# Dark matter and LHC complementarity to constrain new physics

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LAPTh

based on arXiv:1705.02327 with
*D. Barducci, G. Bélanger, B. Fuks, A. Goudelis and B. Zaldivar*

# Outline

- MET searches at the LHC: a brief summary

- Recasting monojet and multijet analyses using MadAnalysis 5

- Possible roads of optimisation: new signal regions and MVA

- LHC combined constraints on pseudoscalar mediated dark matter: complementarity

- Conclusions

# MET searches at the LHC

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

Strategies:

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

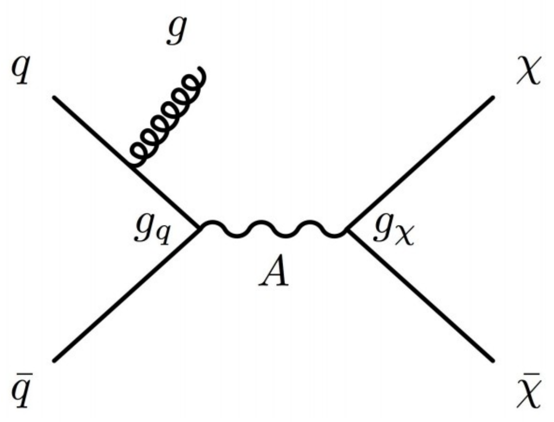
$$\vec{p}^{\,T}_{\rm visible} + \vec{p}^{\,T}_{\rm missing} = \vec{0}$$

- Searches divided in **"Mono-X" (+ MET)** and **Multi-X + MET**

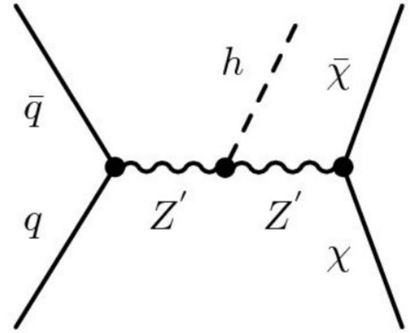
  - X = jet, photon, lepton, Higgs, heavy-quark (single and pair)
  - *Mostly suitable for "Simplified Models of Dark Matter"*

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

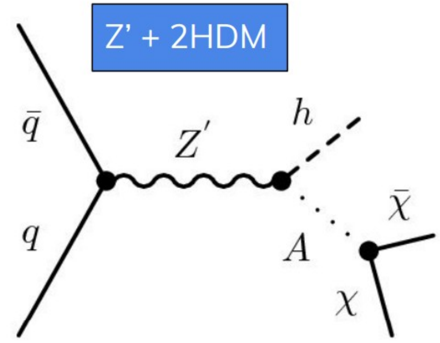
# Some mono-X processes: Mono-jet, mono-W/Z, mono-Higgs and mono-top



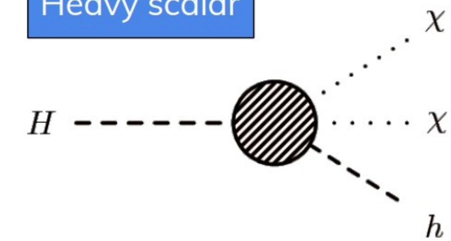

Z' with Higgs boson coupling

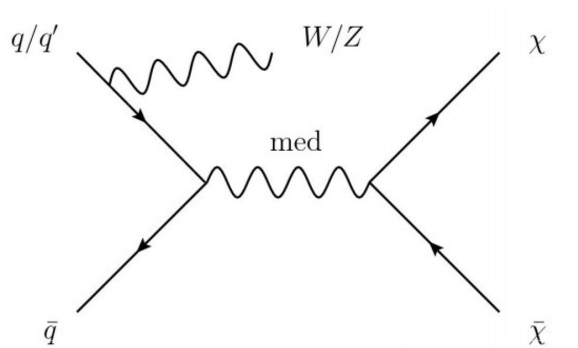


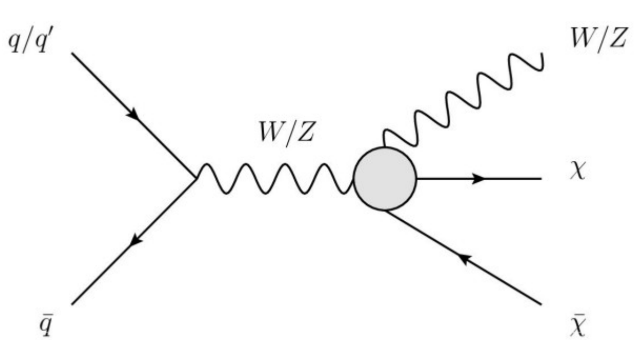

Z' + 2HDM

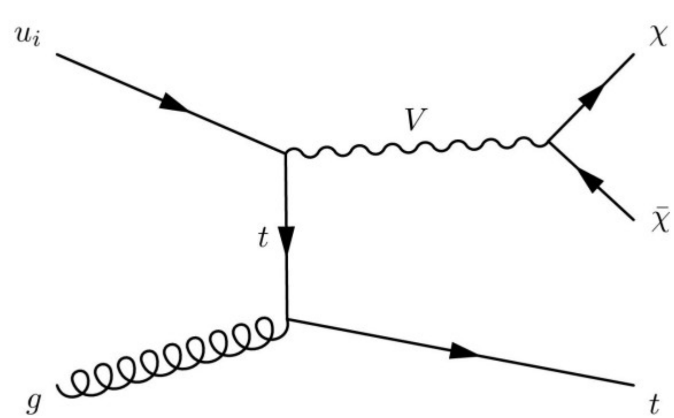



Heavy scalar



# Di-Higgs: one Higgs decaying invisibly

- In presence of a resonance di-Higgs production
- bb + MET final state
- Lower MET than optimised mono-Higgs searches
- Potential to constrain Higgs invisible BR to ~ 5% or less with $L \sim 120\ \mathrm{fb}^{-1}$
- Presence of a heavy scalar ~ 500 GeV

arXiv:1608.08601 (PRD): *SB, B. Batell, M. Spannowsky*

# 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:

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

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

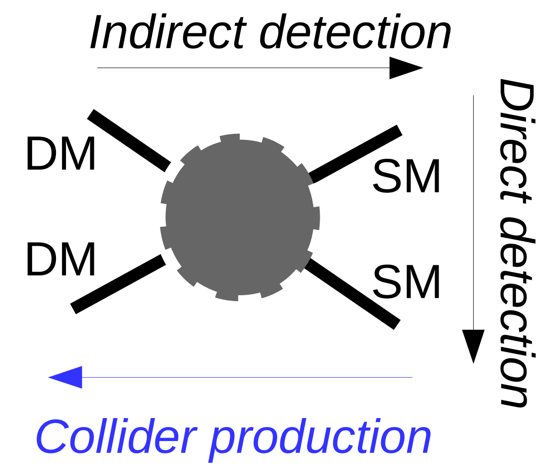
The Yukawa couplings are taken In the spirit of the minimal flavour violation (MFV): proportional to mass of the fermion to the vacuum expectation value.

For UV complete (high-scale valid), gauge invariant models, a non-minimal approach is necessary: Example: 2HDM + pseudoscalar + DM !!!

# Phenomenology of SMDM

*SI = spin-independent, SD = spin-dependent dark matter-nucleon scattering cross-sections*

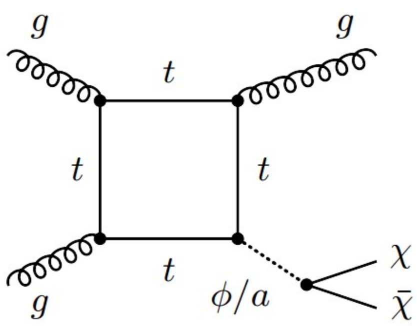
| | Direct Detection | | Indirect Detection |
|---|---|---|---|
| | SI | SD | |
| $\mathcal{L}_{\rm vector}$ | yes | no | yes |
| $\mathcal{L}_{\rm axial}$ | no | yes | $\propto m_f^2$ |
| $\mathcal{L}_{\rm scalar}$ | yes | no | no |
| $\mathcal{L}_{\rm p-scalar}$ | no | yes-but-no | yes |

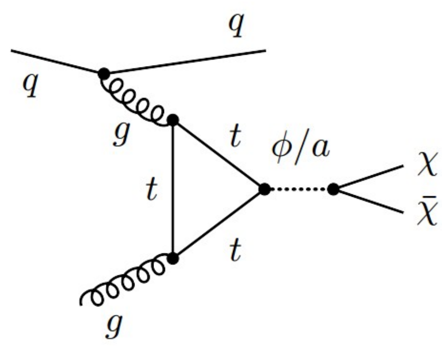



*As for the LHC…(given sizeable couplings to everyone)*

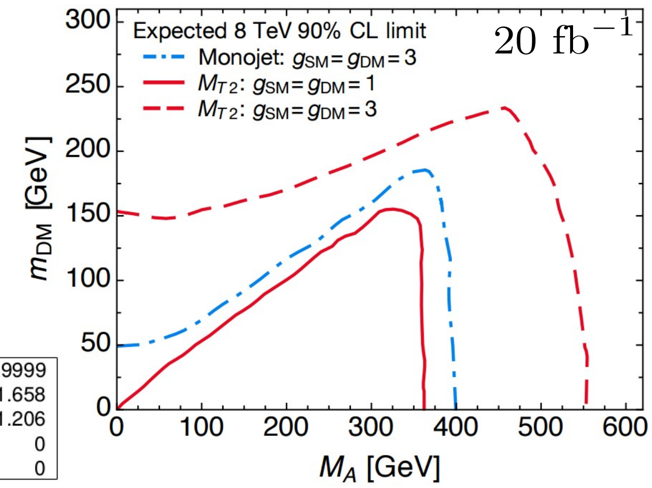
| | vector/axial | scalar/pscalar |
|---|---|---|
| monojet + MET | good | good |
| multijets + MET | not-as-good | potentially better |
| $t\bar{t}(b\bar{b})$ + MET | not-as-good | very good |
| dijets/dileptons | very good | poor |
| diphotons | no | good |
| $t\bar{t}, \tau\bar{\tau}, b\bar{b}$ |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

# Producing spin-0 mediators at the LHC

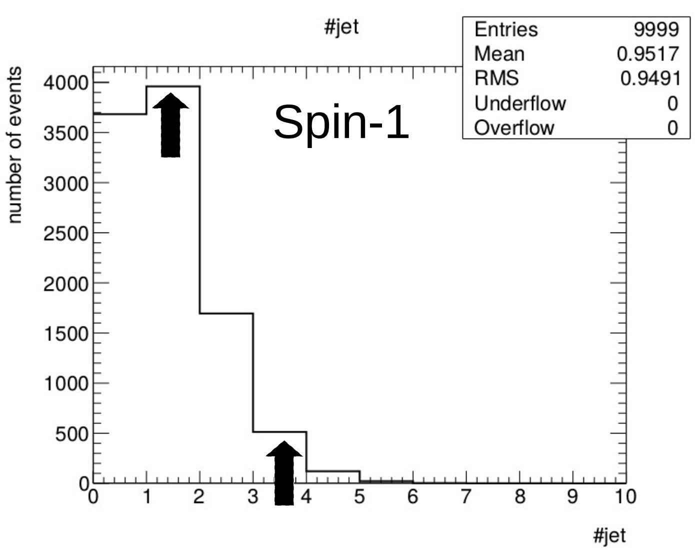


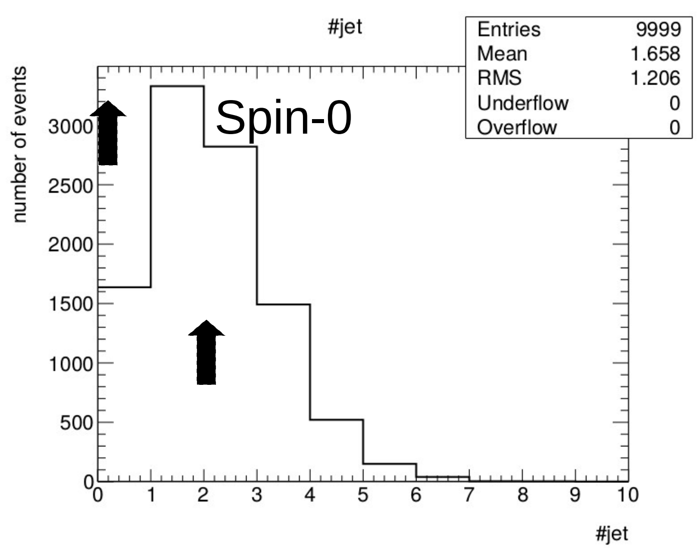




Buchmüller, Malik,
McCabe, Penning, 1505.07826




**Richer hadronic activity:**




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

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

**Allowing for more jets may increase exclusion power**

# Recasting using MadAnalysis 5

- Recasted ATLAS multijet analysis: arXiv: 1605.03814
- 7 signal regions (SRs) based on jet multiplicities

Common cuts: Preselection, $E^{miss}_T > 200$ GeV, $p_T(j_1) > 200$ GeV

- Validated against benchmarks provided by ATLAS colleagues

- Benchmark#1: gluino pair production, with $m_{\text{gluino}} = 1600$ GeV and $m_N = 0$ GeV
- Benchmark#2: gluino pair production, with $m_{\text{gluino}} = 1100$ GeV and $m_N = 700$ GeV
- Benchmark#3: squark pair production, with $m_{\text{squark}} = 1000$ GeV and $m_N = 400$ GeV

# Recasting continued ...

- Samples generated using MadGraph5_aMC@NLO
- Merging [CKKW-L], showering and hadronisation done with Pythia 8
- Delphes 3 used to model detector simulation

```
generate p p > go go $ susysq susysq~ @1
add process p p > go go j $ susysq susysq~ @2
add process p p > go go j j $ susysq susysq~ @3
```

for benchmarks #1 and #2 (gluino pair production), and

```
generate p p > susysq susysq~ $ go @1
add process p p > susysq susysq~ j $ go @2
add process p p > susysq susysq~ j j $ go @3
```

| Selections | benchmark # 1 | | benchmark # 2 | | benchmark # 3 | |
|---|---|---|---|---|---|---|
| | MA5 | Official | MA5 | Official | MA5 | Official |
| Preselection, $E_T^{\rm miss} > 200$ GeV, $p_T(\text{jet}_1) > 300$ GeV | 0.91 | 0.90 | 0.37 | 0.35 | 0.79 | 0.77 |
| Jet multiplicity | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 0.99 |
| $\min\Delta\phi(E_T^{\rm miss}, \text{jet})$ cut | 0.80 | 0.80 | 0.83 | 0.83 | 0.90 | 0.89 |
| $p_T(\text{jet}_2)$ cut | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| $E_T^{\rm miss}/\sqrt{H_T}$ cut | 0.48 | 0.48 | 0.40 | 0.40 | 0.65 | 0.66 |
| $m_{\rm eff}(\text{incl.})$ cut | 0.99 | 0.99 | 0.28 | 0.28 | 0.52 | 0.47 |

TABLE II: Cut flows, expressed in terms of efficiencies, for three signal samples in signal region `SR2jm`

# Recasting continued ...

```
// Declaration of the signal regions
Manager()->AddRegionSelection("2jl");
Manager()->AddRegionSelection("2jm");
Manager()->AddRegionSelection("2jt");
Manager()->AddRegionSelection("4jt");
Manager()->AddRegionSelection("5j");
Manager()->AddRegionSelection("6jm");
Manager()->AddRegionSelection("6jt");
```

```
// Declaration of the preselection cuts
std::string sub2jm[]={"2jl", "2jt","4jt","5j","6jm","6jt"};
Manager()->AddCut("Preselection-all", sub2jm);
Manager()->AddCut("Preselection-2jm","2jm");

// Declaration of the jet multiplicity cuts
std::string SR_2j[]={"2jl", "2jt","2jm"};
std::string SR_6j[]={"6jm","6jt"};
Manager()->AddCut("Njets>=2",SR_2j);
Manager()->AddCut("Njets>=4","4jt");
Manager()->AddCut("Njets>=5","5j");
Manager()->AddCut("Njets>=6",SR_6j);
```

```
// Declaration of the MET-jet separation cuts
std::string SR_DphiA_08[]={"2jl","2jt"};
std::string SR_4j[]={"4jt","5j","6jm","6jt"};
Manager()->AddCut("dphi-nj2",SR_DphiA_08);
Manager()->AddCut("dphi-2jm","2jm");
Manager()->AddCut("dphi-nj4",SR_4j);

// Declaration of the jet-pt cuts
Manager()->AddCut("pT2>100 GeV",SR_4j);
Manager()->AddCut("pT2>200 GeV",SR_DphiA_08);
Manager()->AddCut("pT4>100 GeV",SR_4j);

// Declaration of the aplanarity cuts
Manager()->AddCut("lam3>0.04",SR_4j);
```

```
// Declaration of the MET-to-HT/Meff ratio cuts
std::string SR_METoHT_15[]={"2jl","2jm"};
Manager()->AddCut("METtoHT>15 sqrGeV",SR_METoHT_15);
Manager()->AddCut("METtoHT>20 sqrGeV","2jt");
Manager()->AddCut("METtoMeff4>0.20","4jt");
Manager()->AddCut("METtoMeff5>0.25","5j");
Manager()->AddCut("METtoMeff6>0.25","6jm");
Manager()->AddCut("METtoMeff6>0.20","6jt");

// Declaration of the cuts on Meff
std::string SR_meff_1600[]={"2jm","5j","6jm"};
std::string SR_meff_2000[]={"2jt","6jt"};
Manager()->AddCut("Meff>1200 GeV","2jl");
Manager()->AddCut("Meff>1600 GeV",SR_meff_1600);
Manager()->AddCut("Meff>2000 GeV",SR_meff_2000);
Manager()->AddCut("Meff>2200 GeV","4jt");
```

```
// Electrons
for(unsigned int e=0; e<event.rec()->electrons().size(); e++)
{
  const RecLeptonFormat *CurrentElectron = &(event.rec()->electrons()[e]);
  if(CurrentElectron->pt()>10. && fabs(CurrentElectron->eta())<2.47)
    Electrons.push_back(CurrentElectron);
}
SORTER->sort(Electrons);

// Muons
for(unsigned int mu=0; mu<event.rec()->muons().size(); mu++)
{
  const RecLeptonFormat *CurrentMuon = &(event.rec()->muons()[mu]);
  if(CurrentMuon->pt()>10. && fabs(CurrentMuon->eta())<2.7)
    Muons.push_back(CurrentMuon);
}

// Jets
for(unsigned int j=0; j<event.rec()->jets().size(); j++)
{
  const RecJetFormat *CurrentJet = &(event.rec()->jets()[j]);
  if(CurrentJet->pt()>20. && fabs(CurrentJet->eta())<2.8)
    Jets.push_back(CurrentJet);
}
```

```
// Overlap removal
Jets      = Removal(Jets, Electrons,  0.2);
Electrons = Removal(Electrons, Jets,  0.4);
Electrons = Removal(Electrons, Muons, 0.05);
Electrons = Removal(Electrons, 0.05);

// MET
TLorentzVector pTmiss = event.rec()->MET().momentum();
double MET = pTmiss.Pt();
```

```
// Preselection
bool pre1 = ((Electrons.size()+Muons.size())==0);
bool pre2a = false, pre2b=false;
if(NJets>0)
{
  pre2a = (SignalJets[0]->pt()>200.);
  pre2b = (SignalJets[0]->pt()>300.);
}
bool pre3 = (MET>200.);
if(!Manager()->ApplyCut(pre1 && pre2a && pre3 ,"Preselection-all")) return true;
if(!Manager()->ApplyCut(pre1 && pre2b && pre3 ,"Preselection-2jm")) return true;

// Jet multiplicity
if(!Manager()->ApplyCut(2<=NJets,"Njets>=2")) return true;
if(!Manager()->ApplyCut(4<=NJets,"Njets>=4")) return true;
if(!Manager()->ApplyCut(5<=NJets,"Njets>=5")) return true;
if(!Manager()->ApplyCut(6<=NJets,"Njets>=6")) return true;
```

```
// (MET,jet) separation
if(!Manager()->ApplyCut(dphij_1to3>0.4,"dphi-2jm")) return true;
if(!Manager()->ApplyCut(dphij_1to3>0.8,"dphi-nj2")) return true;
if(!Manager()->ApplyCut(dphij_1to3>0.4 && dphij_gt3>0.2,"dphi-nj4")) return true;

// Jet pt thresholds
if(!Manager()->ApplyCut(100.<SignalJets[1]->pt(),"pT2>100 GeV")) return true;
if(!Manager()->ApplyCut(200.<SignalJets[1]->pt(),"pT2>200 GeV")) return true;
if(NJets>3)
  if(!Manager()->ApplyCut(100.<SignalJets[3]->pt(),"pT4>100 GeV")) return true;

// Aplanarity cut
if(NJets>3)
  if(!Manager()->ApplyCut(0.04<lam3,"lam3>0.04")) return true;
```

```
// Aplanarity cut
if(NJets>3)
  if(!Manager()->ApplyCut(0.04<lam3,"lam3>0.04")) return true;

// MET-to-HT/eff ratio
if(!Manager()->ApplyCut(METtoHT > 15.   ,"METtoHT>15 sqrGeV")) return true;
if(!Manager()->ApplyCut(METtoHT > 20.   ,"METtoHT>20 sqrGeV")) return true;
if(NJets>3)
  if(!Manager()->ApplyCut(METtoMeff4>0.20,"METtoMeff4>0.20")) return true;
if(NJets>4)
  if(!Manager()->ApplyCut(METtoMeff5>0.25,"METtoMeff5>0.25")) return true;
if(NJets>5)
{
  if(!Manager()->ApplyCut(METtoMeff6>0.25,"METtoMeff6>0.25")) return true;
  if(!Manager()->ApplyCut(METtoMeff6>0.20,"METtoMeff6>0.20")) return true;
}

// Meff inclusive cuts
if(!Manager()->ApplyCut(Meff>1200.,"Meff>1200 GeV")) return true;
if(!Manager()->ApplyCut(Meff>1600.,"Meff>1600 GeV")) return true;
if(!Manager()->ApplyCut(Meff>2000.,"Meff>2000 GeV")) return true;
if(!Manager()->ApplyCut(Meff>2200.,"Meff>2200 GeV")) return true;
```

# Recasting continued …

*http://madanalysis.irmp.ucl.ac.be/wiki/PublicAnalysisDatabase*

## Available Analyses

***!! please properly cite all the re-implementation codes you are using; here are a !BibTeX file and a file with plain !LaTeX format for this purpose !!***

### ATLAS analyses, 13 TeV

| Analysis | Short Description | Implemented by | Code | Validation note | Version |
|---|---|---|---|---|---|
| ATLAS-EXOT-2015-03 | Monojet | D. Sengupta | Inspire | PDF | v1.3/Delphes3 |
| ATLAS-SUSY-2015-06 | Multijet + missing transverse momentum | S. Banerjee, B. Fuks, B. Zaldivar | Inspire | PDF | v1.3/Delphes3 |
| ATLAS-CONF-2016-086 | b-pair + missing transverse momentum | B. Fuks & M. Zumbihl | To appear | To appear | v1.6/Delphes3 |

Delphes card for ATLAS-EXOT-2015-03

### CMS analyses, 13 TeV

| Analysis | Short Description | Implemented by | Code | Validation note | Version |
|---|---|---|---|---|---|
| CMS-EXO-16-037 | Monojets | B. Fuks & M. Zumbihl | To appear | To appear | v1.6/Delphes3 |

Here I have listed only the 13 TeV recasted analyses: More analyses coming soon!!!

# Recasting continued ...

# Recasting continued ...

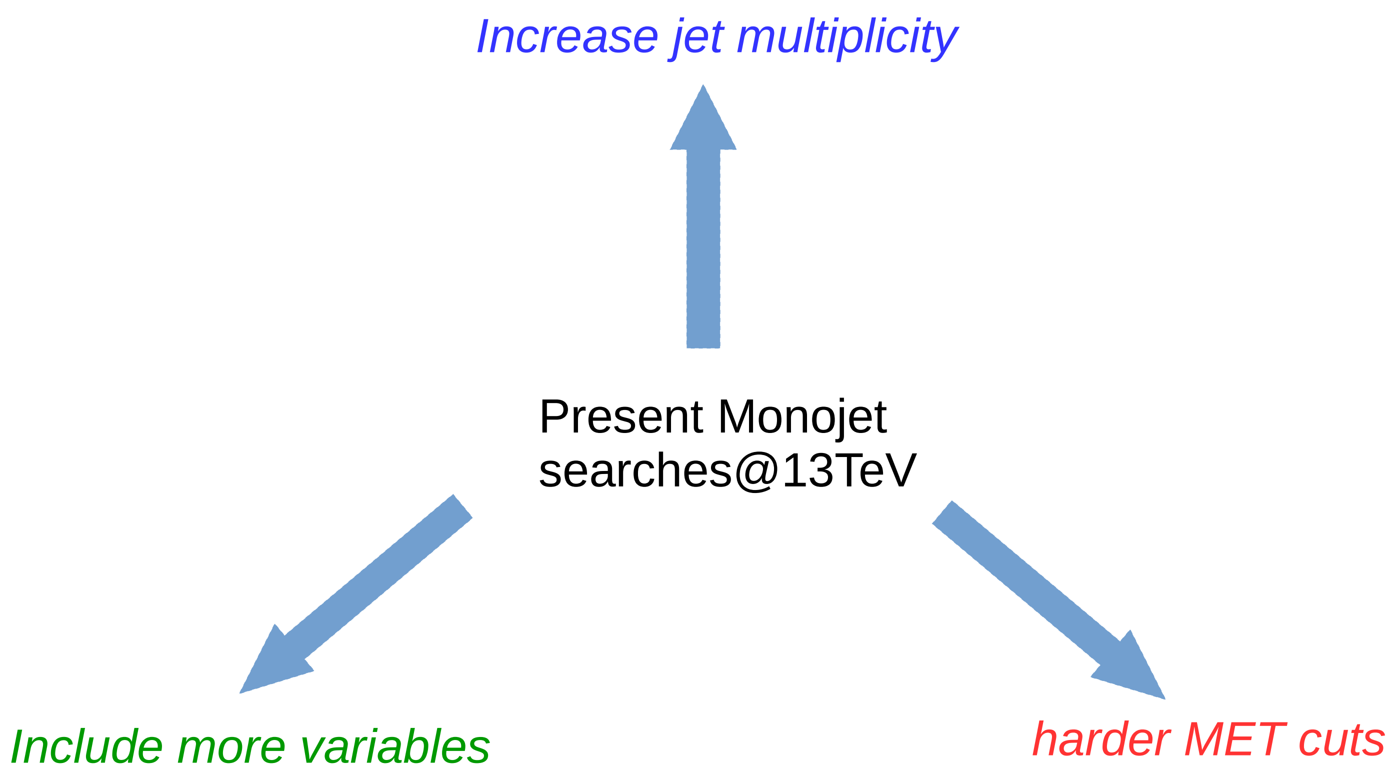
## Easy to use: Fully automatic ...

```
install delphesMA5tune
install PADForMA5tune
install delphes
install PAD
```

```
set main.recast = on
set main.recast.store_root = False
import <path-to-the-event-sample>
submit
```

```
set main.recast.card_path = <path-to-a-recasting-card>
```

# Possible roads to MET searches optimisation



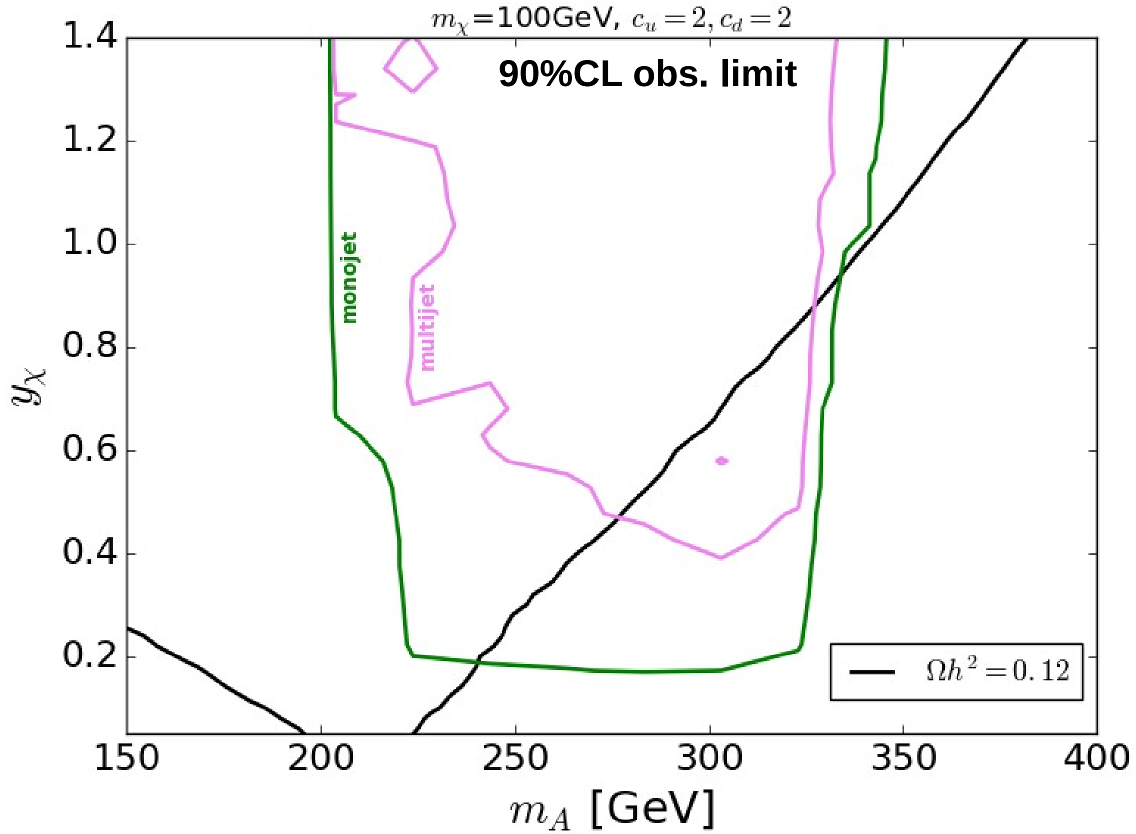
# Increasing jet multiplicity

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

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




***Failure reasons:***
- Monojet is not a monojet anymore
- monojet is tuned for SMDM, whereas multijet is tuned for SUSY models
- see talk by Marc Besançon on how to reduce uncertainties: data driven techniques for background estimation.

# 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

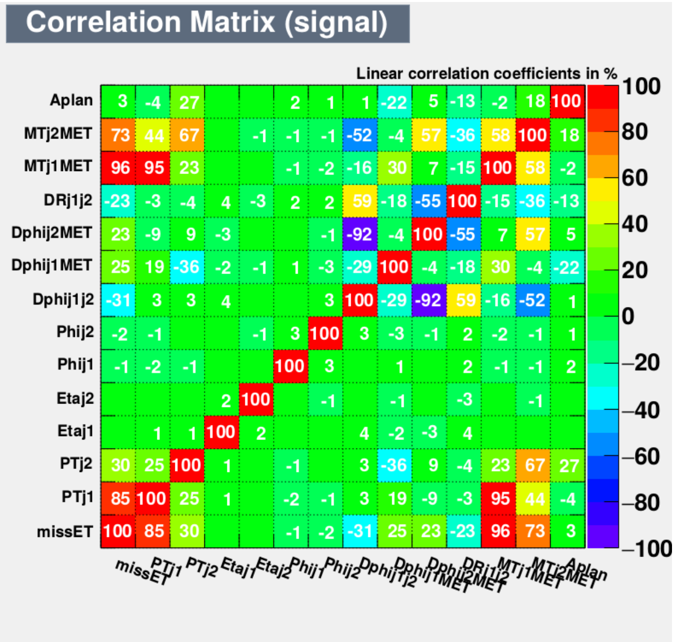
**New Signal Regions:**

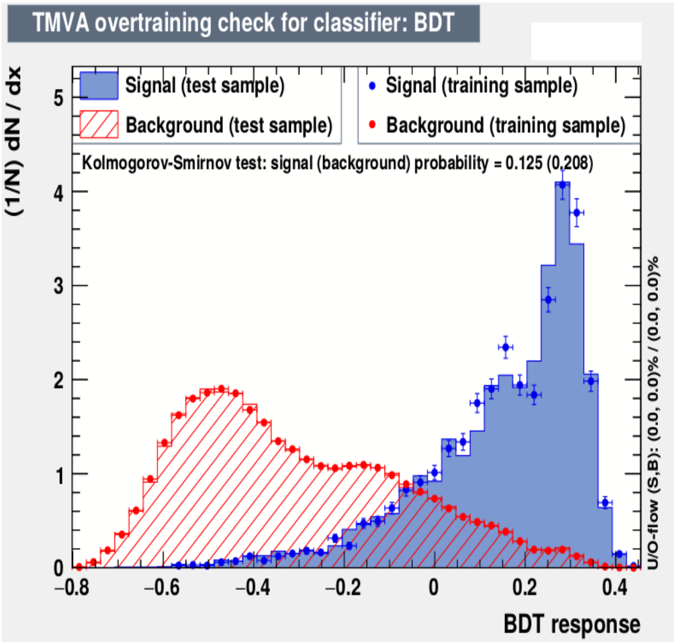
- inclusive signal regions: MET > 800 GeV, 1000 GeV, 1200 GeV

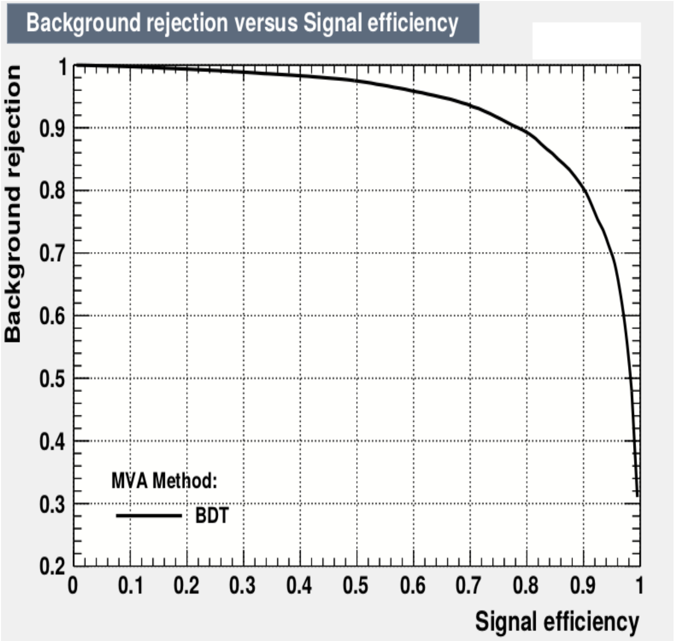
| **Results:** $(c_u = c_d = 3)$ | **CL exclusion** | |
|---|---|---|
| | **Existing** | **New** |
| $m_A = 300\mathrm{GeV},\ m_\chi = 5\mathrm{GeV},\ y_\chi = 0.1$ | 0.9 | 0.97 |
| $m_A = 300\mathrm{GeV},\ m_\chi = 10\mathrm{GeV},\ y_\chi = 0.1$ | 0.91 | 0.98 |
| $m_A = 100\mathrm{GeV},\ m_\chi = 5\mathrm{GeV},\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

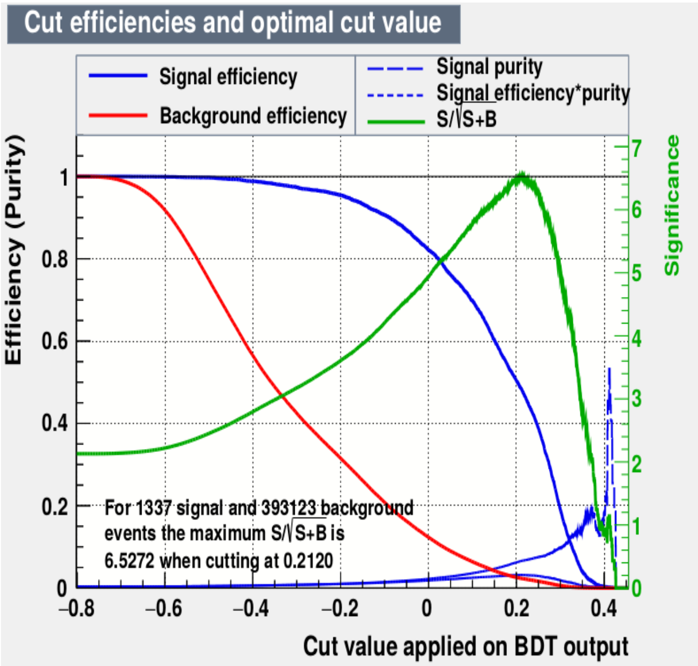
**Null to marginal improvement (too tight MET cuts): unreliable statistics**

# Final attempt: Multivariate analysis




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

**Result (w/o systematics):**

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

compared to:

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

from actual monojet search

**Marginal improvement (again!)**

**- Optimisation for monojet and multijet analyses require:**

- **Computing backgrounds (Z + jets, W + jets, tt …) at higher orders to have lesser theoretical uncertainties**

- **Data driven techniques: Employing Z $\rightarrow$ $\mu\mu$ + jets etc.**

- **Employing ratios of W + jets/Z + jets to reduce uncertainties**

- **Improvements expected but systematic uncertainties ~ 5% might prevail**

# LHC searches for the pseudoscalar model

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

Plethora of additional constraints ...

**- Involving MET:**

$t\bar{t}A(A \to \chi\chi)$ **[CMS-PAS-EXO-16-005, ATLAS-CONF-2016-050 Haisch, 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]**
**Interference effects with SM tt background considered. Can be very large ~ O(100%)**

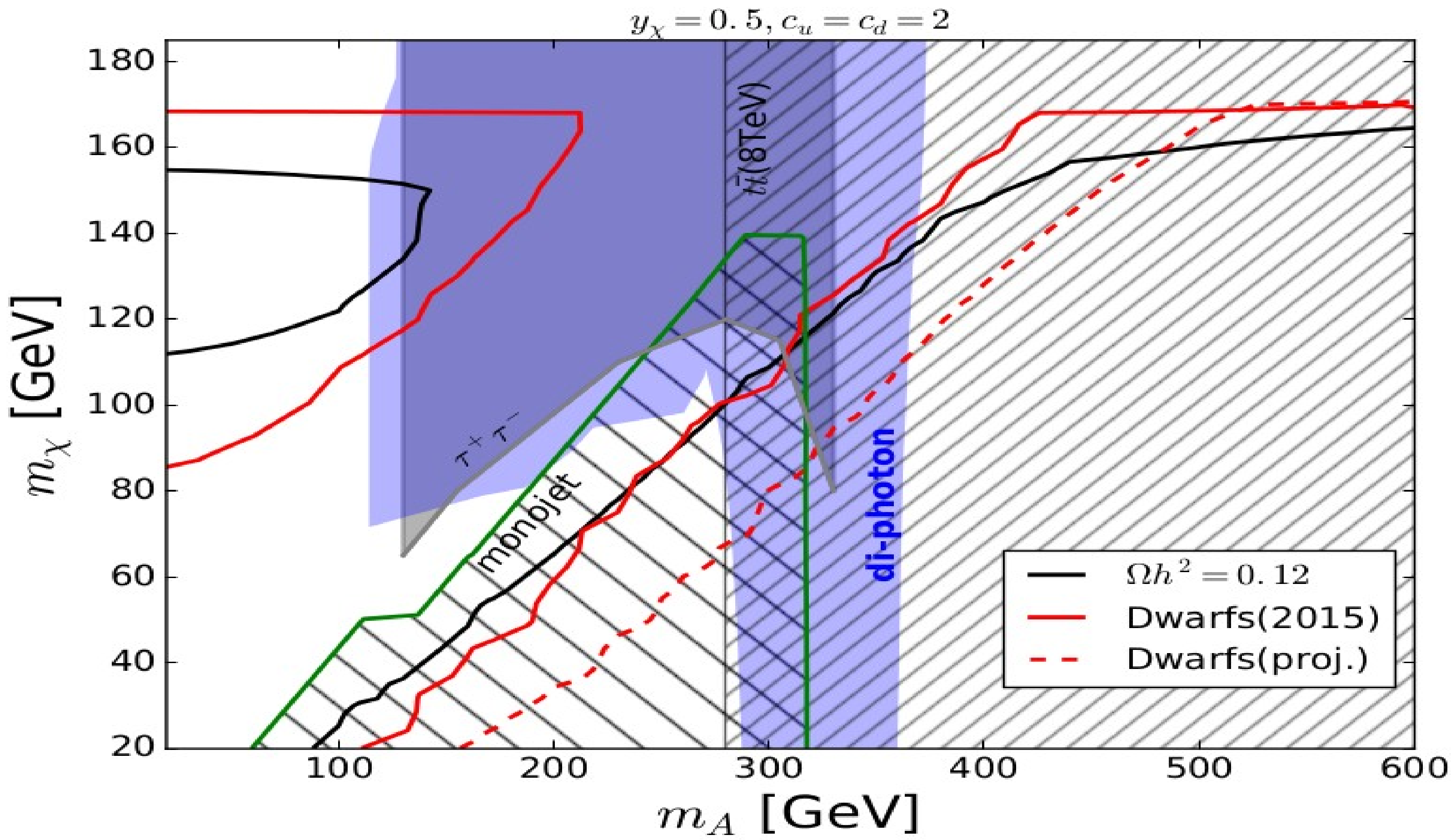
$\gamma\gamma$ **[ATLAS-CONF-2016-059]**

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

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

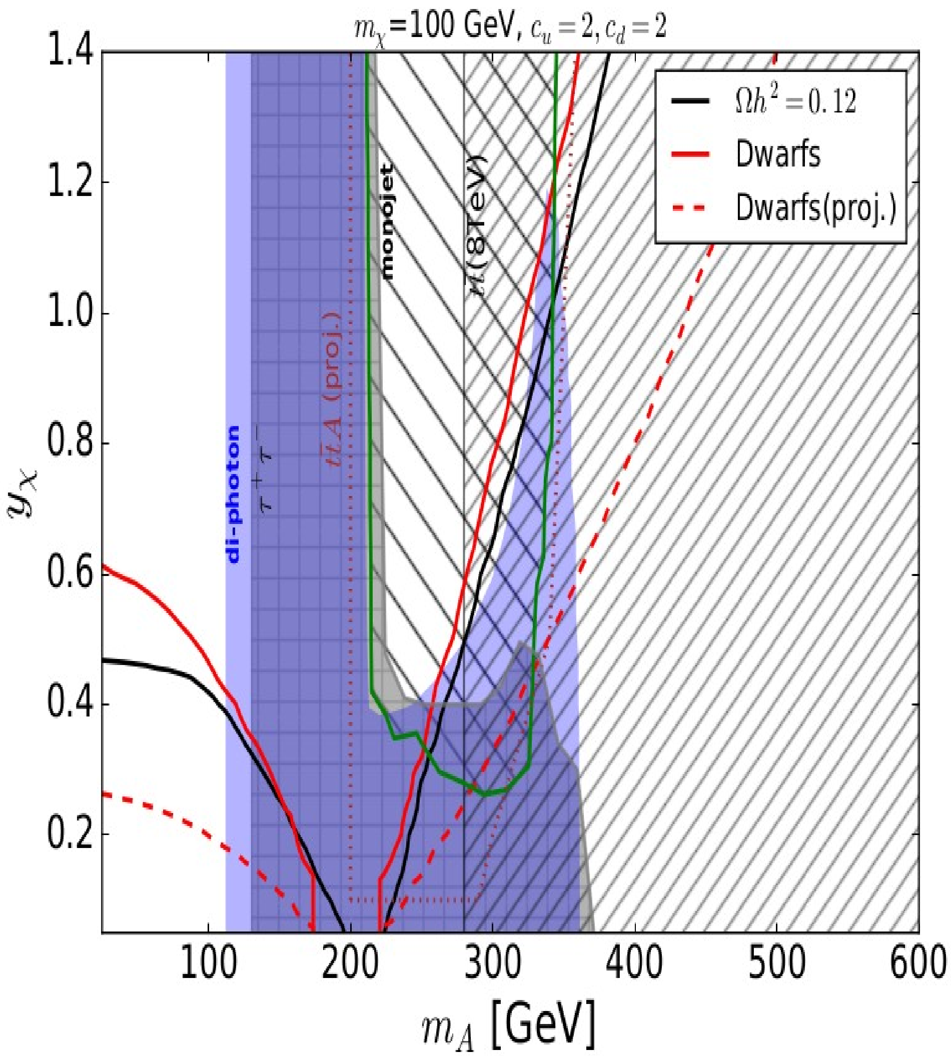
Note:
spin-1 mediator SMDM may not have that many relevant collider constraints!!

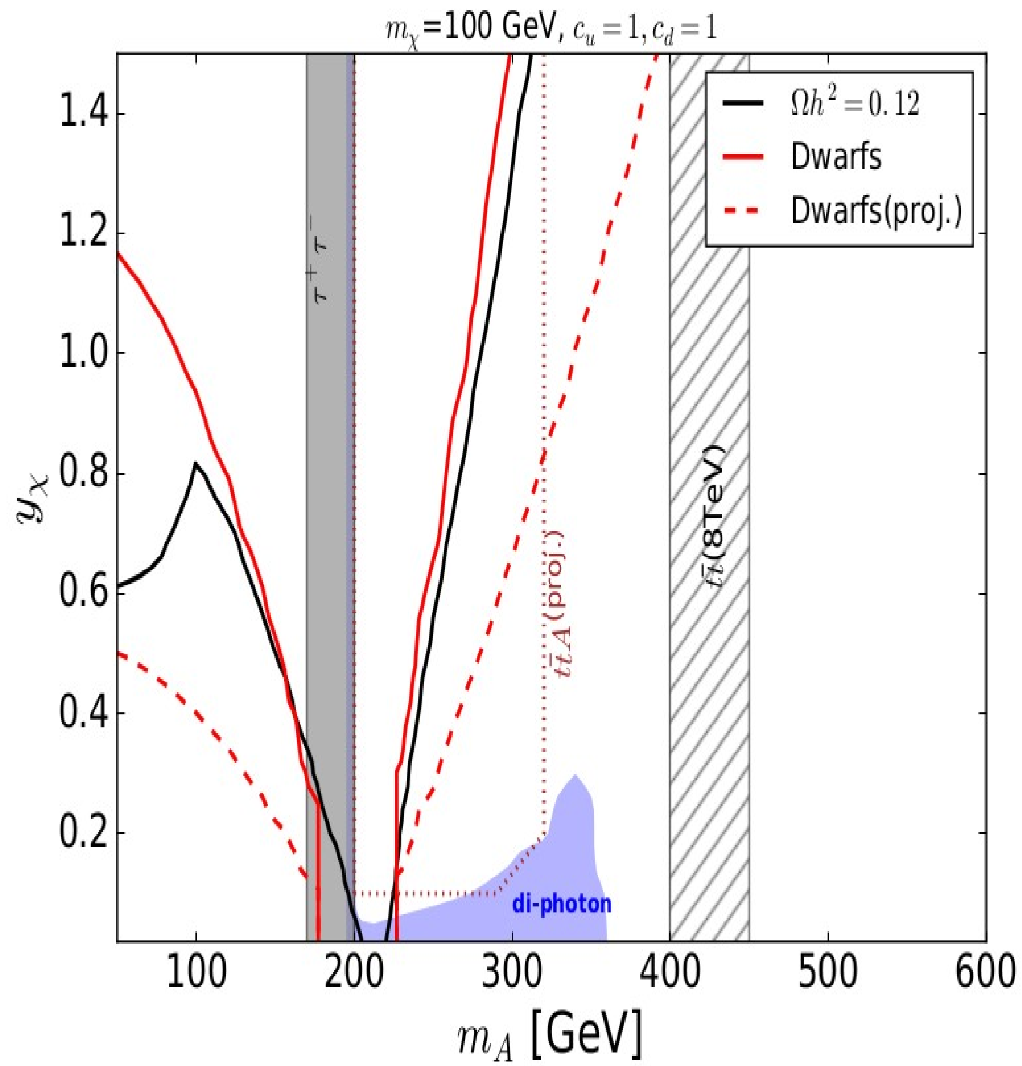
# DM and LHC complementarity I ...




- dark matter only survives in the off-shell region (DM > mediator)
- perfect complementarity between MET and non-MET searches

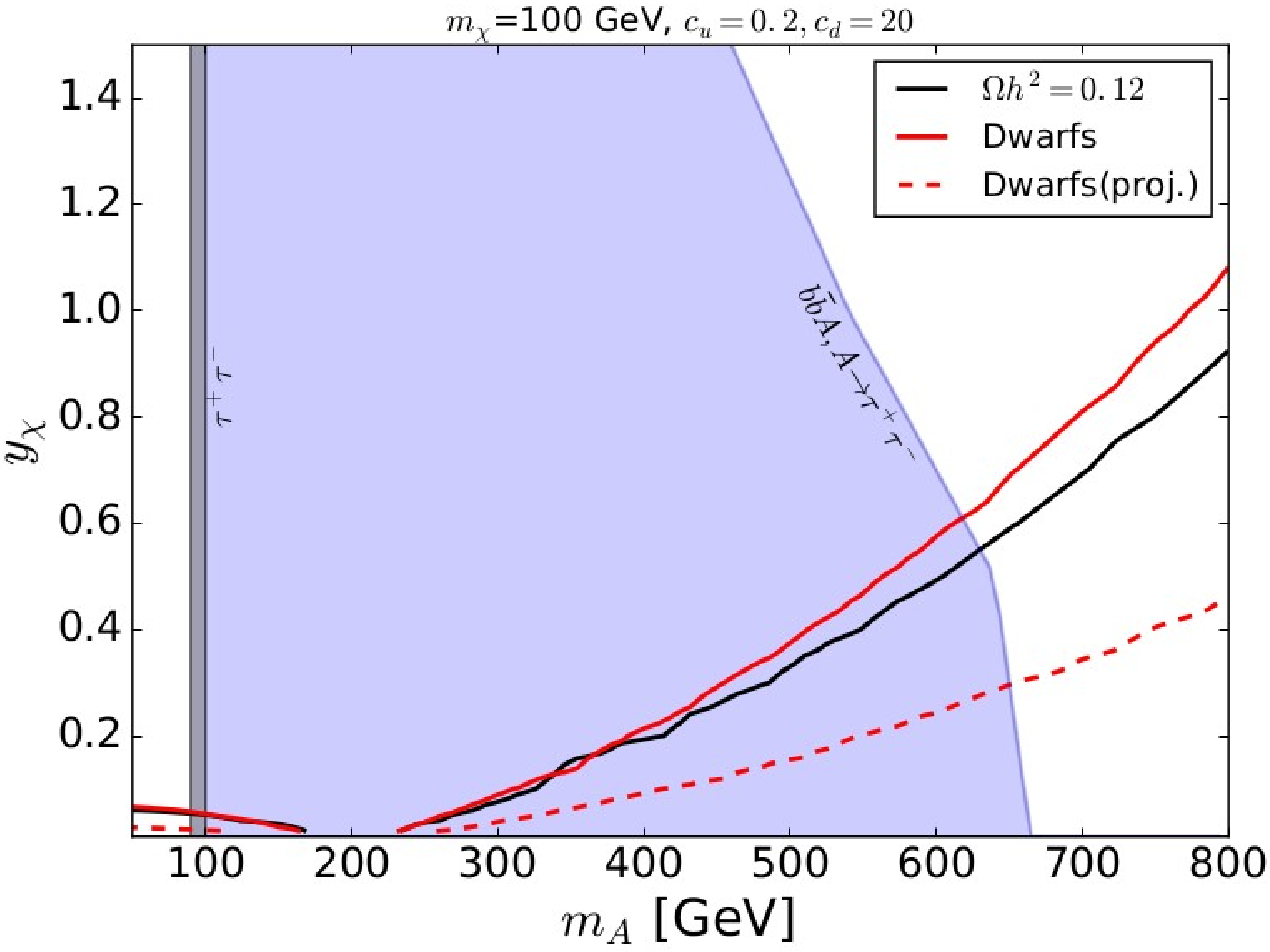
# DM and LHC complementarity II …




- *larger couplings ($c_u = c_d = 3$) to quarks exclude even below 100GeV*
- *larger DM masses less sensitive to LHC constraints*
- *smaller DM masses essentially excluded by Dwarfs*
- *Future dwarf constraints excluding DM below ~250GeV*

# DM and LHC complementarity III …




*- bottom-dominated scenarios excluded up to ~600GeV mediator mass*

# Conclusions

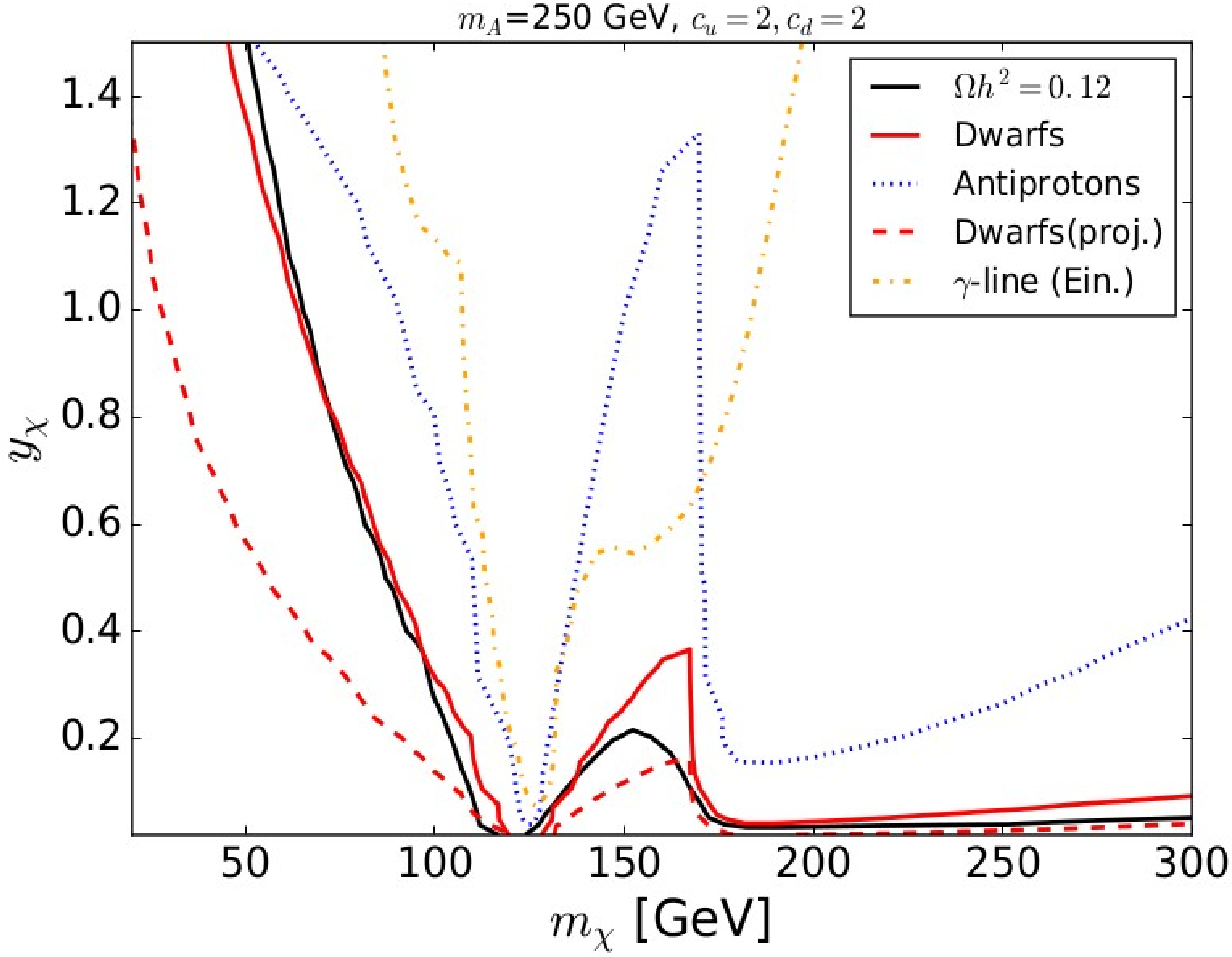
**MET searches at the LHC are already highly optimised**

**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 off-shell regions, unless there are suppressed quark couplings**

**MadAnalysis 5 can be used to recast experimental analyses and can easily be used to test your favourite models!!!**

Dark matter favoured regions



*Thank you!!!*

*Thanks to Bryan Zaldivar for letting me steal his slides!!!*

*:)*