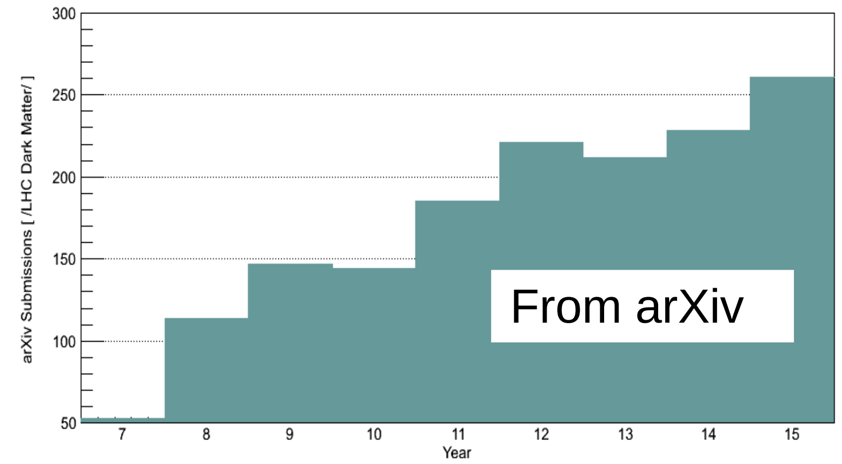
Status & Outlook of the LHC Dark Matter Working Group (LHCDMWG)

Kristian Hahn – Northwestern Univ.
For the LHCDMWG conveners

Dark Matter – Cairo
December 14, 2015

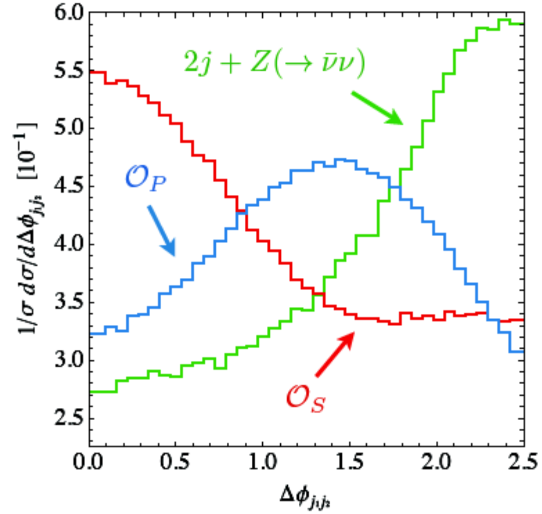
Dark Matter (DM) has gained significant momentum in the LHC community:

- Expanding body of theory & phenomenology work targeting DM@LHC
- Dedicated DM workshops, many conference talks
- Work of the recent LHC Dark Matter Forum (DMF)



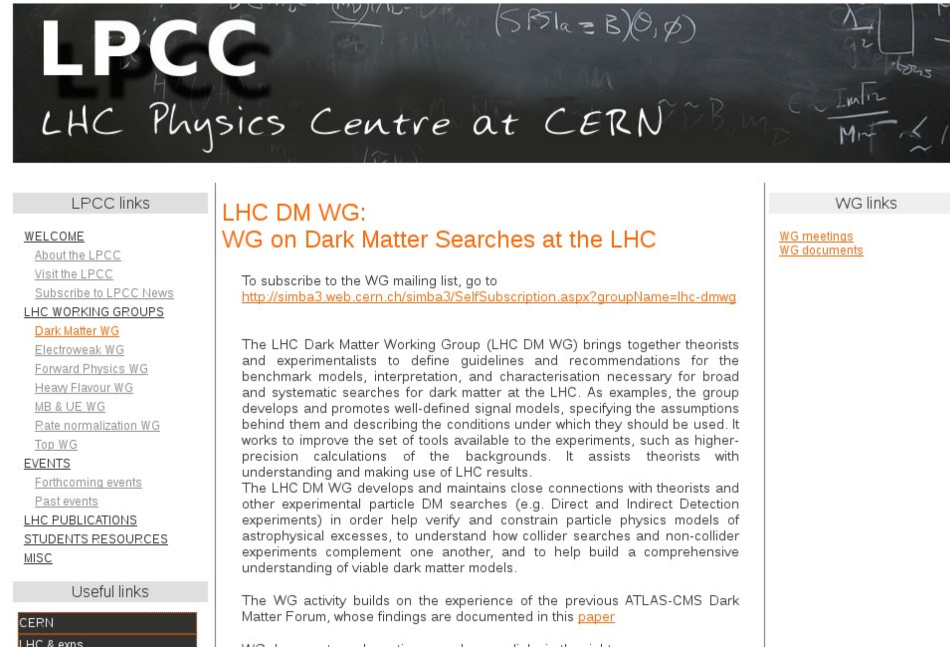
DM now a *major* focus of the LHC experiments in Run-2

- Complimentary discovery reach vs direct/indirect detection
- In some cases, able to distinguish DM scenarios



The LHCDMWG recently organized under the LHC Physics Centre at CERN

- Provides a permanent home for the coordination of broad, systematic searches for DM at the LHC



https://lpcc.web.cern.ch/LPCC/index.php?page=dm_wg

Outline of this presentation:

- Introduction of the LHCDMWG : organization and details
- Status: toward Winter conferences!
    - Summary of the first LHCDMWG open meeting
    - Focus: development of recommendations for the presentation of Run-2 results
- LHCDMWG near-term outlook & future directions

Organizing Principles

- The LHC Dark Matter Working Group (LHC DM WG) brings together theorists and experimentalists to define guidelines and recommendations for the benchmark models, interpretation, and characterisation necessary for broad and systematic searches for dark matter at the LHC. As examples, the group develops and promotes well-defined signal models, specifying the assumptions behind them and describing the conditions under which they should be used. It works to improve the set of tools available to the experiments, such as higher-precision calculations of the backgrounds. It assists theorists with understanding and making use of LHC results.

- The LHC DM WG develops and maintains close connections with theorists and other experimental particle DM searches (e.g. Direct and Indirect Detection experiments) in order help verify and constrain particle physics models of astrophysical excesses, to understand how collider searches and non-collider experiments complement one another, and to help build a comprehensive understanding of viable dark matter models.
- The LHC DM WG is structured to focus most of its attention on clearly delineated topics over short periods. At any one time, it holds discussion on only a small number of these topics, each leading to a report. Within this constraint, the discussions and reports of the working group are open to participation by the wide scientific community.

Conveners

- ATLAS: A. Boveia, C. Doglioni
- CMS: O. Buchmueller, K. Hahn
- Theory: U. Haisch, M. Mangano

(a convener will also be nominated by LHCb)

Subgroups

- Nominated to help address specific topics
- May operate through limited-participation meetings

Open subscription mailing list:
http://cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-dmwg

Open Meetings

- Discuss latest exp. Results, collect input for WG studies
- Stimulate recommendations concerning theoretical issues
- Present for discussion the results and proposals of the WG

First Open Meeting of the DMWG

December 10-11 @ CERN

- Agenda: http://indico.cern.ch/event/459037

Primary goal

- Converge on an initial (but comprehensive) set of recommendations for presentation of results for Winter conferences
- Starting points: conclusions from the DMF and subsequent work
- Workshop summarized in slides that follow
- Soon to be distilled into a set of written recommendations

Discussion topics

- Review of recommendations from the DMF
- Proposal for the presentation of Run-2 results, comparison with DD/ID
- Other important short-term topics: mono-V, heavy flavor, relic calculations
- Future directions

Review of the DMF Report

arXiv:1507.00966

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, Benjamin Fuks, Marie-Helene Genest, Bhawna Gomber, Andreas Goudelis, Johanna Gramling, John Gunion, Kristian Hahn, Ulrich Haisch, Roni Harnik, Philip C. Harris, Kerstin Hoepfner, Siew Yan Hoh, Dylan George Hsu, Shih-Chieh Hsu, Yutaro Iiyama, Valerio Ippolito, Thomas Jacques, Xiangyang Ju, Felix Kahlhoefer, Alexis Kalogeropoulos, Laser Seymour Kaplan, Lashkar Kashif, Valentin V. Khoze, Raman Khurana, Khristian Kotov, Dmytro Kovalskyi, Suchita Kulkarni, Shuichi Kunori, Viktor Kutzner, Hyun Min Lee, Sung-Won Lee, Seng Pei Liew, Tongyan Lin, Steven Lowette, Romain Madar, Sarah Malik, Fabio Maltoni, Mario Martinez Perez, Olivier Mattelaer, Kentarou Mawatari, Christopher McCabe, Théo Megy, Enrico Morgante, Stephen Mrenna, Siddharth M. Narayanan, Andy Nelson, Sérgio F. Novaes, Klaas Ole Padeken, Priscilla Pani, Michele Papucci, Manfred Paulini, Christoph Paus, Jacopo Pazzini, Björn Penning, Michael E. Peskin, Deborah Pinna, Massimiliano Procura, Shamona F. Qazi, Davide Racco, Emanuele Re, Antonio Riotto, Thomas G. Rizzo, Rainer Roehrig, David Salek, Arturo Sanchez Pineda, Subir Sarkar, Alexander Schmidt, Steven Randolph Schramm, William Shepherd, Gurpreet Singh, Livia Soffi, Norraphat Srimanobhas, Kevin Sung, Tim M. P. Tait, Timothee Theveneaux-Pelzer, Marc Thomas, Mia Tosi, Daniele Trocino, Sonaina Undleeb, Alessandro Vichi, Fuquan Wang, Lian-Tao Wang, Ren-Jie Wang, Nikola Whallon, Steven Worm, Mengqing Wu, Sau Lan Wu, Hongtao Yang, Yong Yang, Shin-Shan Yu, Bryan Zaldivar, Marco Zanetti, Zhiqing Zhang, Alberto Zucchetta

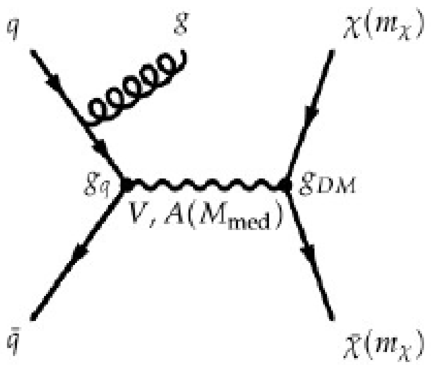
Primary topics considered:

- Simplified DM production models for all MET+X analyses
- Presentation of EFT results

Vector and Axial-Vector s-channel mediators (Simplified Models)

$$\mathcal{L}_{\text{vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi$$

$$\mathcal{L}_{\text{axial-vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \gamma^5 \chi$$



- mediator width dominated by quarks
- minimal set of parameters $\{ g_q, g_\chi, m_\chi, M_{\text{med}}, \}$
  - scan over couplings can be avoided
  - scan over DM and mediator mass can be simplified
  - sufficient to only consider V-V or A-A

    and even then MET shapes are very similar
- the studies in the report show this is a tractable problem

m_χ / GeV	M_{med} / GeV									
1	10	20	50	100	200	300	500	1000	2000	10000
10	10	15	50	100						10000
50	10		50	95	200	300				10000
150	10				200	295	500	1000		10000
500	10						500	995	2000	10000
1000	10							1000	1995	10000

S. Lowette :
https://indico.cern.ch/event/459037/session/0/contribution/22/attachments/1203055/1751787/151008_Lowette_LPCCDMGW_LHCDMFReview.pdf

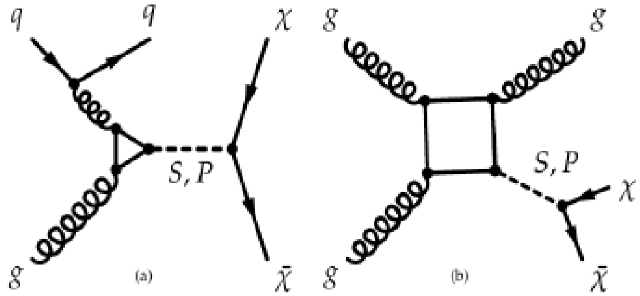
Scalar and pseudoscalar s-channel mediators

(Simplified Models)

- for simplicity, assume no mixing with SM scalar sector

$$\mathcal{L}_\phi = g_\chi \phi \bar{\chi}\chi + \frac{\phi}{\sqrt{2}} \sum_i \left(g_u y_i^u \bar{u}_i u_i + g_d y_i^d \bar{d}_i d_i + g_\ell y_i^\ell \bar{\ell}_i \ell_i \right)$$

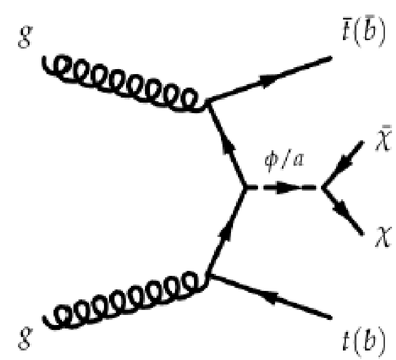
$$\mathcal{L}_a = i g_\chi a \bar{\chi} \gamma_5 \chi + \frac{ia}{\sqrt{2}} \sum_i \left(g_u y_i^u \bar{u}_i \gamma_5 u_i + g_d y_i^d \bar{d}_i \gamma_5 d_i + g_\ell y_i^\ell \bar{\ell}_i \gamma_5 \ell_i \right)$$



- different production than V and AV case
  - loop process dominates (MFV)
  - strong dependence on which decays are available to mediator
- mediator width dominated by DM below top threshold, and by top above
- in general, conclusions for V and AV also apply here

(Pseudo)scalar mediator and HF

- given MFV, tt+DM production can be sizeable
  - like with Higgs production
- also bb+DM possibly important
  - eg. in 2HDM at large tanβ (a la SUSY)
- small dependences on the mediator width
- same scan proposed as for general case, but only up to DM mass 500GeV
  - scalar and pseudoscalar should be done both



S. Lowette :
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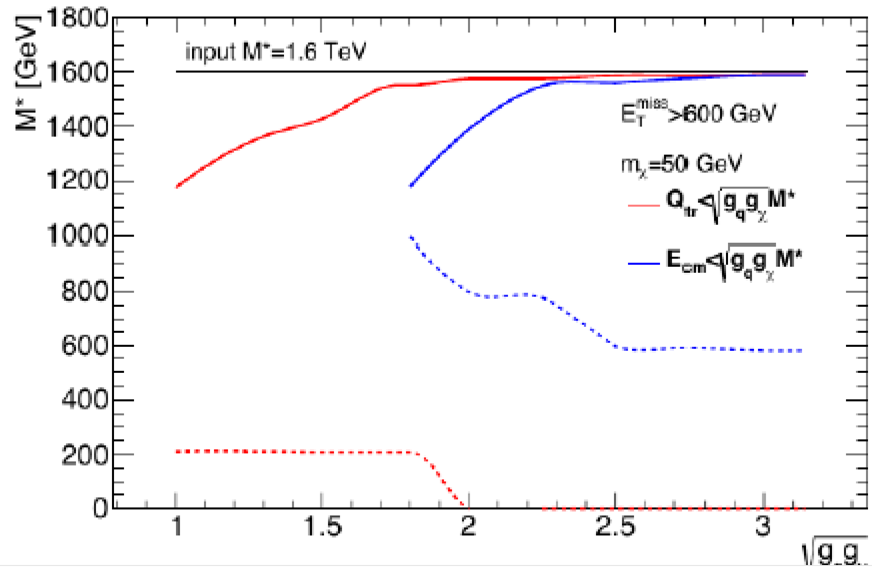
Example result

- experiments are now routinely applying truncation in the EFT results that have come out in the past months



Address limitations of Effective Field Theory (EFT) models

Truncation recipe 2

- avoid using underlying dynamics, place more conservative cut
  - thus weaker limit
- reject events with $E_{cm} < M_{cut}$
  - with eg. $M_{cut} = M_{med}$ in previous example

S. Lowette :
https://indico.cern.ch/event/459037/session/0/contribution/22/attachments/1203055/1751787/151008_Lowette_LPCCDMGW_LHCDMFReview.pdf

Presentation of LHC DM Results

In lead-up to the workshop, WG discussed development of a coherent proposal for the presentation of LHC results, and comparison with DD & ID

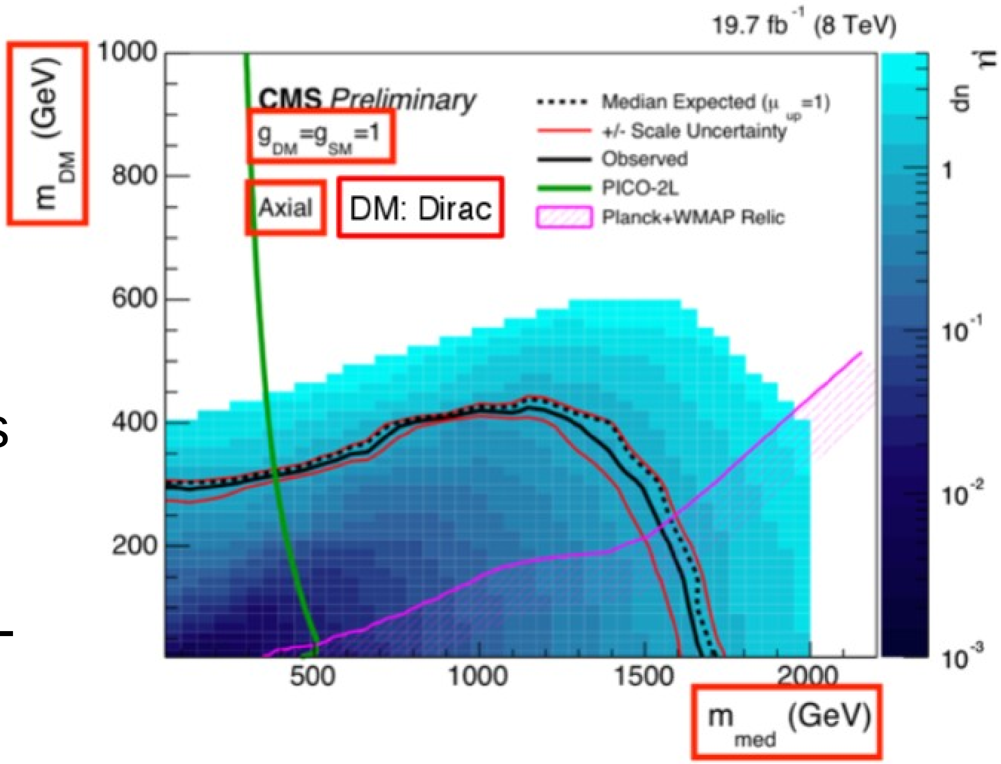
- Input from a first DMWG sub-group (credits in backup)
- Details on DD / ID comparison presented by C. McCabe & F. Kahlhoefer
- Proposal recalibrated, now close to final a iteration

Proposal based on the results of the latest Run-1 CMS DM search (CMS-PAS-EXO-12-055)

- See talk by P. Harris in this workshop for details on the analysis

Mass-Mass plots (mDM vs mMed) are a useful way of presenting LHC results

- Plot limit for fixed choice of couplings, ensure NWA valid
  - Results can be re-scaled for other coupling / model choices
- Signal strength (μ) as z-scale
  - Avoids projection into strongly-coupled / broad width regimes



Must clearly state all model assumptions: coupling choices, dark matter and mediator types, etc...

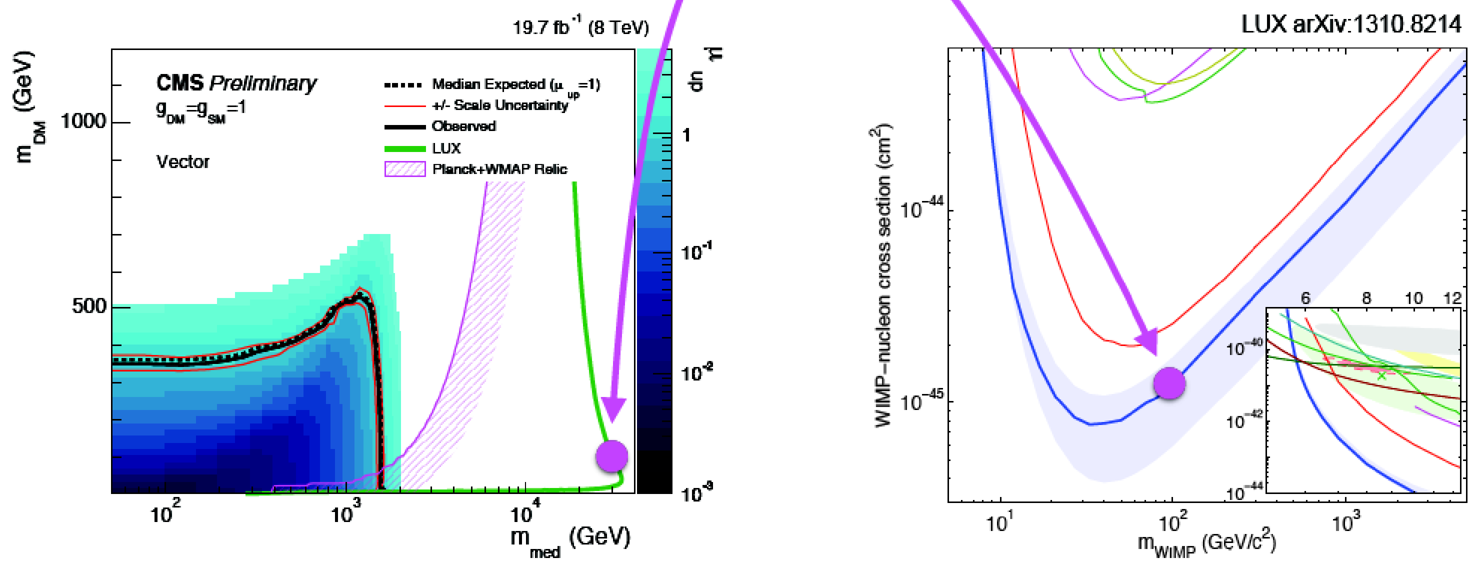
https://indico.cern.ch/event/459037/session/3/contribution/32/attachments/1203672/1753075/20151211_Follow-up_Proposal_Collider_vs_DD_and_ID_2.pdf

Straightforward mapping between DD and LHC for vector / axial mediators

- f(gSM): mediator coupling to nucleon
- μηχ: reduced DM-nucleon mass

Vector: translation

$$\sigma^0 = \frac{f^2(g_{\rm SM}) g_{\rm DM}^2}{\pi} \frac{\mu_{n\chi}^2}{M_{\rm med}^4} \qquad M_{\rm med} = \left(\frac{f^2(g_{\rm SM}) g_{\rm DM}^2}{\pi} \frac{\mu_{n\chi}^2}{\sigma^0} \right)^{1/4}$$



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Spin-independent (vector): assume equal p,n coupling

Spin-dependent (axial): couples only to p *or* n

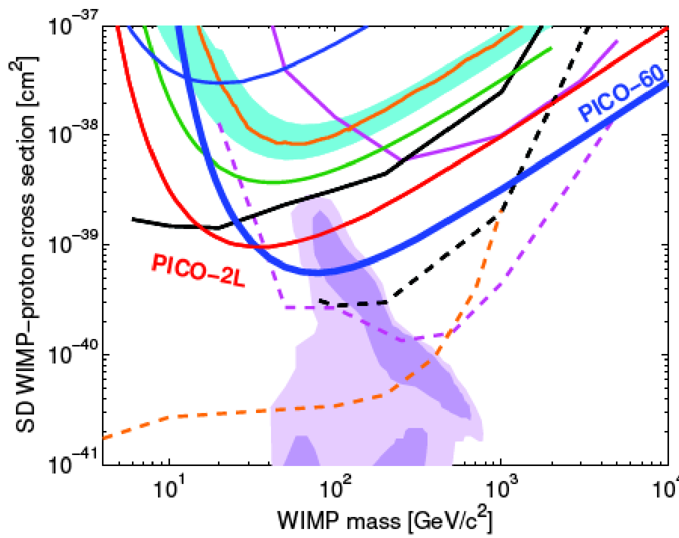
C. McCabe:
https://indico.cern.ch/event/459037/session/1/contribution/5/attachments/1203223/1752093/mccabe_translation.pdf

Sign of g_u vs g_d matters

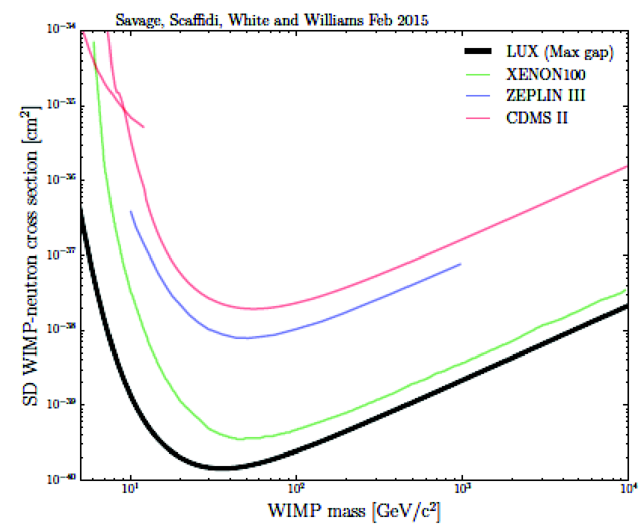
- DD limits in mDM-mMed stronger when $g_u = -g_d$
- SU(2) gauge invariance also prefers $g_u = -g_d$

Axial: which limit?

- PICO strongest proton-only



LUX strongest neutron-only



- $g_u = g_d$: $\sigma_p = \sigma_n$, LUX limit is more constraining
- $g_u = -g_d$: $\sigma_p \approx 1.3\,\sigma_n$, LUX limit is more constraining

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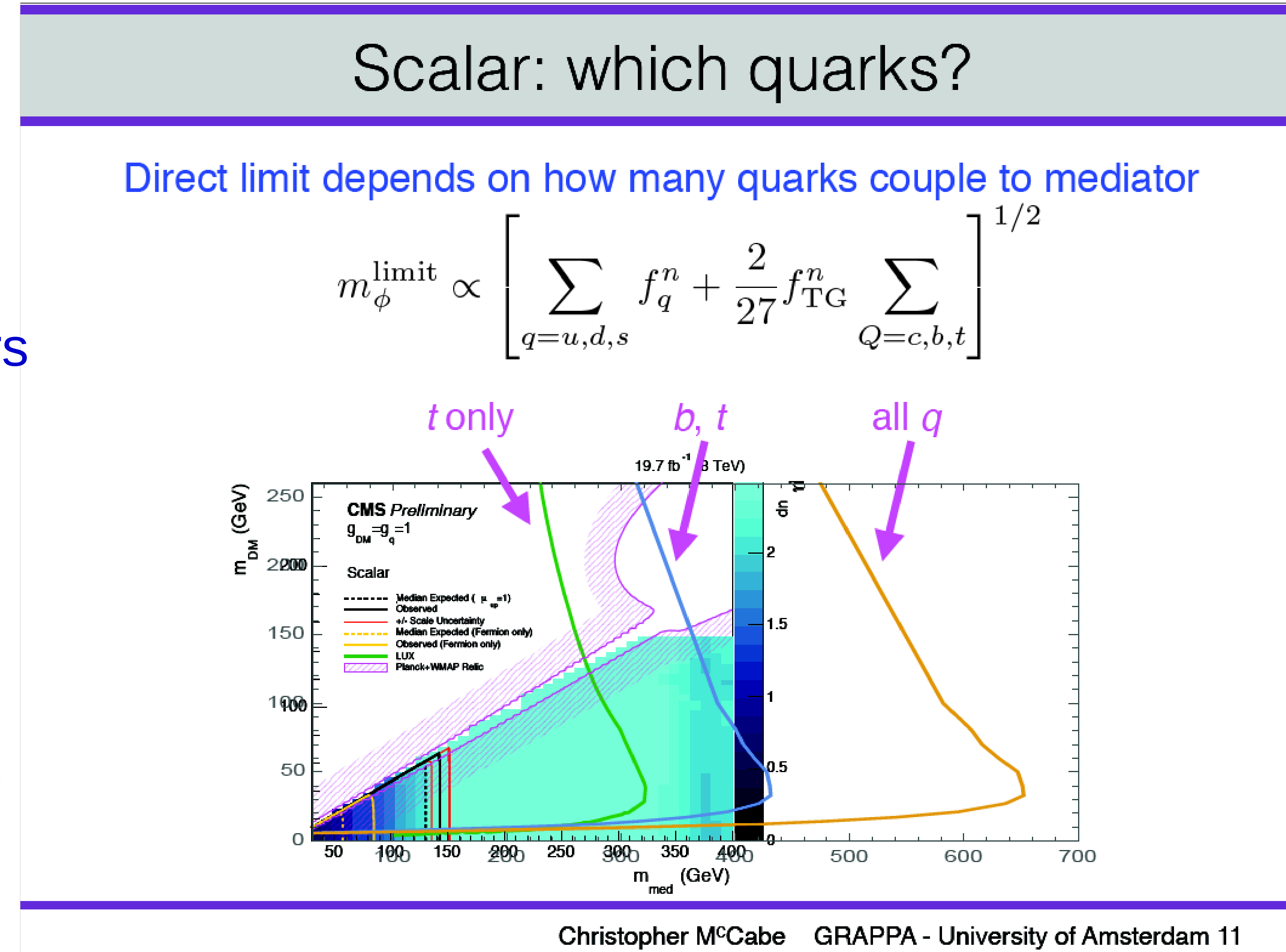
Given universal couplings, strongest bounds from LUX

C. McCabe:
https://indico.cern.ch/event/459037/session/1/contribution/5/attachments/1203223/1752093/mccabe_translation.pdf

Also straightforward mapping between DD and LHC for scalar mediators

- MFV implies universal Yukawa couplings
- Should include contributions from all quarks in limits



C. McCabe:
https://indico.cern.ch/event/459037/session/1/contribution/5/attachments/1203223/1752093/mccabe_translation.pdf

For PS, most appropriate comparison is with ID

- PS velocity suppressed at DD
- Presently, strongest PS bounds from Fermi-LAT

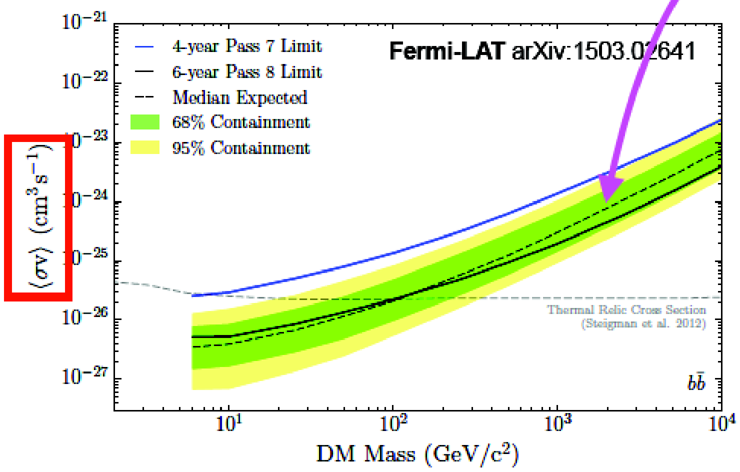
Non 2-2 channels can also contribute …

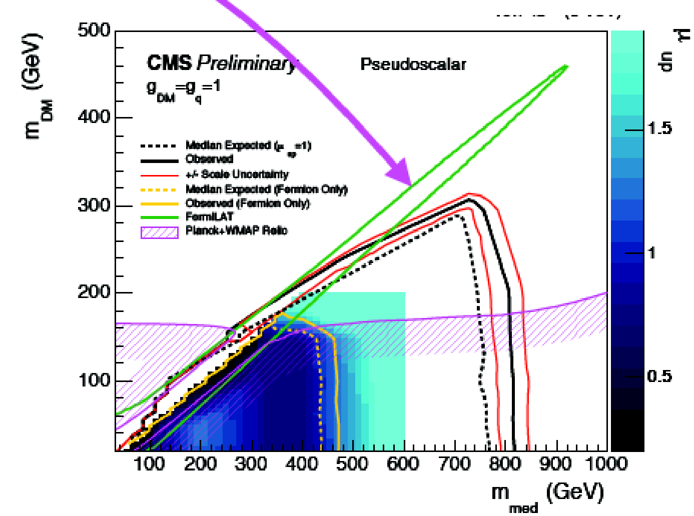
Pseudoscalar

$$\mathcal{L}_{\rm int} = i g_{\rm DM} A \bar{\chi}\gamma^5\chi + i g_{\rm SM} \sum_q \frac{m_q}{v} A\, \bar{q}\gamma^5 q$$

- 2->2 cross-section straightforward to calculate:

$$\langle \sigma v \rangle_q = \frac{N_C m_q^2}{2\pi v^2} \frac{g_{\rm DM}^2 g_{\rm SM}^2 m_{\rm DM}^2}{(m_A^2 - 4m_{\rm DM}^2)^2 + m_A^2 \Gamma_A^2} \sqrt{1 - \frac{m_q^2}{m_{\rm DM}^2}}$$





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C. McCabe:
https://indico.cern.ch/event/459037/session/1/contribution/5/attachments/1203223/1752093/mccabe_translation.pdf

Width effects important in the on-shell and transition regions

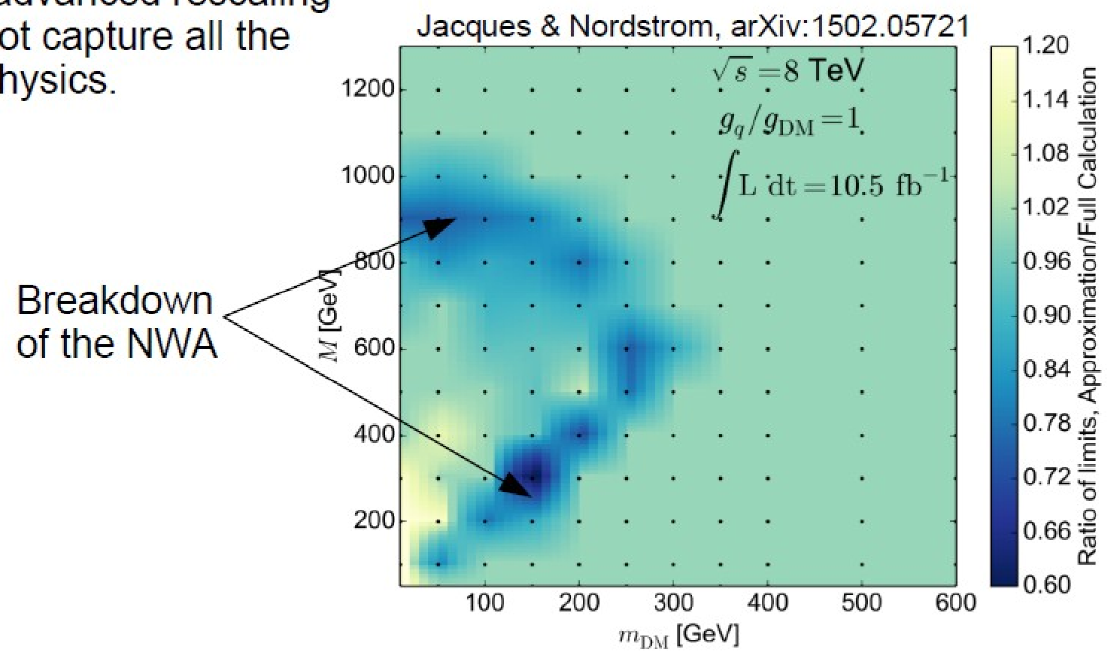
Naive scaling assumptions for cross section breaks down

Advanced rescaling attempts

One could try to use different rescaling rules in the on-shell region and in the off-shell region.

$$\sigma \propto \begin{cases} g_q^2 g_{\rm DM}^2/\Gamma_{\rm OS} & \text{if } M > 2m_{\rm DM} \\ g_q^2 g_{\rm DM}^2 & \text{if } M < 2m_{\rm DM} \end{cases}$$

But even advanced rescaling rules do not capture all the relevant physics.



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DESY

F. Kahlhoefer:
http://indico.cern.ch/event/459037/session/1/contribution/7/attachments/1203033/1751743/DMWG_Kahlhoefer.pdf

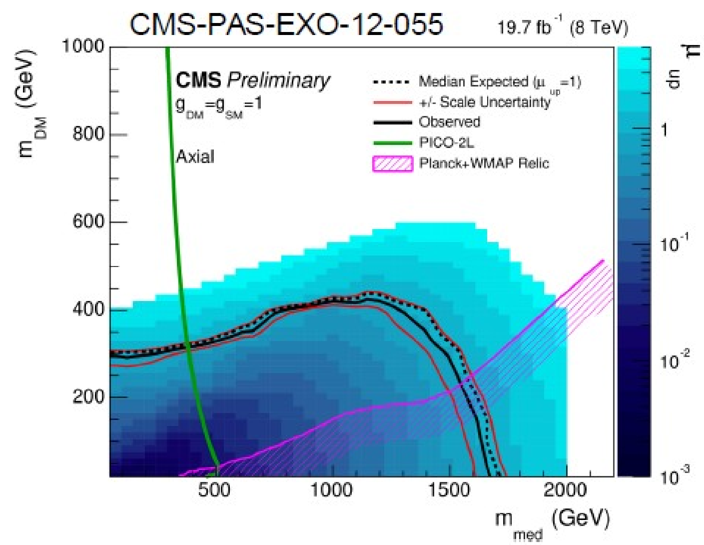
Limits on signal strength for fixed couplings preferred

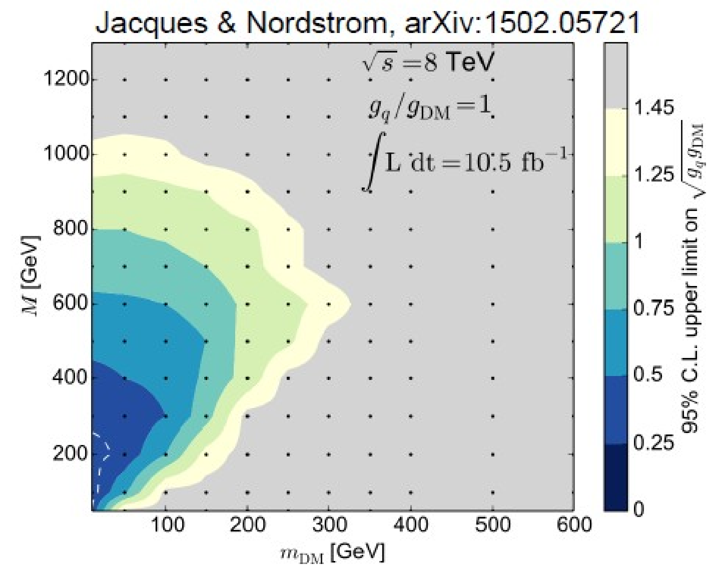
- Only 2 parameters need to be scanned for signal generation
- Easy to include other constraints (eg: dijets, DD) in such plots
- Can naturally aoivd non-perturbative and large width regions

How to present results without assumed rescaling

Option 1: Fix both couplings and quote an upper bound on the signal strength.

Option 2: Fix one coupling (or the ratio of the couplings) and quote an upper bound on the other coupling (or the product of the couplings).





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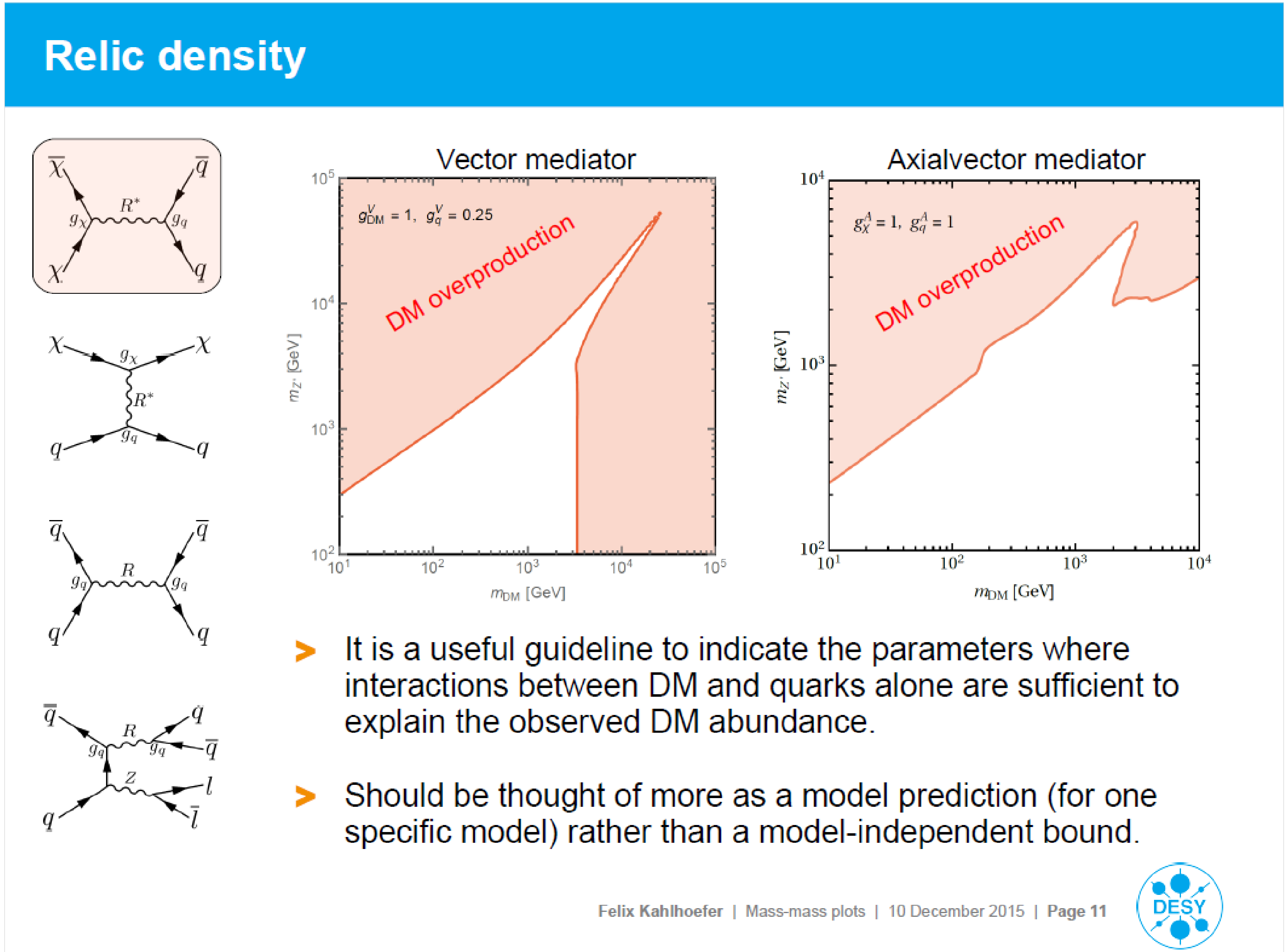
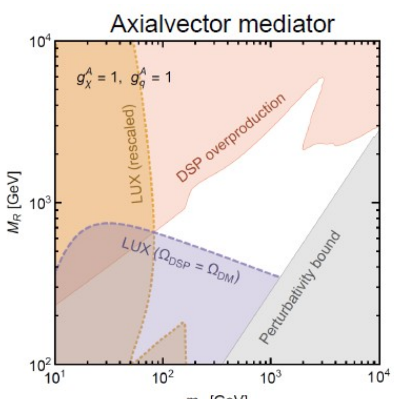
F. Kahlhoefer:
http://indico.cern.ch/event/459037/session/1/contribution/7/attachments/1203033/1751743/DMWG_Kahlhoefer.pdf

Relic density is an interesting benchmark to illustrate

- Noting that a discovery at the LHC could imply non-standard cosmology, Ω_{DSP} != Ω_{DM}

Consider rescaling DD results if relic also shown





Plots become rather busy ...

F. Kahlhoefer:
http://indico.cern.ch/event/459037/session/1/contribution/7/attachments/1203033/1751743/DMWG_Kahlhoefer.pdf

Choices of couplings shown

To avoid limits from dijets ...

Issues with unitarity ...

- Fixed couplings:
  - vector/axial: gq=0.25, gDM=1
    - gu = gd vs gu = -gd
      - monojet open point: phase space differences
      - validity of monoV gu = -gd: needs interaction with theorists
  - scalar/pseudoscalar: gq=1, gDM=1
- Sufficient? How to allow reinterpretation for other couplings?
  - scaling laws (at the theorist's risk)
  - sufficient information for redoing the analysis (e.g. MadAnalysis) given a different signal - see DMF appendix and collaboration policies on presentation of results

https://indico.cern.ch/event/459037/session/3/contribution/32/attachments/1203672/1753075/20151211_Follow-up_Proposal_Collider_vs_DD_and_ID_2.pdf

Recommendation proposal

- Show only the LHC limits and relic density line in the mass-mass plots.
  - Show perturbativity line as well

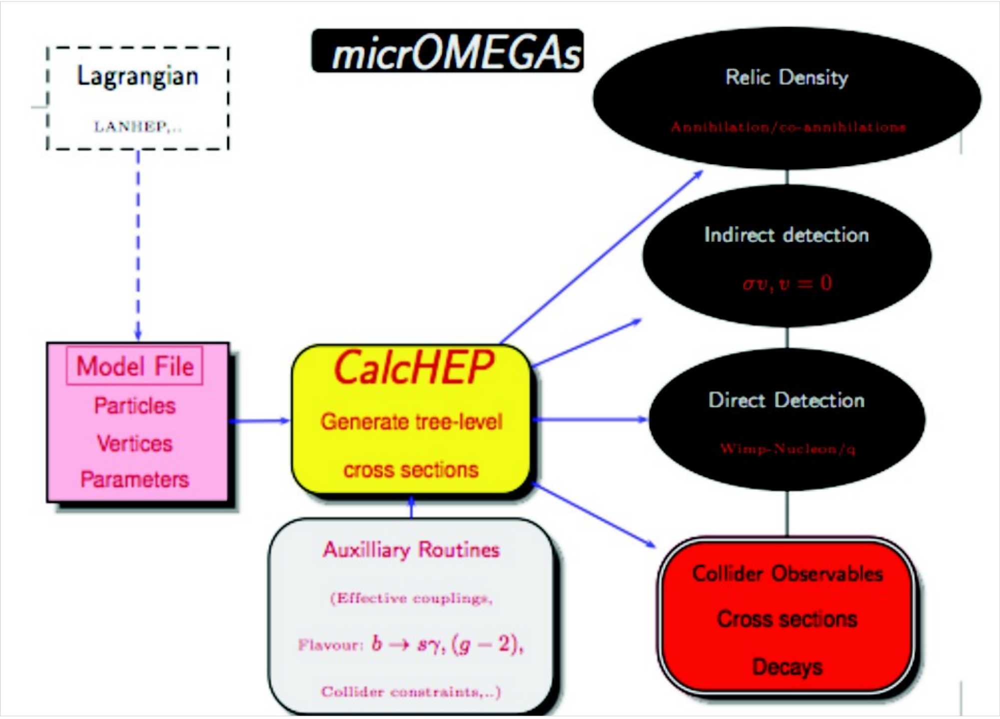
Unitarity issues for axial mediators: arXiv:1510.02110

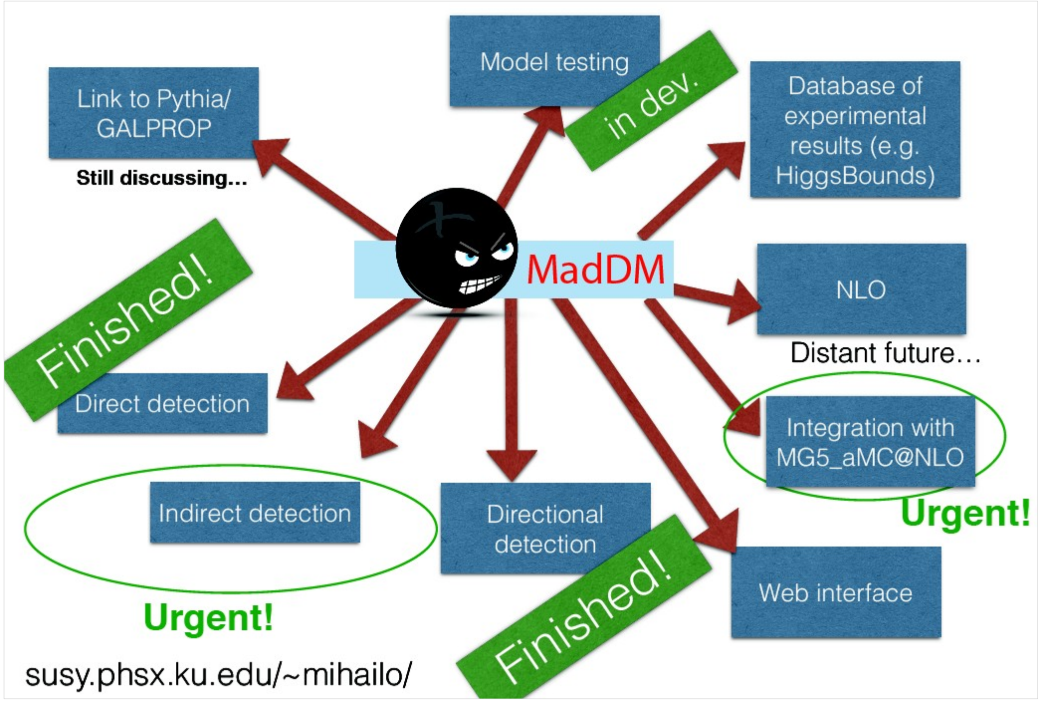
- Do not translate direct detection or indirect detection onto the mass-mass plot.
- Show the comparison with direct detection and indirect detection in their planes (cross-section — mass/cross-section — velocity) only.
  - Couple to all quarks (MFV)

https://indico.cern.ch/event/459037/session/3/contribution/32/attachments/1203672/1753075/20151211_Follow-up_Proposal_Collider_vs_DD_and_ID_2.pdf

Other Items for the Near-Term

Relic Density Calculations





G. Belanger:
https://indico.cern.ch/event/459037/session/1/contribution/1/attachments/1203101/1752041/micromegas_CERN.pdf

M. Backovic:
https://indico.cern.ch/event/459037/session/1/contribution/2/attachments/1203278/1752282/MadDM.pdf

Extensive / flexible tool chains exist for incorporating relic density calculations

Discussion & proposal:

- DMWG to centrally provide relic density bounds for the experiments

Mono-V

$SU(2)_L$ invariance is of particular importance for processes involving an $SU(2)_L$ gauge boson → i.e. mono-W or mono-Z

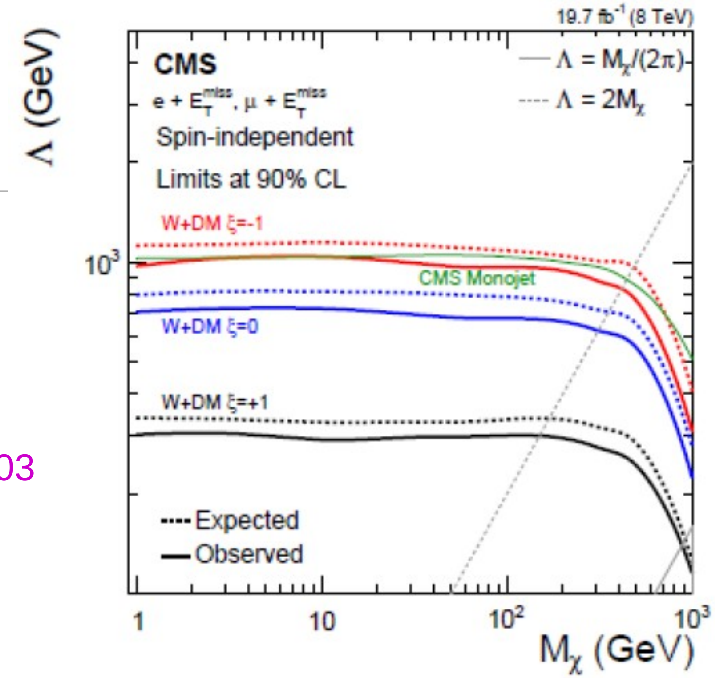
Mono-W signal for SU(2) violating EFT (arXiv:1208.4361):

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

ξ parameterizes relative strength of DM coupling to $\boldsymbol{u}$ and $\boldsymbol{d}$.

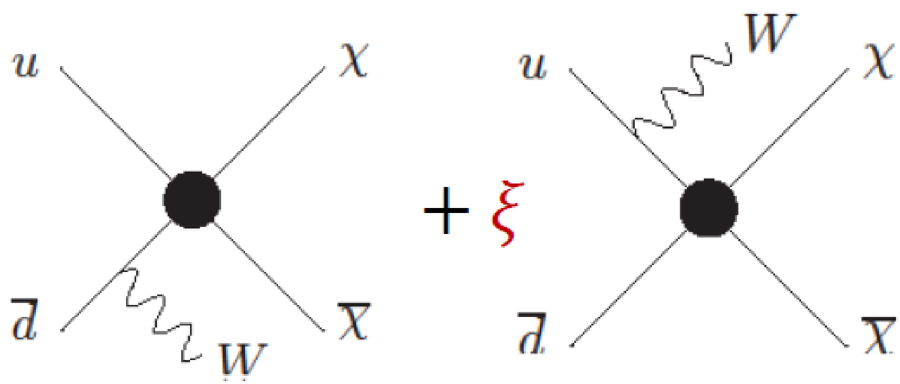
For some parameters, the mono-W results are apparently stronger than those from mono-jets!

This effect has been analysed by both ATLAS and CMS:



N. Bell:
http://indico.cern.ch/event/459037/session/6/contribution/25/attachments/1203369/1752401/LHC_DM_WG_2015_Bell.pdf

Mono-W process



Contributions to the (parton-level) mono-W process $u\bar{d} \to \chi\chi W^+$ in the effective field theory framework

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

- For $\xi = 1$ ($\xi = -1$) a very strong destructive (constructive) interference effect was observed.
- However, this effect is in fact due to unphysical W_L contributions, which arise due to the lack of gauge invariance.

LHC DARK MATTER WORKING GOUP MEETING N. BELL, U. MELBOURNE, 10 DEC 2015 7

Issue can also arise in simplified models ...

N. Bell:
http://indico.cern.ch/event/459037/session/6/contribution/25/attachments/1203369/1752401/LHC_DM_WG_2015_Bell.pdf

Use gauge invariant framework, avoid unphysical enhancement of longitudinal polarizations

SU(2) violating effects can be introduced via mixing, but are suppressed

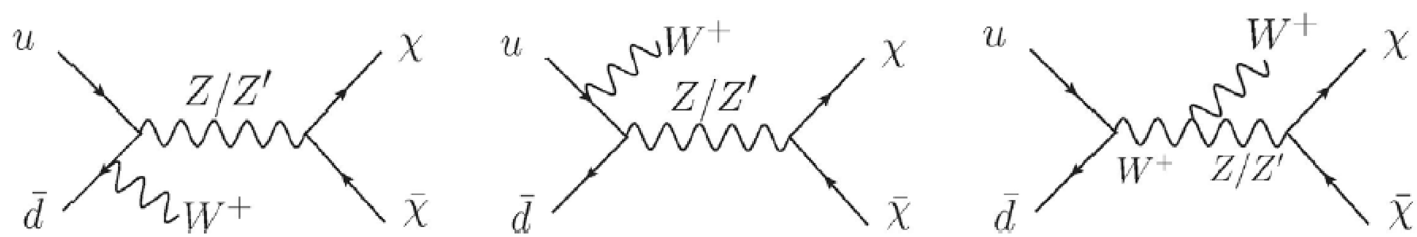
s-channel model

Suppose the Z'-quark couplings arise only due to mixing with the SM Z.

→ Z'-quark couplings proportional to Z-quark couplings

→ opposite sign for (u,d) quarks due to weak isospin assignments $T_3 = \pm\frac{1}{2}$.

- EFT limit is $\frac{1}{\Lambda^2}(\bar{\chi}\gamma^\mu\chi)(\bar{u}\gamma_\mu u + \xi\bar{d}\gamma_\mu d)$ with a negative value of ξ
- But the 3rd diagram is needed to enforce gauge invariance



- High energy W_L production arises only from the 3rd diagram
- Suppressed by the Z-Z' mixing angle, $\sim v_{EW}^2/M_Z'^2$

LHC DARK MATTER WORKING GOUP MEETING N. BELL, U. MELBOURNE, 10 DEC 2015 19

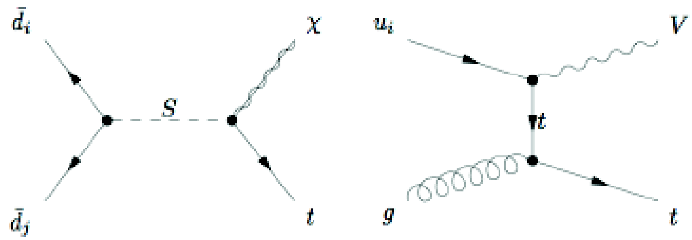
N. Bell:
http://indico.cern.ch/event/459037/session/6/contribution/25/attachments/1203369/1752401/LHC_DM_WG_2015_Bell.pdf

Heavy Flavor: Mono-top

[Andrea, BF, Maltoni (PRD '11)]

✦ Generic monotop production

- Missing energy (dark matter candidate or mediator decaying to dark matter particles)
  - ★ Bosonic or fermonic state
  - ★ One-particle or n-particle state
  - ★ Neutral, weakly-interacting, long-lived/stable/invisible
- Initial state: two possibilities
  - ★ A down-type (anti)quark pair → baryon-number-violating process
  - ★ An up-type quark / gluon associated pair → flavor-changing neutral interactions



Two classes of models

See talk by B. Penning in this workshop for more details on the monotop search

Consistent treatment by ATLAS & CMS of non-resonant monotop

✦ Resonant monotop production

Fits more hardly in the DM context

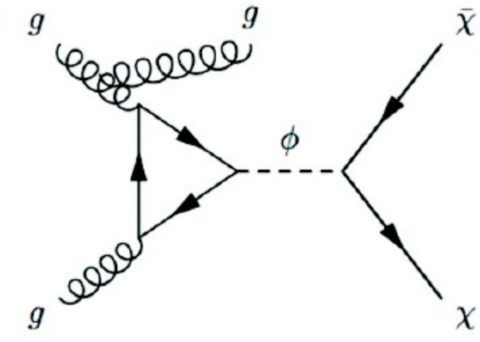
- CMS: SU(3) x U(1) based model
  - ★ Vector (or scalar) resonance with vector (or scalar) couplings
  - ★ The BR of the resonance into a monotop system is 1
  - ★ Several models, simplified ➢ two relevant mass parameters for each model
- ATLAS: SU(3) x SU(2)xU(1) based model
  - ★ Scalar resonance (with a fixed mass) with right-handed couplings taken equal
  - ★ The resonance width must be calculated for each scenario
  - ★ Two parameters
- ATLAS configuration not easy to reinterpret (resonance mass and width issues)

⚠ Discussions needed!

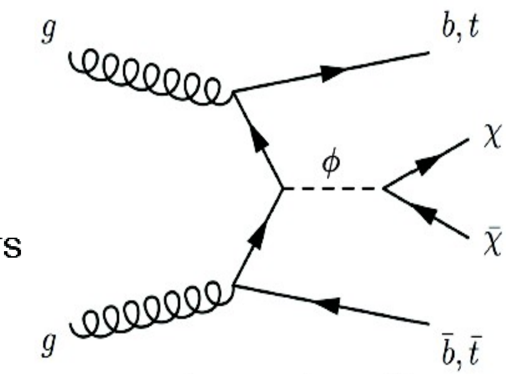
Model differences for resonant case

B. Fuks:
http://indico.cern.ch/event/459037/session/6/contribution/27/attachments/1203355/1752382/fuks_monotops.pdf

Heavy Flavor: tt(bb) + MET



“loop”



“associated”

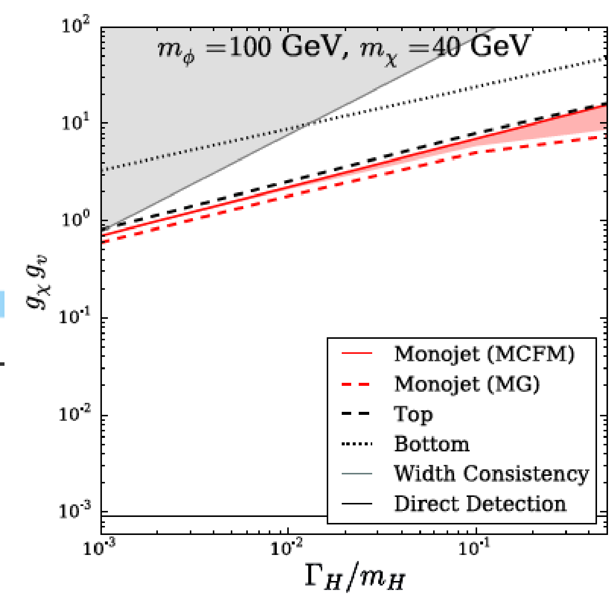
- Dark matter interactions mediated by a (pseudo)scalar

$$\mathcal{L} \supseteq -g_\chi H\bar{\chi}\chi - g_v \frac{y_f}{\sqrt{2}} H\bar{f}f$$

$$\mathcal{L} \supseteq -g_\chi A\bar{\chi}\gamma^5\chi - g_v \frac{y_f}{\sqrt{2}} A\bar{f}\gamma^5 f$$

see also Haisch *et al* 1208.4605, Harris *et al* 1411.0535 and others

- Minimal Flavor Violation: choose SM fermion couplings $\propto m_f$
- “Easy” to imagine this as part of extended Higgs sector
- Couplings to top quark dominate
  - But should keep in mind couplings to *b*-quarks
  - *e.g.* large $\tan\beta$ limit of 2-Higgs Doublet Models



Monojet sensitivity for spin-0 mediators presently better, but top-associated is comparable!

M. Buckley:
http://indico.cern.ch/event/459037/session/6/contribution/28/attachments/1203525/1752720/LPCC_tops_2015.pdf

Combinations

Near/medium term

- Interest in the community for leveraging multiple final states produced from a single DM mediator
- Possible combinations should only consider consistent models, without introducing significant additional assumptions
  - A natural scenario: spin-0 mediated monojet & HF+MET
- Beyond this, no specific recommendations from the WG
  - Allow the experiments to R&D and gather feedback

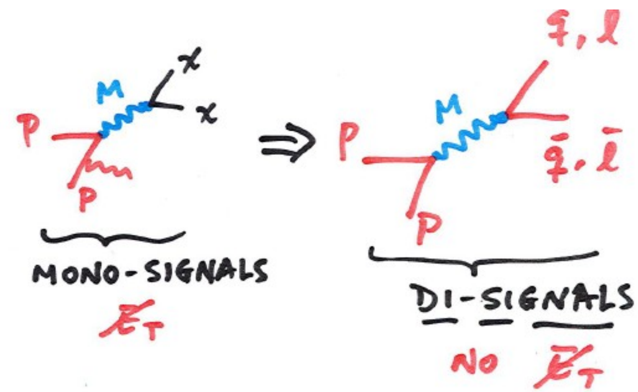
Longer-term

- Combinations between the experiments ...

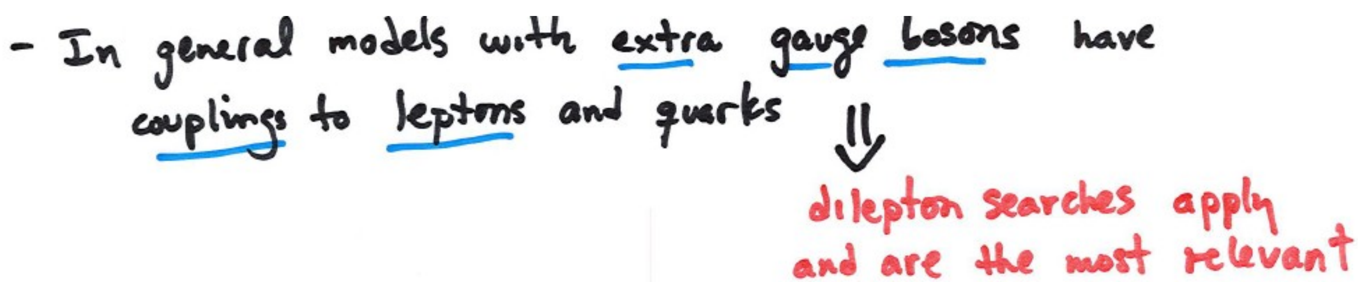
Possible Future Directions

Direct Mediator Searches

Explore interplay between searches for MET+X vs di-objects



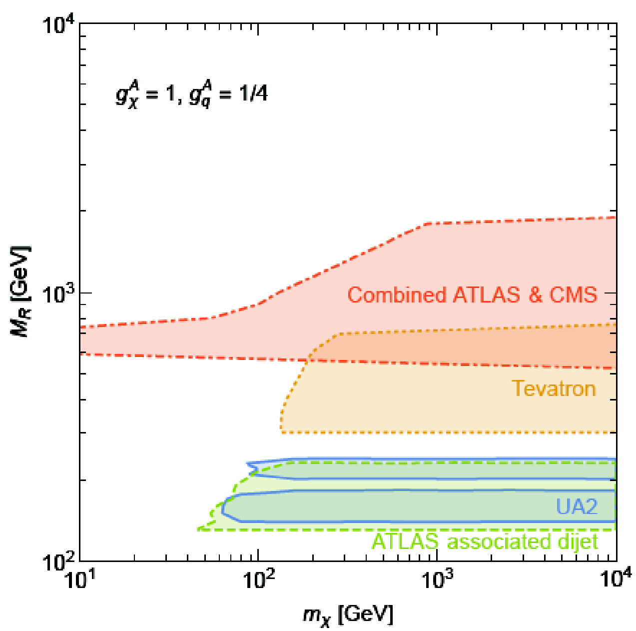
Dileptons



B. Zaldivar:
http://indico.cern.ch/event/459037/session/4/contribution/18/attachments/1203643/1752972/zaldivar_DMWG.pdf

Dijets

M. McCullough:
http://indico.cern.ch/event/459037/session/4/contribution/14/attachments/1203722/1753104/LPCC.pdf



Good coverage from combined collider limits

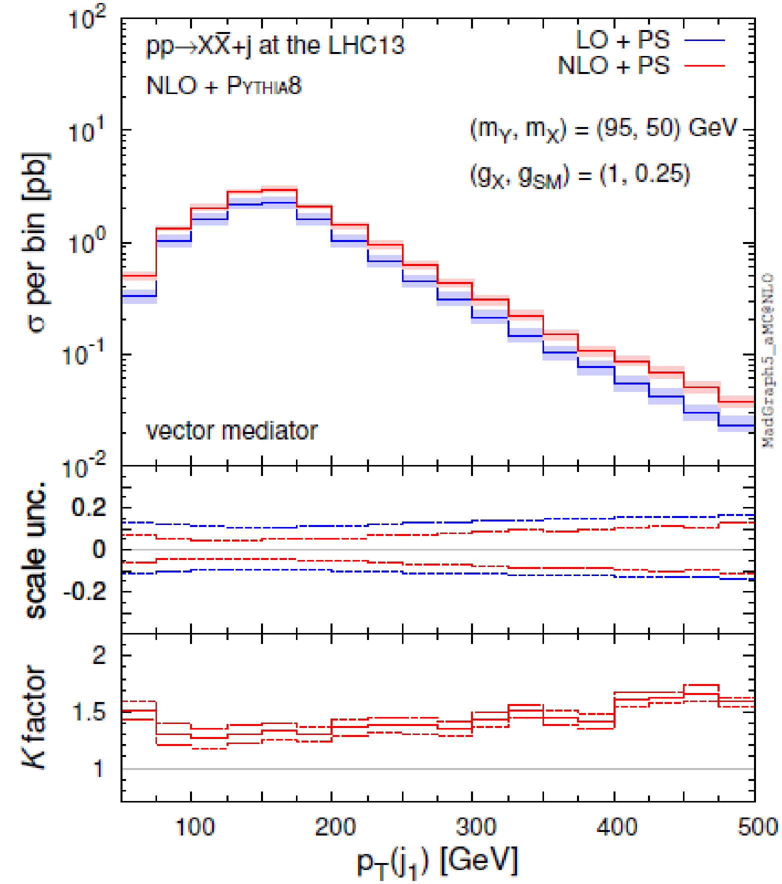
Width effects important!

Combination with MET+X? Practical approach: choose couplings that aren't in tension with dijets

Tools

DM @ higher order

- FeynRules → NLOCT → MGNLO
- Significant kinematic differences
- Big reduction in uncertainties



M. Pellen:
http://indico.cern.ch/event/459037/session/4/contribution/20/attachments/1203073/1751818/PELLEN_CERN_WG_12_2015.pdf

L. Carpenter:
http://indico.cern.ch/event/459037/session/6/contribution/24/attachments/1202876/1751471/DMWG.pdf

Analysis reinterpretation

- MadPAD (public analysis DB)
- Allows theorists to easily recast exp
- ATLAS/CMS monojet,monophoton already implemented/validated

Analysis	Short Description
ATLAS-SUSY-2013-05 (published)	stop/sbottom search: 0 leptons + 2 b-jets
ATLAS-SUSY-2013-11 (published)	EWK-inos, 2 leptons + MET
ATLAS-HIGG-2013-03 (published)	ZH->ll+invisible
ATLAS-EXOT-2014-06 (published)	mono-photons + MET
ATLAS-SUSY-2014-10 (published)	2 leptons + jets + MET
ATLAS-SUSY-2013-21 (published)	0 leptons + mono-jet/c-jets + MET
ATLAS-SUSY-2013-02 (published)	0 leptons + 2-6 jets + MET

Analysis	Short Description
CMS-SUS-13-011 (published)	stop search in the single lepton mode
CMS-SUS-13-012 (published)	gluino/squark search in jet multiplicity and missing energy
CMS-SUS-13-016 (PAS)	search for gluinos using OS dileptons and b-jets
CMS-SUS-14-001 (published)	Searches for third-generation squarks in fully hadronic final states (monojet analysis)
CMS-B2G-12-012 (published)	T5/3 top partners in same-sign dilepton channel

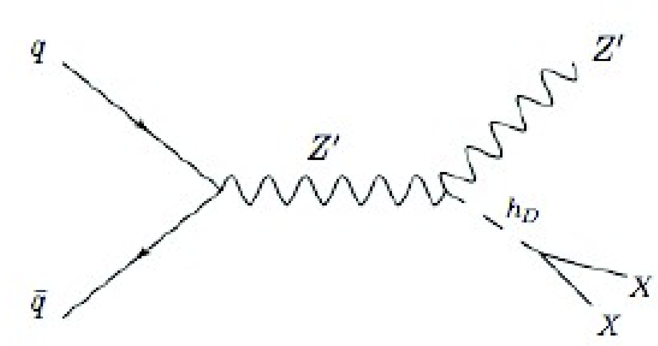
D. Barducci:
http://indico.cern.ch/event/459037/session/4/contribution/19/attachments/1203707/1753293/DMWG_CERN_barducci.pdf

Beyond Mono-X

Explore more novel and complex signatures

- resonances+MET (mono-Z') , di-resonances (+MET), ...

Category (# of models)	New fields	New couplings
Hybrid (7)	DM, X	DM-X-SM_3
s-channel (49)	DM, X, M_s	DM-X-M_s M_s-SM_1-SM_2
t-channel (105)	DM, X, M_t	DM-M_t-SM_1 M_t-X-SM_2



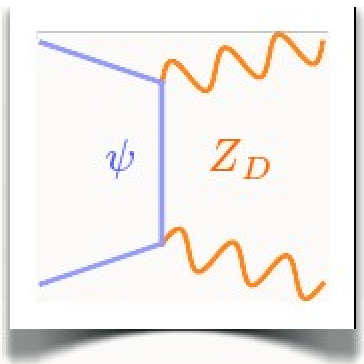
- New final states from a bottom-up framework, utilizing only DM properties (eg: relic)

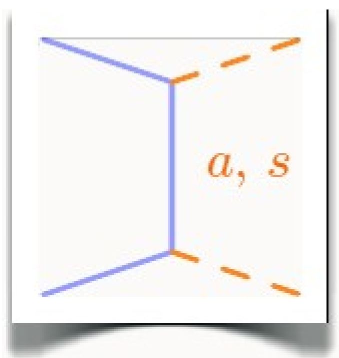
D. Whiteson:
http://indico.cern.ch/event/459037/session/4/contribution/15/attachments/1203636/1752963/lpcc_dm_2015.pdf

F. Yu:
http://indico.cern.ch/event/459037/session/4/contribution/17/attachments/1203749/1753176/FY_Coannihilation.pdf

J. Shelton:
http://indico.cern.ch/event/459037/session/4/contribution/36/attachments/1203642/1753342/151211-LPC_forum.pdf

Dark Sectors





- Dark photon, dark Higgs ...
- Search for direct mediator production
- Possibly soft, displaced, low-mass final states

Summary

The LHCDMWG will guide the development and interpretation of broad DM searches at the LHC

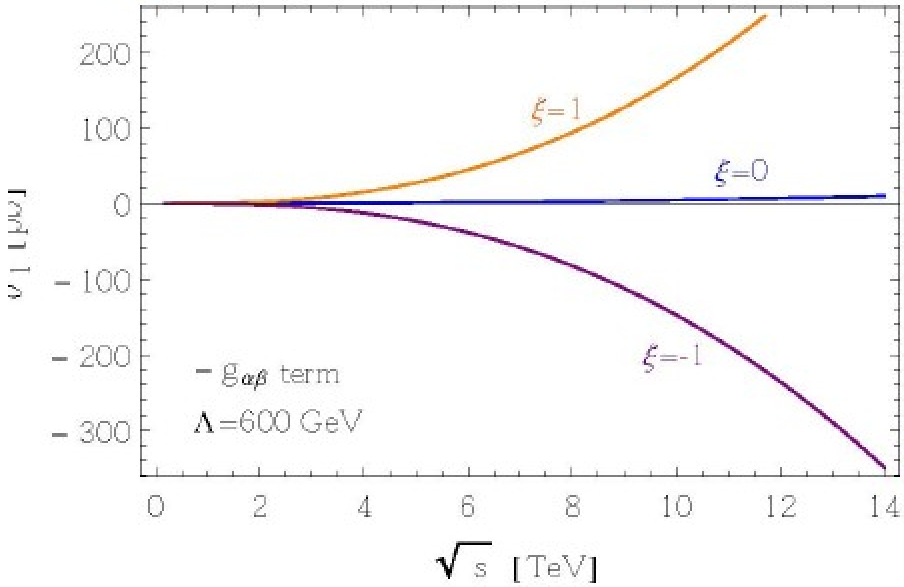
- Building on the enthusiasm of the community, and the success of the recent DMF

Finalizing recommendations for the presentation of Run-2 results for Winter 2016 conferences

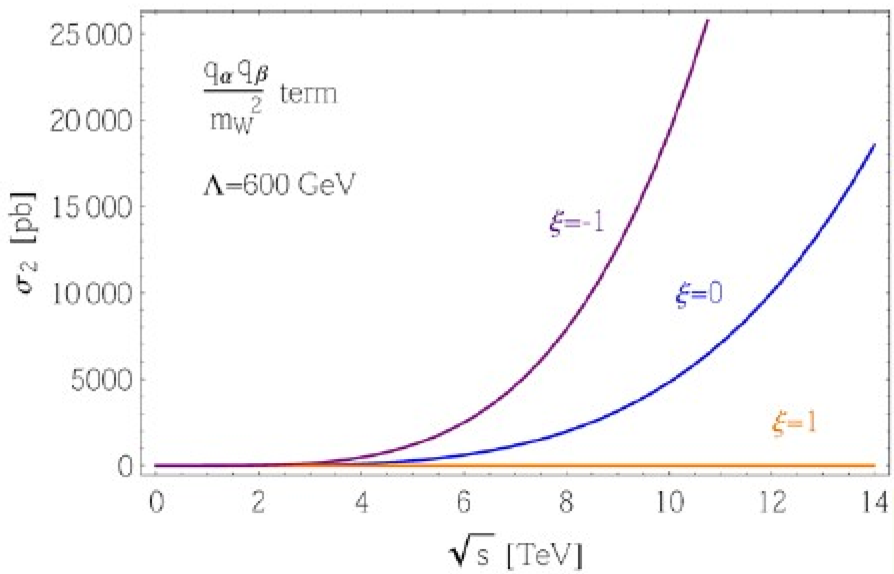
On the horizon: moving beyond single-channel, MET+X searches

Backup

Total parton-level cross sections versus energy, for Λ= 600 GeV.
(Notice the differing vertical scales between the two panels.)



Contribution from the $-g_{\alpha\beta}$ term in the W polarization sum ($\approx W_T$ contribution).



Contribution from the $\frac{q_\alpha q_\beta}{m_w^2}$ term ($\approx W_L$ contribution).

This term dominates at LHC energies (unless $\xi \simeq 1$).

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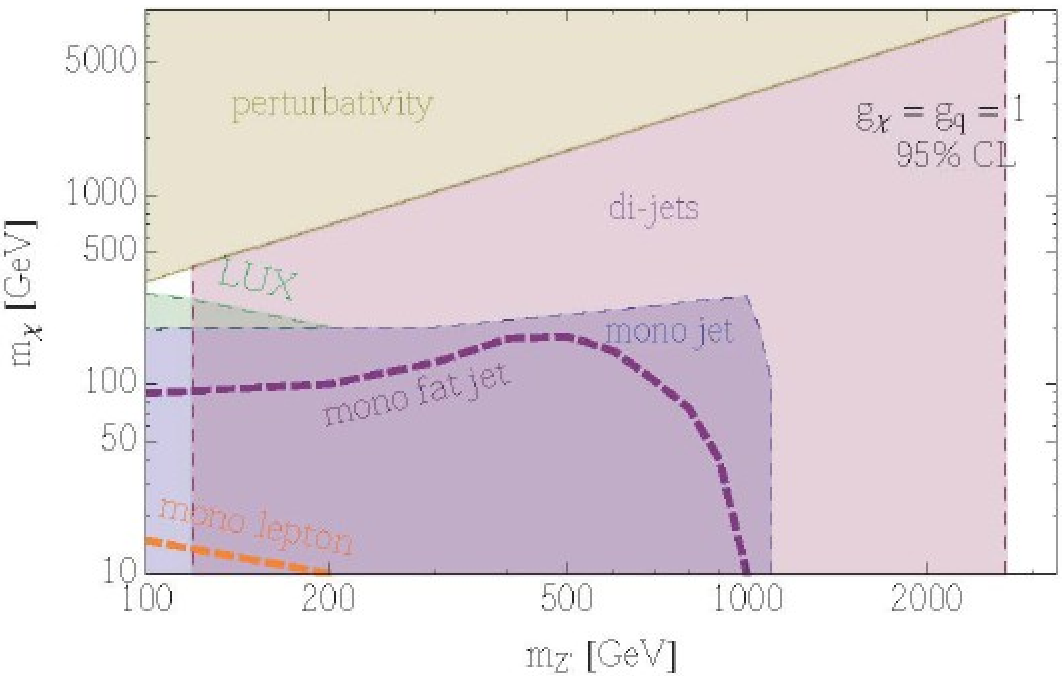
Bell, Cai, Dent, Leane & Weiler, arXiv:1503.07874

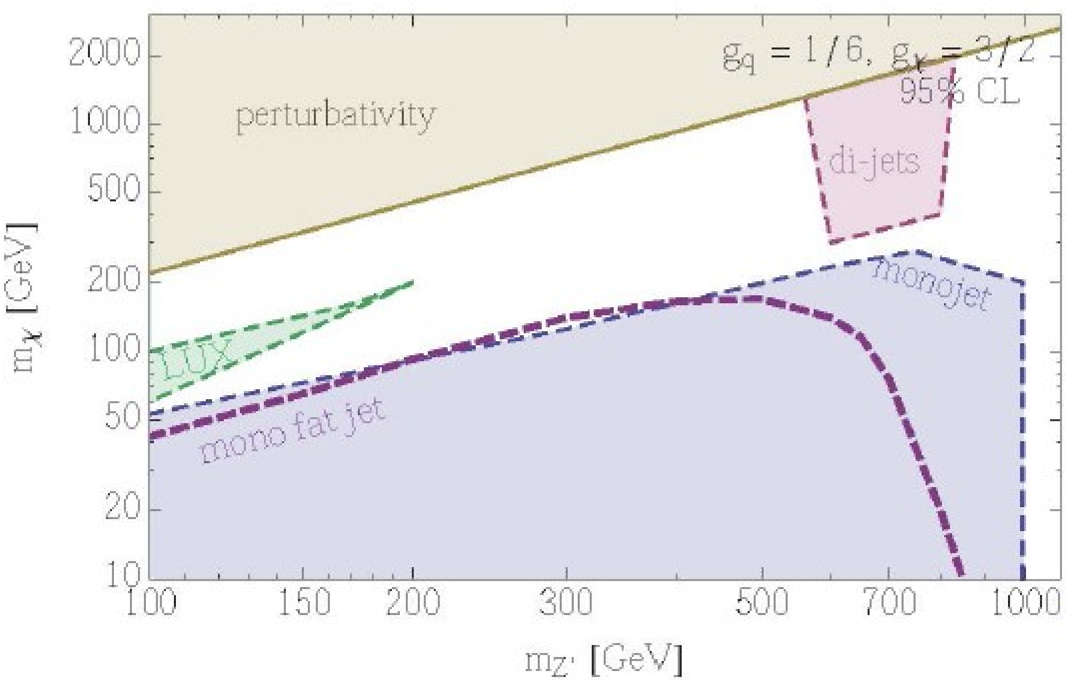
Goldstone boson equivalence theorem & Ward identity

At high energy, Goldstone boson equivalence theorem says:

- We can replace W_L with the corresponding Goldstone boson.
  - Since the Goldstone boson couples to quarks with strength proportional to their mass, these terms are close to zero.
    - We should not get W_L production.

For $\xi \neq 1$, the relevant Ward identity is broken.
→ Missing diagrams?
→ Diagrams where W radiated from the mediator!





s-channel model

"Mono fat jet" = hadronic mono-W/Z estimate, at 14 TeV, 3000fb^{-1}.

Compared with 8 TeV mono-jet and di-jet limits from arXiv:1503.05916 (M.Chala et al.)

→ It will be challenging to see a mono-W signal in this model.

Bell, Cai & Leane, arXiv:1512.00476

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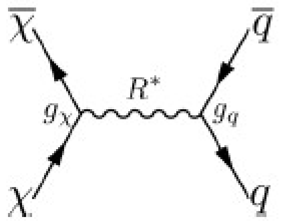
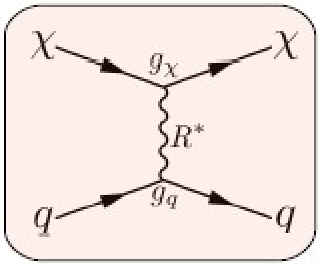
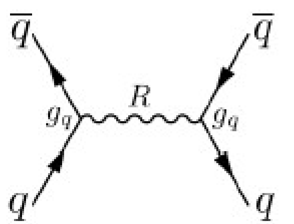
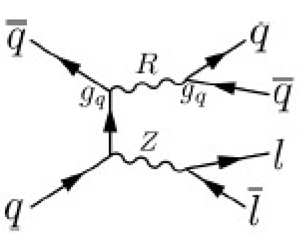
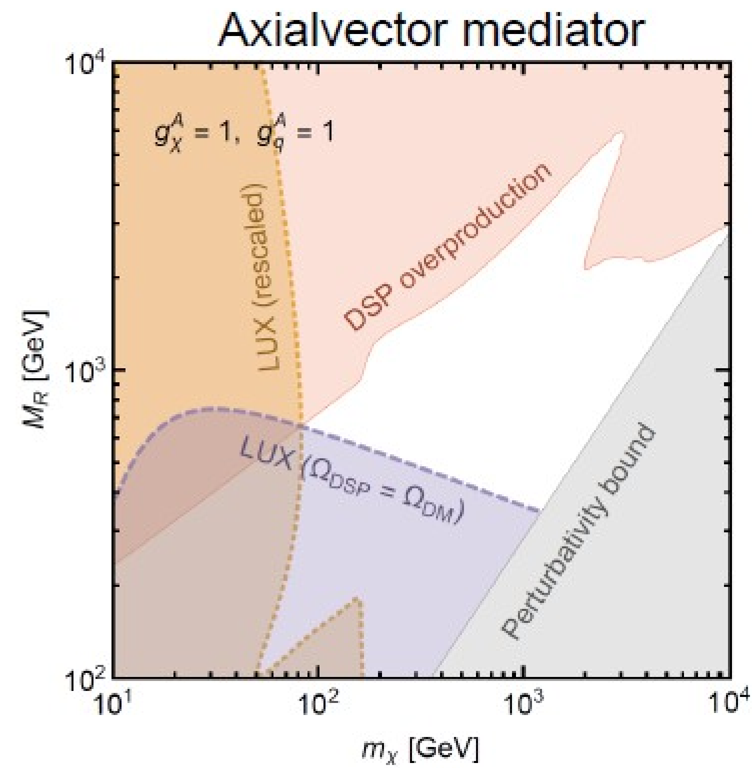
Direct detection







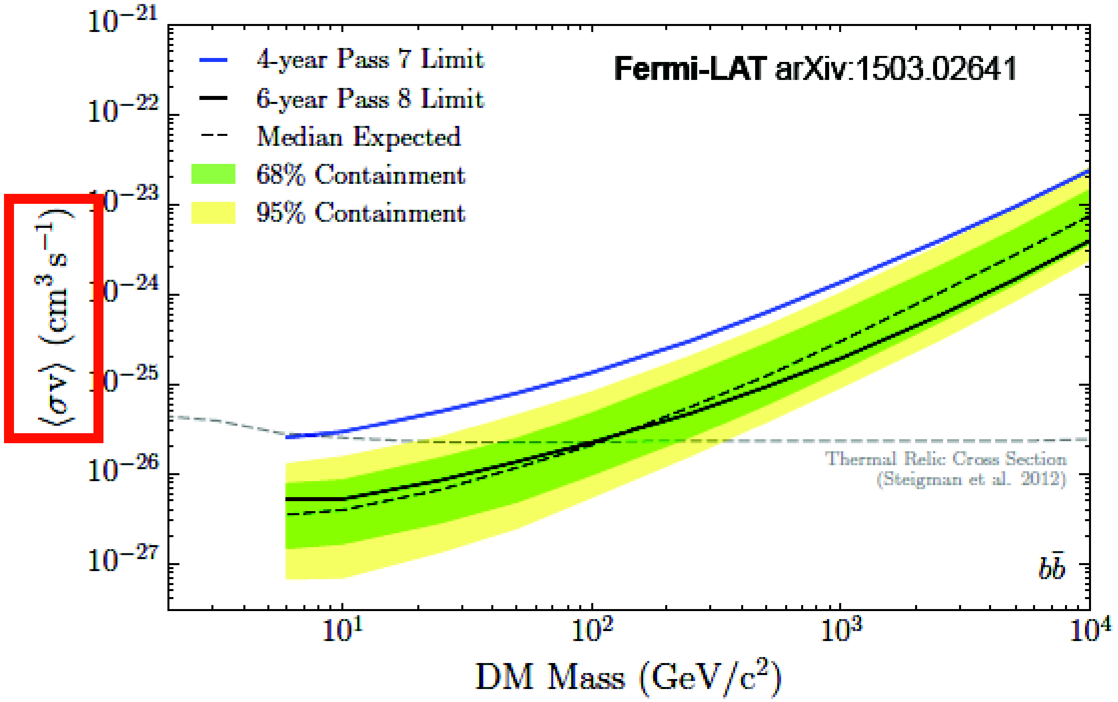




- To show direct detection bounds, two important assumptions are necessary:
  - Relative sign between up-quark coupling and down-quark coupling.
  - Rescaling of direct detection bounds for DM sub-components.

Indirect plane: what does it show?

- Constrains the 2->2 annihilation cross-section



- Limit assumes DM is Majorana fermion (differs by 2 for Dirac)
- Final state is a single channel eg $\bar{b}b$
- DM saturates relic abundance

Vector

$$\mathcal{L}_{\text{vector}} \supset -\sum_q g_q Z'_\mu \bar{q}\gamma^\mu q - g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \chi$$

- The nucleon cross-section is $\sigma^0 = \frac{f^2(g_{\text{SM}}) g_{\text{DM}}^2}{\pi} \frac{\mu_{n\chi}^2}{M_{\text{med}}^4}$

- Protons: $f_p = 2g_u + g_d$, Neutrons: $f_n = g_u + 2g_d$

Proton & neutron couplings equal since we choose g_q equal for all quarks

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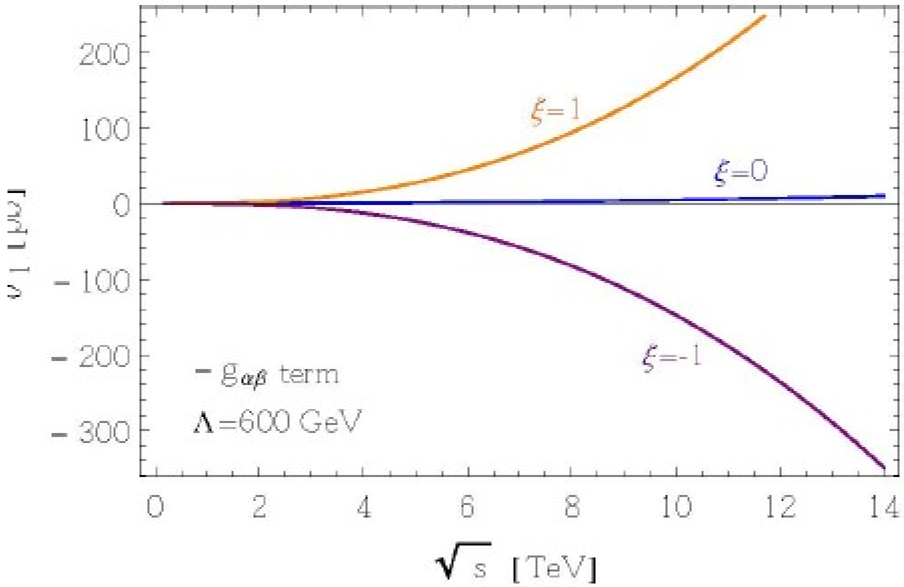

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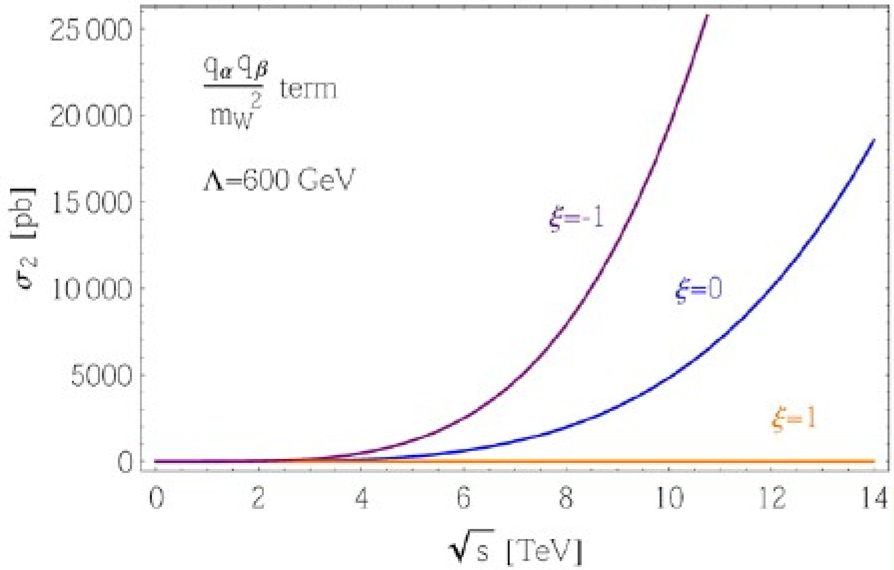

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Proton & neutron couplings equal since we choose g_q equal for all quarks

Scalar

$$\mathcal{L}_{\rm scalar} \supset -g_{\rm DM}\phi\bar{\chi}\chi - \sum_q g_{\rm SM}\frac{m_q}{v}\phi\bar{q}q$$

- The nucleon cross-section is $\sigma^0 = \frac{f^2(g_{\rm SM})g_{\rm DM}^2}{\pi}\frac{\mu_{n\chi}^2}{M_{\rm med}^4}$
- In general: $f^{n,p} = \frac{g_{\rm SM} m_n}{v}\left[\sum_{q=u,d,s} f_q^{n,p} + \frac{2}{27} f_{\rm TG}^{n,p}\sum_{Q=c,b,t} 1\right]$

arXiv: 1506.04142

$$f_u^p = (20.8 \pm 1.5)\times 10^{-3}, \qquad f_d^p = (41.1 \pm 2.8)\times 10^{-3}$$

$$f_u^n = (18.9 \pm 1.4)\times 10^{-3}, \qquad f_d^n = (45.1 \pm 2.7)\times 10^{-3}$$

arXiv: 1301.1114

$$f_s = 0.043 \pm 0.011$$

$$f_{\rm TG}^n = 1 - \sum_{q=u,d,s} f_q^n$$

$$f_{\rm proton}/f_{\rm neutron} = 0.996$$

Axial

$$\mathcal{L}_{\text{axial}} \supset -\sum_q g_q Z'_\mu \bar{q}\gamma^\mu\gamma^5 q - g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu\gamma^5\chi$$

- The nucleon cross-section is $\sigma^0_{\text{SD}} = \dfrac{3f^2\mu^2_{n\chi}}{\pi}$
  - Protons: $f_p = 3\sum_{q=u,d,s} g_q\,\Delta^p_q$
  - Neutrons: $f_n = 3\sum_{q=u,d,s} g_q\,\Delta^n_q$

PDG values (axion review)

$\Delta^p_u = \Delta^n_d \approx 0.84$

$\Delta^p_d = \Delta^n_u \approx -0.43$

$\Delta^p_s \approx \Delta^n_s \approx -0.09$

Choices:

Relative signs of g_q?

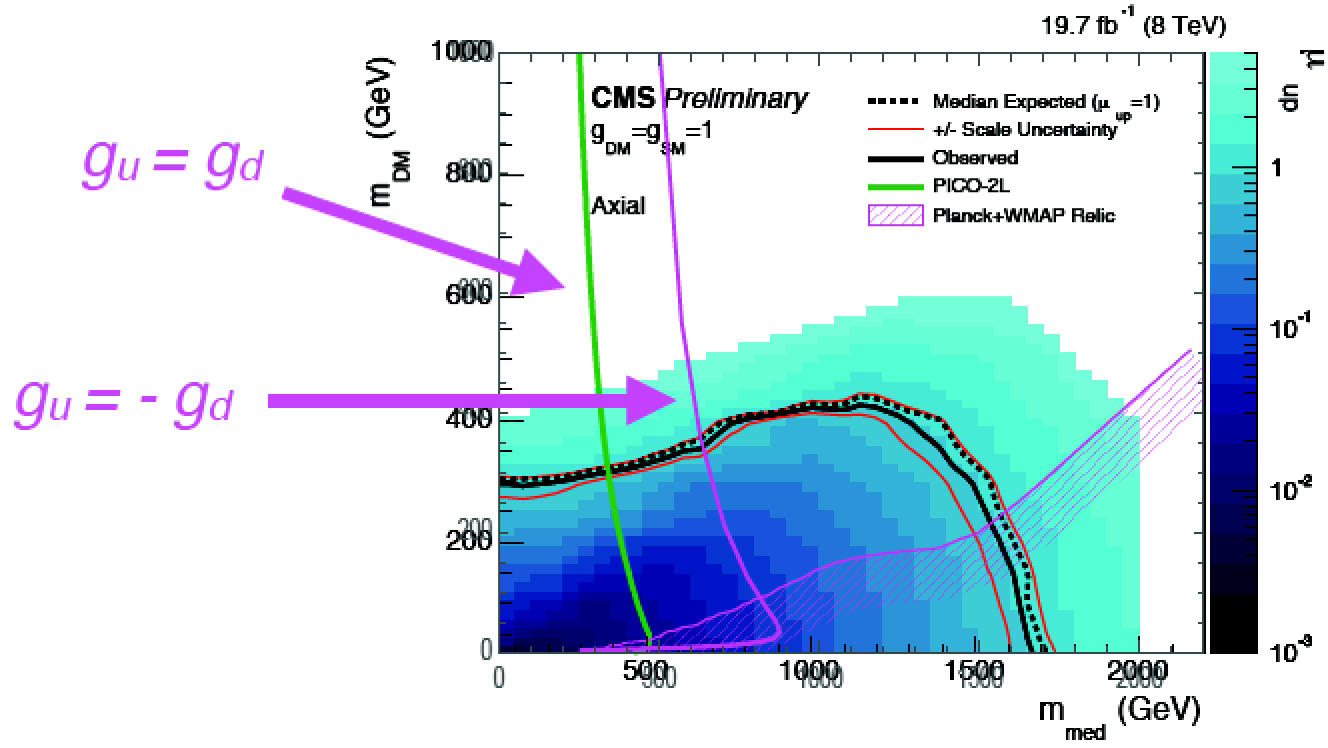
Proton or neutron only limit (PICO or LUX/XENON)?

Axial: sign of g_q

$$\mathcal{L}_{\text{axial}} \supset -\sum_q g_q Z'_\mu \bar{q}\gamma^\mu\gamma^5 q - g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu\gamma^5\chi$$

DM forum recommendation $g_u = g_d$

SU(2) gauge invariance prefers $g_u = - g_d$ see Kahlhoefer et al, arXiv:1510.02110



$g_u = - g_d$ enhances the direct detection limit

Indirect plane: what does it show?

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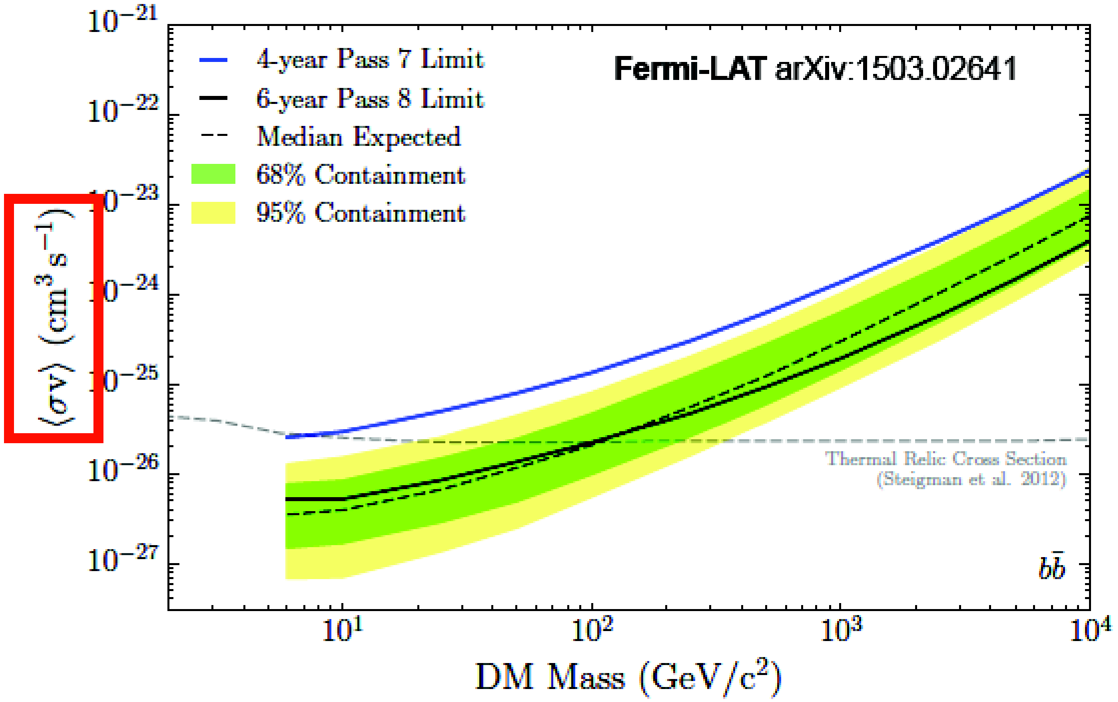

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Thanks to those who contributed to the preliminary discussions

- In particular, Felix Kahlhoefer and Chris McCabe
- ATLAS: Priscilla Pani, Marie-Helene Genest
- CMS: Sarah Malik, Steve Mrenna, Phil Harris
- Theory: Liantao Wang, Tim Tait, Valya Khoze, Matt McCullough, Toni Riotto, Francesco D'Eramo, Kathryn Zurek

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