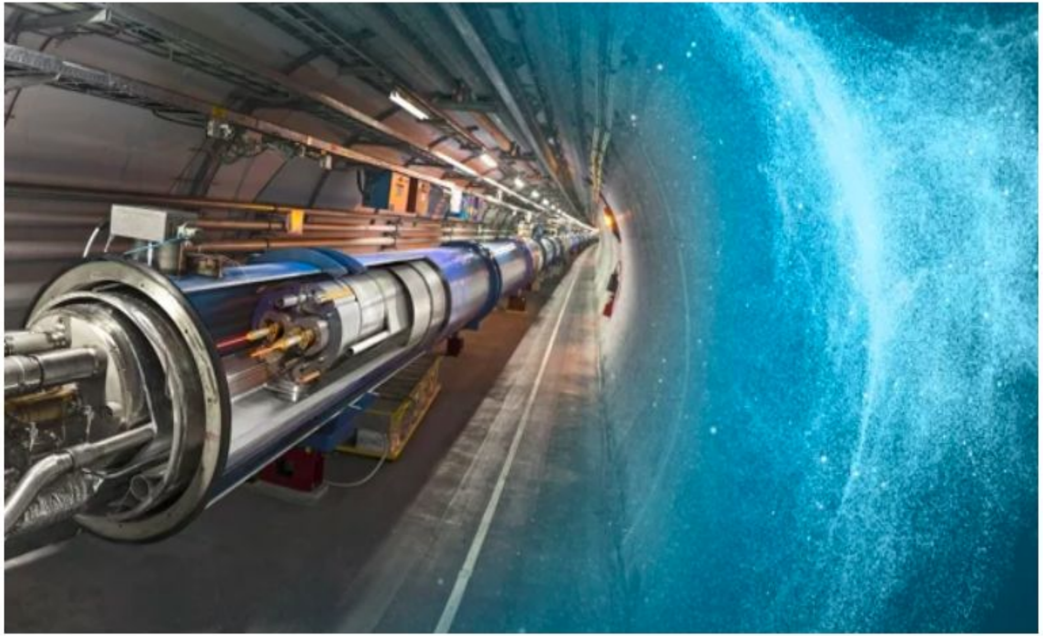
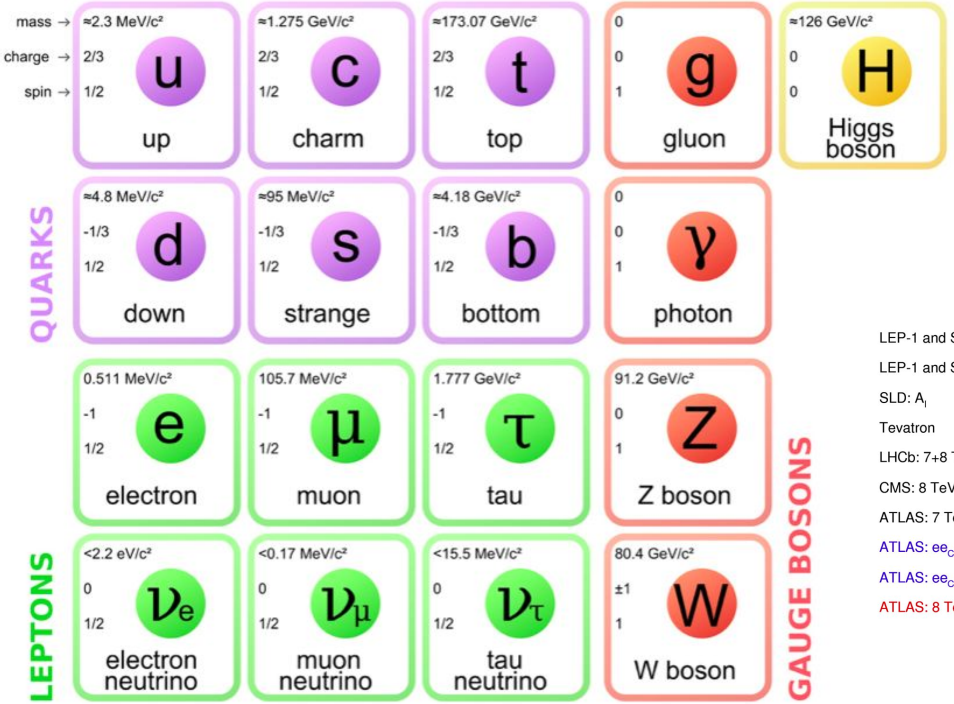
Peeking into the dark with the ATLAS detector



Alvaro Lopez Solis
On behalf of the ATLAS collaboration
CERN LHC seminar
19th July 2022

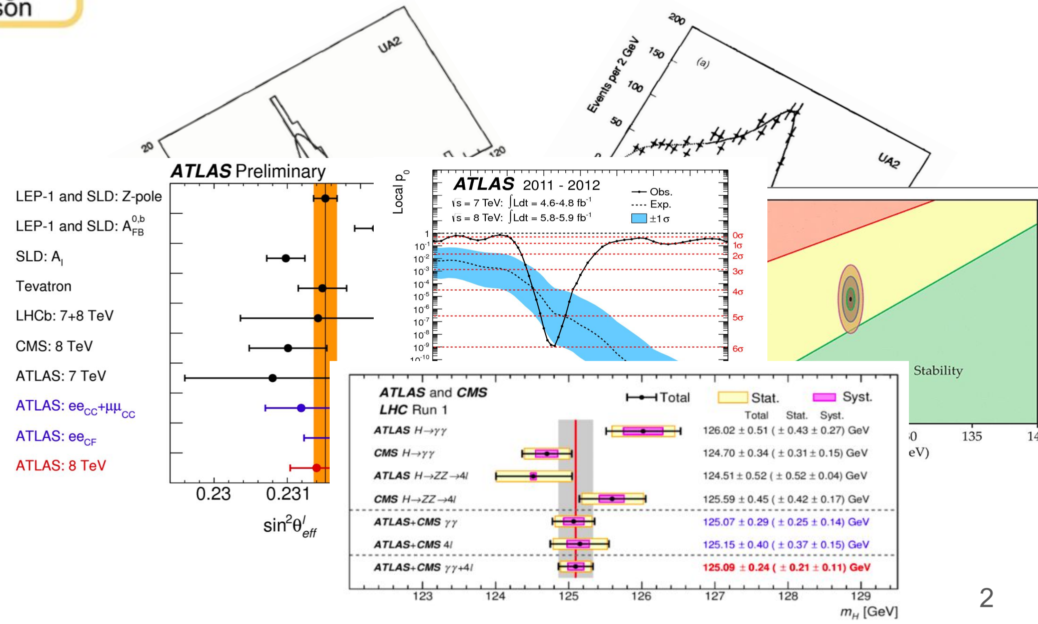
DESY.
HELMHOLTZ
RESEARCH FOR GRAND CHALLENGE
CERN
ATLAS
EXPERIMENT

The Standard Model: successful theory

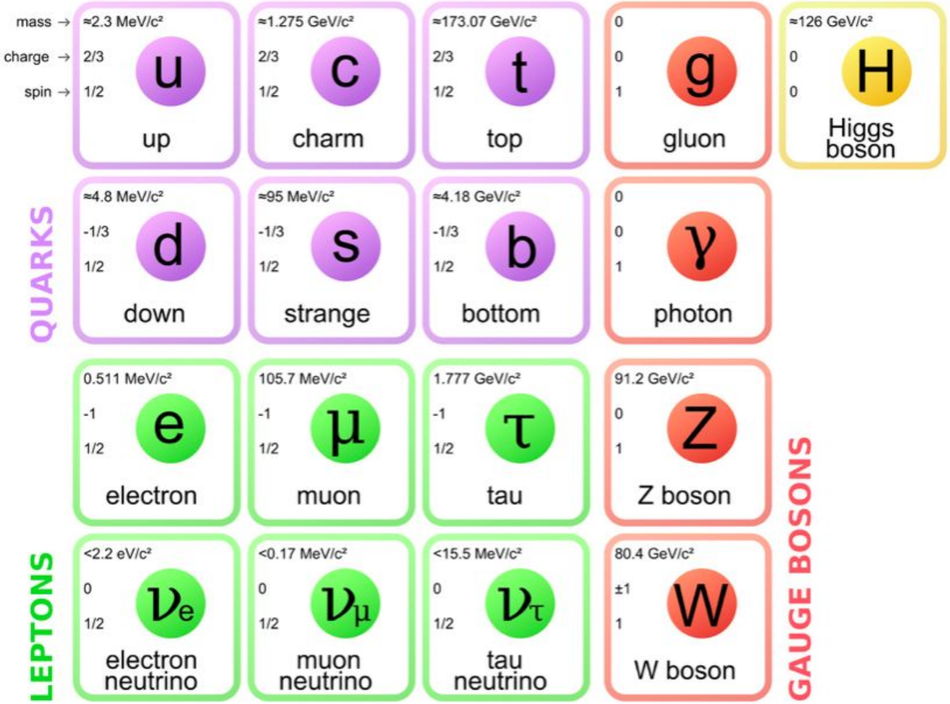


Very successful theory!

- Precision EWK measurements
- Higgs mechanism and Higgs discovery



Why the Standard Model is not enough ?



Very successful theory!

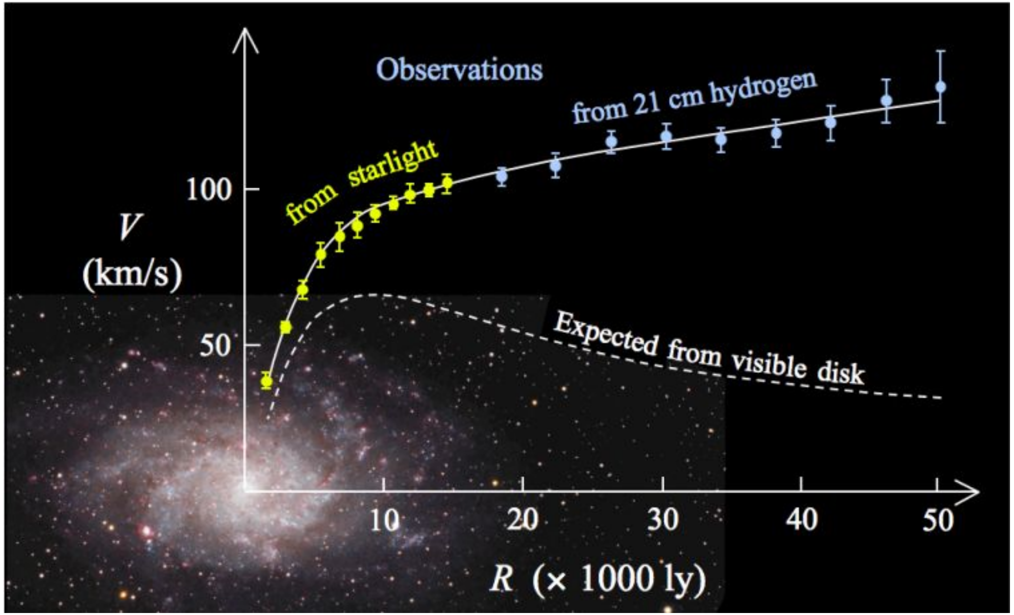
- Precision EWK measurements
- Higgs mechanism and Higgs discovery

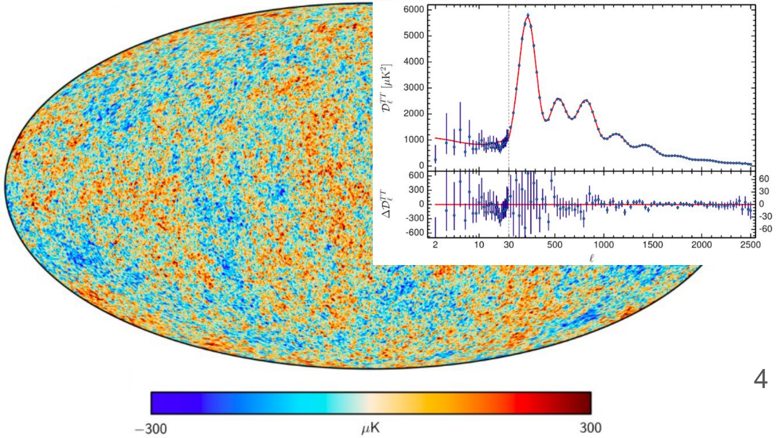
But, many fundamental questions remain unanswered

- Gravity
- Particle mass hierarchy
- Naturalness
- Neutrino oscillations
- Matter-antimatter asymmetry
- Dark matter

……

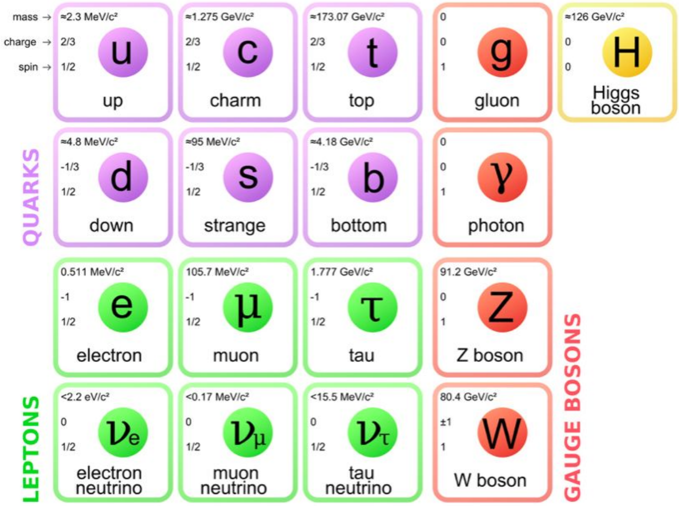
Why dark matter?

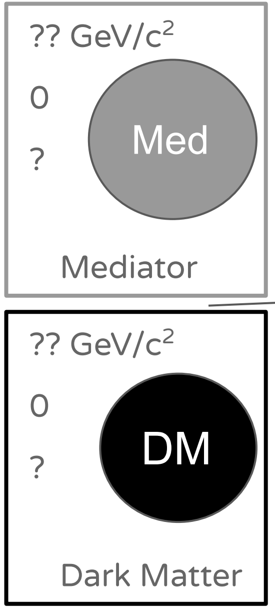


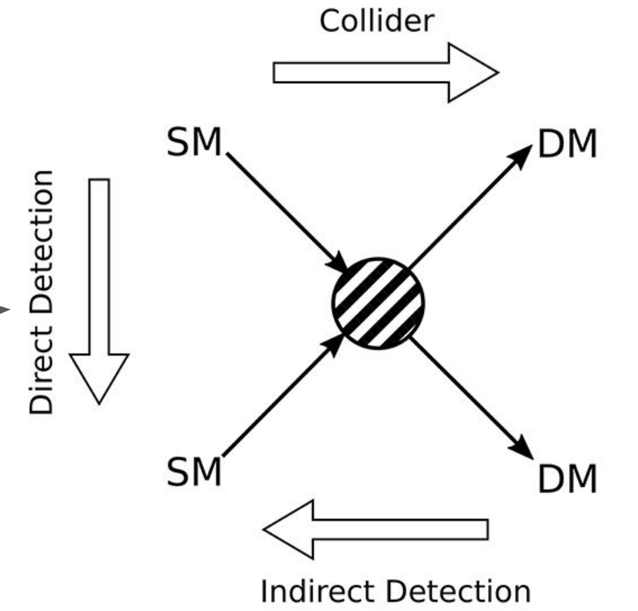


Powerful evidence indicating the existence of particles in the Universe that don't interact with light

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.

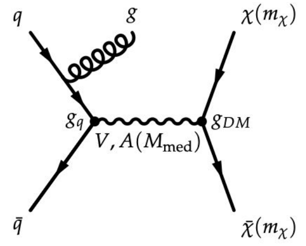
Assuming a interaction between dark matter and SM particles through mediators (either SM or new).

Simplified models: Mono-X searches

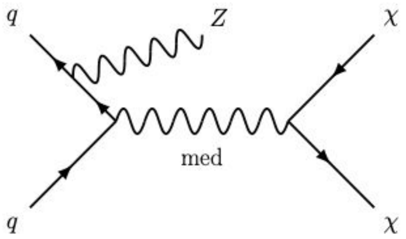
Simple representation of DM connecting to SM as proxy of more complete theories.
SM couples with DM sector via a mediator

- Spin-0 or spin-1 mediator
- Signature of Mono-X (X = SM particle)

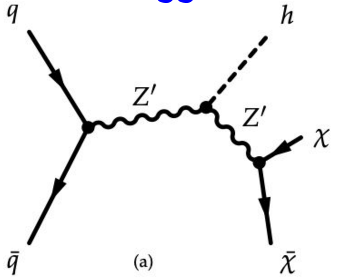
Mono-jet



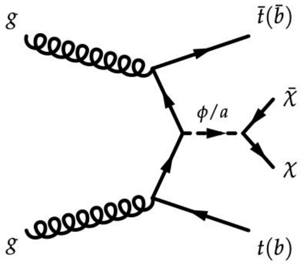
Mono-Z



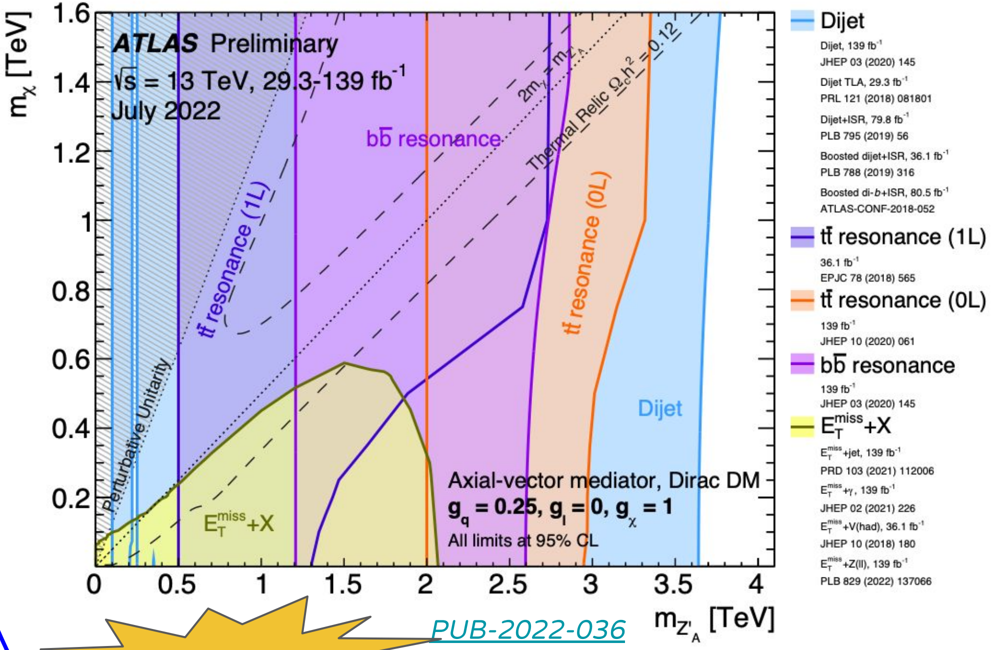
Mono-Higgs



Mono-tt/bb



Exclusion of the combined searches sensitive to mono-X



Today !

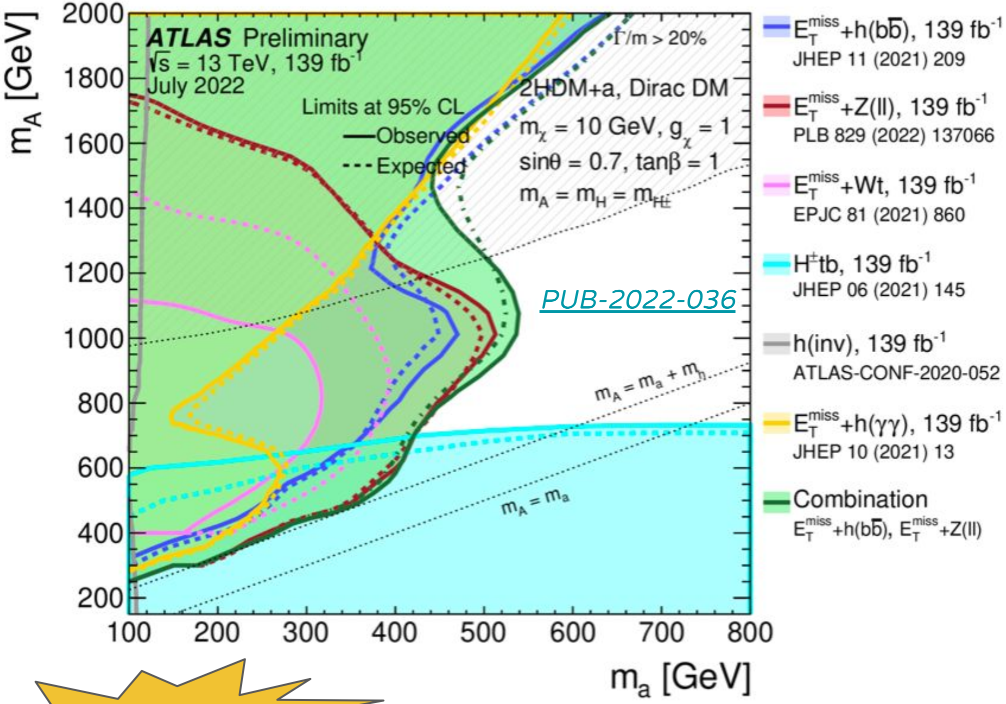
[PUB-2022-036](#)
[Phys. Dark. Univ, Vol 27, 100371](#)

Presenting latest mono-top search in ATLAS

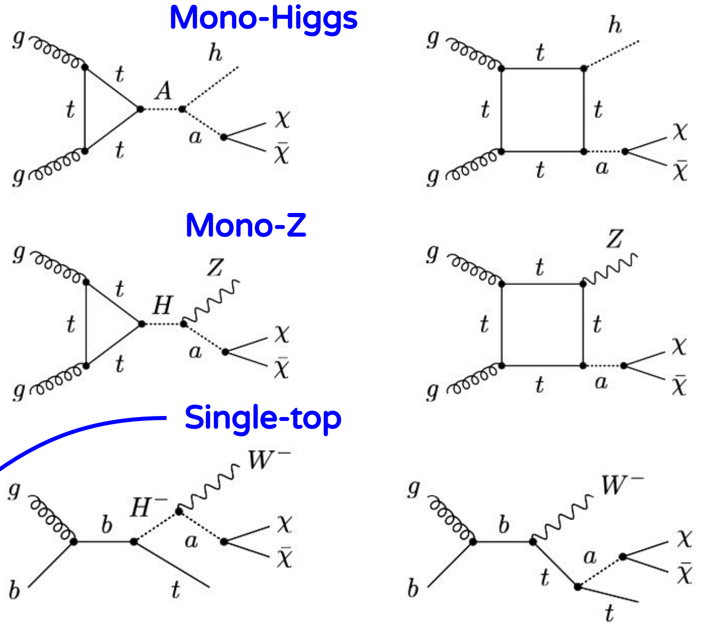
A more UV-complete model: 2HDM+a

[Phys.Dark.Univ Vol 27, 100351](#)

Simplest renormalizable theory with DM singlet
Unitarity.
Rich phenomenology in several final states at colliders.



[PUB-2022-036](#)



Today !

Latest search in tW+DM final state

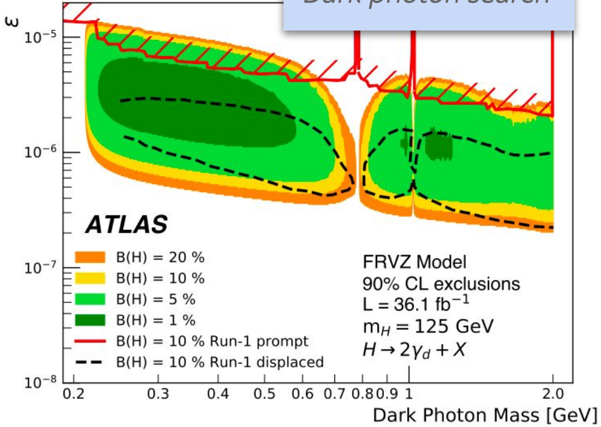
More complex dark sectors ?

Is DM only just a single-flavoured unique particle and a mediator?
The dark sector might be more interesting than we think

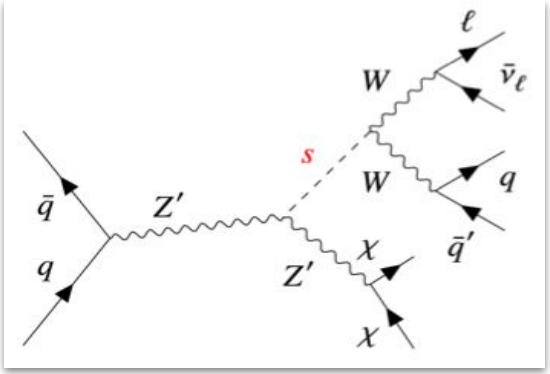
- More than one fermion and boson
- Several mediators with SM
- SM-like interactions between dark matter particles
- Long-lived particles

Today !

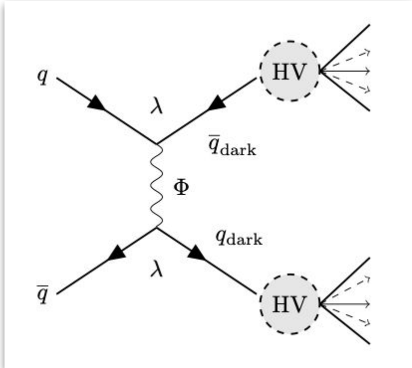
Dark photon search



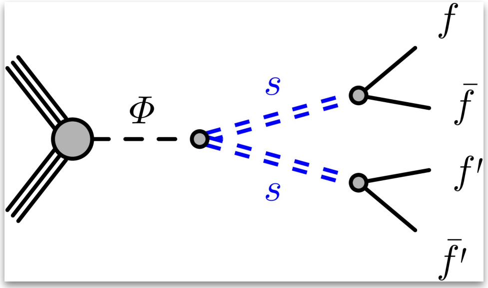
Dark Higgs (S) search
S → WW (qq'lv)



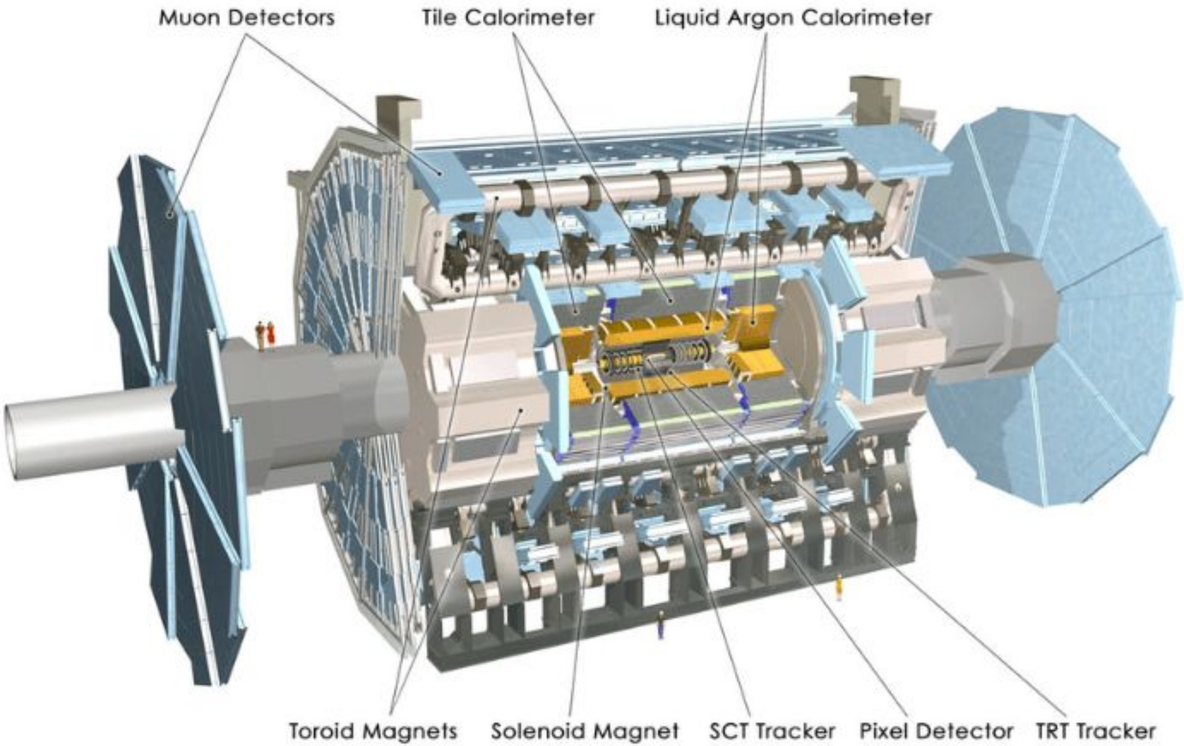
Strongly coupled DM:
Semi-visible jets



Long-lived particles:
Displaced jets



The ATLAS detector



Searches for dark matter particles in association with a top-quark

Mono-top: ATLAS-CONF-2022-036

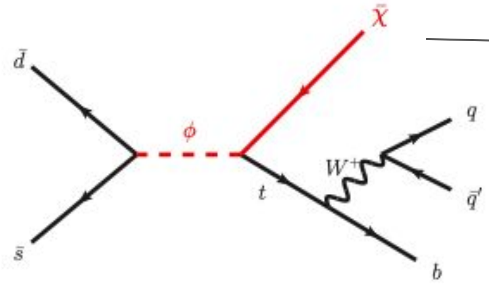
tW+DM: ATLAS-CONF-2022-012

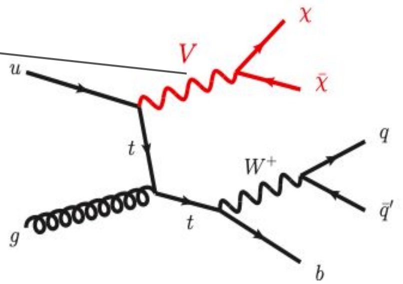
ATLAS-CONF-2022-036

Search for Dark Matter plus a single-top

Resonant production

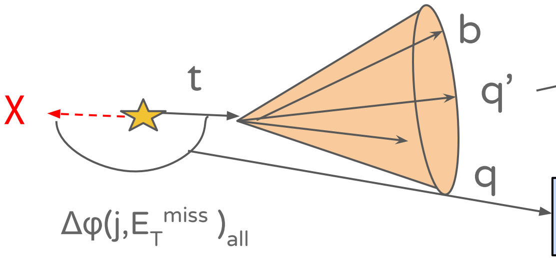
Non-resonant production

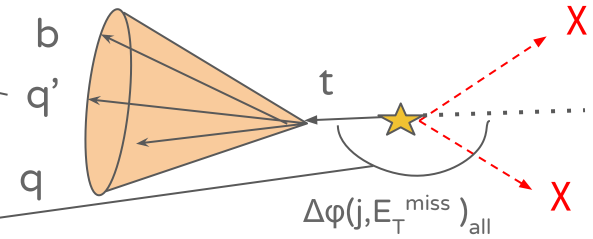




DM: E_T^{miss} trigger and E_T^{miss} > 250 GeV

Boosted top: one top-tagger large-R jet

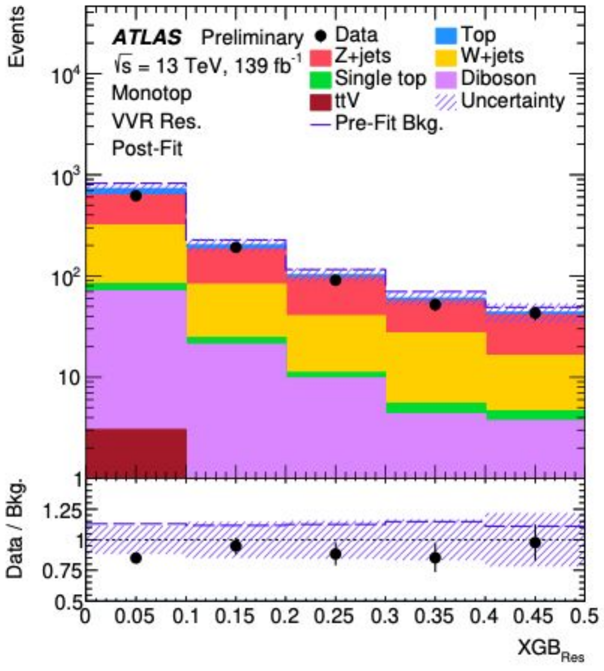


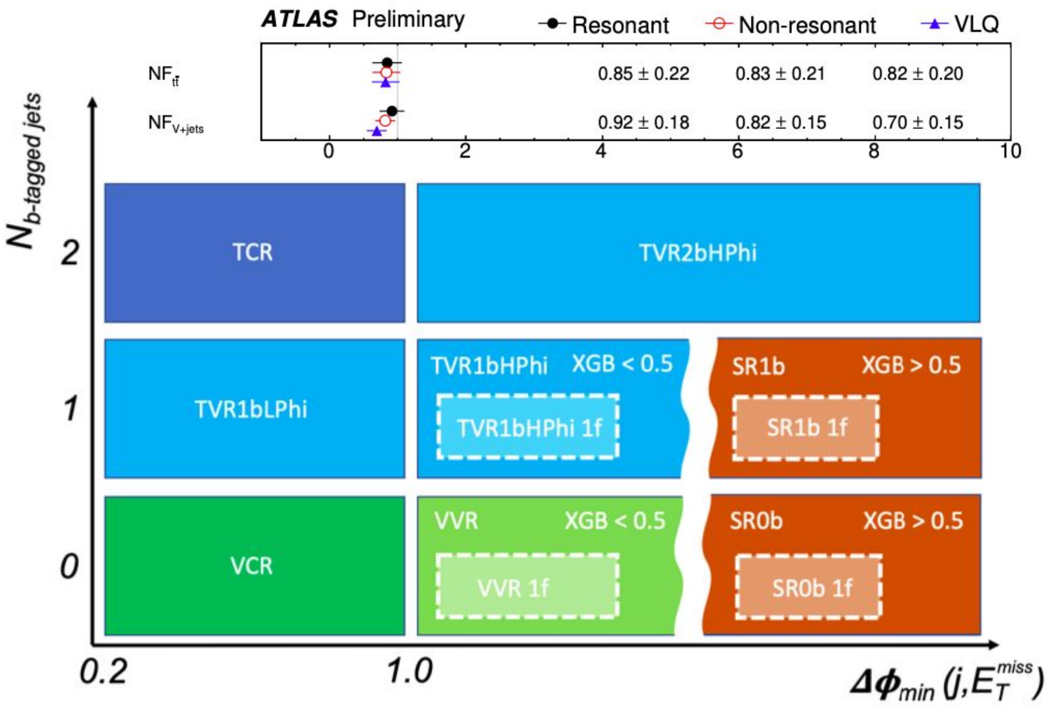


Back-to-back topology: $\Delta\varphi(j,E_T^{miss})_{all} > 1.0$

Analysis strategy

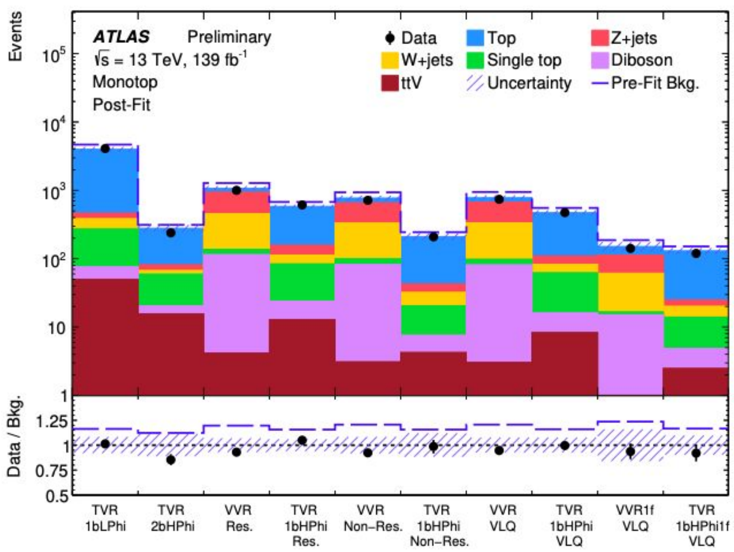
Selection based on a BDT trained on event-level discriminants with good separation power.
Dominant background is V+jets and tt. Defined control and validation regions per production mode.
SRs with 0 and 1 b-jet.



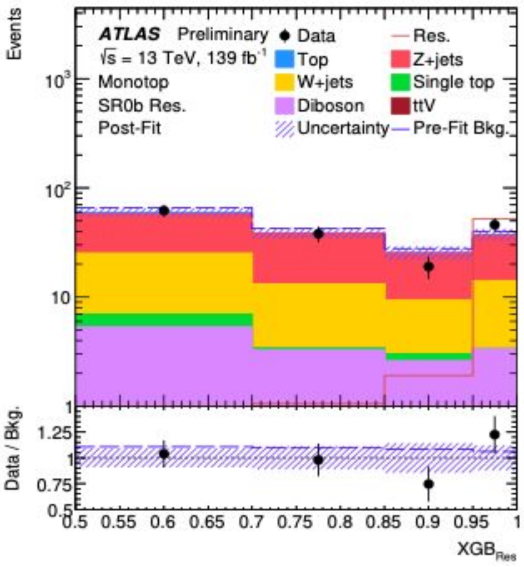


Post-fit results: New Physics ?

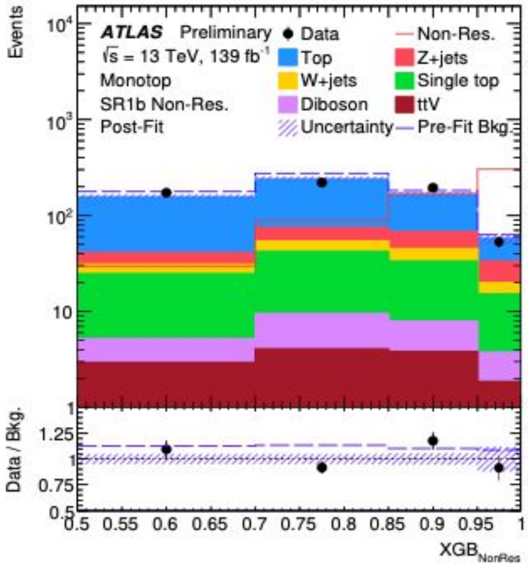
Validation regions



Resonant signal region



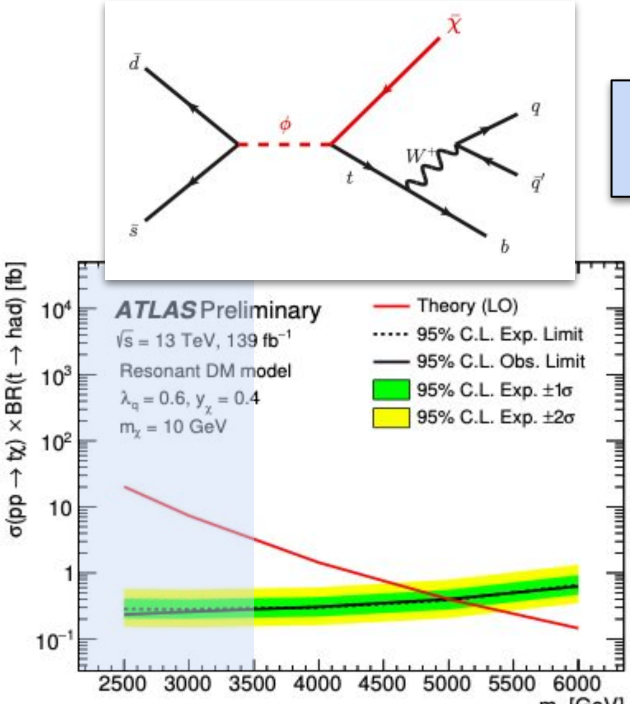
Non-resonant signal region



Good agreement between data and SM.

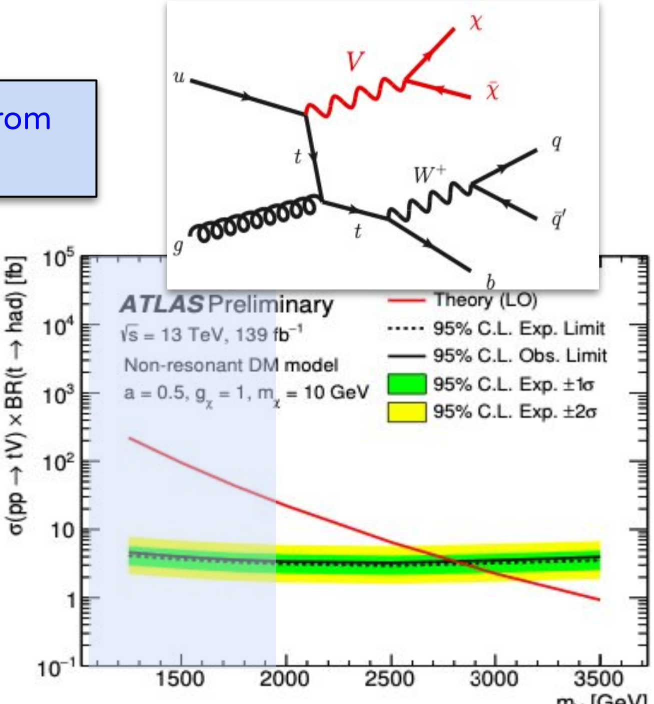
Dominant uncertainties: background theory modelling and large-R jet calibration

Interpretation: simplified model



Excluded 36 fb^{-1}

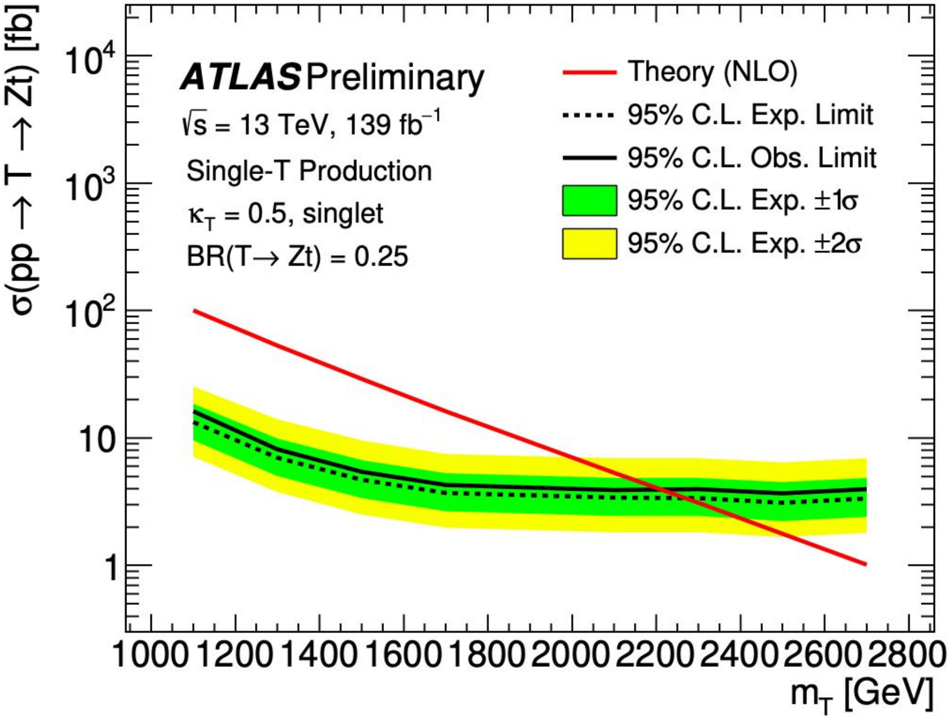
Significant improvements from early Run-2 results !

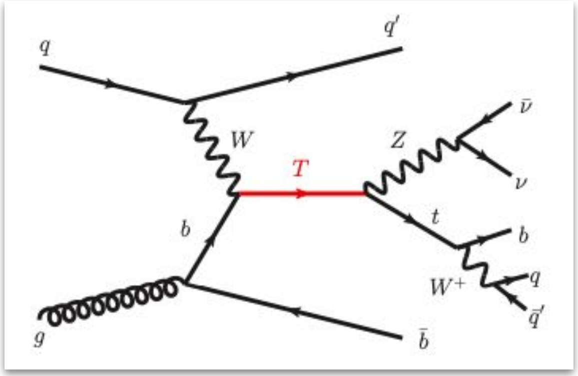


Excluded 36 fb^{-1}

Exclusion limits derived from fit of the BDT output distribution for each production mode, separately.

Interpretation: simplified model and VLQ model



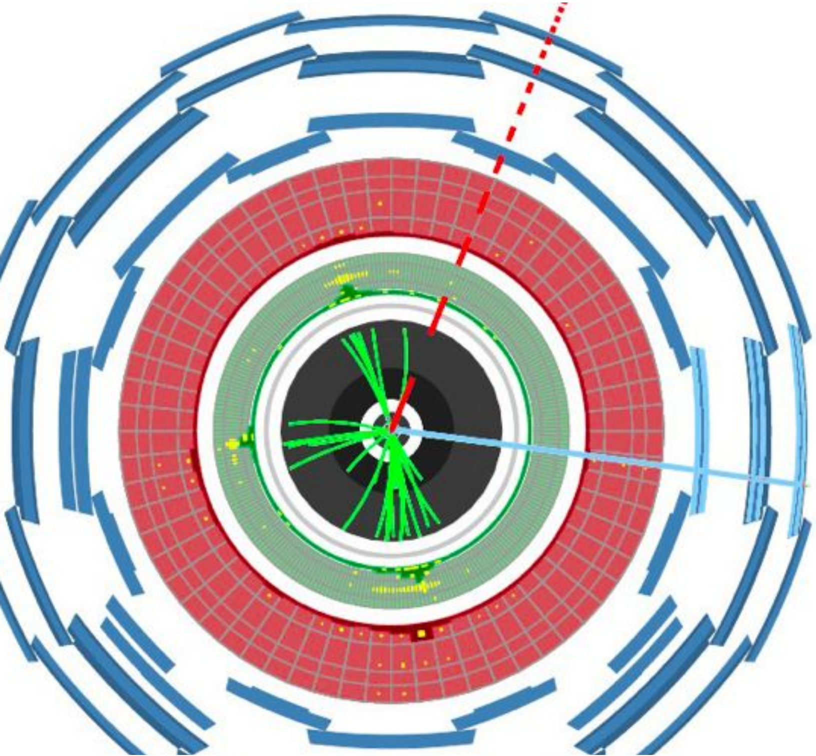


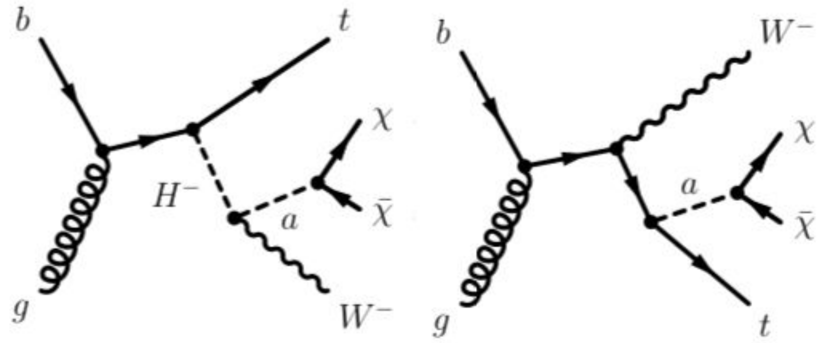
Additional interpretation using a vector-like-quark model.

No exclusion in early Run-2 results !

ATLAS-CONF-2022-012

Search for dark matter in association with tW





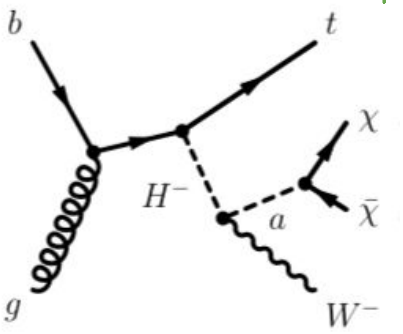
Signals present one top, a W-boson and large missing transverse momentum.

- E_T^{miss} trigger and high offline E_T^{miss}
- Profit of the top quark and W-quark to reduce the background.

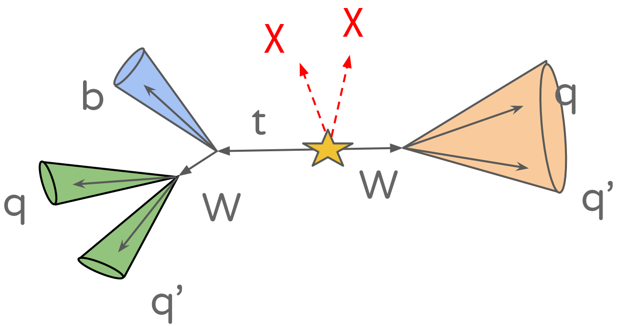
Exploring 0L and 1L channels. 2L from previous results in final interpretation

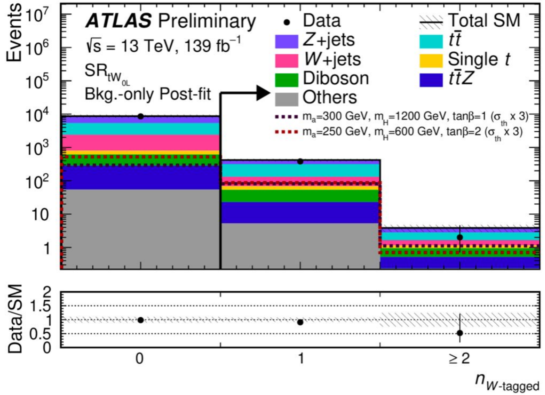
Analysis strategy: the zero-lepton channel

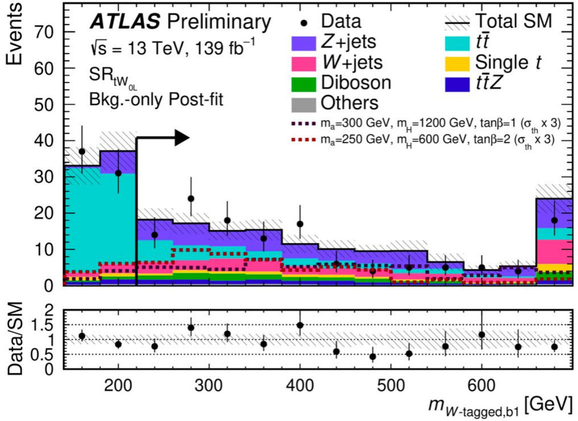
Low-p_T



High-p_T







At least 4 standard jets and at least 1 b-jet and high E_T^{miss}
One W-boson reconstructed as a large-R jet -> W-tagging

- ΔR(b,W) > 1.0 and m(b,W) > 220 GeV.

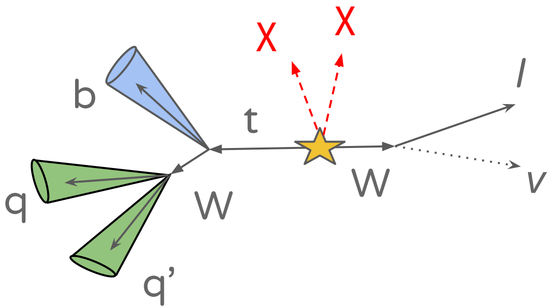
Main bkgs. : Z+jets, W+jets, tt

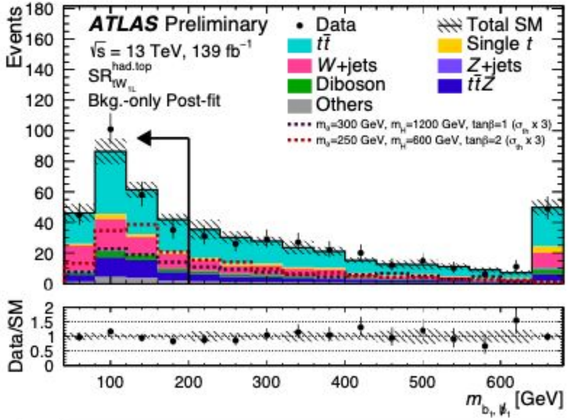
Analysis strategy: the one-lepton channel

Top-decays hadronically: reclustering jets to reconstruct W

- At least 3 jets, 1 b-jet
- $m_T(l, E_T^{miss}) > 200$ GeV
- $am_{T2} > 220$ GeV
- $m_W^{reclus} > 60$ GeV

Main bkgs. : W+jets, tt

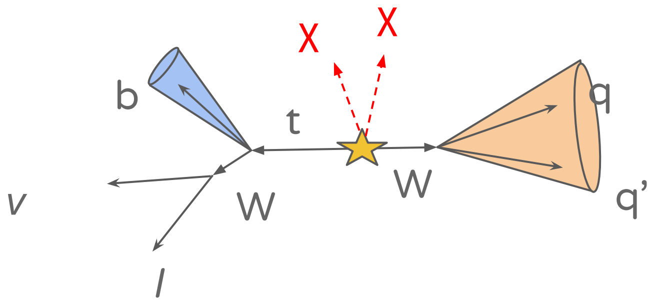


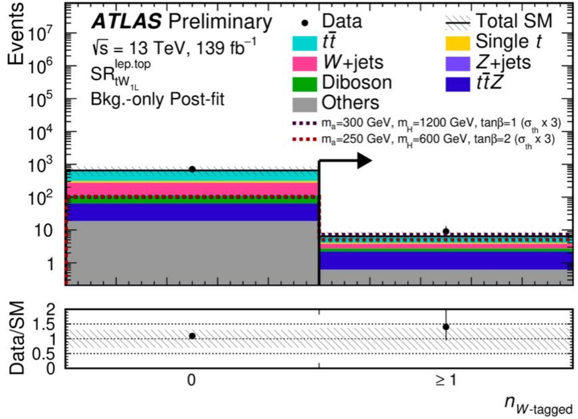


Top-decays leptonically: hadronic W-boson is boosted: W-tagged

- At least 3 jets, 1 b-jet
- $m_T(l, E_T^{miss}) > 130$ GeV
- E_T^{miss} significance > 15

Main bkgs. : ttZ, tt



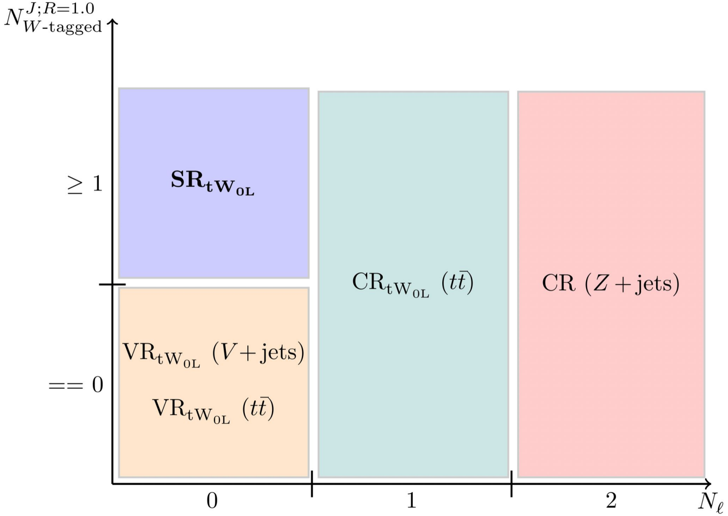


Background estimation

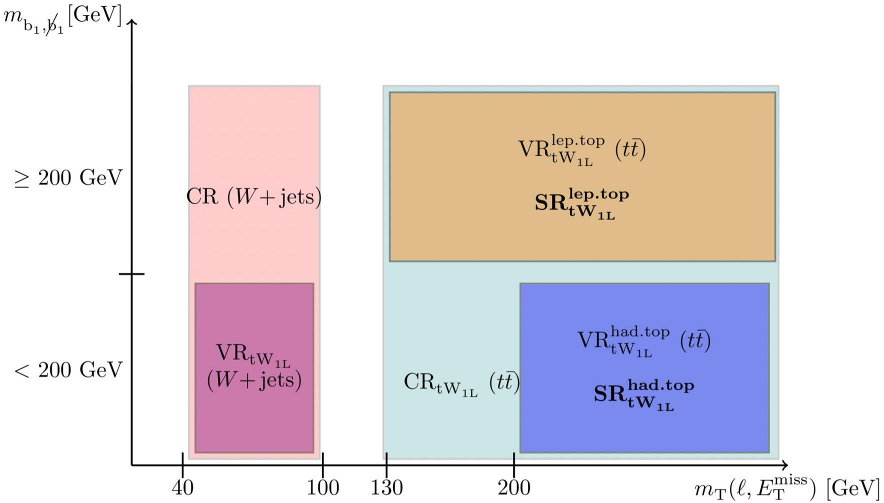
Defining control and validation regions close to the SRs to normalize the most important backgrounds.

Common CRs: Z+jets, W+jets, single-top and ttZ.

Dedicated 0L regions
CR for tt. VRs for V+jets and tt.

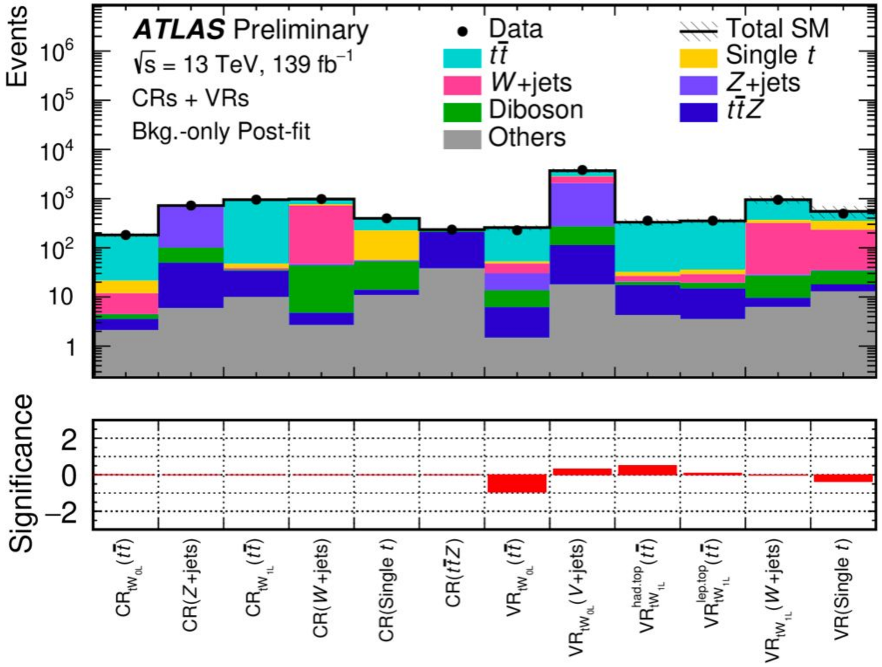


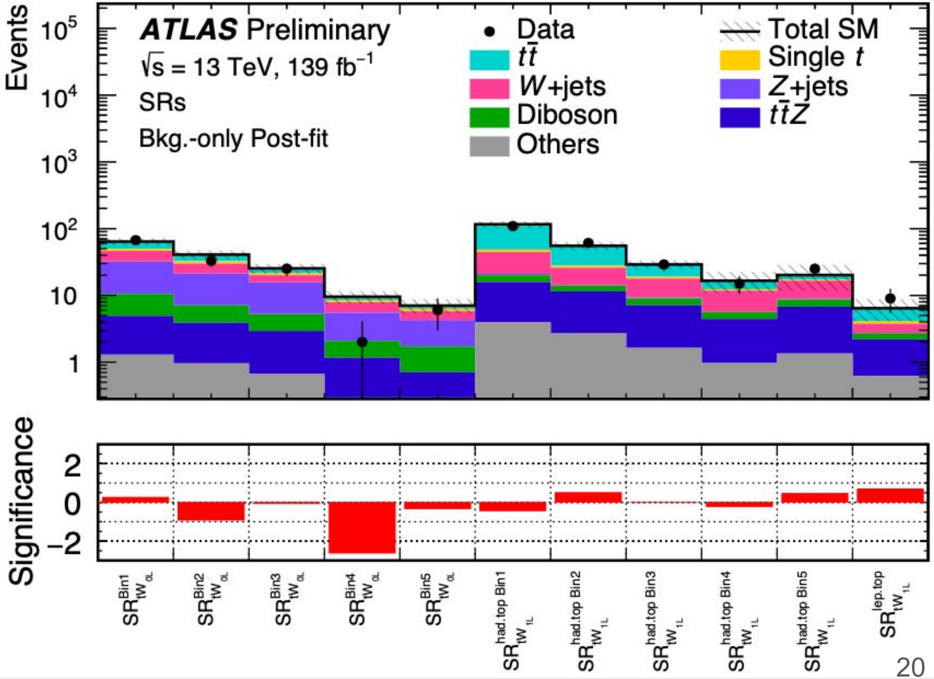
Dedicated 1L regions
CR for tt. VRs for W+jets and tt (hadronic and leptonic)



Background-only fit results

Simultaneous of all the SRs and CRs of the 0L, 1L. No evidence of New Physics observed.
2.5σ deficit in one bin of the 0L channel.

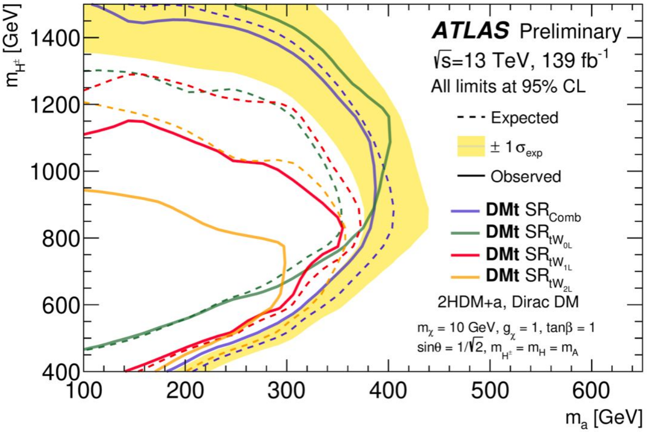


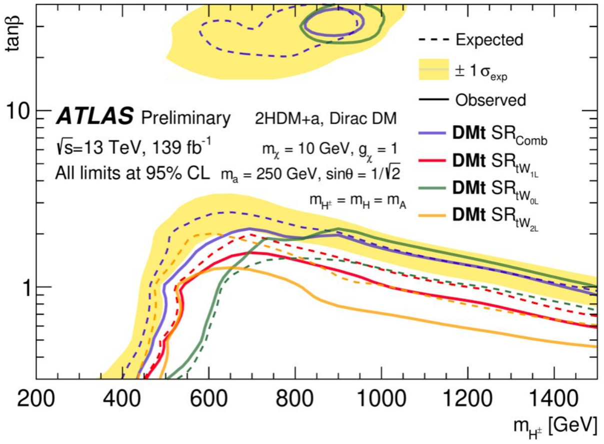


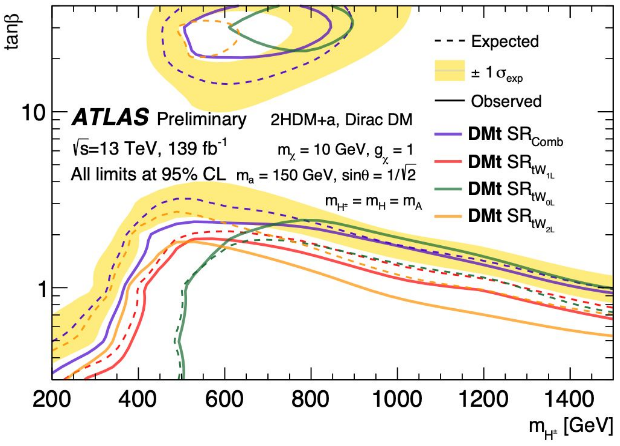
Interpretation of 2HDM+a limits

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

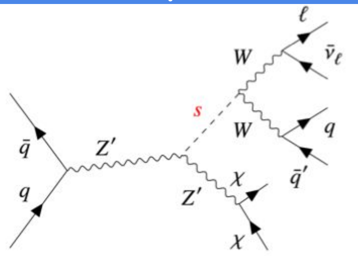
Searches for dark matter from dark heavy bosons and strongly coupled dark sectors

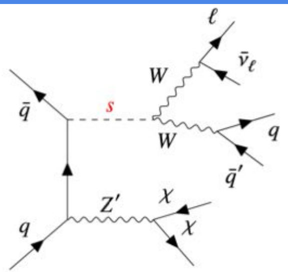
Leptonic mono-S: ATLAS-CONF-2022-029

Semi-visible jets: ATLAS-CONF-2022-038

Search for dark Higgs in WW+E_T^{miss}: strategy

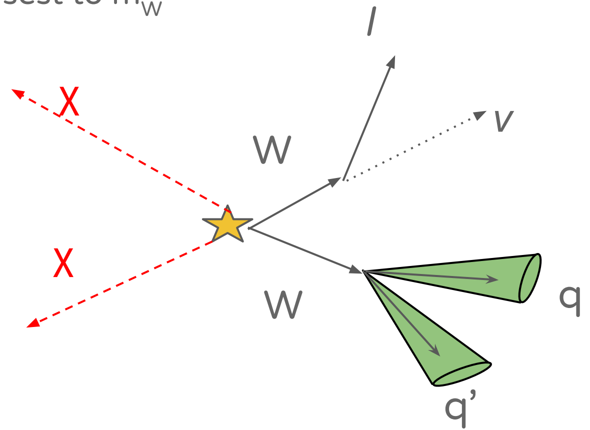
Events with one lepton: E_T^{miss} or muon triggers
Dominant background → W+jets: $m_T(l,E_T^{miss})$ > 220 GeV
Large E_T^{miss} significance





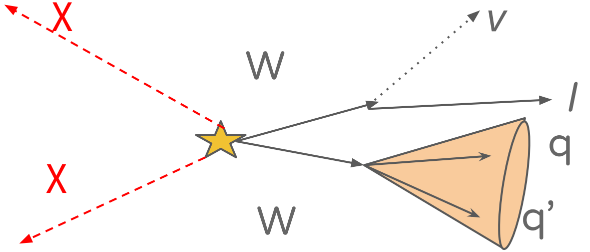
Resolved region

At least 2 jets, but no b-tagged jets
Reconstruction of W-candidate with the two jets with m_{jj} closest to m_W



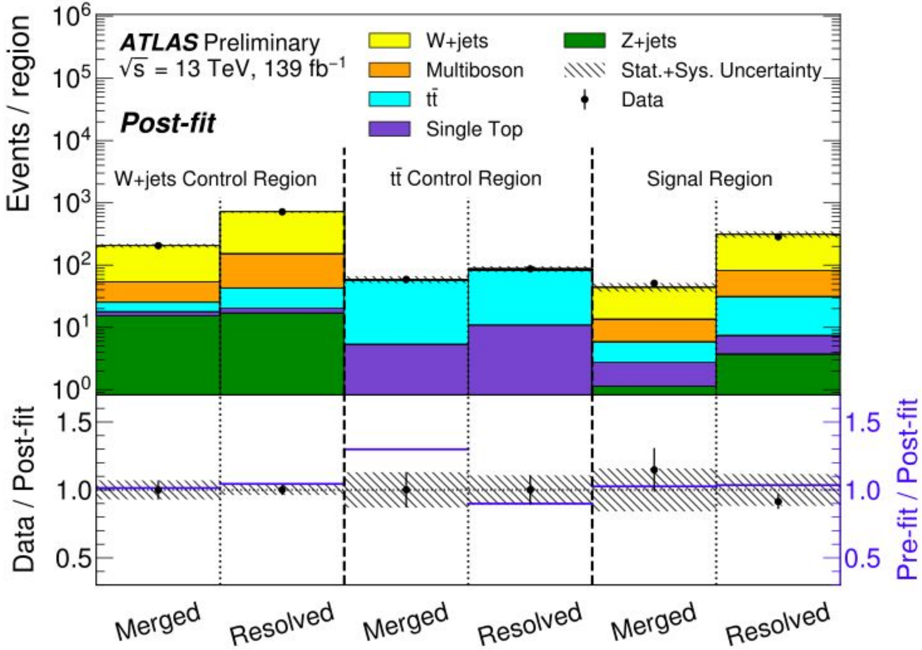
Merged region

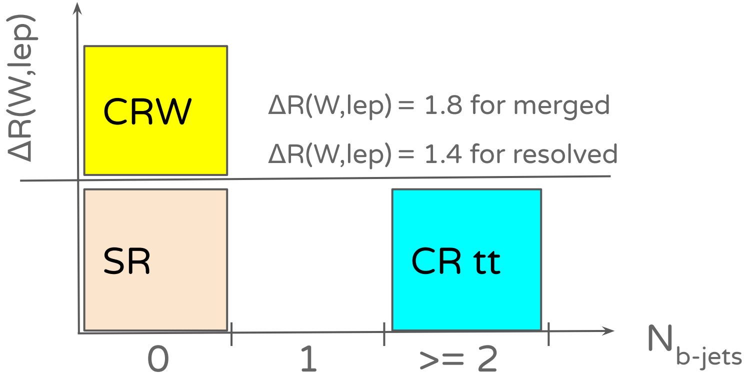
W-tagging from large-R. s → WW boosted and lepton might overlap with hadronic W-boson → TAR jet with $D_2^{\beta=1}$ < 1.1 as W-candidate.

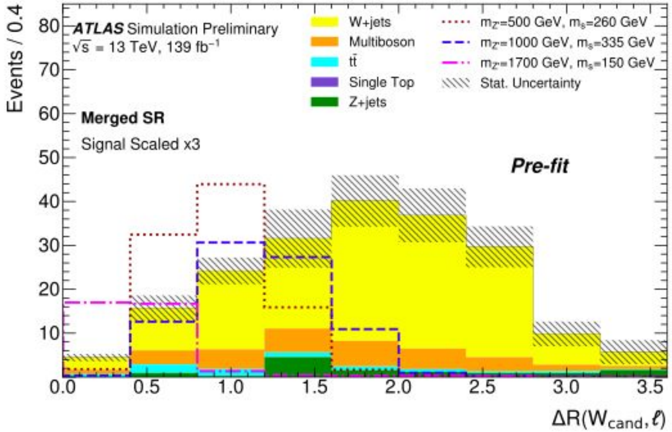


Background estimation

Both regions dominated by W+jets and tt-> Single-bin control regions to normalize background.

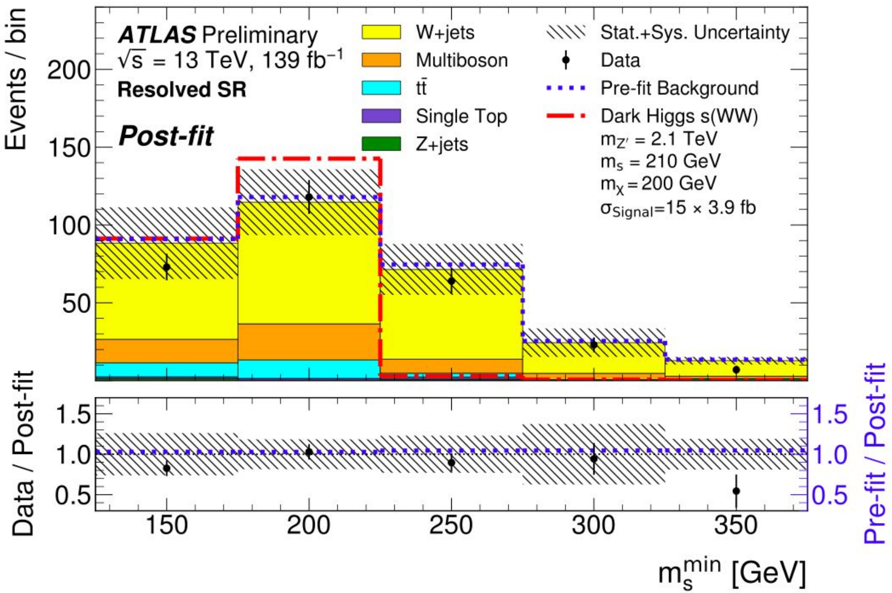


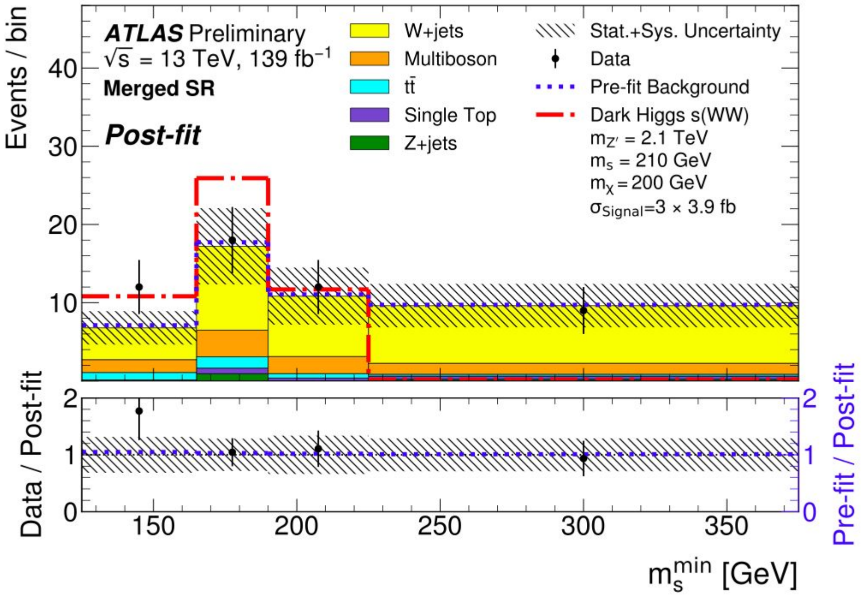




Results

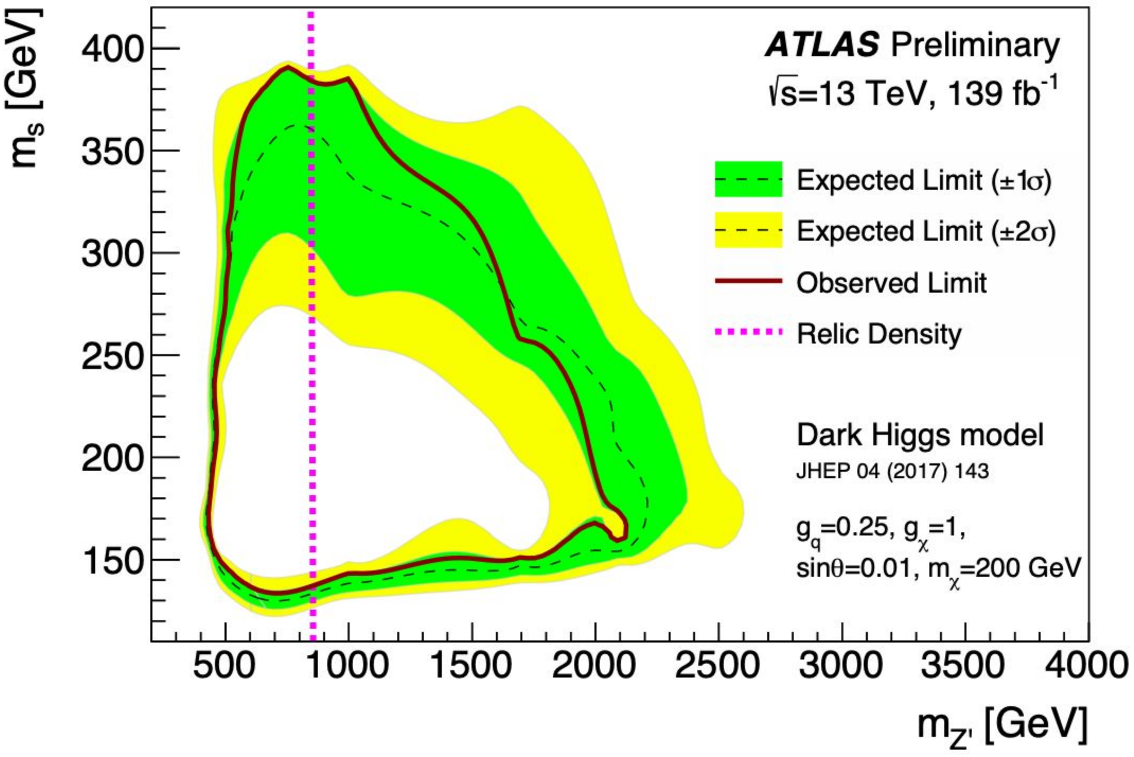
m_s^{min} variable: minimum possible Dark Higgs boson mass from object kinematics→ SRs divided into bins

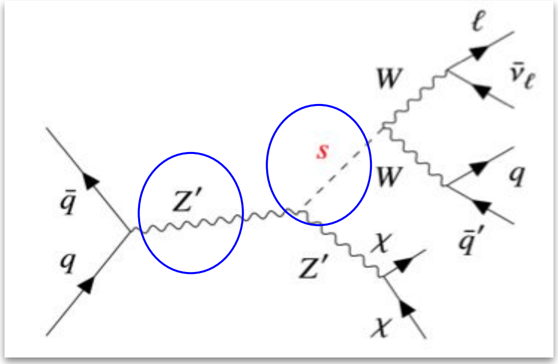




Good agreement between data and SM predictions in the signal region

Limits on Dark Higgs model

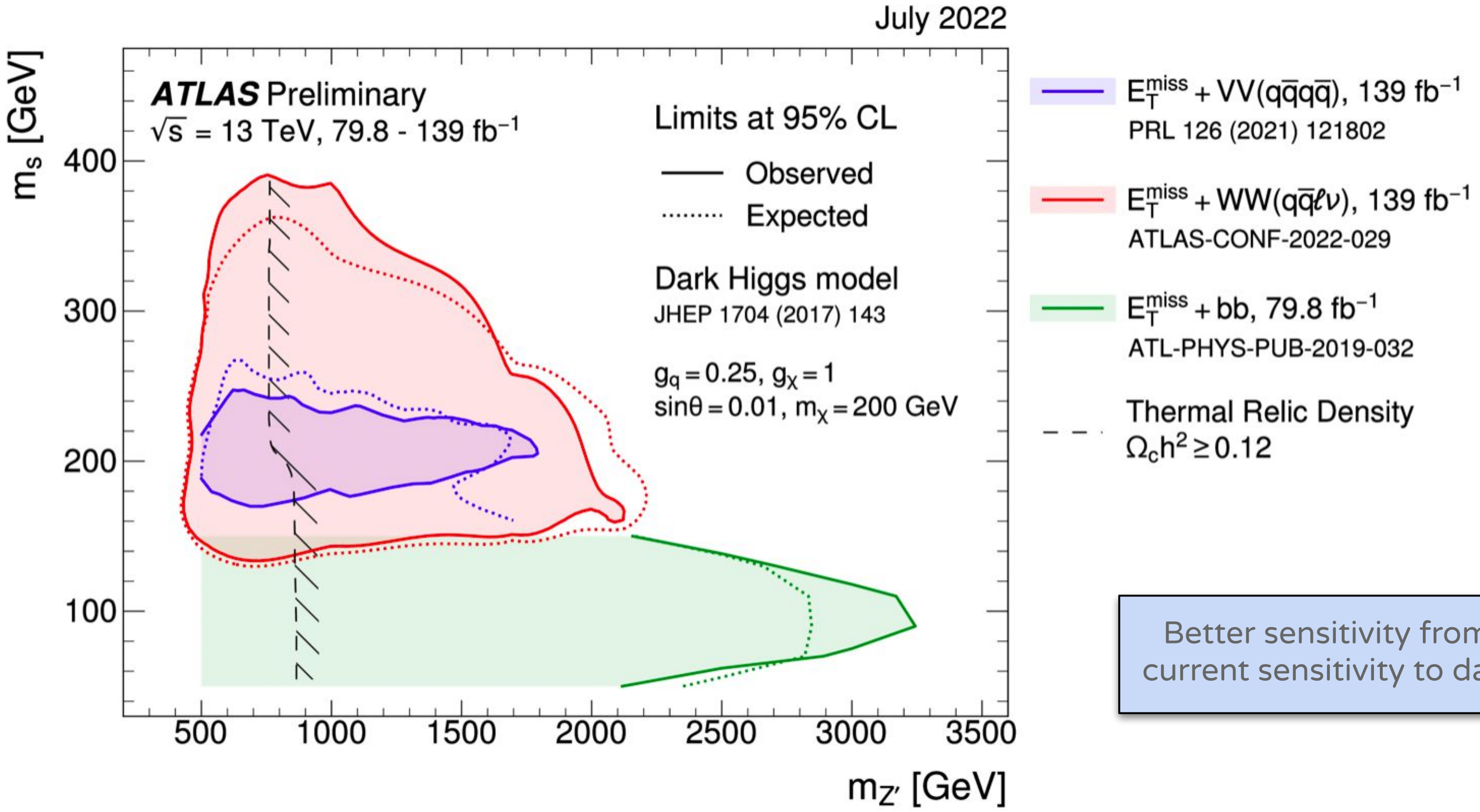




Highest exclusion for m_Z ~ 750 GeV

Exclusion for different m_Z values for m_s in [130,390] GeV

Limits on Dark Higgs model



Better sensitivity from 1L channel on current sensitivity to dark Higgs models

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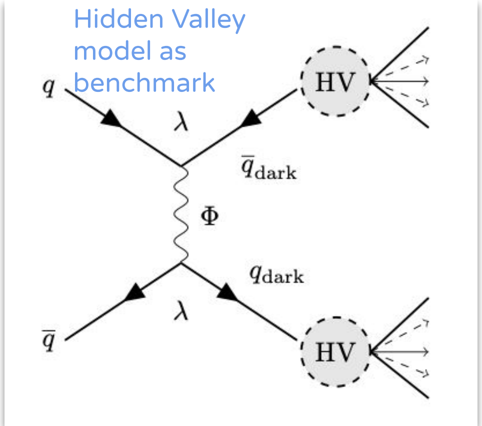
Strongly coupled dark sectors

Dark sector with q_{dark} and interactions similar to QCD. Confinement and hadronization in dark sector (dark hadrons)

- q-q_{dark} interaction leading to some dark hadrons decaying into SM particles
  - Stable hadrons (DM candidates)
  - Unstable hadrons (decay into SM quarks)
- Semi-visible jets, not very explored
  - Ratio of stable dark hadrons over total number of hadrons: R_{inv}



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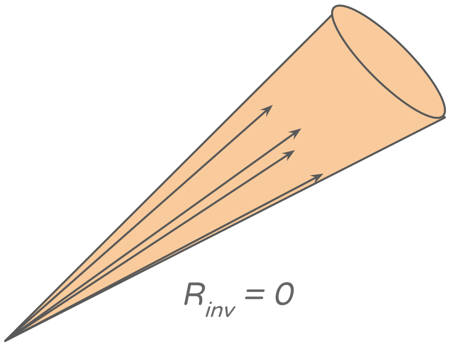
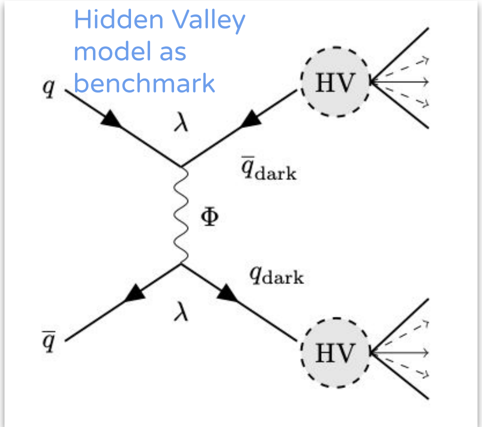


Visible jets.
SM measurements



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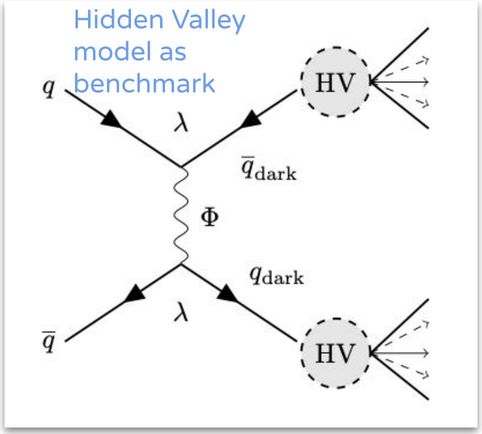

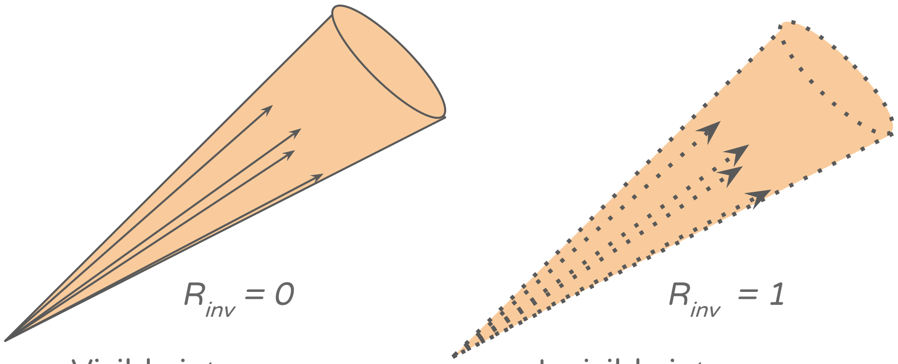

Visible jets.
SM measurements

Invisible jets.
Mono-X DM searches

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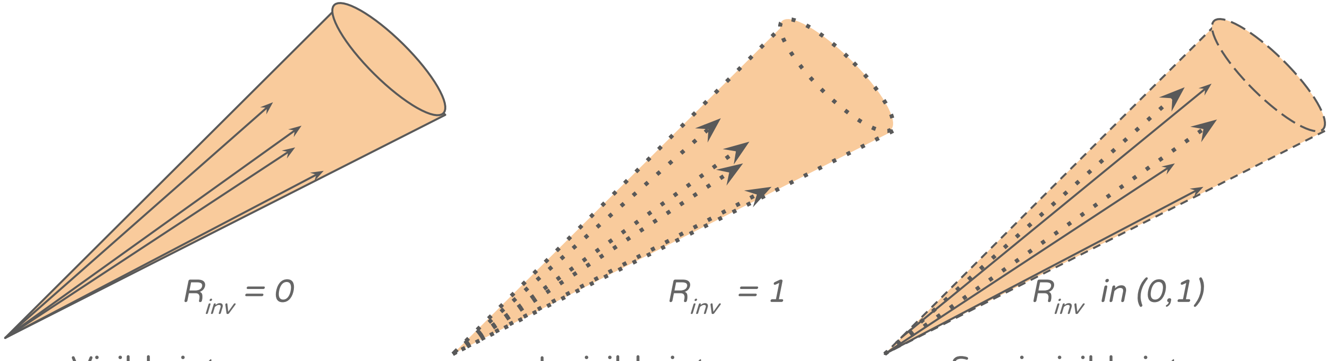
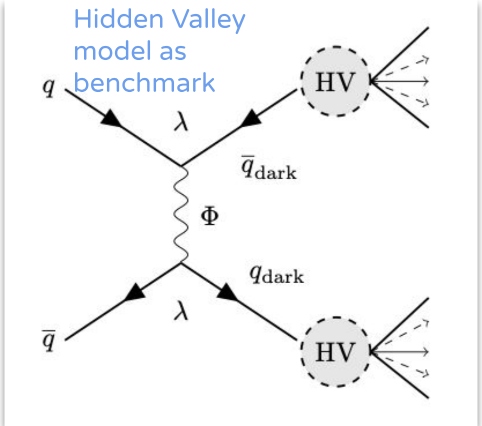


Visible jets.
SM measurements

Invisible jets.
Mono-X DM searches

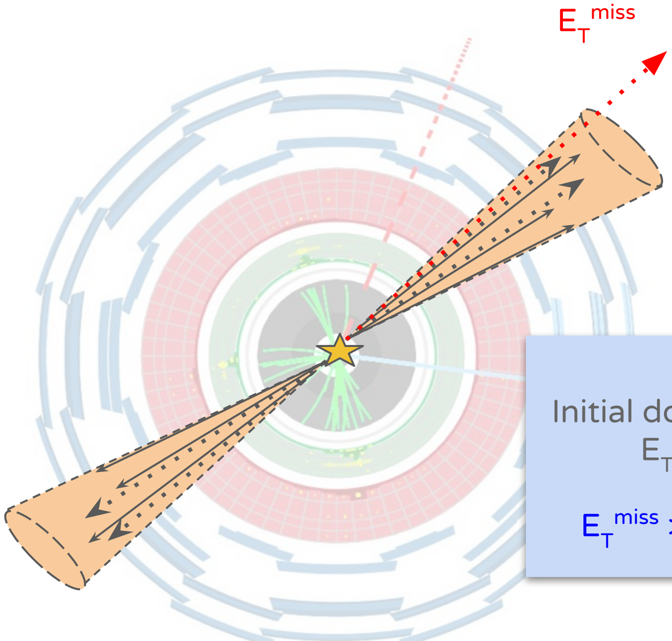
Semi-visible jets.
Little explored !

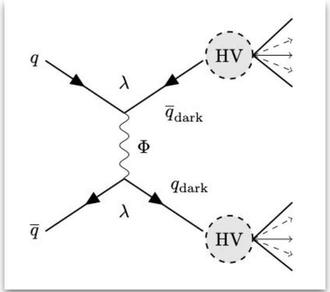


Analysis strategy: signal topology

Leading order signals

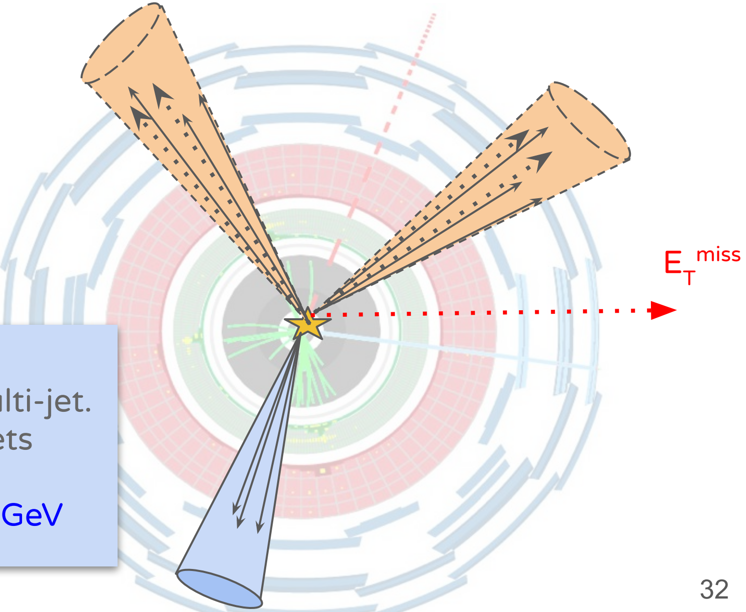
Back-to-back. E_T^{miss} aligned with one of the jets





LO plus additional jets

E_T^{miss} less aligned with one of the jets



0L search: jets + E_T^{miss}

Initial dominant background: multi-jet.

E_T^{miss} from mismeasured jets

E_T^{miss} > 600 GeV and H_T > 600 GeV

Analysis strategy

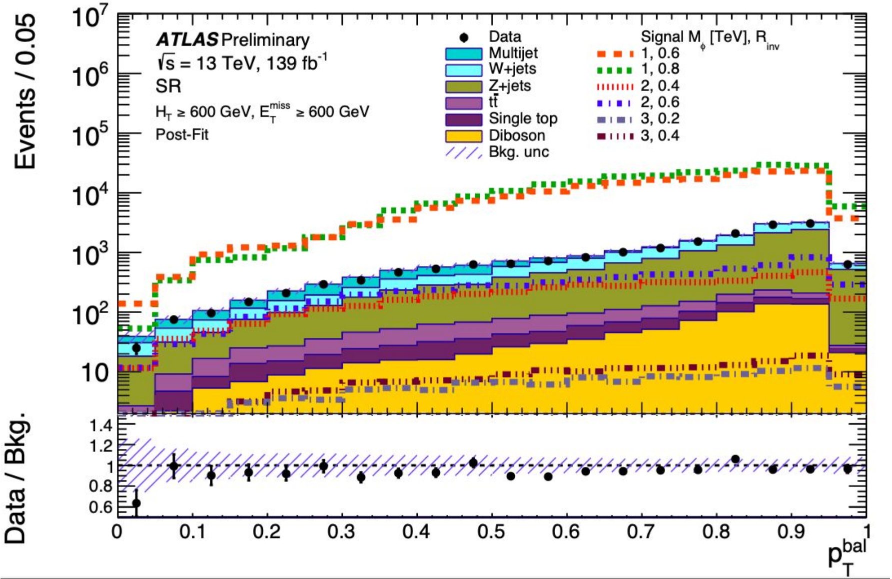
At least two jets with $p_T > 30$ GeV. One with $p_T > 250$ GeV.
$\Delta\Phi(j, E_T^{miss}) < 2.0$ for at least one jet.

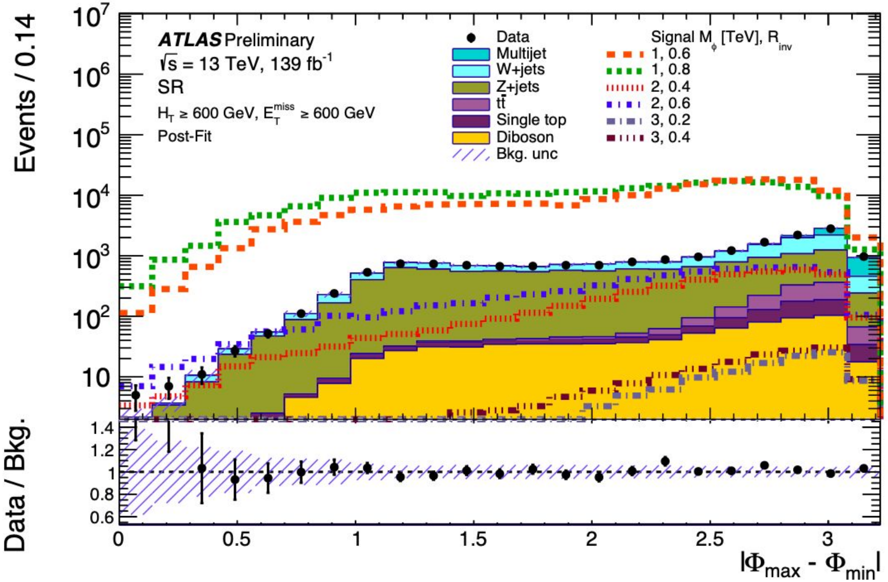
- Closest jet to E_T^{miss} in Φ: j_1. Farthest, j_2

Using p_T^{bal} and $|\Delta\Phi(j_1, j_2)| = |\Phi max - \Phi min|$ as discriminants.

$$p_{\mathrm{T}}^{\mathrm{bal}} = \frac{|\vec{p}_{\mathrm{T}}(j_1)+\vec{p}_{\mathrm{T}}(j_2)|}{|\vec{p}_{\mathrm{T}}(j_1)|+|\vec{p}_{\mathrm{T}}(j_2)|}$$

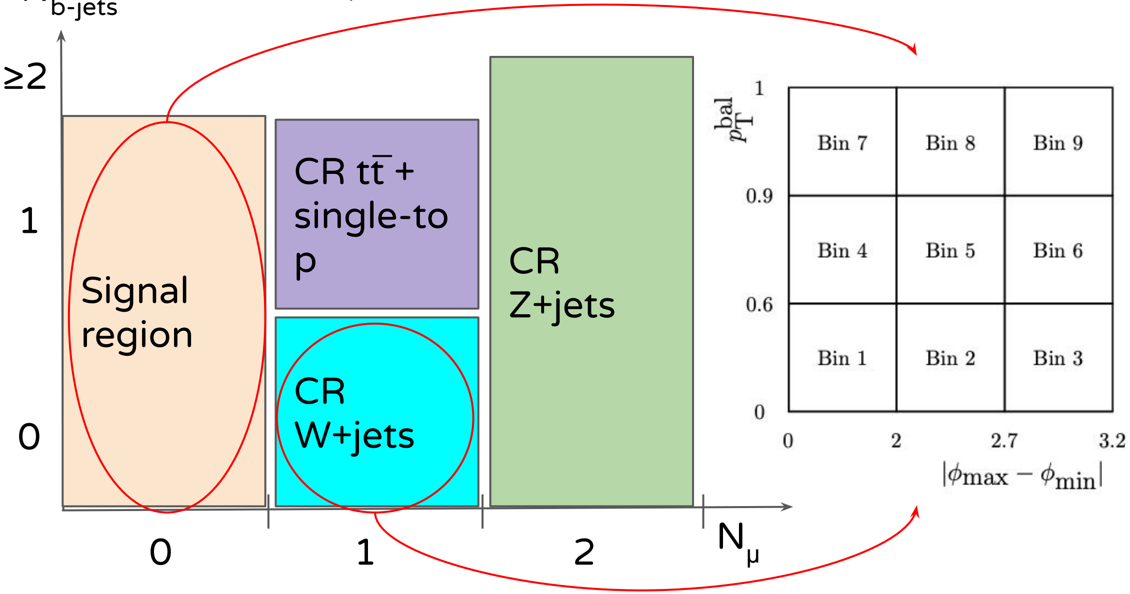
$$|\phi_{\max} - \phi_{\min}|$$

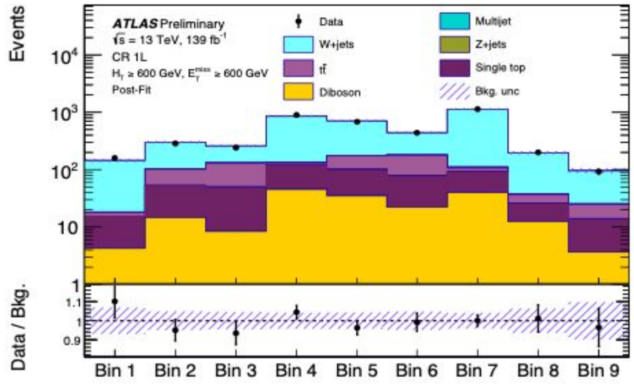


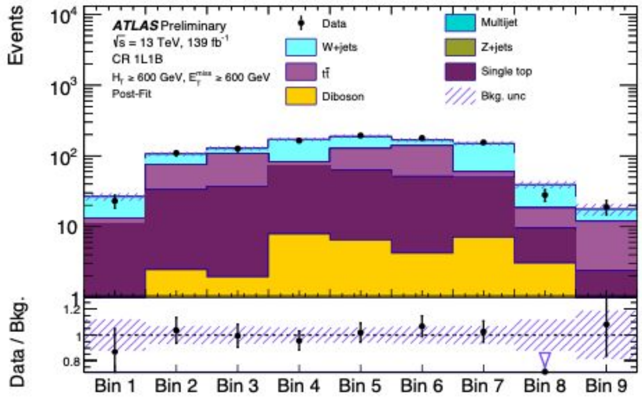


Background estimation

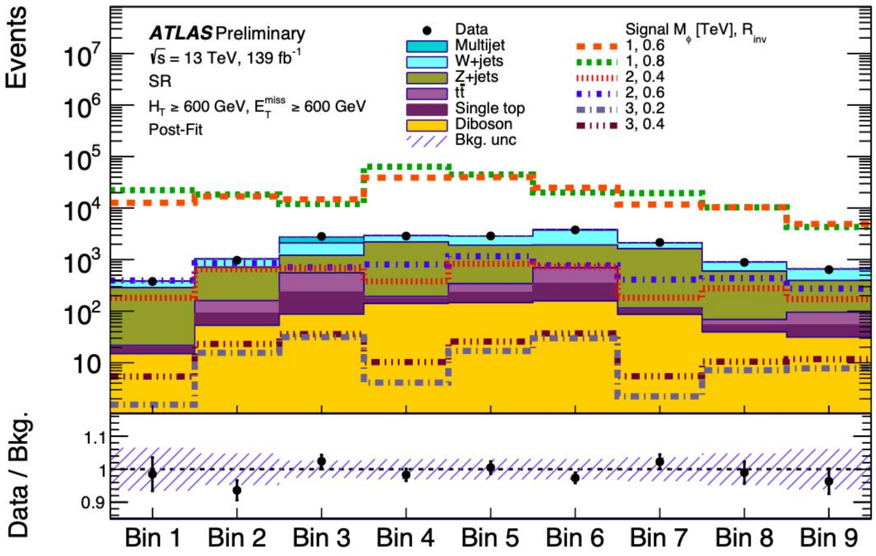
- Backgrounds estimated from dedicated control regions.
  - $t\bar{t}$ and single-top merged into one single contribution
- Each region (SRs and CRs) is divided into 9 bins
  - One norm factor per background.
- Multijet: correction factors in region with E_T^{miss} in [250,300] GeV. VR in E_T^{miss} [300,600] GeV.

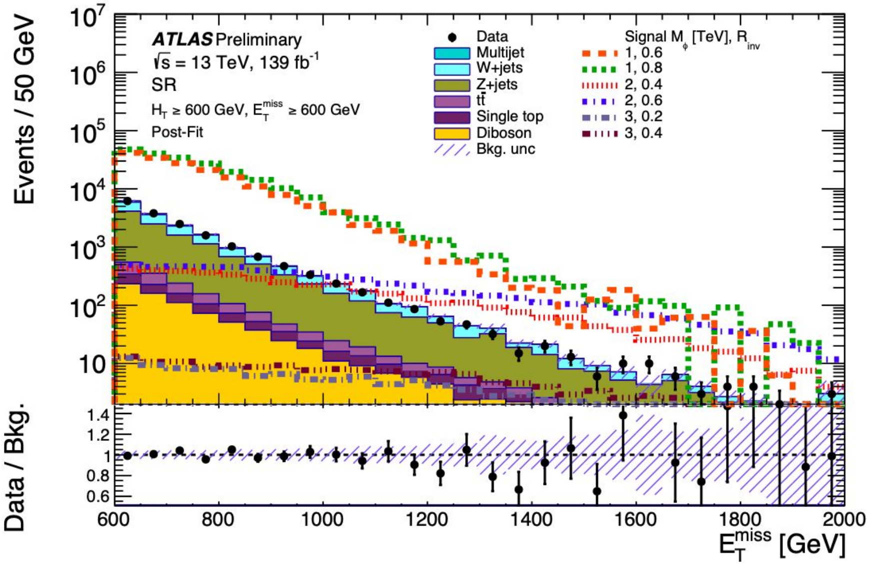






Results





After fit, no BSM signal has been observed and good agreement between data and SM prediction

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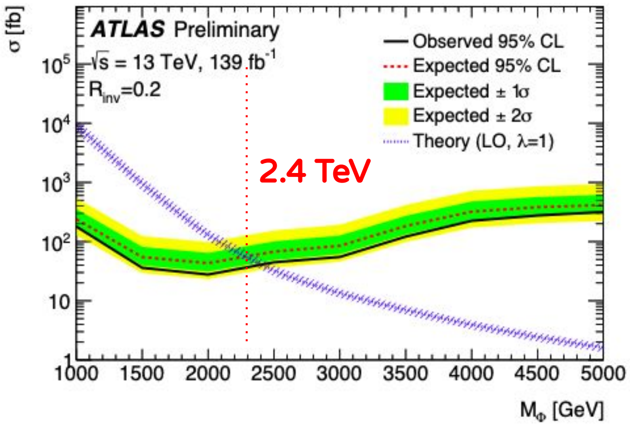
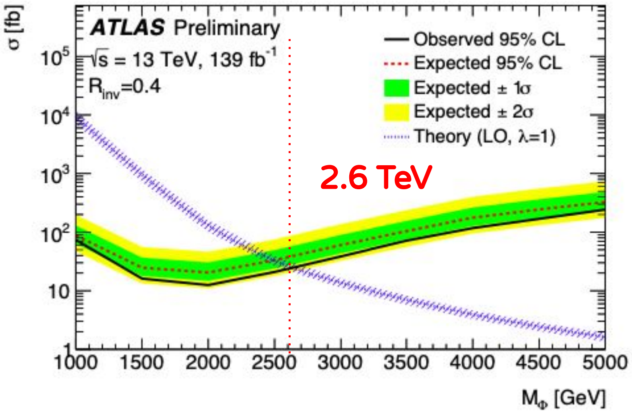
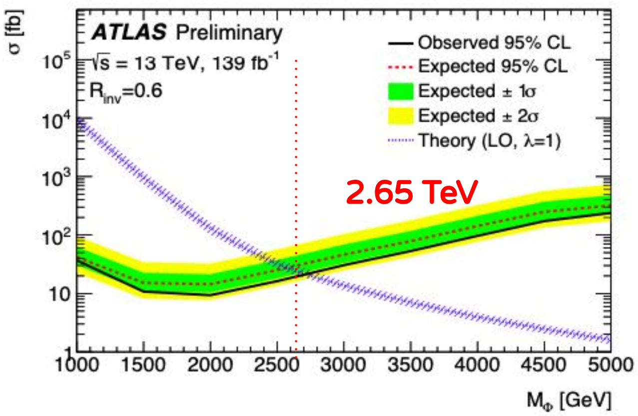
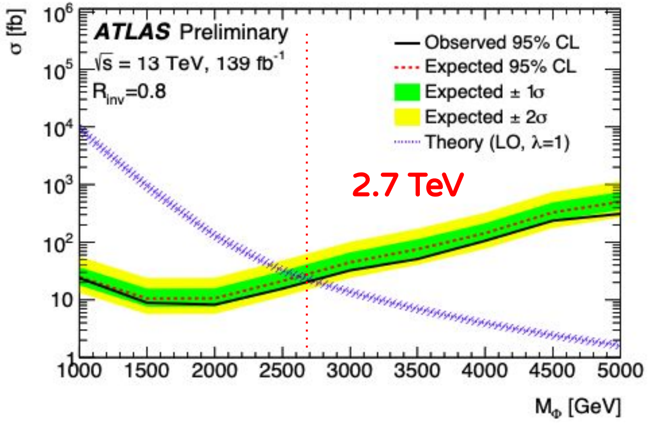
Intepretation of results



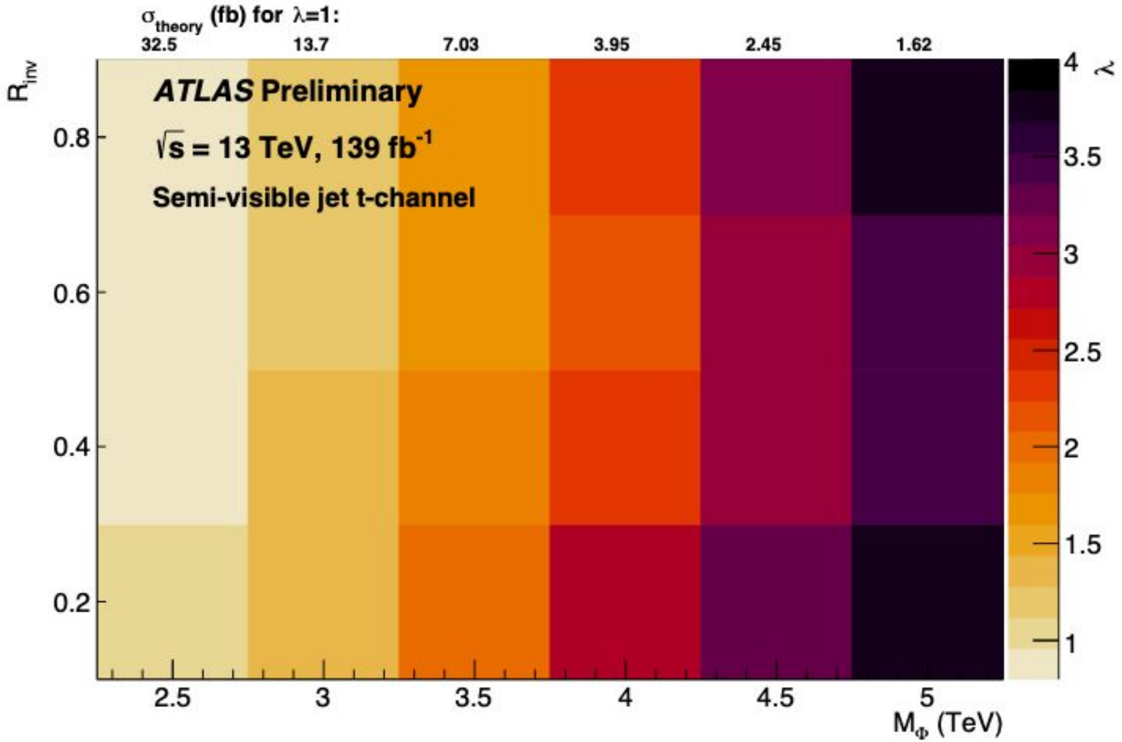




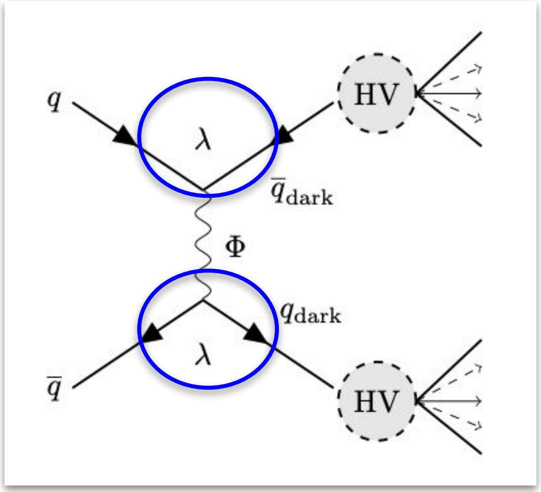


Intepretation of results

Upper limit on λ (coupling strength q'_{dark} - q)



Cross-section dependence with λ^4..



Searches for long-lived particles in displaced hadronic jets

LLP into displaced jets : JHEP 06 (2022) 005

Searches for long-lived particles

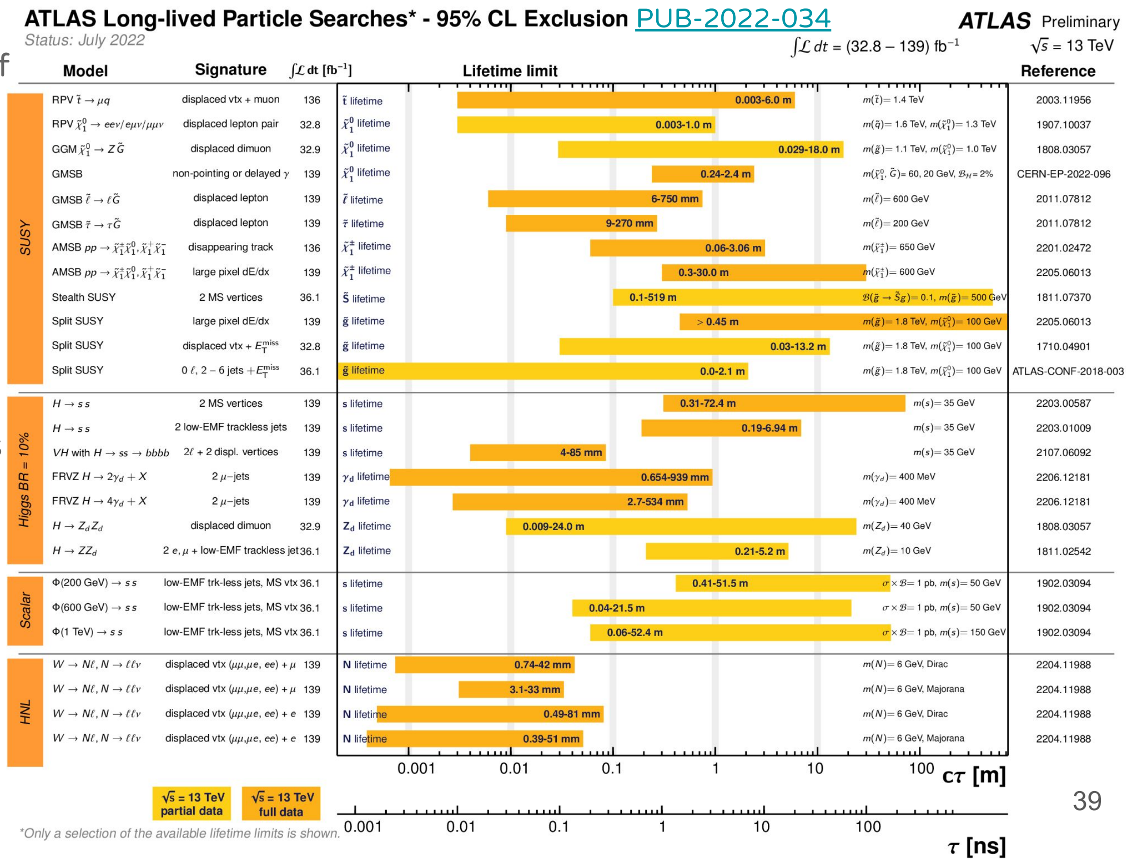
The dark sector might also contain particles of medium lifetime (LLPs)

- Decays within the detectors but displaced from interaction point.

Relatively unexplored during Run-I → Focused on prompt particles searches.

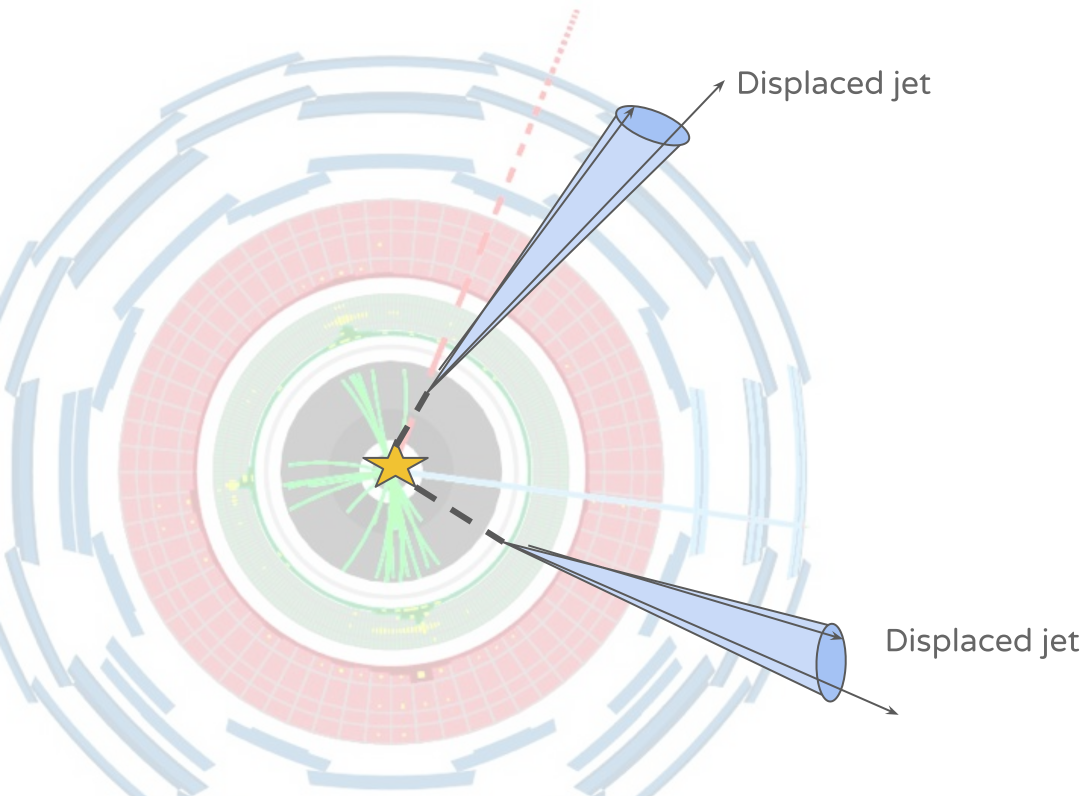
LLP searches have experienced a tremendous advance at LHC during Run-II

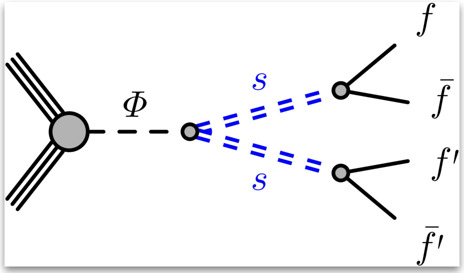
- Displaced vertices
- Displaced leptons and jets
- Pixel dE/dx
- …….



> Presenting a search for displaced jets in the ATLAS hadronic calorimeter

LLP in displaced hadronic jets: signature





Heavy scalar mediator (Φ) decaying to two long-lived scalars (s)

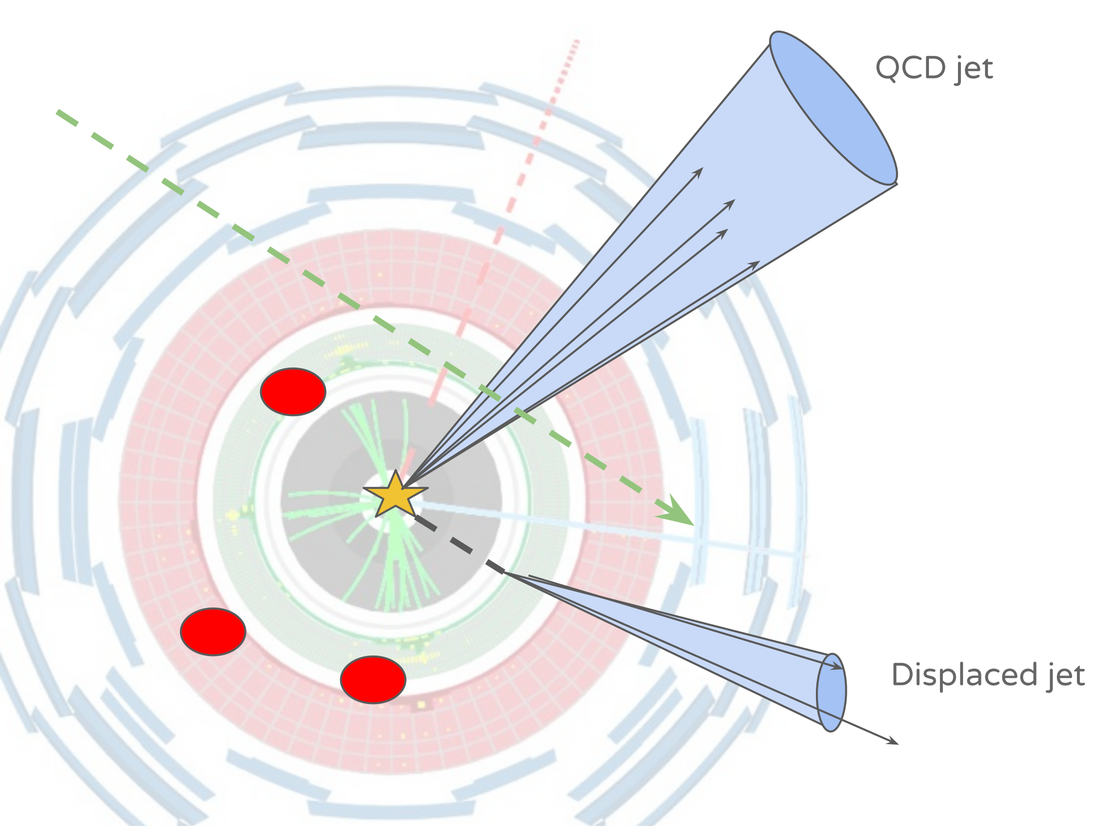
- Scalars decaying to SM fermions (quarks,leptons)

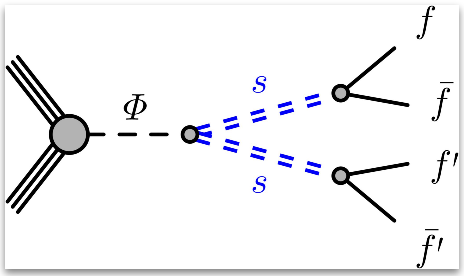
Signature: displaced jets

- Large energy deposit in HCAL and low energy deposits in ECAL
- Trackless jets
- Narrow deposits

[JHEP 06 (2022) 005](#)

LLP in displaced hadronic jets: backgrounds





QCD jets

- Jets usually deposits in all subsystems.
- Large QCD cross-section in pp collisions → dominant

Beam-induced background (BIB):

- LHC beam-gas and beam-halo interactions upstream detector

Cosmic backgrounds:

- Cosmic rays and external radiation to detector

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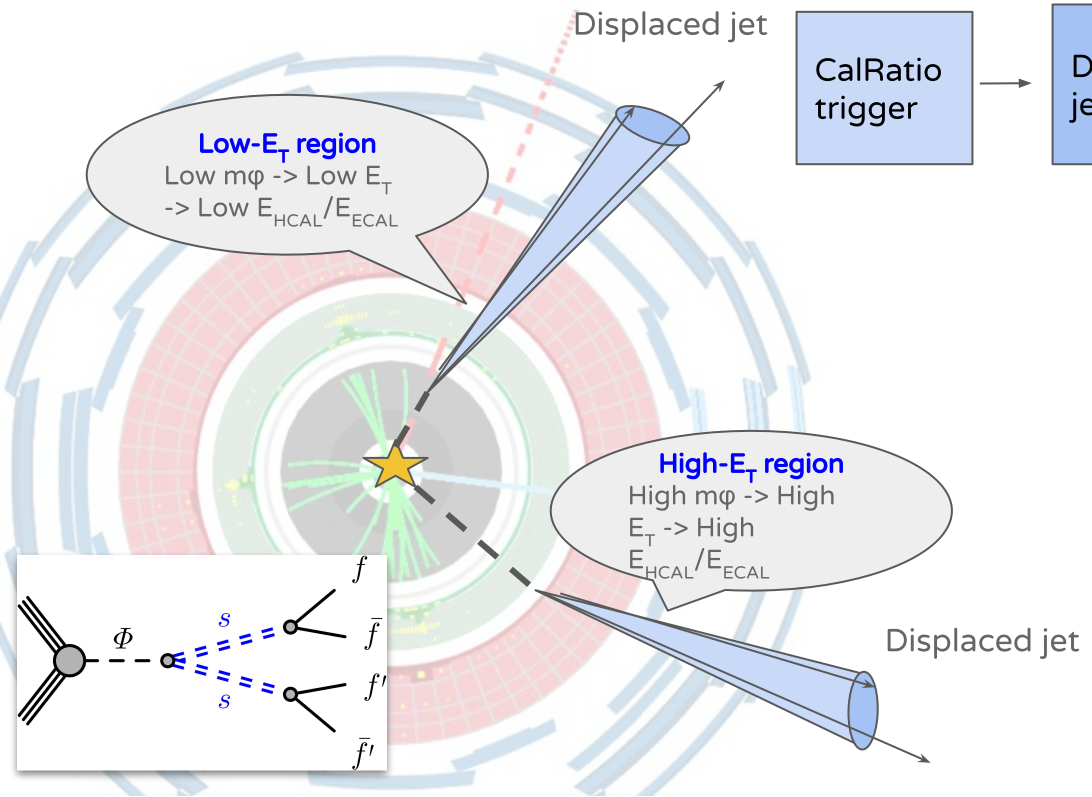
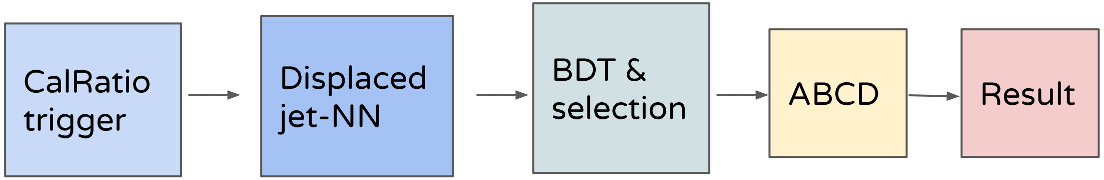
LLP in displaced hadronic jets: analysis strategy





E_{HCAL}/E_{ECAL} depends on mφ

- **Low E_T and high E_T optimization**

Data taking challenging: **dedicated trigger**

- Narrow jets combined with high E_{HCAL}/E_{ECAL} and/or low deposits in ECAL.
- Jet cleaning and BIB removal algorithm

Select displaced jets : **Jet tagging NN**

- Distinguish signal vs BIB and QCD

BDT event selection to improve background rejection

ABCD method to define SR and CRs.

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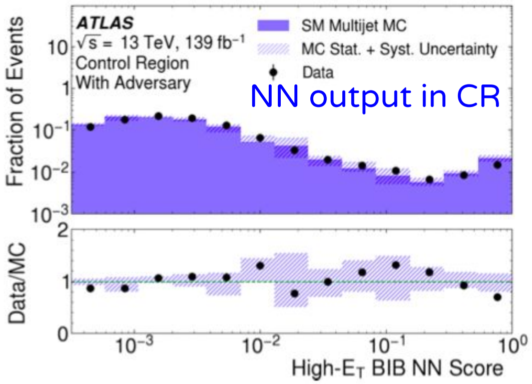
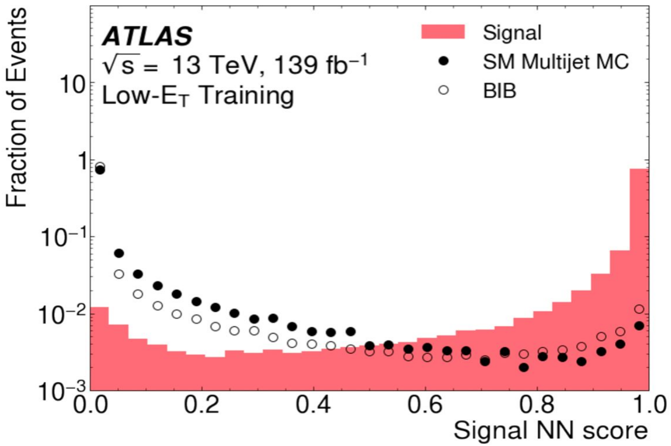
Displaced jet NN

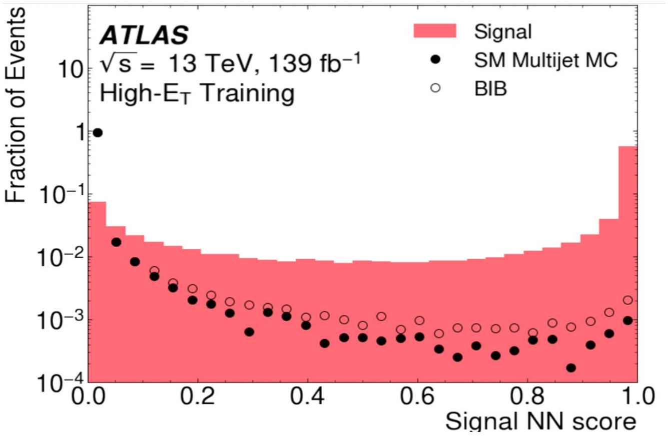
Neural network (CNN plugged on LSTM) to distinguish signal, BIB and QCD.

- Quality, momenta, IP of tracks around candidate jets
- Momenta, timing, energy fraction in ECAL and HCAL of topoclusters.
- Spatial and timing info of muon-tracks arounds jets. Jet variables.
- ANN to reduce dependence on mismodelled key observables.



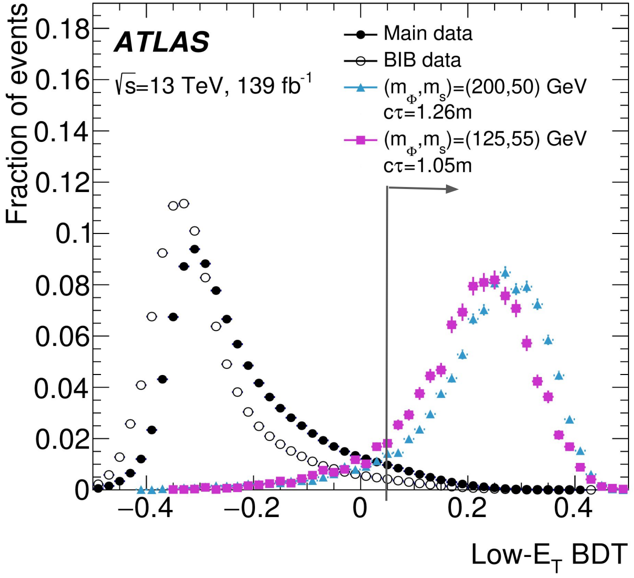
Separate NN for low-E_T and high-E_T.
Good separation between signal and BIB and multi-jet.

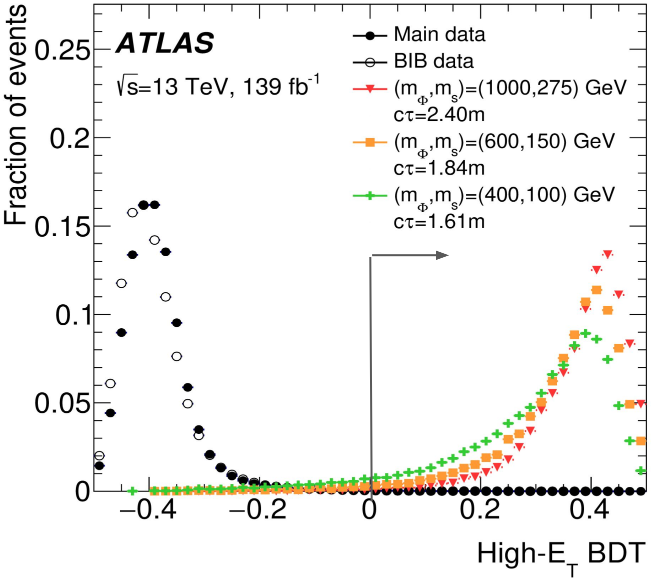




BDT and event selection

BDT defined per-event. Based on jet-NN signal and BIB score of two leading E_T jets and event variables.
Event cleaning: jet time, BDT score cut, trigger matching of one jet and high E_{HCAL}/E_{ECAL}
Final selection to remove BIB and cosmic.





Low-E_T selection
$H_T^{miss}/H_T < 0.6$
$(\sum_{jet^{sig_{1l}},jet^{sig_{2l}}} \log_{10}(E_H/E_{EM})) > 2$
$p_T(jet^{sig_{1l}}) > 80GeV$
$p_T(jet^{sig_{2l}}) > 80GeV$
low-E_T NN product > 0.7

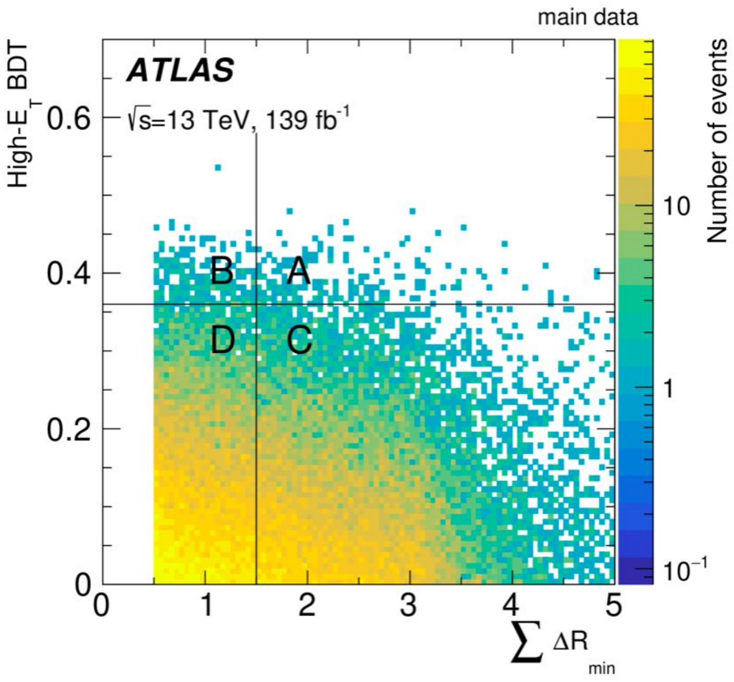
High-E_T selection
$H_T^{miss}/H_T < 0.6$
$(\sum_{jet^{sig_{1h}},jet^{sig_{2h}}} \log_{10}(E_H/E_{EM})) > 1$
$p_T(jet^{sig_{1h}}) > 70GeV$
$p_T(jet^{sig_{2h}}) > 80GeV$
high-E_T NN product > 0.5

Signal and control regions: ABCD method

After event selection, main background is multi-jet. Modified ABCD method to estimate multi-jet background.

- Combined fit of multi-jet background following relation of ABCD method.

Define SR (A) and CRs (B,C, D) based on top of event selection with: BDT score and ΣΔRmin(jet,tracks).



Multi-jet background prediction in SR (A)

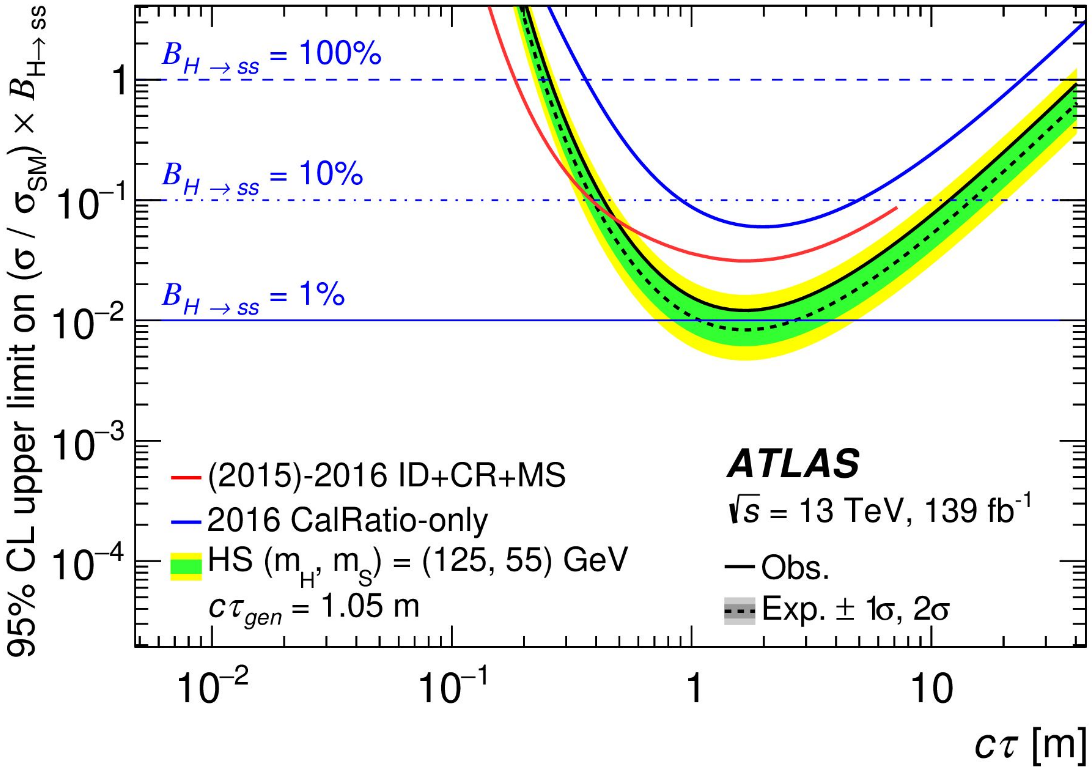
$$N_{\mathrm{A}} = (N_{\mathrm{B}} \cdot N_{\mathrm{C}})/N_{\mathrm{D}}$$

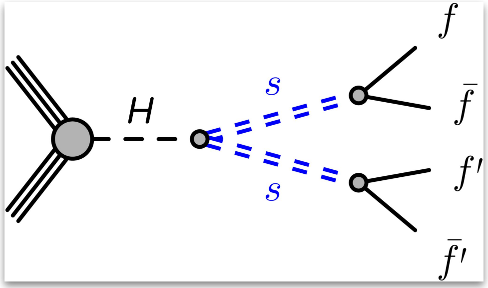
Low-E_{T} selection	A	B	C	D
Observed data	23	3	220	61
a priori				
Estimated background	10.8 ± 6.6	3 ± 1.7	220 ± 15	61 ± 7.8

High-E_{T} selection	A	B	C	D
Observed data	22	7	233	131
a priori				
Estimated background	12.4 ± 4.7	7 ± 2.6	233 ± 15	131 ± 11

Excesses observed (p-value: low-E_T = 0.076, high-E_T = 0.083)
Agreement between data and SM prediction.

Interpretation: limits if Φ is SM Higgs boson





Less sensitive limit from 2016 combination at low *cτ* due to not inclusion of ID

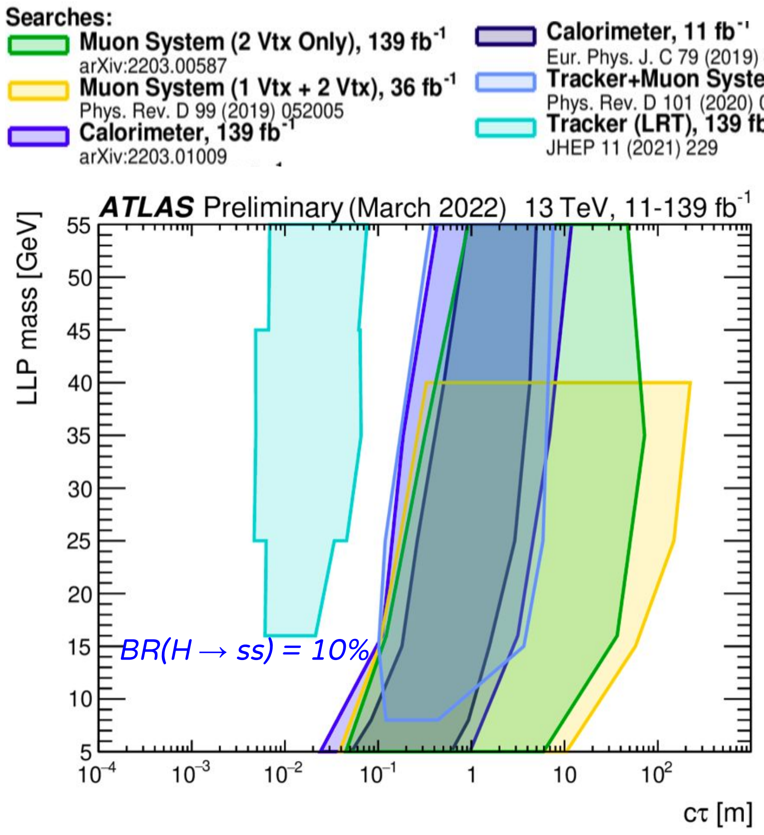
Sensitivity to BR(H → ss) down to 1%

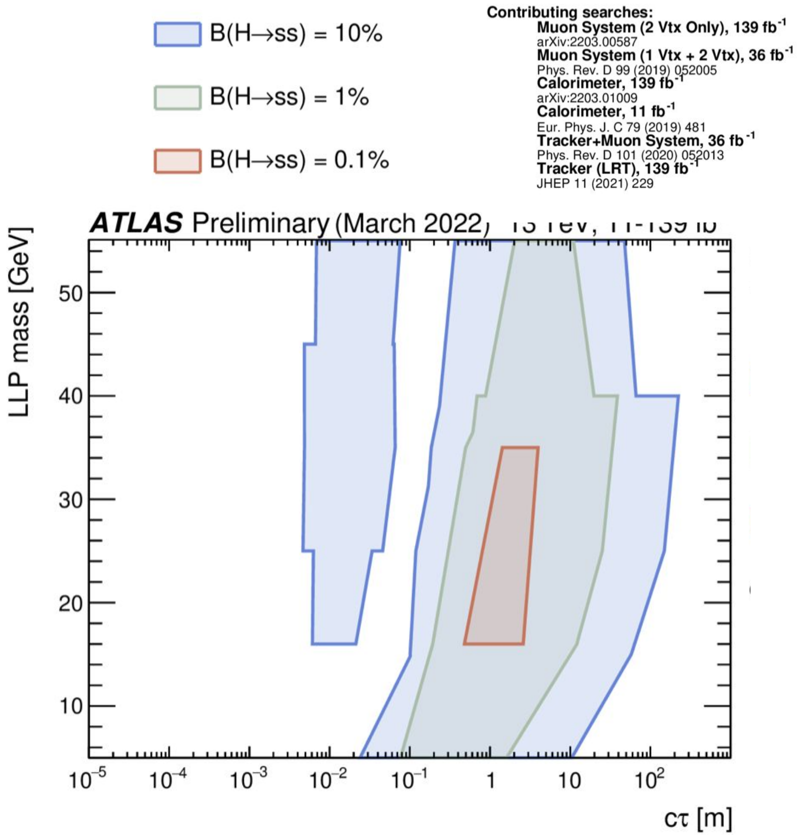
Better sensitivity than previous CalRatio:

- Better trigger.
- Better displaced jet-NN.

PUB-2022-007

Interpretation: limits if Φ is SM Higgs boson





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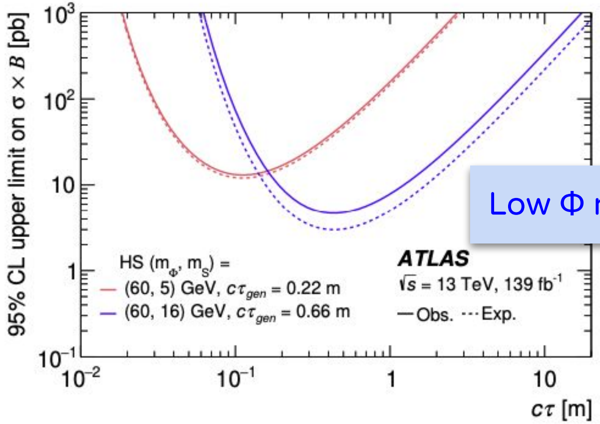
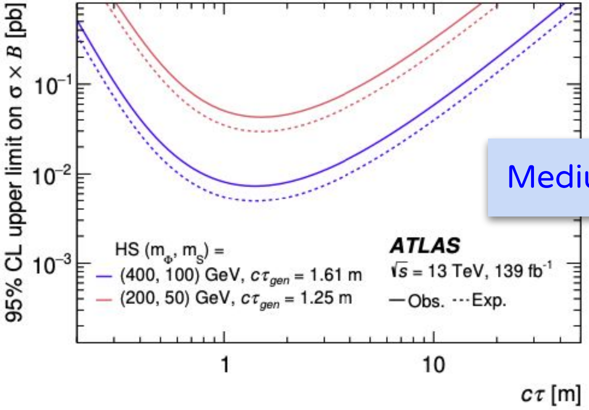
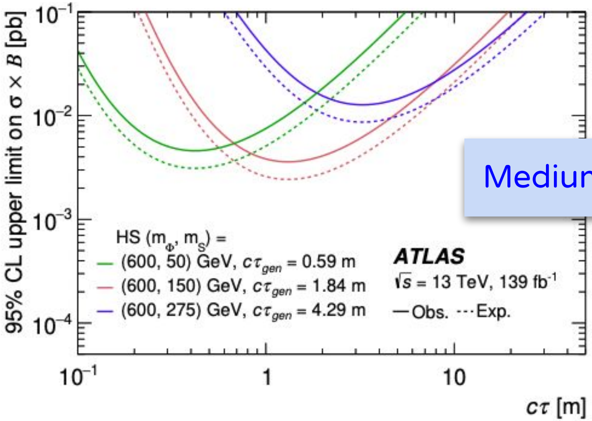
Interpretation: limits if Φ is new heavy scalar



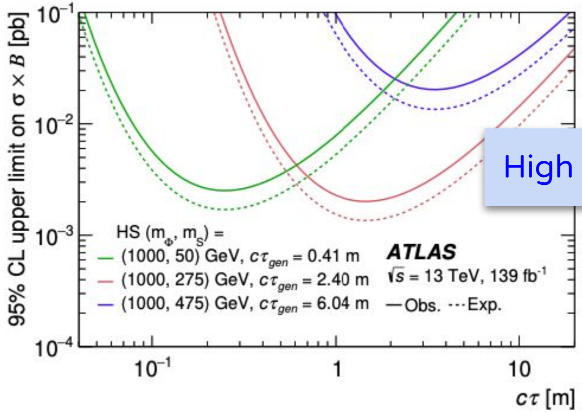
Low Φ mass



Medium Φ mass



Medium Φ mass



High Φ mass

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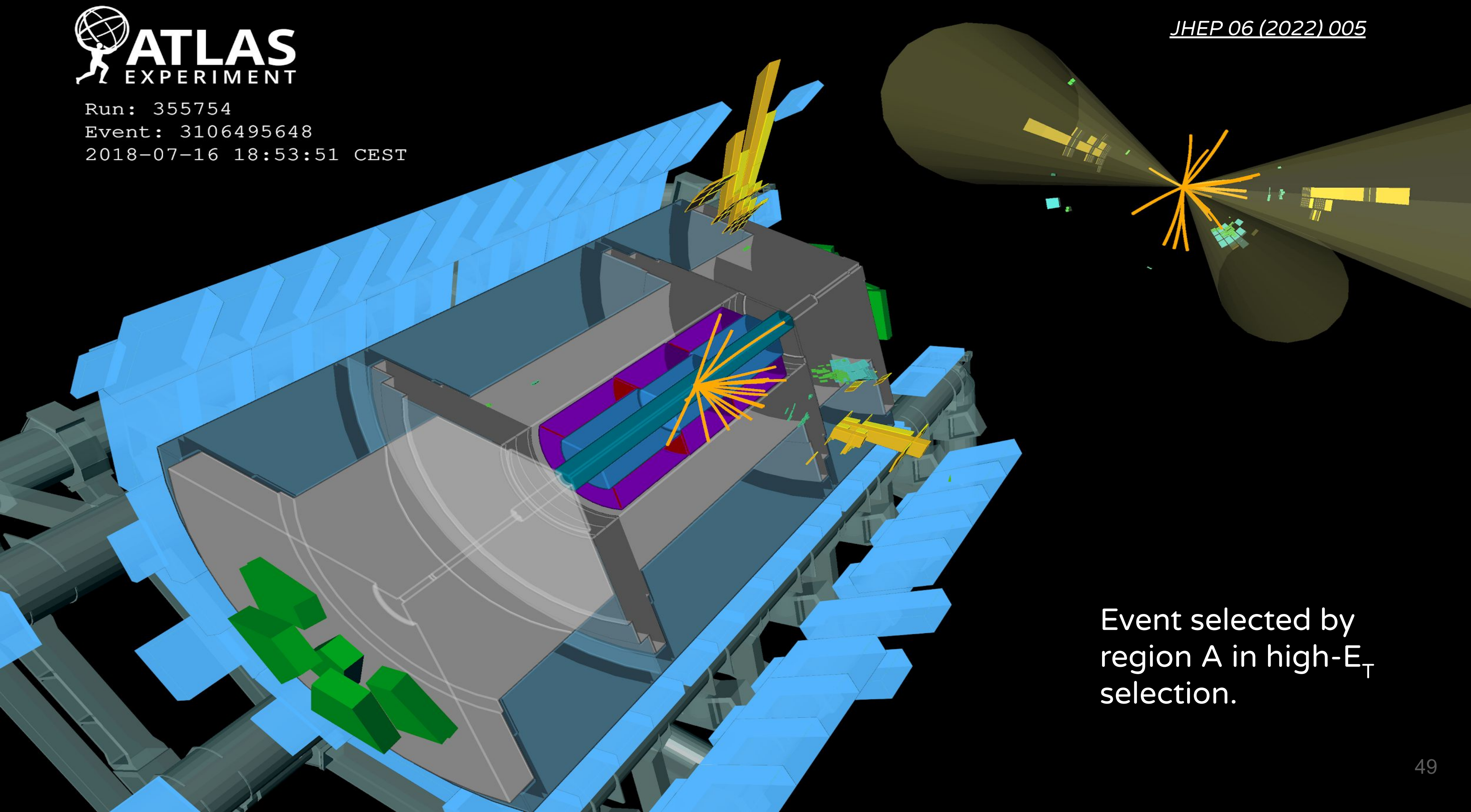


Event selected by region A in high-E_T selection.

Conclusion

Run-2 has provided us with more and improved DM searches and seen the expansion of ATLAS research to long-lived particles

Recent new analyses searching for dark matter in association to a top-quark.

- Mono-top searches greatly improved the current limits with respect to Early Run-2
- Additional channels increase sensitivity in tW+DM searches.

Searches for more complex dark sectors presented

- First results on strongly coupled DM sector in semi-visible jets with ATLAS and in the single-lepton channel for dark Higgs into WW.

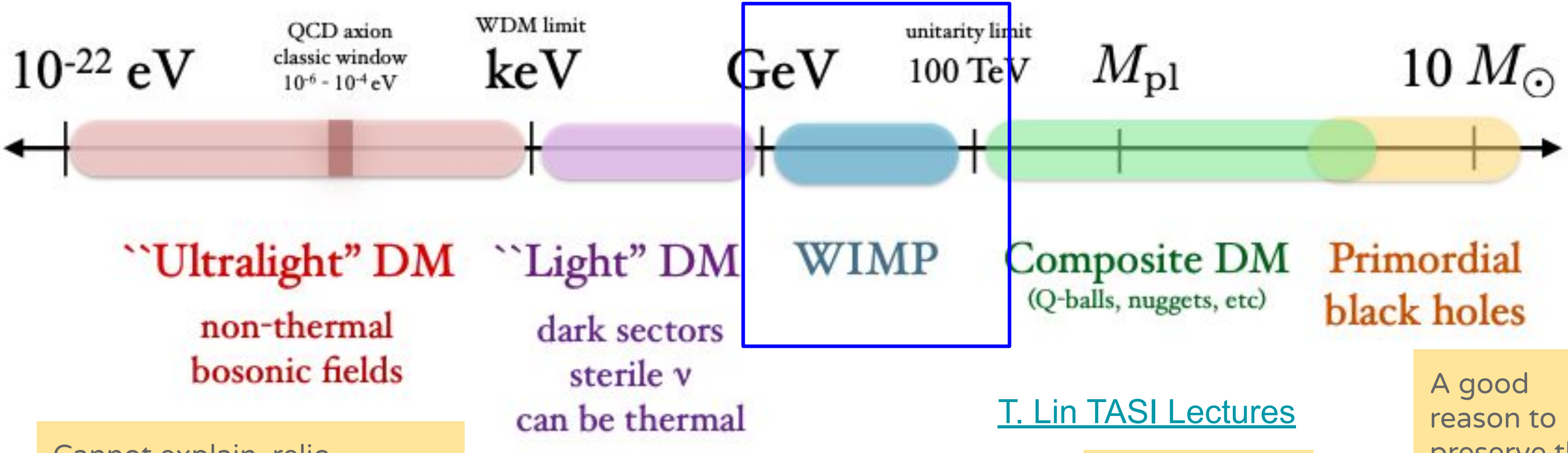
New search for long-lived particles using displaced jets

- Improving early Run-2 limits and sensitivity at middle $c\tau$

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

Backup

Where to find it ? Is it big or small?



[T. Lin TASI Lectures]

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

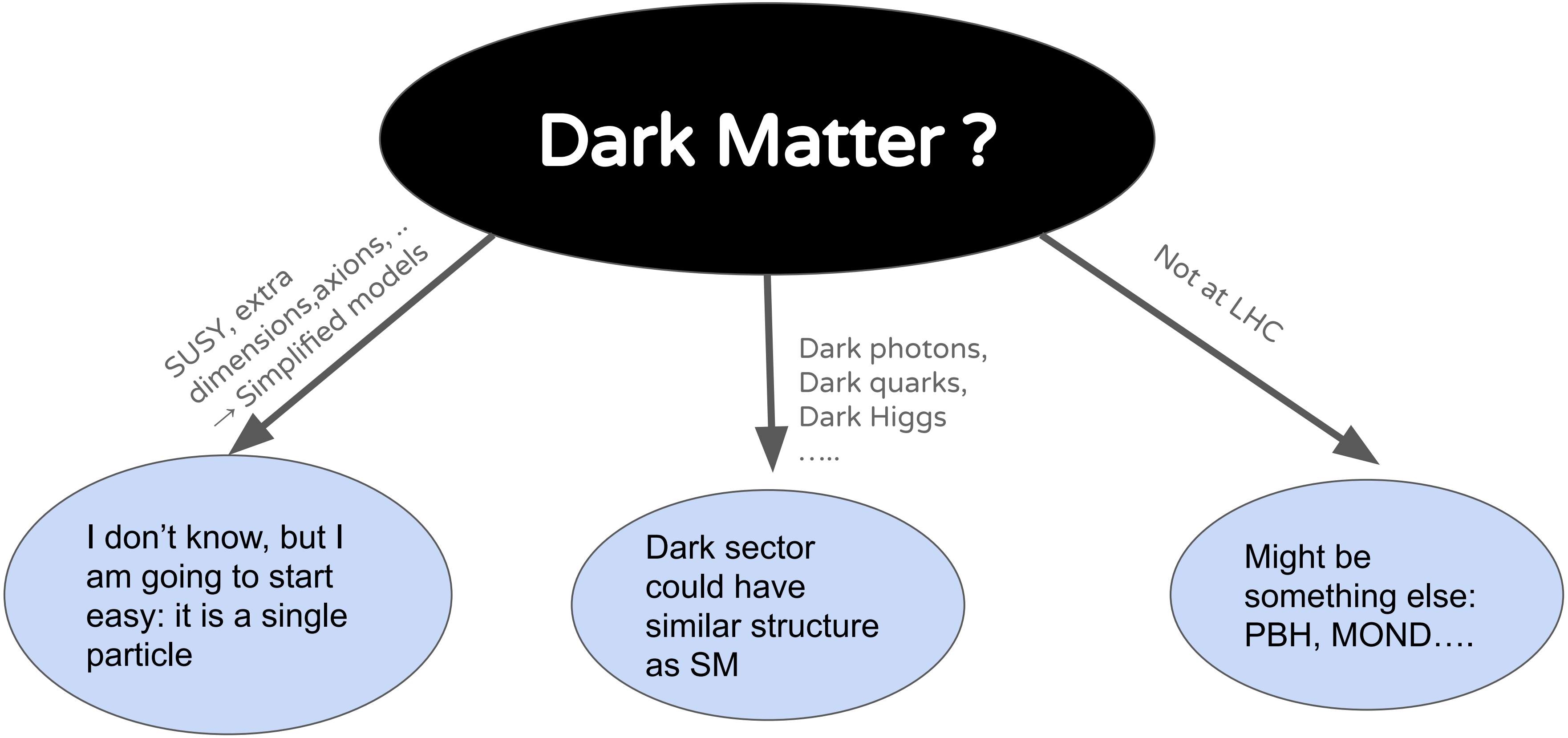
Can explain relic abundance from thermal freeze-out at Early Universe. And masses similar to what we know

Big structures formed of new particles or SM particles

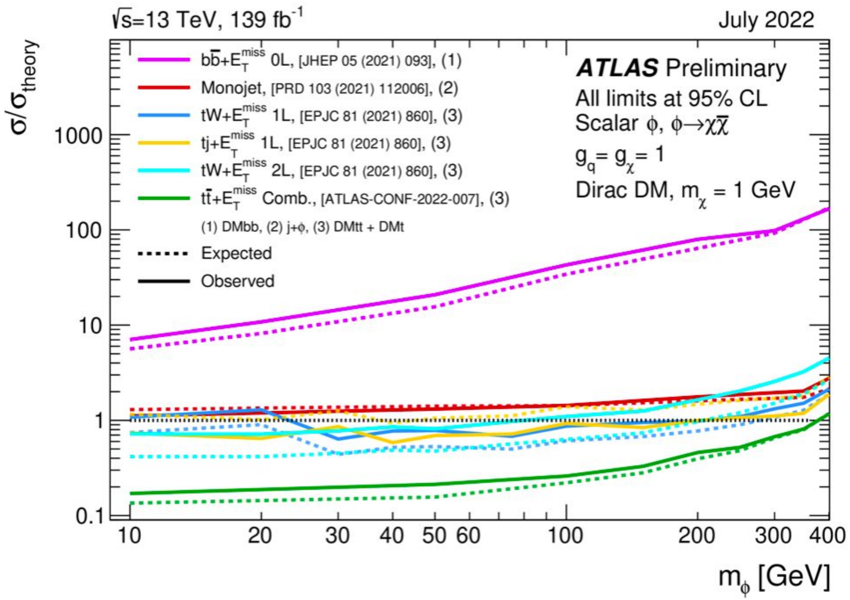
A good reason to preserve the Earth. Things out there could be dark and full of terrors ….

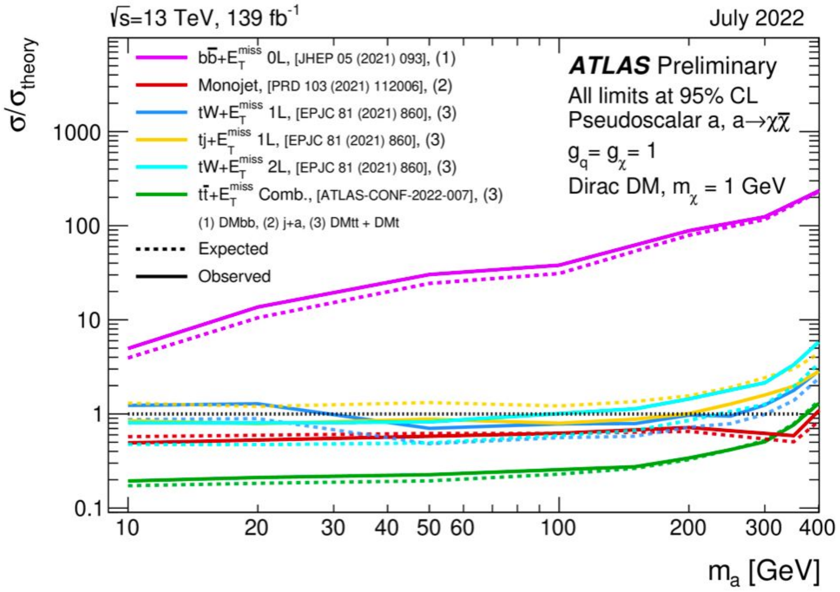
The most favoured theory is that it is a WIMP (weakly interacting particle).

What kind of particle ?



Scalar and pseudo-scalar mediators DMtt

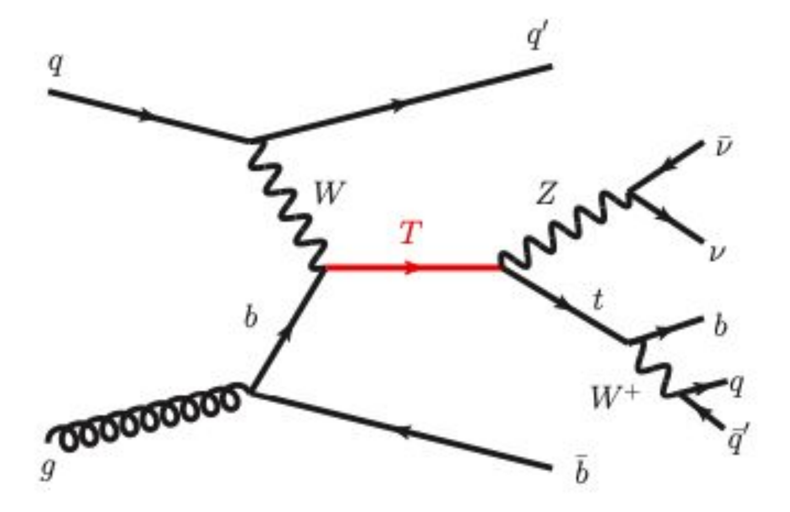


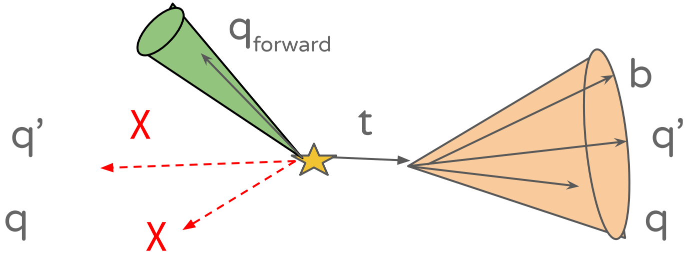


Mono-top backup

Search for Dark Matter plus a single-top

Vector-like quark (VLQ)

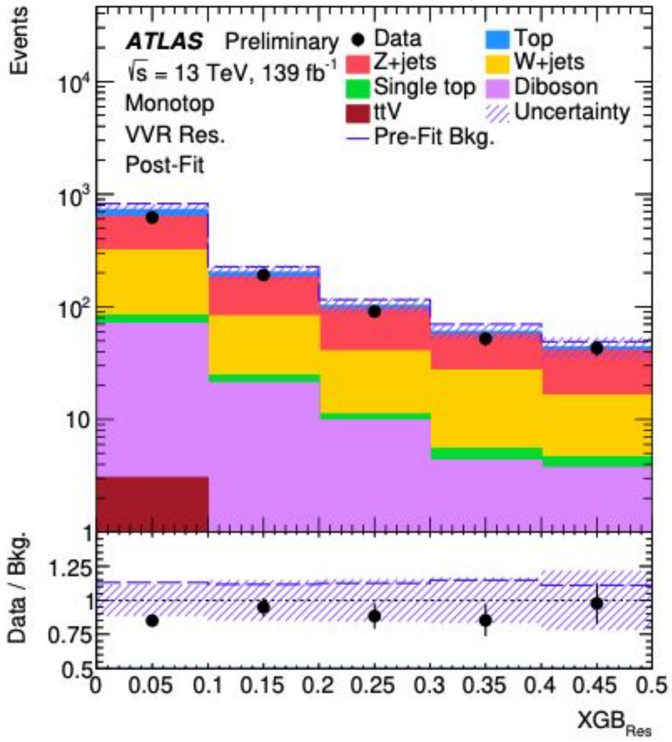




E_T^{miss} trigger and E_T^{miss} > 250 GeV
At least one top-tagged large-R jet $\Delta\varphi(j,E_T^{miss})$ > 1.0
At least one forward jet.

Mono-top: BDT selection

Variable	Description	Resonant DM model	Non-resonant DM model	VLQ
E_T^{miss}	Missing transverse momentum	✓	✓	✓
Ω	E_T^{miss} and large-R jet p_T balance: $\frac{E_T^{miss}-p_T(J)}{E_T^{miss}+p_T(J)}$	✓	✓	✓
N_{jets}	Small-R jet multiplicity	✓	✓	✓
ΔR_{max}	Maximum ΔR between two small-R jets	✓	✓	✓
$m_{T,min}(E_T^{miss}, b\text{-jet})$	Transverse mass of E_T^{miss} and the closest b-tagged jet.	✓	✓	✓
$m_{top\text{-}tagged\ jet}$	Mass of the large-R top-tagged jet	✓		✓
$\Delta p_T\ (J,\text{jets})$	Scalar difference of large-R jet p_T and the sum of p_T of all small-R jets.	✓	✓	
H_T	Sum of all small-R jet p_T		✓	✓
H_T/E_T^{miss}	Ratio of H_T and E_T^{miss}		✓	✓
$\Delta E(E_T^{miss}, J)$	Energy difference between E_T^{miss} and the large-R jet		✓	✓
$\Delta\phi(E_T^{miss}, J)$	Angular distance in the transverse plane between E_T^{miss} and large-R jet		✓	✓
p_T(J)	Large-R jet p_T			✓
$m_T(E_T^{miss}, J)$	Transverse mass of the E_T^{miss} and large-R jet			✓
$\Delta\phi(b\text{-tagged jet}, J)$	Angular distance in the transverse plane between the large-R jet and the leading b-jet			✓

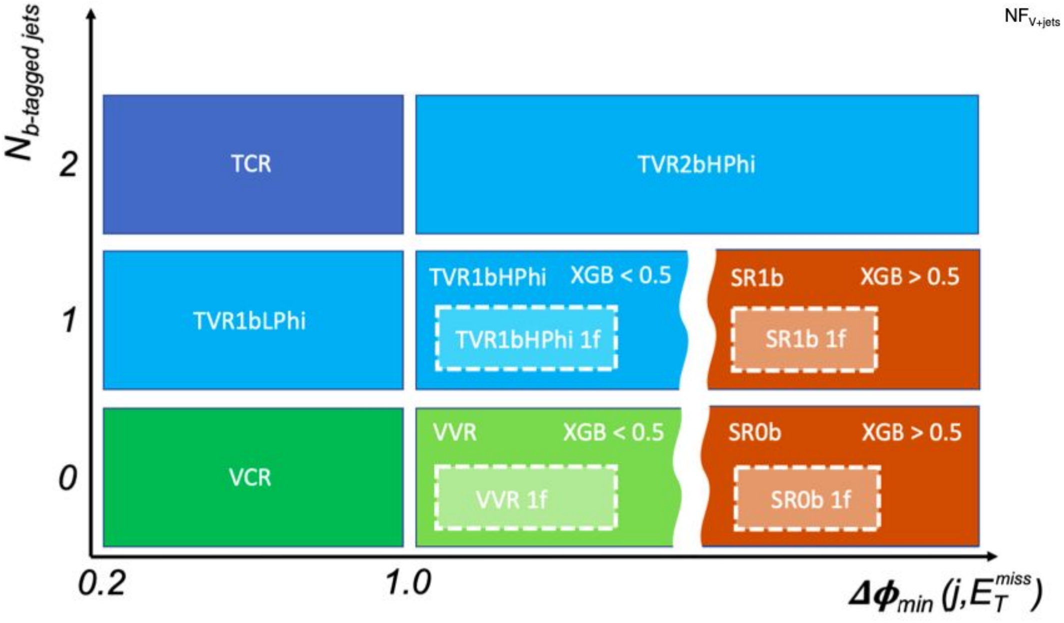


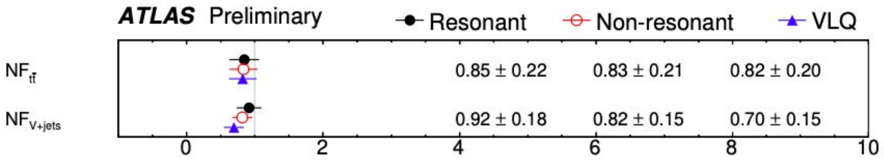
BDT < 0.5 → VR ; BDT > 0.5 → SRs

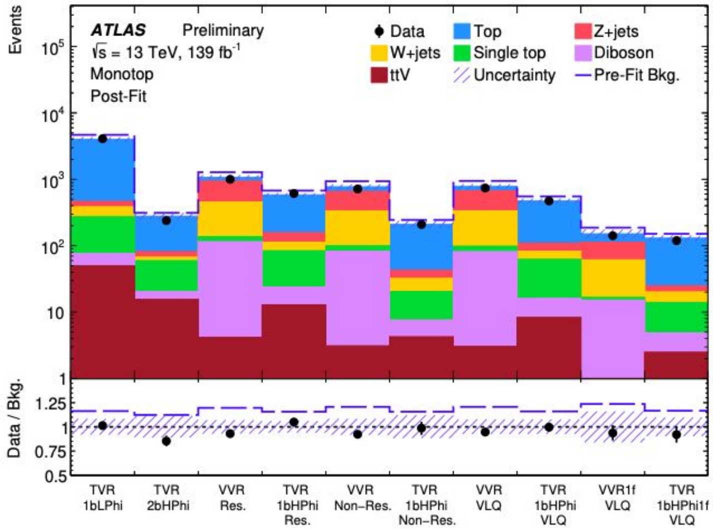
ATLAS-CONF-2022-036

Background estimation

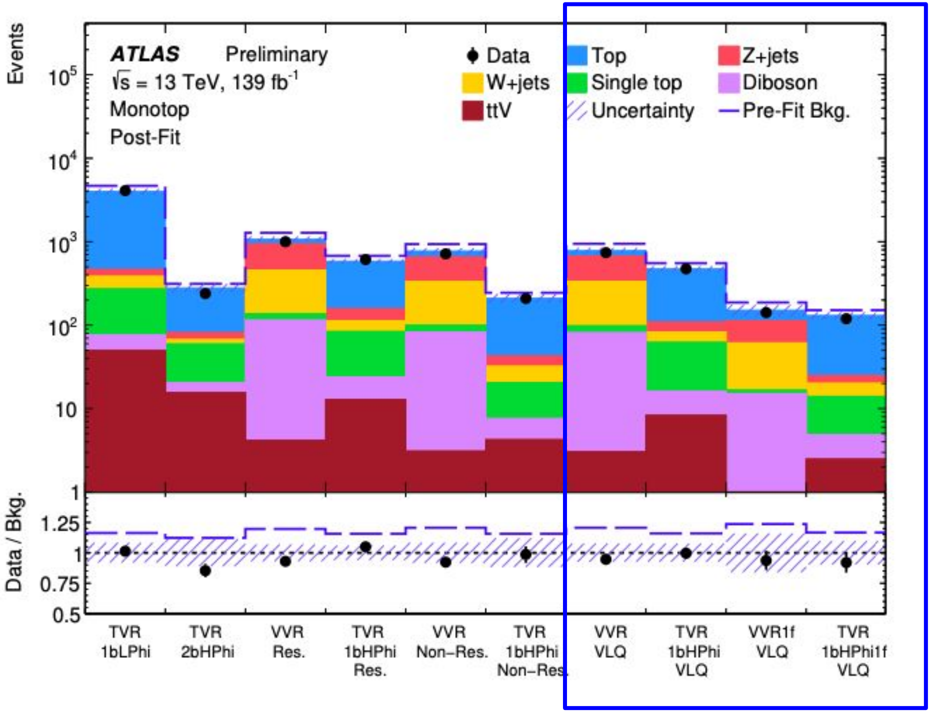
Dominant background is V+jets and tt. Defined control and validation regions per production mode.
Same definitions for three production modes
+ 1forward jet for VLQ model.

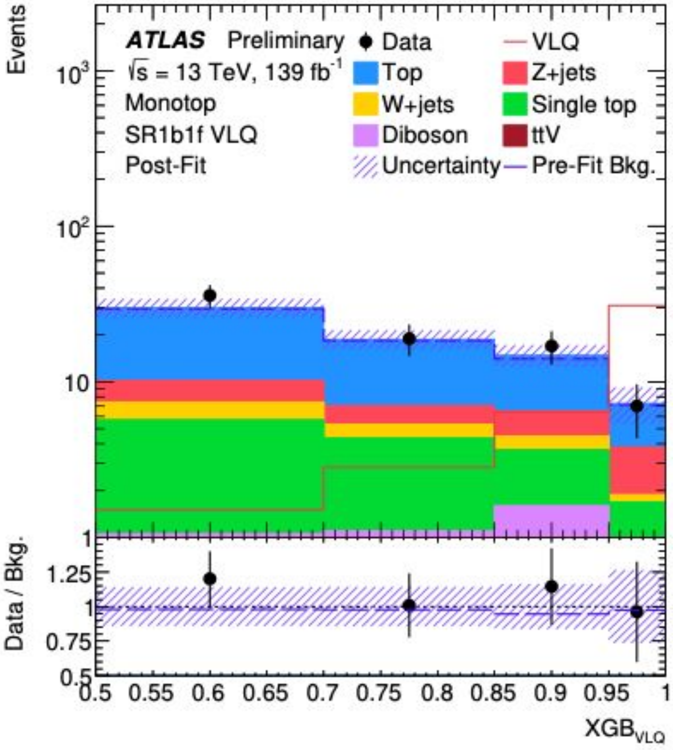






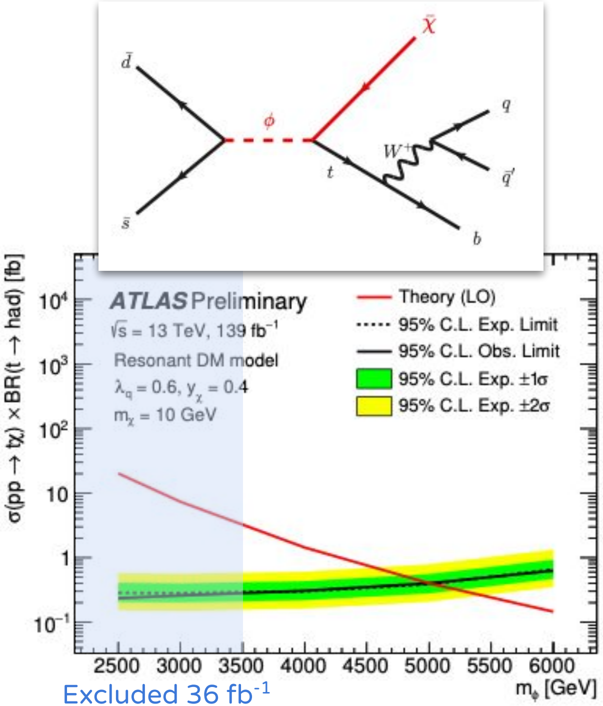
Post-fit results: VLQ



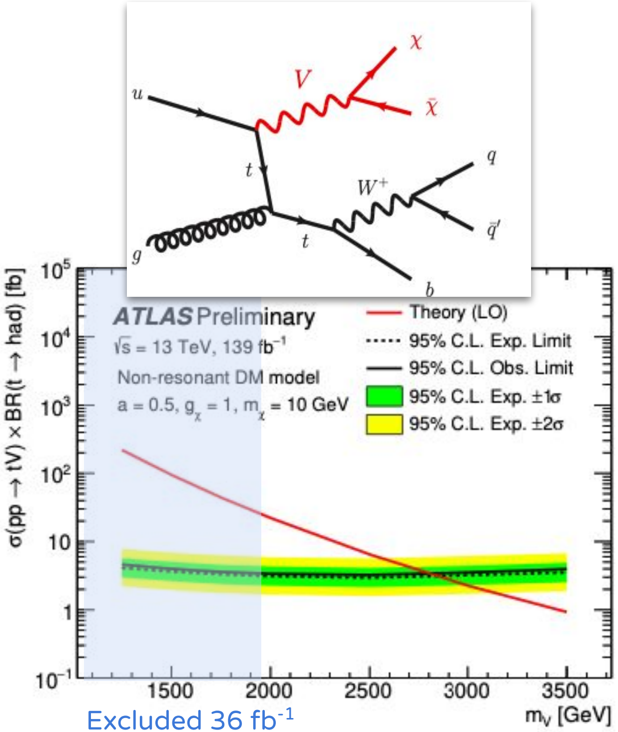


Good agreement between data and SM. Dominant uncertainties: large-R jet calibration and modelling

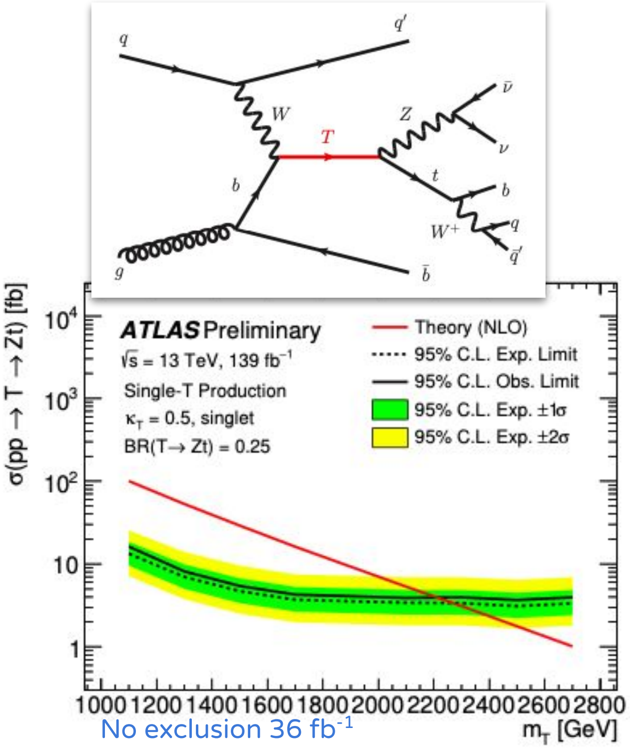
Interpretation: simplified model and VLQ model



Excluded 36 fb^{-1}



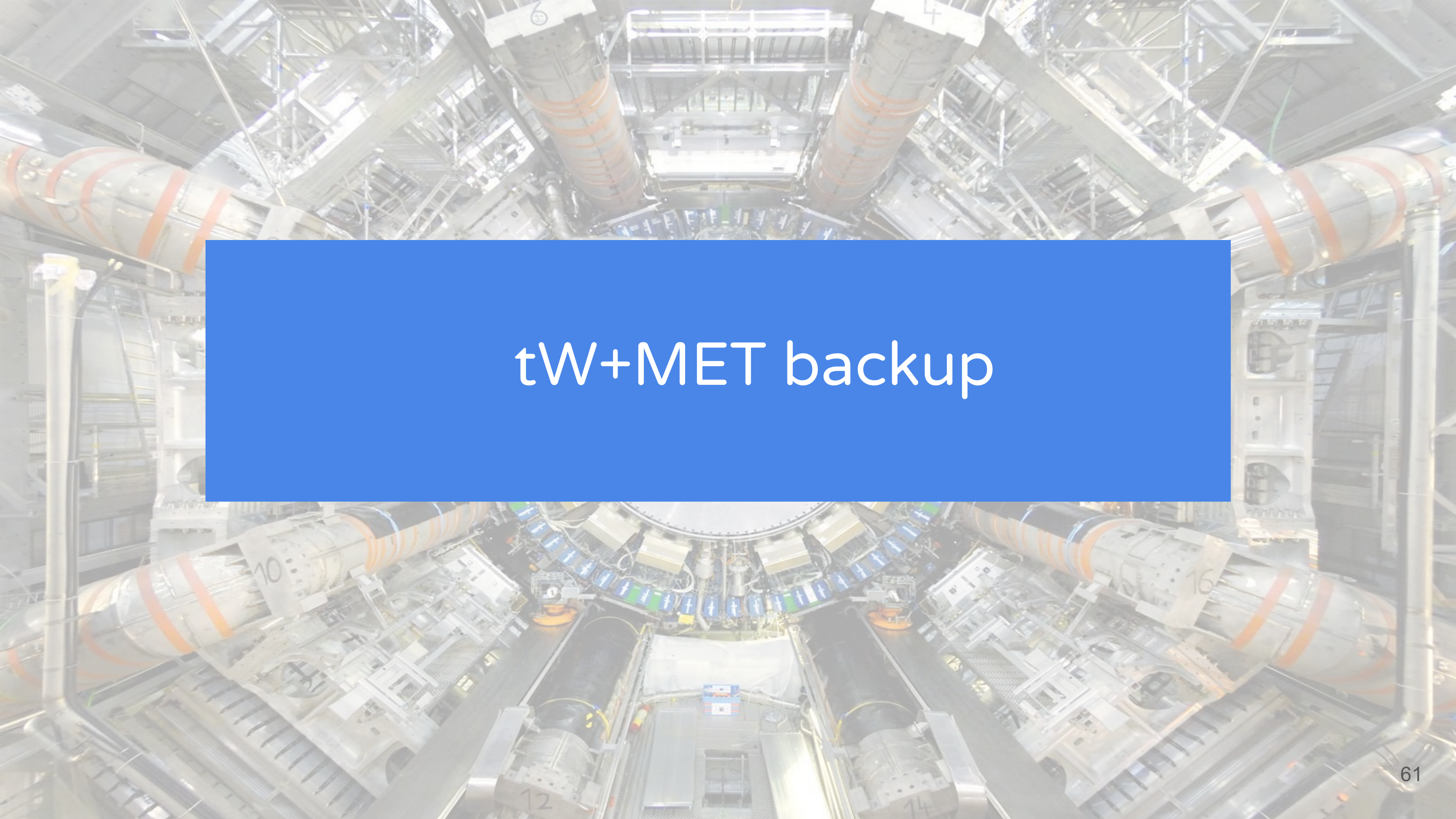
Excluded 36 fb^{-1}



No exclusion 36 fb^{-1}

Exclusion limits derived from fit of the BDT output distribution for each production mode, separately.

Significant improvements from early Run-2 results !



tW+MET backup

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

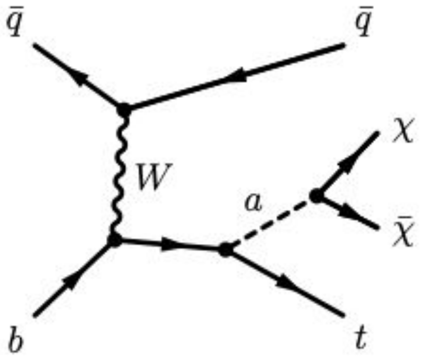
Single-top quark production and Dark Matter

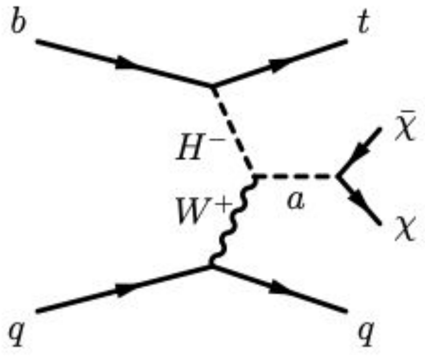
s-channel

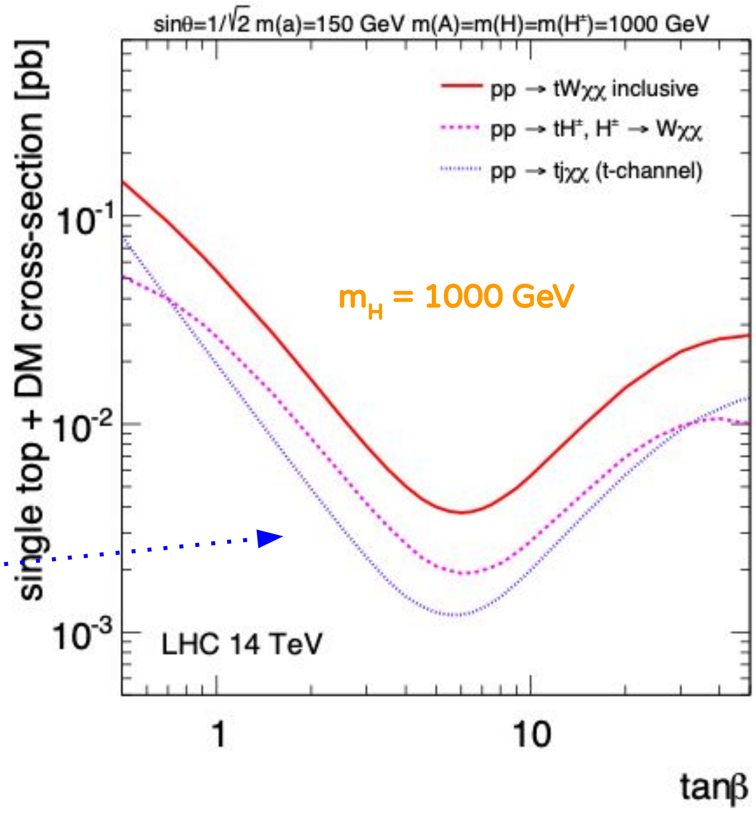
Negligible contributions

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

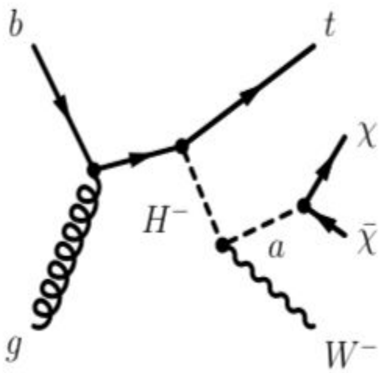
Single-top quark production and Dark Matter

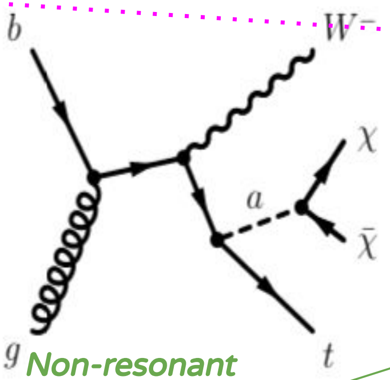
tW-channel

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

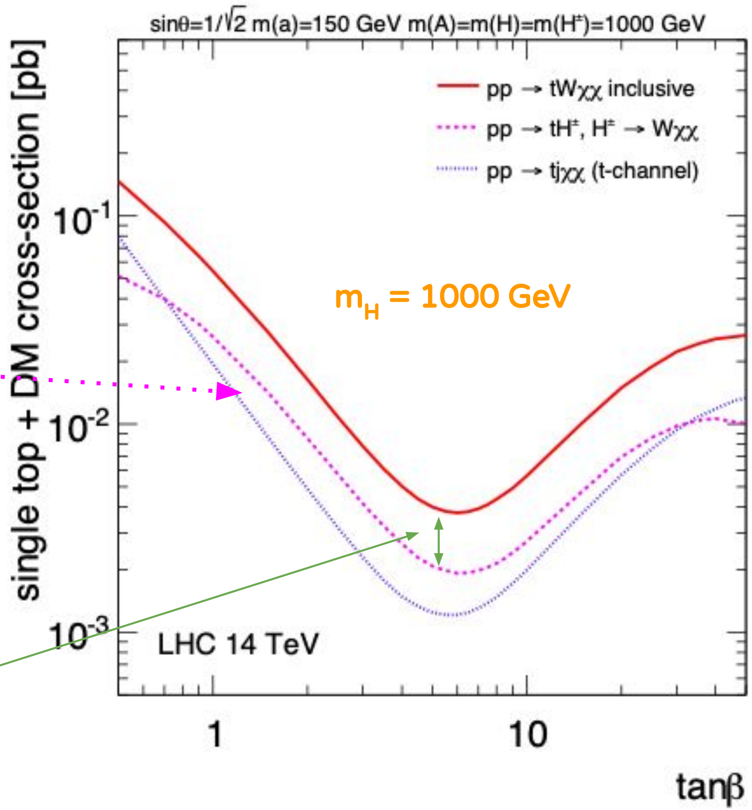
- Resonant dominating at mH ~ [400,1200]

Resonant tW-channel





Non-resonant tW-channel

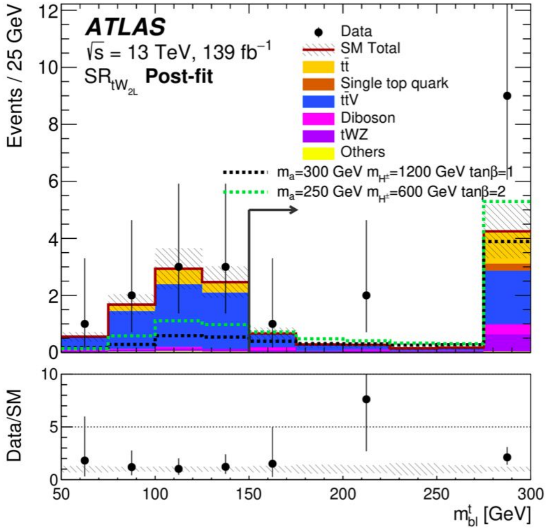


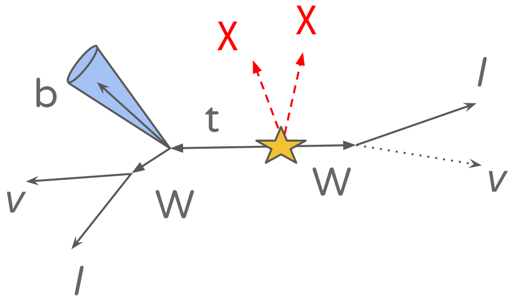
Analysis strategy: the two-lepton channel

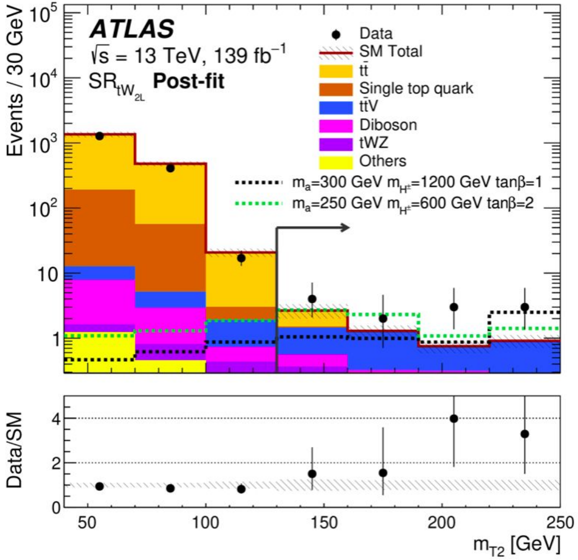
Pseudo-reconstruct top quark to discriminate. m_{T2} , m_{bl}^{min} and m^{t}_{bl}-> Endpoints for SM tt and single-top.

- At least 1 b-jet and 1 additional jet
- m_{T2} > 130 GeV
- m_{bl}^{min} < 170 GeV
- m^{t}_{bl} > 150 GeV

Main bkgs. : Z+jets, ttZ, tt and single-top







$$m^{t}_{b\ell} = \min[\max(m_{\ell_1 j_1}, m_{\ell_2 j_2}), \max(m_{\ell_1 j_2}, m_{\ell_2 j_1})] \quad m^{\min}_{b\ell} = \min(m_{b_1\ell_1}, m_{b_1\ell_2})$$

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

Background estimation

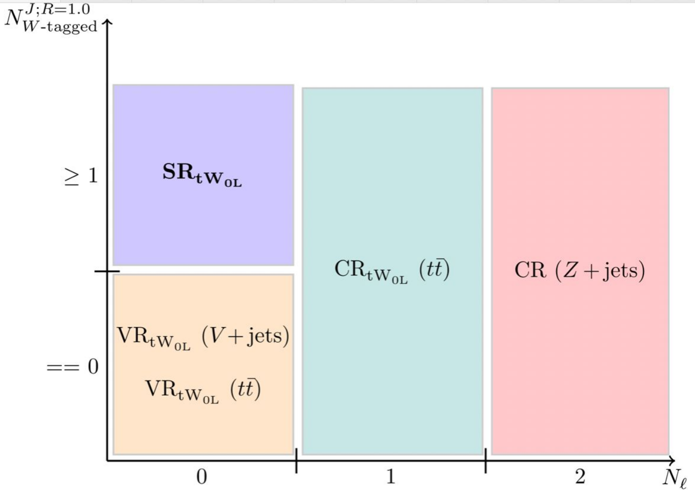
Defining control and validation regions close to the SRs to normalize the most important backgrounds.

0L and 1L channels

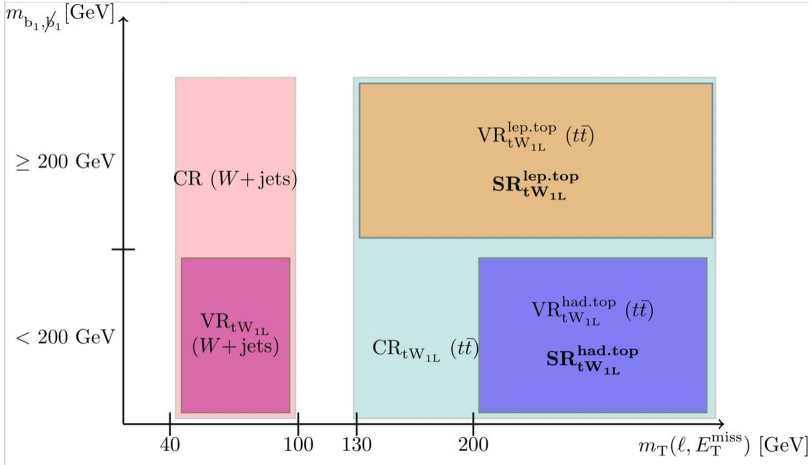
- Common CRs for Z+jets, W+jets, single-top and ttZ.
- tt normalized separately for 0L and 1L regions.

2L channel

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



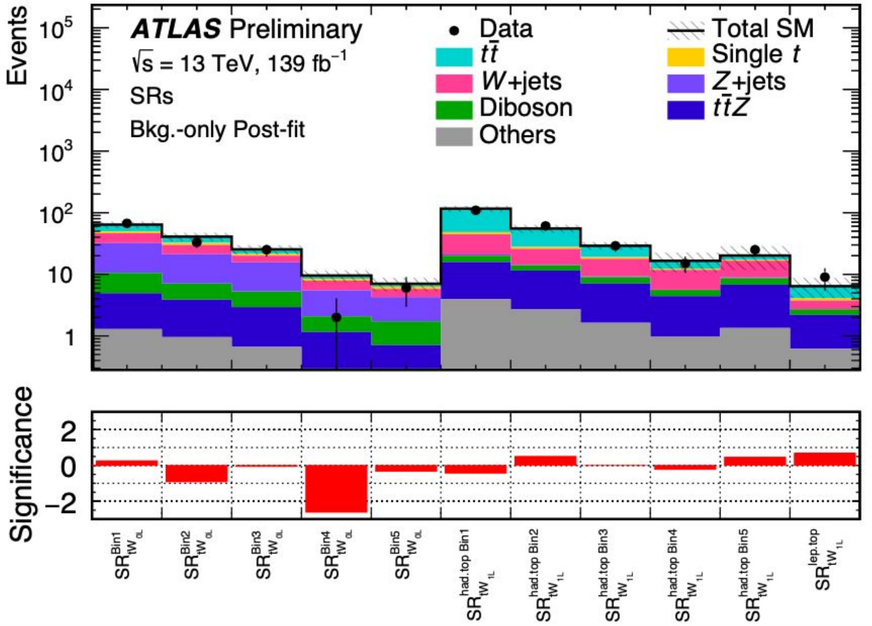
Variable	SR	CR($t\bar{t}$)	CR($t\bar{t}Z$)	CR(WZ)	VR($t\bar{t}$)	VR(3ℓ)
N_ℓ^{signal}	= 2 (OS)	= 2 (OS)	= 3 (≥ 1 SFOS)	= 3 (≥ 1 SFOS)	= 2 (OS)	= 3 (≥ 1 SFOS)
$p_T(\ell_3)$ [GeV]	-	-	> 20	> 20	-	> 20
$m_{ee/\mu\mu}$ [GeV]	∉ [71, 111]	∉ [71, 111]	∈ [71, 111]	∈ [71, 111]	∉ [71, 111]	∈ [71, 111]
N_{jet}	≥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



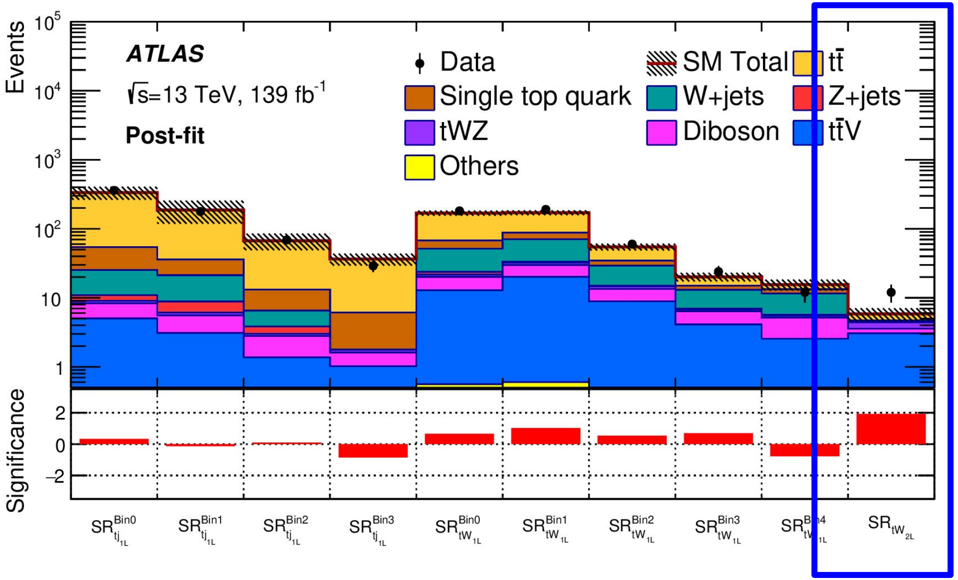
Background-only fit results

Simultaneous of all the SRs and CRs of the 0L, 1L and 2L regions
No DM evidence observed. 2σ excess observed in 2L and 2.5σ deficit in one bin of the 0L channel.

0L+1L combined fit



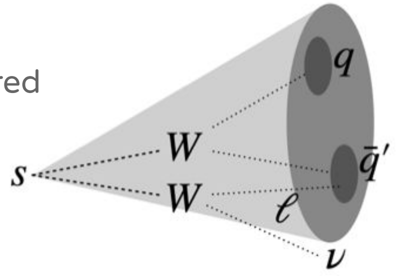
ATLAS 1L+2L fit

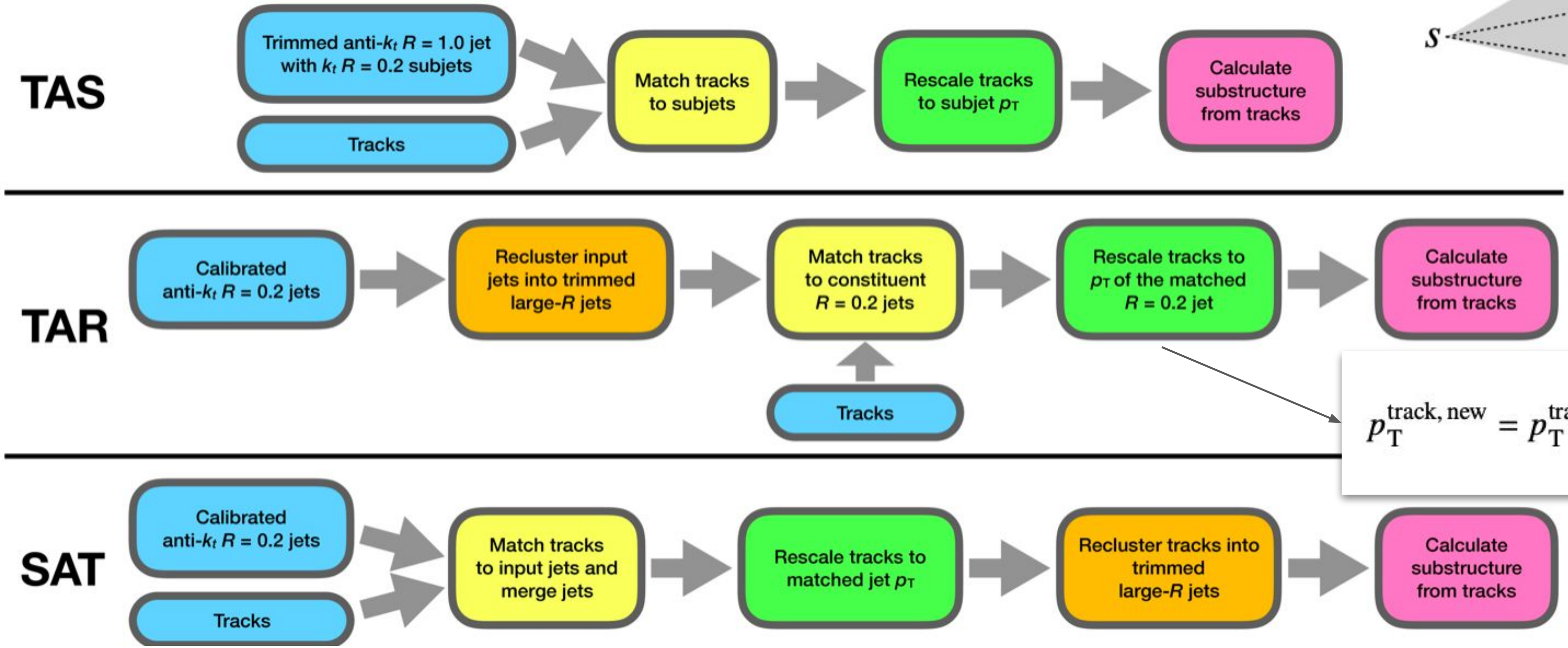


Dark Higgs backup

TAR jets for W-tagging in Dark Higgs search

Beneficial due to overlapping electrons with hadronic W-jet in the WW+E_T^{miss}.
TAR: Track-assisted reconstruction→ Mass and substructure from track jets
R=0.2 jets overlapping with electron and tracks coming associated to electrons not considered

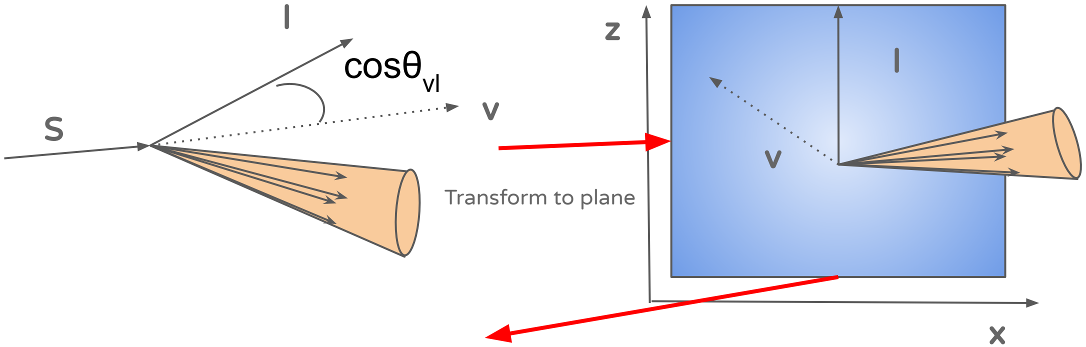




$$p_{\mathrm{T}}^{\text{track, new}} = p_{\mathrm{T}}^{\text{track, old}} \times \frac{p_{\mathrm{T}}^{R=0.2}}{\sum_i p_{\mathrm{T},i}^{\text{track, old}}}$$

Fit configuration: the m_s^{min} variable

Reconstructing m_S challenging. But beneficial as **discriminant variable for fit (resolved and merged)**

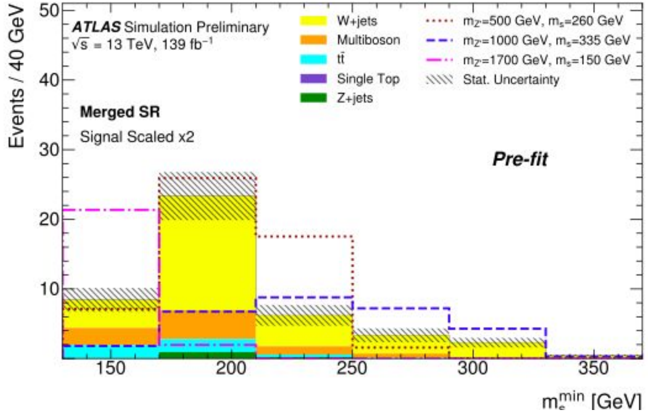


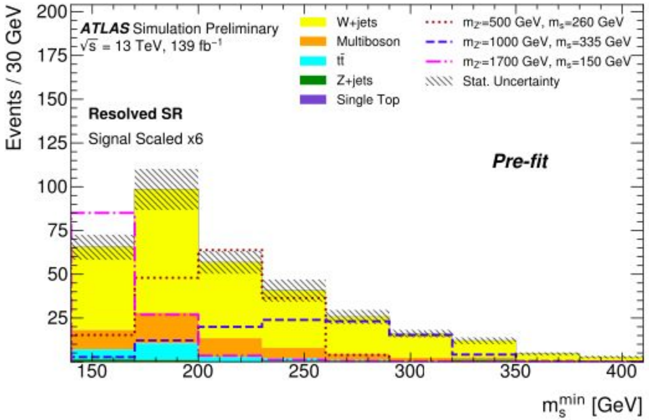
$$m_s^2 = \left(E_\ell + \frac{m_W^2}{2E_\ell(1-\cos\theta_{\ell\nu})} + E_{W_{\text{cand}}}\right)^2 - \left(\left|\vec{p}_{W_{\text{cand}}}\right| \sin\theta_{W_{\text{cand}}\ell} + \frac{m_W^2\sqrt{1-\cos^2\theta_{\ell\nu}}}{2E_\ell(1-\cos\theta_{\ell\nu})}\right)^2 - \left(E_\ell + \left|\vec{p}_{W_{\text{cand}}}\right| \cos\theta_{W_{\text{cand}}\ell} + \frac{m_W^2\cos\theta_{\ell\nu}}{2E_\ell(1-\cos\theta_{\ell\nu})}\right)^2,$$

$m_S = f(\cos\theta_{vl})$

minimize over all possible $\cos\theta_{vl}$

$$m_s^{\text{min}} \equiv \min_{\cos\theta_{\ell\nu}} (m_s)$$





LLP CalRatio backup

Searches for long-lived particles

Apart from dark matter, many BSM theories predict particles of medium lifetime (LLPs)

- Decays within the detectors

Relatively unexplored during Run-I → Focused on prompt particles searches.

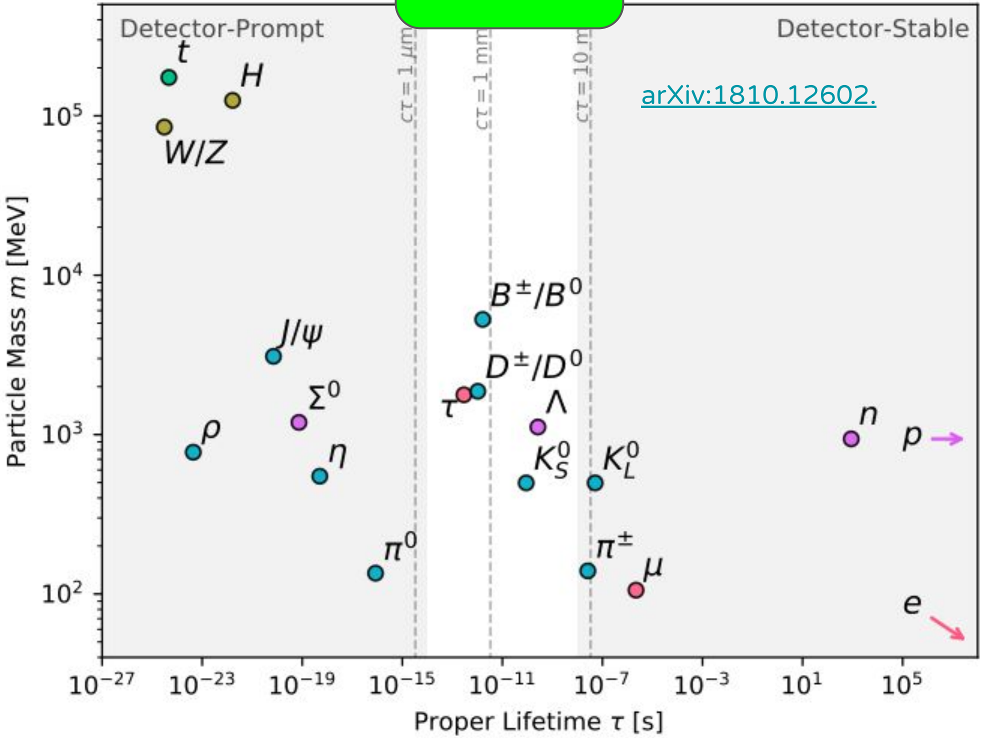
LLP searches have experienced a tremendous advance at LHC during Run-II

- Displaced vertices
- Displaced leptons and jets
- Pixel dE/dx
- Displaced vertices

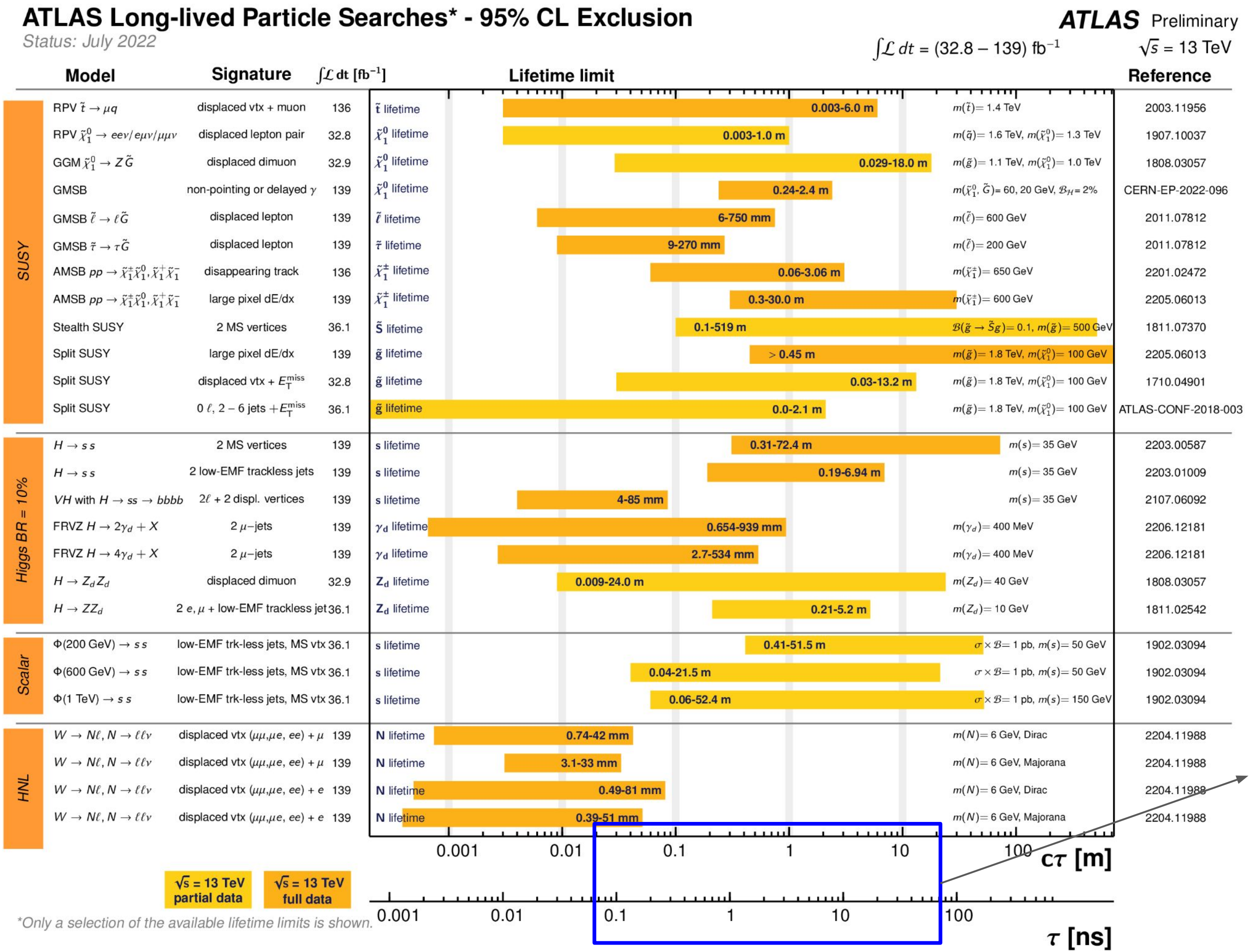
Usual ATLAS and CMS searches

But what about these ??

Usual ATLAS and CMS searches



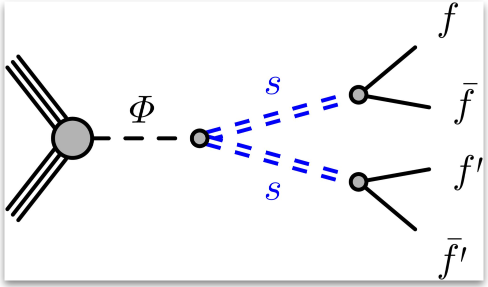
arXiv:1810.12602.



ATL-PHYS-PUB-2022-034

Presenting a search for displaced jets

- LLP decaying after ATLAS tracker.
- Large deposits in hadronic calorimeter
- Sensitive between 20mm and 20m

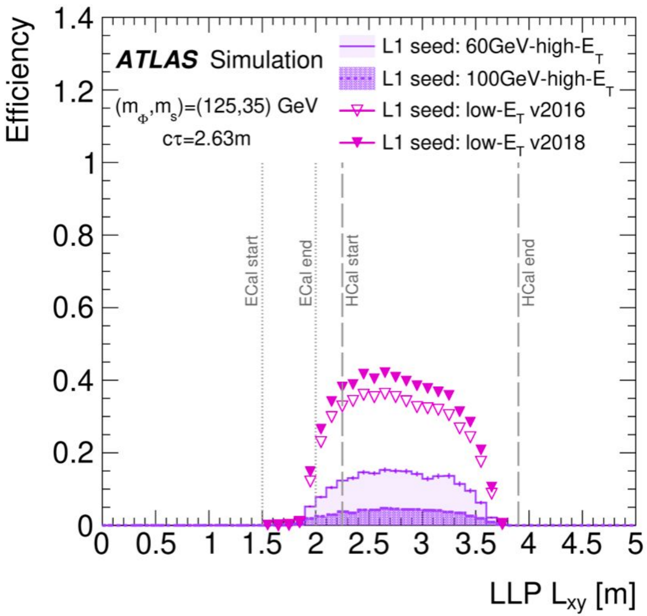


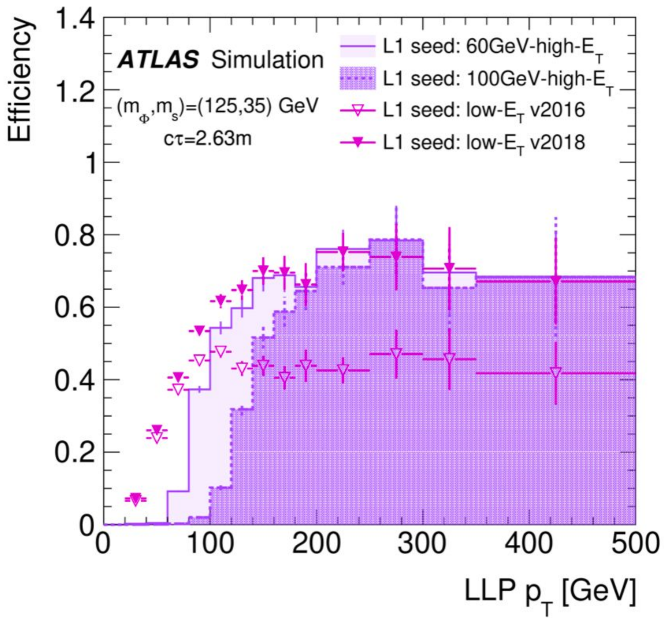
CalRatio triggers

Two step trigger: L1 and HLT. L1 seeds the candidates to HLT

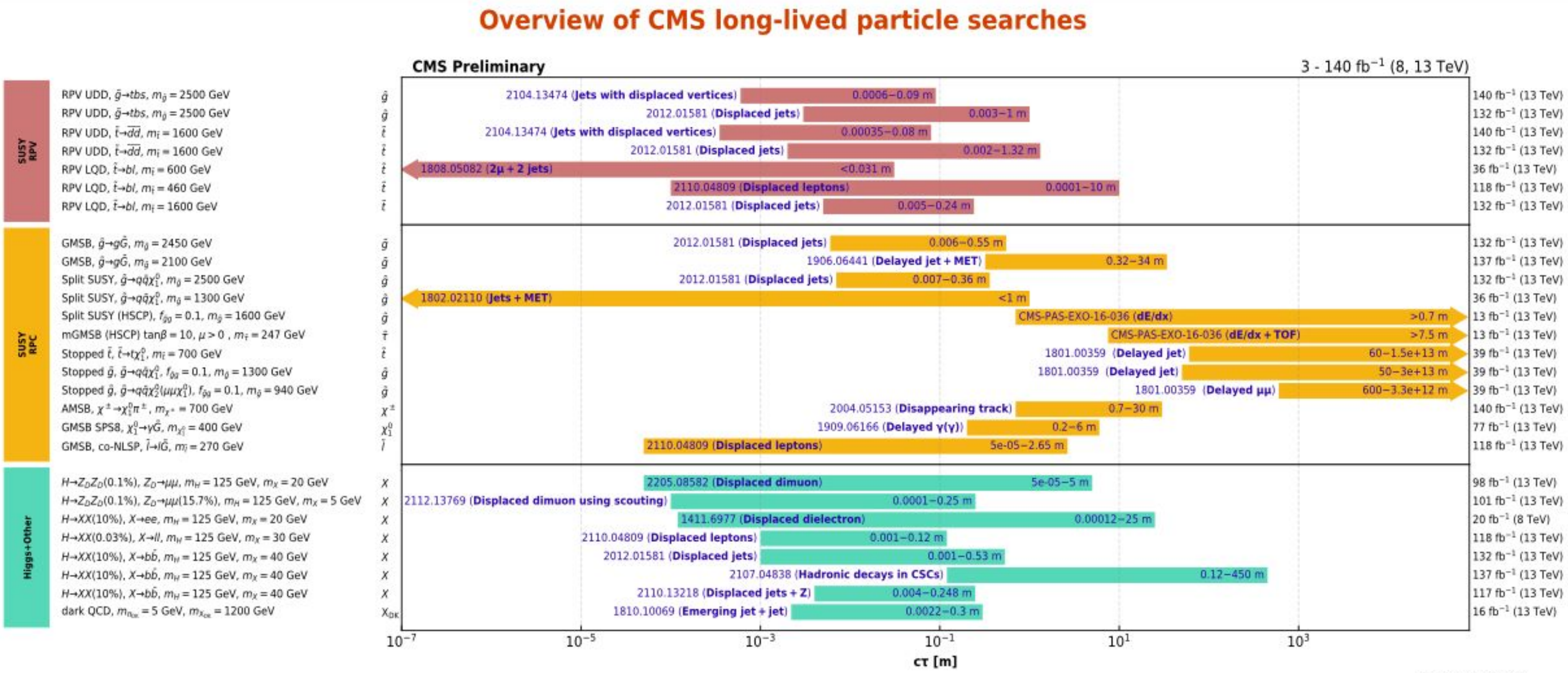
- L1: Triggering on events with narrow deposits ($\Delta\eta \times \Delta\varphi = 0.2 \times 0.2$) in calorimeter and $E_{HCAL}/E_{ECAL} > 9$
- HLT: CalRatio dedicated jet cleaning (standard jet cleaning minus E_{HCAL}/E_{ECAL})and BIB removal (no jet with deposits in 4 cells in φ and timing) applied

Efficiency dependent on LLP p_T and decay position.





CMS long-lived particles summary



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.