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Exploring selections across channels in Dark Matter searches with top quarks at the ATLAS experiment of the LHC

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Master thesis presentation

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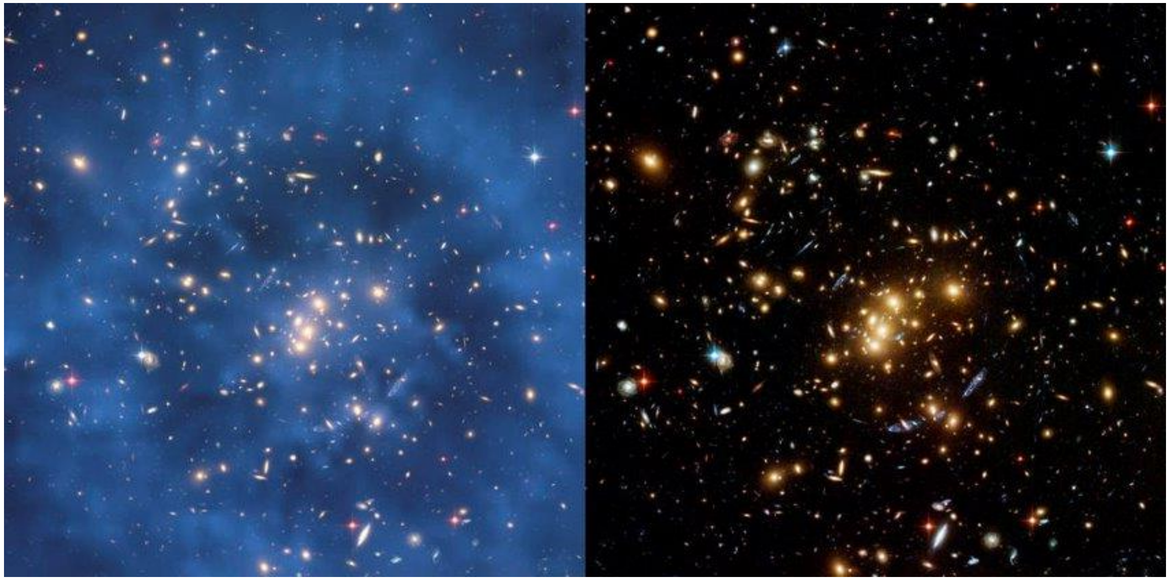
Introduction

- Dark Matter makes up 26% of the energy-matter budget of the universe
- If made up of a new particle species – could be found at the Large Hadron Collider
- Searches within ATLAS target various final states of Dark Matter production
- Two such final states are tW+DM, tt+DM
  - Similar final states
  - Interference at NLO
  - Is there overlap between the analyses?

Outline

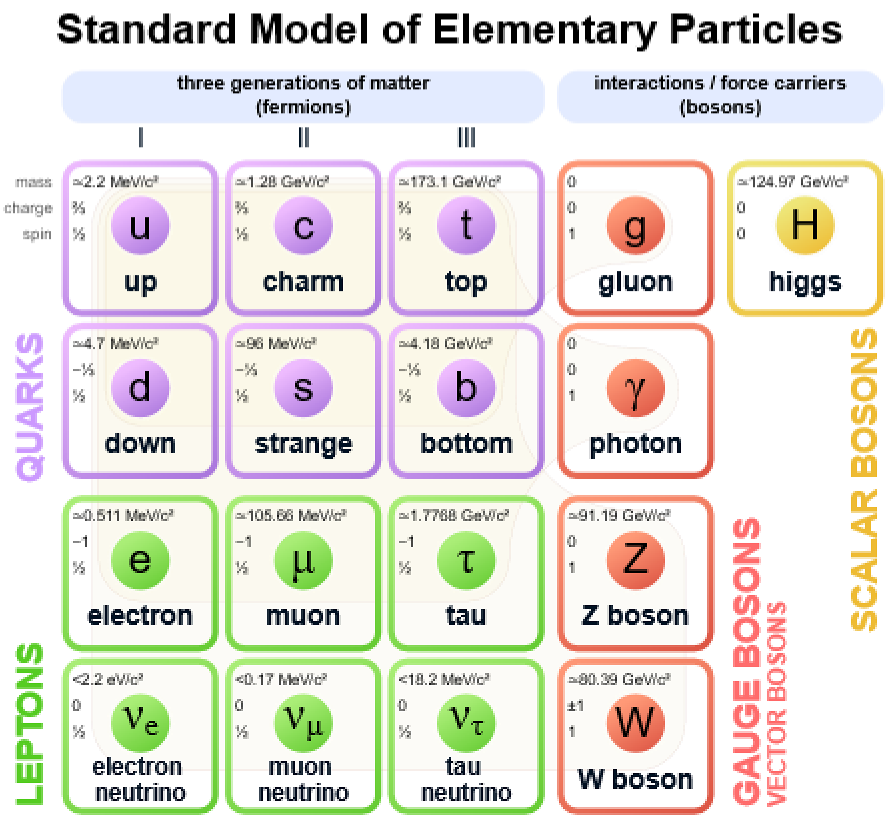
- Background
  - Dark Matter
  - Large Hadron Collider and ATLAS detector
  - Dark Matter as beyond Standard Model physics
- Objective
  - tW+DM, tt+DM
- Overlap analysis
  - Event generation
  - Signal region definition
- Conclusion

Dark Matter



- Astronomers noticed more mass in the universe than could be explained by observable stars: Missing mass problem
- Studied: planets, non-luminous stars, primordial black holes, MONDs...
- Today: Dark Matter used to refer to an unknown substance/particle
  - Interacts through gravity
  - Interacts not at all or very weakly through other forces

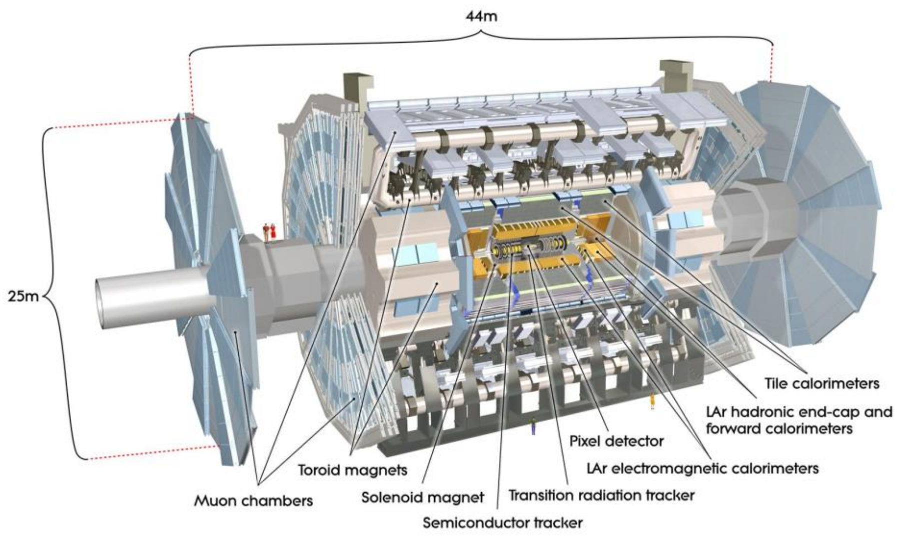
Dark Matter as beyond SM physics



- The Standard model covers our current understanding of particle physics
  - Cannot explain Dark Matter
- Many theories beyond the Standard Model (BSM) try to explain Dark Matter
- Experimental approaches:
  - Direct detection
  - Indirect detection
  - Collider experiments

The ATLAS detector at the LHC

- The LHC is a proton-proton collider between France and Switzerland
  - 27 km in circumference
  - Center of mass energy 13 TeV
- ATLAS is a general-purpose detector at the LHC
  - Study the widest possible range of physics phenomena
  - In particular BSM searches

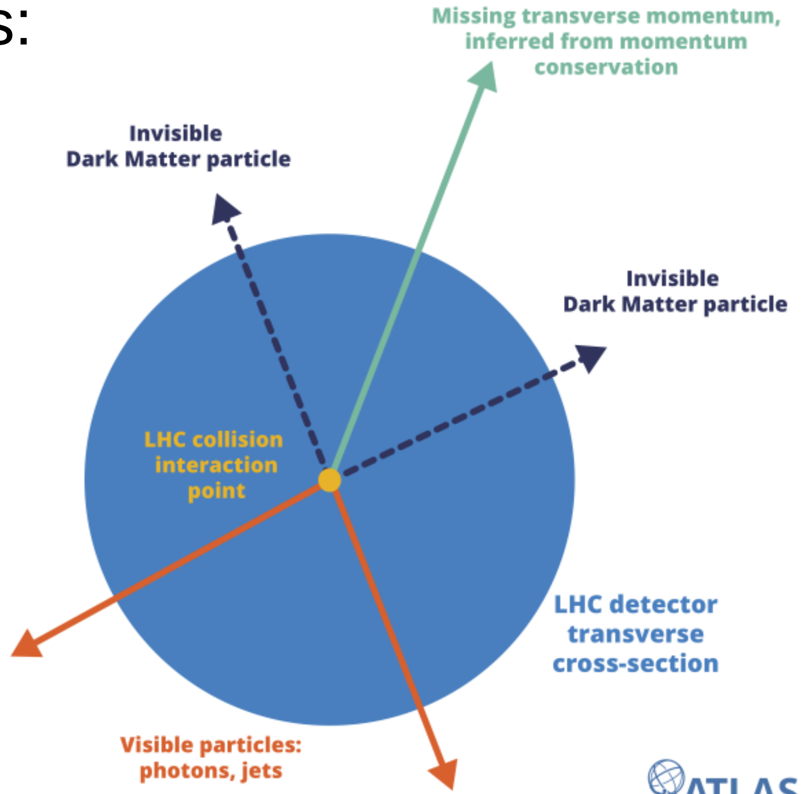


The ATLAS detector

Part of the LHC

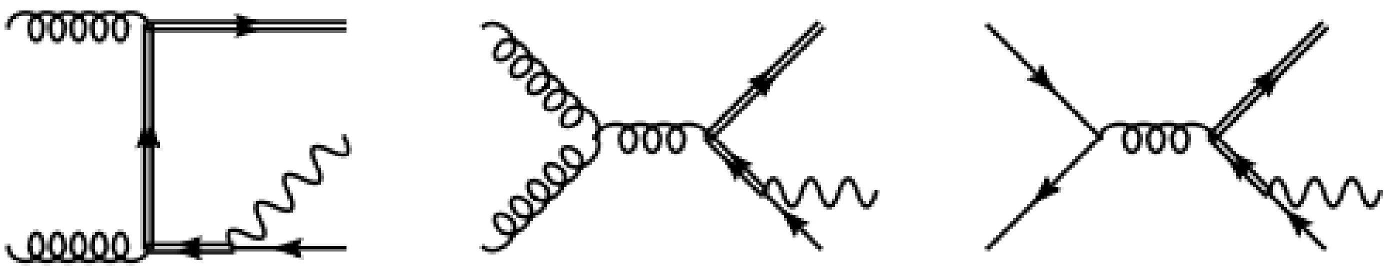
Dark Matter Searches with ATLAS

- Dark Matter is invisible to the detector
- Common feature: high missing transverse energy (MET)
- Use models to focus the searches:
  - EFTs
    - Valid at energies at which the mediator is not resolved
  - Simplified models
    - Represent several different theories
    - Small number of parameters
    - Restricted phenomenology
  - Full theories
    - Complete
    - Not as general



The tW+MET and $t\bar{t}$+MET analyses

- Interested in two similar final states with top quarks and Dark Matter:
  - **tW + DM** and **$t\bar{t}$+ DM**
  - $t\bar{t}$+ and tW signals mix at NLO in the SM



JHEP11(2009)074

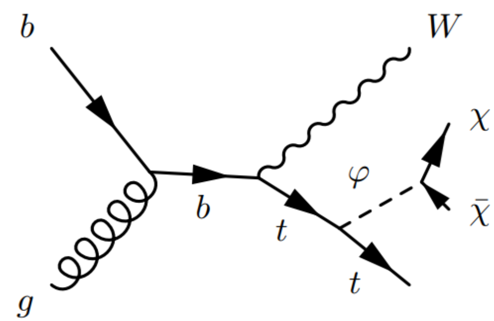
Some diagrams contributing to tW at NLO with a tt pair

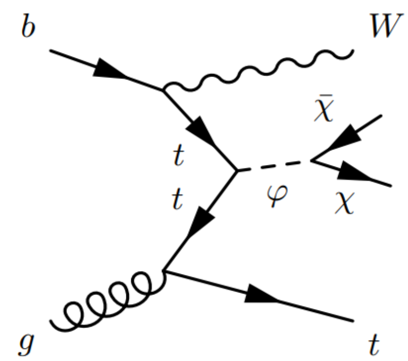
- Two independent ATLAS searches:
  - tW+MET: ongoing in the exotics group [Glance page]
  - $t\bar{t}$+MET: ongoing in the SUSY group [INT note]
- Two different Dark Matter models
  - **Simplified spin-0 pseudoscalar model** and **2HDM+a**

The models

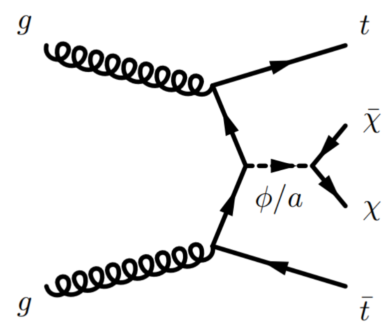
Simplified spin-0 pseudoscalar model

- Extends the SM by adding
  - Dirac DM fermion χ
  - pseudoscalar singlet a
- a mediates the interaction between χ and SM particles
- Model used in tt̄+MET analysis
- arXiv:1507.00966





arXiv:1701.05195



CDS

The models

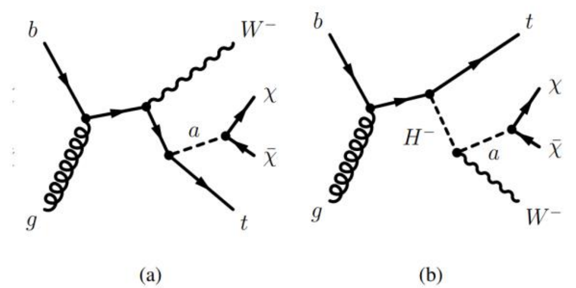
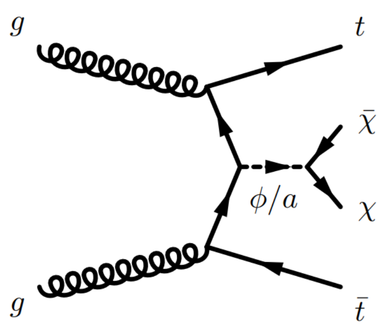


Figure 2: Representative diagrams for tW production of DM in association with a single top quark and a W boson.

arXiv:1712.03874



arXiv:1711.11520

2HDM+a

- Extends the SM by adding
  - an additional Higgs doublet
  - Pseudoscalar P
  - Dirac DM fermion χ
- Particle content:
  - Neutral scalar H
  - Charged scalars H ±
  - Pseudoscalar A
  - Pseudoscalar a (mediator between χ and SM particles)
  - Higgs boson h
- Model used in tW+MET analysis
- arXiv:1810.09420

Objective of this thesis

- Investigate the **overlap** between the two analyses
  - In both Dark Matter models
  - Only at generation level

First study of its kind in ATLAS

Event generation

- Generated 6 samples with 10 000 events each. For each final state:
  - 2HDM+a with pseudoscalar masses m_a=250 GeV, m_A=350 GeV, DM mass 10 GeV
  - 2HDM+a with pseudoscalar masses m_a=250 GeV, m_A=1200 GeV, DM mass 10 GeV
  - Simplified model with pseudoscalar mass m_a=250 GeV, DM mass 10 GeV

    Benchmark scenarios suggested by HQT group
- Madgraph5_AMC@NLO + Pythia8
- Generated at LO

Model	Final state	Number of generated events	$M_{H^\pm}$	Cross-section (pb)	Filter efficiency
Simplified	tt + DM	10,000	-	0.1165	0.6707
Simplified	tW + DM	10,000	-	0.0300	0.7907
2HDM+a	tt + DM	10,000	350 GeV	0.0433	0.7265
2HDM+a	tW + DM	10,000	350 GeV	0.0335	0.5457
2HDM+a	tt + DM	10,000	1200 GeV	0.0308	0.7217
2HDM+a	tW + DM	10,000	1200 GeV	0.0230	0.8723

Event preselection

- Study made in the semileptonic final state – events with one lepton – and the lepton is required to be a muon
- Event selection was made with the following object definitions
  - Similar object definitions in both analyses
  - When differing, the wider one was chosen

	p_T [GeV]	$\lvert\eta\rvert$	**Criterion**
Muons	> 3	< 2.8	MuLoose
Electrons	> 3	< 2.47	ELooseBLLH
Taus	> 20	< 2.5	One or three tracks
Baseline jets	> 20	2.8	
b-jets	> 20	2.5	BTag77MV2c10

Kept only events that contain exactly one baseline muon and no additional leptons

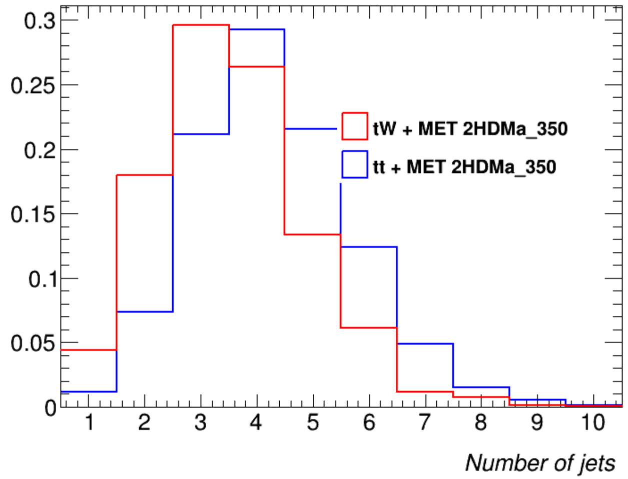
Distributions after preselection

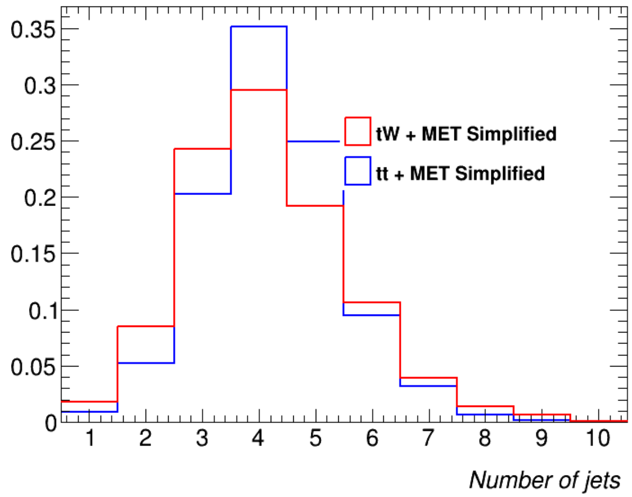
- Some basic kinematic distributions after preselection across models and final states:
  - Muon pT
  - Leading jet pT
  - Leading b-jet pT
  - Number of jets
  - Number of b-jets
  - MET

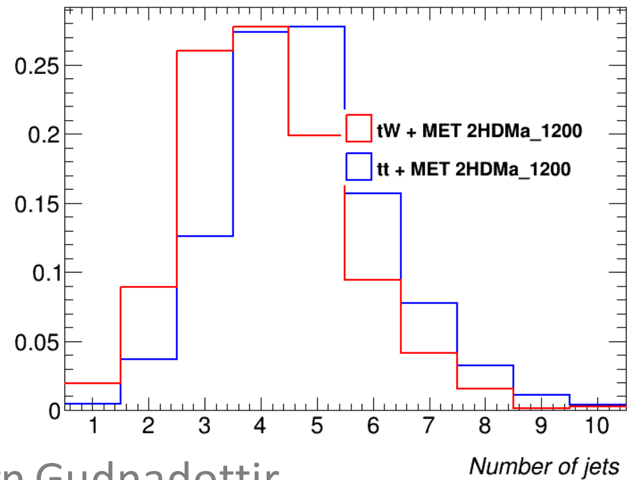
Number of jets

Exactly one lepton, which is a muon

Histograms normalized to 1





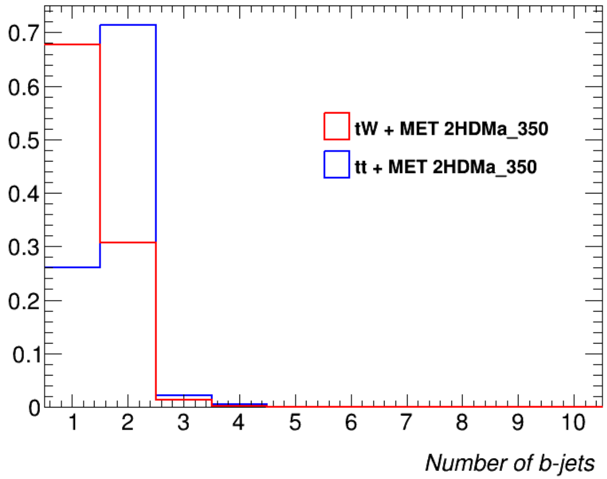


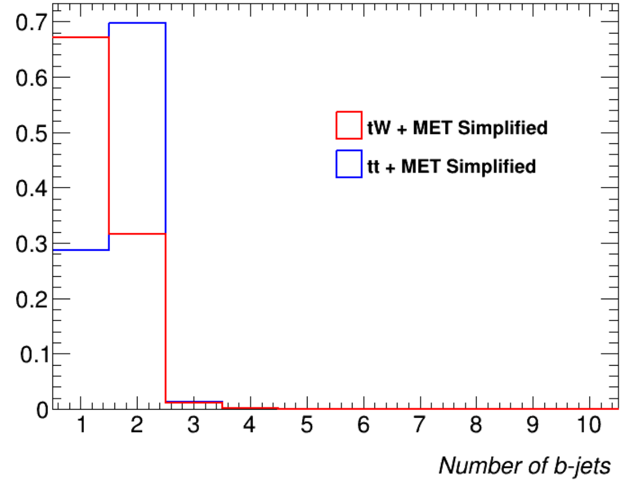
Jets: pT > 20 GeV, |eta|< 2.8

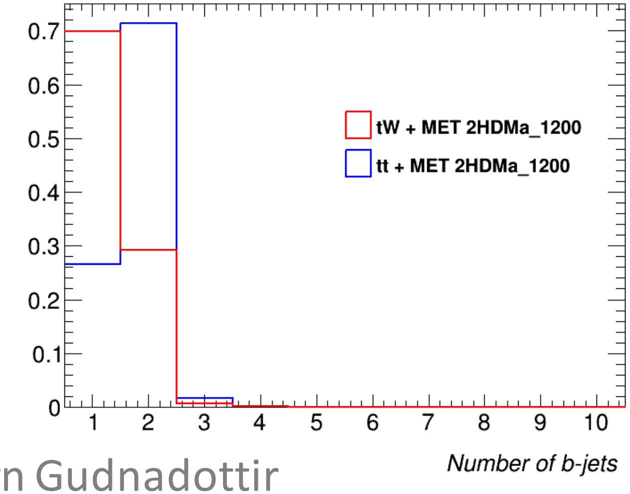
Number of b-jets

Exactly one lepton, which is a muon

Histograms normalized to 1



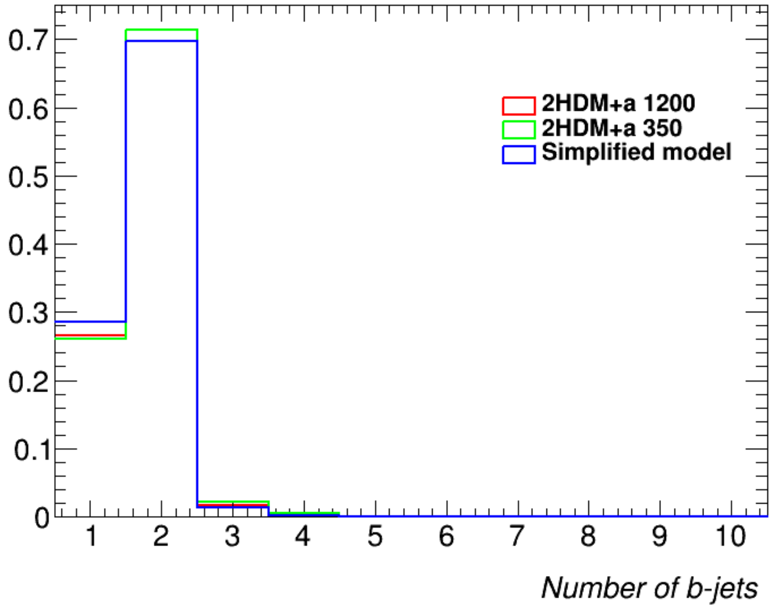




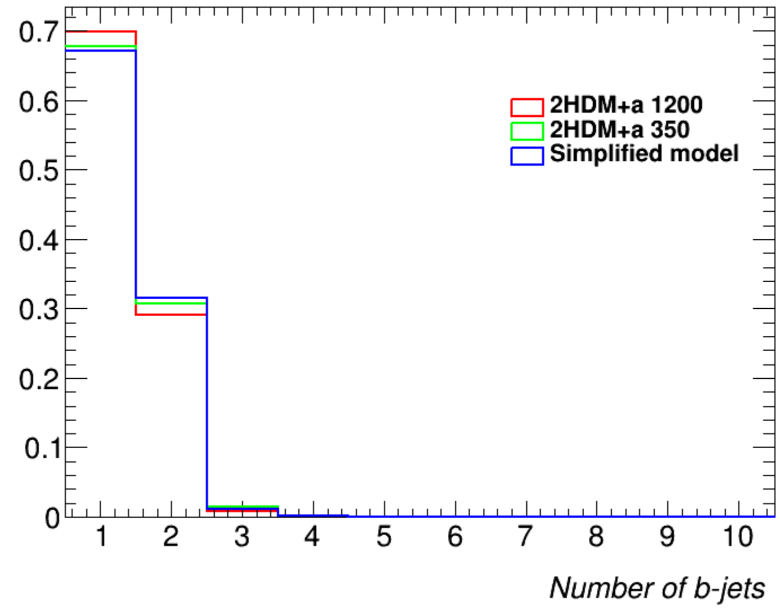
Number of b-jets

Exactly one lepton, which is a muon

Histograms normalized to 1



tt + MET

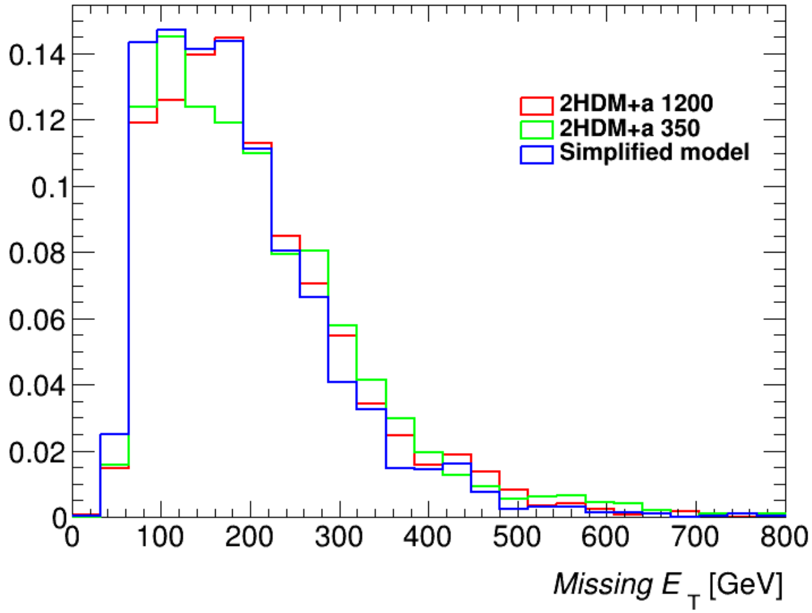


tW + MET

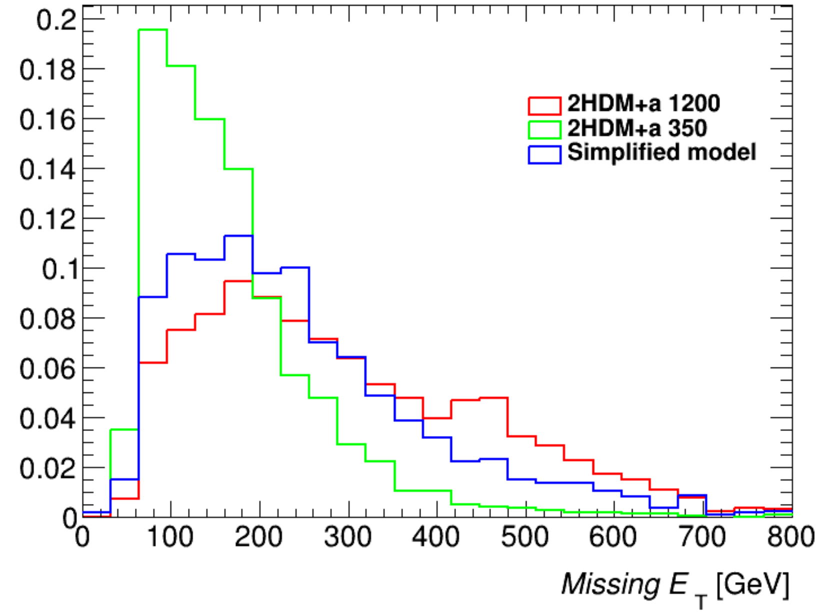
MET

Exactly one lepton, which is a muon

Histograms normalized to 1



tt + MET



tW + MET

The rest in back-up...

Signal region definition

- Defined two signal regions "tWMET" and "ttMET"
- Based on the two analyses
  - Simplified in the tt + MET case
    - The full selection contains variables discriminating against background, which is not present in this study
  - tW + MET is currently being optimized

	ttMET	**tWMET**
Muon p_T	27 GeV	30 GeV
Muon $\|\eta\|$	2.7	2.7
Muon criteria	MuMedium or MuIsoFixedCutTightTrackOnly	MuMedium
Number of jets	≥ 4	≥ 3
Number of b-tags	≥ 2	≥ 1
Jet p_T	>(80,60,30,25)GeV	>20 GeV
Leading b-jet p_T	$>$ 80 GeV	$>$ 50 GeV
MET	230 GeV	250 GeV

ttMET signal region

- Normalized to 150 /fb
- (% relative efficiency/% absolute efficiency)
- Statistical uncertainty only

	Simplified model $t\bar{t}$+MET	Simplified model tW+MET	2HDM+a $m_{H^\pm}$=350 GeV $t\bar{t}$+MET	2HDM+a $m_{H^\pm}$=350 GeV tW+MET	2HDM+a $m_{H^\pm}$=1200 GeV $t\bar{t}$+MET	2HDM+a $m_{H^\pm}$=1200 GeV tW+MET
Initial	11720±108	3552±60	4722±69	2744±52	3334±58	3008±55
Pre-selection	2379±49 (20%/100%)	676±26 (19%/100%)	925±30 (20%/100%)	627±25 (23%/100%)	654±26 (20%/100%)	553±24 (18%/100%)
After cuts on muon p_T	1800±42 (76%/76%)	547±23 (81%/81%)	741±27 (80%/80%)	505±22 (81%/81%)	505±22 (77%/77%)	474± 22 (86%/86%)
After cuts on number of jets/b-jets	846±29 (57%/20%)	129±11 (24%/19%)	416±20 (56%/45%)	112±11 (22%/18%)	286±17 (57%/44%)	102±10 (22%/19%)
After cuts on jet p_T	479±22 (40%/8%)	84±9 (65%/12%)	289±17 (70%/31%)	72±9 (65%/12%)	196±14 (69%/30%)	69 ±8 (68%/13%)
After cuts on MET	192±14 (65%/12%)	42±7 (50%/6%)	132±11 (46%/14%)	22±5 (30%/3%)	85±9 (43%/13%)	44±7 (63%/8%)

- tt+MET analysis optimized for simplified model
- Largest tW contribution (~50% of the tt signal) for the 2HDM+a with high mass pseudoscalar

tWMET signal region

- Normalized to 150 /fb
- (% relative efficiency/% absolute efficiency)
- Statistical uncertainty only

	Simplified model tW+MET	Simplified model $t\bar{t}$+MET	2HDM+a $m_{H^\pm}$=350 GeV tW+MET	2HDM+a $m_{H^\pm}$=350 GeV $t\bar{t}$+MET	2HDM+a $m_{H^\pm}$=1200 GeV tW+MET	2HDM+a $m_{H^\pm}$=1200 GeV $t\bar{t}$+MET
Initial	3552±60	11720±108	2744±52	4722±69	3008±55	3334±58
Pre-selection	676±26 (19%/100%)	2379±49 (20%/100%)	627±25 (23%/100%)	925±30 (20%/100%)	553±24 (18%/100%)	654±26 (20%/100%)
After cuts on muon p_T	526±23 (78%/78%)	1699±41 (71%/71%)	477±22 (76%/76%)	702±26 (76%/76%)	461±21 (84%/84%)	483±22 (74%/74%)
After cuts on number of jets/b-jets	433±21 (82%/64%)	1558±39 (92%/65%)	382±20 (80%/61%)	655±26 (93%/71%)	377±19 (82%/68%)	453±21 (94%/69%)
After cuts on jet p_T	342±18 (79%/51%)	1346±37 (86%/57%)	301±17 (79%/48%)	583±24 (89%/63%)	300±17 (80%/54%)	411±20 (91%/63%)
After cuts on MET	139±12 (41%/21%)	336±18 (25%/14%)	301±7 (18%/9%)	187±14 (32%/20%)	160±13 (53%/29%)	120±11 (29%/18%)

- tt a large background in tW
  - Most in the simplified model (more than double the signal!)
- The 2HDM+a scenario with lower mass mediator has the best tW/tt ratio (60% tt)

Conclusion and discussion

- Studied the overlap of the signal regions of two Dark Matter searches in ATLAS – tW + MET, tt + MET – in the context of two different BSM models
- Overlap across signal regions found in both models
- Caveats:
  - No discriminating variables from tt+MET taken into account
  - No optimization made in tW+MET signal region at the time of the study
  - Study done only at the generation level
  - Statistically limited – more events should be simulated
  - LO study – even more overlap at NLO
- More sophisticated methods should be used in order to follow up this study
  - If these still show a significant overlap, the sensitivity of these Dark Matter searches could be improved by combining both final states

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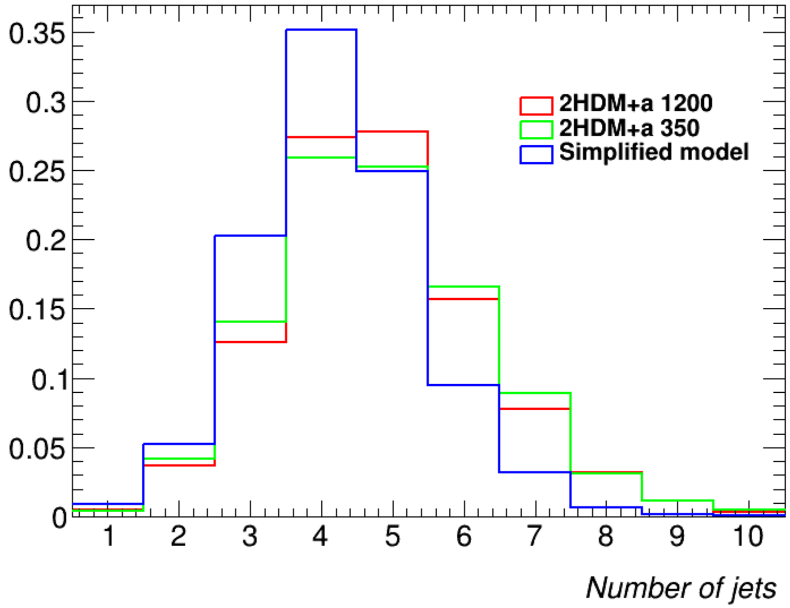
Finally, a thank you to my supervisor Rebeca Gonzalez Suarez, my subject reader Arnaud Ferrari, and the ATLAS group at UU

BACKUP

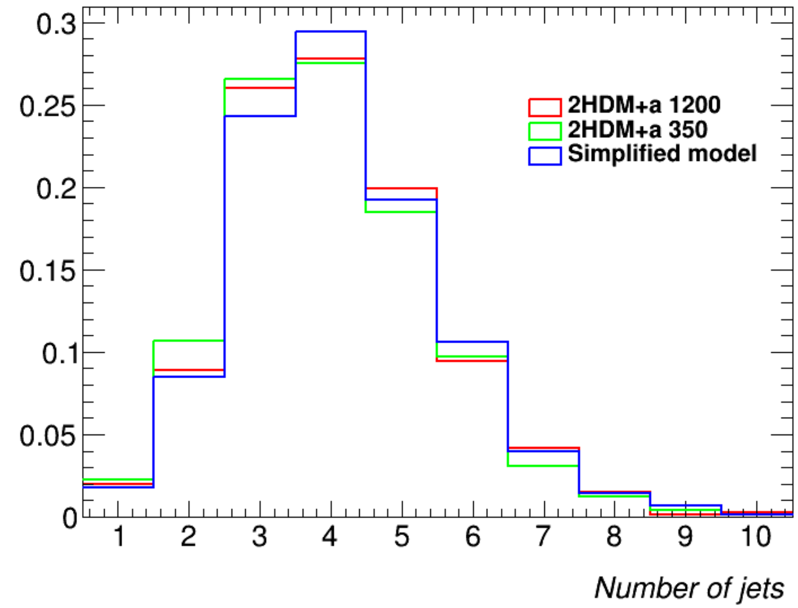
Number of jets

Exactly one lepton, which is a muon

Histograms normalized to 1



tt + MET



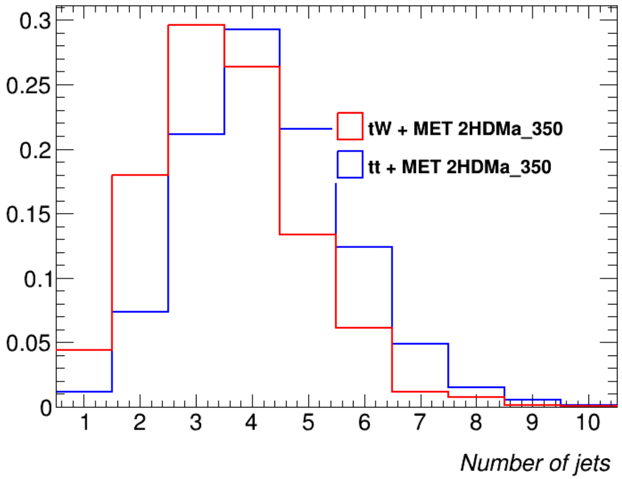
tW + MET

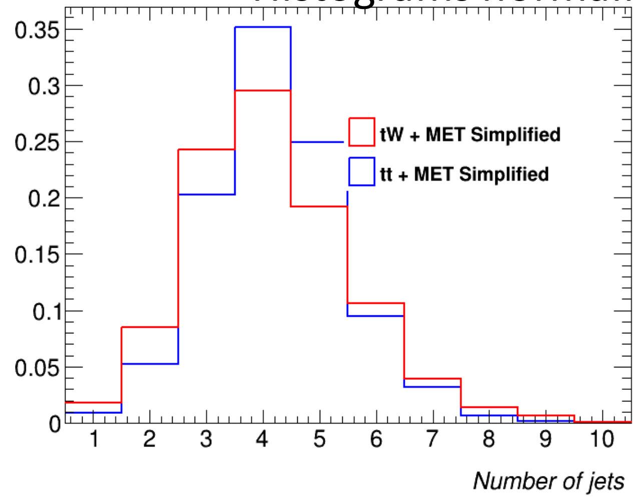
Jets: pT > 20 GeV, |eta| < 2.8

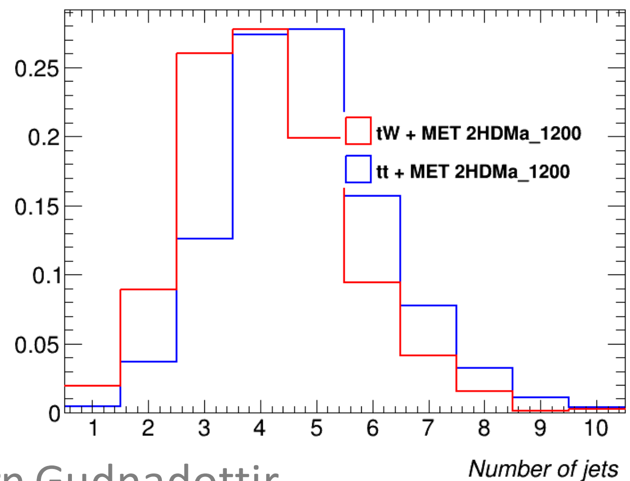
Number of jets

Exactly one lepton, which is a muon

Histograms normalized to 1





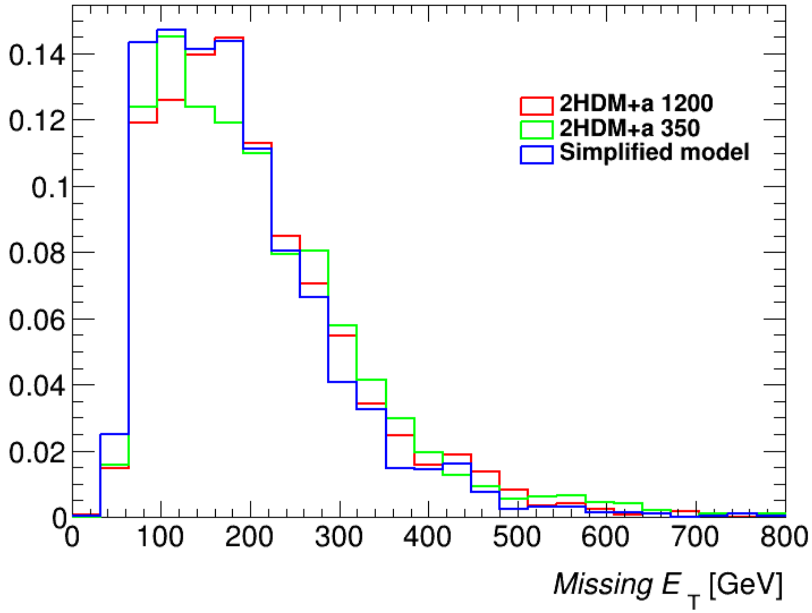


Jets: pT > 20 GeV, |eta|< 2.8

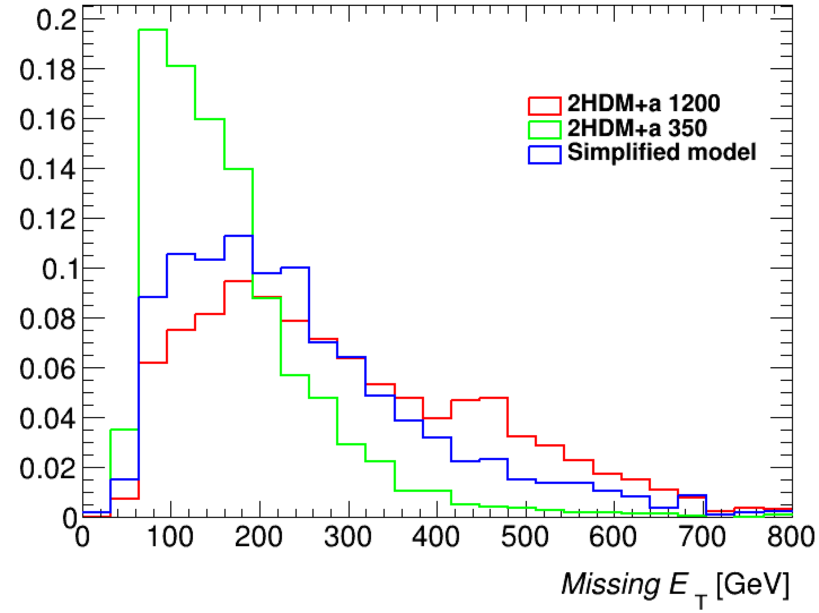
MET

Exactly one lepton, which is a muon

Histograms normalized to 1



tt + MET

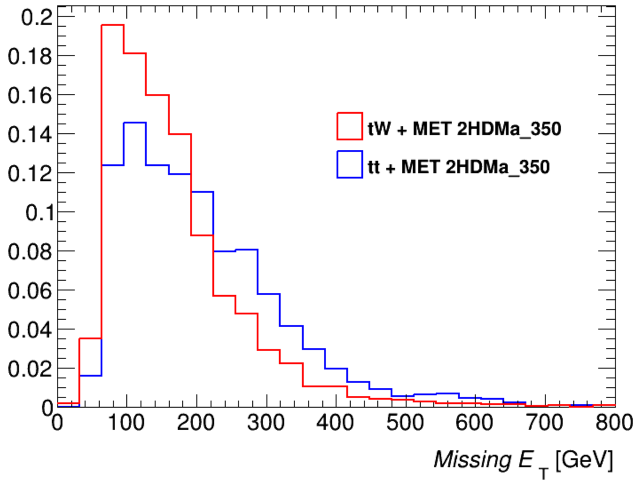


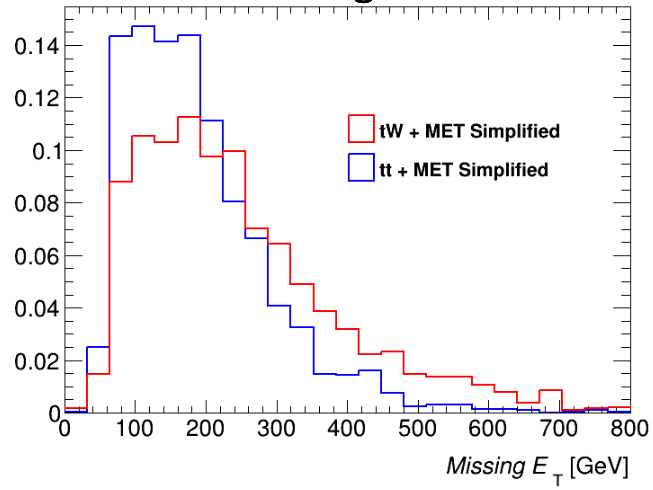
tW + MET

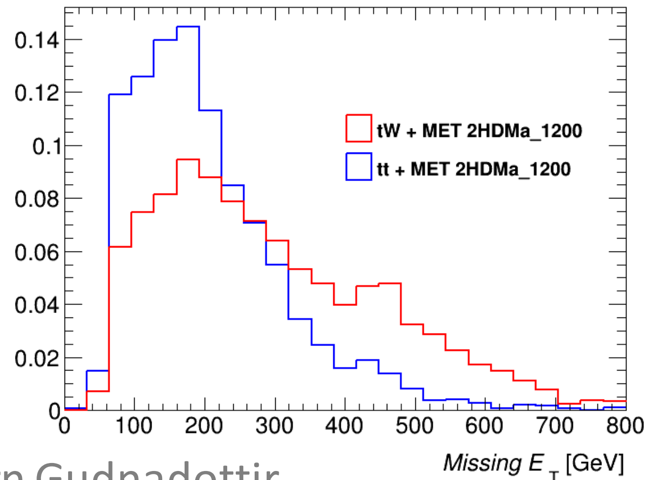
MET

Exactly one lepton, which is a muon

Histograms normalized to 1







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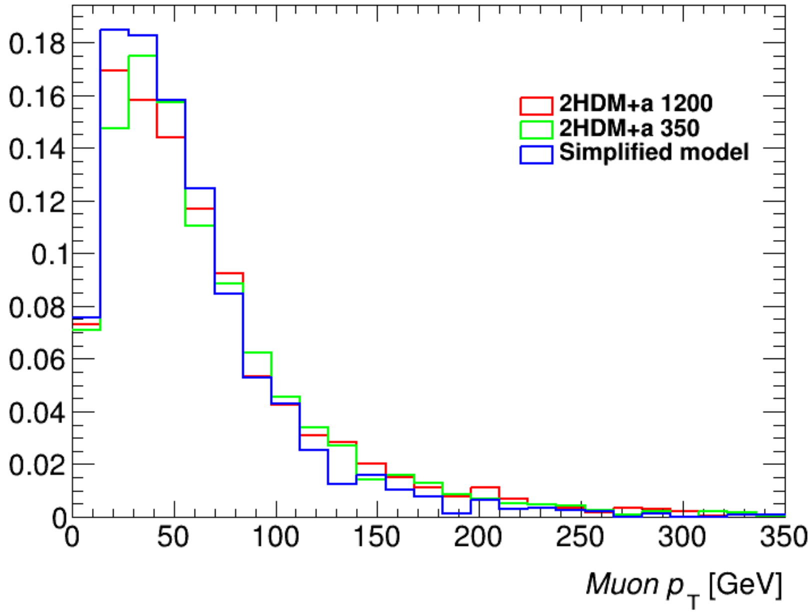
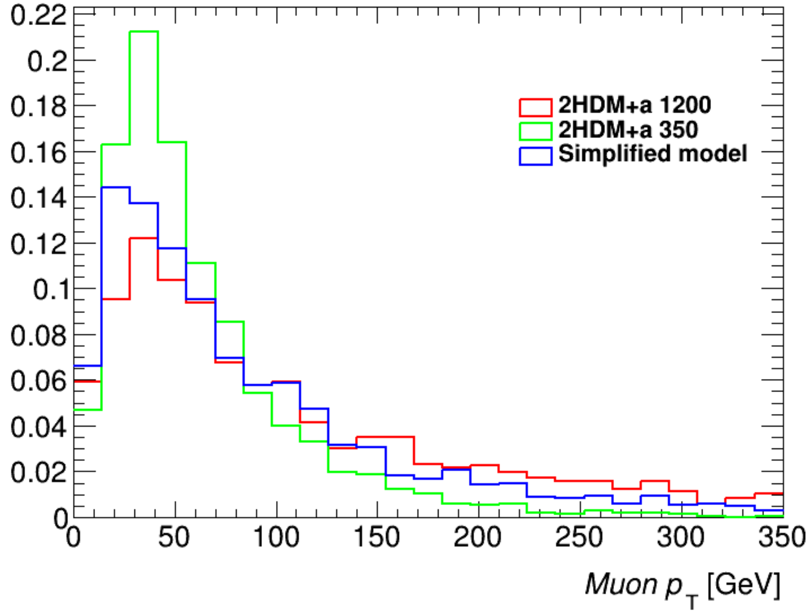
Muon pT

Exactly one lepton, which is a muon

Histograms normalized to 1



tt + MET

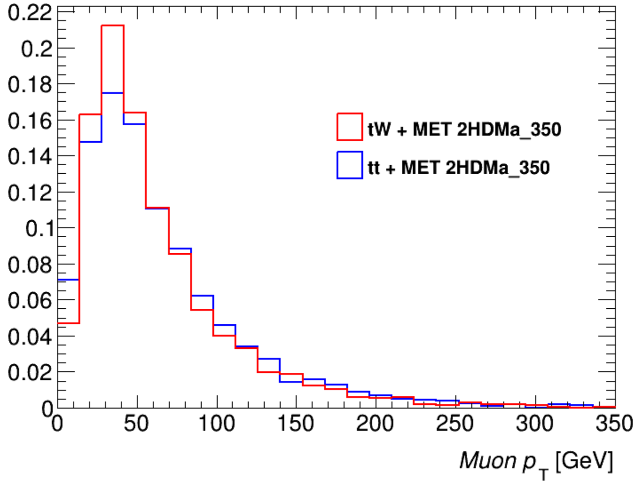


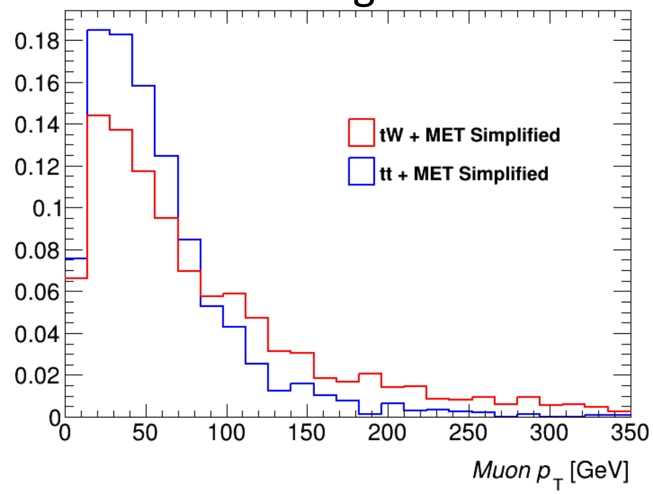
tW + MET

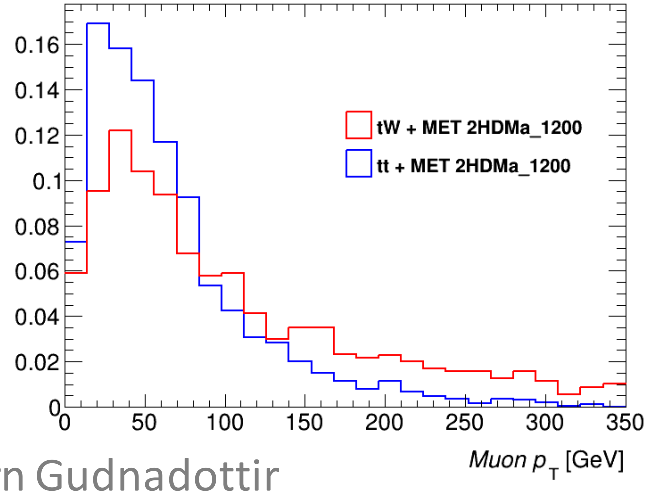
Muon pT

Exactly one lepton, which is a muon

Histograms normalized to 1







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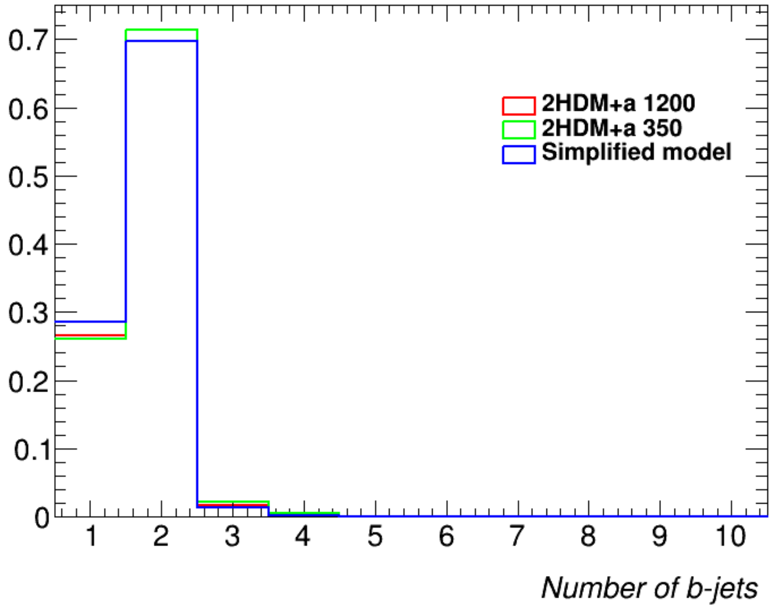
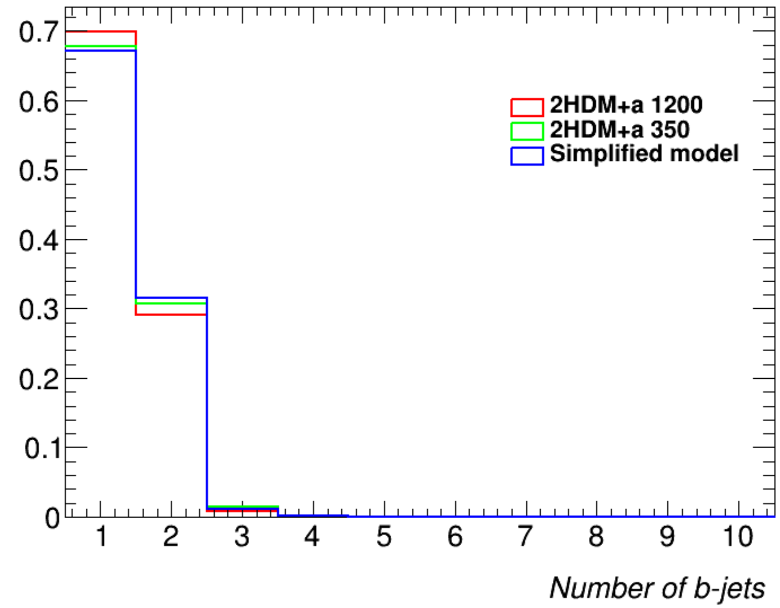
Number of b-jets

Exactly one lepton, which is a muon

Histograms normalized to 1



tt + MET



tW + MET

Number of b-jets

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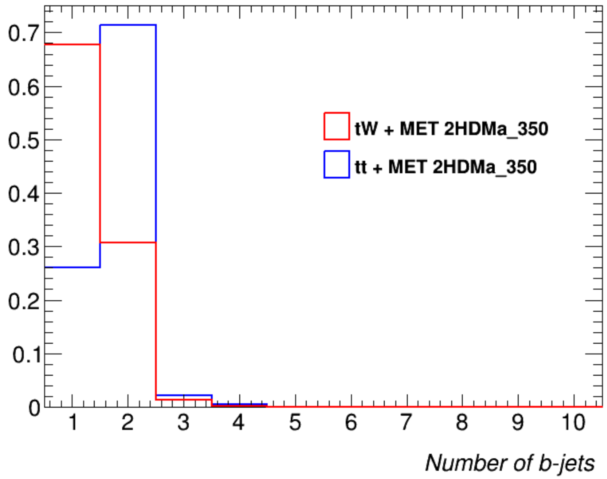
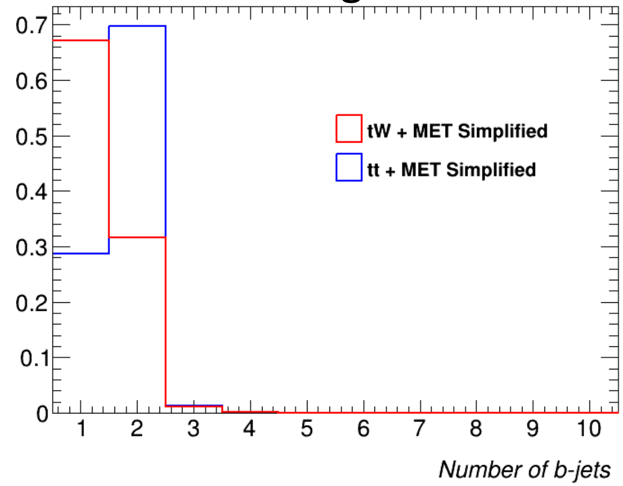
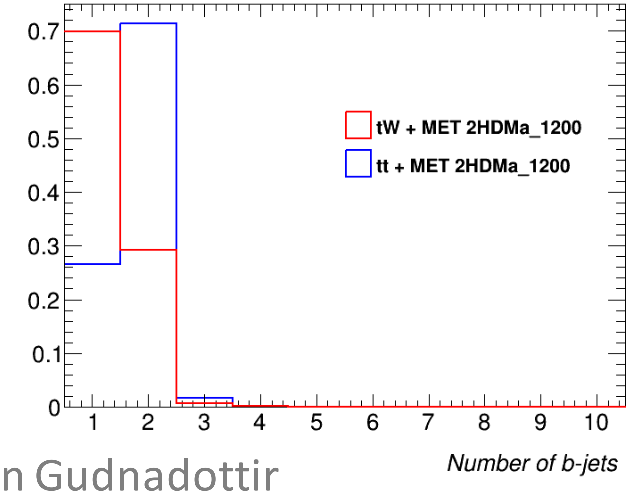


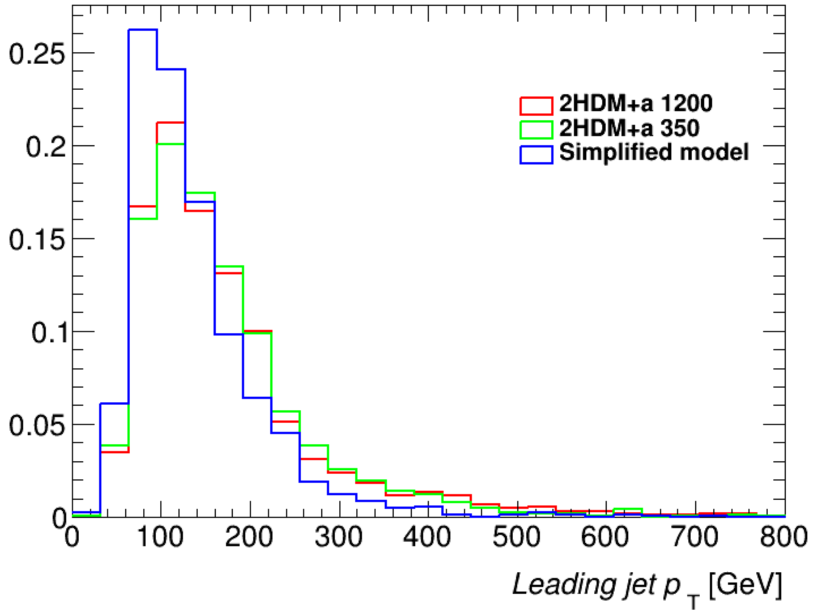




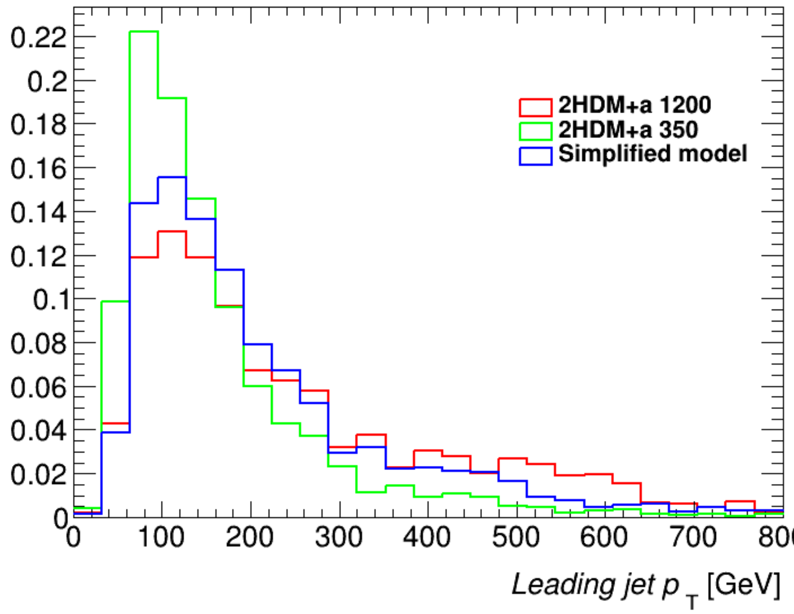
Leading Jet pT

Exactly one lepton, which is a muon

Histograms normalized to 1



tt + MET



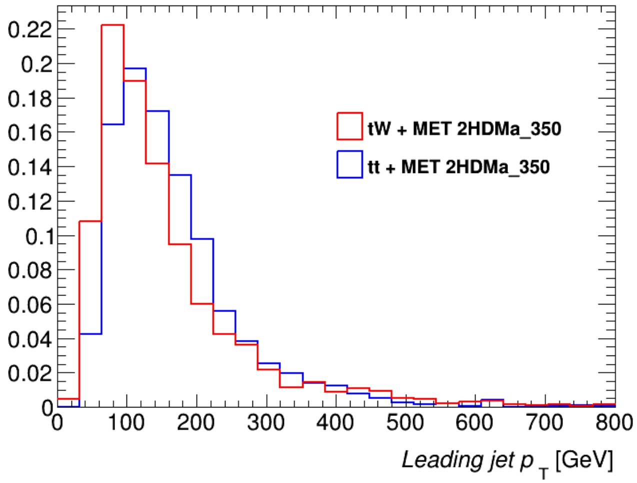
tW + MET

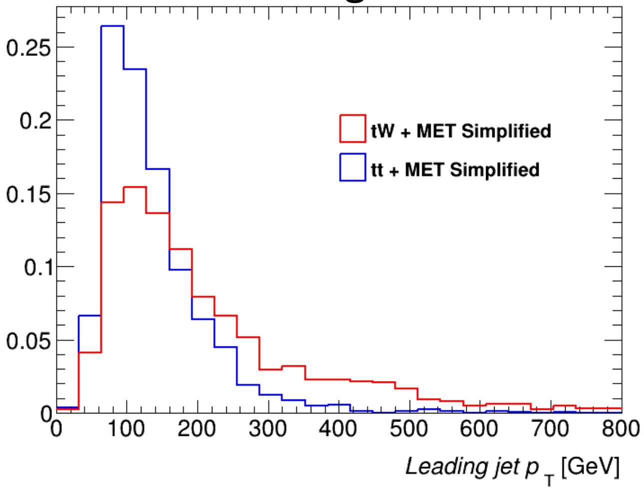
Jets: pT > 20 GeV, |eta| < 2.8

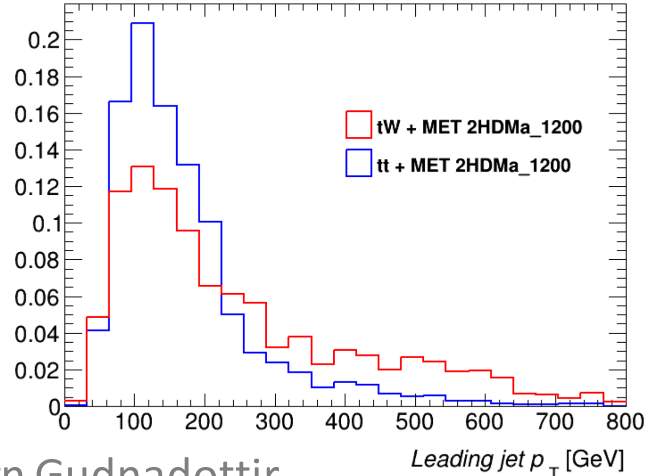
Leading jet pT

Exactly one lepton, which is a muon

Histograms normalized to 1





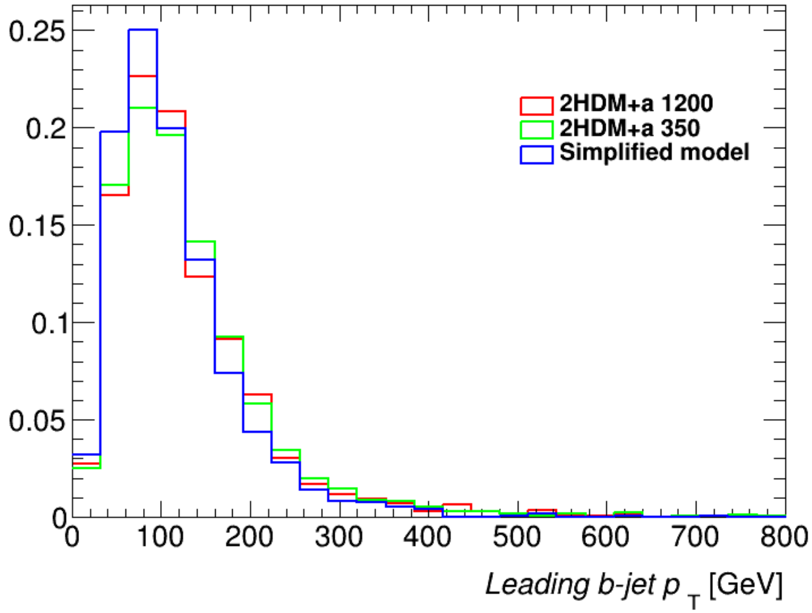


Jets: pT > 20 GeV, |eta|< 2.8

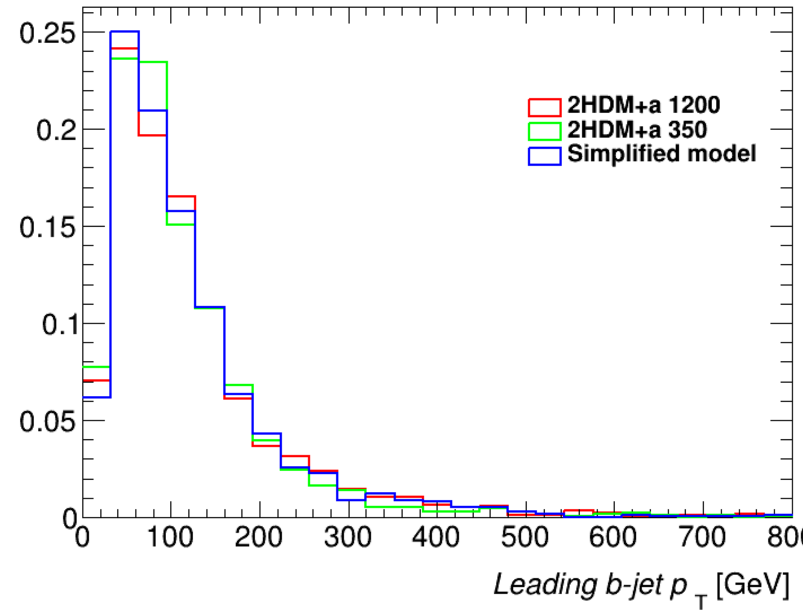
Leading b-jet pT

Exactly one lepton, which is a muon

Histograms normalized to 1



tt + MET



tW + MET

Jets: pT > 20 GeV, |eta| < 2.8

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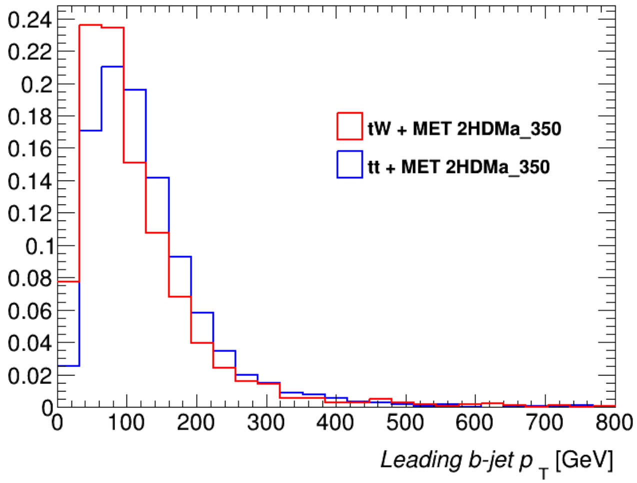
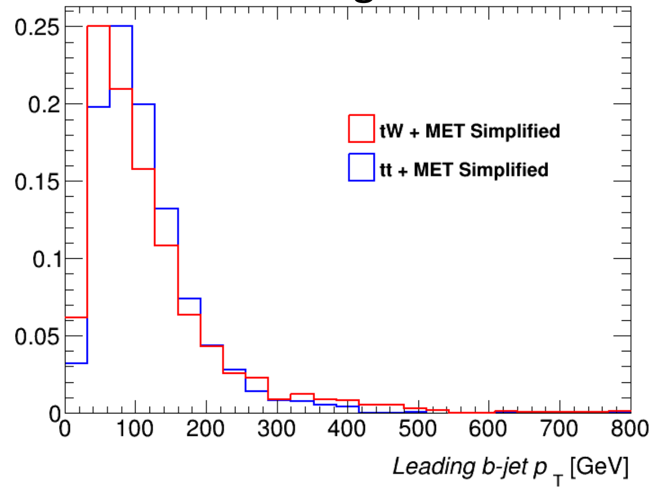
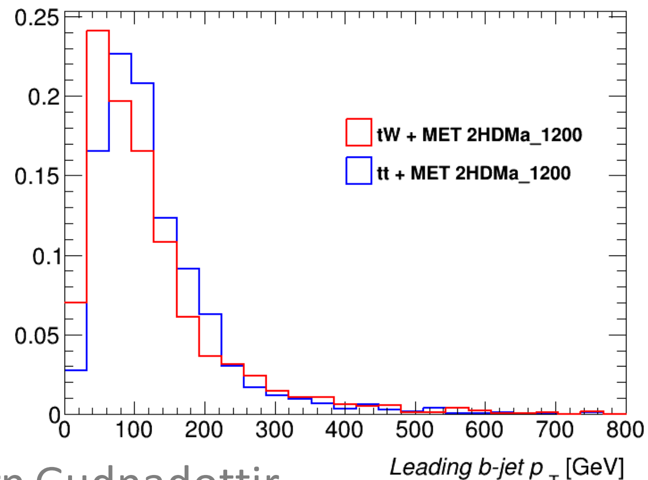
Leading b-jet pT

Exactly one lepton, which is a muon

Histograms normalized to 1







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Samples – 2HDM+a

Parameters

```
THDMparams = {}
THDMparams['gPXd'] = 1.0 # The coupling of the additional pseudoscalar mediator to dark matter (DM). This coupling is called $y_\chi$ in (2.5) of arXiv:1701.07427.
THDMparams['tanbeta'] = 1.000000 # The ratio of the vacuum expectation values of the Higgs doublets $H_2$ and $H_1$, as defined in Section 2.1 of arXiv:1701.07427.
THDMparams['sinbma'] = 1.0 # The sine of the difference of the mixing angles in the scalar potential containing only the Higgs doublets. This quantity is defined in Section 3.1 of arXiv:1701.07427.
THDMparams['lam3'] = 3.0 # The quartic coupling of the scalar doublets $H_1$ and $H_2$. This parameter corresponds to the coefficient $\lambda_3$ in (2.1) of arXiv:1701.07427.
THDMparams['laP1'] = 3.0 # The quartic coupling between the scalar doublets $H_1$ and the pseudoscalar $P$. This parameter corresponds to the coefficient $\lambda_{P1}$ in (2.2) of arXiv:1701.07427.
THDMparams['sinp'] = 0.707100 # The sine of the mixing angle theta, as defined in Section 2.1 of arXiv:1701.07427.
THDMparams['MXd'] = 10.000000 # The mass of the fermionic DM candidate denoted by $m_\chi$ in arXiv:1701.07427.
THDMparams['mh1'] = 125. # The mass of the lightest scalar mass eigenstate $h$, which is identified in arXiv:1701.07427 with the Higgs-like resonance found at the LHC.
THDMparams['mh2'] = 1200.000000 # The mass of the heavy scalar mass eigenstate $H$. See Section 2.1 of arXiv:1701.07427 for further details.
THDMparams['mh3'] = 1200.000000 # The mass of the heavy pseudoscalar mass eigenstate $A$. See Section 2.1 of arXiv:1701.07427 for further details.
THDMparams['mhc'] = 1200.000000 # The mass of the charged scalar eigenstate $H^\pm$. See Section 2.1 of arXiv:1701.07427 for further details.
THDMparams['mh4'] = 250.000000 # The mass of the pseudoscalar mass eigenstate $a$ that decouples for $\sin    heta = 0$. See Section 2.1 of arXiv:1701.07427 for further details.

evt_multiplier = 10
include("MadGraphControl_Pythia8EvtGen_NNPDF30lo_A14NNPDF23LO_2HDMa_tWDM.py")
```

Samples – 2HDM+a

Generation

```
define p = g d u s c b d~ u~ s~ c~ b~
define j = g d u s c b d~ u~ s~ c~ b~
define l+ = e+ mu+ ta+
define l- = e- mu- ta-
define vl = ve vm vt
define vl~ = ve~ vm~ vt~
generate p p > w+ t~ xd~ xd
generate p p > w- t xd~ xd
(add process p p > t t~ xd~ xd)
output -f
""")
```

```
if (filter_string == "1L0L"):
    evgenLog.info('1lepton and MET 60 filter or MET 150 is applied')
    include ( 'MC15JobOptions/LeptonFilter.py' )
    filtSeq.LeptonFilter.Ptcut  = 20000.
    filtSeq.LeptonFilter.Etacut = 2.8

include('MC15JobOptions/MissingEtFilter.py')
    filtSeq.MissingEtFilter.METCut = 60000.

    filtSeq += MissingEtFilter("MissingEtFilterHard")
    filtSeq.MissingEtFilterHard.METCut = 150000.

    filtSeq.Expression = "(LeptonFilter and MissingEtFilter) or MissingEtFilterHard"
```

Samples – 2HDM+a

Generation

```
if (filter_string == "1L0L"):
   mscard.write("""
   set max_weight_ps_point
400  # number of PS to estimate
the maximum for each event
   set
seed %i


   # specify the decay for the final
state particles
```

```
   define vl = ve vm vt
   define vl~ = ve~ vm~ vt~
   define l+ = e+ mu+ ta+
   define l- = e- mu- ta-
   decay t > w+ b, w+ > l+ vl
   decay t~ > w- b~, w- > l- vl~
   decay w+ > l+ vl
   decay w- > l- vl~
   # running the
actual code
   launch"""%runArgs.randomSeed)
mscard.close()
```

Samples – Simplified model

tW + MET generation

```
elif model_string == "Wtpseudo":
    fcard.write("""
import model DMPseudoscalarMed_loop  --modelname
define  p = g u c d s u~ c~ d~ s~ b b~
define  j = g u c d s u~ c~ d~ s~ b b~
generate  p p > t w- chi~ chi
add process p p > t~ w+  chi~ chi
output -f
""")

    xptb = 0
    ptj = 20
    drjj = 0.4

    nJetMax=0
    ktdurham=0
    dokt = "F"
    lhaid = "263000"
    maxjetflavor  = "5"
    evgenConfig.process  = "pp>tWchichi"
```

tt + MET generation

```
elif model_string == "ttpseudo":
    fcard.write("""
import model DMPseudoscalarMed_loop  --modelname
define  p = g u c d s u~ c~ d~ s~ b b~
define  j = g u c d s u~ c~ d~ s~ b b~
generate  p p > t t~ chi chi~
add process p p > t t~ j chi chi~
output -f
""")

    xptb = 0
    ptj = 20

    nJetMax=1
    ktdurham=40
    if mphi/4 > 40:
       ktdurham = mphi/4
    evgenLog.info('ktdurham  set to %i' %ktdurham)
    process="pp>{phi,1000000}tt~"
    removedecays  = "on"
    dokt = "T"
    lhaid = "263000"
    maxjetflavor  = "5"
    evgenConfig.process  = "pp>ttchichi"
```

Samples – Simplified model

Generation

```
if (filter_string == "1LMET60orMET150"):
    evgenLog.info('1lepton  and MET 60 filter or MET 150 is applied')
    include ( 'MC15JobOptions/LeptonFilter.py'  )
    filtSeq.LeptonFilter.Ptcut  = 20000.
    filtSeq.LeptonFilter.Etacut = 2.8

    include('MC15JobOptions/MissingEtFilter.py')
    filtSeq.MissingEtFilter.METCut  = 60000.


    filtSeq += MissingEtFilter("MissingEtFilterHard")
    filtSeq.MissingEtFilterHard.METCut  = 150000.

    filtSeq.Expression = "(LeptonFilter  and MissingEtFilter) or
        MissingEtFilterHard"
```

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Symbol	Definition	Value
	Definitions and values of parameters in the 2HDM+a model	
α	mixing angle of the two neutral CP-even weak eigen-states	$\cos(\beta-\alpha)=0$
θ	mixing angle of the two neutral CP-odd weak eigen-states	varied
$\tan\beta$	ratio of the vacuum expectation values of the two Higgs doublets	varied
v	electroweak vacuum expectation value	246 GeV
λ_{P1}	quartic coupling between the scalar doublets H_1 and the additional pseudo-scalar	$=\lambda_3$
λ_{P2}	quartic coupling between the scalar doublets H_1 and the additional pseudo-scalar	$=\lambda_3$
λ_3	The quartic coupling between the scalar doublets H_1 and H_2	3
y_χ	coupling between the DM and the additional pseudo-scalar	1
m_h	mass of the lightest CP-even mass eigenstate	125 GeV
m_H	mass of the heaviest CP-even mass eigenstate	$=m_A$
m_A	mass of the heaviest CP-odd mass eigenstate	varied
m_a	mass of the lightest CP-odd mass eigenstate	varied
$m_{H^\pm}$	mass of the charged Higgs eigenstate	$=m_A$
m_χ	mass of the DM particle	10 GeV