

# Searches for heavy quarks and other signatures with the ATLAS detector at the LHC

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on behalf of the ATLAS Collaboration

**DIS 2015**

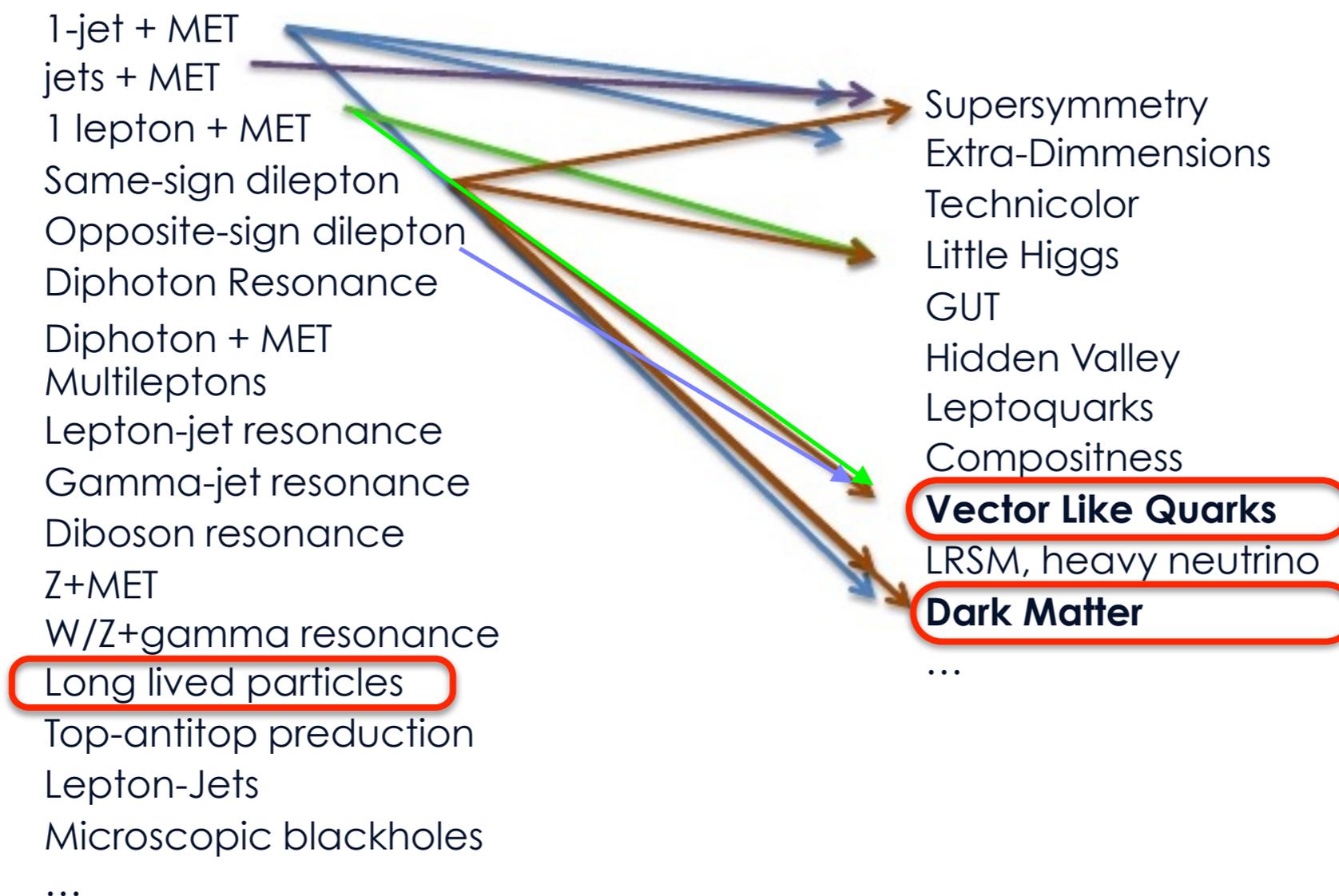
Apr 30, 2015





# Signature based searches

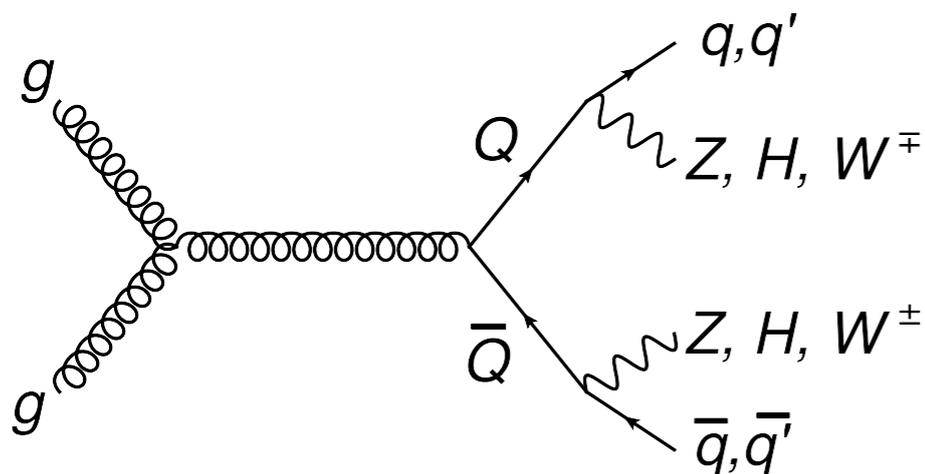
- Strategy:
  - Use models as guidance where to look
  - Perform signature-based searches
  - Interpret results using benchmark models



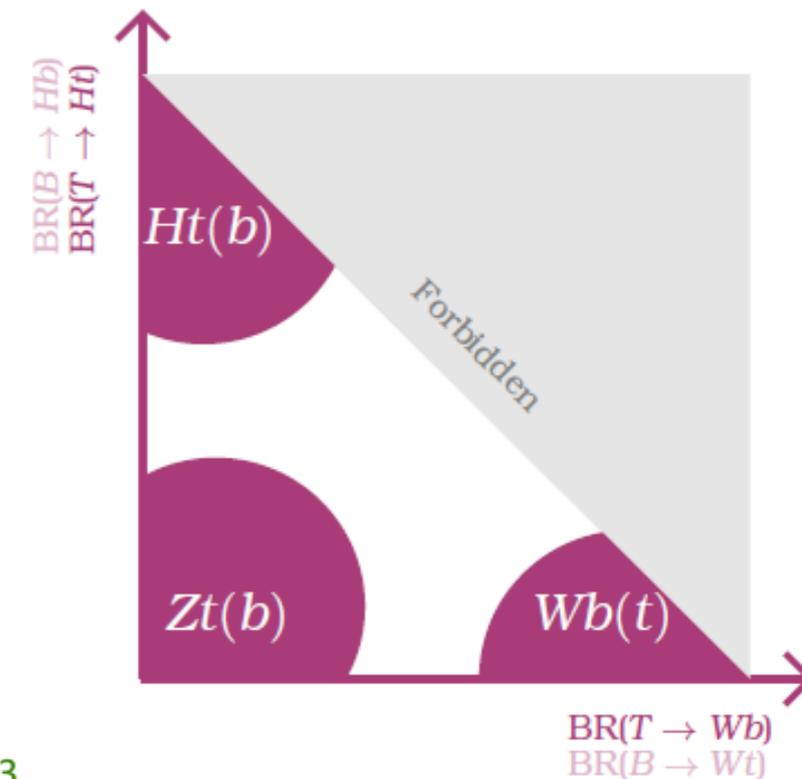
- This talk highlights ATLAS searches on **Vector Like Quarks**, **dark matter**, and **long lived particles** (non-SUSY)

# VLQ searches at ATLAS

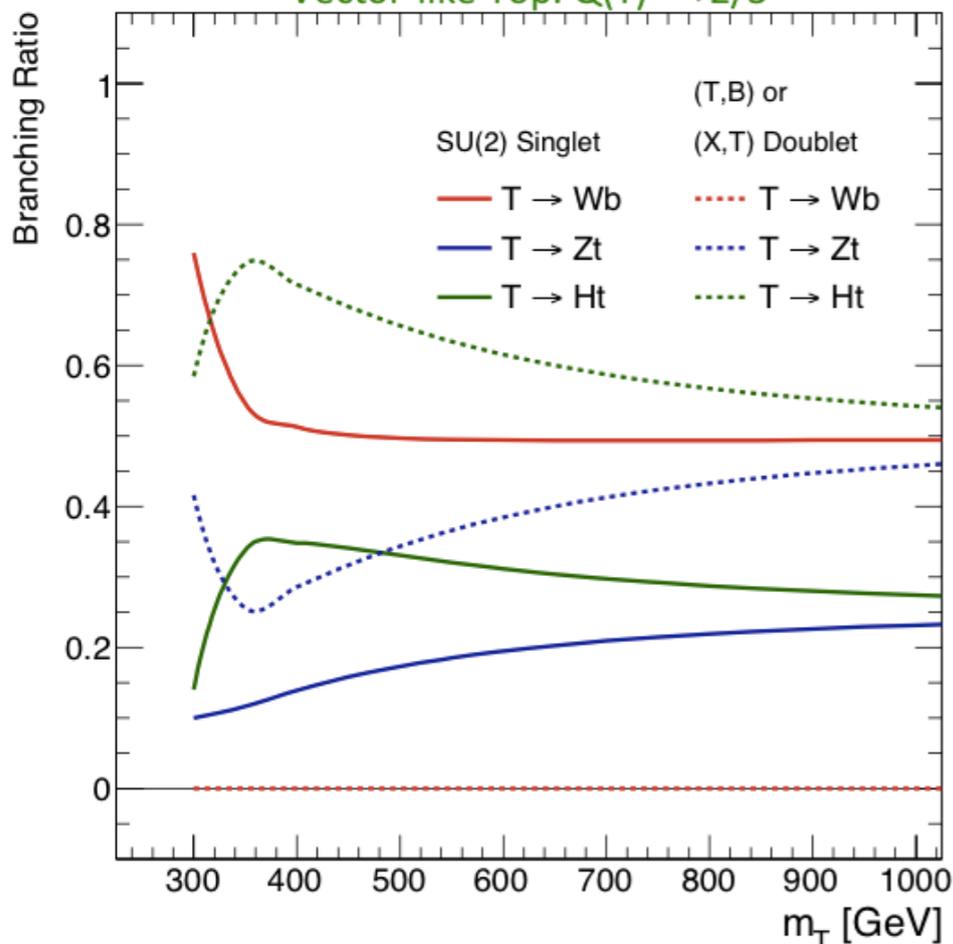
## VLQ pair production and VLQ decay



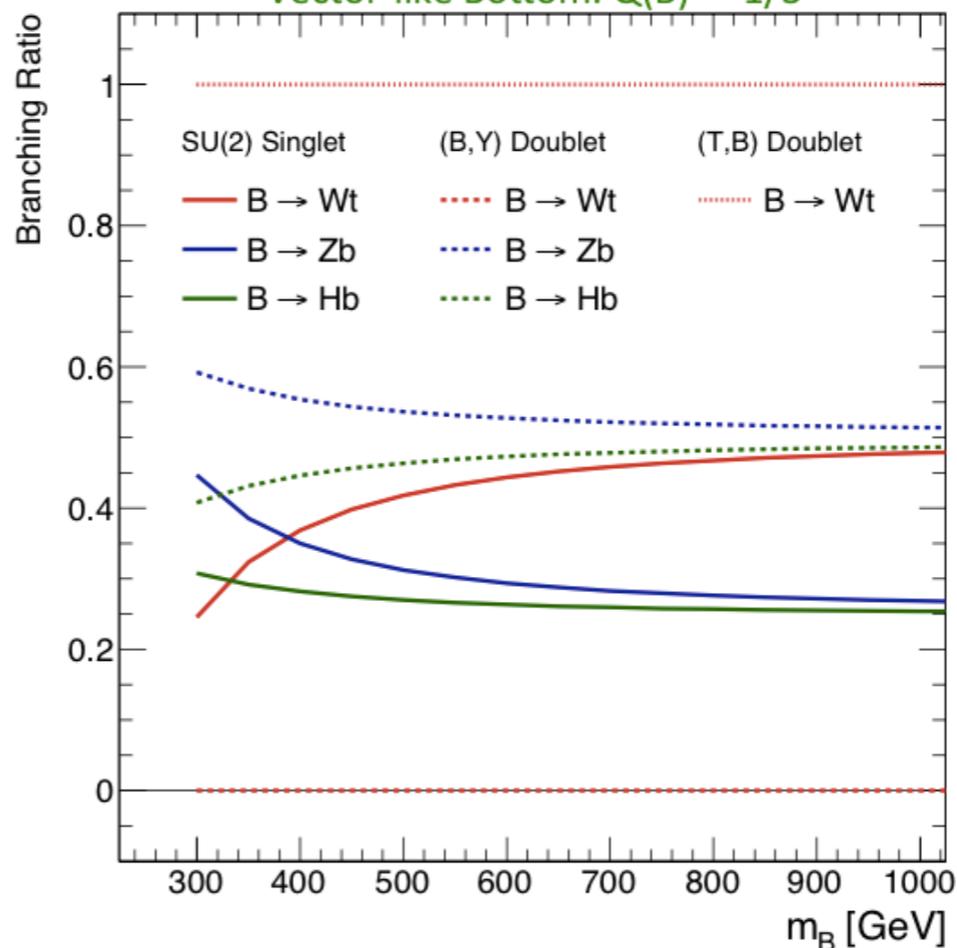
- Can perform both model dependent searches and **model “independent”** (i.e., allowing decay branching ratios to vary) searches
- **Complementary searches** in different final states



Vector-like Top:  $Q(T) = +2/3$



Vector-like Bottom:  $Q(B) = -1/3$



[[arxiv:0907.3155](https://arxiv.org/abs/0907.3155)]

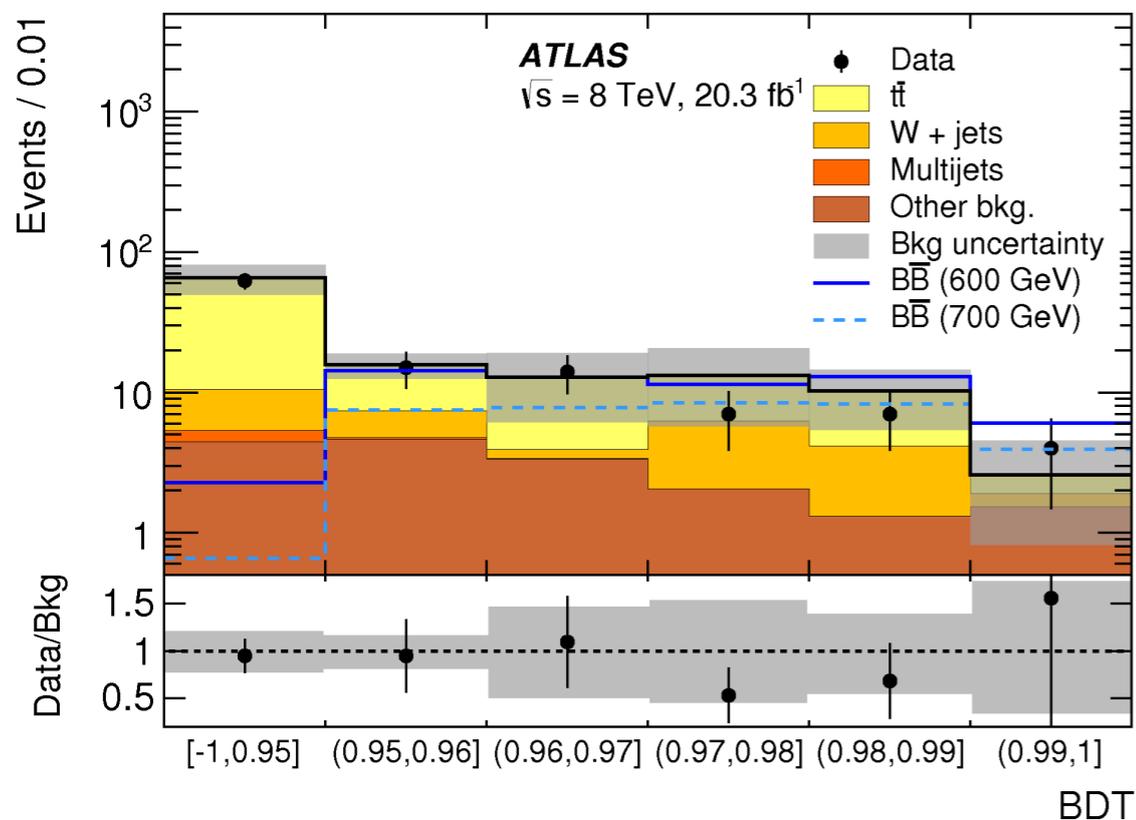
\*: though not described on this slide, searches have also been performed for  $T_{5/3}$ , as well as single production of T and B



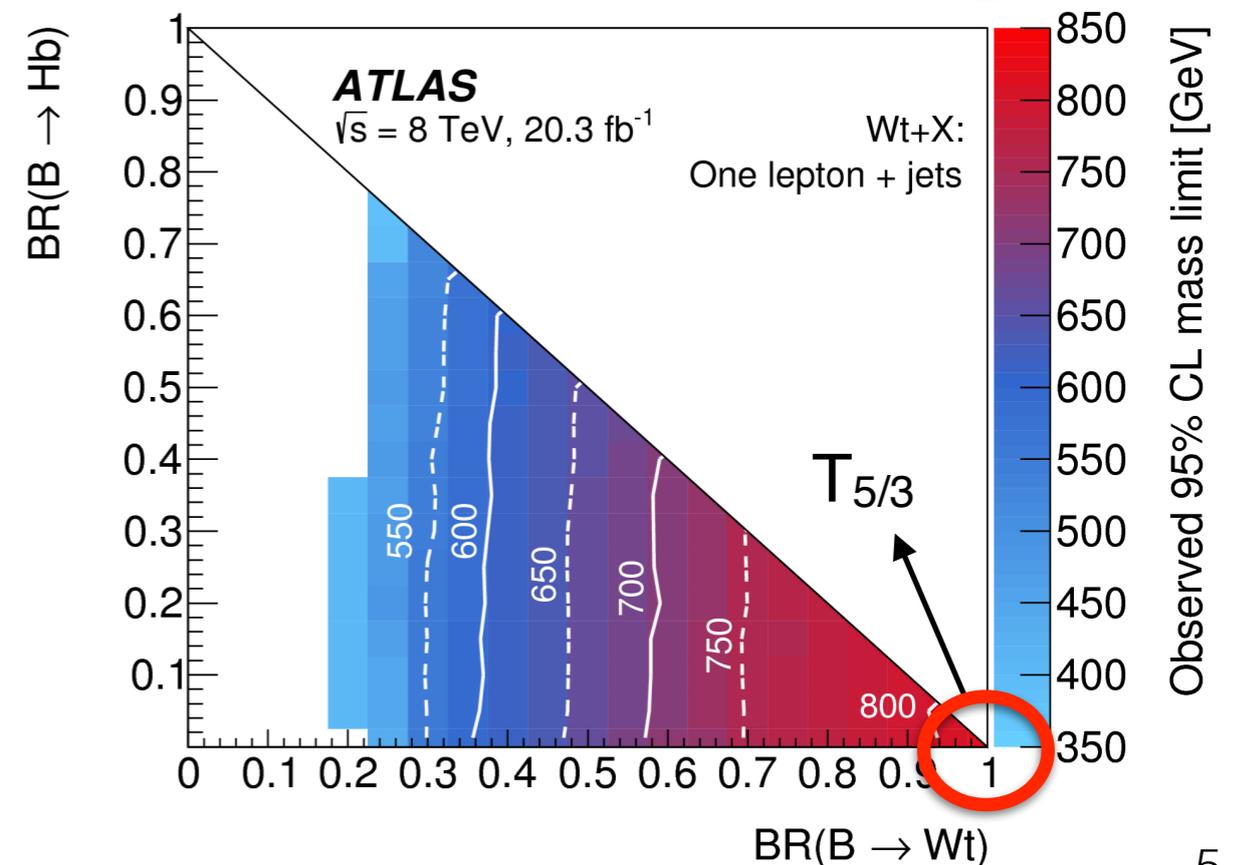
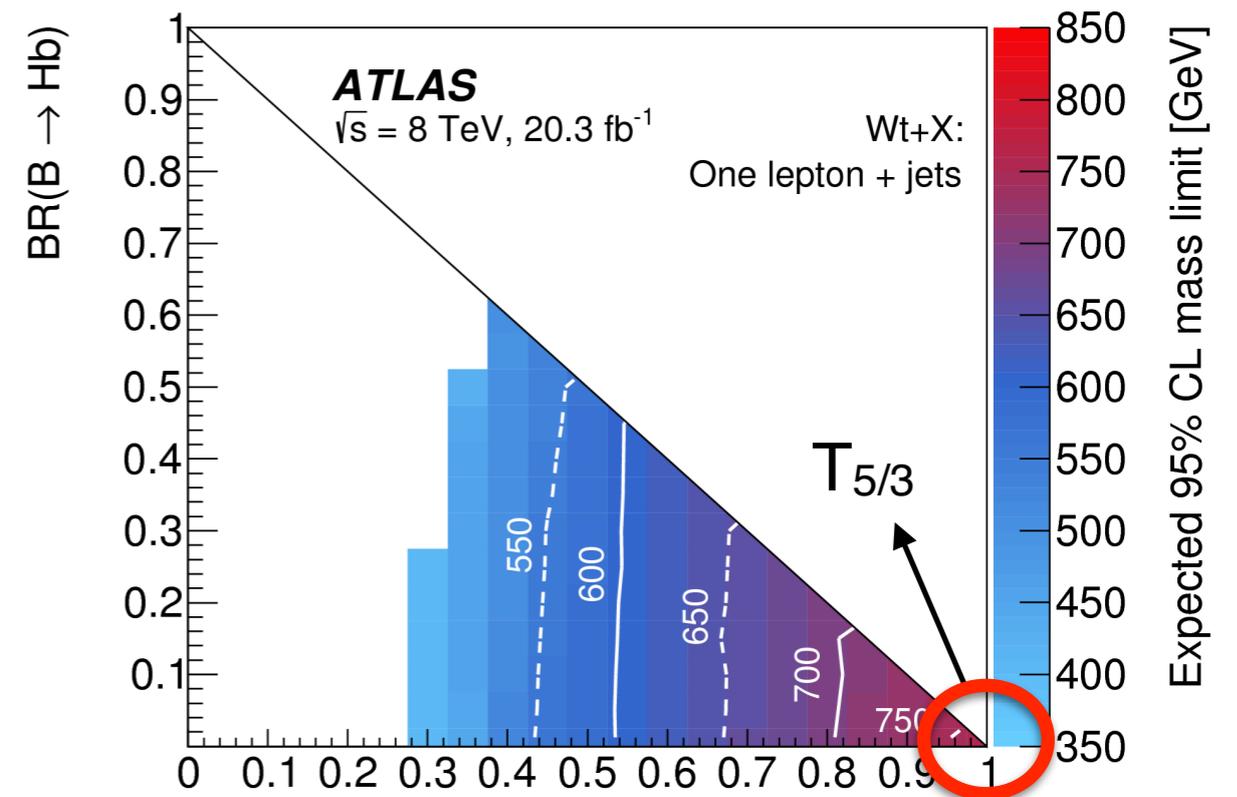
# Search for BB using l+jets events

Targets the **Wt+X** final state

- Preselects events with
  - ==1 good electron/muon ( $p_T > 25$  GeV)
  - $\geq 4$  good jets ( $p_T > 25$  GeV)
  - MET  $> 20$  GeV, MET+MT(W)  $> 60$  GeV
  - $H_T > 300$  GeV
- Signal region defined by
  - $\geq 6$  jets,  $\geq 1$  b-jets
  - $\geq 1$  hadronic W/Z candidate
  - $H_T > 800$  GeV (cut-based analysis), or  $H_T > 600$  GeV (**BDT analysis**)
- Backgrounds ( $t\bar{t}$ , W+jets) validated in various control regions



Results interpreted for **BB** and  $T_{5/3}$   $T_{5/3}$

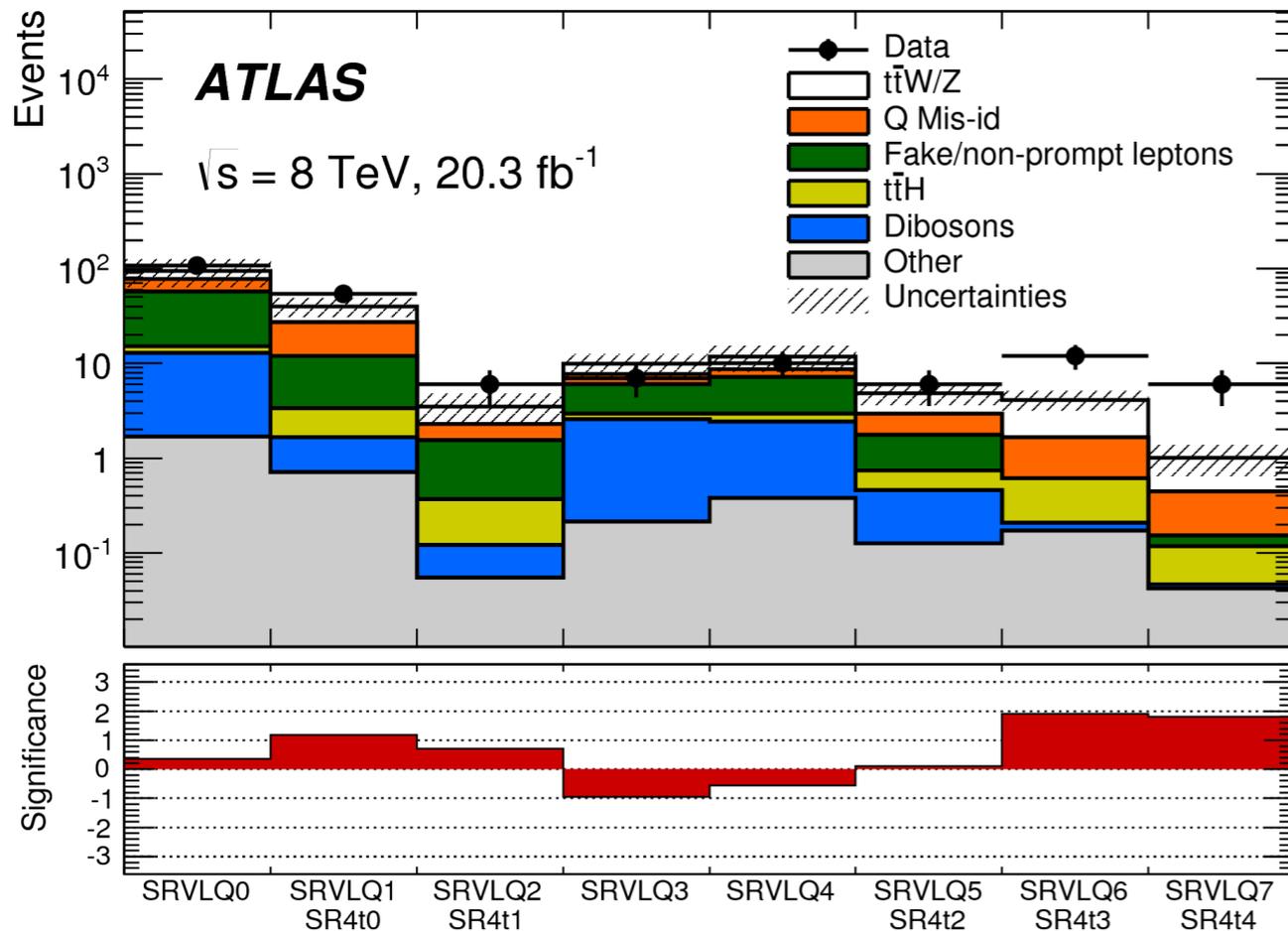


# NEW! Search for VLQ using SS+b-jets events

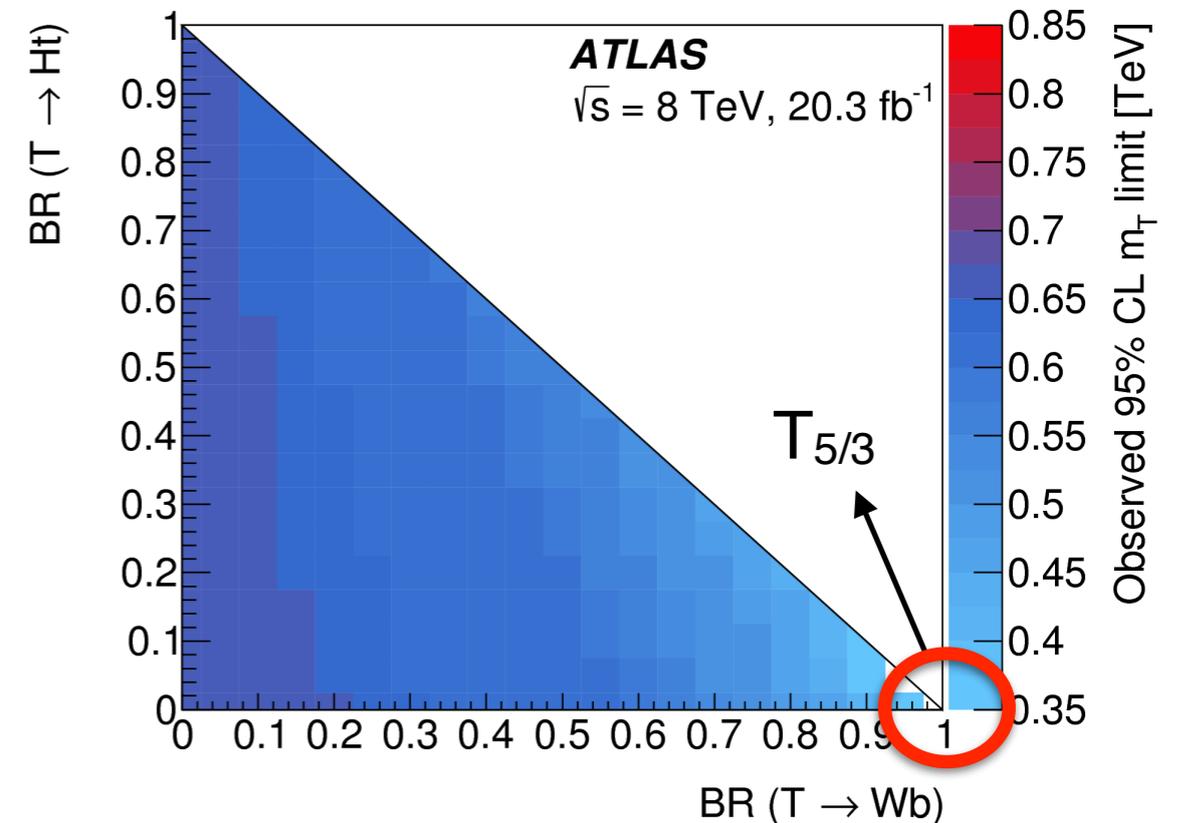
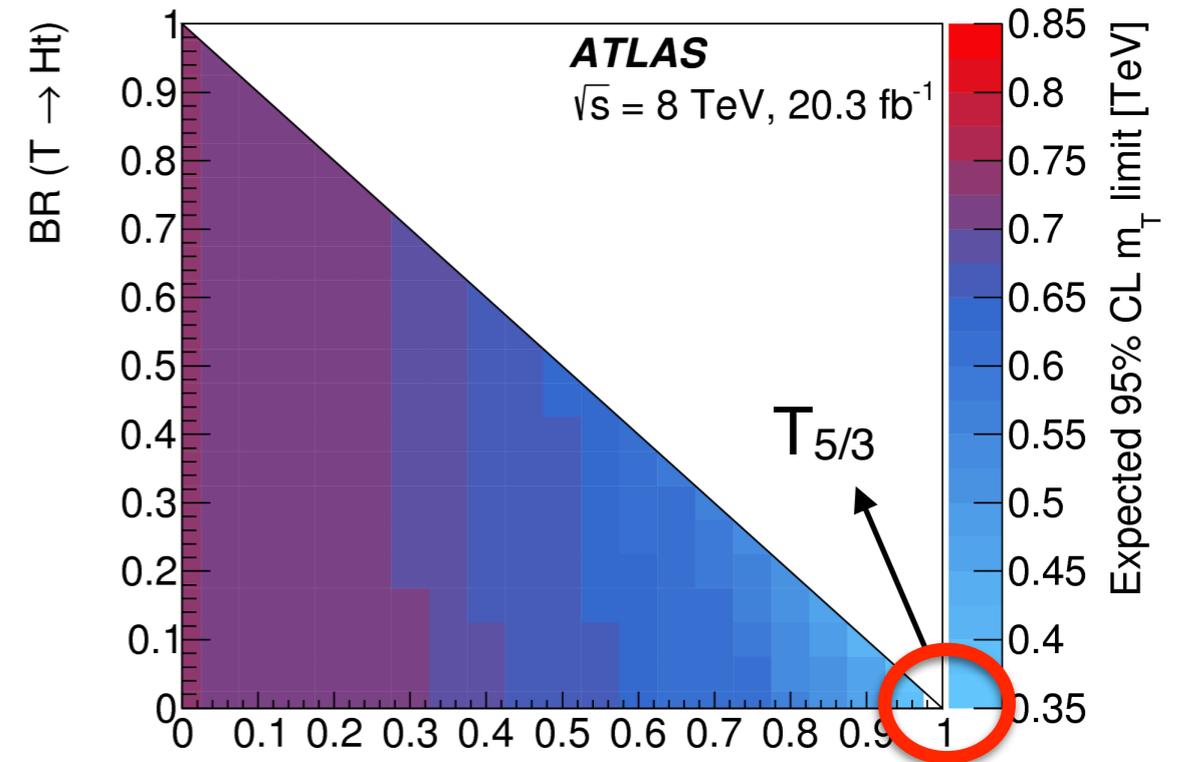
arxiv:1504.04605  
submitted to JHEP: 04/17/15

Cross-checks and/or complements the other searches targeting specific decay channels

- Main motivation is **very low SM background**
- Preselects events with a same-sign lepton pair and at least two jets including b-jets
  - Events with three or more leptons included
- **Eight exclusive signal regions** defined by varying cuts on number of b-jets, MET, and  $H_T$
- Perform simple **cut and count analysis** in each signal region and combine results
- **Up to  $2.5\sigma$  excess** is observed



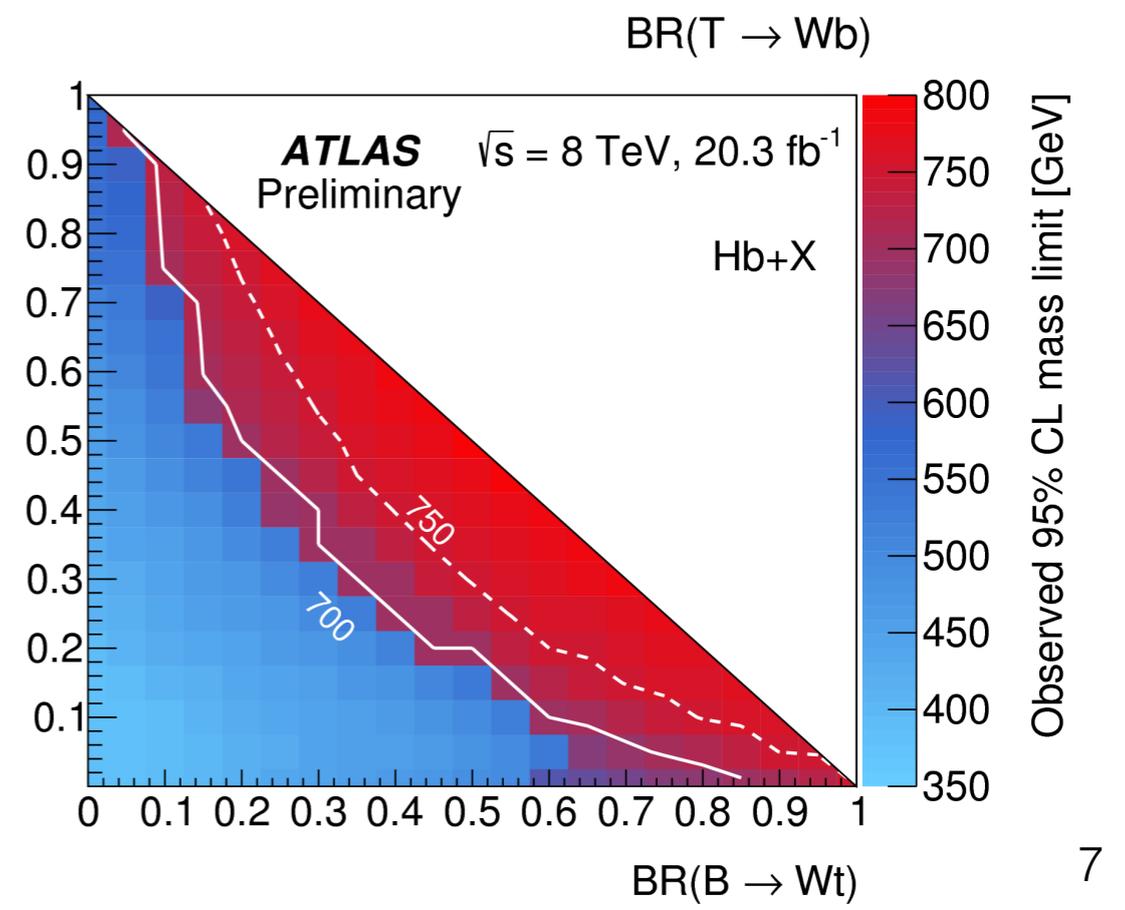
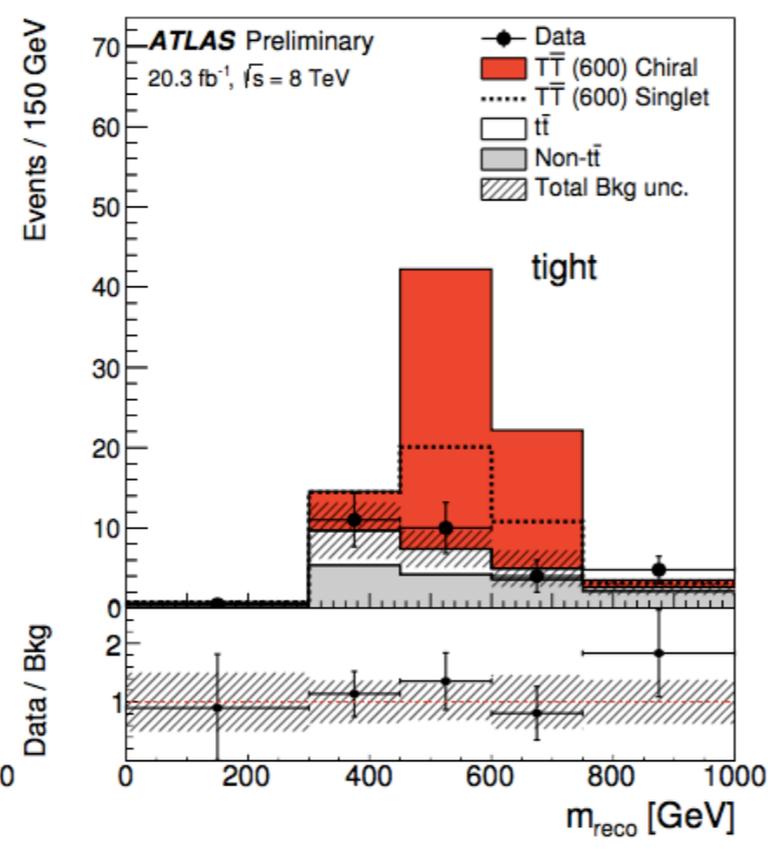
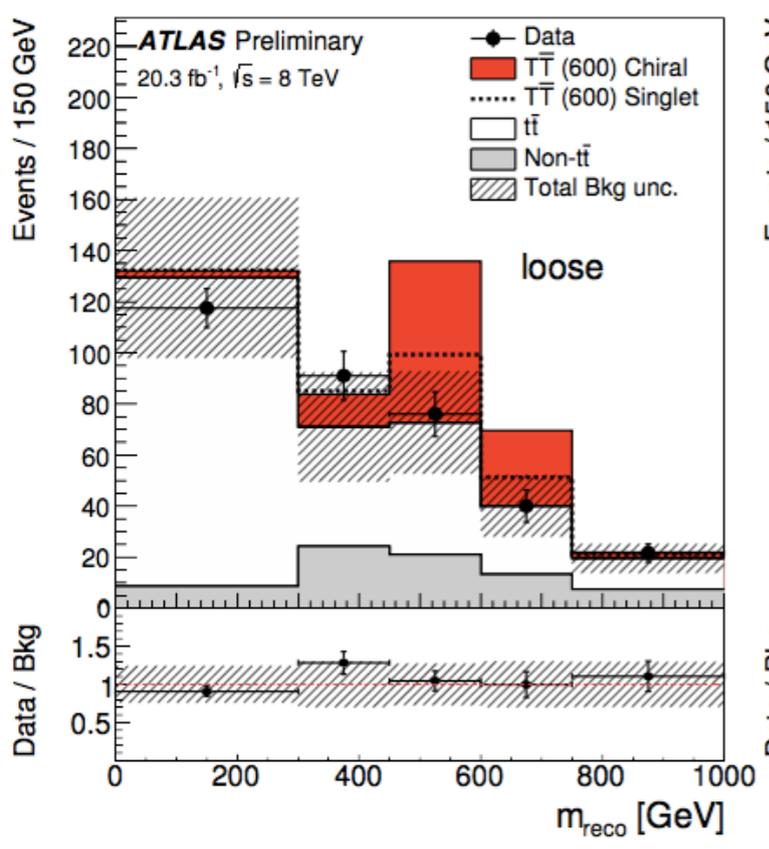
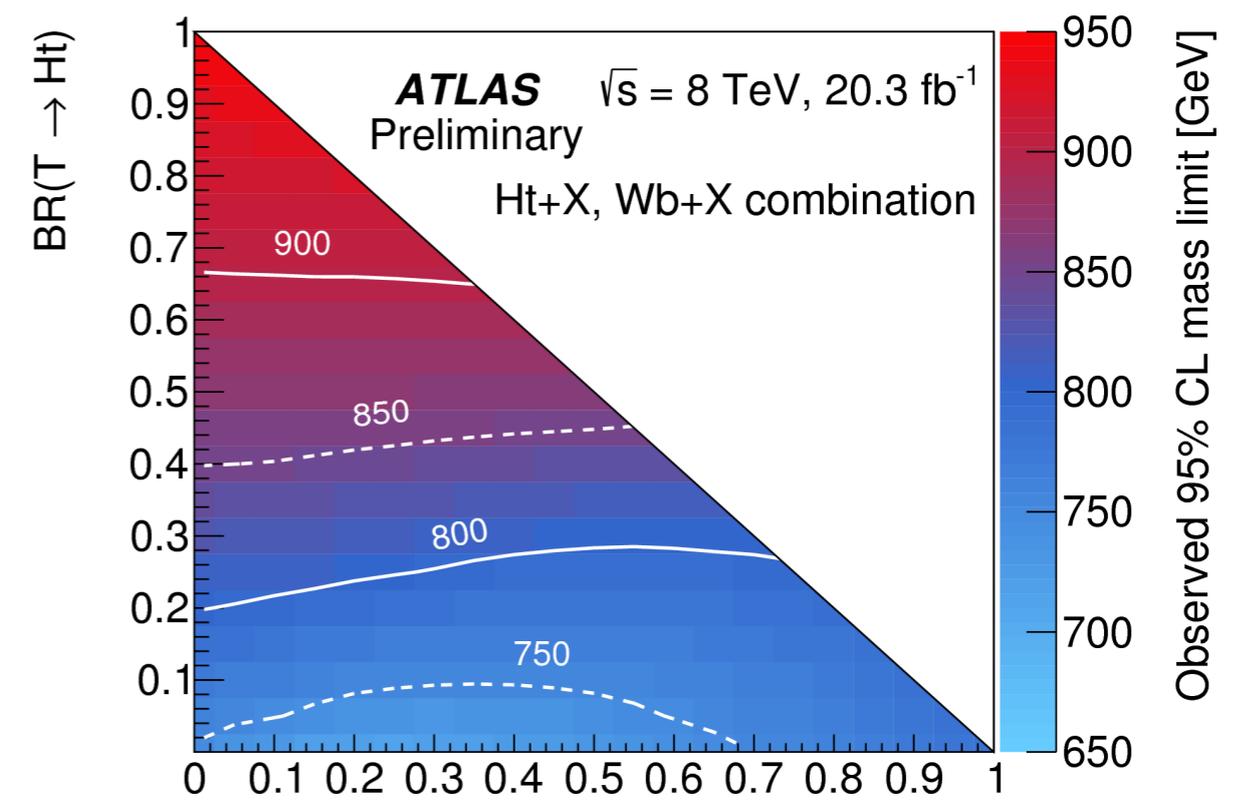
Results interpreted for **BB, TT,  $T_{5/3}T_{5/3}$ ,  $T_{5/3}$**



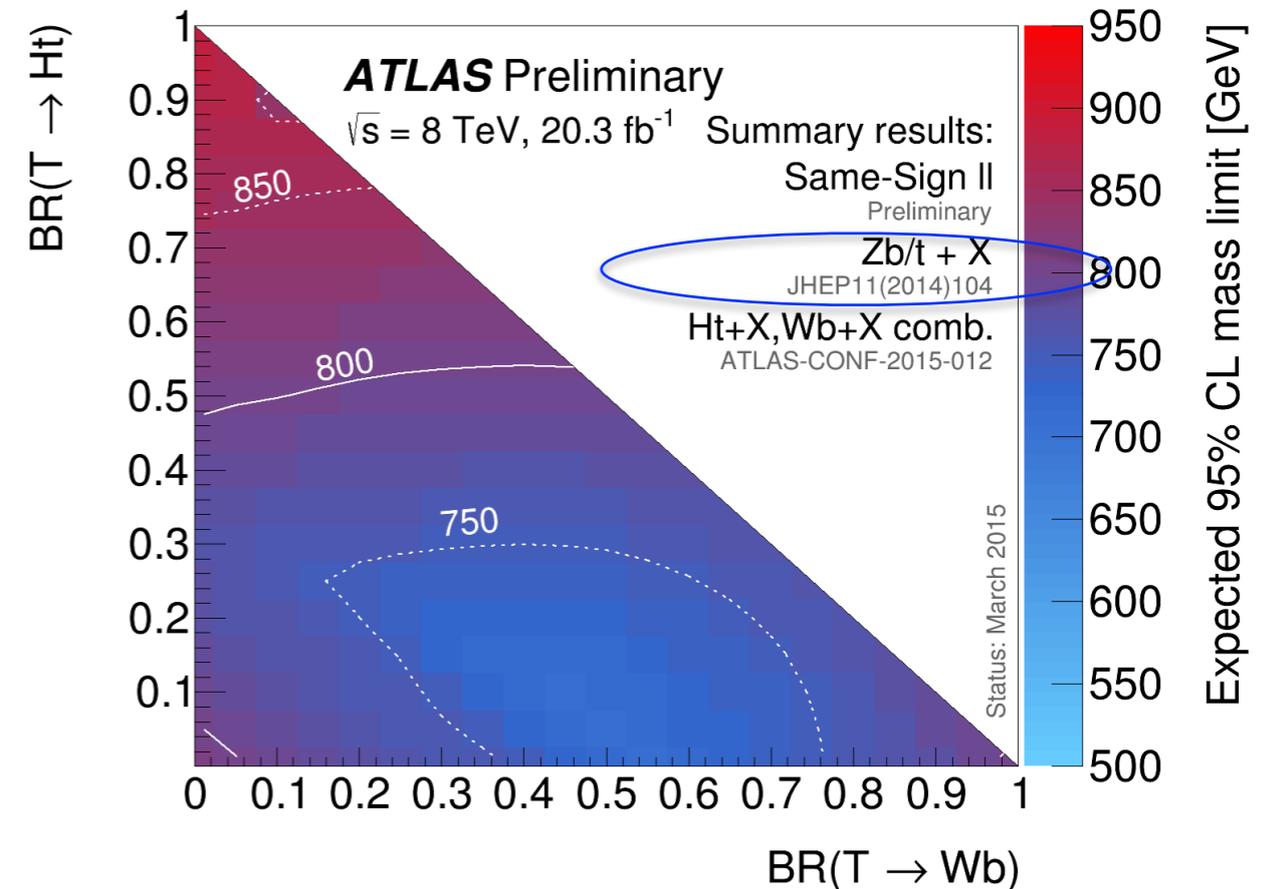
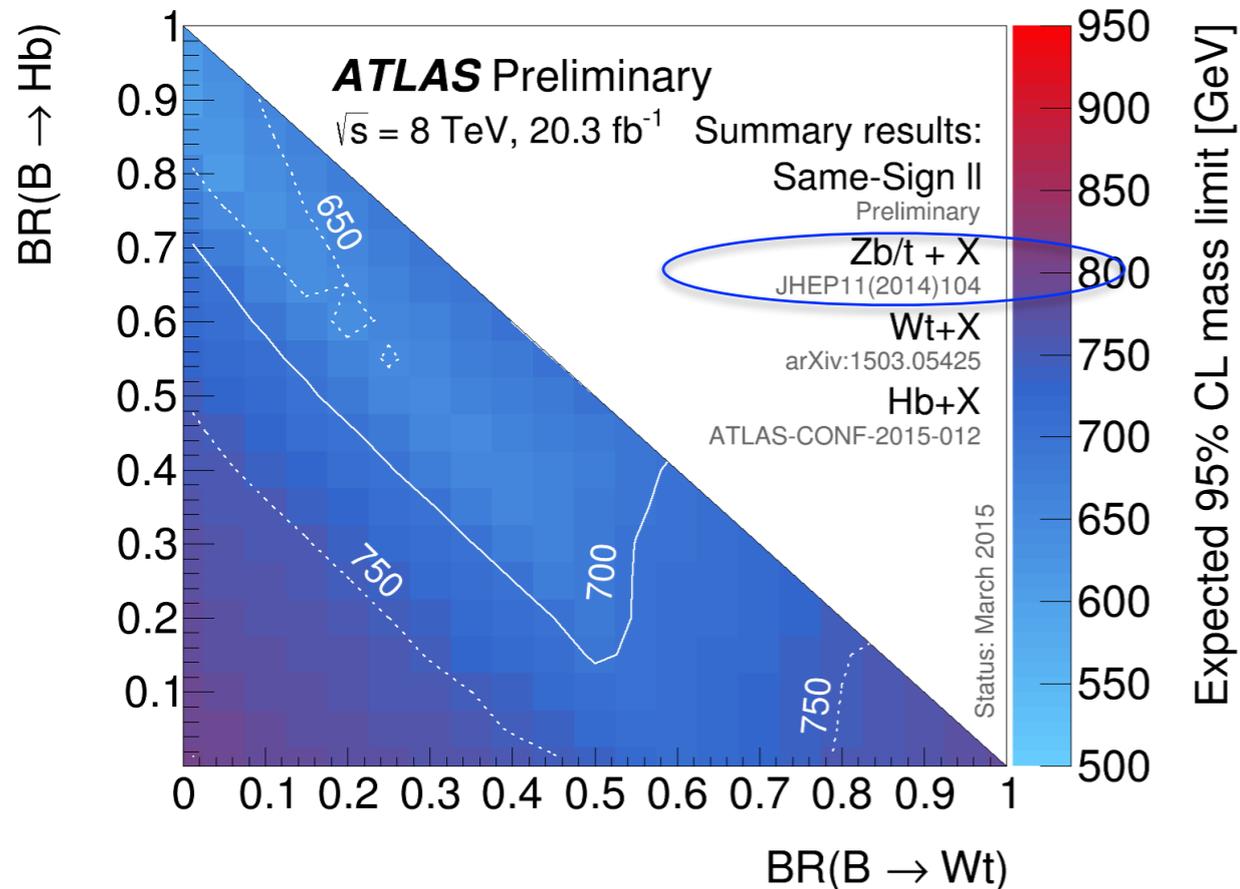
Dedicated analyses for  $TT \rightarrow W_{had}b+X$ ,  $TT \rightarrow Ht+X$ , and  $BB \rightarrow Hb+X$

- All: require single isolated electron or muon, large MET and/or  $MT(W)$ , and multiple jets including b-jets
- $W_{had}b+X$ : requires a **boosted** (or semi-boosted) hadronically-decaying W boson
- $Ht+X$  and  $Hb+X$ : exploring the final state with Higgs decaying to bb, resulting in high b-jet multiplicity
- $W_{had}b+X$  and  $Ht+X$  are combined to set limits on TT

Results interpreted for **BB** and **TT**

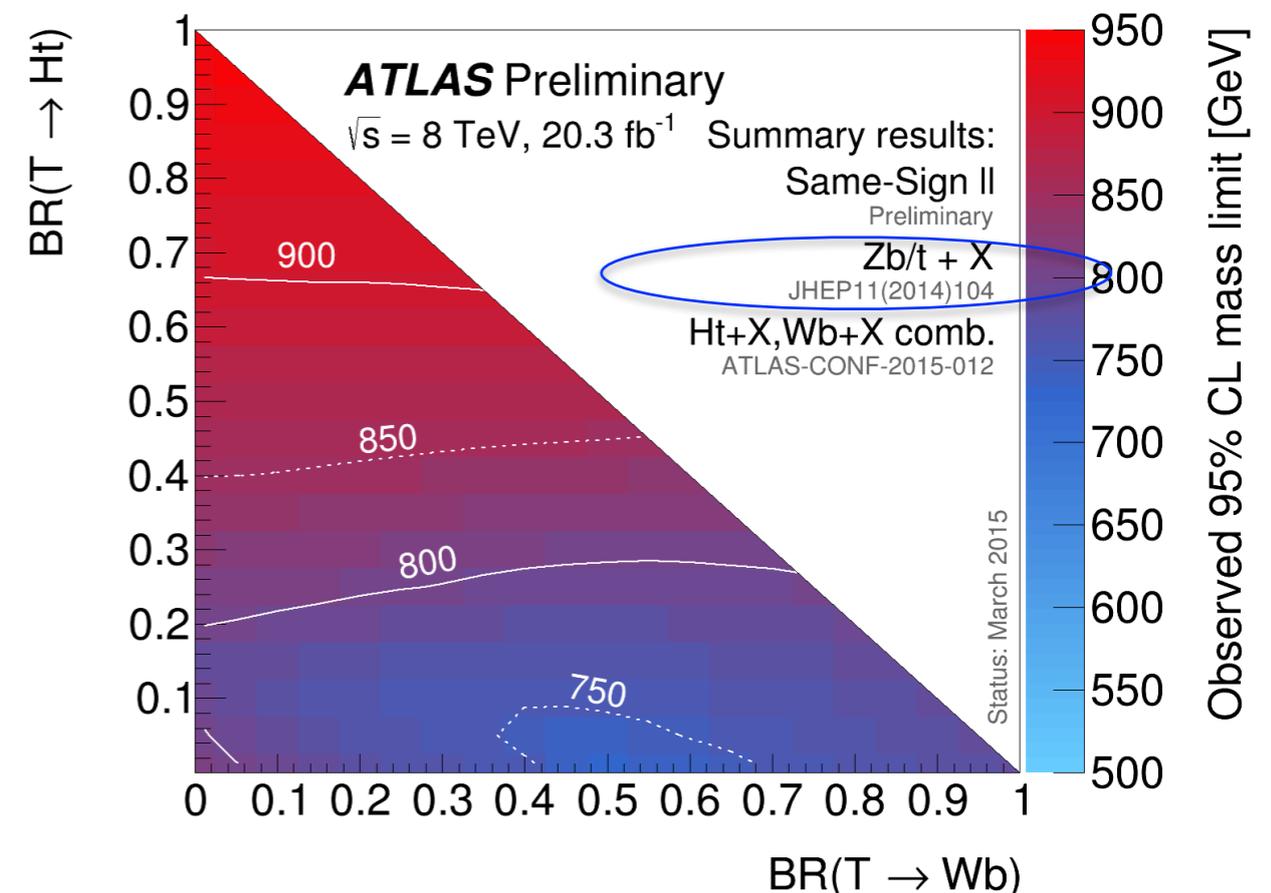
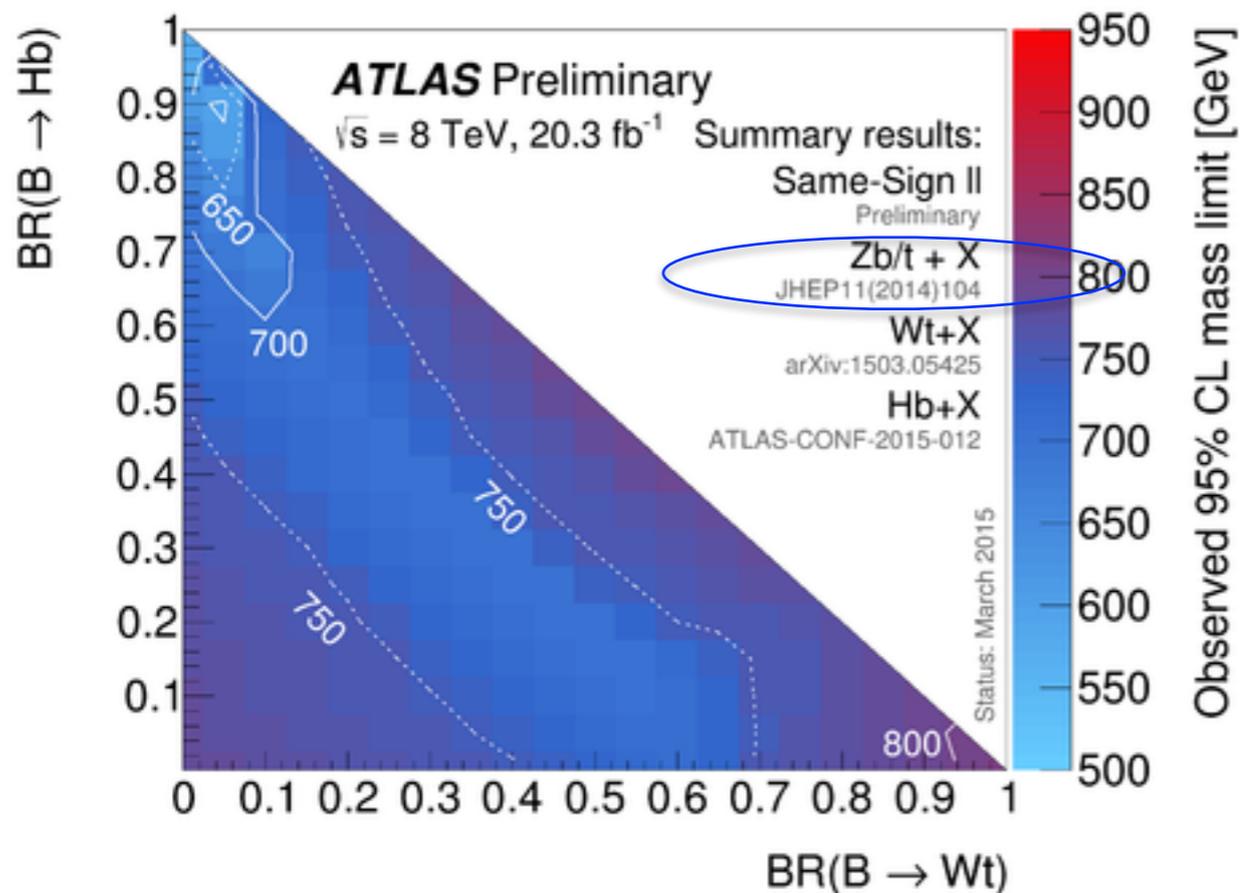


- Expected limits



- Sensitivity reaches up to  $\sim 750 \text{ GeV}$  for B and  $\sim 850 \text{ GeV}$  for T
  - Pushing near the naturalness limit of  $\sim 1 \text{ TeV}$

- Observed limits

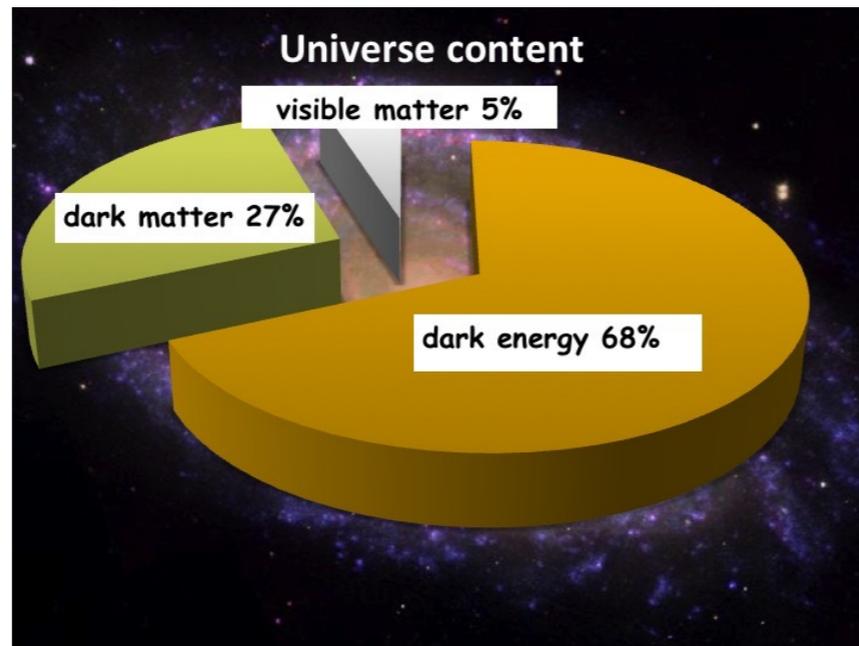


- Observed limits more stringent: up to  $\sim 800$  ( $\sim 950$ ) GeV for B(T)
  - Meaning a deficiency is observed in data
  - But this is not true for some of the search channels, like the **SS+b-jets**

# Dark matter searches at ATLAS

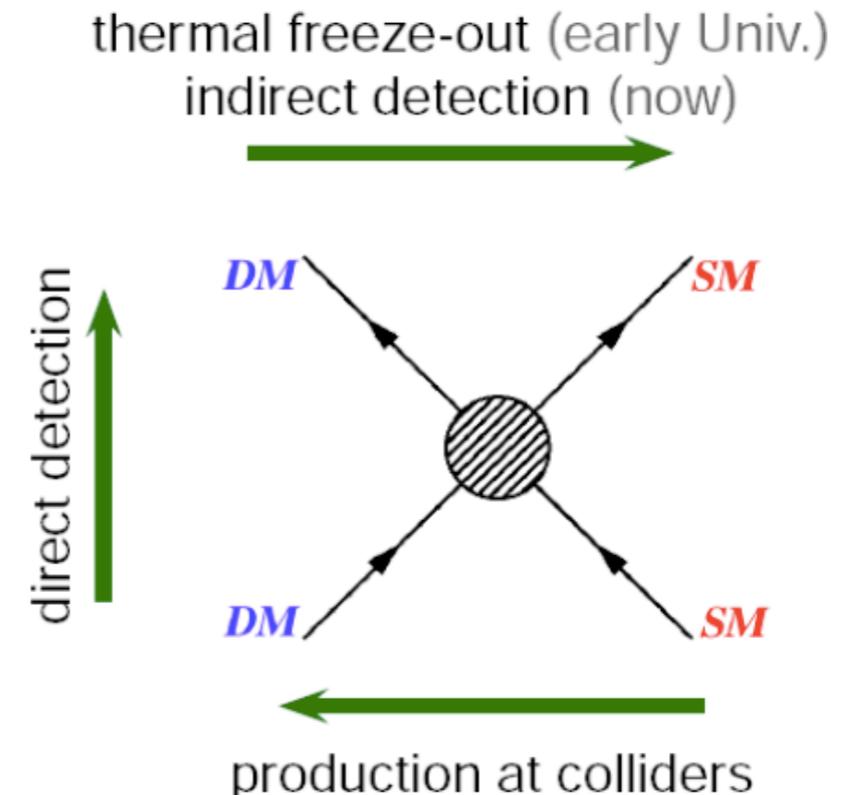
- Dark matter: **one example of BSM physics we are certain of**

~27% of the matter-energy content of the universe

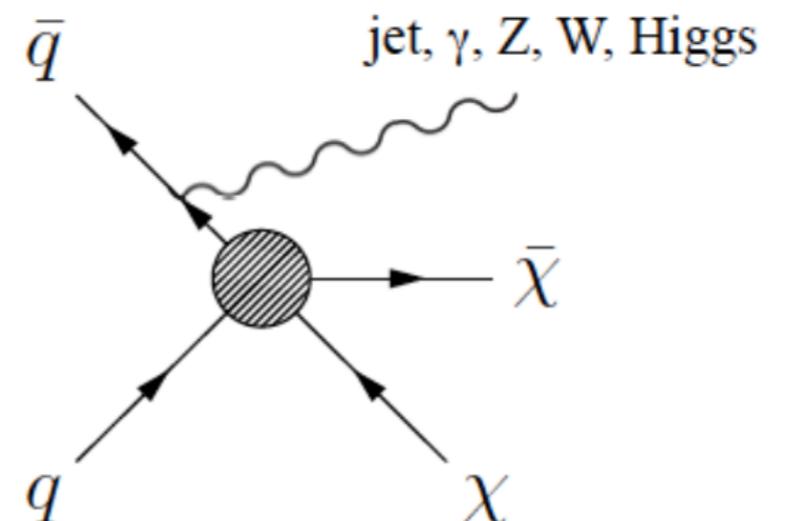


- What is dark matter? One possibility is **WIMPS** (Weakly Interacting Massive Particles)
  - matches cosmological observations (e.g., thermal relic abundance)
  - dark, stable, cold; weakly interacting with standard model particles
  - masses up to **a few TeV**
  - can be described with EFT operators if assuming low momentum transfer ([arxiv:1008.1783](https://arxiv.org/abs/1008.1783))

- EFT contact interaction
  - complementary search strategies at different experiments



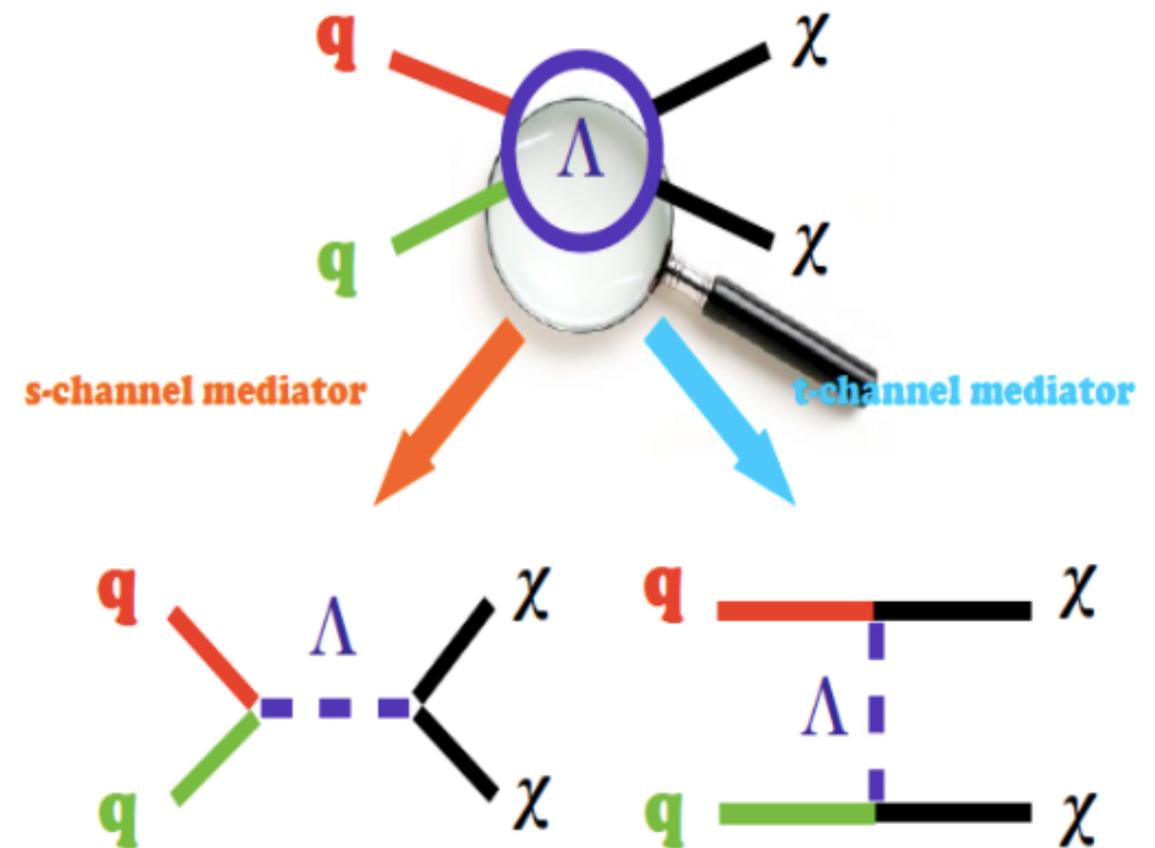
- Searches at ATLAS focuses on **“Mono-X”** (sensitive to light WIMPs)



# EFT model and simplified models

- The EFT description provides a simple, convenient benchmark for DM searches, to avoid being dependent on details of a specific theory
  - Various operators, and two free parameters: suppression scale  $M_*$  and dark matter mass  $m_\chi$
  - Minimum requirement to be valid:  $Q_{tr} < M_{med} = f(g_i, M_*)$ .** Possible solutions:
    - Remove events failing to pass this constraint (“truncation”)
    - Use simplified models with an explicit mediator which is integrated out in EFT
- Simplified models: s-channel or t-channel, free parameters:  $M_{med}$ ,  $m_\chi$ , and  $g_{SM}g_{DM}$

Name	Initial state	Type	Operator
C1	$qq$	scalar	$\frac{m_q}{M_*^2} \chi^\dagger \chi \bar{q} q$
C5	$gg$	scalar	$\frac{1}{4M_*^2} \chi^\dagger \chi \alpha_s (G_{\mu\nu}^a)^2$
D1	$qq$	scalar	$\frac{m_q}{M_*^3} \bar{\chi} \chi \bar{q} q$
D5	$qq$	vector	$\frac{1}{M_*^2} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q$
D8	$qq$	axial-vector	$\frac{1}{M_*^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu \gamma^5 q$
D9	$qq$	tensor	$\frac{1}{M_*^2} \bar{\chi} \sigma^{\mu\nu} \chi \bar{q} \sigma_{\mu\nu} q$
D11	$gg$	scalar	$\frac{1}{4M_*^3} \bar{\chi} \chi \alpha_s (G_{\mu\nu}^a)^2$



Spin independent: C1, C5, D1, D5, D11

Spin dependent: D8, D9



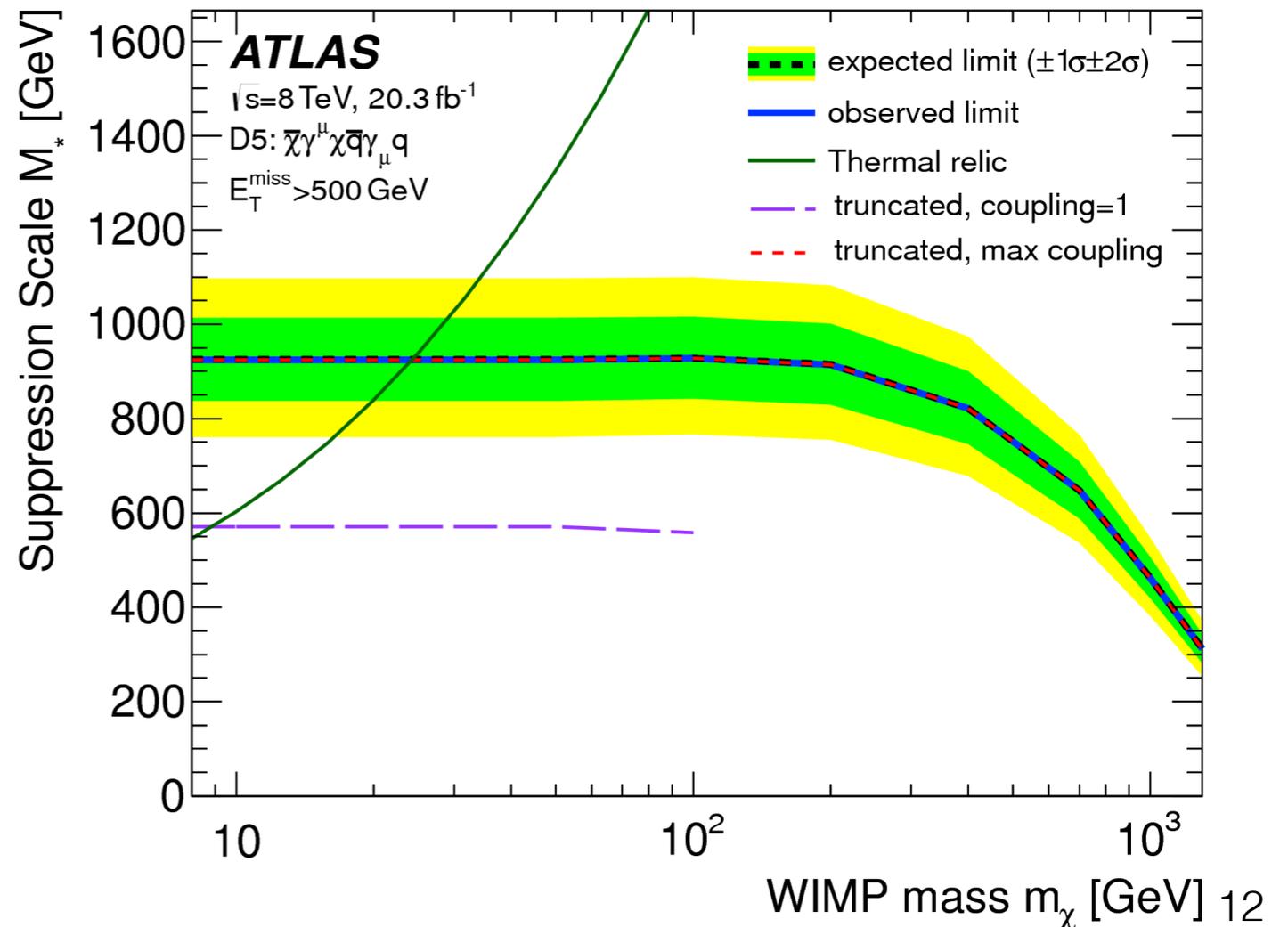
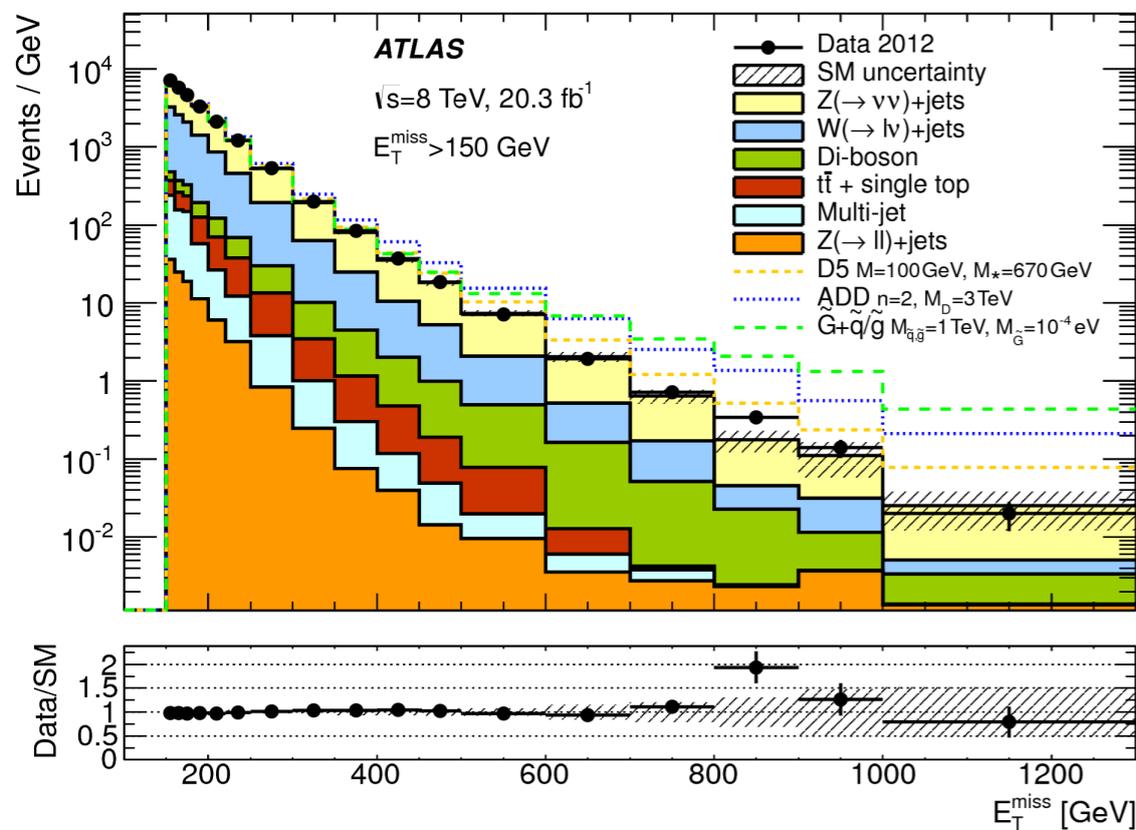
## Event selection

- MET > 150 GeV and at least one jets with  $p_T > 30$  GeV and  $|\eta| < 4.5$
- Leading jet:  $p_T > 120$  GeV,  $|\eta| < 2.0$ , and also satisfying  $p_T / \text{MET} > 0.5$
- All selected jets:  $\Delta\Phi(\text{jet}, \text{MET}) > 1$
- Veto electrons and muons
- SR1 – SR9: increasing MET thresholds from 150 to 700 GeV

- No significant excess observed. Limits set at 95% CL, both in the **EFT framework** and in a **simplified model where the mediator is a Z'** (corresponding to D5)
- In the EFT framework, set limits on  $M_*$  as a function of  $m_\chi$ , in the most sensitive SR for each operator
  - D5:  $M_* > \sim 900$  GeV for low  $m_\chi$

## Major backgrounds

- Z( $\nu\nu$ )+jets, W( $lv$ )+jets

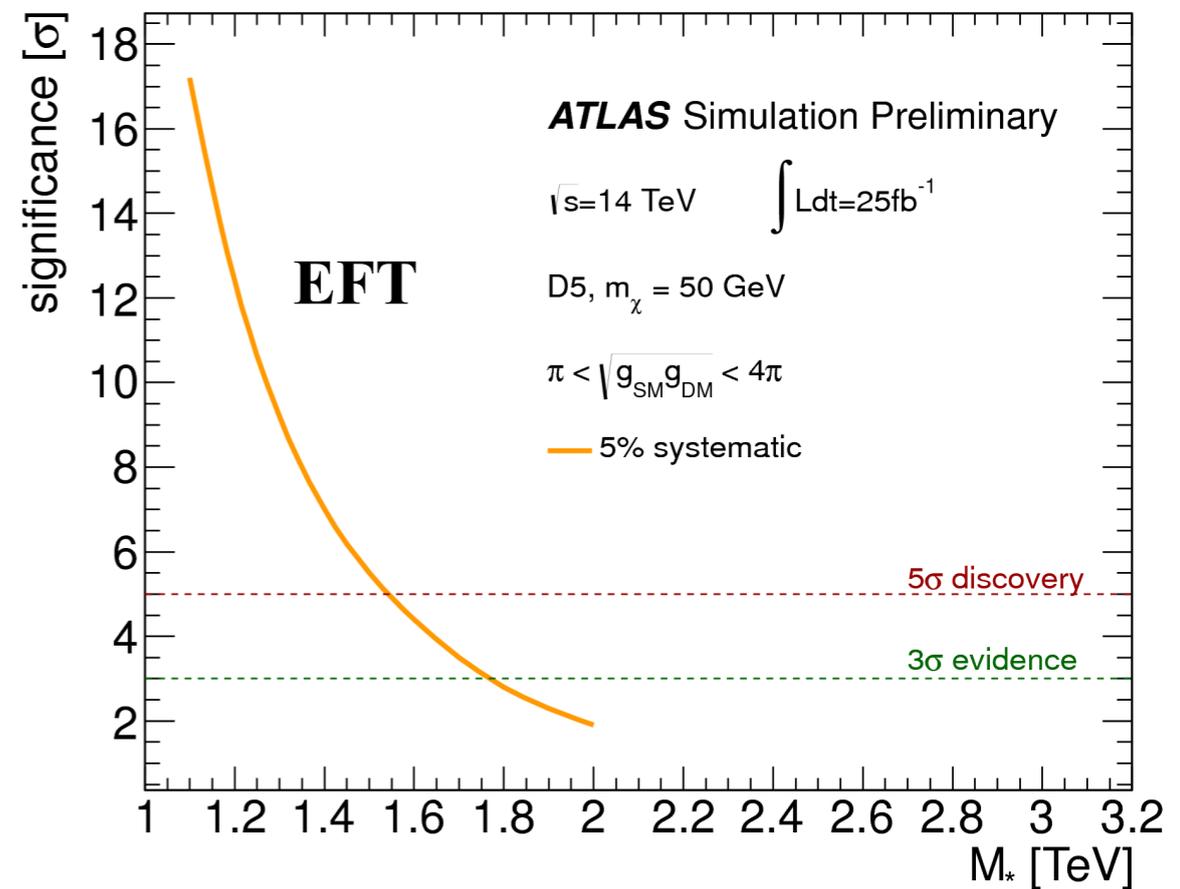
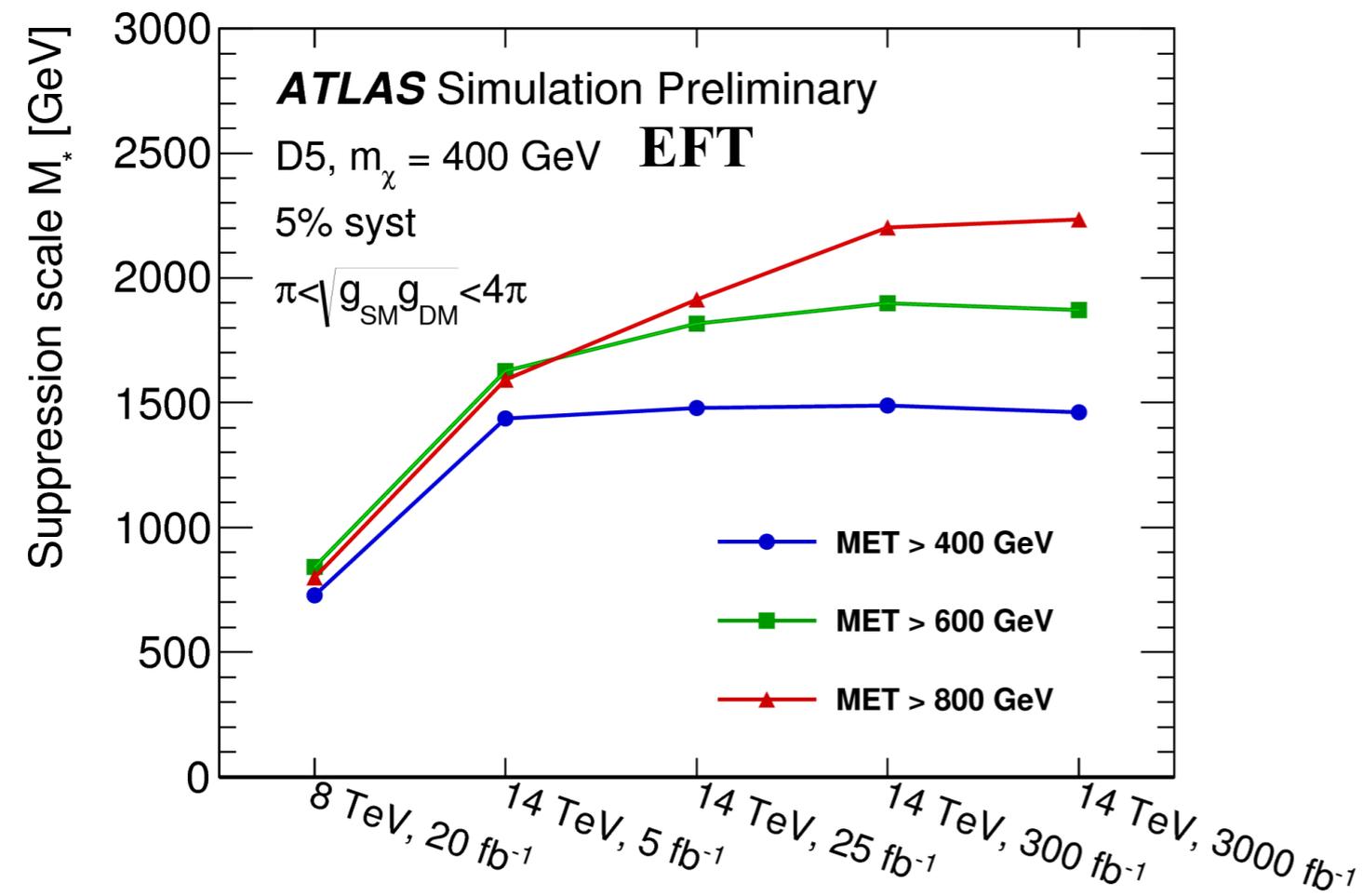


# Prospects for Mono-jet search at 14 TeV [ATLAS-PHYS-PUB-2014-007](#)

- Adopting similar analysis strategy as 8 TeV
- Generator-level distributions + smearing for pile-up and detector conditions
- ATLAS and CMS are agreeing on the simplified model benchmarks for Run 2, and on a common definition of the EFT validity

- **Surpassing previous limits within 1st year of data taking**

	$\sqrt{s}$ [TeV]	$\mu$	$L$ [ $\text{fb}^{-1}$ ]
	8	20	20
Phase 0 upgrade (2014-2015)	14	60	25
Phase 1 upgrade (2018)	14	60	300
Phase 2 upgrade (2022)	14	140	3000

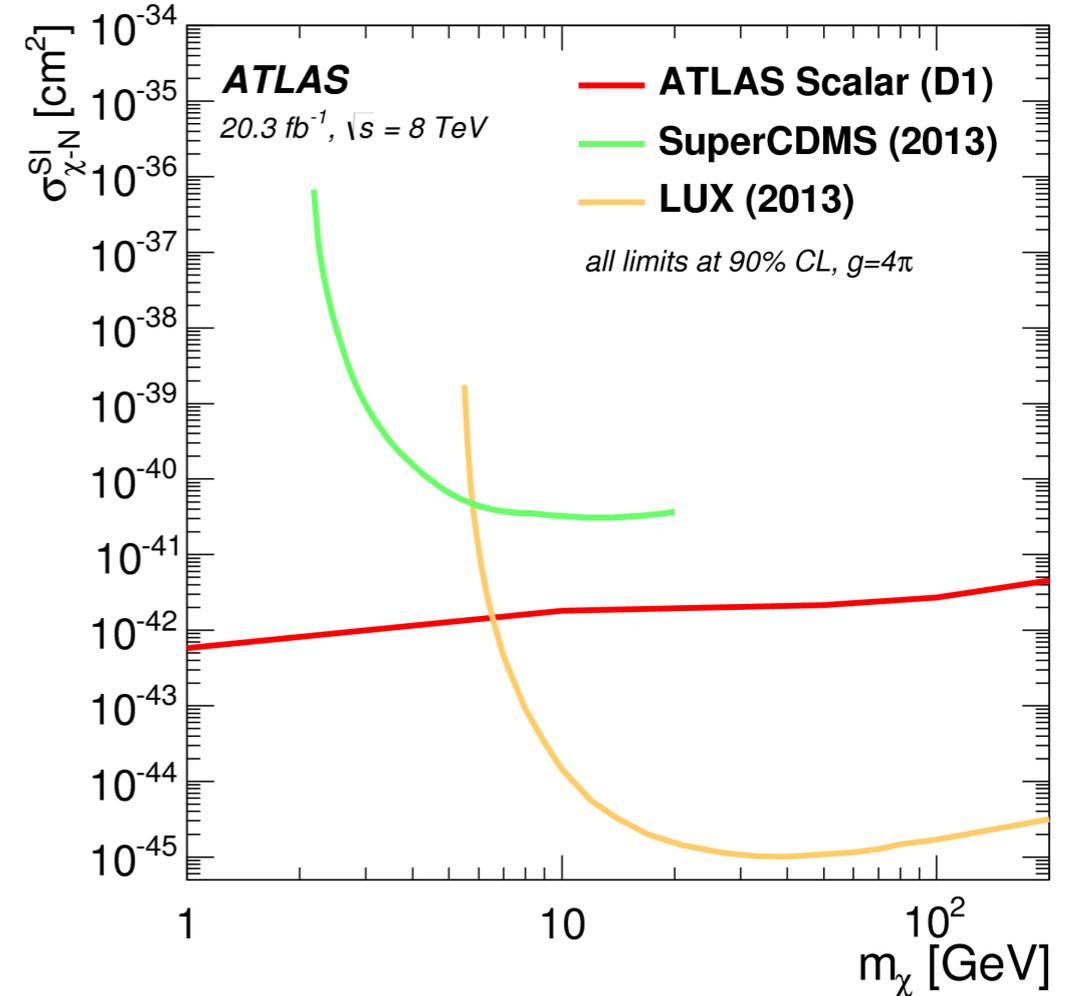
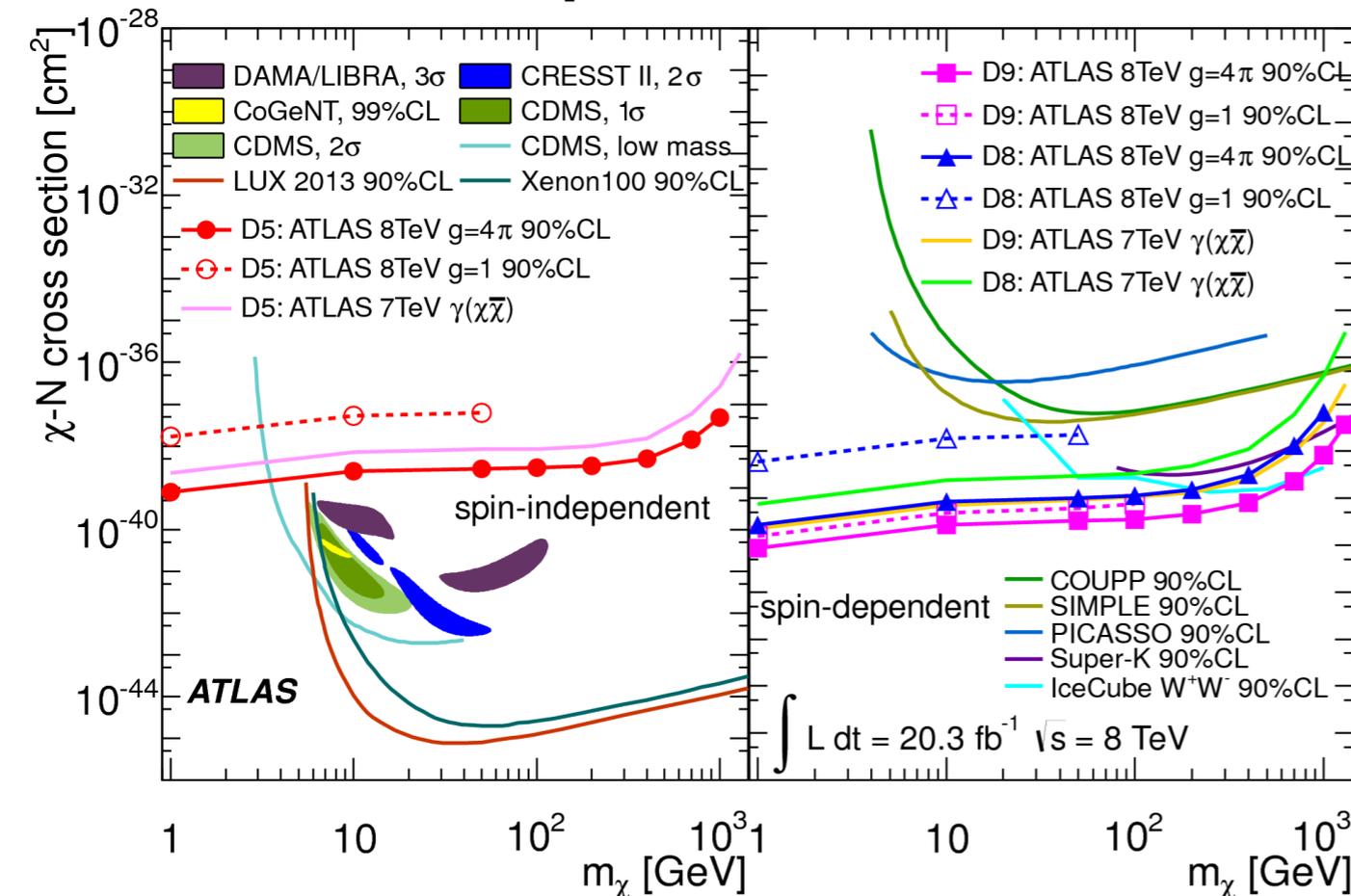


# ATLAS “Mono-X” search program

- Extensive search program conducted by ATLAS. Higgs is also entering the game

**Mono- $\gamma$ :** [arxiv:1411.1559](https://arxiv.org/abs/1411.1559)

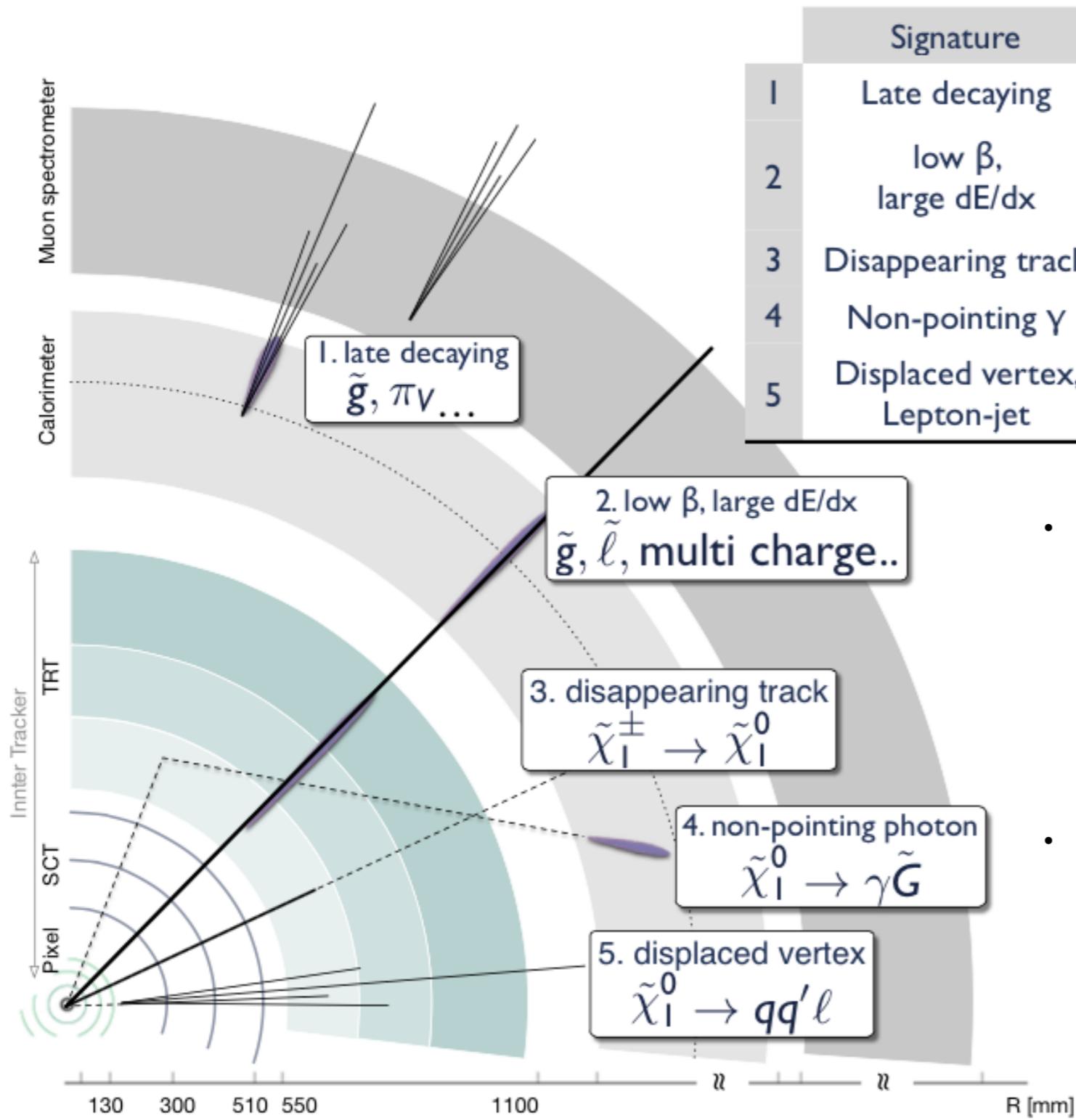
**Mono-HF:** [arxiv:1410.4031](https://arxiv.org/abs/1410.4031)



- Other (less recent) results using full 8 TeV data:
  - **Mono-Z(II):** [arxiv:1404.0051](https://arxiv.org/abs/1404.0051); **Mono-Z/W (jj):** [arxiv:1309.4017](https://arxiv.org/abs/1309.4017)
- Specific single top plus dark matter model: [arxiv:1410.5404](https://arxiv.org/abs/1410.5404)
- Summary of best limits on the suppression scale,  $M_*$ :**

EFT D5 operator (Dirac)	$M_*$	974 GeV	at 90% CL for $m(\chi) < 100$ GeV	1502.01518
EFT D9 operator (Dirac)	$M_*$	2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017

# Long lived particles: signatures and BSM models



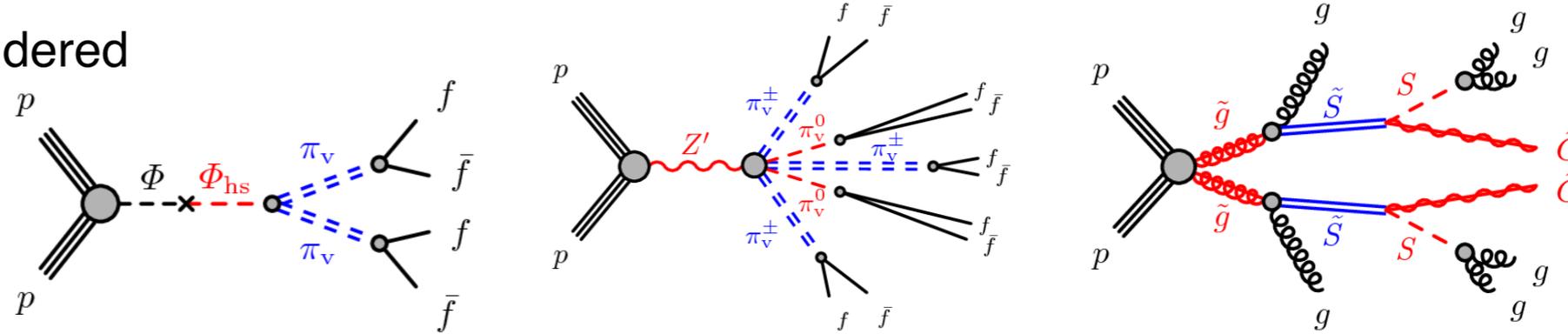
	Signature	Scenario	decay-length sensitivity
1	Late decaying	split SUSY, Hidden Valley	—
2	low $\beta$ , large $dE/dx$	GMSB, Split-SUSY, Stealth SUSY, Multi-charged	>1000mm
3	Disappearing track	AMSB (wino-LSP)	O(100-1000)mm
4	Non-pointing $\gamma$	GMSB	O(100-1000)mm
5	Displaced vertex, Lepton-jet	RPV, GMSB, Hidden Valley	O(10-100)mm

- Comprehensive searches at ATLAS, covering almost all possible experimental signatures with innovative analysis techniques
  - Presenting results from the ATLAS Exotics group here
- Low SM background in general. **Instrumental background dominates.** Requires good understanding of:
  - material effects
  - alignment
  - timing calibration
  - non-collision background

# Displaced jets in inner/muon detector

arxiv:1504.03634  
submitted to PRD: 04/14/15

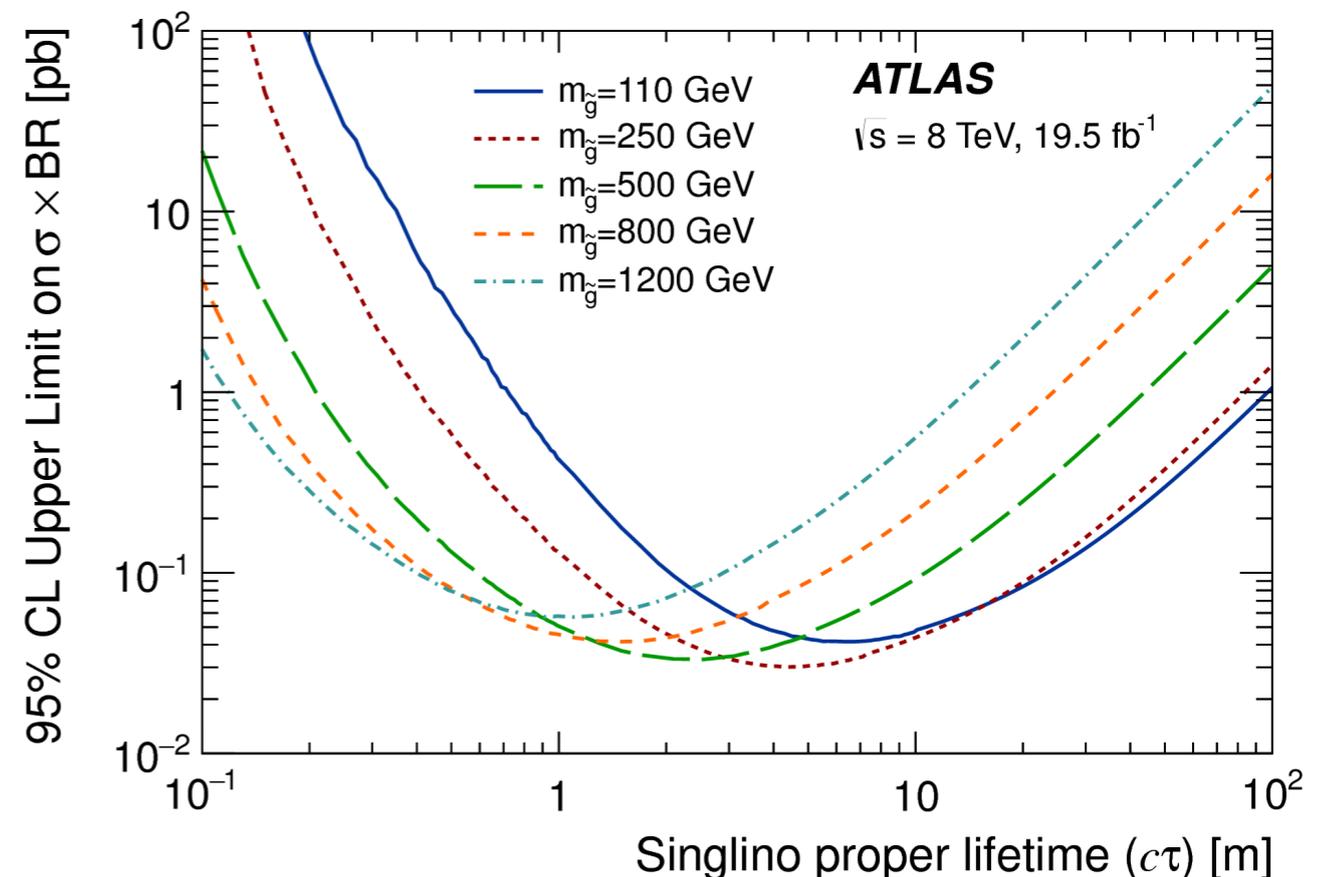
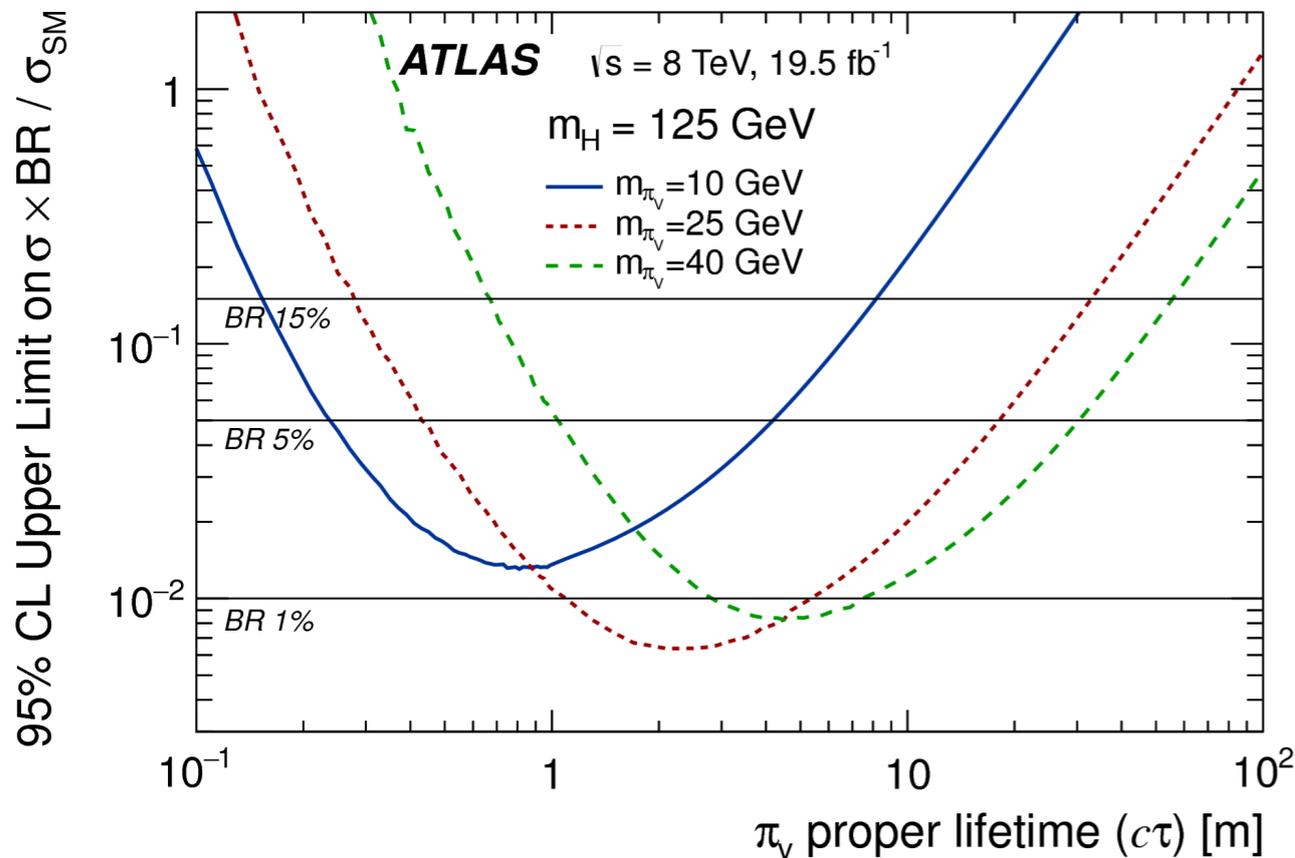
- Three benchmark models considered
  - Two hidden valley models:
    - scalar boson
    - heavy  $Z'$
  - Stealth SUSY



- Two channels defined by triggers: muon RoI trigger and jet+MET trigger
- Select events with good vertex in inner detector and/or muon detector

TABLE I. The topologies considered in the analysis and the corresponding triggers and benchmark models.

Trigger	Applicable topologies	Benchmarks
Muon RoI Cluster	IDV <sub>x</sub> +MSV <sub>x</sub> , 2MSV <sub>x</sub>	Scalar boson, Stealth SUSY
Jet+ $E_T^{\text{miss}}$	2IDV <sub>x</sub> , IDV <sub>x</sub> +MSV <sub>x</sub> , 2MSV <sub>x</sub>	$Z'$



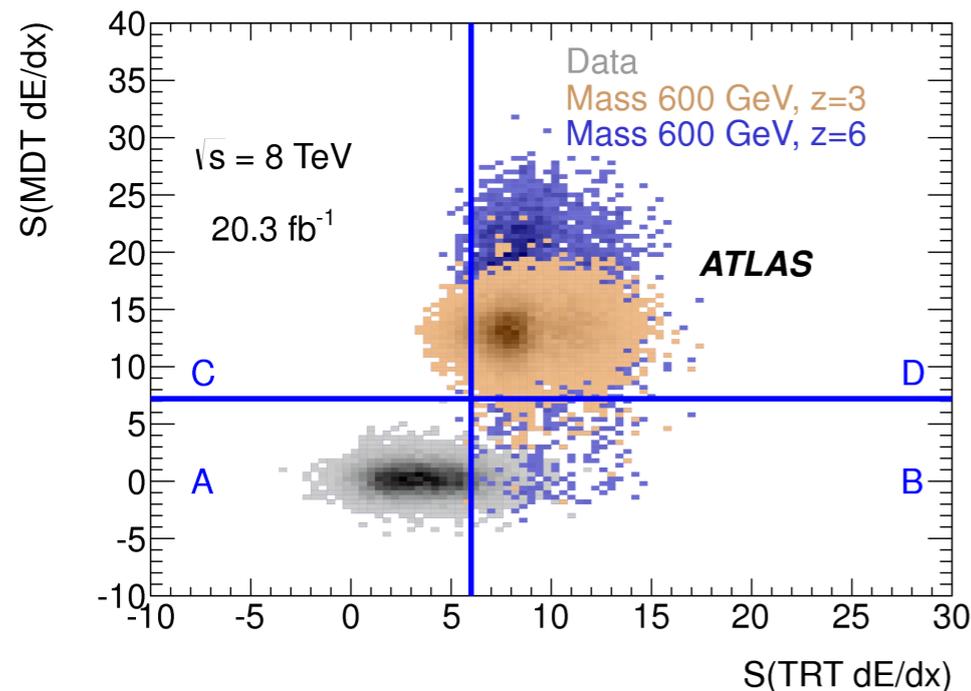
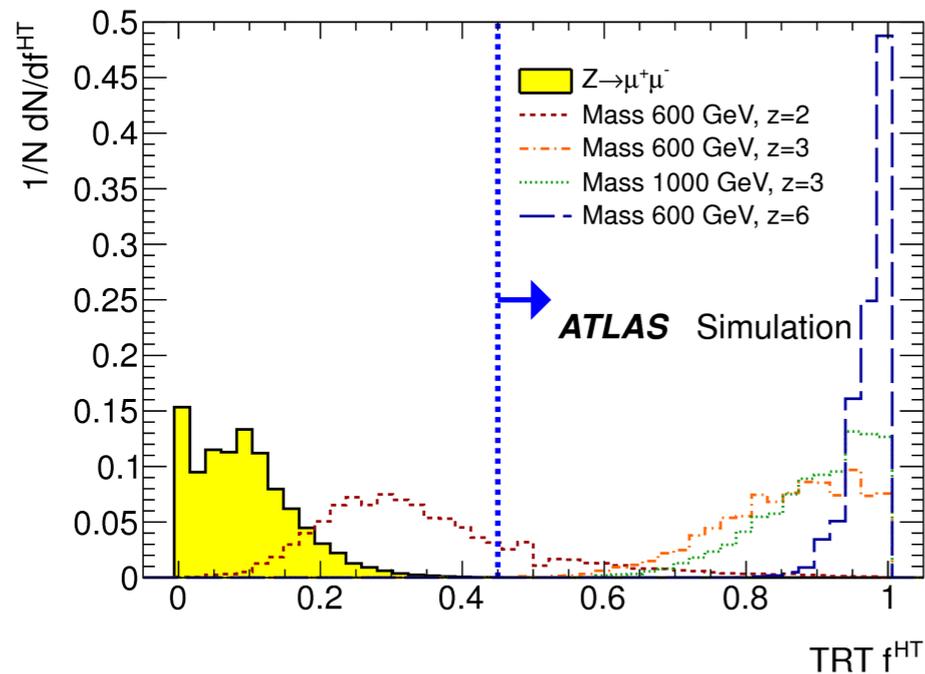


# Heavy long-lived multi-charge particles

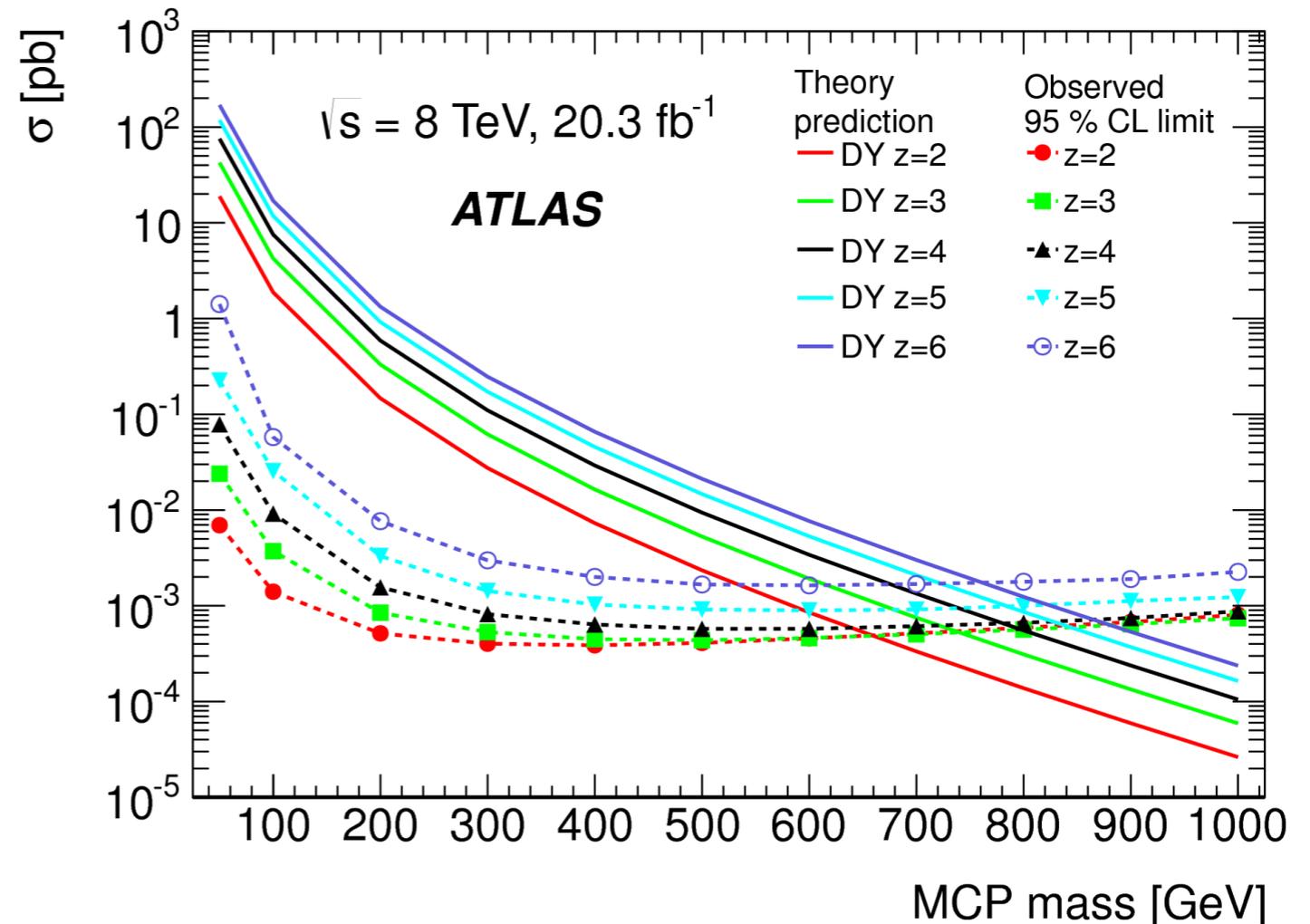
arxiv:1504.04188

submitted to EPJC: 04/16/15

- Particles predicted by many models (composite dark matter, doubly charged Higgs)
- Search for  $|q|=ze$  ( $z=2,3,4,5,6$ ) particles: **highly ionizing**  $\rightarrow$  **large  $dE/dx$**
- Select events with “muon” pairs (assuming Drell-Yan production)
- Signal regions defined by high  **$dE/dx$  significances** in muon and inner detectors, and the fraction of TRT hits passing the high threshold ( $f^{HT}$ )



- No signal candidate events observed
- Mass limits between **660 GeV** and **785 GeV**



# Summary of limits on lifetime of LLPs

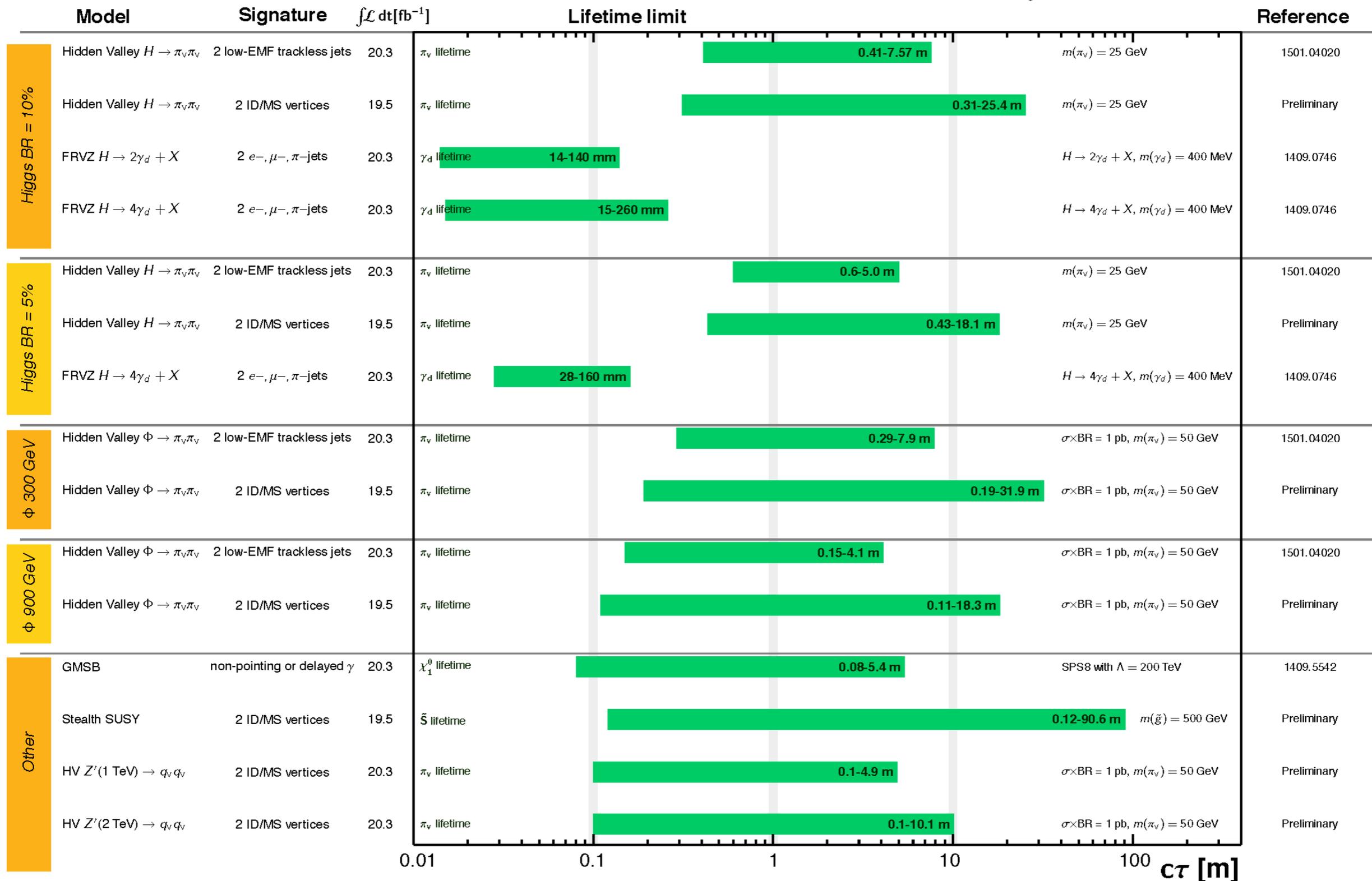
Status of figure: March 2015

## ATLAS Exotics Long-lived Particle Searches\* - 95% CL Exclusion

Status: March 2015

ATLAS Preliminary

$\int \mathcal{L} dt = (19.5 - 20.3) \text{ fb}^{-1}$   $\sqrt{s} = 8 \text{ TeV}$



$\sqrt{s} = 8 \text{ TeV}$

\*Only a selection of the available lifetime limits on new states is shown.

# Conclusions

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- Impressive Run 1 results on VLQ, dark matter, and long lived particles
  - No new physics has been reached, but very stringent limits have been set
- Run 2 is just around the corner
  - Tremendously exciting opportunity to find new physics
  - Several searches will surpass the Run 1 sensitivities with very small datasets ( $\sim 1 \text{ fb}^{-1}$ )
  - **Stay tuned!**

# Conclusions

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THANK YOU !

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  - **Stay tuned!**

# Back-up slides

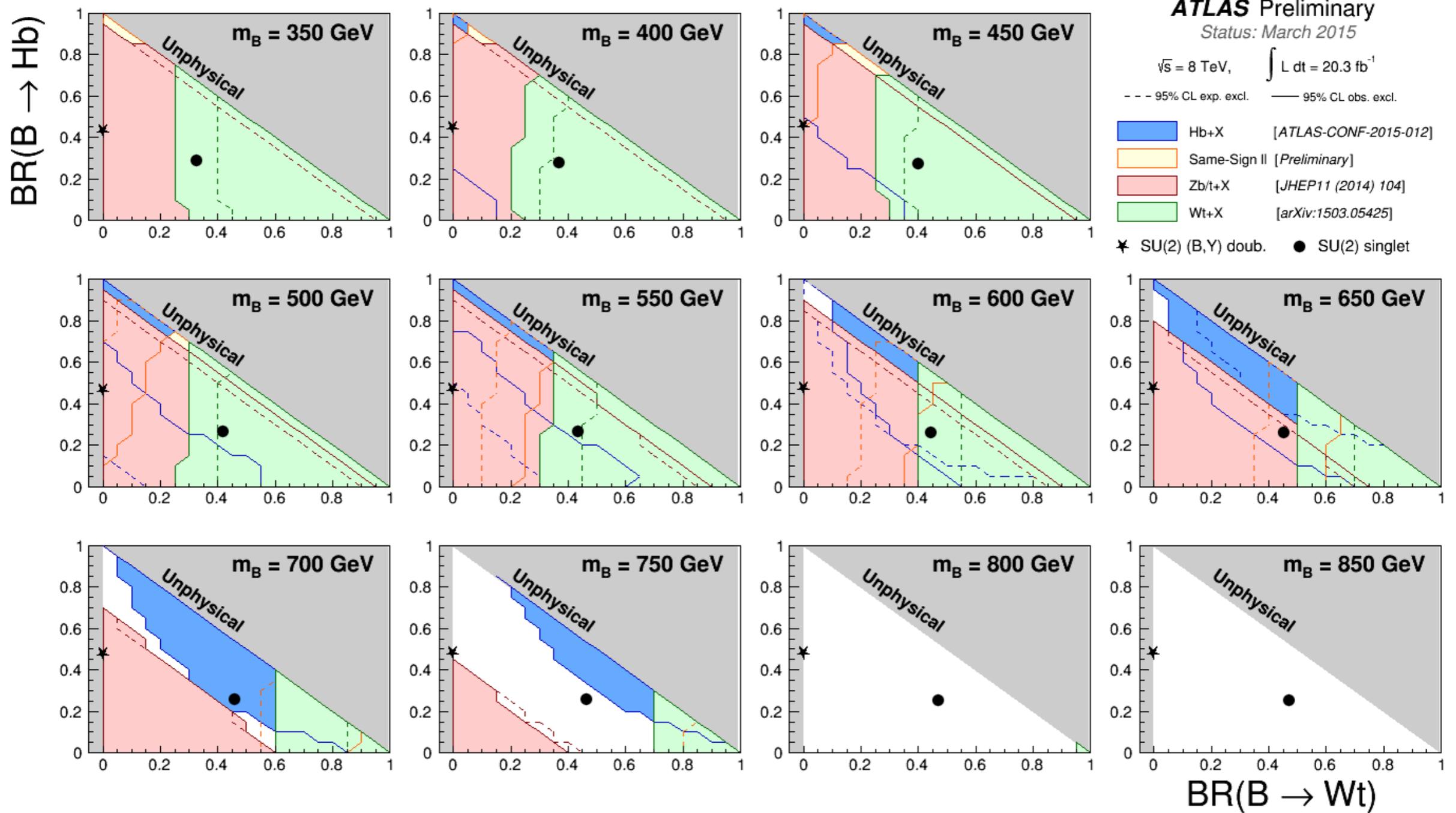
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- Back-up slides

# Limits on VLQ (BB)

Status of figure: March 2015

- BB



# Limits on VLQ (TT)

Status of figure: March 2015

• TT

