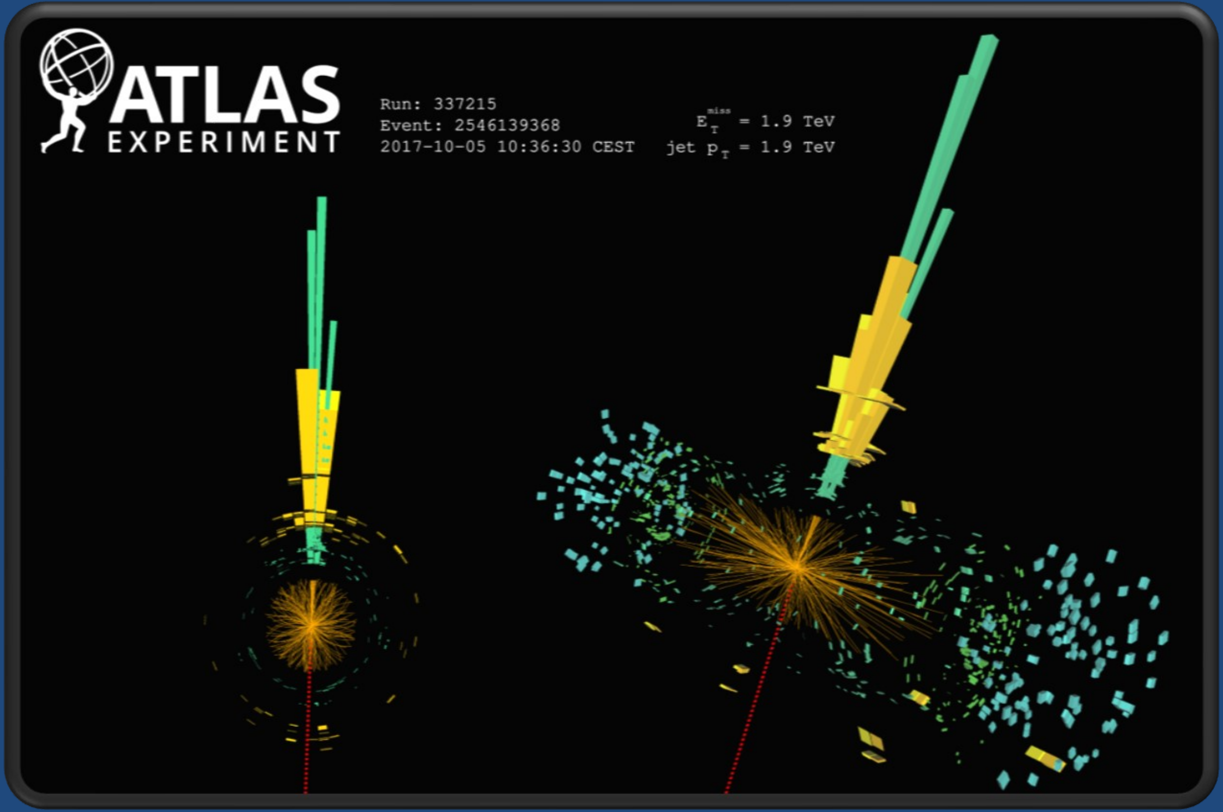
Dark Matter Searches with the ATLAS Detector



5th International Conference on Particle Physics and Astrophysics

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Institute of Particle Physics & University of Toronto

Oct 7, 2020

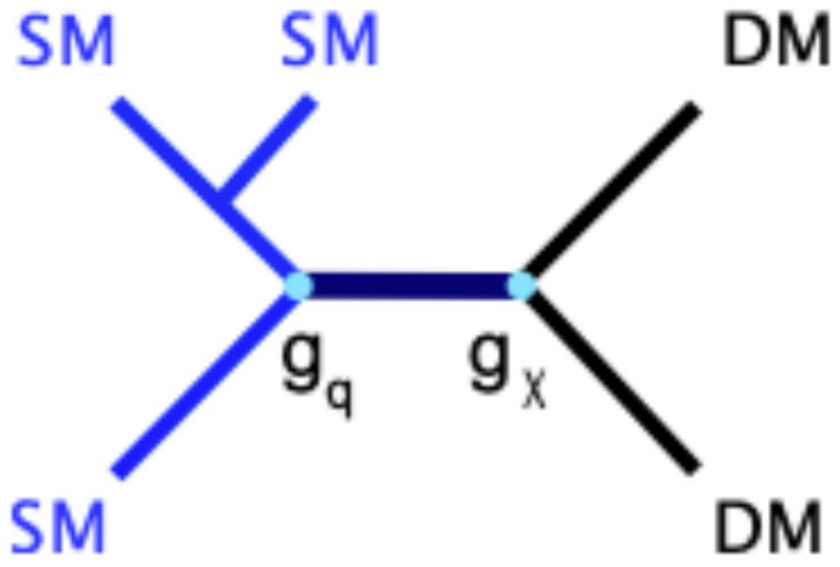
INSTITUTE OF PARTICLE PHYSICS

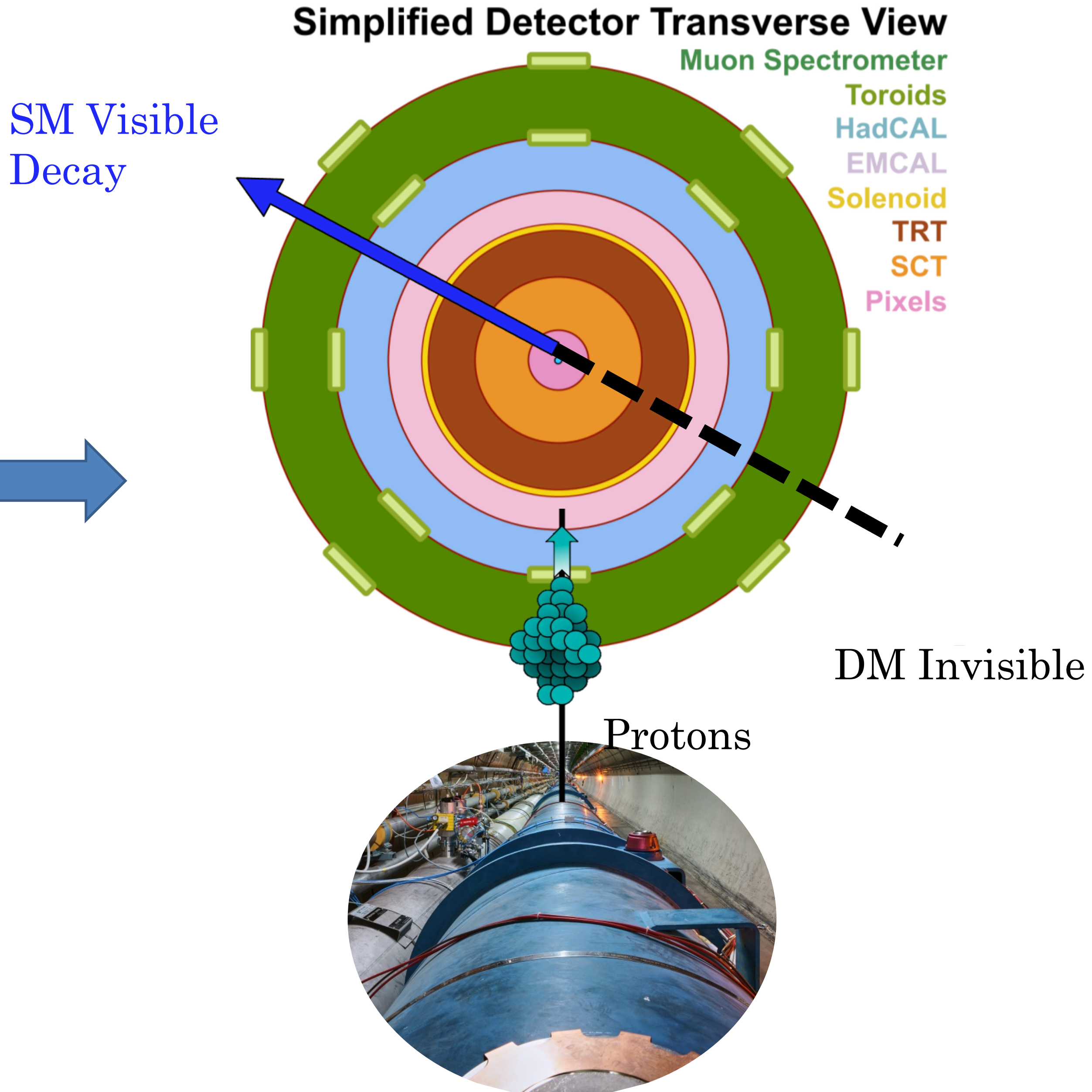
UNIVERSITY OF TORONTO

Outline

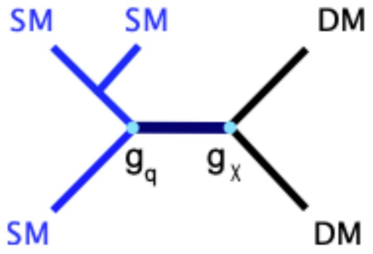
- Dark Matter at Colliders
- ATLAS DM Searches (a small subset!)
  - MET + jet
  - MET + Wt
  - MET + VV (hadronic)
  - Combinations
- Summary

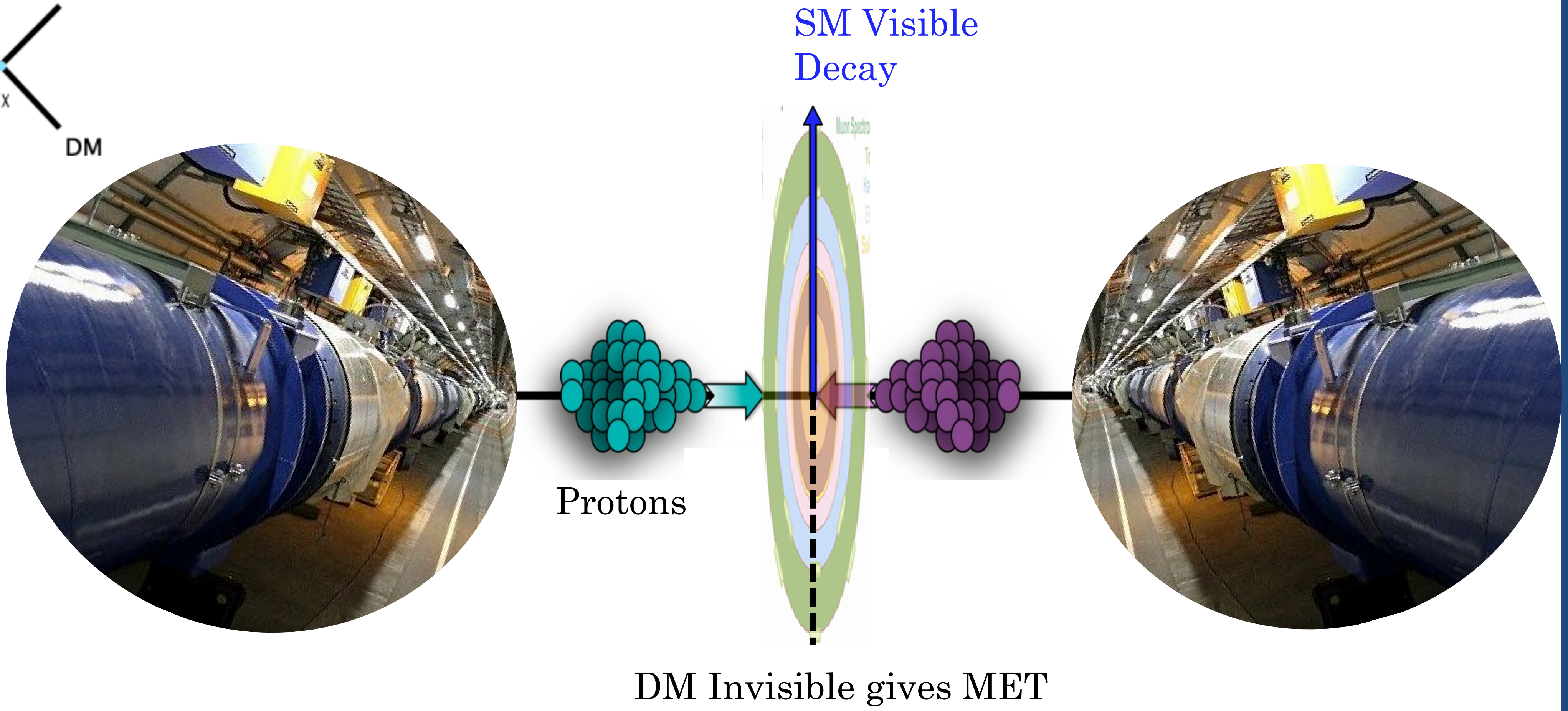
Dark Matter at Colliders





Dark Matter at Colliders





In only visible decays, momentum in transverse plane must be 0 before and after collision. DM presence means non zero Missing Transverse Energy **(MET)**

Dark Matter at Colliders

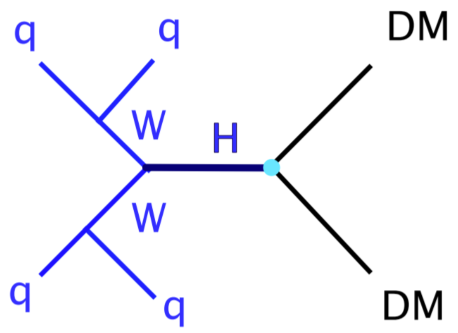
Simplified Models

- Benchmark models with simplified mediator, look for MET + X final states
- Harmonized choices, common to all experiments, under guidance of LHC DM working group

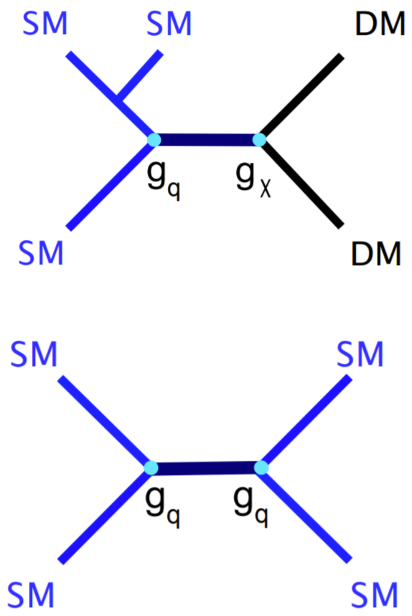
Complete Models

- Fully theoretically developed models, final states depend on model assumptions

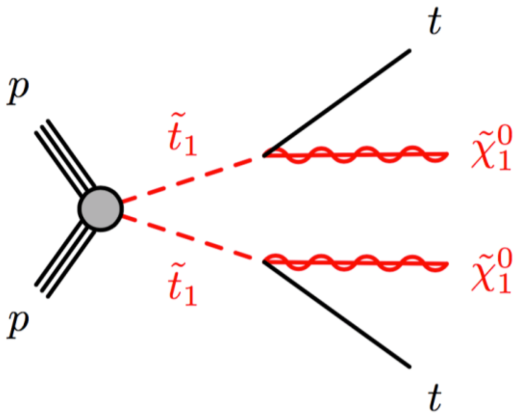
SM mediators
(Z/H portal)



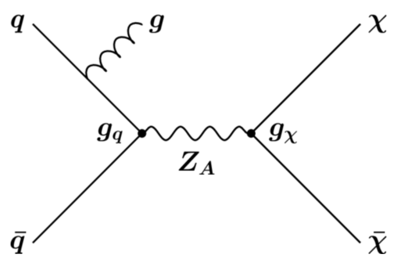
Beyond-SM mediator
(scalar/vector/etc.)



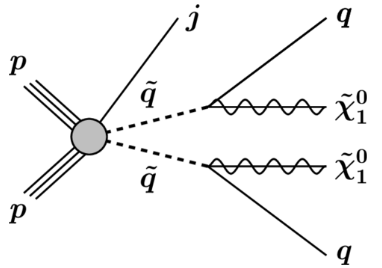
Supersymmetry, etc.



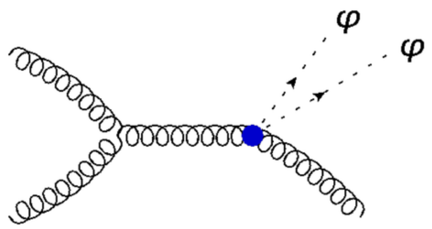
MET + Jet



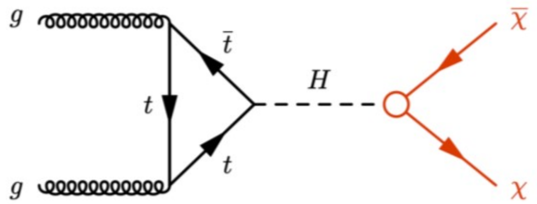
Simplified models.
Simplified axial-vector,
vector, pseudo-scaler
mediator



Supersymmetry: small $\Delta m = m_{\tilde{q}} - m_{\tilde{\chi}^0_1}$, with initial state radiation JET



Effective field theory,
scaler dark energy
field couples to SM

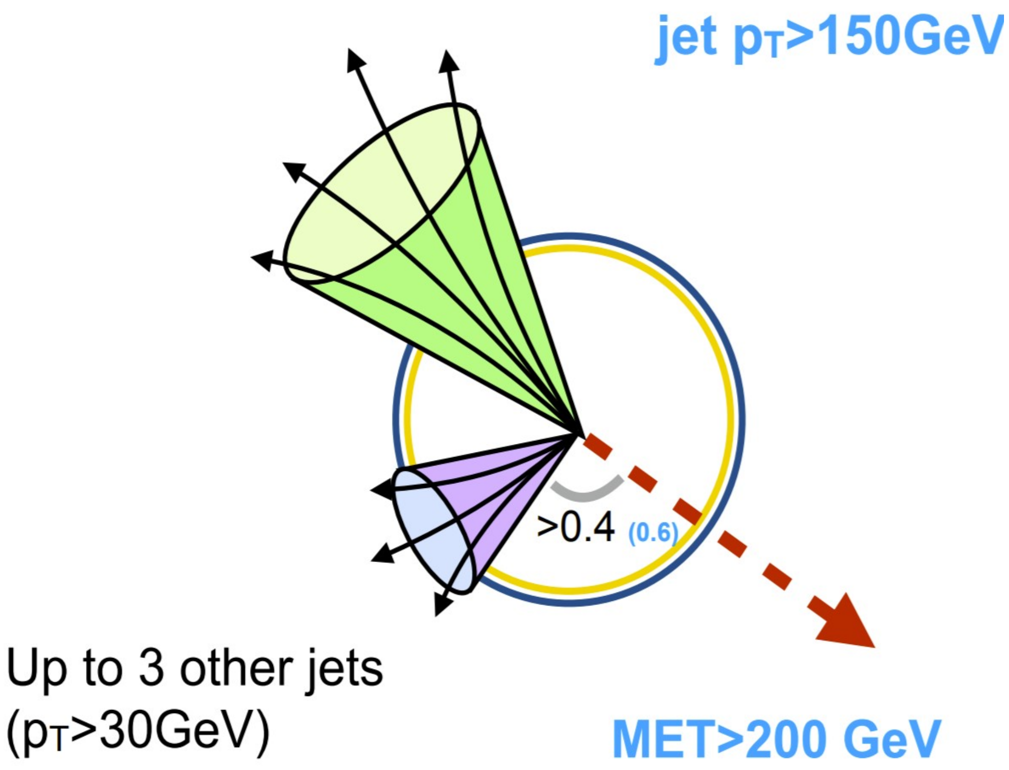


Higgs decay to DM

+ Axion-like particles
with gluon

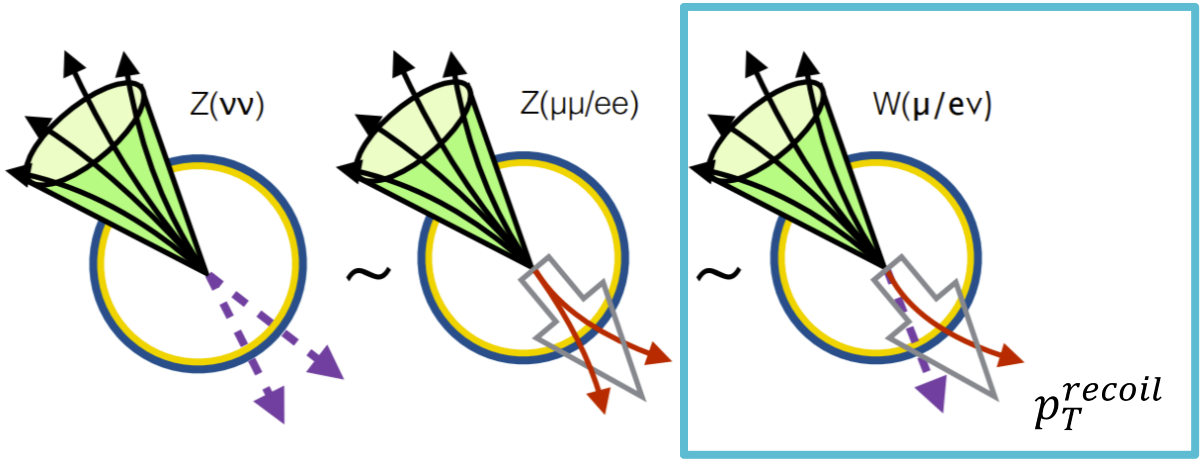
Signal-rich Signal Region (SR)

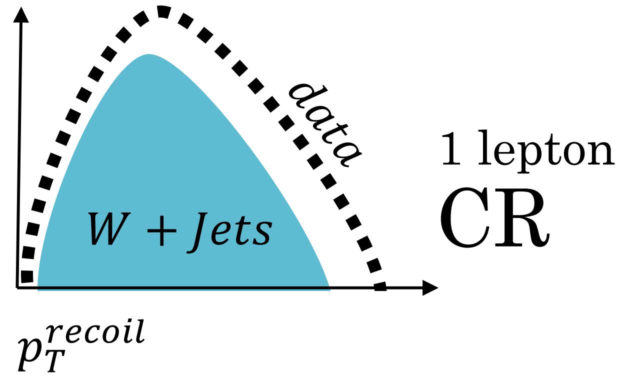
Require 0 leptons/photons



MET + Jet

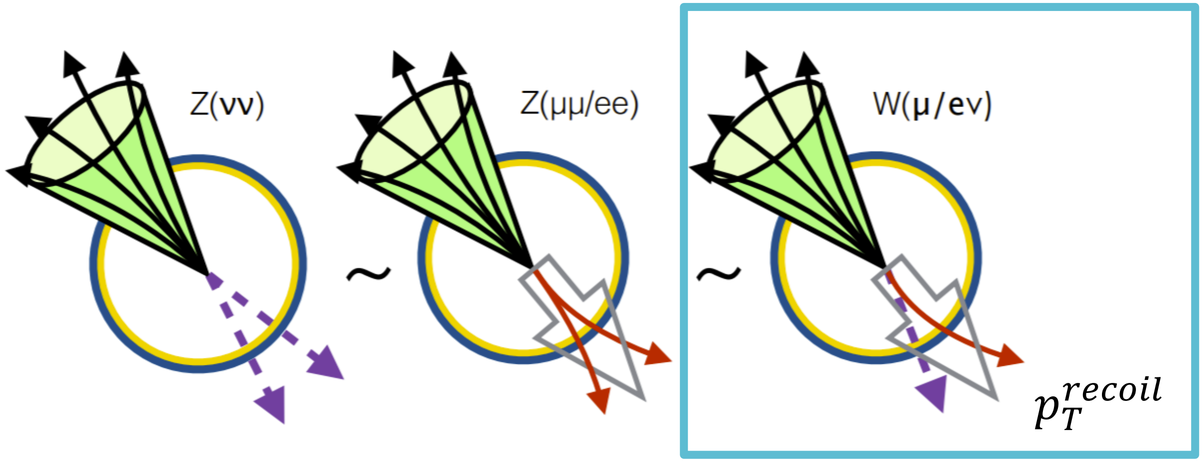
Largest backgrounds Z+jets/W+jets/top estimated from 5 background-rich control regions (CR), differentiated from SR by number of leptons

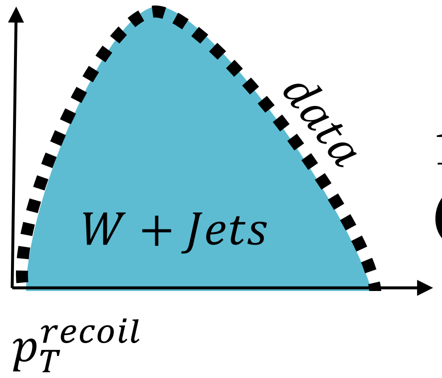




MET + Jet

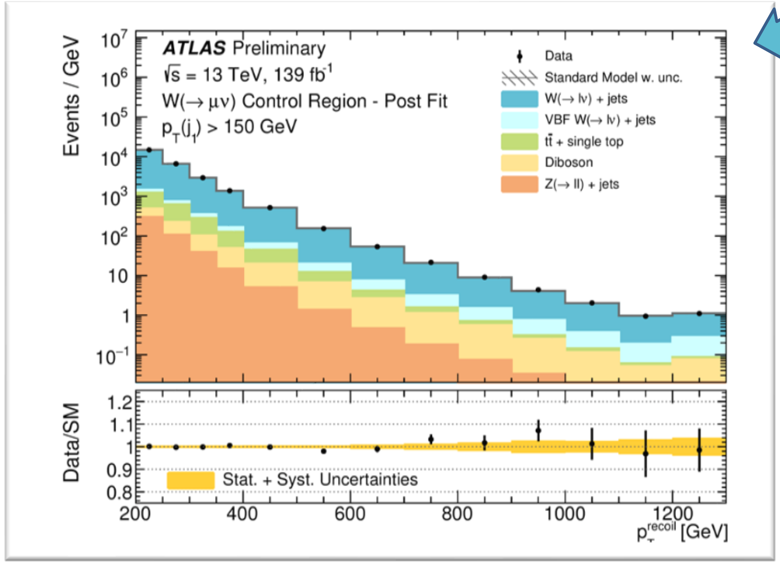
Z+jets is correlated with W+jets in order to increase sensitivity via reweighting MC (NLO in QCD)





1 lepton
CR

μ_{V+jets}



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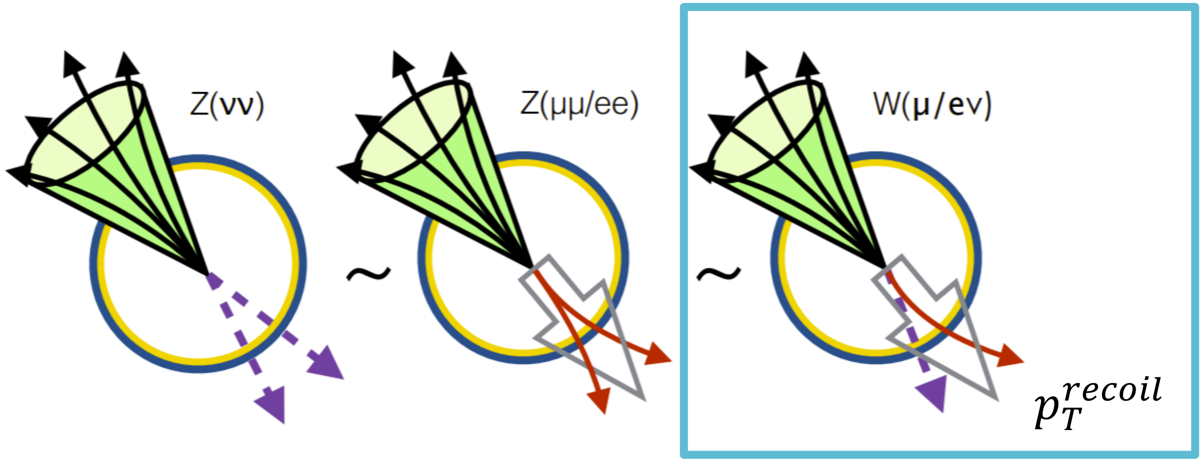
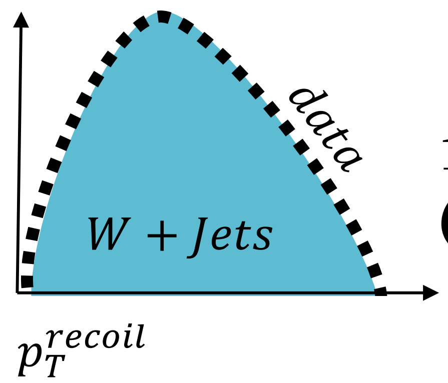
MET + Jet

Reaches percent-level precision on the backgrounds, thanks to theory work on V+jets (10.1140/epjc/s10052-017-5389-1), and improved reconstruction performance



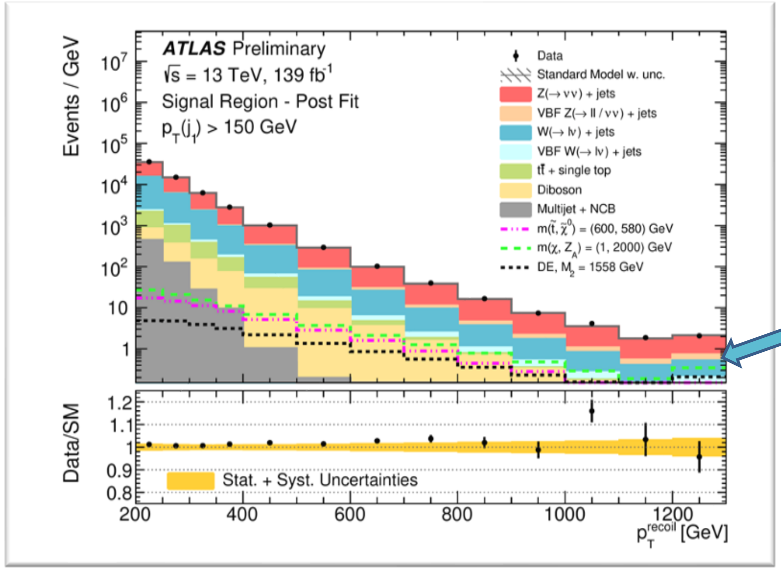


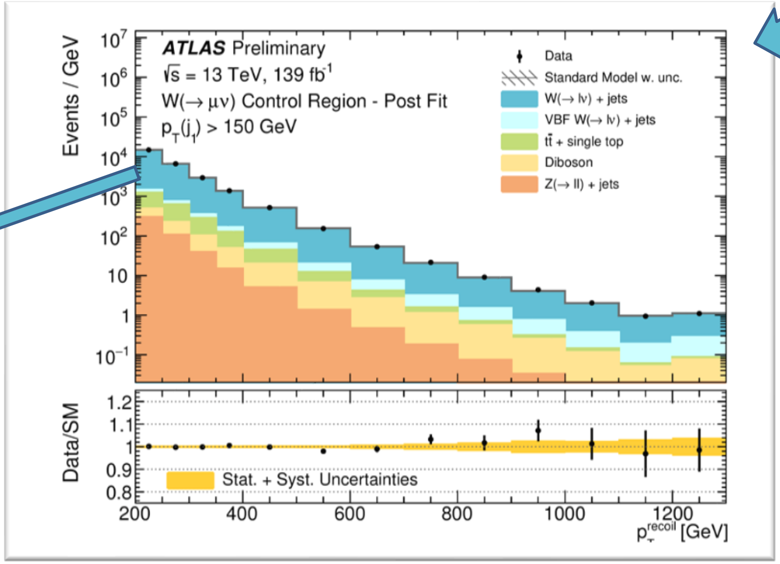
1 lepton
CR

μ_{V+jets}

μ_{V+jets}

SR





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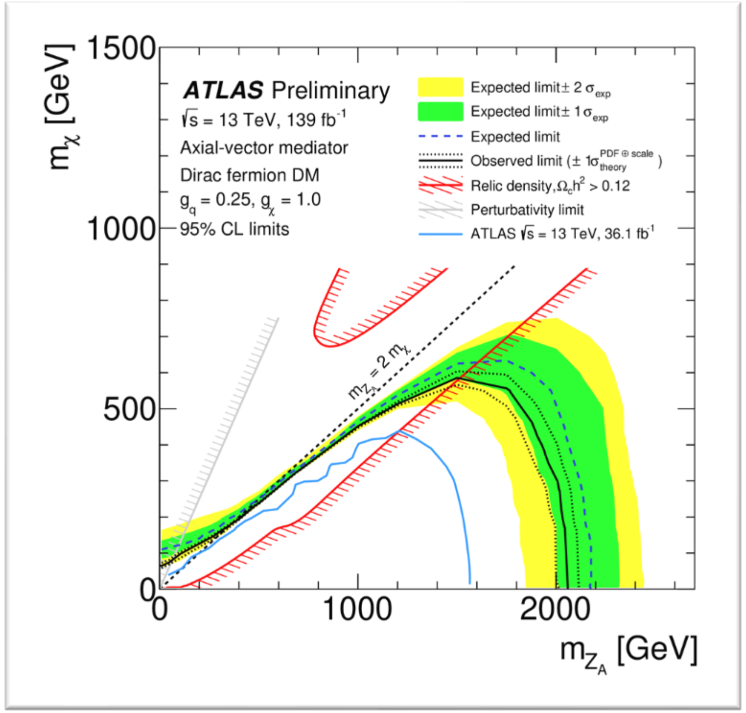
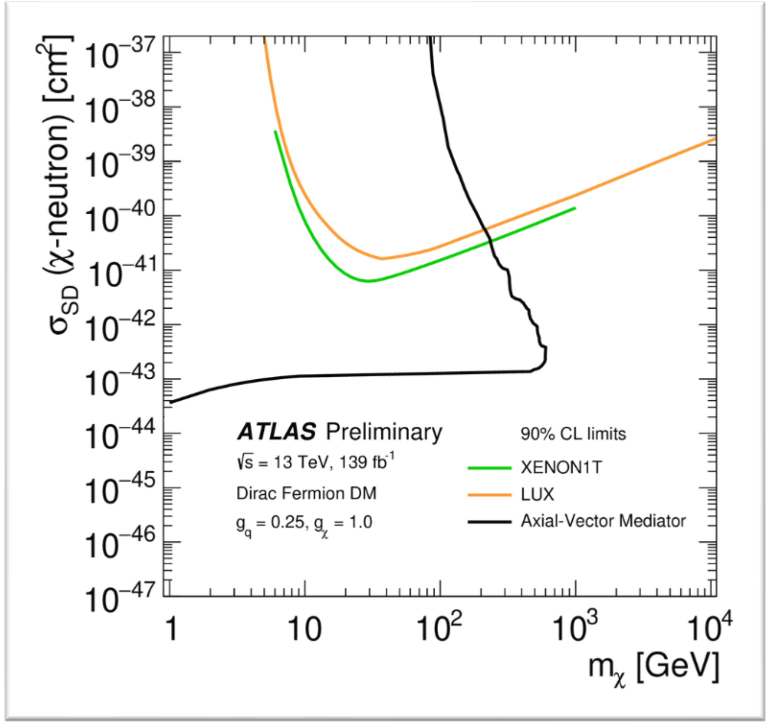
MET + Jet

Fit exploits shape of p_T of vector boson. No significant excess over SM predictions.



Dirac fermion DM
Axial-vector mediator
$g_q = 0.25, g_\chi = 1.0$



Dirac Fermion DM
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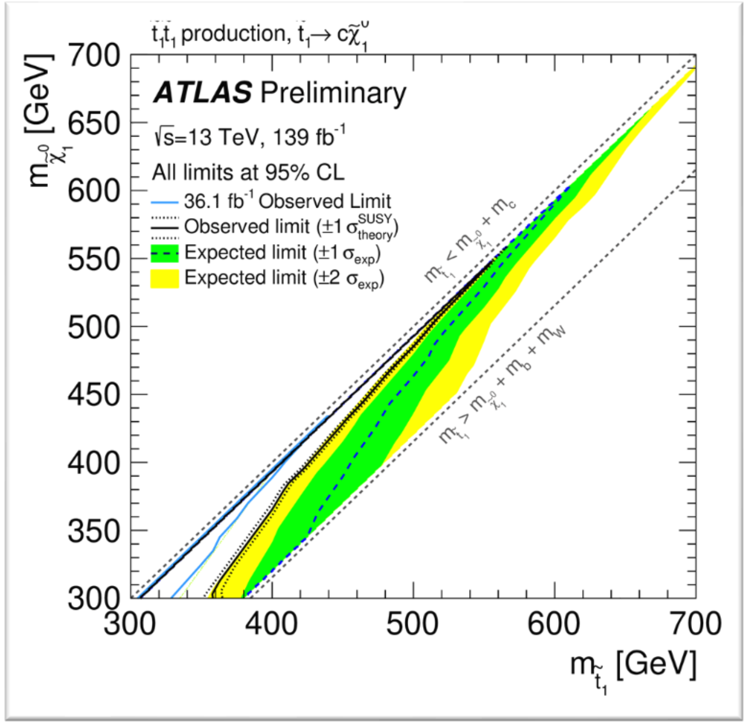

Supersymmetry

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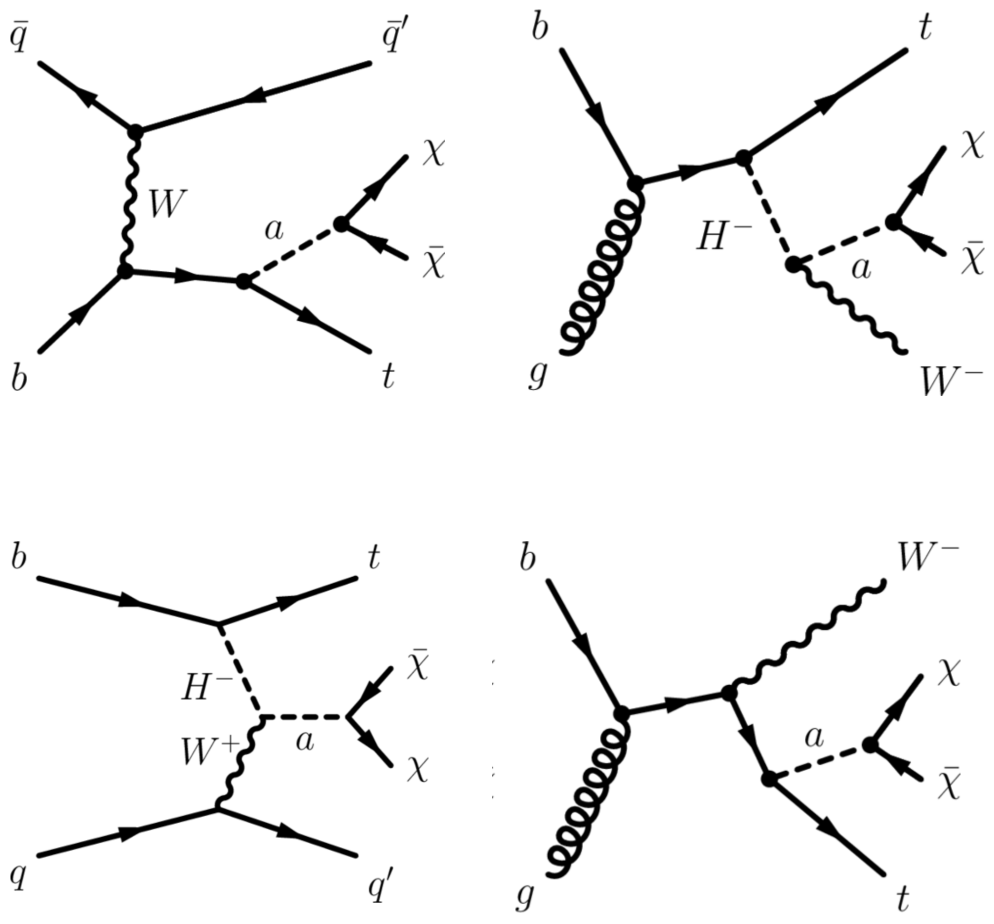
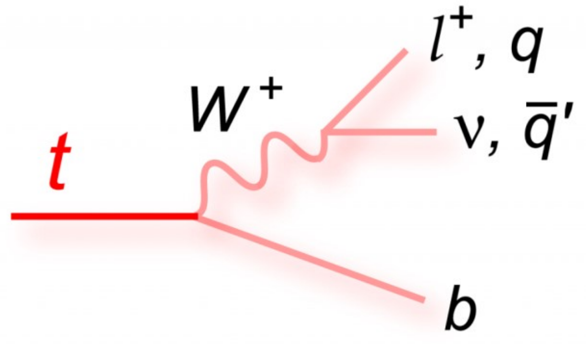
Dominant uncertainties: data statistics

MET + Wt



- Simplified DM models are a good benchmark, but have some theoretical inconsistencies (arXiv 1510.02110, arXiv 1503.07874), and limited signatures (MET + mono-X)

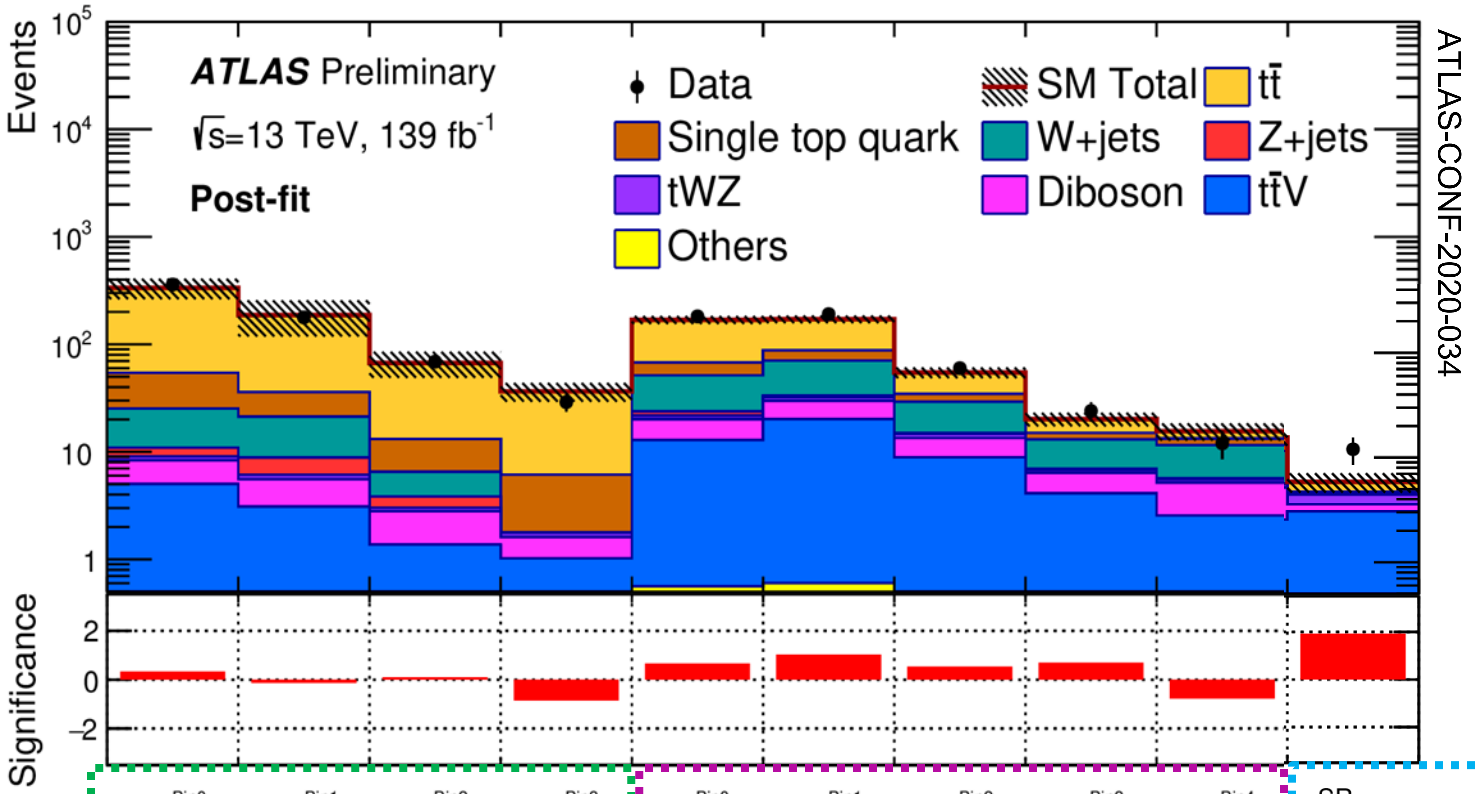
- Next-generation LHC DM model: 2 Higgs Double Models (2HDM+a)
  - New signatures & rich phenomenology
  - Additional Higgs particles (h, H0 , H± , A) & pseudo-scalar (a) that couples to DM



Final states with various combinations of leptons, jets/b-jets define the SR

MET + Wt

Main backgrounds $t\bar{t}$, W+jets, tt Z, WZ are normalized from CR, which is differentiated from SR by discriminating variables



$SR^{Bin0}_{tj_{1L}}$ $SR^{Bin1}_{tj_{1L}}$ $SR^{Bin2}_{tj_{1L}}$ $SR^{Bin3}_{tj_{1L}}$

1 lepton, 1-4 jets, 1-2 b-jet
Fit to BDT

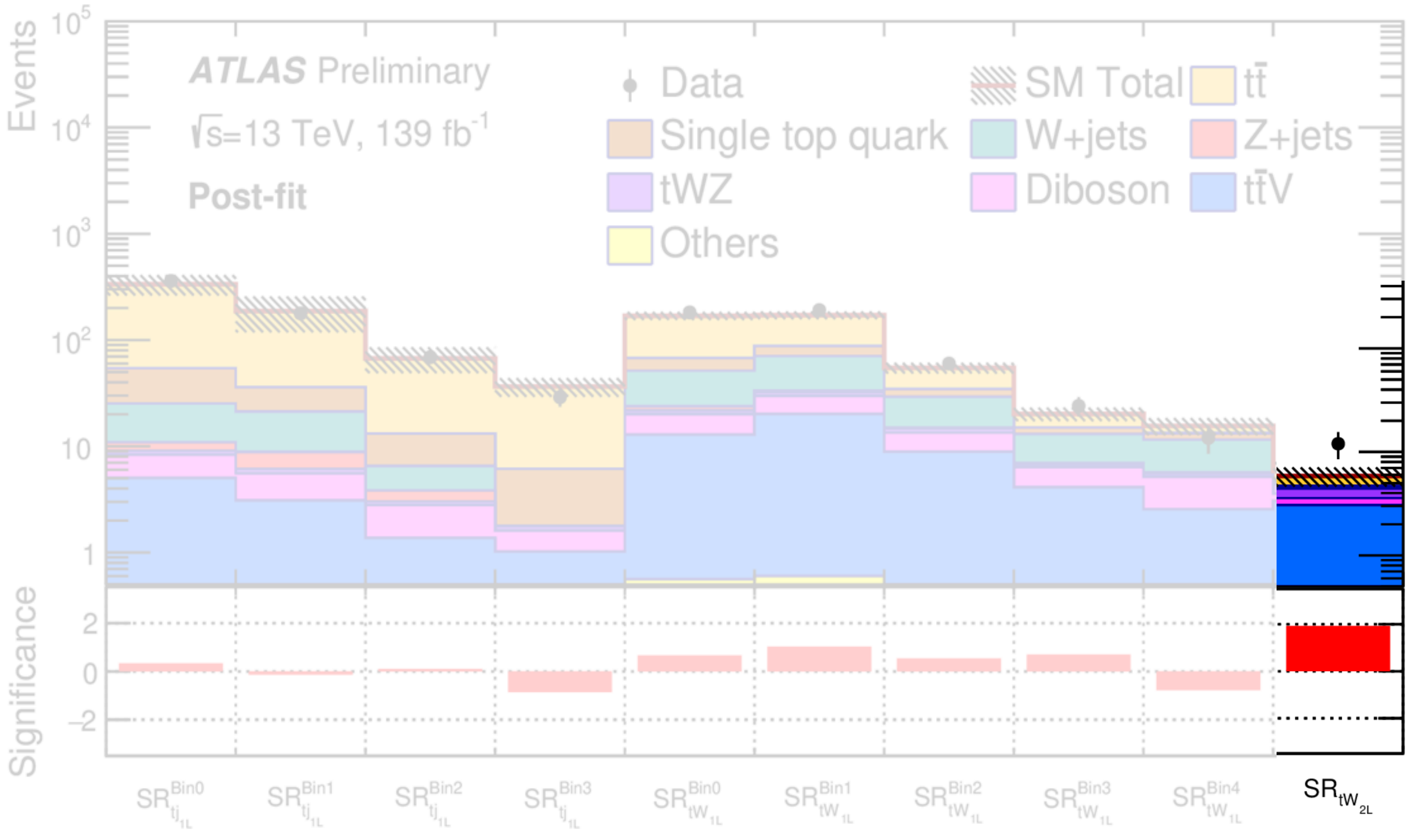
$SR^{Bin0}_{tW_{1L}}$ $SR^{Bin1}_{tW_{1L}}$ $SR^{Bin2}_{tW_{1L}}$ $SR^{Bin3}_{tW_{1L}}$ $SR^{Bin4}_{tW_{1L}}$

1 lepton, ≥ 3 jets,1 b-jet
Fit to MET

$SR_{tW_{2L}}$

2 lepton, ≥ 1 jet, ≥ 1b-jet
1 bin SR

MET + Wt



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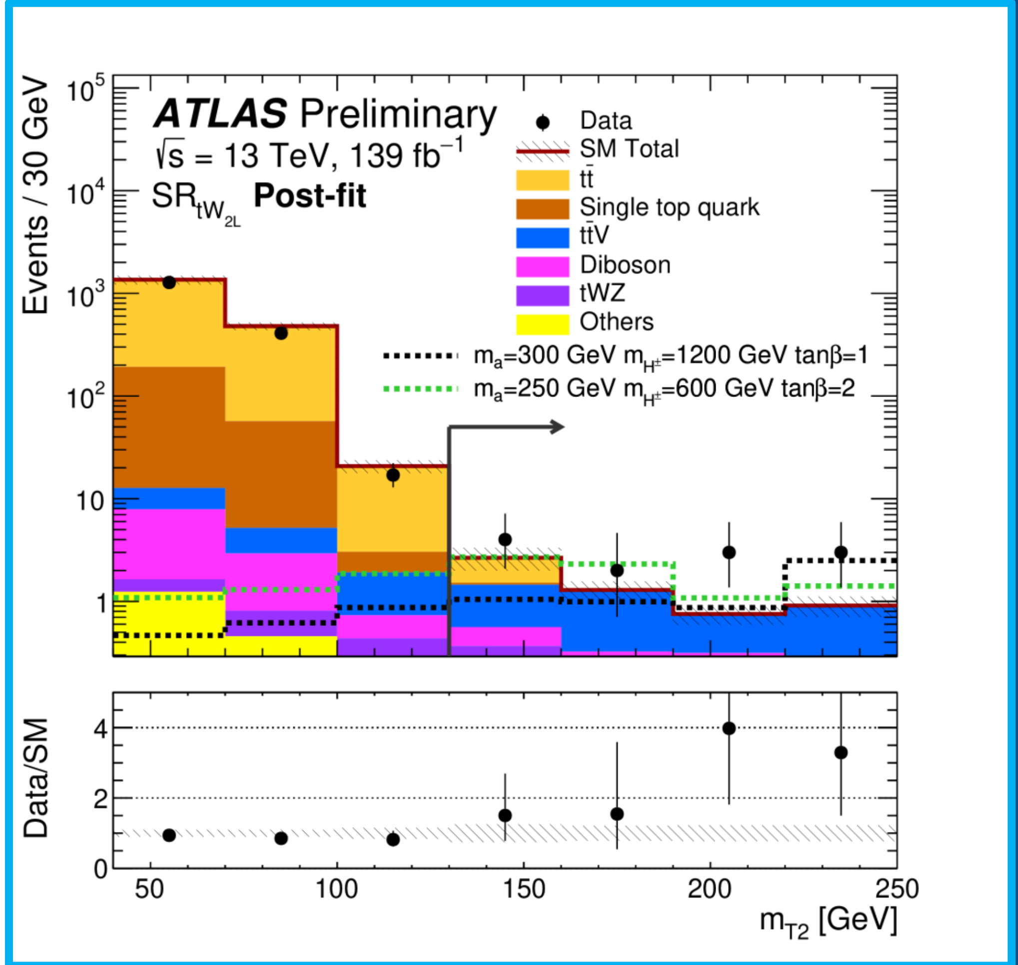
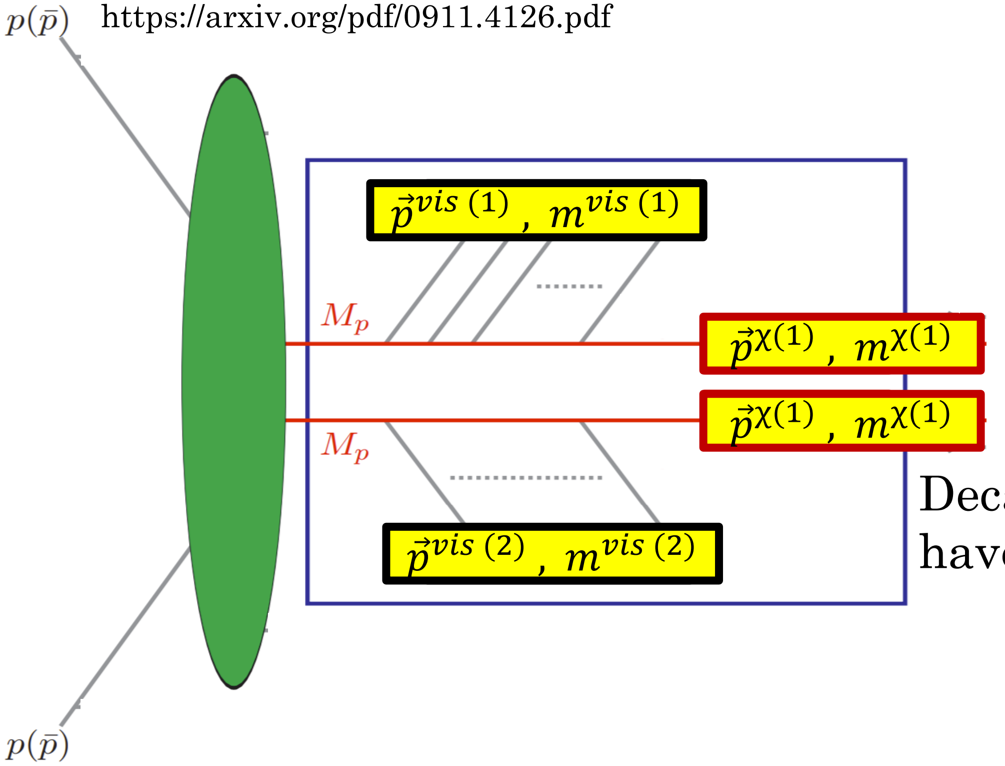


2 lepton, ≥ 1 jet, ≥ 1b-jet

Differentiate SR from CR with
m_{T2}: **stransverse mass** and similar variables defined with b-jets

MET + Wt

https://arxiv.org/pdf/0911.4126.pdf



Decay particles have same mass

$$(M_T^{(i)})^2 = (m^{\mathrm{vis}(i)})^2 + m_X^2 + 2\left(E_T^{\mathrm{vis}(i)} E_T^{X(i)} - \vec{p}_T^{\,\mathrm{vis}(i)} \cdot \vec{p}_T^{\,X(i)}\right)$$

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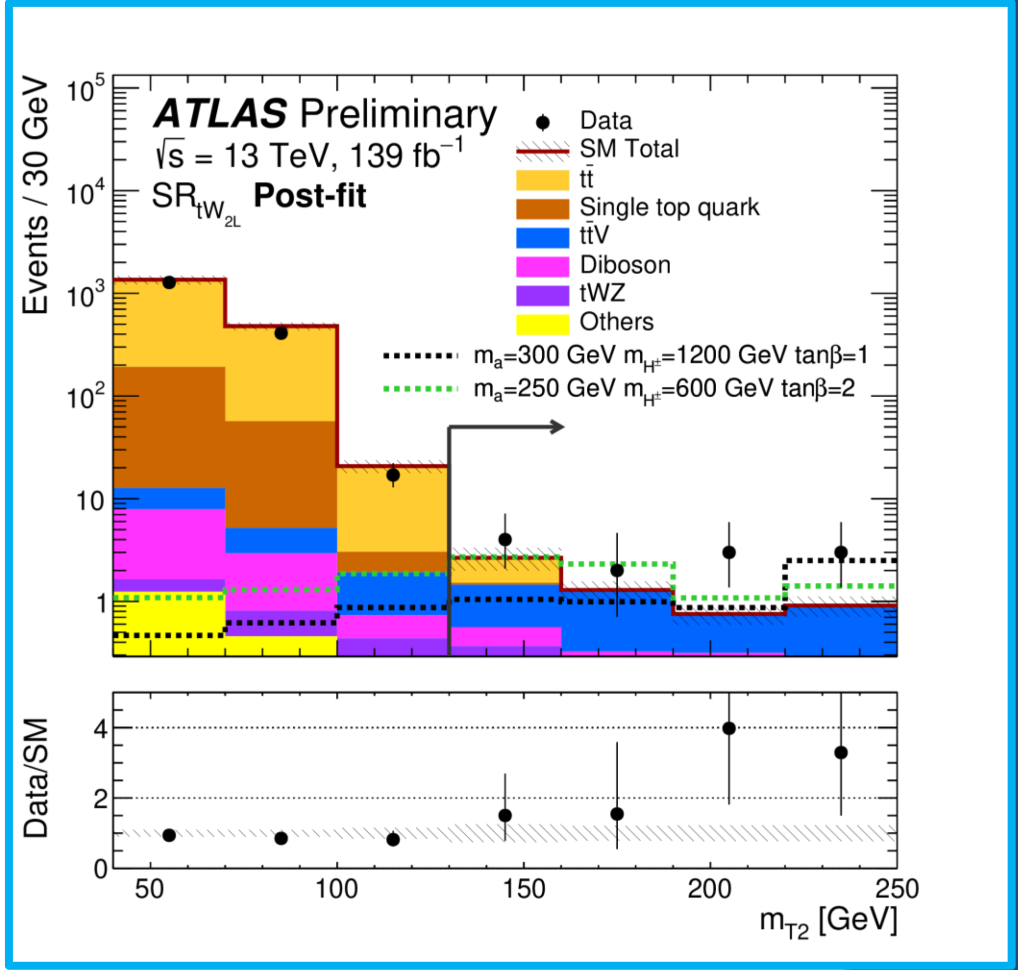
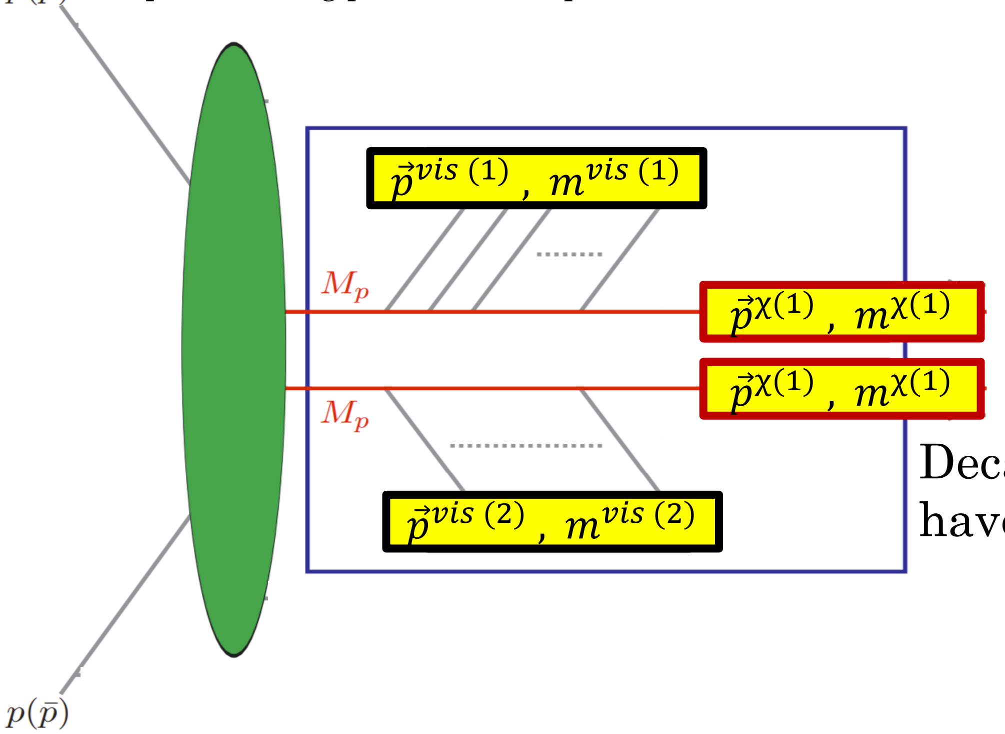


2 lepton, ≥ 1 jet, ≥ 1b-jet

MET + Wt

https://arxiv.org/pdf/0911.4126.pdf



Decay particles have same mass

$$(M_T^{(i)})^2 = (m^{\mathrm{vis}(i)})^2 + m_X^2 + 2\left(E_T^{\mathrm{vis}(i)} E_T^{X(i)} - \vec{p}_T^{\,\mathrm{vis}(i)} \cdot \vec{p}_T^{\,X(i)}\right)$$

$$M_{T2}(m_X) = \min_{\vec{p}_T^{\,X(1)} + \vec{p}_T^{\,X(2)} = \vec{p}_T^{\,\mathrm{miss}}} \left[\max\left(M_T^{(1)}, M_T^{(2)}\right)\right]$$

M_T^1 or M_T^2 must be smaller than M_P, so larger of the two is chosen

M_{T2} smaller than original particle mass, so minimize over possible DM momenta

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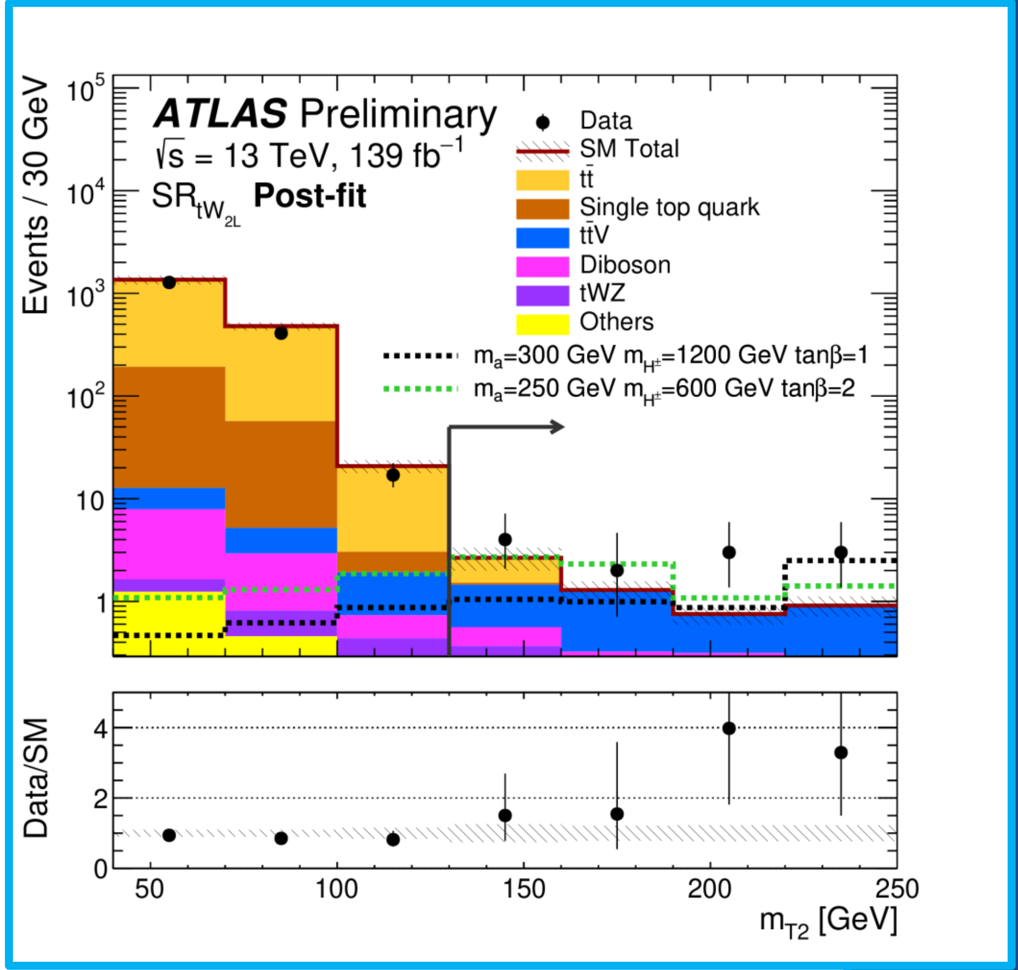
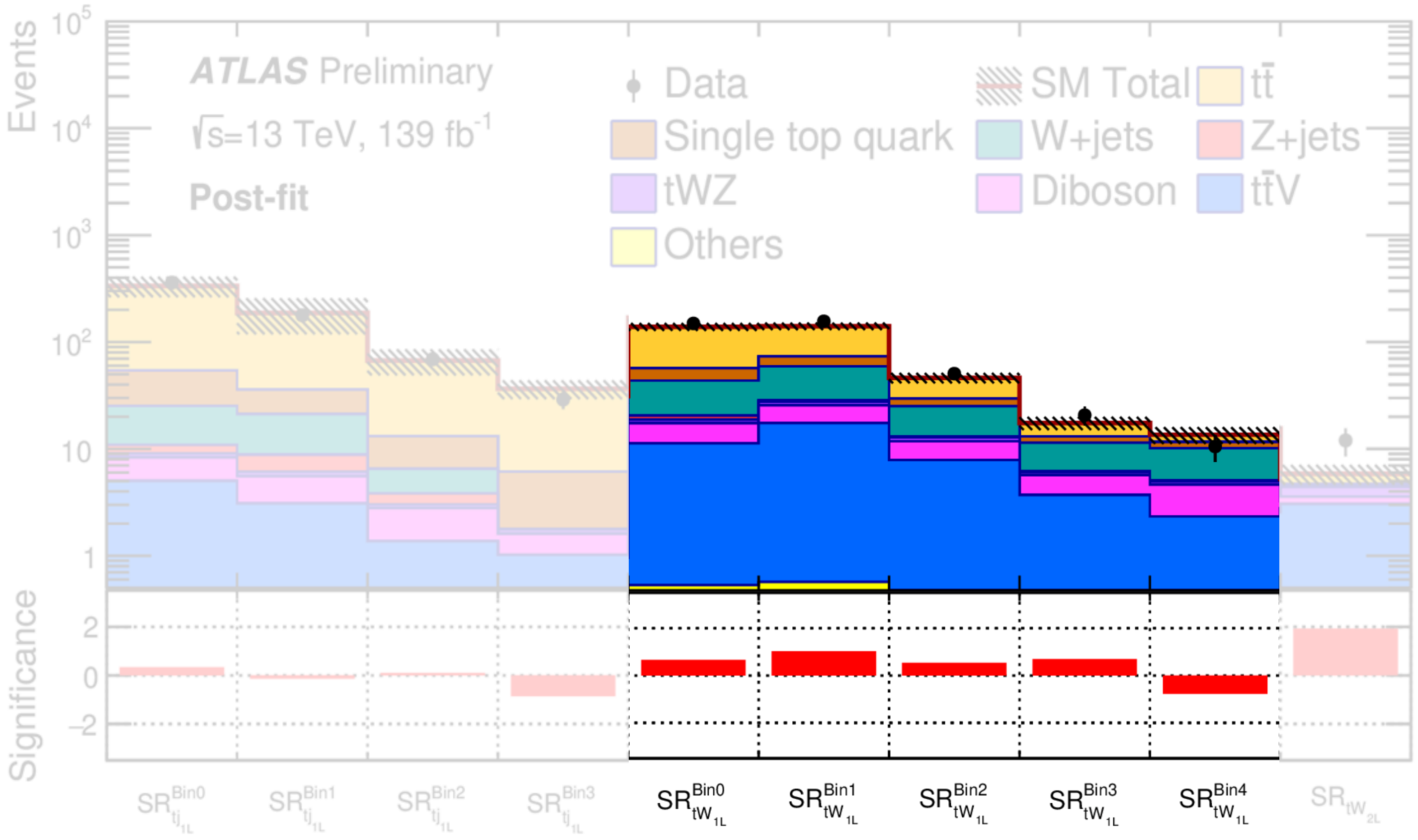


2 lepton, ≥ 1 jet, ≥ 1b-jet

MET + Wt



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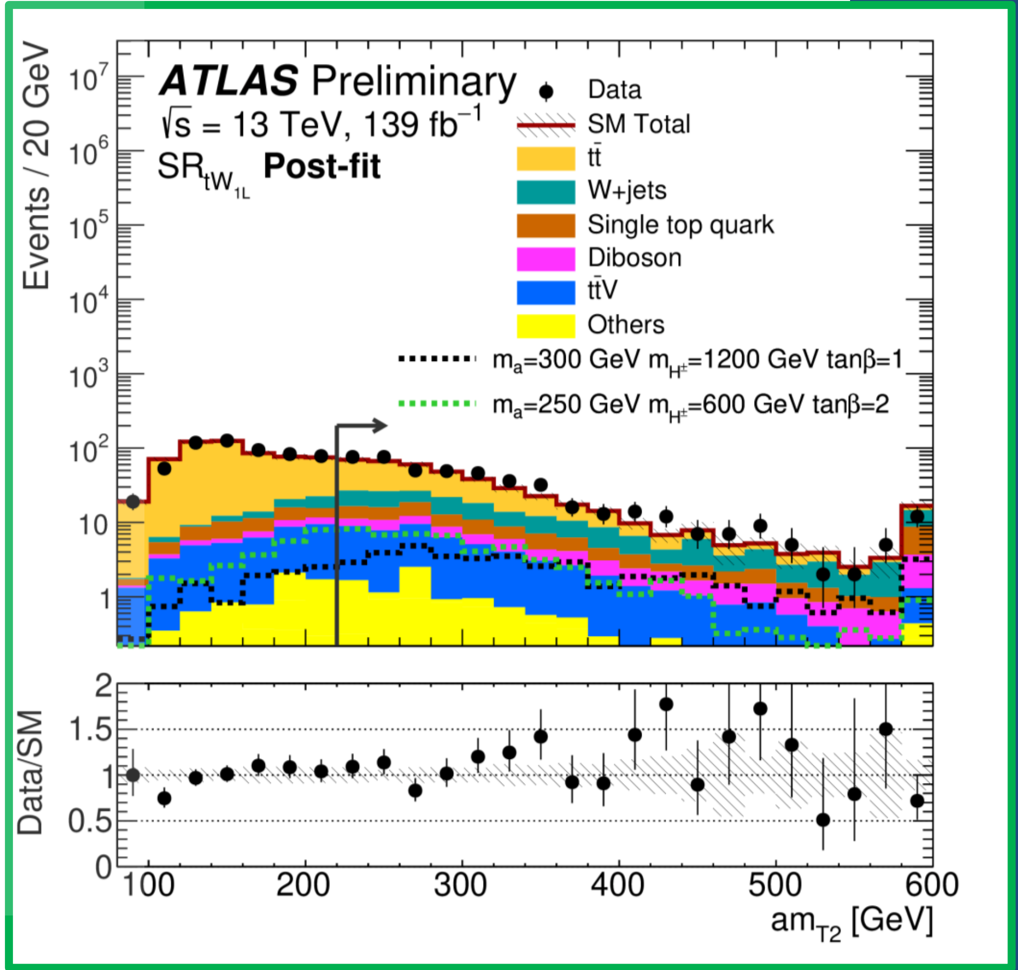
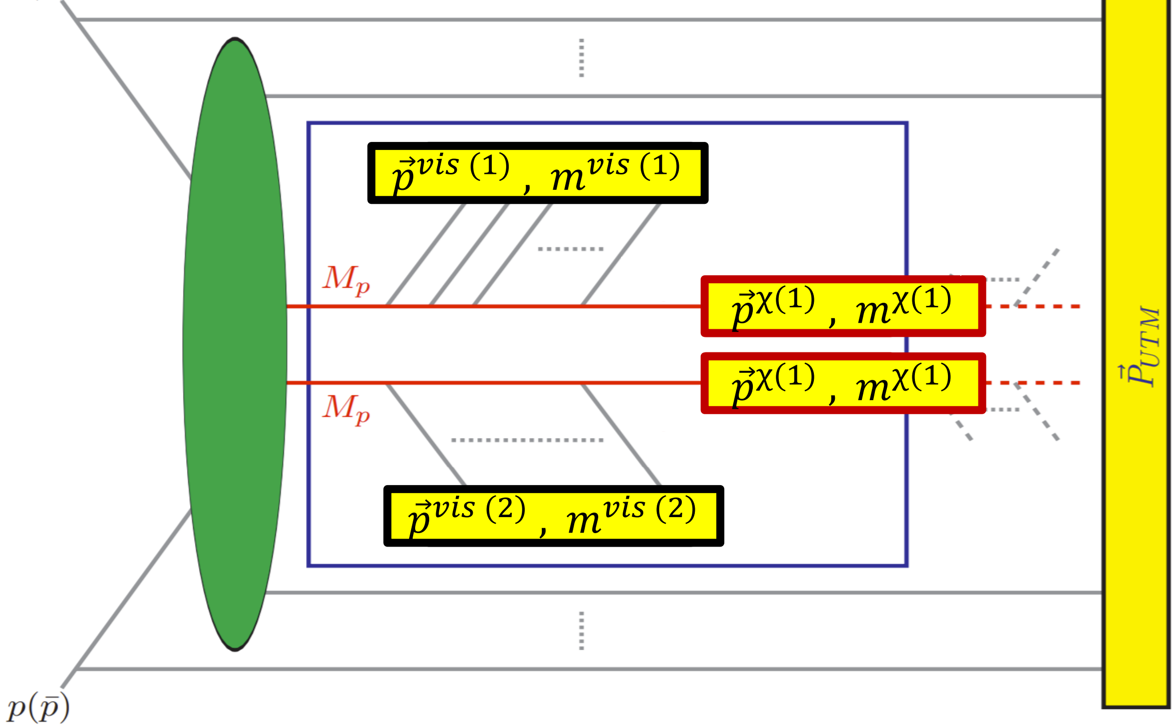


1 lepton, 1-4 jets, 1-2 b-jet

Differentiate SR from CR with
am_{T2} **: asymmetric stransverse mass**, MET, m_T , m_W

MET + Wt

https://arxiv.org/pdf/0911.4126.pdf



Decay particles have different masses

Asymmetric is generalized $M_{T2}(m_X)$ (am_{T2}) version of $M_{T2}(m_X)$

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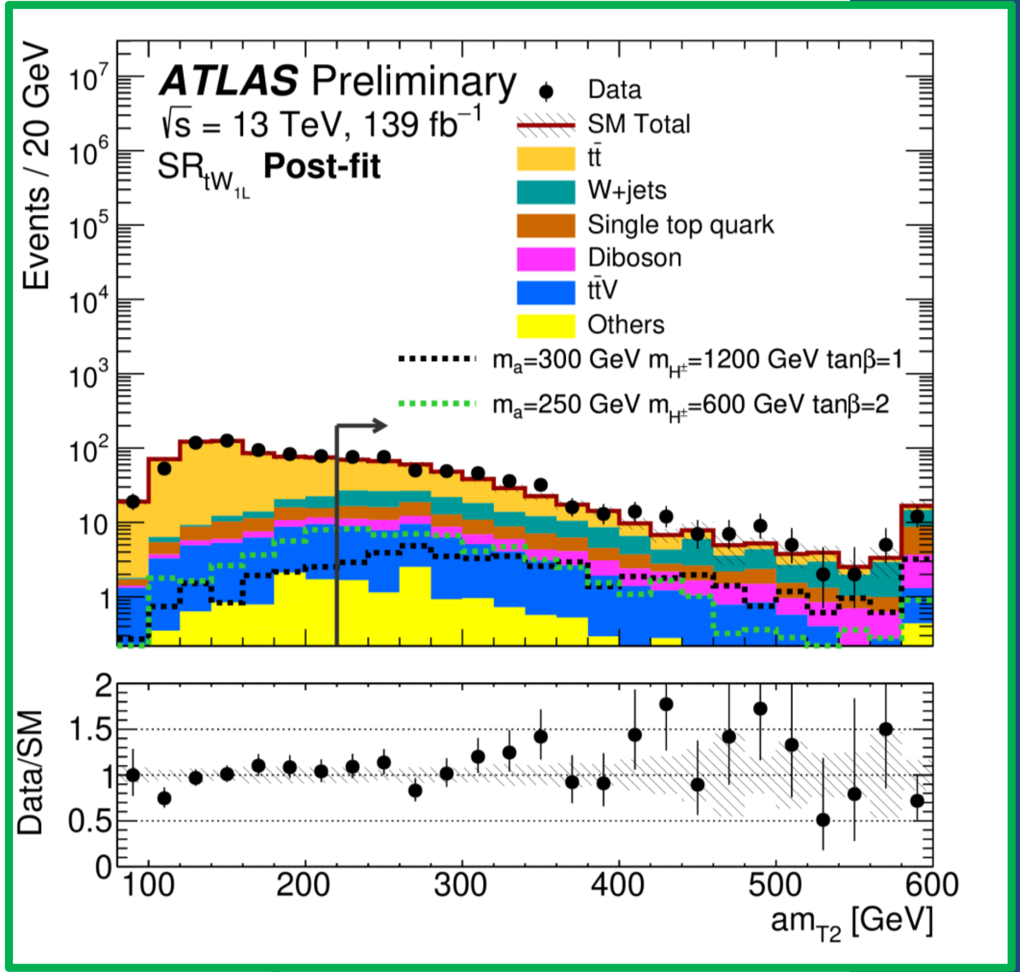

1 lepton, 1-4 jets, 1-2 b-jet

MET + Wt

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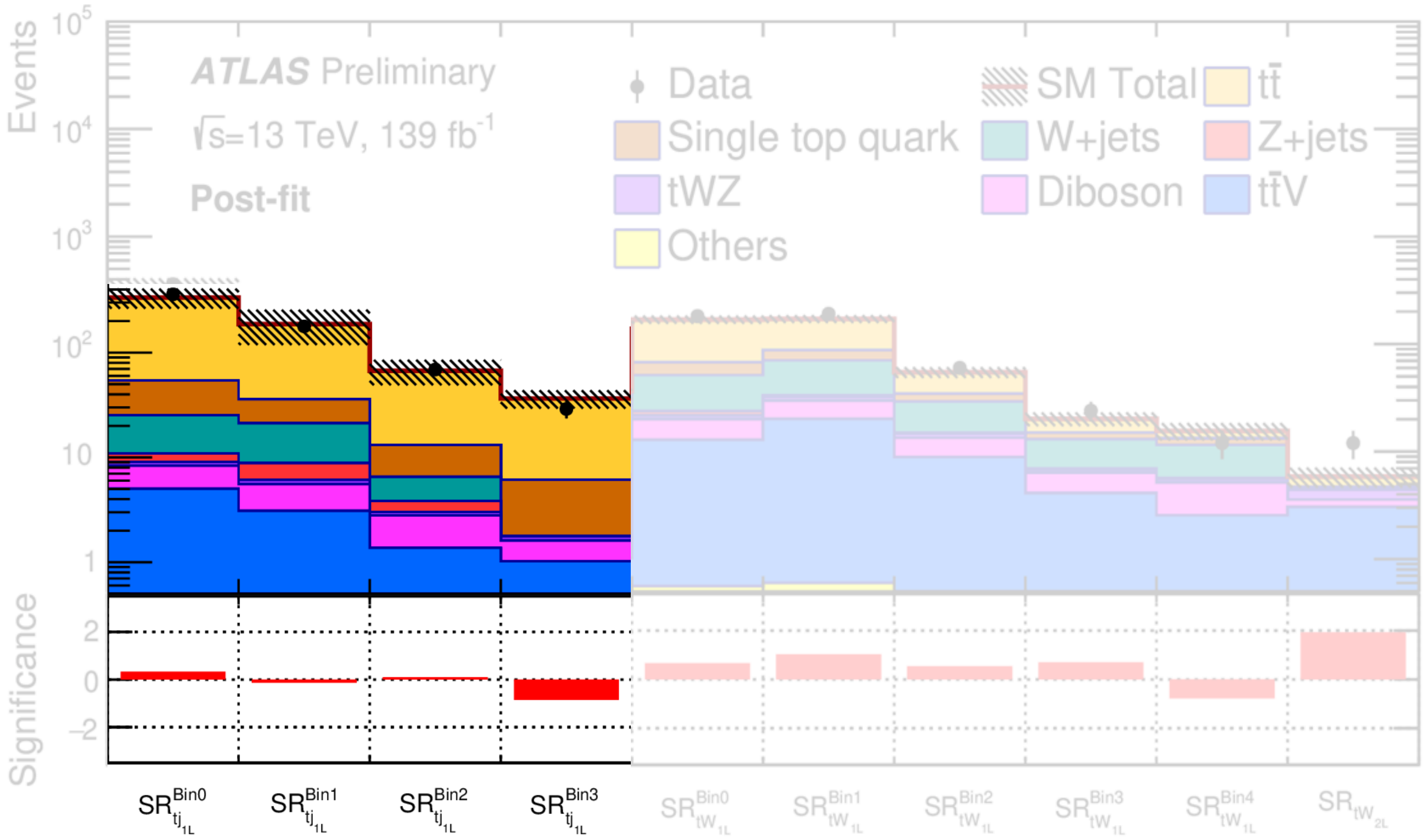

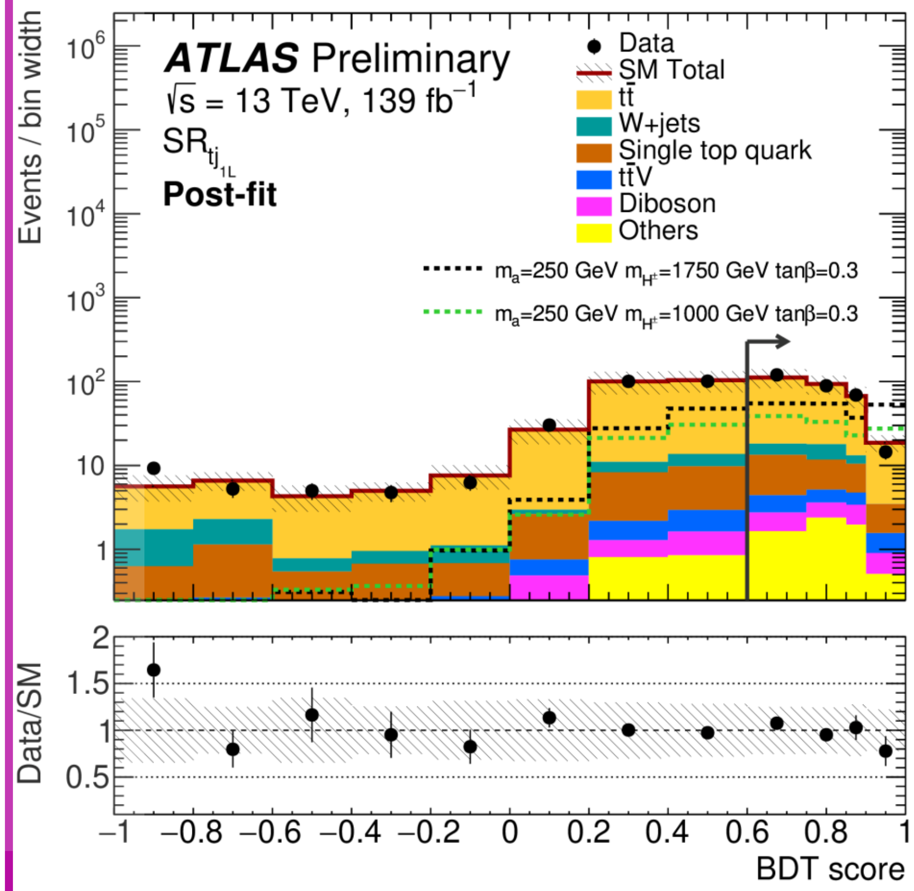

Differentiate SR from CR with Boosted Decision Tree (BDT) that uses as inputs MET, m_T, number of jets and lepton/b-jet separation

1 lepton, ≥ 3 jets (1 b-jet)

MET + Wt

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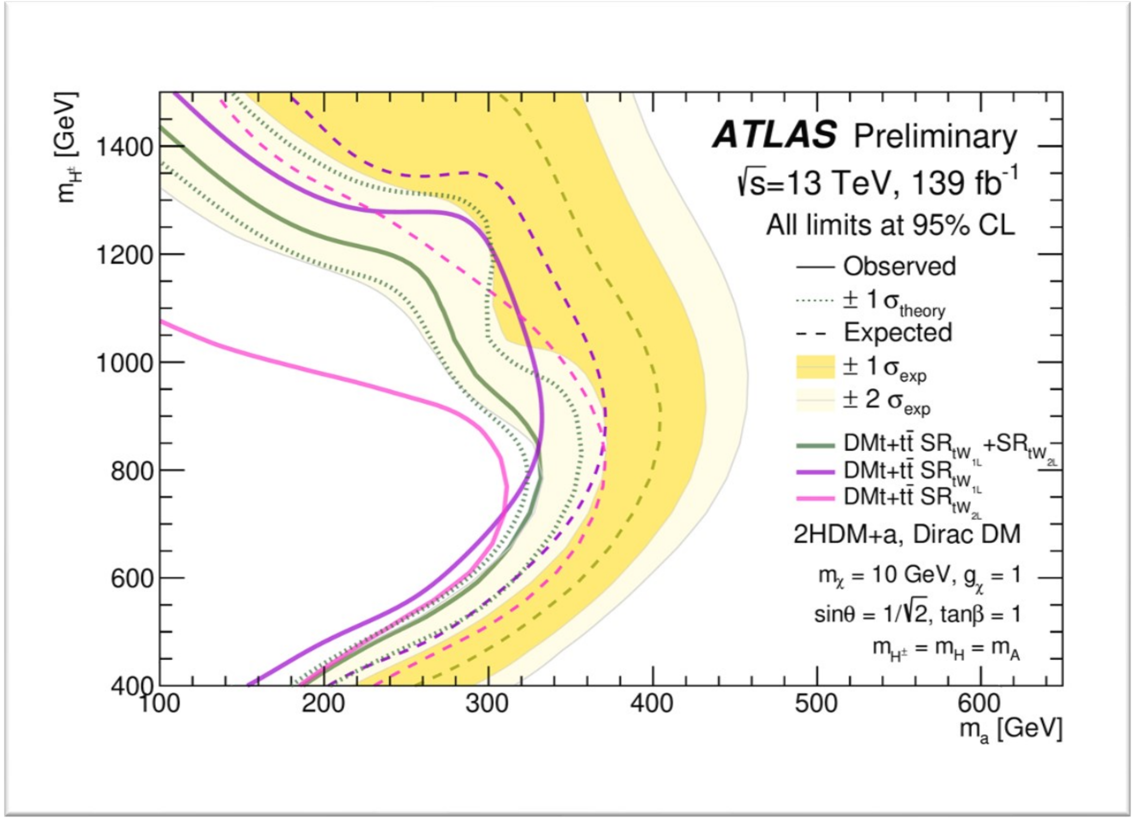
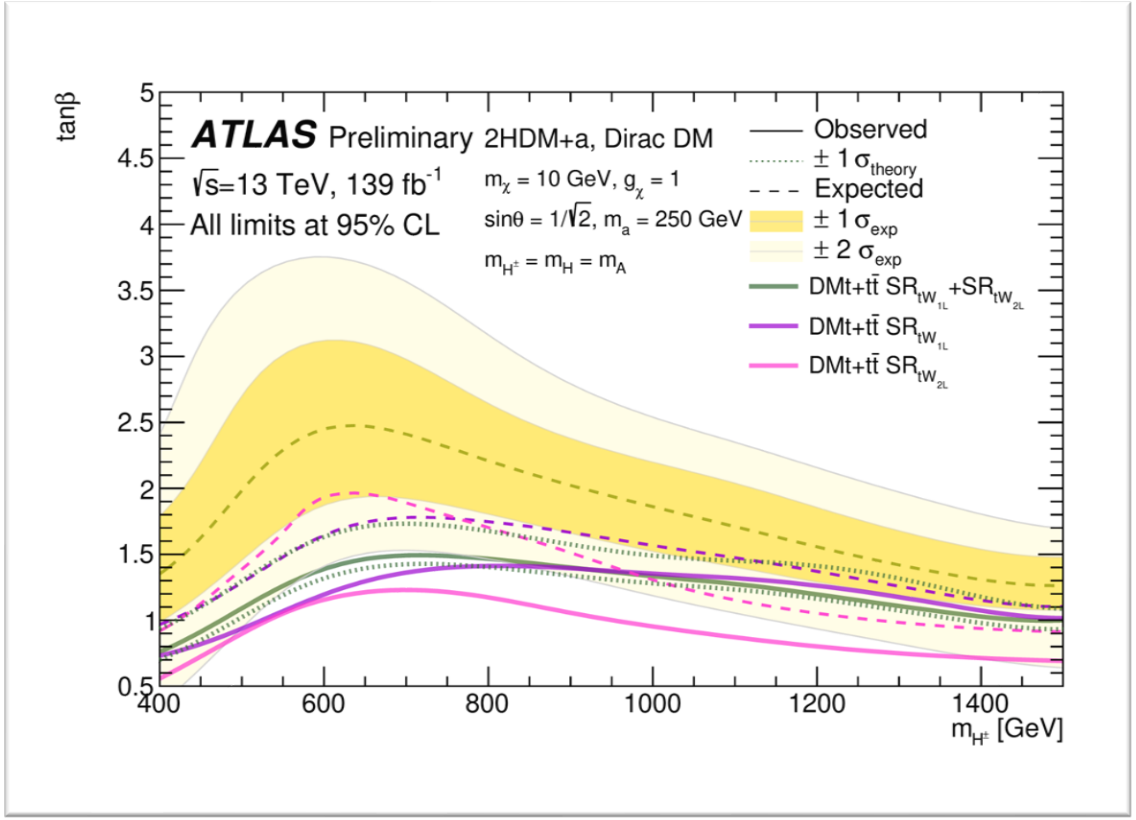


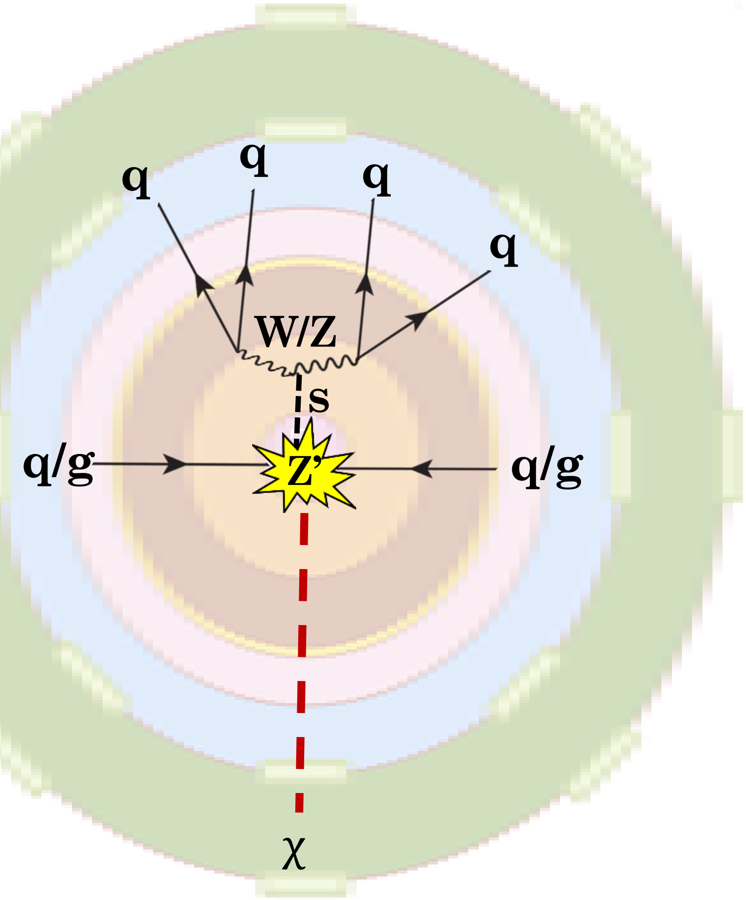
Charged Higgs vs Pseudo-scalar (a)
$m_\chi = 10$ GeV, $g_\chi = 1$



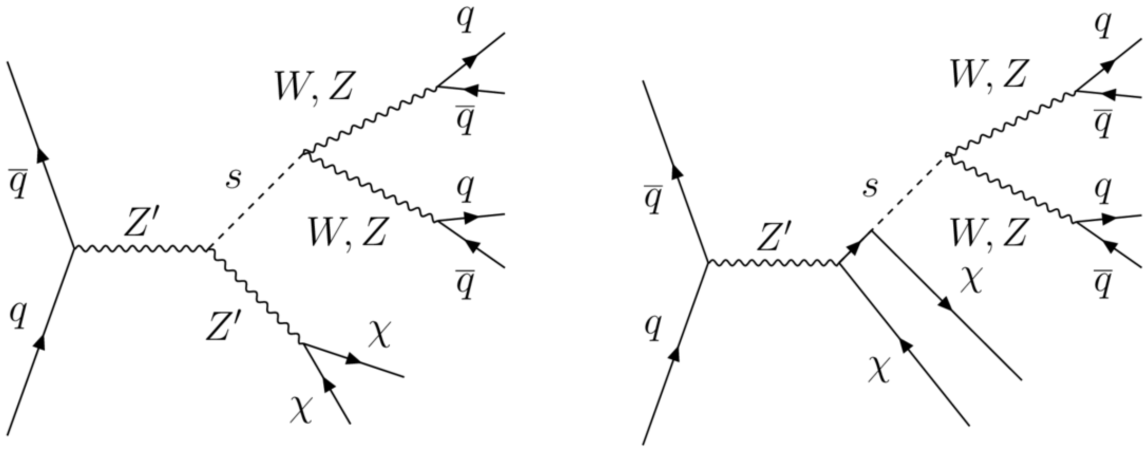
$\tan\beta$ vs Charged Higgs ($H^{\pm}$)
$m_\chi = 10$ GeV, $g_\chi = 1$

$\tan\beta$ = ratio of vacuum expectation values of the Higgs Doublets
Dominant uncertainties: data statistics

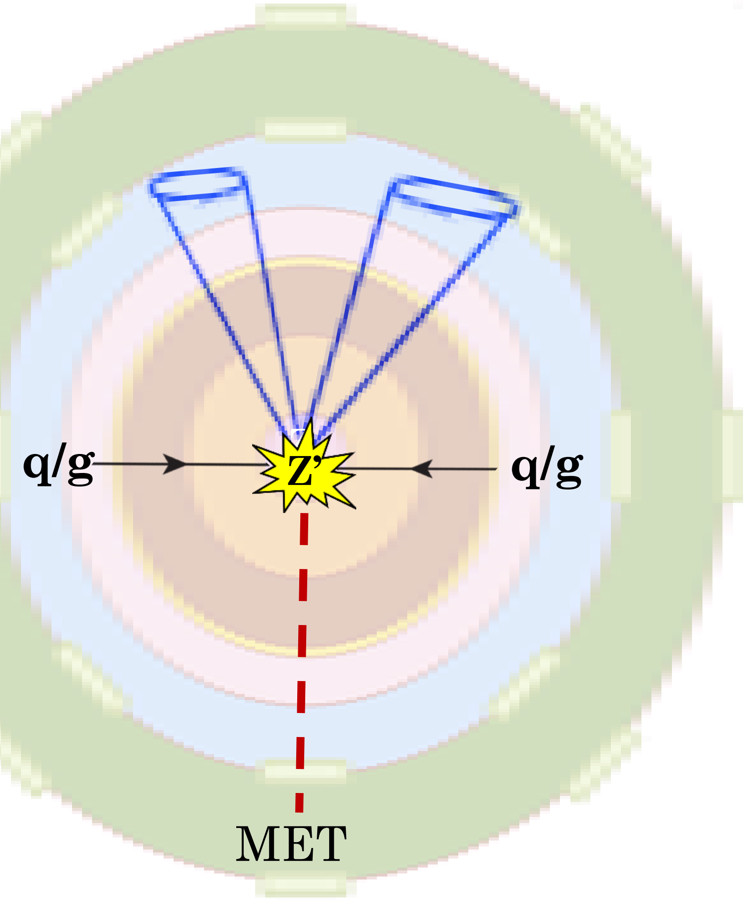
MET + VV (hadronic)



- Dark Higgs model: simplified model for dark matter production (novel signature)
- At high momentum, the hadronic decays of the W/Z are very collimated (merged)
- Close to granularity limits of calorimeter – use angular track information to improve spatial resolution – Track Assisted Reclustured **(TAR) jets**



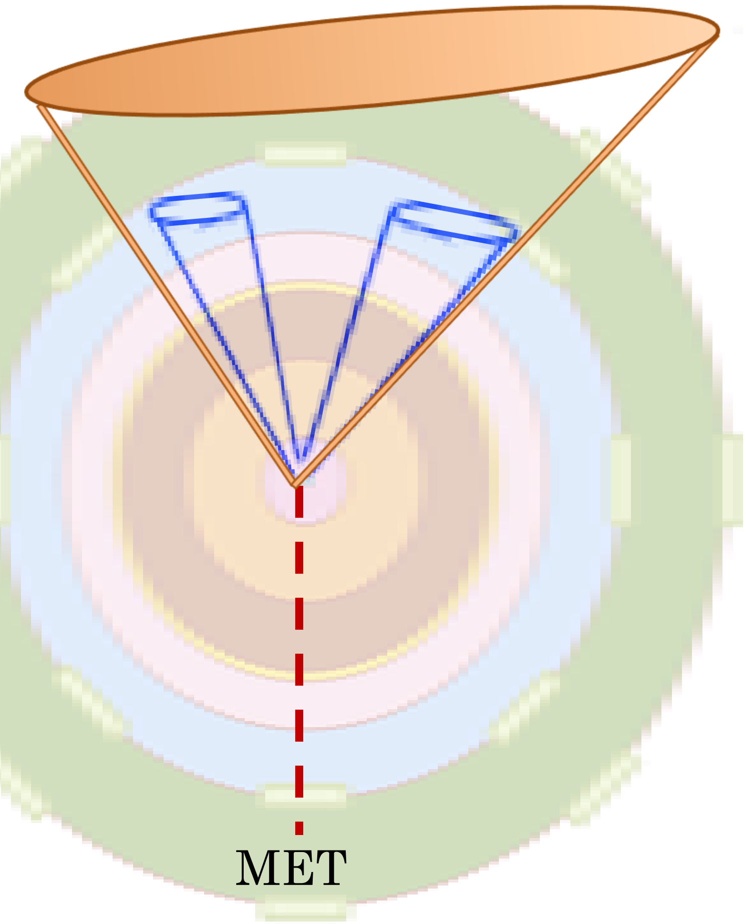
MET + VV (hadronic)



Track Assisted Reclustered (TAR) jets

- Identify small-radius jets

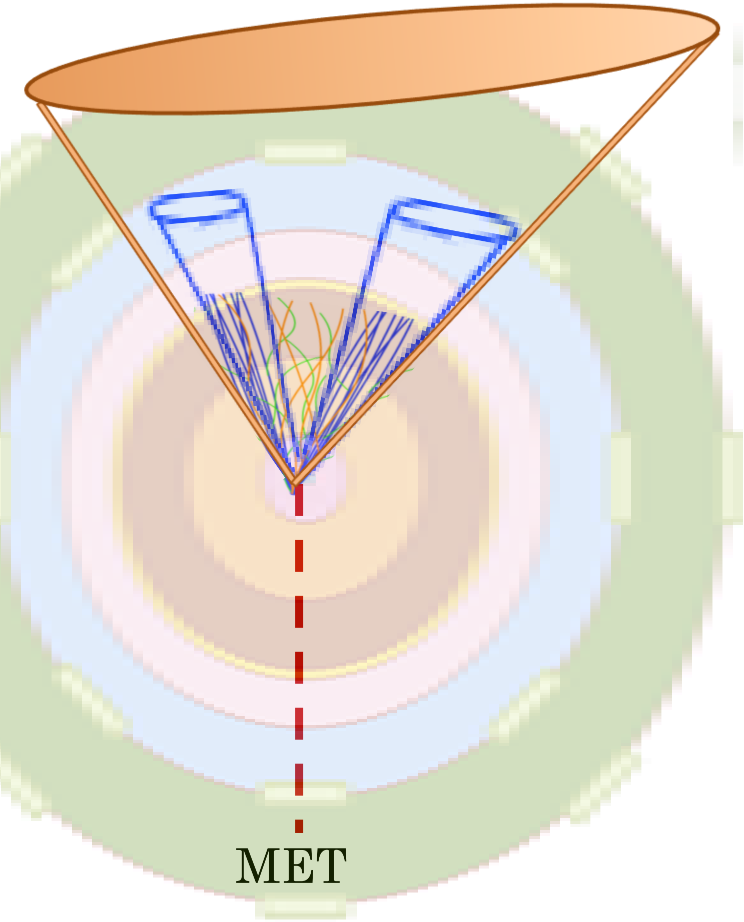
MET + VV (hadronic)



Track Assisted Reclustered (TAR) jets

- Identify small-radius jets
- Recluster input jets to large radius jets (R=0.8)
    - Remove soft components from pileup (trimming)

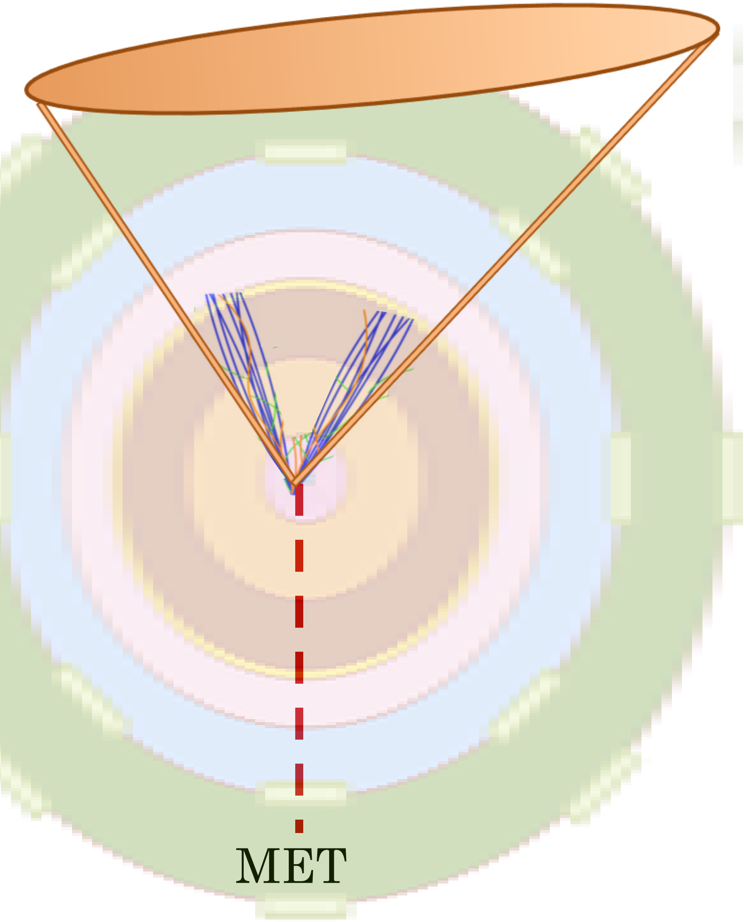
MET + VV (hadronic)



Track Assisted Reclustered (TAR) jets

- Identify small-radius jets
- Recluster input jets to large radius jets (R=0.8)
  - Remove soft components from pileup (trimming)
- Match tracks to small-radius jets

MET + VV (hadronic)



Track Assisted Reclustered (TAR) jets

- Identify small-radius jets
- Recluster input jets to large radius jets (R=0.8)
  - Remove soft components from pileup (trimming)
- Match tracks to small-radius jets
- Rescale tracks to the momentum of the small radius jets

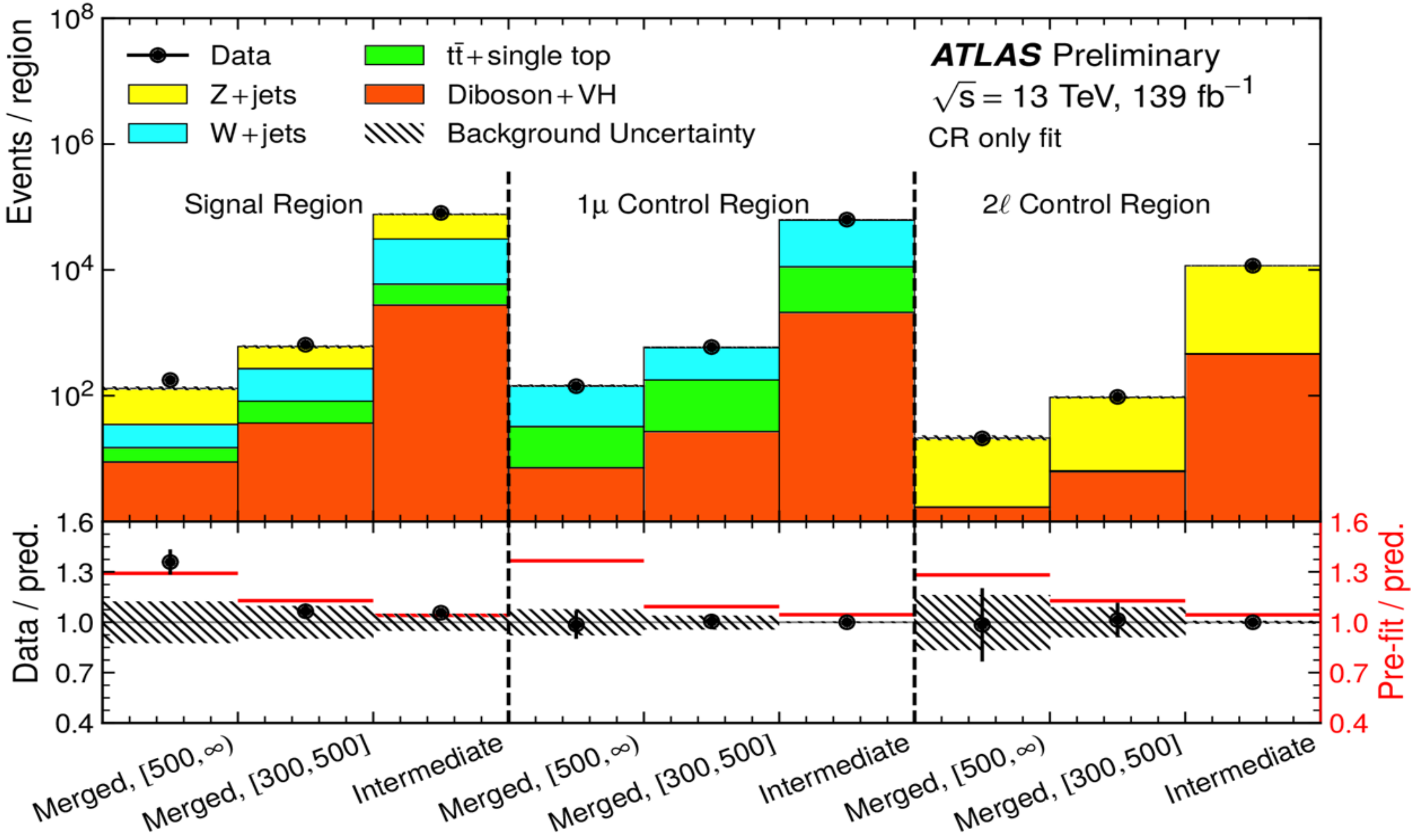
$$p_T^{\text{track,new}} = p_T^{\text{track,old}} \times \frac{p_T^j}{\sum_{i \in j} p_T^i}$$

where the index *i* runs over all tracks matched to subjet

- Calculate jet properties from tracks

MET + VV (hadronic)

Main background Z to $\nu\nu$+jets and W+jets (from CR in 2/1 lepton regions respectively)



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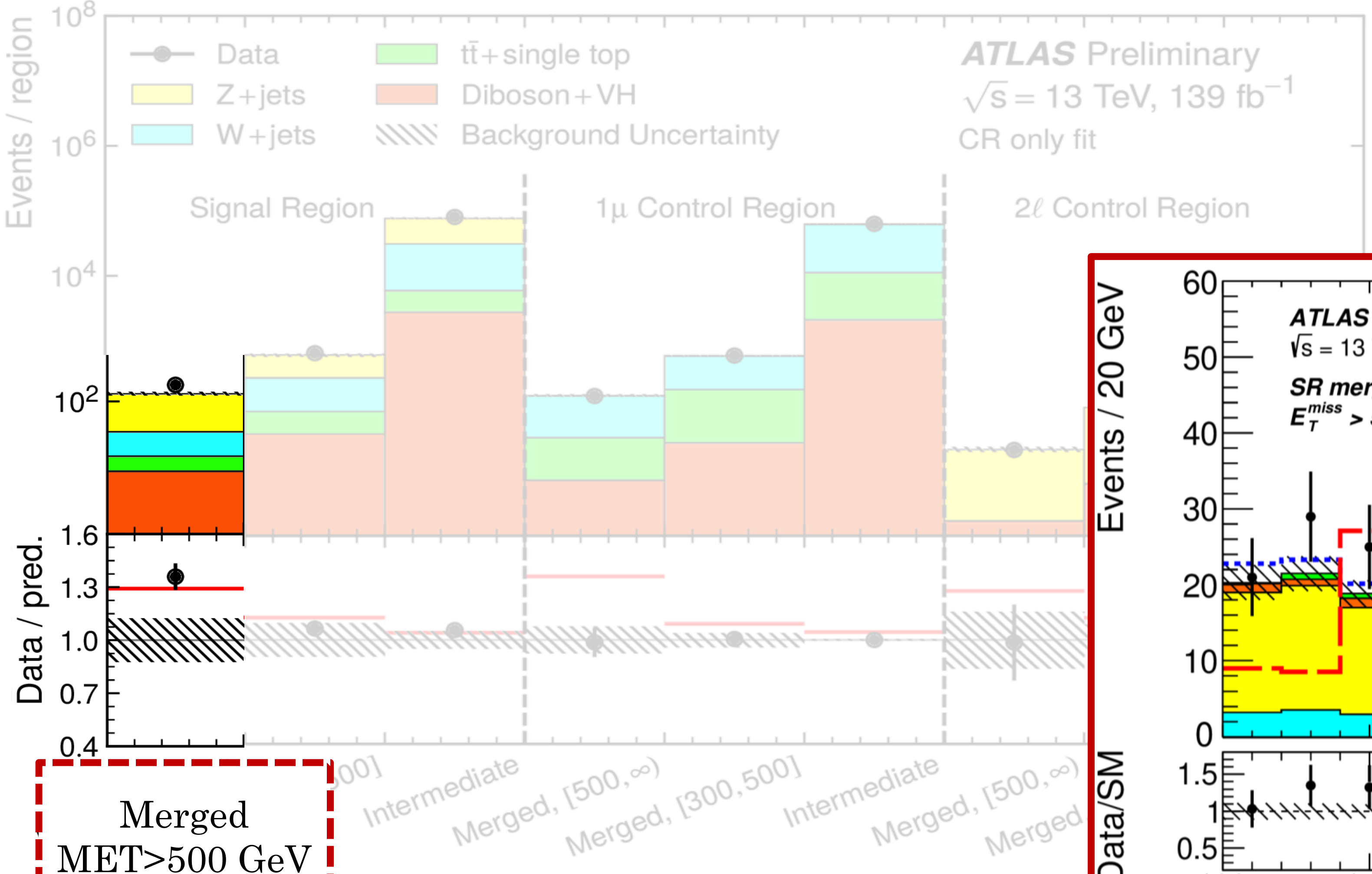
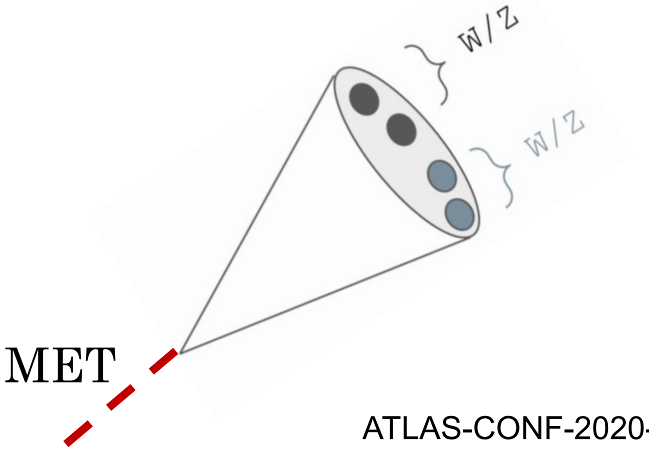
MET + VV (hadronic)



Merged
MET>500 GeV



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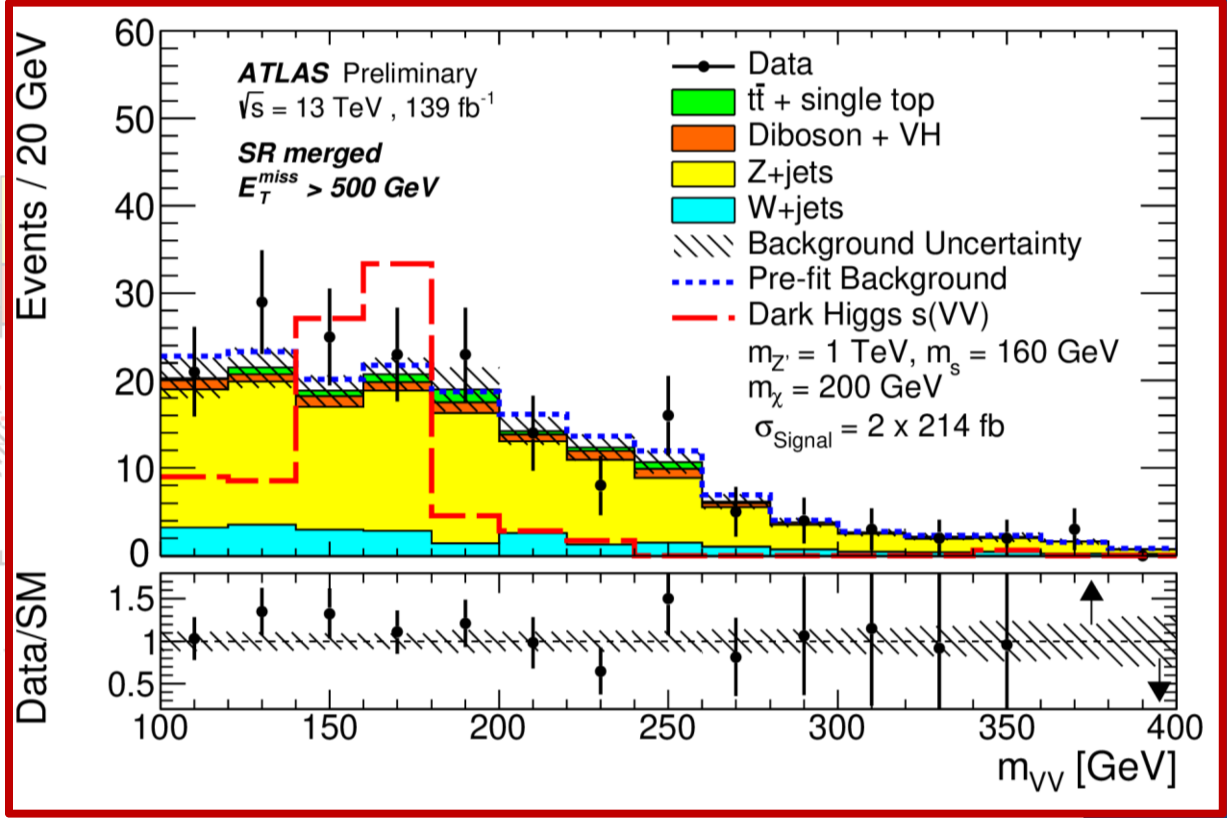
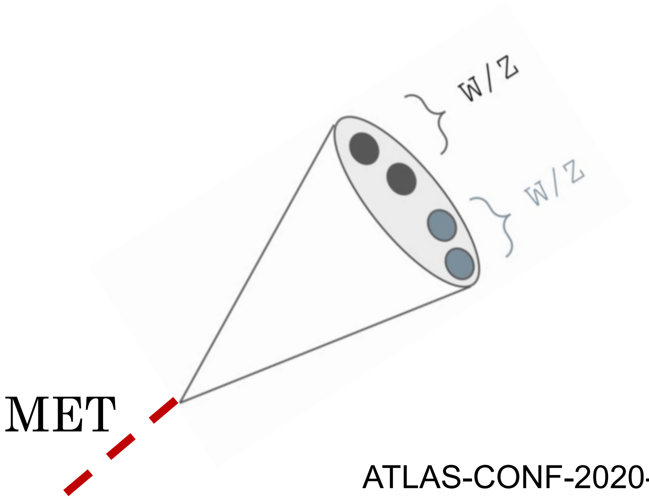


MET + VV (hadronic)



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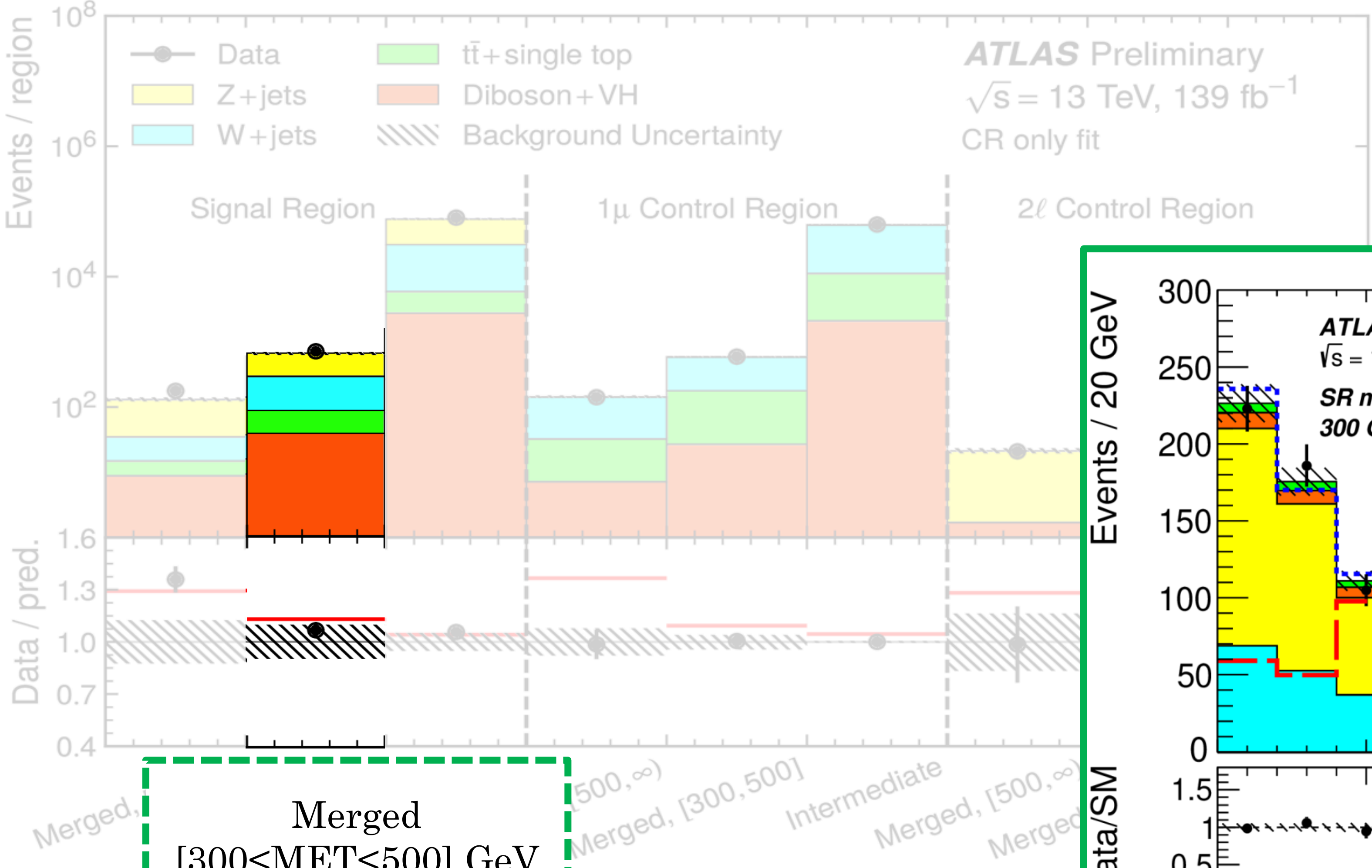
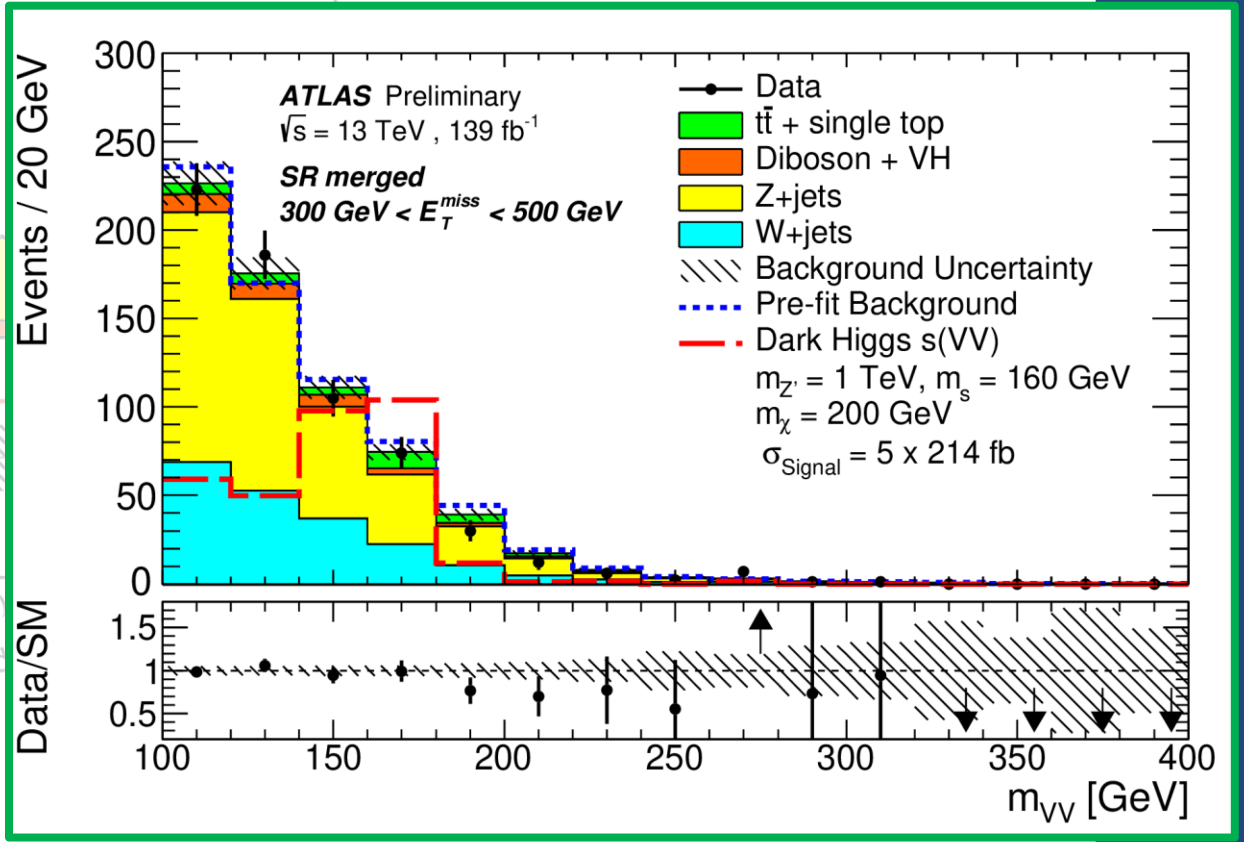
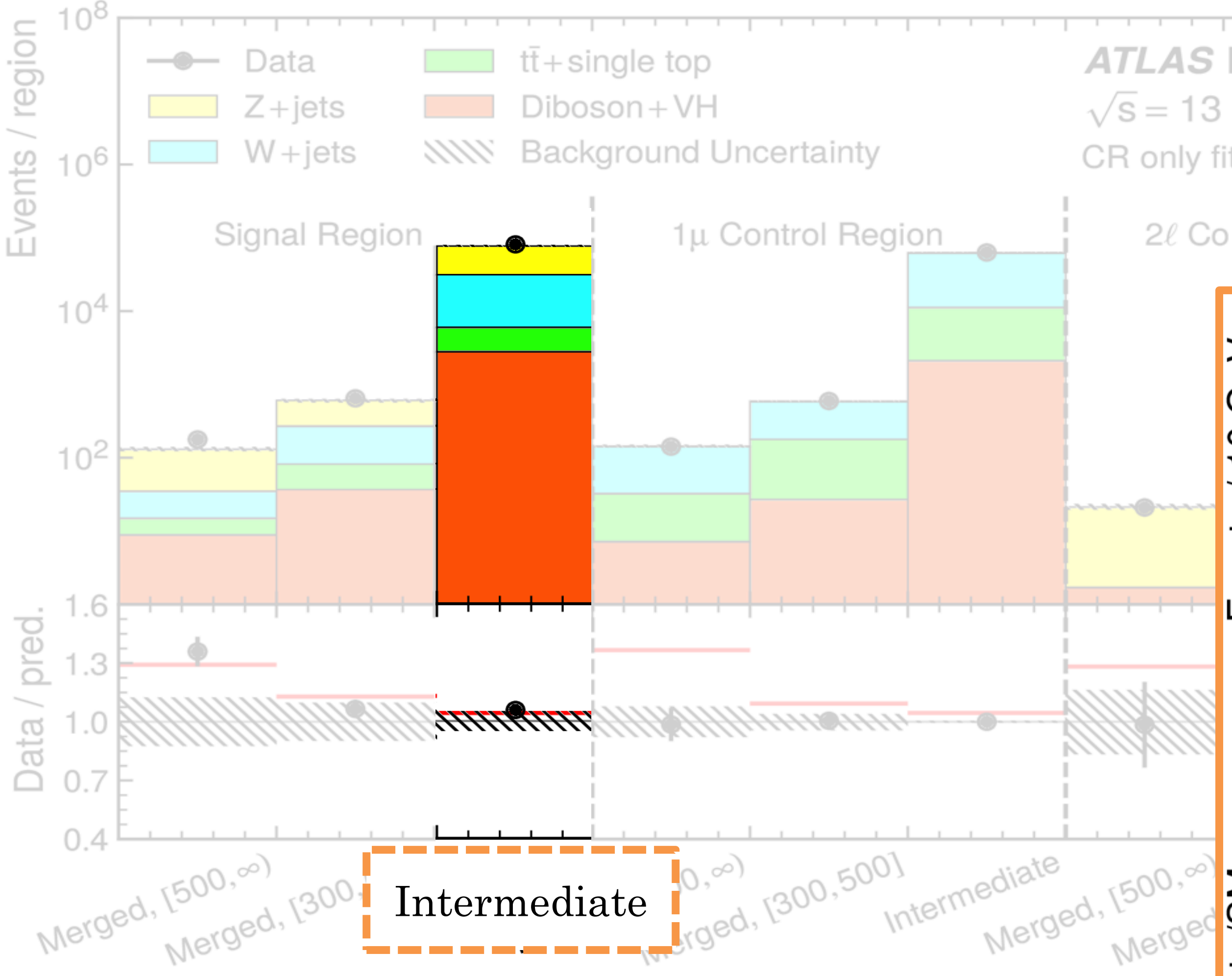


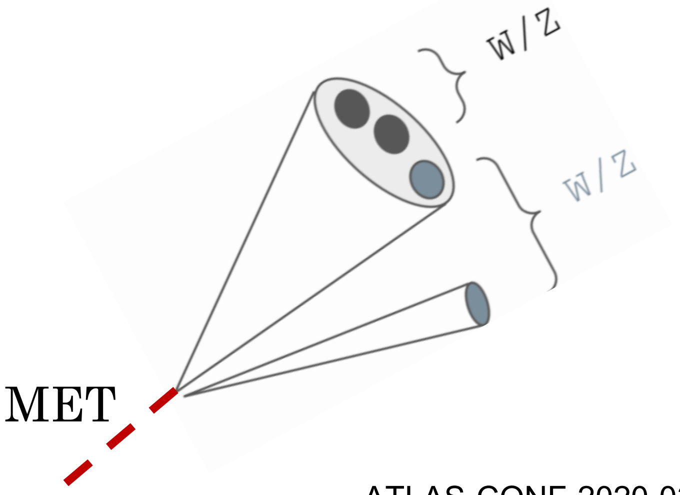
Merged
[300<MET<500] GeV



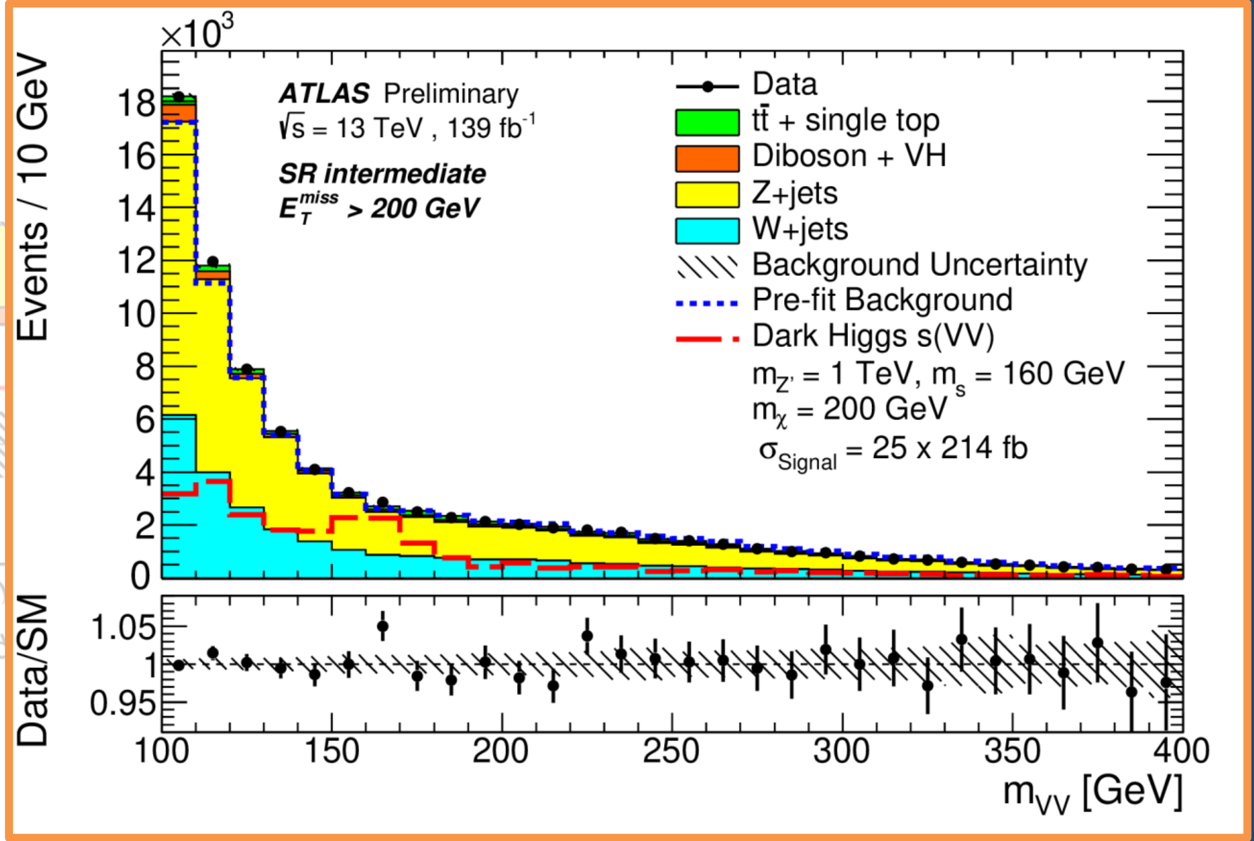
MET + VV (hadronic)



Intermediate

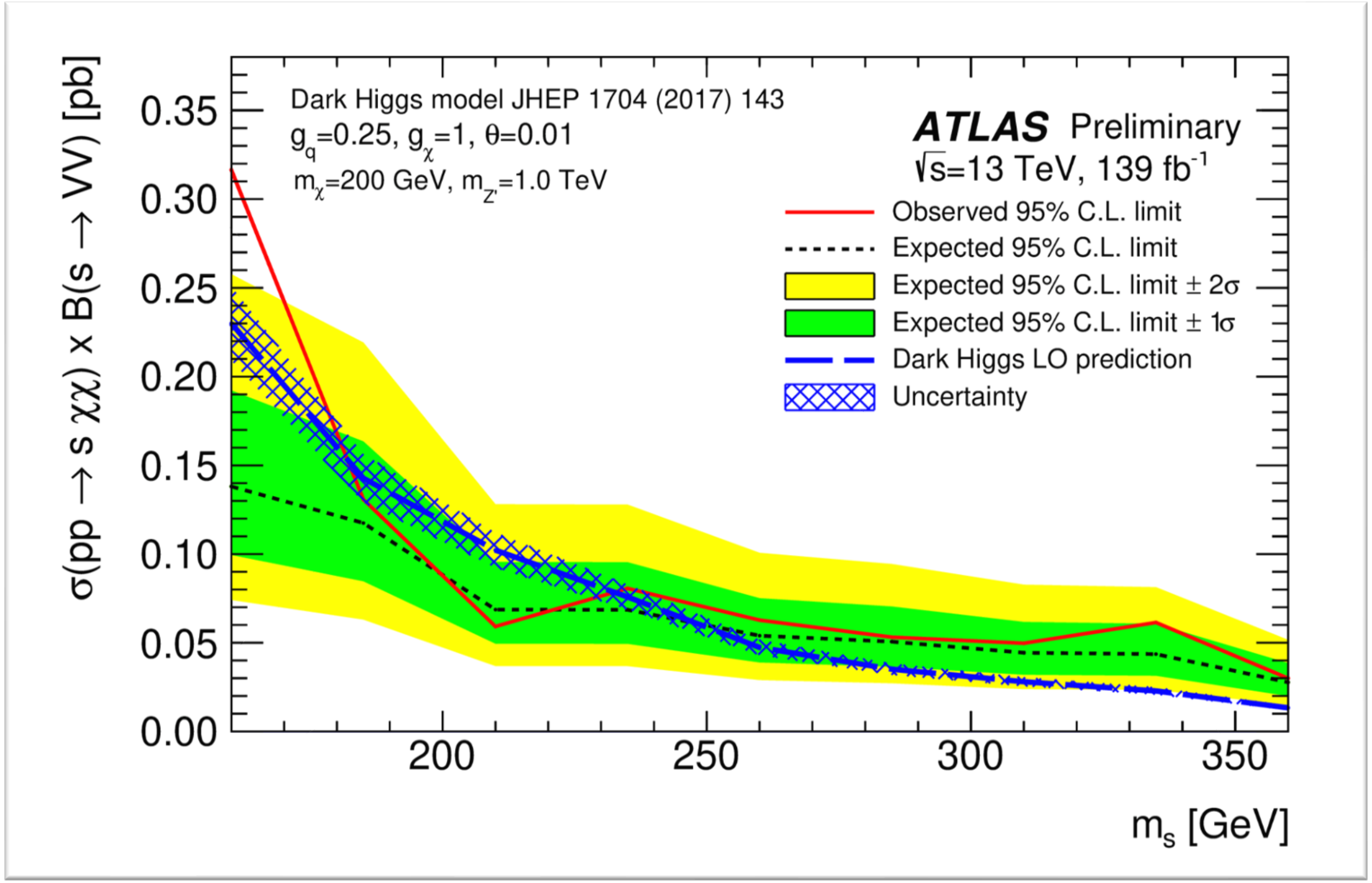


ATLAS-CONF-2020-036



MET + VV (hadronic)

ATLAS-CONF-2020-036

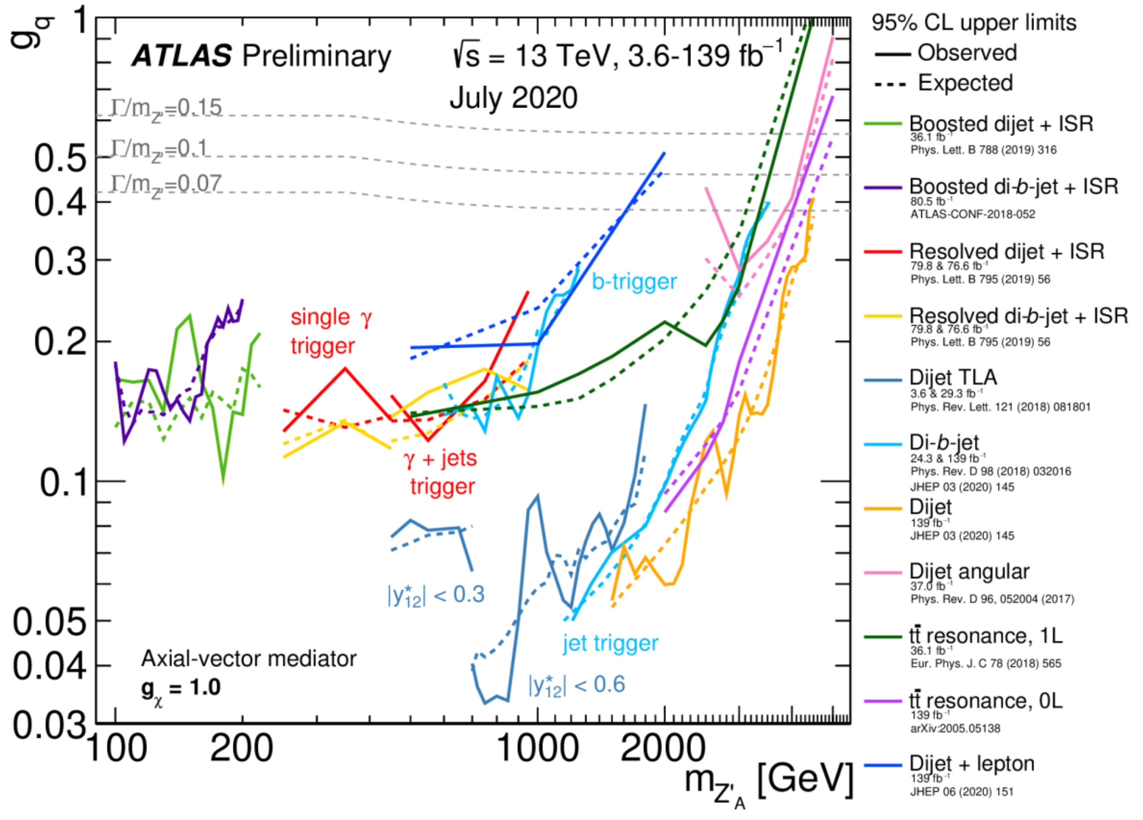


No significant excesses found

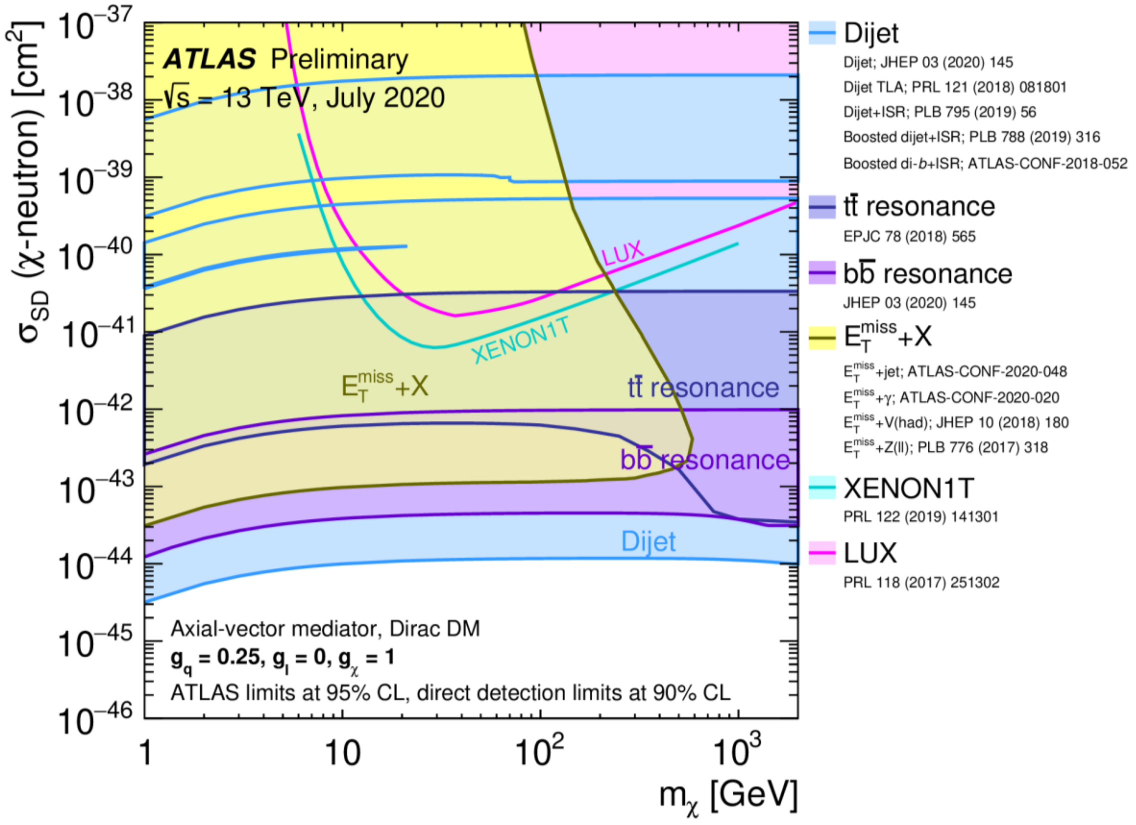
Dominant Uncertainties: jet energy scale/resolution, signal & W/Z+jets modelling

Putting it All Together

ATL-PHYS-PUB-2020-021



leptophobic axial-vector Z'_A mode



leptophobic axial-vector mediator simplified models

Summary

- Subset of ATLAS Dark Matter searches presented in MET + jet, MET + Wt, MET + VV (hadronic) final states
- Many SUSY searches also include DM interpretations, please see posters:
  - 3L search for EWK SUSY w/ neutralino LSP: https://indico.particle.mephi.ru/event/35/contributions/2398/
  - 4L+ search for SUSY (which includes intrpretations in which the gravitino could be a DM candidate): https://indico.particle.mephi.ru/event/35/contributions/2419/
- Many other new results with improved measurement techniques:
  - Vector Boson Fusion + MET (ANA-EXOT-2018-51)
  - MET + Photon (ATLAS-CONF-2020-020)
  - Mono-H(bb) (ATLAS-CONF-2018-039)
- No significant excesses found, limits set on many models
- ATLAS results highlight complementarity between LHC and direct dark matter searches

BACKUP

MET + Wt

ATLAS-CONF-2020-034

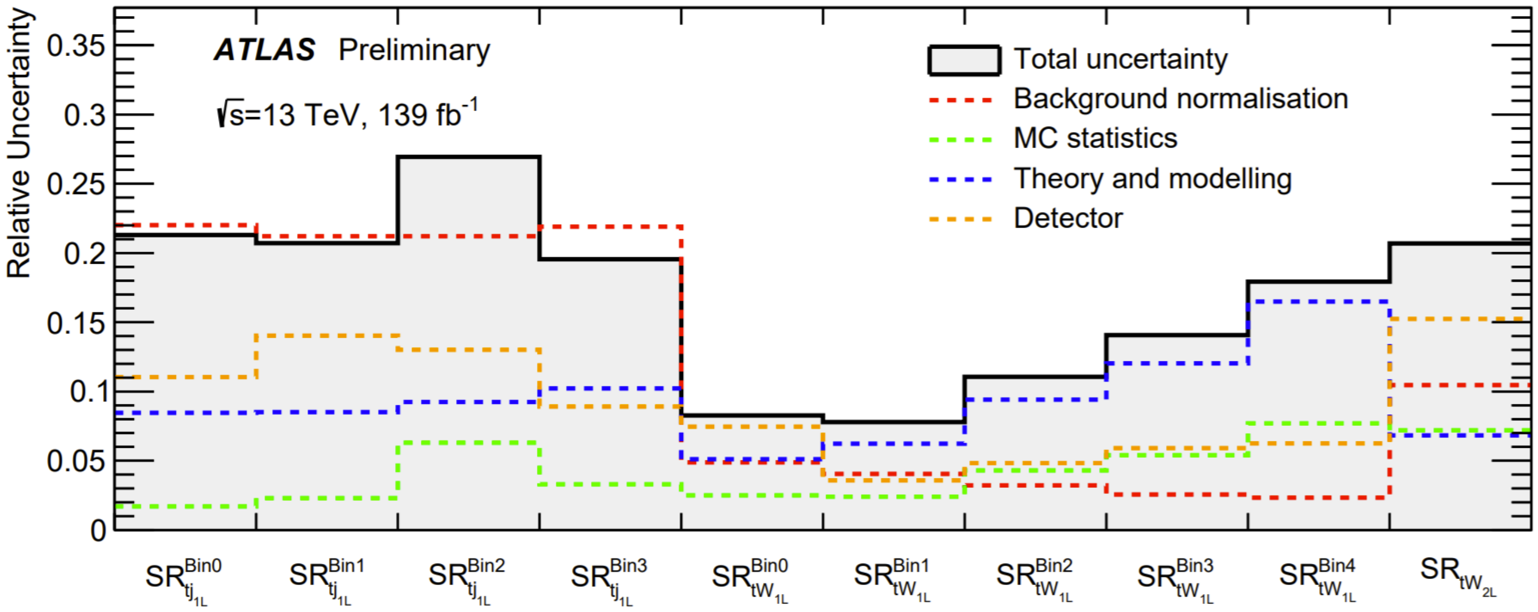


Figure 8: Relative uncertainties for the total background yield in each SR for the three analysis channels, including the contribution from the different sources of uncertainty. The 'Detector' category contains all detector-related systematic uncertainties and is dominated by jet energy scale and resolution. The 'Background normalisation' represents the uncertainty on the fitted normalisation factors, including the available event counts in the CRs. Individual uncertainties can be correlated, and do not necessarily add up quadratically to the total background uncertainty.

MET + VV (hadronic)

ATLAS-CONF-2020-036

Source of uncertainty	Uncertainty [%] (a)	(b)	(c)
Signal modeling	11	10	10
W+jets modeling	9	21	14
Z+jets modeling	7	12	13
MC statistics	11	14	23
Jet Energy Scale	8	17	24
Jets Energy Resolution	11	18	15
Lepton reconstruction	8	9	5
Track reconstruction	6	7	5
Systematic uncertainty	30	42	55
Statistical uncertainty	16	25	50
Total uncertainty	34	49	74

Table 1: Dominant sources of uncertainty for three Dark Higgs scenarios after the fit to Asimov data generated from the expected values of the maximum likelihood estimators including predicted signals with $(m_{Z'}, m_s)$ of (a) $(1\text{ TeV}, 160\text{ GeV})$, (b) $(1\text{ TeV}, 235\text{ GeV})$, and (c) $(1\text{ TeV}, 310\text{ GeV})$. The uncertainty on the fitted signal yield relative to the theory prediction is presented. Total is the quadrature sum of statistical and total systematic uncertainties.

Spin Independent Results