Comparison of collider and non-collider DM results

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on behalf of CMS and ATLAS Collaborations

Physics at LHC and beyond,
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    - ➡ Hadronic
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- Preparation for LHC Run2 / HL-LHC
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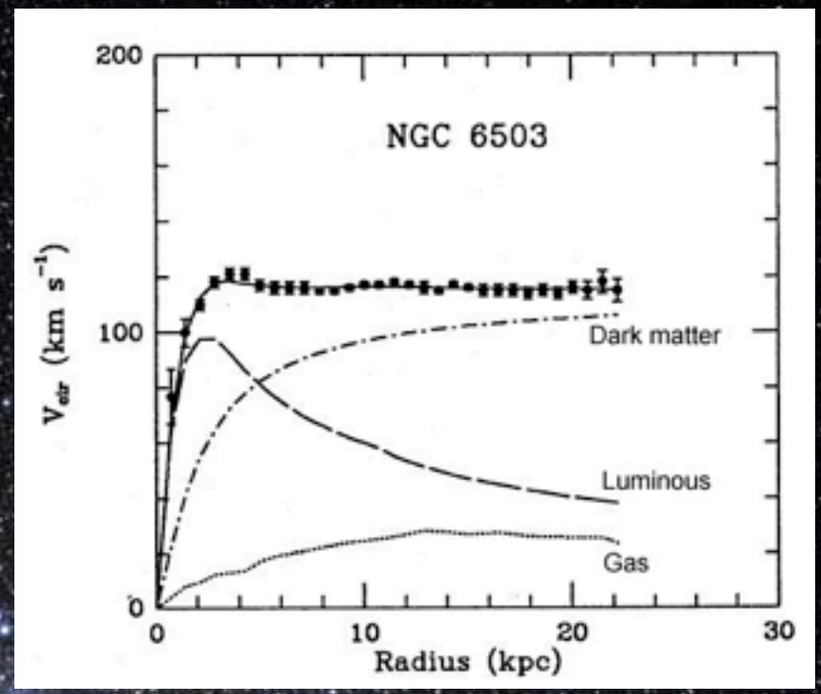
Dark matter

Bullet cluster

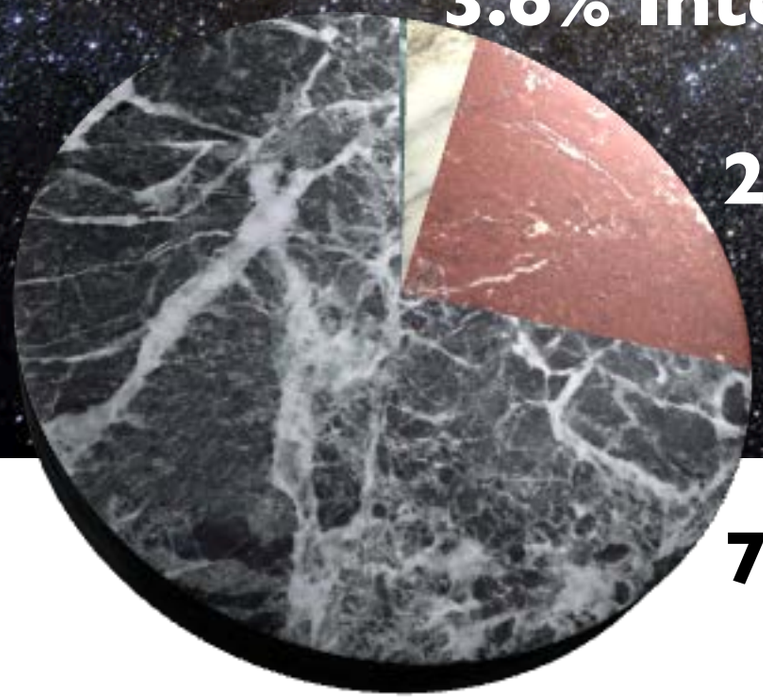


Galactic rotation curves

0.4% Stars, Organic forms, etc.

3.6% Intergalactic Gas

23% Dark Matter

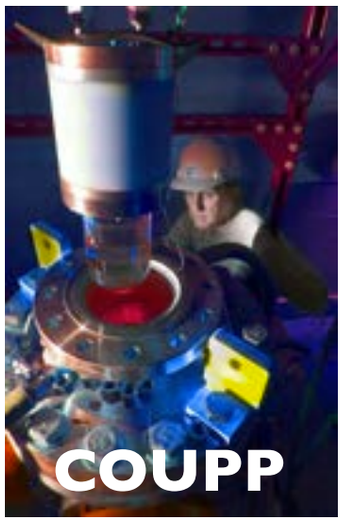


73% Dark Energy

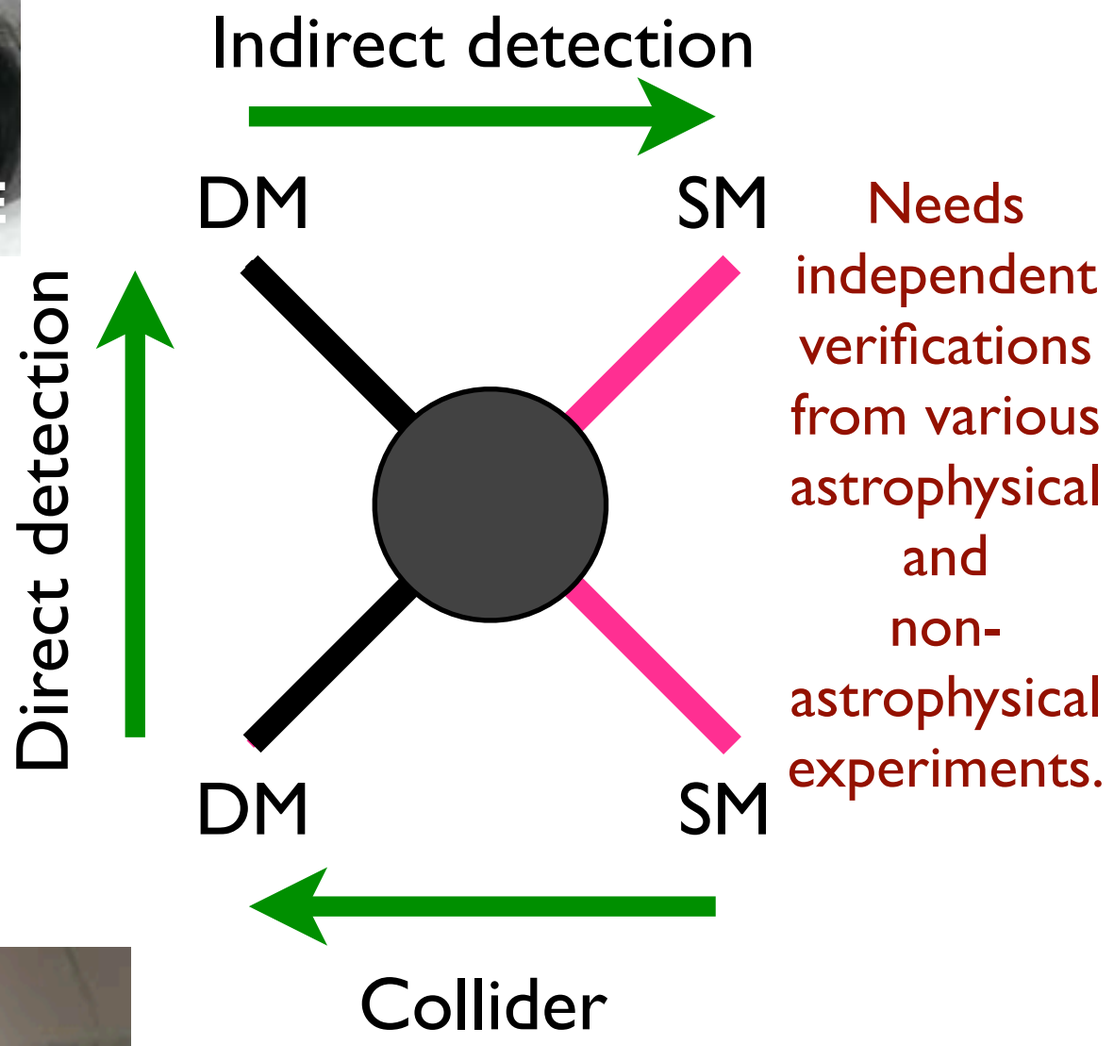
Strong Gravitational Lensing

Searches for dark matter

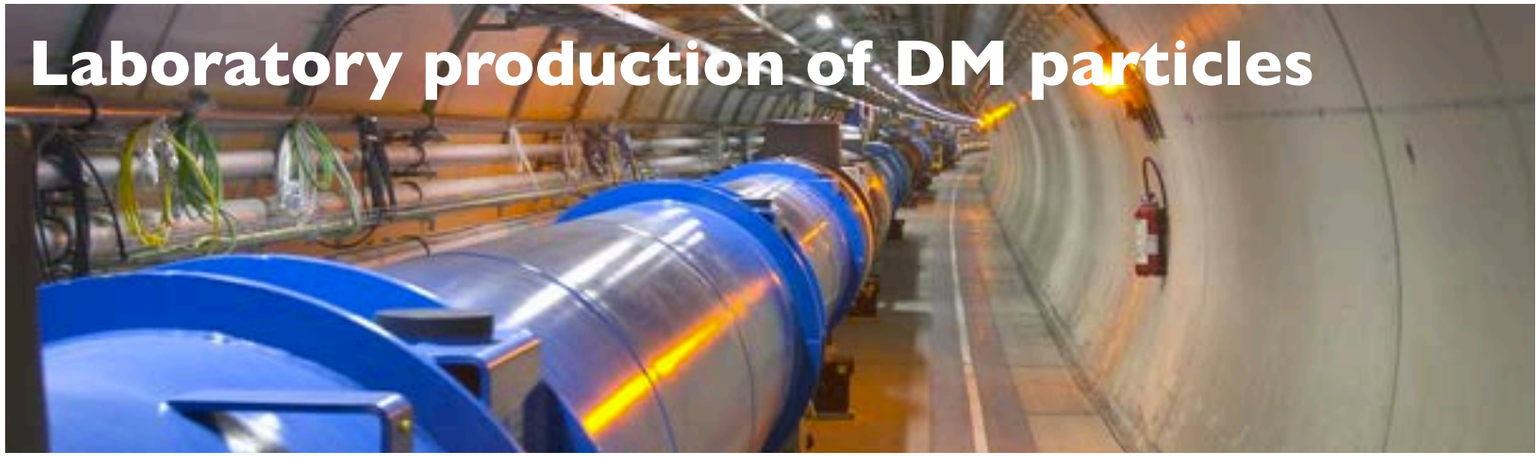
Dark Matter-nucleus scattering

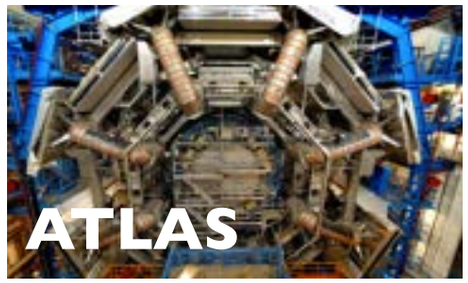


Observe DM annihilation products



Laboratory production of DM particles

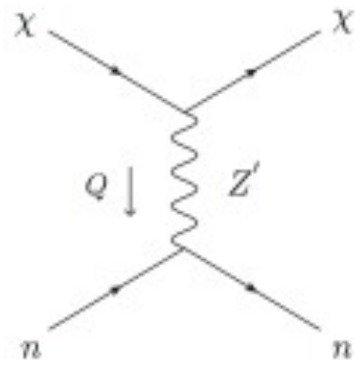


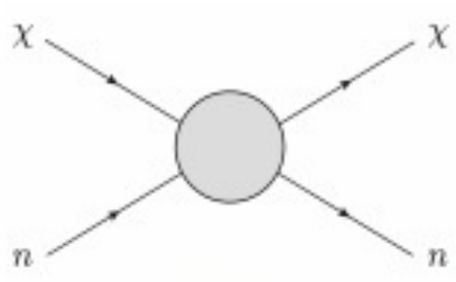


Current dark matter interpretations

- Limits are quoted in terms of the WIMP-Nucleon cross-section.

Direct detection



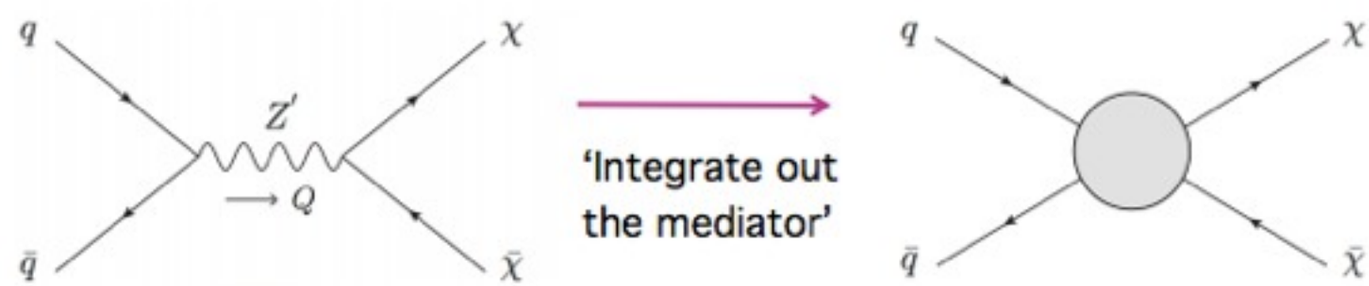


$$\sigma_n \sim \left(\frac{g_n g_\chi}{Q^2 - m_{Z'}^2}\right)^2 \approx \frac{g_n^2 g_\chi^2}{m_{Z'}^4}\left(1 + \frac{Q^2}{m_{Z'}^2} + \cdots\right)^2$$

- Contact interaction if

$$m_{Z'} \gg Q = \sqrt{2 m_n E_{\mathrm{R}}} \approx 50 \text{ MeV}$$

Collider



- Use of effective field theory (EFT) to place a limit on the contact interaction scale

$$\Lambda \equiv \frac{m_{Z'}}{\sqrt{g_q g_\chi}}$$

- EFT will be valid if $m_{Z'} \gg Q \sim$ TeV

Dark Matter models @ Collider

Dirac fermion, 1008.1783

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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Majorana fermion, 1005.1286

M1	qq	$m_q/2M_*^3$
M2	qq	$im_q/2M_*^3$
M3	qq	$im_q/2M_*^3$
M4	qq	$m_q/2M_*^3$
M5	qq	$1/2M_*^2$
M6	qq	$1/2M_*^2$
M7	GG	$\alpha_s/8M_*^3$
M8	GG	$i\alpha_s/8M_*^3$
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$

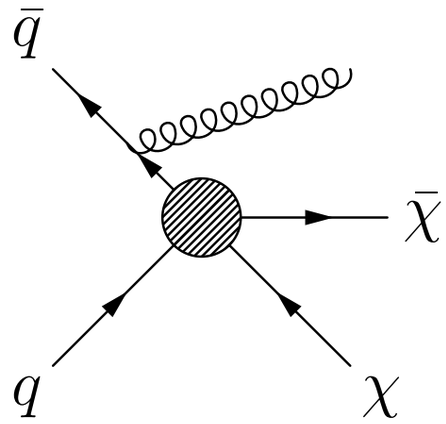
Real scalar, 1008.1783

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	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

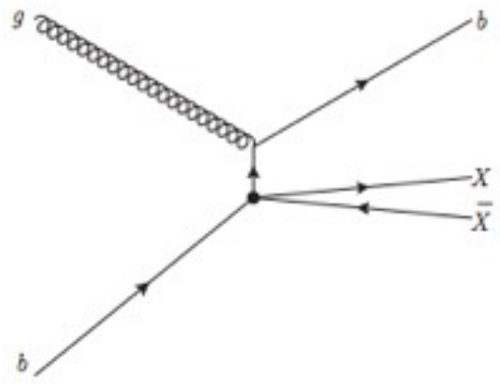
Complex scalar, 1008.1783

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	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$

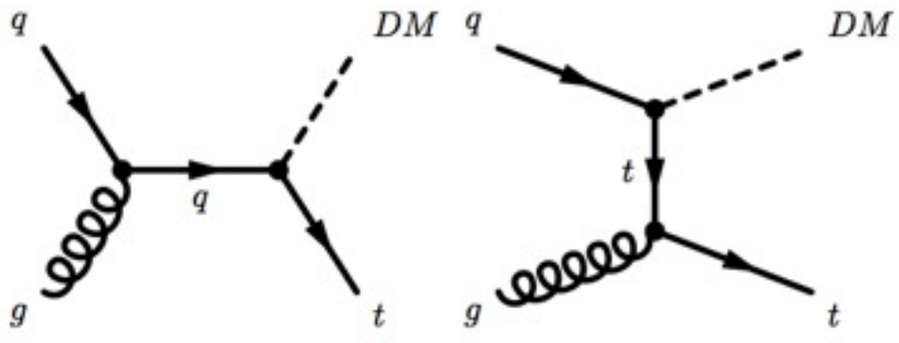
X + Missing Transverse Energy



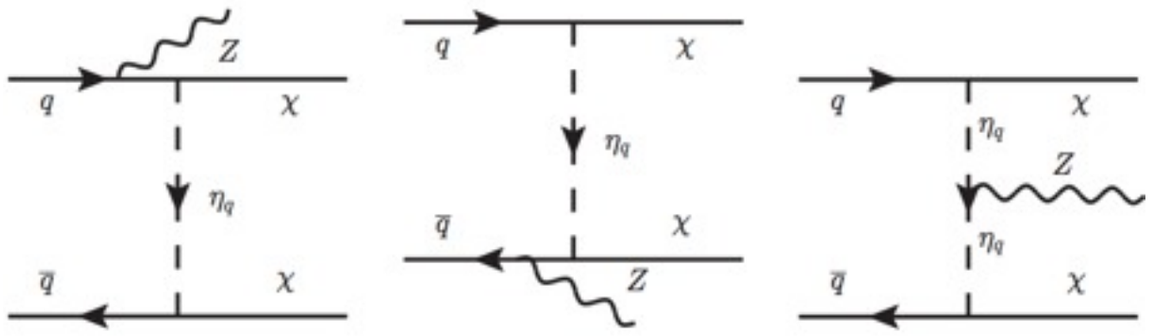
MonoJet



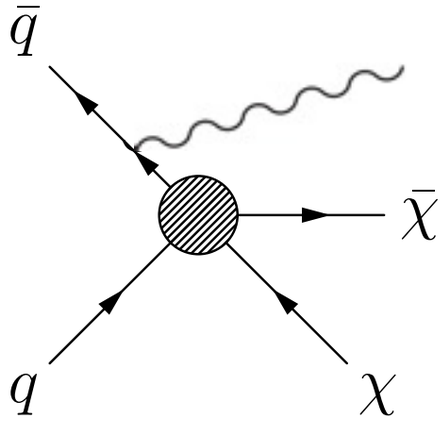
MonoB



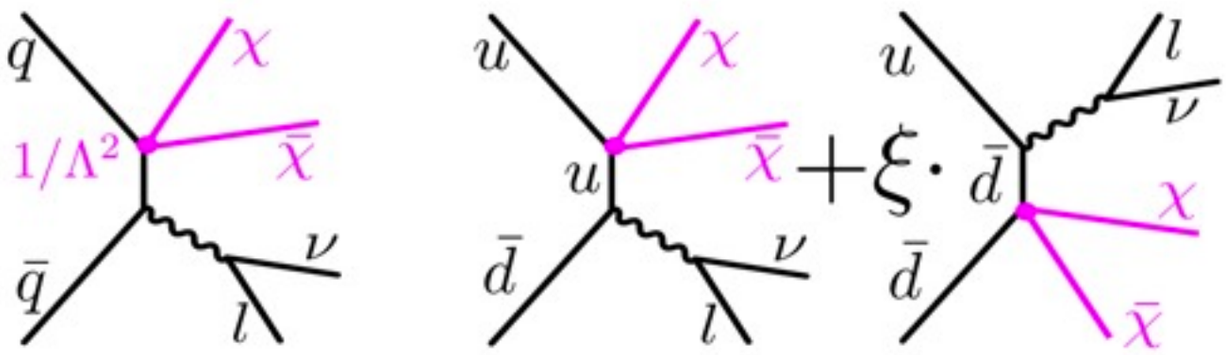
MonoTop



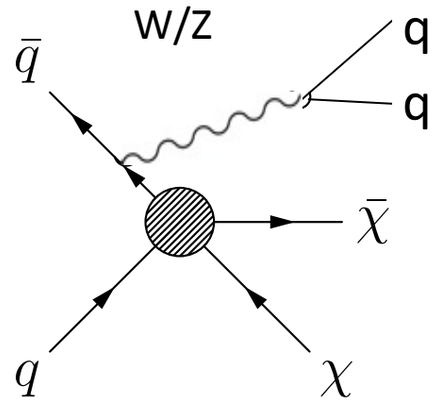
MonoZ



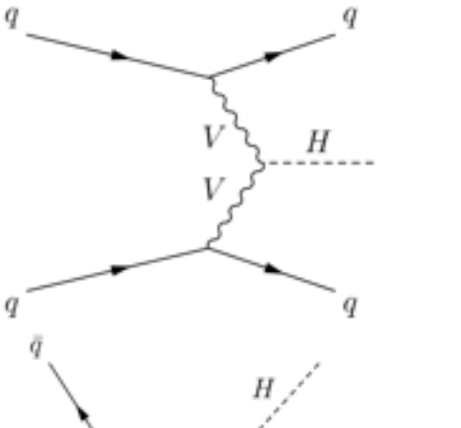
MonoPhoton



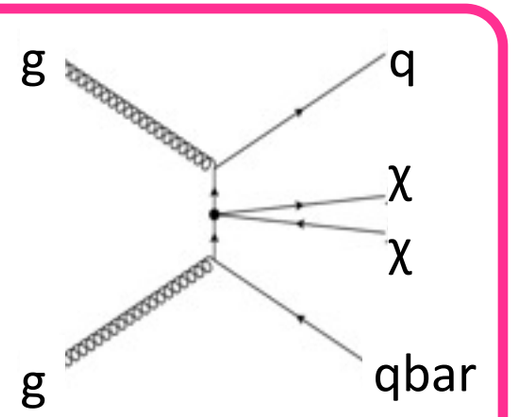
MonoW (monoLepton)



MonoW/Z (Hadronic)



Higgs Portal



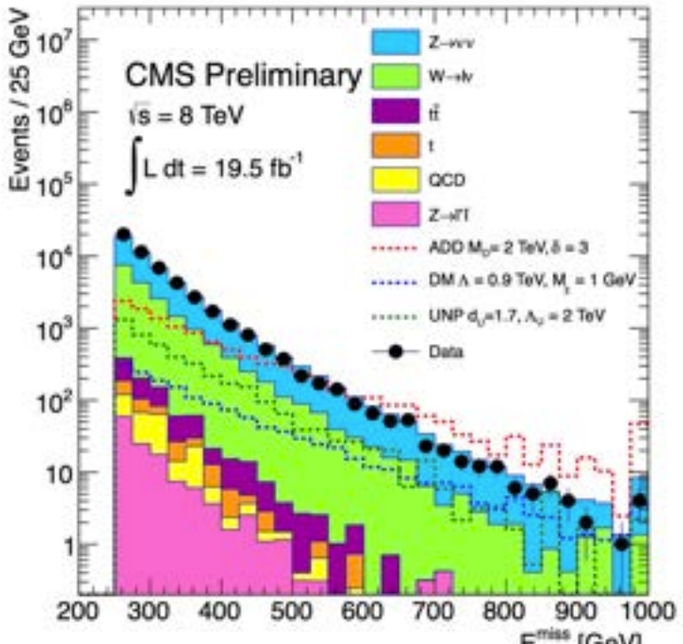
BBbar /TTbar

MonoJet

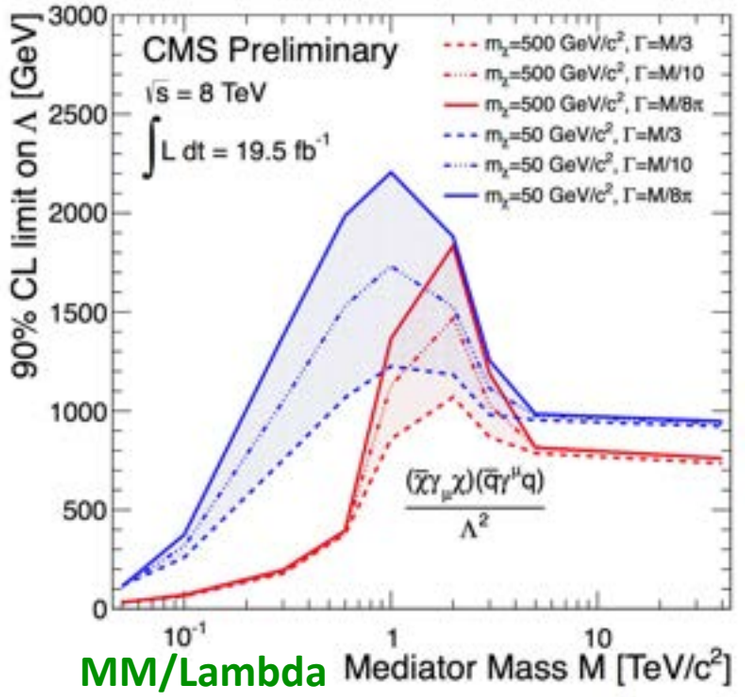
Event selection

- MET > 250 GeV
- One energetic jet, p_T > 110 GeV, $|\eta|$ < 2.4, and allow an additional jet (p_T > 30 GeV)
- Veto event if j_3 p_T > 30 GeV
- Veto event if DeltaPhi(j_1,j_2)>2.5
- Veto event if they contain isolated electrons, isolated muons, or hadronic tau with p_T >10 GeV (20 GeV for tau)

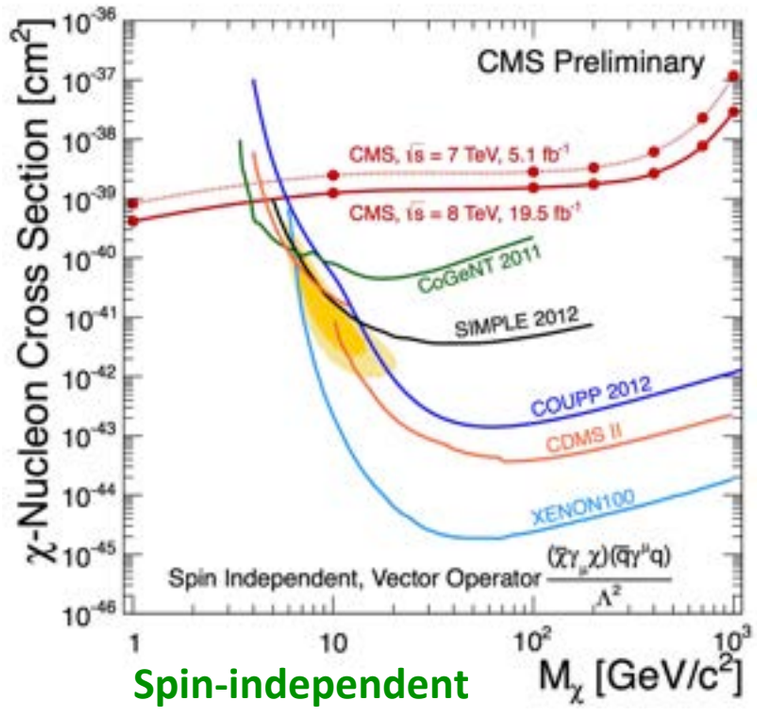
EXO-12-048: http://cds.cern.ch/record/1525585



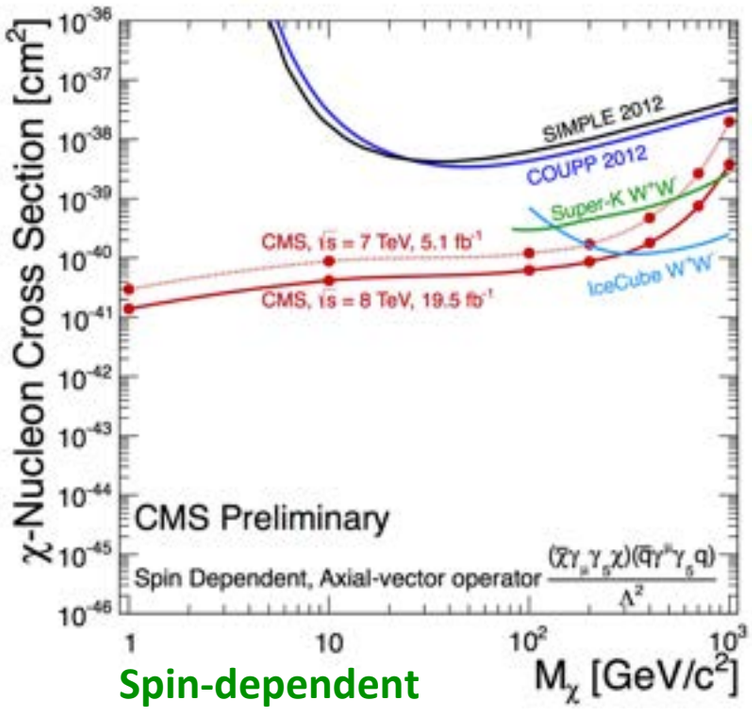
MET



MM/Lambda



Spin-independent



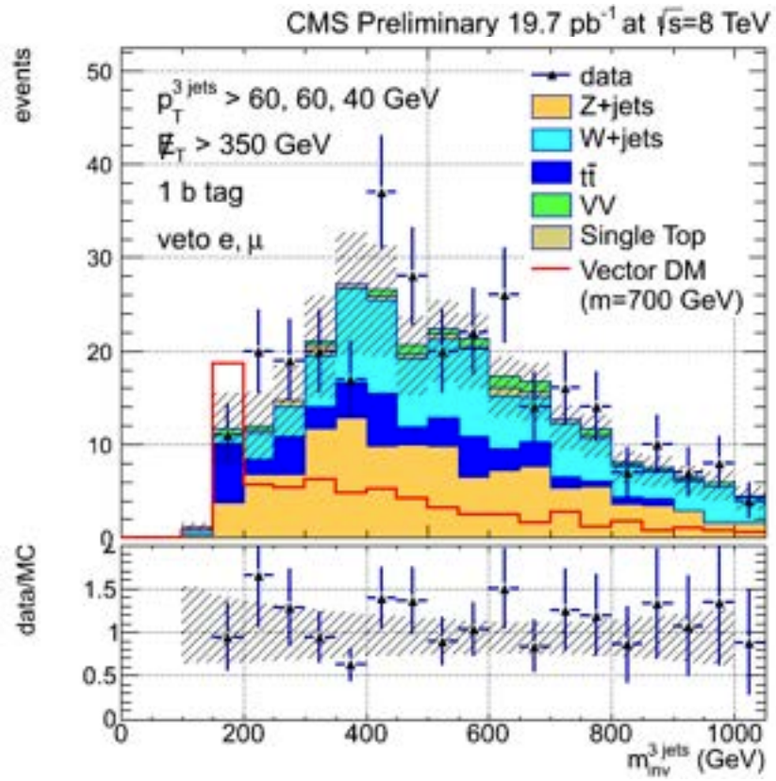
Spin-dependent

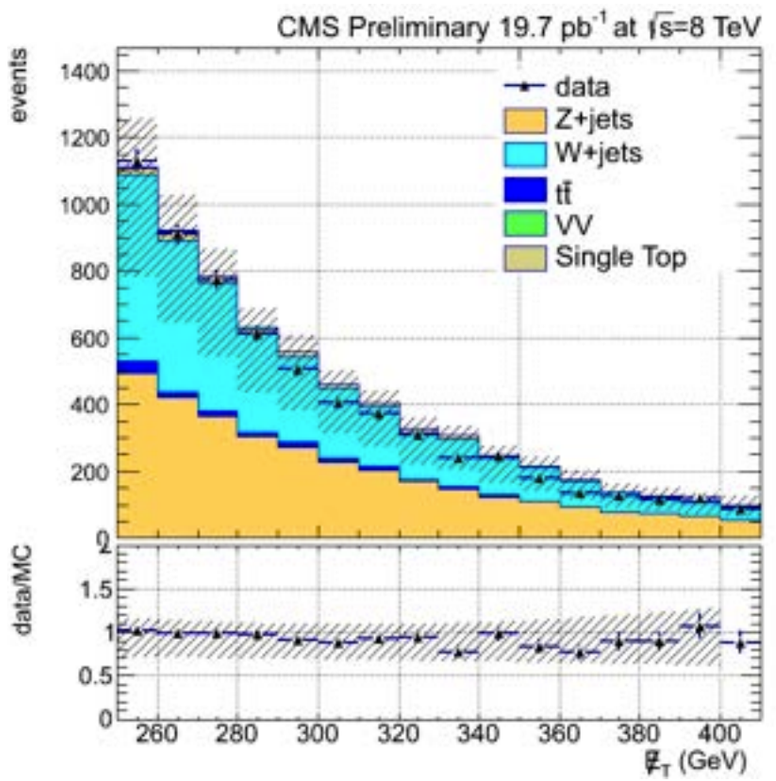
MonoTop (top decays hadronically)

B2G-12-022: http://cds.cern.ch/record/1668115

Event selection

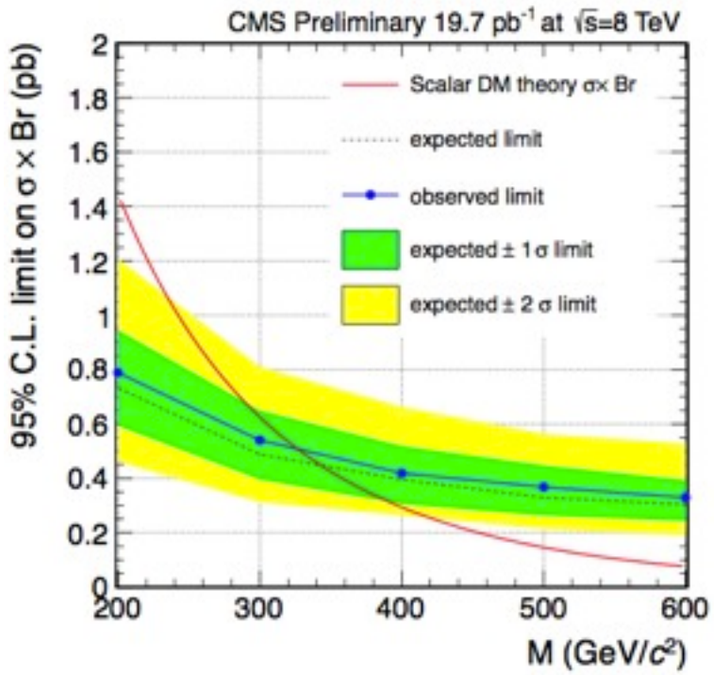
- Three jets, with j_1, and j_2 p_T > 60 GeV and j_3 p_T > 40 GeV
- One jet is tagged b-jet
- Veto events with j_4 p_T > 35 GeV or isolated e(μ) p_T > 20(10) GeV
- $M(j_1 j_2 j_3)$ < 250 GeV
- MET> 350 GeV

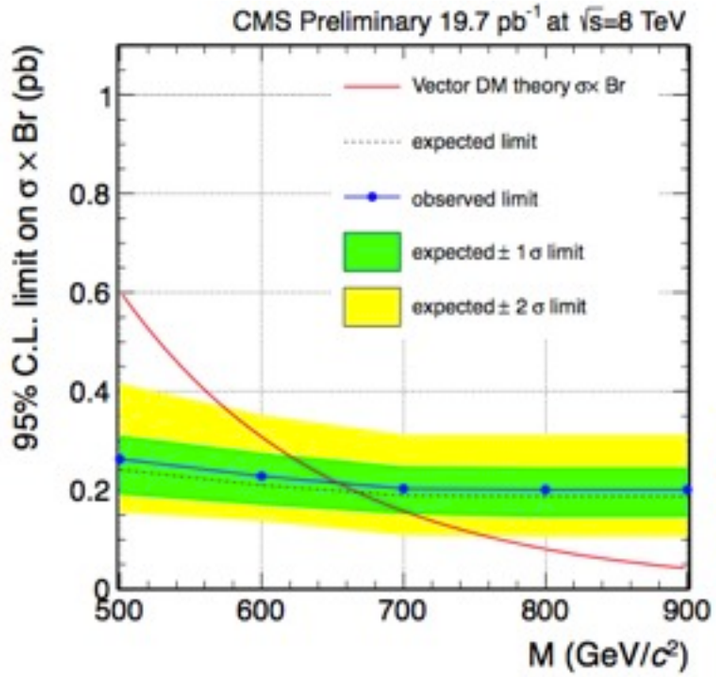




Results

- Excellent agreement with data
- DM coupling set to 0.1 for q=u/d [arXiv:1106.199]
- Exclude scalar (vector) DM masses below 327 (655) GeV





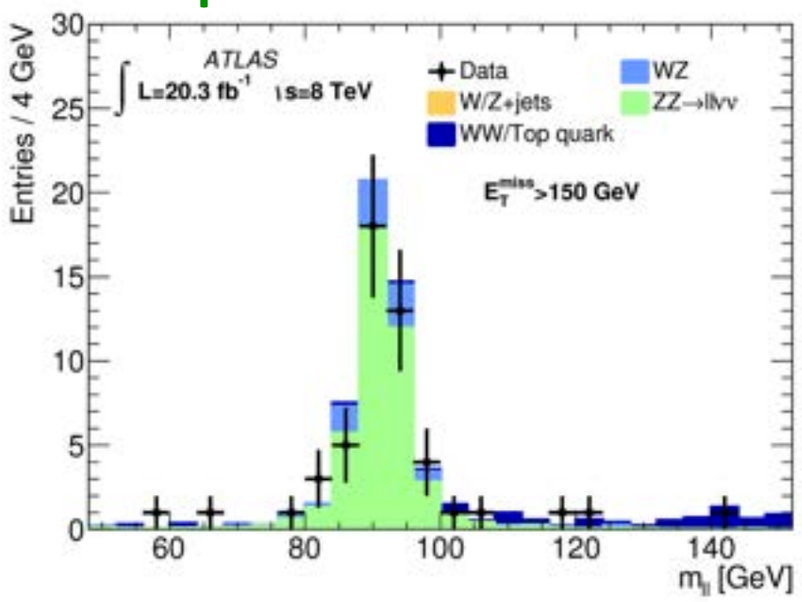
MonoZ (Z decays leptonically)

PhysRevD.90.012004

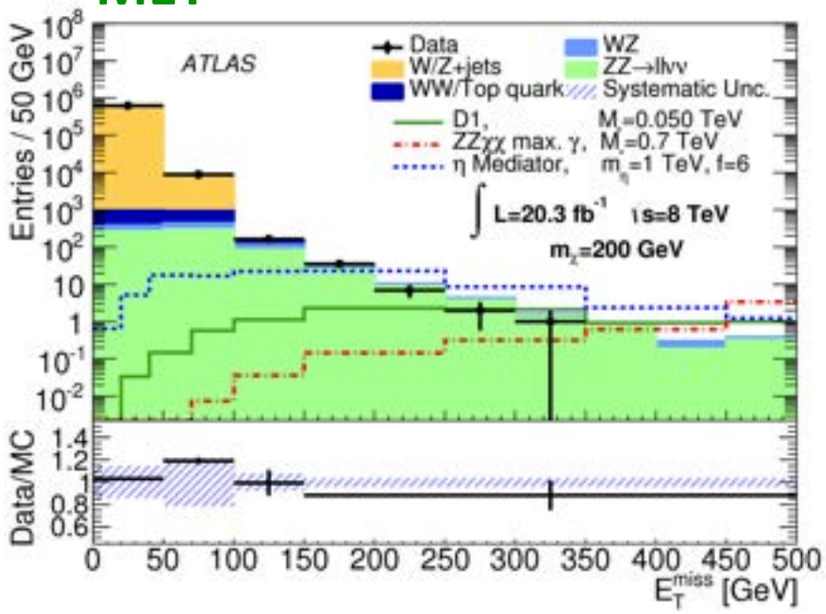
Event selection

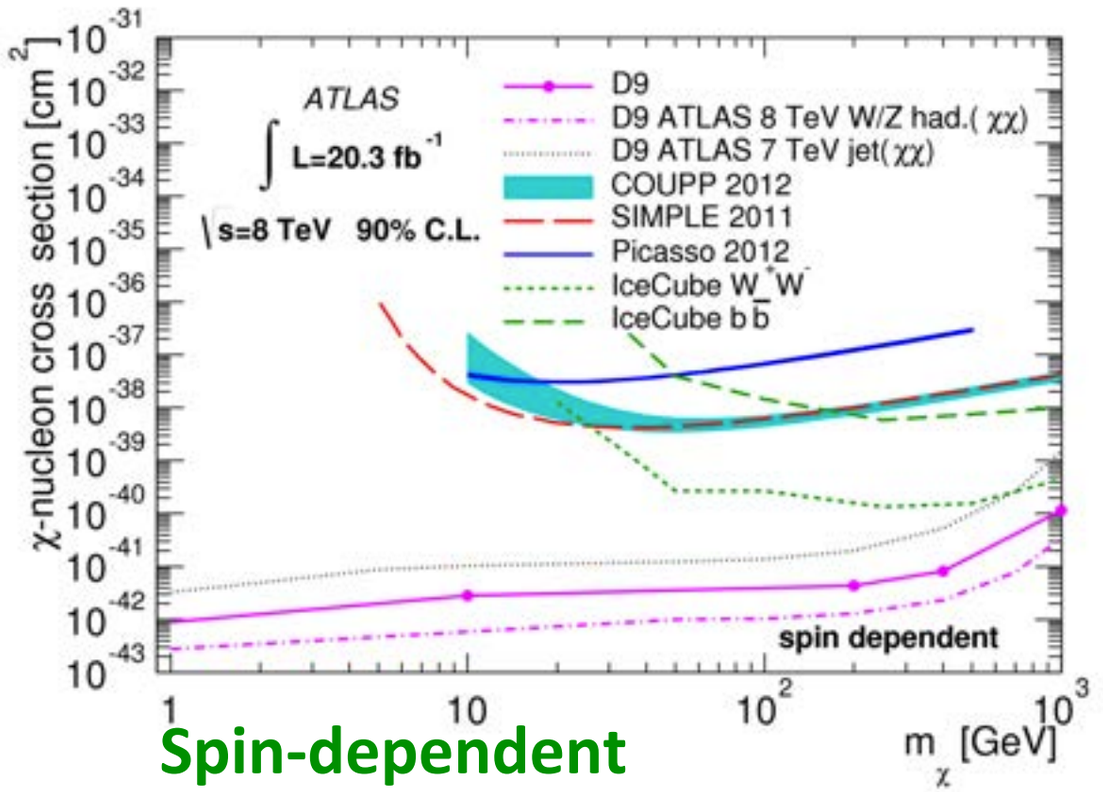
- Muon (Electron) P_T (E_T) > 20 GeV, $|\eta|$ < 2.5 (2.47)
- 76 < M(ll) < 106
- DeltaPhi(P_T(ll),MET) > 2.5
- $|\eta^{ll}|$ < 2.5
- (P_T(ll) - MET)/P_T(ll) < 0.5

Dilepton inv. mass

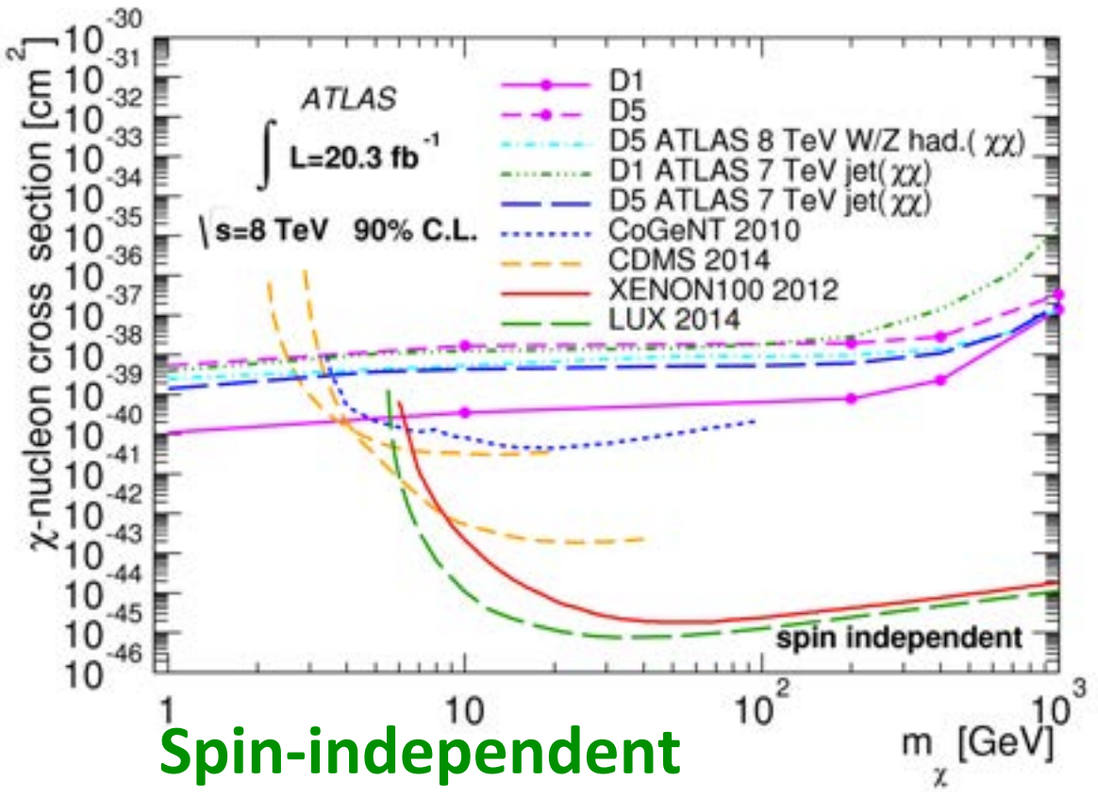


MET





Spin-dependent



Spin-independent

MonoW (W decays leptonically)

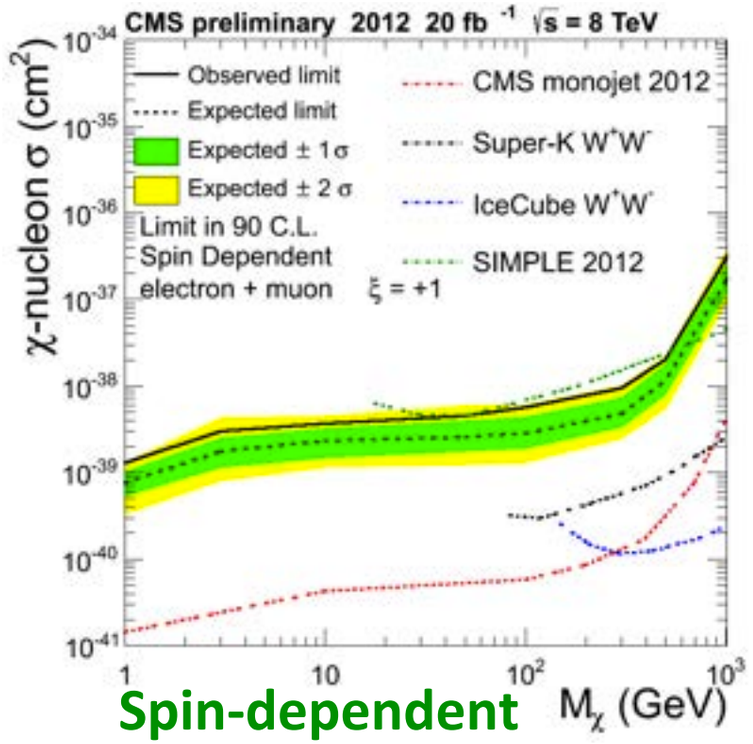
EXO-13-004: http://cds.cern.ch/record/1563245

Dark Matter production with a W

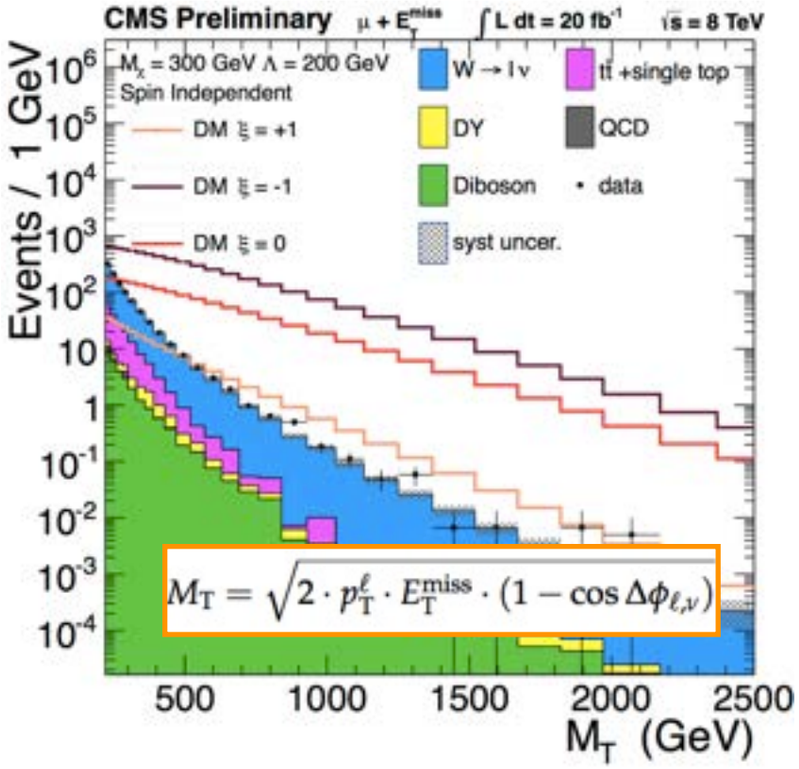
- W recoiling against pair-produced DM
- Vector- and axial-vector couplings considered
- Interference effects parameterized by ξ (W+)

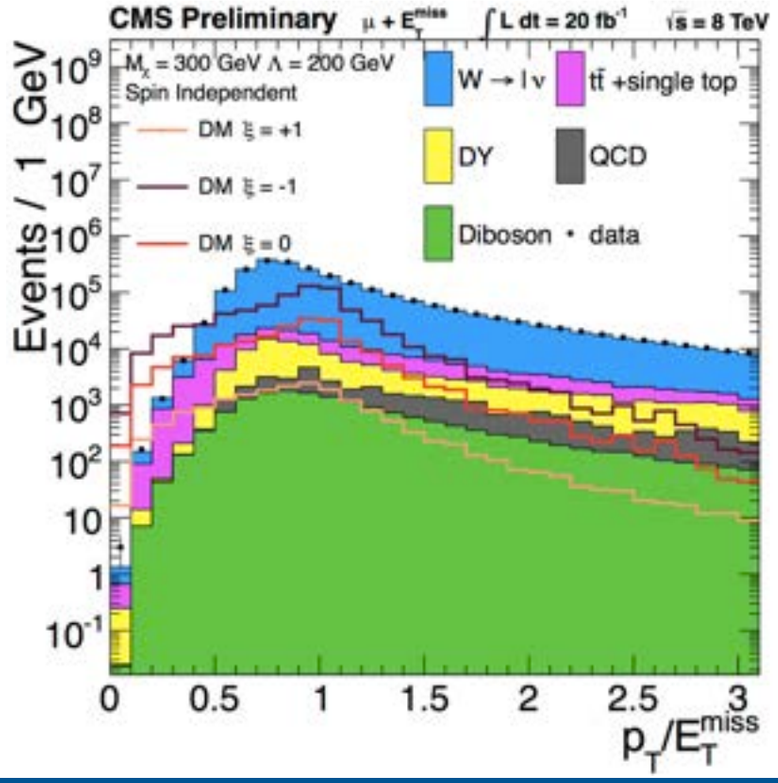
Event selection

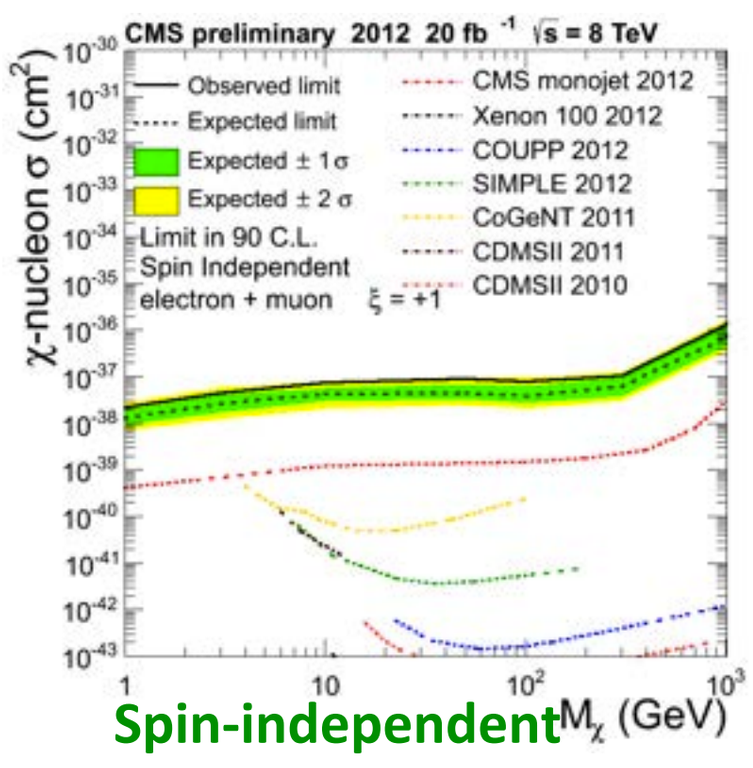
- Muon (Electron) P_T > 45 (100) GeV
- 0.4 < P_T/MET < 1.5
- DeltaPhi(lepton,MET) > 0.8*Pi



Spin-dependent

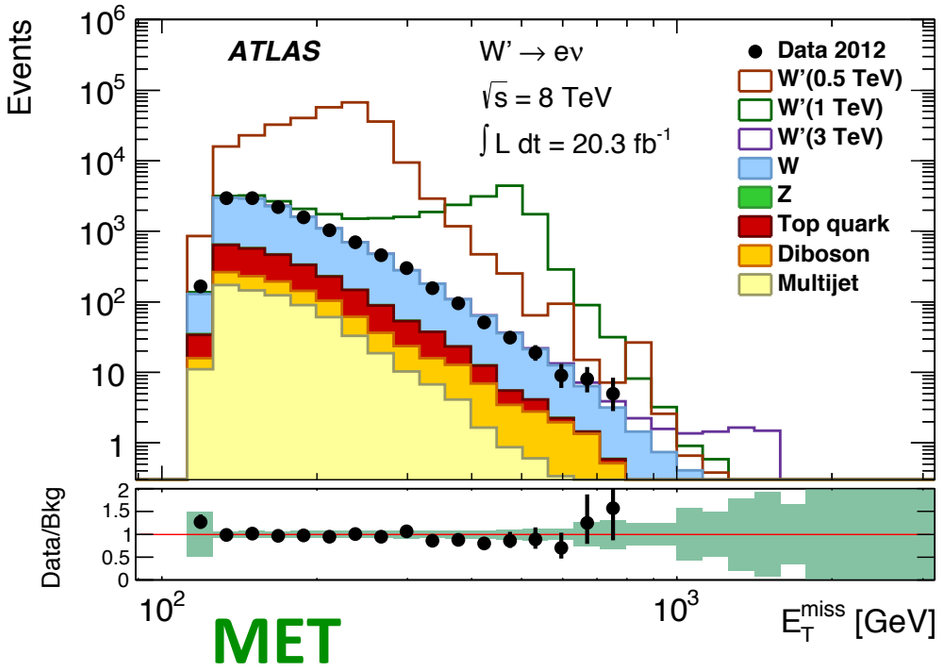






Spin-independent

MonoW (W decays leptonically)



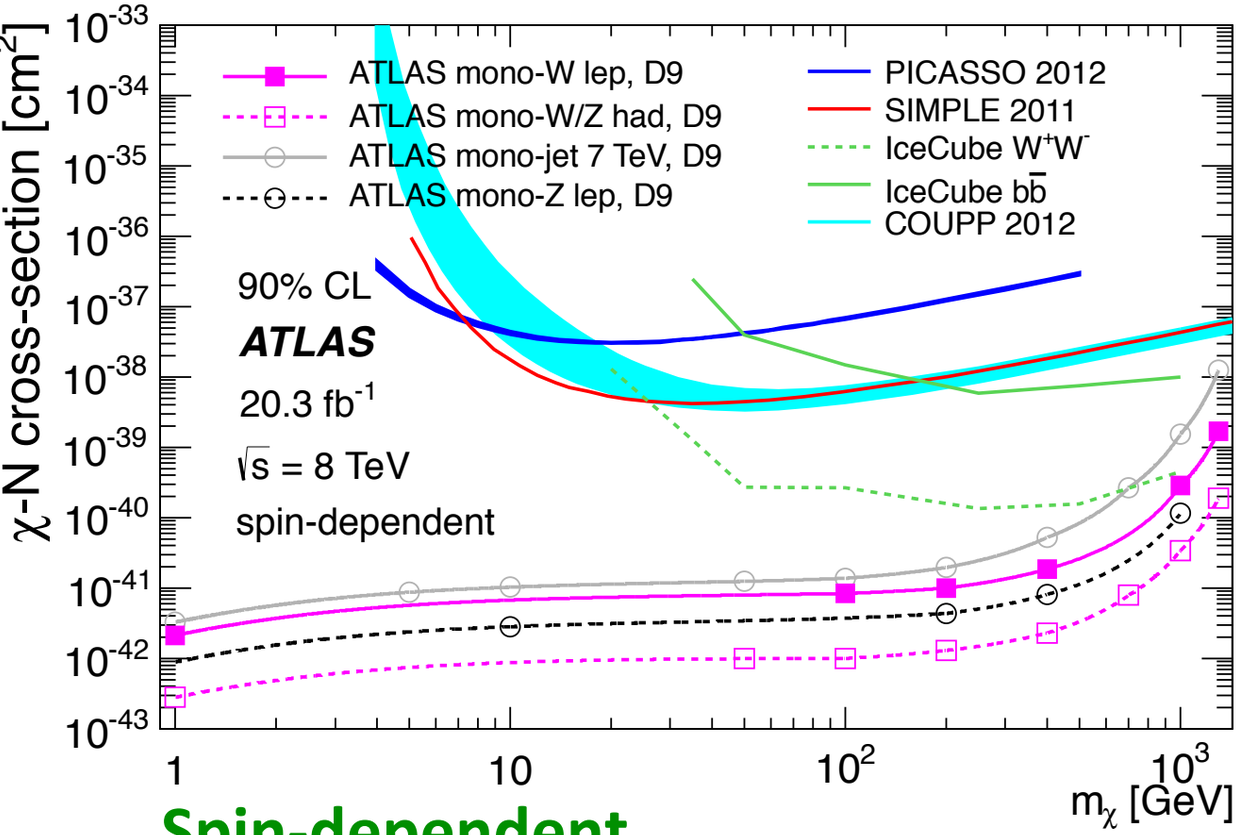
MET

arXiv:1407.7494

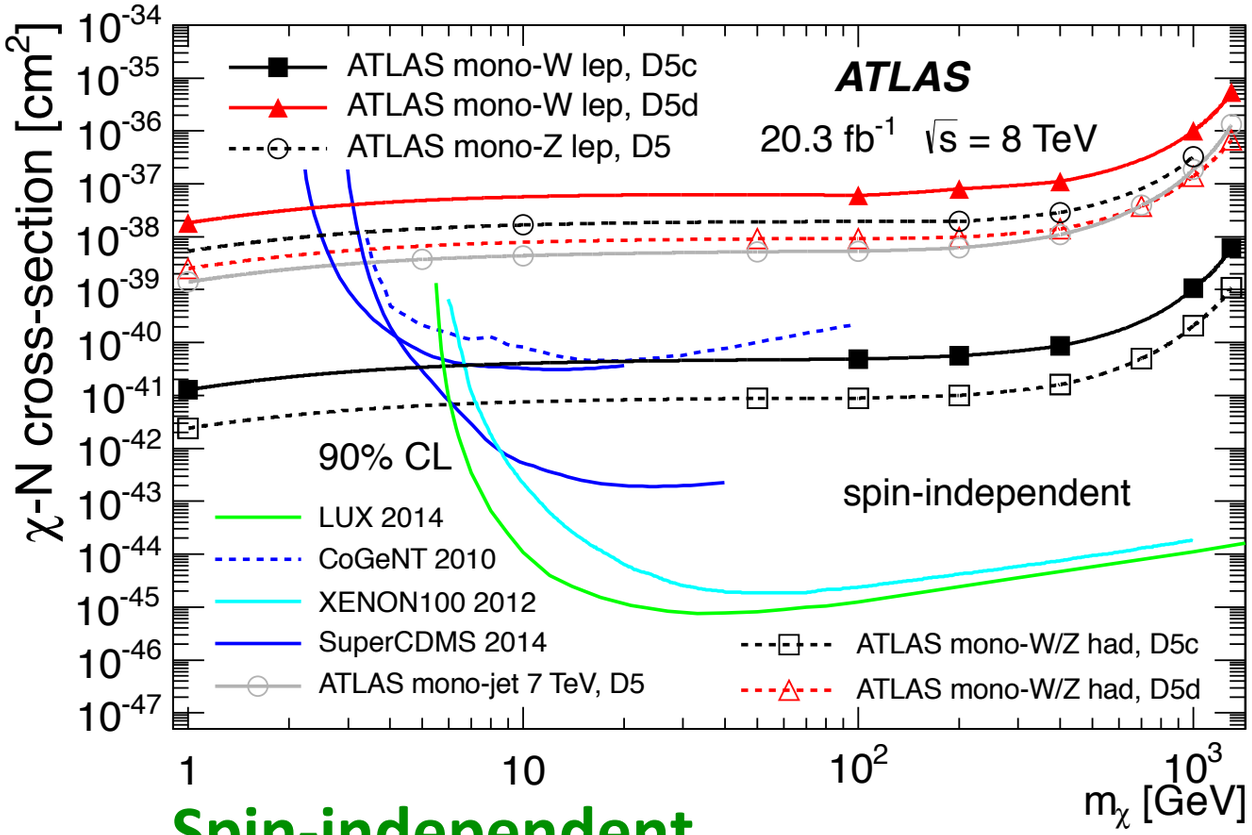
Event selection

- Muon (Electron) P_T > 45 (125) GeV
- MET > 45 GeV (Muon), 125 GeV (Electron)
- M_T > 252 GeV

$$M_{\mathrm{T}} = \sqrt{2 \cdot p_{\mathrm{T}}^{\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$



Spin-dependent



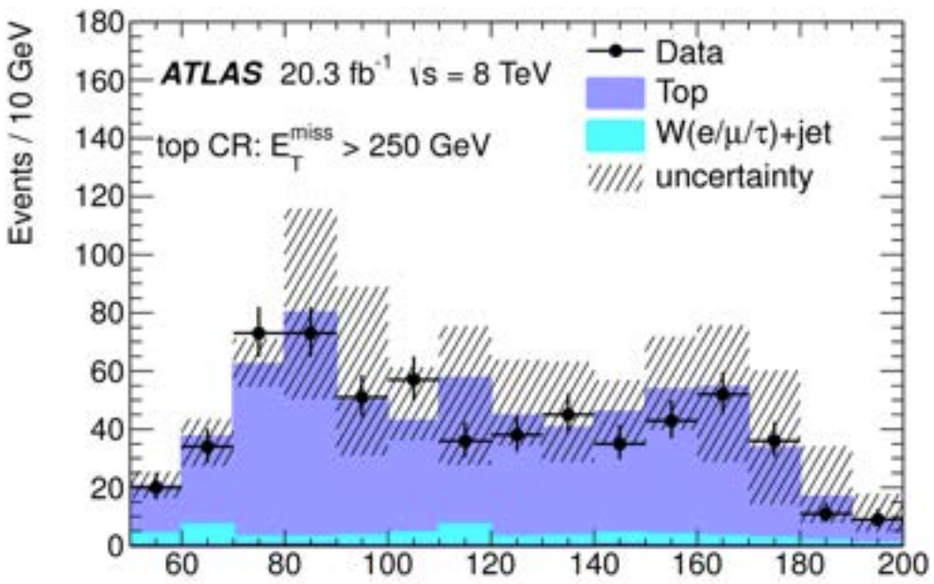
Spin-independent

MonoW, Z (W,Z decays hadronically)

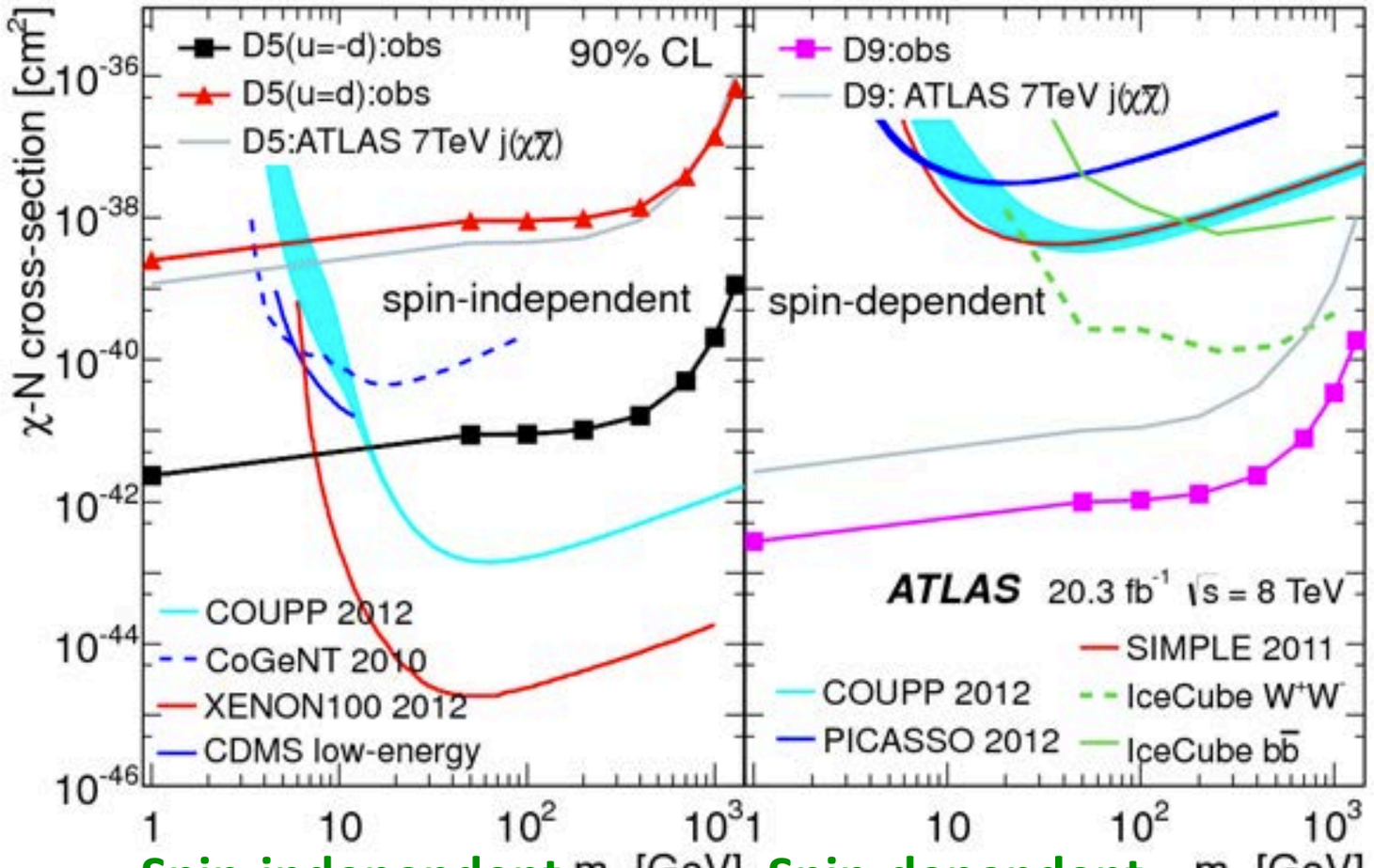
PhysRevLett.112.041802

Event selection

- MET > 150 GeV
- At least, a CA1.2 jet with PT > 250 GeV, $|\eta| < 2.5$, $50 < m_{jet} < 120$
- Reject if there are more than one AK0.4 jet with PT > 40 GeV, $|\eta| < 4.5$ which is not completely overlapping with CA1.2
- Reject if events contain electron, photon, or muon candidates



m_{jet} in the control region

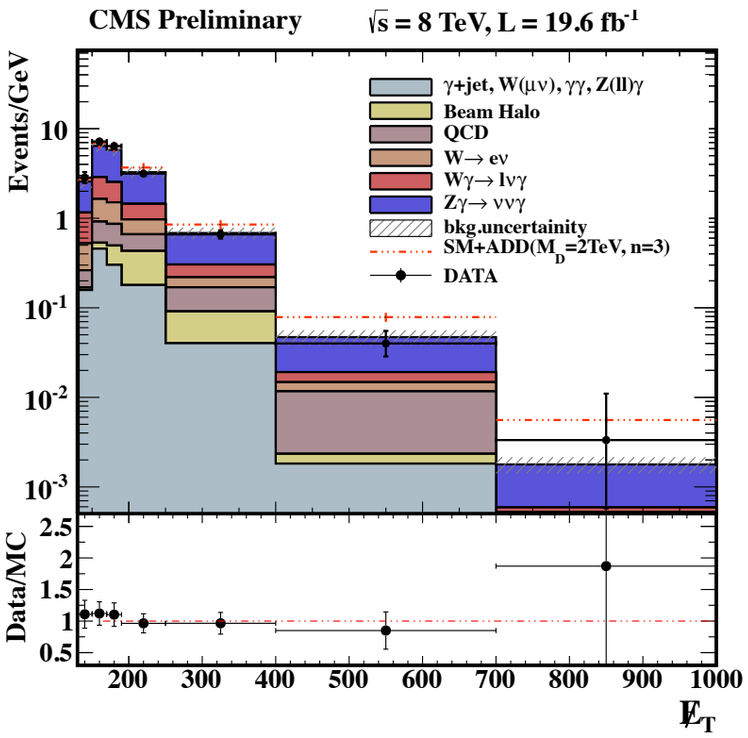


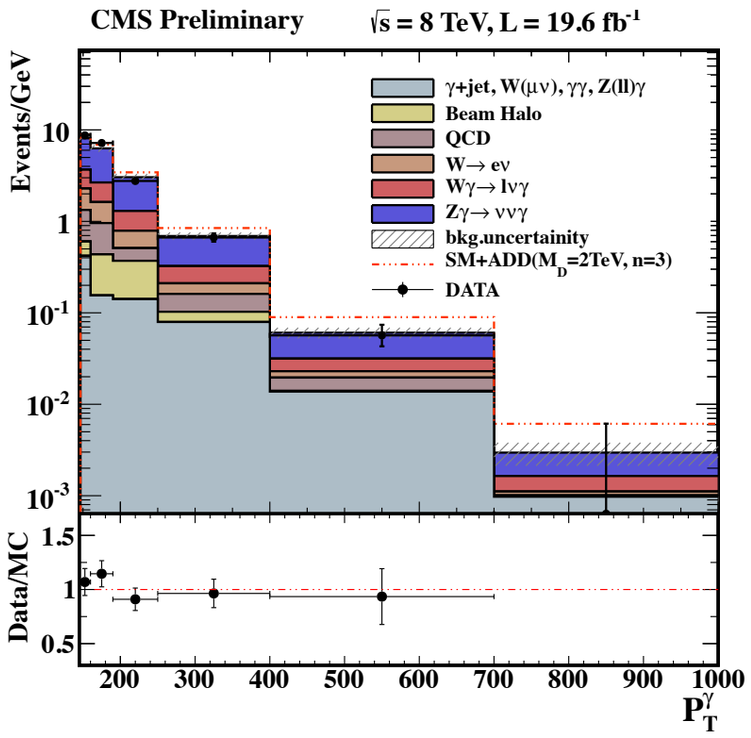
Spin-independent **Spin-dependent**

MonoPhoton

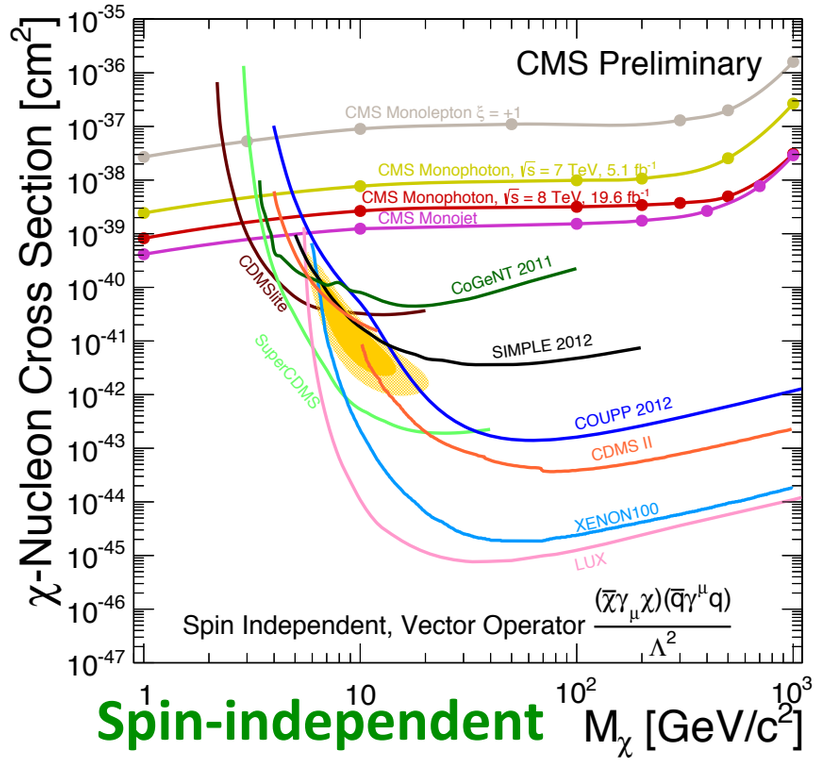
Event selection

- MET > 140 GeV
- One energetic photon, p_T > 145 GeV, $|\eta|$ < 1.4442
- Veto on jets, leptons, and pixel seeds (hit pattern in the pixel detector)
- DeltaPhi(photon,MET) > 2
- MinMET > 120 GeV, Prob(χ^2) (Reduce fake MET events)

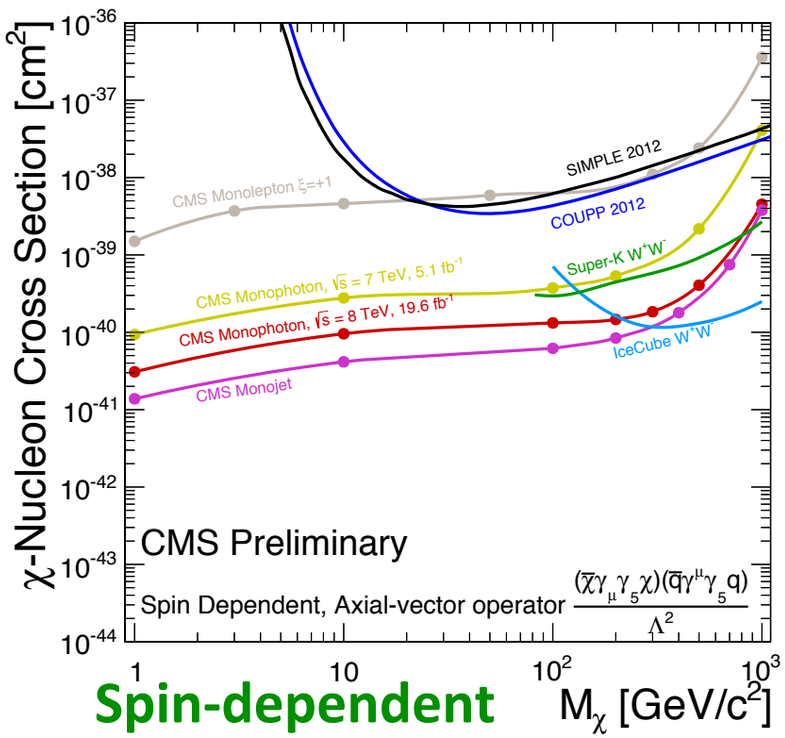




EXO-12-047: http://cds.cern.ch/record/1702015



Spin-independent



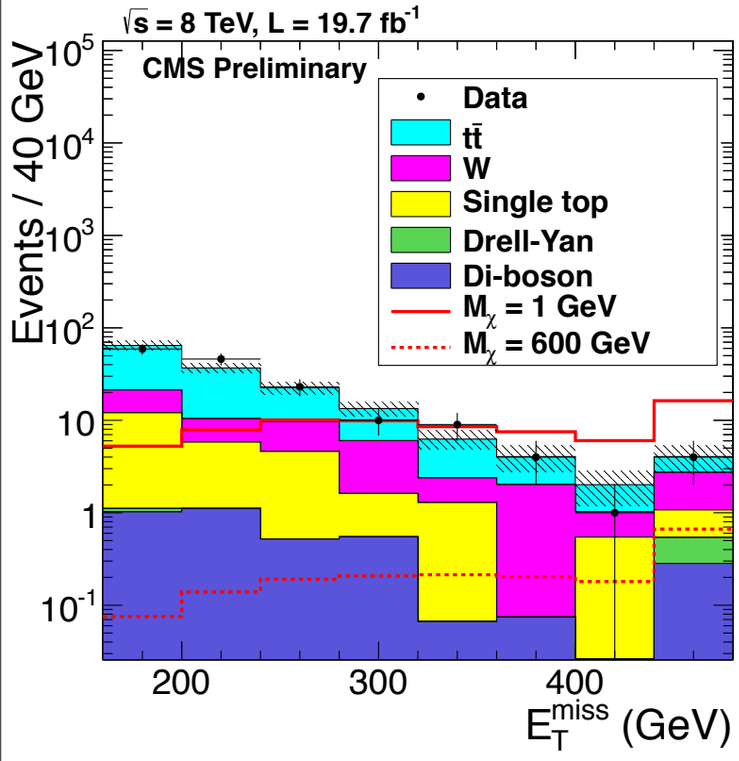
Spin-dependent

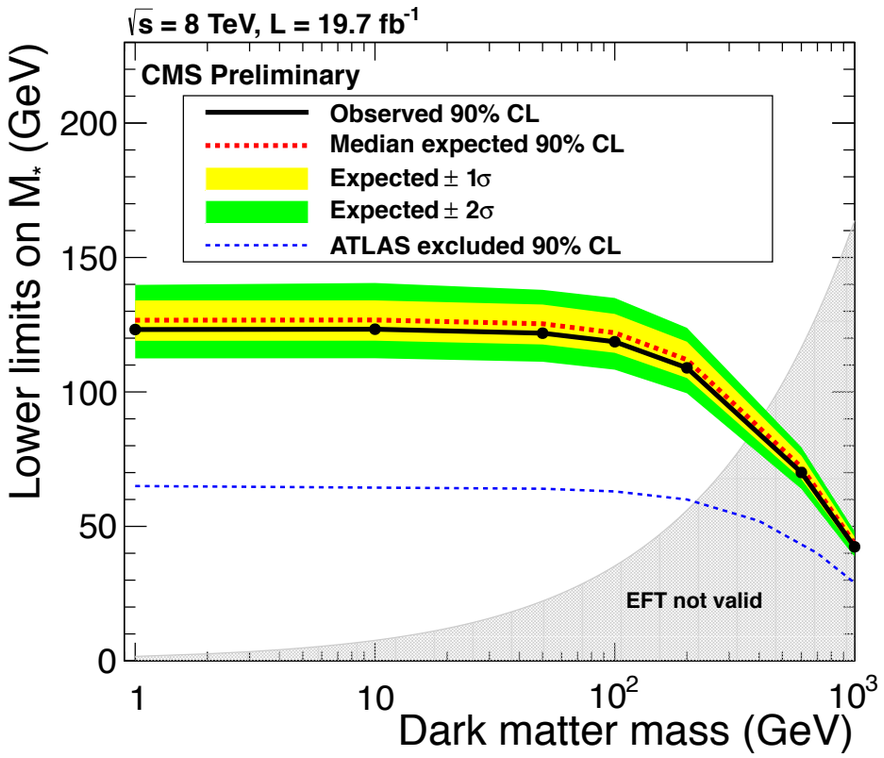
Top quark pair

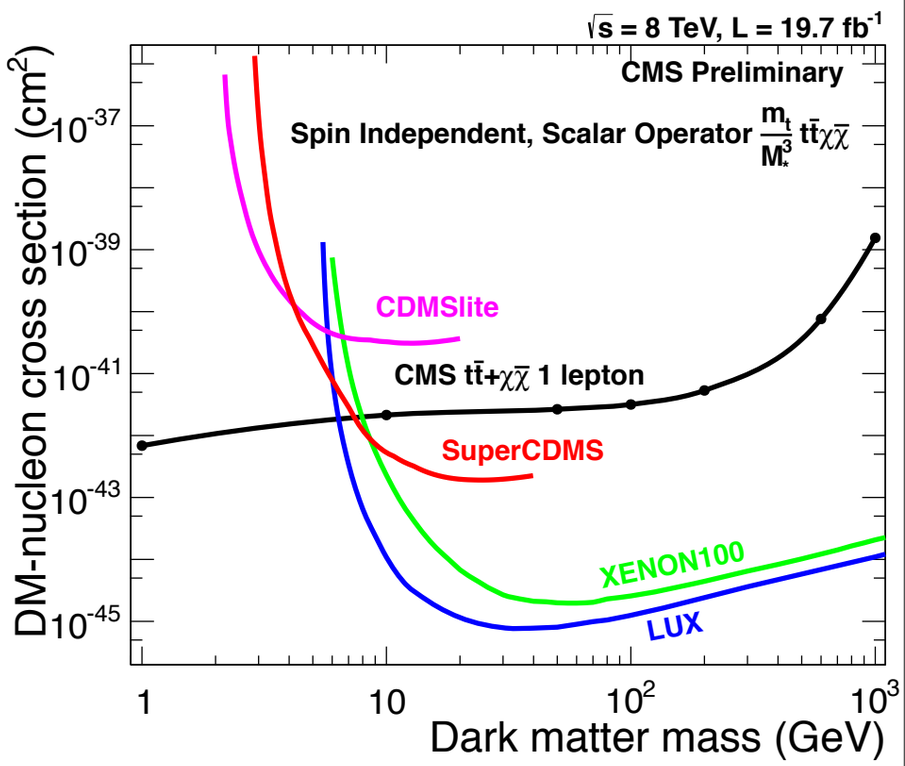
Event selection

B2G-14-004: http://cds.cern.ch/record/1749153

- Select pairs of top quarks in the di-lepton channels
- Exactly two identified leptons, and at least two jets are selected.
- M(ll) > 20 GeV and |M(ll) − 91 GeV| > 15 GeV
- MET > 320 GeV
- HT(j_1, j_2) < 400 GeV, HT(l_1, l_2) > 120 GeV, DeltaPhi(l_1, l_2) < 2





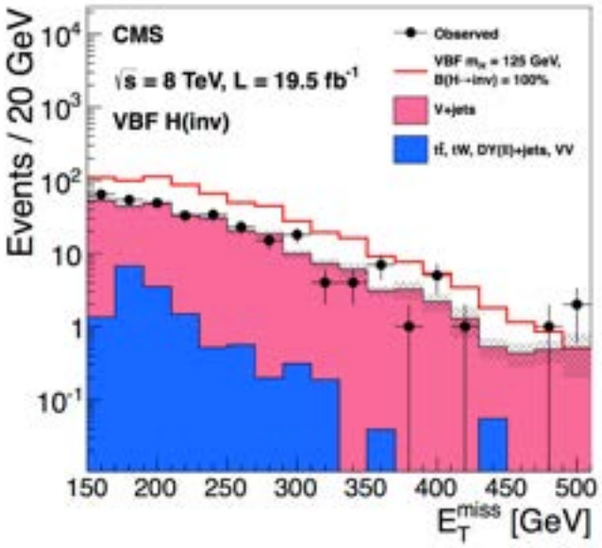


Higgs Portal to Dark Matter

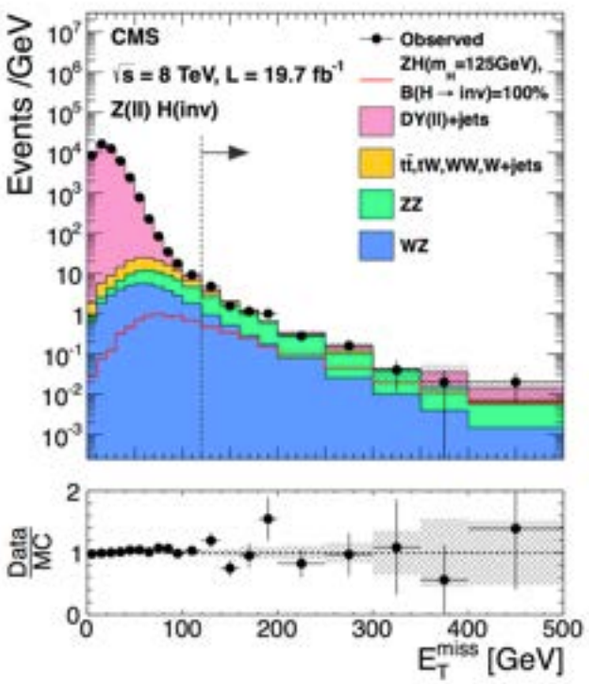
arXiv:1404.1344v2

DM particles have the direct couplings to the SM Higgs sector, $H \rightarrow X\,X$

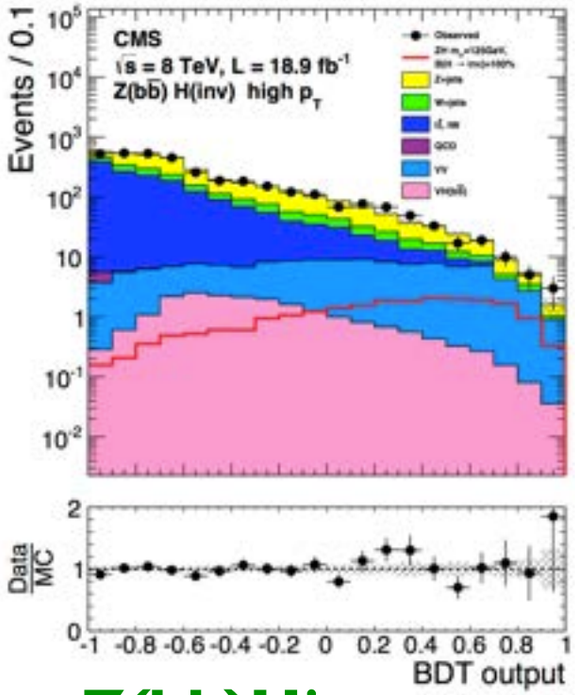
- Limits on branching fraction of Higgs to "invisible" particles used for limits on DM
- Can be scalar, vector or fermionic couplings
- Limits only up to DM mass $M_X < M_H/2$



VBF Hinv

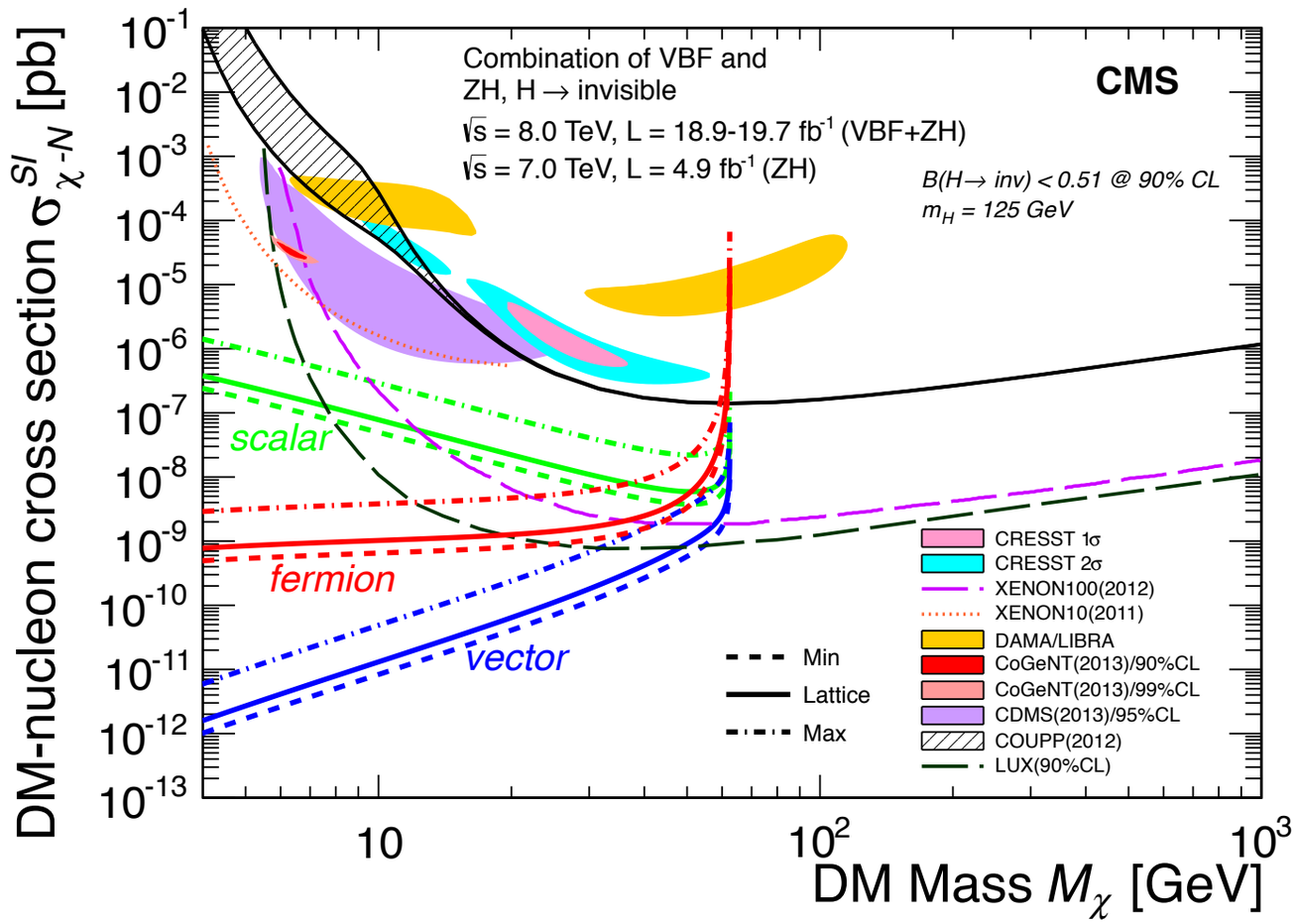


Z(ll)Hinv



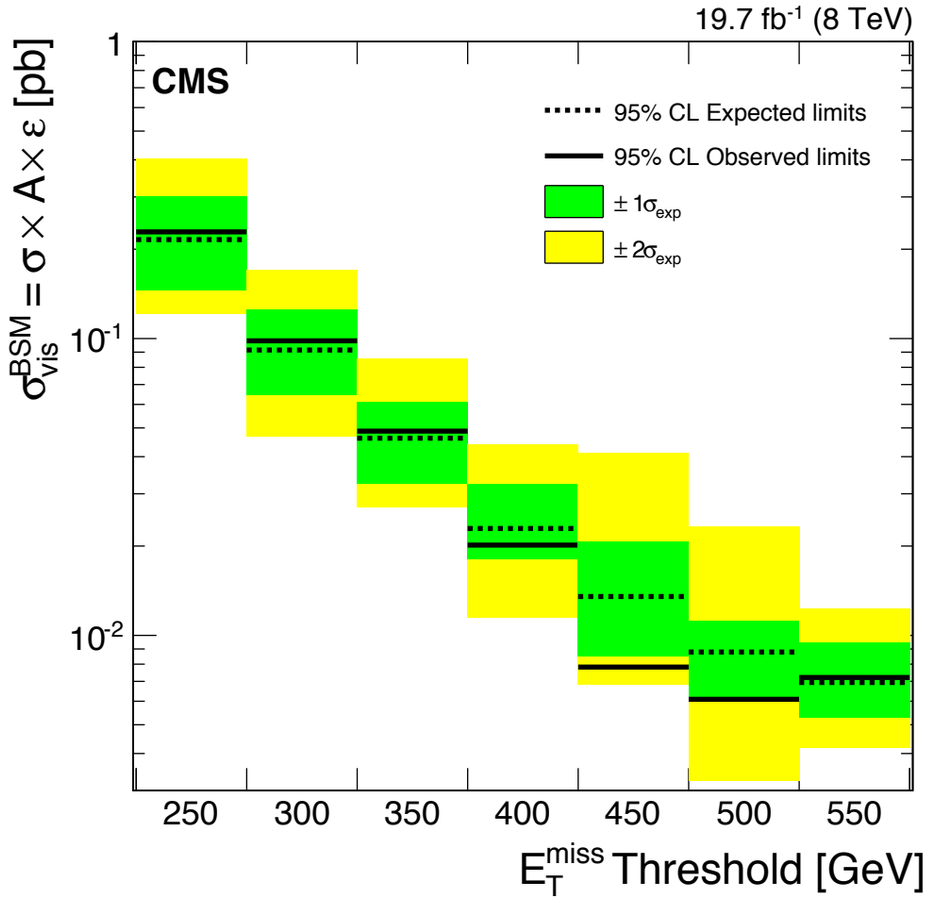
Z(bb)Hinv

mH=125GeV, and B(H→inv) < 0.51 at 90% CL, as a function of the DM mass.



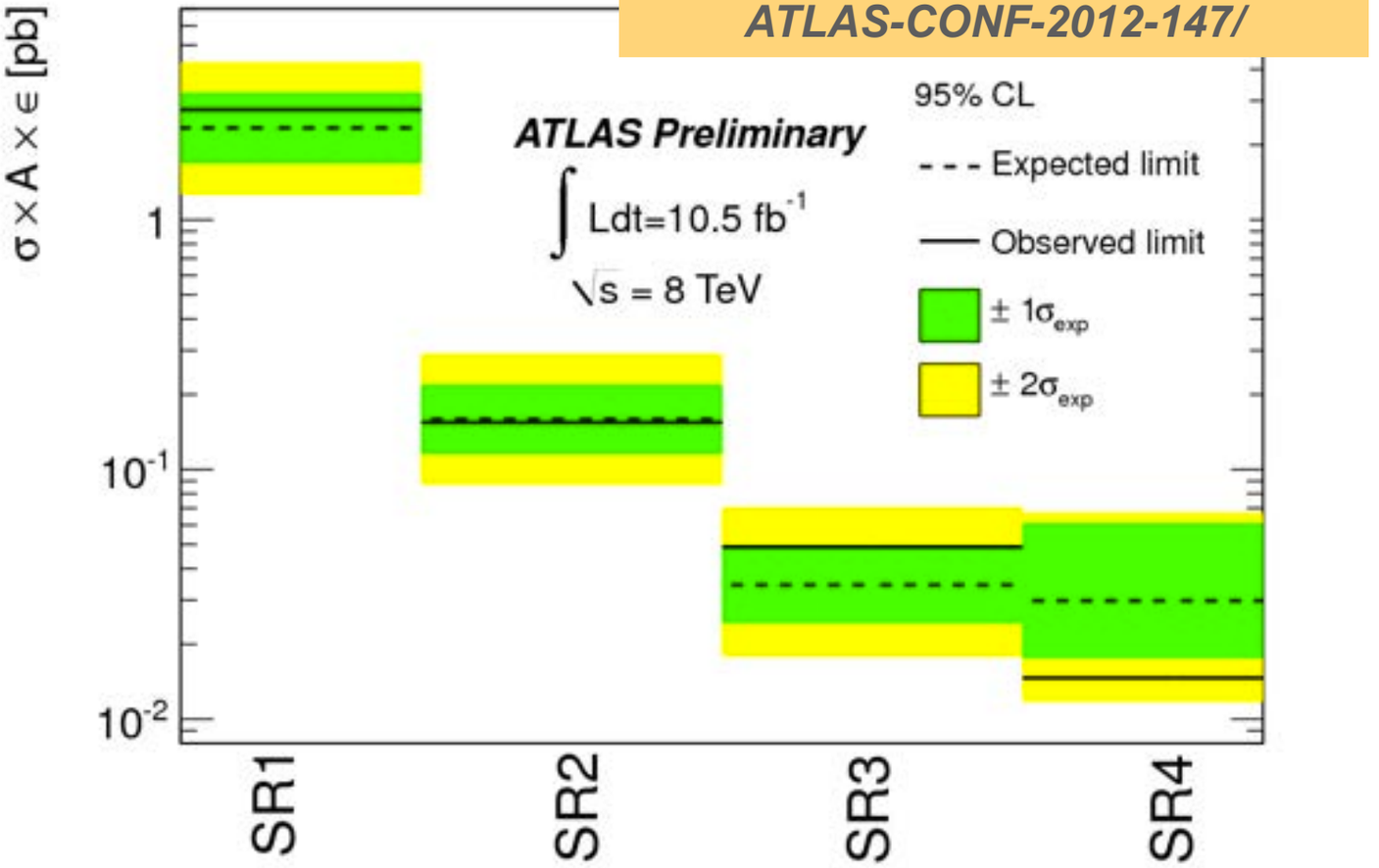
Preparation for LHC Run2 / HL-LHC

- Develop for X + MET Triggers
- Object IDs for Run2
- Background estimations, and uncertainties (Reduce bkg uncertainties)
  - Challenging goal for HL-LHC (next slide)
- Experiments should firstly provide the model independent limits



EXO-12-048: http://cds.cern.ch/record/1525585

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-147/



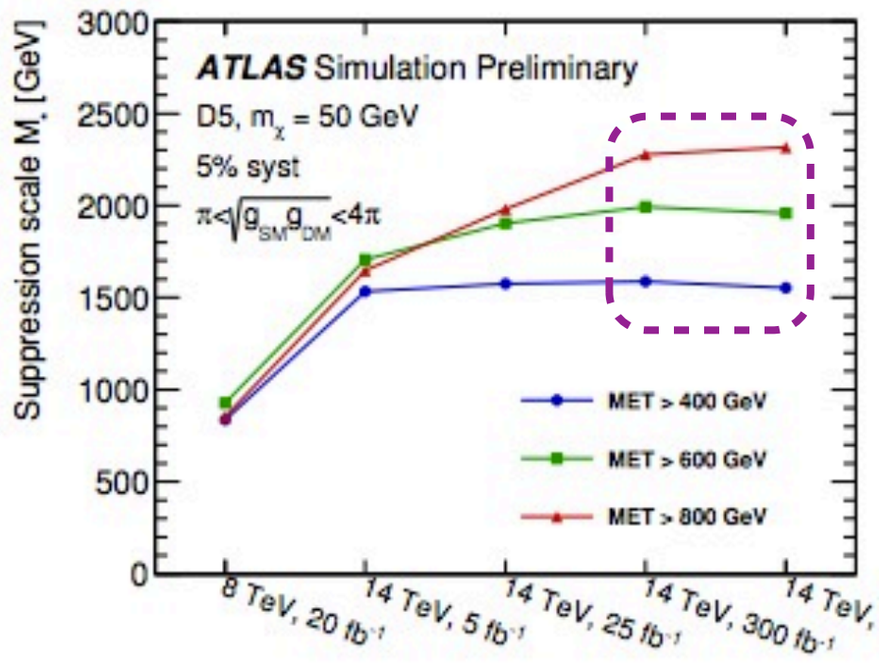
Preparation for LHC Run2 / HL-LHC

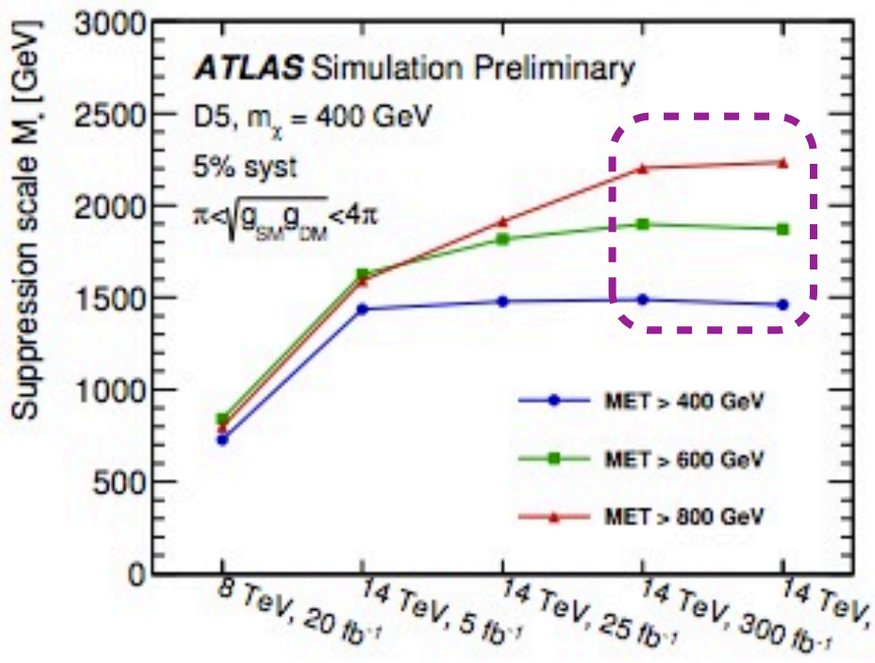
ATL-PHYS-PUB-2014-007

- Projection study (assume that EFT is valid)

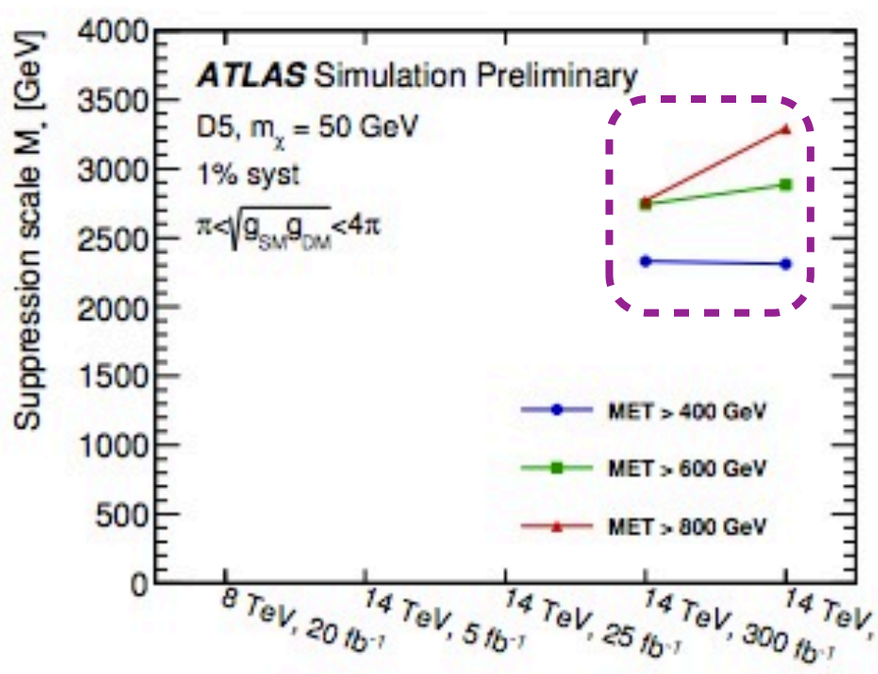
mDM = 50 GeV | **mDM = 400 GeV**

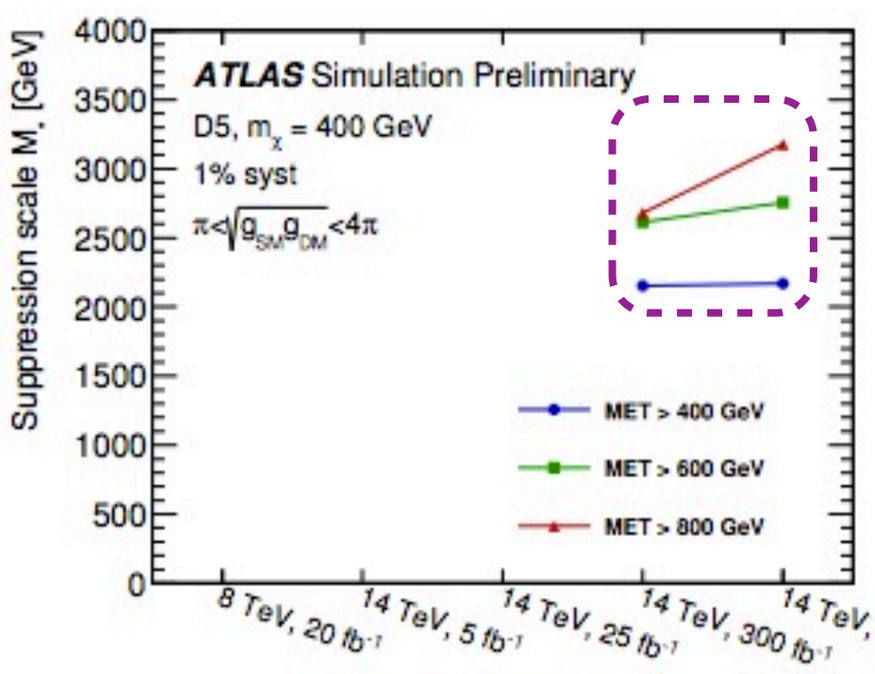
5% unc





1% unc

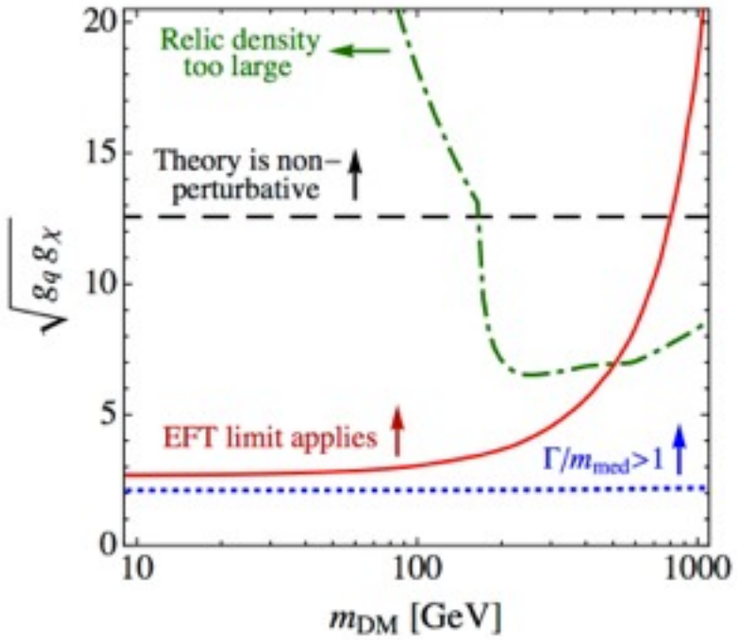


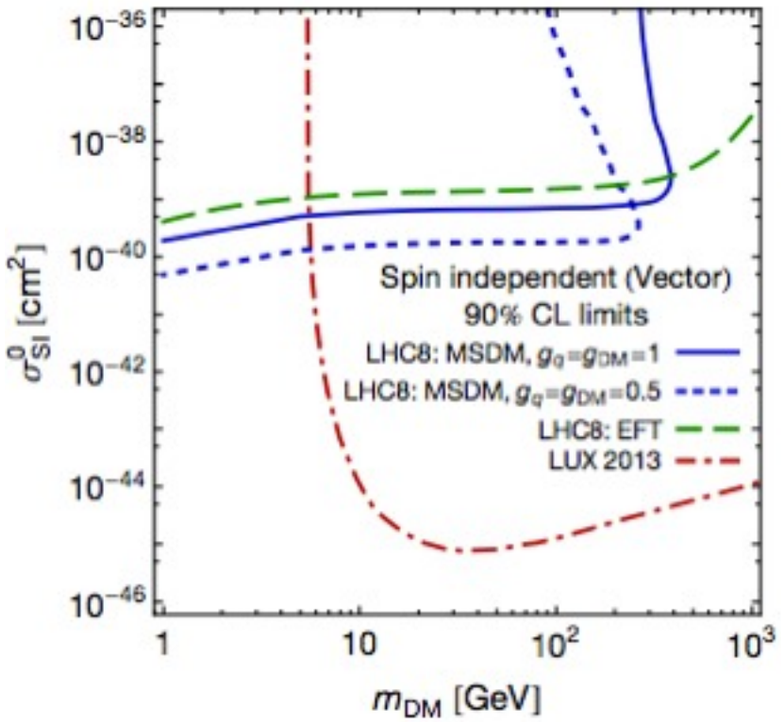


Preparation for LHC Run2 / HL-LHC

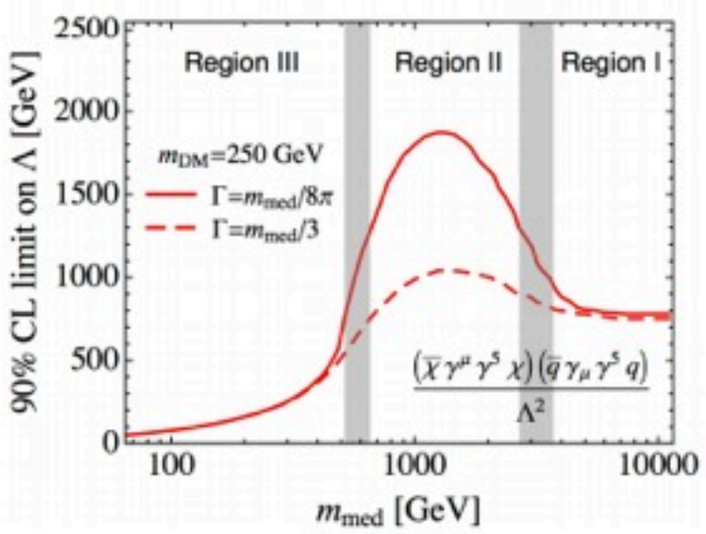
arXiv:1404.8257

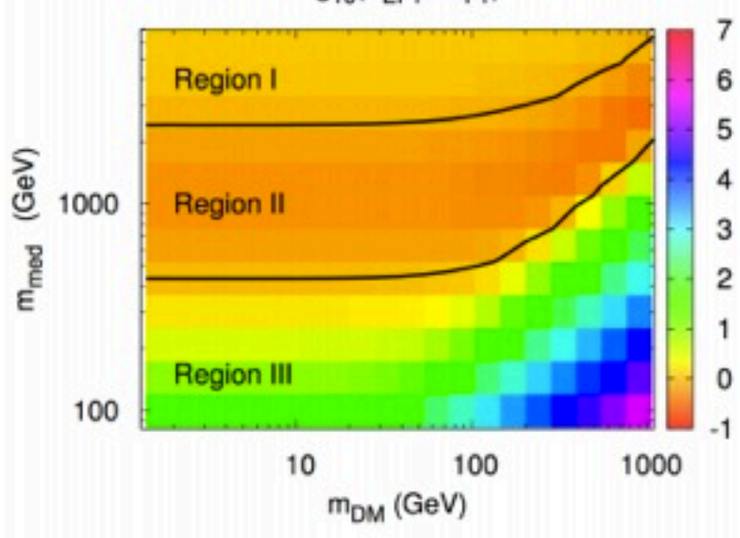
- Physics models
  - No one knows the correct theory to describe particle dark matter
  - EFT and its validity

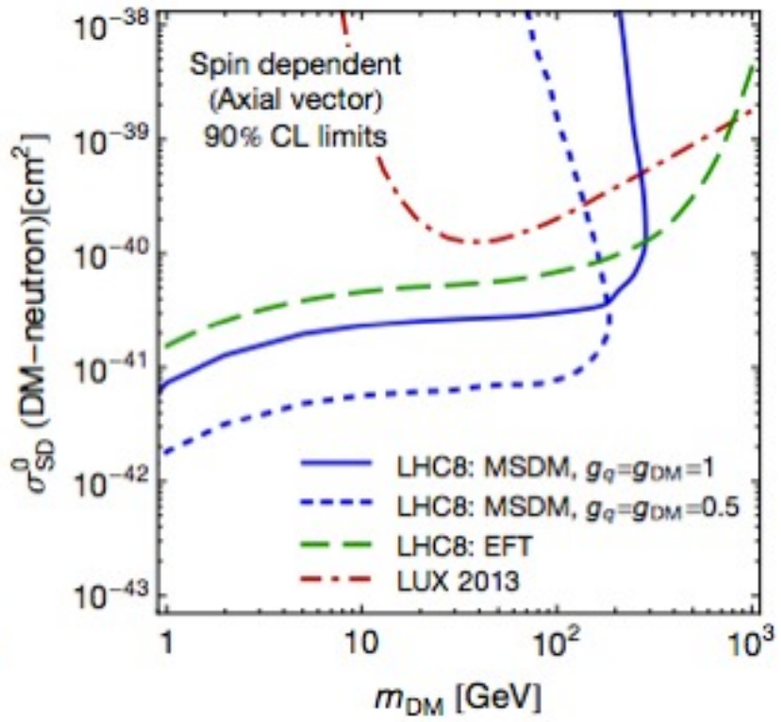




- Look at limit on $\Lambda = \dfrac{m_{\rm med}}{\sqrt{g_q g_\chi}}$





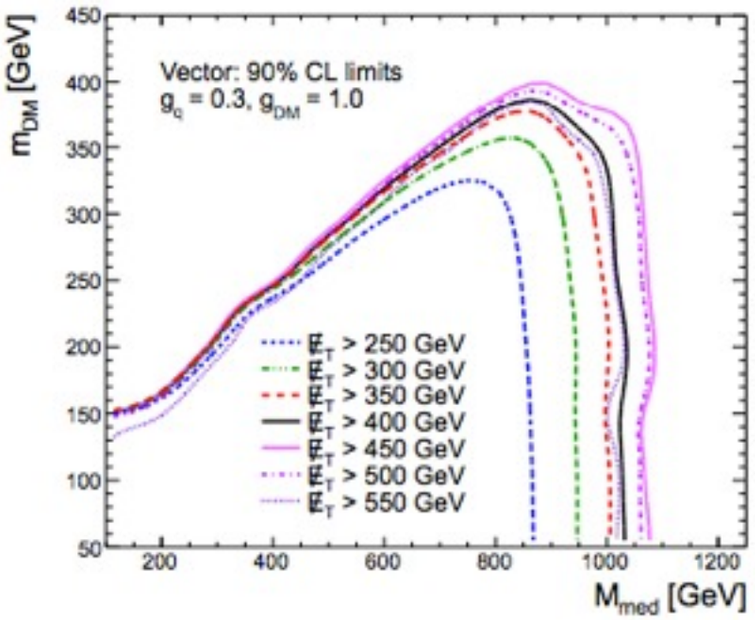


- Region I: EFT limit is good $m_{\rm med} \gtrsim 3$ TeV
- Region II: EFT limit is too weak
- Region III: EFT limit is too strong $m_{\rm med} \lesssim 500$ GeV

http://agenda.albanova.se/contributionDisplay.py?contribId=280&sessionId=254&confId=4115

Preparation for LHC Run2 / HL-LHC

- Physics models

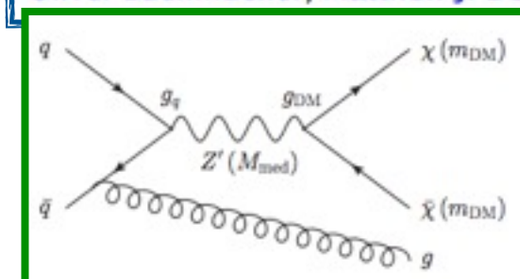


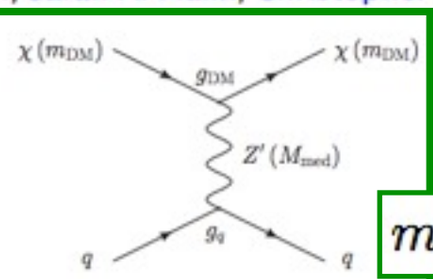
arXiv.org > hep-ph > arXiv:1407.8257

High Energy Physics - Phenomenology

Characterising dark matter searches at colliders and direct detection experiments: Vector mediators

Oliver Buchmueller, Matthew J. Dolan, Sarah A. Malik, Christopher McCabe





m_{DM}, M_{med}, g_{DM} and g_q

arXiv.org > hep-ph > arXiv:1304.0711

High Energy Physics - Phenomenology

Natural GeV Dark Matter and the Baryon-Dark Matter Coincidence Puzzle

Rouzbeh Allahverdi, Bhaskar Dutta

(Submitted on 2 Apr 2013)

arXiv.org > hep-ph > arXiv:1308.0612

High Energy Physics - Phenomenology

Fermion Portal Dark Matter

Yang Bai, Joshua Berger

arXiv.org > hep-ph > arXiv:1208.4605

High Energy Physics - Phenomenology

The impact of heavy-quark loops on LHC dark matter searches

Ulrich Haisch, Felix Kahlhoefer, James Unwin

2012 (v1), last revised 2 Aug 2013 (this version, v2))

arXiv.org > hep-ph > arXiv:1401.1825

High Energy Physics - Phenomenology

Probing Light Nonthermal Dark Matter at the LHC

Bhaskar Dutta, Yu Gao, Teruki Kamon

(Submitted on 8 Jan 2014)

Preparation for LHC Run2 / HL-LHC

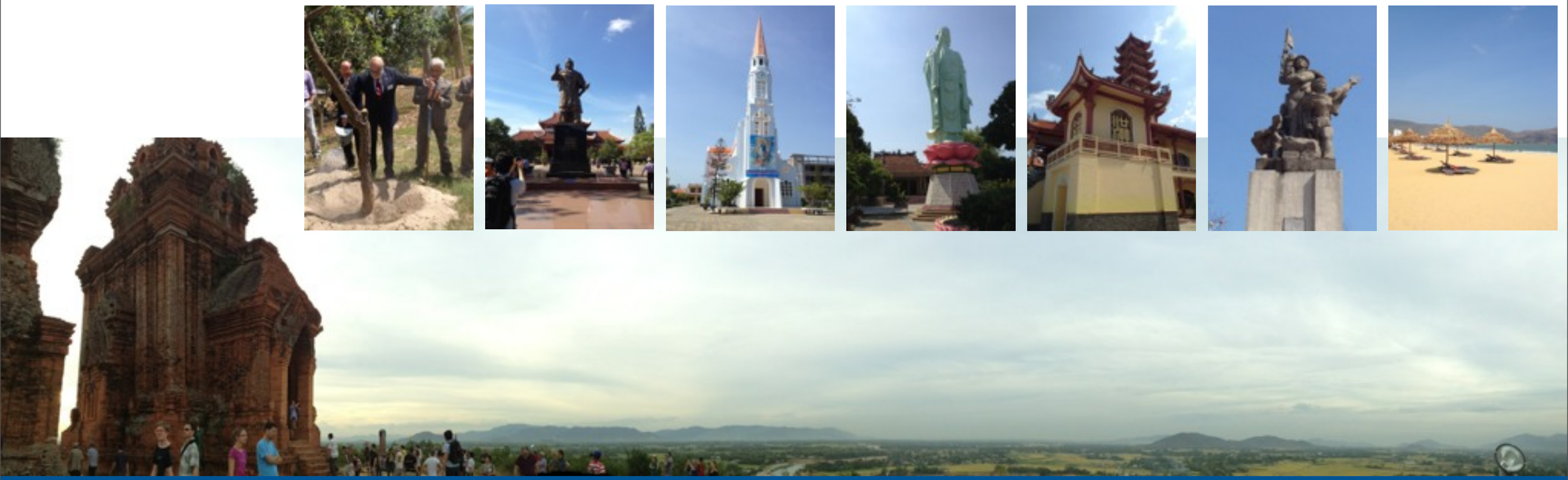
A workshop to further develop simplified models and effective field theory approaches to DM, taking stock of the final results of the 8 TeV LHC run, and to prepare for the next phase of data-taking at higher energies.

Summary

- Presented the collider based search results for Dark Matter at ATLAS and CMS detectors, and comparisons with direct, and indirect DM searches.

- Preparing for LHC Run2, HL-LHC
  - Model independent / Reduce the uncertainty of background prediction
  - Various models of DM production @ collider

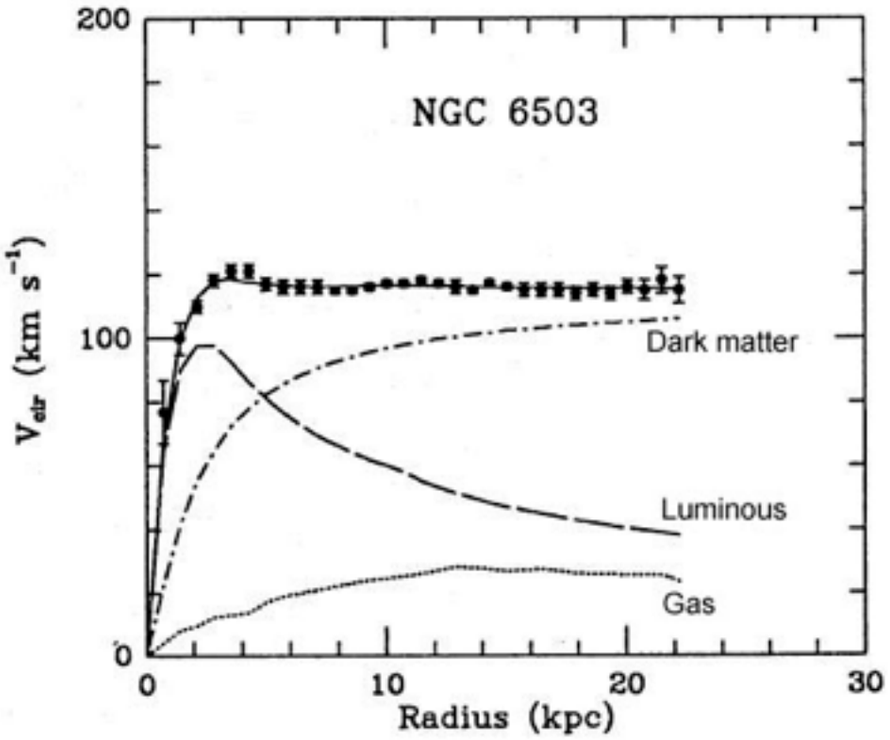
- Since we don't know what is/are the particle DMs, their couplings, or masses, the powerful future collider can help us to scan the wide range of possibilities of DM productions.



Backup

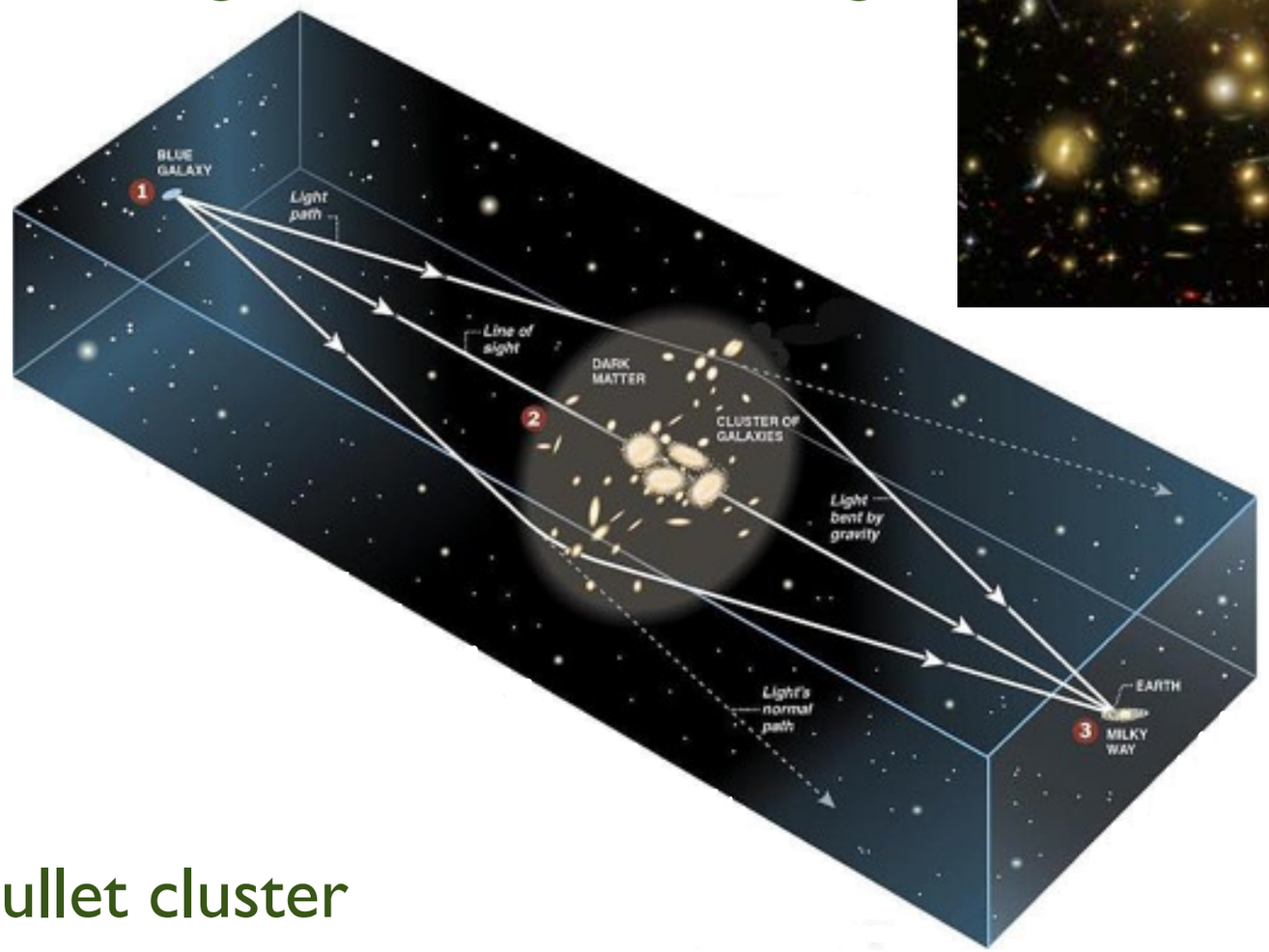
Dark matter

Strong evidences for the existence of dark matter, i.e. :



Galactic rotation curves

Strong Gravitational Lensing

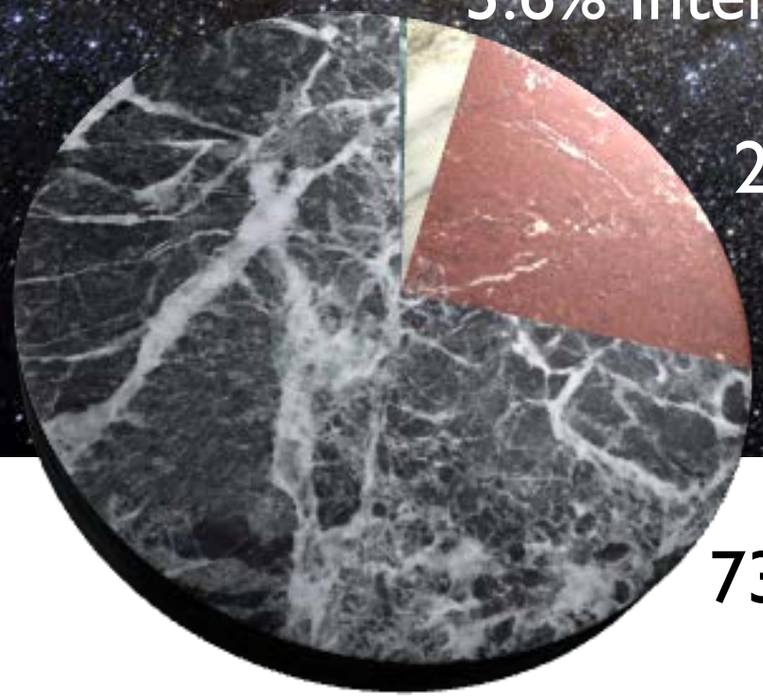


Bullet cluster

Dark matter

0.4% Stars, Organic forms, etc.

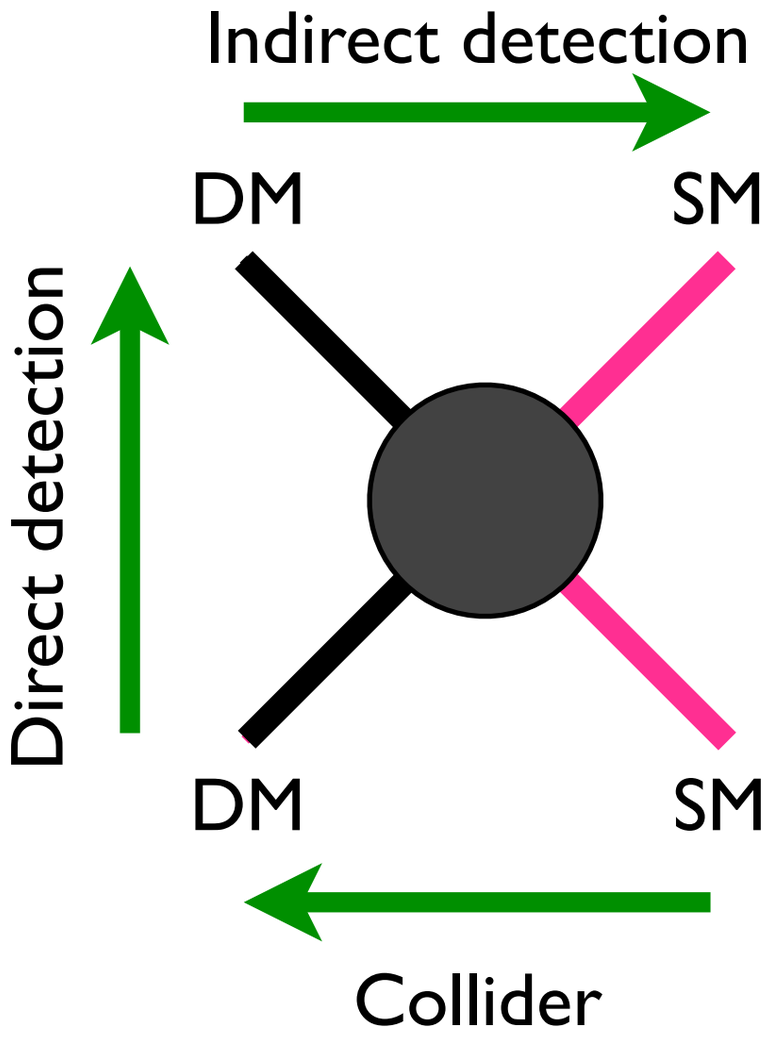
3.6% Intergalactic Gas



23% Dark Matter

73% Dark Energy

Searches for dark matter



1. Direct Detection Experiments
- Dark Matter-nucleus scattering.
- Low mass DM particles not probed yet.
- Less sensitive to spin-dependent coupling.
- XENON-100, CDMS, CoGeNT

2. Indirect Detection Experiments
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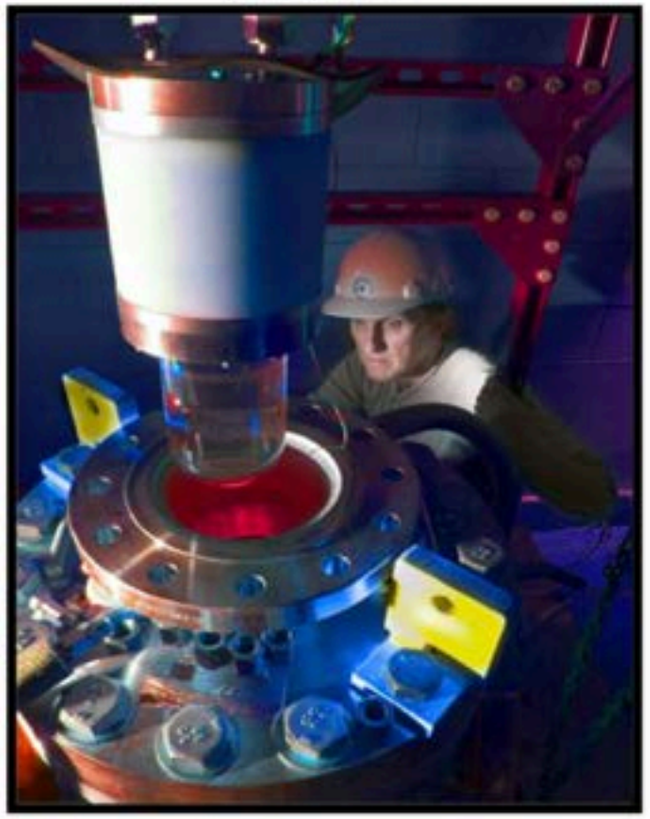
- Tevatron, LHC

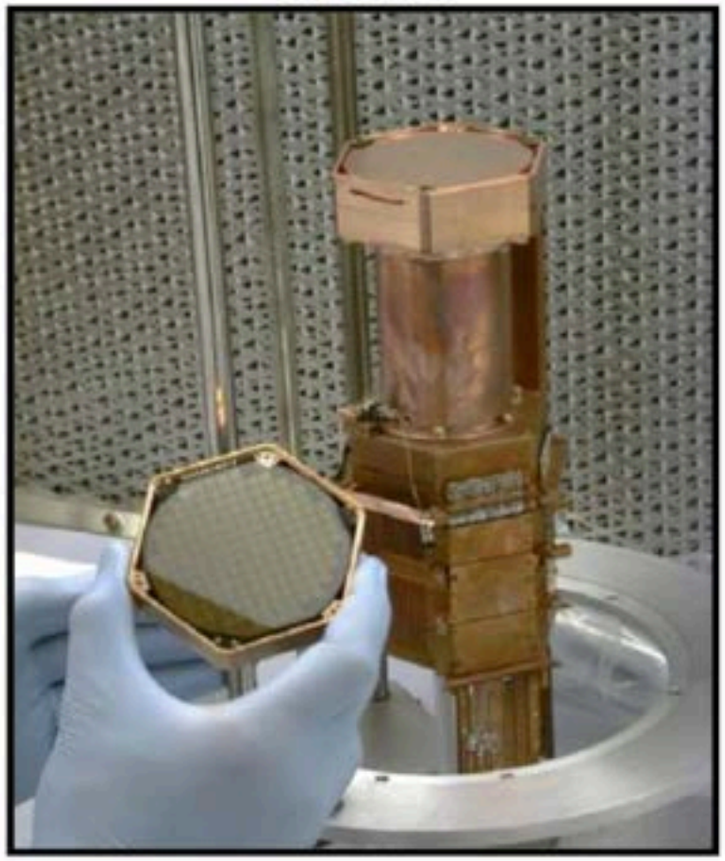
Needs independent verifications from various astrophysical and non-astrophysical experiments.

Direct detection

COUPP

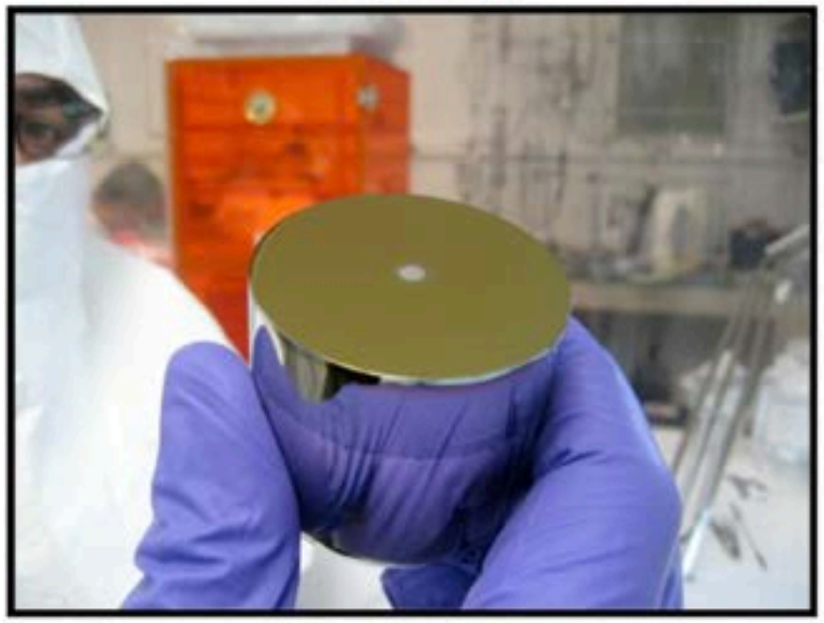


CDMS



CRESST

CoGeNT

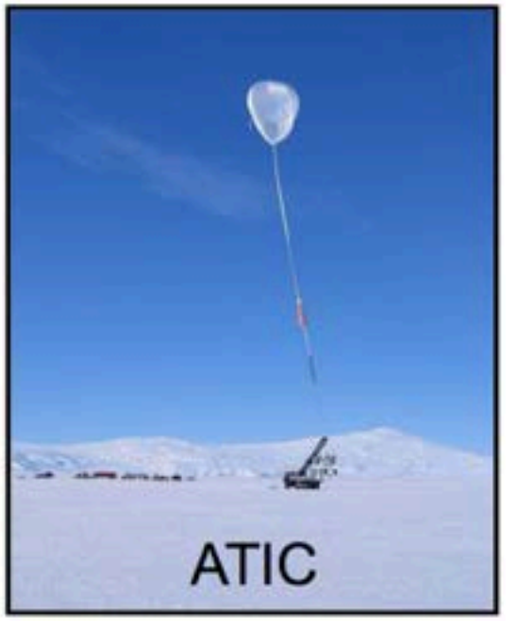


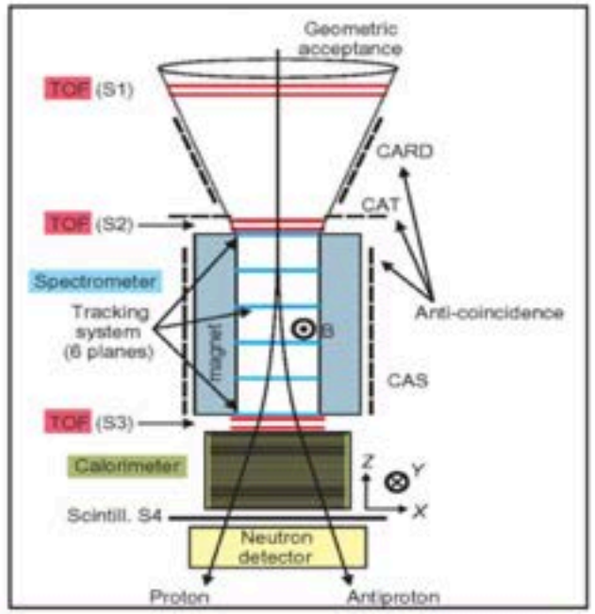
(+ EDELWEISS, DAMA, EURECA, ZEPLIN, DEAP, ArDM, WARP, LUX, SIMPLE, PICASSO, DMTPC, DRIFT, KIMS, …)

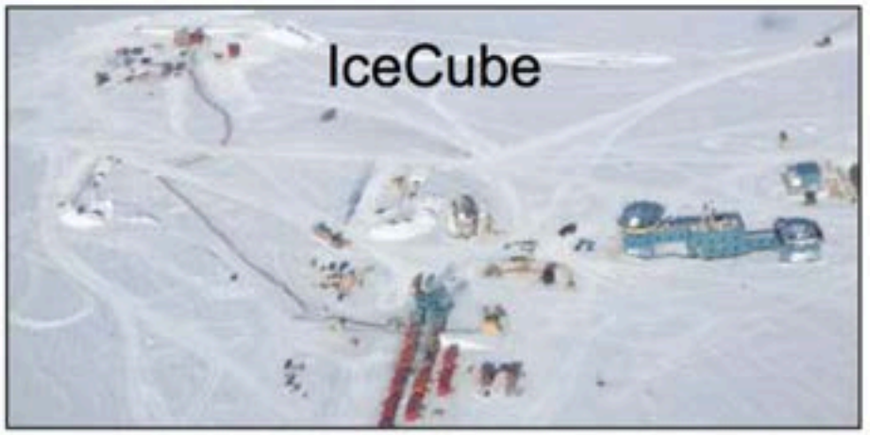
Xenon

S. Worm

Indirect detection

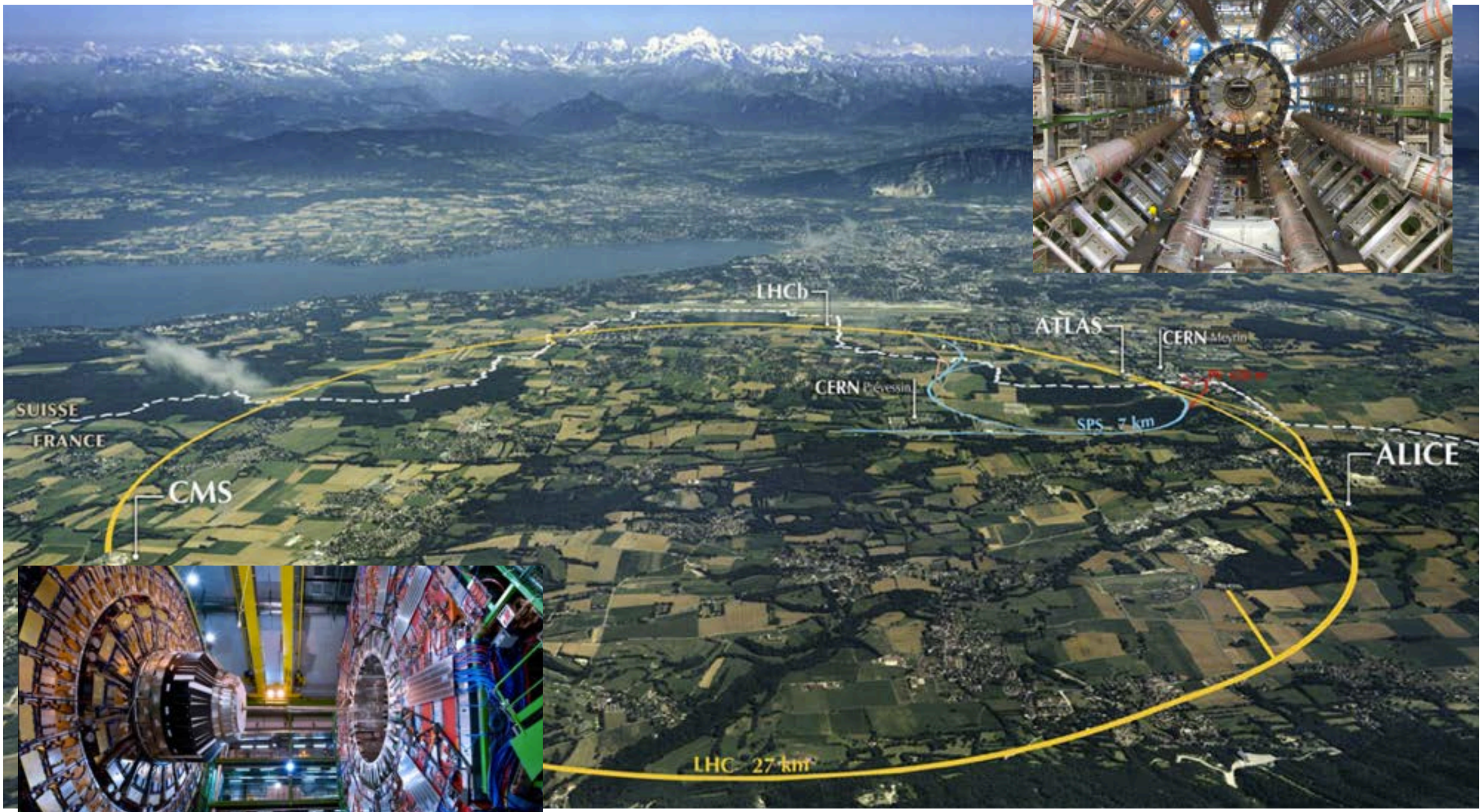






S. Worm

Collider


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SUISSE
FRANCE
SPS 7 km
ALICE
CMS
LHC 27 km

minMET (monophoton)

MHT Minimization

A way to identify and reduce the fake met contribution, where you minimize the unclustered energy in the event by trying to re-distribute the energy back into the visible objects.

$$\hat{\not{E}}_{x,y} = \not{E}^{reco}_{x,y} + \sum_{i=objects} (p^{reco}_{x,y})_i - (\hat{p_{x,y}})_i$$

$$\not{E}_T{}^2 = \not{E}_x^2 + \not{E}_y^2$$

$$\chi^2 = \sum_{i=objects} \left(\frac{(p_T^{reco})_i - (\hat{p}_T)_i}{(\sigma_{p_T})_i} \right)^2 + \left(\frac{\hat{\not{E}}_x}{\sigma_{\not{E}_x}} \right)^2 + \left(\frac{\hat{\not{E}}_y}{\sigma_{\not{E}_y}} \right)^2 .$$

If the Met is intrinsic, balancing the object momenta wouldn't be easy and will result in high χ^2 .

The variables that give good discrimination are the Prob(χ^2) and the recalculated minimized Met.

BDT parameters, Z(bb)+H(inv)

Table 6: Input variables to the $Z(b\bar{b})H(inv)$ BDT.

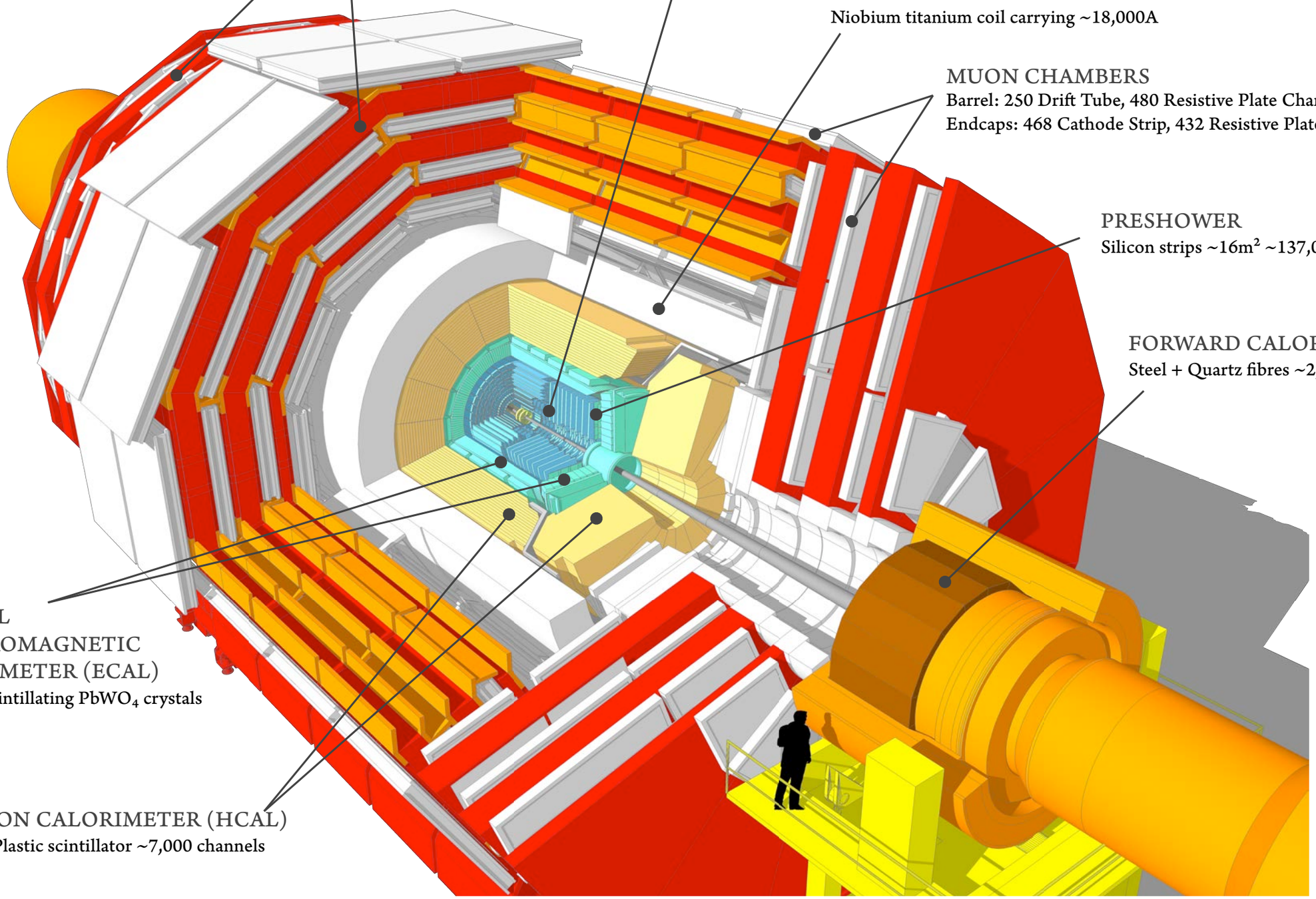
Variable	
p_T^{j1}, p_T^{j2}	Transverse momentum of each Z boson daughter
M_{jj}	Dijet invariant mass
p_T^{jj}	Dijet transverse momentum
E_T^{miss}	Missing transverse energy
N_{aj}	Number of additional jets ($p_T > 25\,GeV$ and $\|\eta\| < 4.5$)
CSV_{max}	Value of CSV for the Z boson daughter with largest CSV value
CSV_{min}	Value of CSV for the Z boson daughter with second largest CSV value
$\Delta\phi(Z,H)$	Azimuthal angle between E_T^{miss} and dijet
$\Delta\eta_{jj}$	Difference in η between Z daughters
ΔR_{jj}	Distance in η-ϕ between Z daughters
$\Delta\theta_{pull}$	Color pull angle [62]
$\Delta\phi(E_T^{miss},j)$	Azimuthal angle between E_T^{miss} and the closest jet
CSV_{aj}	Maximum CSV of the additional jets in an event
$\Delta R(H,aj)$	Minimum distance between an additional jet and the Z boson candidate
m_T	Transverse mass of the ZH system

Compact Muon Solenoid (CMS)

CMS DETECTOR

Total weight	: 14,000 tonnes
Overall diameter	: 15.0 m
Overall length	: 28.7 m
Magnetic field	: 3.8 T

Schematic view of the CMS Detector showing its main components.



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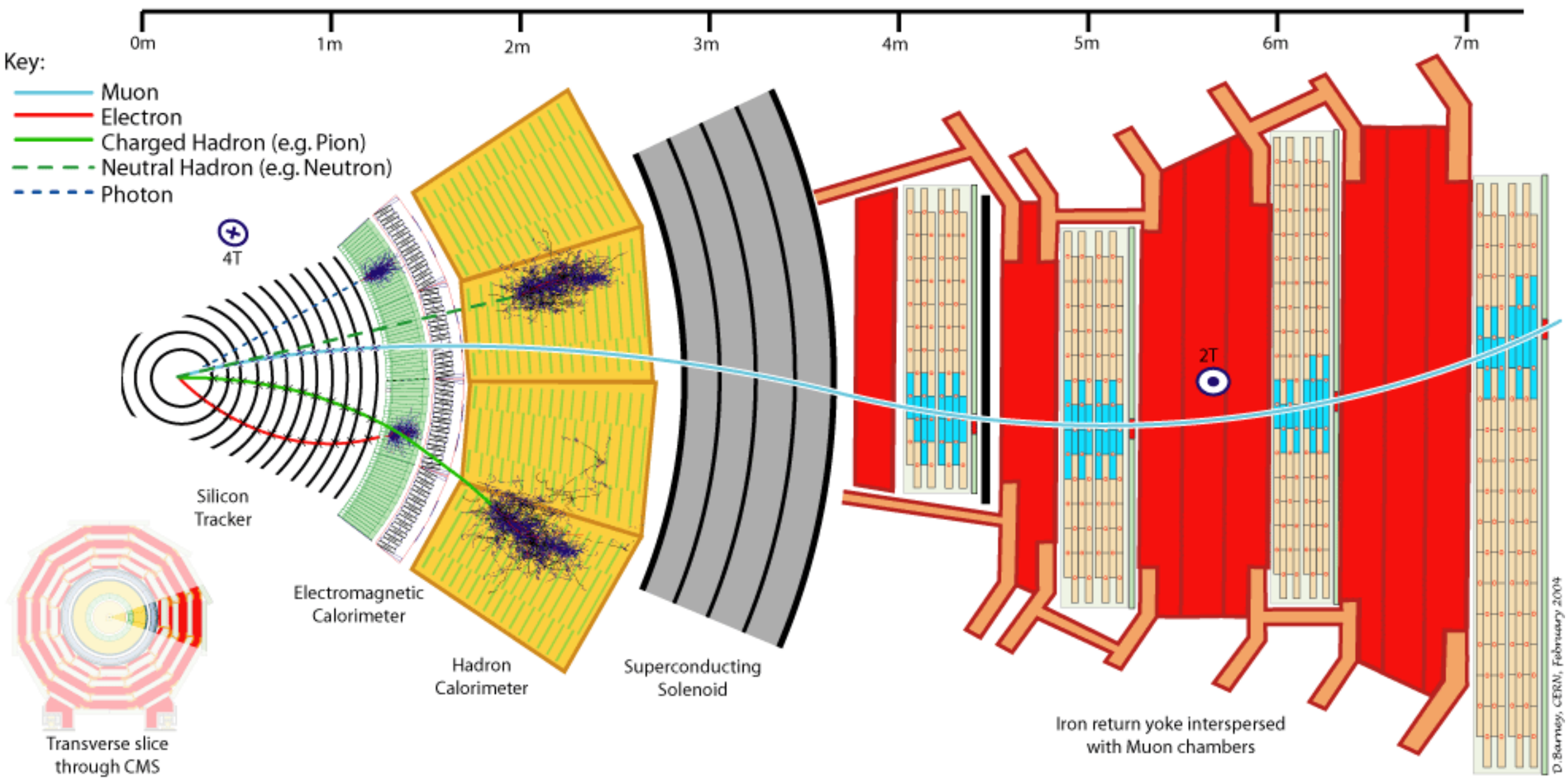

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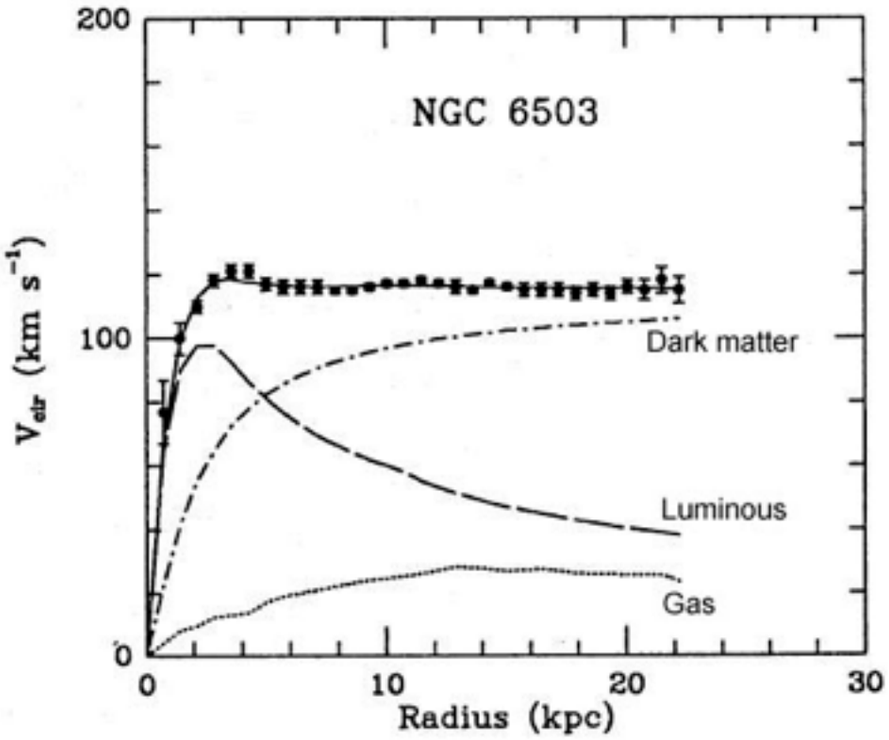

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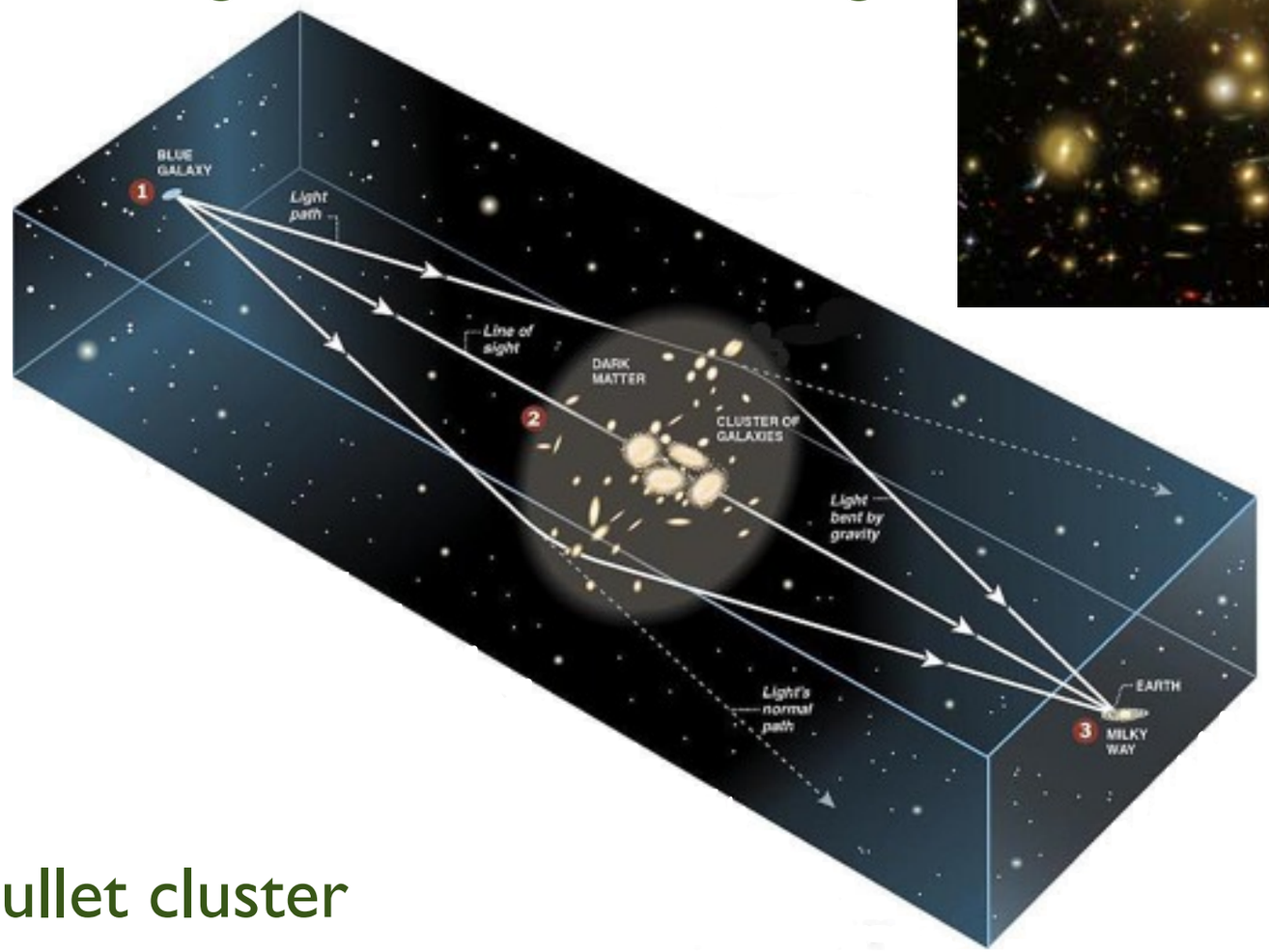

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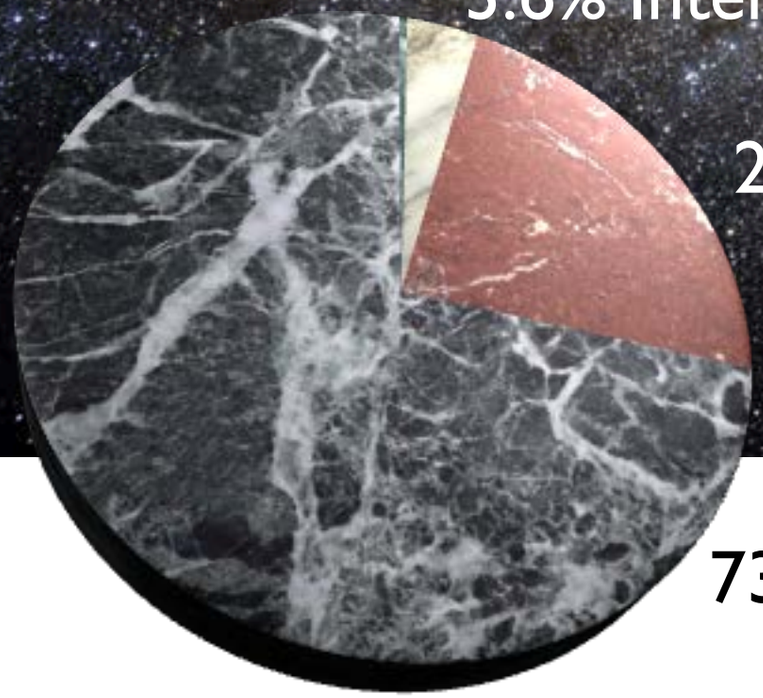

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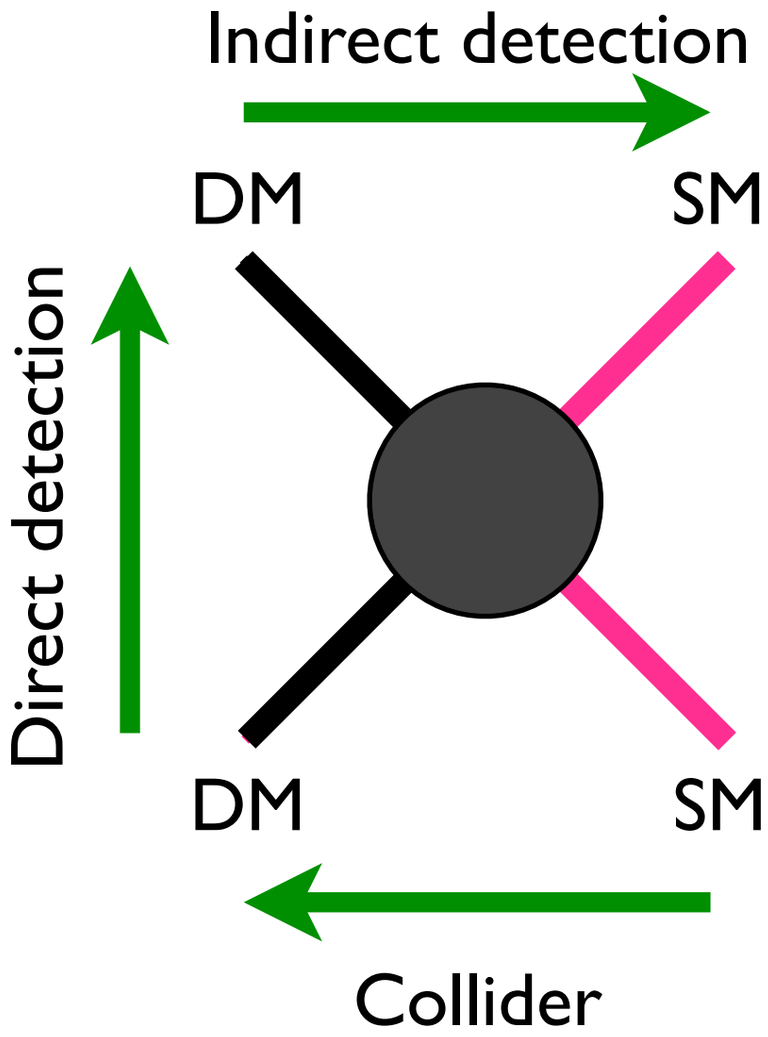

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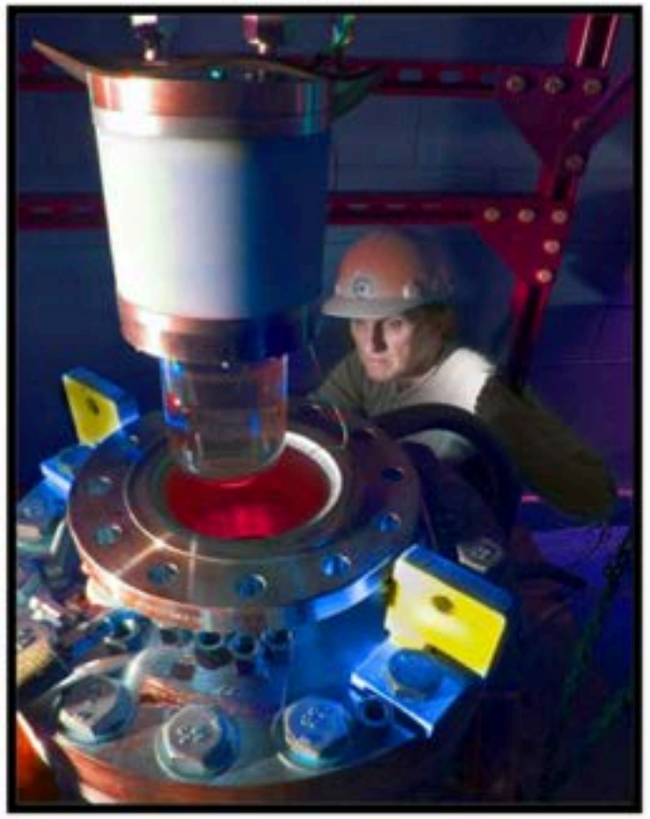
Direct detection

COUPP



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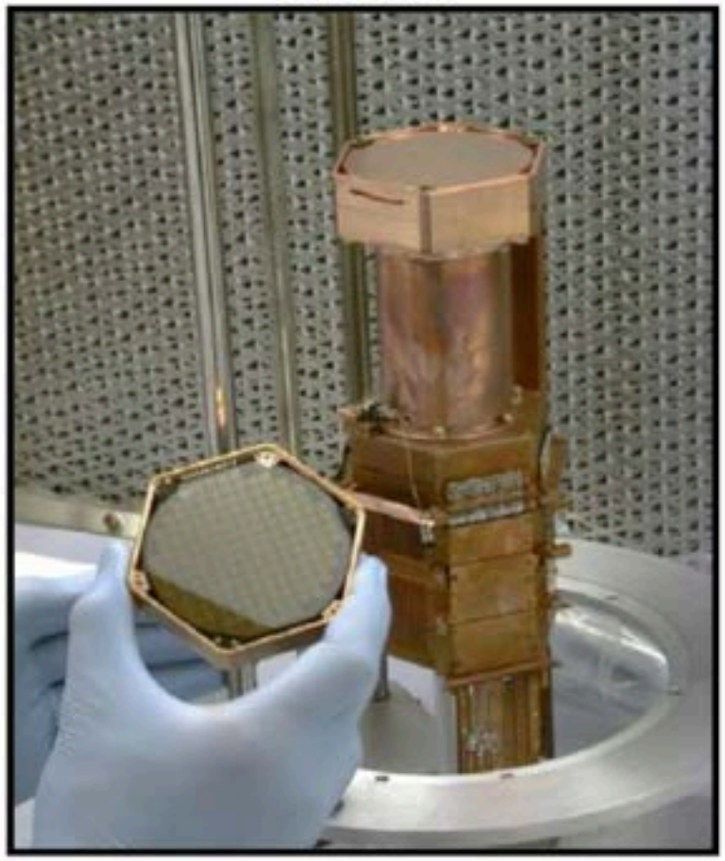
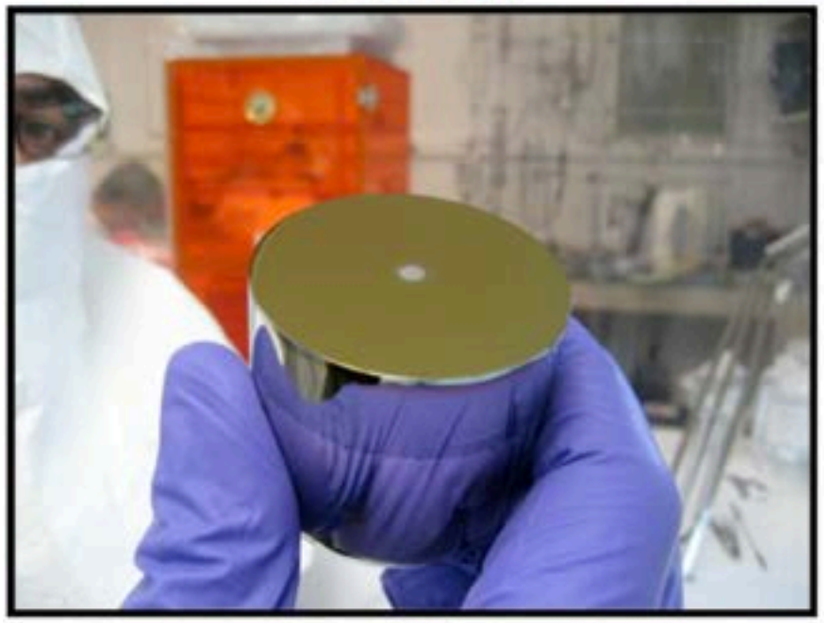


CRESST

CoGeNT

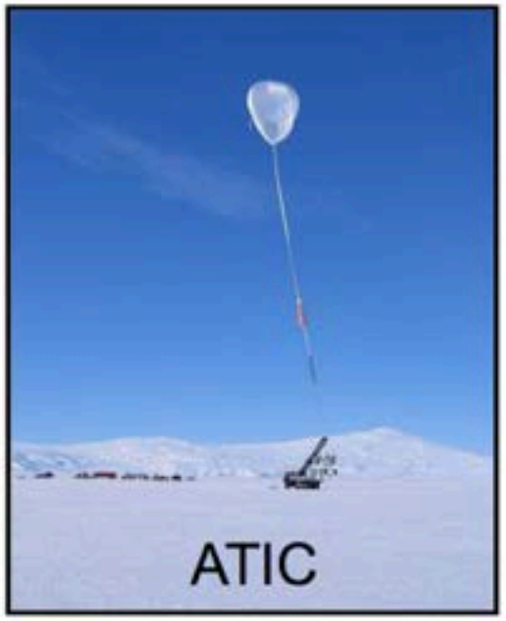


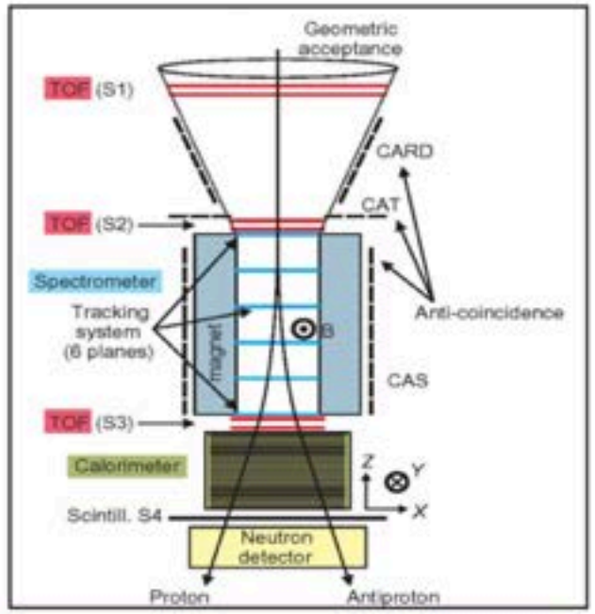
(+ EDELWEISS, DAMA, EURECA, ZEPLIN, DEAP, ArDM, WARP, LUX, SIMPLE, PICASSO, DMTPC, DRIFT, KIMS, …)

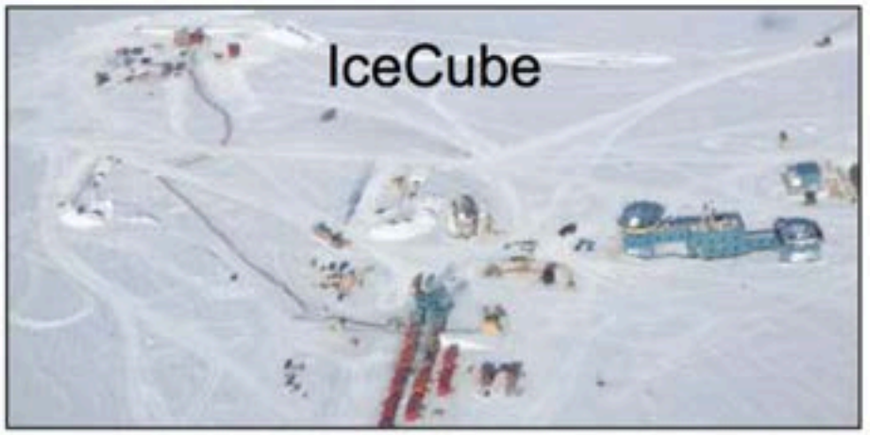
Xenon

S. Worm

Indirect detection

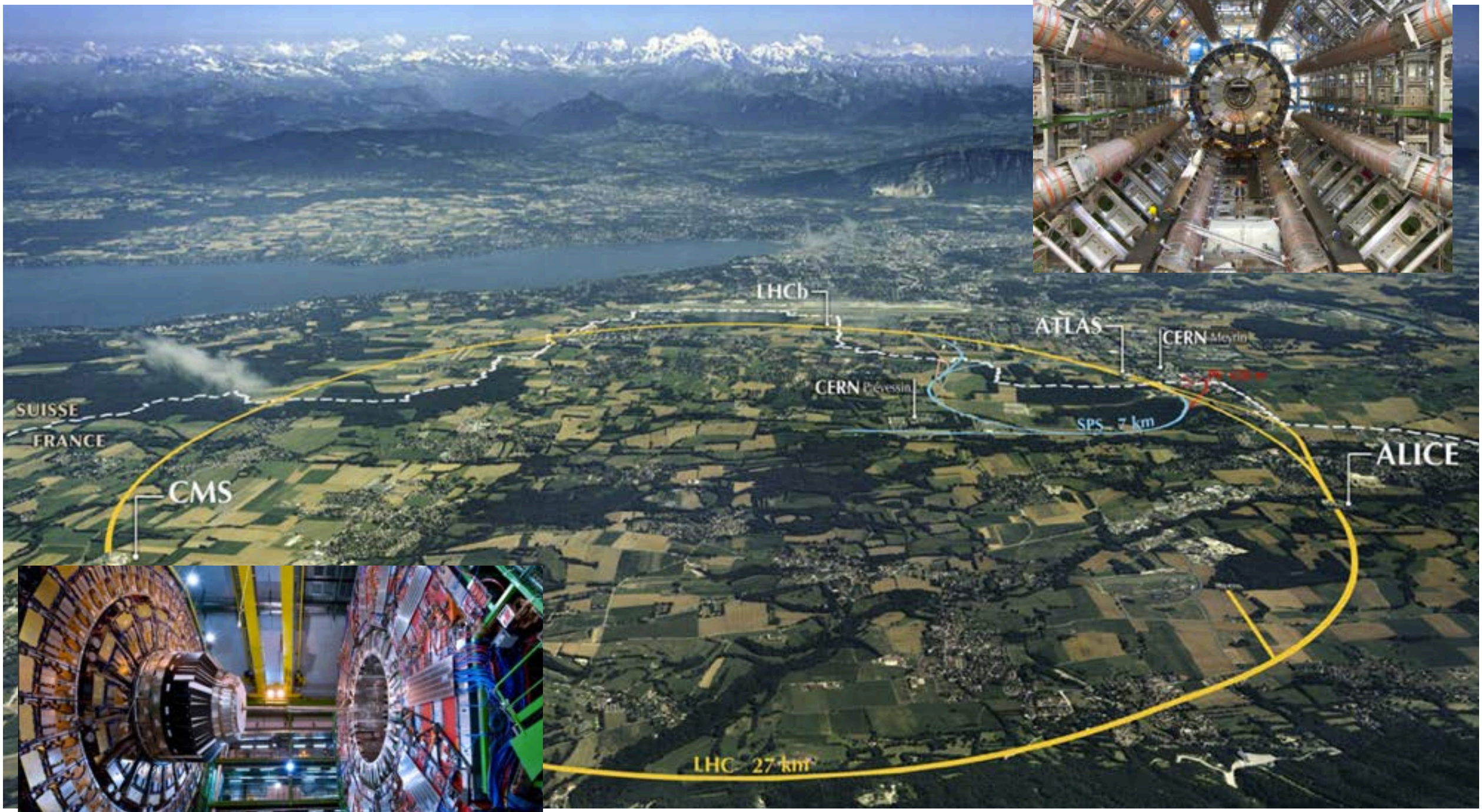






S. Worm

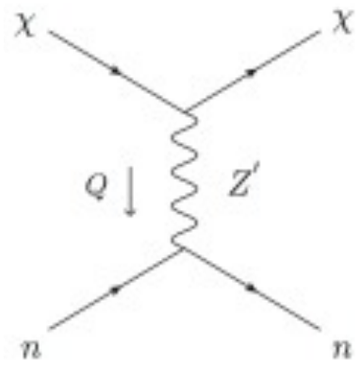
Collider

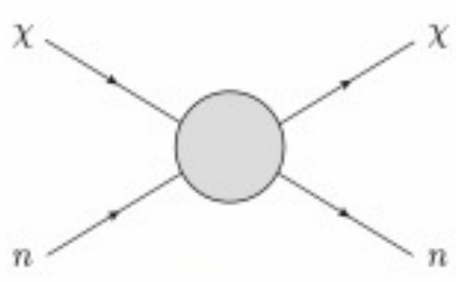

LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SUISSE
FRANCE
SPS 7 km
ALICE
CMS
LHC 27 km

Current dark matter interpretation

- Limits are quoted in terms of the WIMP-Nucleon cross-section.

Direct detection





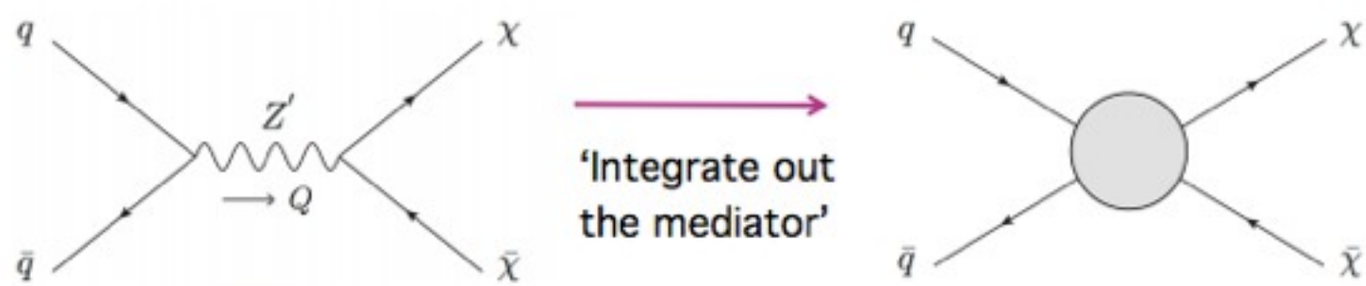
$$\sigma_n \sim \left(\frac{g_n g_\chi}{Q^2 - m_{Z'}^2}\right)^2 \approx \frac{g_n^2 g_\chi^2}{m_{Z'}^4}\left(1 + \frac{Q^2}{m_{Z'}^2} + \cdots\right)^2$$

- Contact interaction if

$$m_{Z'} \gg Q = \sqrt{2 m_n E_R} \approx 50 \text{ MeV}$$

MCCABE, Christopher: http://agenda.albanova.se/contributionDisplay.py?contribId=280&sessionId=254&confId=4115

Collider



- Use of effective field theory (EFT) to place a limit on the contact interaction scale

$$\Lambda \equiv \frac{m_{Z'}}{\sqrt{g_q g_\chi}}$$

- EFT will be valid if $m_{Z'} \gg Q \sim$ TeV

Dark Matter models

Dirac fermion, 1008.1783

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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Majorana fermion, 1005.1286

M1	qq	$m_q/2M_*^3$
M2	qq	$im_q/2M_*^3$
M3	qq	$im_q/2M_*^3$
M4	qq	$m_q/2M_*^3$
M5	qq	$1/2M_*^2$
M6	qq	$1/2M_*^2$
M7	GG	$\alpha_s/8M_*^3$
M8	GG	$i\alpha_s/8M_*^3$
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$

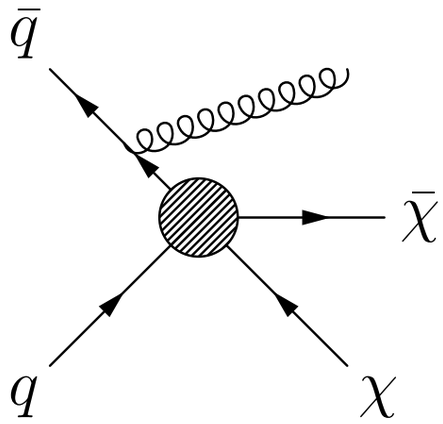
Real scalar, 1008.1783

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	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

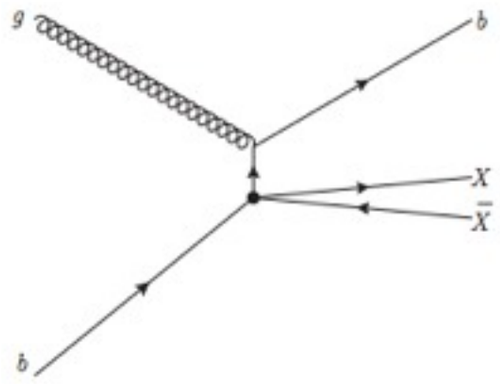
Complex scalar, 1008.1783

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	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$

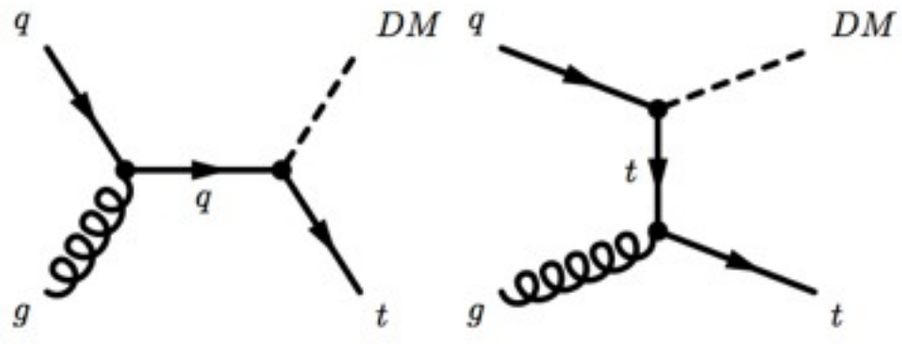
X + Missing Transverse Energy



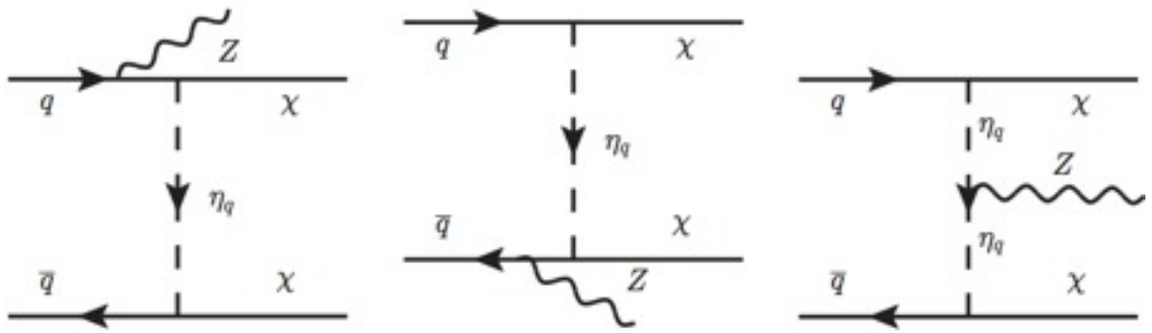
MonoJet



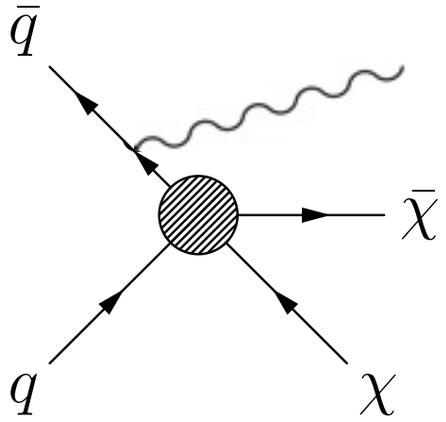
MonoB



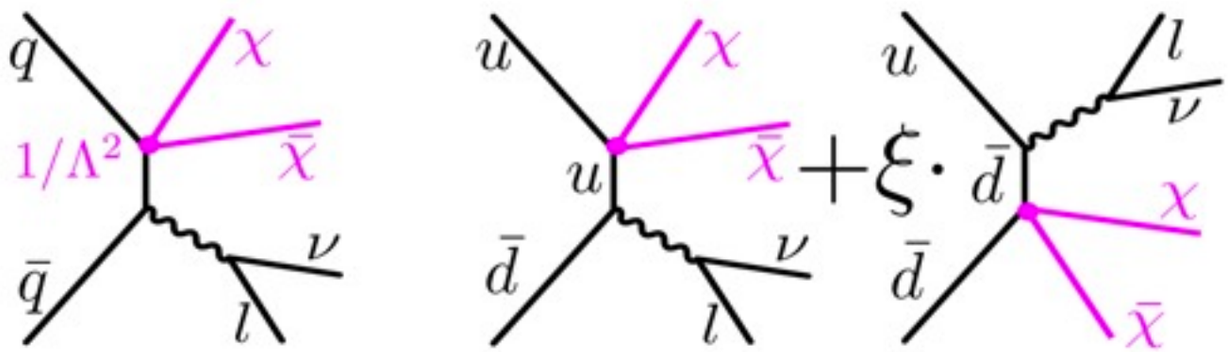
MonoTop



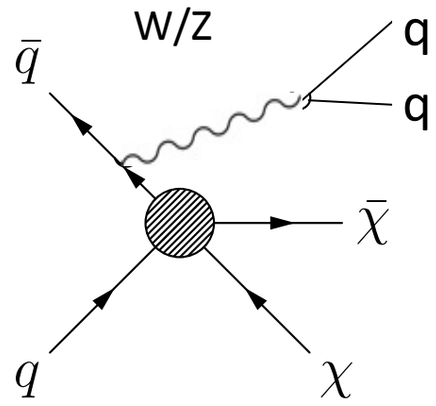
MonoZ



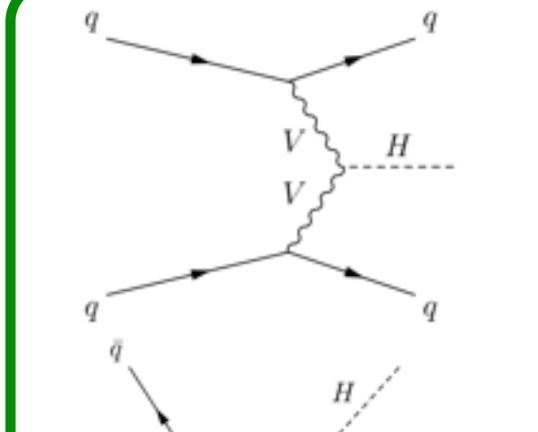
MonoPhoton



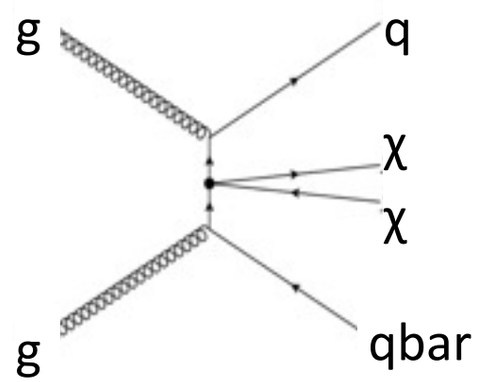
MonoW (monoLepton)



MonoW/Z (Hadronic)



Higgs Portal



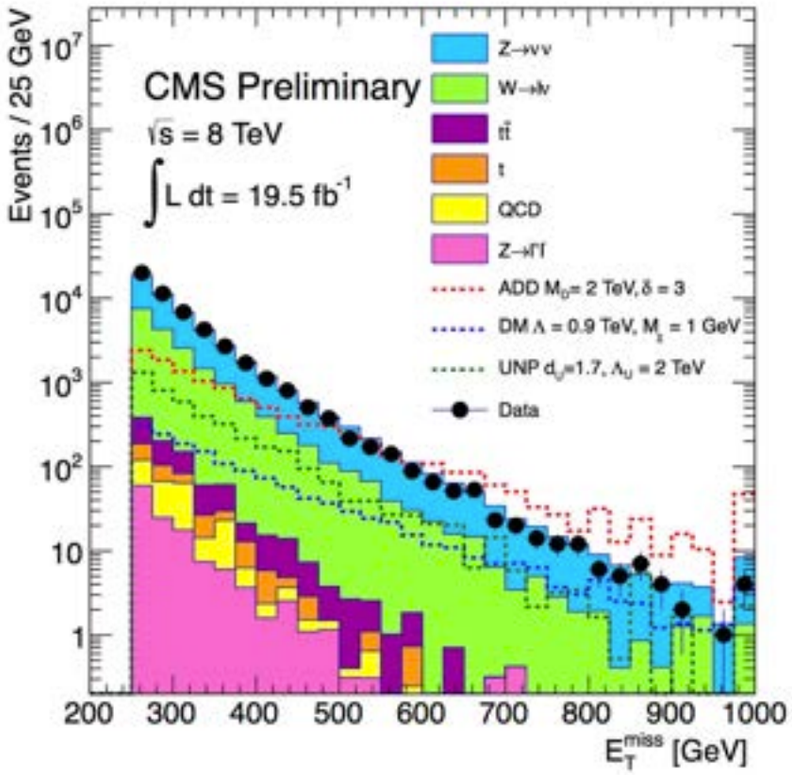
BBbar /TTbar

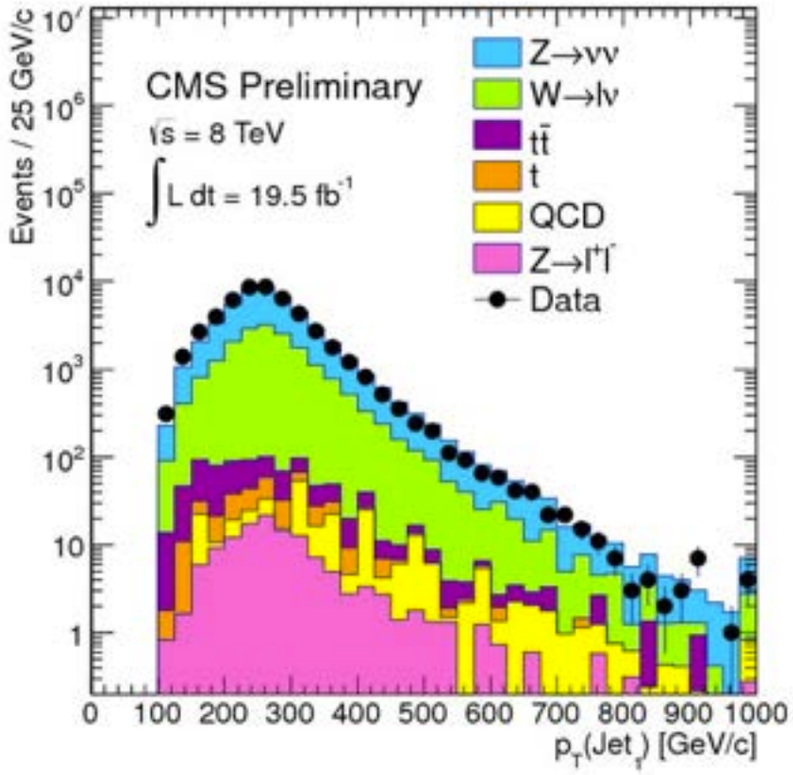
MonoJet

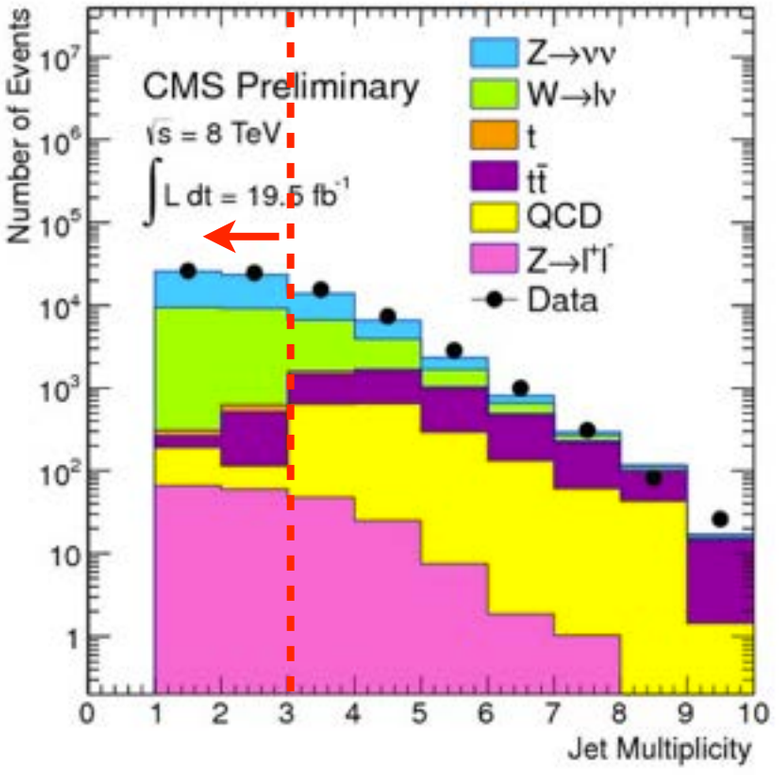
EXO-12-048: http://cds.cern.ch/record/1525585

Event selection

- MET > 400 GeV
- One energetic jet, p_T > 110 GeV, $|\eta|$ < 2.4, and allow an additional jet (p_T > 30 GeV)
- Veto event if j_3 p_T > 30 GeV
- Veto event if DeltaPhi(j_1,j_2)>2.5
- Veto event if they contain isolated electrons, isolated muons, or hadronic tau with p_T >10 GeV (20 GeV for tau)



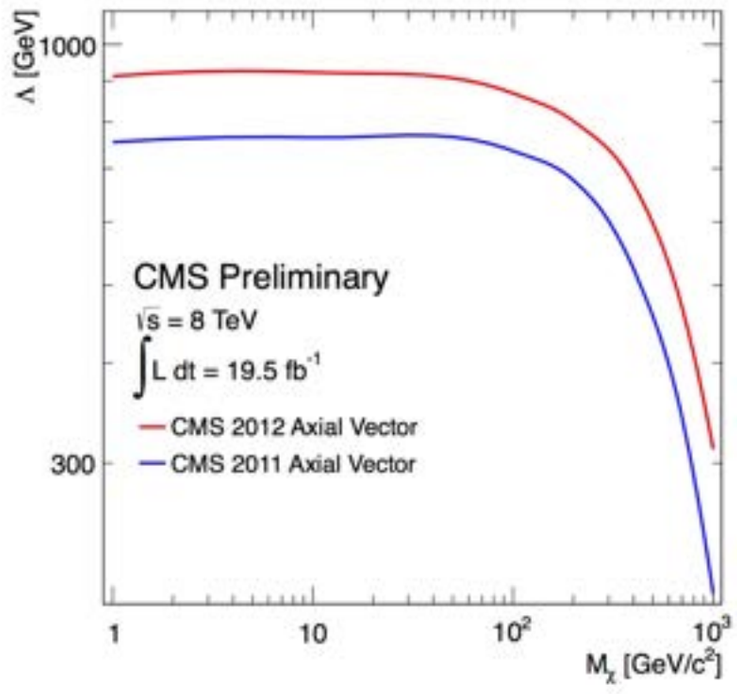


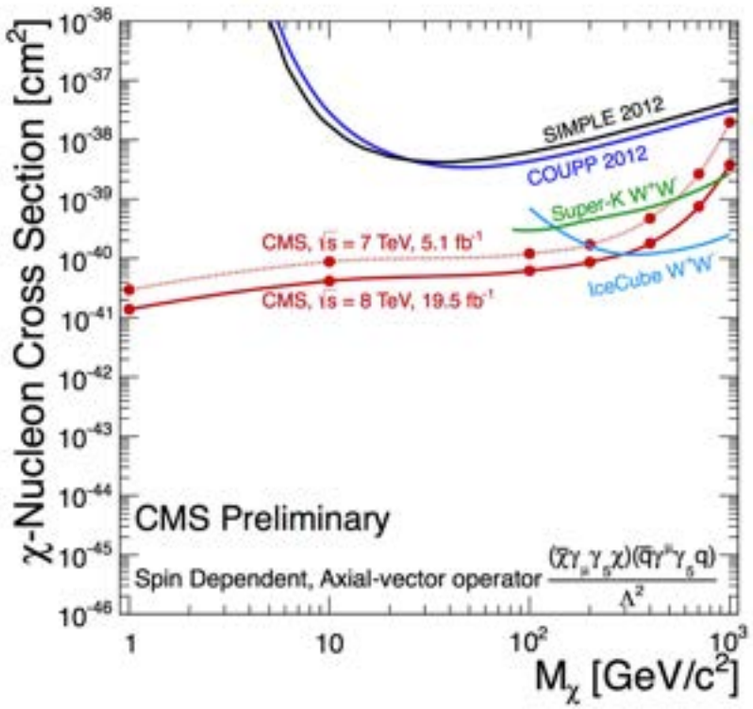


MonoJet

Results

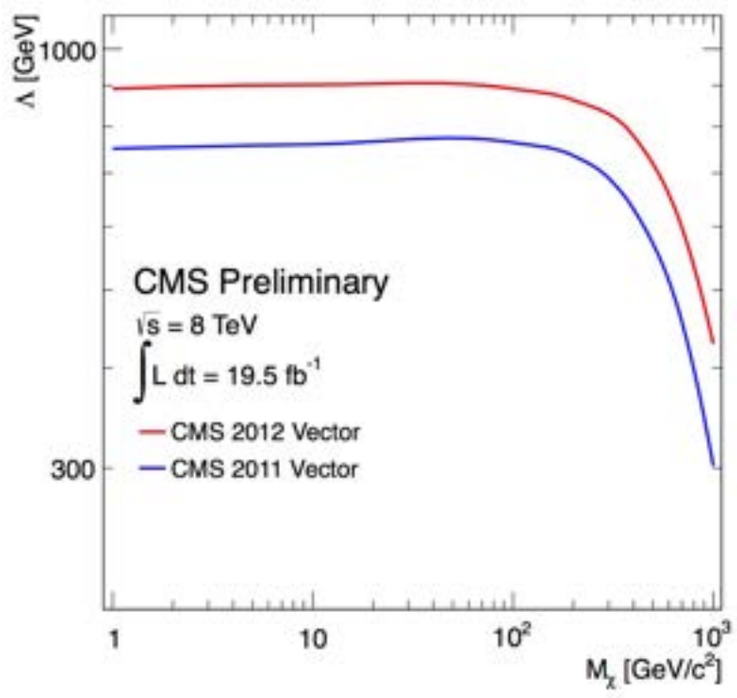
EXO-12-048: http://cds.cern.ch/record/1525585

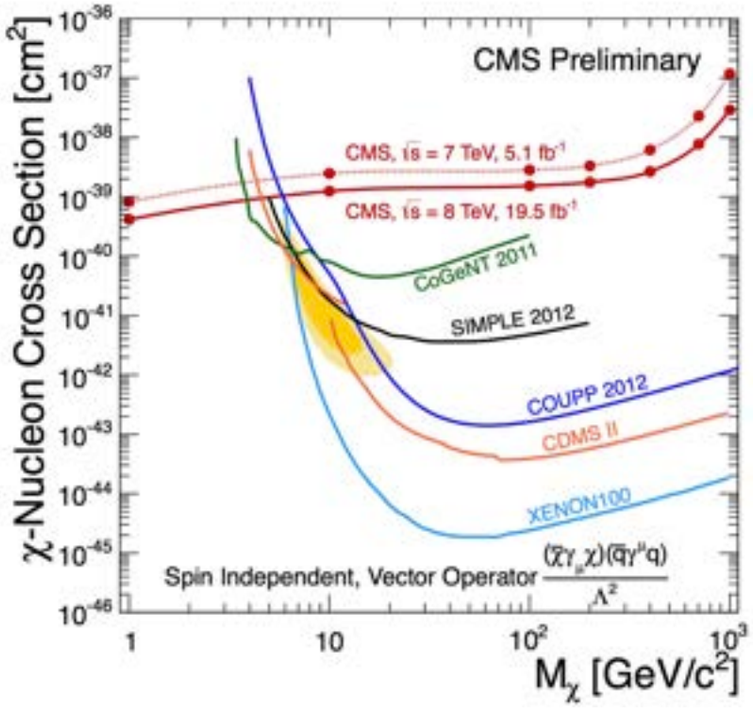




Axial-vector operator
spin-dependent (SD)

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





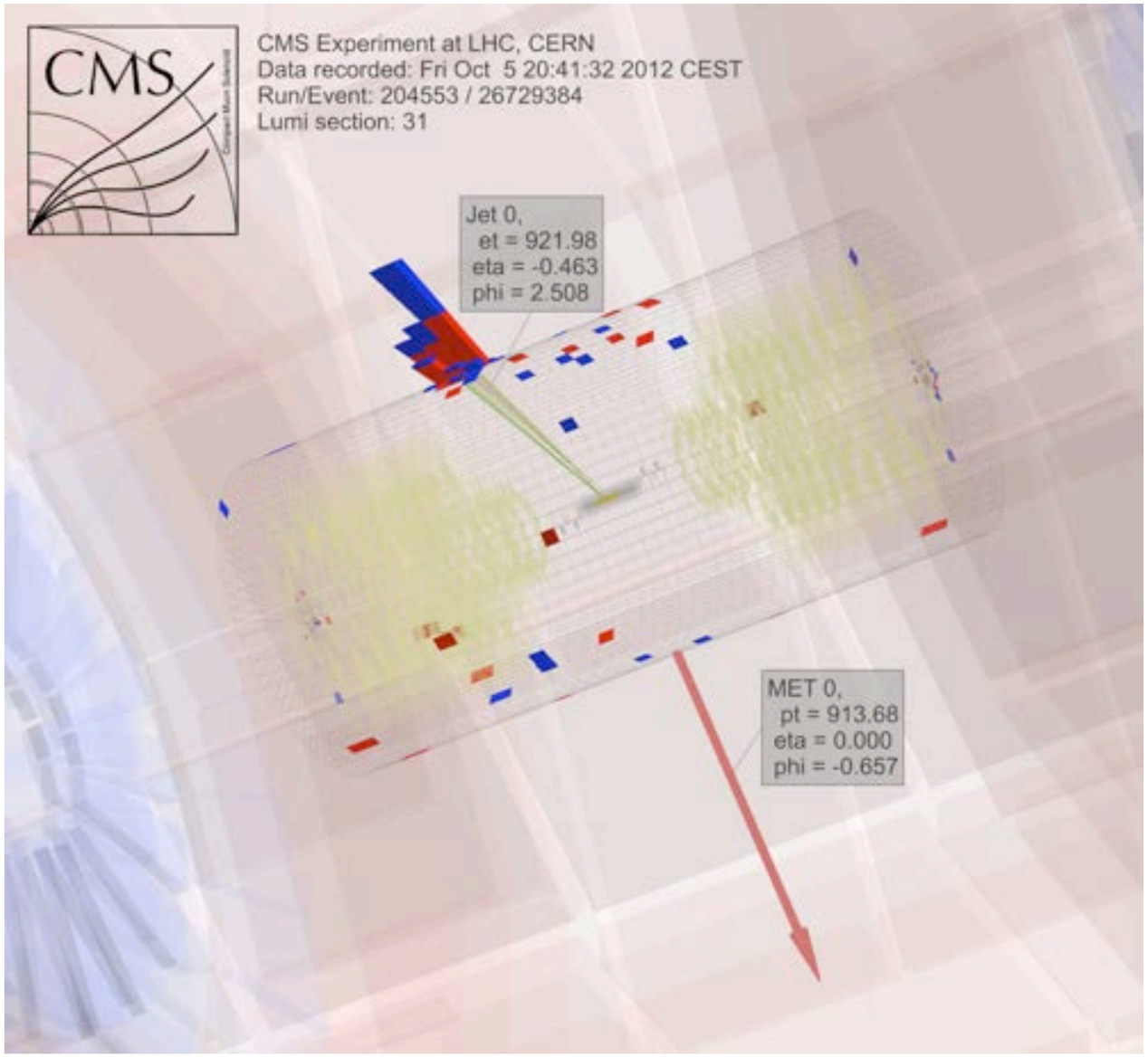
Vector operator
spin independent (SI)

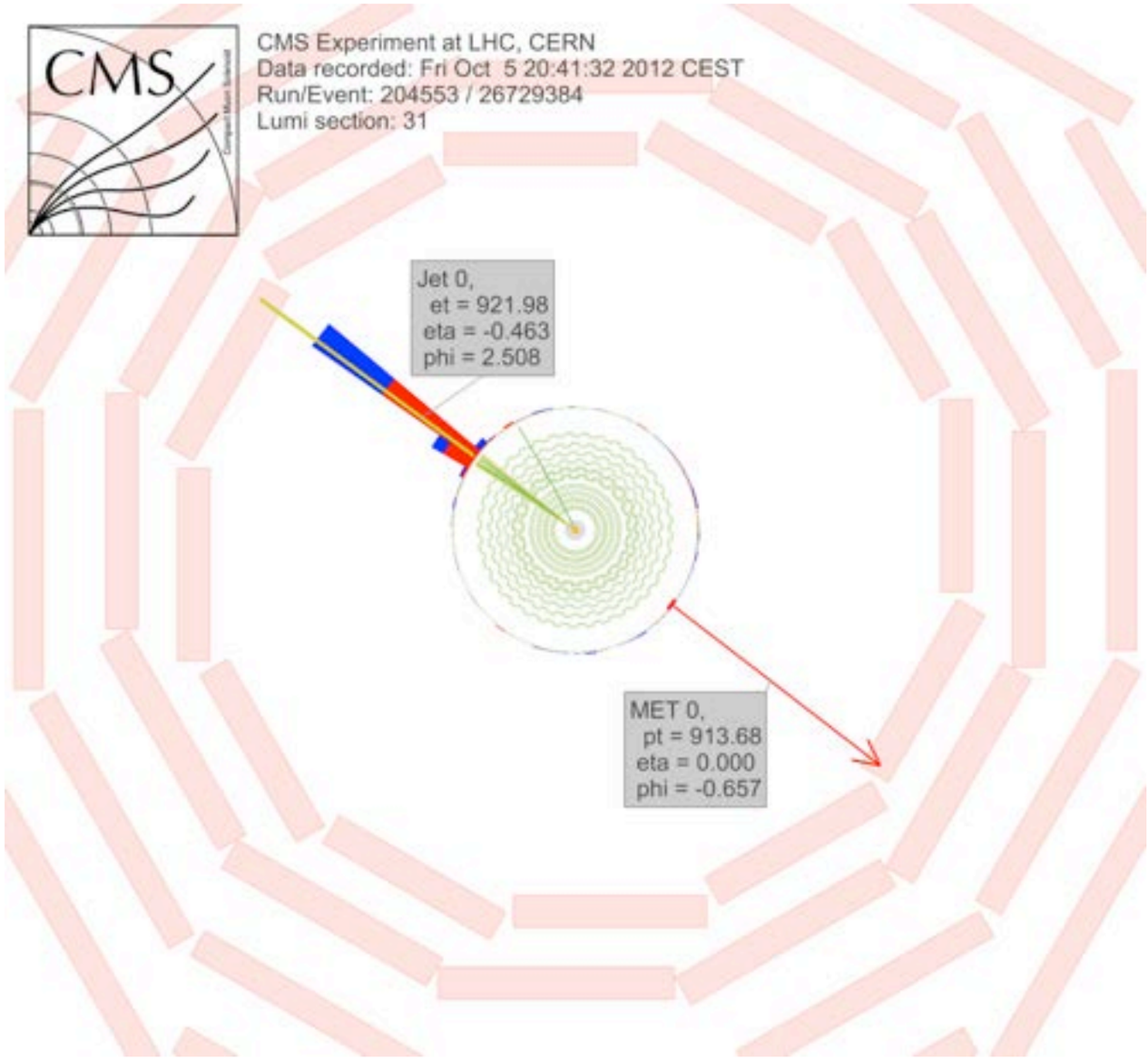
$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

Monojet

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO12048

Event display

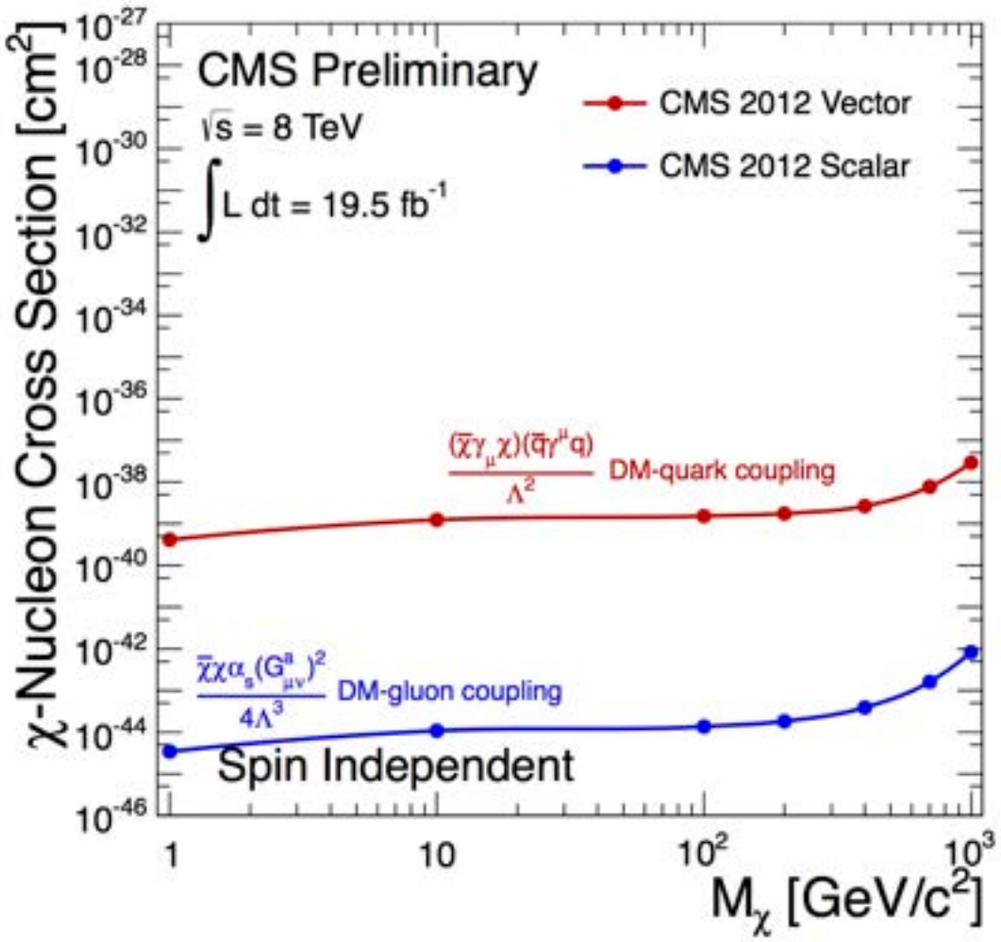


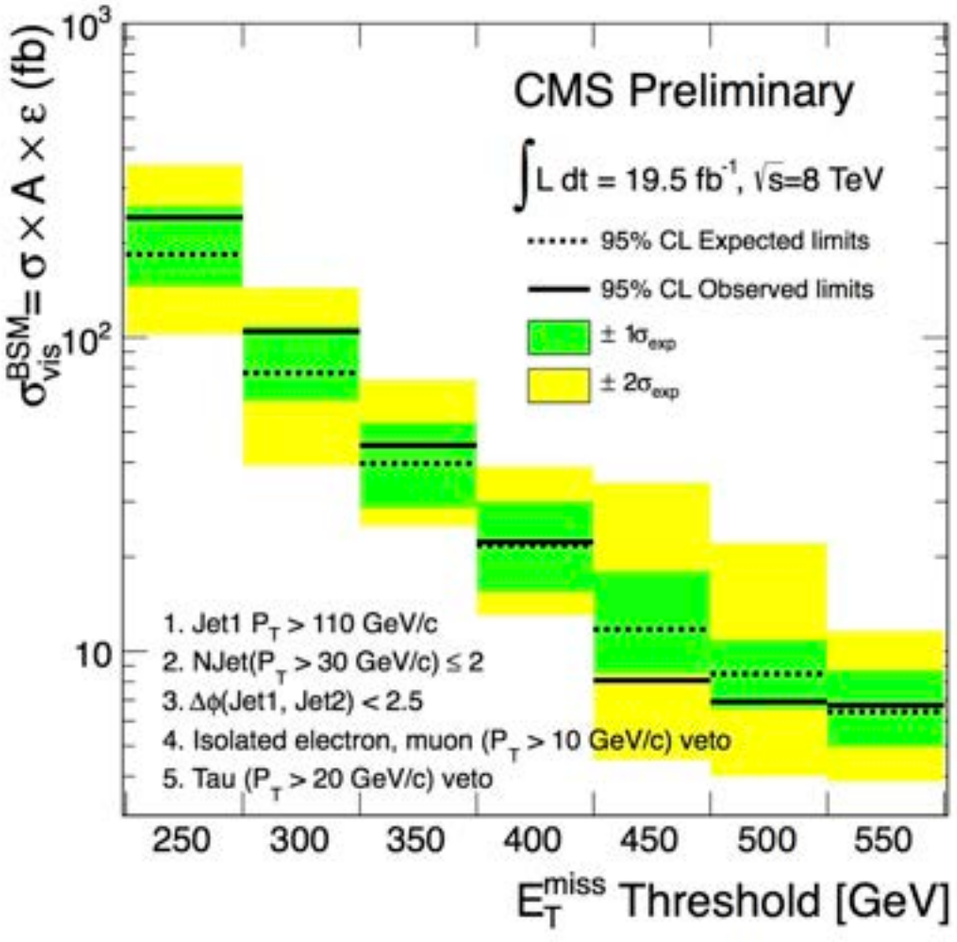


Monojet

Results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO12048



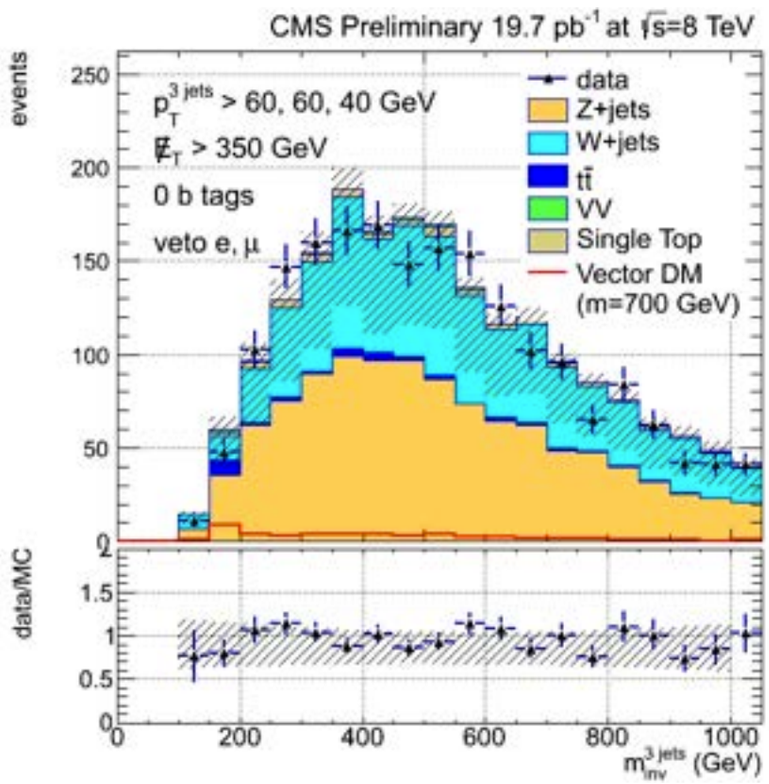


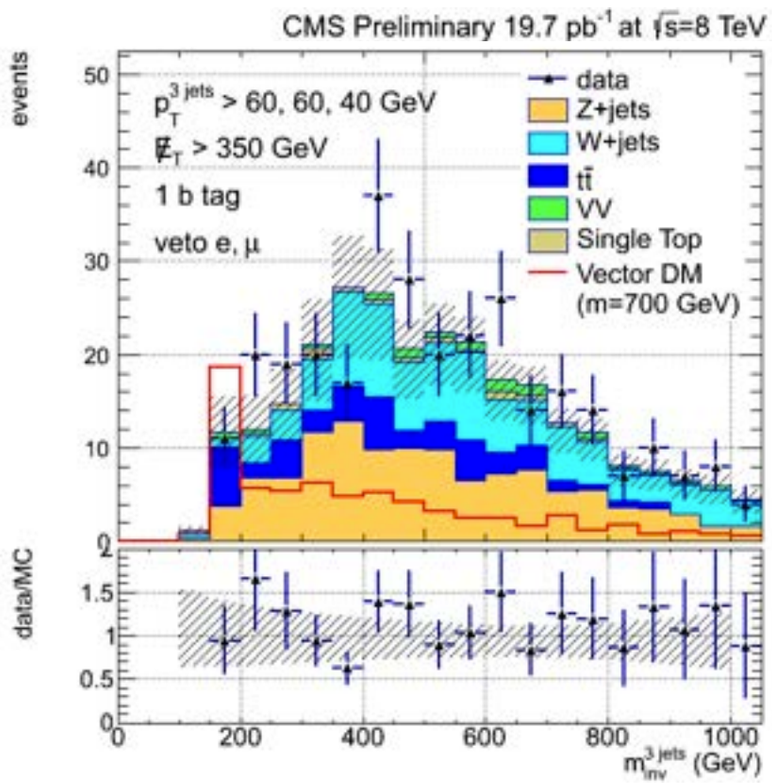
MonoTop (top decays hadronically)

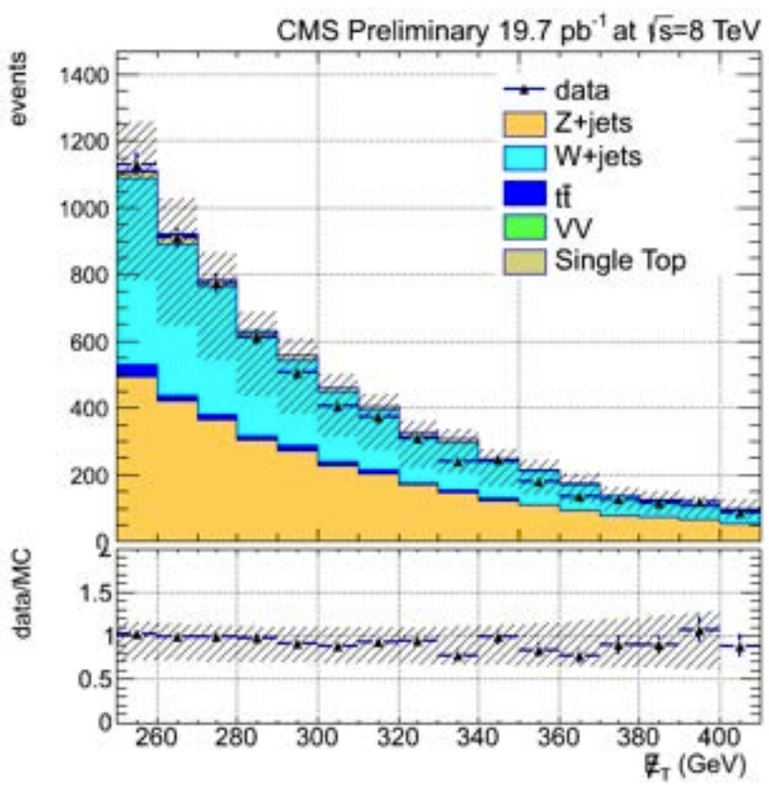
B2G-12-022: http://cds.cern.ch/record/1668115

Event selection

- Three jets, with j_1, and j_2 p_T > 60 GeV and j_3 p_T > 40 GeV
- One jet is tagged b-jet
- Veto events with j_4 p_T > 35 GeV or isolated e(μ) p_T > 20(10) GeV
- M($j_1 j_2 j_3$) < 250 GeV
- MET> 350 GeV







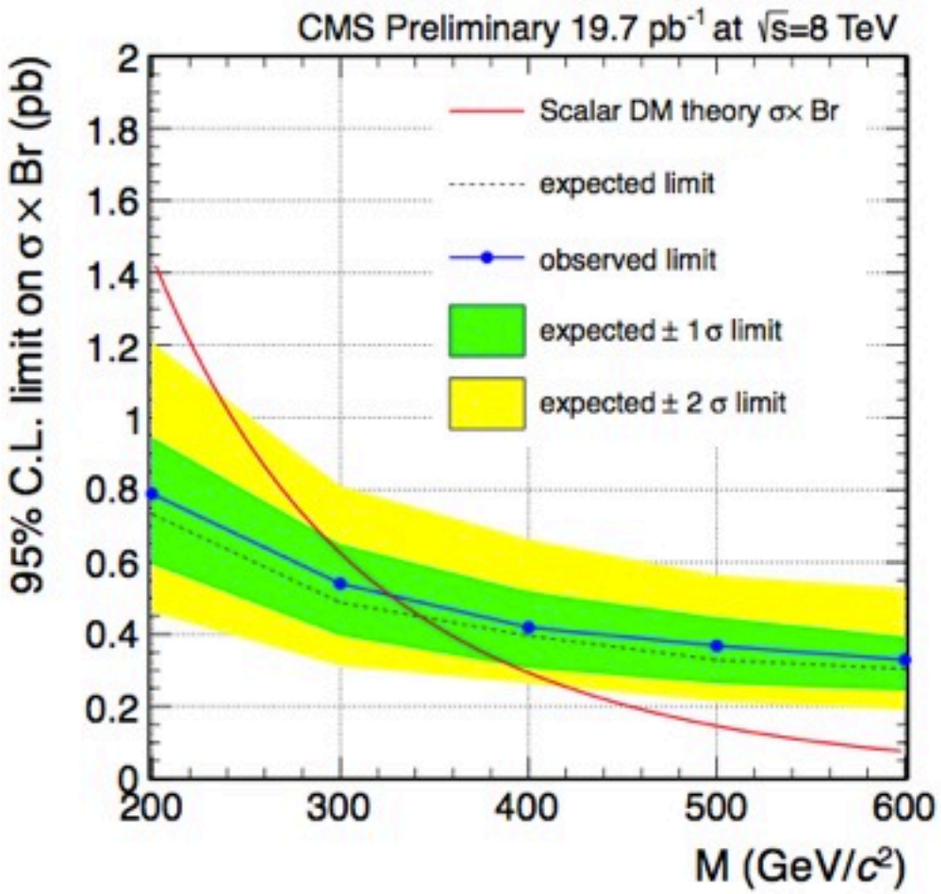
MonoTop (top decays hadronically)

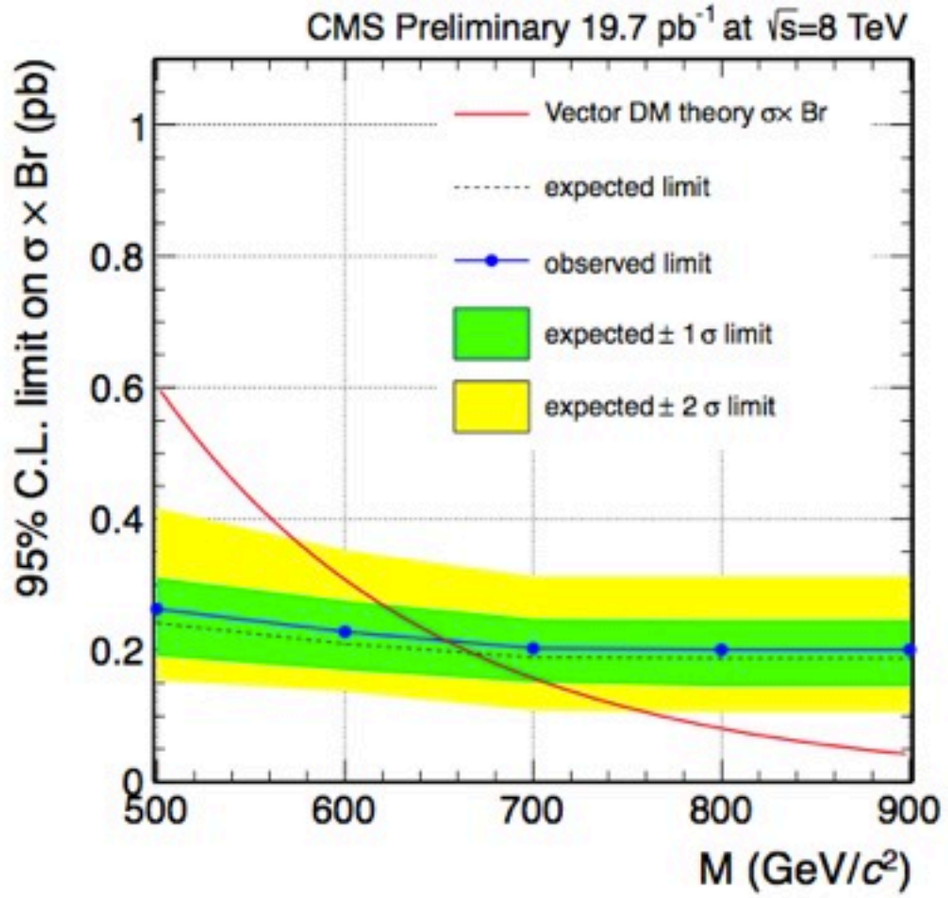
Results

B2G-12-022: http://cds.cern.ch/record/1668115

- Excellent agreement with data
- DM coupling set to 0.1 for q=u/d [arXiv:1106.199]
- Exclude scalar (vector) DM masses below 327 (655) GeV

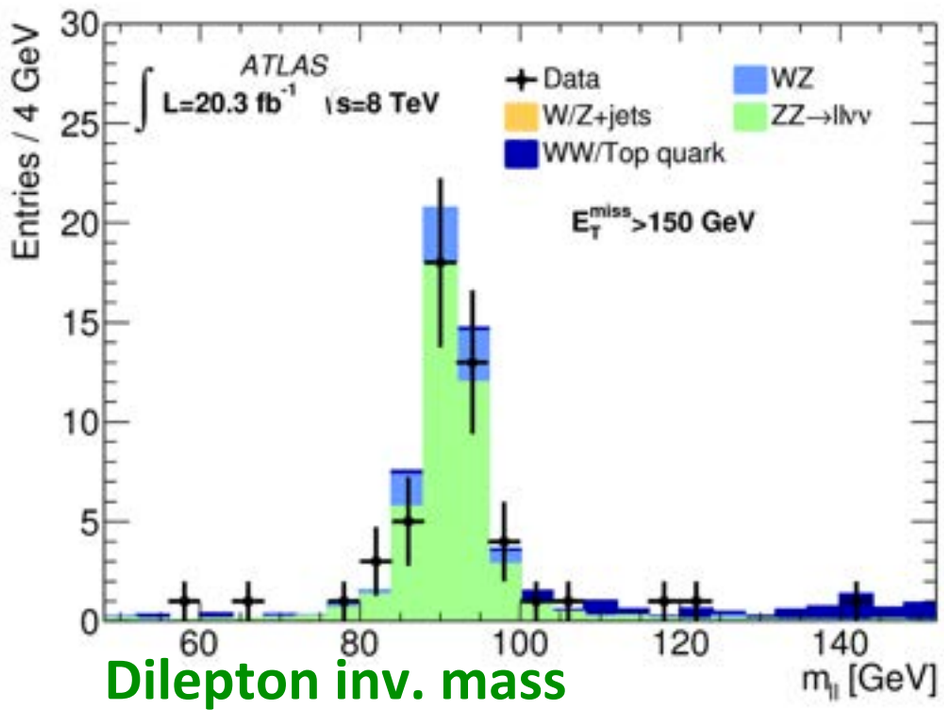
# of b tags	Zero CSVm b tag	One CSVm b tag
$t\bar{t}$	6±0±5	12±0±12
W+jets	18±9±7	3±1±2
Z+jets	103±33±9	11±10±1
Single top	2±1±1	1±1±1
VV	5±0±0	0±0±0
QCD	6	1
sum	140±36	28±16
Data	143	30





MonoZ (Z decays leptonically)

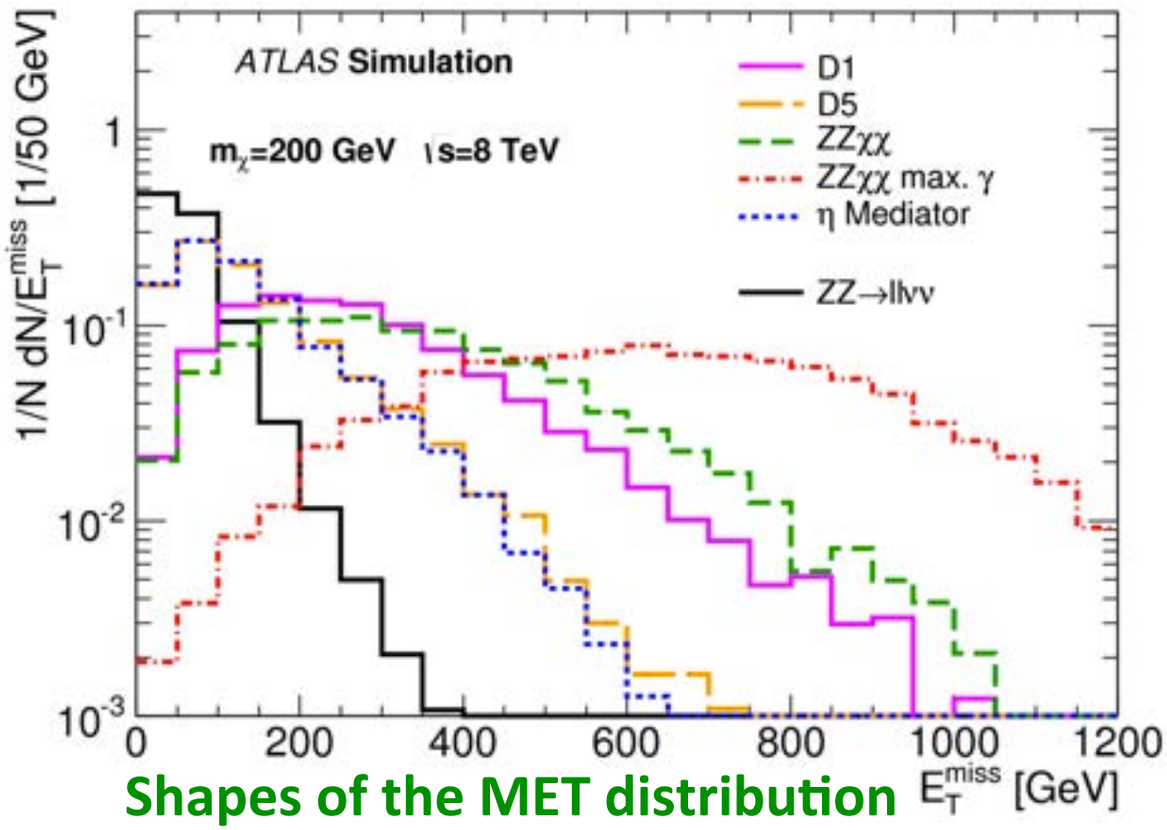
PhysRevD.90.012004



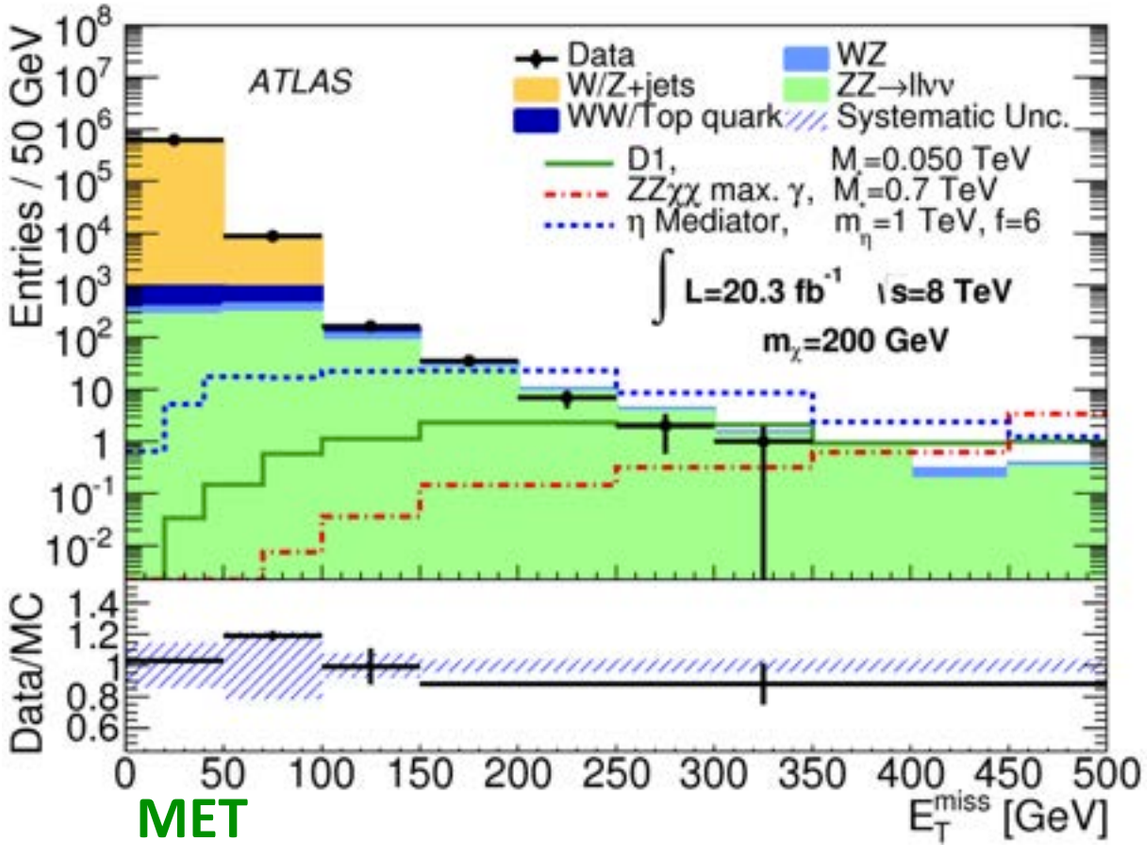
Dilepton inv. mass

Event selection

- Muon (Electron) P_T (E_T) > 20 GeV, $|\eta|$ < 2.5 (2.47)
- 76 < M(ll) < 106
- DeltaPhi(P_T(ll),MET) > 2.5
- $|\eta^{ll}|$ < 2.5
- (P_T(ll) - MET)/P_T(ll) < 0.5



Shapes of the MET distribution

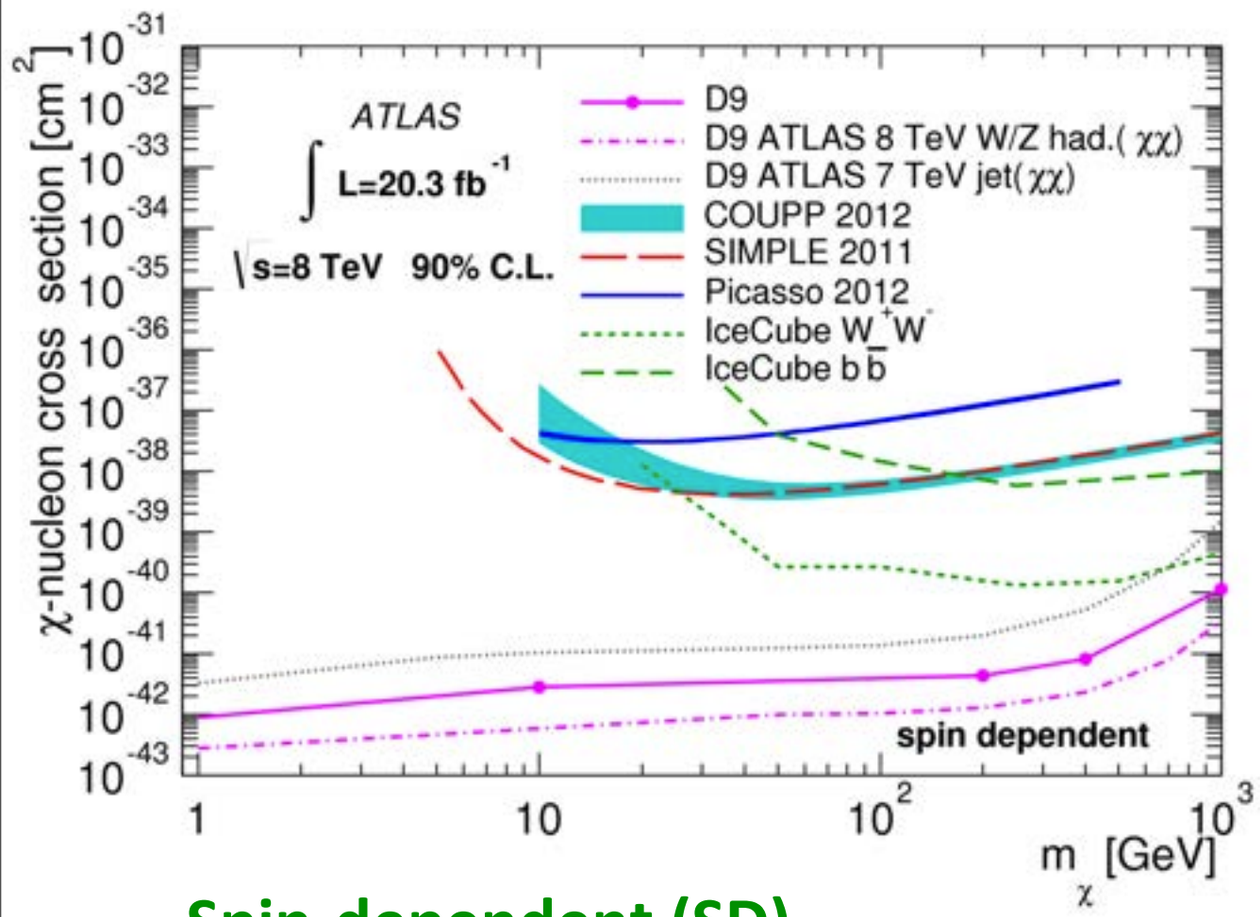


MET

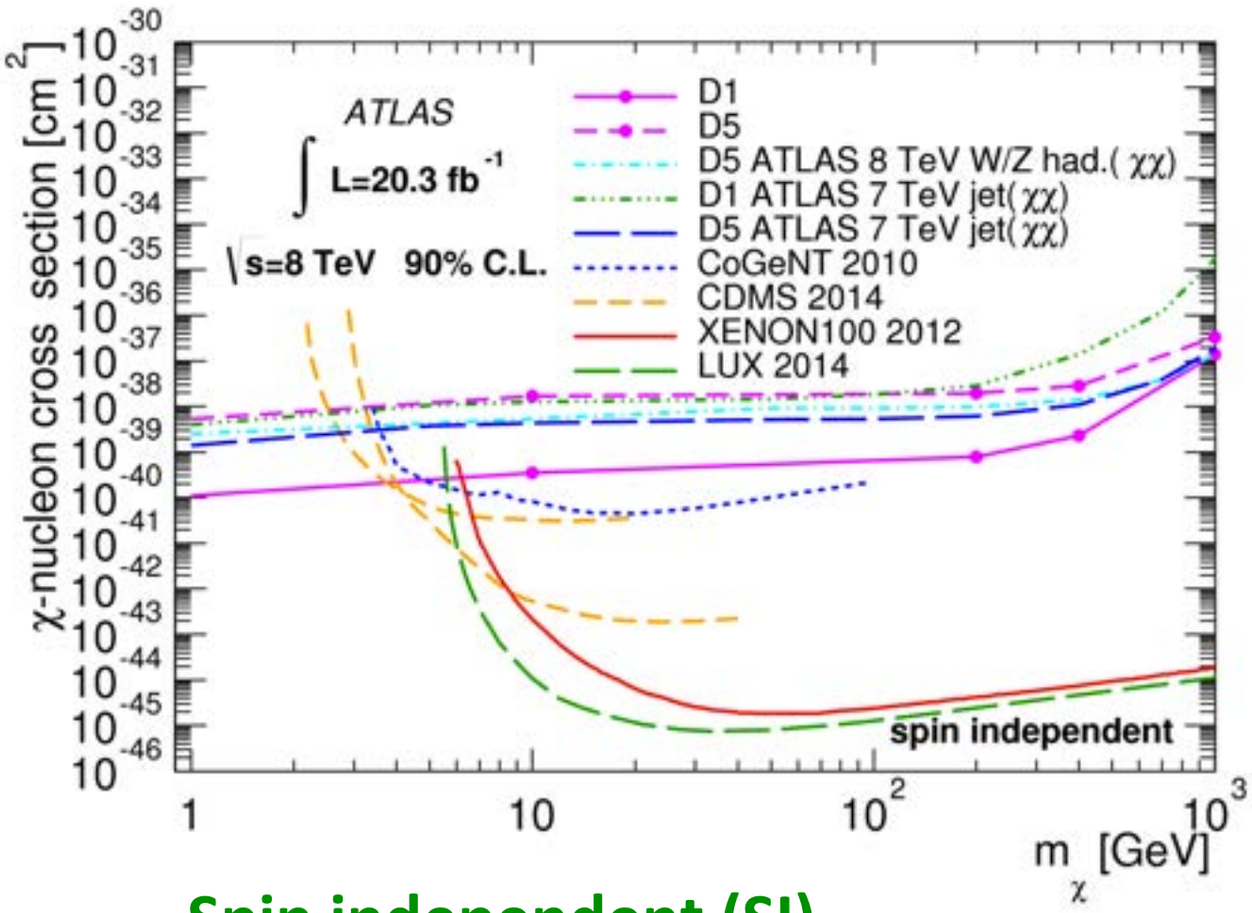
MonoZ (Z decays leptonically)

Results

PhysRevD.90.012004



Spin-dependent (SD)



Spin independent (SI)

MonoW (W decays leptonically)

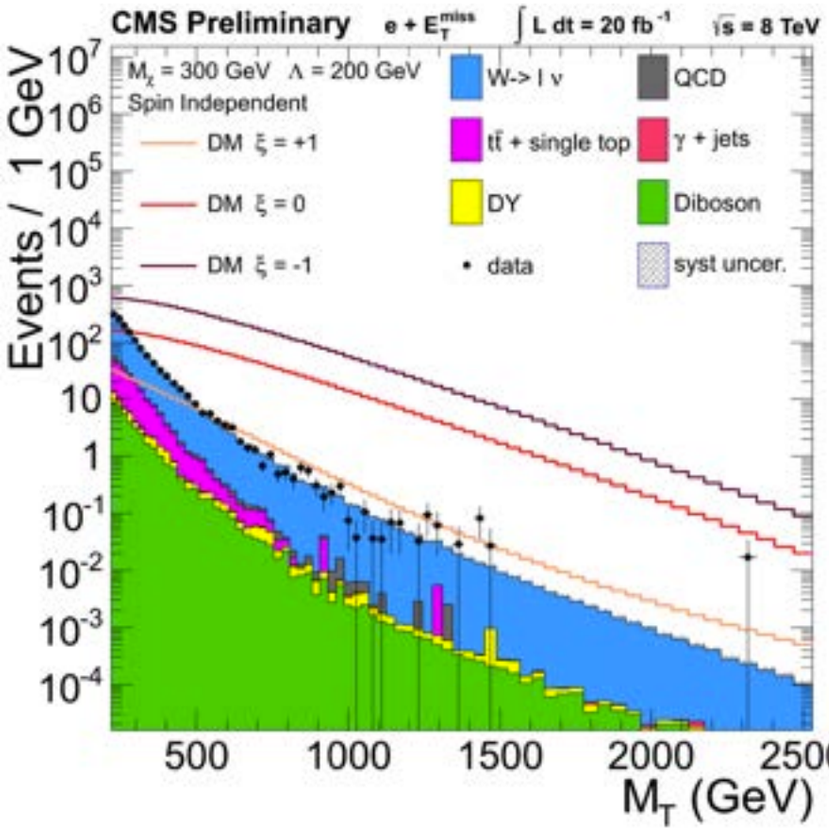
EXO-13-004: http://cds.cern.ch/record/1563245

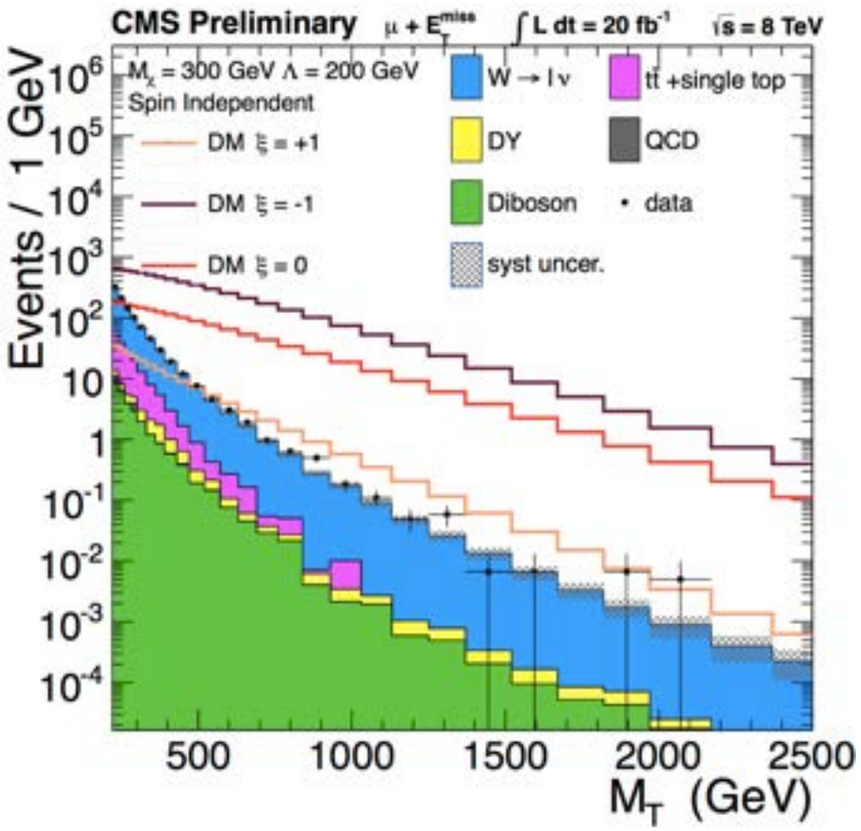
Dark Matter production with a W

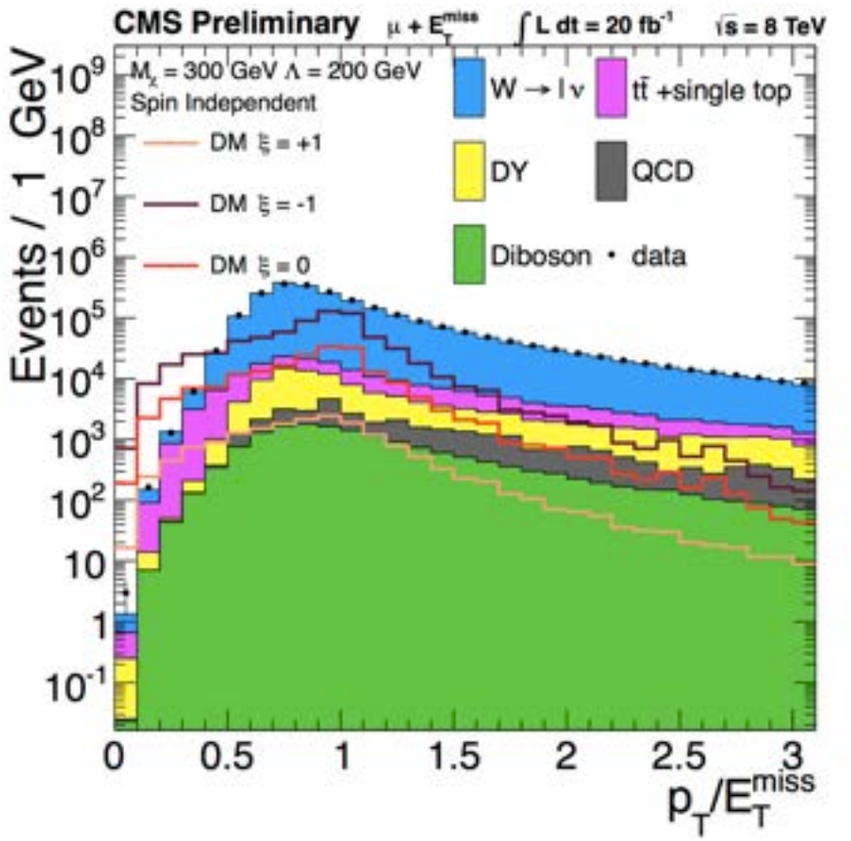
- W recoiling against pair-produced DM
- Vector- and axial-vector couplings considered
- Interference effects parameterized by ξ (W+)

Event selection

- Muon (Electron) P_T > 45 (100) GeV
- 0.4 < P_T/MET < 1.5
- DeltaPhi(lepton,MET) > 0.8*Pi





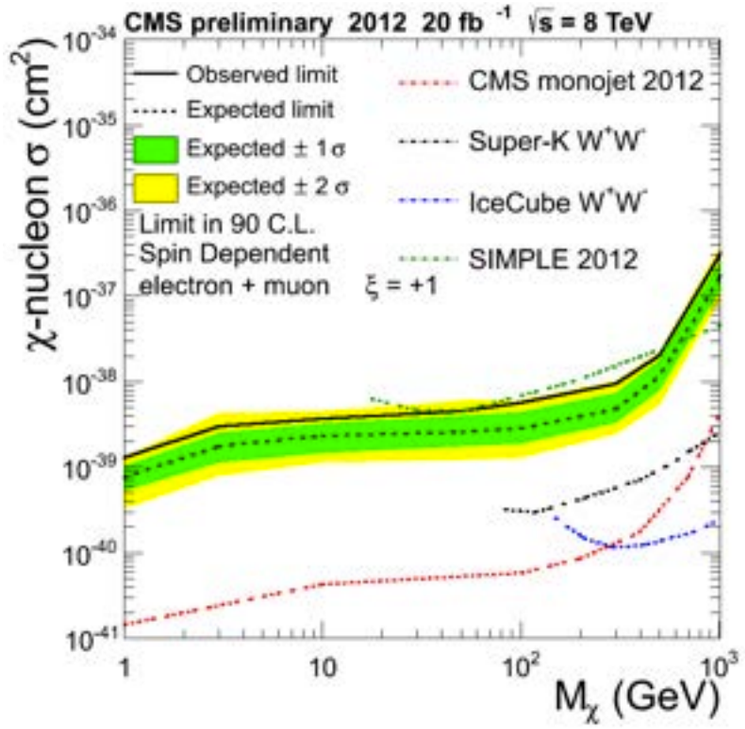


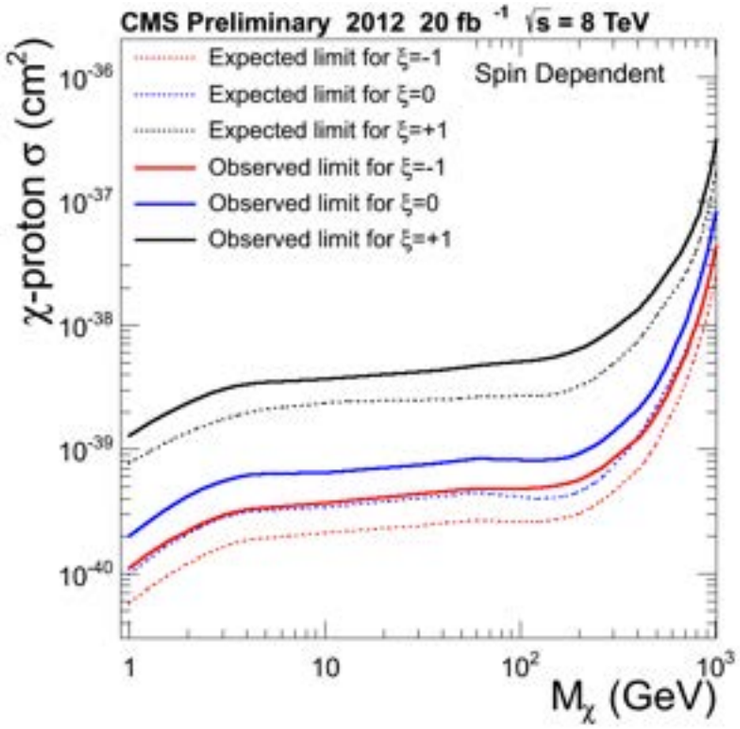
$$M_{\mathrm{T}} = \sqrt{2 \cdot p_{\mathrm{T}}^{\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

MonoW (W decays leptonically)

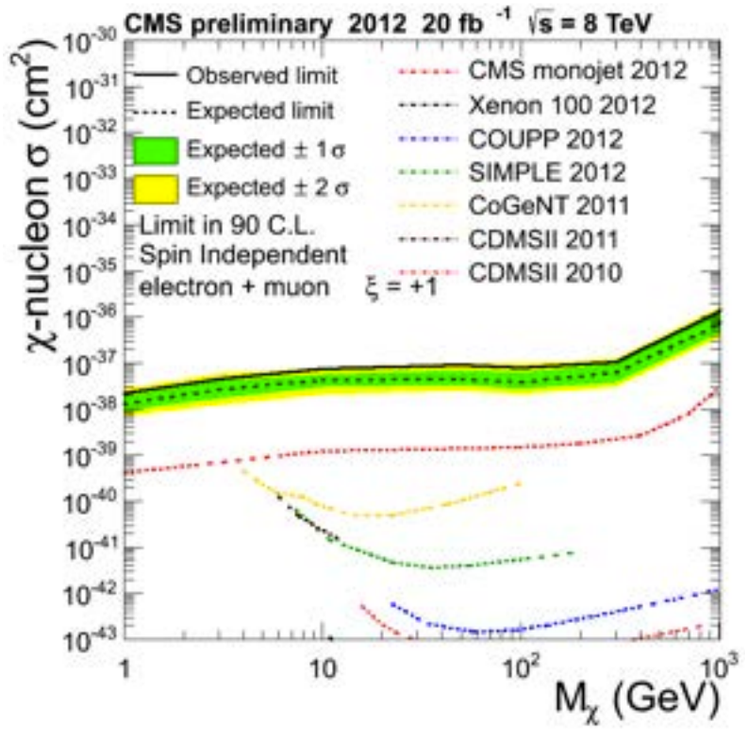
Results

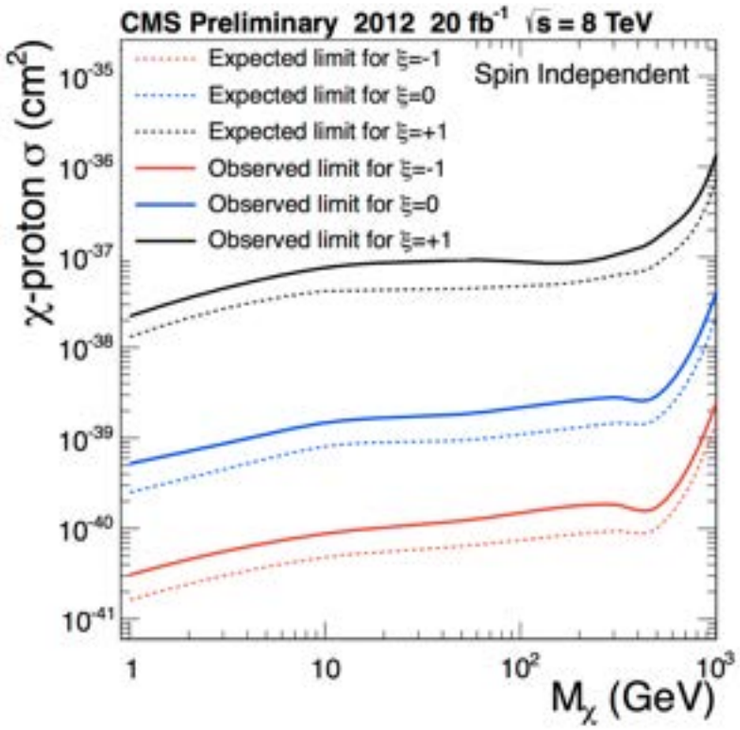
EXO-13-004: http://cds.cern.ch/record/1563245





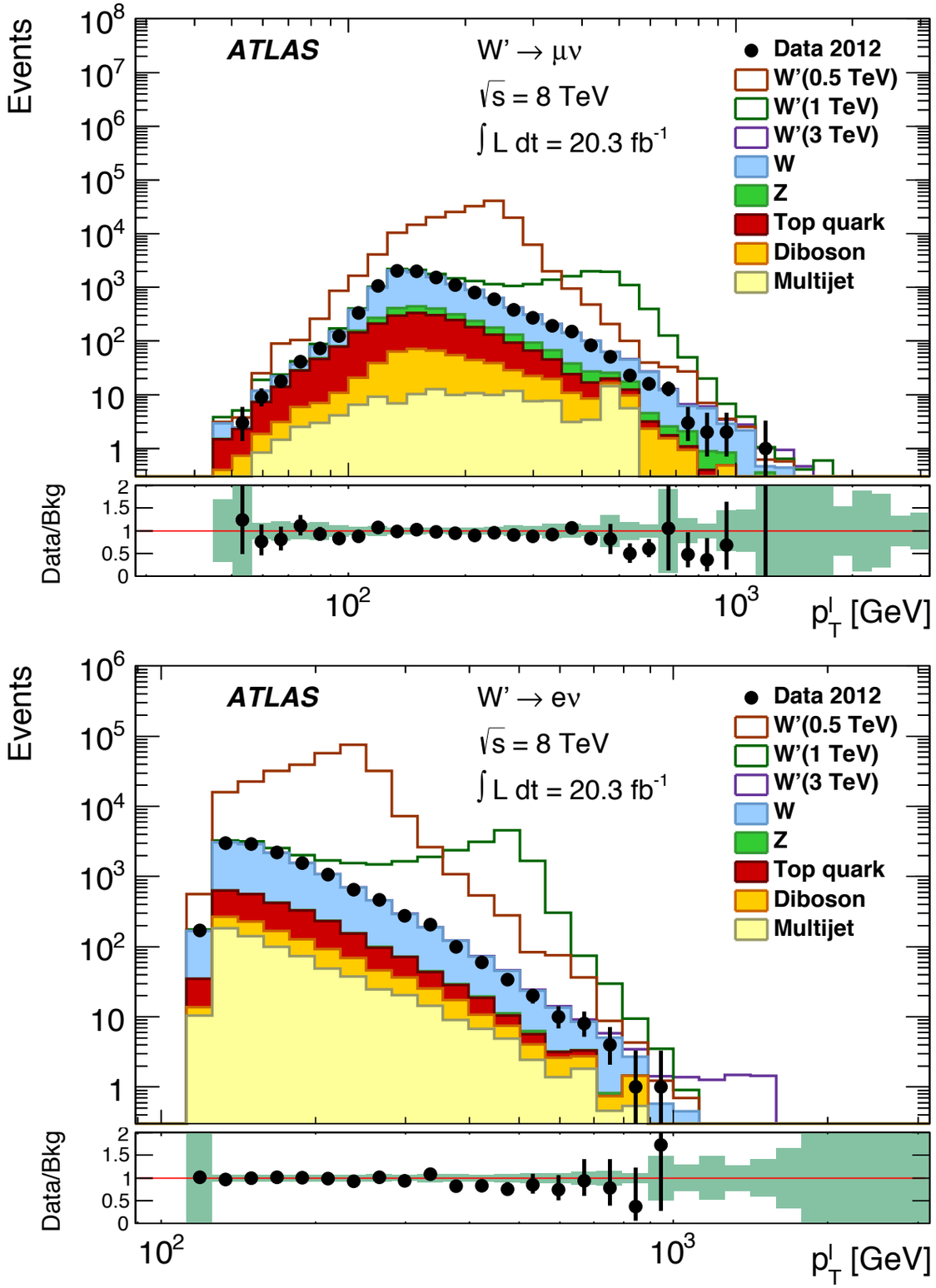
Axial-vector operator spin-dependent (SD)

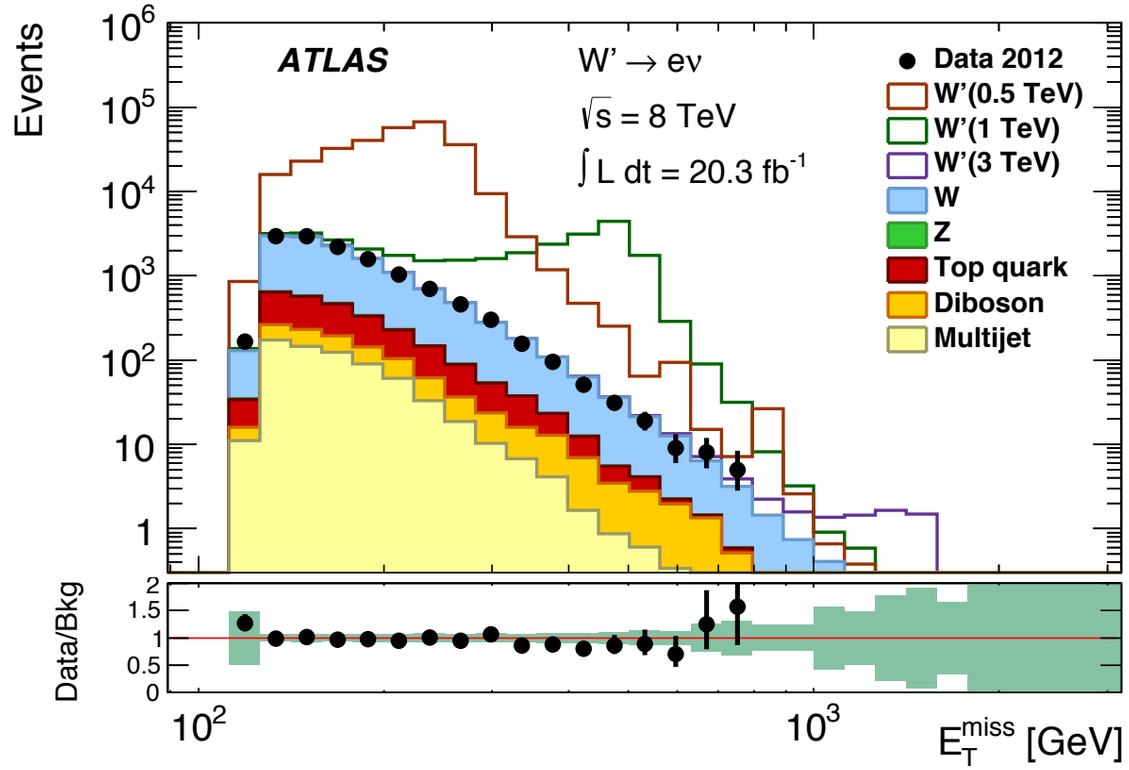




Vector operator spin independent (SI)

MonoW (W decays leptonically)





arXiv:1407.7494

Event selection

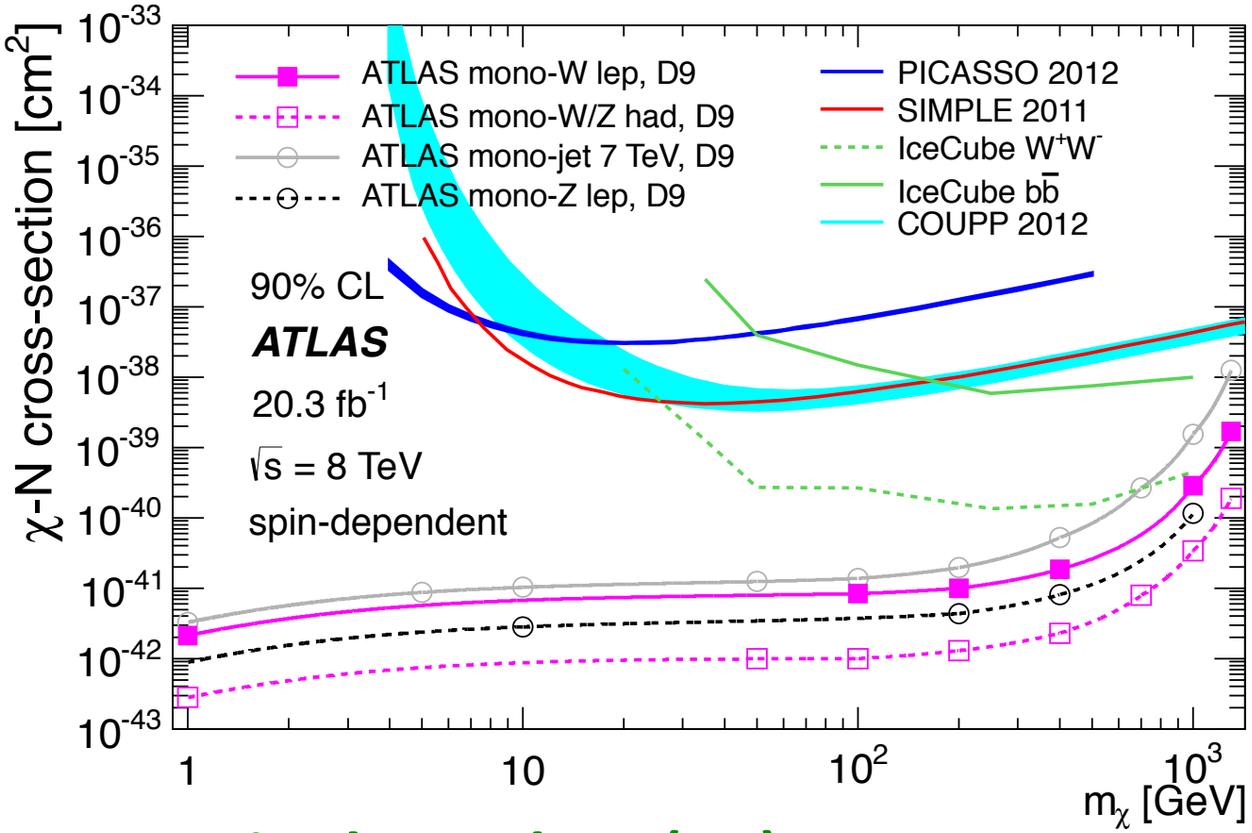
- Muon (Electron) P_T > 45 (125) GeV
- MET > 45 GeV (Muon), 125 GeV (Electron)
- M_T > 252 GeV

$$M_{\mathrm{T}} = \sqrt{2 \cdot p_{\mathrm{T}}^{\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

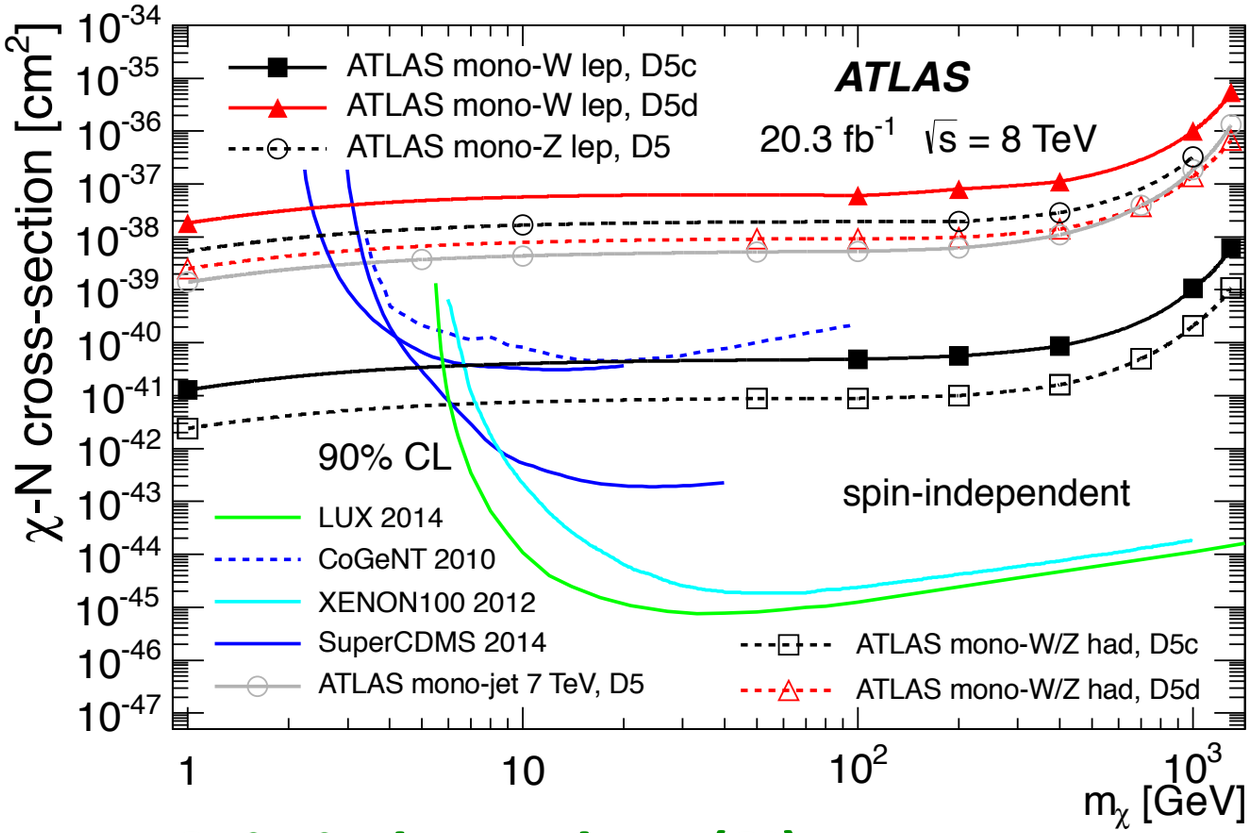
MonoW (W decays leptonically)

Results

arXiv:1407.7494



Spin-dependent (SD)



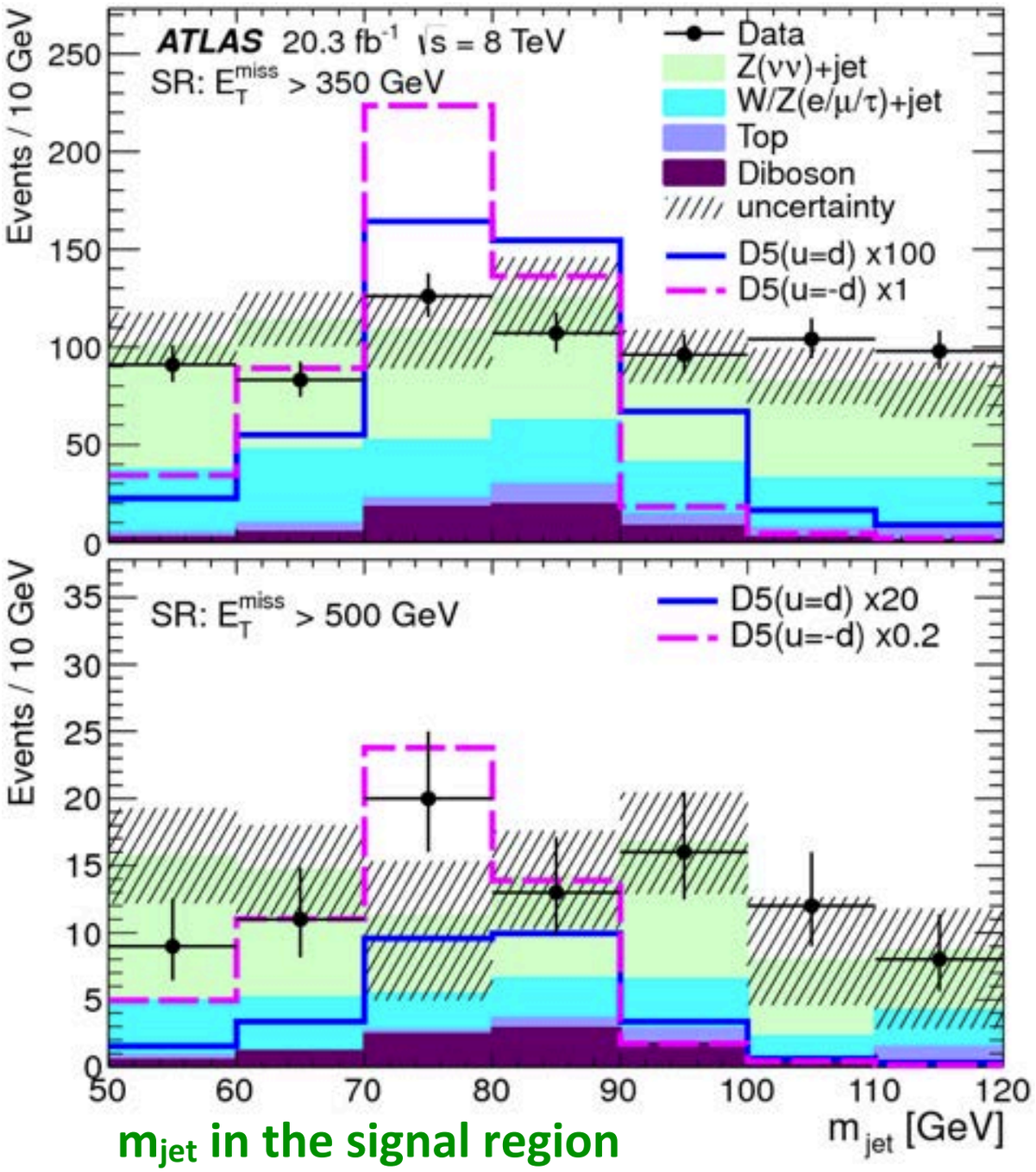
Spin independent (SI)

MonoW, Z (W,Z decays hadronically)

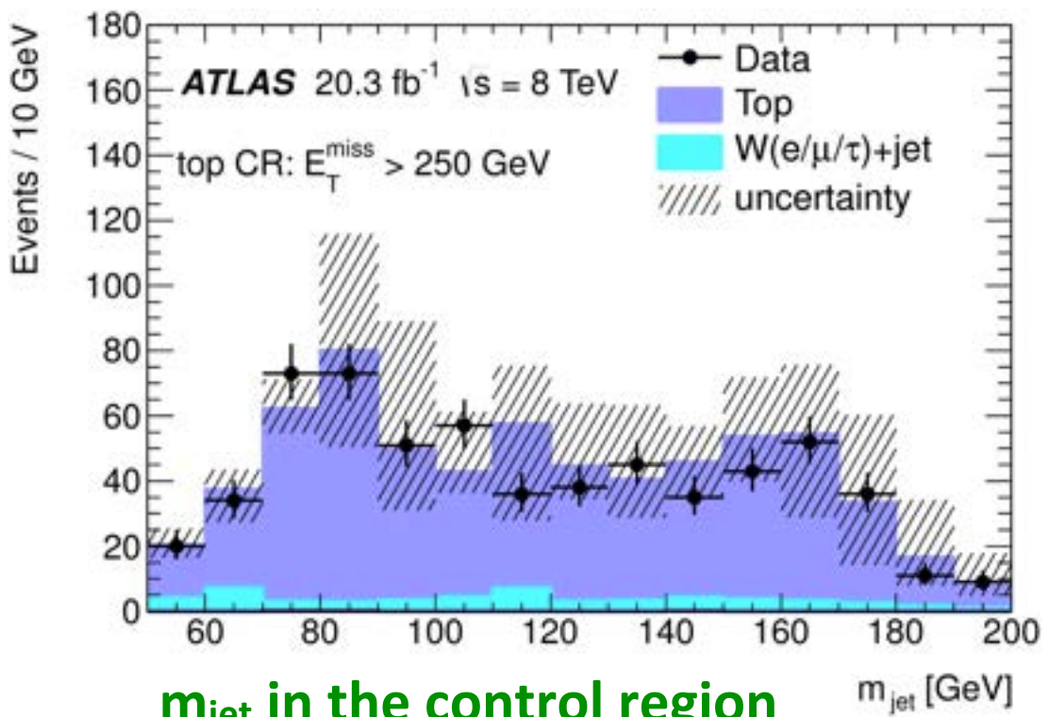
Event selection

PhysRevLett.112.041802

- MET > 150 GeV
- At least, a CA1.2 jet with PT > 250 GeV, $|\eta| < 2.5$, $50 < m_{jet} < 120$
- Reject if there are more than one AK0.4 jet with PT > 40 GeV, $|\eta| < 4.5$ which is not completely overlapping with CA1.2
- Reject if events contain electron, photon, or muon candidates



m_{jet} in the signal region

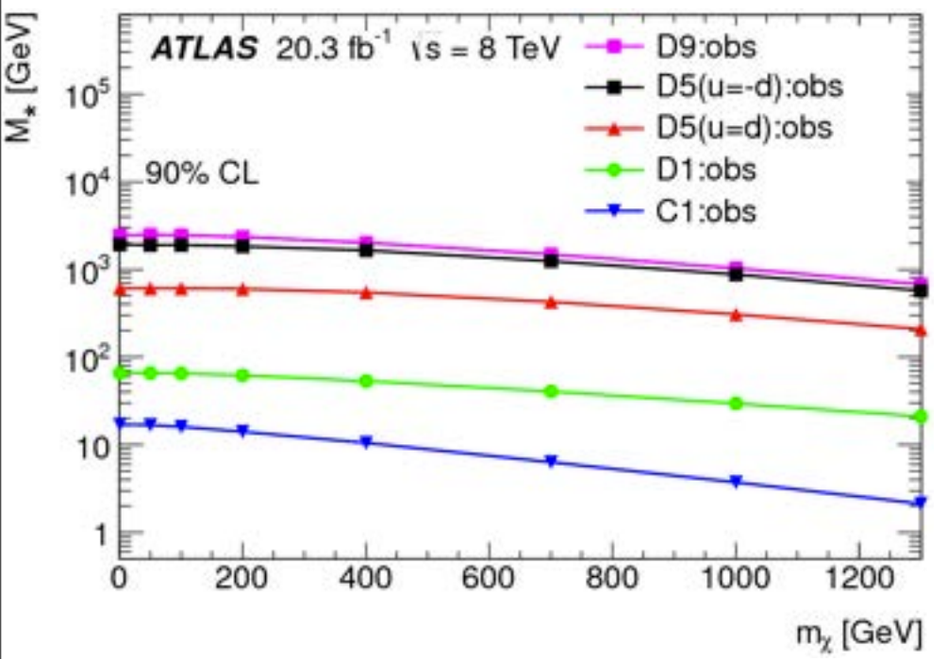


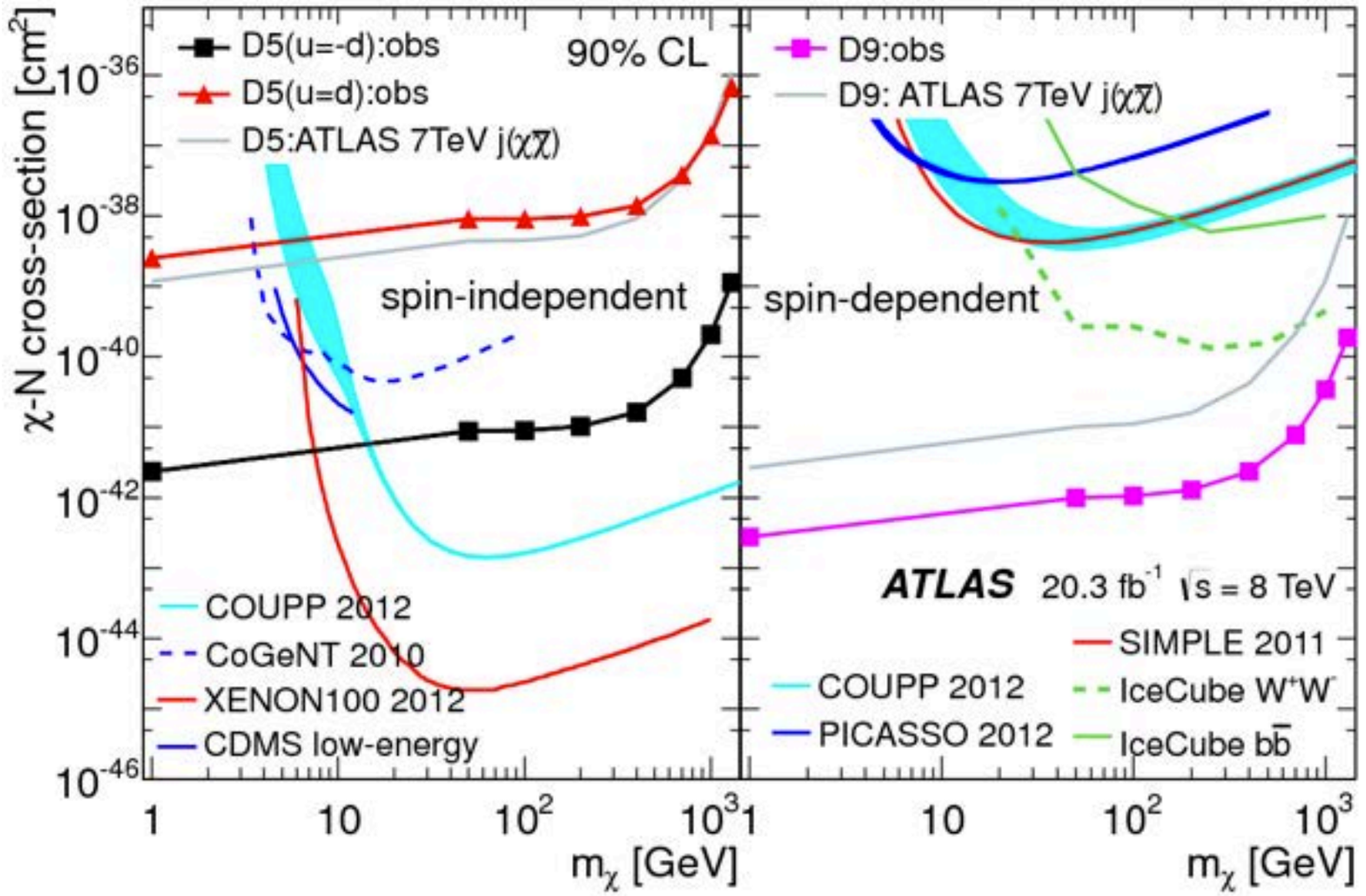
m_{jet} in the control region

MonoW, Z (W,Z decays hadronically)

Results

PhysRevLett.112.041802





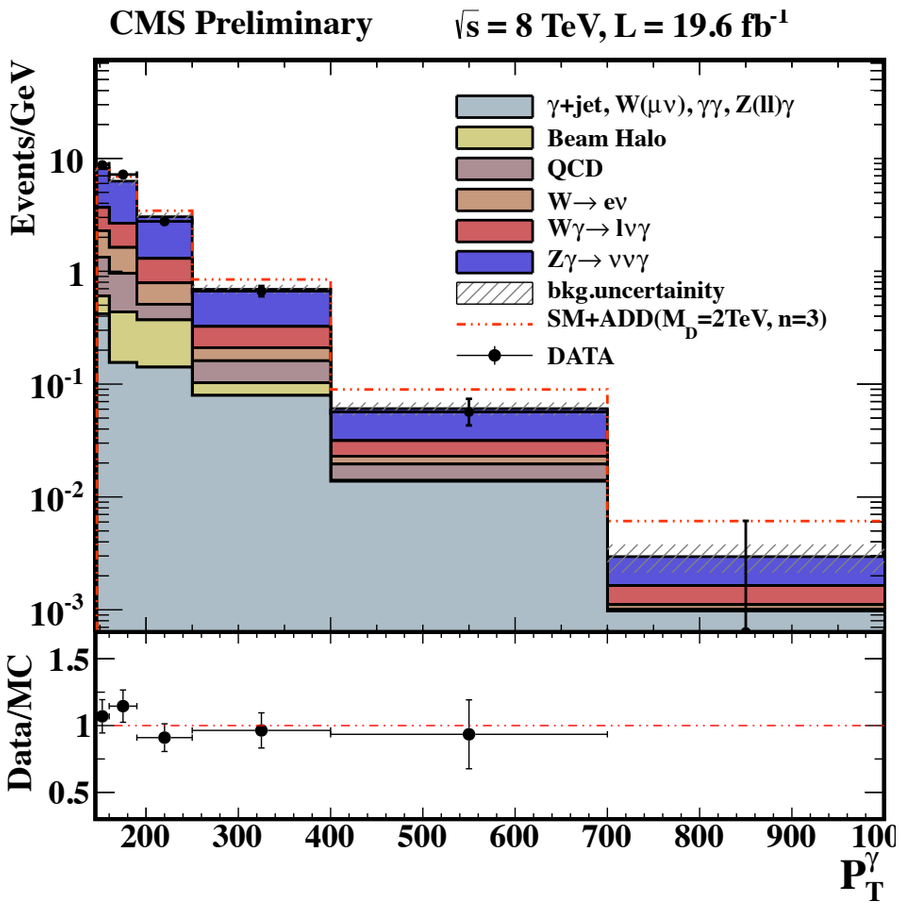
Spin independent (SI) **Spin-dependent (SD)**

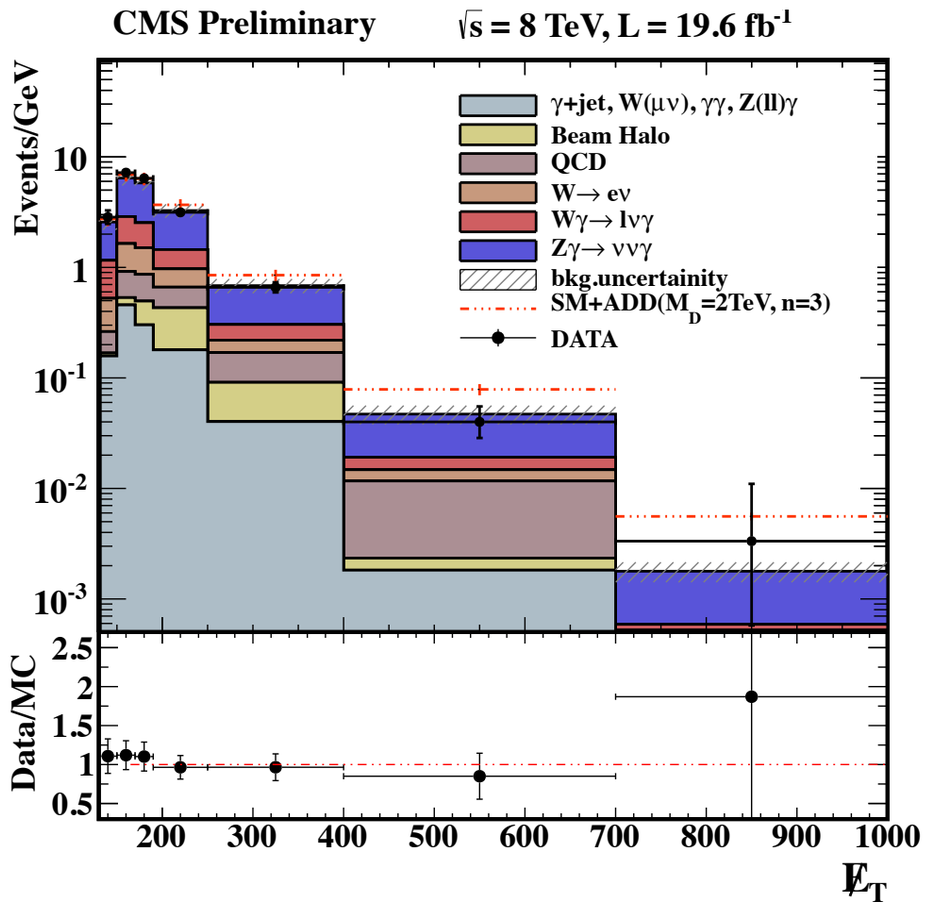
MonoPhoton

EXO-12-047: http://cds.cern.ch/record/1702015

Event selection

- MET > 140 GeV
- One energetic photon, p_T > 145 GeV, $|\eta|$ < 1.4442
- Veto on jets, leptons, and pixel seeds (hit pattern in the pixel detector)
- DeltaPhi(photon,MET) > 2
- MinMET > 120 GeV, Prob(χ^2) (Reduce fake MET events)

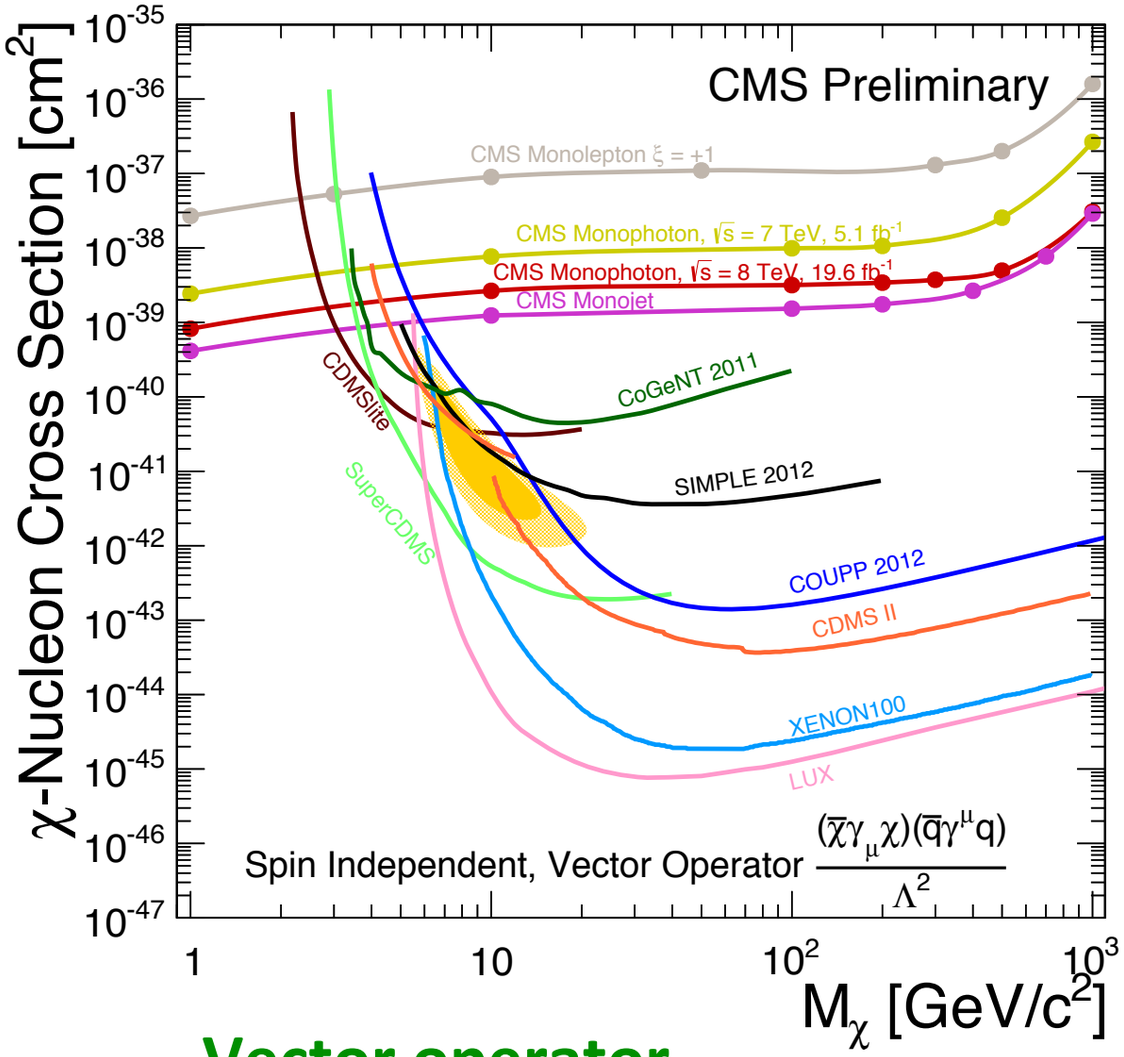




MonoPhoton

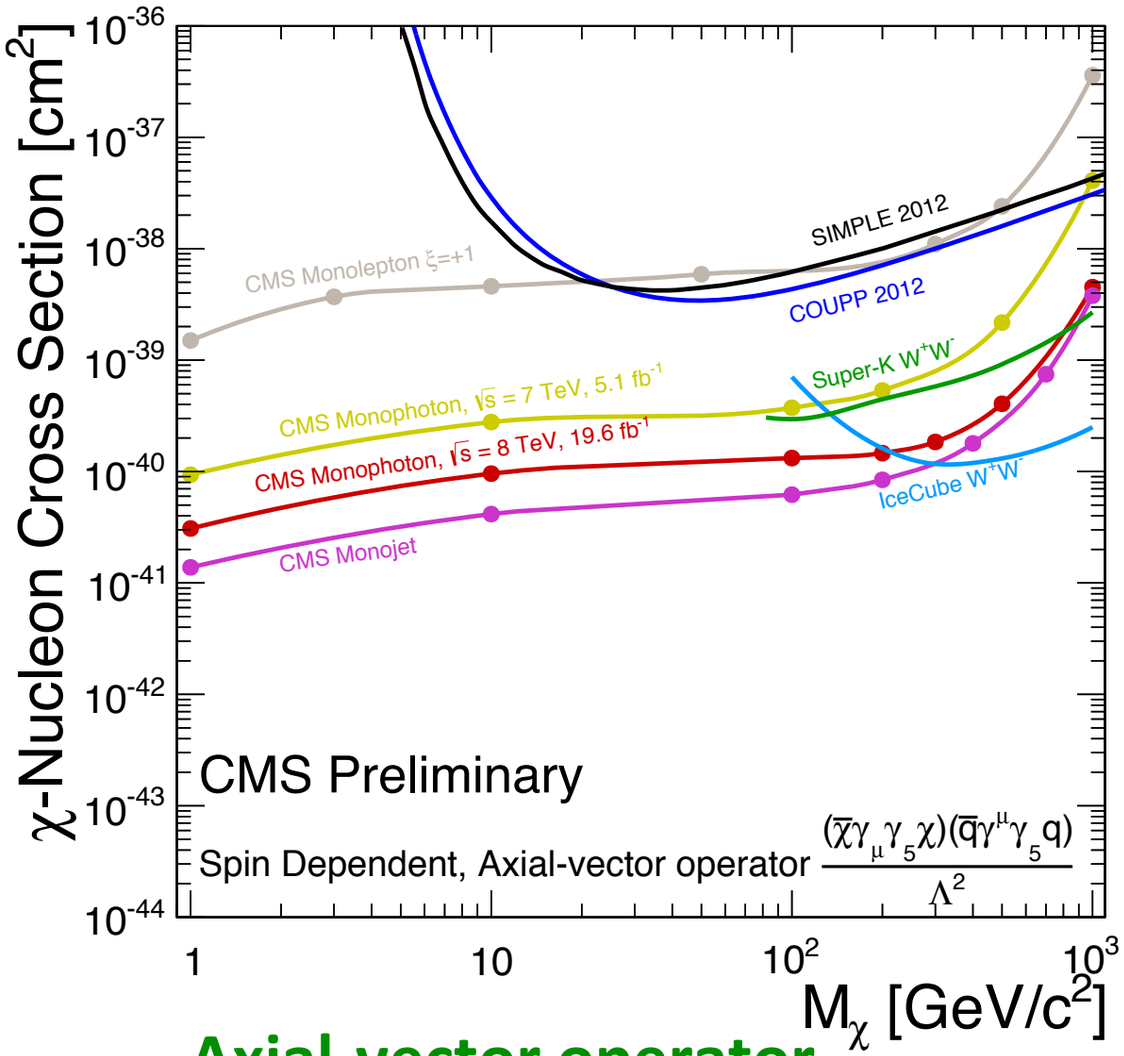
Results

EXO-12-047: http://cds.cern.ch/record/1702015



Vector operator
spin independent (SI)

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



Axial-vector operator
spin-dependent (SD)

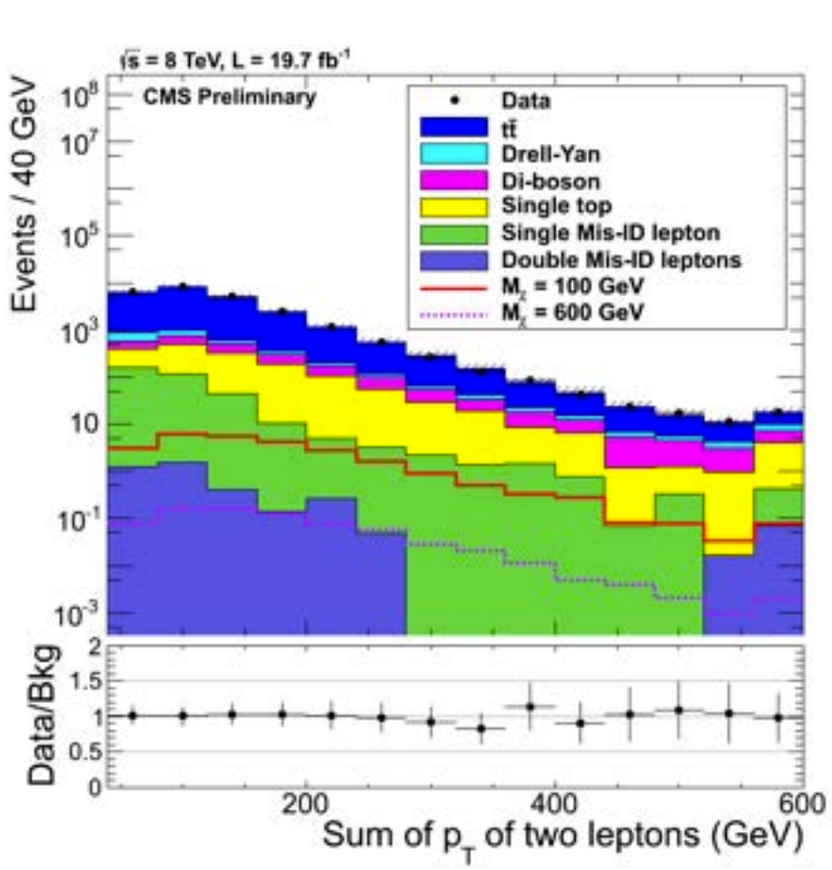
$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma 5\chi)(\bar{q}\gamma^\mu\gamma 5 q)}{\Lambda^2}$$

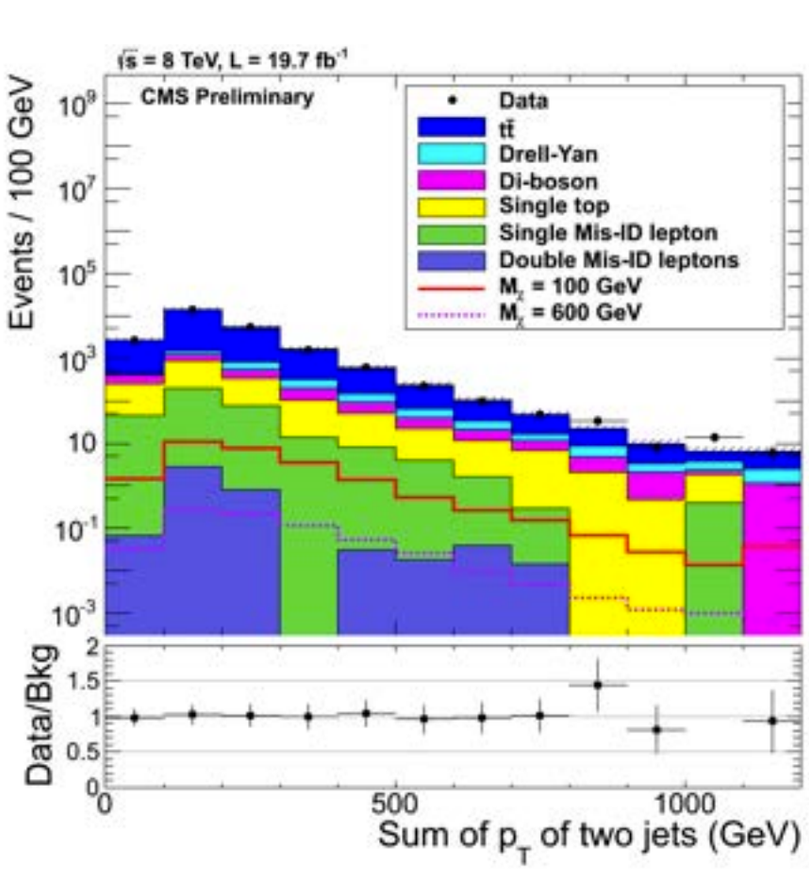
Top quark pair

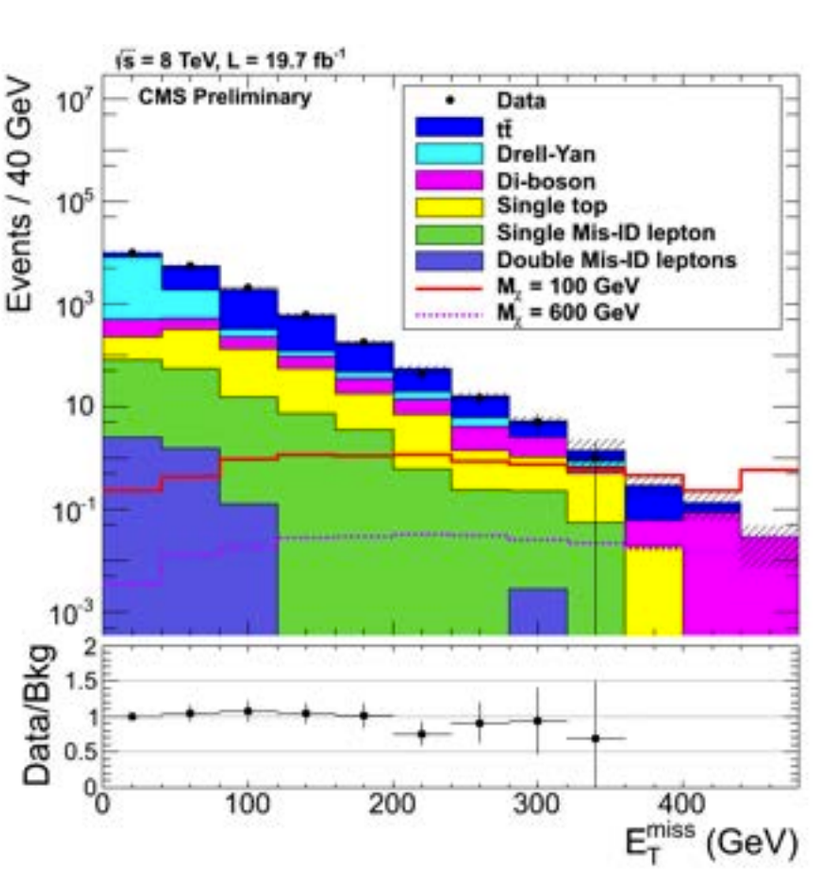
B2G-13-004: http://cds.cern.ch/record/1697173

Event selection

- Select pairs of top quarks in the di-lepton channels
- Exactly two identified leptons, and at least two jets are selected.
- M(ll) > 20 GeV and |M(ll) − 91 GeV| > 15 GeV
- MET > 320 GeV
- HT(j_1, j_2) < 400 GeV, HT(l_1, l_2) > 120 GeV, DeltaPhi(l_1, l_2) < 2



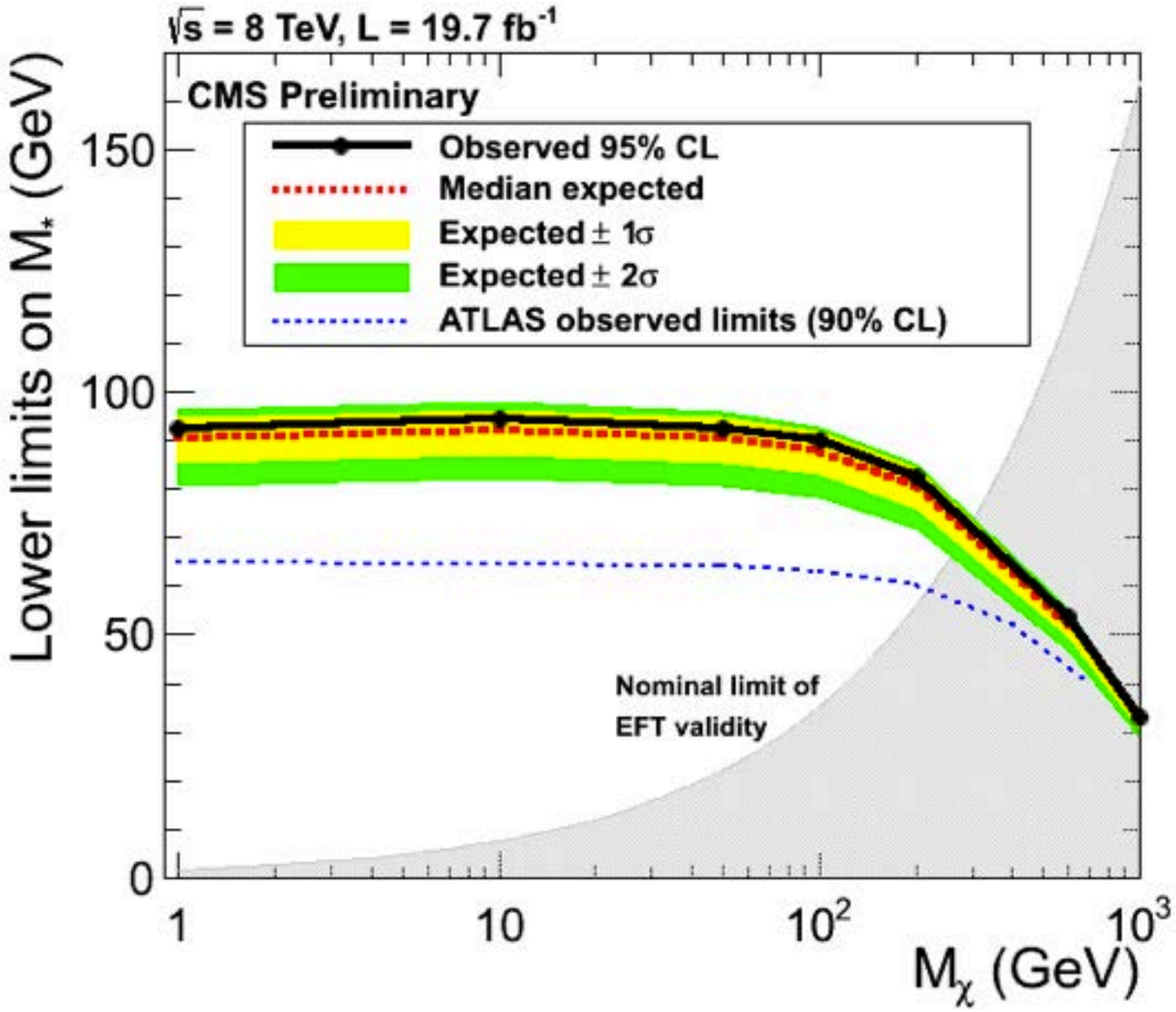




Top quark pair

B2G-13-004: http://cds.cern.ch/record/1697173

Results



Background Source	Yield
$t\bar{t}$	$0.87 \pm 0.18 \pm 0.27$
Single top	$0.48 \pm 0.46 \pm 0.09$
Di-boson	$0.32 \pm 0.09 \pm 0.05$
Drell-Yan	$0.19 \pm 0.14 \pm 0.03$
One Mis-ID lepton	$0.02 \pm 0.07 \pm 0.02$
Double Mis-ID leptons	$0.00 \pm 0.00 \pm 0.00$
Total Bkg	$1.89 \pm 0.53 \pm 0.39$
Data	1
Signal	$1.88 \pm 0.11 \pm 0.07$

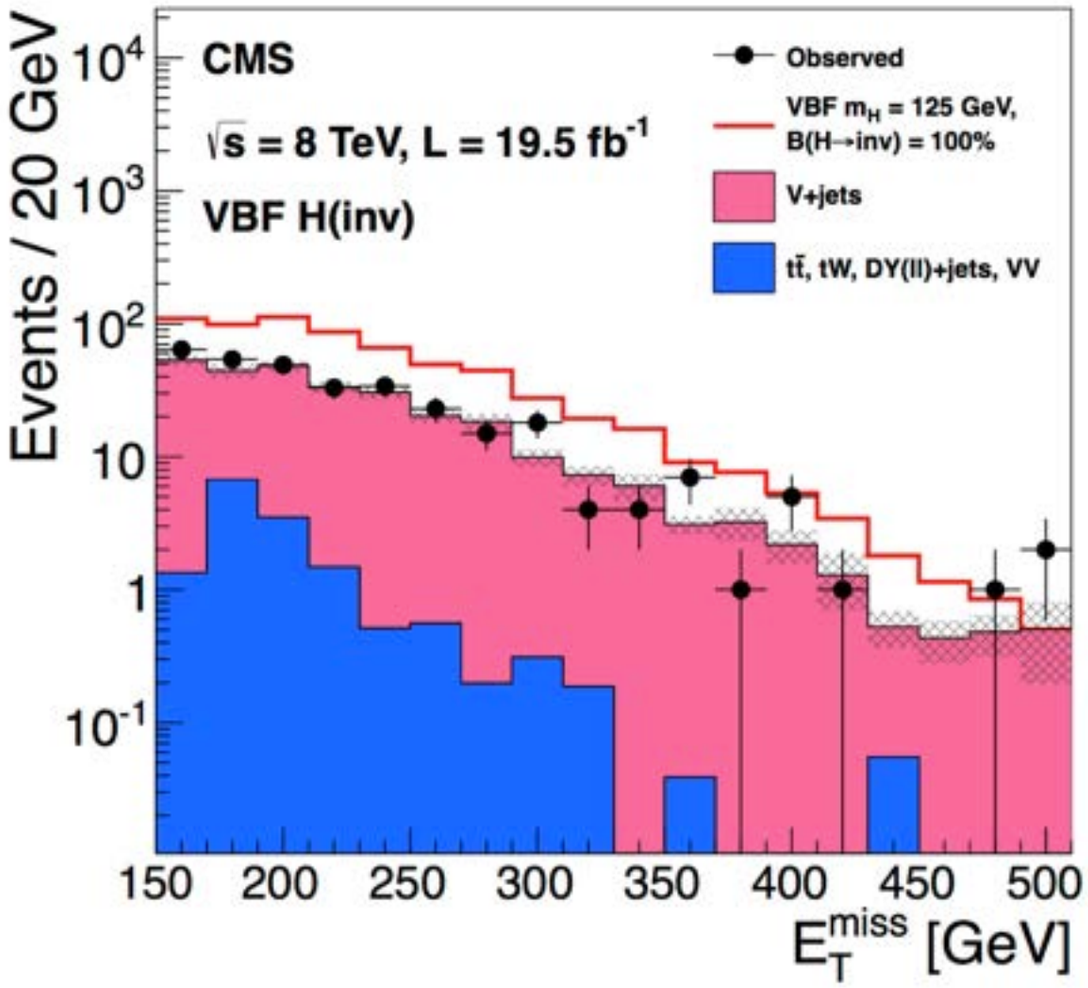
M_χ (GeV)	Signal efficiency (%)	$\sigma^{\text{lim}}_{\text{exp}}$	$\sigma^{\text{lim}}_{\text{obs}}$
1	$1.28 \pm 0.09 \pm 0.04$	0.35	0.31
10	$1.45 \pm 0.10 \pm 0.05$	0.31	0.27
50	$1.65 \pm 0.11 \pm 0.05$	0.27	0.24
100	$1.96 \pm 0.12 \pm 0.06$	0.23	0.20
200	$2.31 \pm 0.12 \pm 0.05$	0.19	0.17
600	$3.45 \pm 0.17 \pm 0.09$	0.13	0.11
1000	$4.35 \pm 0.24 \pm 0.10$	0.10	0.09

Higgs Portal to Dark Matter

arXiv:1404.1344v2

DM particles have the direct couplings to the SM Higgs sector, $H \rightarrow X X$

- Limits on branching fraction of Higgs to "invisible" particles used for limits on DM
- Can be scalar, vector or fermionic couplings
- Limits only up to DM mass $M_X < M_H/2$



Event selection: VBF+H(inv)

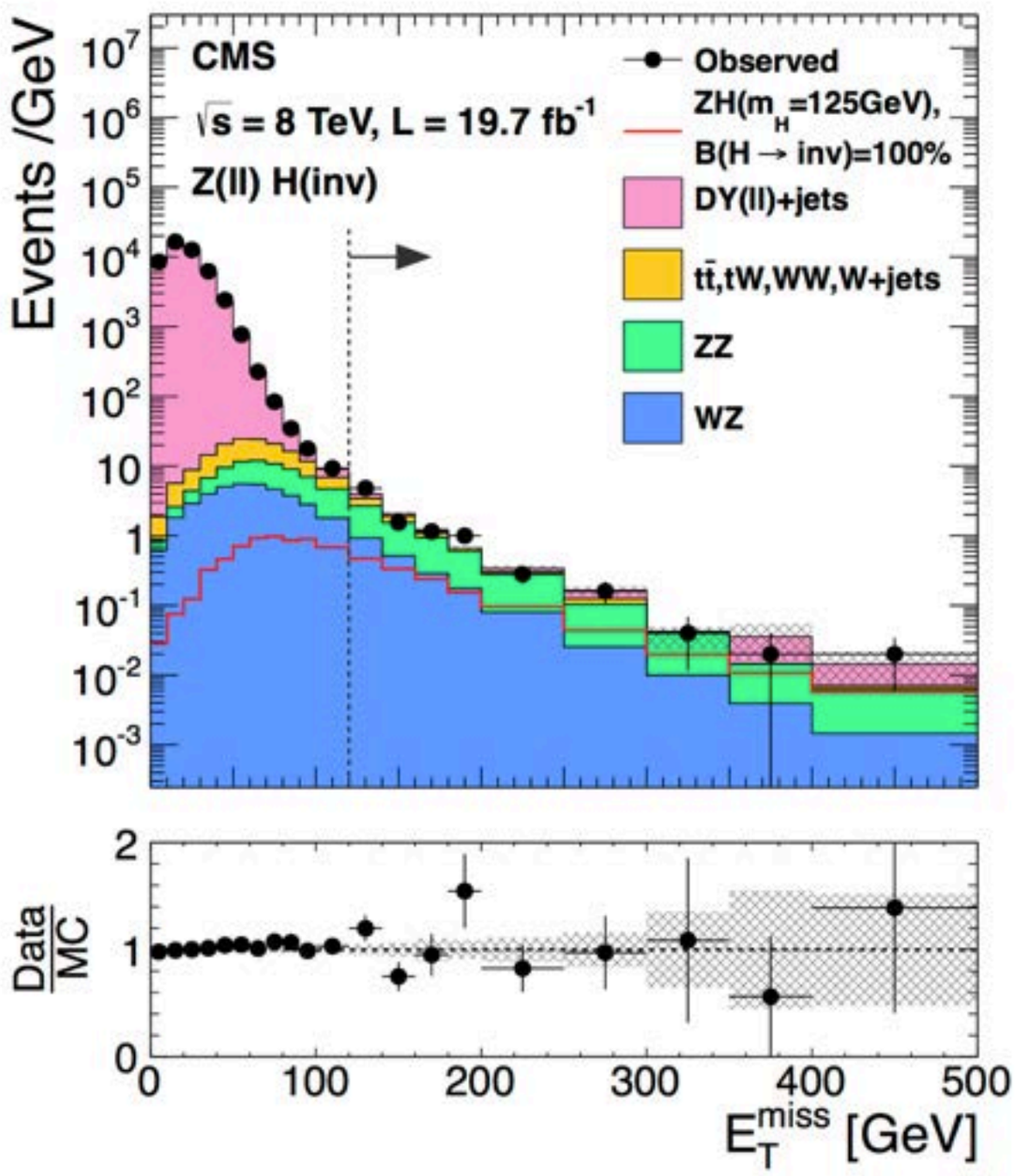
- Veto events with an identified electron, or muon with p_T > 10 GeV.
- VBF tag jet pair, $p_{T,j1}$, $p_{T,j2}$ > 50 GeV, $|\eta|$ < 4.7, η_{j1}, η_{j2} < 0, $\Delta\eta_{jj}$ > 4.2, and M_{jj} > 1100 GeV
- MET > 130 GeV
- DeltaPhi(j_1,j_2)< 1.0
- Central jet veto (event that has an additional jet with p_T > 30 GeV and pseudorapidity between those of the two tag jets)

Higgs Portal to Dark Matter

arXiv:1404.1344v2

Event selection: Z(ll)+H(inv)

- Two well-identified, isolated leptons of the same flavor and opposite sign with P_T > 20 GeV, M(ll) is within +/- 15 GeV of Z mass
- Veto event if there are two or more jets with P_T > 30 GeV
- Veto event containing a bottom-quark decay identified by either the presence of a soft-muon or by the CSV b-tagging algorithm
- MET > 120 GeV
- $\Delta\phi(\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}}) > 2.7$
- $|E_{\mathrm{T}}^{\mathrm{miss}} - p_{\mathrm{T}}^{\ell\ell}| / p_{\mathrm{T}}^{\ell\ell} < 0.25$

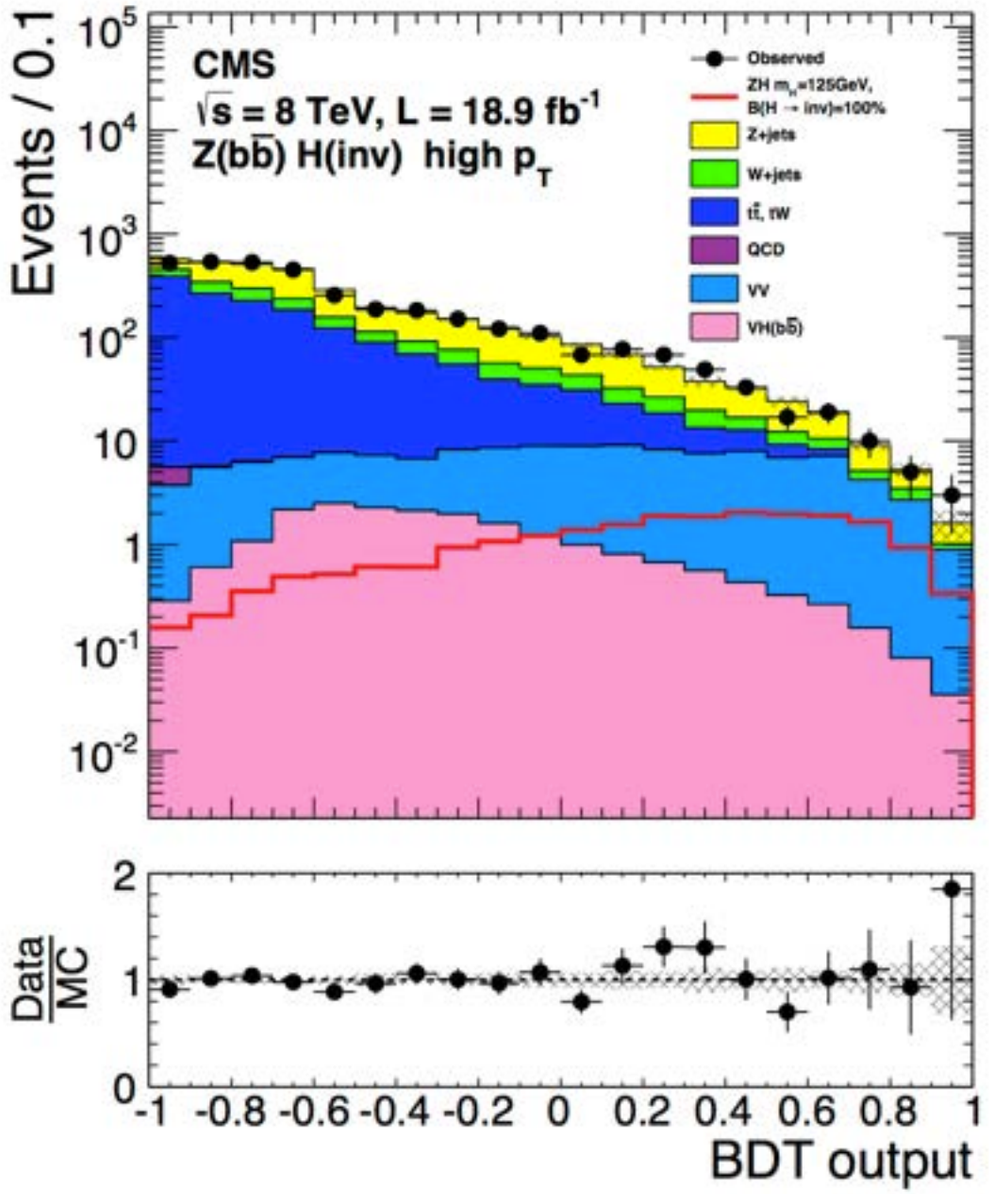


Higgs Portal to Dark Matter

Event selection: Z(bb)+H(inv)

arXiv:1404.1344v2

Variable	Selection		
	Low p_T	Intermediate p_T	High p_T
E_T^{miss}	100–130 GeV	130–170 GeV	>170 GeV
p_T^{j1}	>60 GeV	>60 GeV	>60 GeV
p_T^{j2}	>30 GeV	>30 GeV	>30 GeV
p_T^{jj}	>100 GeV	>130 GeV	>130 GeV
M_{jj}	<250 GeV	<250 GeV	<250 GeV
CSV_{max}	>0.679	>0.679	>0.679
CSV_{min}	>0.244	>0.244	>0.244
N additional jets	<2	—	—
N leptons	=0	=0	=0
$\Delta\phi(Z,H)$	>2.0 radians	>2.0 radians	>2.0 radians
$\Delta\phi(E_T^{miss},j)$	>0.7 radians	>0.7 radians	>0.5 radians
$\Delta\phi(E_T^{miss},E_T^{miss}{}_{trk})$	<0.5 radians	<0.5 radians	<0.5 radians
E_T^{miss} significance	>3	not used	not used



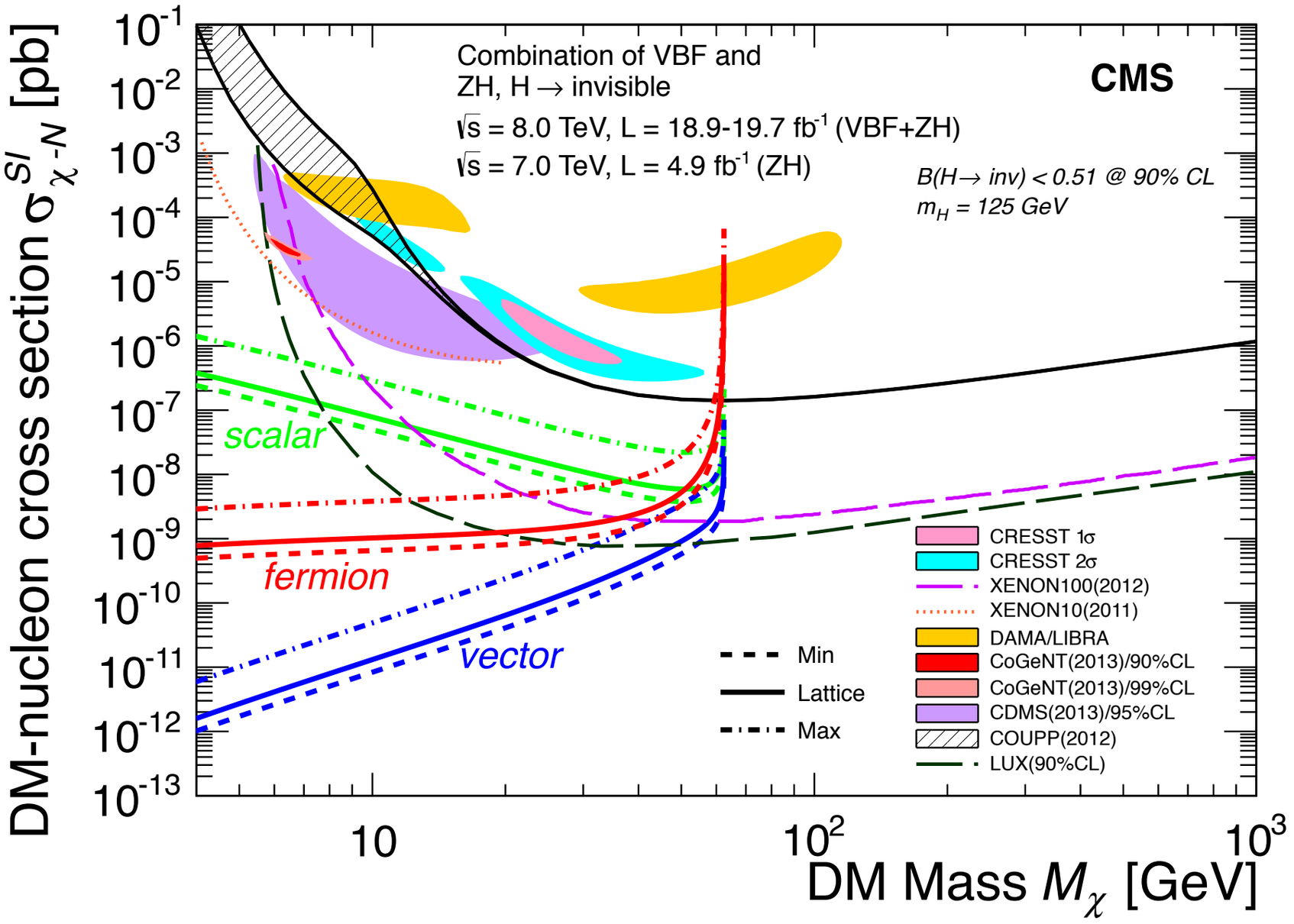
Results (Combine)

- Assuming the SM production cross section and acceptance. mH = 125 GeV
- 95% CL observed upper (expected) limit = 0.58 (0.44)
- 90% CL observed upper (expected) limit = 0.51 (0.38)

Higgs Portal to Dark Matter

Results

arXiv:1404.1344v2



Upper limits on the spin-independent DM-nucleon cross section in Higgs-portal models, derived for mH=125GeV, and B(H→inv) < 0.51 at 90% CL, as a function of the DM mass.