Simplified models for the DM production at the LHC in Run-2

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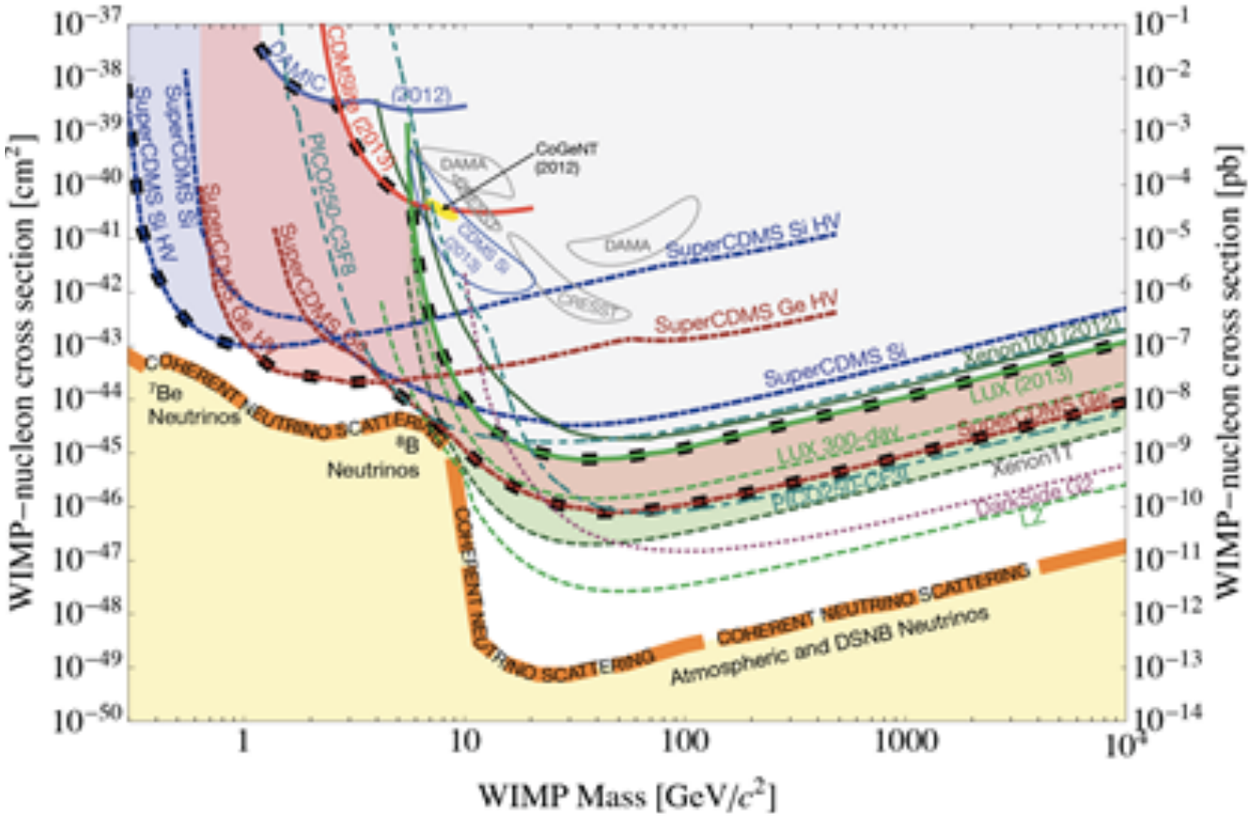
based on the discussions during the DM@LHC Workshop in Oxford:

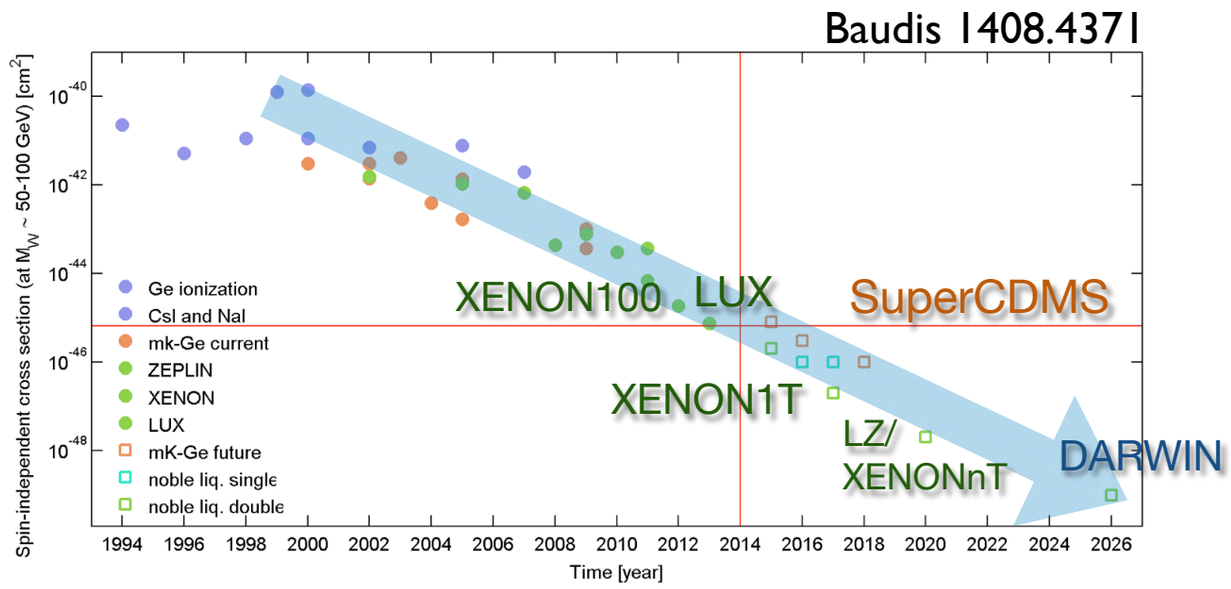
http://indico.cern.ch/event/312657/overview

workshop summary by Tim Tait:

http://indico.cern.ch/event/312657/session/4/contribution/31/material/slides/0.pdf

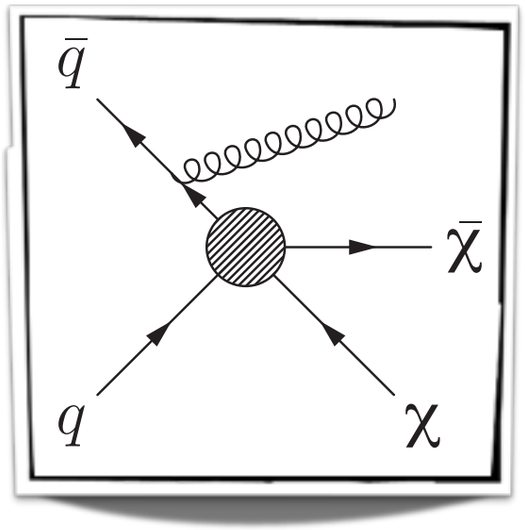
Direct detection



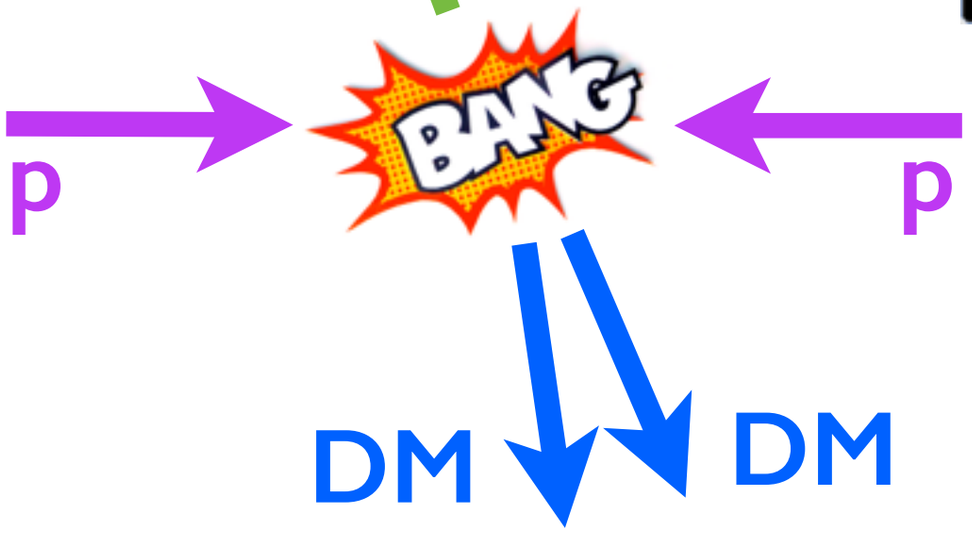


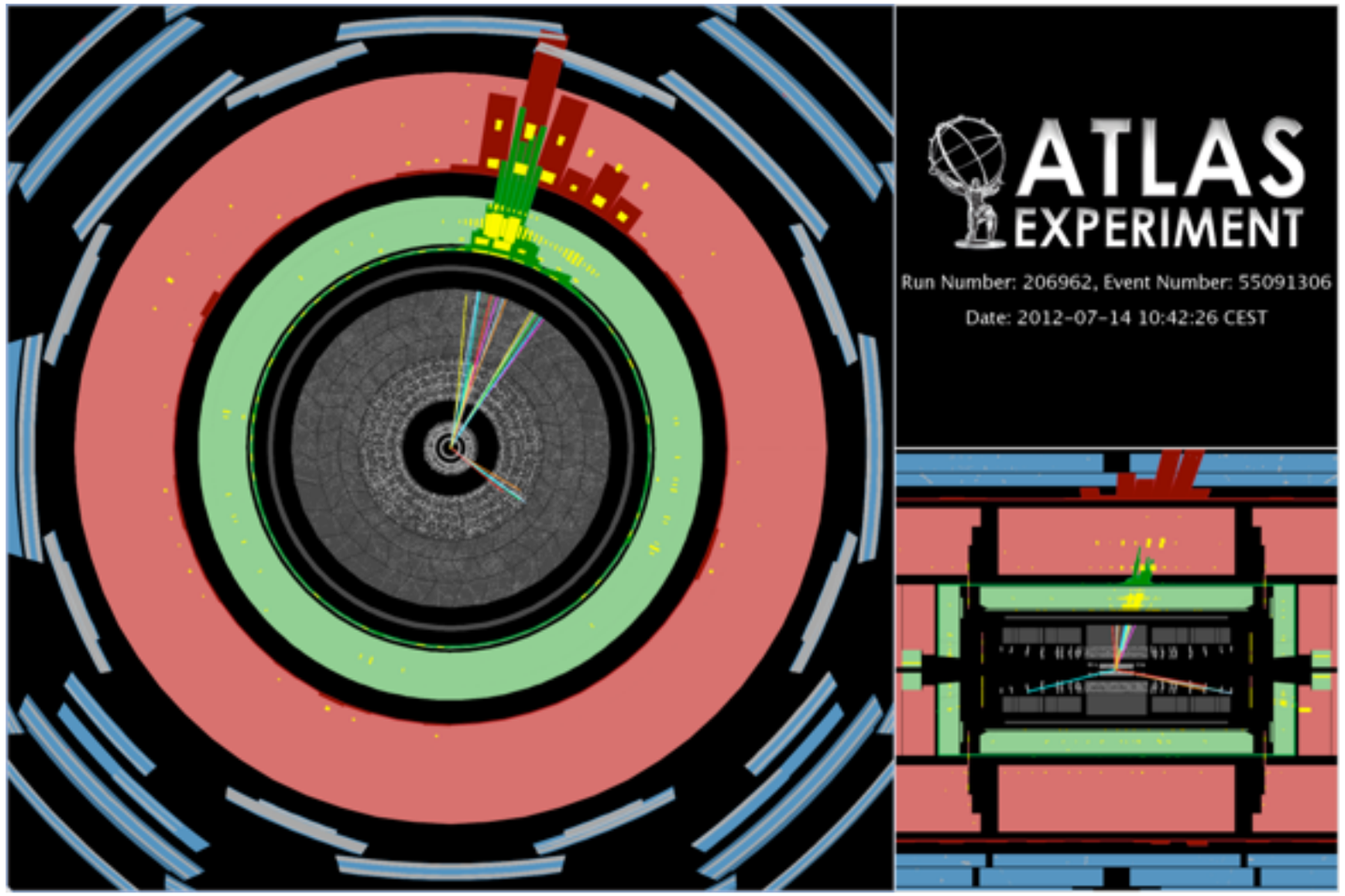
- Neutrino floor is getting near.
  - Measurement of the direction is needed in order to overcome this background (experimentally challenging).
- The message for Dark Matter requires interpretation of the experimental data.
- Be aware of uncertainties and assumptions such as velocity distribution and nuclear form factors.

DM production at the LHC



jet, γ, W, Z, ...





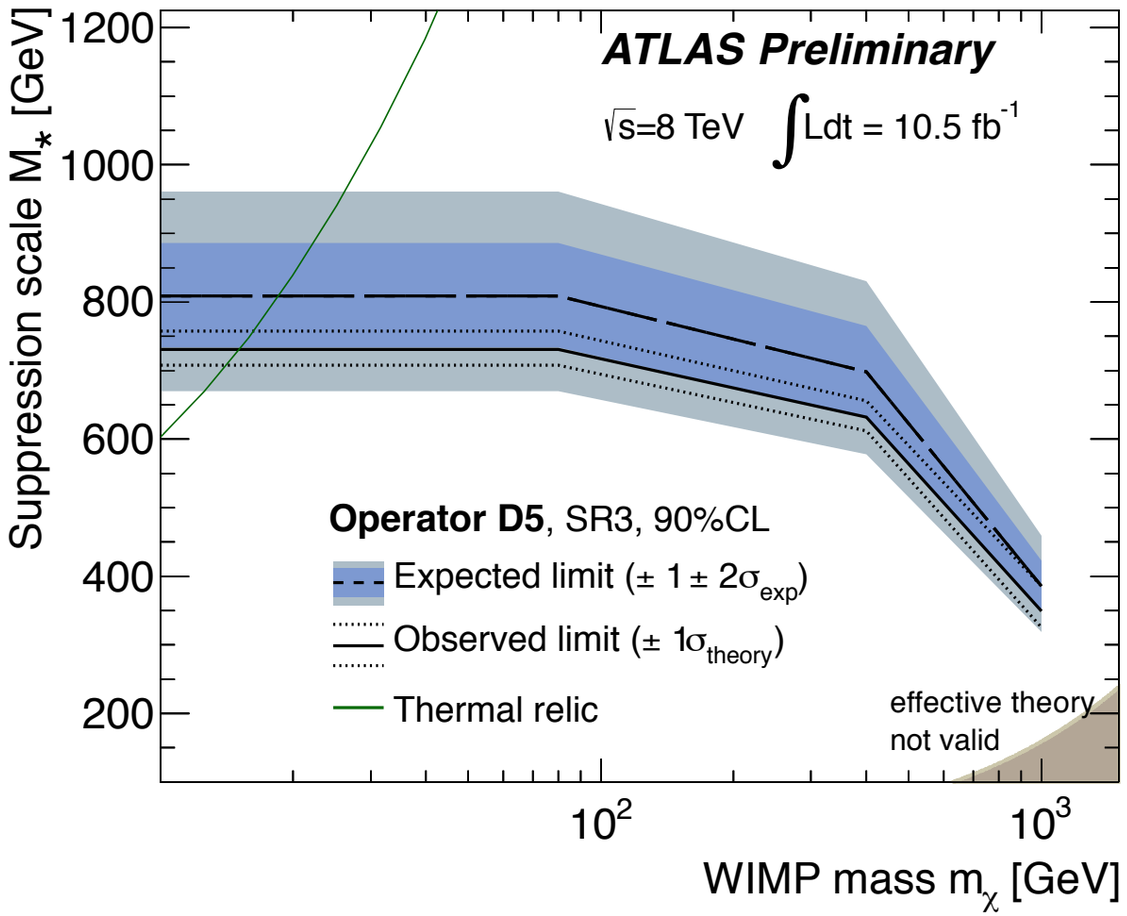
mono-jet event from 7 TeV data

JHEP 1304 (2013) 075

mono-jet

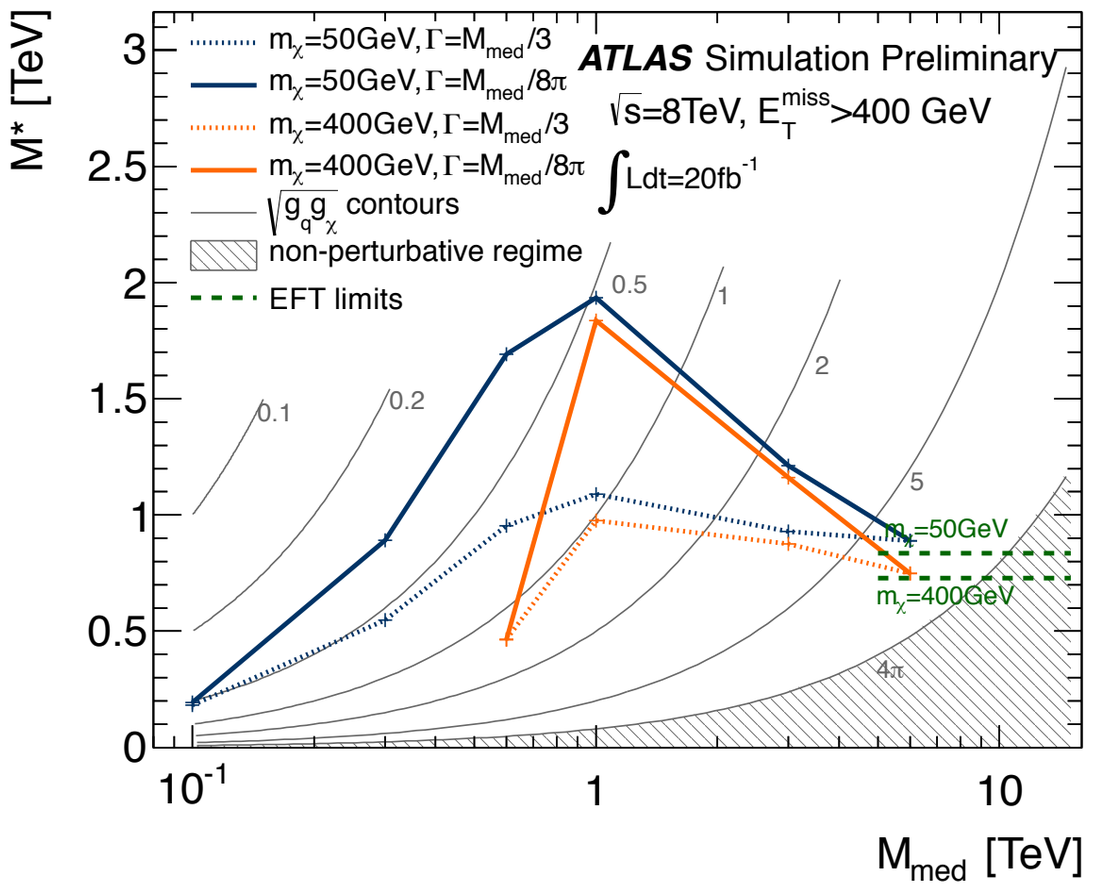
ATLAS-CONF-2012-147

- Limits on the suppression scale of the EFT operators are set assuming full EFT validity.



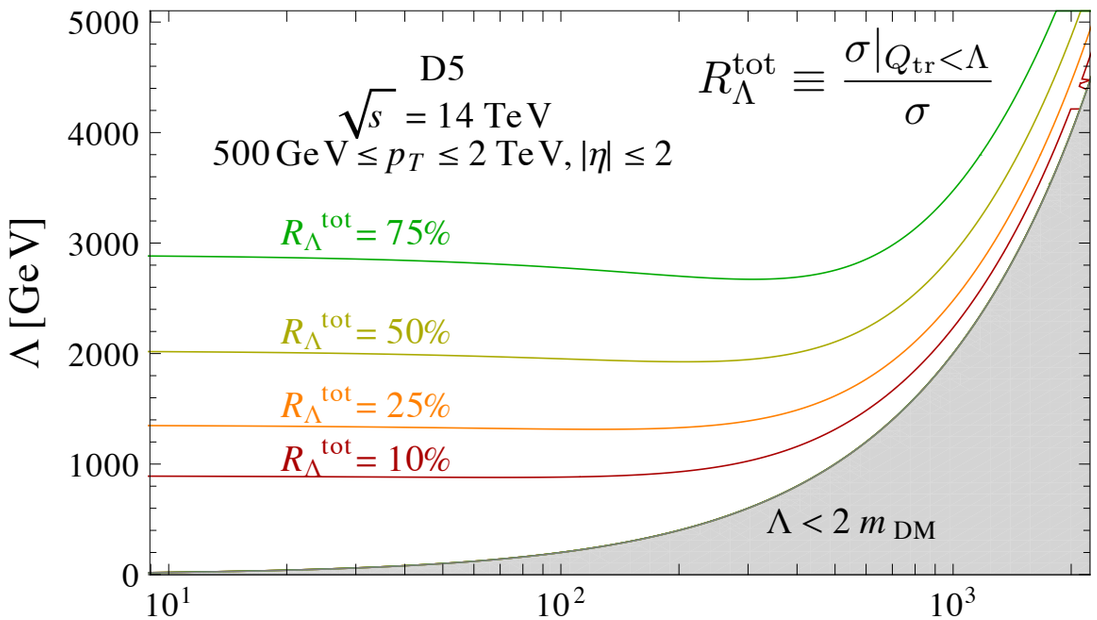
ATL-PHYS-PUB-2014-007

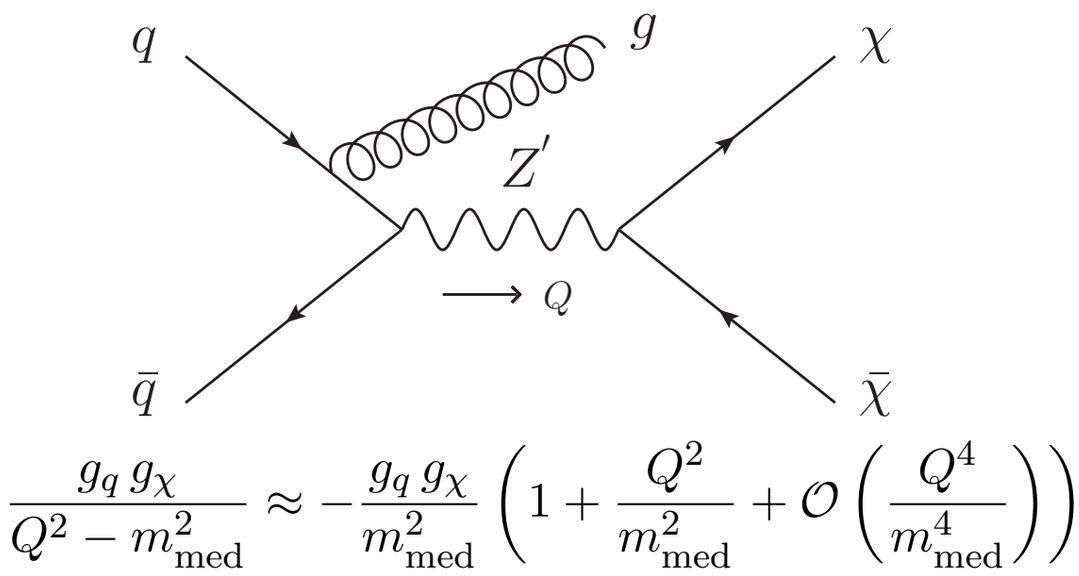
- Simplified models with Z'-like mediators reveal that
  - EFT limits are conservative in the resonant region.
  - EFT limits are not valid for light mediators.



EFT vs. simplified models

- fraction of valid events at the LHC energies:

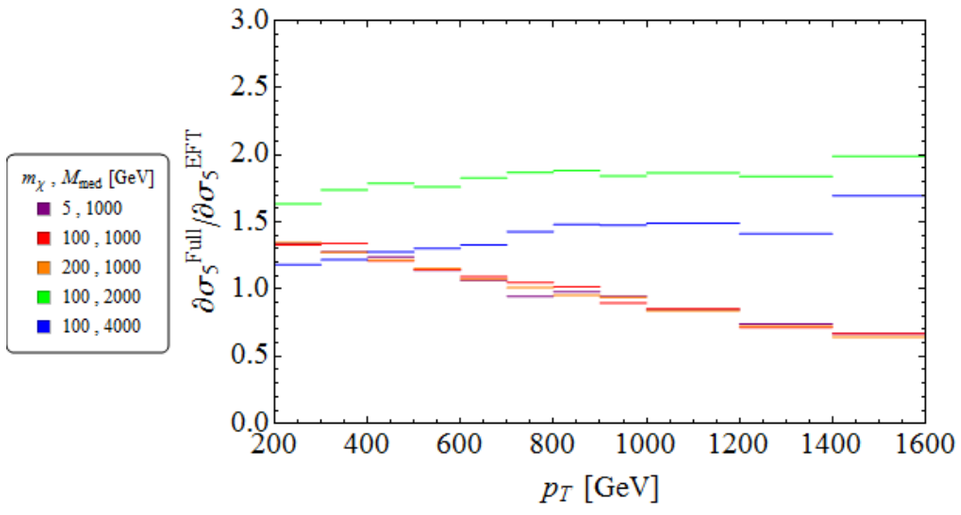


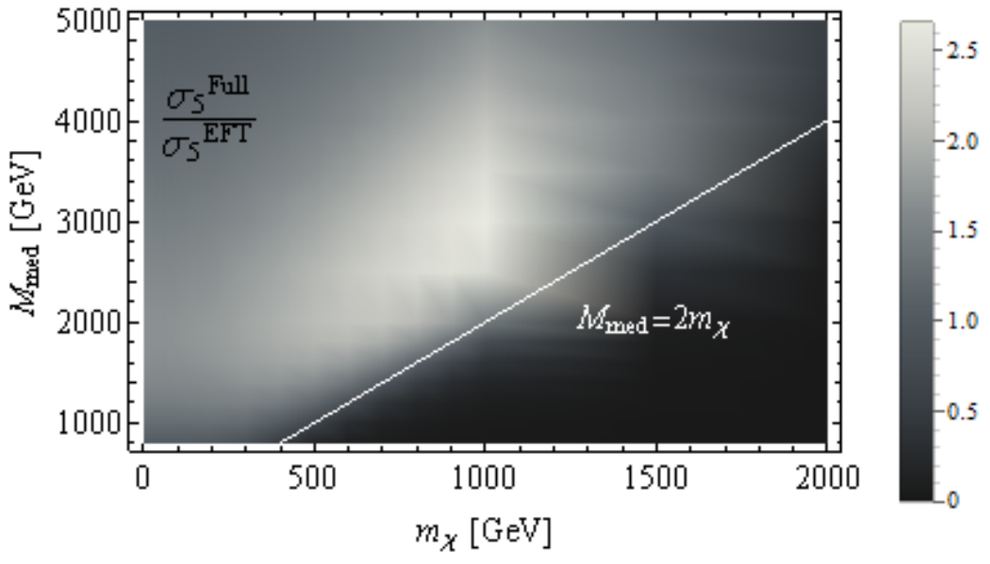


$$\frac{g_q\, g_\chi}{Q^2 - m_{\rm med}^2} \approx -\frac{g_q\, g_\chi}{m_{\rm med}^2}\left(1 + \frac{Q^2}{m_{\rm med}^2} + \mathcal{O}\left(\frac{Q^4}{m_{\rm med}^4}\right)\right)$$

- differences between EFT and simplified models:

$$\left(\frac{\mathrm{d}^2\hat{\sigma}}{\mathrm{d}\eta \mathrm{d}p_{\rm T}}\right)_{\rm full} \Big/ \left(\frac{\mathrm{d}^2\hat{\sigma}}{\mathrm{d}\eta \mathrm{d}p_{\rm T}}\right)_{\rm EFT} = \frac{M_{\rm med}^4}{\left(Q_{\rm tr}^2 - M_{\rm med}^2\right)^2 + \Gamma^2 M_{\rm med}^2}$$





EFT validity

- Minimum requirement for EFT being a valid approximation of UV-complete models is $Q_{tr} < M_{med} = \sqrt{g_q\, g_\chi}\ M^*$.
- Not all events generated in EFT are valid at the LHC energies.
- As a consequence, the M* limits decrease.
- For D5, the EFT approach is fully valid for $\sqrt{g_q\, g_\chi} \gtrsim \pi$.

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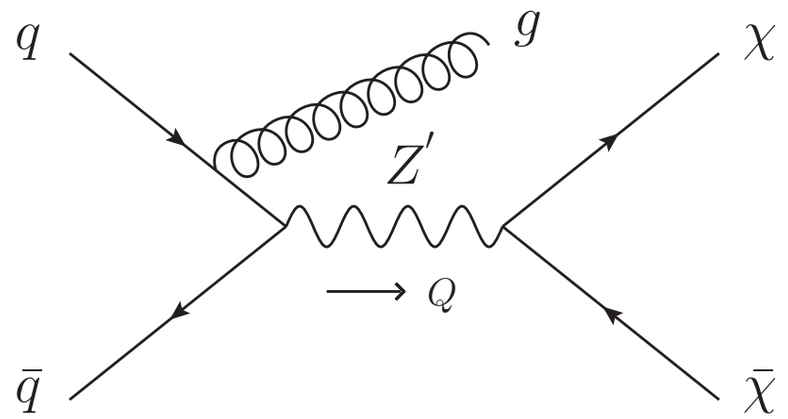
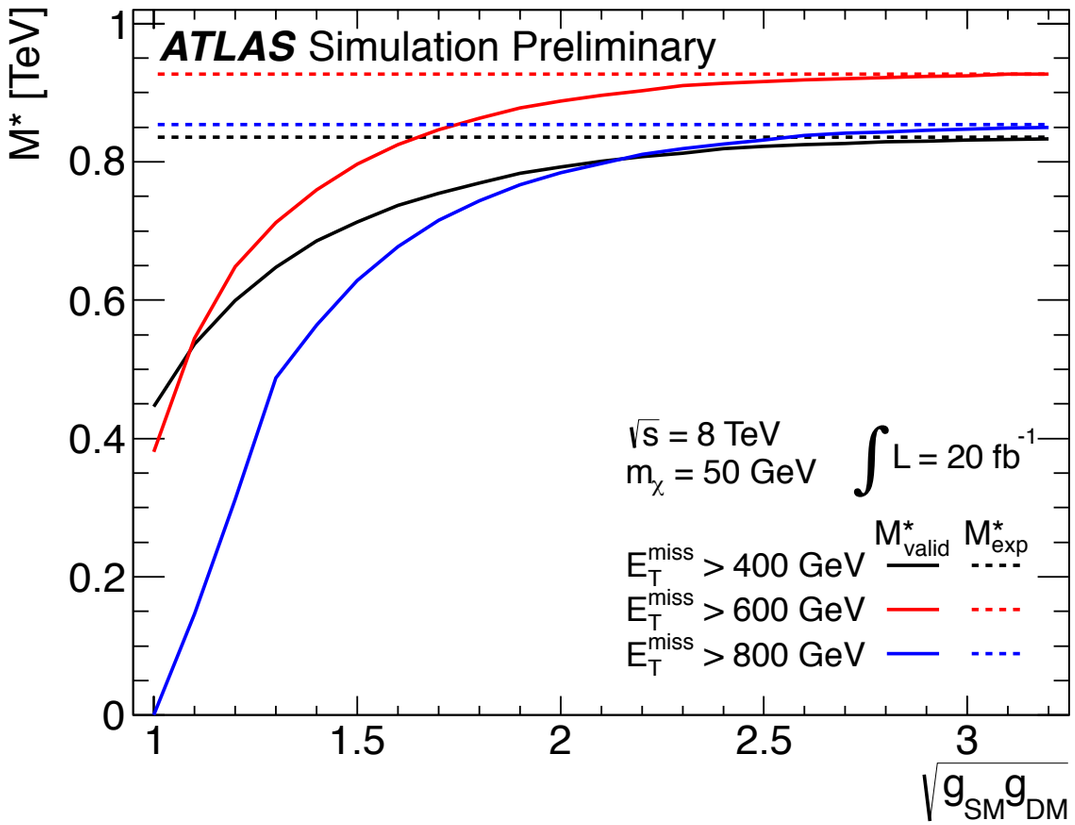
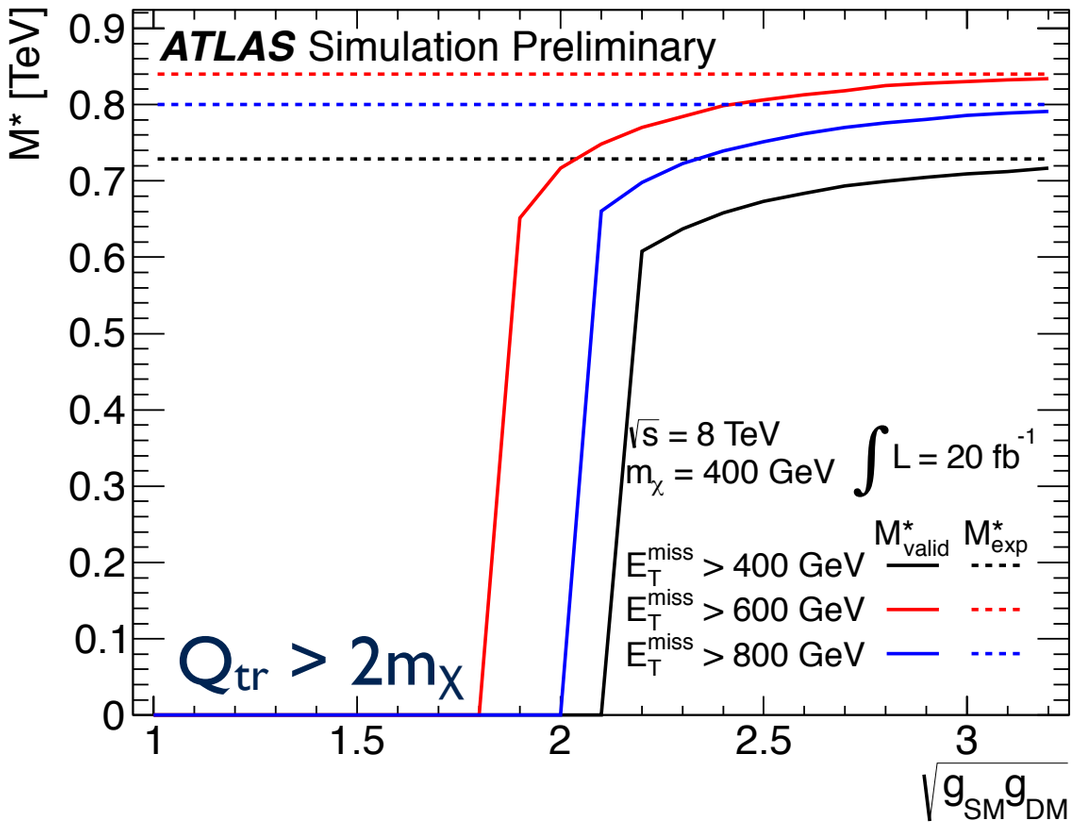


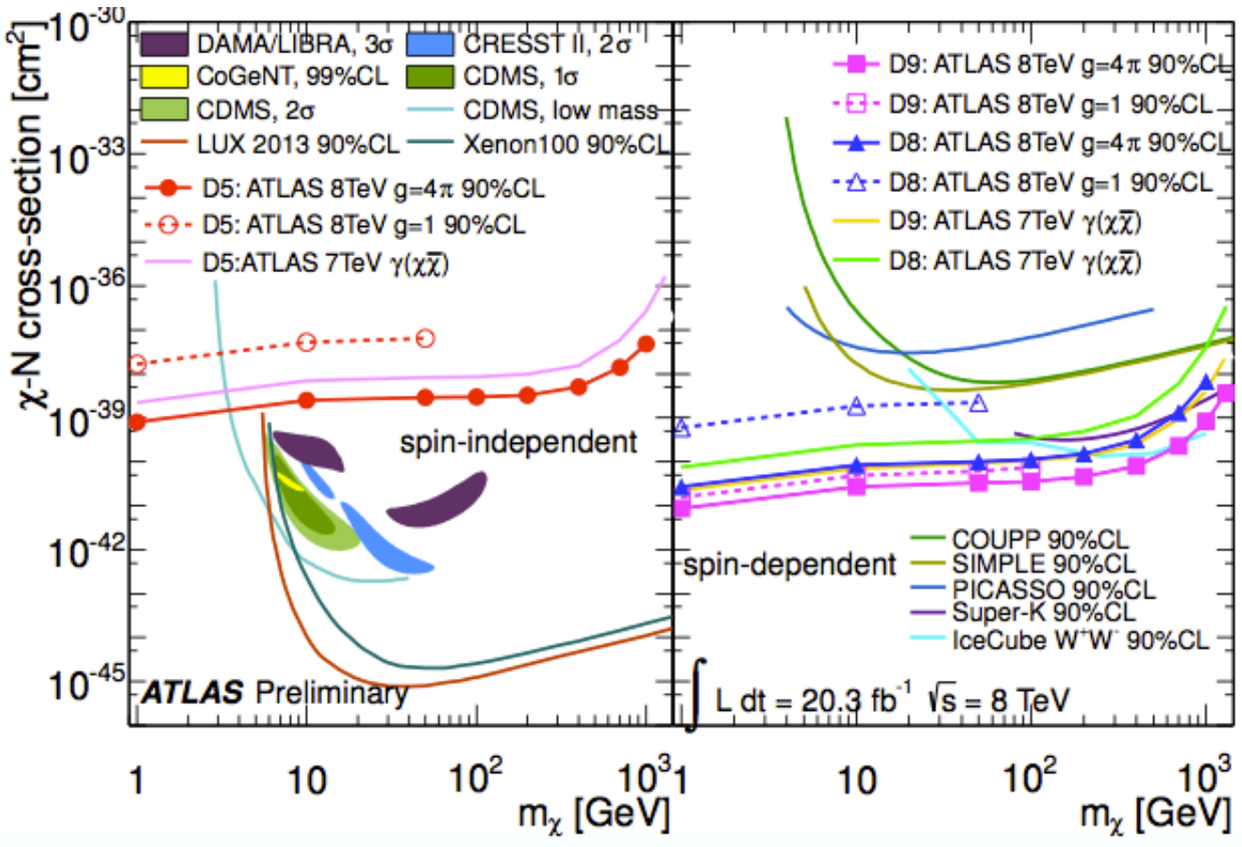
$$\frac{g_q\, g_\chi}{Q^2 - m^2_{\mathrm{med}}} \approx -\frac{g_q\, g_\chi}{m^2_{\mathrm{med}}}\left(1 + \frac{Q^2}{m^2_{\mathrm{med}}} + \mathcal{O}\left(\frac{Q^4}{m^4_{\mathrm{med}}}\right)\right)$$



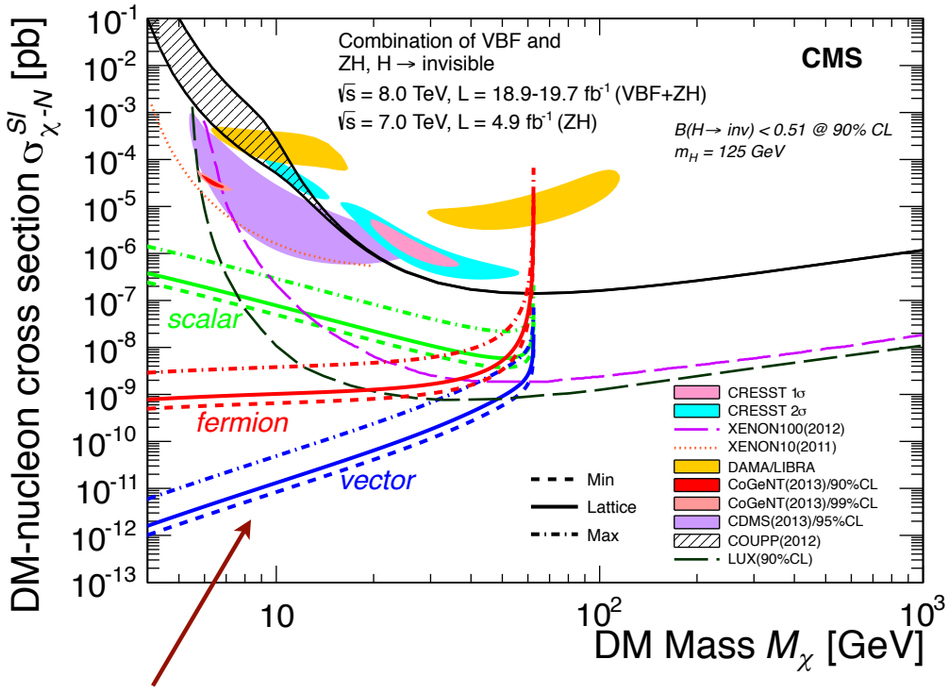


LHC

mono-photon analysis
ATLAS-CONF-2014-51



CMS VBF+ZH combination
Eur. Phys. J. C 74 (2014) 2980



Competitive with direct searches at low mass...

EFT for fermion and vector DM have received criticism... see eg arXiv:1405.3530

- LHC keeps providing new results from Run-1.
- The ways of the result interpretations improve and reflect the recent advancements (and criticism) on the theory side.
- Plans for the DM interpretations of Run-2 results?

Two recent white papers

- Simplified Models for Dark Matter and Missing Energy Searches at the LHC
  http://arxiv.org/abs/1409.2893
  http://indico.cern.ch/event/312657/session/4/contribution/52/material/slides/1.pdf

Simplified Models for Dark Matter and Missing Energy Searches at the LHC

Jalal Abdallah,[1] Adi Ashkenazi,[2] Antonio Boveia,[3] Giorgio Busoni,[4] Andrea De Simone,[4] Caterina Doglioni,[5] Aielet Efrati,[6] Erez Etzion,[2] Johanna Gramling,[5] Thomas Jacques,[5] Tongyan Lin,[7] Enrico Morgante,[5] Michele Papucci,[8,9] Bjoern Penning,[3,10] Antonio Walter Riotto,[5] Thomas Rizzo,[11] David Salek,[12] Steven Schramm,[13] Oren Slone,[2] Yotam Soreq,[6] Alessandro Vichi,[8,9] Tomer Volansky,[2] Itay Yavin,[14,15] Ning Zhou,[16] and Kathryn Zurek[8,9]

- Interplay and Characterization of Dark Matter Searches at Colliders and in Direct Detection Experiments
  http://arxiv.org/abs/1409.4075
  http://indico.cern.ch/event/312657/session/4/contribution/18/material/slides/0.pdf

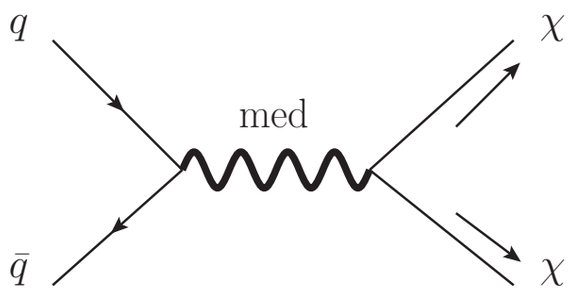
Interplay and Characterization of Dark Matter Searches at Colliders and in Direct Detection Experiments

Sarah A. Malik,[a] Christopher McCabe,[b,c] Henrique Araujo,[a] Alexander Belyaev,[d,e] Céline Bœhm,[b] Jim Brooke,[f] Oliver Buchmueller,[a] Gavin Davies,[a] Albert De Roeck,[g,h] Kees de Vries,[a] Matthew J. Dolan,[i] John Ellis,[g,j] Malcolm Fairbairn,[j] Henning Flaecher,[f] Loukas Gouskos,[k] Valentin V. Khoze,[b] Greg Landsberg,[l] Dave Newbold,[f] Michele Papucci,[m] Timothy Sumner,[a] Marc Thomas[d,e] and Steven Worm[e]

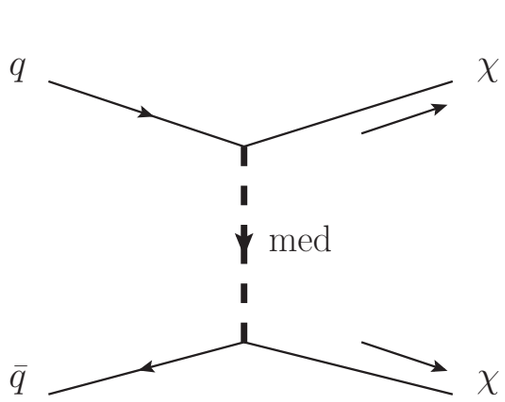
Simplified models

- What is the minimal full set of simplified models allowing for reinterpretations?

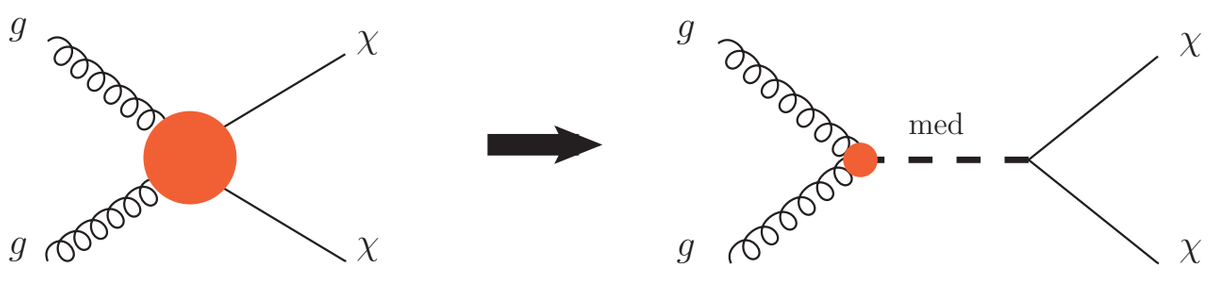
- s-channel Z’

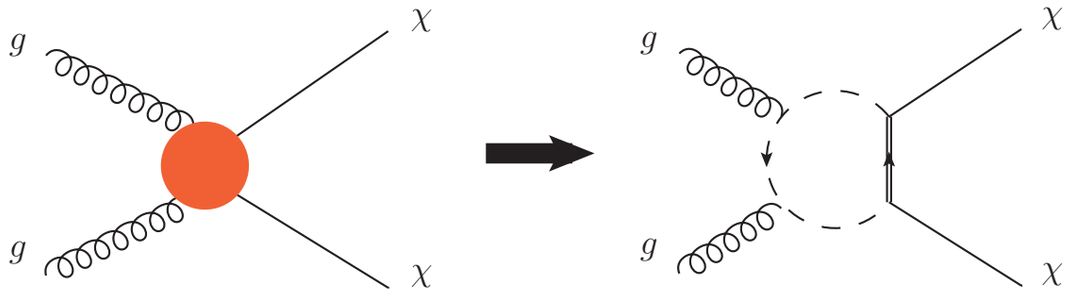


- t-channel



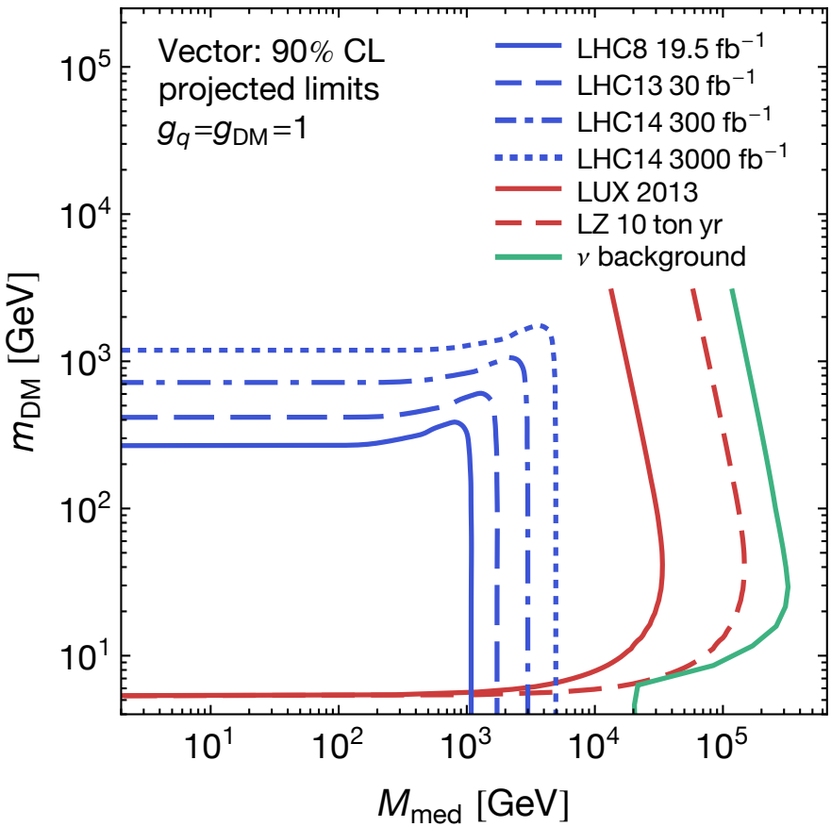
- s-channel with gluons in the initial state

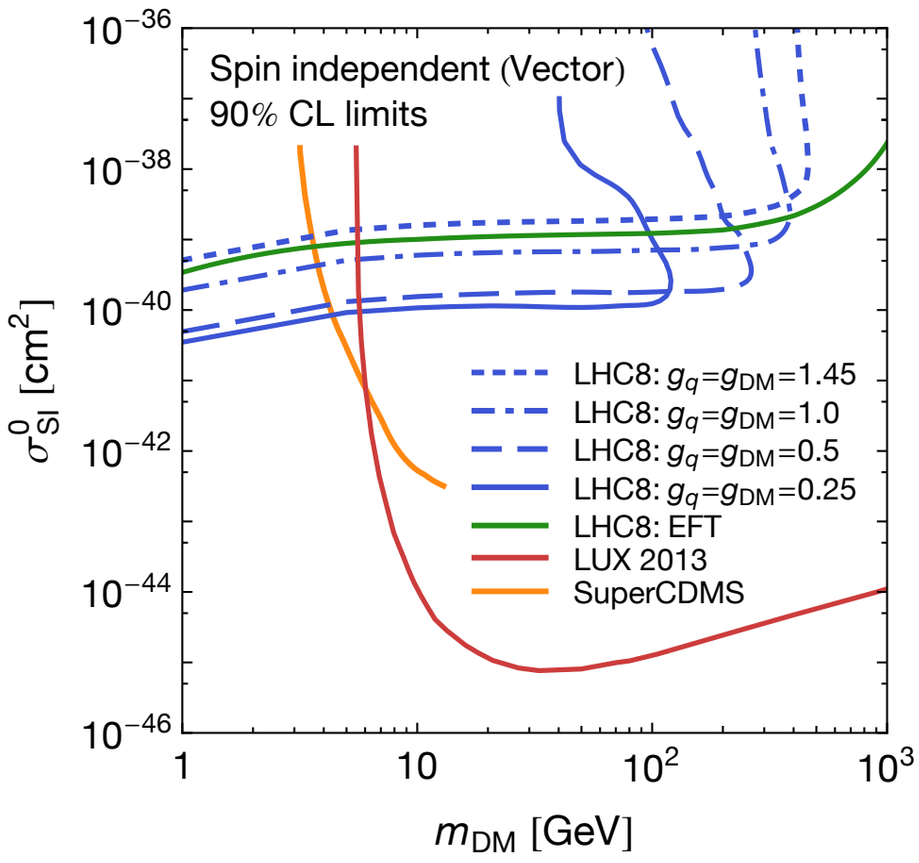




Simplified models

- How can we best show the results with simplified models?
- How can we best compare to the DD and ID results?



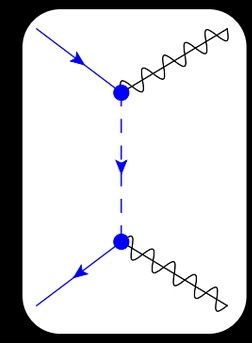


Input from Tim

T-Channel

- A simple t-channel model selects either uR, dR, or qL quarks to interact with.
  - More than one of the above is fine.
- MFV tells us the mediators come in flavor triplets, just like the SM quarks. (And just like the MSSM squarks)
  - (Alternative: flavored dark matter)
- The first two generation mediators will have very close to degenerate masses and couplings.
- The third generation mediators can have different masses and mixings.

Parameters: $\{M_{\mathrm{DM}}, M_{(1,2)}, M_3, g_{(1,2)}, g_3\}$



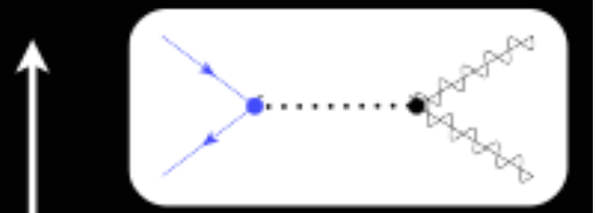
The width cannot be chosen as a free parameter if the theory is UV-complete.

In the very least it is bounded.

Input from Tim

S-Channel : Scalar

- A singlet scalar could be real or complex.
- Scalar couplings are chirality flipping. The scalar mediator consistent with MFV couples proportionally to Yukawa couplings.
- In the SM, the only relevant parameters are the masses, and the degree of mixing with the SM Higgs through electroweak breaking.
- If the SM is extended to a two (or more) Higgs doublet model, the coupling to up-quarks, down-quarks, and/or leptons become decorrelated.
  - Inside each sector, they still go like Yukawa couplings.

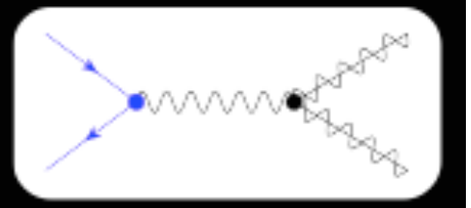


Parameters: $\{M_{\rm DM}, g_{\rm DM}, M_S, \theta_H\}$ or maybe $\{M_{\rm DM}, g_{\rm DM}, M_S, g_u, g_d, g_\ell\}$

Input from Tim

S-Channel :Vector

- Vector models have more parameters consistent with MFV.
- uR, dR, qL, eR, lL all have family-universal but distinct charges, as does H.
  - We would like to be able to write down the SM Yukawa interactions.
  - Quarks need not have universal couplings.
- There could be kinetic mixing with $U(1)_Y$.
- There is a dark Higgs sector. It may not be very important for LHC phenomenology.
- Gauge anomalies must cancel, which also may not be very important for LHC phenomenology.



Parameters: $\{M_{\rm DM}, g, M_{Z'}, z_q, z_u, z_d, z_\ell, z_e, z_H, \eta\}$ + ...

Future?

- The EFT approach is heavily criticised for being used at the LHC energies.
- There is huge variety of theories of Dark Matter.
- Simplified models are in-between and seem to be an optimal way forward.

- The experimental community needs to converge on a common set of simplified models soon (Run-2 is just around the corner).
  - which models/generators?
  - which parameter ranges to consider? (e.g. restrictions from thermal relic)
  - Combinations of different LHC analyses will be relevant with simplified models (e.g. mono-jet + di-jet using a Z' model).

next DM @ LHC Workshop

NIKHEF

GRAPPA

GRavitation AstroParticle Physics Amsterdam

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exact dates to be announced

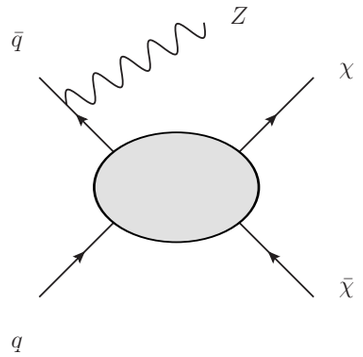
Looking forward to seeing you in Amsterdam!

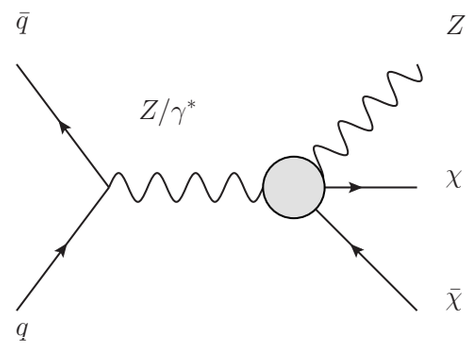
extra material

mono-X searches

Effective Field Theory

- simple benchmark models
  - couplings to quarks and gluons
  - couplings to vector bosons
- only two free parameters: m_χ, suppression scale M*
- validity concerns at the LHC energies





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

Simplified models

- UV-complete
- s-channel or t-channel
- parameters: m_χ, mediator mass and width, couplings
- Higgs-portal DM