Where is Dark Matter at the LHC?

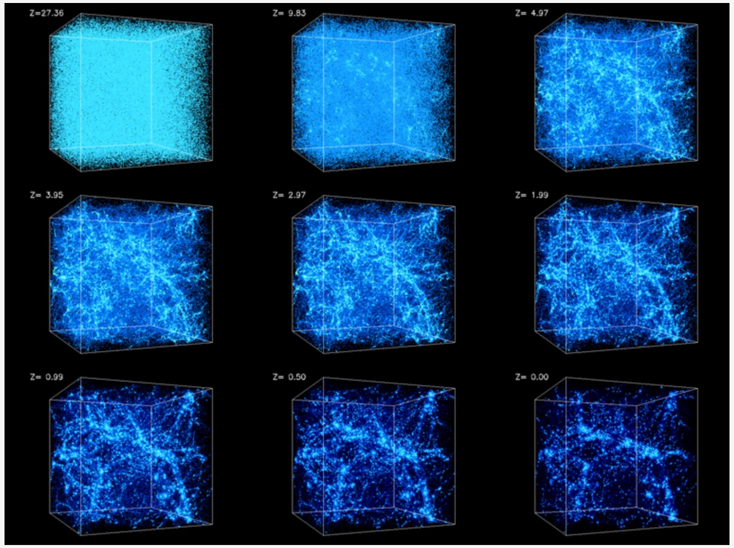
Antonio Boveia (Ohio State University)

The Particle Physics of Dark Matter

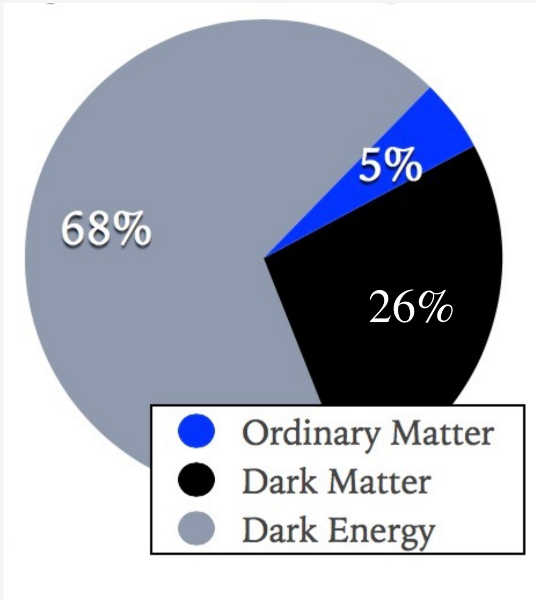
If dark matter is a particle like the other matter in the Standard Model…

It interacts gravitationally

It is dark and cosmologically stable
(other effective couplings to SM are zero or small)

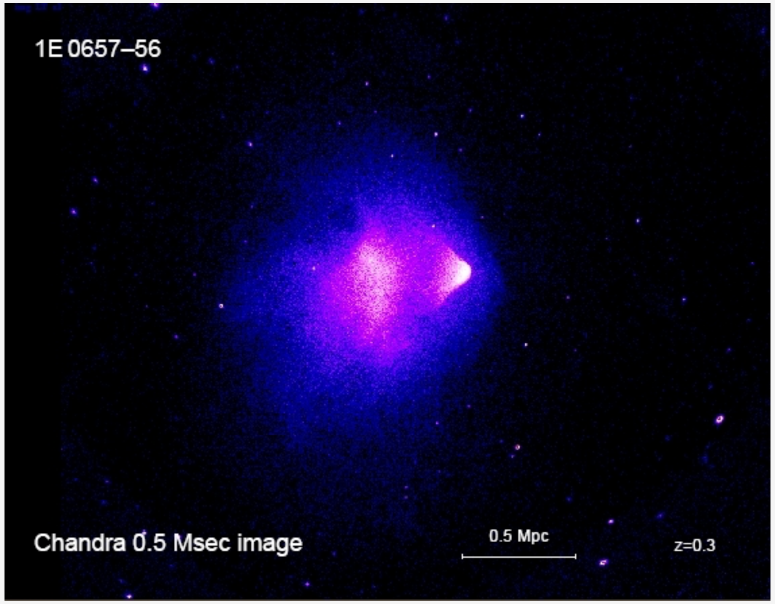


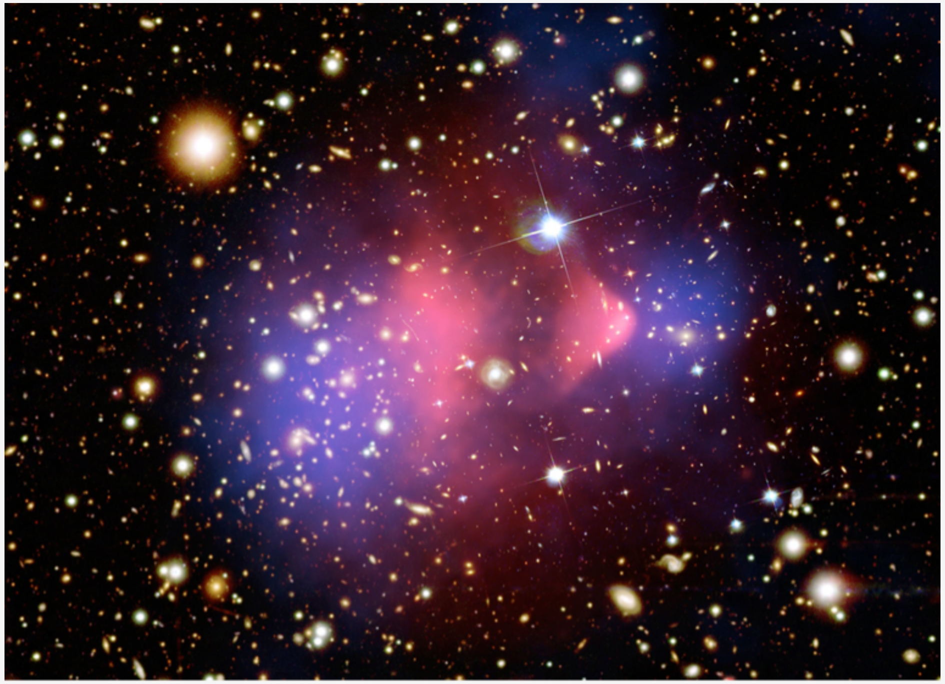
It is approximately cold / non-relativistic



5x as much DM as SM

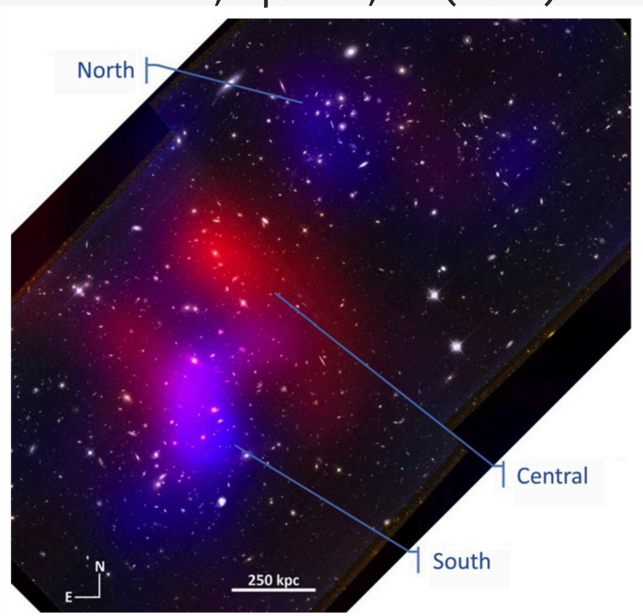
Cluster Collisions—Is the Best Data on New Particle Physics in ApJ?

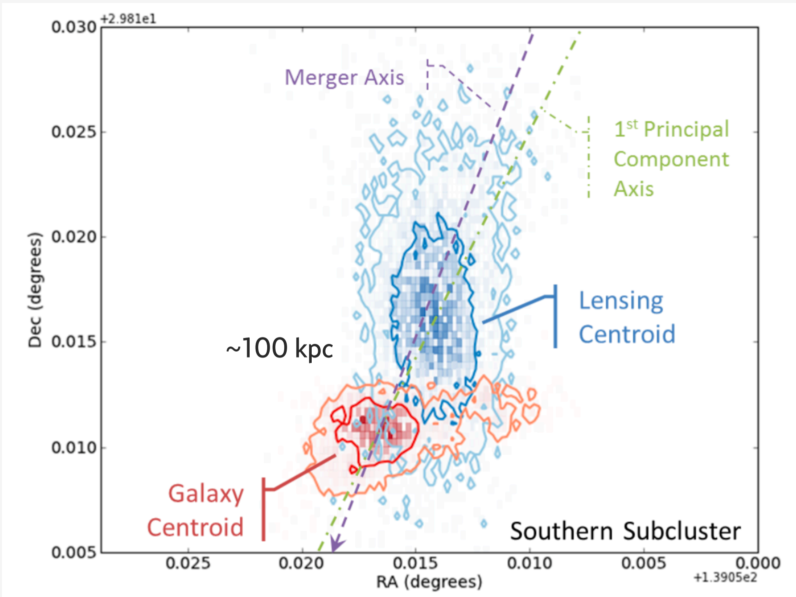




“Bullet” Cluster Clowe et al., ApJ 648 2 (2006)

“Musket Ball” Cluster
Dawson et al, ApJ 747, 42 (2012)



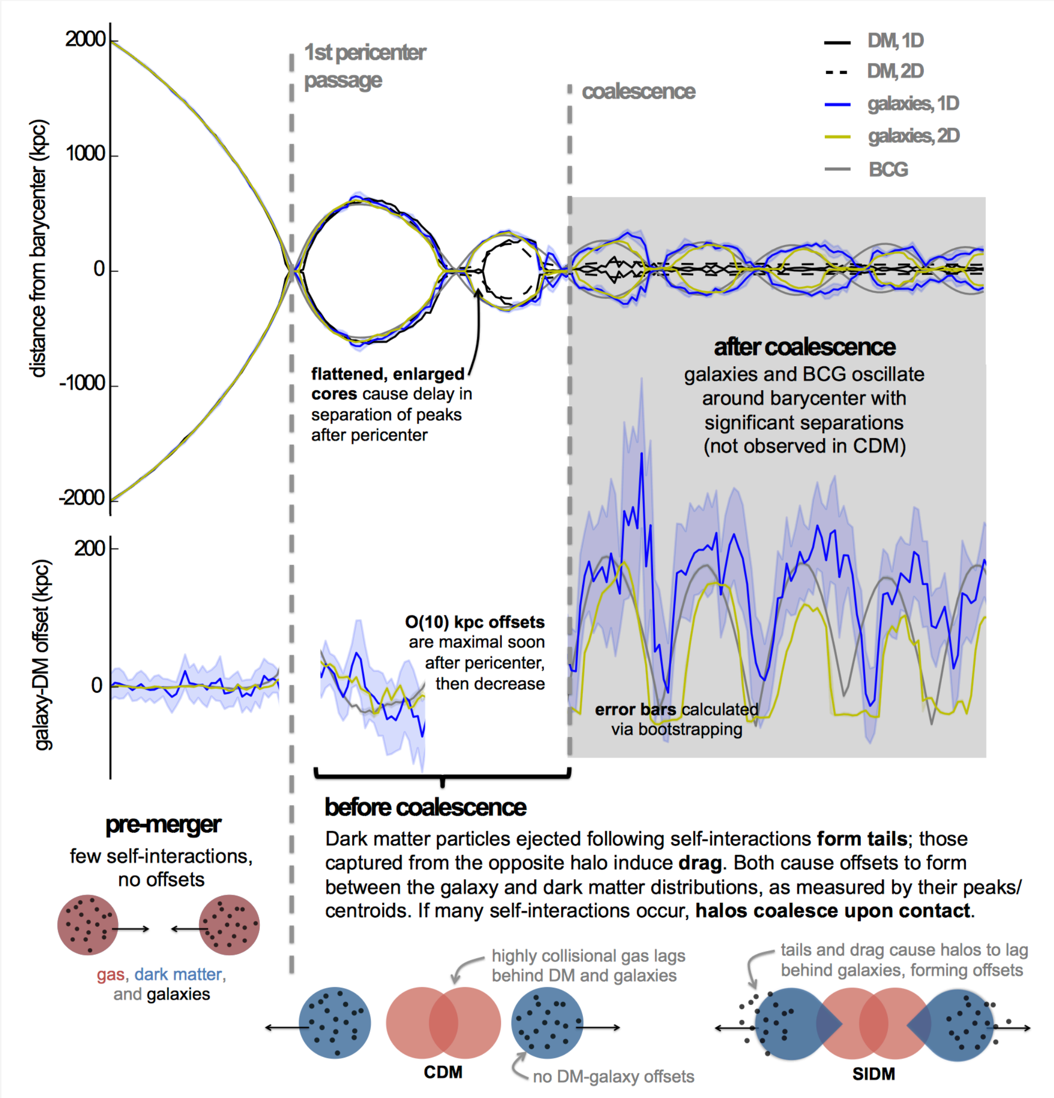


Dark matter (and clustered matter) offset from diffuse gas

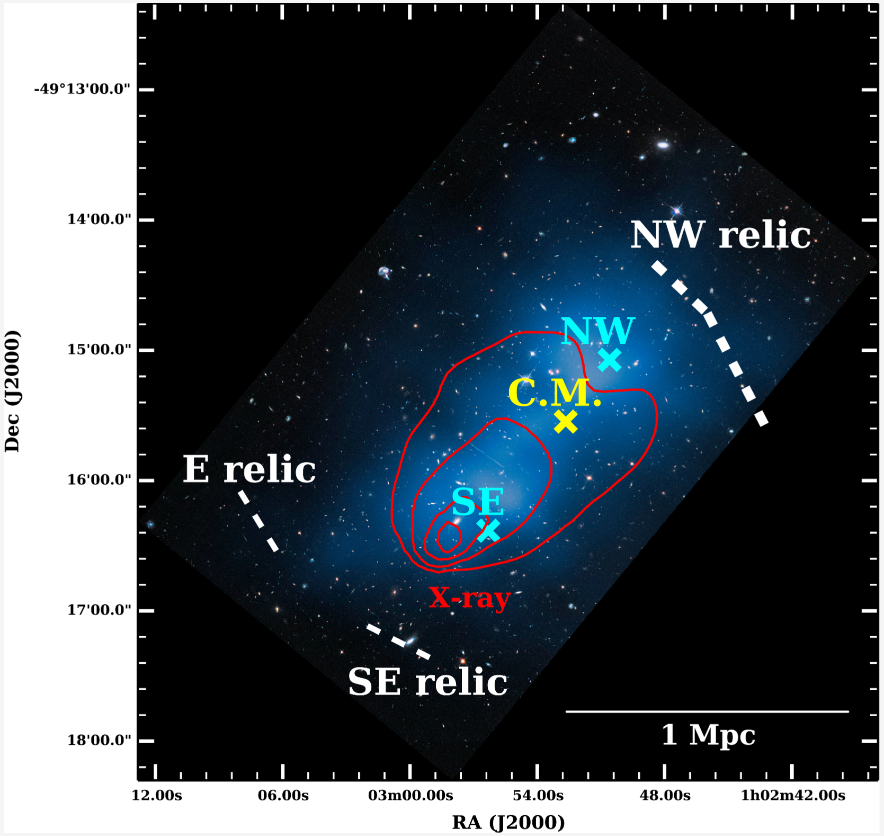
Some evidence of offset between DM and clustered matter in clusters with largest physical separation
(=> $\sigma_{DM}\, m_{DM}^{-1} <= 7\ cm^2 g^{-1}$)

Not so fast...

Kim, Peter, Wittman arXiv:1608.08630



"El Gordo"
MNRAS 453, 1531–1549 (2015)



Lee and Komatsu, ApJ 718 60–65 (2010)
Zhang et al., ApJ 813 2 (2015)

In equal-mass galaxy cluster merger simulations,

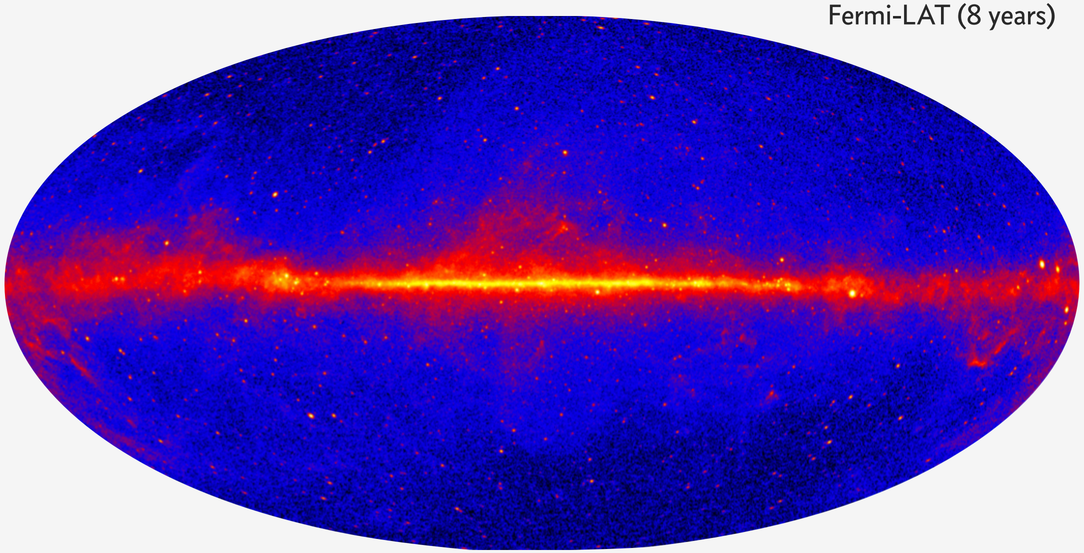
- Large matter-DM offsets are not a generic consequence of DM self-interactions
- (more promising: evolution of mergers)

High velocity collisions, like El Gordo or Bullet Cluster, are in tension with CDM structure formation

Also many 'puzzles' at galactic scale

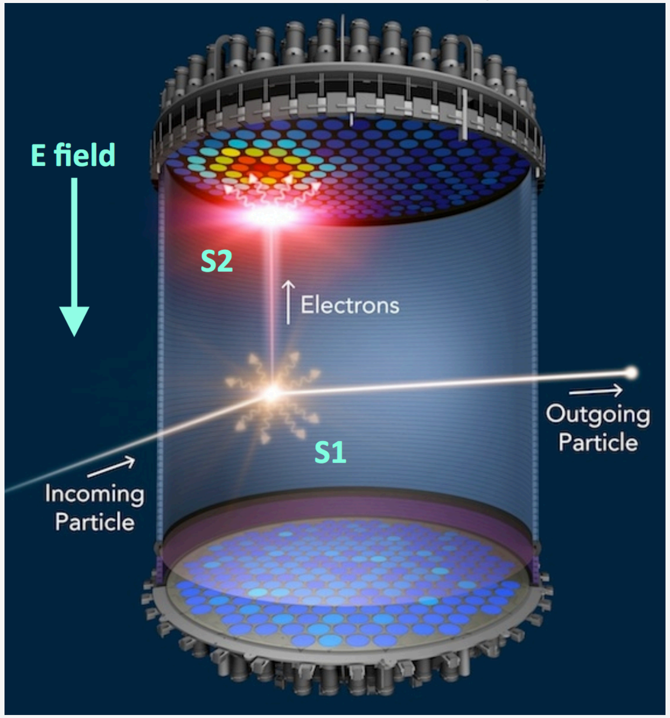
Meanwhile, closer to Planet Earth

Fermi-LAT (8 years)



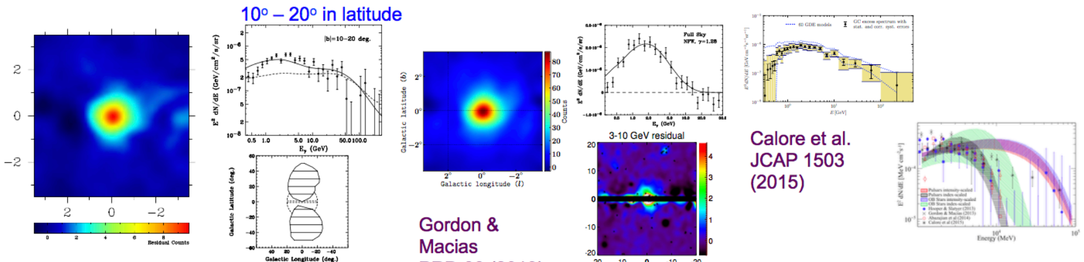
Indirect Detection

figure: M. Monzani



Direct Detection

“Galactic Center” Excess—over complex background



Abazajian & Kaplinghat PRD 87 (2012)

Hooper & Slatyer Phys.Dark Univ. 2 (2013)

Gordon & Macias PRD 88 (2013)

Daylan et al. Phys.Dark Univ. 12 (2016)

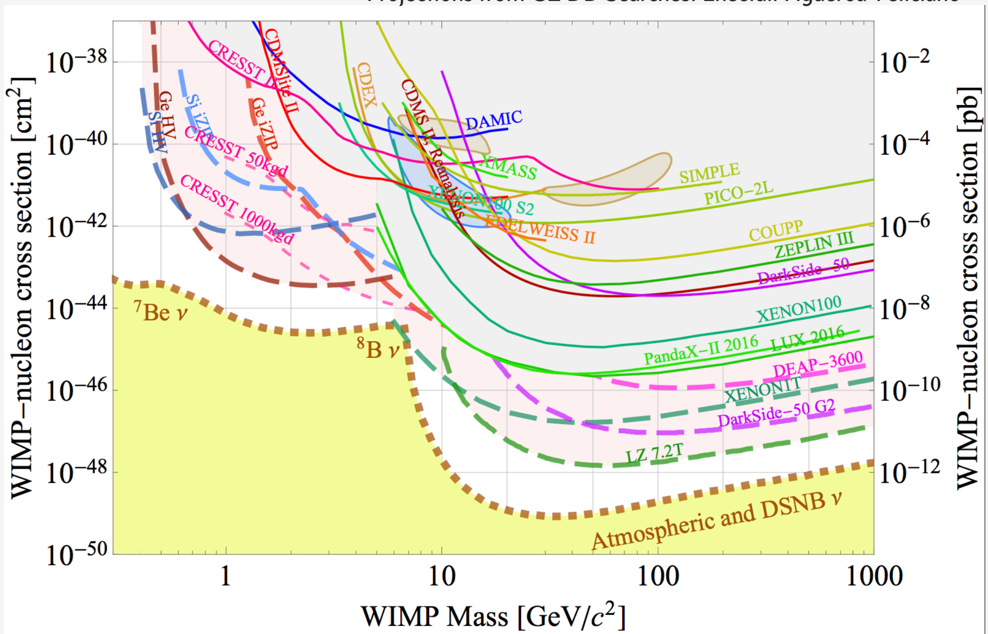
Calore et al. JCAP 1503 (2015)

Ajello et al. ApJ 819 (2016)

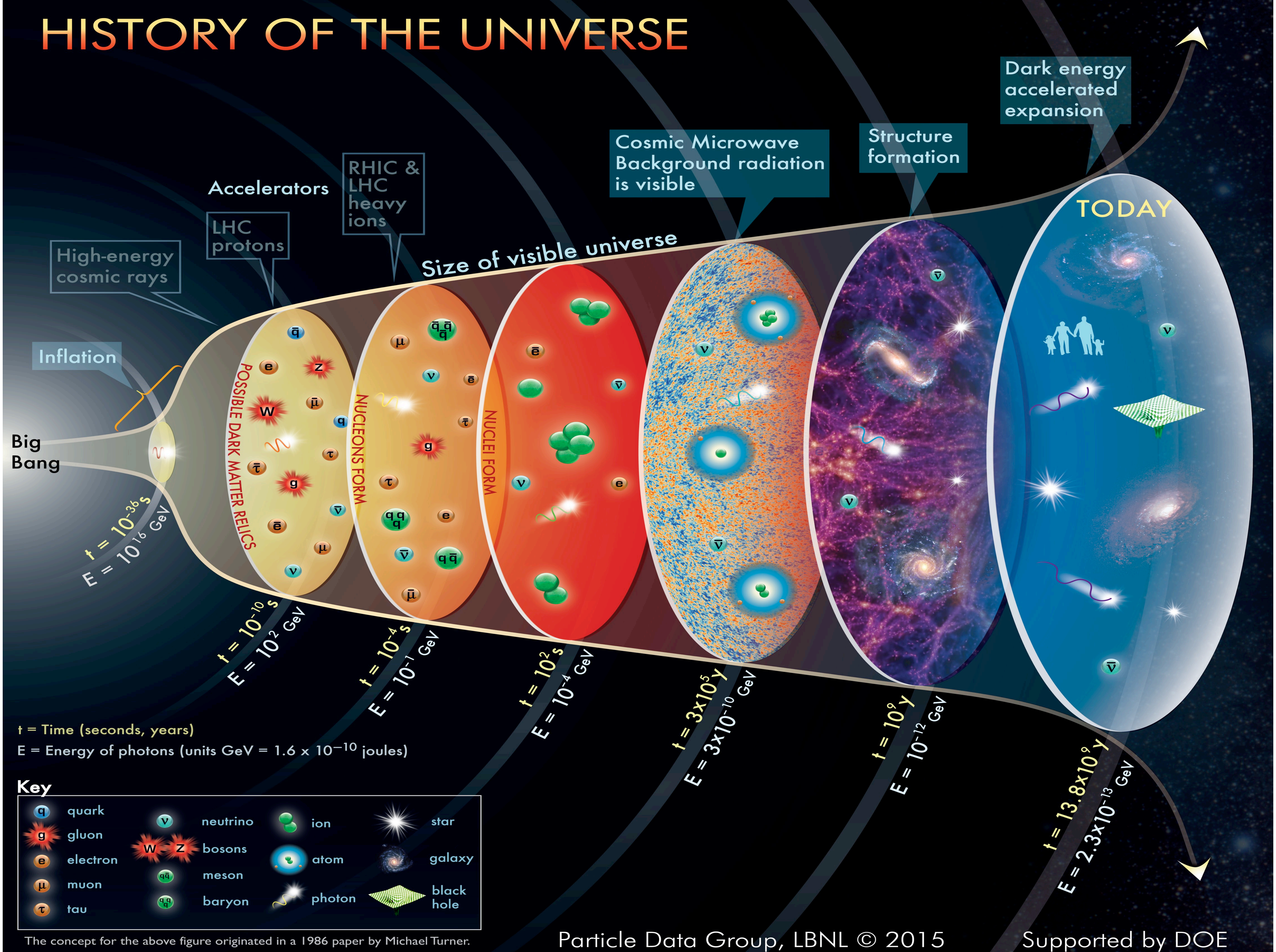
- **Possible interpretations:**
  - **DM annihilation, millisecond pulsars** (e.g., Brand&Kocsis 2015), **cosmic-ray sources near the GC** (e.g., Carlson et al 2016)

(credit: D. Malyshev)

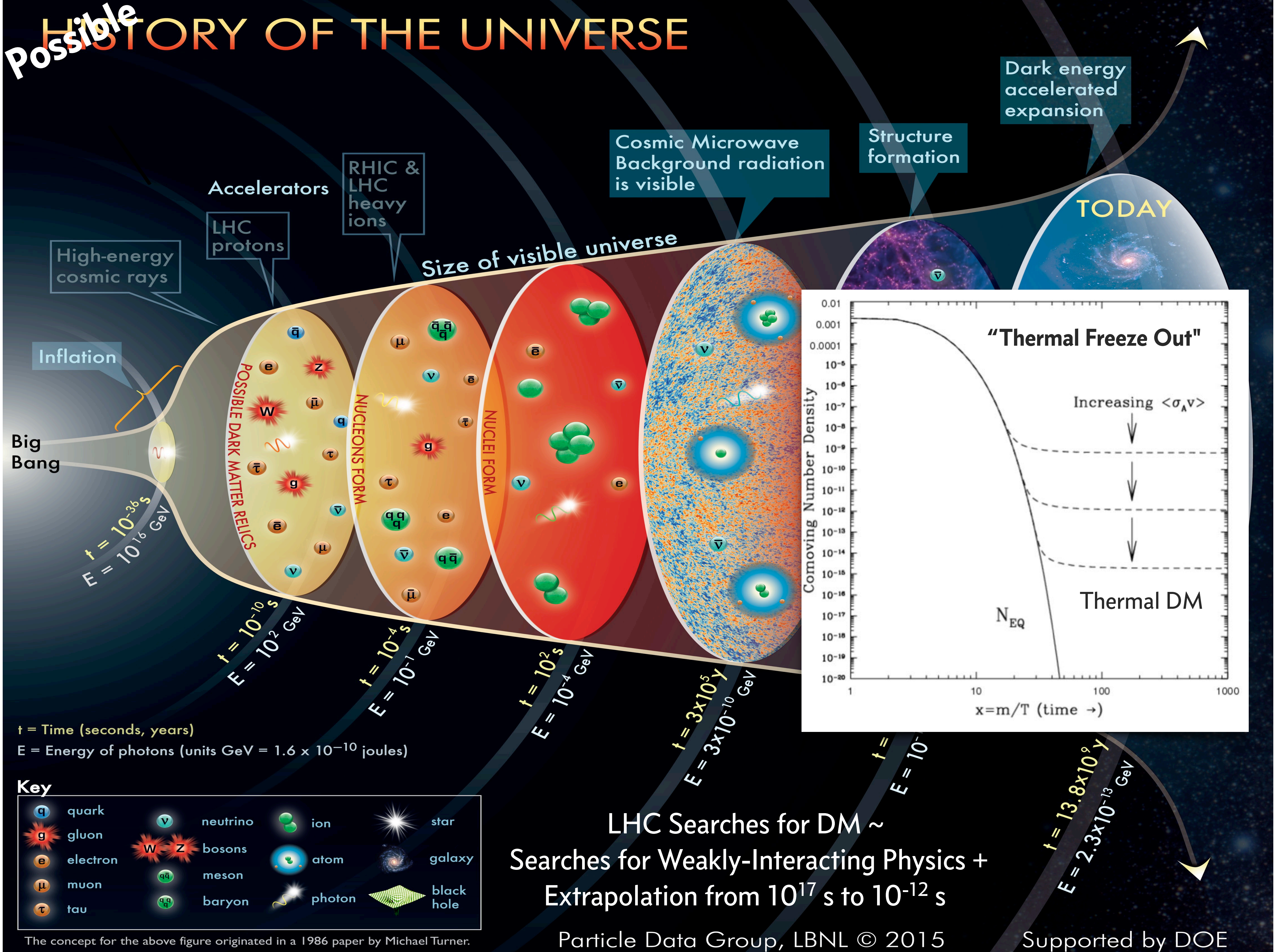
Projections from G2 DD Searches: Enectalí Figueroa-Feliciano



Possibilities for interactions between SM and Dark Sectors



HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Inflation
Size of visible universe
TODAY
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE



Possible HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
TODAY
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
"Thermal Freeze Out"
Increasing <σ_A v>
Thermal DM
N_EQ
Comoving Number Density
x=m/T (time →)
0.01
0.001
0.0001
10^-5
10^-20
1
10
100
1000
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
LHC Searches for DM ~
Searches for Weakly-Interacting Physics +
Extrapolation from 10^17 s to 10^-12 s
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

If the Z boson mediates SM-DM interaction...

PDG (LEP) Invisible Decay Width of the Z

VALUE (MeV)	EVTS	DOCUMENT ID		TECN
499.0 ± 1.5	**OUR FIT**			
503 ± 16	**OUR AVERAGE** Error includes scale factor of 1.2.			
498 ±12 ±12	1791	ACCIARRI	1998G	L3
539 ±26 ±17	410	AKERS	1995C	OPAL
450 ±34 ±34	258	BUSKULIC	1993L	ALEP
540 ±80 ±40	52	ADEVA	1992	L3

Number from e^+e^- Colliders

Number of Light ν Types

Our evaluation uses the invisible and leptonic widths of the Z boson from our combined fit shown in the Particle Listings for the Z Boson, and the Standard Model value $\Gamma_\nu/\Gamma_\ell = 1.9908 \pm 0.0015$.

VALUE	DOCUMENT ID		TECN
2.994±0.012 OUR EVALUATION	Combined fit to all LEP data.		
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3.00 ±0.05	[1] LEP	92	RVUE

[1] Simultaneous fits to all measured cross section data from all four LEP experiments.

Number of Light ν Types from Direct Measurement of Invisible Z Width

In the following, the invisible Z width is obtained from studies of single-photon events from the reaction $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. All are obtained from LEP runs in the E^{ee}_{cm} range 88–94 GeV.

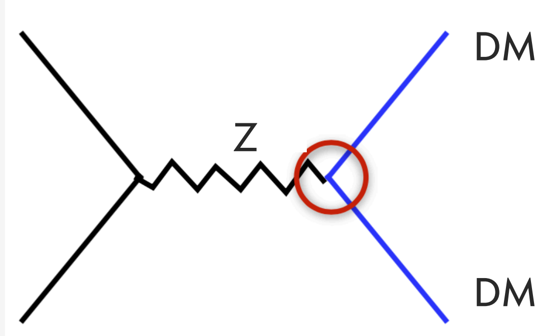
VALUE	DOCUMENT ID		TECN	COMMENT
3.00±0.06 OUR AVERAGE				
3.01±0.08	ACCIARRI	99R	L3	1998 LEP run
2.98±0.07±0.07	ACCIARRI	98G	L3	LEP 1991–1994
2.89±0.32±0.19	ABREU	97J	DLPH	1993–1994 LEP runs
3.23±0.16±0.10	AKERS	95C	OPAL	1990–1992 LEP runs
2.68±0.20±0.20	BUSKULIC	93L	ALEP	1990–1991 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.1 ±0.6 ±0.1	ADAM	96C	DLPH	$\sqrt{s} = 130, 136$ GeV

Limits from Astrophysics and Cosmology

Number of Light ν Types

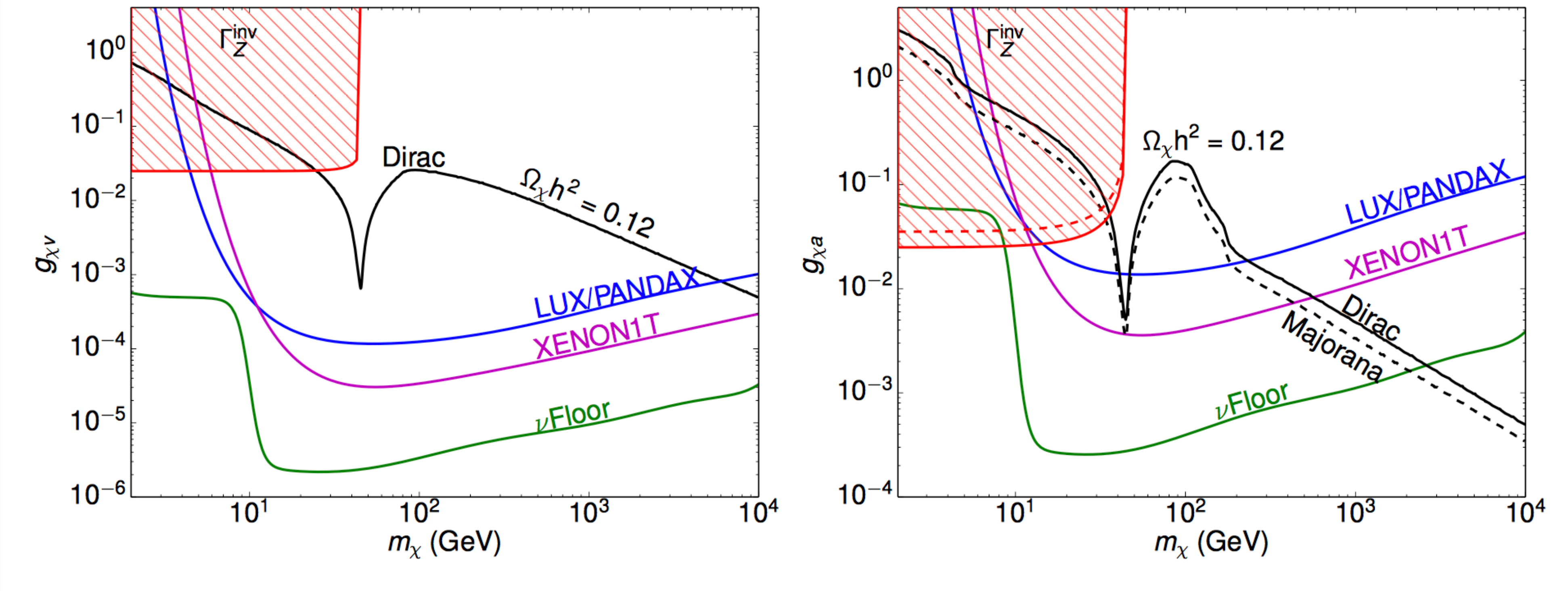
("light" means < about 1 MeV). See also OLIVE 81. For a review of limits based on Nucleosynthesis, Supernovae, and also on terrestial experiments, see DENEGRI 90. Also see "Big-Bang Nucleosynthesis" in this *Review*.

VALUE	DOCUMENT ID	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •		

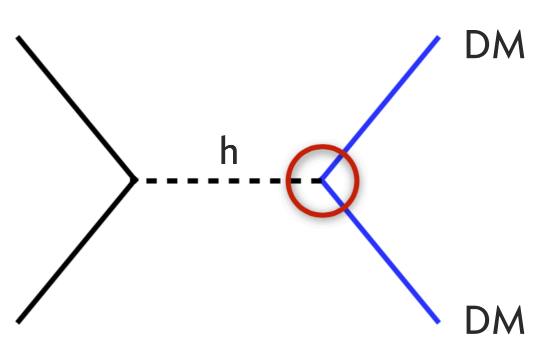


Fermionic DM

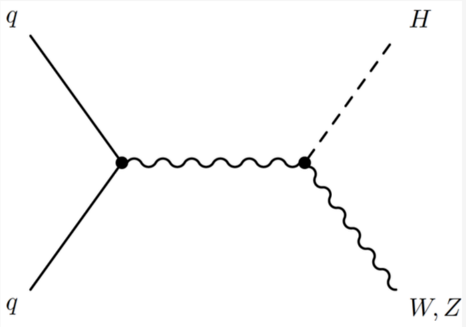
Escudero et al., arXiv:1609.09079

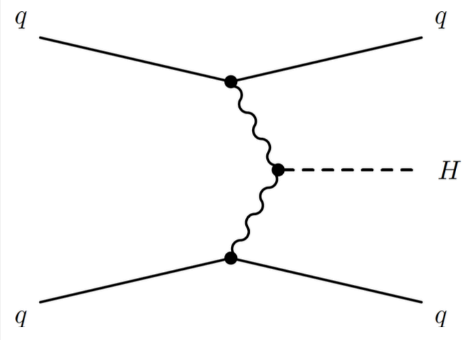


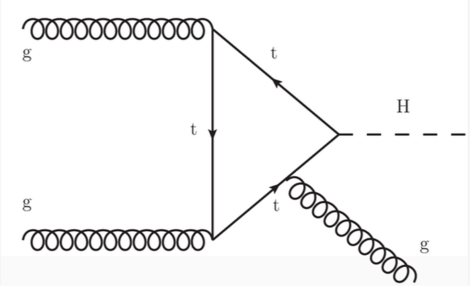
If the Higgs boson mediates SM-DM interaction...

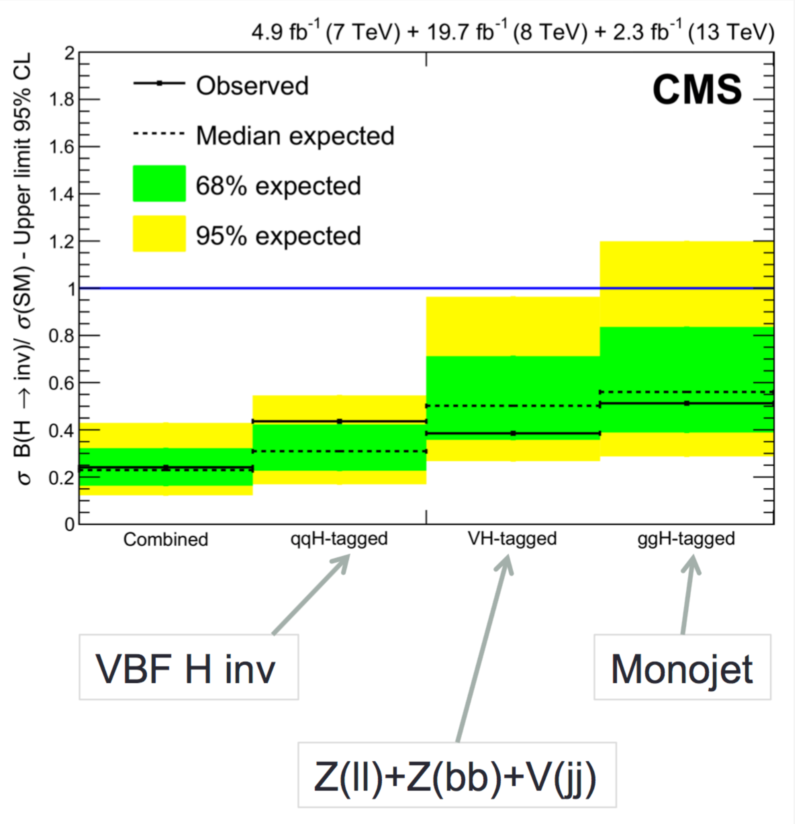


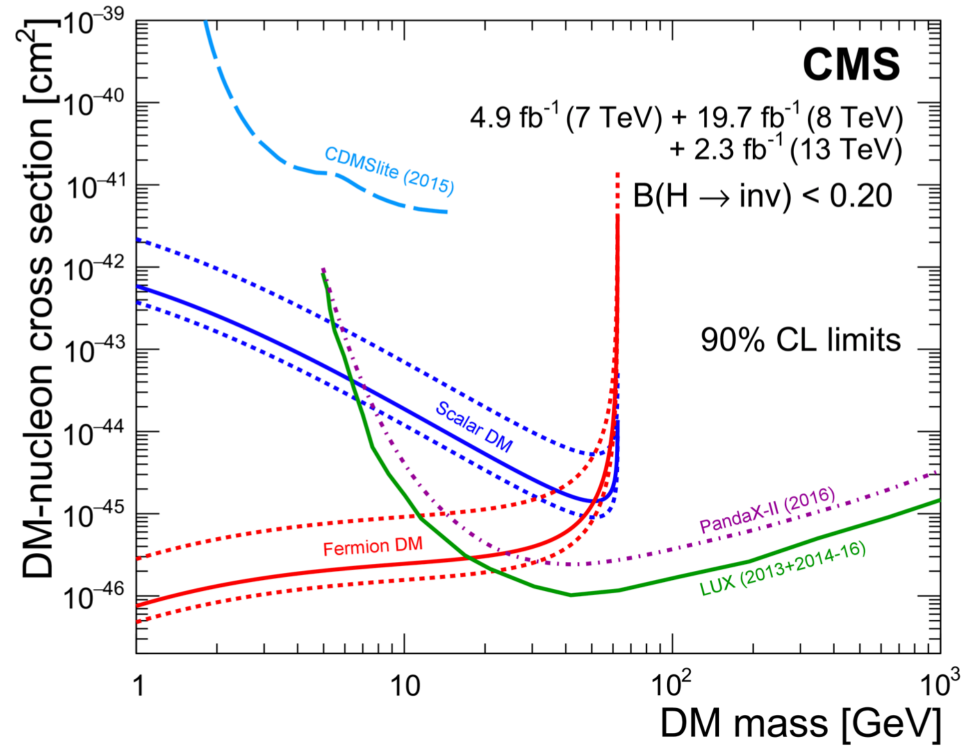
LHC data can constrain the Higgs→invisible branching fraction, which is 10^{-3} in the SM



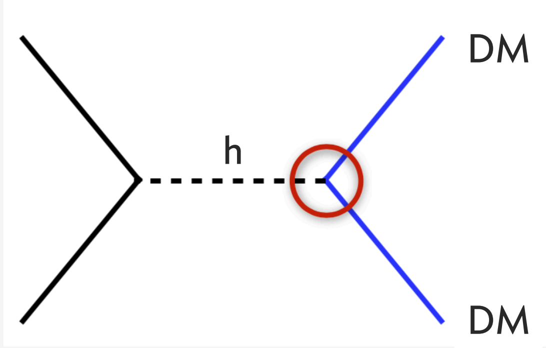




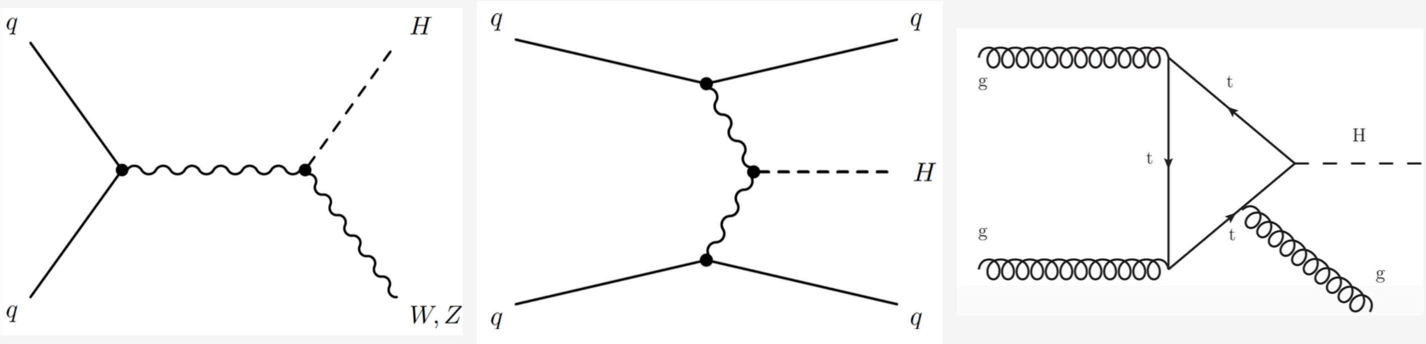




If the Higgs boson mediates SM-DM interaction...

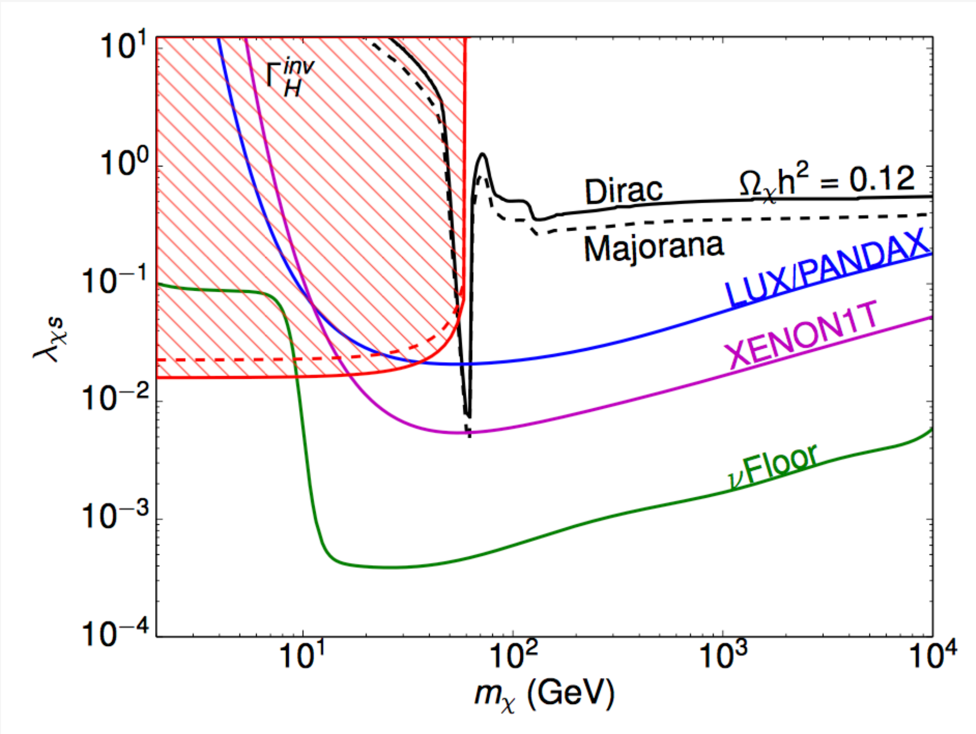


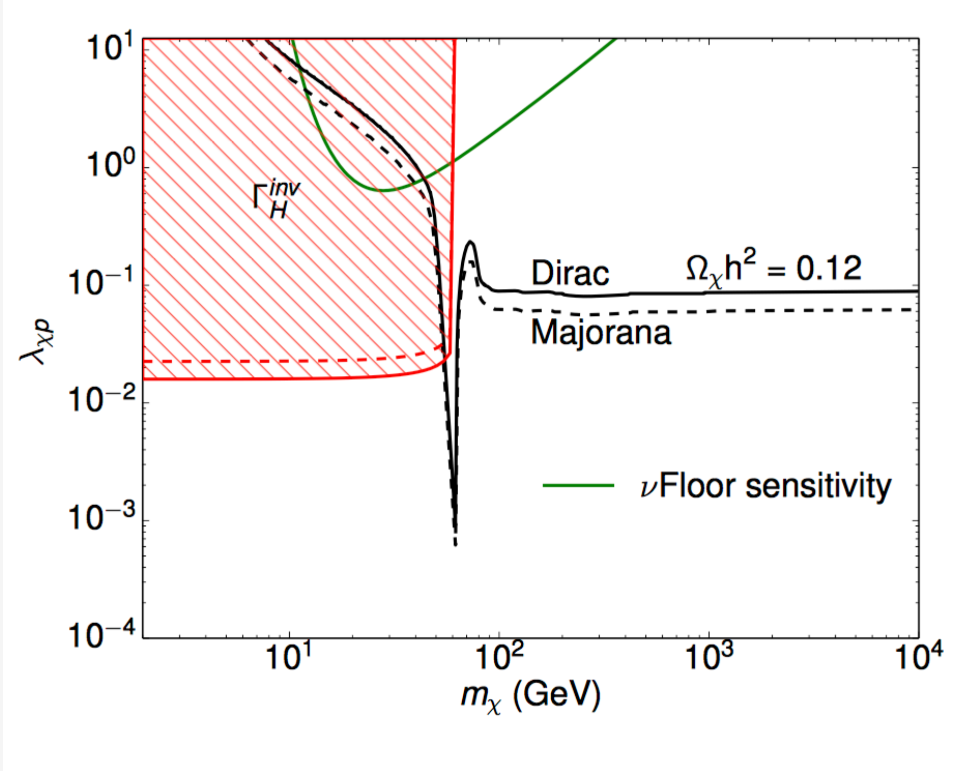
LHC data can constrain the Higgs→invisible branching fraction, which is 10^{-3} in the SM



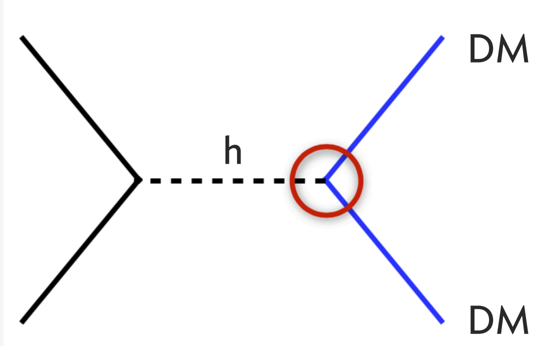
Fermionic DM

Escudero et al., arXiv:1609.09079

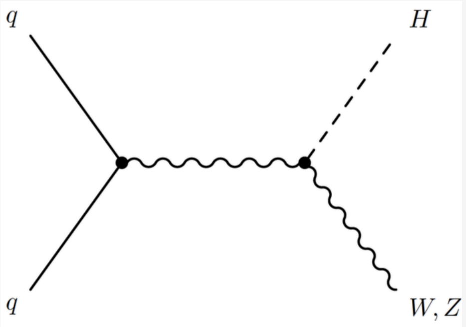


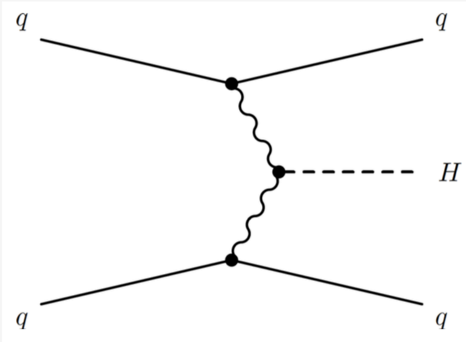


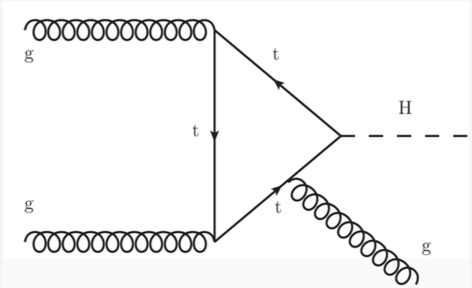
If the Higgs boson mediates SM-DM interaction...



LHC data can constrain the Higgs→invisible branching fraction, which is 10^{-3} in the SM

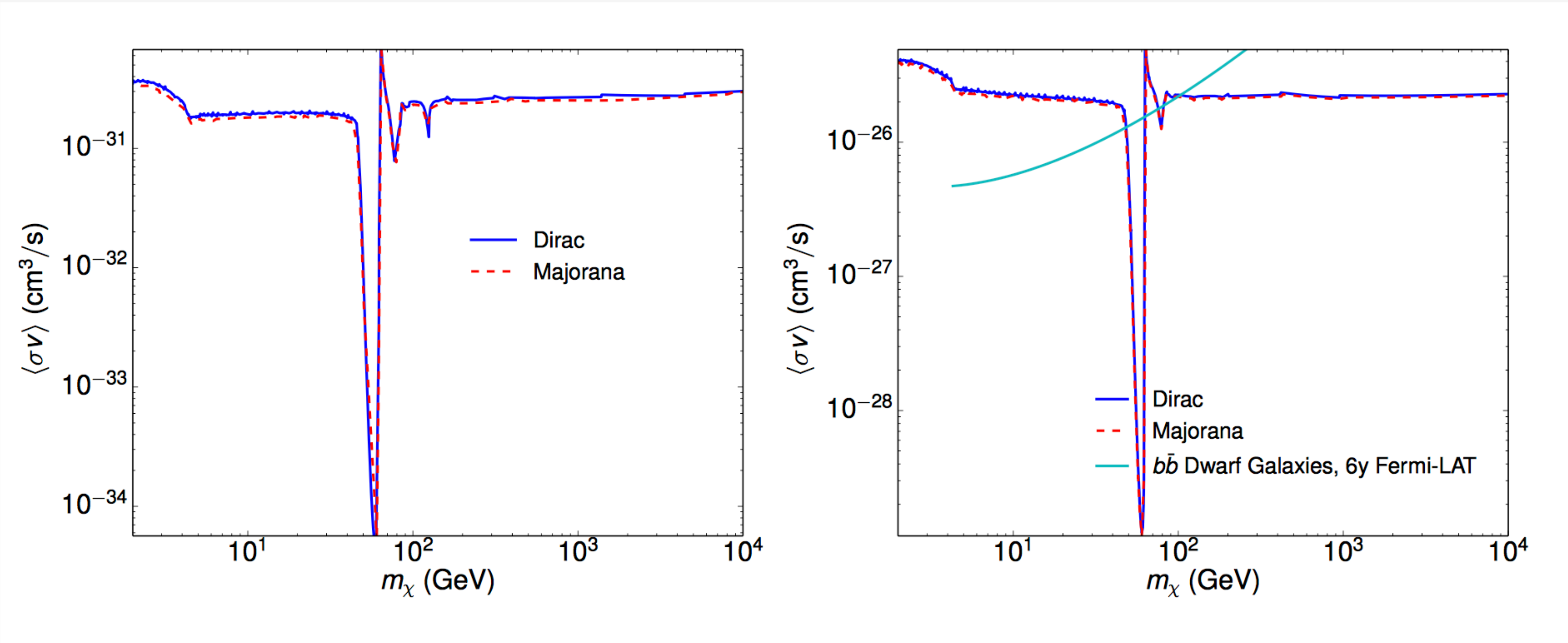






Fermionic DM

Escudero et al., arXiv:1609.09079



If the mediator is also a new particle…

Cornell University Library

We gratefully acknowledge support from the Simons Foundation and member institutions

arXiv.org > hep-ex > arXiv:1507.00966

Search or Article-id (Help | Advanced search) All papers Go!

High Energy Physics – Experiment

Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

Daniel Abercrombie, Nural Akchurin, Ece Akilli, Juan Alcaraz Maestre, Brandon Allen, Barbara Alvarez Gonzalez, Jeremy Andrea, Alexandre Arbey, Georges Azuelos, Patrizia Azzi, Mihailo Backović, Yang Bai, Swagato Banerjee, James Beacham, Alexander Belyaev, Antonio Boveia, Amelia Jean Brennan, Oliver Buchmueller, Matthew R. Buckley, Giorgio Busoni, Michael Buttignol, Giacomo Cacciapaglia, Regina Caputo, Linda Carpenter, Nuno Filipe Castro, Guillelmo Gomez Ceballos, Yangyang Cheng, John Paul Chou, Arely Cortes Gonzalez, Chris Cowden, Francesco D'Eramo, Annapaola De Cosa, Michele De Gruttola, Albert De Roeck, Andrea De Simone, Aldo Deandrea, Zeynep Demiragli, Anthony DiFranzo, Caterina Doglioni, Tristan du Pree, Robin Erbacher, Johannes Erdmann, Cora Fischer, Henning Flaecher, Patrick J. Fox, et al. (94 additional authors not shown)

(Submitted on 3 Jul 2015)

This document is the final report of the ATLAS-CMS Dark Matter Forum, a forum organized by the ATLAS and CMS collaborations with the participation of experts on theories of Dark Matter, to select a minimal basis set of dark matter simplified models that should support the design of the early LHC Run-2 searches. A prioritized, compact set of benchmark models is proposed, accompanied by studies of the parameter space of these models and a repository of generator implementations. This report also addresses how to apply the Effective Field Theory formalism for collider searches and present the results of such interpretations.

Subjects: High Energy Physics – Experiment (he
(hep-ph)

Cite as: arXiv:1507.00966 [hep-ex]
(or arXiv:1507.00966v1 [hep-ex] for t

Submission history

From: Antonio Boveia [view email]
[v1] Fri, 3 Jul 2015 16:54:32 GMT (3860kb,D)

Download:

- PDF
- Other formats

(license)

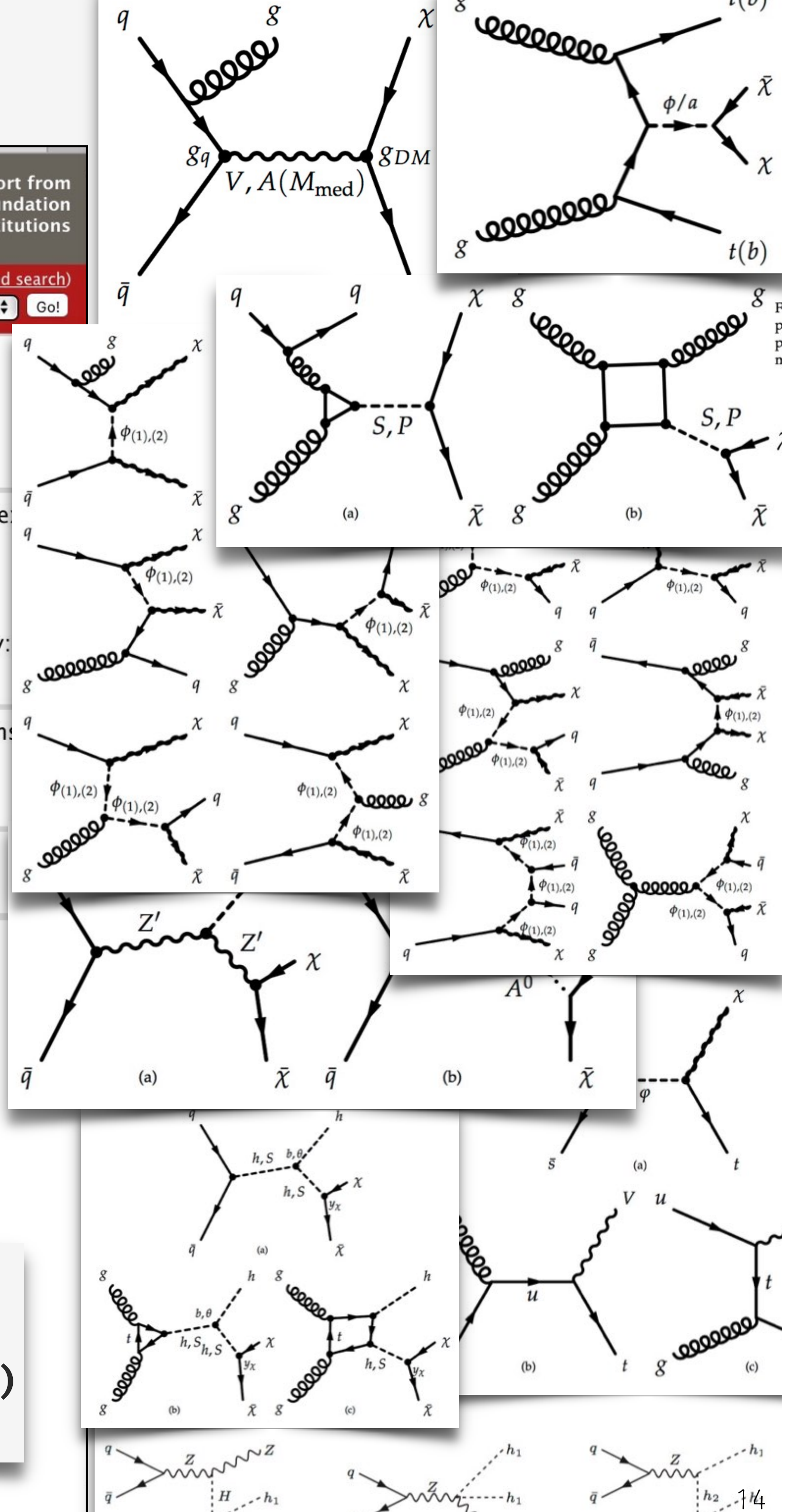
Current browse conte
hep-ex
< prev | next >
new | recent | 1507

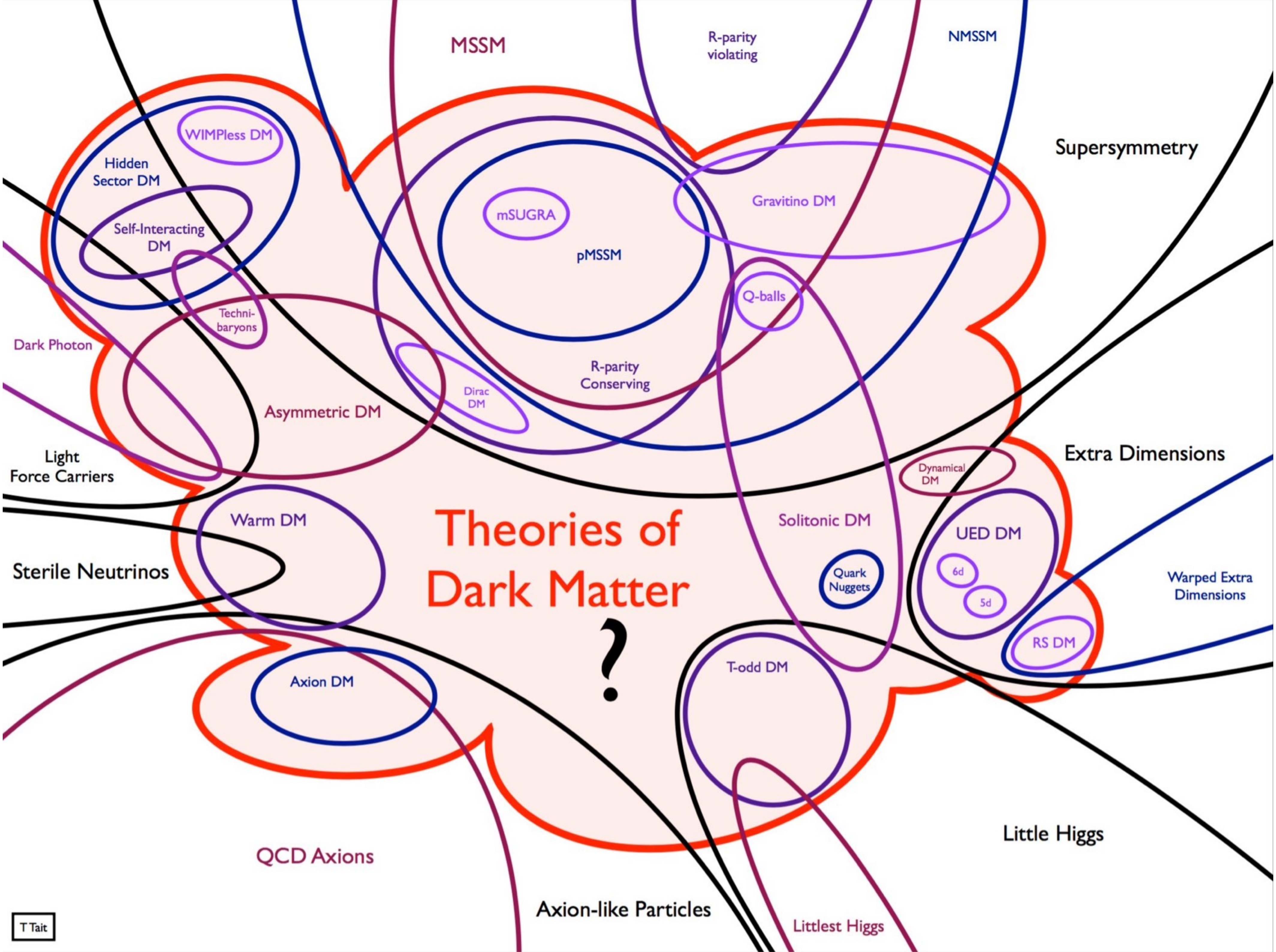
Change to browse by:
hep-ph

References & Citation
- INSPIRE HEP (refers to | cited by)
- NASA ADS

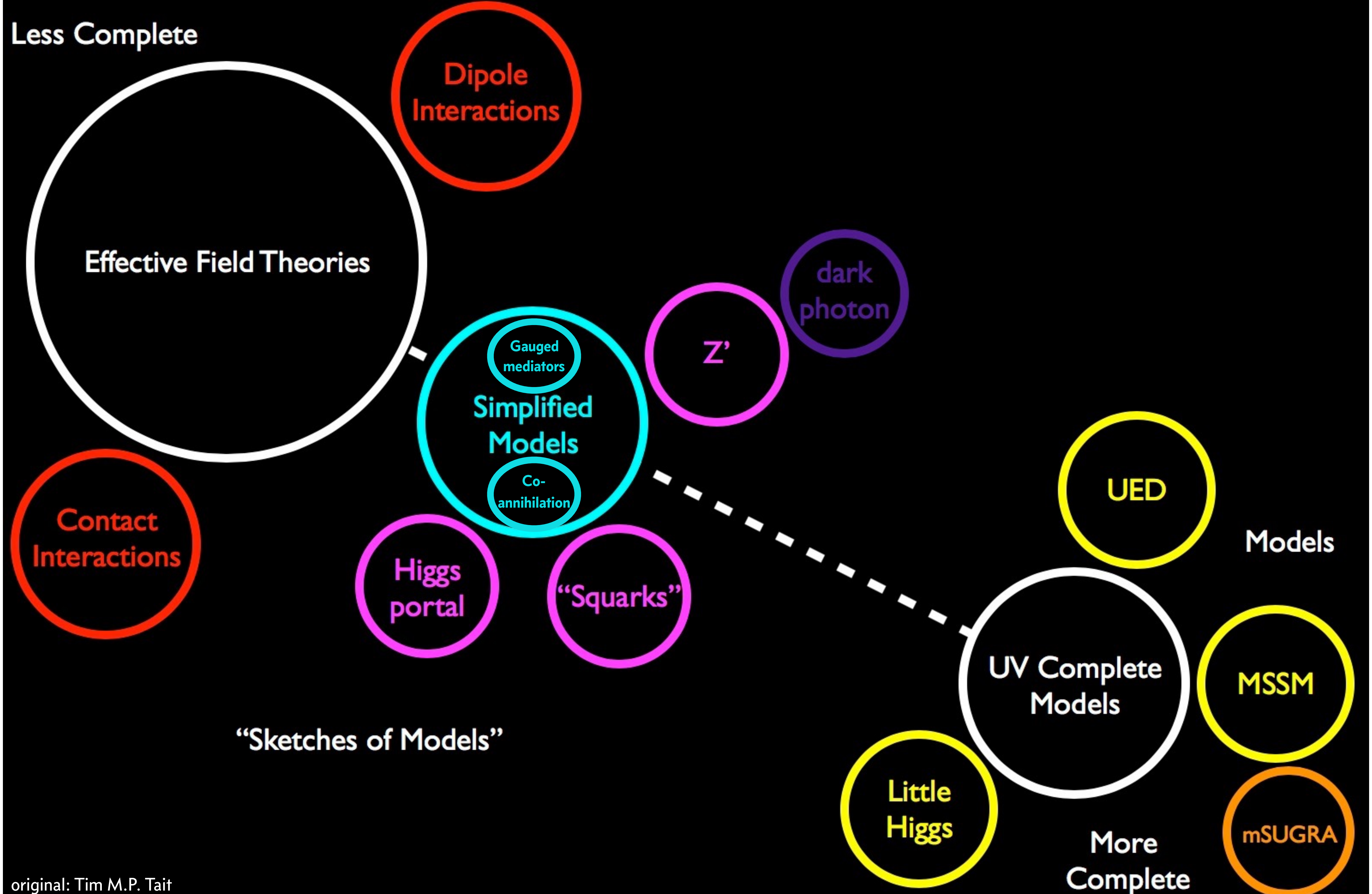
Bookmark (what is this?)

Dirac WIMP mediators:
t- and s-channel exchange
vector/axial-vector/scalar/pseudo-scalar (MFV)
MET+heavy flavor, W, Z, and Higgs




MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
Dirac DM
R-parity Conserving
Asymmetric DM
Light Force Carriers
Dynamical DM
Extra Dimensions
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

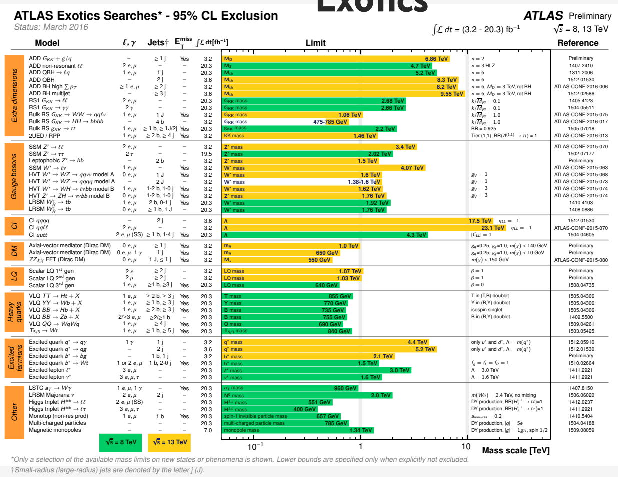
Spectrum of Theory Space

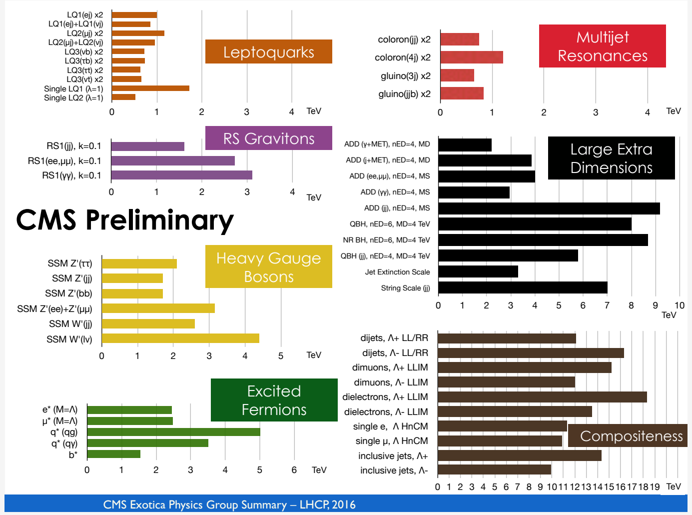


original: Tim M.P. Tait

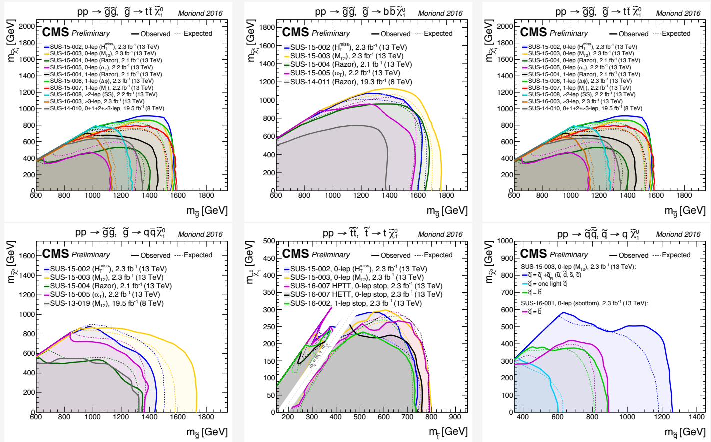
Searches for New Physics

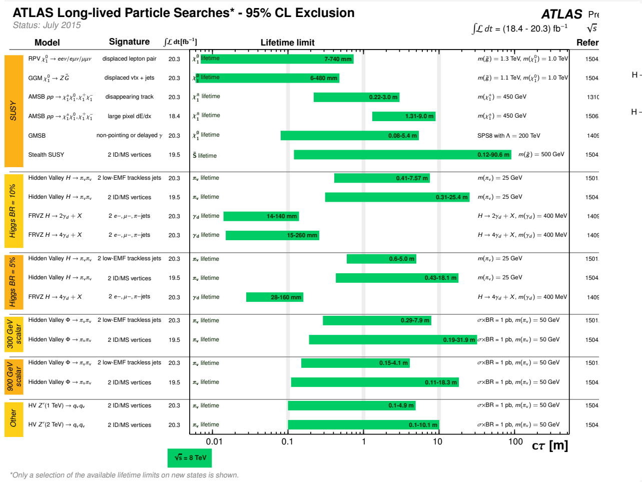
Exotics

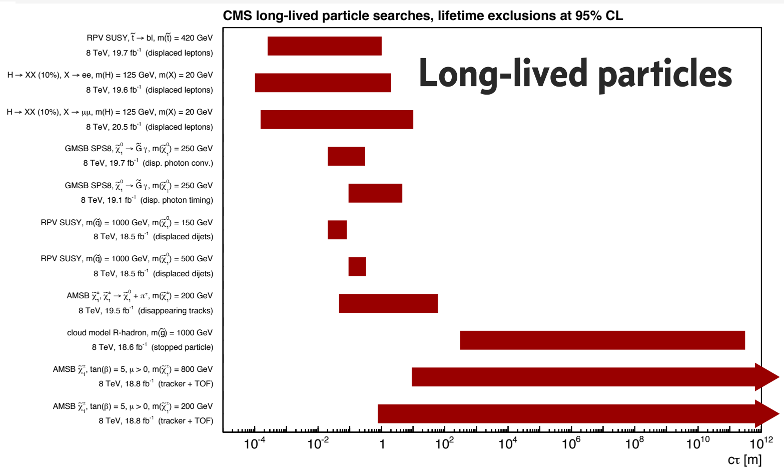


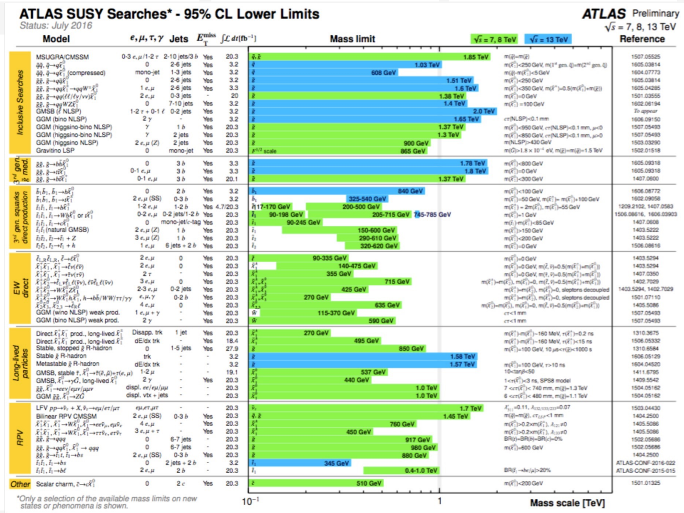


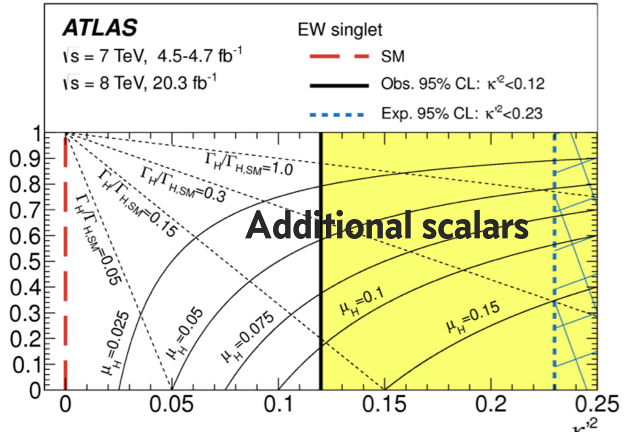
SUSY









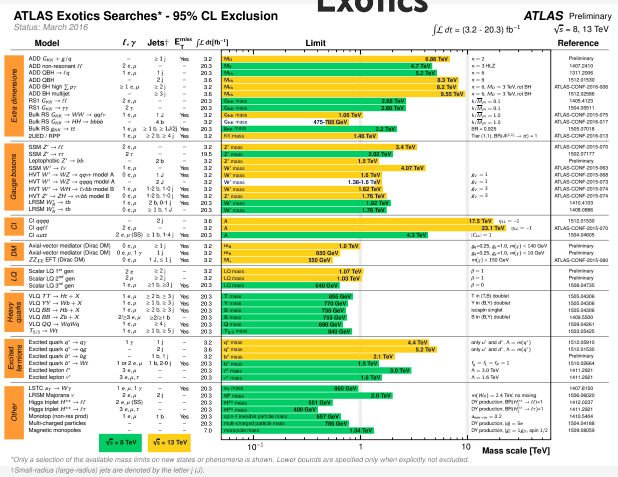


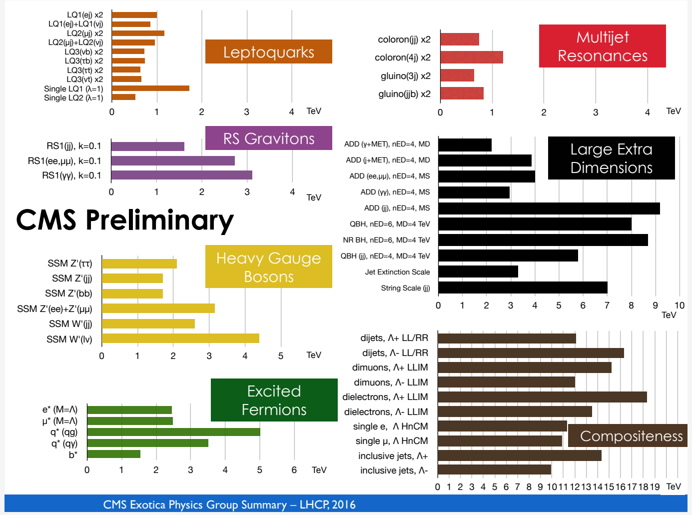
[ATLAS Summary Plots]

[CMS Summary Plots]

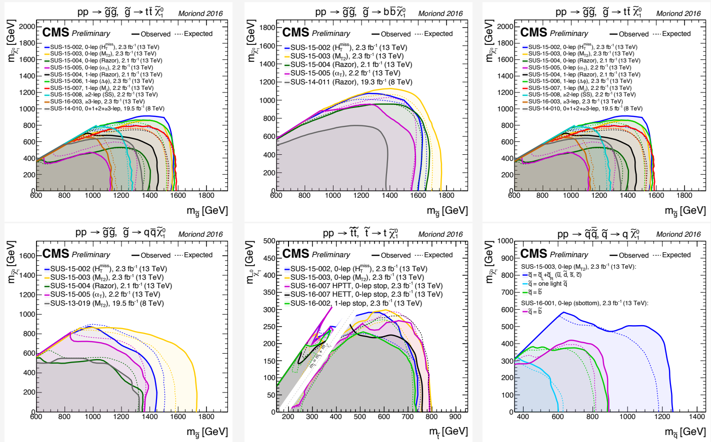
Searches for New Physics Searches for Dark Matter

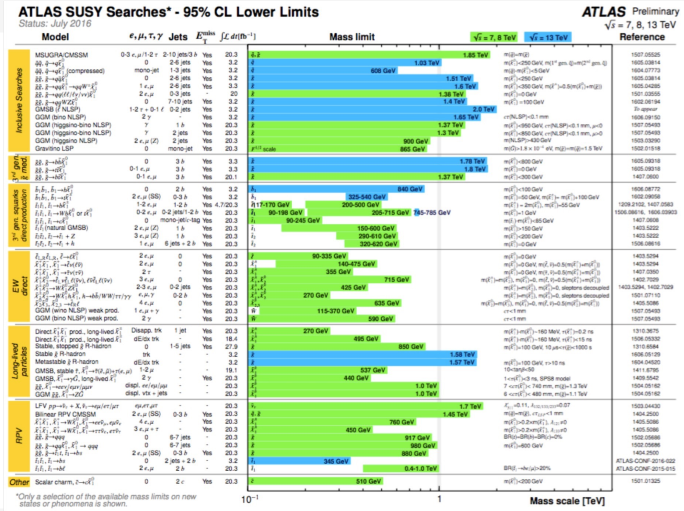
Exotics

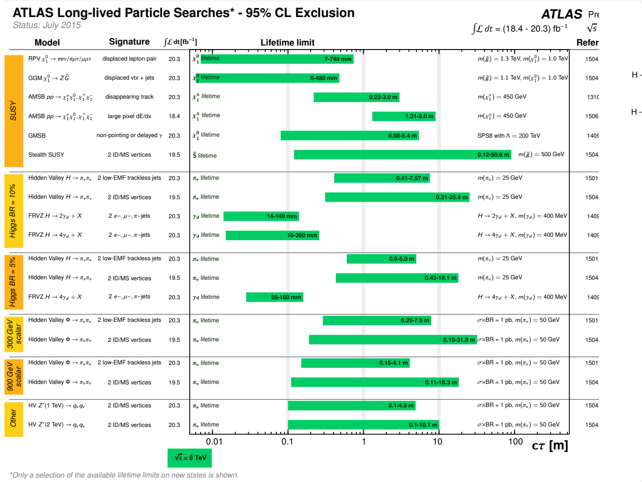




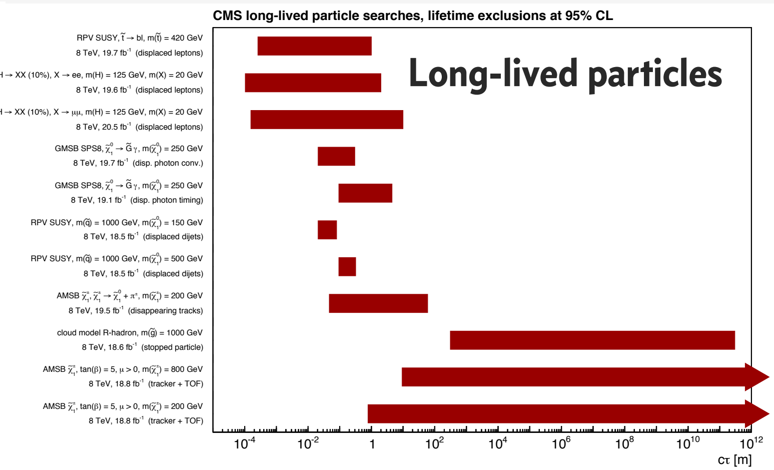
SUSY



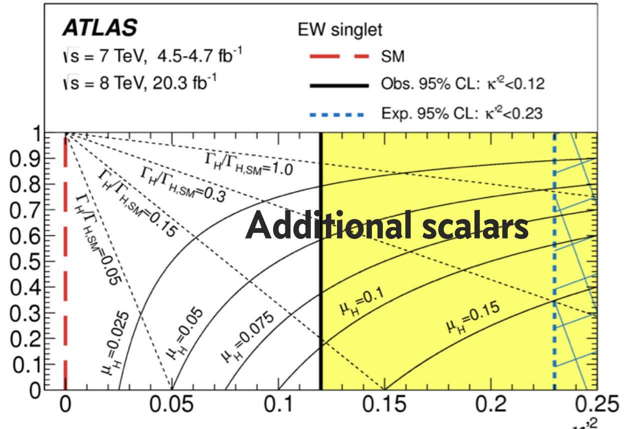




Long-lived particles



Additional scalars



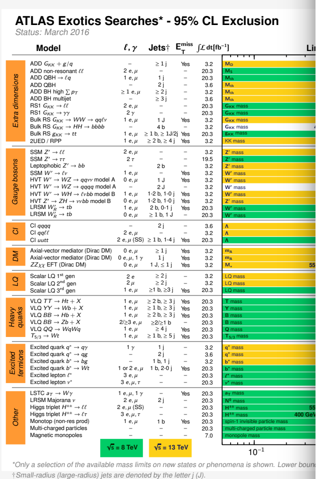
ATLAS Summary Plots

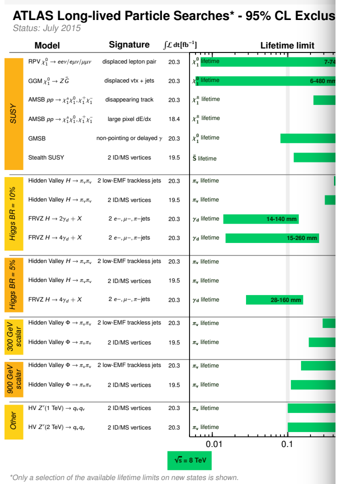
CMS Summary Plots

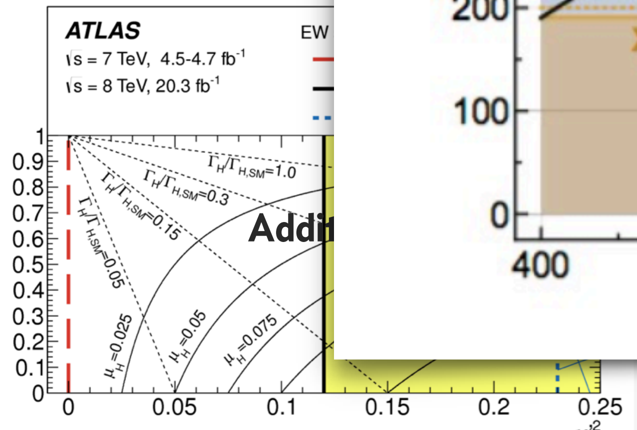
Most of these models already have a DM candidate, or can be easily modified to provide one

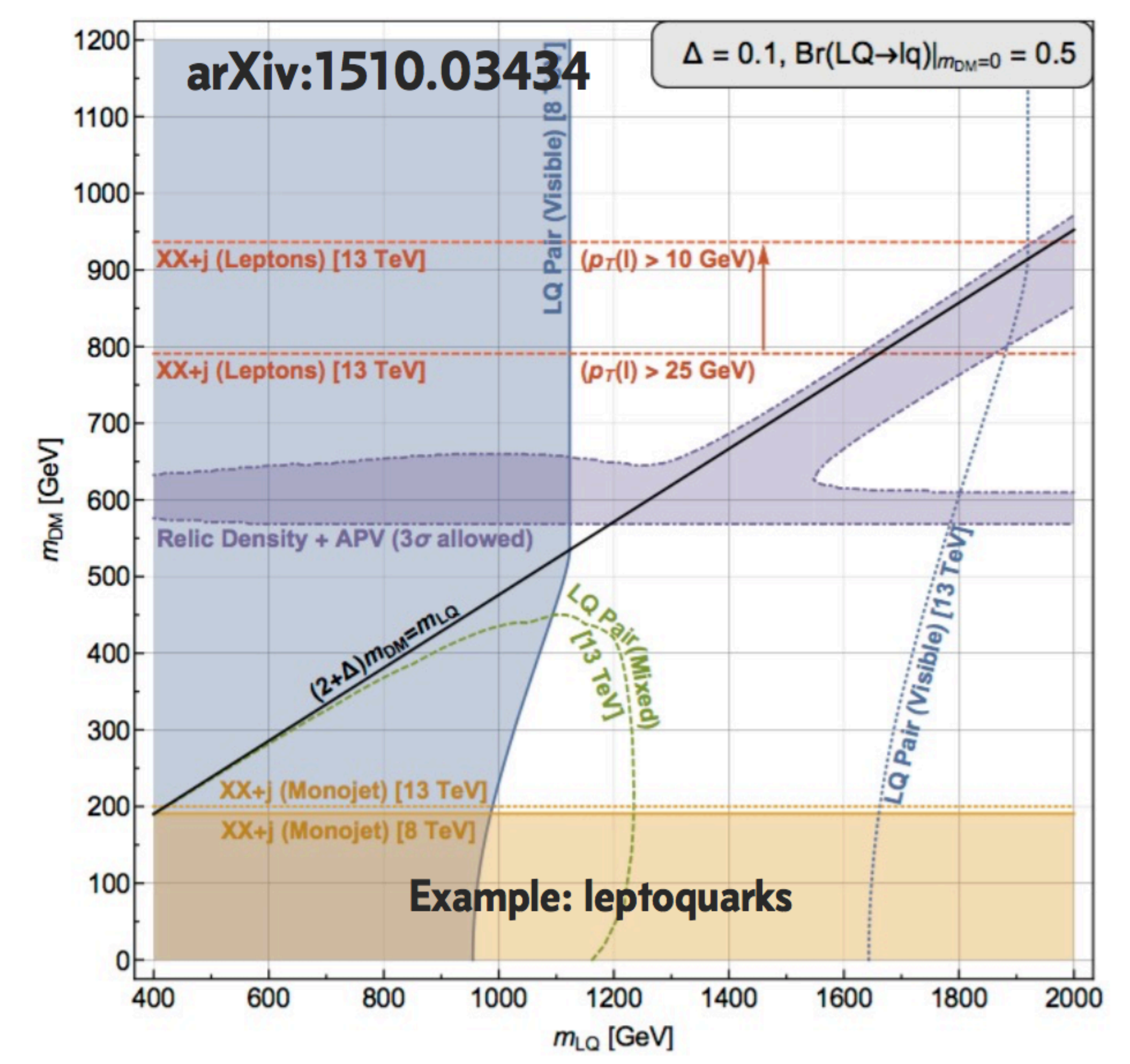
Searches for New Physics

Searches for Dark Matter

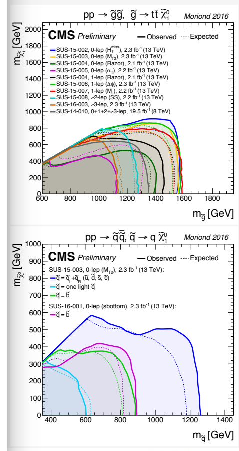


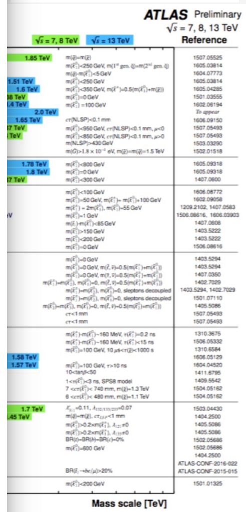






SUSY





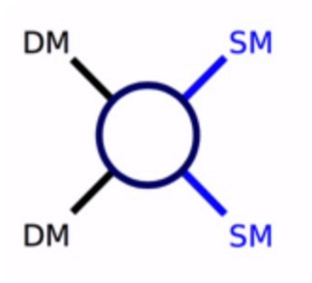
ts

But what are we missing?

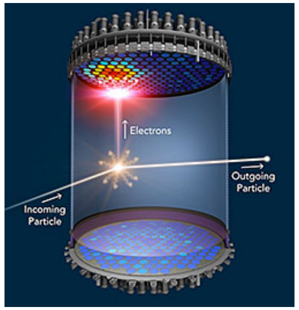
Collider DM “EFT” Framework

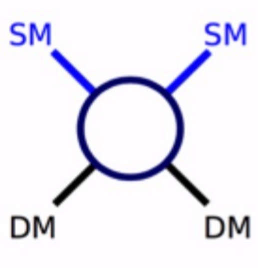
Collider Models of Particle Dark Matter: Complementarity

General-purpose collider searches focus on models **emphasizing complementarity**
- with **effective baryon coupling**: scattering off **nuclei** and production in **pp collisions**
- do **signature-based searches** applicable to broad classes of possible models
- balance between model agnosticism, setting priorities, and using models to translate astro-physical/-particle knowledge

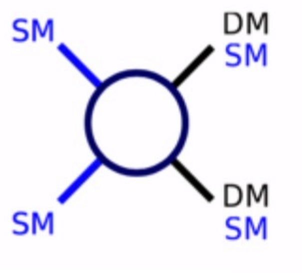


Indirect Detection

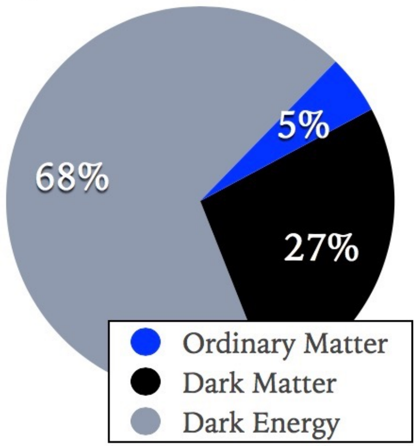




Direct Detection



Colliders

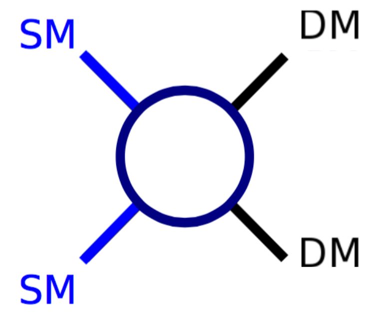


Collider searches have many advantages, but
- dark matter must have **non-gravitational interactions with the SM** to produce it
- a missing energy signal may not be astrophysical DM
- the results cannot be related to other knowledge of DM without a model (and, for DM, we know very little)

PHYSICAL REVIEW D **82**, 116010 (2010)

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

Name	Operator	Coefficient
D1	$\bar\chi\chi\bar q q$	m_q/M_*^3
D2	$\bar\chi\gamma^5\chi\bar q q$	im_q/M_*^3
D3	$\bar\chi\chi\bar q\gamma^5 q$	im_q/M_*^3
D4	$\bar\chi\gamma^5\chi\bar q\gamma^5 q$	m_q/M_*^3
D5	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu q$	$1/M_*^2$
D6	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu q$	$1/M_*^2$
D7	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar\chi\sigma^{\mu\nu}\chi\bar q\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar\chi\sigma_{\mu\nu}\gamma^5\chi\bar q\sigma_{\alpha\beta} q$	i/M_*^2
D11	$\bar\chi\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar\chi\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar\chi\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar\chi\gamma^5\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$\alpha_s/4M_*^3$
C1	$\chi^\dagger\chi\bar q q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar q\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar q\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar q\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar q q$	$m_q/2M_*^2$
R2	$\chi^2\bar q\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/8M_*^2$



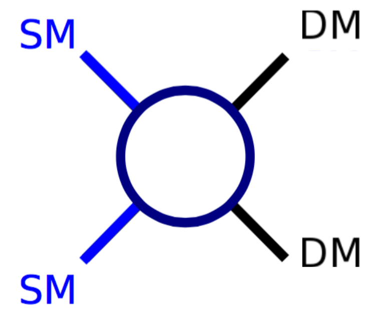
Colliders (EFT)

Try to do something very general and systematic…

PHYSICAL REVIEW D **82**, 116010 (2010)

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

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$



Colliders (EFT)

Problem (when applying to LHC):

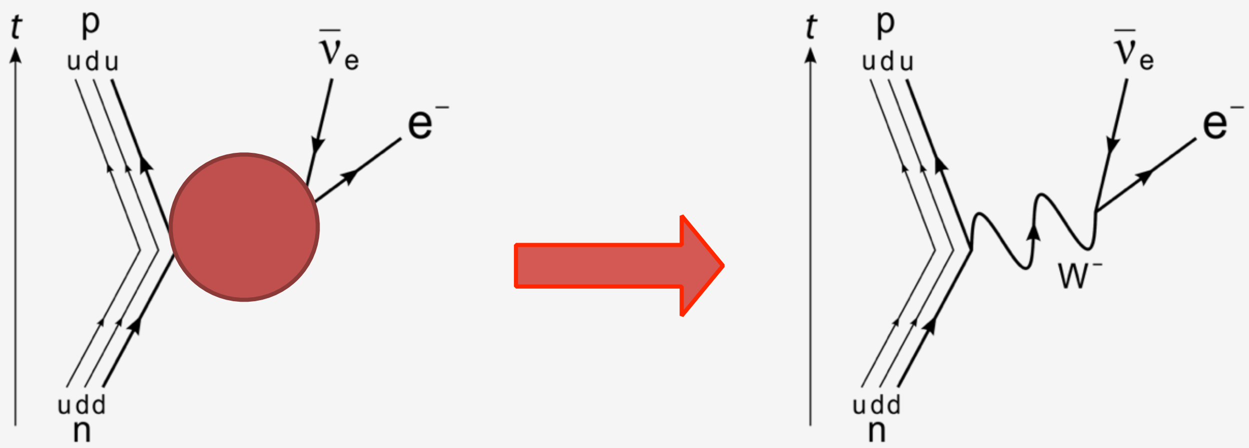
In typical completions, the inaccessible physics must be too strongly coupled to produce observable signals

e.g. s-channel mediator: rate depends on

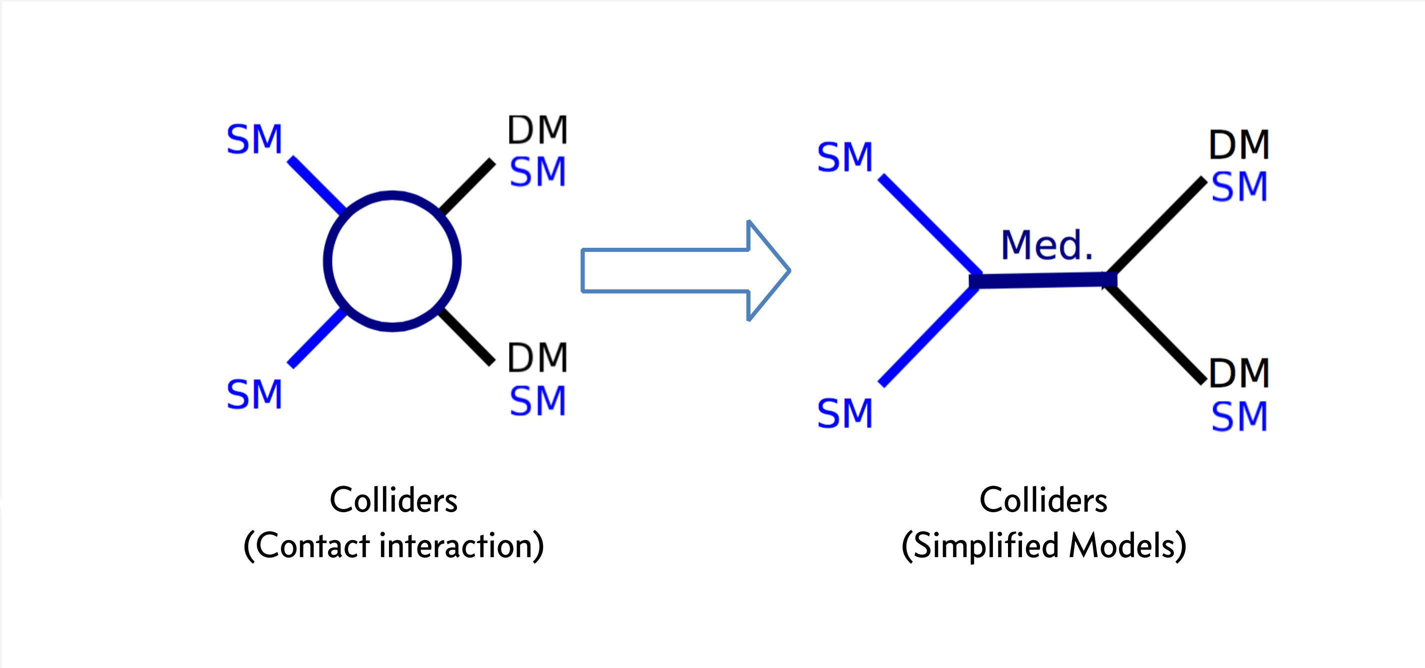
$$M_\star = M_{\rm med}/\sqrt{g_q\, g_\chi}$$

High enough rate implies either:

- heavy mediator, non-perturbative couplings
- light mediator (EFT incorrect theory)



LHC probes 'high' energy scales
If 'high' is high enough, it can discovery and characterize the interactions between normal and dark matter



LHC probes 'high' energy scales

If 'high' is high enough, it can discovery and characterize the interactions between normal and dark matter

Requires more model assumptions (and parameters)

If the mediator is also a new particle...

Cornell University Library

We gratefully acknowledge support from the Simons Foundation and member institutions

arXiv.org > hep-ex > arXiv:1507.00966

Search or Article-id (Help | Advanced search)

All papers Go!

High Energy Physics – Experiment

Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

Daniel Abercrombie, Nural Akchurin, Ece Akilli, Juan Alcaraz Maestre, Brandon Allen, Barbara Alvarez Gonzalez, Jeremy Andrea, Alexandre Arbey, Georges Azuelos, Patrizia Azzi, Mihailo Backović, Yang Bai, Swagato Banerjee, James Beacham, Alexander Belyaev, Antonio Boveia, Amelia Jean Brennan, Oliver Buchmueller, Matthew R. Buckley, Giorgio Busoni, Michael Buttignol, Giacomo Cacciapaglia, Regina Caputo, Linda Carpenter, Nuno Filipe Castro, Guillelmo Gomez Ceballos, Yangyang Cheng, John Paul Chou, Arely Cortes Gonzalez, Chris Cowden, Francesco D'Eramo, Annapaola De Cosa, Michele De Gruttola, Albert De Roeck, Andrea De Simone, Aldo Deandrea, Zeynep Demiragli, Anthony DiFranzo, Caterina Doglioni, Tristan du Pree, Robin Erbacher, Johannes Erdmann, Cora Fischer, Henning Flaecher, Patrick J. Fox, et al. (94 additional authors not shown)

(Submitted on 3 Jul 2015)

This document is the final report of the ATLAS-CMS Dark Matter Forum, a forum organized by the ATLAS and CMS collaborations with the participation of experts on theories of Dark Matter, to select a minimal basis set of dark matter simplified models that should support the design of the early LHC Run-2 searches. A prioritized, compact set of benchmark models is proposed, accompanied by studies of the parameter space of these models and a repository of generator implementations. This report also addresses how to apply the Effective Field Theory formalism for collider searches and present the results of such interpretations.

Subjects: High Energy Physics – Experiment (he
(hep-ph)
Cite as: arXiv:1507.00966 [hep-ex]
(or arXiv:1507.00966v1 [hep-ex] for t

Submission history

From: Antonio Boveia [view email]
[v1] Fri, 3 Jul 2015 16:54:32 GMT (3860kb,D)

Download:

- PDF
- Other formats

(license)

Current browse conte

hep-ex

< prev | next >

new | recent | 1507

Change to browse by:

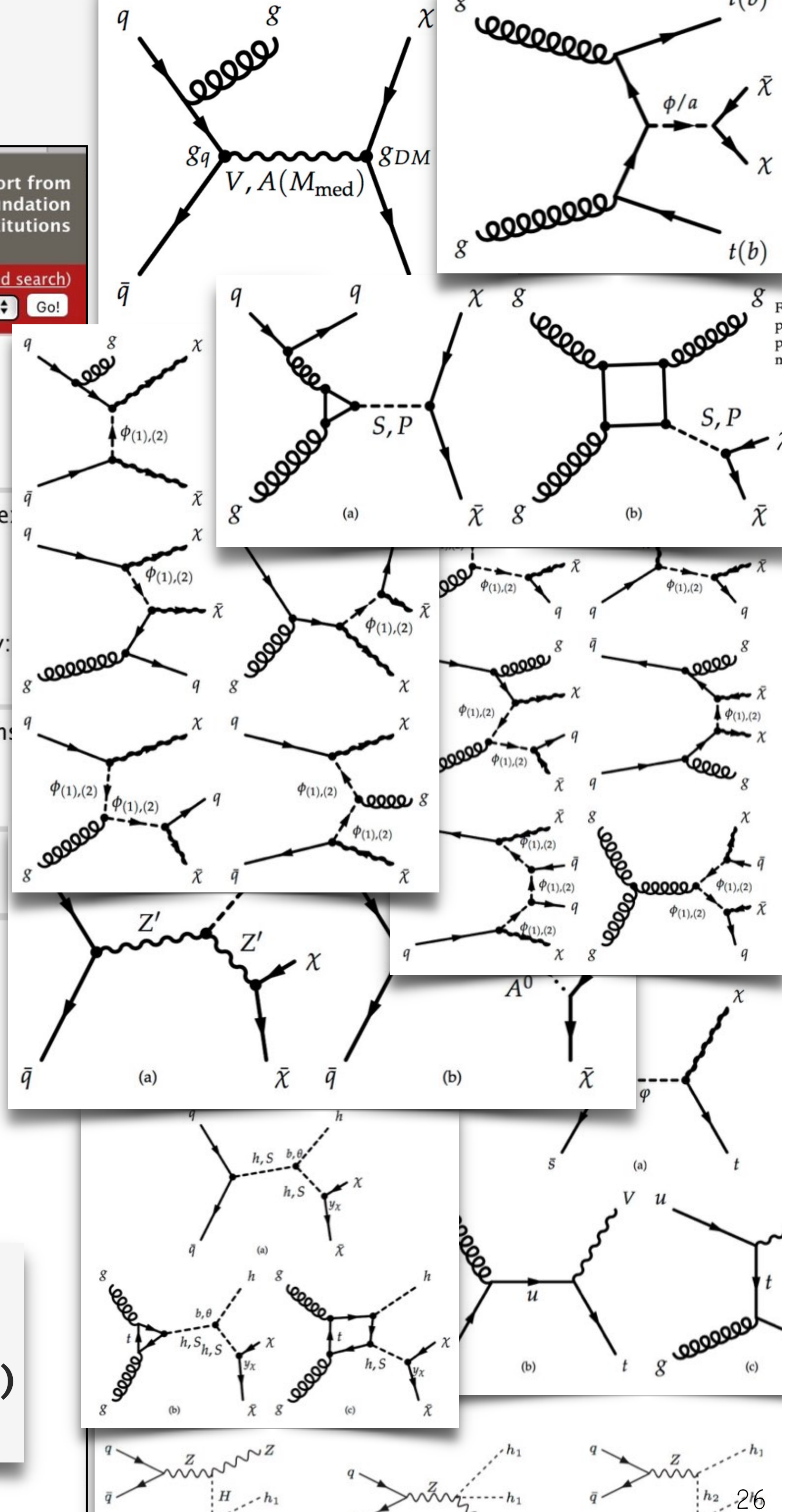
hep-ph

References & Citations

- INSPIRE HEP (refers to | cited by)
- NASA ADS

Bookmark (what is this?)

Dirac WIMP mediators:
t- and s-channel exchange
vector/axial-vector/scalar/pseudo-scalar (MFV)
MET+heavy flavor, W, Z, and Higgs

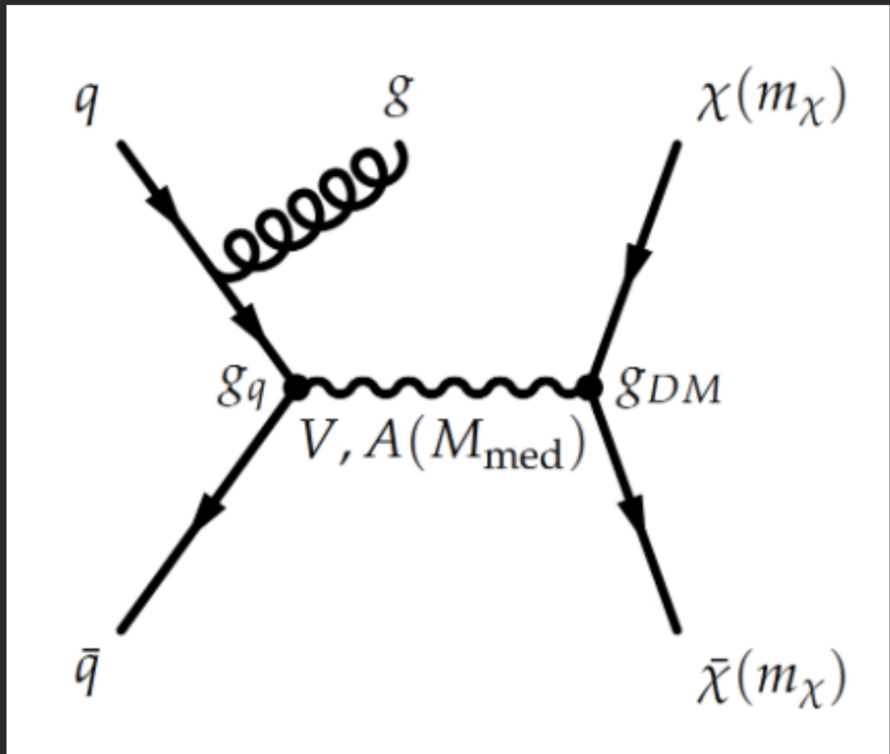


Going After Z Copies

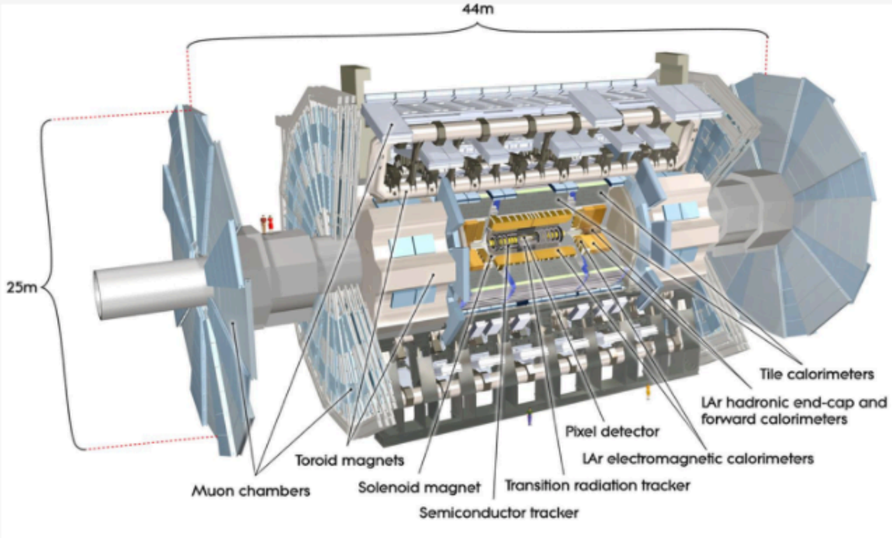
(the rest of today's talk)

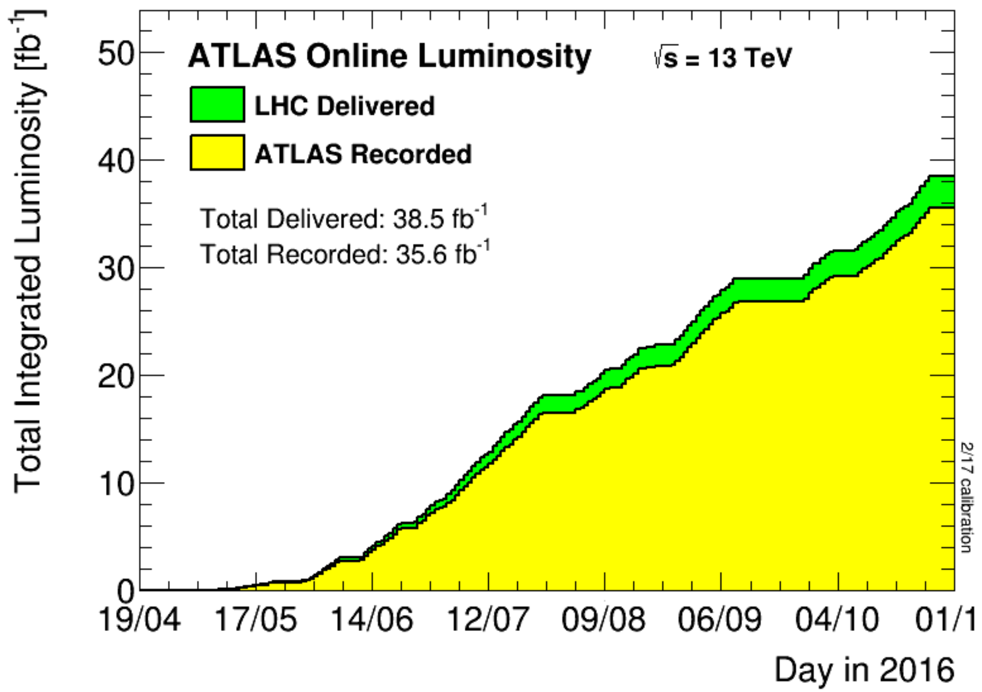
Searching for Dark Matter Production

(or: collider-stable weakly-interacting particles)

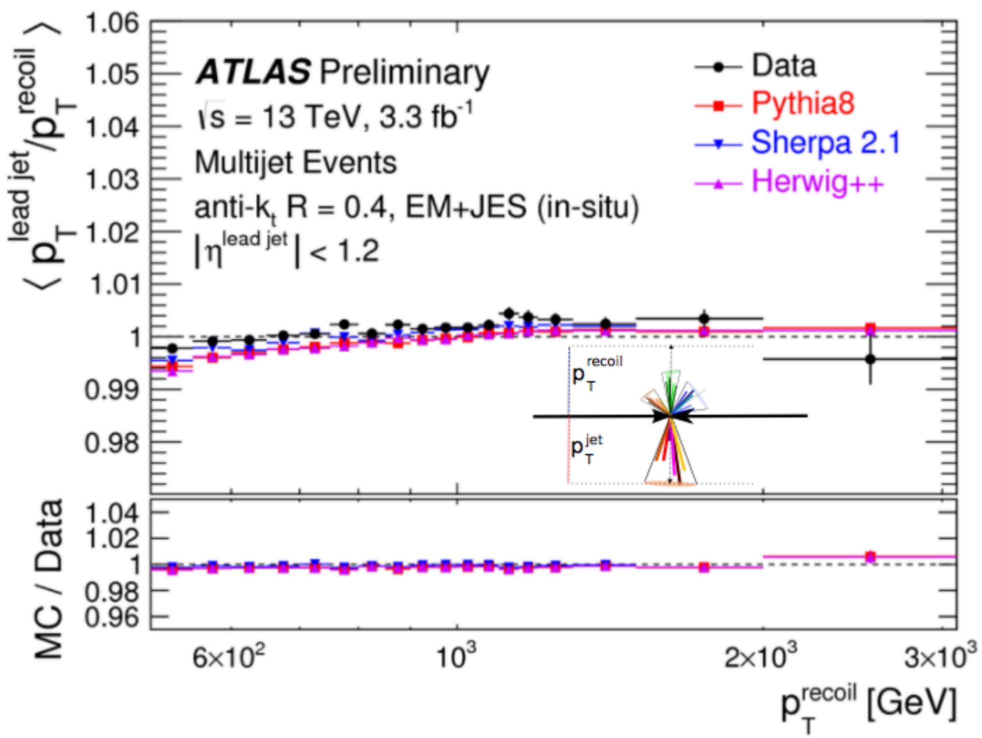


Experimental performance for DM signatures

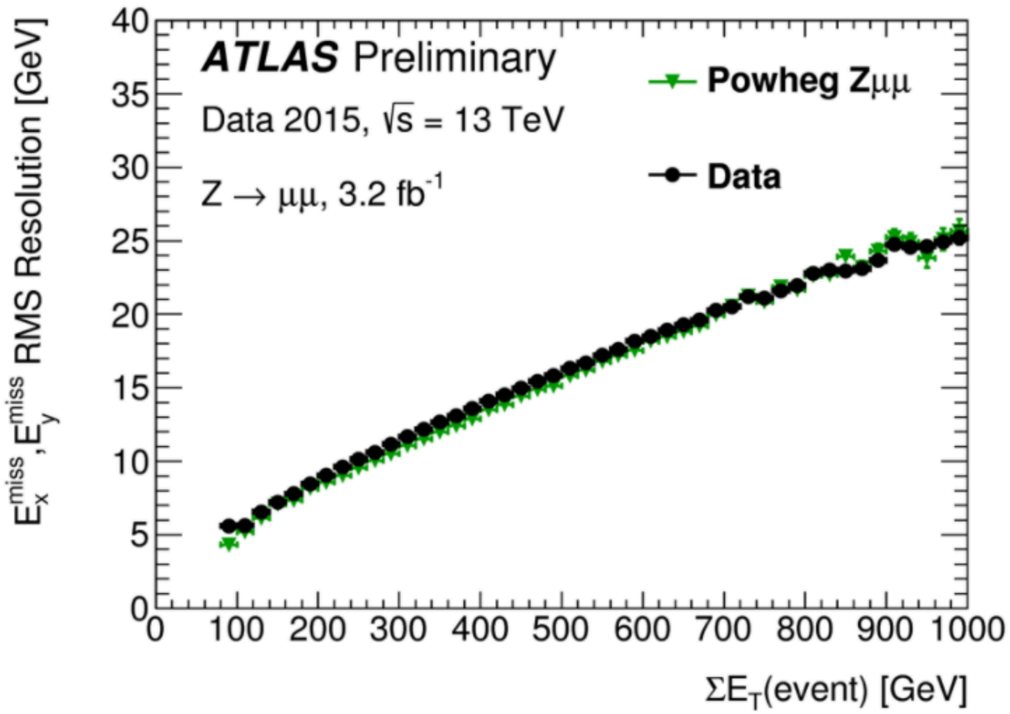




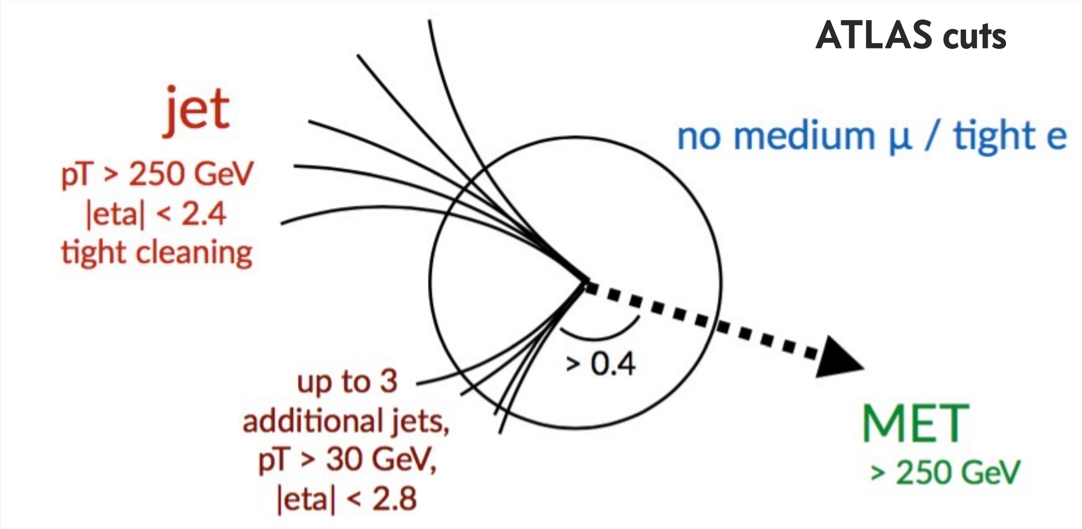
Jet calibration well understood up to multi-TeV scale



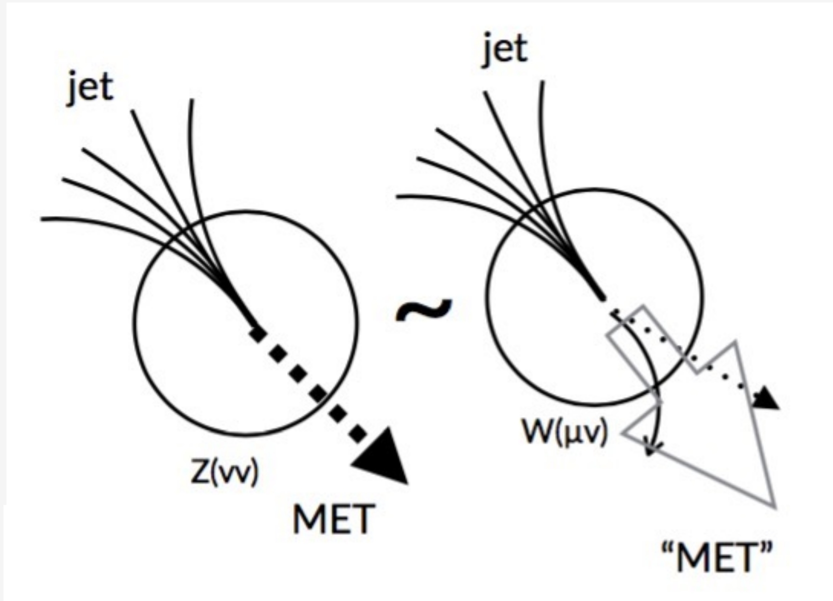
Excellent MET performance

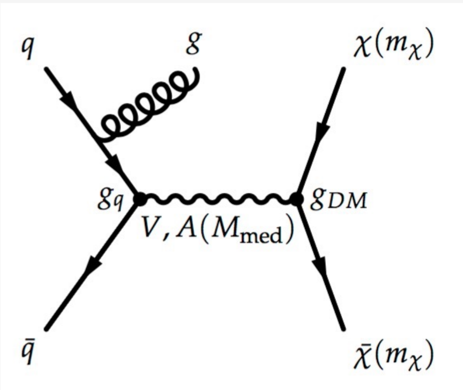


MET+X searches, or "mono-X"

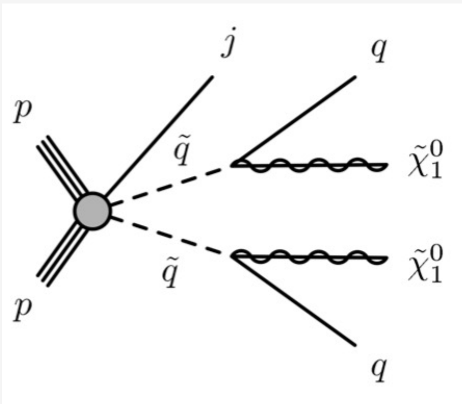


Backgrounds





Signals



+...

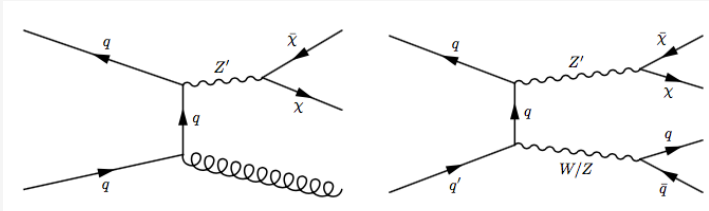
CMS Mono-W/Z/jet

PAS EXO-16-048

Look for large MET and ≥1 high p_T jet; veto e, μ, tau, γ, b-jet

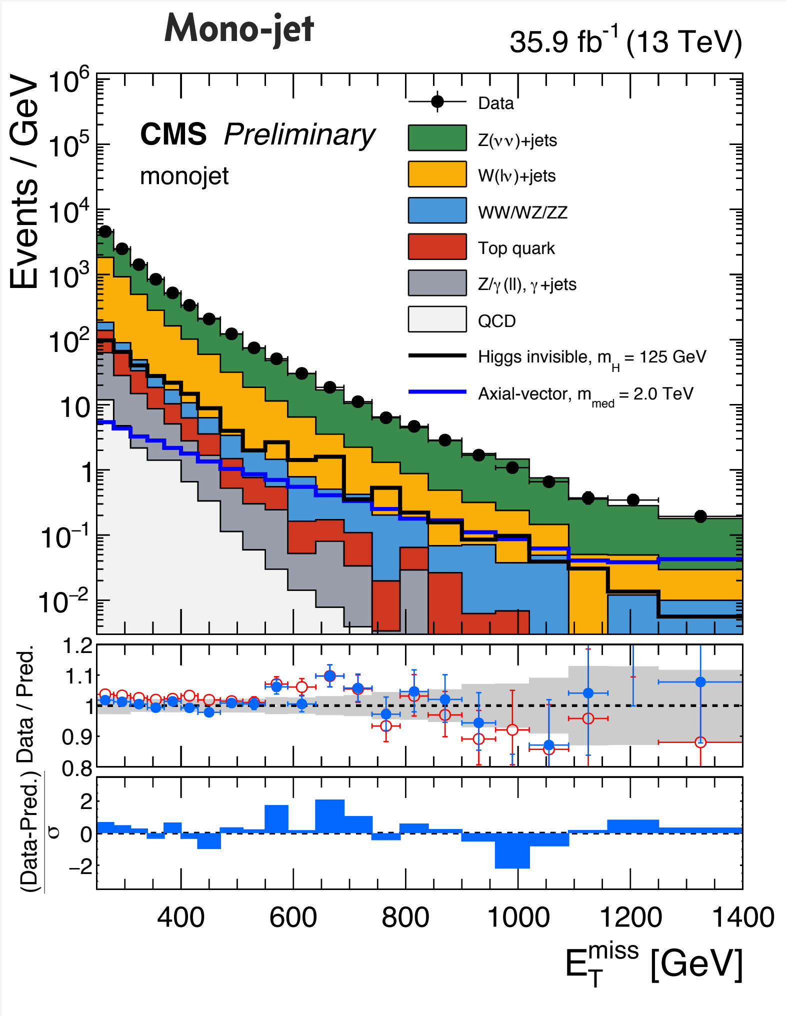
- Mono-V: p_{Tj1}^{AK8}, MET > 250 GeV, mass 65-105 GeV, tau_{21} < 0.6
- Mono-jet: remaining events p_{Tj1}^{AK4} > 100 GeV, MET > 200 GeV

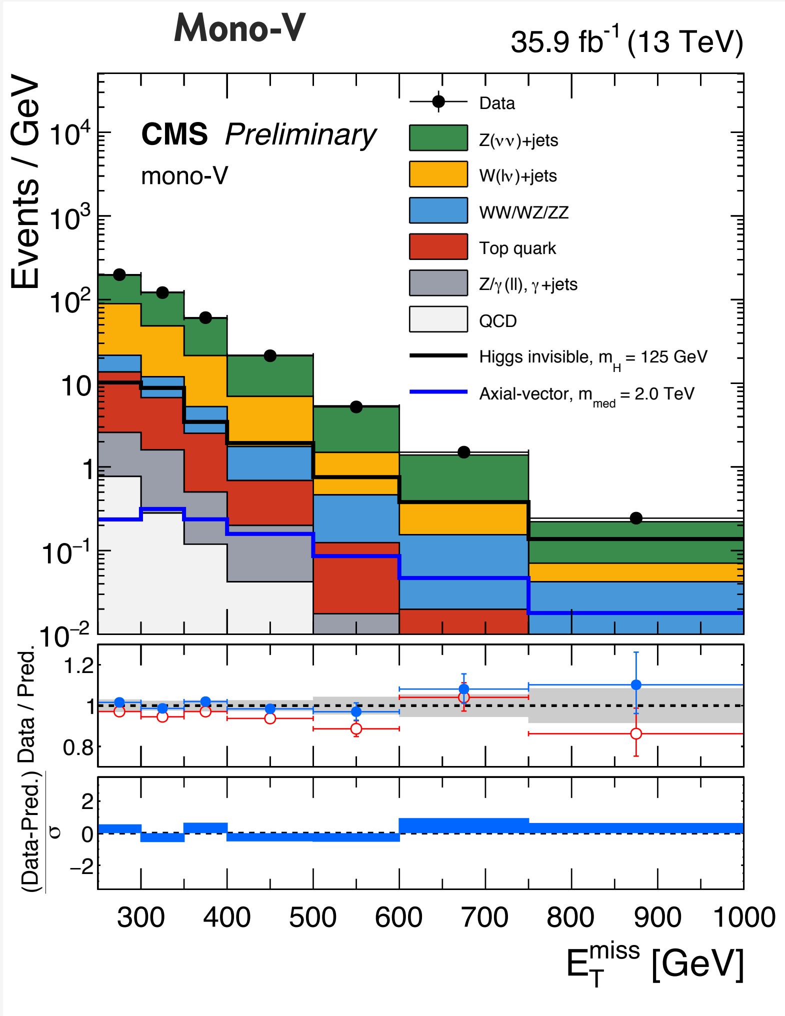
Fit background and signal predictions to MET control regions (ee/μμ/e/μ/γ+jets)



Light mediator (125 GeV), Light DM

Heavy mediator (2 TeV), Light DM





CMS Mono-W/Z/jet

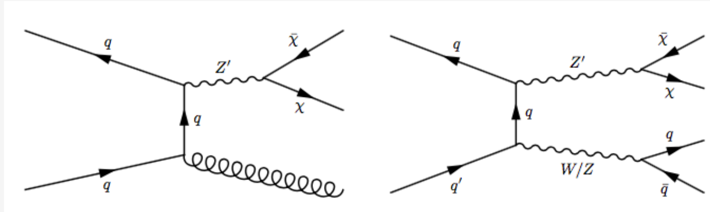
PAS EXO-16-048

(currently strongest public mono-jet result)

Look for large MET and ≥1 high p_T jet; veto e, μ, tau, γ, b-jet

- Mono-V: $p_{Tj1}{}^{AK8}$, MET > 250 GeV, mass 65-105 GeV, tau_{21} < 0.6
- Mono-jet: remaining events $p_{Tj1}{}^{AK4}$ > 100 GeV, MET > 200 GeV

Fit background and signal predictions to MET control regions (ee/μμ/e/μ/γ+jets)



E_T^{miss} (GeV)	Observed	$Z \to \nu\nu$+jets	$W \to \ell\nu$+jets	Top	Dibosons	Other	Total Bkg.
250-280	136865	79700 ± 2300	49200 ± 1400	2360 ± 200	1380 ± 220	1890 ± 240	134500 ± 3700
280-310	74340	45800 ± 1300	24950 ± 730	1184 ± 99	770 ± 120	840 ± 110	73400 ± 2000
310-340	42540	27480 ± 560	13380 ± 260	551 ± 53	469 ± 77	445 ± 63	42320 ± 810
340-370	25316	17020 ± 350	7610 ± 150	292 ± 28	301 ± 51	260 ± 39	25490 ± 490
370-400	15653	10560 ± 220	4361 ± 91	157 ± 17	198 ± 33	152 ± 26	15430 ± 310
400-430	10092	7110 ± 130	2730 ± 47	104 ± 12	133 ± 23	84 ± 15	10160 ± 170
430-470	8298	6110 ± 100	2123 ± 37	75.2 ± 7.9	110 ± 19	67 ± 11	8480 ± 140
470-510	4906	3601 ± 75	1128 ± 22	38.6 ± 5.3	75 ± 12	21.0 ± 3.9	4865 ± 95
510-550	2987	2229 ± 39	658 ± 12	18.5 ± 3.3	51.7 ± 9.5	12 ± 2.4	2970 ± 49
550-590	2032	1458 ± 27	398 ± 8	12.3 ± 2.6	35.9 ± 7.1	9.7 ± 1.9	1915 ± 33
590-640	1514	1182 ± 26	284 ± 7	5.5 ± 1.4	30.9 ± 5.7	2.6 ± 0.7	1506 ± 32
640-690	926	667 ± 15	151 ± 4	4.6 ± 1.7	16.7 ± 3.9	4.0 ± 0.8	844 ± 18
690-740	557	415 ± 12	90.4 ± 3.0	3.8 ± 1.5	15.6 ± 3.6	1.7 ± 0.4	526 ± 14
740-790	316	259 ± 9.6	55.2 ± 2.3	0.8 ± 0.5	9.14 ± 2.3	0.2 ± 0.1	325 ± 12
790-840	233	178 ± 7.1	35.3 ± 1.7	1.7 ± 0.8	5.35 ± 1.7	1.4 ± 0.3	223 ± 9
840-900	172	139 ± 6.2	25.2 ± 1.3	1.5 ± 1.2	2.52 ± 1.05	0.04 ± 0.03	169 ± 8
900-960	101	88.1 ± 4.9	14.7 ± 0.9	0.3 ± 0.3	3.88 ± 1.42	0.03 ± 0.02	107 ± 6
960-1020	65	73.8 ± 4.7	12.0 ± 0.8	0.4 ± 0.3	1.83 ± 0.92	0.02 ± 0.01	88.1 ± 5.3
1020-1090	46	42.6 ± 3.1	6.7 ± 0.6	0.0 ± 0.0	3.42 ± 1.33	0.01 ± 0.01	52.8 ± 3.9
1090-1160	26	21.5 ± 2.1	3.5 ± 0.4	0.0 ± 0.0	0.00 ± 0.00	0.01 ± 0.00	25.0 ± 2.5
1160-1250	31	21.0 ± 2.2	3.3 ± 0.4	0.0 ± 0.0	1.07 ± 0.69	0.01 ± 0.00	25.5 ± 2.6
1250-1400	29	22.5 ± 2.4	2.9 ± 0.3	0.0 ± 0.0	1.49 ± 0.91	0.01 ± 0.00	26.9 ± 2.8

Effort hosted by the LHC DM WG to produce a O(1%) theoretical estimate for this analysis (See arXiv:1705.04664 and Pozzorini's talk at DM@LHC 2017)

CMS Mono-W/Z/jet

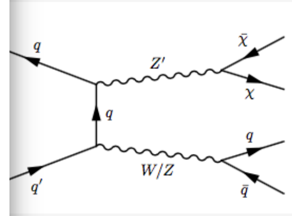
PAS EXO-16-048

(currently strongest public

Look for large MET and ≥

- Mono-V: p_{Tj1}^{AK8}, MI
- Mono-jet: remaining

Fit background and signal



E_T^{miss} (GeV)	Observ	otal Bkg.
250-280	13686.	500 ± 3700
280-310	74340	00 ± 2000
310-340	42540	320 ± 810
340-370	25316	490 ± 490
370-400	15653	430 ± 310
400-430	10092	160 ± 170
430-470	8298	80 ± 140
470-510	4906	865 ± 95
510-550	2987	970 ± 49
550-590	2032	915 ± 33
590-640	1514	506 ± 32
640-690	926	44 ± 18
690-740	557	26 ± 14
740-790	316	25 ± 12
790-840	233	223 ± 9
840-900	172	169 ± 8
900-960	101	107 ± 6
960-1020	65	8.1 ± 5.3
1020-1090	46	2.8 ± 3.9
1090-1160	26	5.0 ± 2.5
1160-1250	31	5.5 ± 2.6
1250-1400	29	6.9 ± 2.8

CERN-TH-2017-102
CERN-LPCC-2017-02
FERMILAB-PUB-17-152-T
IPPP/17/38
ZU–TH 12/17

Precise predictions for V+jets dark matter backgrounds

J. M. Lindert[1], S. Pozzorini[2], R. Boughezal[3], J. M. Campbell[4], A. Denner[5], S. Dittmaier[6], A. Gehrmann-De Ridder[2,7], T. Gehrmann[2], N. Glover[1], A. Huss[7], S. Kallweit[8], P. Maierhöfer[6], M. L. Mangano[8], T.A. Morgan[1], A. Mück[9], F. Petriello[3,10], G. P. Salam*[8], M. Schönherr[2], and C. Williams[11]

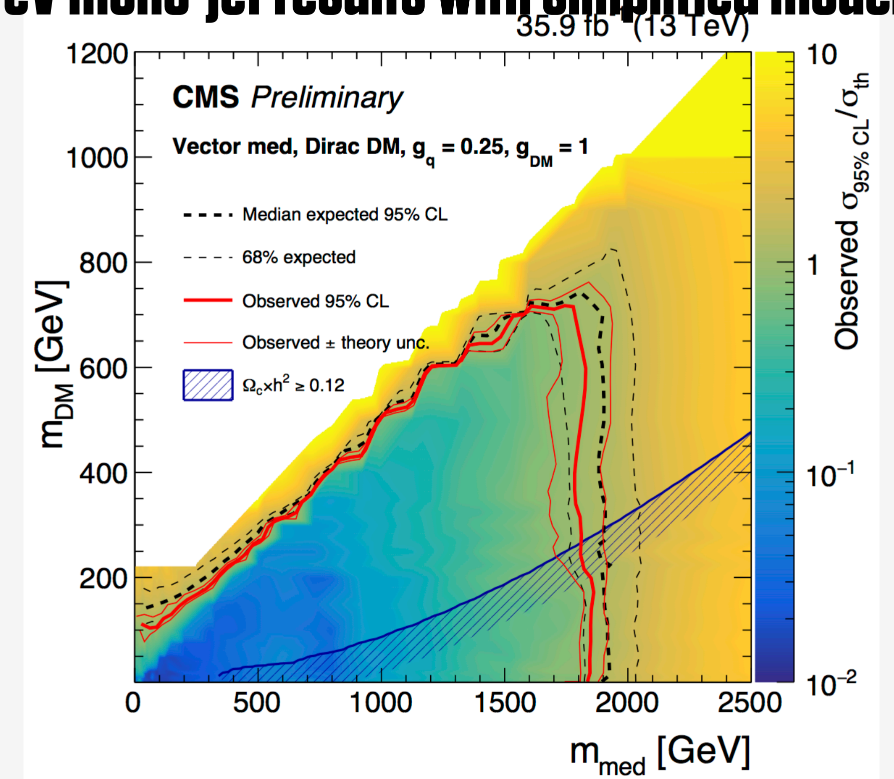
[1] *Institute for Particle Physics Phenomenology, Department of Physics, University of Durham, Durham, DH1 3LE, UK*
[2] *Physik-Institut, Universität Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland*
[3] *High Energy Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA*
[4] *Fermilab, P.O.Box 500, Batavia, IL 60510, USA*
[5] *Universität Würzburg, Institut für Theoretische Physik und Astrophysik, 97074 Würzburg, Germany*
[6] *Albert-Ludwigs-Universität Freiburg, Physikalisches Institut, 79104 Freiburg, Germany*
[7] *Institute for Theoretical Physics, ETH, CH-8093 Zürich, Switzerland*
[8] *Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland*
[9] *Institut für Theoretische Teilchenphysik und Kosmologie, RWTH Aachen University, D-52056 Aachen, Germany*
[10] *Department of Physics & Astronomy, Northwestern University, Evanston, IL 60208, USA*
[11] *Department of Physics, University at Buffalo, The State University of New York, Buffalo 14260 USA*

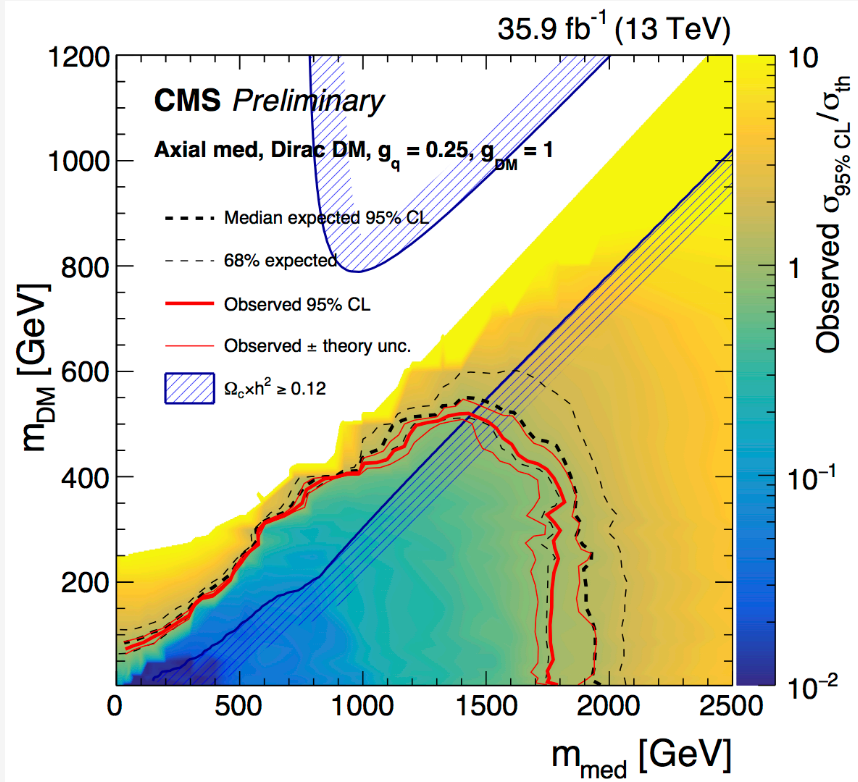
Abstract

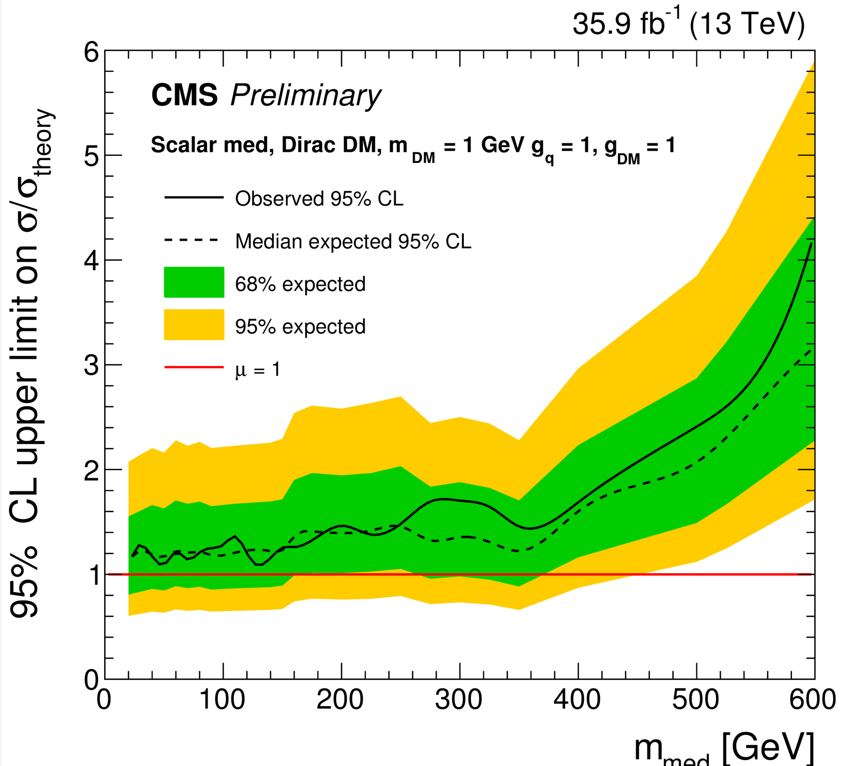
High-energy jets recoiling against missing transverse energy (MET) are powerful probes of dark matter at the LHC. Searches based on large MET signatures require a precise control of the $Z(\nu\bar{\nu})$+jet background in the signal region. This can be achieved by taking accurate data in control regions dominated by $Z(\ell^+\ell^-)$+jet, $W(\ell\nu)$+jet and γ+jet production, and extrapolating to the $Z(\nu\bar{\nu})$+jet background by means of precise theoretical predictions. In this context, recent advances in perturbative calculations open the door to significant sensitivity improvements in dark matter searches. In this spirit, we present a combination of state-of-the-art calculations for all relevant V+jets processes, including throughout NNLO QCD corrections and NLO electroweak corrections supplemented by Sudakov logarithms at two loops. Predictions at parton level are provided together with detailed recommendations for their usage in experimental analyses based on the reweighting of Monte Carlo samples. Particular attention is devoted to the estimate of theoretical uncertainties in the framework of dark matter searches, where subtle aspects such as correlations across different V+jet processes play a key role. The anticipated theoretical uncertainty in the $Z(\nu\bar{\nu})$+jet background is at the few percent level up to the TeV range.

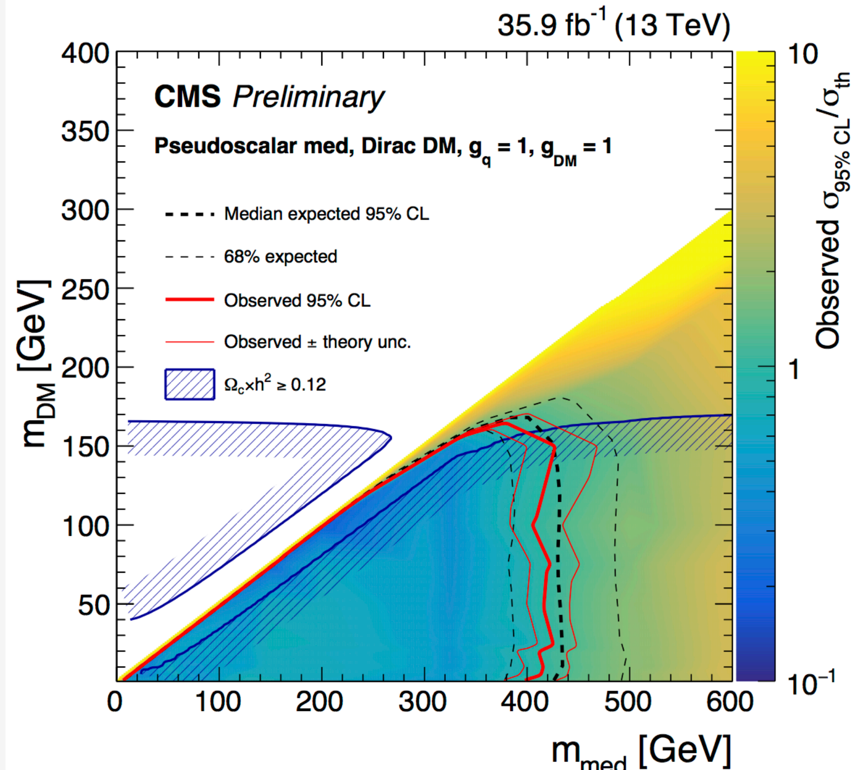
Effort hosted by the LHC DM WG … at DM@LHC 2017)

13 TeV mono-jet results with simplified models

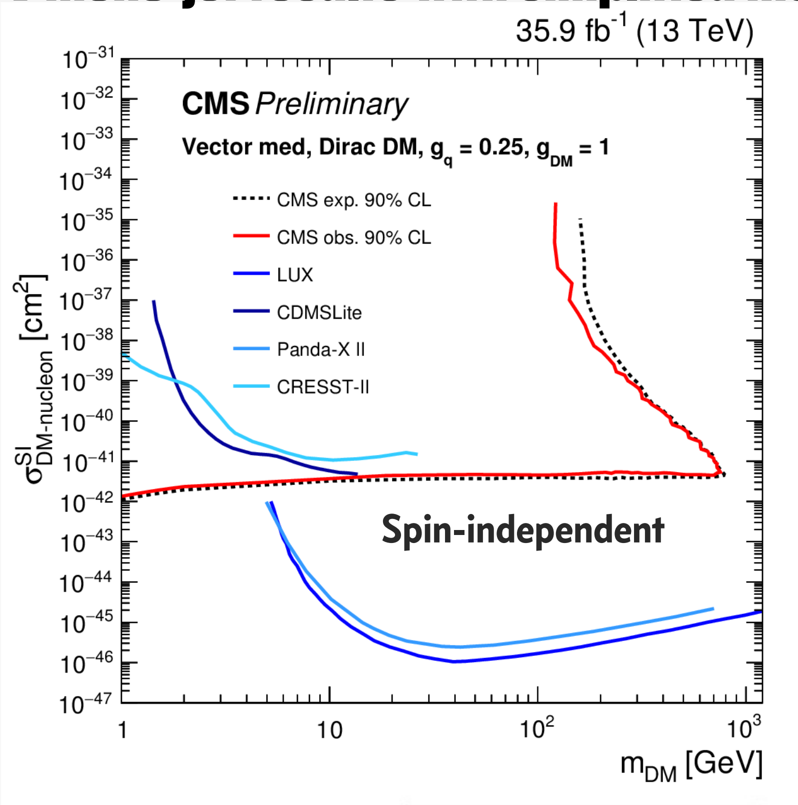


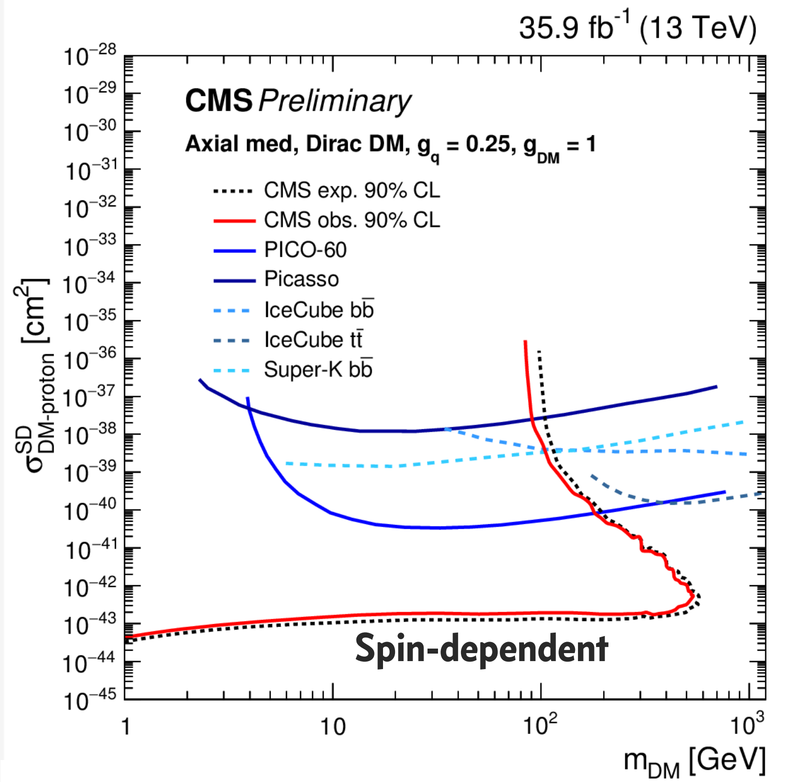


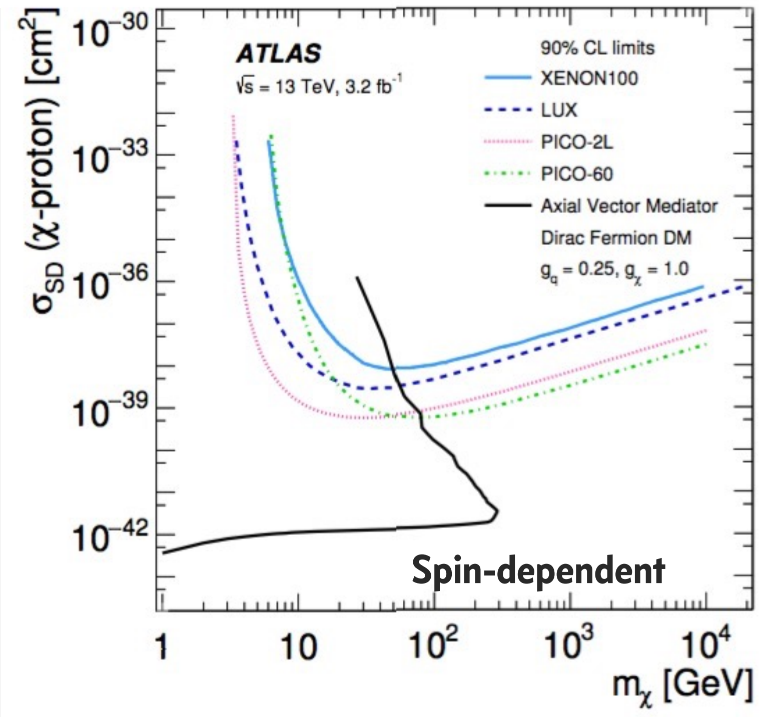


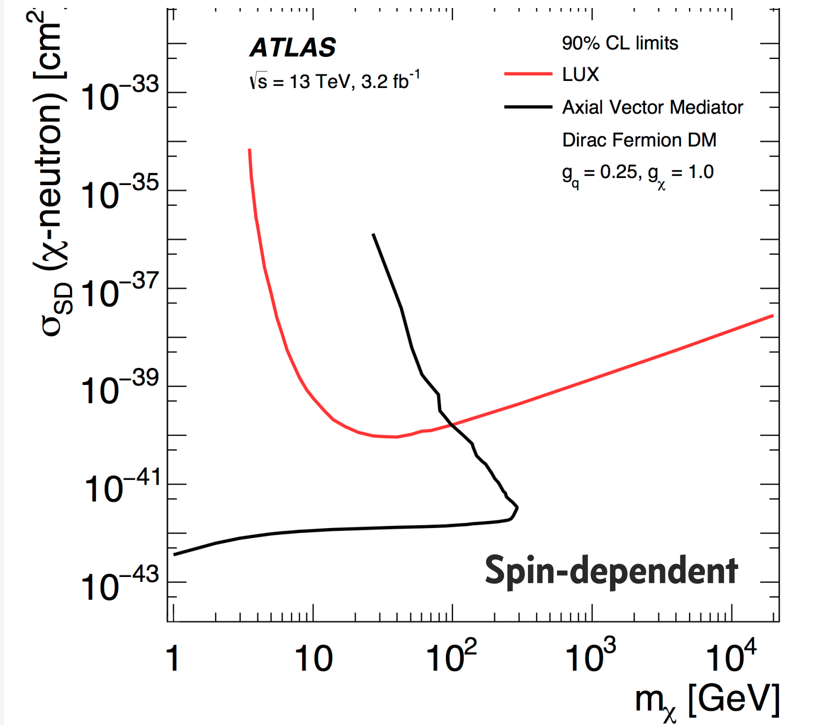


13 TeV mono-jet results with simplified models









Translation from simplified model to nucleon-WIMP cross section described in arXiv:1603.04156