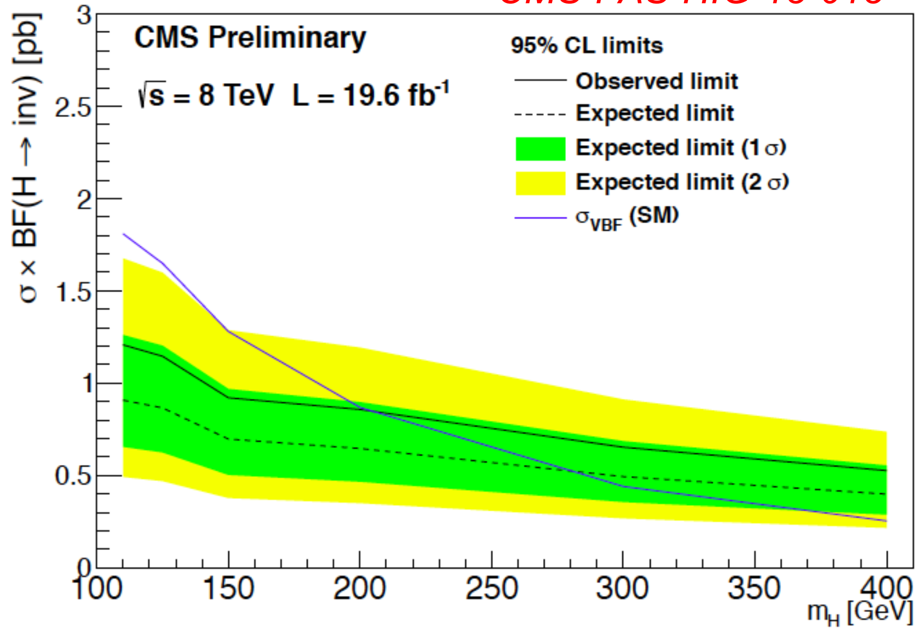


CMS-PAS-HIG-13-013

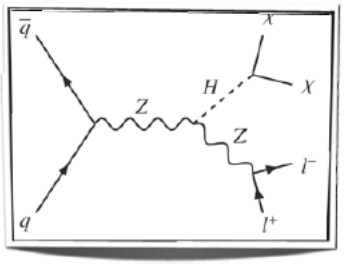


BR(H→inv)<65%(84% expected) @ 95% CL

BR(H→inv)<69%(53% expected) @ 95% CL

Direct Searches for H→invisible: Prospects

- Upper limits on production cross section times BR(H→inv) are set as a function of M_H.
- Assuming the SM cross section prediction for M_H=125 GeV, upper limits on BR(H→inv) are obtained.



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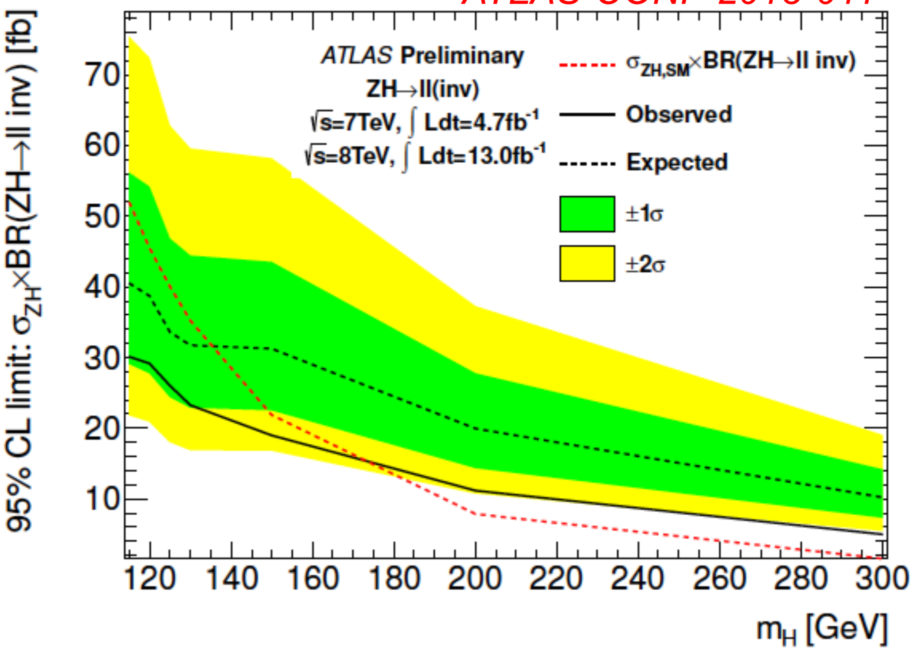
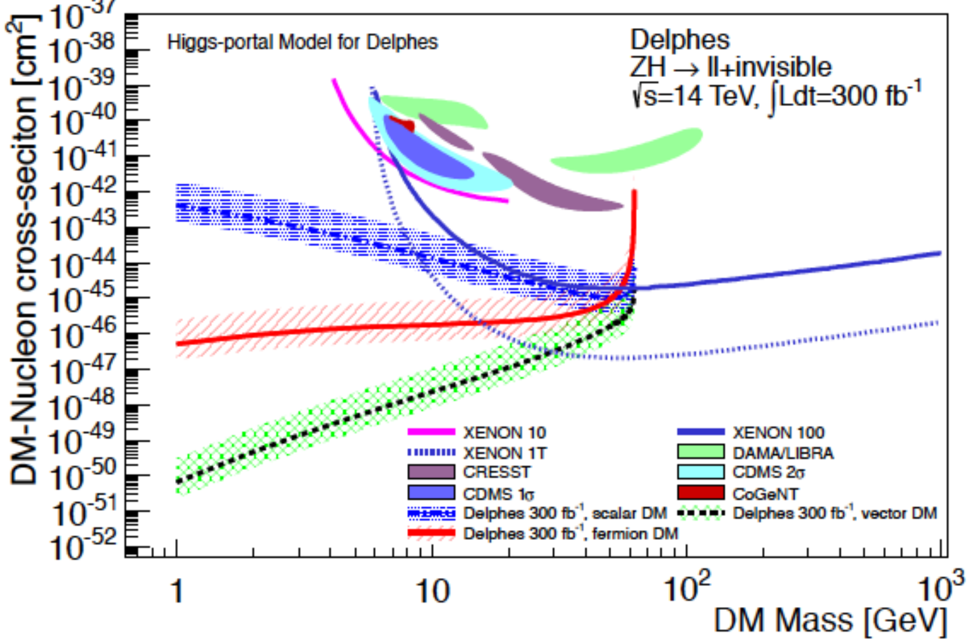


BR(H→inv)<65%(84% expected) @ 95% CL

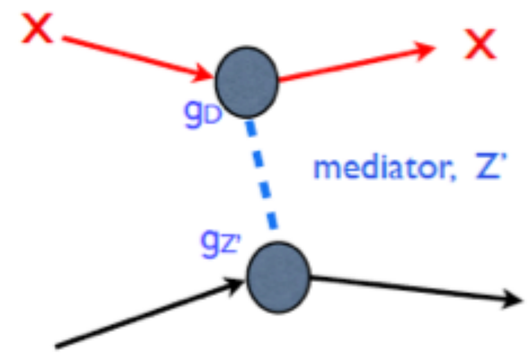
arXiv:1309.7925



BR(H→inv)<20% @ 95% CL (14 TeV, 300 fb^{-1})

Z' Mediator

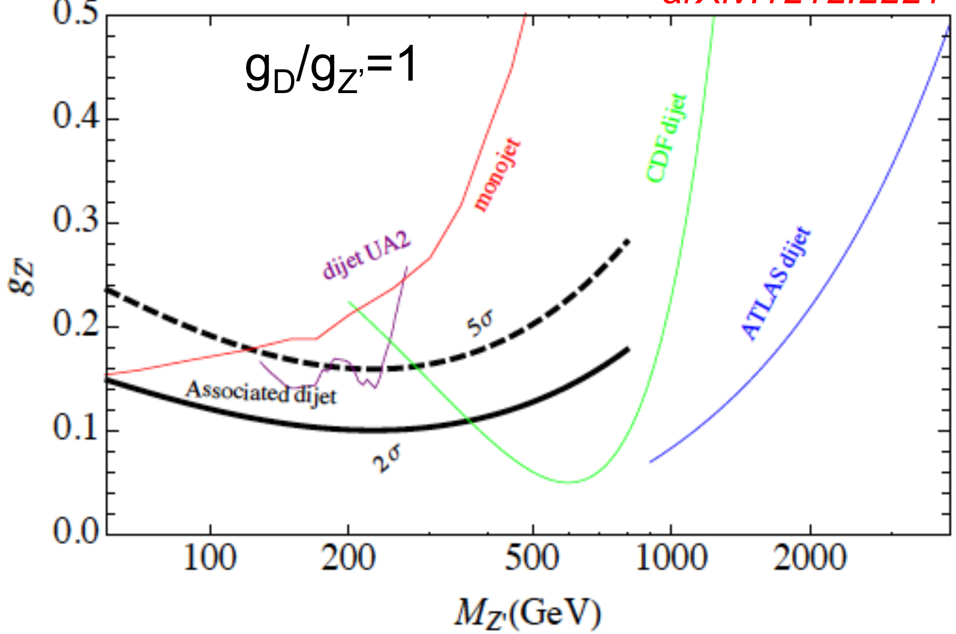
- In the low DM mass region, a light Z' with M~O(100) GeV is required in order to obtain the correct relic density.
- Consider a leptophobic Z', in order to evade direct searches for dilepton resonances.
- Standard dijet mass resonance searches challenging at low $M_{Z'}$. Can improve sensitivity by considering associated production modes: Z'+X (X=jet, γ, W, Z).
- Monojet and dijet searches complementary, probing high and low $g_D/g_{Z'}$ respectively.



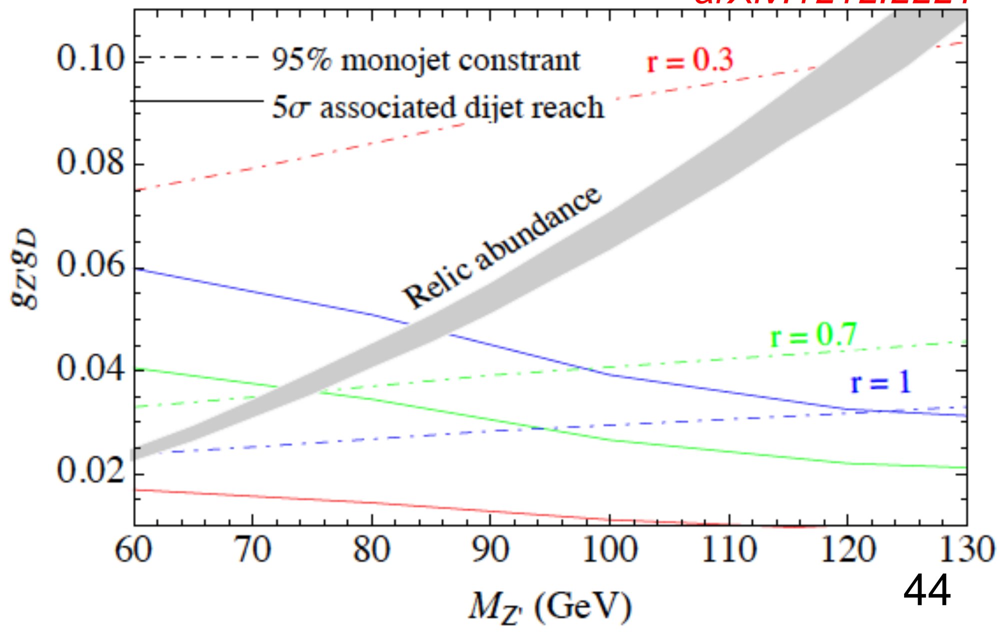
N= Ar, Ge, Xe, ...

$$\mathcal{L} \ni g_{Z'}\bar{q}\gamma^\mu q Z'_\mu + g_D \bar{\chi}\gamma^\mu \chi Z'_\mu,$$

arXiv:1212.2221



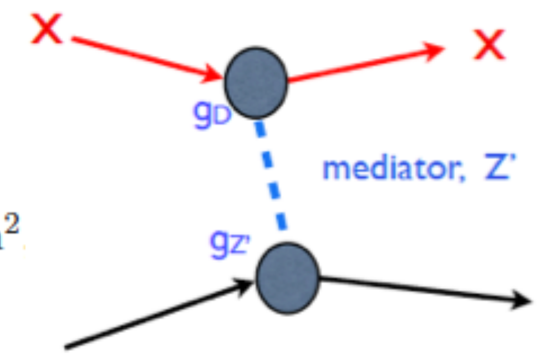
arXiv:1212.2221



Z' Mediator

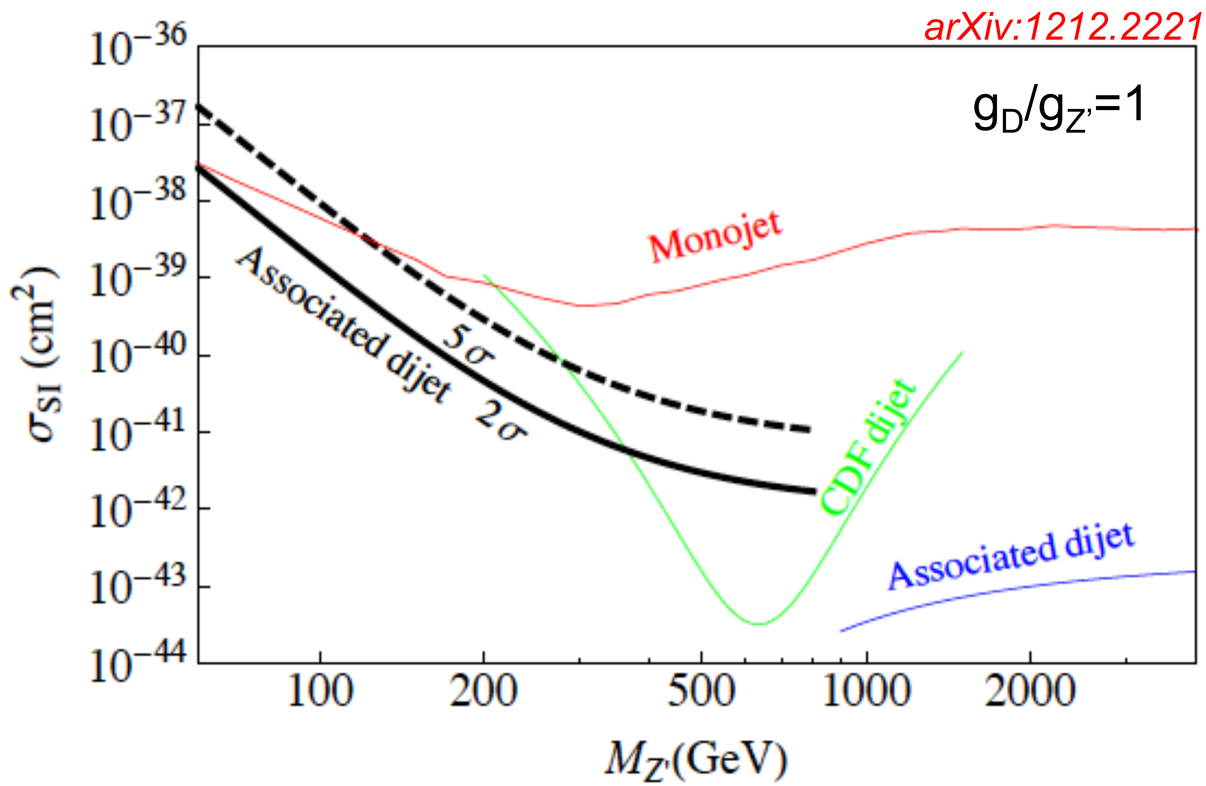
- The constraint on $g_{Z'}g_D$ can be mapped onto constraints on DM direct detection cross section.

$$\sigma_{SI} \simeq \frac{9 g_{Z'}^2 g_D^2 M_N^2 M_D^2}{\pi M_{Z'}^4 (M_D + M_N)^2} \simeq 7.7 \times 10^{-40} \left(\frac{g_{Z'}}{0.1}\right)^2 \left(\frac{g_D}{0.1}\right)^2 \left(\frac{100\text{GeV}}{M_{Z'}}\right)^4 \text{cm}^2$$



N= Ar, Ge, Xe, ...

- Improved sensitivity for $M_{Z'}$<400 GeV by using the associated dijet mode.

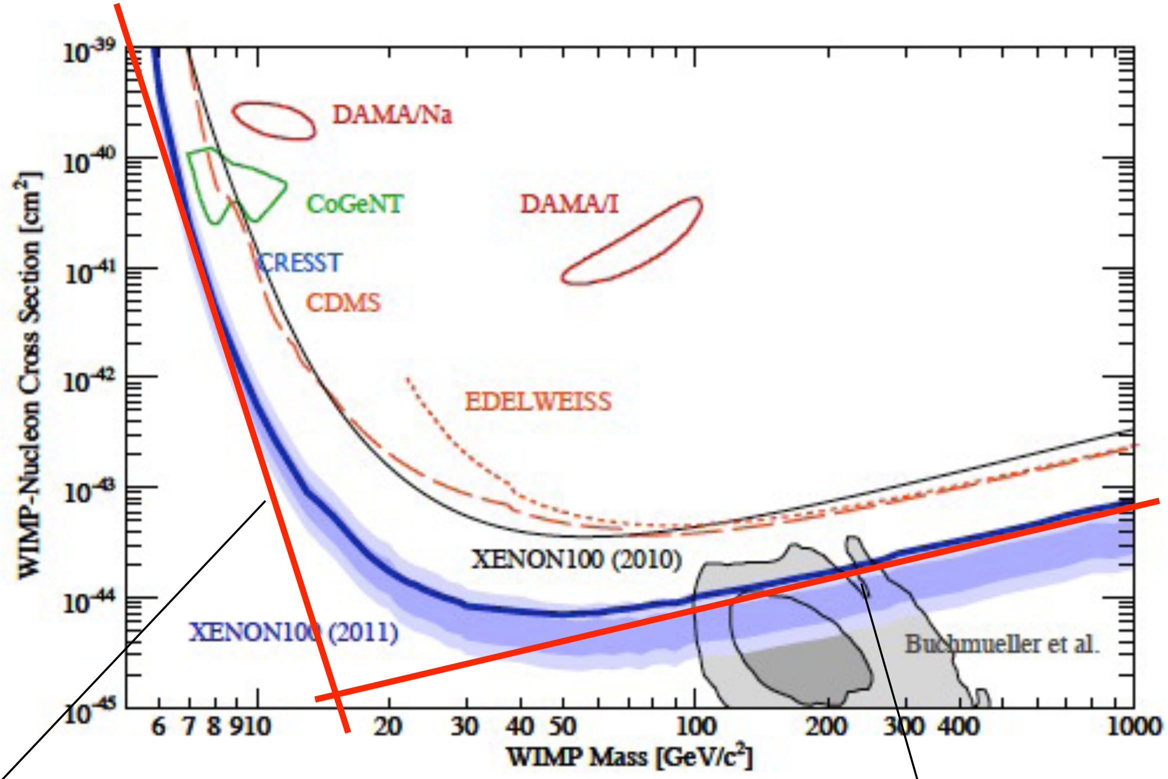


- This study assumed 15 fb^{-1} at 8 TeV for the dijet associated search.
- Significant potential with LHC Run 2 datasets!

Extended Models

Light Dark Matter and Light Higgs Bosons

- Many SM extensions include the possibility of light Higgs bosons.
- The NMSSM was proposed to solve the "μ problem" of the MSSM.
- Three CP-even mass eigenstates (h_1, h_2, h_3) and two CP-odd ones (a_1, a_2)
  - a_1 is light << EW scale (pseudo - Goldstone boson)



M_{DM}~O(10) GeV
Benchmark scenario: "dark light Higgs"

M_{DM}~O(100) GeV
Benchmark scenario: MSSM LSP

Light Dark Matter in Upsilon Decays

- If $m_\chi < m_\Upsilon/2$, could increase the invisible decay width of the $\Upsilon(1S)$ predicted by SM by orders of magnitude:

  $BF(\Upsilon(1S) \rightarrow \chi\chi) \sim 4.2 \times 10^{-4}$ (s-wave)

  $BF(\Upsilon(1S) \rightarrow \chi\chi) \sim 1.8 \times 10^{-3}$ (p-wave)

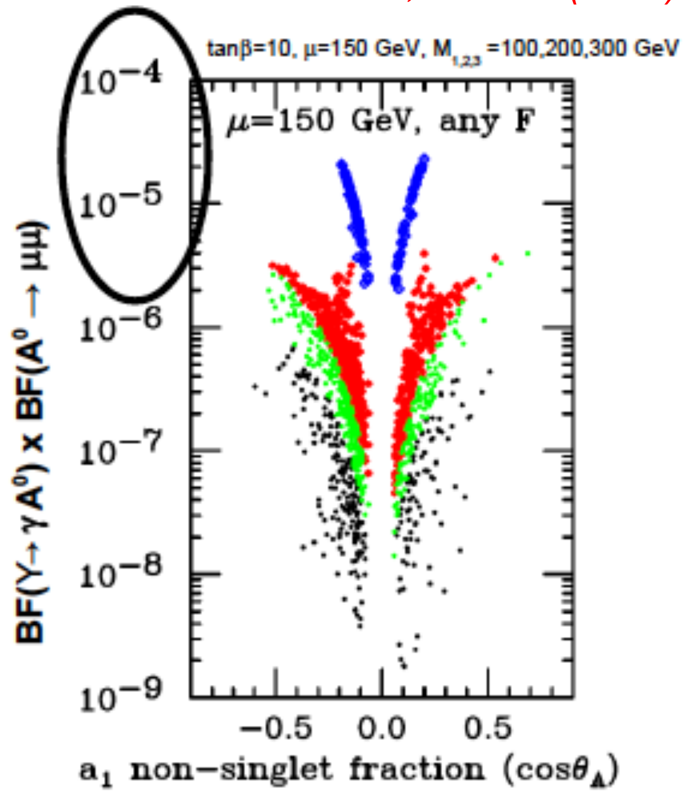
  $BF(\Upsilon(1S) \rightarrow \nu\nu) \sim 9.9 \times 10^{-6}$

  - CP-odd a_1 boson serves as s-channel mediator
  - a_1 decays dominantly to $\chi\chi$ if kinematically allowed.

- Radiative decays $\Upsilon(nS) \rightarrow \gamma a_1$ (n=1,2,3) can also have a large branching fraction.

  ➔ look for $\Upsilon(1S) \rightarrow \gamma$+invisible

PRD 81, 075003 (2010)



$A^0 = \cos\theta_A A_{MSSM} + \sin\theta_A A_S$

$0 < m_{A0} < 2m_\tau$

$2m_\tau < m_{A0} < 7.5$ GeV

$7.5 < m_{A0} < 8.8$ GeV

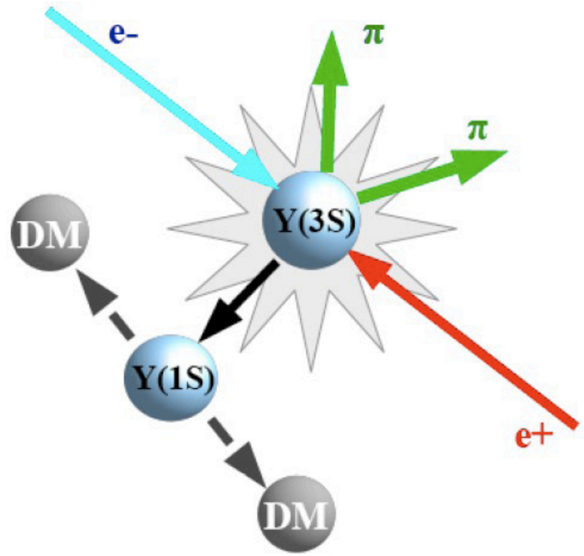
$8.8 < m_{A0} < 9.2$ GeV

BABAR data sample contains

~470 x 10^6	$\Upsilon(4S)$	
~120 x 10^6	$\Upsilon(3S)$	(10x Belle)
~100 x 10^6	$\Upsilon(2S)$	(10x CLEO)
~ 18 x 10^6	$\Upsilon(1S)$	from $\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S)$

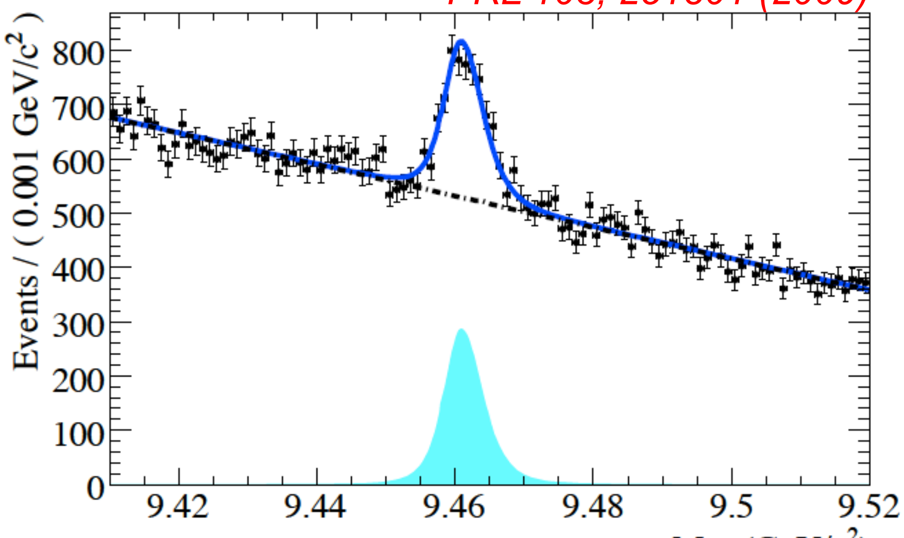
ϒ(1S)→invisible

- Signature:
  - Tag ϒ(1S) mesons in ϒ(3S)→$\pi^+\pi^-$ϒ(1S) transition
  - Only two oppositely-charged tracks (no additional activity)
- Backgrounds:
  - Non-peaking (random combinations)
  - Peaking (indistinguishable from the signal): ϒ(3S)→$\pi^+\pi^-$ϒ(1S), ϒ(1S)→l^+l^- (undetected)



- Fit recoil mass distribution:

PRL 103, 251801 (2009)

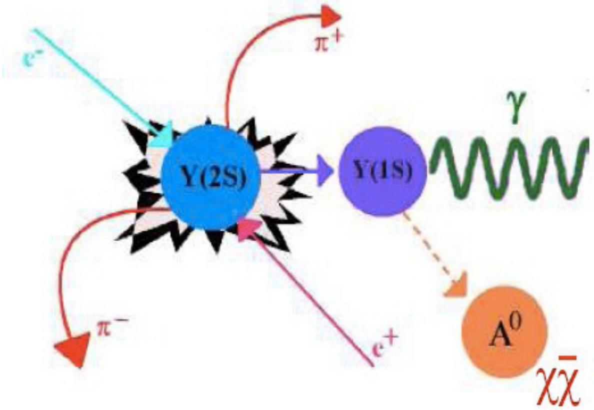


$$M_{rec} = \sqrt{s + M_{\pi\pi}^2 - 2sE_{\pi\pi}^*}$$

- Results:
  Fit yield 2326 ±105
  Peaking bkg (MC) 2444 ± 124
  Signal only -118 ± 105 ± 124
- 90% CL Upper limit:
  BF(ϒ(1S)→invisible)<3.0x10^{-4}

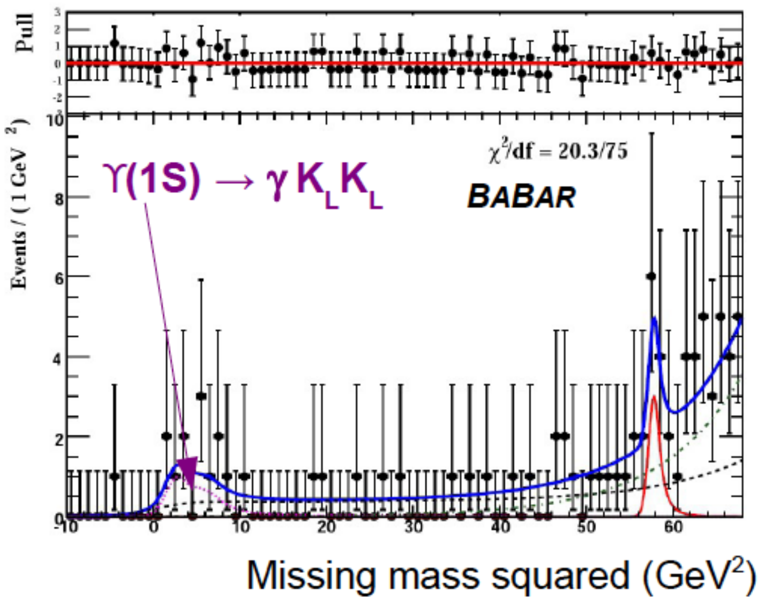
ϒ(1S)→γ+invisible

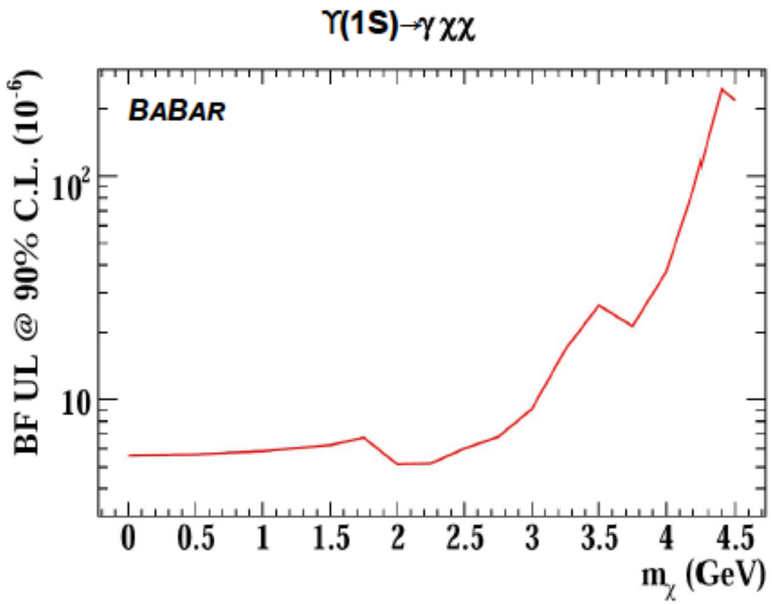
- Signature:
  - Tag ϒ(1S) mesons in ϒ(2S)→$\pi^+\pi^-$ϒ(1S) transition
  - Two oppositely-charged tracks and a photon (no additional activity).
- Signal extraction:
  - 2D fit to the recoil mass and missing mass distributions.



$$M^2_{\rm recoil} = M^2_{\Upsilon(2S)} + m^2_{\pi\pi} - 2M_{\Upsilon(2S)}E^*_{\pi\pi}$$
$$M^2_X = (\mathcal{P}_{e^+e^-} - \mathcal{P}_{\pi\pi} - \mathcal{P}_\gamma)^2$$

PRL107, 021804 (2011)



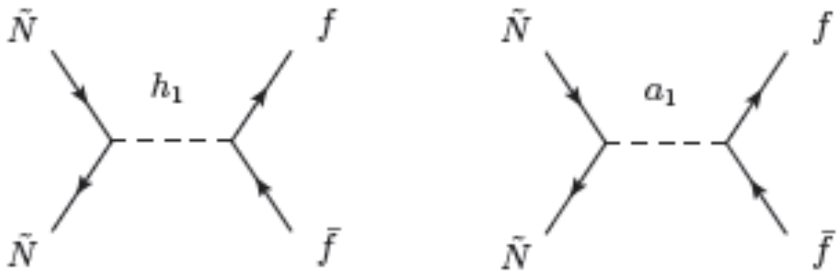


- 90% CL Upper limits:
  BF(ϒ(1S)→γ+a_1, a_1→inv) < (1.9-37)x10^{-6}
  BF(ϒ(1S)→γχχ) < (0.5-25)x10^{-5}

Dark Light Higgs Scenario

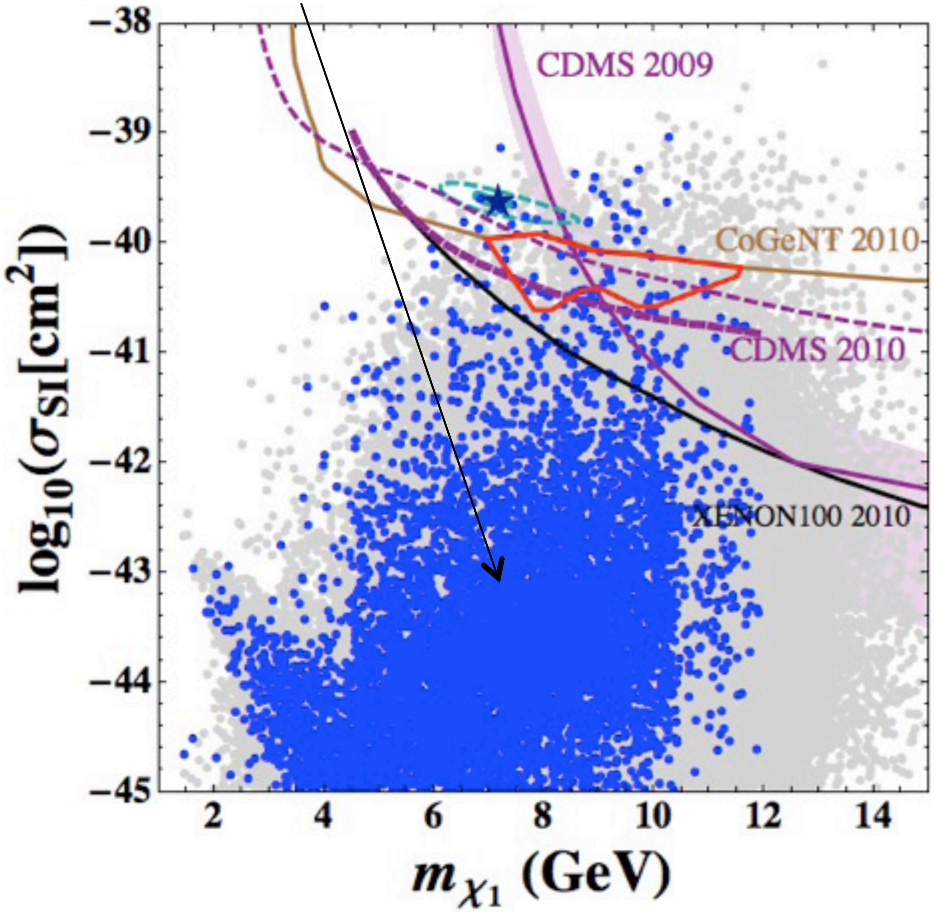
- NMSSM near Peccei-Quinn limit:
  - h_1 is very light ~O(1) GeV
  - h_2 is the SM-like Higgs boson
  - a_1 is light ~15 GeV
  - X_1 is light ~7 GeV

- Spin-independent cross section driven by h_1 exchange (large enhancement from low h_1 mass).
- Annihilation via a_1 exchange gives right relic density (Breit-Wigner enhancement).



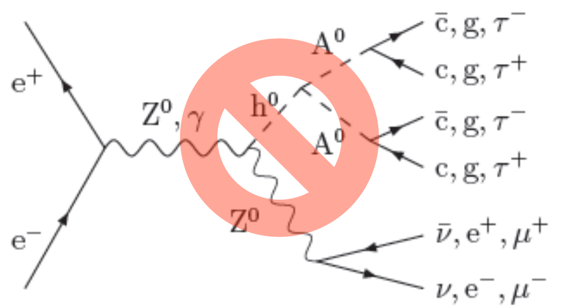
PRL 106, 121805 (2011)

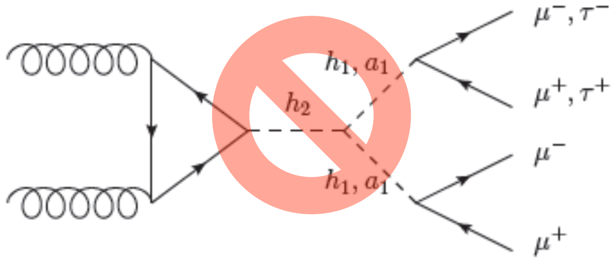
$0.09 \leq \Omega h^2 \leq 0.13$



Probing Dark Light Higgs

- Higgs physics phenomenology quite altered compared to NMSSM-like scenarios usually considered!
    - SM-like Higgs decays to h_1h_1 and a_1a_1 suppressed
    - h_1 too light to be searched for directly
    - a_1 too light to be searched for in $gg \rightarrow a_1$, suppressed couplings to W/Z and top

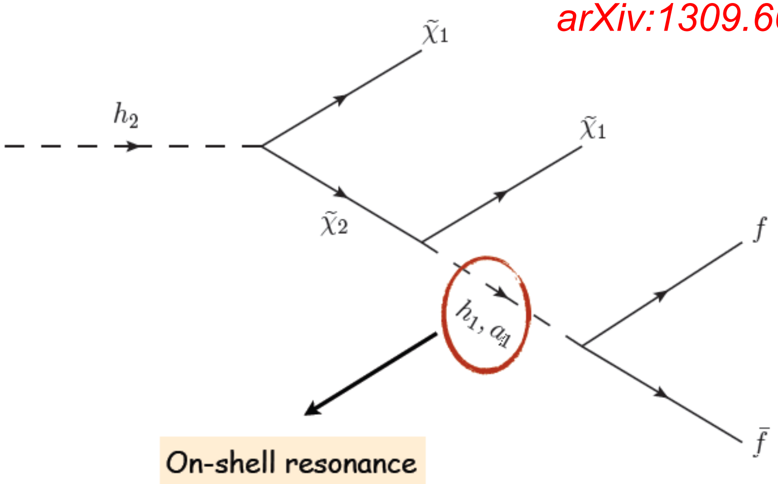


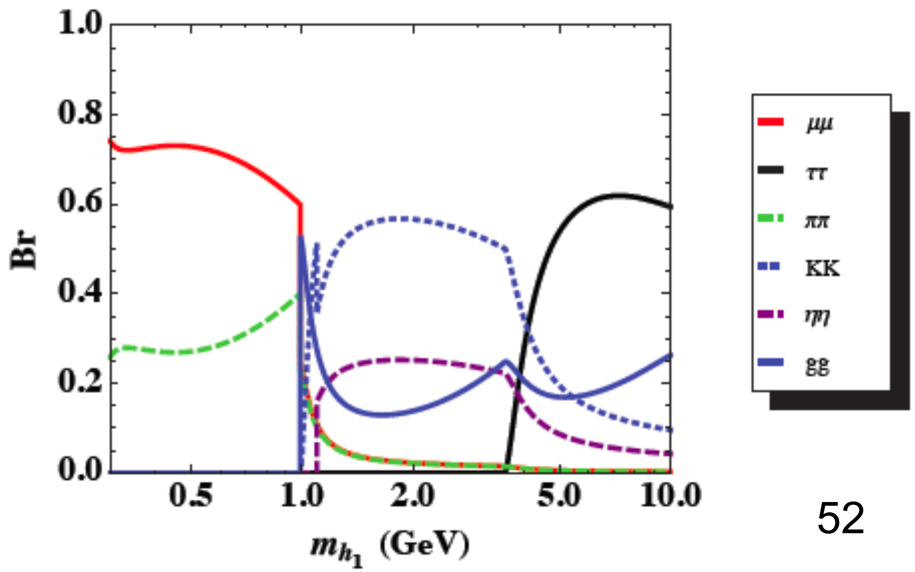


- However, BR($h_2 \rightarrow \chi_2\chi_1$) can be sizable if kinematically allowed:

➔ Non-standard Higgs decay modes (e.g. $\mu\mu+E_{Tmiss}$)

arXiv:1309.6633



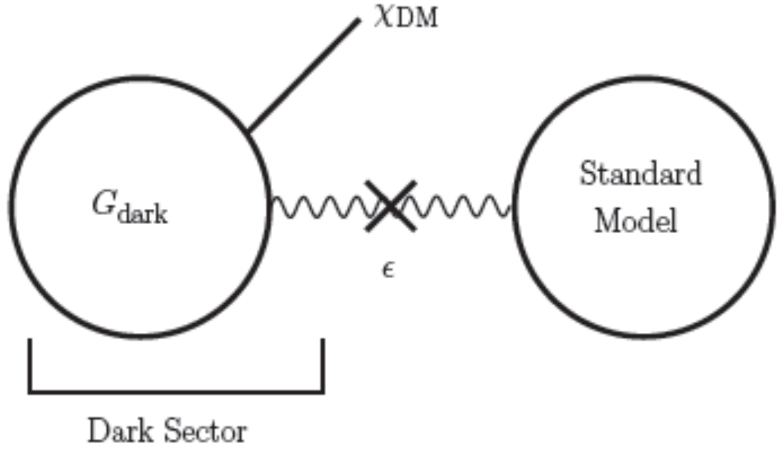


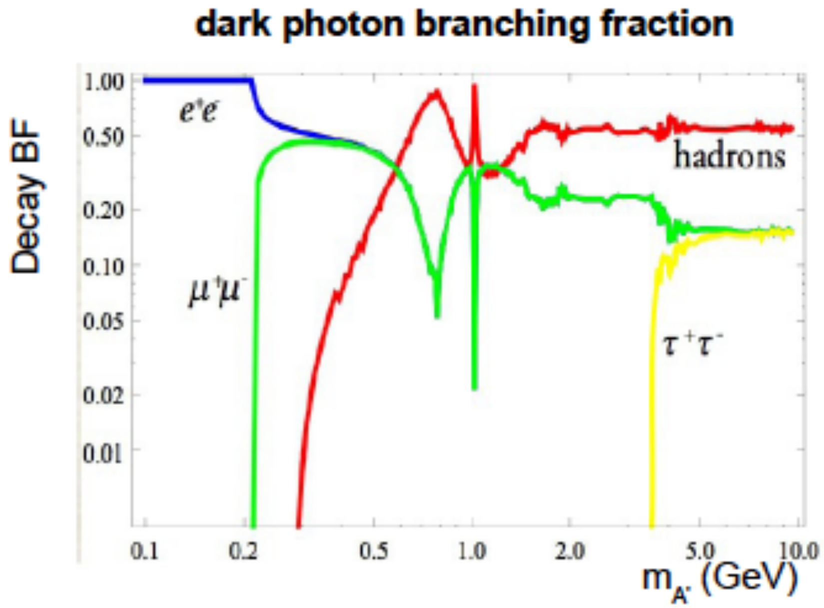
DM Embedded in a Dark Sector?

- Models introducing a new “dark” force mediated by a new gauge boson with a mass around a GeV have been proposed to explain the observations of PAMELA, FERMI, DAMA/LIBRA, CREST,...

- WIMP-like TeV-scale DM particles can annihilate into e.g. pairs of dark photons, which subsequently decay to pairs of leptons.

- New dark forces:
  - $G_{Dark} \supset U(1)_D$
    ➔ dark photon A’
  - $G_{Dark} \supset SU(2)_D x U(1)_D$
    ➔ 4 dark bosons (A’, W’, W’’, W’’’)
  - A’ mass generated via Higgs mechanism
    ➔ dark Higgs h’

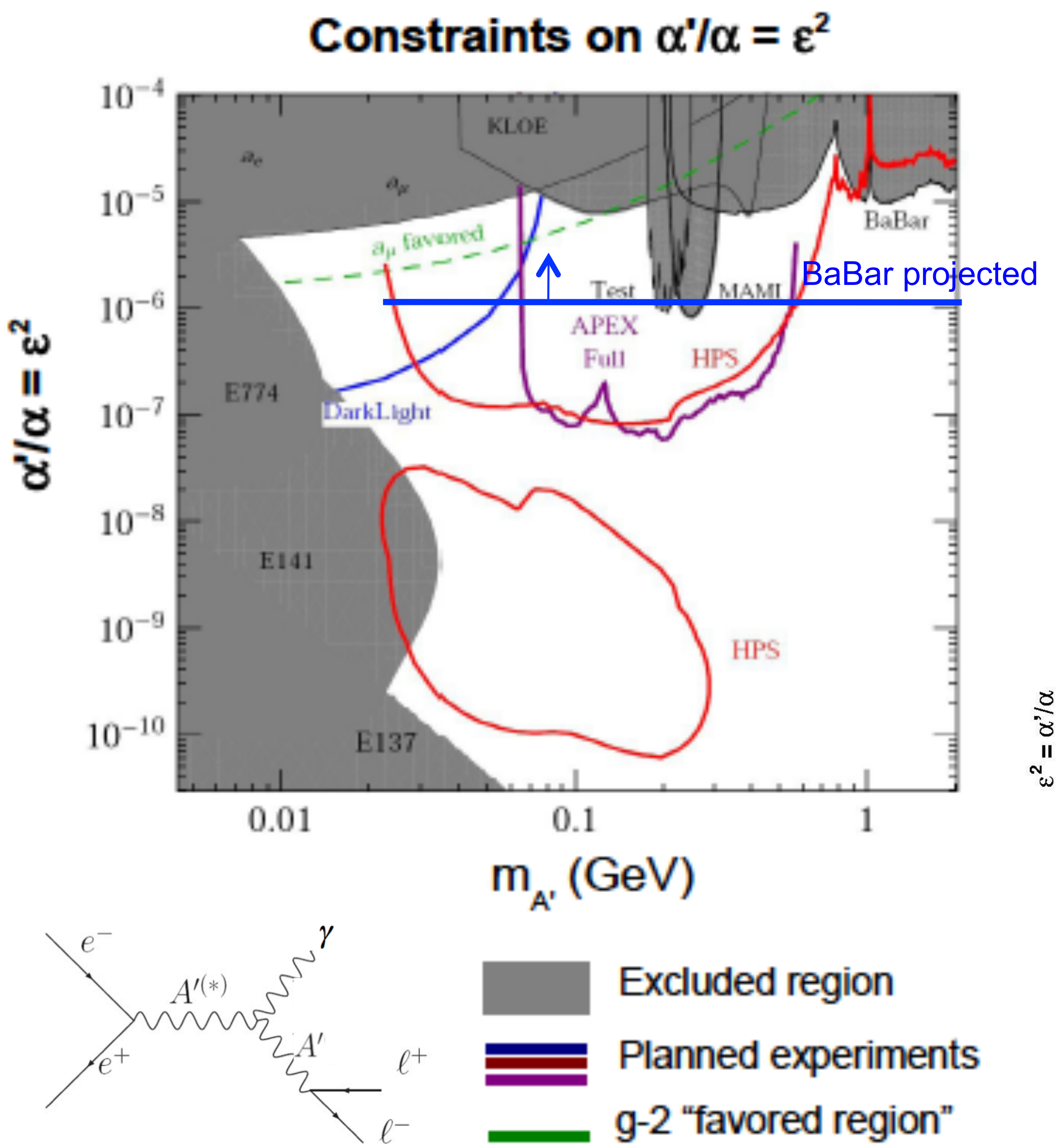




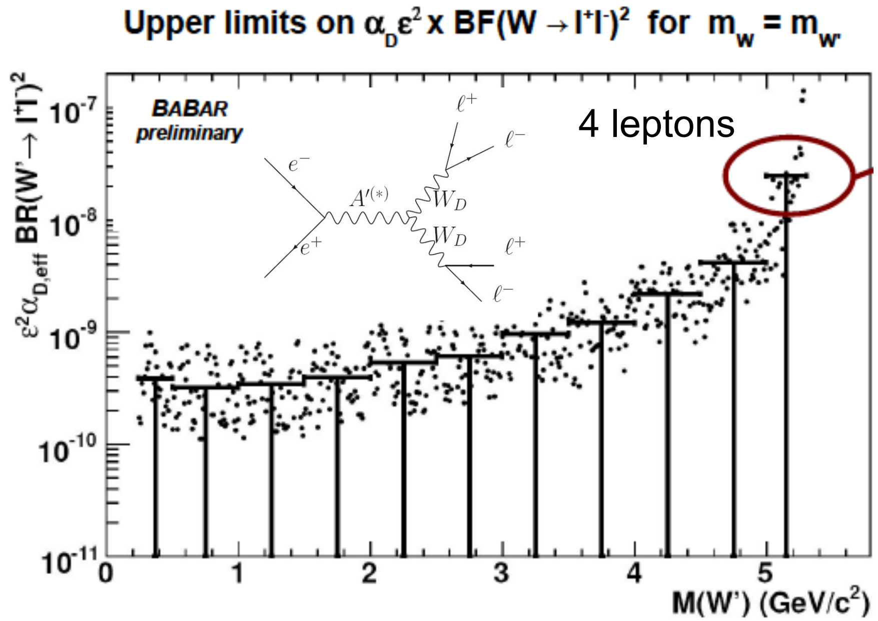
- Low-energy e^+e^- colliders provide a clean environment to explore MeV/GeV scale dark matter and dark sector (including its structure).

Searches at Low Energy e⁺e⁻ Colliders

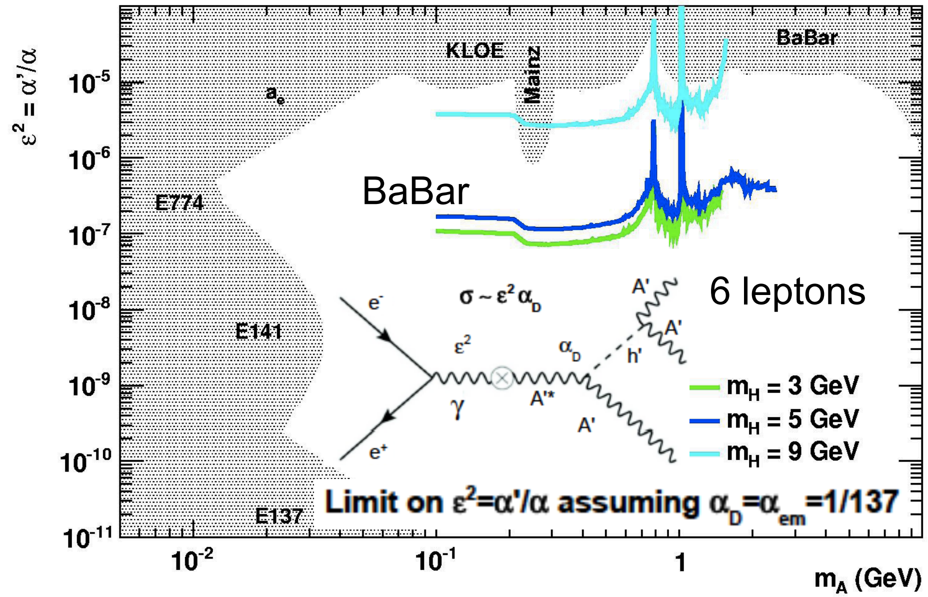
PRD 80, 075018 (2009)



arXiv:0908.2821



PRL 108, 211801 (2012)



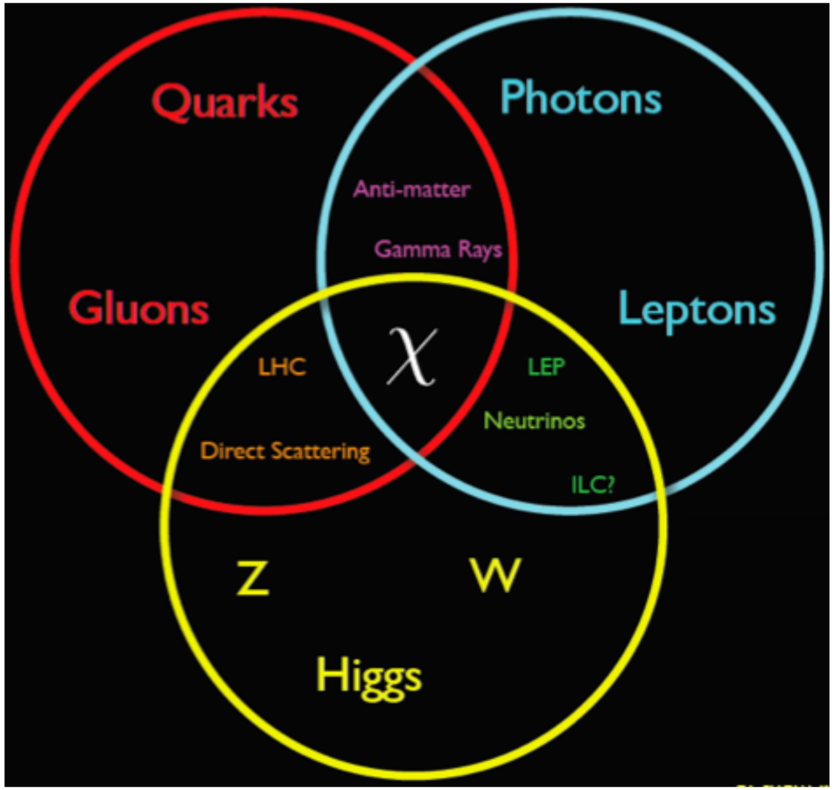
Summary and Conclusions

- Unraveling the nature of DM and measuring its properties is one of the most exciting challenges ahead, at the interface between particle physics, astrophysics and cosmology.

- Particle colliders (and in particular the LHC), will play a crucial and complementary role in this pursuit.

- Many strategies followed in parallel to cast a wide net over the many signatures a DM particle (and its relatives) could exhibit at colliders.

- Much juice to squeeze out of LHC Run 2 beginning in 2015!



Exciting Times Ahead!

Backup

LHC: A Long Road Ahead