Status of searches for direct production of Dark Matter at the Large Hadron Collider

Priscilla Pani

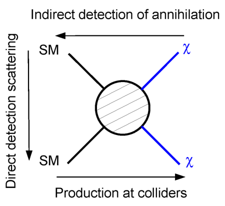
on behalf of the ATLAS and CMS Collaborations

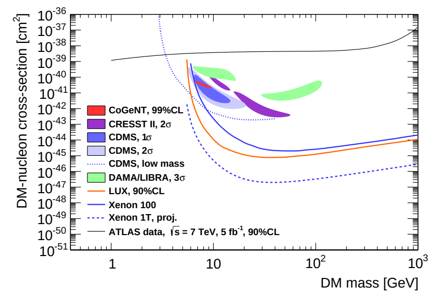
Stockholm University, Sweden

24 August 2015

Why Dark Matter (DM) and why at the LHC

- DM existance has **compelling proofs**.
- We don't know anything about it except it interacts **gravitationally** and is **stable**



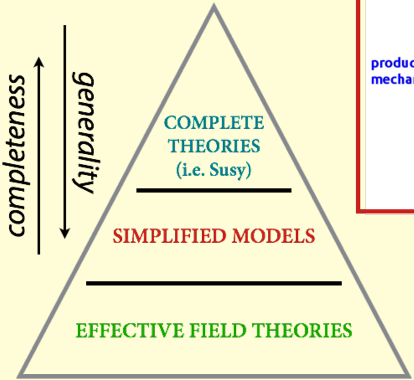


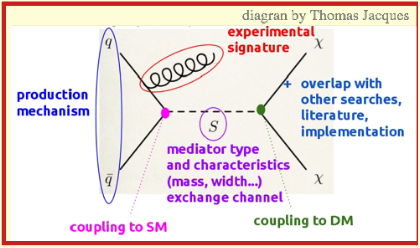
- Tantalising (**but controversial**) hints of direct and indirect searches (FERMI, PAMELA/AMS) point to a WIMP-DM[1].
- If this is the case, DM can be **produced at the LHC**.

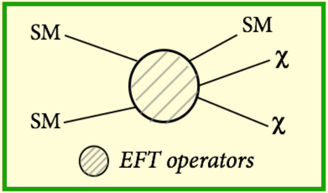
[1] other DM candidates exist and are studied, but for sake of time will not be included in this talk

Theoretical approach to the collider DM searches

Benchmark models and paradigms



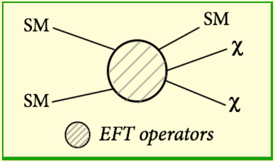




- **EFTs** have been the Run I paradigm
- **Simplified Models** will become the Run II paradigm

Effective Field Theories (EFT)

$$L_{eff} = \sum_{quarks} G_\chi O(\chi, q) + G_\chi O(\chi, G).$$



$$G_\chi = \left(\frac{\sqrt{g_q g_\chi}}{M_\Psi}\right)^x \equiv \left(\frac{1}{M_*}\right)^x \rightarrow$$ **one parameter** (+ χ mass)

WIMP-DM (χ)	ID	interaction	Operator	G_χ
Dirac scalar	D1	quarks	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
Dirac vector	D5	quarks	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
Dirac axial-vector	D8	quarks	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
Dirac tensor	D9	quarks	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
Dirac scalar	D11	gluons	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
complex scalar	C1	quarks	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
complex scalar	C5	gluons	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$

Each **operator** can be classified in a systematic way. Different **signatures have different sensitivity to each operator**.

Interpretation of EFTs

Results are translated in terms of lower limits on M_*

$$M_*^{limit} = M_*^{gen} \left(\frac{\sigma_{th}}{\sigma_{excl}} \right)^{1/y}$$

(y depends on the operator)

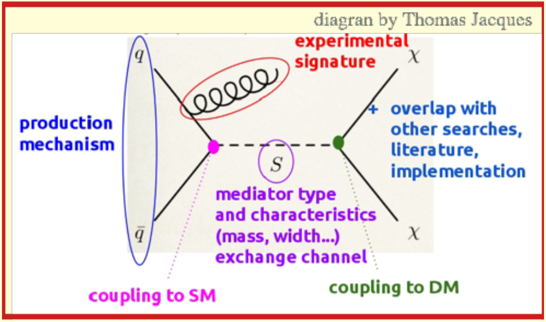
At the LHC energy, EFT assumption ($Q_{transf} << M_{med}$) might not hold. To verify this we need to assume something about the underlying physics

Different *truncation* strategies are used:

- assume simplest interaction structure and *correct* the cross section for only valid events ($Q_{transf} < f(g_q g_\chi, M_*)$)
- Evaluate the fraction of valid events R_{M_*} using an effective coupling $Q_{transf} < g_{eff} M_*$

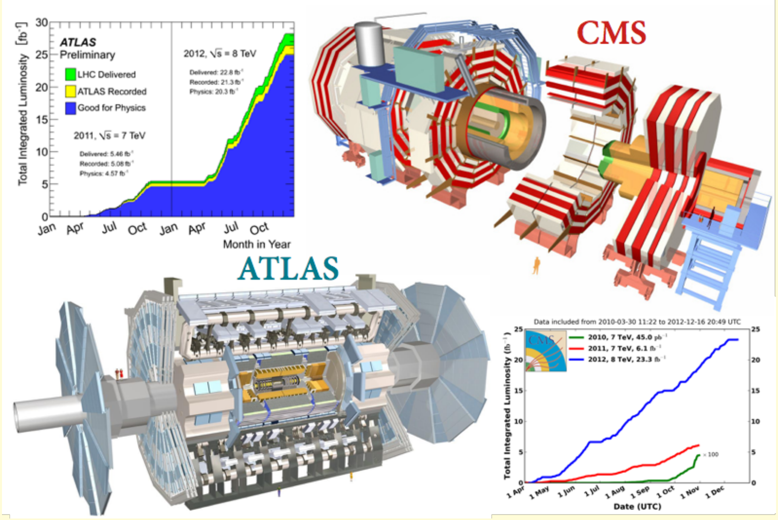
Simplified Models

- Reduce a complex model to a simple one with DM, a mediator between the SM and the Dark Sector, one interaction channel
- **Few free parameters:** m_{med}, m_{DM}, g_{SM}, g_{DM}, Γ_{med}
  + nature of mediator and DM and their interaction



- Simplified models can (also) be systematically classified
- They are always theoretically valid, although is up to the theorists to re-connect them back to the complete models

Experimental approach: ATLAS and CMS



Experimental approach: signatures

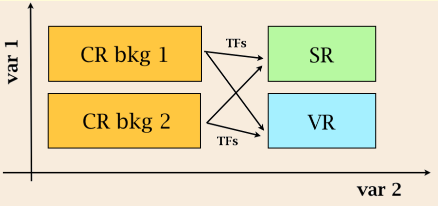
Dark Matter searches all rely on high amount of transverse momentum imbalance in the detector, indicating the presence of weakly interacting particles that escape undetected.

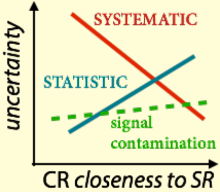
DM searches have a very rich phenomenology:

jet+E_T^{miss}	*V. Ippolito and B. Gomber's talks*
$\gamma + E_T^{miss}$	*V. Ippolito and B. Gomber's talks*
$W^{\pm}/Z^0 + E_T^{miss}$ (had, lep)	*V. Ippolito and B. Gomber's talks*
$t/t\bar{t} + E_T^{miss}$ (0L, 1L, 2L)	*J. Piedra's talk*
$b/b\bar{b} + E_T^{miss}$	*P. Srimanobhas's talk*
$H + E_T^{miss}$, $H \to \chi\chi$	

Experimental approach: strategy

1. Definition of a set of Signal enriched Regions (SR)
2. Definition of a set of Control Regions (CR) to derive[2] a data-driven normalisation of MC with *transfer factors* (TF).





3. Validation of the TF in the Validation Region (VR)
4. **Unblinding** → check whether an excess is observed (p-value)
5. If no excess is found the results are interpreted in terms of limits on selected models.

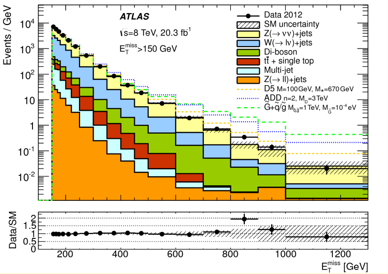
[2] This is a simplification, most of the cases CRs and corresponding SR are fitted simultaneously in a likelihood fit and multiple SR or shape fits can be used

An example - mono-jet searches

Eur. Phys. J. C 75 (2015) 235, CMS-PAS-EXO-14-004, Eur. Phys. J. C (2015) 75:299

E_T^{miss} + 1 jet

- 1 central jet with $pT > min(120\ \text{GeV}, 0.5E_T^{miss})$
- $\Delta\phi(\text{jets}, E_T^{miss}) > 1$
- veto leptons
- 9 E_T^{miss} bins

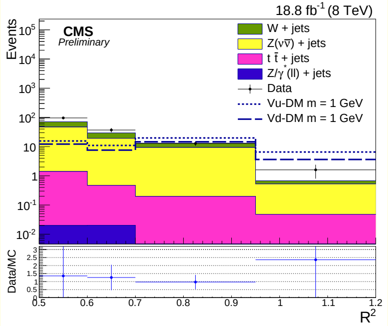


dijet with Razor

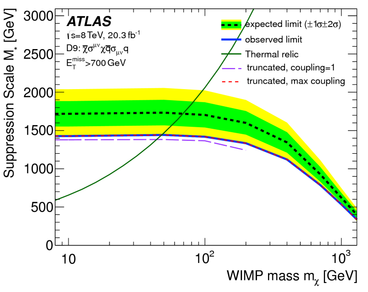
- at least 2 jets ($pT > 80$ GeV)
- form 2 megajets with all preselected jets.

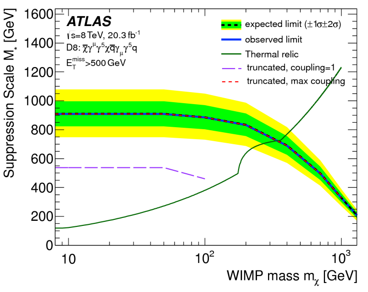
$M_R = \sqrt{(|\vec{p_1}| + |\vec{p_2}|)^2 - (p_{z1} + p_{z2})^2}$ $M_R^T = \sqrt{E_T^{miss}(p_{T1} + p_{T2}) - \vec{E}_T^{miss} \cdot (\vec{p_{T1}} + \vec{p_{T2}})}/2$

- bin in $R = M_R^T / M_R$ and M_R.

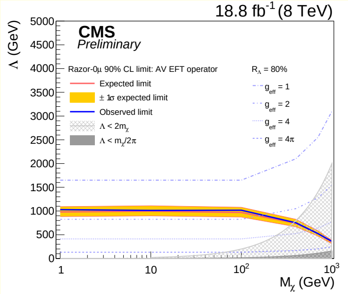


Mono-jet results



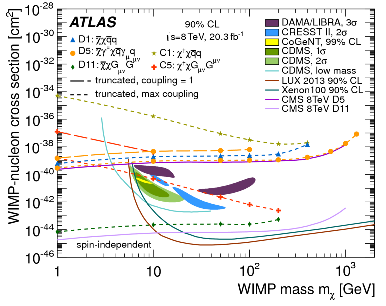


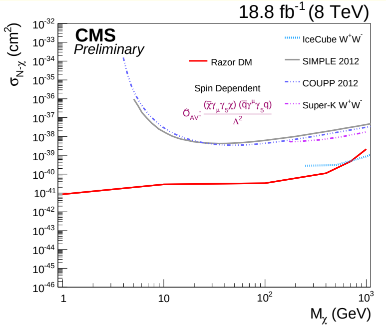
- D9 (tensor), D8/AV (axial vector)
- truncation weakens limits
- the weaker the scale that is probed, the more the truncation affects the limits



THE PLOT

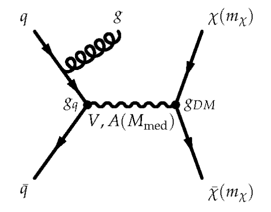
- Complex plot to interpret and compare with other experiments
- nevertheless it highlights the great **complementarity** with direct searches





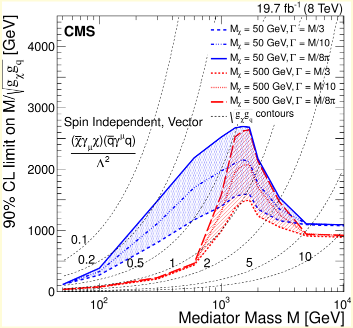
If it's not on this plot, it's "speculative". If it's on the wrong side of a line on this plot it's "excluded". [..] These plots are totally misleading except when they convey important informations. (N. Weiner, DM@LHC, 2014)

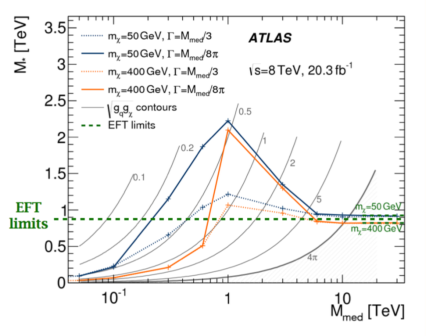
Monojet simplified models: Z′ mediator



Free parameters:

- Mediator mass
- Dark Matter mass
- Mediator width

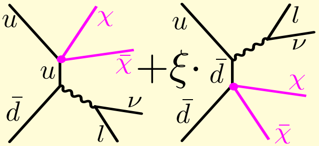


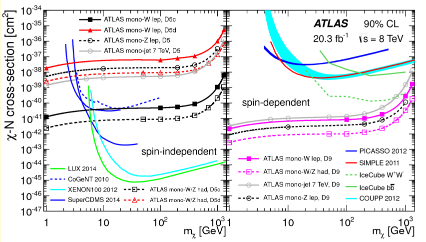


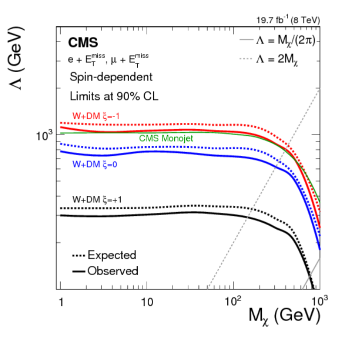
A rich pheno: DM plus Gauge Bosons

arXiv:1408.2745, arXiv:1407.7494

- Search for DM events with gauge boson radiation[3]
- complements mono-jet signatures
- lower background
- Possible interference for W





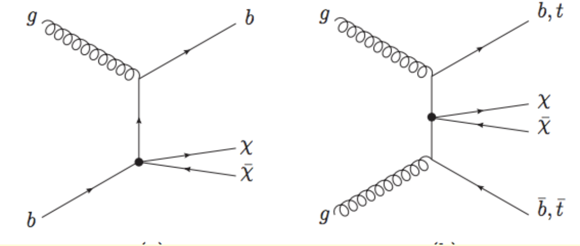


[3] not discussed Ref: PRL 112 041802 (2014), PRD 90, 012004 (2014), JHEP 09 (2014) 037, PRD 91, 012008 (2015), arXiv:1408.2745, arXiv:1410.8812

Dark Matter with Heavy Flavours

$$O_{D1} = \sum_{quarks} \frac{\mathbf{m_q}}{M_*^3} \bar{\chi}\chi\bar{q}q \qquad O_{C1} = \sum_{quarks} \frac{\mathbf{m_q}}{M_*^2} \chi^\dagger\chi\bar{q}q$$

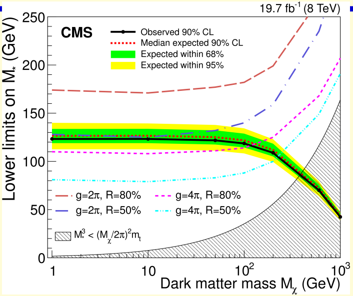
- m_q motivated by MVF constraint, **enhanced coupling to top quark**
- investigation of bottom quark couplings interesting in case of only down-type interaction.

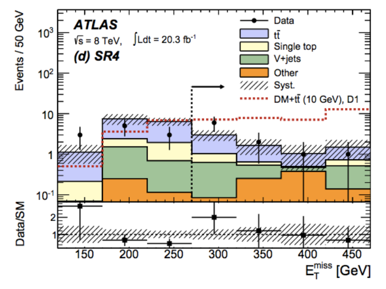


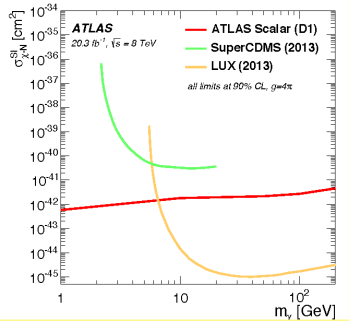
DM plus top quarks

EPJC (2015) 75:92, JHEP 06 (2015) 121, CMS-PAS-B2G-13-004

- Strongest signature with 1L
- uses many "susy" quantities (ATLAS is even a stop search recast)
- 0L (ATLAS) and 2L (ATLAS) also powerful

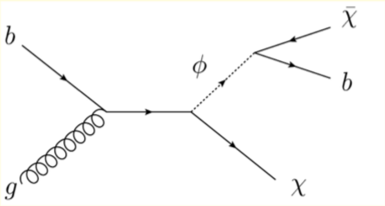






DM plus bottom quarks: simplified models

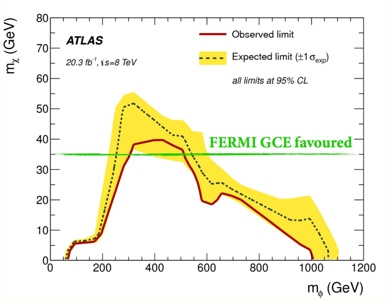
EPJC (2015) 75:92



Three free parameters: m_ϕ, m_χ, g

- m_ϕ spanned from 1 GeV to 1.2 TeV
- m_χ spanned from 1 to 100 GeV
- coupling g fixed by relic density

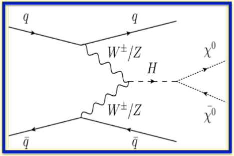
- bottom flavoured DM model (arXiv:1404.1373)
- explain the Galactic Center Excess (GDE) from Fermi via DM annihilation
- complementary search strategy for EFT

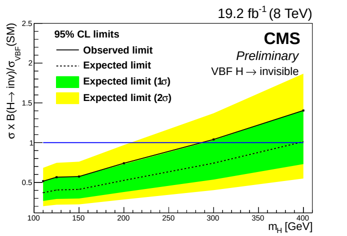


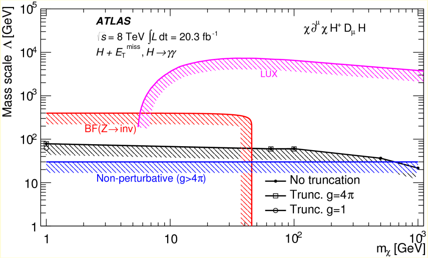
Higgs Portal model

ATLAS-CONF-2015-004, CMS-PAS-HIG-14-038, arXiv:1408.2745

- Higgs could mediate the interaction with the Dark Sector
- If $m_{DM} < M_H/2$: Measure BR(H→ inv.)
- If $m_{DM} > M_H/2$: Higgs + E_T^{miss} searches







CMS VBF/ZH combined

BR(H→ inv.) < 47% (35%)

	ATLAS VBF	ATLAS WH/ZH
BR(H→ inv.) <	29% (35%)	78% (86%)

Run II roadmap
arXiv:1507.00966, arXiv:1506.03116

ATLAS, CMS and the theoretical community, have decided to focus on simplified models in Run II[4]

DM@LHC-2014 proceedings followed by the DMForum Report have agreed upon a minimal set of models which cover a wide range of phenomenology

They will allow to systematically probe *all* corners of the phase space and maximise possibilities for early discovery of DM with the upcoming data!

[4]Without completely forgetting the EFT paradigm but using it more for interpretation than search optimisation

Run II roadmap

Signatures:

jet + E_T^{miss}

EW Boson + E_T^{miss}

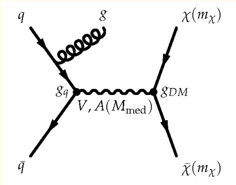
Higgs + E_T^{miss}

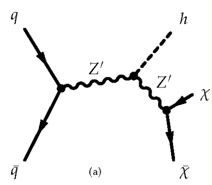
HF + E_T^{miss}

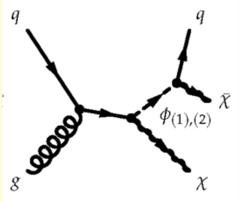
Channels:

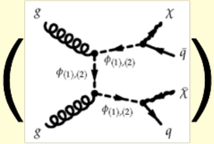
s-channel

t-channel

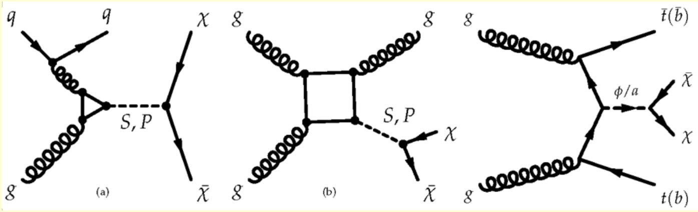






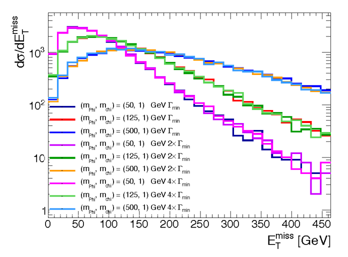


Run II roadmap
Spin-0 simplified models - an example

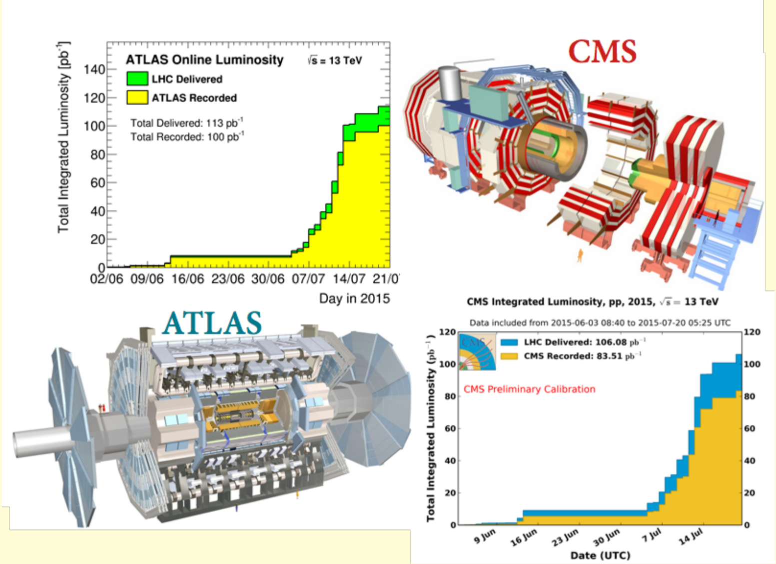


- Free parameters
  $g(= g_{SM} = g_{DM}), m_\chi, m_{med}$
- no dependence of the kinematics on the Γ_{med}

m_χ (GeV)	M_{med} (GeV)								
1	10	20	50	100	200	300	500	1000	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	10000
1000	10							1000	10000

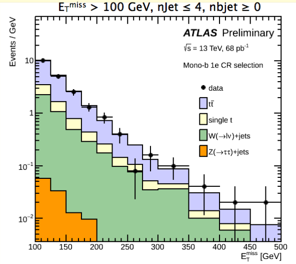


Run II has started!

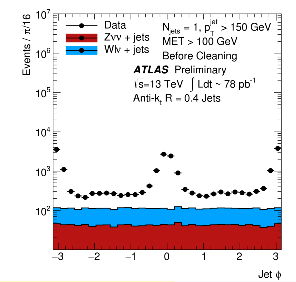


Run II has started!

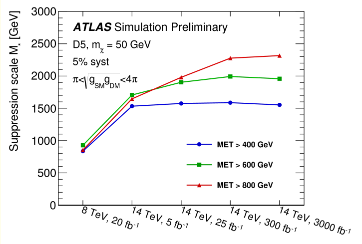
$b + E_T^{miss}$ 1e Control Region



$jet + E_T^{miss}$ Non-collision bkg



- So far good performance of the machine and the experiments
- Analyses ready for quick and effective analysis of incoming data
- Many DM searches will exceed the Run I sensitivity with the first 1-5 fb^{-1}



Summary and conclusions

Disclaimer

This talk did not aim to be a complete nor exhaustive summary of all possible ways we are looking for Dark Matter in ATLAS and CMS as it has obviously left out a lot of material, on purpose or by oversight.

Nevertheless, let me conclude it with a few wishes:

1. I hope it was an interesting introduction.

Summary and conclusions

Disclaimer

This talk did not aim to be a complete nor exhaustive summary of all possible ways we are looking for Dark Matter in ATLAS and CMS as it has obviously left out a lot of material, on purpose or by oversight.

Nevertheless, let me conclude it with a few wishes:

1. I hope it was an interesting introduction.
2. I hope the LHC and the ATLAS and CMS experiments keep having the great performance they had so far during the entire Run II and beyond

Summary and conclusions

Disclaimer

This talk did not aim to be a complete nor exhaustive summary of all possible ways we are looking for Dark Matter in ATLAS and CMS as it has obviously left out a lot of material, on purpose or by oversight.

Nevertheless, let me conclude it with a few wishes:

1. I hope it was an interesting introduction.
2. I hope the LHC and the ATLAS and CMS experiments keep having the great performance they had so far during the entire Run II and beyond
3. I hope we will find Dark Matter hidden somewhere!

Thanks for your attention

References

ATLAS DM searches:

- jet+E_T^{miss}: EPJ C (2015) 75:299, ATL-PHYS-PUB-2014-007,
- HF+E_T^{miss}: EPJ C (2015) 75:79, EPJ C (2015) 75:92
- V+E_T^{miss}: PRL 112, 041802 (2014), PRD 90, 012004 (2014), PRD 91, 012008 (2015)
- Higgs: arxiv:1504.04324, ATLAS-CONF-2015-004, arXiv:1506.01081

CMS DM searches:

- jet + E_T^{miss}: EPJ C 75 (2015) 235, CMS-PAS-EXO-14-004
- HF+E_T^{miss}: CMS-PAS-B2G-13-004, JHEP. 06 (2015) 121, PRL 114 (2015) 101801
- V+E_T^{miss}: CMS-PAS-EXO-13-004, PRL 108 (2012) 261803, CMS-EXO-12-055
- Higgs: EPJC 74:2980, CMS-PAS-HIG-14-038

EFT Validity discussion

- Busoni et al. arXiv:1307.2253
- Busoni et al. arXiv:1402.1275
- Busoni et al. arXiv:1405.3101

Simplified models and Run II roadmaps

- DMForum report arXiv:1507.00966
- DM@LHC proceedings arXiv:1506.03116

  and references therein.

BACKUP

ATLAS EFT truncation procedure

In order to perform EFT truncation, the simplest interaction structure is assumed, then the couplings perturbative ranges and the $M_* \leftrightarrow M_{med}$ relation is deduced.

Table 8 Relations between the mediator mass $M_{\rm med}$ and the suppression scale $M_\star$ for the simplest interaction vertices matching the EFT operators considered here.

Operator(s)	Relation between $M_{\rm med}$ and $M_\star$	Coupling term range
D1	$M_{\rm med} = \sqrt{y_{\rm q} g_\chi}\ \sqrt{M_\star^3/m_q}$	$0 < \sqrt{y_{\rm q} g_\chi} < 4\pi$
C1	$M_{\rm med} = y_{\rm q}\lambda_\chi\zeta_\lambda\ M_\star^2/m_q$	$0 < y_{\rm q}\lambda_\chi\zeta_\lambda < (4\pi)^2\zeta_\lambda$
D5, D8, D9	$M_{\rm med} = \sqrt{g_{\rm q} g_\chi}\ M_\star$	$0 < \sqrt{g_{\rm q} g_\chi} < 4\pi$
D11	$M_{\rm med} = \sqrt[3]{a g_\chi}\ M_\star$	$0 < \sqrt[3]{a g_\chi} < \sqrt[3]{16\pi}$
C5	$M_{\rm med} = \sqrt{a\lambda_\chi\zeta_\lambda}\ M_\star$	$0 < \sqrt{a\lambda_\chi\zeta_\lambda} < 4\sqrt{\pi\zeta_\lambda}$

ATLAS monojet selections

Dark Matter searches at the LHC

Table 2 Event selection criteria applied for the selection of monojet-like signal regions, SR1–SR9.

Selection criteria									
Preselection									
Primary vertex									
$E_T^{miss} > 150$ GeV									
Jet quality requirements									
At least one jet with $p_T > 30$ GeV and $\lvert\eta\rvert < 4.5$									
Lepton and isolated track vetoes									
Monojet-like selection									
The leading jet with $p_T > 120$ GeV and $\lvert\eta\rvert < 2.0$									
Leading jet $p_T/E_T^{miss} > 0.5$									
$\Delta\phi(\text{jet}, \mathbf{p}_T^{miss}) > 1.0$									
Signal region	SR1	SR2	SR3	SR4	SR5	SR6	SR7	SR8	SR9
Minimum E_T^{miss} [GeV]	150	200	250	300	350	400	500	600	700

Table 3 Summary of the methods and control samples used to constrain the different background contributions in the signal regions.

Background process	Method	Control sample
$Z(\to \nu\bar{\nu})$+jets	MC and control samples in data	$Z/\gamma^*(\to \ell^+\ell^-)$, $W(\to \ell\nu)$ ($\ell = e, \mu$)
$W(\to e\nu)$+jets	MC and control samples in data	$W(\to e\nu)$ (loose)
$W(\to \tau\nu)$+jets	MC and control samples in data	$W(\to e\nu)$ (loose)
$W(\to \mu\nu)$+jets	MC and control samples in data	$W(\to \mu\nu)$
$Z/\gamma^*(\to \ell^+\ell^-)$+jets ($\ell = e, \mu, \tau$)	MC-only	
$t\bar{t}$, single top	MC-only	
Diboson	MC-only	
Multijets	data-driven	
Non-collision	data-driven	

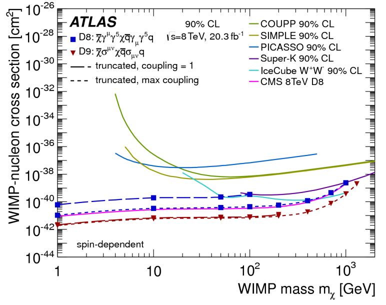
CMS monojet (razor) selections

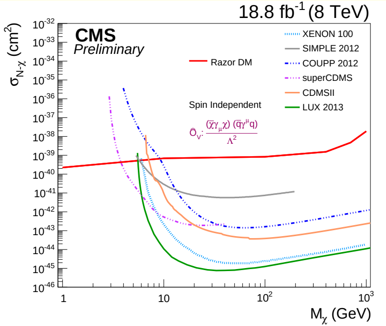
Table 2: Definition of the event categories based on the M_R value, the muon multiplicity, and the output of the CSV b-tagging algorithm. For all the samples, $R^2 > 0.5$ is required.

Sample	b-tagging selection	M_R selection
0μ, 1μ, and 2μ	no CSV loose jet	$200 < M_R \leq 300$ GeV (VL) $300 < M_R \leq 400$ GeV (L) $400 < M_R \leq 600$ GeV (H) $M_R > 600$ GeV (VH)
0μbb	≥ 2 CSV tight jets	$M_R > 200$ GeV
0μb	=1 CSV tight jets	
1μb	≥ 1 CSV tight jets	
2μb		
$Z(\mu\mu)$b	≥ 1 CSV loose jets	

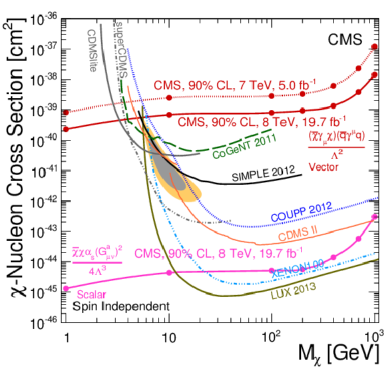
CMS monojet non razor results

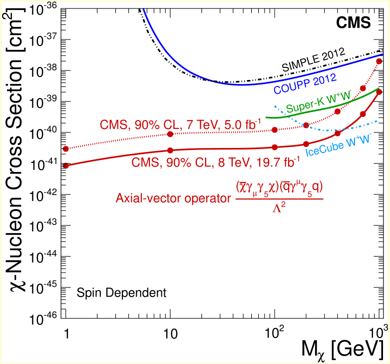
The plot


ATLAS
90% CL
$\sqrt{s}$=8 TeV, 20.3 fb^{-1}
D8: $\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\bar{q}\gamma_{\mu}\gamma^{5}q$
D9: $\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
truncated, coupling = 1
truncated, max coupling
COUPP 90% CL
SIMPLE 90% CL
PICASSO 90% CL
Super-K 90% CL
IceCube W$^+$W$^-$ 90% CL
CMS 8TeV D8
spin-dependent
WIMP-nucleon cross section [cm^2]
WIMP mass m_χ [GeV]

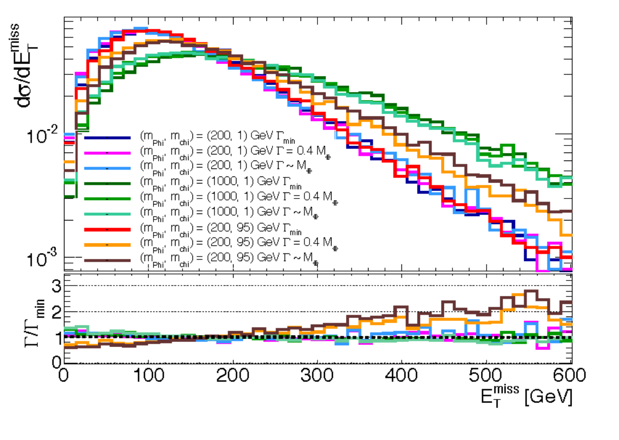

18.8 fb^{-1} (8 TeV)
CMS
Preliminary
Razor DM
XENON 100
SIMPLE 2012
COUPP 2012
superCDMS
CDMSII
LUX 2013
Spin Independent
$\hat{O}_V$: $\frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$
$\sigma_{N\text{-}\chi}$ (cm^2)
M_χ (GeV)

The plot (CMS no razor)





Details on the spin-0 simplified model width



$H(\gamma\gamma)$+$E_{\mathrm{T}}^{\mathrm{miss}}$ searches - arXiv:1506.01810

- not ISR, probe coupling structure
- both EFT and simpl. models
- $H \rightarrow \gamma\gamma$: distinct resonance, low $E_{\mathrm{T}}^{\mathrm{miss}}$ bkg events
- major irr. bkg: $Z(\nu\nu)H$, $Z\gamma$, non res diphoton prod.

Selections:

- tight isolated photons (trigger $P_T > 35 GeV$),
- $m_{\gamma\gamma} \in [105, 160]$, $p_{T,1/2}^{\gamma} > 0.35(0.25)m_{\gamma\gamma}$, $p_T^{\gamma\gamma} > 90$ GeV
- $E_{\mathrm{T}}^{\mathrm{miss}} > 90$ GeV

$H(\gamma\gamma)$+E_T^{miss} searches - arXiv:1506.01810

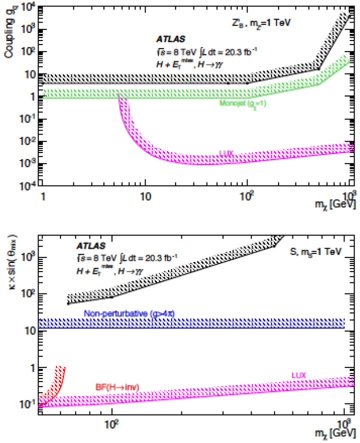


FIG. 5: Limits on coupling parameters for simplified models with a heavy mediator with mass of 1 TeV. All constraint contours exclude larger couplings or mixing angles. Regions excluded due to perturbativity arguments are indicated; red, green and pink contours denote results from collider searches for invisible H decays [52], and monojet [6] searches, and the LUX Collaboration [51], respectively.

VBF Higgs to invisible - ATLAS-CONF-2015-004, CMS-PAS-HIG-14-038

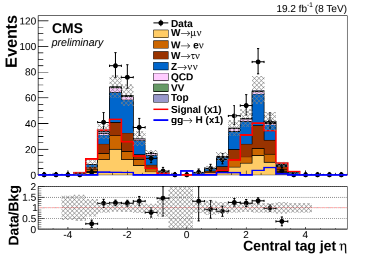
ATLAS

Process	Yield	±	Stat	±	Syst
ggH Signal	20	±	6	±	10
VBF Signal	286	±	5	±	49
$Z \to \nu\nu$+jets	339	±	22	±	13
$W \to \ell\nu$+jets	237	±	17	±	18
Multijet	2	±	2		
Other Backgrounds	0.7	±	0.2	±	0.3
Total Background	578	±	38	±	30
Data	539				

Selections:

- 2 jets $p_T > 75, 50$ GeV, b-jets, τ and lepton vetoes
- $m_{jj} > 1$TeV and VBF cuts on jets
- $E_T^{miss} > 150$ GeV

CMS



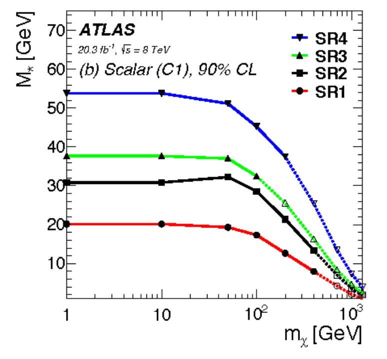
Process	Event yields
$Z \to \nu\nu$	$158.1 \pm 37.3 \pm 21.2$
$W \to \mu\nu$	$102.5 \pm 6.2 \pm 11.7$
$W \to e\nu$	$57.9 \pm 7.4 \pm 7.7$
$W \to \tau\nu$	$94.6 \pm 13.1 \pm 23.8$
top	5.5 ± 1.8
VV	3.9 ± 0.7
QCD multijet	17 ± 14
Total Background	$439.4 \pm 40.7 \pm 43.5$
Signal(VBF)	273.1 ± 31.2
Signal(ggH)	23.1 ± 15.9

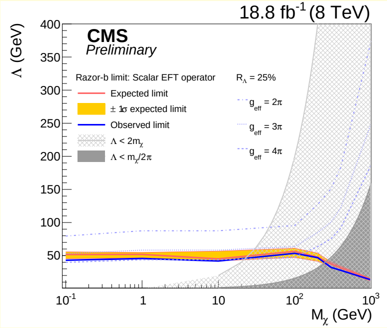
DM plus bottom quarks

EPJC (2015) 75 92, CMS-PAS-EXO-14-004

ATLAS

- 1 or 2 jets, $\geqslant$ 1 b-jet, E_T^{miss} and b-jet p_T requirements
- 3 or4 jets, $\geqslant$ 1 b-jet, E_T^{miss} and jets p_T reqirements





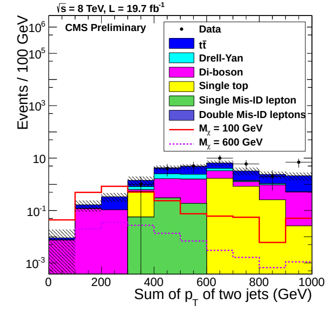
CMS

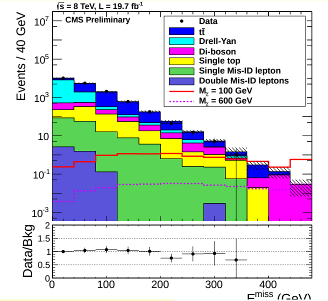
- Razor variables
- 1 or 2 b-jets

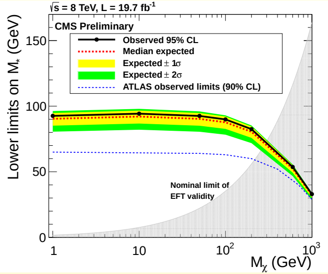
DM+tt dilepton

Dark Matter searches at the LHC

- 2 leptons $p_T >$, $m_{ll} > 20$, Z veto
- $E_T^{miss} > 320$ GeV
- at least 2 jets, $H_T^{2j} < 400 GeV$





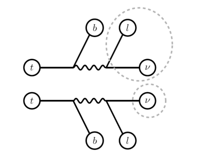


DM+HF ATLAS - arXiv:1410.4031v2

Table 1 Selections for signal regions 1–4. Variables $p_T^{j_i}$ ($p_T^{b_i}$) represent the transverse momentum of the i-th jet (b-tagged jet). The asymmetric transverse mass am_{T2} [29–31], *topness* [32], m_{jjj} and Razor R [33] are used to reject the abundant top quark background.

	SR1	SR2	SR3	SR4
Trigger	E_T^{miss}	E_T^{miss}	5 jets || 4jets(1b)	E_T^{miss} || 1 lepton (no τ)
Jet multiplicity n_j	1–2	3–4	≥5	≥4
b-jet multiplicity n_b	>0 (60% eff.)	>0 (60% eff.)	>1 (70% eff.)	>0 (70% eff.)
Lepton multiplicity n_ℓ	0	0	0	1 ℓ ($\ell = e, \mu$)
E_T^{miss}	>300 GeV	>300 GeV	>200 GeV	>270 GeV
Jet kinematics	$p_T^{b_1} > 100$ GeV	$p_T^{b_1} > 100$ GeV $p_T^{j_2} > 100$ (60) GeV	$p_T^{j} > 25$ GeV	$p_T^{b_1} > 60$ GeV $p_T^{1\text{-}4} > 80, 70, 50, 25$ GeV
Three-jet invariant mass				$m_{jjj} < 360$ GeV
$\Delta\phi\left(j_i, E_T^{miss}\right)$	$> 1.0,\ i = 1,2$	$> 1.0,\ i = 1-4$	-	$> 0.6,\ i = 1,2$
Angular selections	-	-	$\Delta\phi\left(b_1, E_T^{miss}\right) \geq 1.6$	$\Delta\phi\left(\ell, E_T^{miss}\right) > 0.6$ $\Delta R\left(\ell, j_1\right) < 2.75$ $\Delta R\left(\ell, b\right) < 3.0$
Event shape	-	-	Razor R >0.75	*topness* >2
am_{T2}	-	-	-	>190 GeV
$m_T^{\ell+E_T^{miss}}$	-	-	-	>130 GeV
$E_T^{miss}/\sqrt{H_T^{4j}}$	-	-	-	>9 $\sqrt{\text{GeV}}$

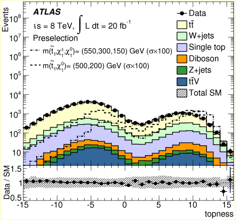
Details on topness



W from missed lepton

top from identified lepton

$$S(P_{wx}, P_{wy}, P_{wz}, p_{\nu z}) = \frac{\left(m_W^2 - p_W^2\right)^2}{\sigma_W^4} + \frac{\left(m_t^2 - (p_{b1} + p_\ell + p_\nu)^2\right)^2}{\sigma_t^4} + \frac{\left(m_t^2 - (p_{b2} + p_W)^2\right)^2}{\sigma_t^4} + \frac{\left(4m_t^2 - (\sum_i p_i)^2\right)^2}{\sigma_{CM}^4}$$

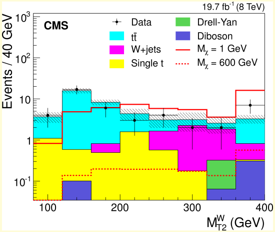


top from missed lepton

reconstructed CM energy of the event minimised

[4] arXiv:1212.4495v1

Details on stransverse masses

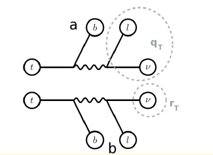


$\tilde{X} \to l\tilde{\chi}$ or any particle, pair produced which decay into a visible and invisible particle.

$m_{T2} \leqslant m_{\tilde{X}}$

visible decay products

$$m_{T2} \equiv \bigcup_{\vec{q}_T+\vec{r}_T=\vec{p}_T^{\text{miss}}} \min\{ \max \; [m_T(\vec{p}_a, \vec{q}_T), m_T(\vec{p}_b, \vec{r}_T)]\}$$



decompose the $\vec{p}_T^{\text{miss}}$ into two vectors and minimise over all combinations

[4] Physics Letters B 463 (1999) 99-103