
# Can the MET searches at the LHC be optimised further?

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based on a almost-submitted paper with:
*Banerjee, Barducci, Belanger, Fuks and Goudelis*

(dorénavant  refered-to as "BBBFGZ")

# Outline

- MET searches at the LHC
- Possible roads of optimisation
- LHC combined constraints on pseudoscalar mediated dark matter
- Conclusion

# MET searches at the LHC

DM is assumed to be a Weakly Interacting Massive Particle (WIMP):

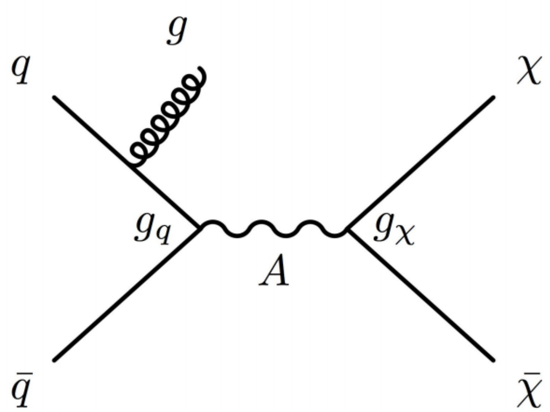
- Search for ***missing transverse momentum (MET)***
- Tag the process with unbalanced emission of other visible stuff

$$\vec{p}^{\,T}_{\rm visible} + \vec{p}^{\,T}_{\rm missing} = \vec{0}$$

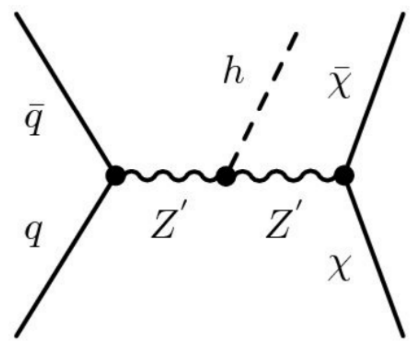
- Searches divided in **"Mono-X" (+ MET)** and **Multi-X + MET**
    - X = jet, photon, lepton, Higgs, heavy-quark
    - *Mostly suitable for "Simplified Models of Dark Matter"*

    - X = jets, leptons, etc…
    - *Mostly suitable for Supersymmetry*

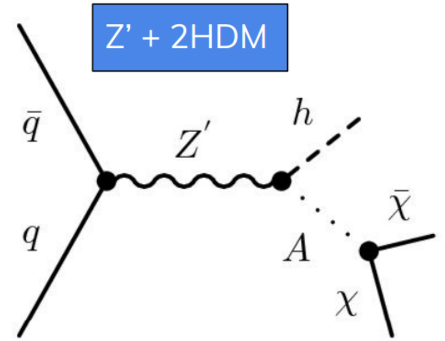
# Some mono-X processes



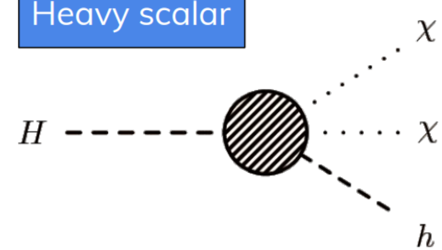

Z’ with Higgs boson coupling

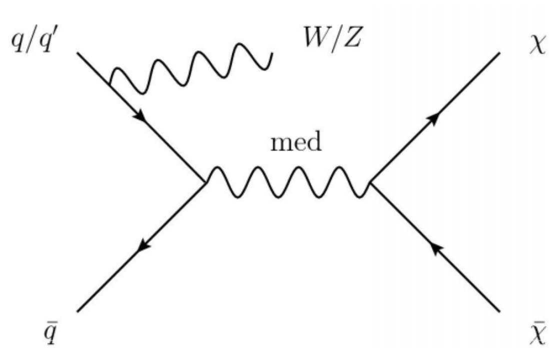


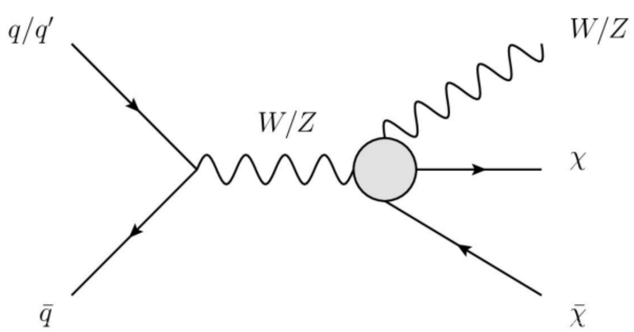

Z’ + 2HDM

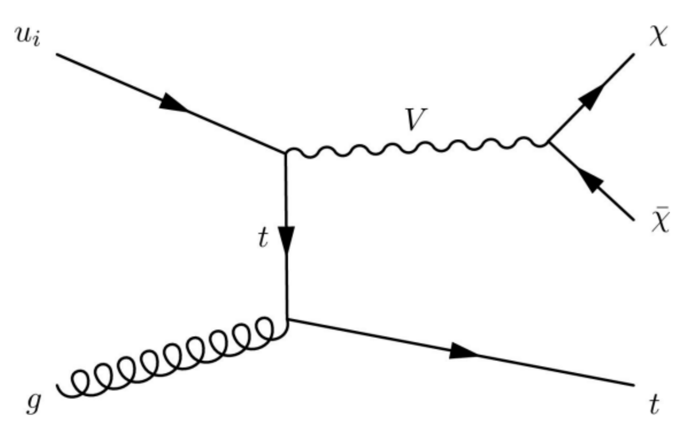



Heavy scalar



# Simplified models of DM (SMDM)

Spin-1 mediators:

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

$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}}\, Z'_\mu\, \bar{\chi}\gamma^\mu\gamma_5\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu\, \bar{q}\gamma^\mu\gamma_5 q - g_\ell \sum_{\ell=e,\mu,\tau} Z'_\mu\, \bar{\ell}\gamma^\mu\gamma_5\ell\,.$$

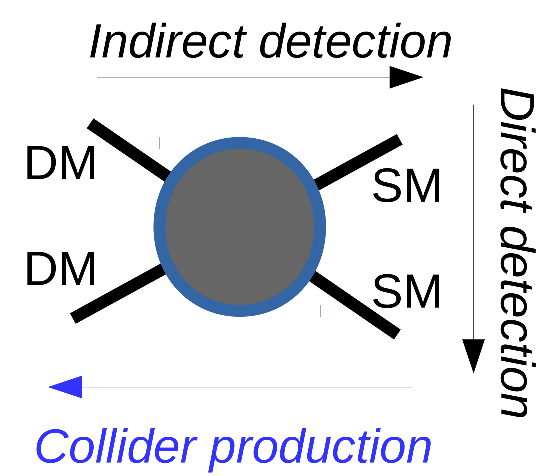
Spin-0 mediators:

$$\mathcal{L}_{\text{scalar}} = -y_\chi S\bar{\chi}\chi - \sum_{f_u} c_u \frac{m_{f_u}}{v} S\bar{f}_u f_u - \sum_{f_d} c_d \frac{m_{f_d}}{v} S\bar{f}_d f_d$$

$$\mathcal{L}_{\text{p}-\text{scalar}} = -iy_\chi S\bar{\chi}\gamma^5\chi - i\sum_{f_u} c_u \frac{m_{f_u}}{v} S\bar{f}_u\gamma^5 f_u - i\sum_{f_d} c_d \frac{m_{f_d}}{v} S\bar{f}_d\gamma^5 f_d$$

# Phenomenology of SMDM

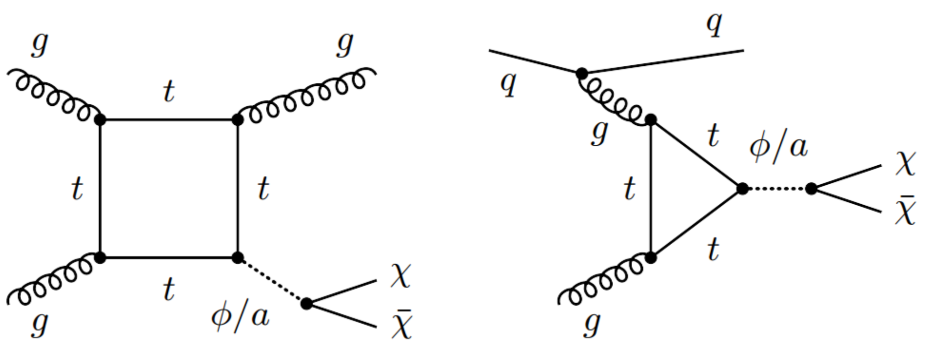
| | Direct Detection | | Indirect Detection |
|---|---|---|---|
| | SI | SD | |
| $\mathcal{L}_{\rm vector}$ | yes | no | yes |
| $\mathcal{L}_{\rm axial}$ | no | yes | $\propto m_f^2$ |
| $\mathcal{L}_{\rm scalar}$ | yes | no | no |
| $\mathcal{L}_{\rm p-scalar}$ | no | yes-but-no | yes |



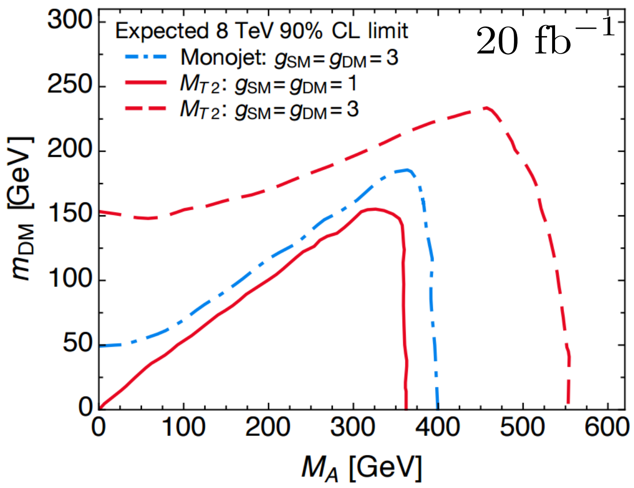

*As for the LHC…(given sizeable couplings to everyone)*

| | vector/axial | scalar/pscalar |
|---|---|---|
| monojet + MET | good | good |
| multijets + MET | not-as-good | potentially better |
| $t\bar{t}(b\bar{b})$ + MET | not-as-good | very good |
| dijets/dileptons | very good | poor |
| diphotons | no | good |
| $t\bar{t}, \tau\bar{\tau}, b\bar{b}$ | not-as-good | very good |

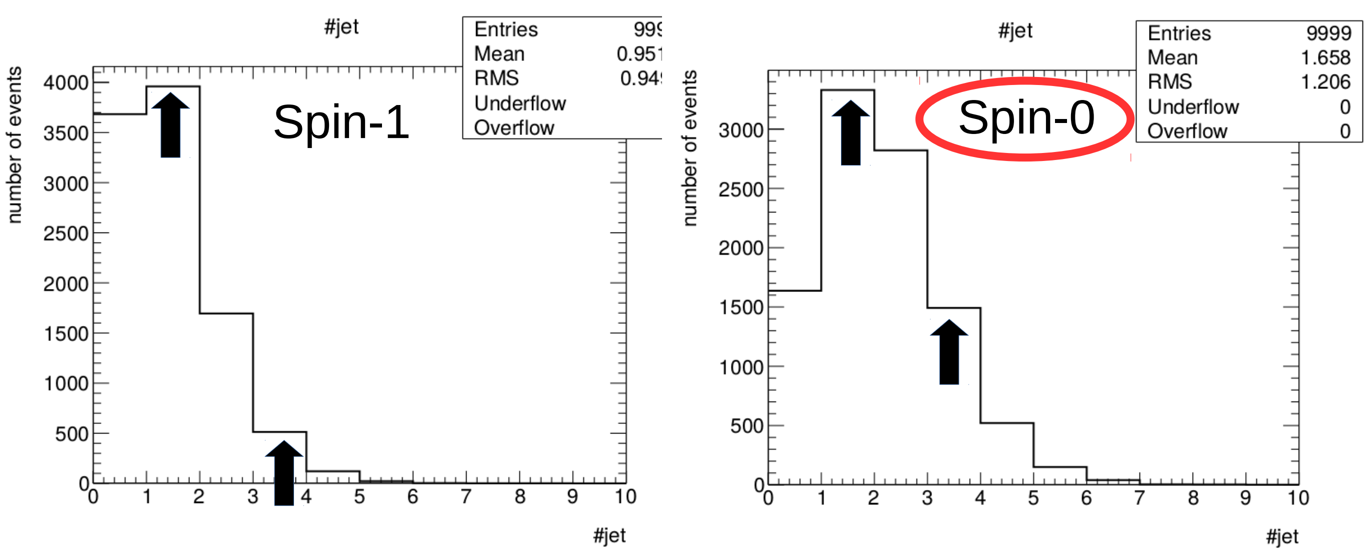
# Producing spin-0 mediators at the LHC




Buchmüller, Malik,
McCabe, Penning, 1505.07826




**Richer hadronic activity:**

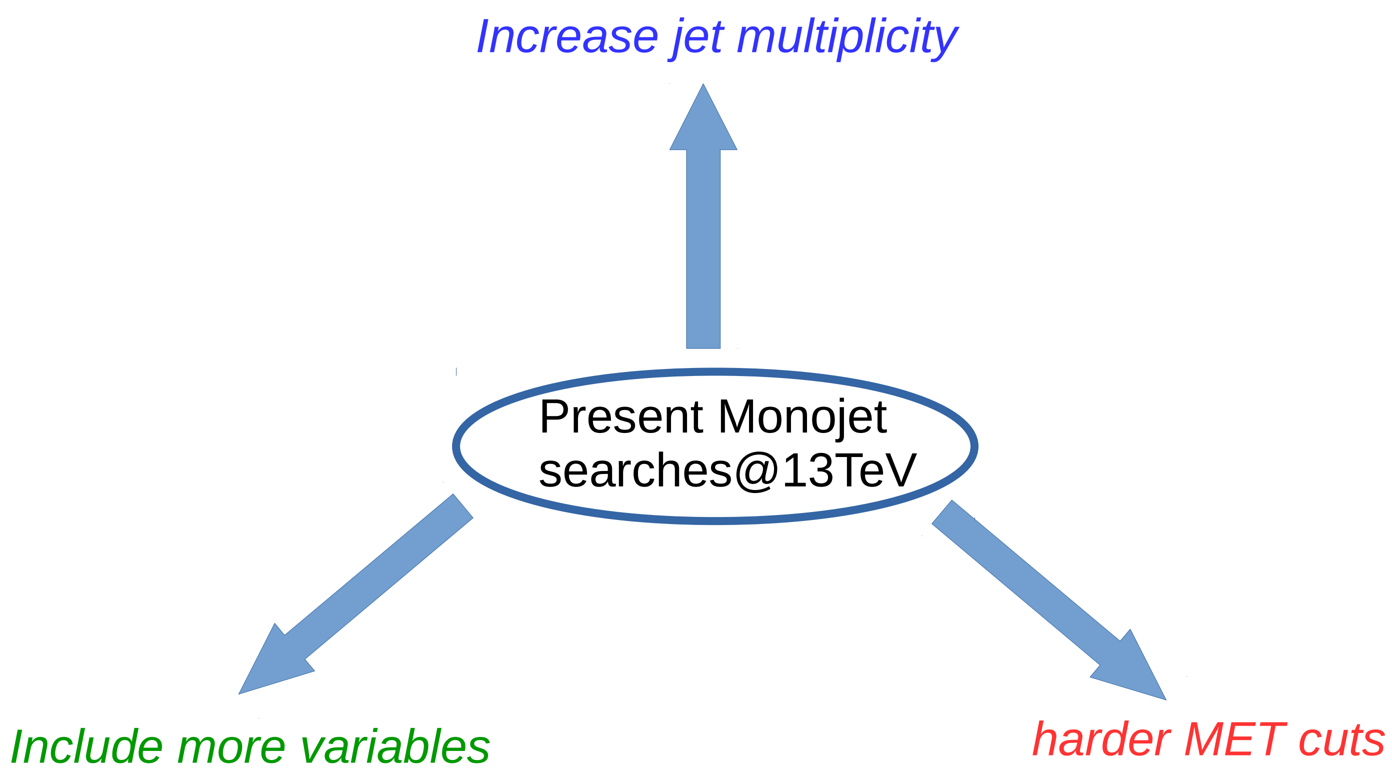



$N_{3j}/N_{1j} \sim 0.12$ $\qquad$ $N_{3j}/N_{1j} \sim 0.44$

above based on
a CMS MT2-analysis,
a priori similar results
for other multijet
searches

**allowing for more jets should increase exclusion power**

# Possible roads to MET searches optimisation




*Disclaimer:*
This is a poor theorist’s approach to the problem;
not intended to be exhaustive in all possible directions

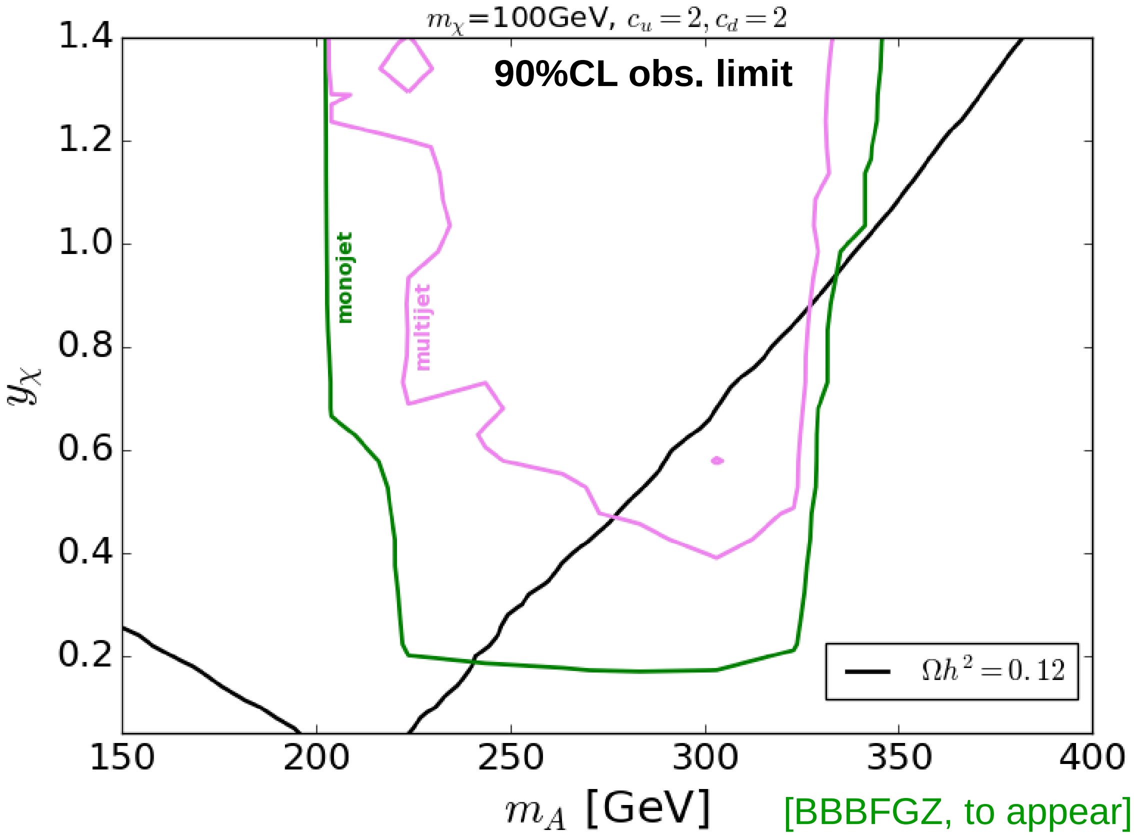
# Increasing jet multiplicity

$$\mathcal{L}_{\rm p-scalar} = -iy_\chi S\bar{\chi}\gamma^5\chi - i\sum_{f_u} c_u \frac{m_{f_u}}{v} S\bar{f}_u\gamma^5 f_u - i\sum_{f_d} c_d \frac{m_{f_d}}{v} S\bar{f}_d\gamma^5 f_d$$

Take the last analyses:

**- monojet: ATLAS, 1604.07773**
wrt previous analysis:
(ATLAS-8TeV, 1502.01518)
- harder MET preselection
- up to 4 jets with pt >30GeV

**- multijet: ATLAS, 1605.03814**
wrt to previous analysis:
(ATLAS-8TeV, 1405.7875)
- similar event selection




[BBBFGZ, to appear]

***Failure reasons:***
- Monojet is not a monojet anymore
- monojet is tuned for SMDM, whereas multijet is tuned for SUSY models

# Harder MET cuts

**Existing analysis:** (ATLAS, 1604.07773)

- inclusive signal regions up to MET > 700 GeV
- exclusive signal regions up to 600 GeV < MET < 700 GeV

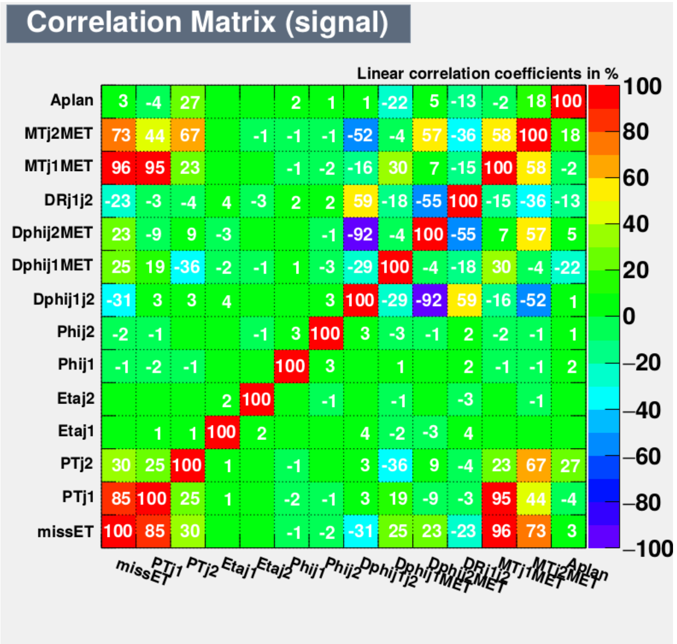
**New Signal Regions:**

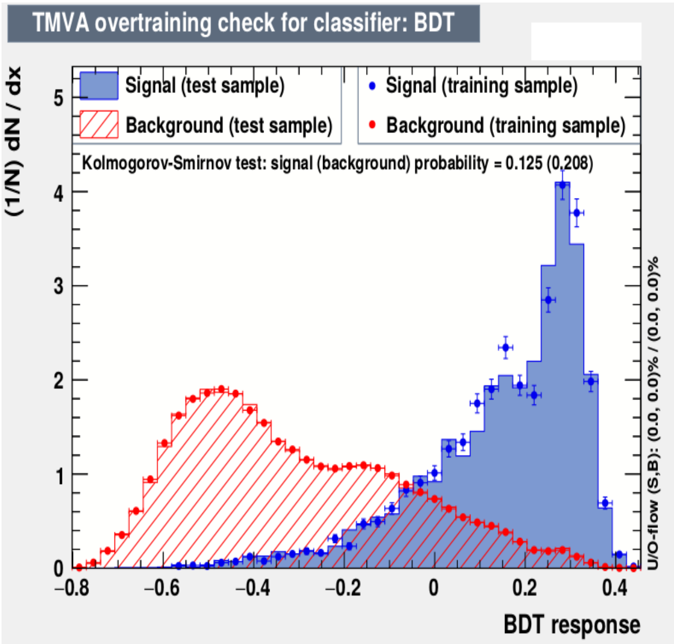
- inclusive signal regions: MET > 800 GeV, 1000 GeV, 1200 GeV

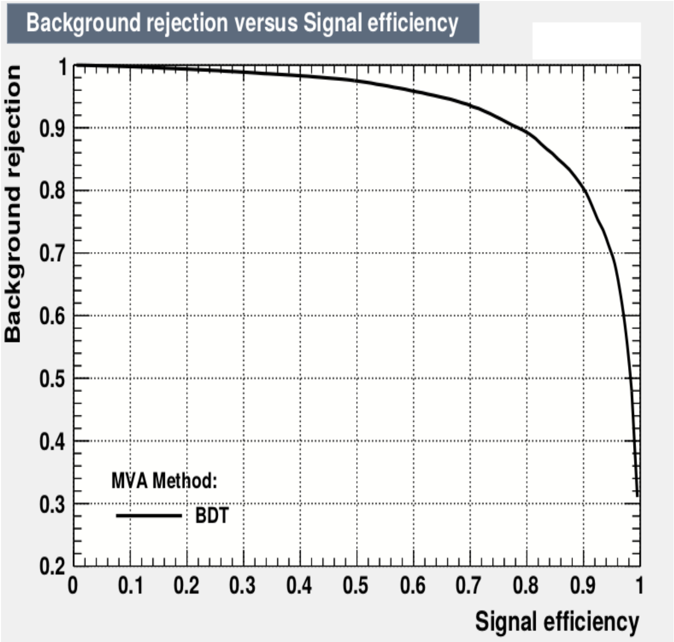
| **Results:** $(c_u = c_d = 3)$ | CL exclusion | |
|---|---|---|
| | Existing | New |
| $m_A = 300\text{GeV},\ m_\chi = 5\text{GeV},\ y_\chi = 0.1$ | 0.9 | 0.97 |
| $m_A = 300\text{GeV},\ m_\chi = 10\text{GeV},\ y_\chi = 0.1$ | 0.91 | 0.98 |
| $m_A = 100\text{GeV},\ m_\chi = 5\text{GeV},\ y_\chi = 0.05$ | 0.53 | 0.50 |
| $m_A = 100\text{GeV},\ m_\chi = 20\text{GeV},\ y_\chi = 0.05$ | 0.53 | 0.49 |

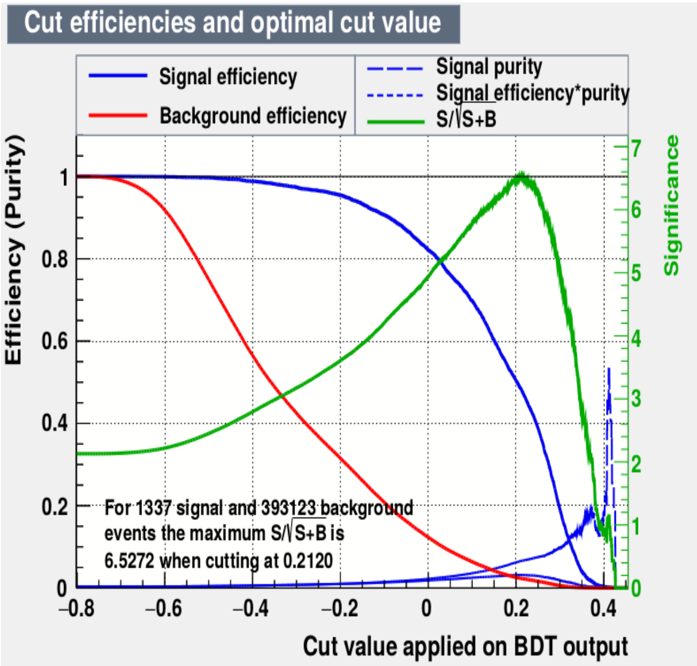
**Null to marginal improvement (too tight MET cuts)**

# Ultimate try: Multivariate analysis




- **Boosted Decision Tree** (`ROOT`, ~ 200 trees)
- Many more kinematical variables
- Loose preselection cuts

**Result:**

$$S/\sqrt{S+B} \sim 6.53$$

compared to:

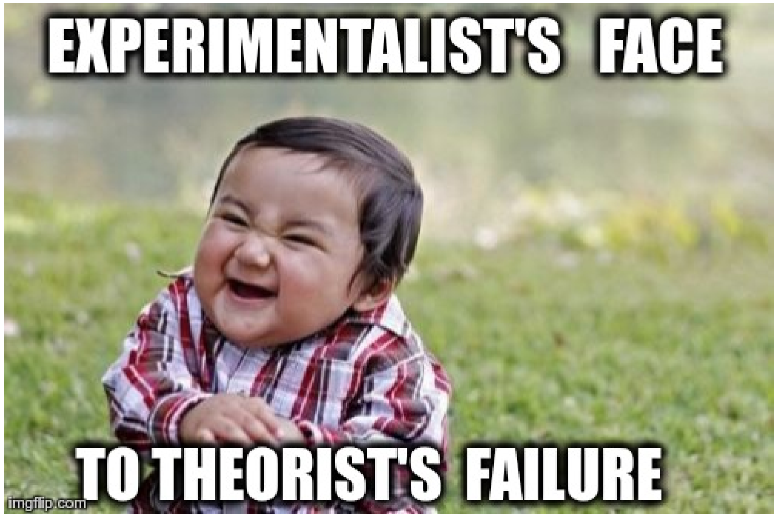
$$S/\sqrt{S+B} \sim 6.49$$

from actual monojet search

**Marginal improvement (again!)**

*Conclusions for the "entreacte":*

**- Optimisation of nowadays monojet analyses is marginal at best**




**- Not even great improvement at high lumi (large-ish syst. uncert. ~ 5-11%)**

# But back to the model...

$$\mathcal{L}_{\rm p-scalar} = -i y_\chi S \bar{\chi}\gamma^5\chi - i\sum_{f_u} c_u \frac{m_{f_u}}{v} S\bar{f}_u\gamma^5 f_u - i\sum_{f_d} c_d \frac{m_{f_d}}{v} S\bar{f}_d\gamma^5 f_d$$

Plenty of constraints apart from mono/multijets+MET !

**- Involving MET:**

$t\bar{t}A(A\to\chi\chi)$ [CMS-PAS-EXO-16-005, ATLAS-CONF-2016-050 Haish, Pani, Polesello, 1611.09841]

$b\bar{b}A(A\to\chi\chi)$ [CMS-PAS-B2G-15-007, ATLAS-CONF-2016-050]

**- Not Involving MET:**

$\tau^+\tau^-$ [CMS-PAS-HIG-16-037]

$t\bar{t}$ [ATLAS 1406.5375, ATLAS 1505.07018, CMS-TOP-16-006]

$\gamma\gamma$ [ATLAS-CONF-2016-059]

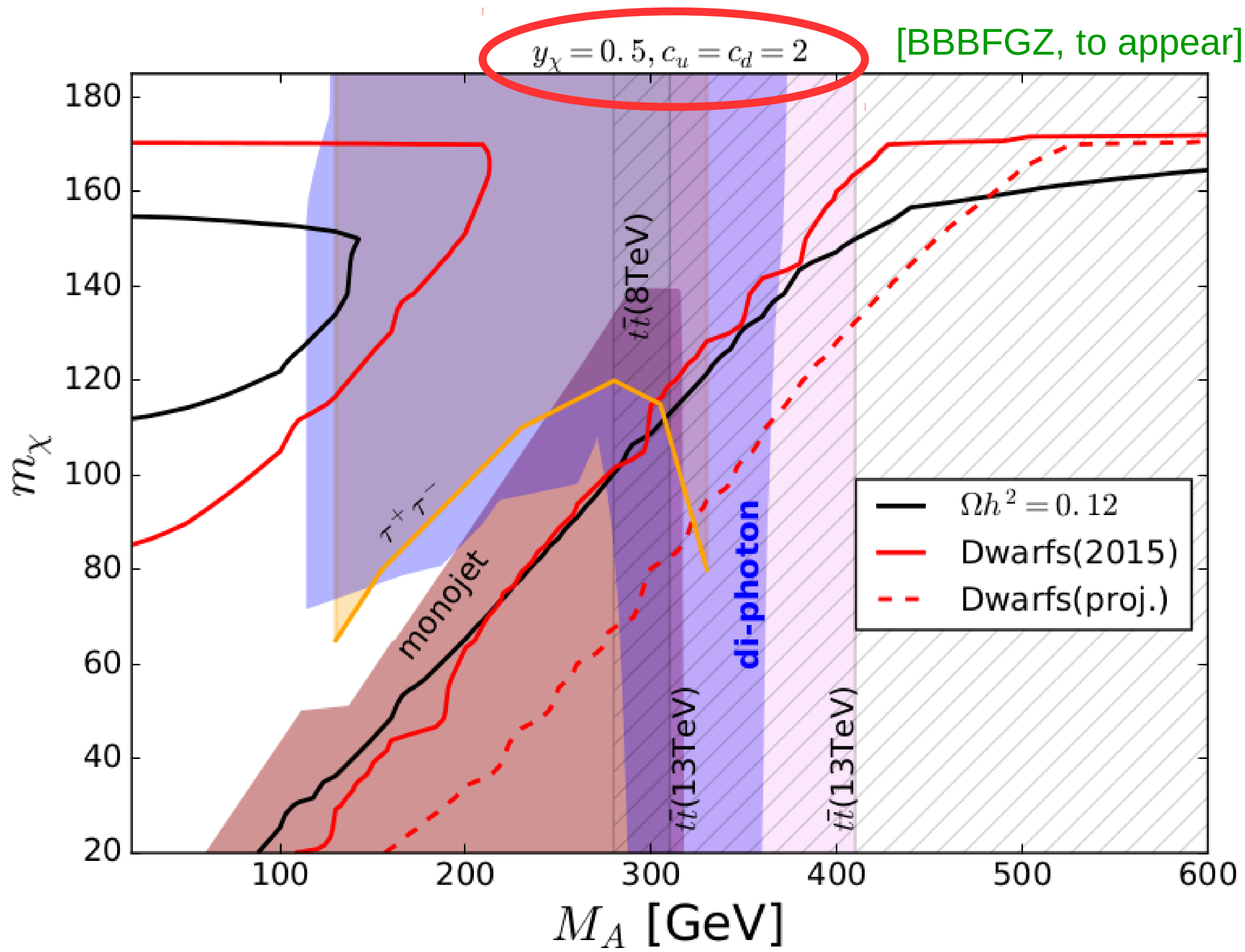
$\tau^+\tau^-, b\bar{b}$ (LEP) [DELPHI hep-ex/0410017]

**- others…**
dijets, monophoton, EWPT**, flavour, etc.

*Note:*
*spin-1 mediator SMDM may not have that many relevant collider constraints*!!

# Cornering the model (i)

*For the mass-mass enthusiasts...*



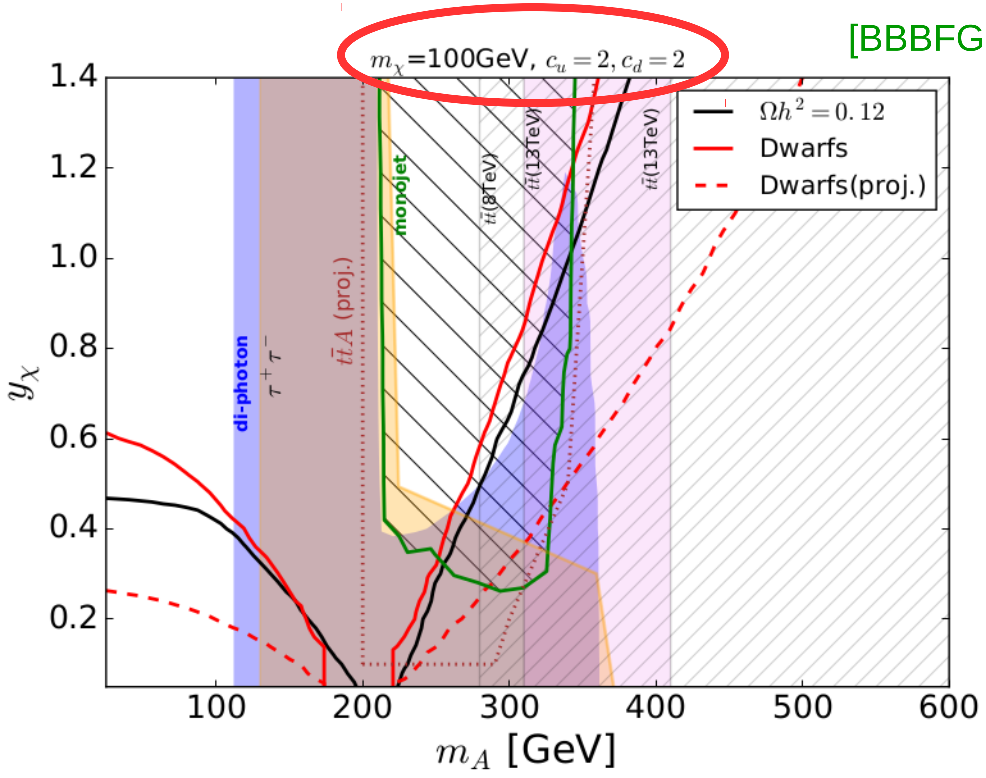

*- dark matter only survives in the off-shell region (DM > mediator)*

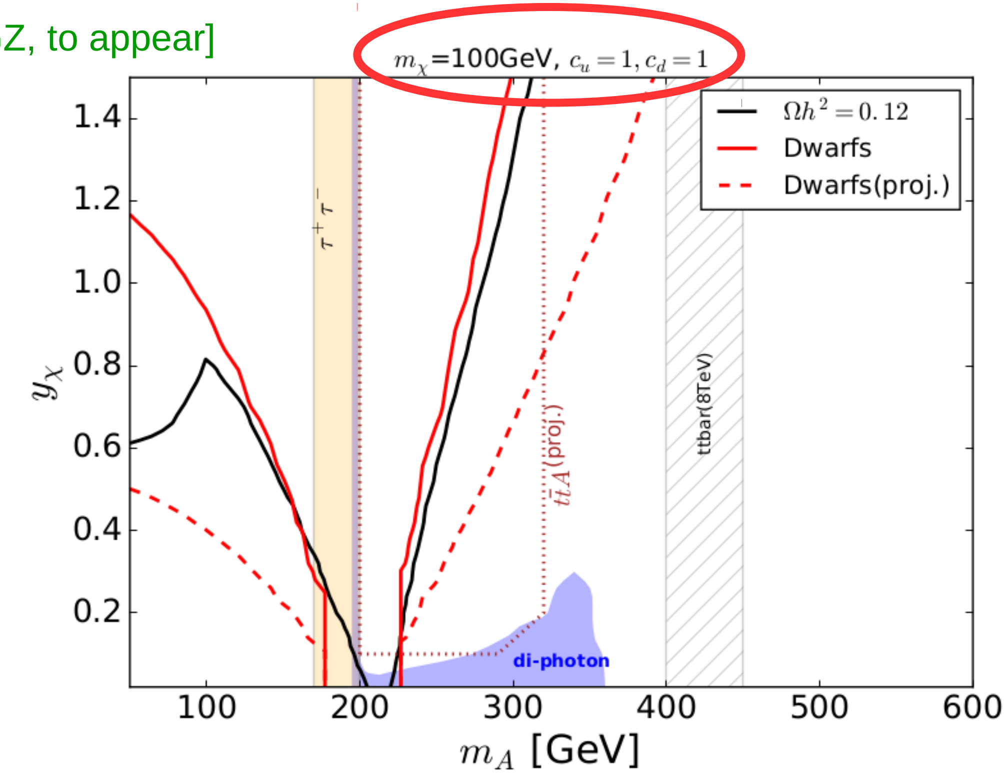
*- perfect complementarity between MET and non-MET searches*

# Cornering the model (ii)

*A -maybe- more illustrative way to look at it….*

[BBBFGZ, to appear]




*- larger couplings to quarks exclude even below 100GeV*
*- larger DM masses less sensitive to LHC constraints*
*- bottom-dominated scenarios excluded up to ~600GeV mediator*
*- smaller DM masses essentially excluded by Dwarfs*
*- Future dwarf constraints excluding DM below ~250GeV*

# Conclusions

**MET searches at the LHC are already highly optimised**
**(a.k.a. rediscovering the hot water)**

**Pseudoscalar model quite rich in LHC constraints**
- Complementarity between MET and not-MET searches
- top searches strongest if couplings are sizeable

**Dark matter favoured regions cornered to the of-shell regime, unless suppressed quark couplings**

**Grant marci!!**

# Dark matter favoured regions