

Summary of the LHC Dark Matter Forum Report

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8 October 2015
HEP@VUB Meeting



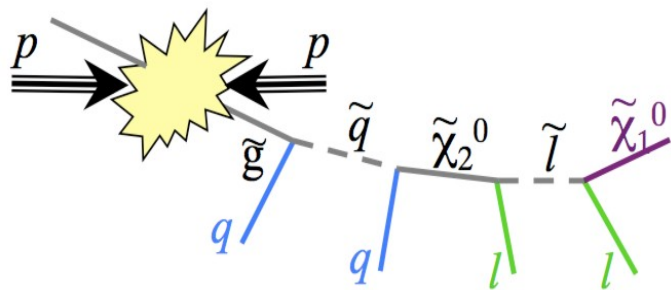
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1-slide intro/recap on LHC DM searches

- experimental signature for dark matter production is transverse momentum imbalance **MET + X**

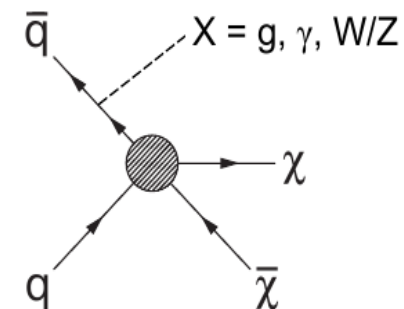
DM produced in cascade decays from heavier new states

- example: **SUSY**
 - LSP stable if R-parity conserved
 - always 2 LSP's yielding observable momentum imbalance (MET)

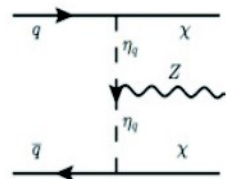
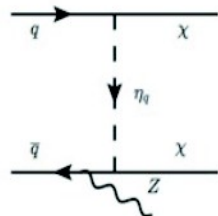
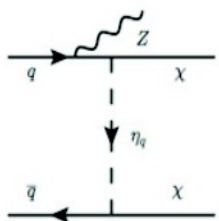
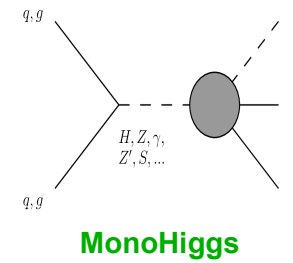
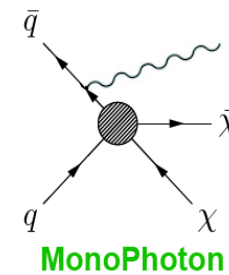
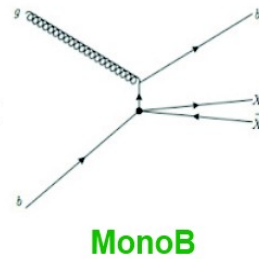
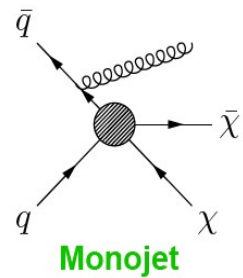


DM produced directly

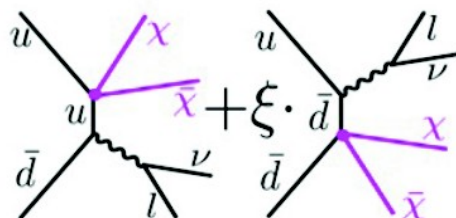
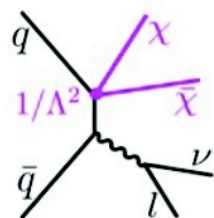
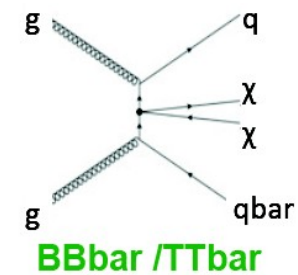
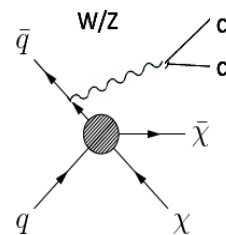
- pair production
 - but back-to-back DM particles are invisible
- higher-order diagrams provide **probe recoiling against DM pair**



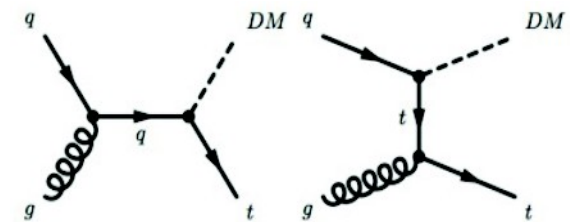
Searches for direct DM production



MonoZ



MonoW (monoLepton)



1-slide on EFTs versus SMs

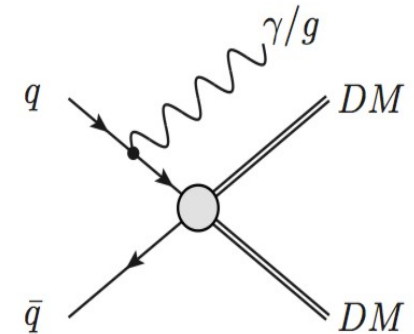
- **effective theories**: collapse SM-DM interaction in effective 4-point operator

- different operator depending on mediator's couplings
- only **few parameters**: m_{DM} , EFT scale $\Lambda = M / \sqrt{g_\chi g_q}$
- **easy to translate** to DM-nucleon cross section

$$\sigma(\chi N \rightarrow \chi N) \sim \frac{g_q^2 g_\chi^2}{M^4} \mu_{\chi N}^2$$

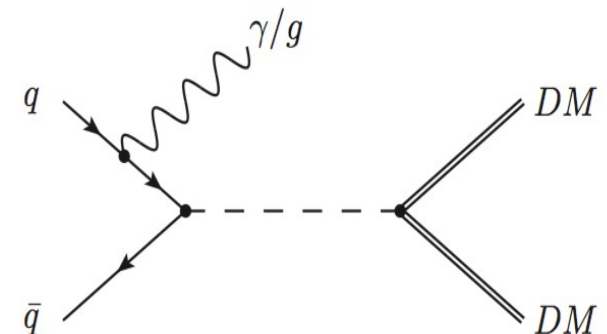
- **M must be (much) larger than the energy scale of the collision**

truncation procedures allow to restrict to “sensitive” events



- **simplified models**: only SM + few particles

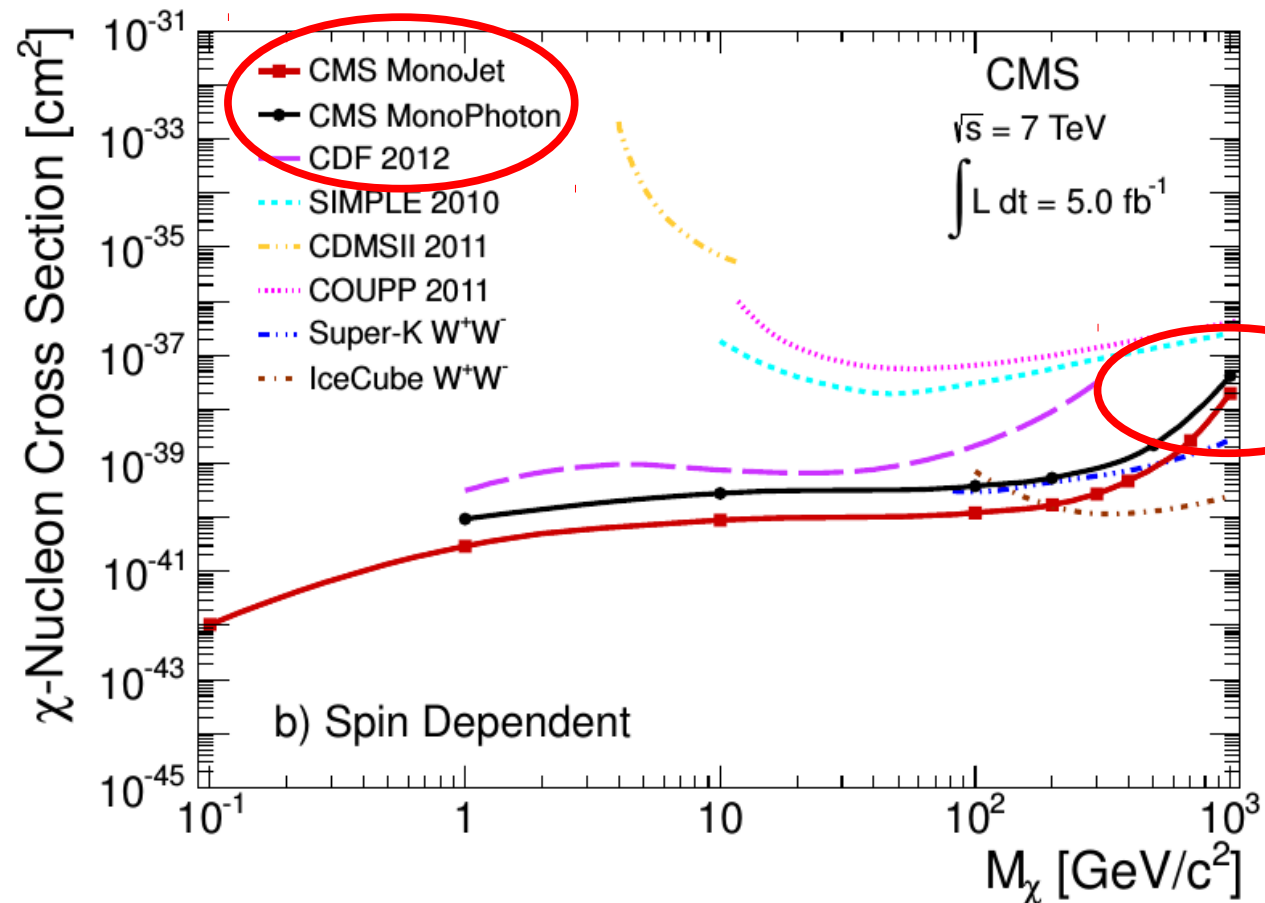
- new physics **restricted to what is relevant** for a certain topology
- aim for **maximal experimental coverage** of that topology
- mediator and interactions **specified explicitly**
- usable as **building blocks for recasting** results in full models



How it came about

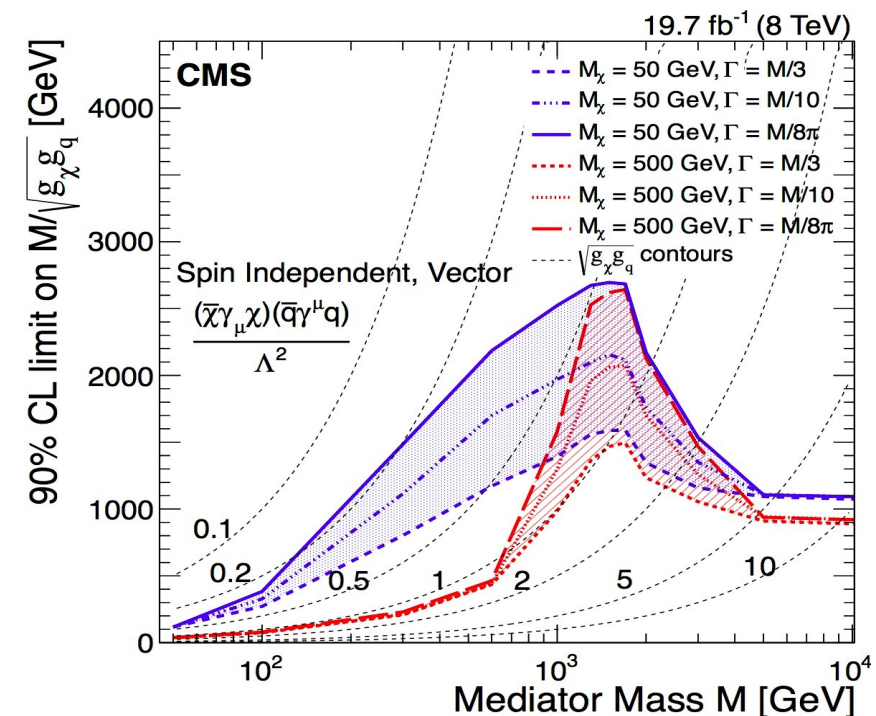
- in LHC Run-1, the dark matter searches were a bit of a niche
 - small analysis teams
 - pheno side of the story still heavily developing
 - but eventually **large impact** → hot topic for Run-2
 - eg. more than 100 citations and counting for rather recent final CMS monojet paper
- LHC Run-1 DM publications have drawn **substantive criticism**
 - comparisons of limits to non-LHC experiments with **insufficient assessment of model dependence or assumptions**
 - **EFT interpretations outside range of applicability or in non-physical contexts**
 - it's not all bad: **very useful exploration of complementarities** collider searches are bringing to the challenging search for the nature of DM

JHEP 09 (2012) 094



- 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 proposing to transition to **interpretations with simplified models**
 - avoid 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 CMS, ATLAS, and theorists
 - simulations take time!

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How it was organised

- CMS and ATLAS management was asked and agreed to make a joint forum of limited scope and duration
 - bottom-up
 - kickoff January 2015
- experiment representatives were “assigned”
 - Antonio Boveia (CERN, ATLAS), Caterina Doglioni (Lund, ATLAS), Sarah Malik (ICLondon, CMS), Stephen Mrenna (FNAL, CMS), SL (VUB, CMS)
- 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 the community](#), with 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 \(top!\) 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

- **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**

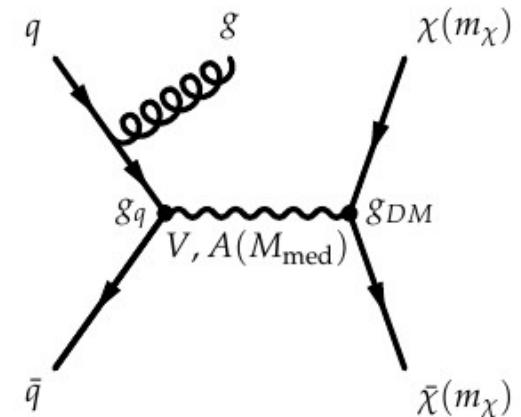
- we assume existence of **interactions between DM and hadrons**
- DM is assumed to consist of **a single particle**
- the DM particle is assumed to be **stable** on collider timescales and **non-interacting** with the detector
- the DM particle is assumed to be a **Dirac fermion**
 - most studied option, and often not dramatically different from other cases
- 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
 - beyond the scope and timescale of the forum, left for future

Vector and Axial-Vector s-channel mediators

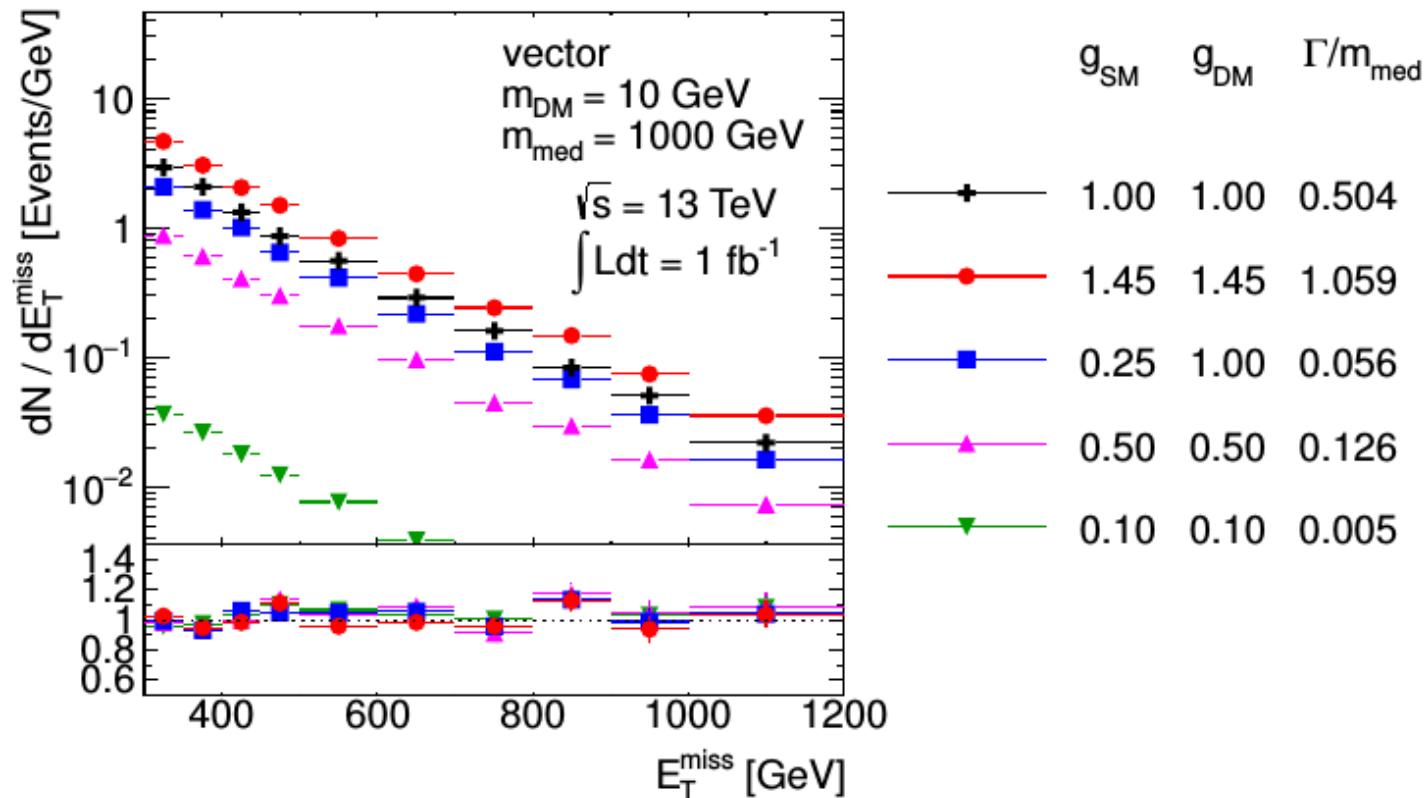
$$\mathcal{L}_{\text{vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu q + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \chi$$

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

- 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

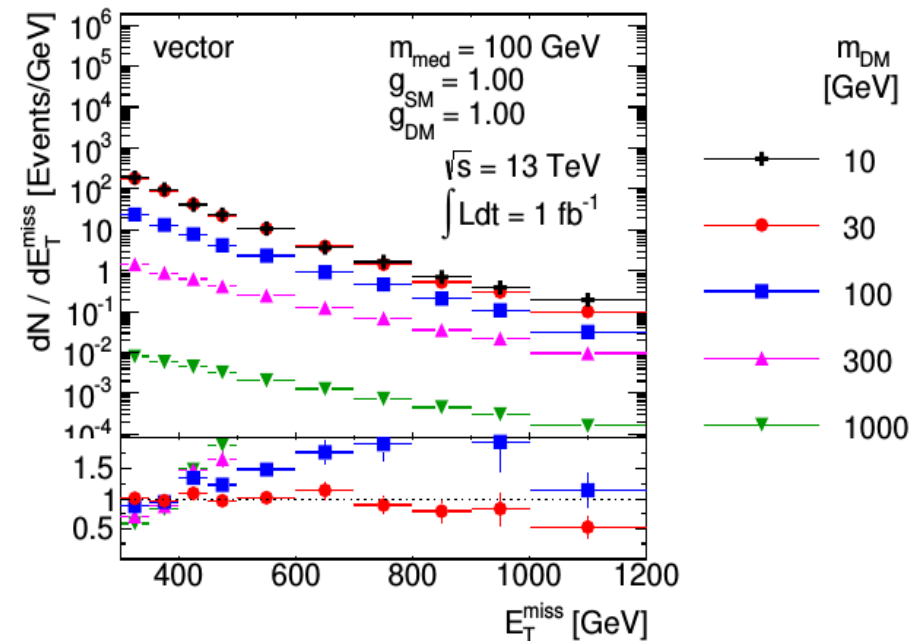
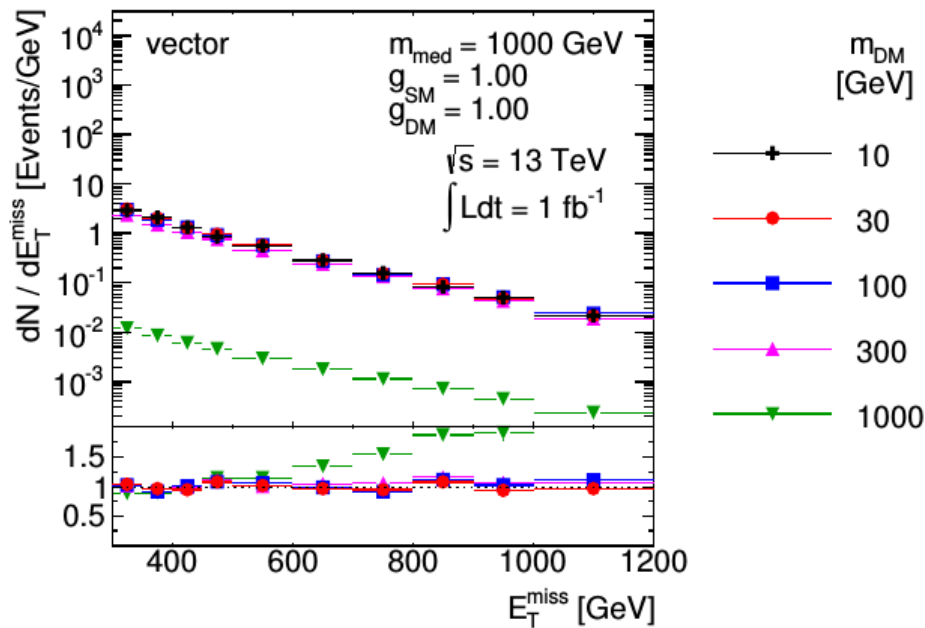


- avoid coupling scans: MET shape not coupling dependent
 - **simplify scanning**: choose one coupling combination, and **extrapolate with simple cross section scaling**
 - small caveat for on-shell/off-shell transition and at high mediator masses



General: MET + X Searches

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



- adopted scan proposal

m_χ / GeV	$M_{\text{med}} / \text{GeV}$									
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 $g_\chi = 1$
- 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 are simulating for their interpretations

Scalar and pseudoscalar s-channel mediators

- for simplicity, **assume no mixing with SM scalar sector**

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

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

- different production** than V and AV case

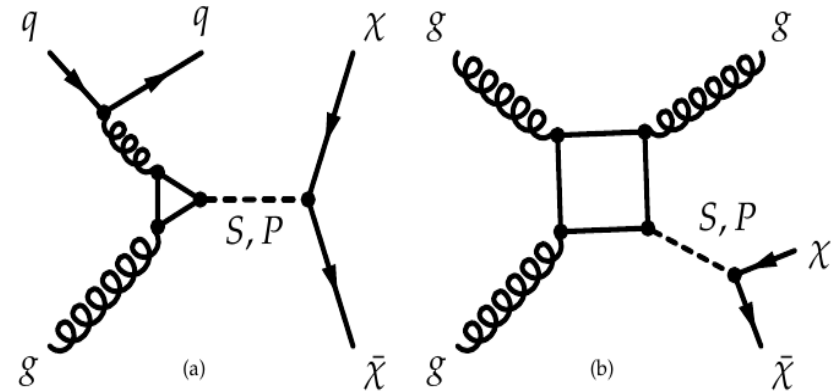
- loop process dominates (MFV)
- strong dependence on which decays are available to mediator

- mediator width dominated by DM below top threshold, and by top above

- in general, **conclusions for V and AV also apply here**

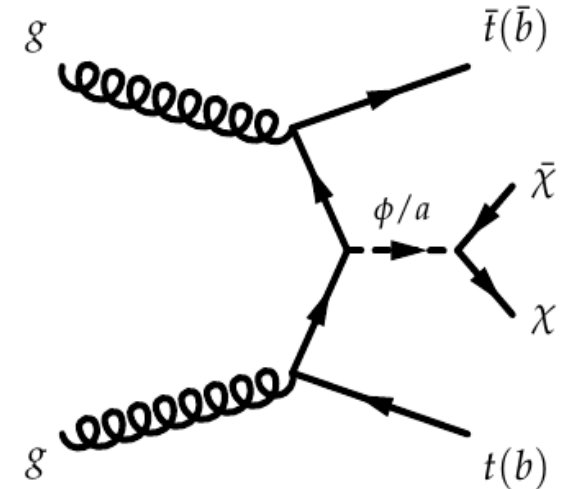
- S and PS quasi identical

- same scan proposed, except for highest M_{med} dropped \rightarrow no sensitivity



(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 $\tan\beta$ (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

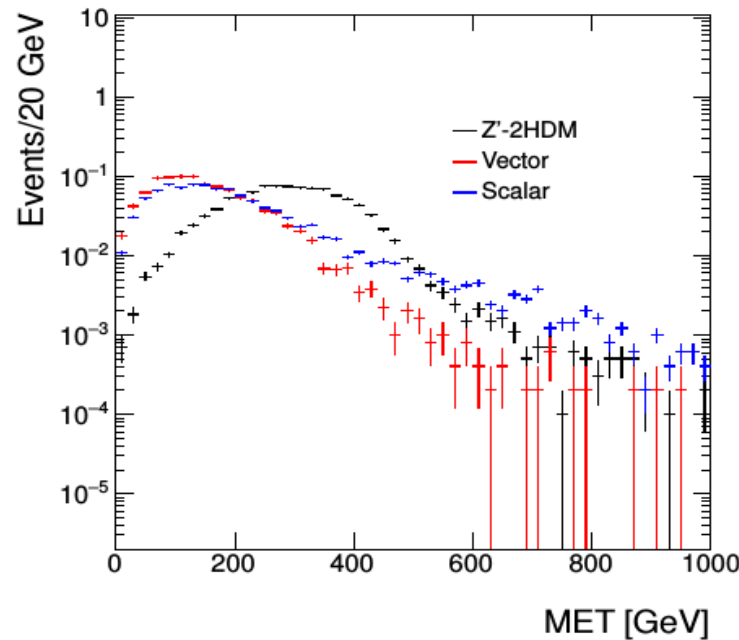


Also considered

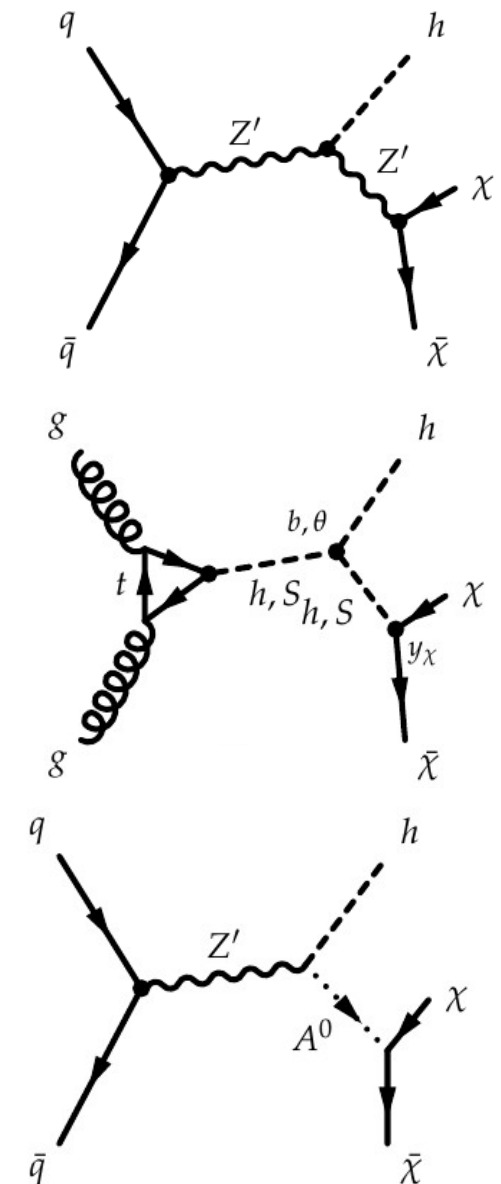
- **t-channel production** with coloured scalar mediator
 - more general than the SUSY case
- references to spin-2 mediator mentioned for completeness

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

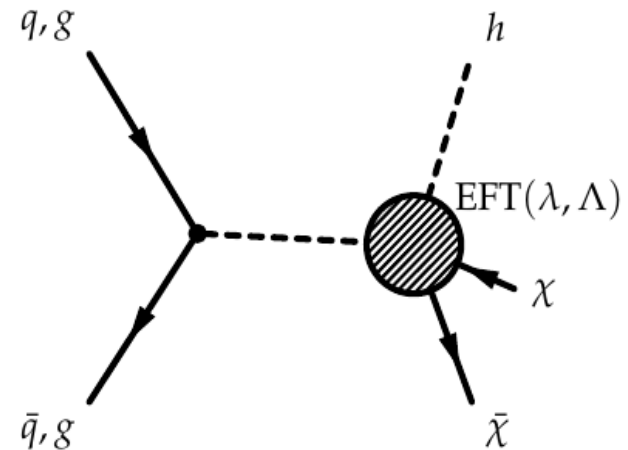


(a) High mediator mass



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



Truncation recipe 1

- example of Z' mediator

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

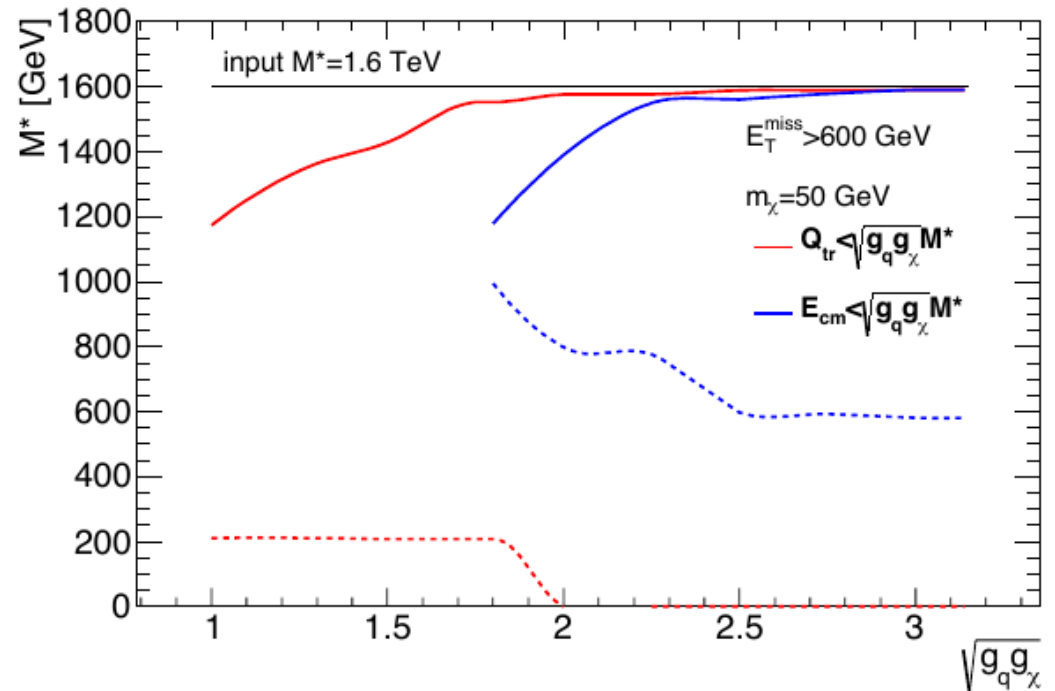
- **minimal validity condition for EFT approximation: $Q_{\text{tr}} < M_{\text{med}}$**
- recipe: **reject events that don't satisfy this condition**
 - smaller effective cross section, leading to new, weaker limit
- caveat: one uses knowledge of simplified model to constrain EFT
 - thus one could just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

Truncation recipe 2

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

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 + \cancel{E}_T	NLO+PS (powheg, SVN r3059)	[Forl; Foro]	[HKR13; HR15; Ali+10; Naso4; FNO07]
	NLO+PS (<i>DMsimp</i> UFO + MadGraph5_aMC@NLO v2.3.0) NLO (MCFM v7.0)	[New] Upon request	[Alw+14; All+14; Deg+12] [FW13; Har+15]
W/Z/ γ + \cancel{E}_T	LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)	[Fora]	[Alw+14; All+14; Deg+12]
	NLO+PS (<i>DMsimp</i> 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 + \cancel{E}_T	LO+PS, top loop (powheg, r3059)	[Form; Form]	[HKR13; HR15; Ali+10; Naso4; FNO07]
	LO+PS, top loop (<i>DMsimp</i> UFO + MadGraph5_aMC@NLO v2.3.0)	[New]	[Alw+14; Hir+11; All+14; Deg+12]
	LO, top loop (MCFM v7.0)	Upon request	[FW13; Har+15]
W/Z/ γ + \cancel{E}_T	LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)		[Alw+14; All+14; Deg+12]
	NLO+PS (<i>DMsimp</i> UFO + MadGraph5_aMC@NLO v2.3.0)	[Ford] [New]	[Alw+14; All+14; Deg+12] [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) + \cancel{E}_T (2-quark gens.)	LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)	[Forj]	[PVZ14; Alw+14; All+14; Deg+12]
jet(s) + \cancel{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/ γ + \cancel{E}_T	LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)	TBC	[Bel+12; Alw+14; All+14; Deg+12]
b + \cancel{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 + \cancel{E}_T , vector med.	LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)	[Forh]	[Car+14; BLW14b; Alw+14; All+14; Deg+12]
Higgs + \cancel{E}_T , scalar med.	LO+PS (UFO + MadGraph5_aMC@NLO v2.2.3)	[Forh]	[Car+14; BLW14b; Alw+14; All+14; Deg+12]
Higgs + \cancel{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/ γ + \cancel{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 + \cancel{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 + \cancel{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.

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. always provide model-independent limits
- **a sore point** that we often still haven't gotten right after years of data
- **an excellent read** if you are in CMS and don't know why theorists sometimes choose one over another result to reinterpret or refer to

Future of the LHC DM Forum

- this was an [ad-hoc forum](#)
- [bottom-up](#), to serve the short-term need of the experiments
- conclusion of [discussion on the future](#) with CMS/ATLAS, and MLM
 - re-shape the forum to something more permanent
 - move under the umbrella and infrastructure of the LPCC
 - expand the audience
 - give also theorists a leading role
 - rotation of conveners
- first task of new working group will be to zoom in on the question [how to best present together results from DD, ID, and collider](#)
 - thus involve also non-LHC experimental community
- further work: how to [incorporate external LHC and non-LHC constraints](#) and which ones