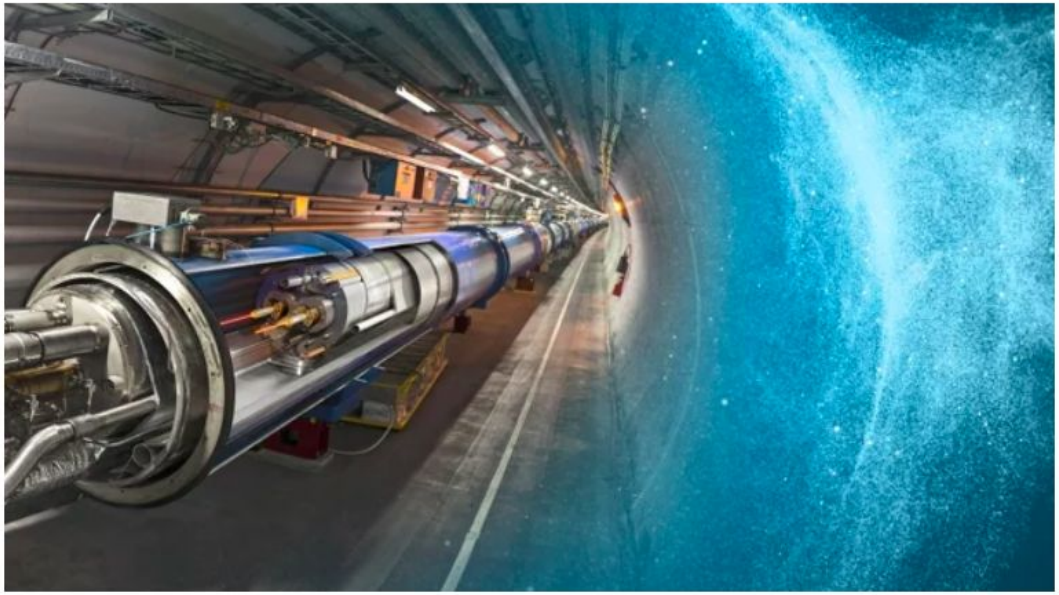
Search for dark matter production in association with a single top and a W boson with the ATLAS experiment



Alvaro Lopez Solis
Summarising work from Ben Brueers, Paul Moder, Claudia Seitz, Priscilla Pani and Marco Rimoldi

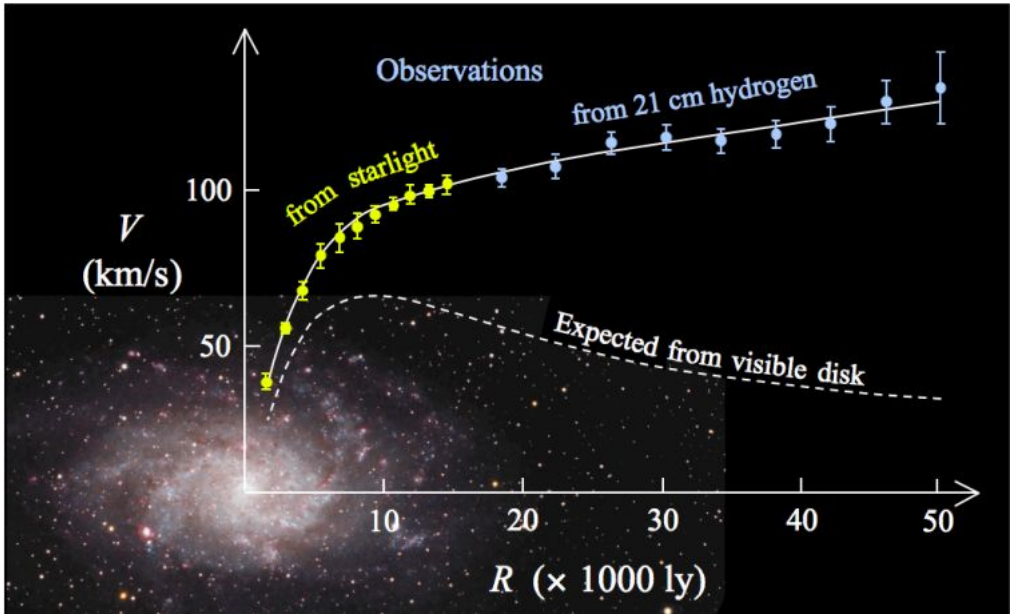
Pizza day!
20th February 2023

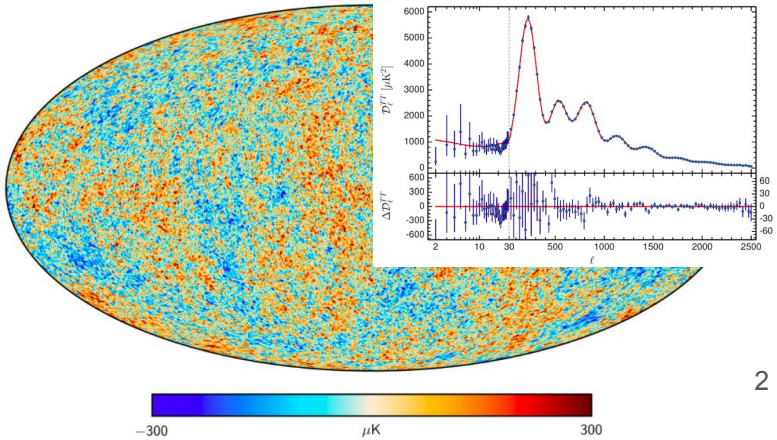
ATLAS EXPERIMENT

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

DESY.

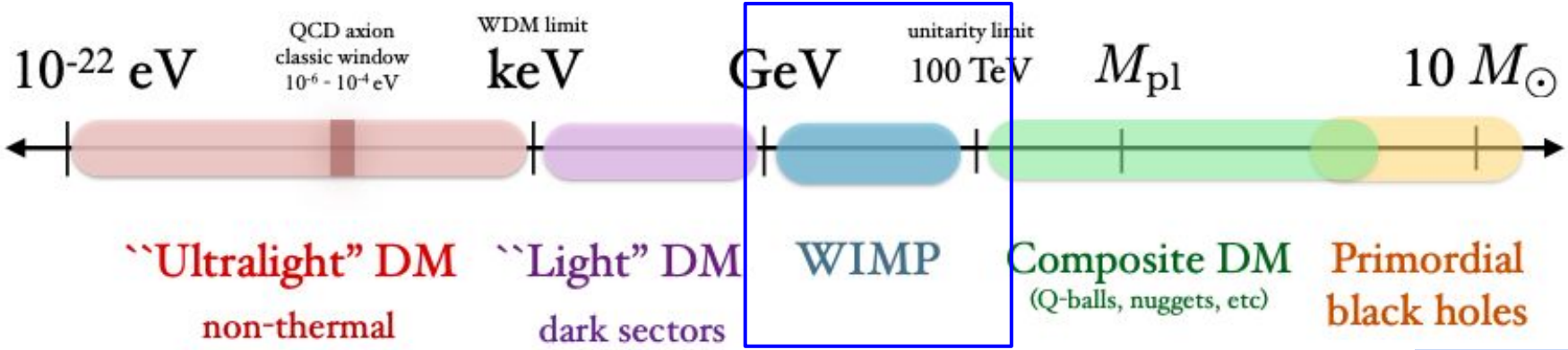
Why dark matter ?





Powerful evidence indicating the existence of weakly interacting non-luminous particles in the Universe

Where to find it ? Is it big or small?



Cannot explain relic abundance but other SM problems (e.g. strong CP violation)

Can explain relic abundance from thermal freeze-out at Early Universe. And masses similar to EWK scale.

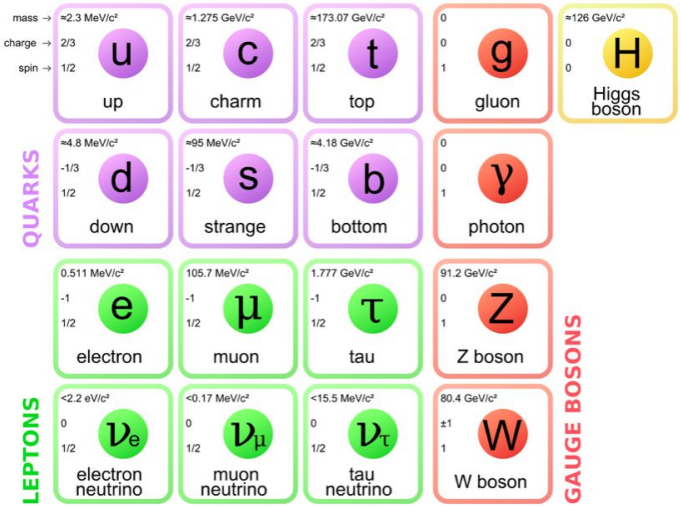
T. Lin TASI Lectures

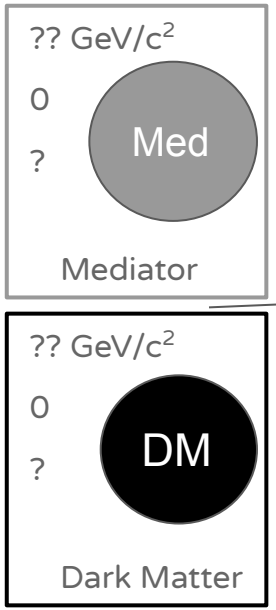
Big structures formed of new particles or SM particles

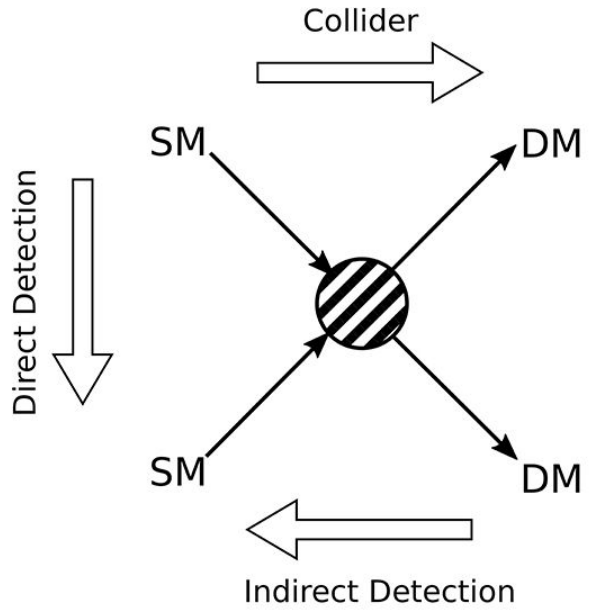
A good reason to preserve the Earth. Things out there could be dark and full of terrors ….

One of the most common theories is that DM is composed of WIMPs (weakly interacting particles).

What is DM? How can we detect it ?







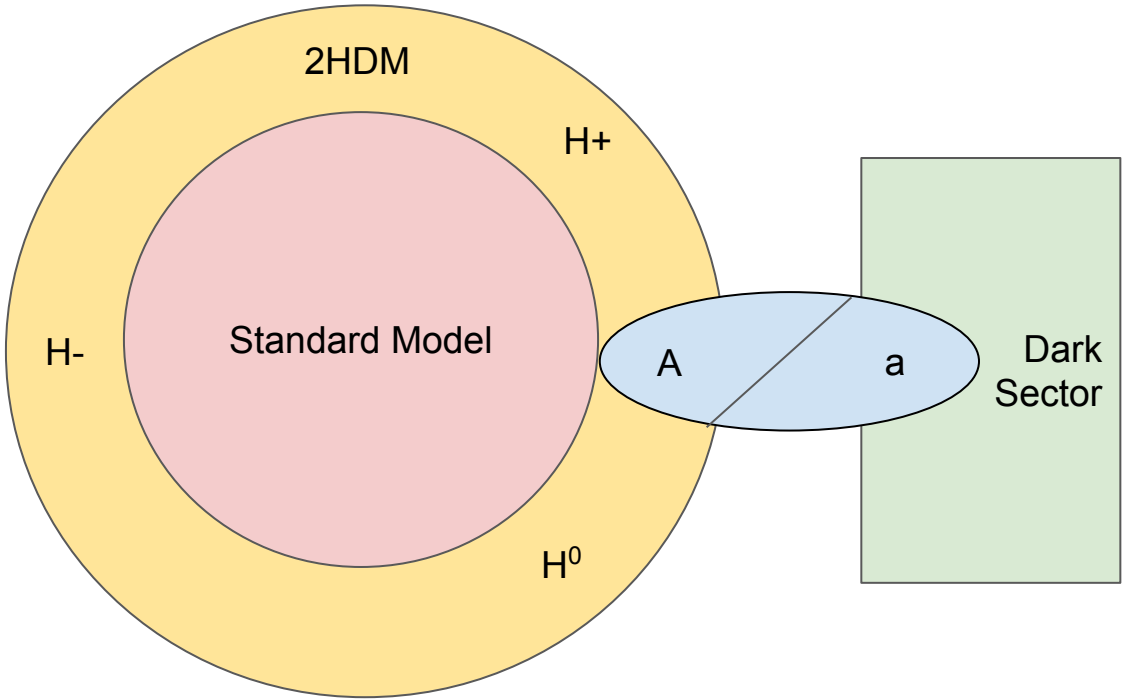
DM couples to SM ? -> We can see it at colliders ! ($pp \rightarrow$ SM + DM)

Many theories predicting DM + SM interactions. ATLAS DM searches widely use simplified models.

Assuming a interaction between dark matter and SM particles through mediators (either SM or new).

Phys.Dark.Univ Vol 27, 100351

2HDM+a models



Simplified model with an extended 2HDM Higgs sector

Assuming a Dirac fermion χ with a WIMP mass in dark sector.

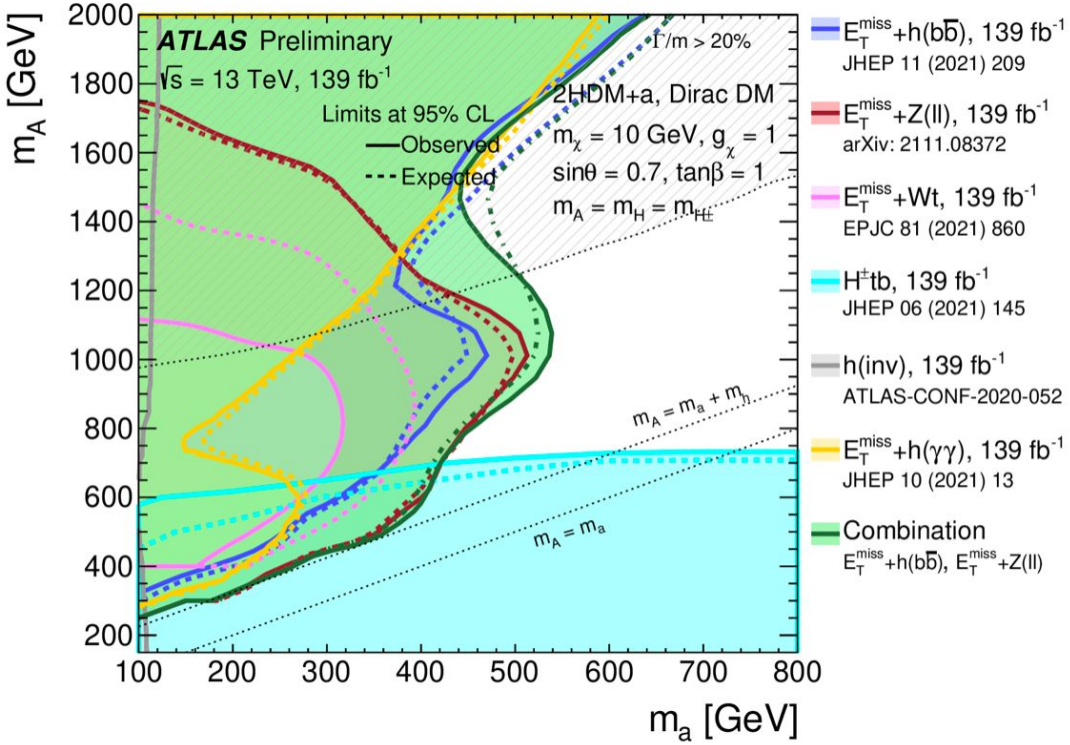
Connection between dark sector and SM+2HDM though a pseudo-scalar mediator (***a***) mixed with CP-odd Higgs (***A***)

Important params for pheno:

- Masses: $m_{H^-,A,H}$ ma, mχ,
- Couplings: g_χ
- sinθ (mixing angle between A and a)
- tanβ (= vu/vd)

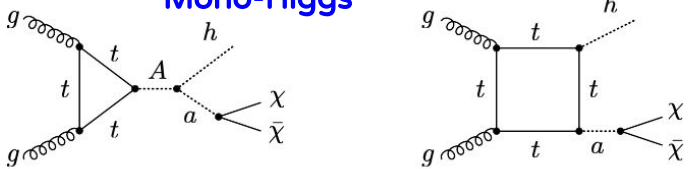
Phys.Dark.Univ Vol 27, 100351

2HDM+a models interest

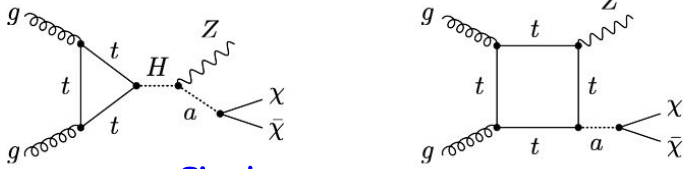


- Simplest renormalizable theory with a single DM candidate.
- Unitarity.
- Rich phenomenology in several final states at colliders.

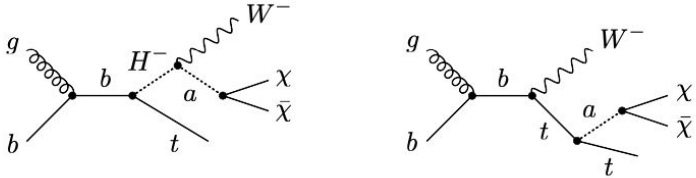
Mono-Higgs



Mono-Z



Single-top



Phys.Dark Univ. 21 (2018) 8-15

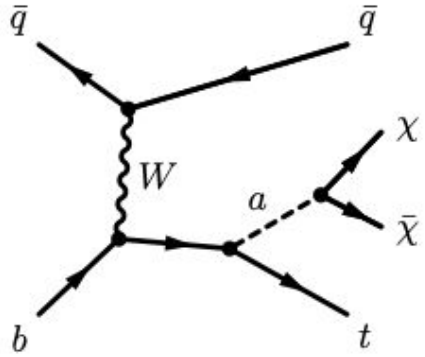
Single-top quark production and Dark Matter

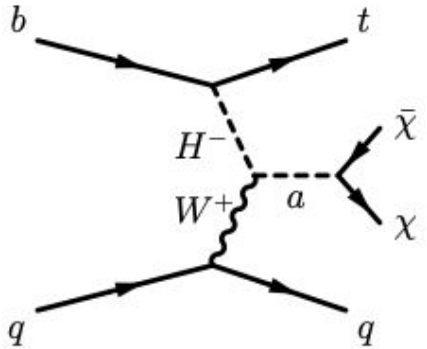
s-channel

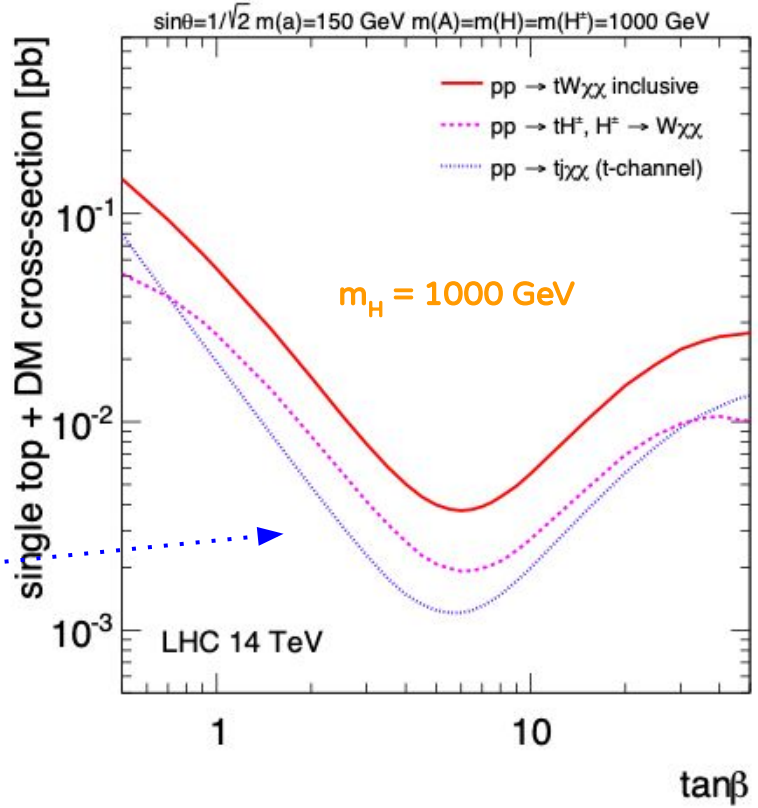
Negligible contributions

t-channel

Subdominant production mode of single-top quark in association to dark matter in 2HDM+a model







Phys.Dark Univ. 21 (2018) 8-15

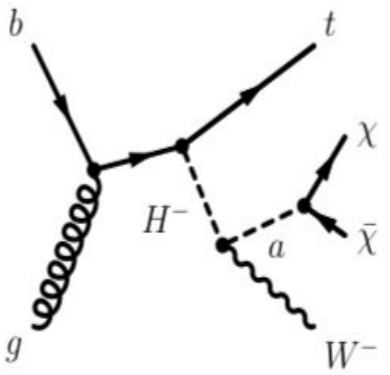
Single-top quark production and Dark Matter

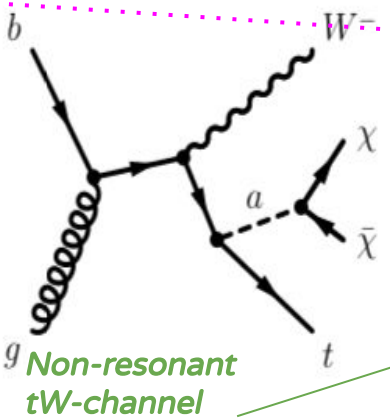
tW-channel

Dominates the cross-section of the single-top production with dark matter
Resonant and non-resonant production mode

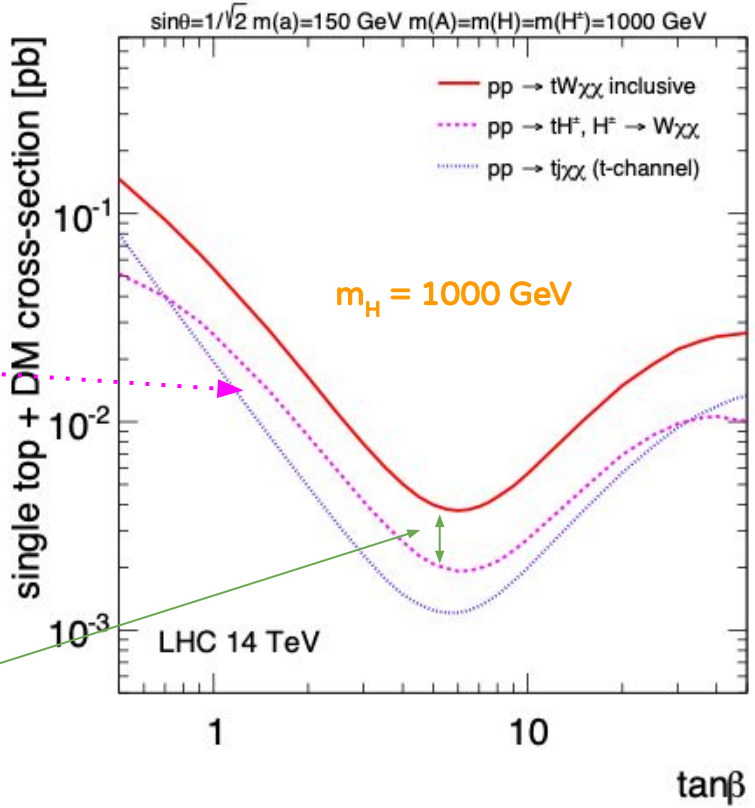
- Resonant dominating at m_H ~ [400,1200] GeV

Resonant tW-channel





Non-resonant tW-channel

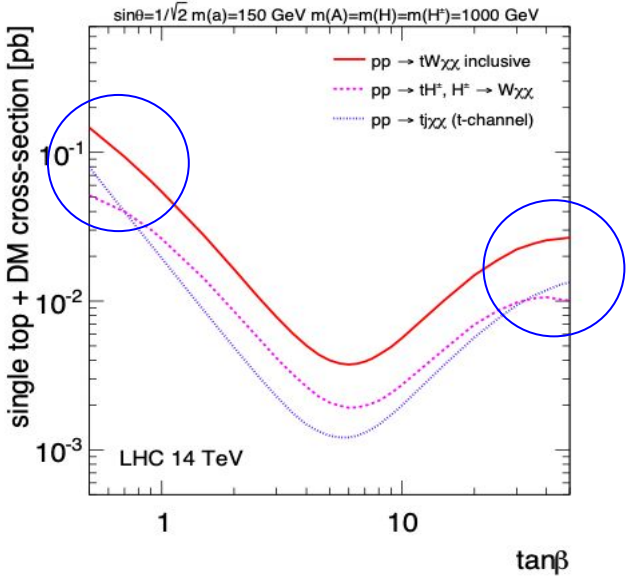


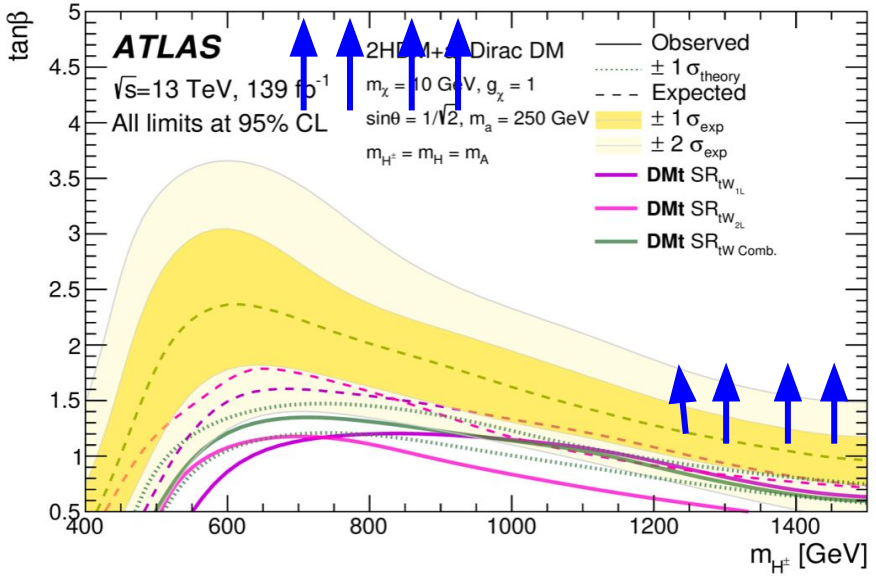
Single-top quark production and Dark Matter

Cross-section presenting two maxima. At low tanβ and at high tanβ (~[20,30])

1L+2L final states: *Eur. Phys. J. C 81 (2021) 860*
0L+1L+2L: *ATLAS-CONF-2022-012* ->Today !

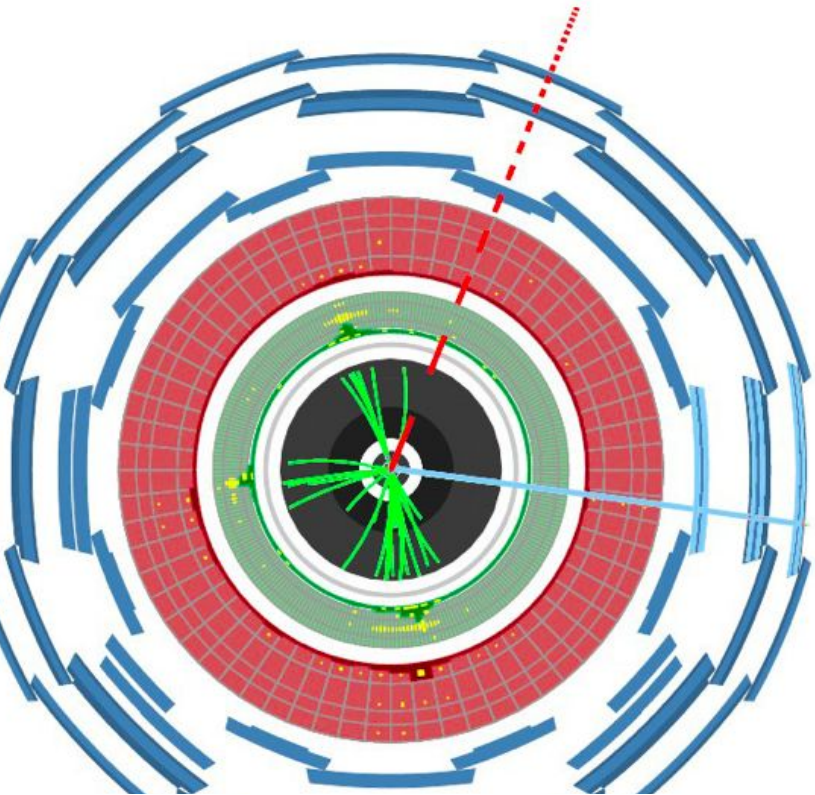
- 2L from previous analysis. Combined with new 0L+1L.





Aim of this analysis: improve sensitivity at high tanβ and at higher mH using the tW-channel

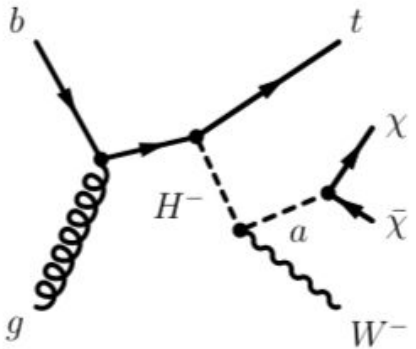
Analysis strategy at a glance

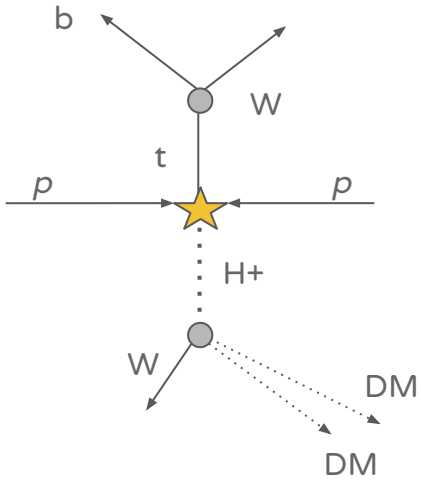


Signals present one top, a W-boson and large missing transverse momentum

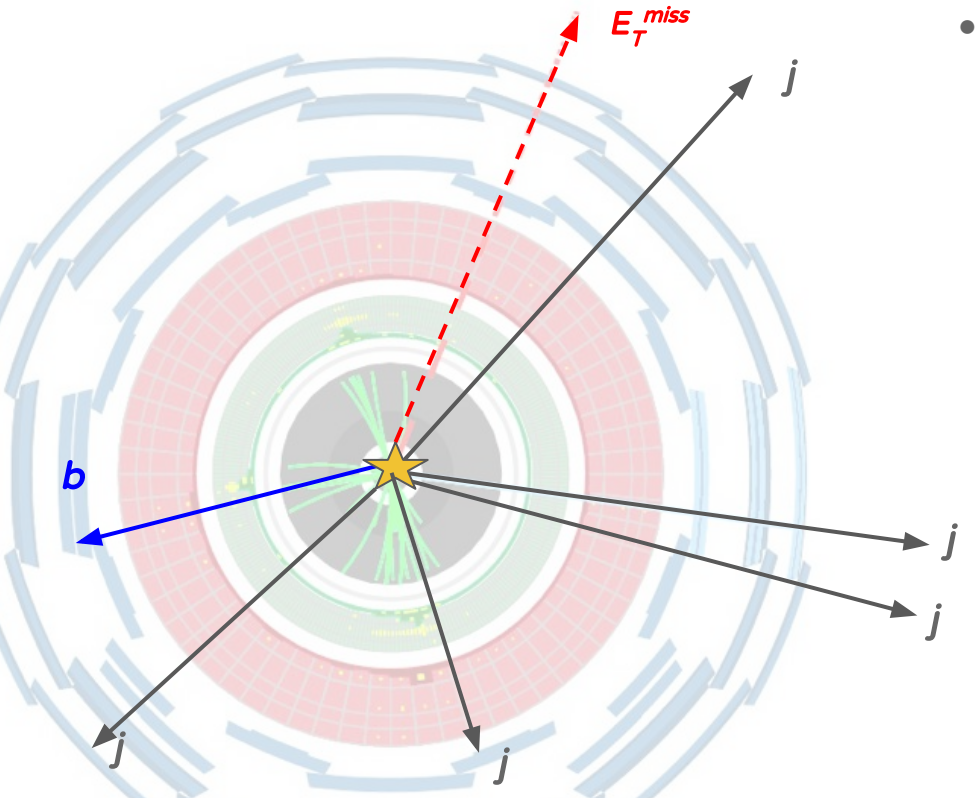
- Trigger events based on E_T^{miss}
- Profit of the top quark and W-quark to reduce significantly the background

BR(t -> bW) ~ 99% and BR(W->qq') ~ 67% / BR(W->lv) ~ 33%. Possible channels are : 0L, 1L and 2L



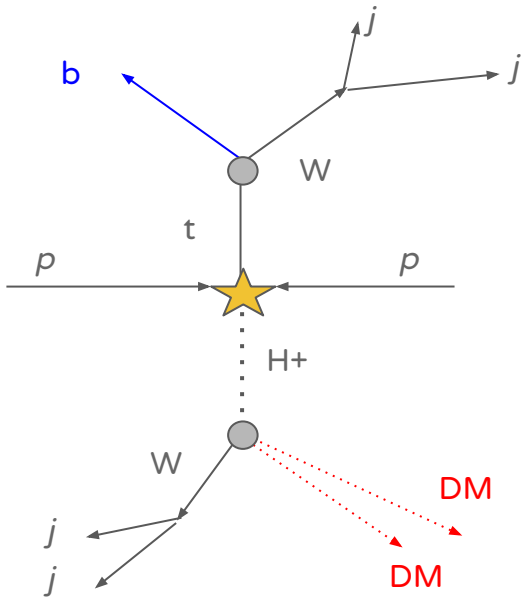


Analysis strategy: the zero-lepton channel



0L channel: 0 leptons, jets, 1 b-jet and high E_T^{miss}.

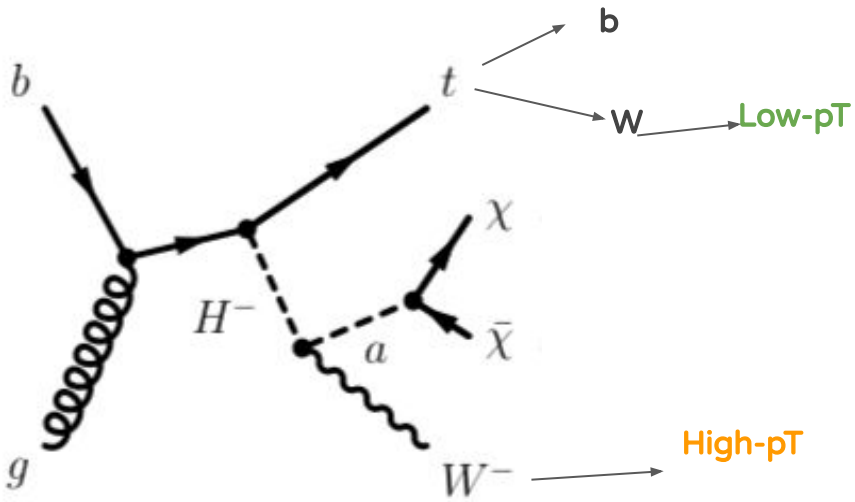
- Potential important backgrounds:
  - Z+jets, W+jets, single-top
  - Semileptonic ttbar with one lepton missing.



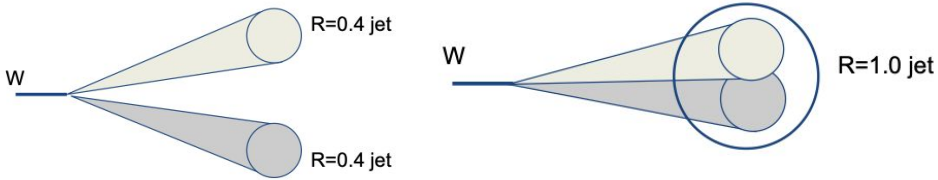
W-tagging

Hadronically decaying W-bosons in this channel

Expected a large fraction of events to have a collimated W-boson from H+ decay.



Low-p_T High-p_T



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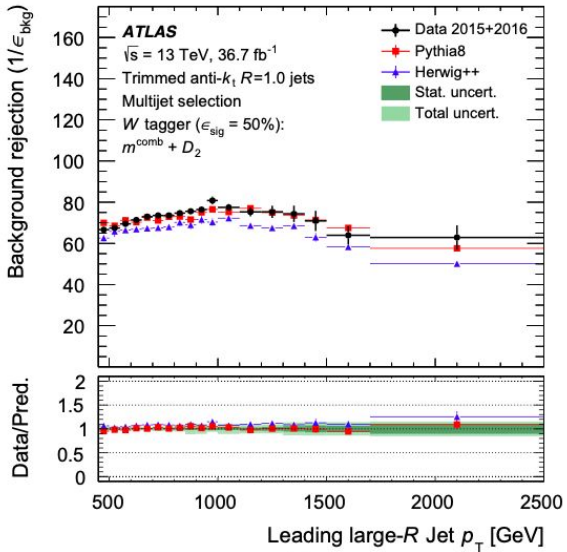
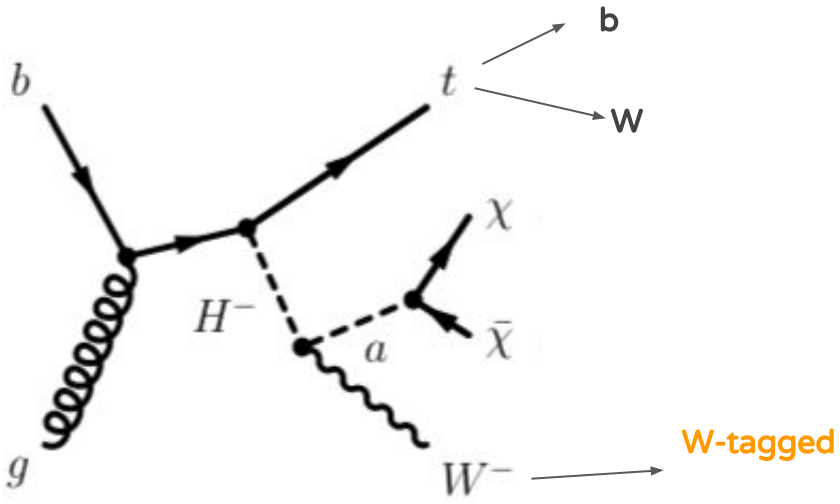
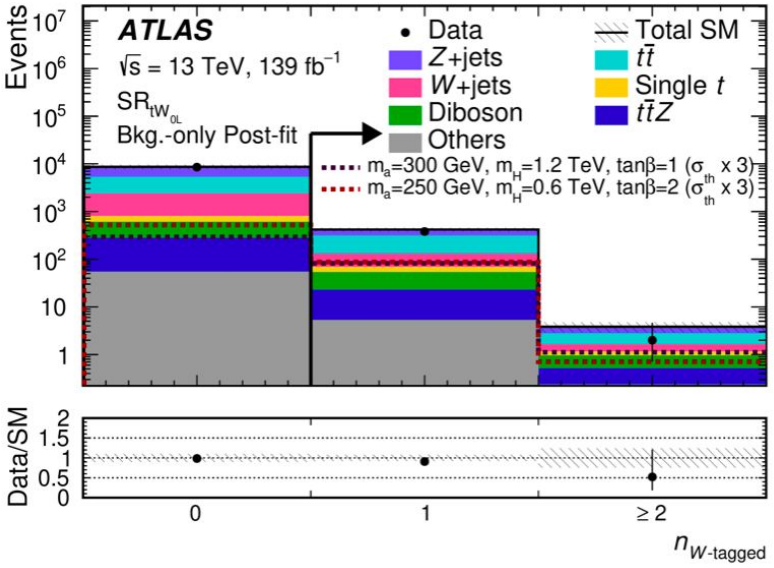


The zero-lepton channel

W-tagging

Requirement of at least presenting a W-tagged large-R jet in the event. → reduce V+jets and semi-leptonic tt.
Build m(b,W) and ΔR(b,W) using the leading W-tagged jet and the leading large-R jet.





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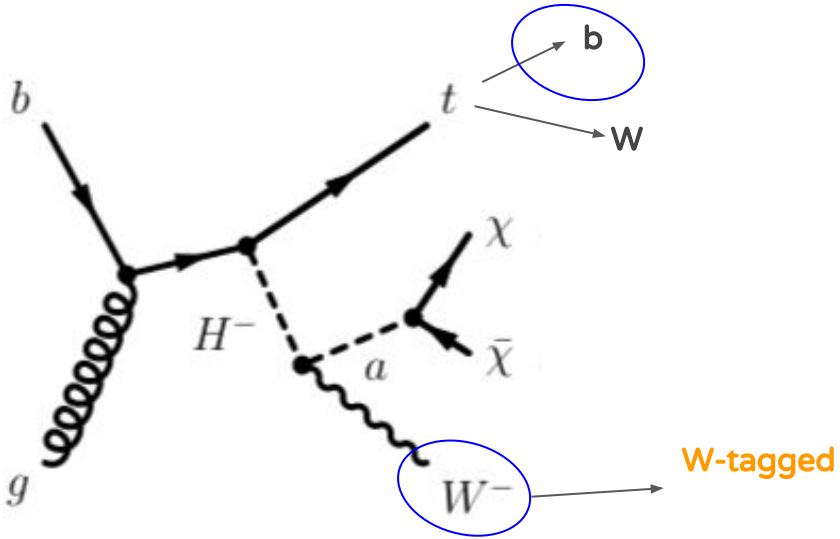
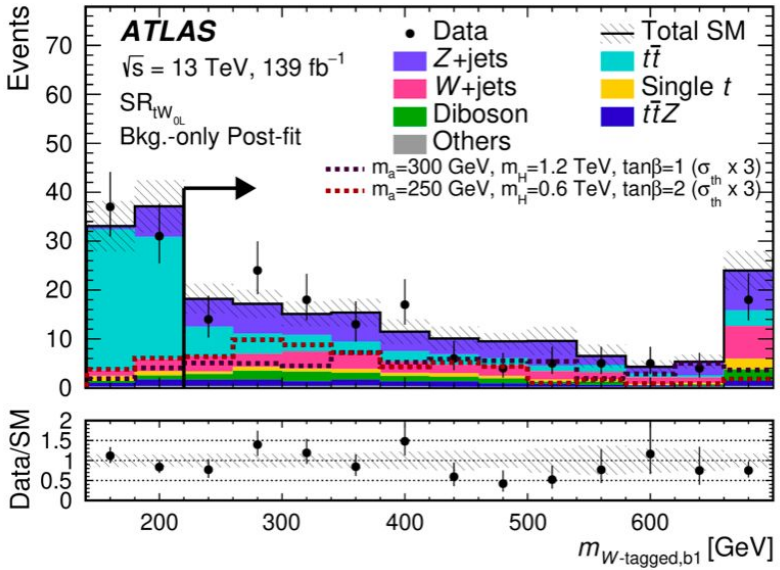
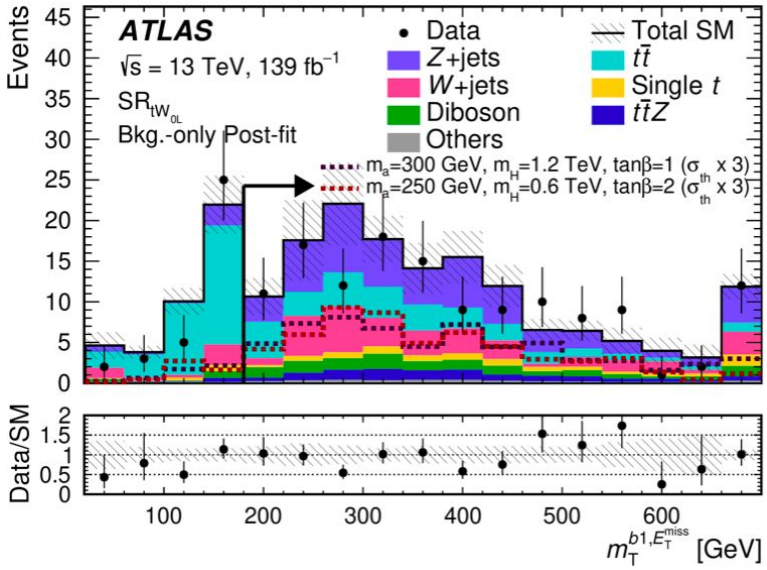


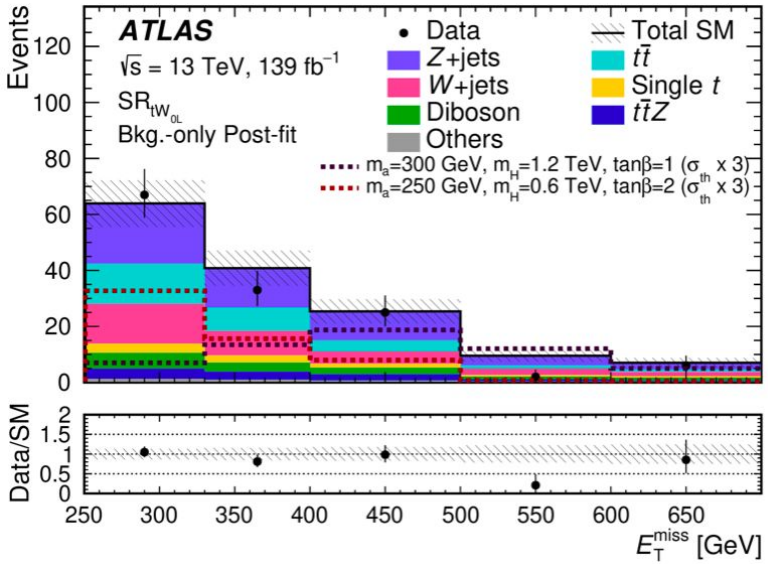


The zero-lepton channel

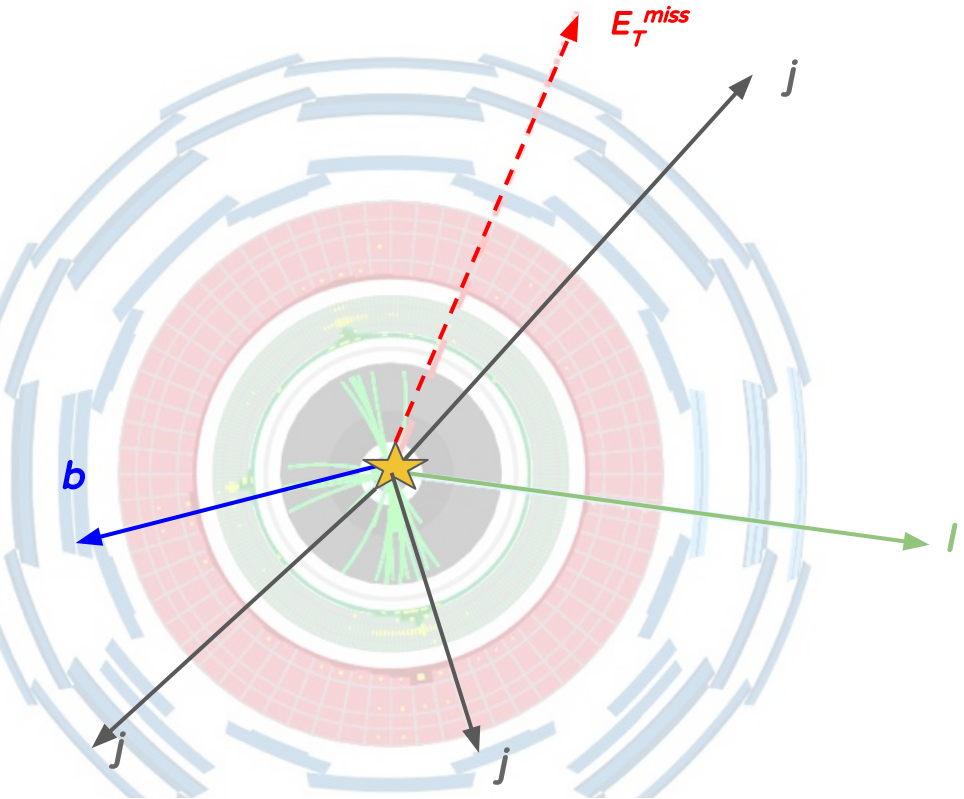
E_T^{miss} variables

High E_T^{miss} and high E_T^{miss} significance allow to reduce considerably the background. Bin in E_T^{miss} the regions $m_T(b,E_T^{miss})$ has an endpoint for some ttbar events but not signal.



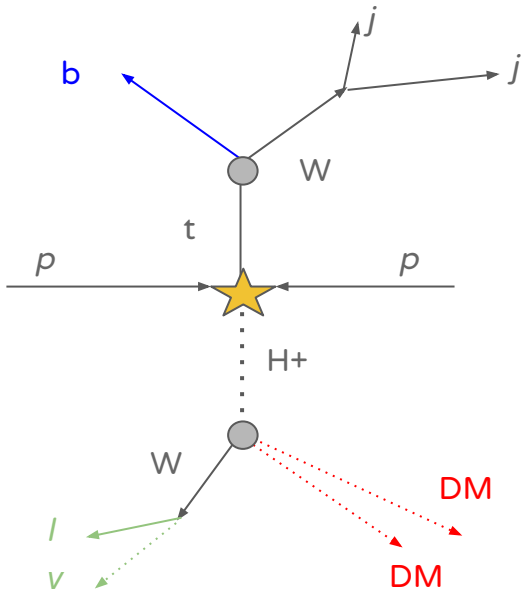


Analysis strategy: the one-lepton channel



1L: 1 lepton, jets, 1 b-jet and high E_T^{miss}.

- Potentially important backgrounds:
  - W+jets, single-top.
  - Semileptonic tt.
  - Dileptonic tt with one lepton missing



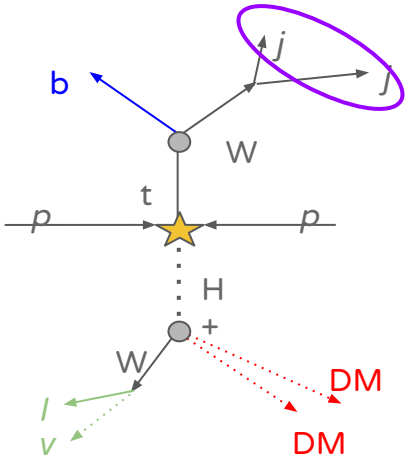
The one-lepton channel

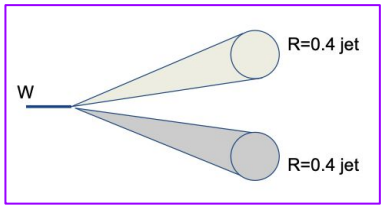
Categorise events depending on what W-boson decays leptonically: hadronic and leptonic top.

- Interest: W-tagging can be applied to events with leptonic top.

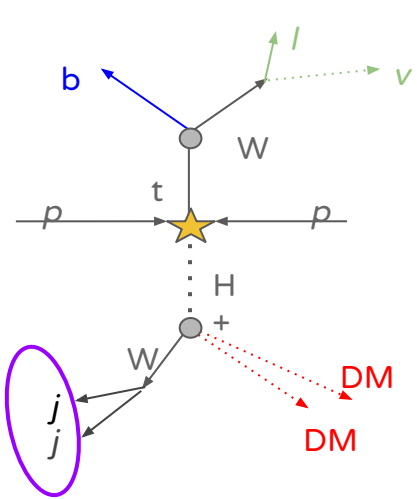
Split SRs using m(b,j): invariant mass of leading b-jet and light-jet.

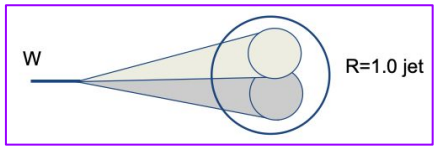
Hadronic top

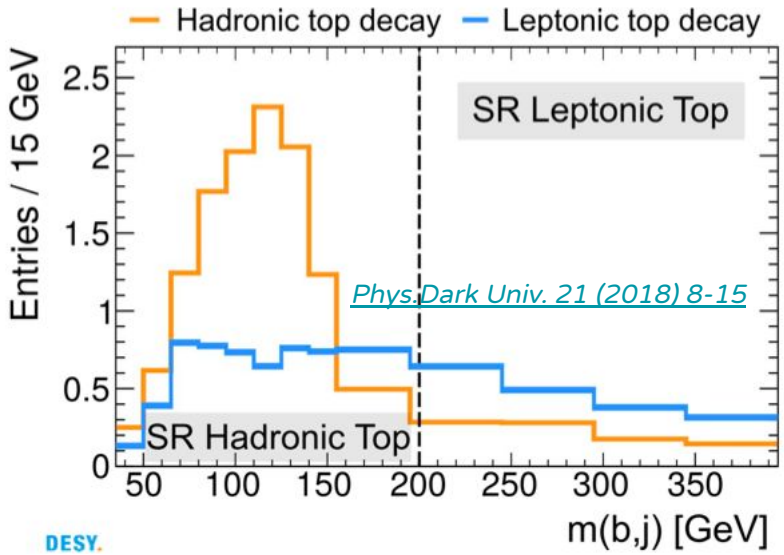




Leptonic top

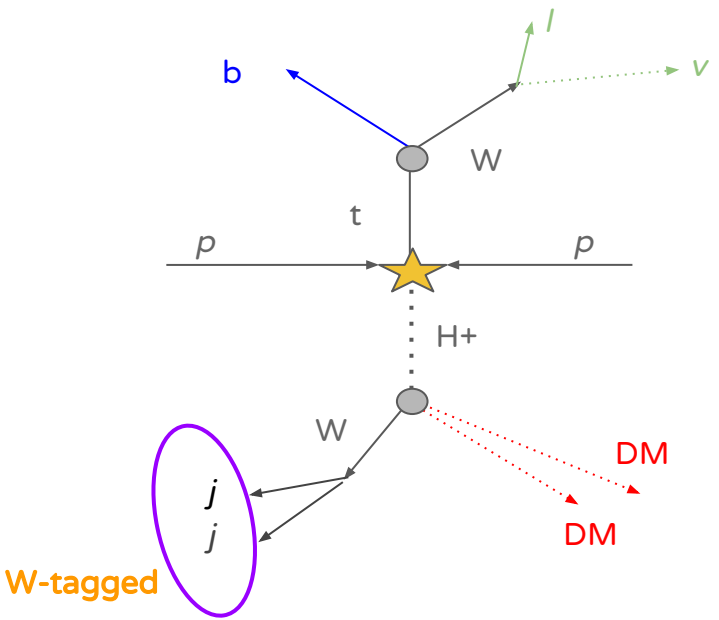


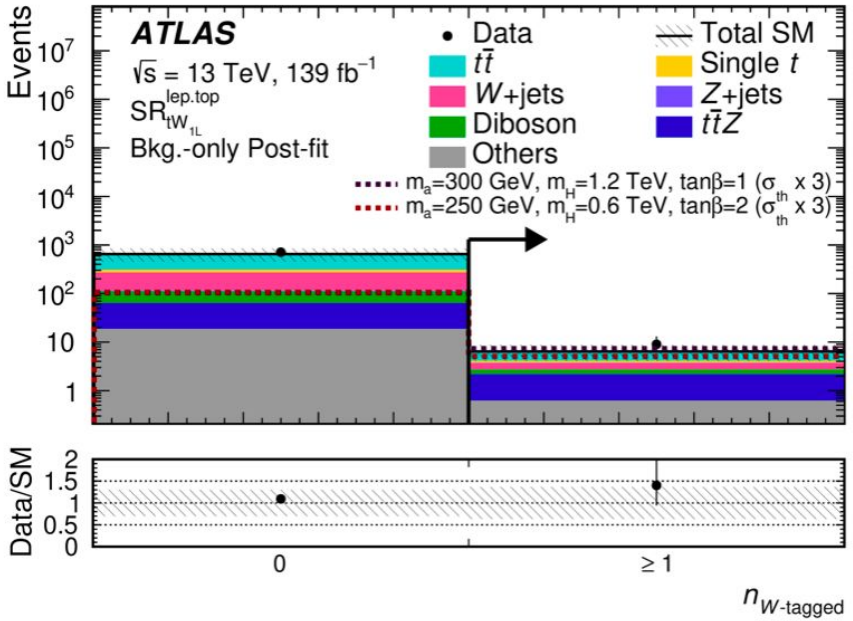




The one-lepton channel: leptonic top

Reduce the semileptonic ttbar contamination by requiring $m_T(l_{ep}, E_T^{miss}) > 130$ GeV and high E_T^{miss} significance
Remaining ttbar is dileptonic -> W-tagging





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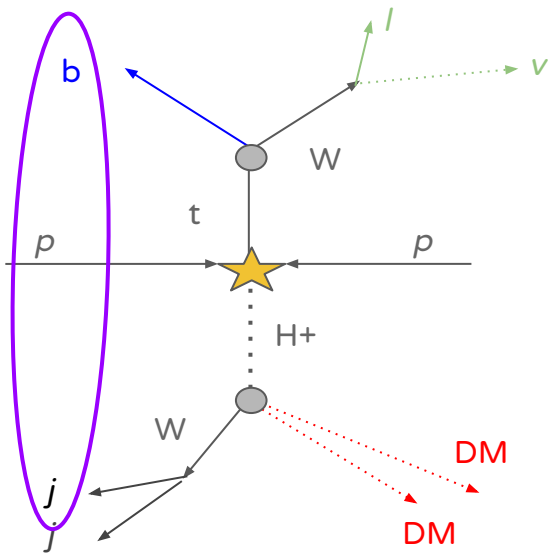
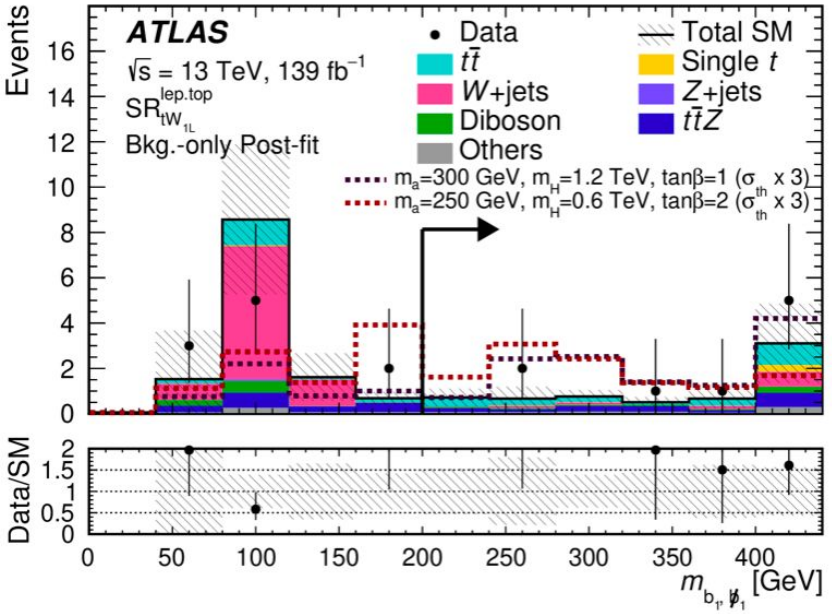
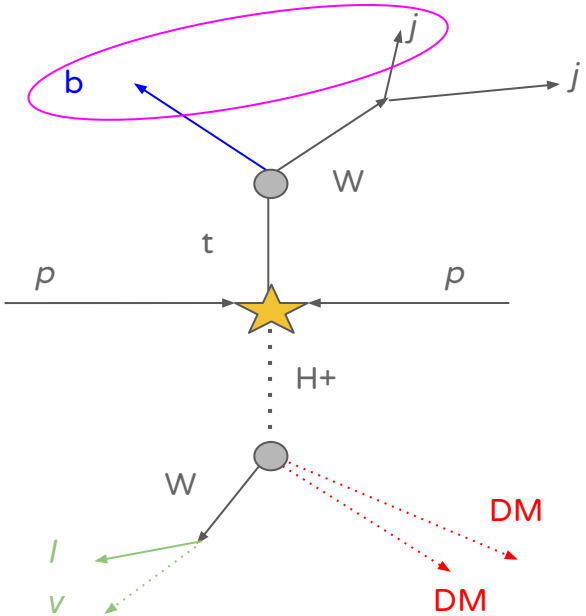


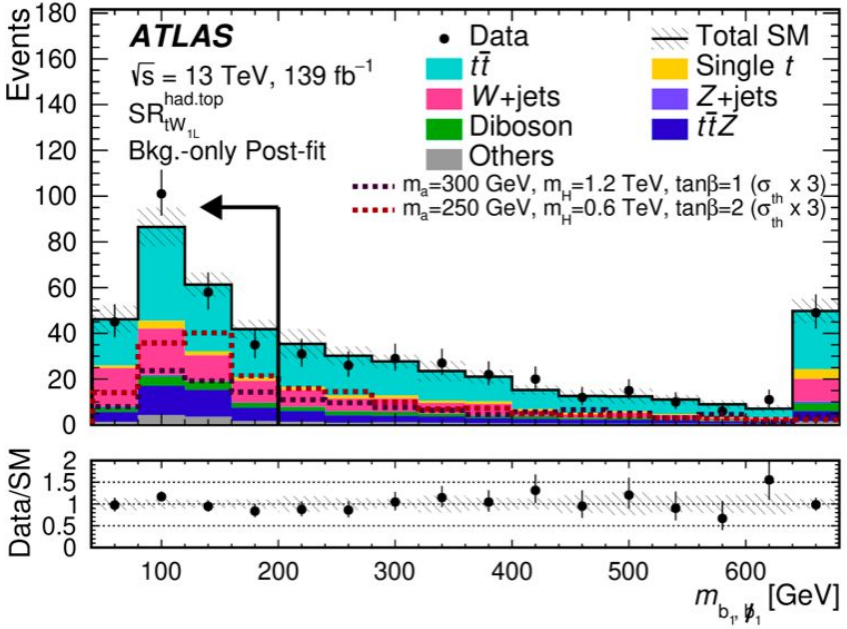


The one-lepton channel: hadronic top

Remove semileptonic ttbar using $m_T(l_{ep}, E_T^{miss}) > 200$ GeV.
Remaining ttbar is dileptonic and W+jets. Use asymmetric stransverse mass R.Mahbubani et al.

- Stransverse mass from SUSY to pseudo-reconstruct particles decaying to visible particles and neutralinos
- Useful in cases where signals contain a pair of particles decaying into MET and visible particles.





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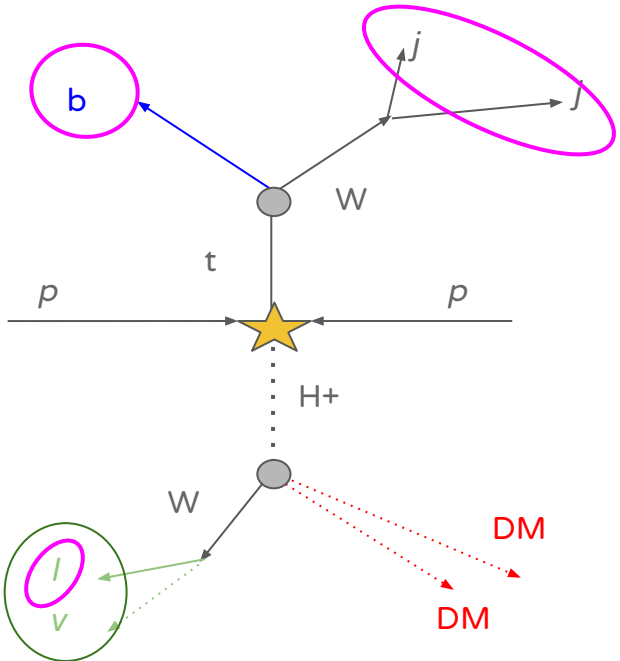
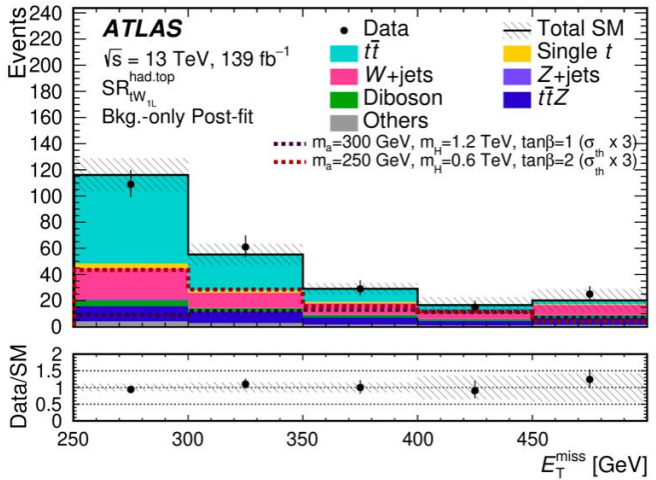


$$m_{\mathrm{T}}^{\mathrm{lep}} = \sqrt{2p_{\mathrm{T}}^{\ell}E_{\mathrm{T}}^{\mathrm{miss}}\left(1-\cos\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\ell},\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})\right)}$$

$$am_{T2}(\mathbf{p}_{\mathrm{T},b1},\mathbf{p}_{\mathrm{T},b2},\mathbf{p}_{\mathrm{T},\ell},\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}) = \min[m_{\mathrm{T2}}(\mathbf{p}_{\mathrm{T},b1}+\mathbf{p}_{\mathrm{T},\ell},\mathbf{p}_{\mathrm{T},b2},\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}), m_{\mathrm{T2}}(\mathbf{p}_{\mathrm{T},b1},\mathbf{p}_{\mathrm{T},b2}+\mathbf{p}_{\mathrm{T},\ell},\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})]$$



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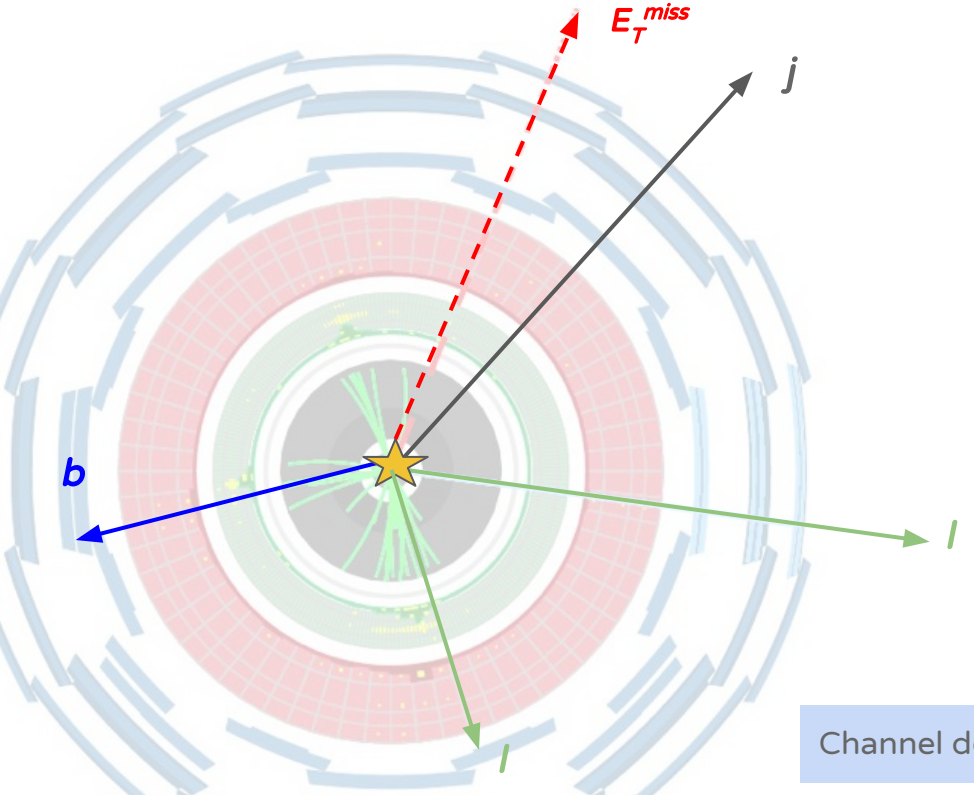
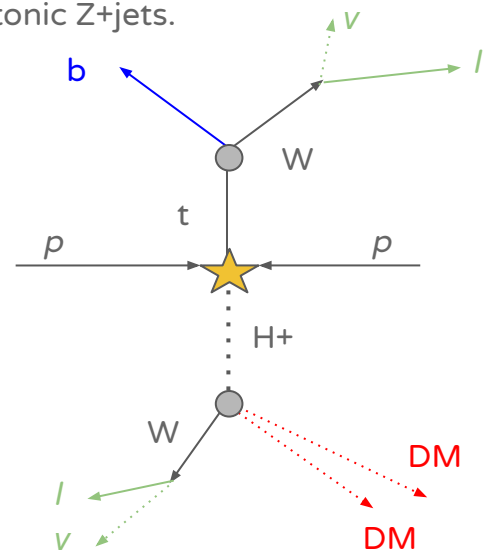
Analysis strategy: the two-lepton channel



2L: 2 leptons, jets, 1 b-jet and high E_T^{miss}

- Potentially important backgrounds:
  - Dileptonic tW produced single-top.
  - ttZ and dileptonic tt.
  - Leptonic Z+jets.



Channel developed in first iteration and combined with 0L and 1L

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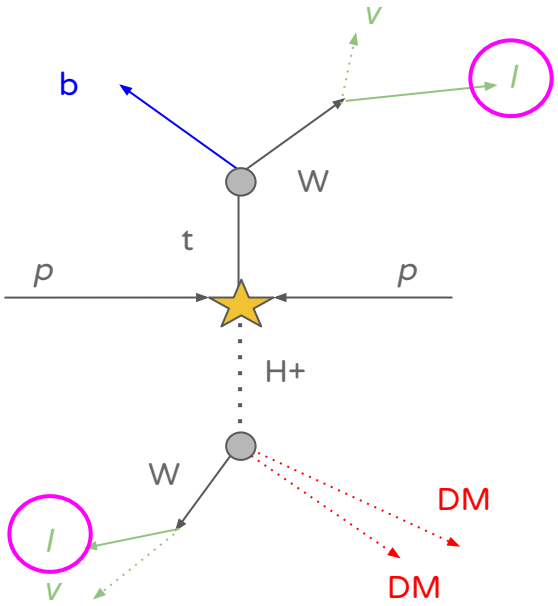
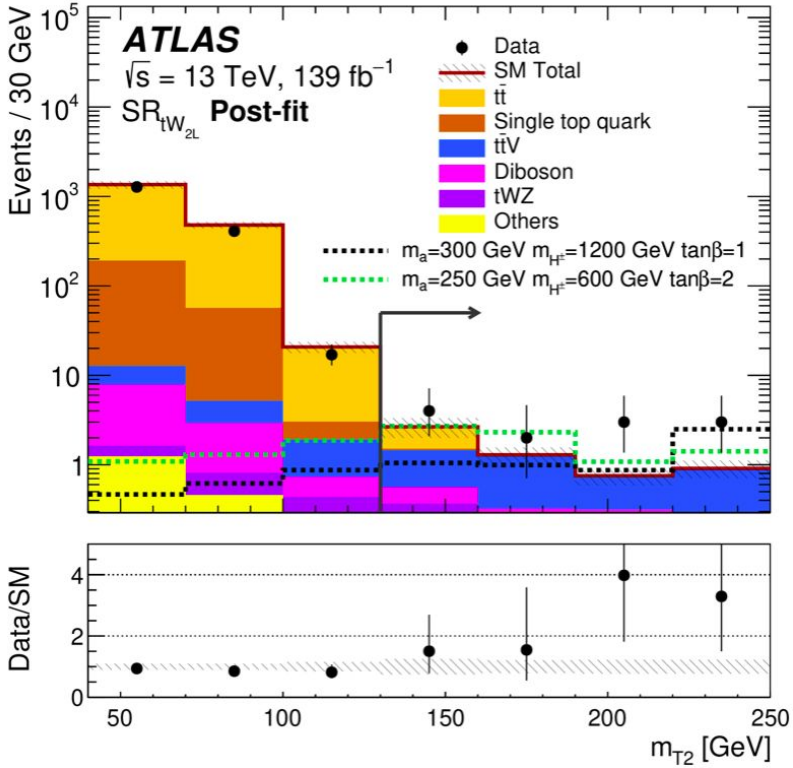
The two-lepton channel

Using variables separating dileptonic ttbar from single top m_{T2} , m_{bl}^{min} and m^{t}_{bl}-> Endpoints for SM tt and single-top.

Removing the Z-mass peak (m_{ll} in [71,111] GeV)



$$m_{\mathrm{T2}}(\vec{p}_{\mathrm{T}}^{\,\ell_1}, \vec{p}_{\mathrm{T}}^{\,\ell_2}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}) = \min_{\vec{q}_{\mathrm{T}}} \left[\max \left(m_{\mathrm{T}}^{\mathrm{lep}}(\vec{p}_{\mathrm{T}}^{\,\ell_1}, \vec{q}_{\mathrm{T}}), m_{\mathrm{T}}^{\mathrm{lep}}(\vec{p}_{\mathrm{T}}^{\,\ell_2}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} - \vec{q}_{\mathrm{T}}) \right) \right]$$



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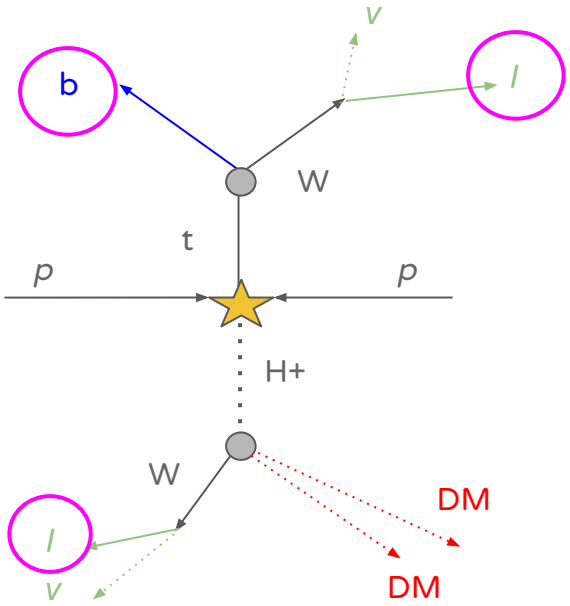
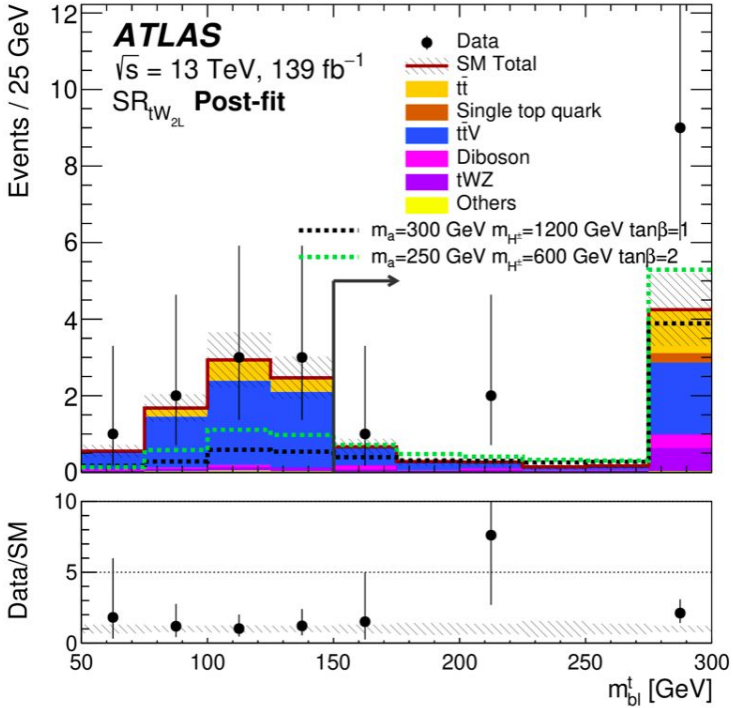




$$m_{b\ell}^{\min} = \min(m_{b_1\ell_1}, m_{b_1\ell_2})$$

$$m_{b\ell}^{\mathrm{t}} = \min[\max(m_{\ell_1 j_1}, m_{\ell_2 j_2}), \max(m_{\ell_1 j_2}, m_{\ell_2 j_1})]$$

Background estimation

Defining control and validation regions close to the SRs to normalize the most important backgrounds.

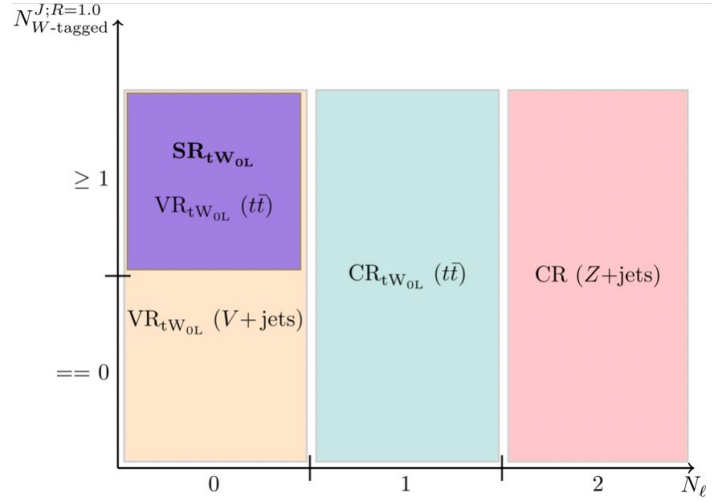
0L and 1L channels:

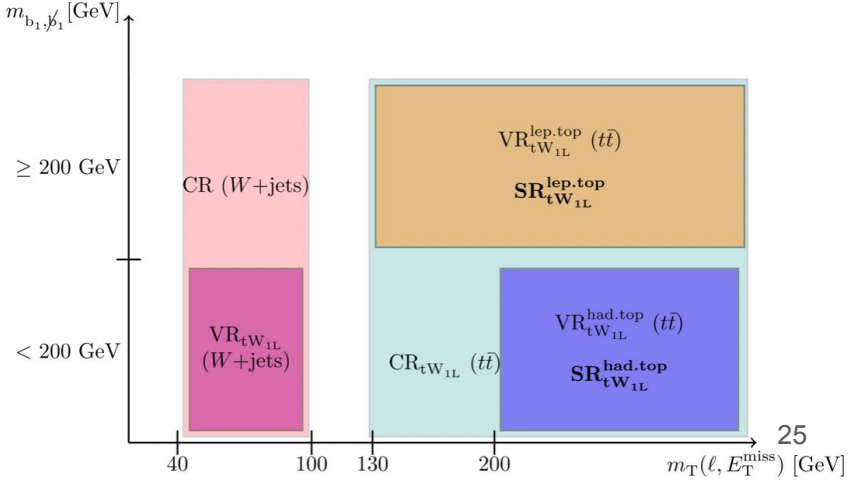
- Common CRs for Z+jets, W+jets, single-top and ttZ.
- ttbar normalized separately for 0L and 1L regions.

2L channel:

- CRs for tt and ttZ
- Additional control region for WZ

Variable	SR	CR($t\bar{t}$)	CR($t\bar{t}Z$)	CR(WZ)	VR($t\bar{t}$)	VR(3ℓ)
N_ℓ^{signal}	= 2 (OS)	= 2 (OS)	= 3 (≥ 1 SFOS)	= 3 (≥ 1 SFOS)	= 2 (OS)	= 3 (≥ 1 SFOS)
$p_T(\ell_3)$ [GeV]	-	-	> 20	> 20	-	> 20
$m_{ee/\mu\mu}$ [GeV]	$\notin$ [71, 111]	$\notin$ [71, 111]	$\in$ [71, 111]	$\in$ [71, 111]	$\notin$ [71, 111]	$\in$ [71, 111]
N_{jet}	≥ 1	≥ 1	≥ 3	$\in$ [1, 3]	≥ 1	≥ 1
$N_{b\text{-jet}}$	≥ 1	≥ 1	≥ 1 (≥ 2 if $N_{\text{jet}} = 3$)	= 1	≥ 1	≥ 1
$m_{b\ell}^{\min}$ [GeV]	< 170	< 170	< 170	> 170	< 170	varies
$m_{b\ell}^{1}$ [GeV]	> 150	< 150	–	–	> 150	–
m_{T2} [GeV]	> 130	$\in$ [40, 80]	> 90	> 90	$\in$ [40, 80]	> 90
$\Delta\phi_{\min}$ [rad]	> 1.1	> 1.1	–	–	> 1.1	–

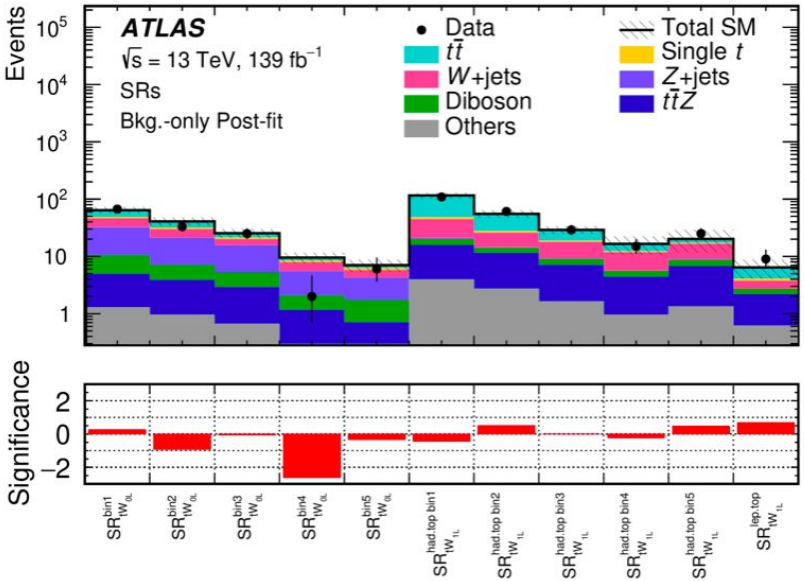




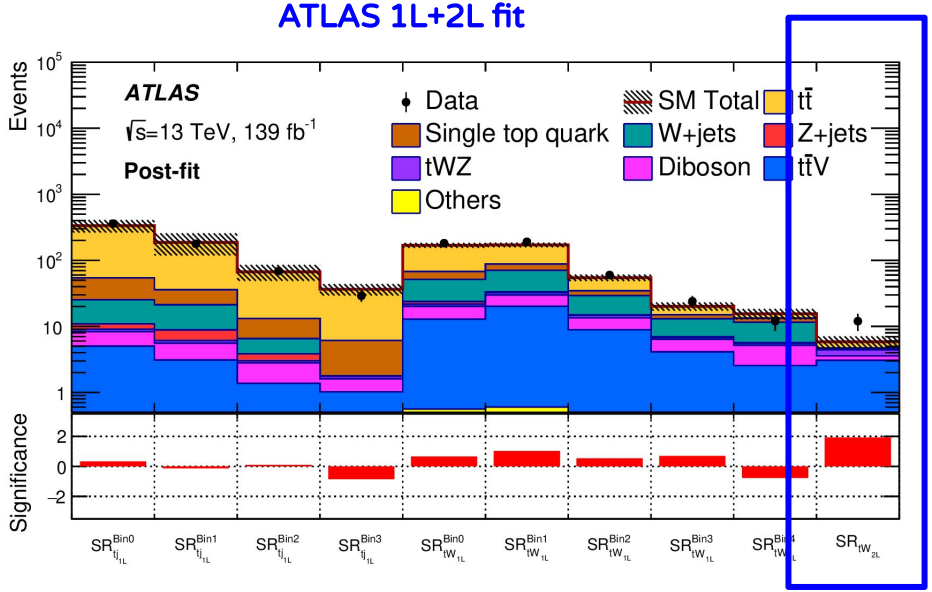
Background-only fit results

- Simultaneous of all the SRs and CRs of the 0L+1L. Result of 2L in previous ATLAS paper with 1L+2L.
- No DM evidence observed. 2σ excess observed in 2L and 2.5σ deficit in one bin of the 0L channel.

0L+1L combined fit

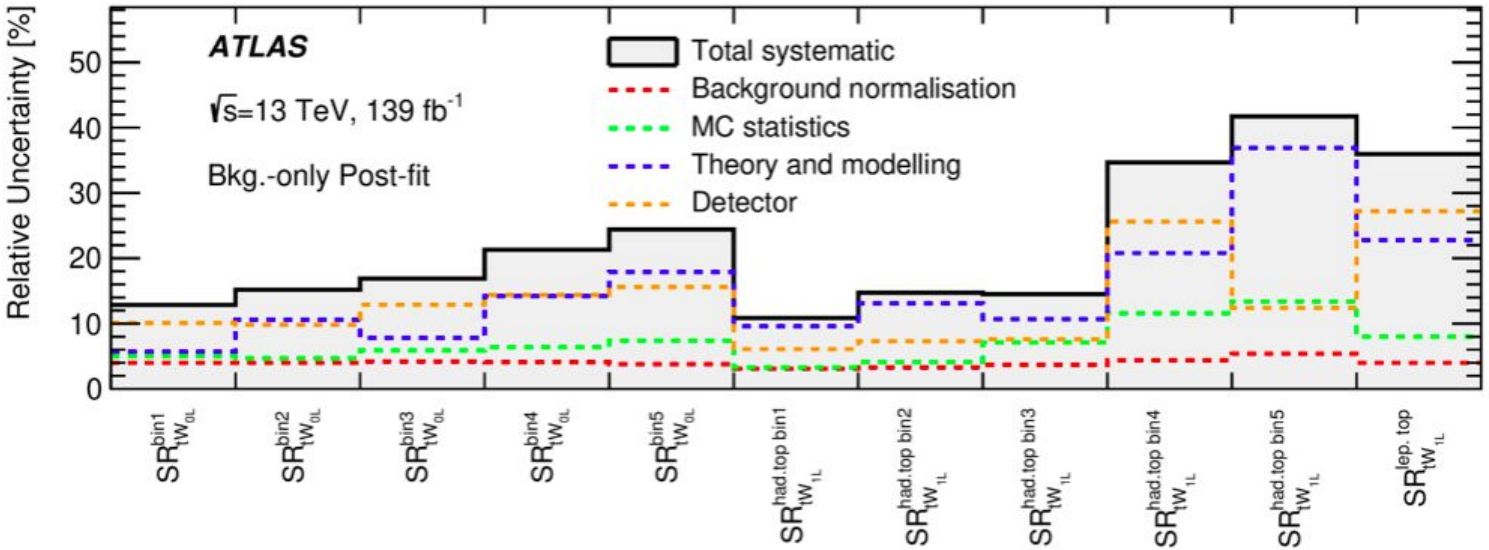


ATLAS 1L+2L fit



Uncertainties

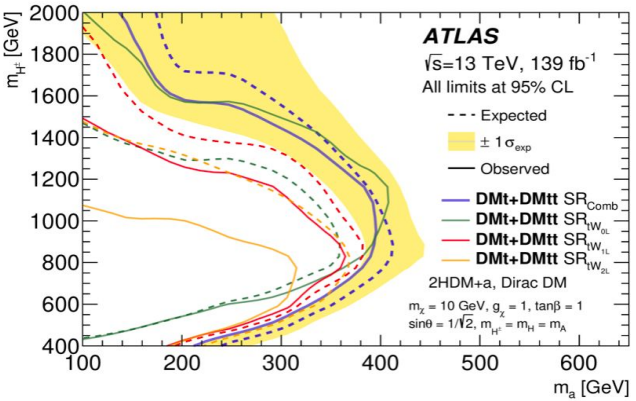
- 0L and 1L regions dominated by the theory and detector uncertainties
  - 0L by W-tagging and ttbar and Z+jets theory uncertainties
  - 1L by small-R jets and W+jets theory uncertainties.
- 2L channel dominated by detector uncertainties -> Mainly jet energy scale and b-tagging uncertainties

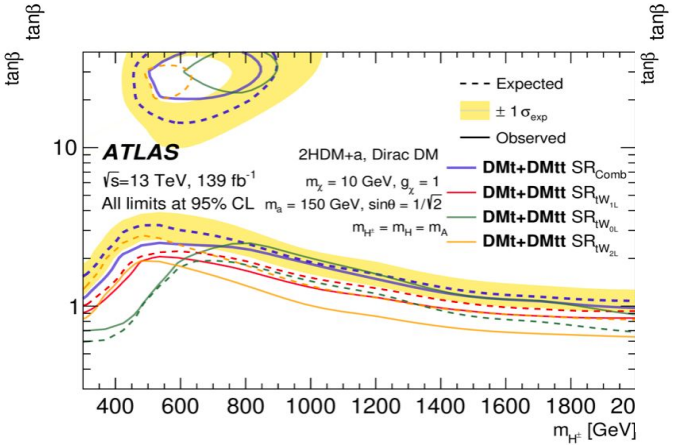


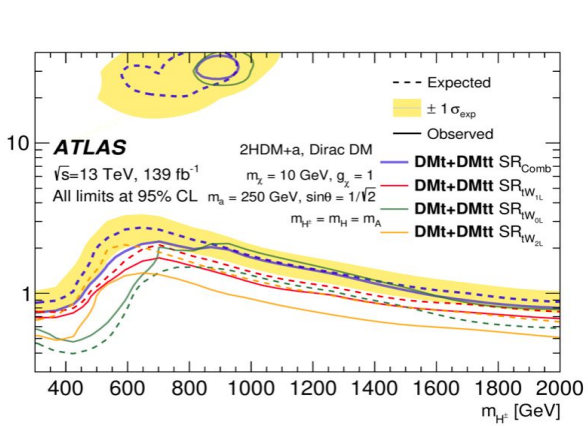
Interpretation of 2HDM+a limits

Free parameters of the model : m_{H+}, m_a, m_χ, tanβ (= vu/vd), sinθ (a-A mixing).

Combined limit **0L individual limit** **1L individual limit** **2L individual limit**







Final interpretation combining 0L and 1L channels with 2L from previous analysis in tW+DM.
Exclusion at high tanβ due to process *σ x B* evolution

Conclusion

Dark matter is one of current open questions in Particle Physics

Dark matter models used at LHC predict observable signals of dark matter in single-top final states

- 2HDM+a models predict a significant contribution on tW+E_T^{miss} final states

Performed a search for single-top production in association to dark matter in tW+E_T^{miss} final states.

Sensitivity increased for ATLAS tW+E_T^{miss} final states.

But unfortunately no dark matter has been observed in this analysis

LHC Run-3 started. New and exciting results await us. Stay tuned !

Backup