Review of the LHC Dark Matter Forum Report

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How it came about

- in early LHC Run-1, the dark matter searches were a bit of a niche
  - small analysis teams
  - pheno side of the story being developed
- LHC Run-1 DM publications
  - model dependence or assumptions not always sufficiently explicit
  - EFT interpretations sometimes outside range of applicability or in non-physical contexts
  - very useful exploration of the complementarities which collider searches are bringing to the challenging search for the nature of DM
  - large impact, heavily cited papers → hot topic for Run-2

The LHC Dark Matter Forum

- vibrant field: several workshops in the past years
- DM@LHC in Oxford, September 2014
  - perfect timing before LHC restart
- two papers were prepared prior to that workshop with concrete proposals to transition to interpretations with simplified models
  - tackle EFT criticisms
  - not a new idea, both CMS and ATLAS had first simplified model interpretations in their final LHC Run-1 publications
- participants agreed we needed a dedicated effort preparing a baseline for the use in LHC Run-2 searches
  - between experiment and theory
  - urgency – simulations take time!

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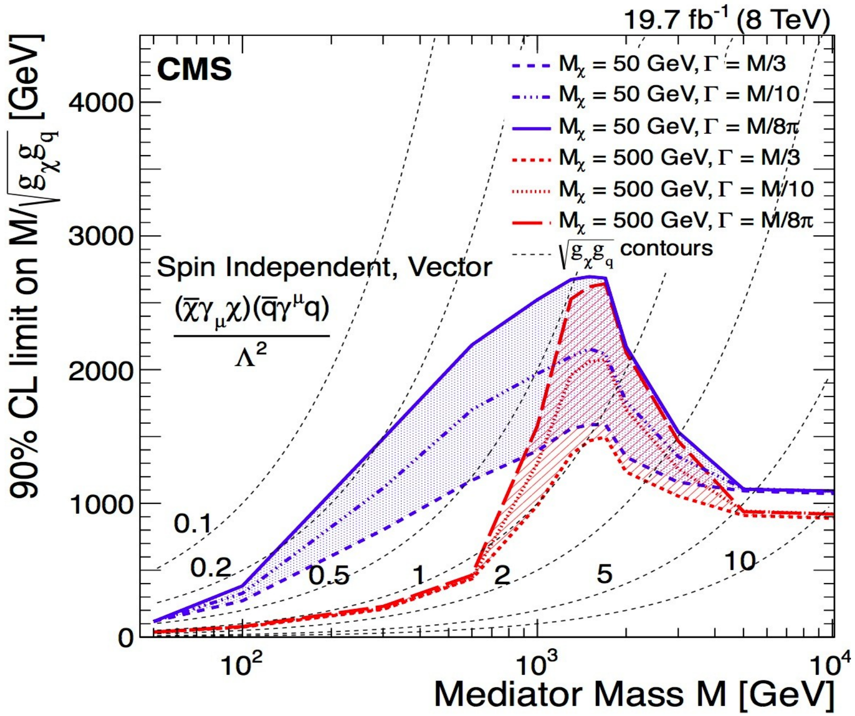


How it was organised

- A joint forum was created
  - bottom-up, supported by ATLAS and CMS
  - limited scope and duration
  - kickoff January 2015
- experiment representatives were assigned
  - ATLAS: Antonio Boveia, Caterina Doglioni
  - CMS: Sarah Malik, Stephen Mrenna, SL
- a mandate was drafted with and agreed by both experiments
  - agree on a small, prioritized list of benchmark models for Run-2 searches, including parameter scans and other practicalities
  - harmonize choices for LO vs. NLO, PS matching, scales, etc.
  - discuss how to apply the EFT formalism and how to present EFT interpretations
  - summarize in an arxiv document as internal CMS/ATLAS, as well as external reference

What we achieved

- reached out to over 200 experimental and theoretical participants on the main mailinglist
- we held ~7 very well attended meetings
  - to assess the state of the art in theory and experiment
  - to lay out a baseline we all agreed on
  - to identify what pieces were missing and would be worked on
  - in particular the pieces needed to timely prepare the experiment's simulations
- many people contributed a lot of their time
  - producing studies or plots to explore avenues or substantiate simplifications
  - balancing arguments for the choices that needed to be made
  - writing and reviewing the report
- in the end, a report was submitted to the arXiv on July 3rd
  - arXiv:1507.00966 [hep-ex] ; 160 pages, 139 authors and endorsers

Report Contents

- introduction: grounding assumptions
- simplified models for all MET + X analyses
  - s-channel vector and axial vector mediator
  - s-channel scalar and pseudoscalar mediator
  - t-channel coloured scalar mediator; spin-2 mediator
- specific models for signatures with EW bosons
  - specific mono-Higgs models
  - EFT models with direct DM-boson couplings
- implementation of models
- presentation of EFT results
- evaluation of theoretical uncertainties
- appendices

Grounding assumptions

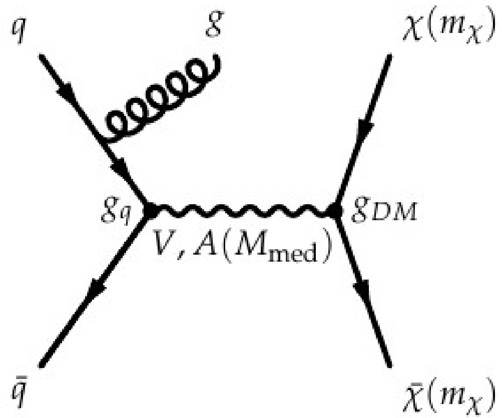
- we assume existence of interactions between DM and hadrons
- DM is assumed to consist of a single particle
- the DM particle is assumed to be stable on collider timescales and non-interacting with the detector
- the DM particle is assumed to be a Dirac fermion
  - most studied option
- central role for new mediating particle
  - 1 type of SM – DM interaction at a time
  - unique playground for accelerator searches
- assume minimal flavour violation
  - flavour couplings like in SM, so scalar mediators couple like SM Higgs
- minimal mediator decay width
  - no other new particles or channels
- no external LHC and non-LHC constraints taken into account, and no connection to DD / ID
  - beyond the scope and timescale of the forum, left for future

General: MET + X Searches

Vector and Axial-Vector s-channel mediators

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

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

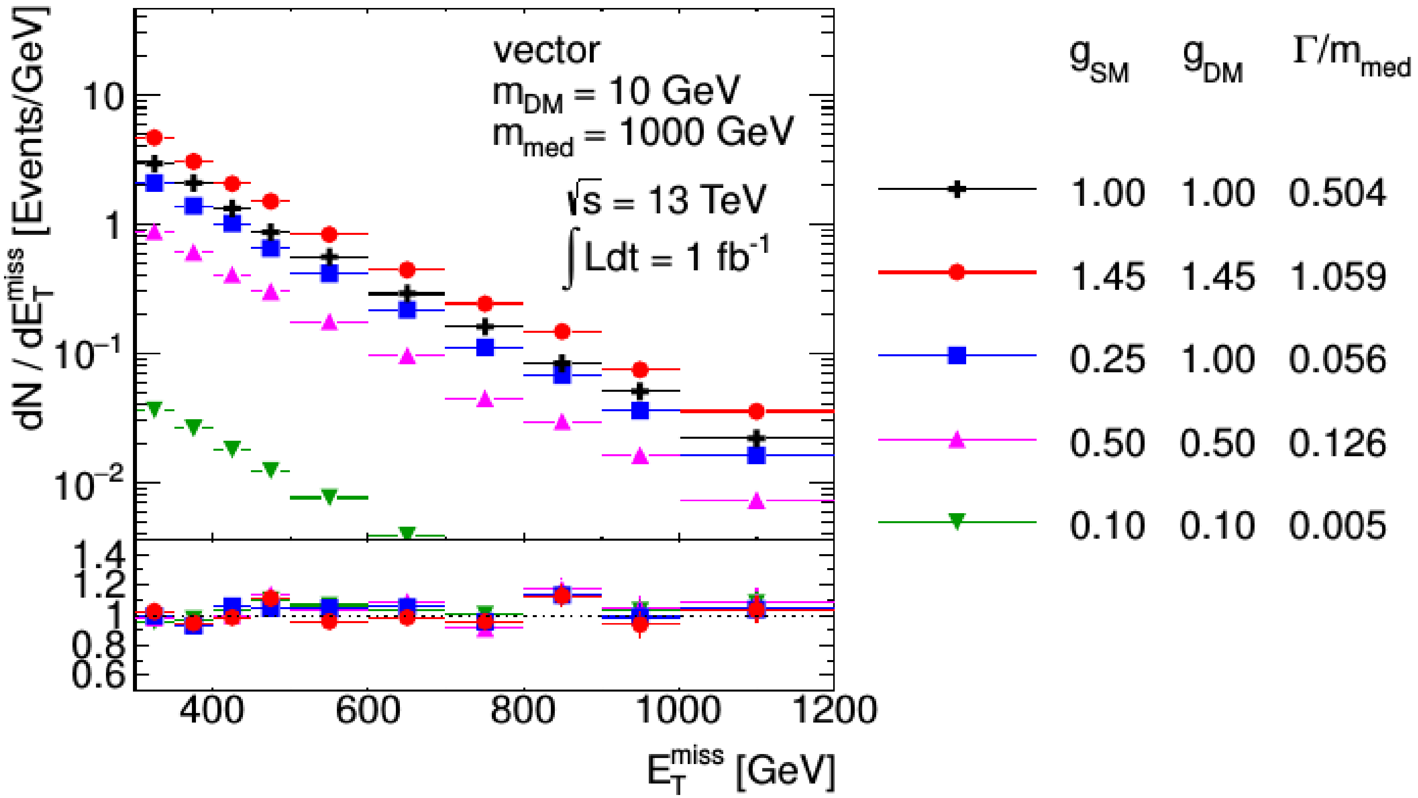


- mediator width dominated by quarks
- minimal set of parameters $\{ g_{\mathrm{q}}, g_{\chi}, m_{\chi}, M_{\mathrm{med}}, \}$
  - scan over couplings can be avoided
  - scan over DM and mediator mass can be simplified
  - sufficient to only consider V-V or A-A

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

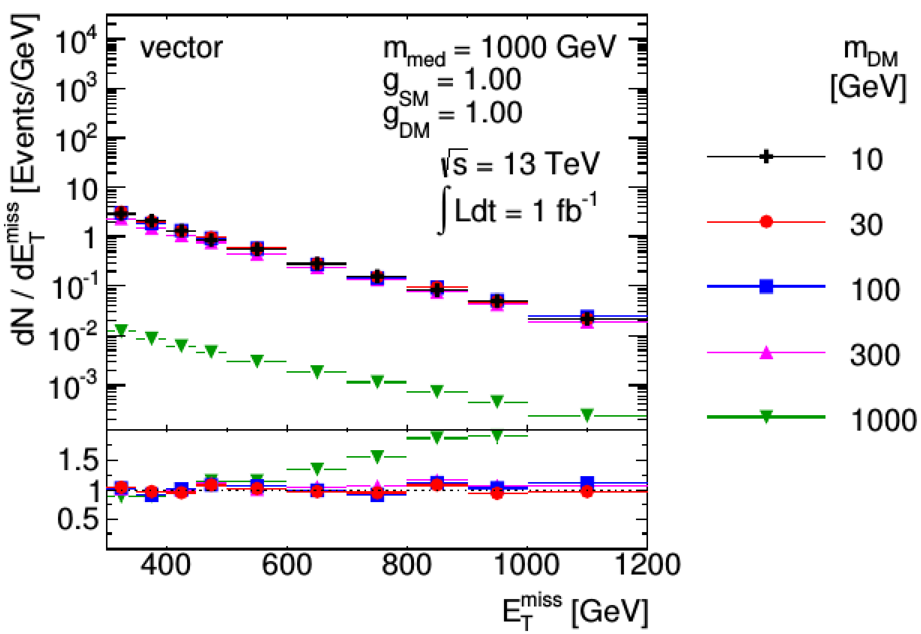
General: MET + X Searches

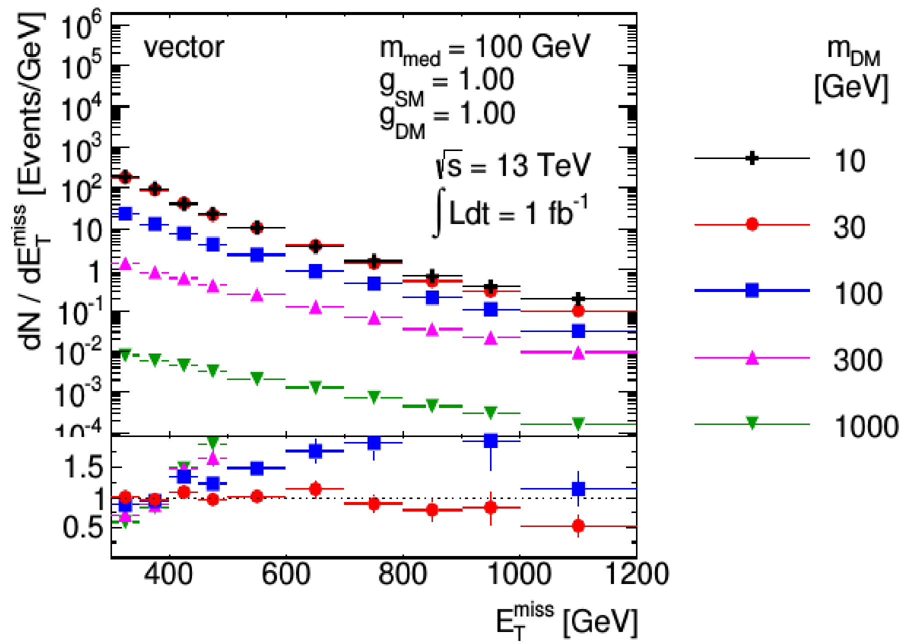
- avoid coupling scans: MET shape not coupling dependent
  - simplify scanning: choose one coupling combination, and extrapolate with simple cross section scaling
  - small caveat for on-shell/off-shell transition and at high mediator masses



General: MET + X Searches

- simplify mass scans: divide phase space in different regimes
  - $M_{med} \gg 2\,m_\chi$: most mediators are on-shell, and the MET distribution is independent from m_χ
  - $M_{med} \ll 2\,m_\chi$: off-shell mediator, strong cross-section suppression, no detailed scan needed since no sensitivity
  - need finer binning in transition region





General: MET + X Searches

- adopted scan proposal

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

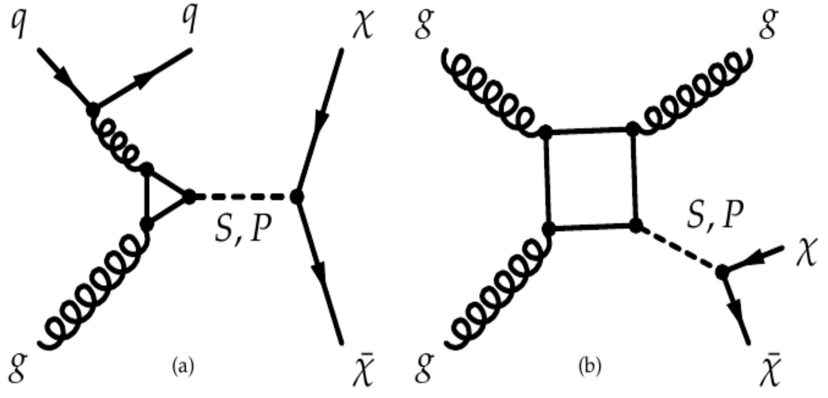
  - g_q = 0.25 and g_χ = 1
  - recipe provided to scale the cross section for other coupling choices
  - highest M_{med} mass point checked to coincide with kinematics of EFT
- this is the baseline which the experiments use for their interpretations

Scalar and pseudoscalar s-channel mediators

- for simplicity, assume no mixing with SM scalar sector

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

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

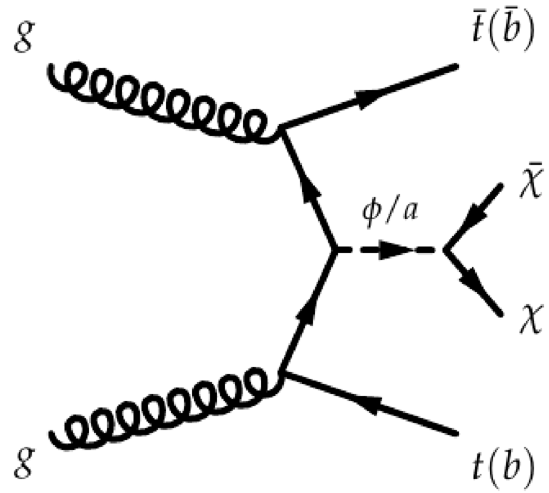


- different production than V and AV case
  - loop process dominates (MFV)
  - strong dependence on which decays are available to mediator
- mediator width dominated by DM below top threshold, and by top above
- in general, conclusions for V and AV also apply here
  - S and PS quasi identical
- same scan proposed, except for highest M_{med} dropped → no sensitivity

Special case: MET + HF

(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

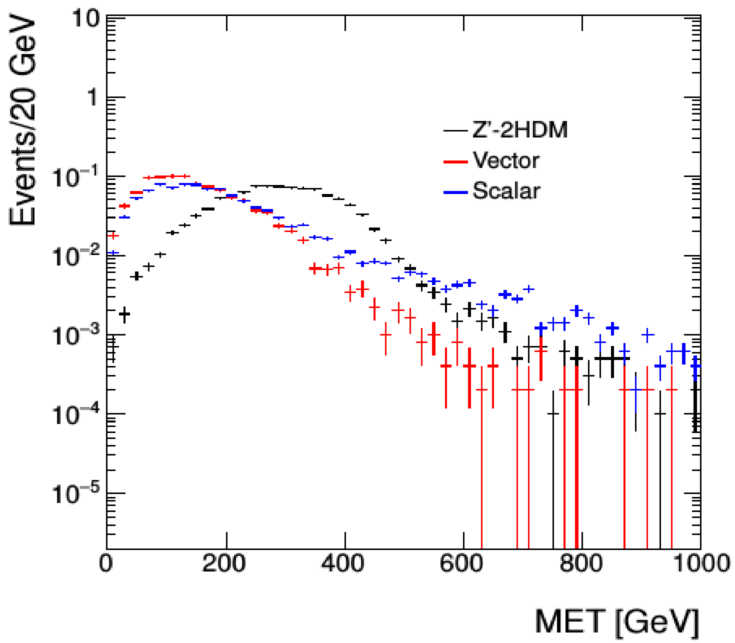


Also considered

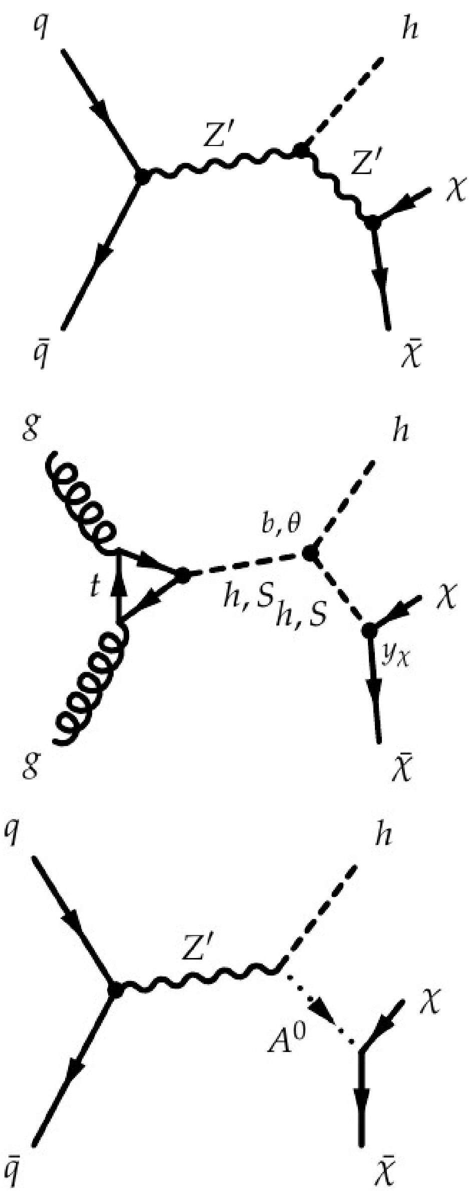
- t-channel production with coloured scalar mediator
  - more general than the SUSY case
- references to spin-2 mediator mentioned for completeness

Special mono-Higgs models

- mono-Higgs in the standard MET + X signals is tiny
- mono-Higgs can arise from dedicated models, though
  - vector mediator radiating h
  - scalar mediator radiating h
  - vector mediator, decaying into additional pseudoscalar
- each model its own kinematics
- dedicated scans proposed

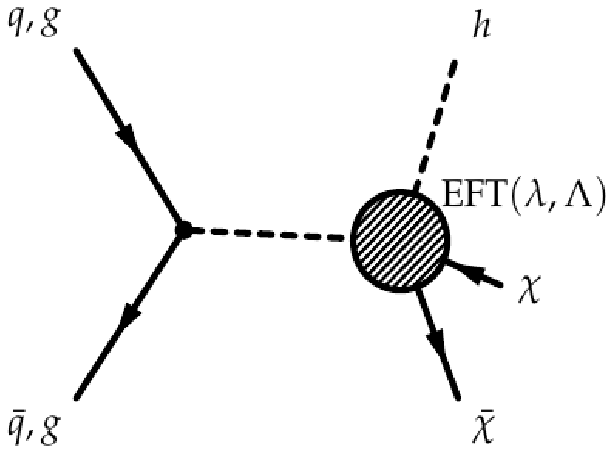


(a) High mediator mass



Special models with direct DM-boson couplings

- a few additional EFT models are considered
  - non-renormalizable operators of dimension 5, dimension 7, and higher
  - no UV completion or simplified model equivalent
  - but some theorists actively working on such models
- unique kinematical features
  - so worthwhile to consider, given our goal to cast an as wide as possible experimental net
- explicit recommendations on how to present results with such EFT models



Presentation of EFT Results

Truncation recipe 1

- example of Z' mediator

$$\frac{g_\chi g_q}{Q_{tr}^2 - M_{med}^2} = -\frac{g_\chi g_q}{M_{med}^2}\left(1 + \frac{Q_{tr}^2}{M_{med}^2} + \mathcal{O}\left(\frac{Q_{tr}^4}{M_{med}^4}\right)\right) \simeq -\frac{1}{M_*^2}$$

- minimal validity condition for EFT approximation: $Q_{tr} < M_{med}$
- recipe: reject events that don't satisfy this condition
  - smaller effective cross section, leading to new, weaker limit
- caveat: one uses knowledge of simplified model to constrain EFT
  - thus one could just as well use the simplified model...

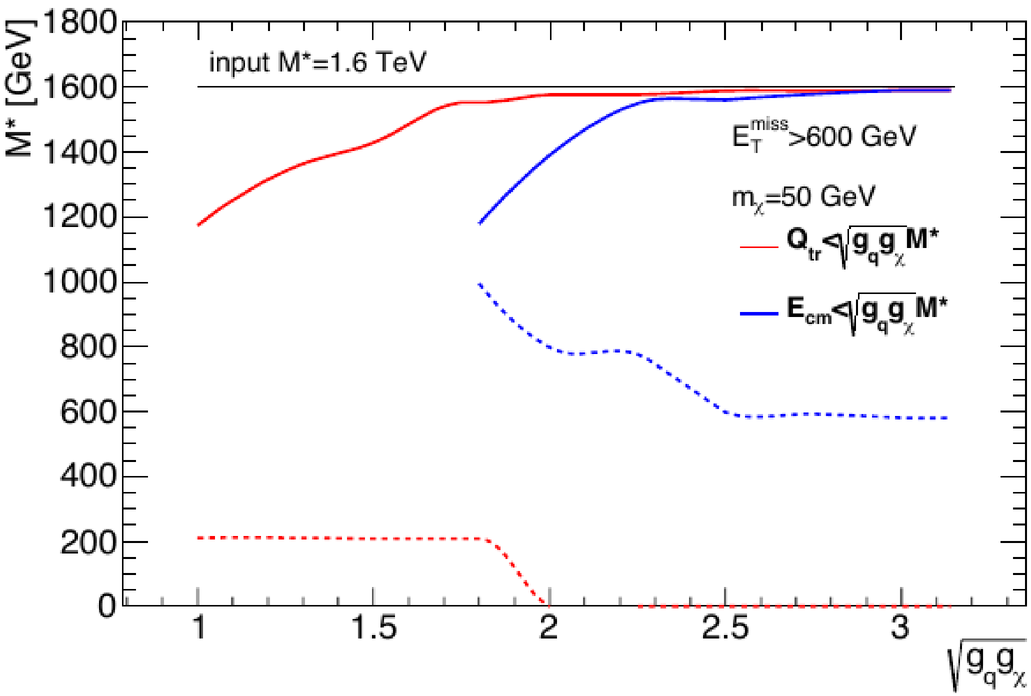
Truncation recipe 2

- 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

Presentation of EFT Results

Example result

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



- side remark: also beware of unitarity bounds

Recommendation

- use recipe 2, and quote limit for a certain fraction of events being accepted

Summary Table

- state-of-the-art snapshot as in June 2015
- recommendation to use the highest order available at any time

Benchmark models for ATLAS and CMS Run-2 DM searches			
vector/axial vector mediator, s-channel (Sec. 2.1)			
Signature	State of the art calculation and tools	Implementation	References
jet + $\not\!\!E_T$	**NLO+PS (powheg, SVN r3059)**	[Forl; Foro]	[HKR13; HR15; Ali+10; Naso4; FNO07]
	NLO+PS (*DMsimp* UFO + MadGraph5_aMC@NLO v2.3.0)	[New]	[Alw+14; All+14; Deg+12]
	NLO (MCFM v7.0)	Upon request	[FW13; Har+15]
$W/Z/\gamma$ + $\not\!\!E_T$	**LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)**	[Fora]	[Alw+14; All+14; Deg+12]
	NLO+PS (*DMsimp* UFO + MadGraph5_aMC@NLO v2.3.0)	[New]	[Alw+14; All+14; Deg+12]
scalar/pseudoscalar mediator, s-channel (Sec. 2.2)			
Signature	State of the art calculation and tools	Implementation	References
jet + $\not\!\!E_T$	**LO+PS, top loop (powheg, r3059)**	[Forn; Form]	[HKR13; HR15; Ali+10; Naso4; FNO07]
	LO+PS, top loop (*DMsimp* UFO + MadGraph5_aMC@NLO v.2.3.0)	[New]	[Alw+14; Hir+11; All+14; Deg+12]
	LO, top loop (MCFM v7.0)	Upon request	[FW13; Har+15]
$W/Z/\gamma$ + $\not\!\!E_T$	**LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)**		[Alw+14; All+14; Deg+12]
$t\bar{t}, b\bar{b}$+ $\not\!\!E_T$	**LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)**	[Ford]	[Alw+14; All+14; Deg+12]
	NLO+PS (*DMsimp* UFO + MadGraph5_aMC@NLO v2.3.0)	[New]	[Alw+14; All+14; Deg+12]
scalar mediator, t-channel (Sec. 2.3)			
Signature	State of the art calculation and tools	Implementation	References
jet(s) + $\not\!\!E_T$ (2-quark gens.)	LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)	[Forj]	[PVZ14; Alw+14; All+14; Deg+12]
jet(s) + $\not\!\!E_T$ (3-quark gens.)	**LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)**	[Fori]	[Bel+12; Alw+14; All+14; Deg+12]
$W/Z/\gamma$ + $\not\!\!E_T$	**LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)**	TBC	[Bel+12; Alw+14; All+14; Deg+12]
b + $\not\!\!E_T$	**LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)**	[Forg]	[LKW13; Agr+14b; Alw+14; All+14; Deg+12]
Specific simplified models with EW bosons (Sec. 3.1)			
Signature and model	State of the art calculation and tools	Implementation	References
Higgs + $\not\!\!E_T$, vector med.	**LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)**	[Forh]	[Car+14; BLW14b; Alw+14; All+14; Deg+12]
Higgs + $\not\!\!E_T$, scalar med.	**LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)**	[Forh]	[Car+14; BLW14b; Alw+14; All+14; Deg+12]
Higgs + $\not\!\!E_T$, 2HDM	**LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)**	[Forb]	[BLW14b; Alw+14; All+14; Deg+12]
Contact interaction operators with EW bosons (Sec. 3.1)			
Signature and model	State of the art calculation and tools	Implementation	References
$W/Z/\gamma$ + $\not\!\!E_T$, dim-7	**LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)**	[Forc]	[Cot+13; Car+13; CHH15; BLW14b; Alw+14; All+14; Deg+12]
Higgs + $\not\!\!E_T$, dim-4/dim-5	**LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)**	[Fore]	[Car+14; PS14; BLW14b; Alw+14; All+14; Deg+12]
Higgs + $\not\!\!E_T$, dim-8	**LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)**	[Forh]	[Car+14; PS14; BLW14b; Alw+14; All+14; Deg+12]

Table 6.1: Summary table for available benchmark models considered within the works of this Forum. The results in this document have been obtained with the implementations in bold.

Appendices

Appendix A: additional models

- monotop
- W+MET models with possible cross-section enhancement
- inert 2HDM

Appendix B:

- recommendations for experimentalists on what and how to make publicly available, such that results can be re-interpreted
    - eg. to please provide model-independent limits
- an excellent read if you are an experimentalist and don't know why theorists sometimes choose one over another result to reinterpret or to refer to

Thanks to all involved!

Cornell University Library

arXiv.org > hep-ex > arXiv:1507.00966

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 (hep-ex)**; High Energy Physics - Phenomenology (hep-ph)

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