Searches for New Physics with top quarks using the ATLAS detector

Simran Gurdasani, on behalf of the ATLAS Collaboration

LHCP 2024 Boston

Search for new physics

The Standard Model of Particle Physics $\rightarrow$ state-of-the-art theory probed to extreme precision!

⬇

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Where did all the antimatter go?

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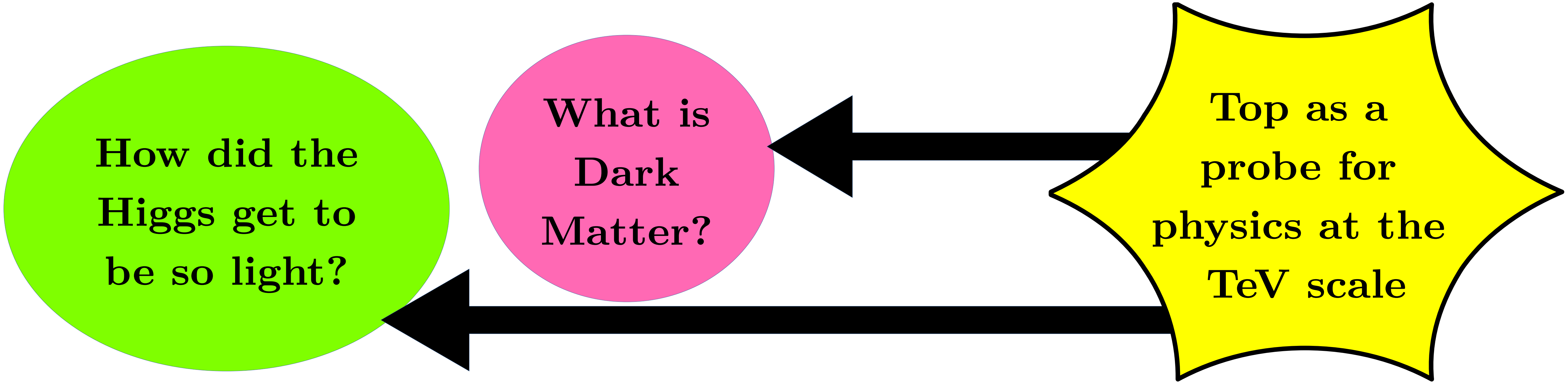

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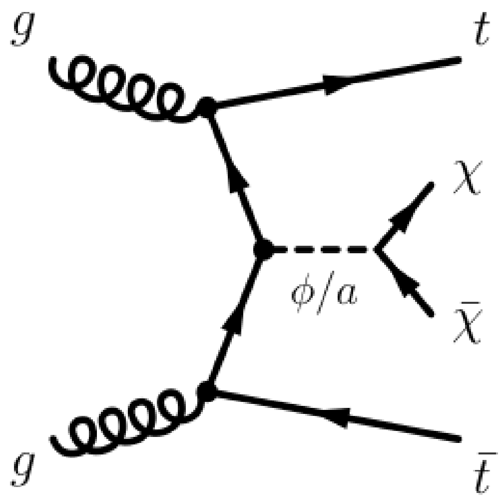
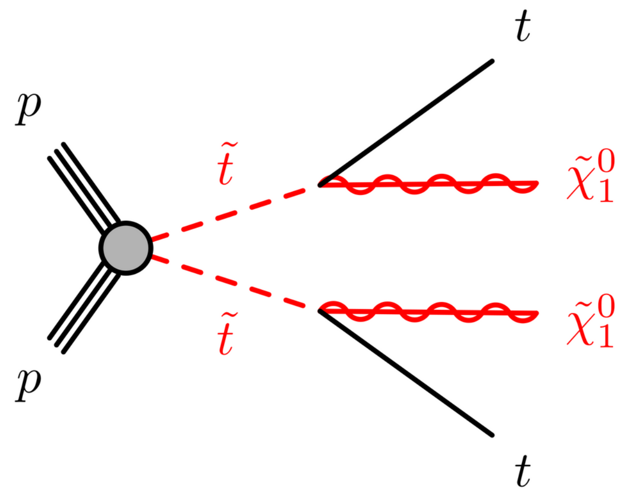
- **ttMET:** Examines top quark pairs with MET in search of new SUSY and DM particles.





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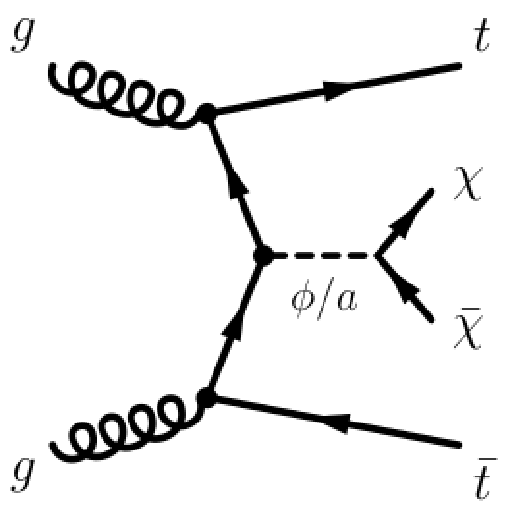

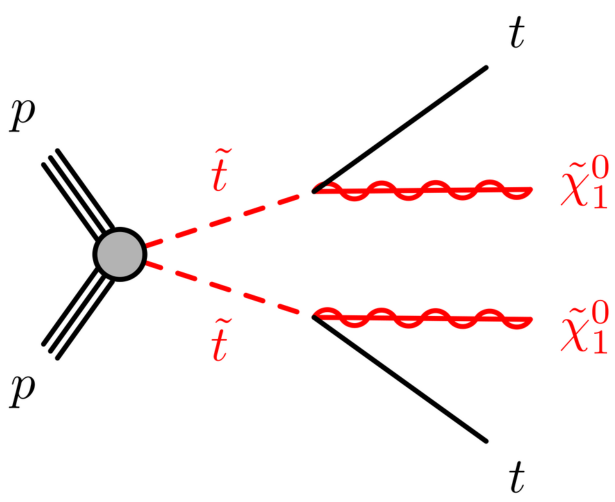

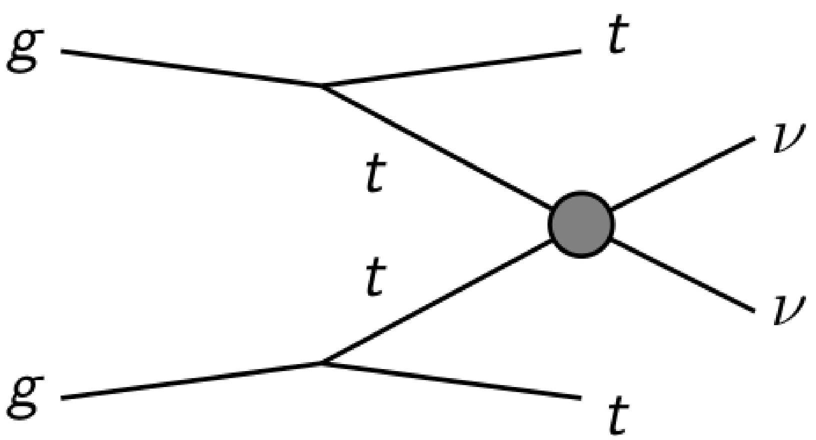

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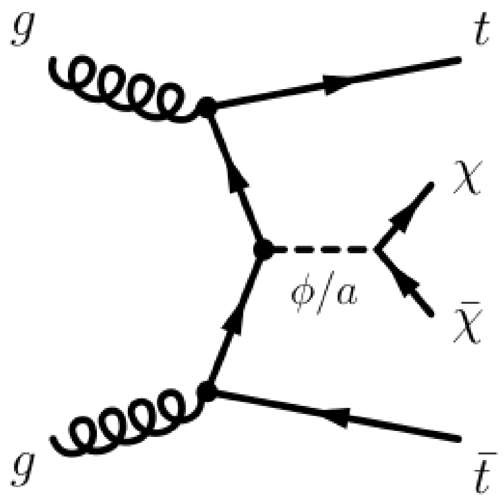

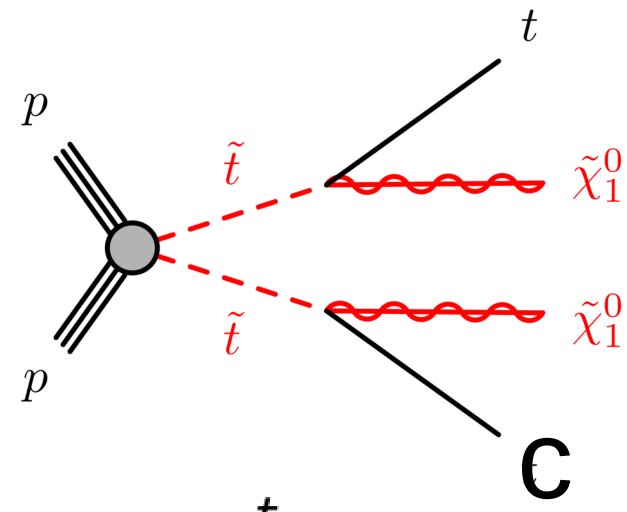

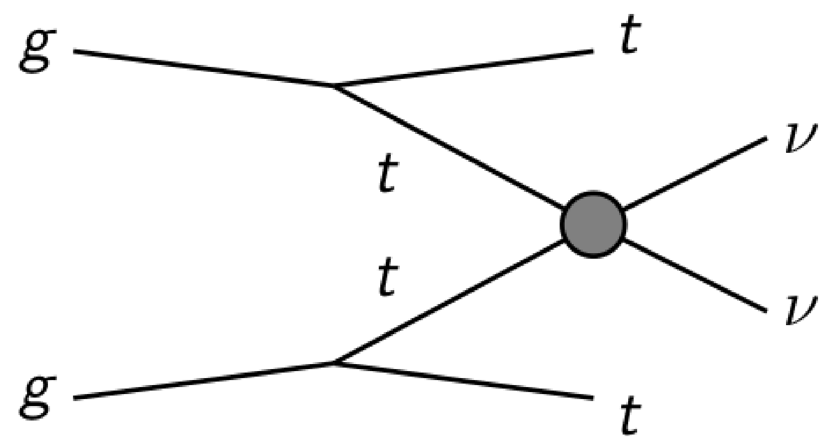

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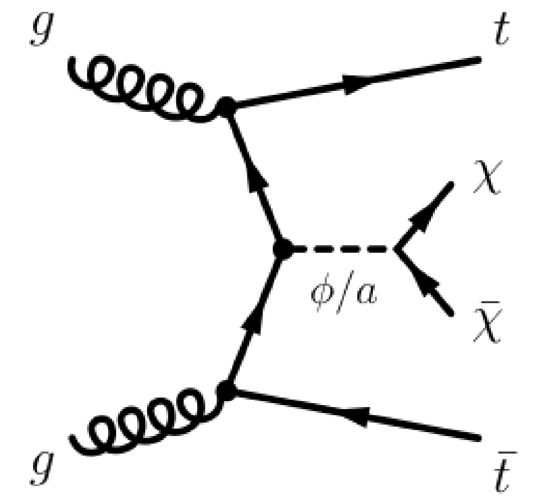

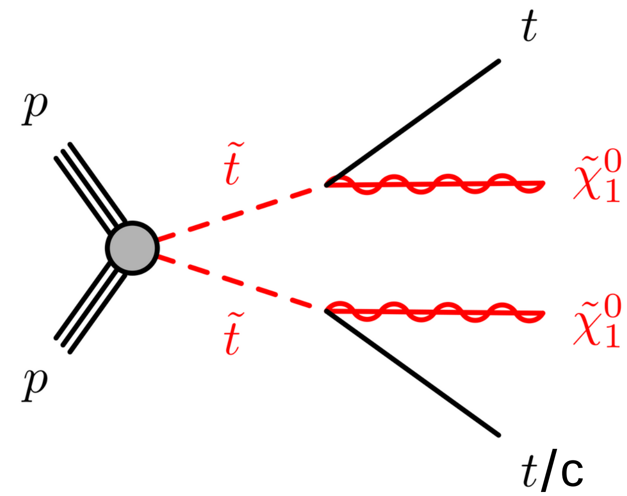

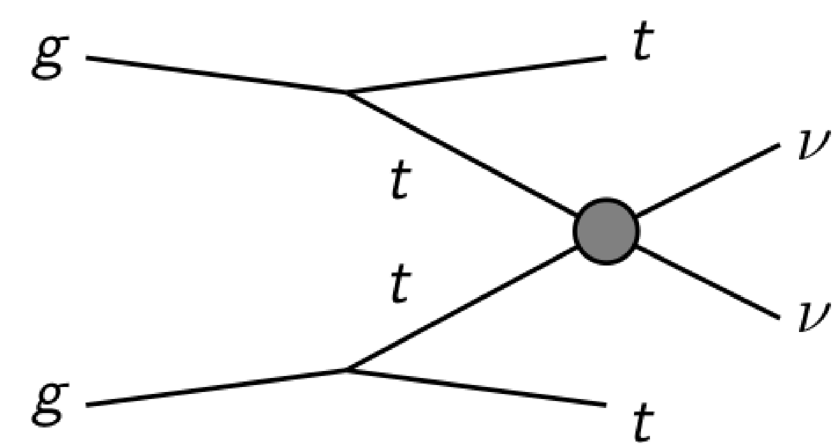

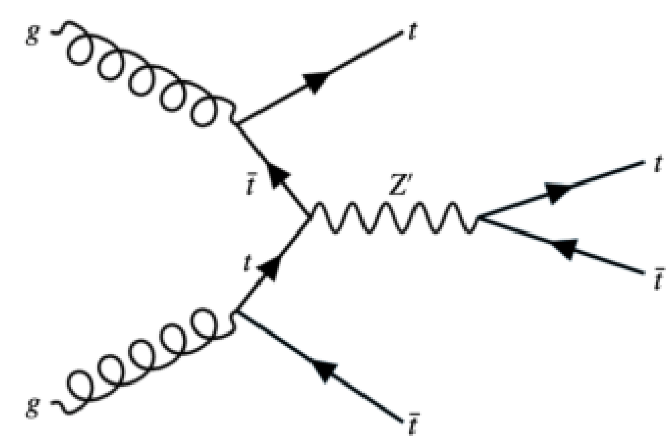

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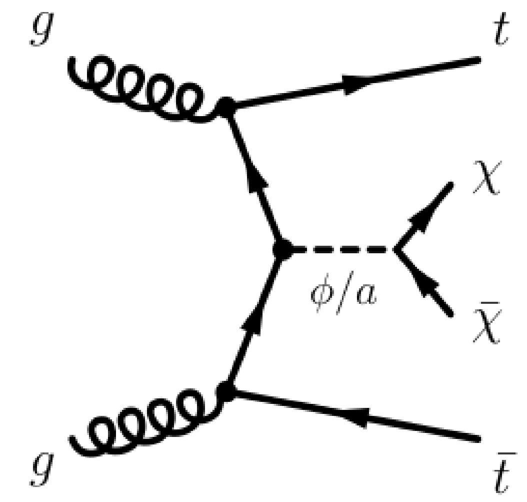

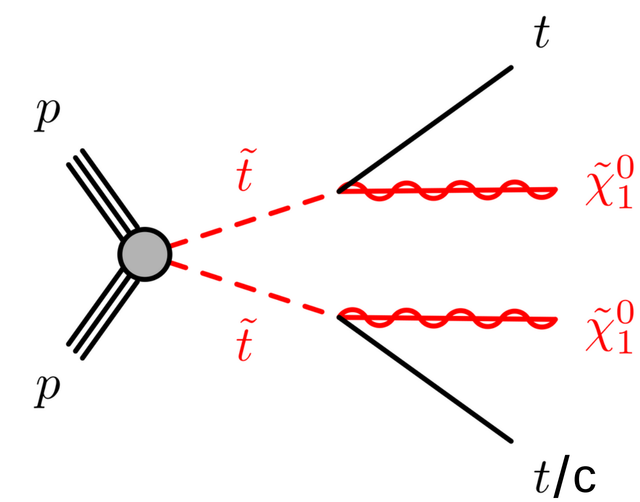

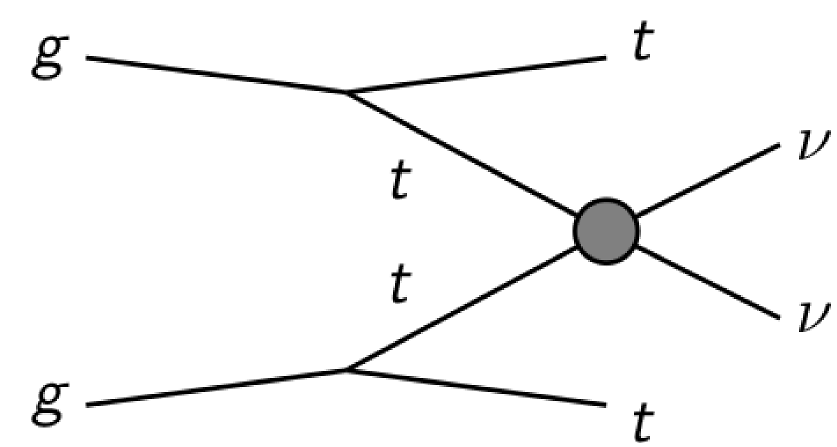

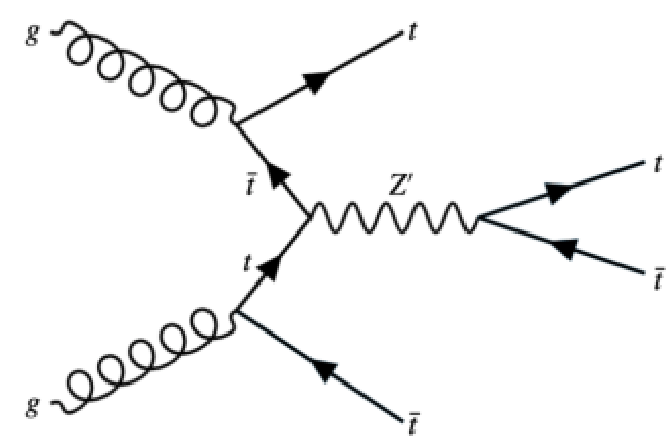

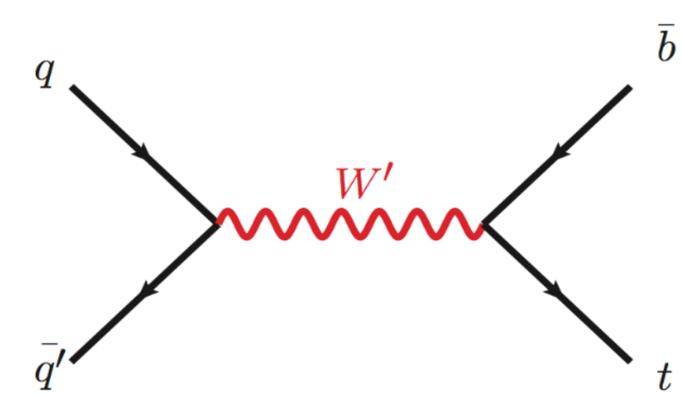

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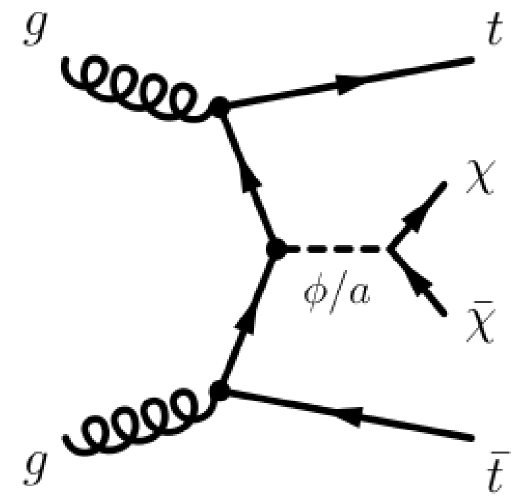
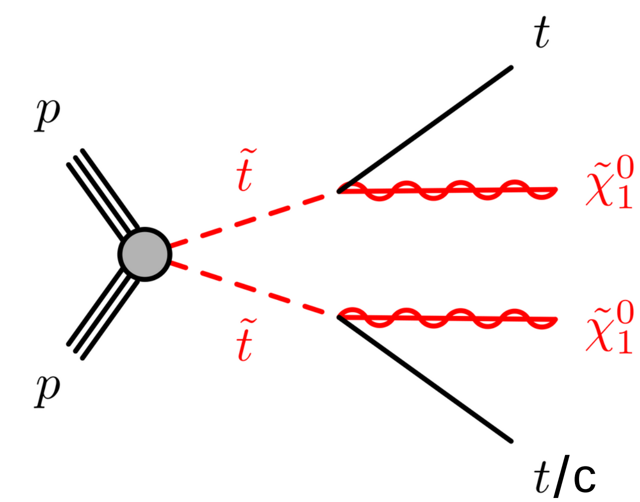
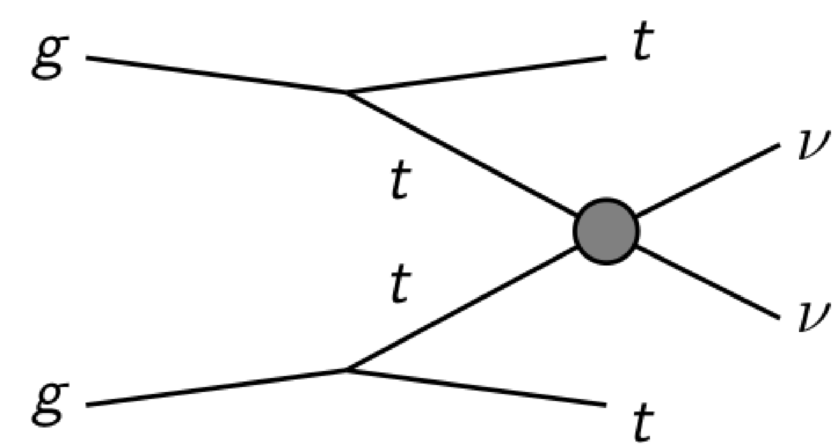
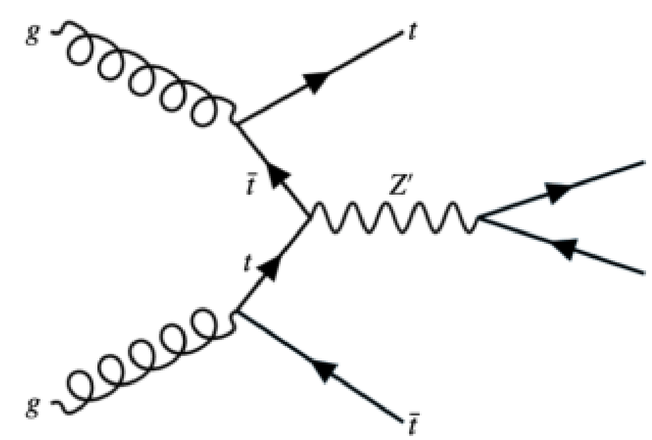
- **<u>Mono-top</u>**
- **<u>Dark Mesons</u>**

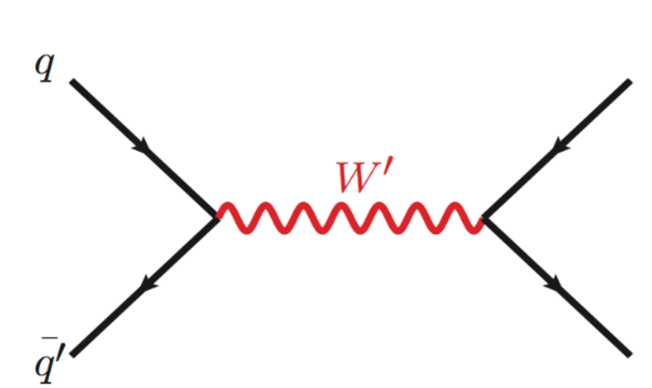
} <u>Presented by Anindya Ghosh on Monday</u>







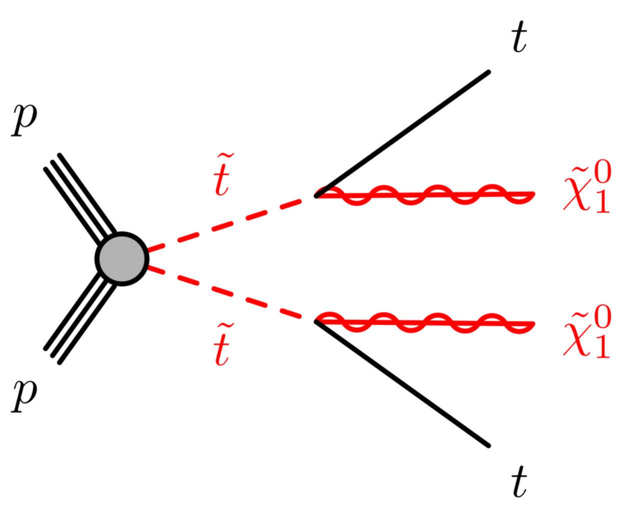




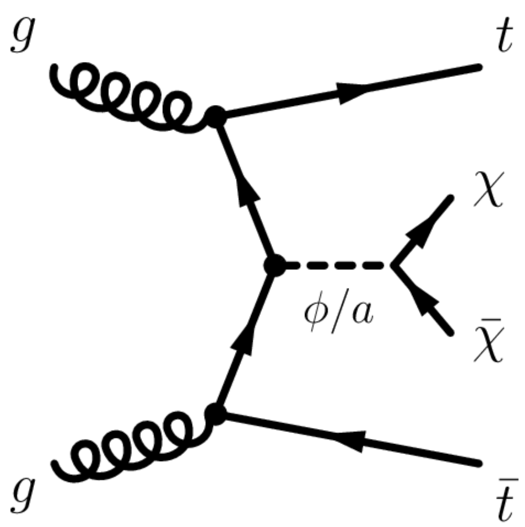
$t\bar{t}+E_T^{miss}$ – new and improved 1-lepton

- Using an improved analysis strategy (inclusive event categories and Neural Networks), the 1L final state is used to probe:

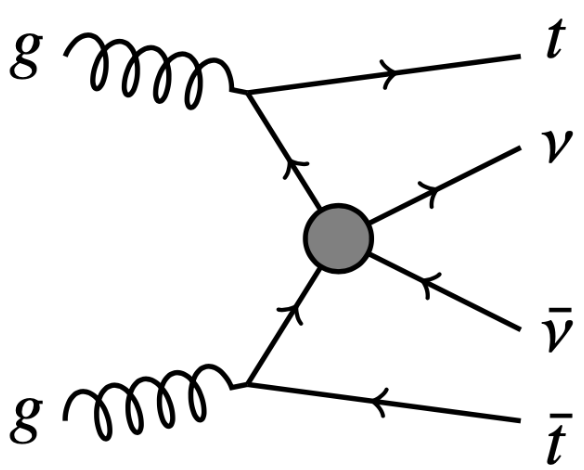
Stop Pair Production



Simplified DM Production



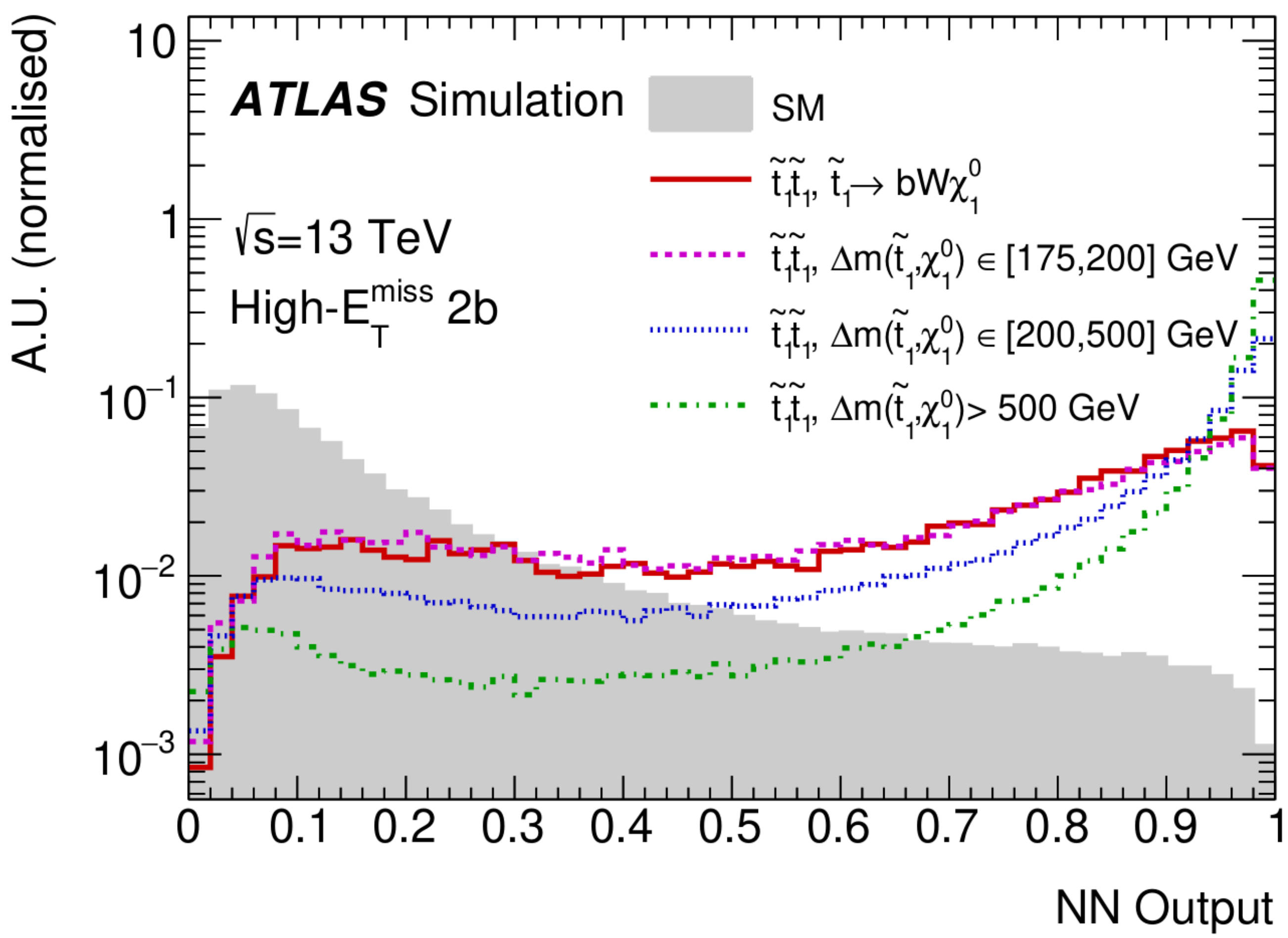
Contact Interactions



- Range of masses for DM and SUSY models are targeted with two NNs (one for DM and one for SUSY).
- Special resolved and boosted top reconstruction strategy developed using DNNs.
- For the first time, $tt\nu\nu$ operators are probed using the EFT framework.

$t\bar{t}+E_T^{miss}$ – new and improved 1-lepton

Stop NN



The DNN is designed to be sensitive to different signals with different NN distributions simultaneously.

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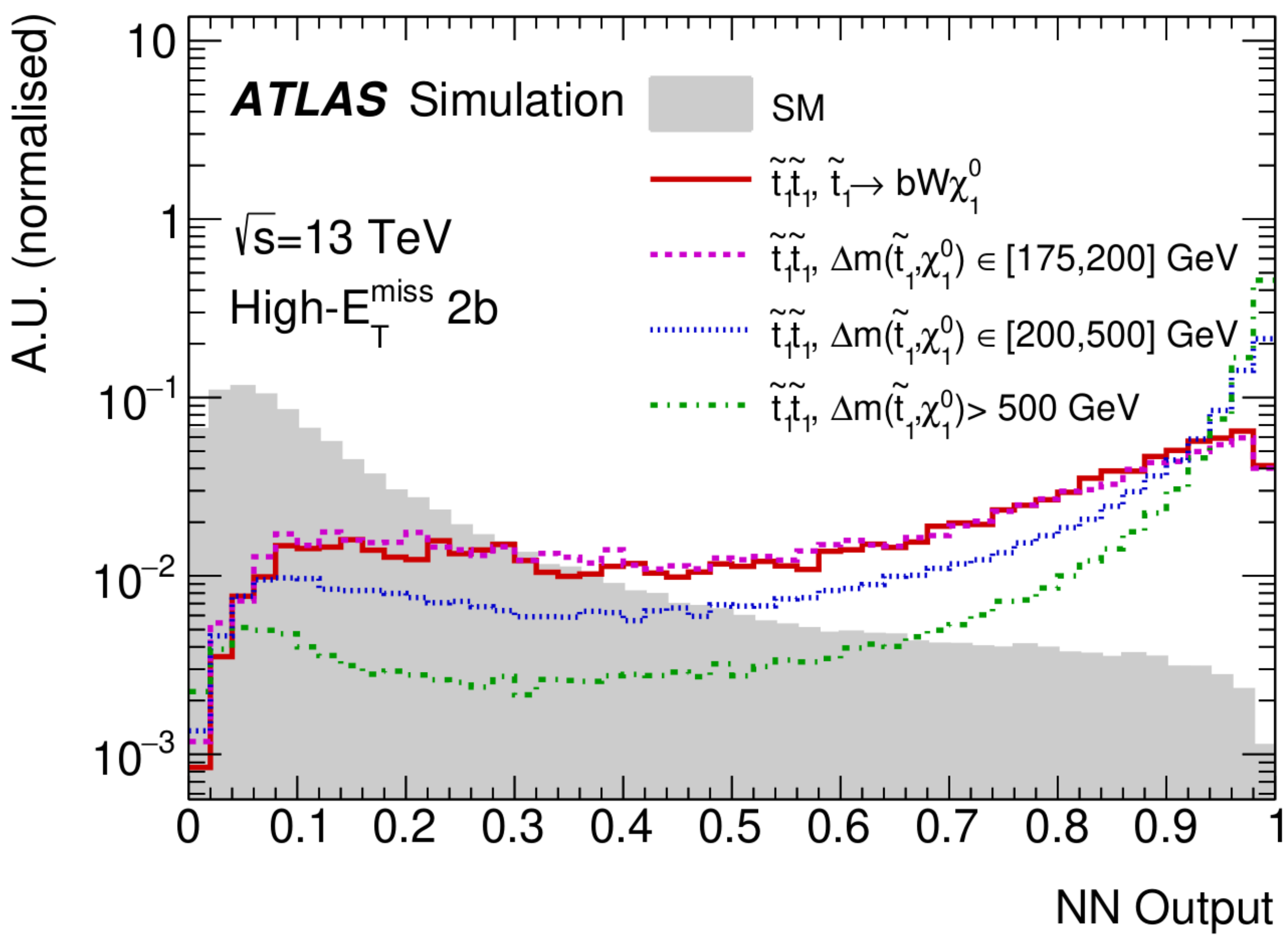

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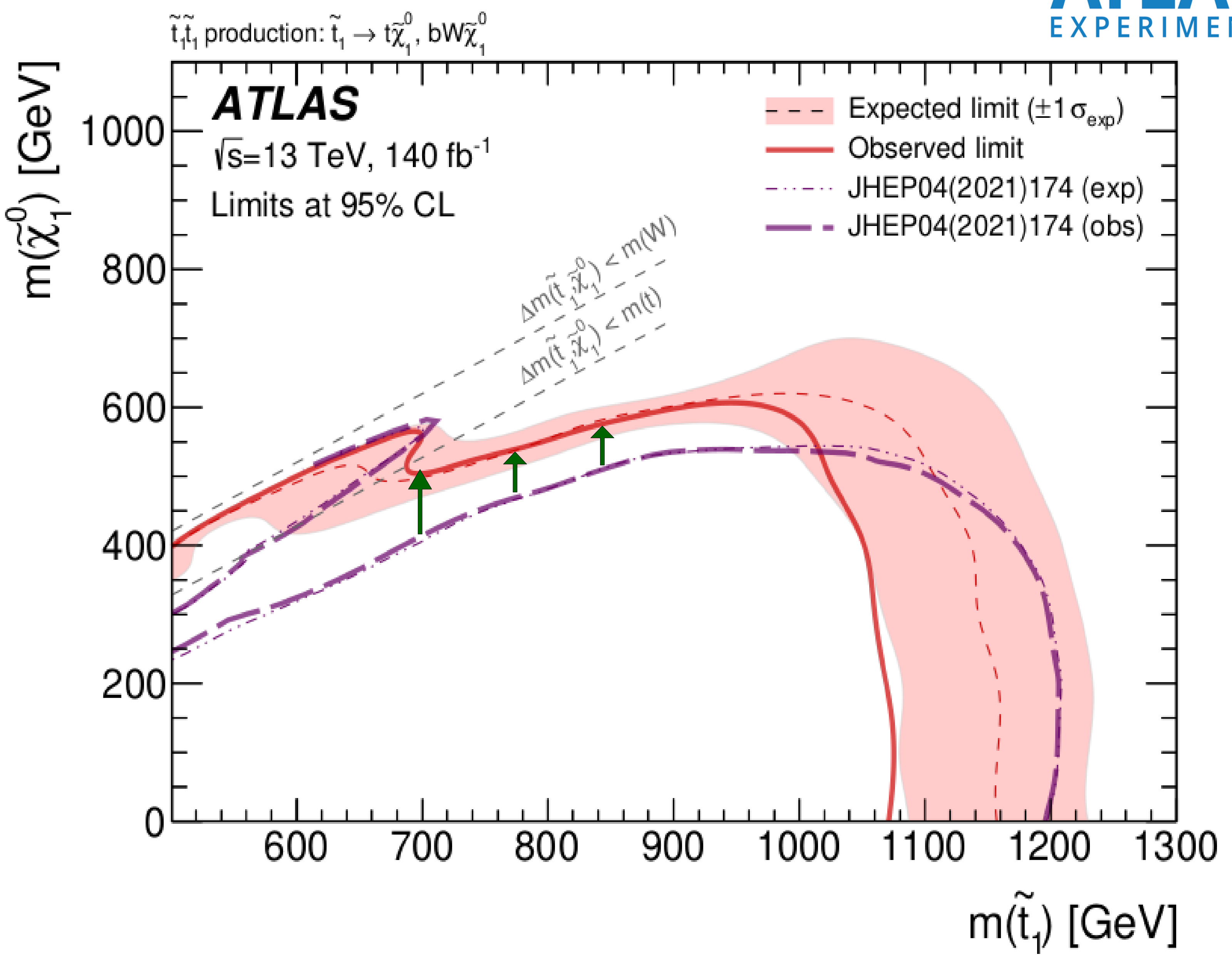
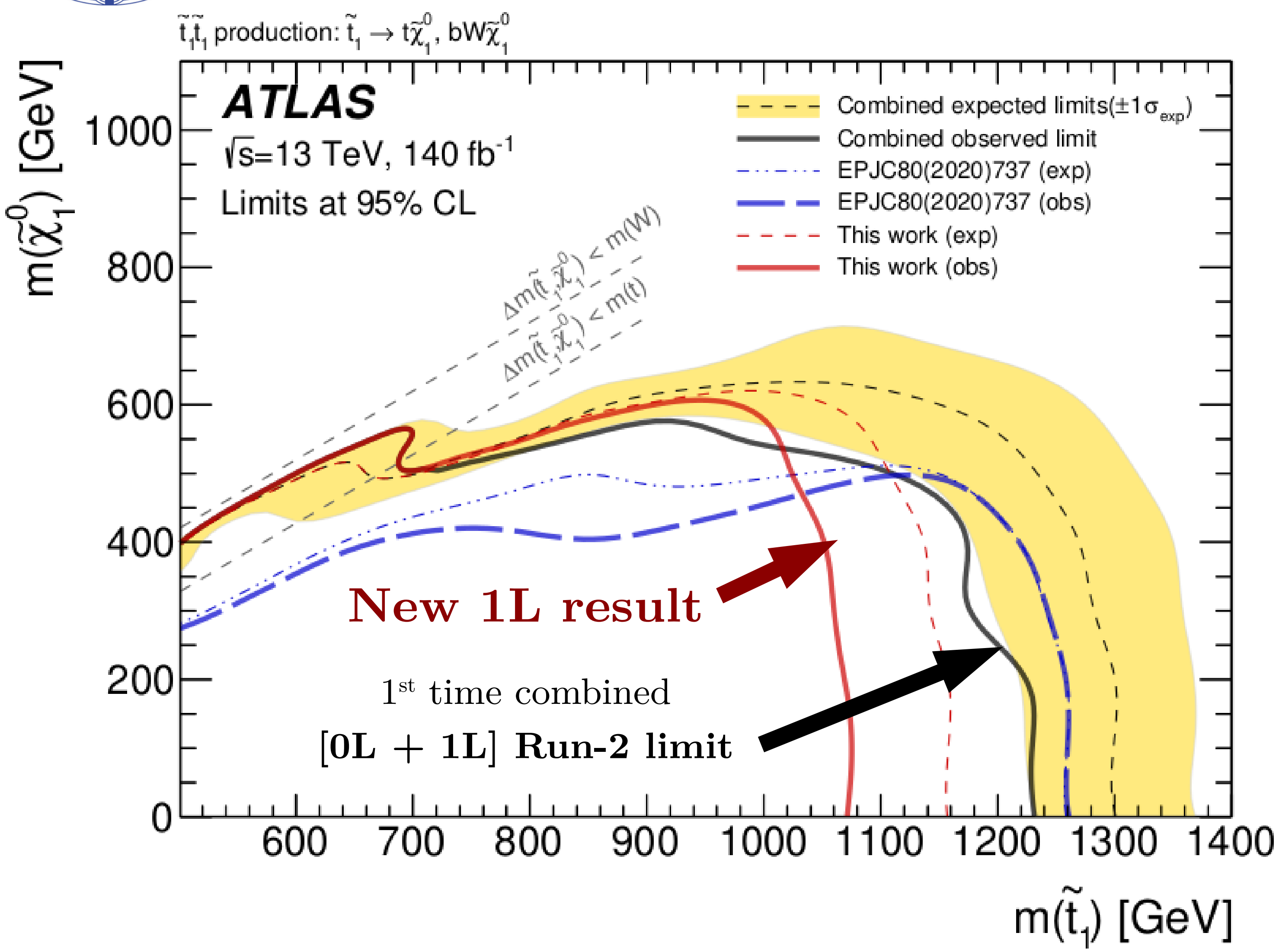


Improvements in analysis strategy help probe the compressed region.
→ with the SAME dataset ←

$t\bar{t}+E_T^{miss}$ Combination



- [0L + 1L] combined limit → now the best exclusion limit for stop pair production in ATLAS with Run2 data!!

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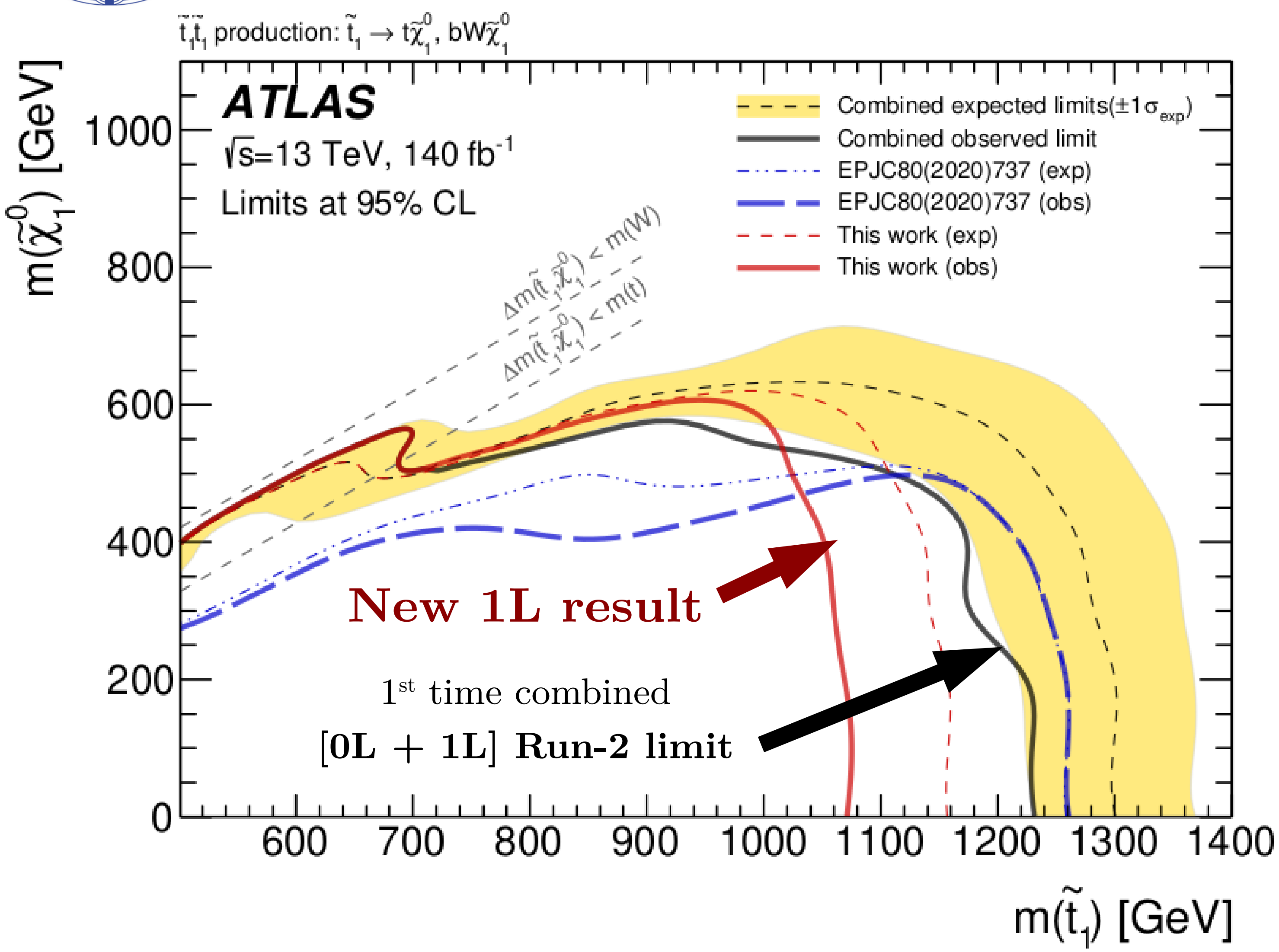

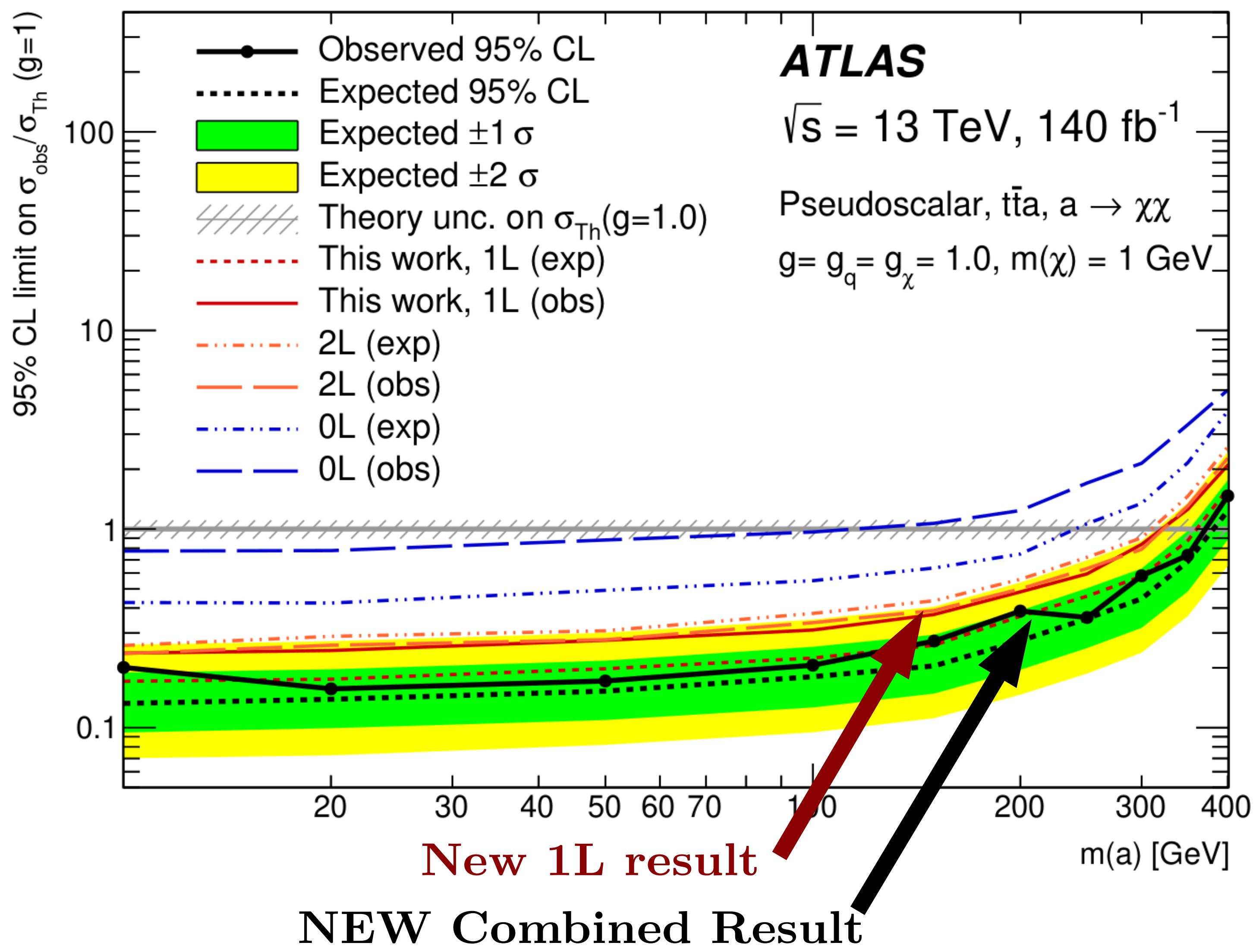

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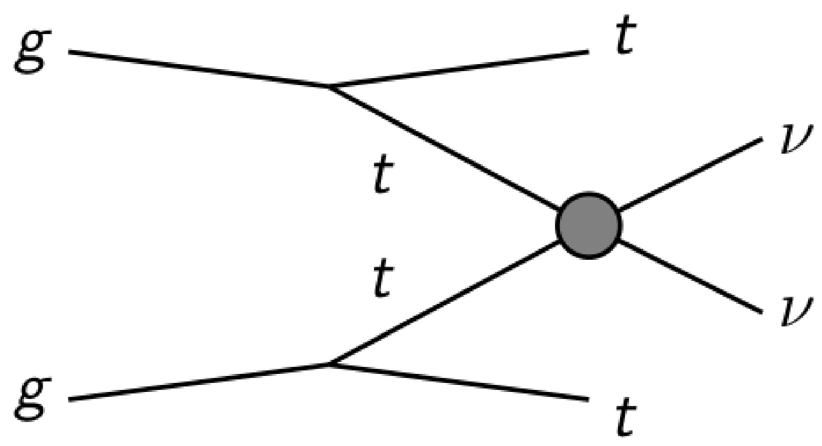
- Limits are set for simplified DM models.
- The new 1L result drives the ATLAS combination result.

1^{st} time ever! → Interpretation for Contact Interaction

- Using the same Neural Nets from the new 1L analysis, an interpretation is performed in the context of a search for effective vector contact interactions between top quarks and all three generations of left-handed neutrinos.
  - Initially motivated by flavor anomalies that are now reduced
  - Remains a good probe of SM predictions at high energies



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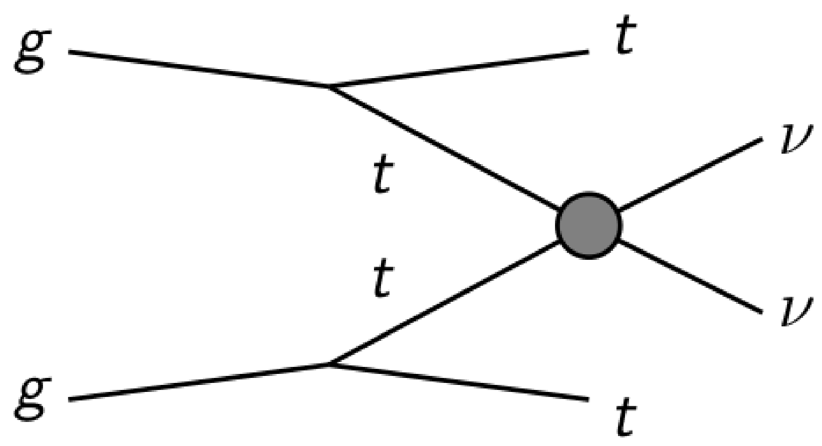

$$\mathcal{L}_{t\bar{t}\nu\bar{\nu}} = \frac{1}{\Lambda^2}\left[V_{LL}(\bar{\nu}\gamma_\mu P_L\nu)(\bar{t}\gamma^\mu P_L t) + V_{LR}(\bar{\nu}\gamma_\mu P_L\nu)(\bar{t}\gamma^\mu P_R t)\right]$$

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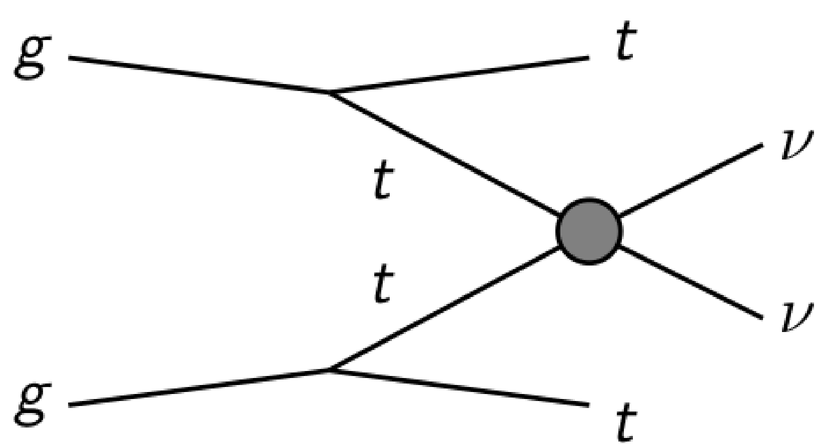

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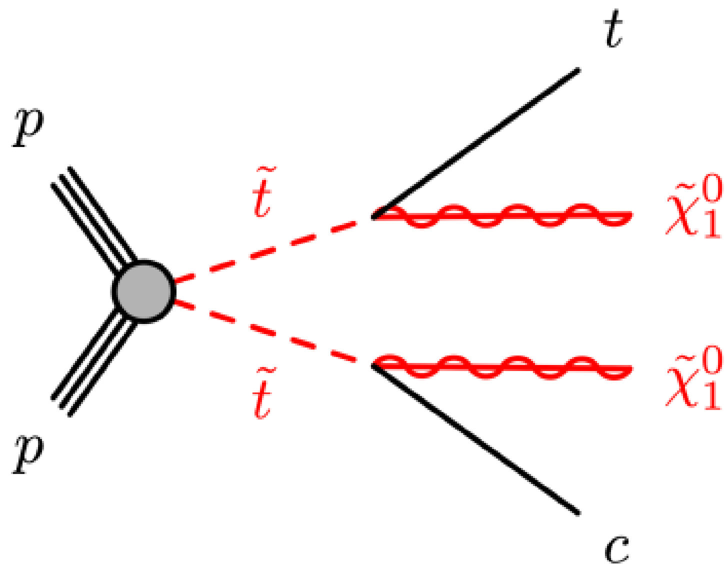
- Assuming the Wilson coefficients to be $|V_{ij}| = 4\pi$, lower limits on Λ at 95% confidence level range are set depending on the **chirality of the top quarks** involved in the CI and the sign (+)/(-) of the Wilson coefficient.

	Wilson coefficient	Observed (Expected) upper limit on $\sqrt{|V_{ij}|}/\Lambda$ [TeV^{-1}]	Observed (Expected) lower limit on Λ for $|V_{ij}| = 4\pi$ [TeV]
Left chiral top	$V_{LL} > 0$	$1.59\ (1.44^{1.58}_{1.31})$	$2.23\ (2.47^{2.71}_{2.25})$
	$m_{\nu\bar{\nu}} < 1$ TeV	$1.84\ (1.66^{1.82}_{1.51})$	$1.93\ (2.14^{2.35}_{1.95})$
	$m_{\nu\bar{\nu}} < 2$ TeV	$1.62\ (1.46^{1.61}_{1.36})$	$2.18\ (2.42^{2.66}_{2.21})$
	$V_{LL} < 0$	$1.66\ (1.52^{1.66}_{1.40})$	$2.13\ (2.33^{2.53}_{2.14})$
	$m_{\nu\bar{\nu}} < 1$ TeV	$1.96\ (1.80^{1.95}_{1.66})$	$1.81\ (1.97^{2.13}_{1.82})$
	$m_{\nu\bar{\nu}} < 2$ TeV	$1.70\ (1.56^{1.69}_{1.44})$	$2.08\ (2.28^{2.47}_{2.10})$
Right chiral top	$V_{LR} > 0$	$1.67\ (1.53^{1.66}_{1.40})$	$2.12\ (2.32^{2.53}_{2.13})$
	$m_{\nu\bar{\nu}} < 1$ TeV	$1.92\ (1.78^{1.94}_{1.64})$	$1.84\ (1.99^{2.16}_{1.82})$
	$m_{\nu\bar{\nu}} < 2$ TeV	$1.70\ (1.56^{1.70}_{1.44})$	$2.08\ (2.27^{2.47}_{2.08})$
	$V_{LR} < 0$	$1.63\ (1.49^{1.63}_{1.36})$	$2.17\ (2.38^{2.60}_{2.18})$
	$m_{\nu\bar{\nu}} < 1$ TeV	$1.86\ (1.72^{1.89}_{1.58})$	$1.91\ (2.06^{2.25}_{1.88})$
	$m_{\nu\bar{\nu}} < 2$ TeV	$1.66\ (1.52^{1.67}_{1.40})$	$2.13\ (2.33^{2.54}_{2.13})$

$tc+E_T^{miss}$

- $tc+E_T^{miss}$ signature → probed for the 1st time ever at the LHC.
- Probes stop-pair production in non-minimal flavour SUSY scenario.
- Hadronic top decay is targeted → final state with many jets, large MET and c-jet.



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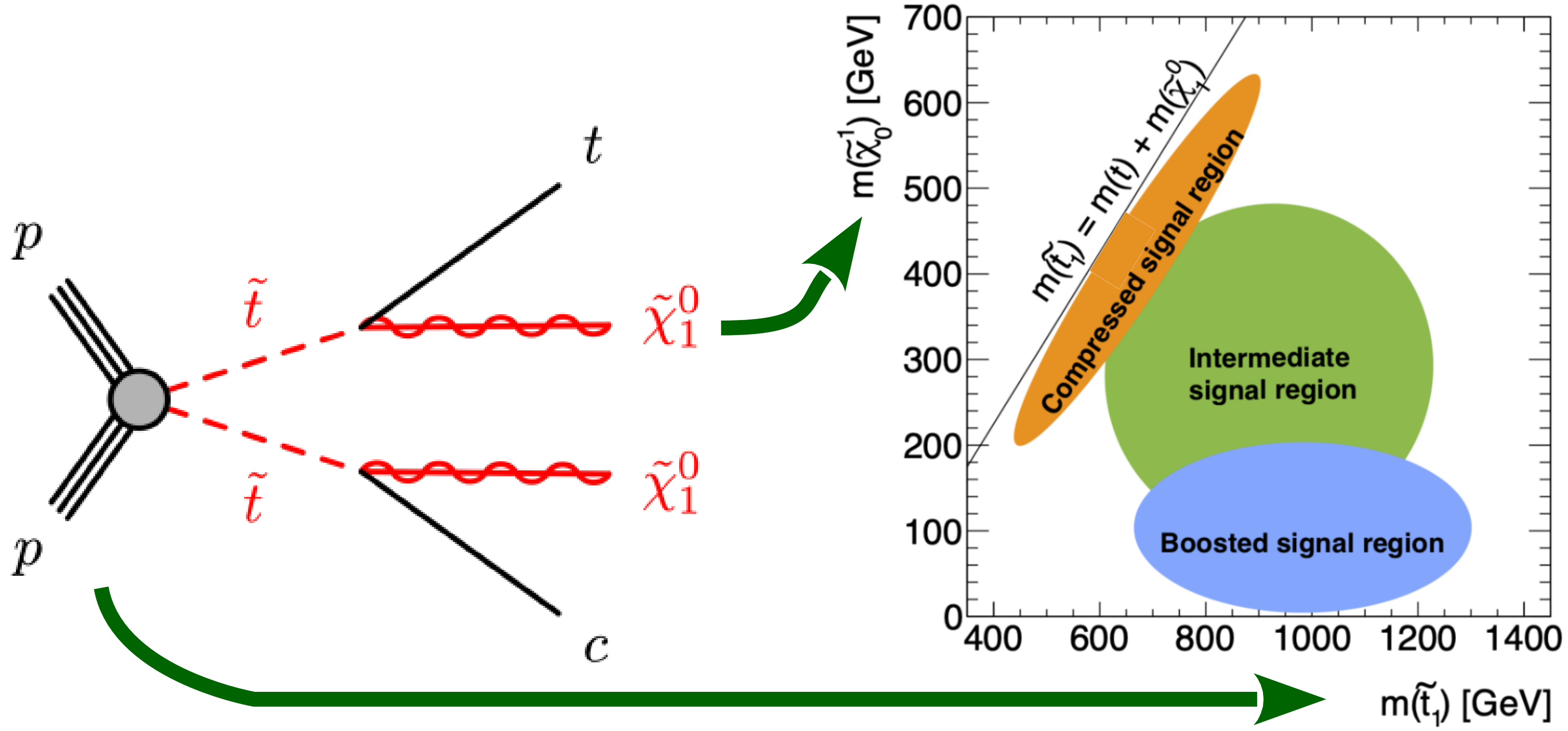

- Different kinematic regions in the stop-neutralino mass plane are probed.
- Special multi-class DNN optimization for compressed region.
- Top tagging also used → DNN for boosted tops
- Special c-tagging developed for the analysis!

tc+E_T^{miss} – Signal Regions

- Each kinematic region has CRs used to control background processes, VRs to validate the fit model and SRs that are enhanced in signal processes.

- Each signal region is binned to increase sensitivity.

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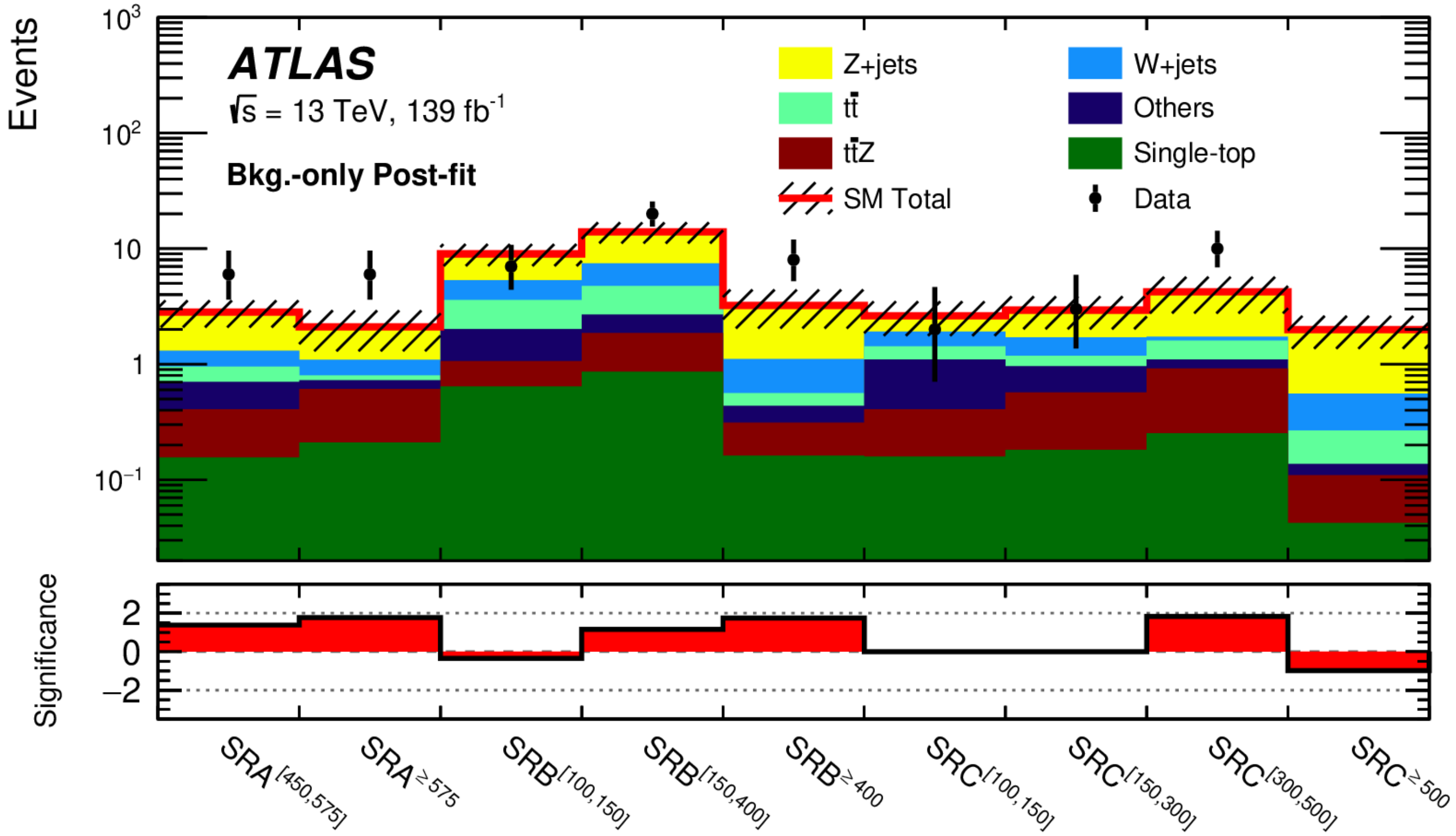

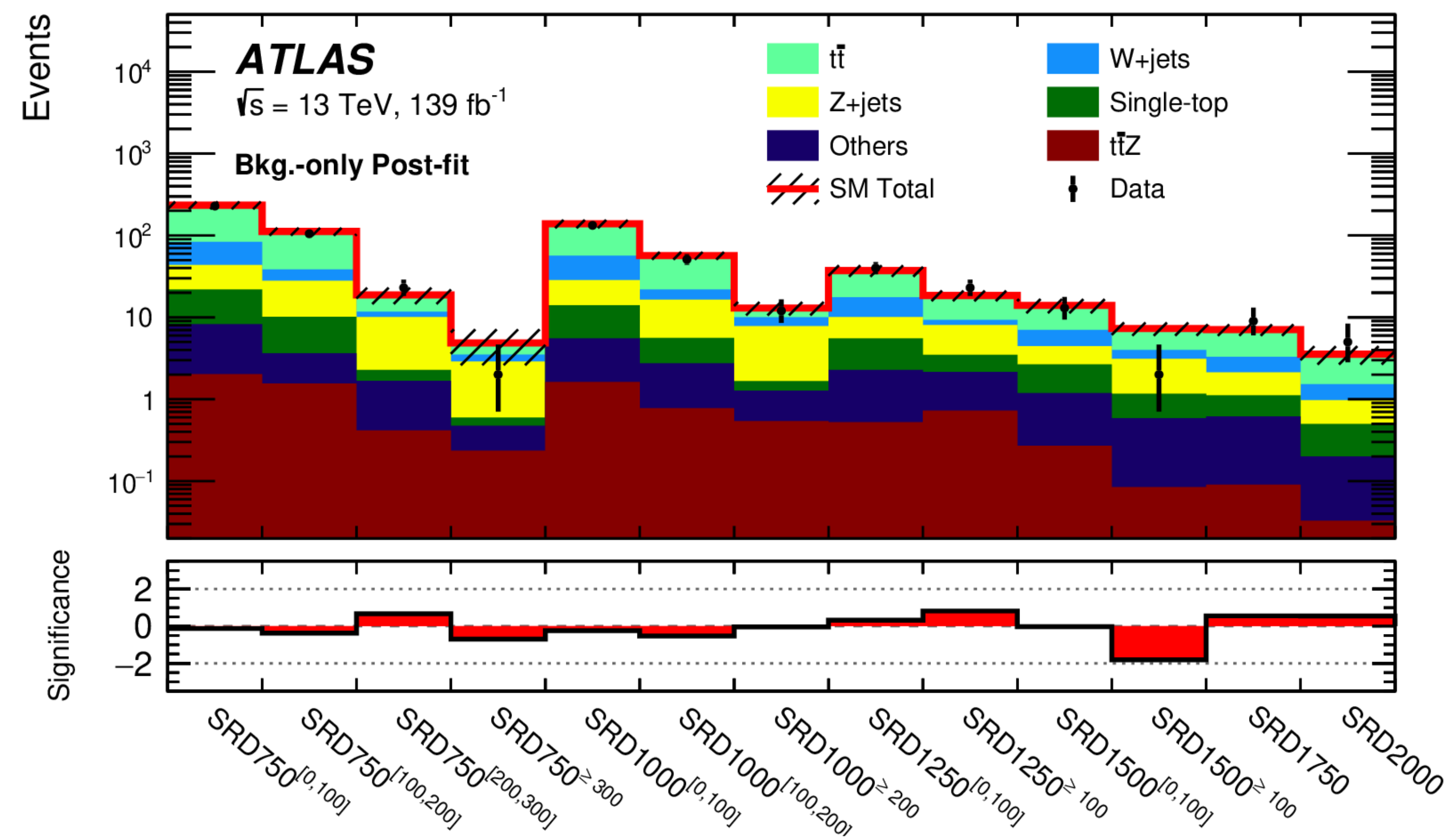

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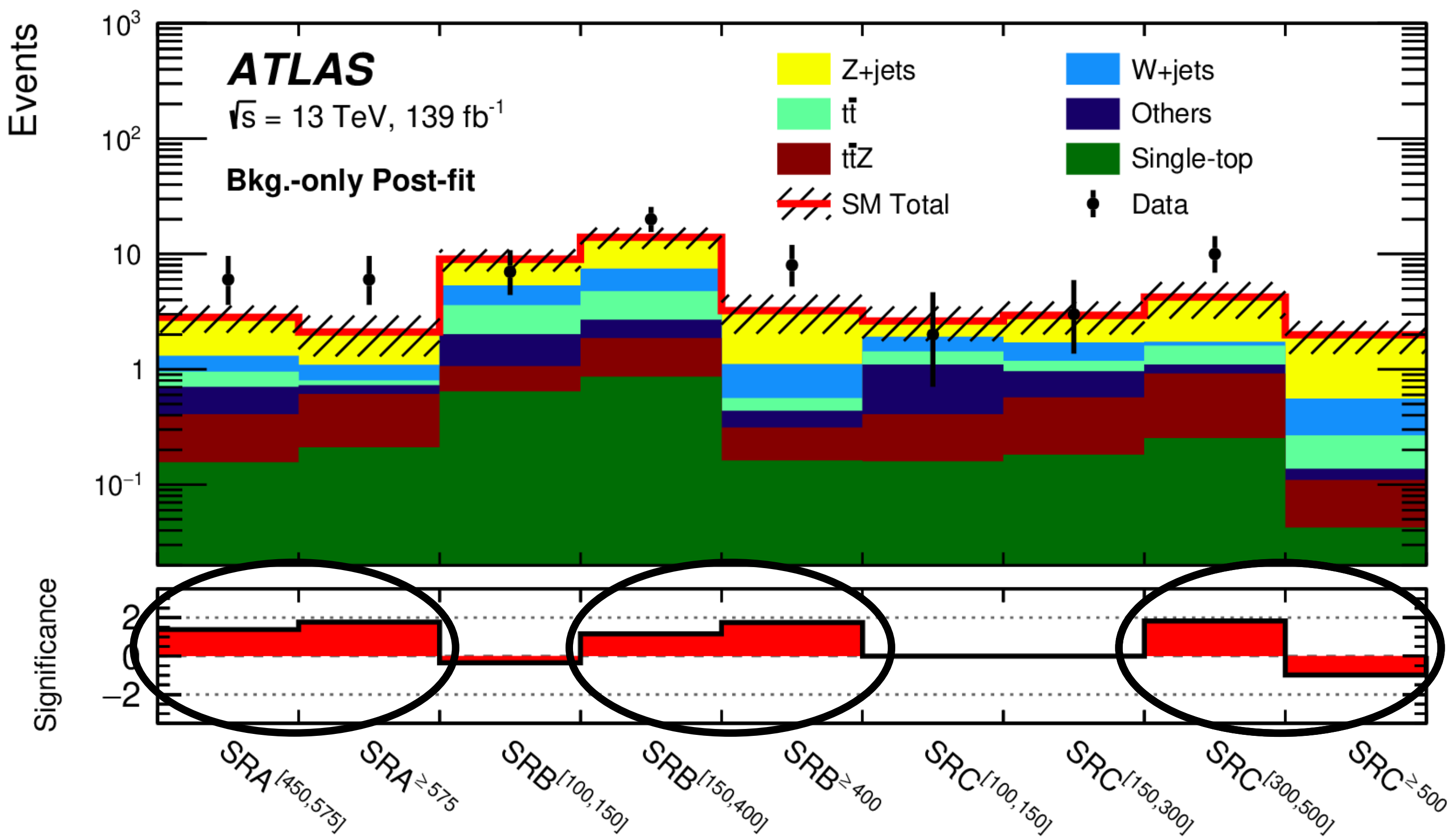
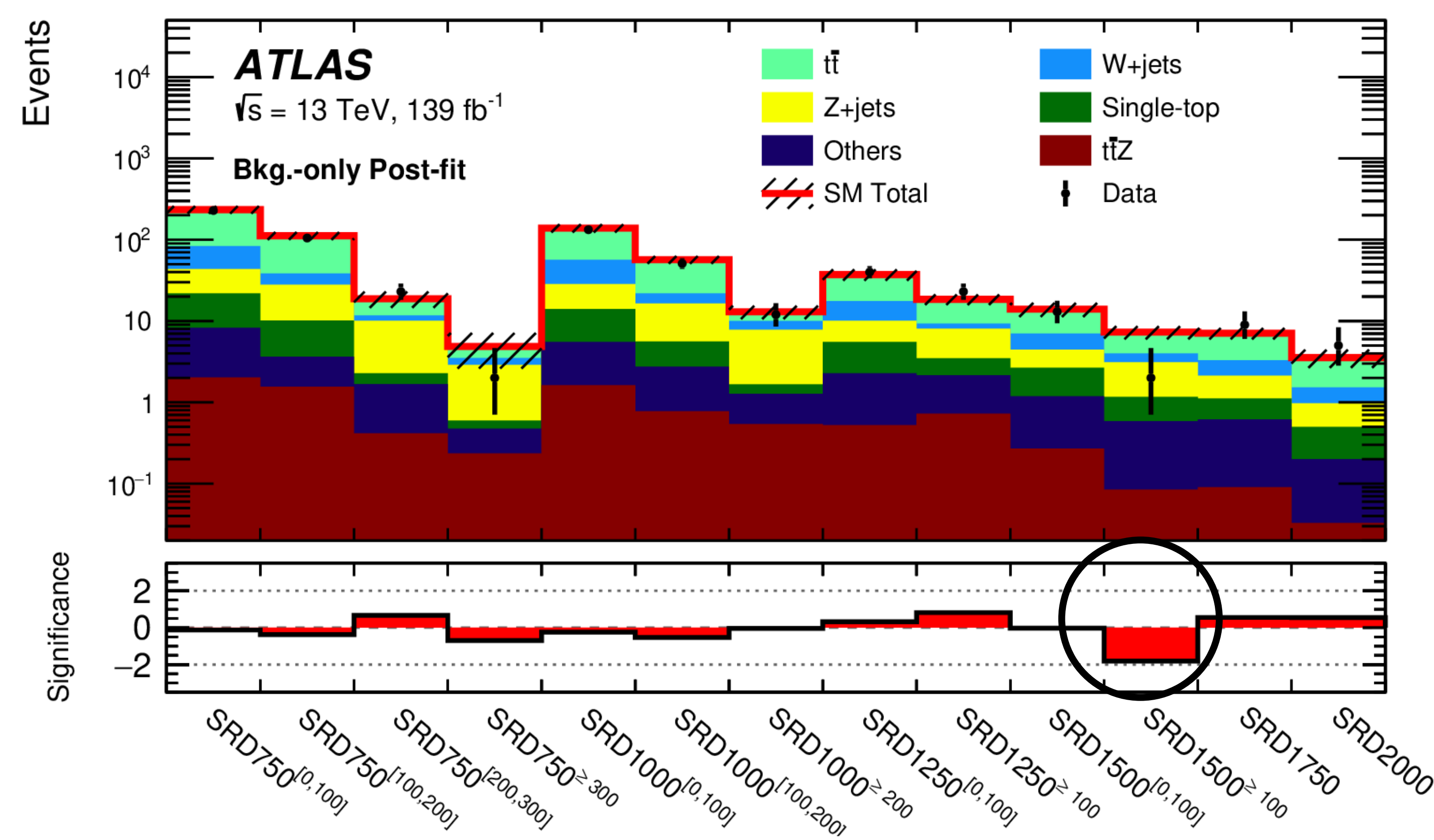
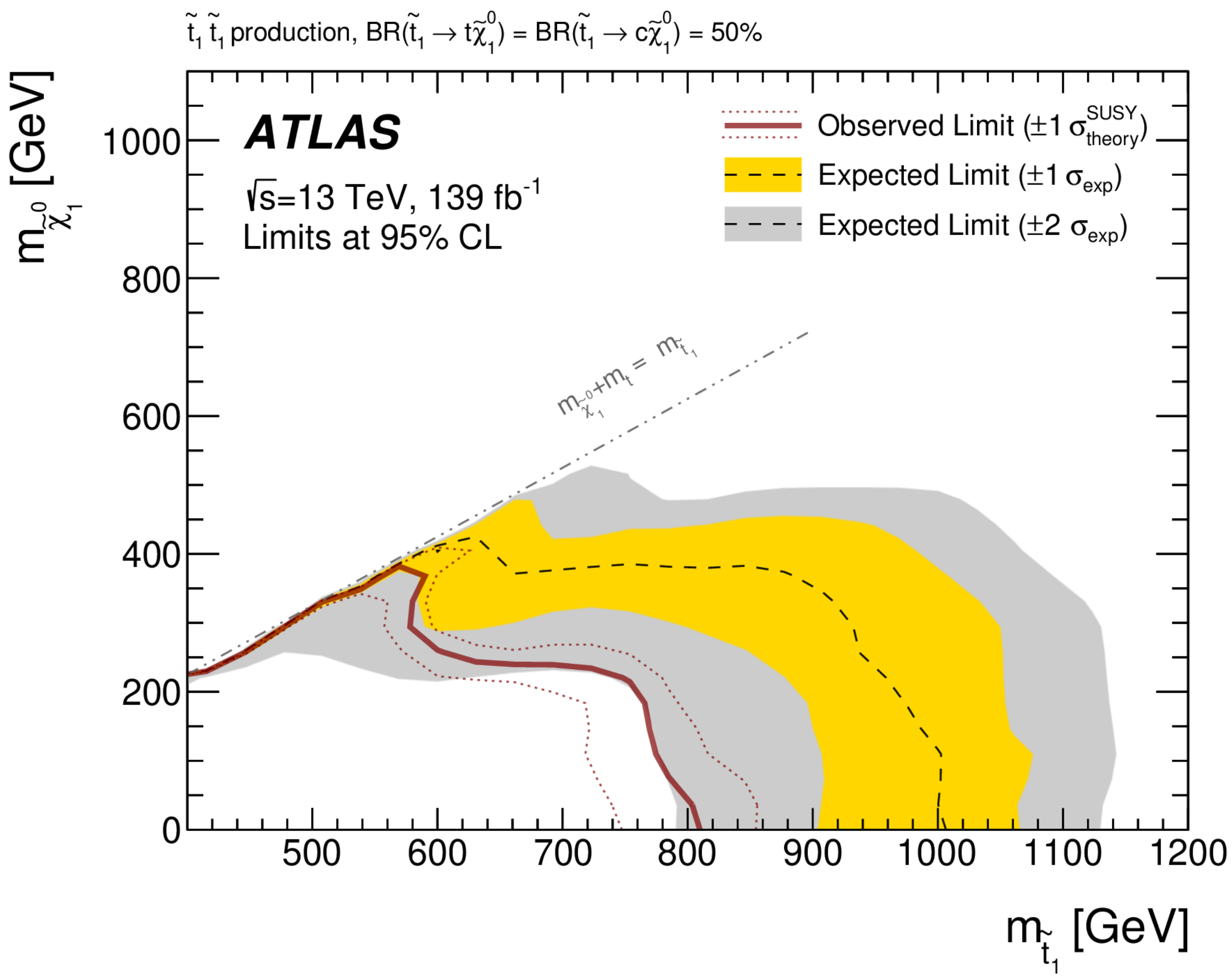




- Some Signal Region bins have disagreements but all are within 2 sigma. Largest deficit ~ 1.8 sigma
- Overall, data agrees well with SM prediction.

tc+E_T^{miss} – Model Dependent Fit

- The stop-neutralino plane shows exclusions for stop-quarks up to 800 GeV and neutralino masses up to 400 GeV.
- Best limits achieved for a maximal mixing scenario: BR(tcMET)=50%, BR(ttMET)=25%, BR(ccMET)=25% → not probed before.



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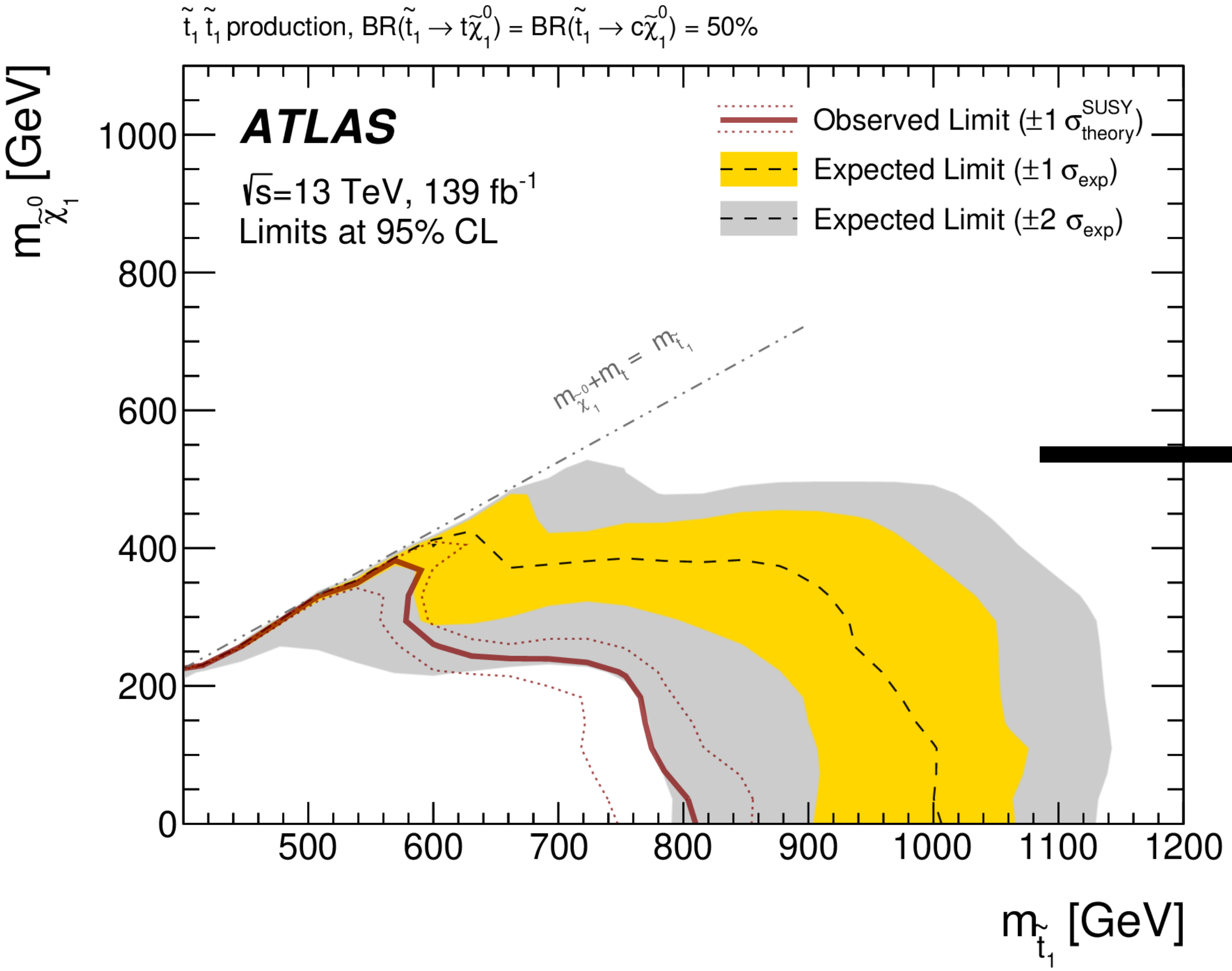
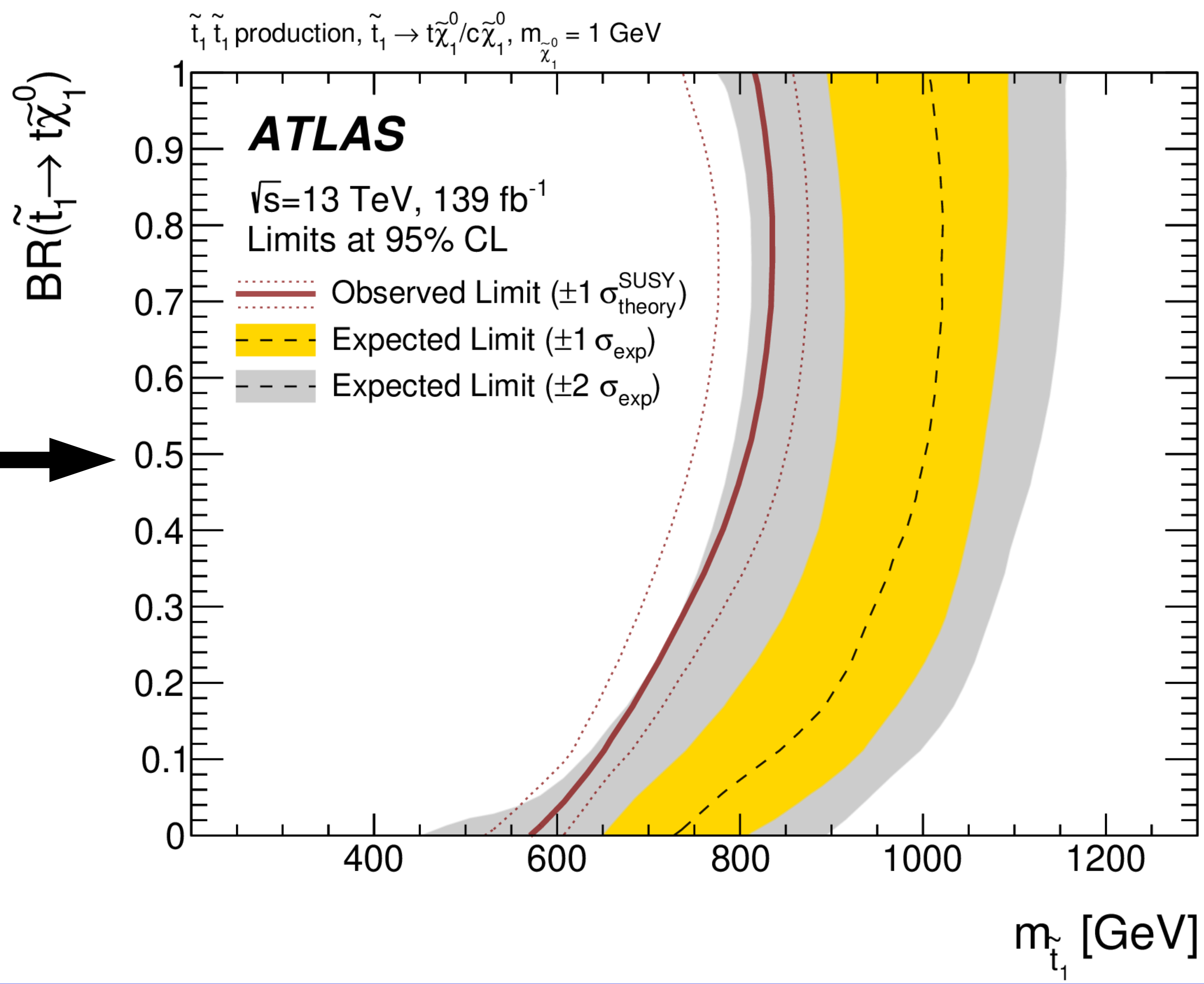
- Good sensitivity is retained even when varying BR.

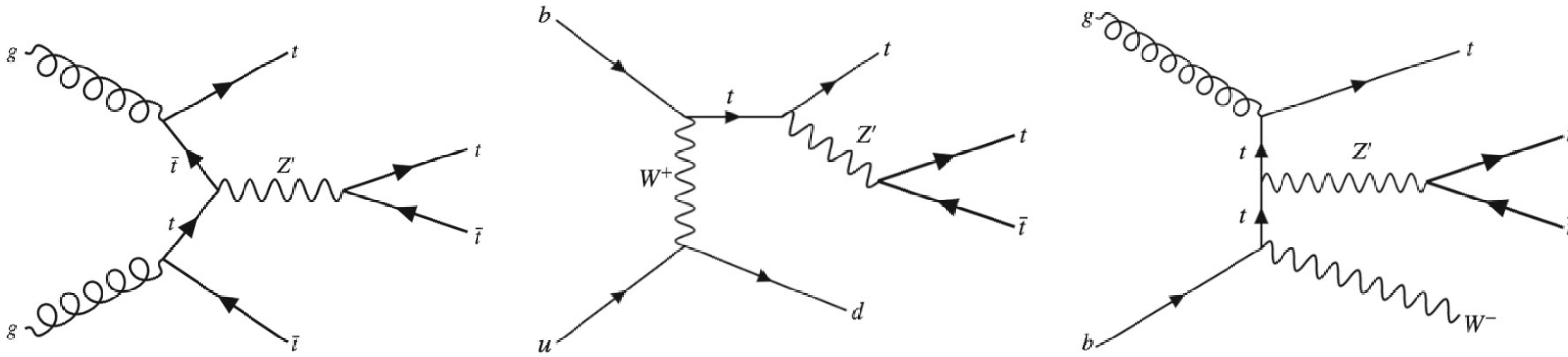




4-top with $t\bar{t}$ resonance

- Investigation of top-phillic vector resonances predicted by BSM extensions like composite Higgs models. A new Z' decaying to $t\bar{t}$ can be probed using:

$$\mathcal{L} = c_t \bar{t} \gamma_\mu (\cos\theta P_L + \sin\theta P_R) t Z'^\mu$$



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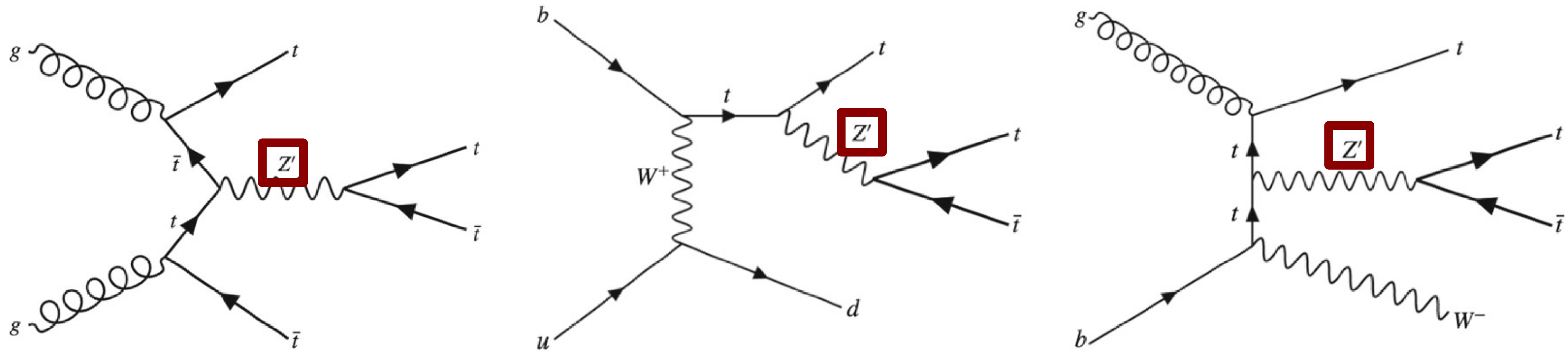
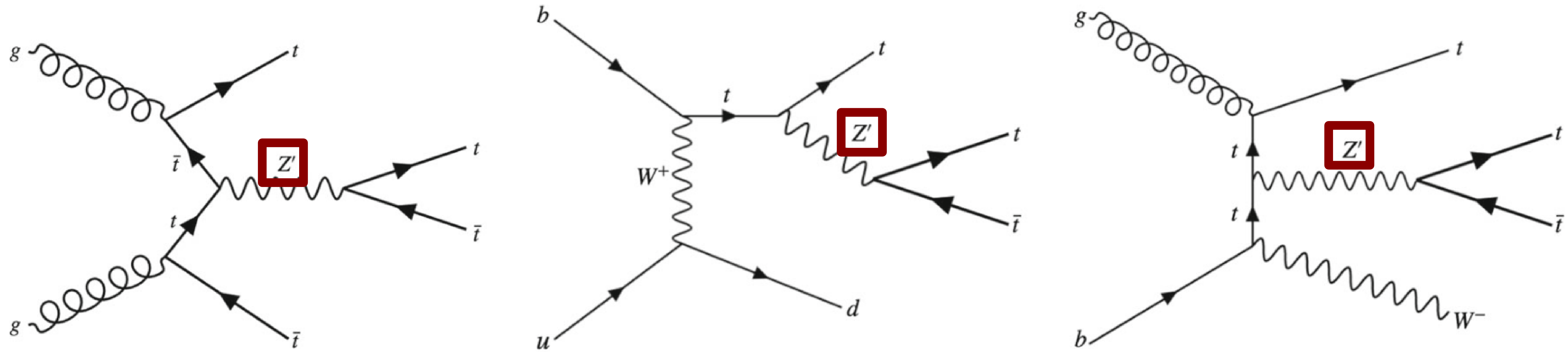


- The models are probed for different values of resonance mass ($m_{Z'}$), coupling to top quarks (c_t) and chirality parameter (θ).

4-top with $t\bar{t}$ resonance

- Investigation of top-phillic vector resonances predicted by BSM extensions like composite Higgs models. A new Z' decaying to $t\bar{t}$ can be probed using:

$$\mathcal{L} = c_t \bar{t} \gamma_\mu \left(\cos\theta P_L + \sin\theta P_R \right) t Z'^\mu$$



- The models are probed for different values of resonance mass ($m_{Z'}$), coupling to top quarks (c_t) and chirality parameter (θ).
- Final state where Z' decays to two hadronically decaying boosted top quarks is investigated. Background is estimated in control region data using functional fit with MC-based extrapolation functions.
- For the other two top-quarks in the final state, the semi-leptonic decay channel is considered.

4-top with $t\bar{t}$ resonance - Results

- The variable of interest is the m_{JJ} distribution for which a specific background estimate strategy is developed. The results are analyzed using two approaches:

4-top with $t\bar{t}$ resonance - Results

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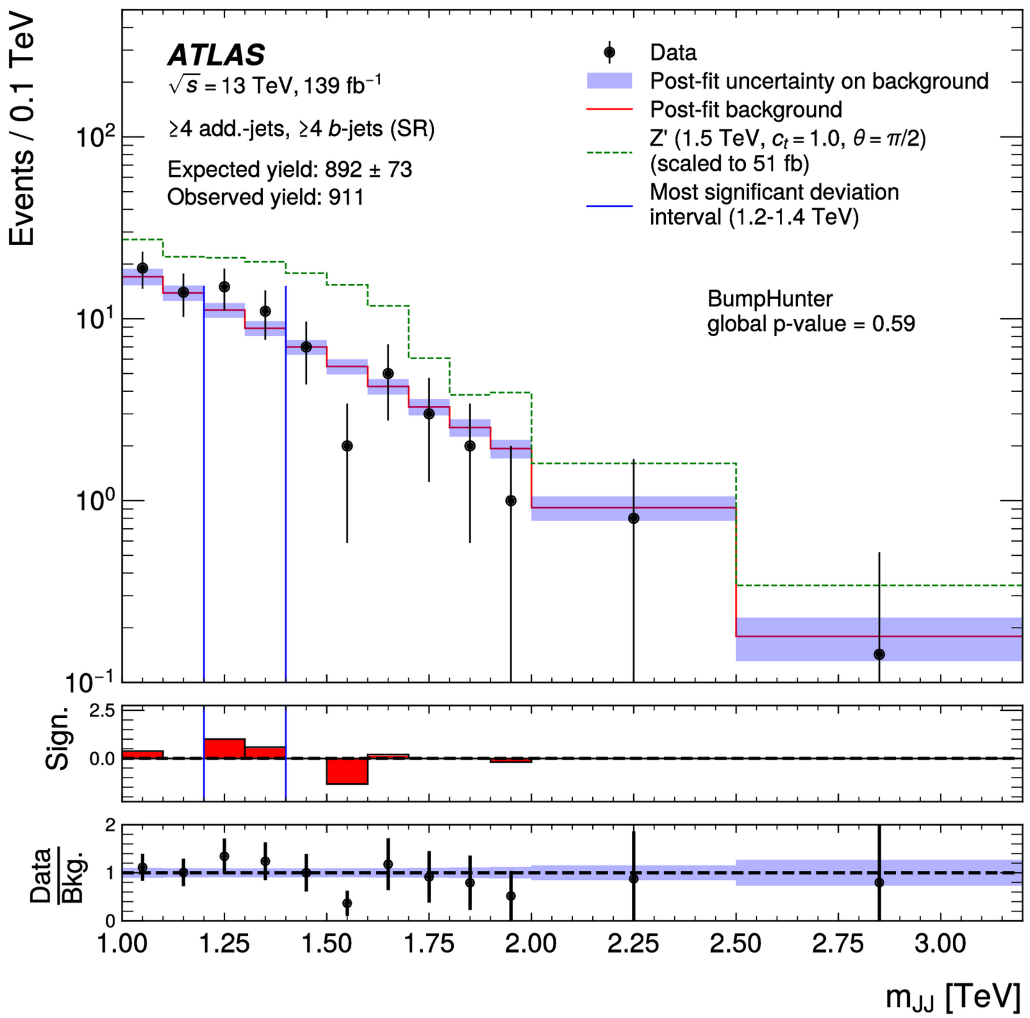

- One of the two most sensitive SRs shown as an example. No significant excesses are obtained.

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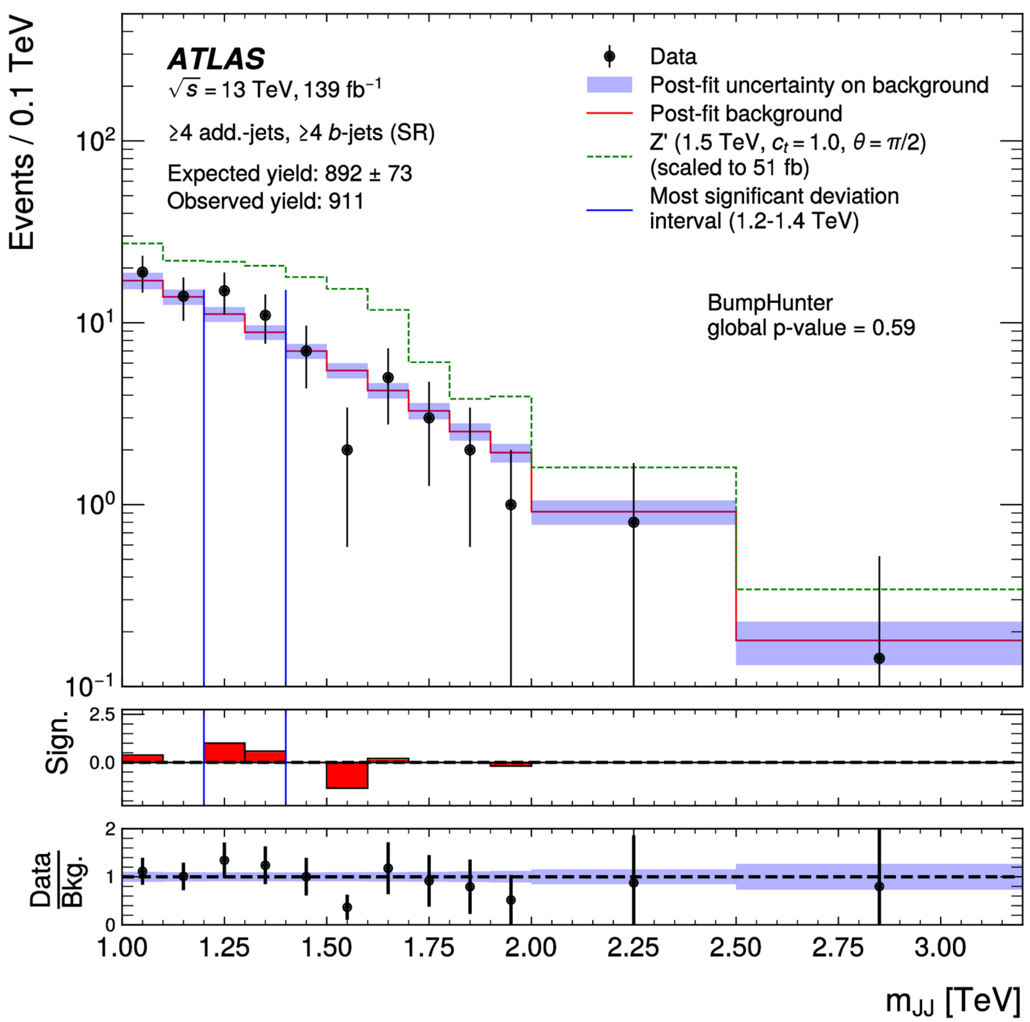
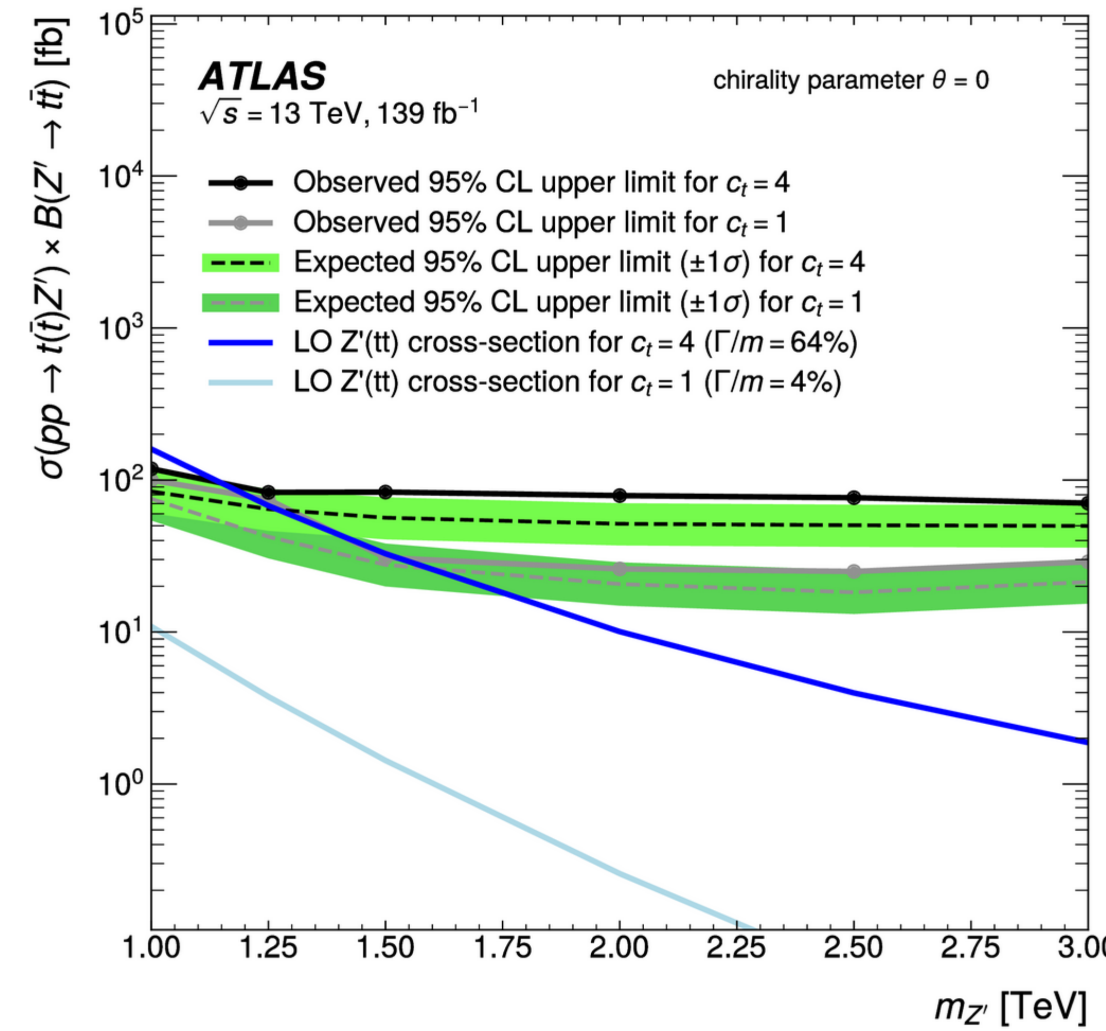


- One of the two most sensitive SRs shown as an example. No significant excesses are obtained.

Second → model-dependent approach → Limits on simplified model that predicts the production of top-philic spin-1 Z' resonances.



- Small region is excluded for a specific Z' model and upper limits on xsec are set for 1-3 TeV masses

W' → tb resonance

- ***W′*** → mediator of a new massive charged vector current. Appears in BSM scenarios, such as extra dimensions, strong dynamics or composite Higgs.

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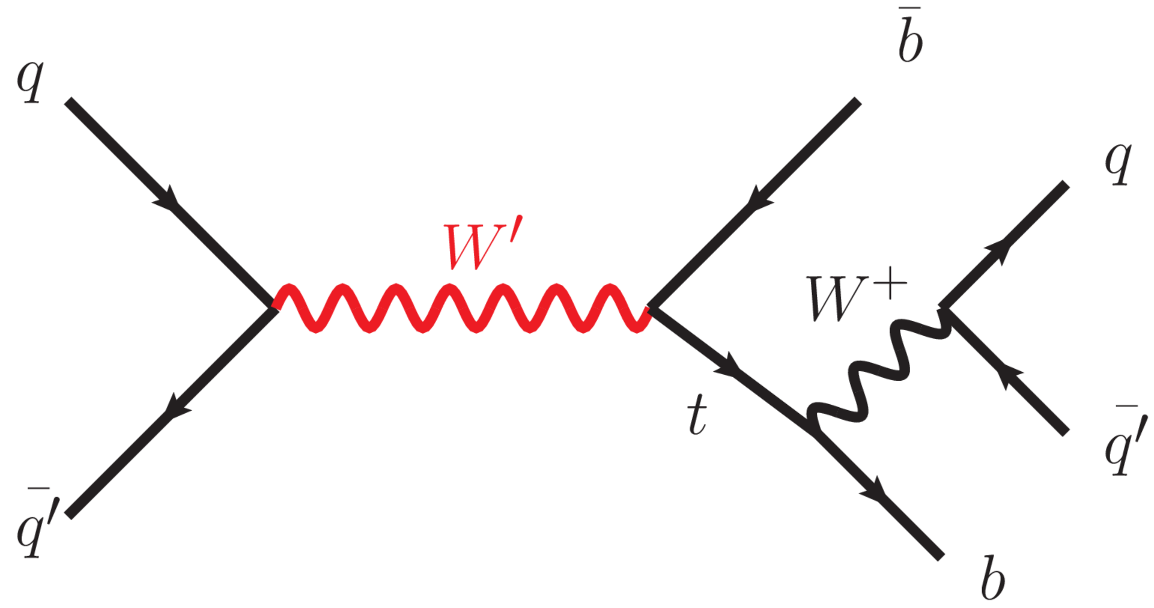
- For left-handed W's, the interference with the SM W-boson is specifically handled.



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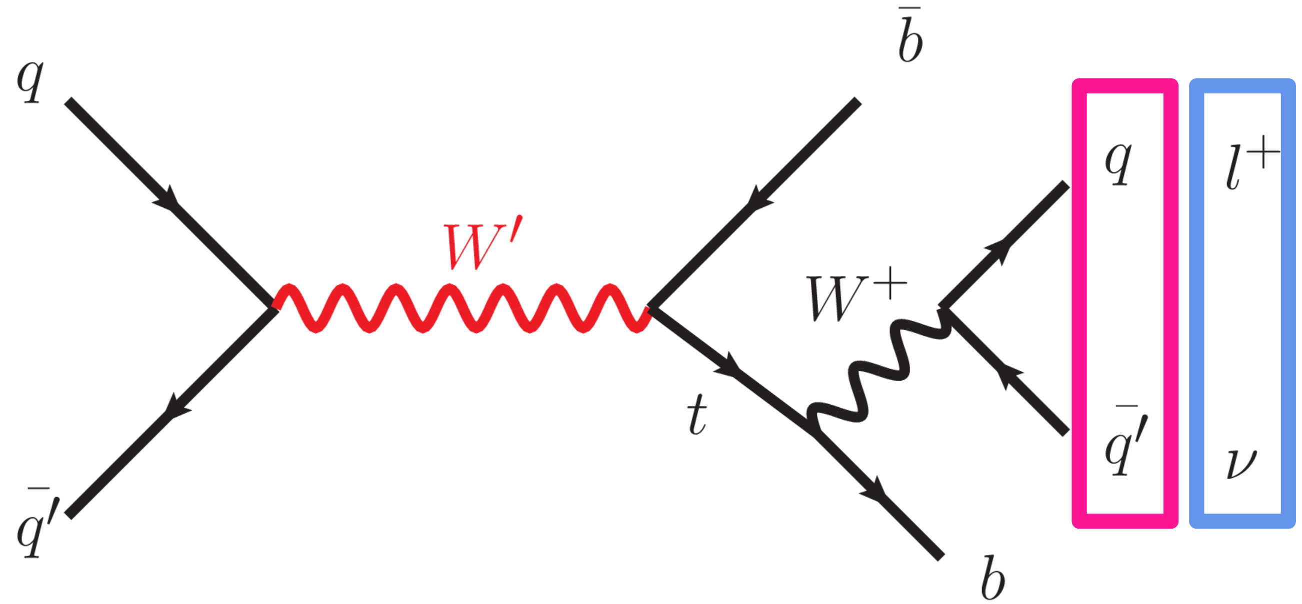

Fully reconstruct *tb* system is used:

- 0L: large-R jet + small-R jet
- 1L: 1 lepton + neutrino (MET) + 2 small-R jets

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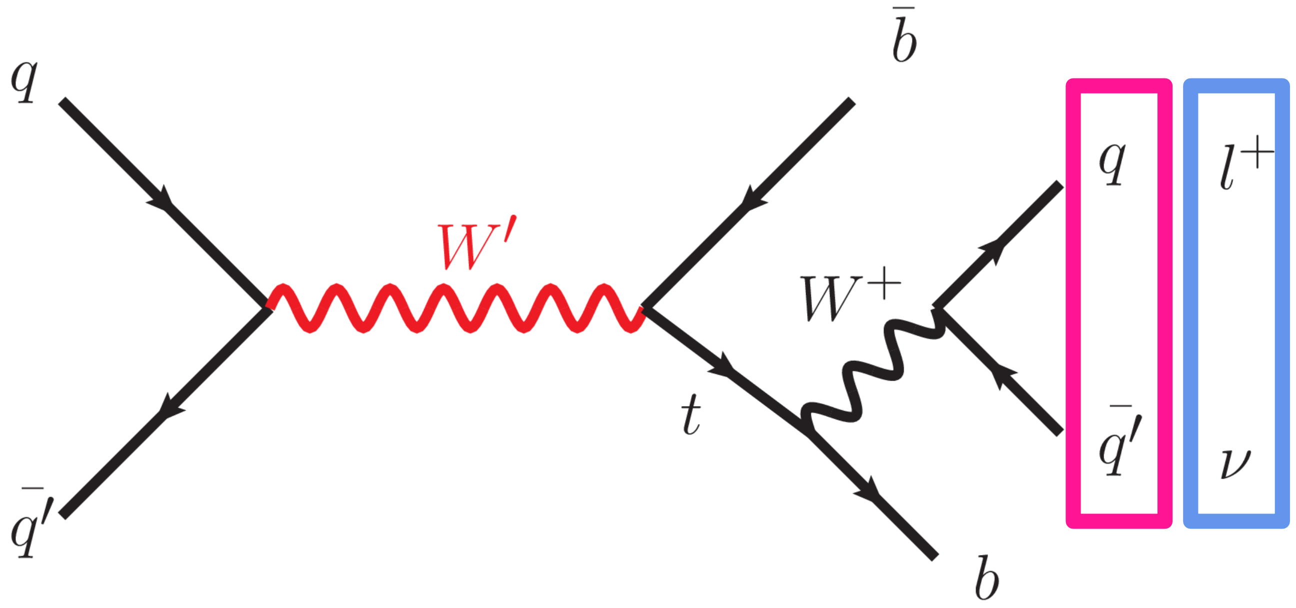
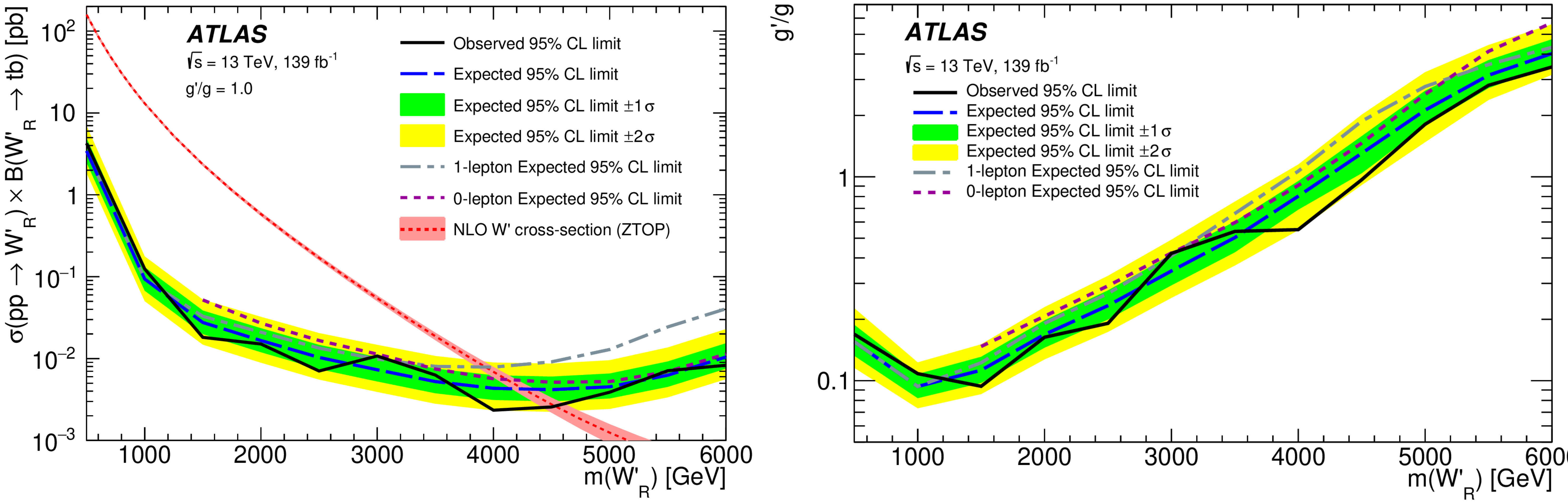


Fully reconstruct *tb* system is used:

- 0L: large-R jet + small-R jet
- 1L: 1 lepton + neutrino (MET) + 2 small-R jets

- For the background estimation, Monte Carlo simulations with data-driven methods are used.
- The sensitivity is obtained by performing a profile-likelihood on the m_{tb} variable in control and signal regions.

W' → tb resonance



- For g'/g = 1, right-handed (left-handed) W' bosons are excluded up to 4.6 TeV (4.2 TeV).
- A scan in g'/g is also performed for both chiralities.

Conclusion

- Top-quarks are used to probe many different BSM models using the full ATLAS Run-2 dataset.
- Boosted/resolved top taggers and c-taggers have played a crucial role in obtaining new results.
- A combination of machine learning techniques, data-driven methods and MC simulations have been developed to squeeze as much as possible out of the dataset.

Conclusion

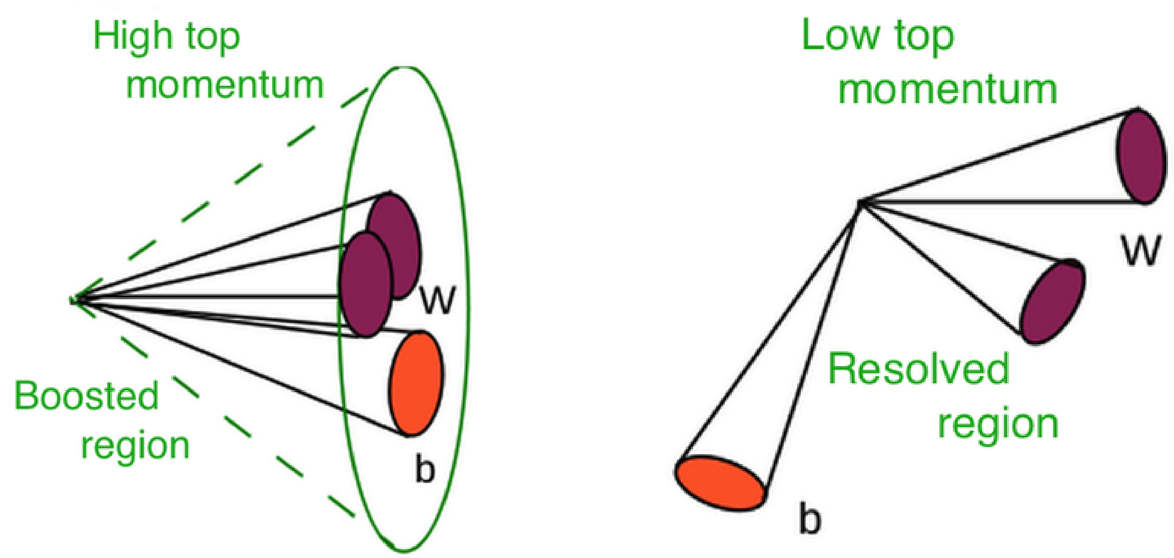
- Top-quarks are used to probe many different BSM models using the full ATLAS Run-2 dataset.
- Boosted/resolved top taggers and c-taggers have played a crucial role in obtaining new results.
- A combination of machine learning techniques, data-driven methods and MC simulations have been developed to squeeze as much as possible out of the dataset.
- Both the tcMET (0L) and ttMET (1L) analyses have ~ 2 sigma excesses in independent regions of phase space.
- The 4-top process has been effectively probed for resonance searches for the first time since the full Run-2 dataset makes it possible to study the SM 4-top final state.
- While the search for new bosons have not yielded significant excesses, the searches have been made as model-independent possible, making it easier to explore a wider theory space.

Thank You!

Backup

Neural Net Strategy

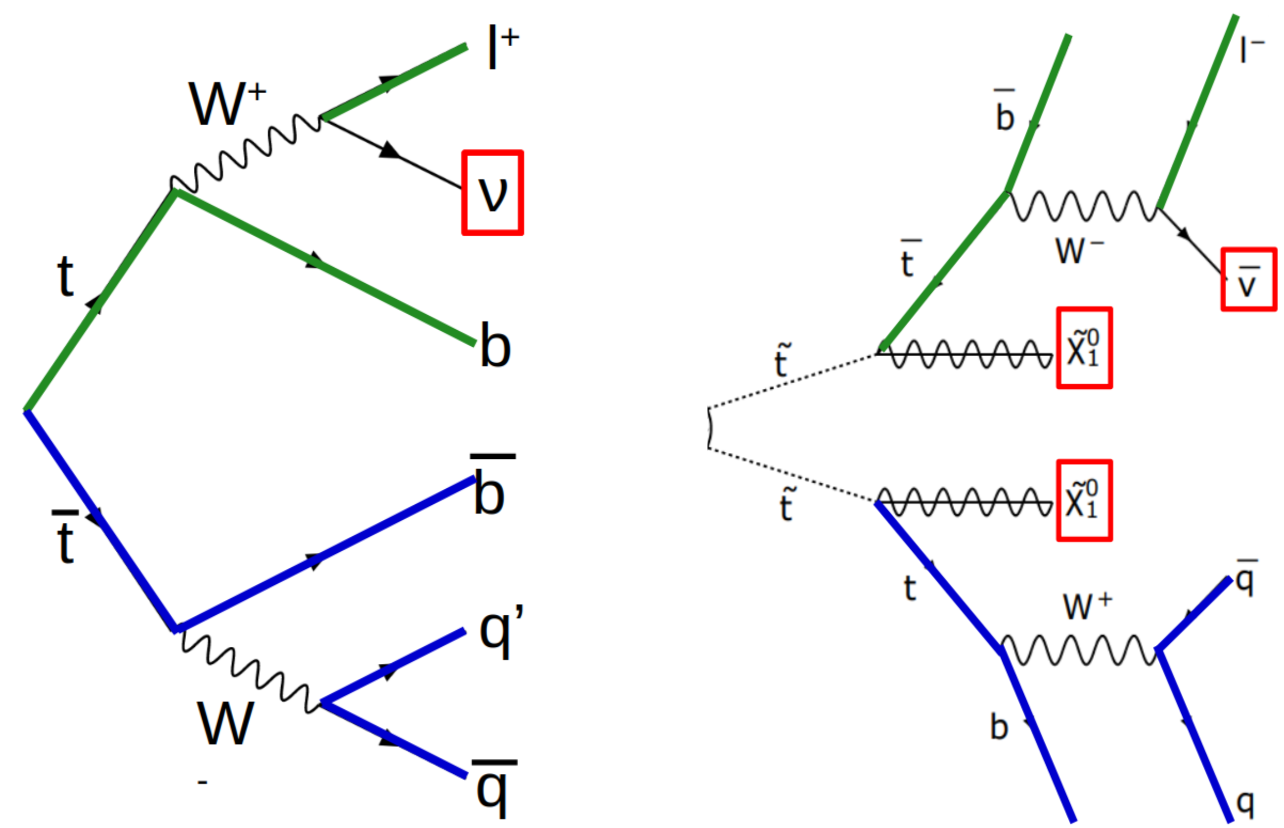
1. Top reconstruction with DNN



- For **boosted** (high pT) tops, large-R jets are selected and a DNN developed by the jet group is used to tag these jets as tops.
- For **resolved** (mid pT) tops, a dedicated NN is developed to reconstruct the top pair from 3 leading jets (2 b-tagged) and 1 leading lepton in the event.

2. Event Discrimination with DNN

- Exploit full kinematic properties of the events.
- Inputs - both top 4-vectors together with met, jet and lepton 4-vectors + high-level variables.

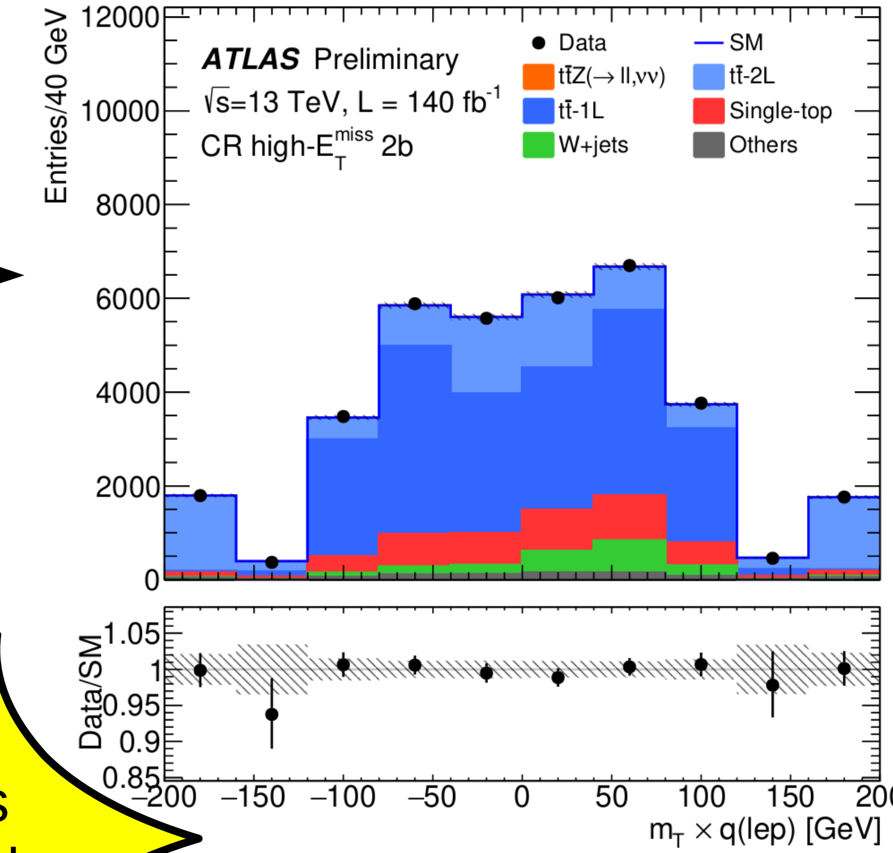


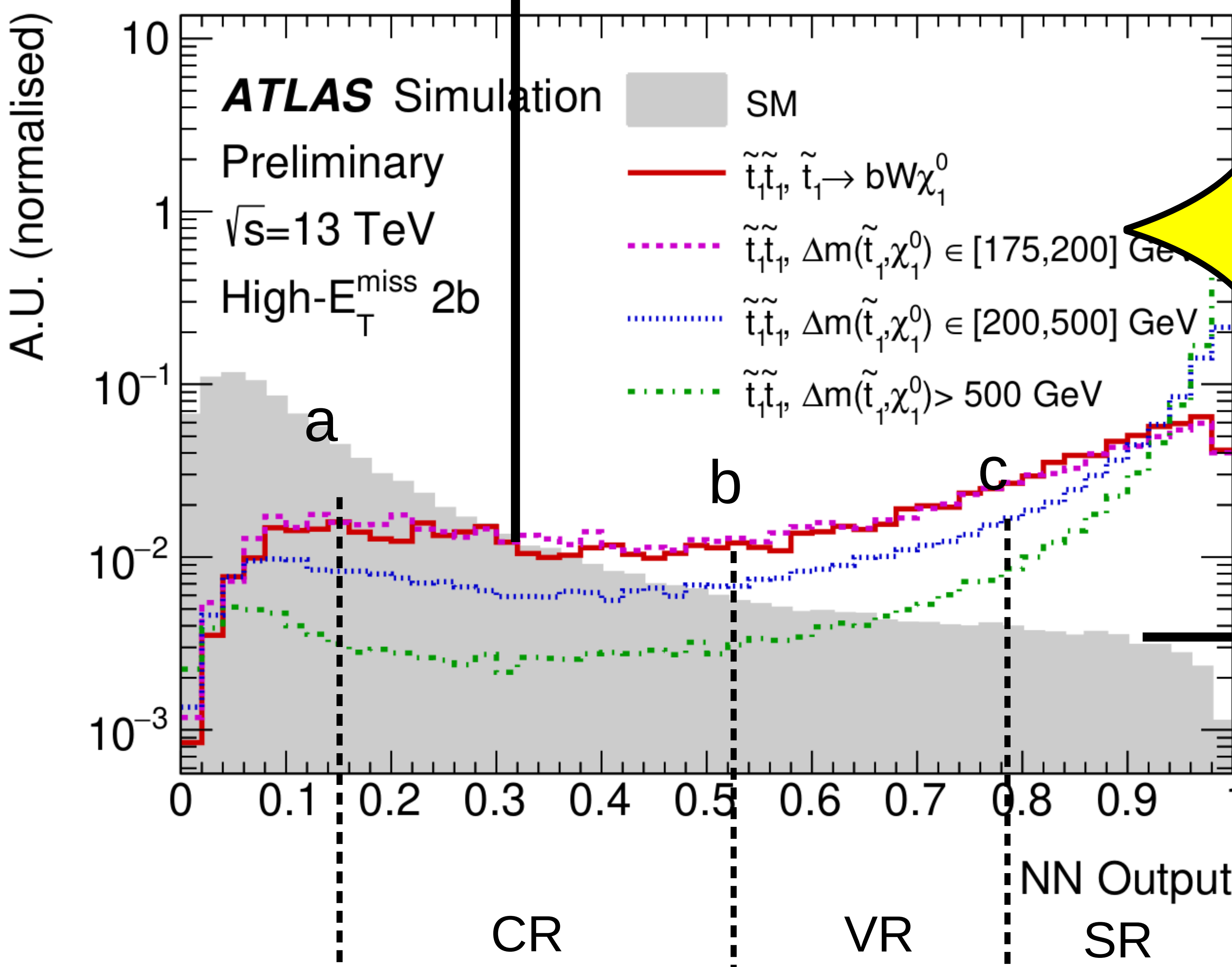
Two flavors of NNs are trained one for stop and one for DM

$t\bar{t}+E_T^{miss}$ (1L) - NN Fit Strategy

Re-binned in relevant variable
[$m_T(l,E_T^{miss})$ * q(l) or yield]

Used for the background fit

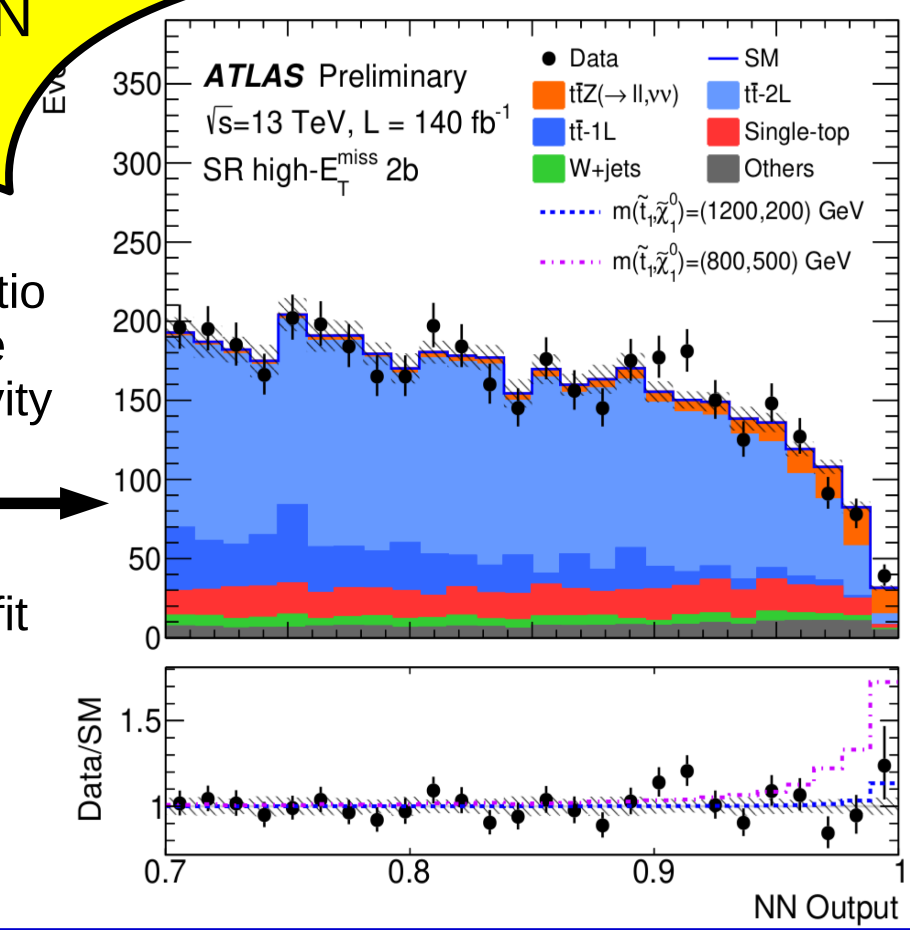




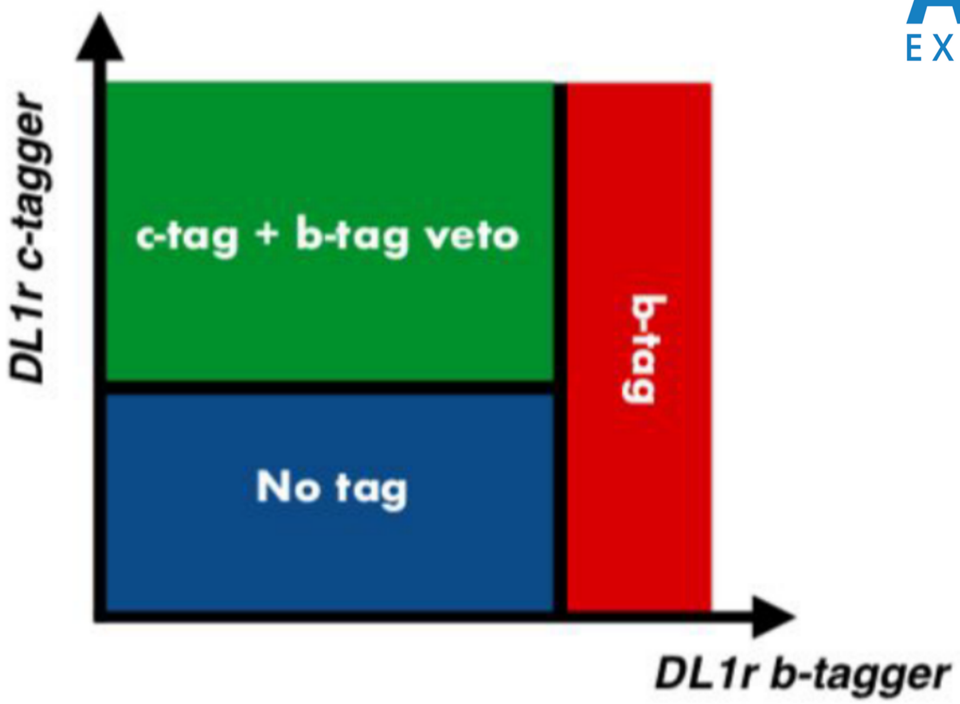
Sensitive to different signals with different NN distributions

Changing S/B ratio used to achieve maximum sensitivity

With a multi-bin fit



tc+E_T^{miss} - Improved c-tagging



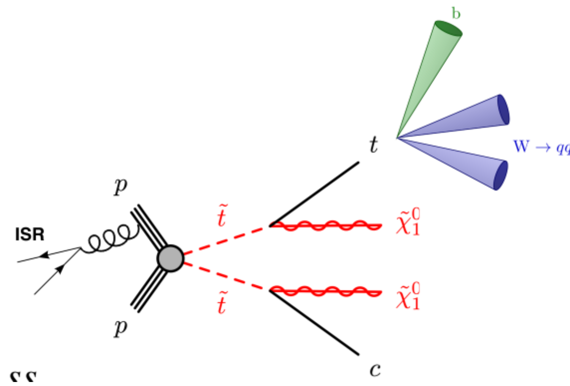
c-tagging with b-veto technique

Step 1: DL1r → b-tagging algorithm

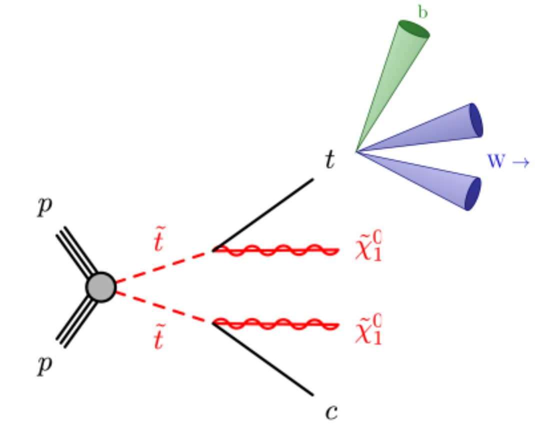
Step 2: $DL1r_c$ (modified DL1r) → c-tagging algorithm

- very helpful to avoid a large rate of b-jets misidentified as c-jets
- DL1r (b-tagger) is used at the 77% working point which corresponds to 20% fake c-tags.
- Overall algorithm yields → 20% c-jet efficiency, with rejection factors of 29 for b-jets and 5 for light-jets
- What remains is a high rate of fake hadronic taus ~ 15% → dealt with at later stage.

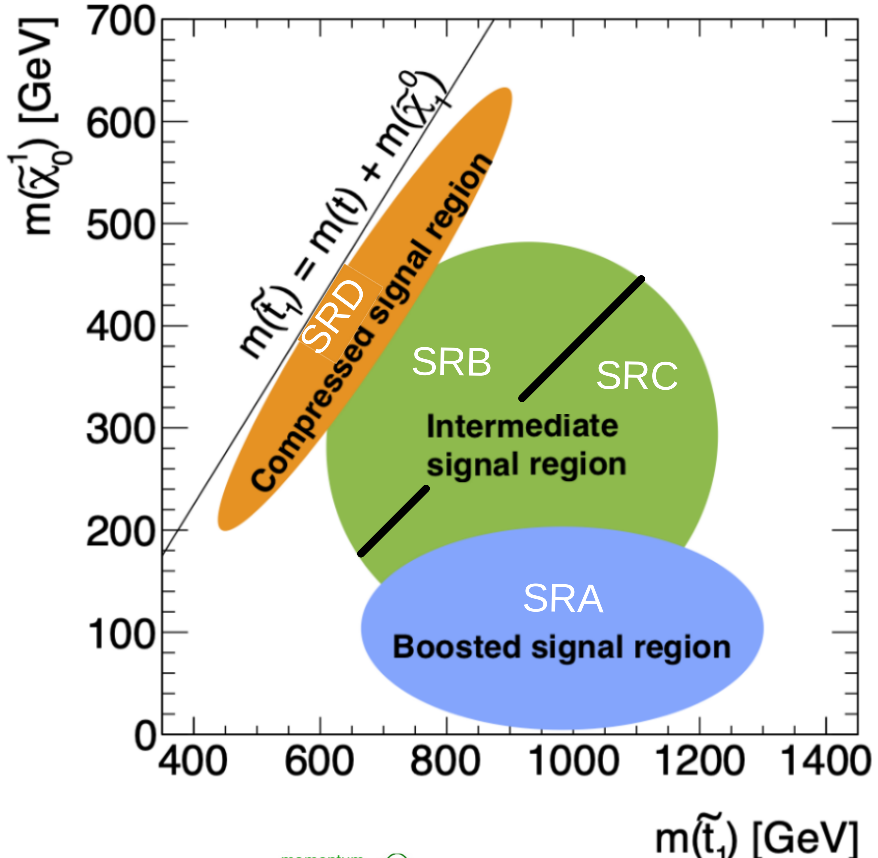
tc+E_T^{miss} - Event Phase Space

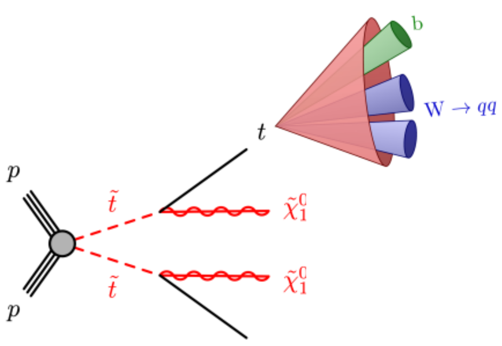


- **Main Backgrounds:**
  - ttbar (semi-leptonic with missed lepton – fake MET)
  - Z + jets where Z decays to neutrinos
  - W + jets where the jets look like a top
- Orthogonality: Leading jet ≠ b/c (ISR)

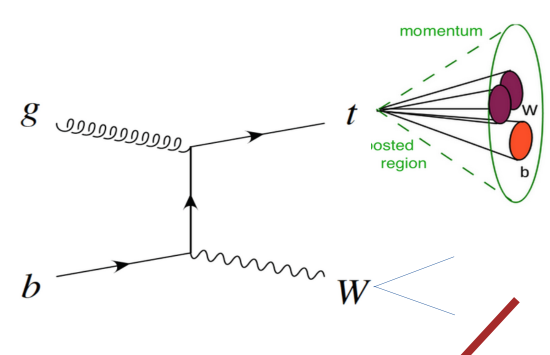


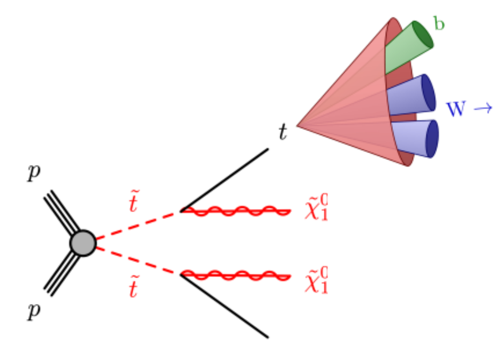
- **Main Backgrounds:** Z+jets, W+jets
  - Without a top tag, mainly V+jets remain where b and c jets are present
- Orthogonality: Leading jet = b/c

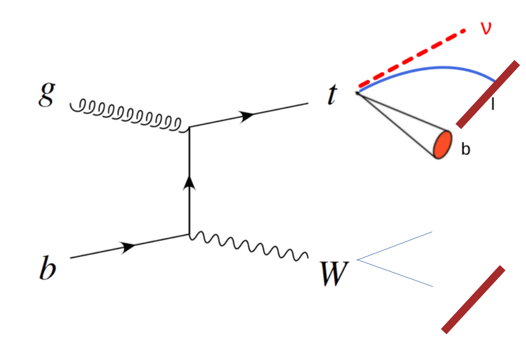




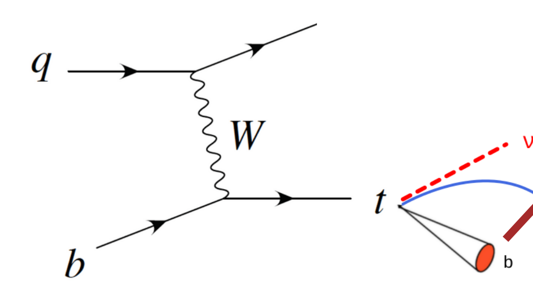
- **Main Backgrounds:**
  - Zjets where Z decays to neutrinos
  - Singletop [tW(tau → c)]
- Orthogonality: MT2 <= 450 GeV





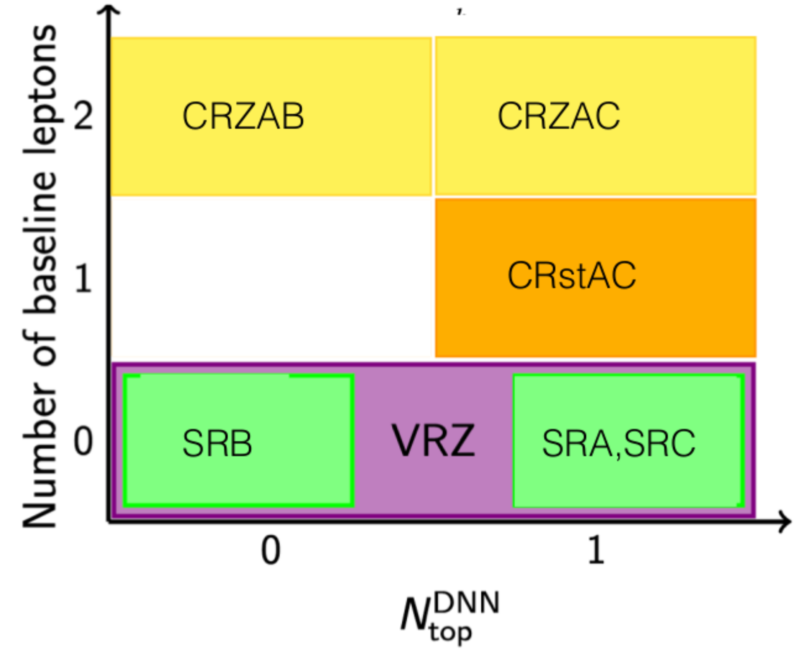


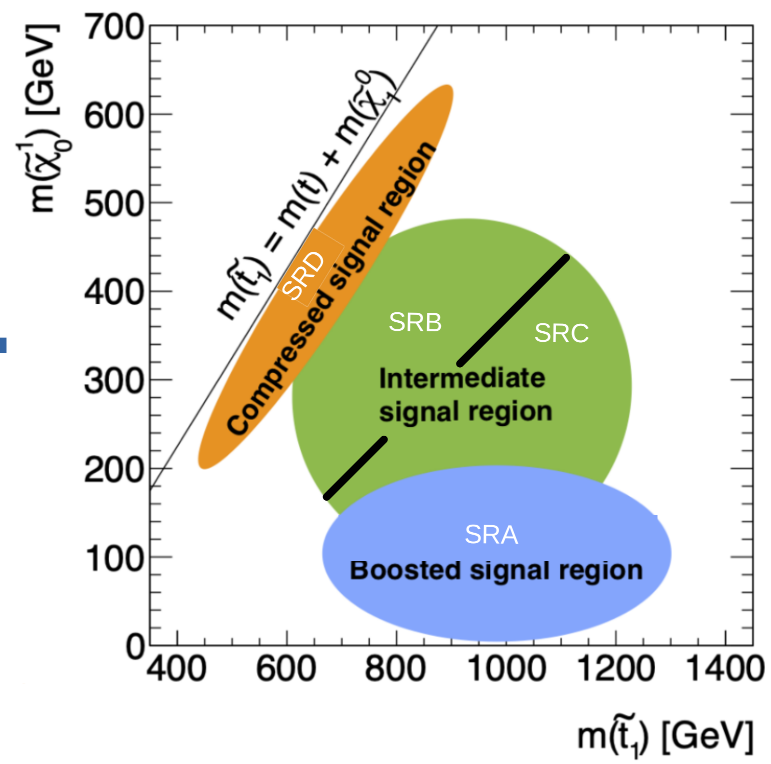
- **Main Backgrounds:**
  - Zjets where Z decays to neutrinos
  - Singletop [tW(tau → c)], [t-chan (t+j)]
- Orthogonality: MT2 > 450 GeV

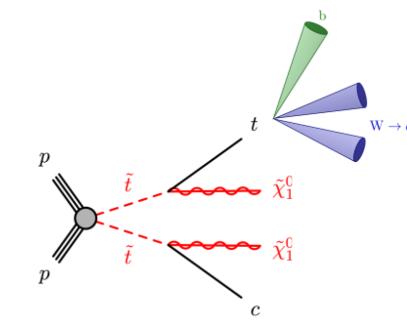


$tc+E_T^{miss}$ - Background Estimation – Regions ABC

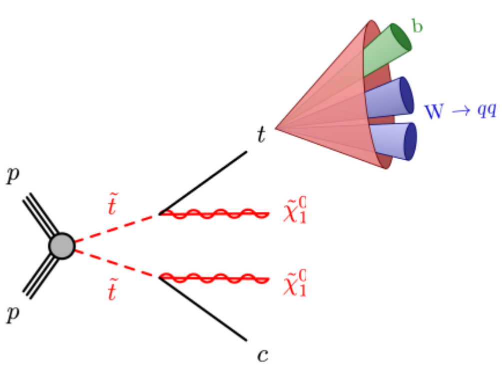
- Common control regions for SRA and SRC – events with a boosted top + same SM backgrounds:
  - singletop: CRstAC (1L events) + Zjets: CRZAC (2L events)
- Control regions for SRB – events without boosted top:
  - Z+jets: CRZB (2L events)
- One validation region for SRA, SRB, SRC
  - Z+jets: VRZABC (0L events)



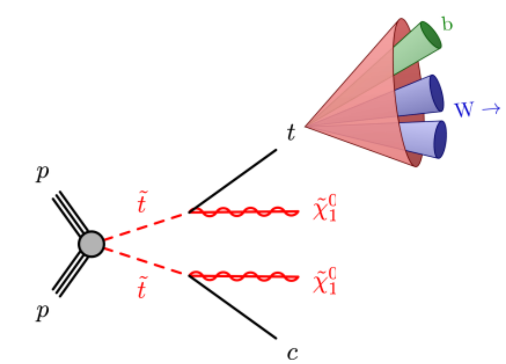




- **Main Backgrounds:** Z+jets, W+jets



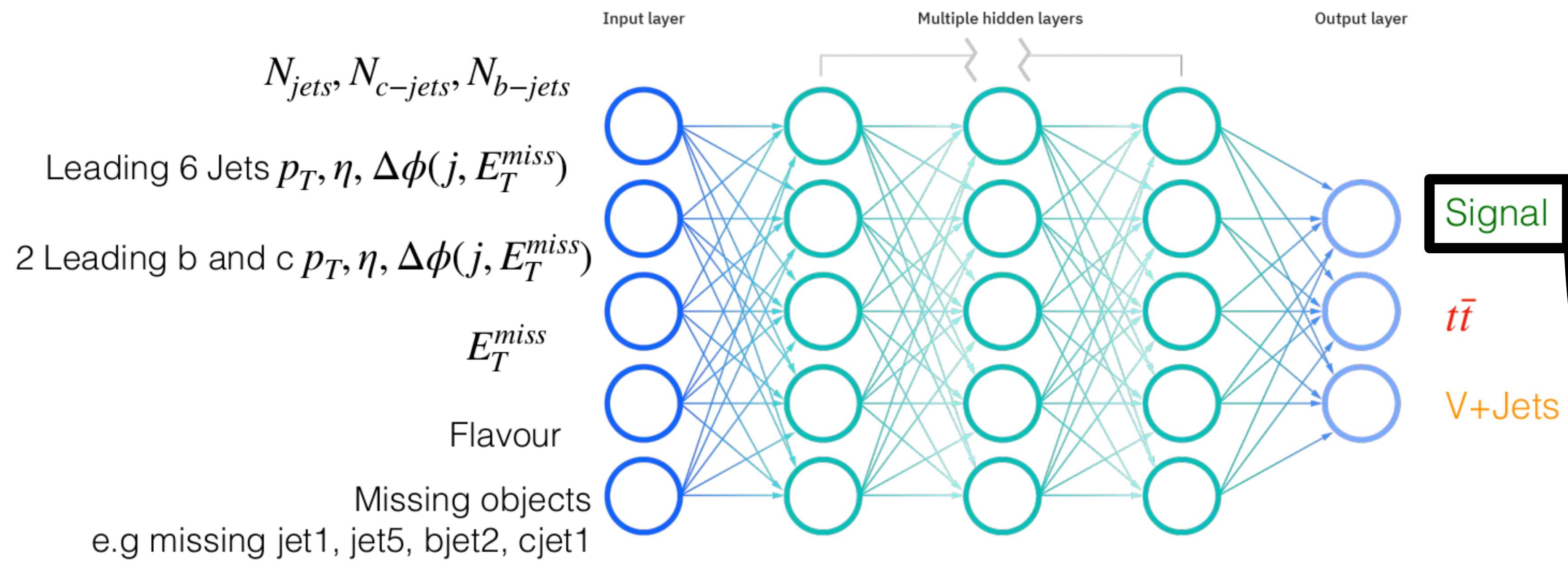
- **Main Backgrounds:** Z+jets, singletop
- Orthogonality: MT2 <= 450 GeV

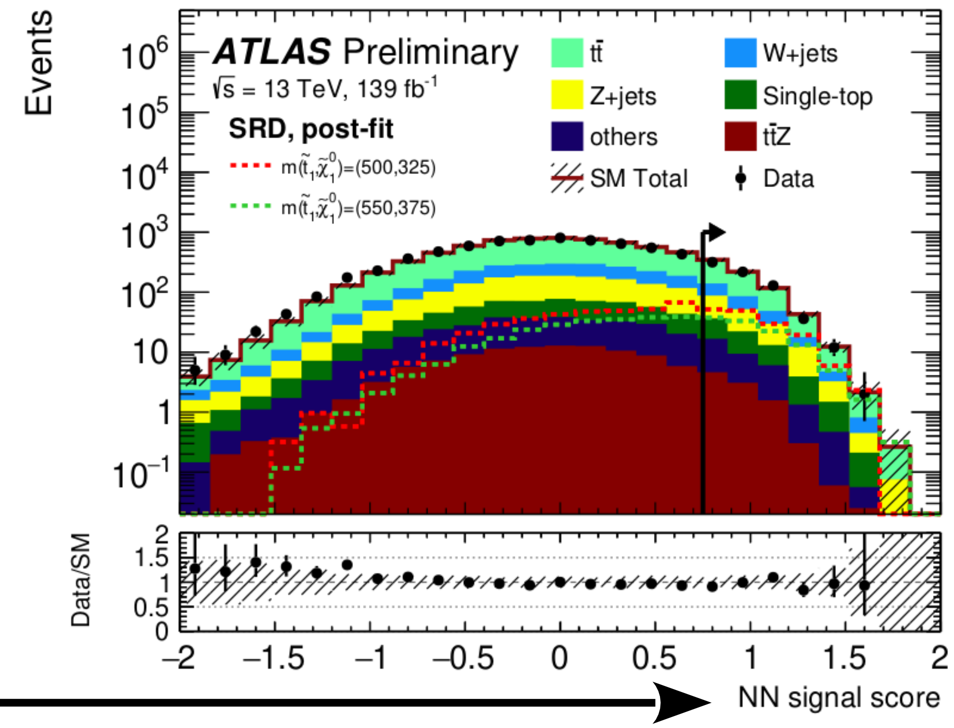


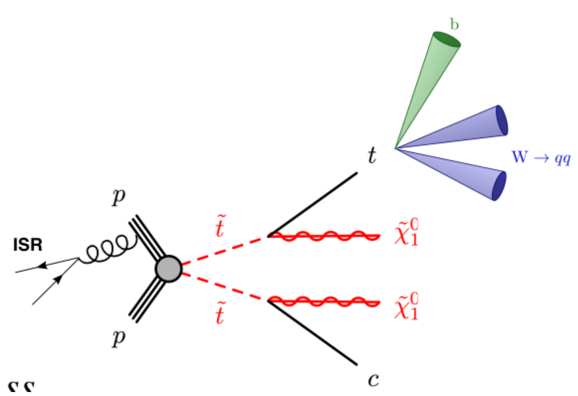
- **Main Backgrounds:** Z+jets, singletop
- Orthogonality: MT2 > 450 GeV

tc+E_T^{miss} - Analysis Strategy – Region D

Uses a multi-classifier DNN





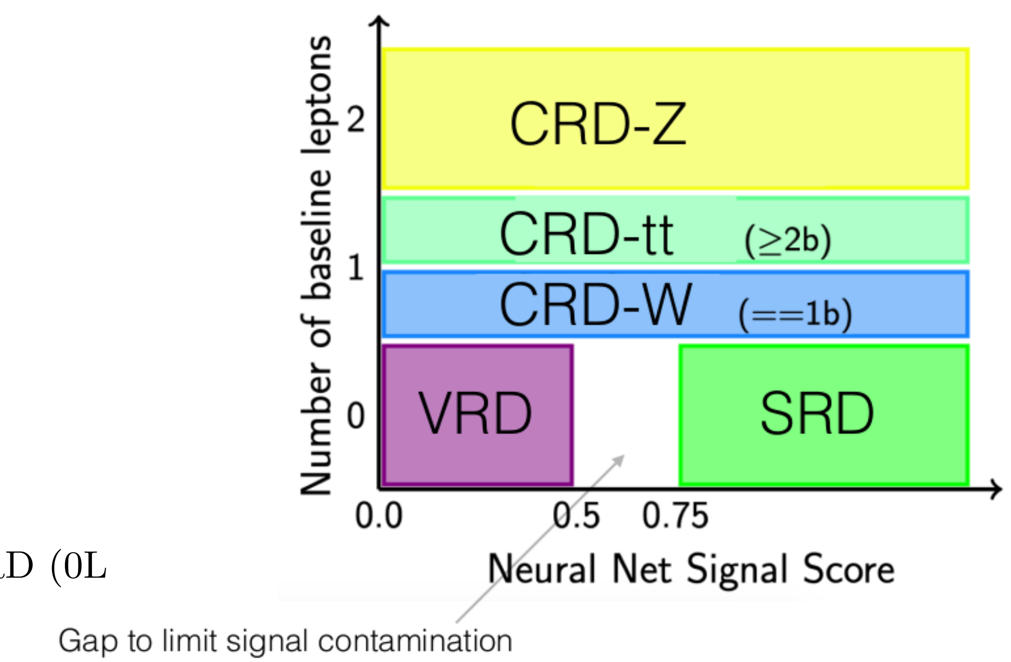


- **<u>Main Backgrounds:</u>** ttbar, Z+jets, W+jets

Each backgorund gets a CR:

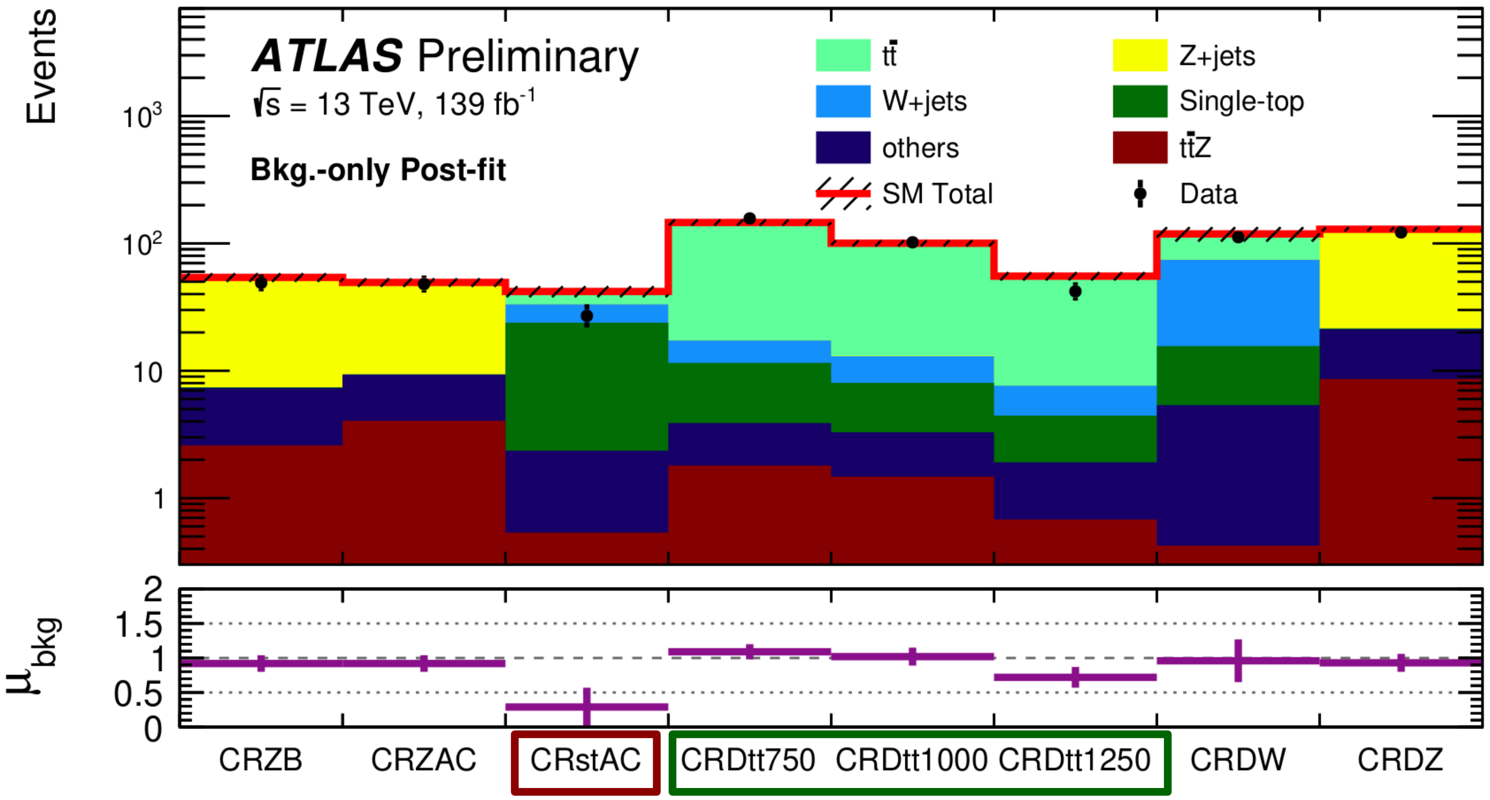
- Zjets CR for SRD (2L events)
- Ttbar CR for SRD (1L events) + (>=2b)
- Wjets CR for SRD (1L events) + (==1b)

- Low NN score validation region for SRD
  - Validate all three backgrounds at once → VRD (0L events)



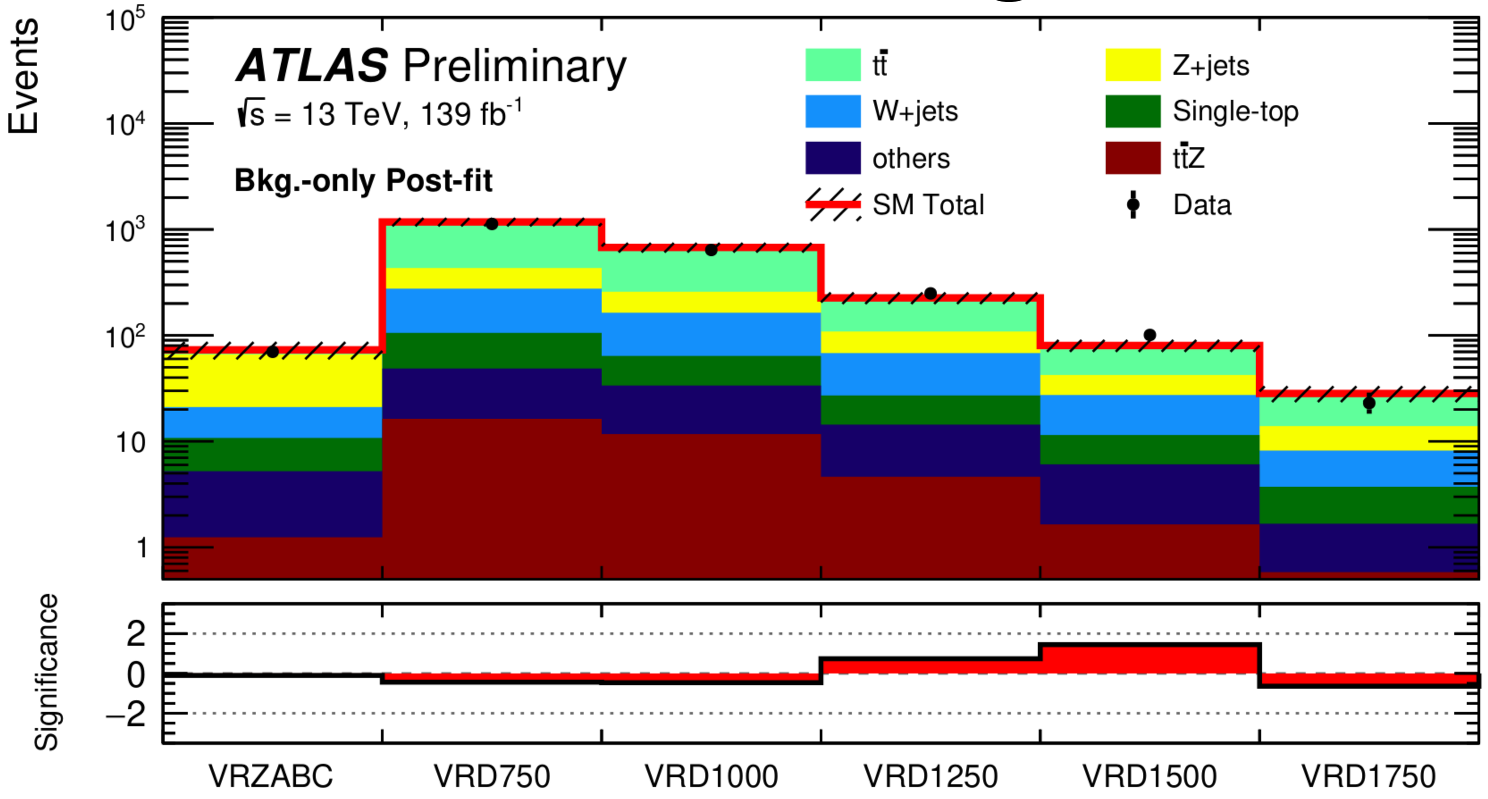
tc+E_T^{miss} - Results – Bkg-Only Fit

Control Regions



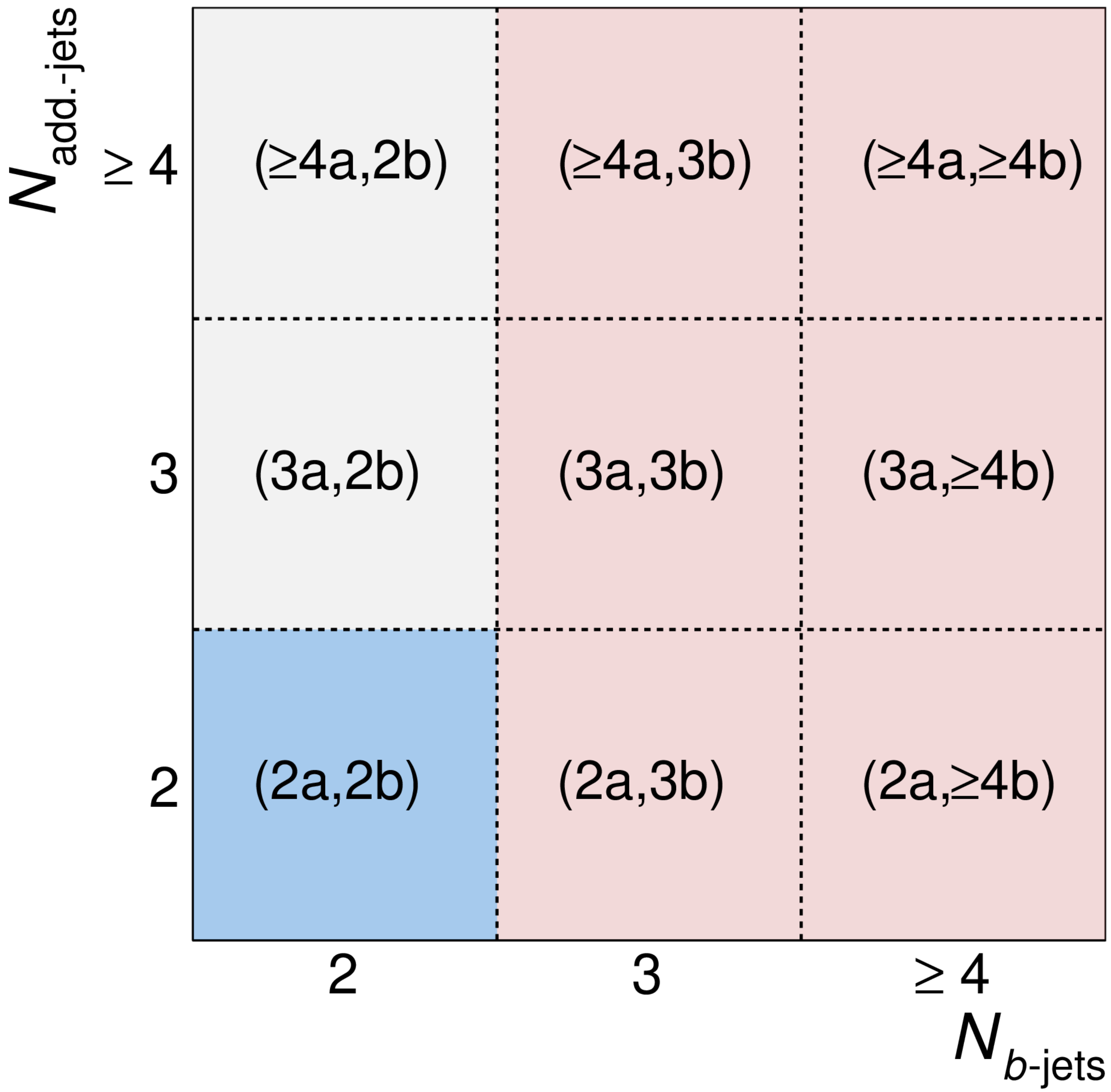
- A profile-likelihood fit is done yielding almost all normalization factors consistent with 1
  - Exception: singletop – this is quite common in the extreme phase spaces in SUSY
  - Three different ttbar normalization factors are considered
    - CRD tt750 → tt1000 → tt1250 binned in H_T
    - Highly correlated with increasing pT ttbar events → need increasing correction

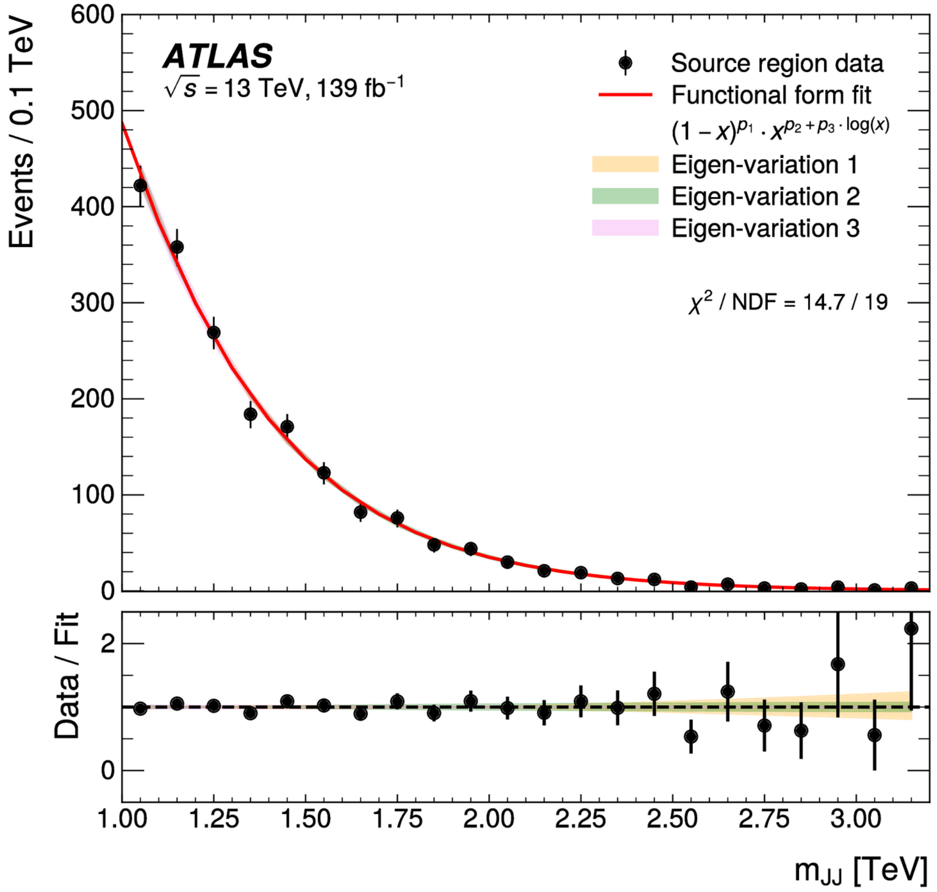
Validation Regions



- Normalization factors (to correct the different background processes) from Control Regions extracted to corresponding Validation Regions
- Post-fit excesses in VRs < 2 sigma
- These are not used in the fit, they are used to validate the profile-likelihood fit in Control Regions

4-top – Signal Region Definition



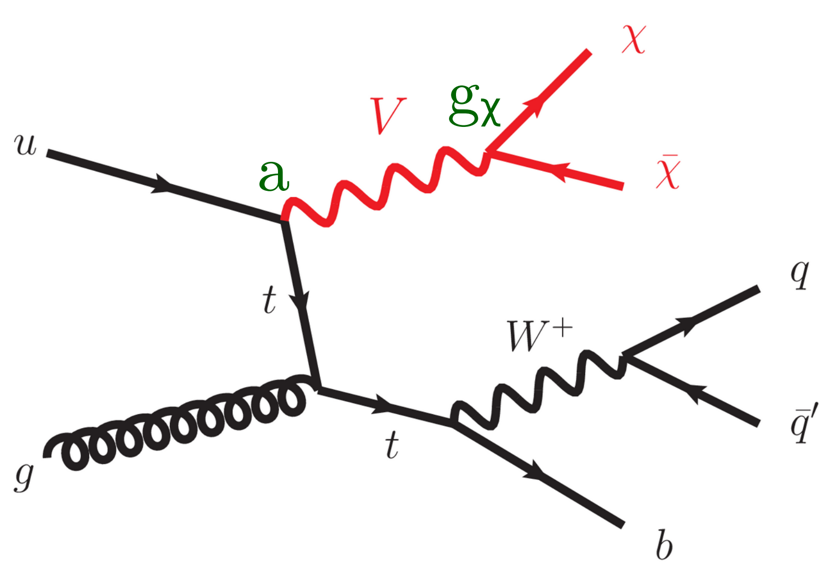


- **Source Region:** used to estimate the background from fit to data.
- **Validation Regions:** used to check the background estimation and profile likelihood fit setup.
- **Signal Regions:** Regions most sensitive to signal used for profile likelihood fits.

Mono-top

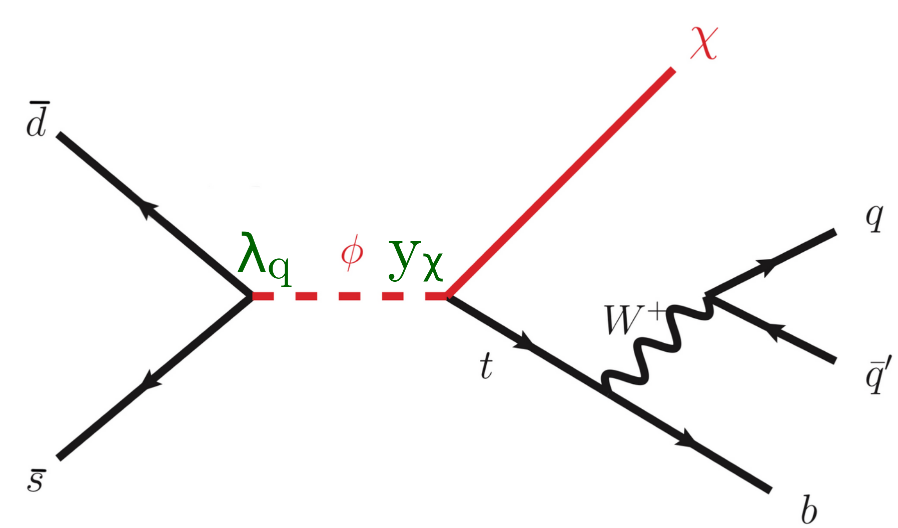
- Investigates two simplified models for dark matter interpretation: scalar and vector mediator models and the single production of a Vector-Like Top-quark.
- Analyzed signal processes dependent on various model parameters, including masses and couplings.

Vector DM mediator



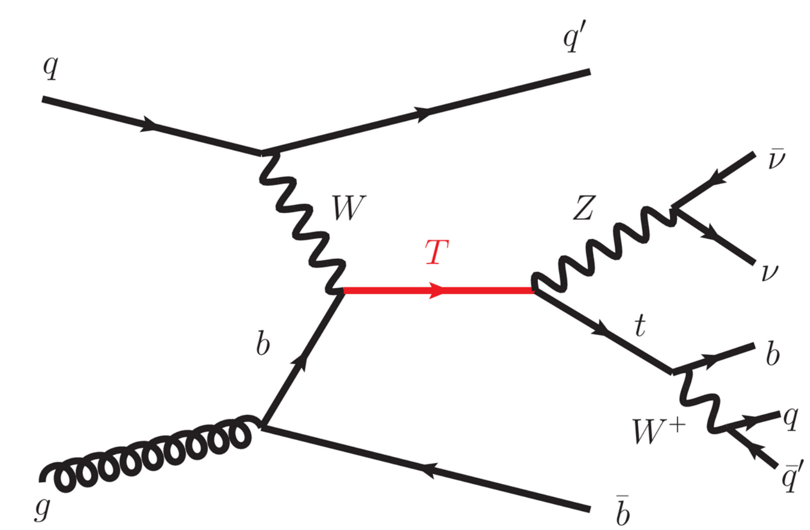
Parameters: m_V, m_χ, a, g_χ

Scalar DM mediator



Parameters: m_ϕ, m_χ, λ_q, y_χ

Vector-like Top

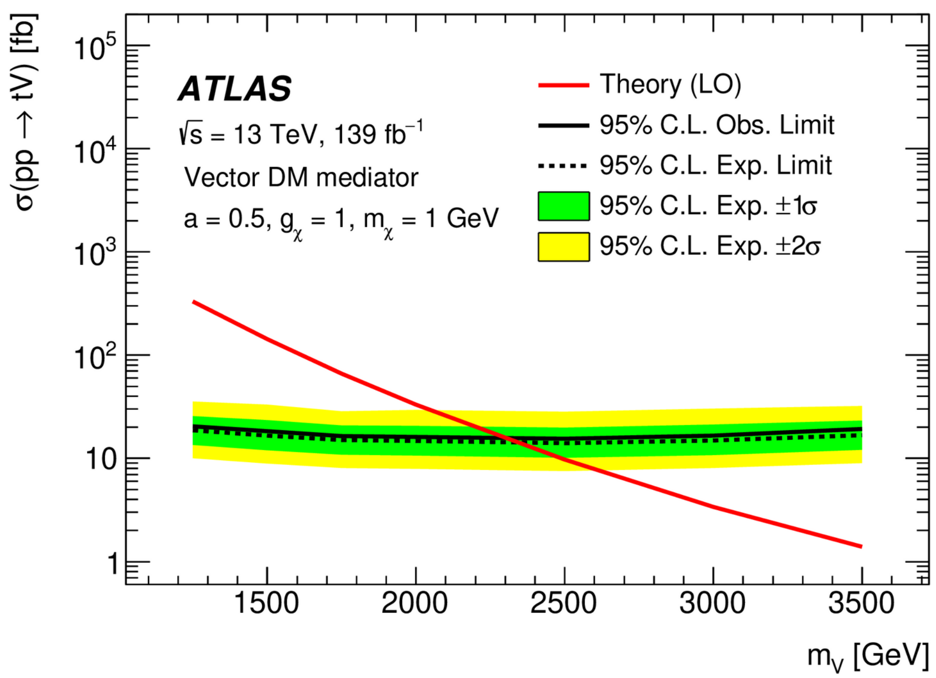


Parameters: κ_T, m_T

- Events with a boosted top quark and large E_T^{miss} are used. An MVA strategy is used with three different BDTs trained to separate background and from the three different signal models.
- A binned distribution of the BDT output score is used to get maximum sensitivity. Common control regions are used for backgrounds: ttbar and V+jets.

Mono-top - 1D Results

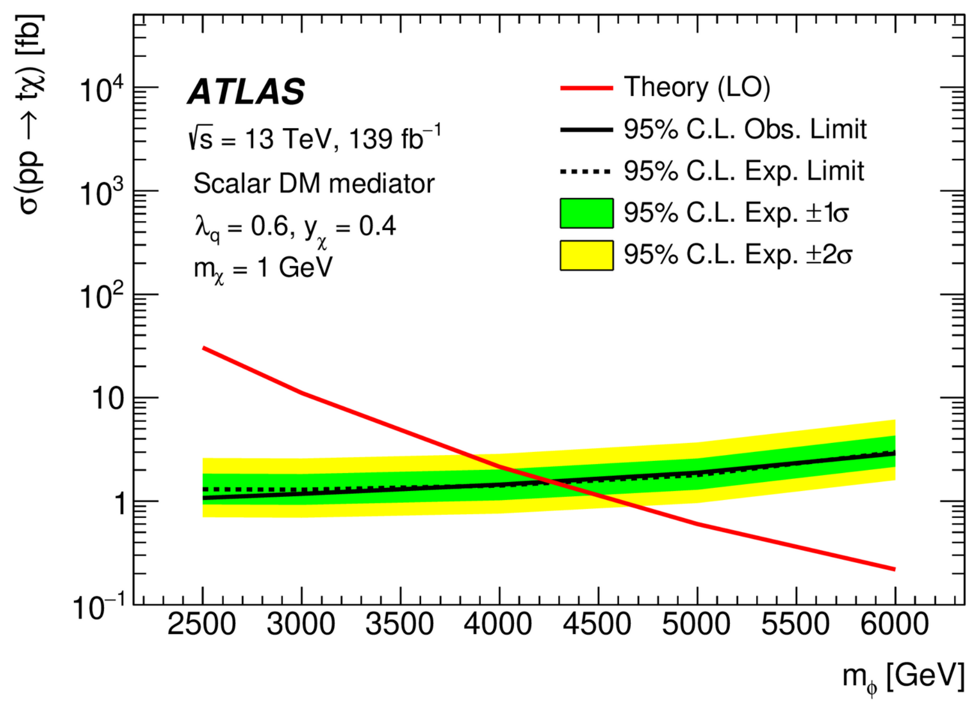
Vector DM mediator



$m_V < 2.3$ TeV excluded

$$\left(\begin{array}{c}\text{For } a = 0.5 \text{ and } g_\chi = 1, \\ \text{and } m_\chi = 1 \text{ GeV}\end{array}\right)$$

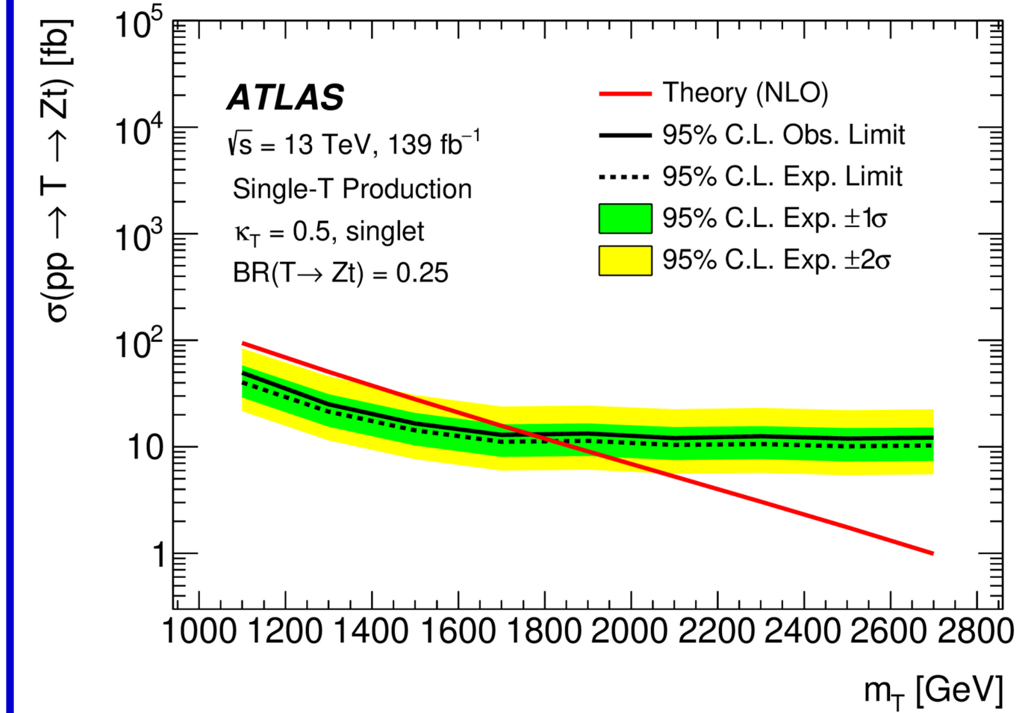
Scalar DM mediator



$m_\phi < 4.3$ TeV excluded

$$\left(\begin{array}{c}\text{For } \lambda_q = 0.6 \text{ and } y_\chi = 0.4, \\ \text{and } m_\chi = 1 \text{ GeV}\end{array}\right)$$

Vector-like Top

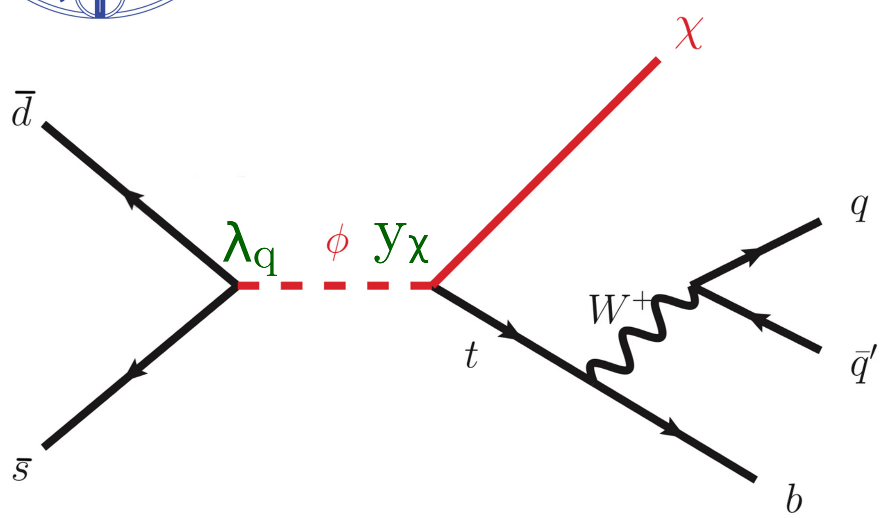


$m_{\mathrm{T}} < 1.8$ TeV excluded

$$\left(\begin{array}{c}\text{For } \kappa_{\mathrm{T}} = 0.5 \text{ and} \\ \mathrm{BR}(T \to Zt) = 25\%\end{array}\right)$$

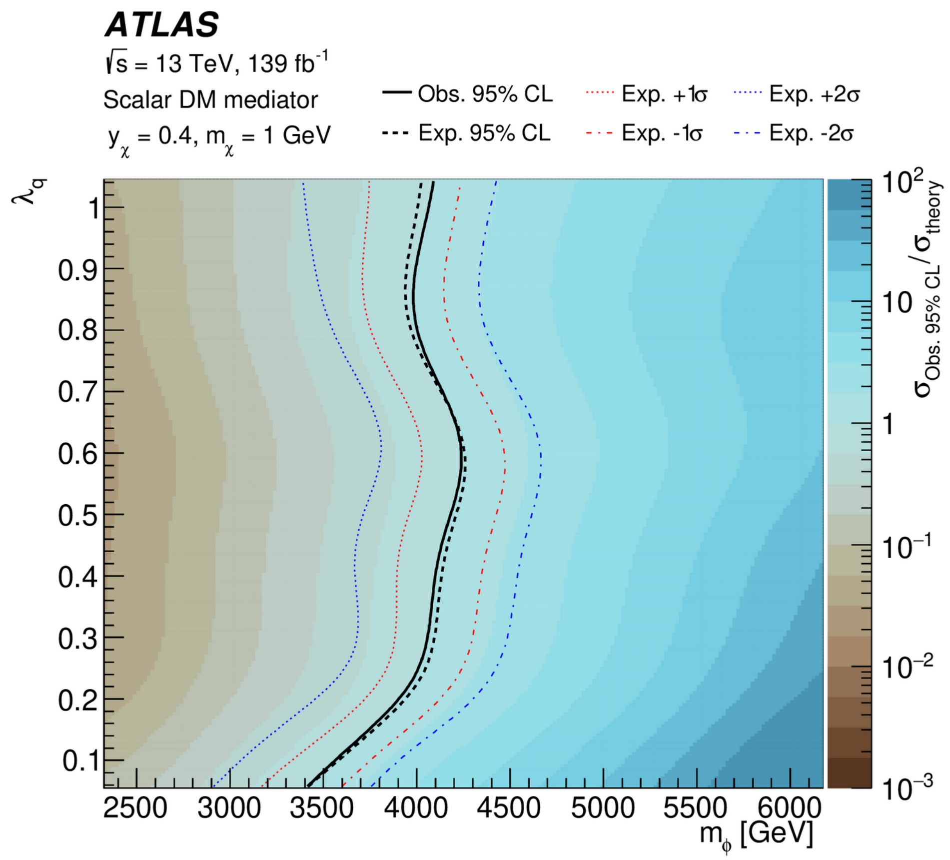
To provide more generalizable results, a multi-dimensional scan is performed in mass and coupling parameters.

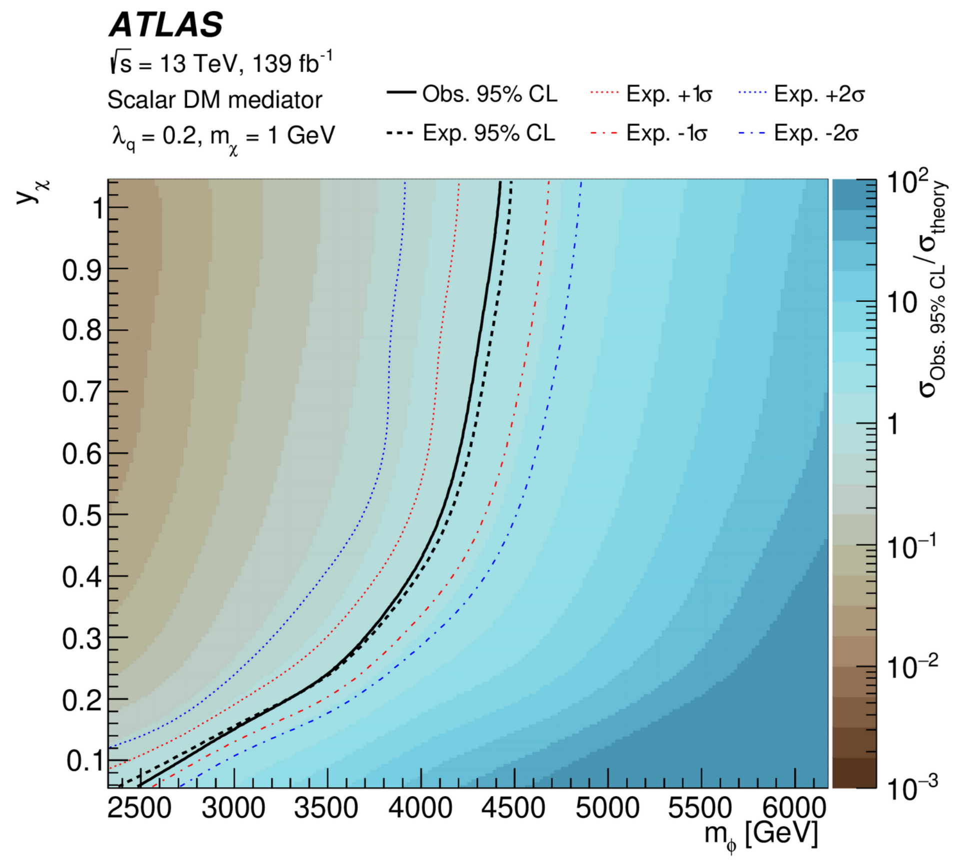
Mono-top - 2D Projections

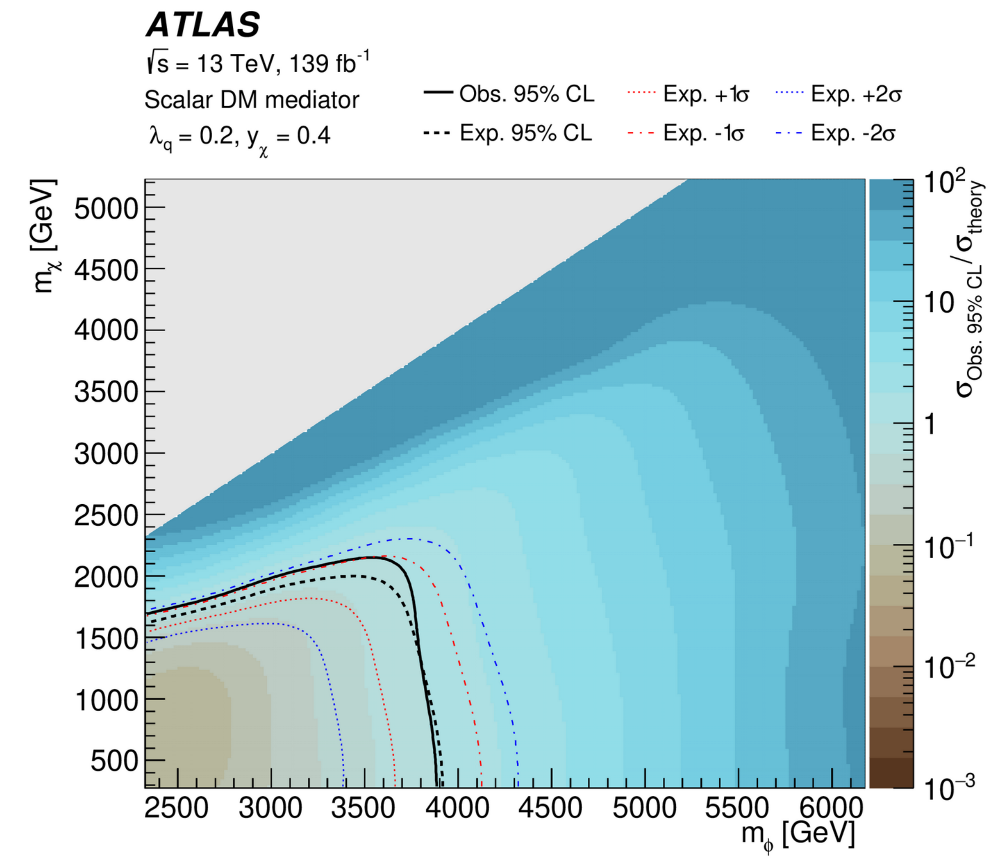


- Kinematics of this model are dependent on the mass and couplings used.
- A small grid of scalar DM models in m_ϕ, m_χ, λ_q, y_χ are simulated and a re-weighting procedure is applied for points not simulated using acceptance, cross-section and a binned distribution in MET.

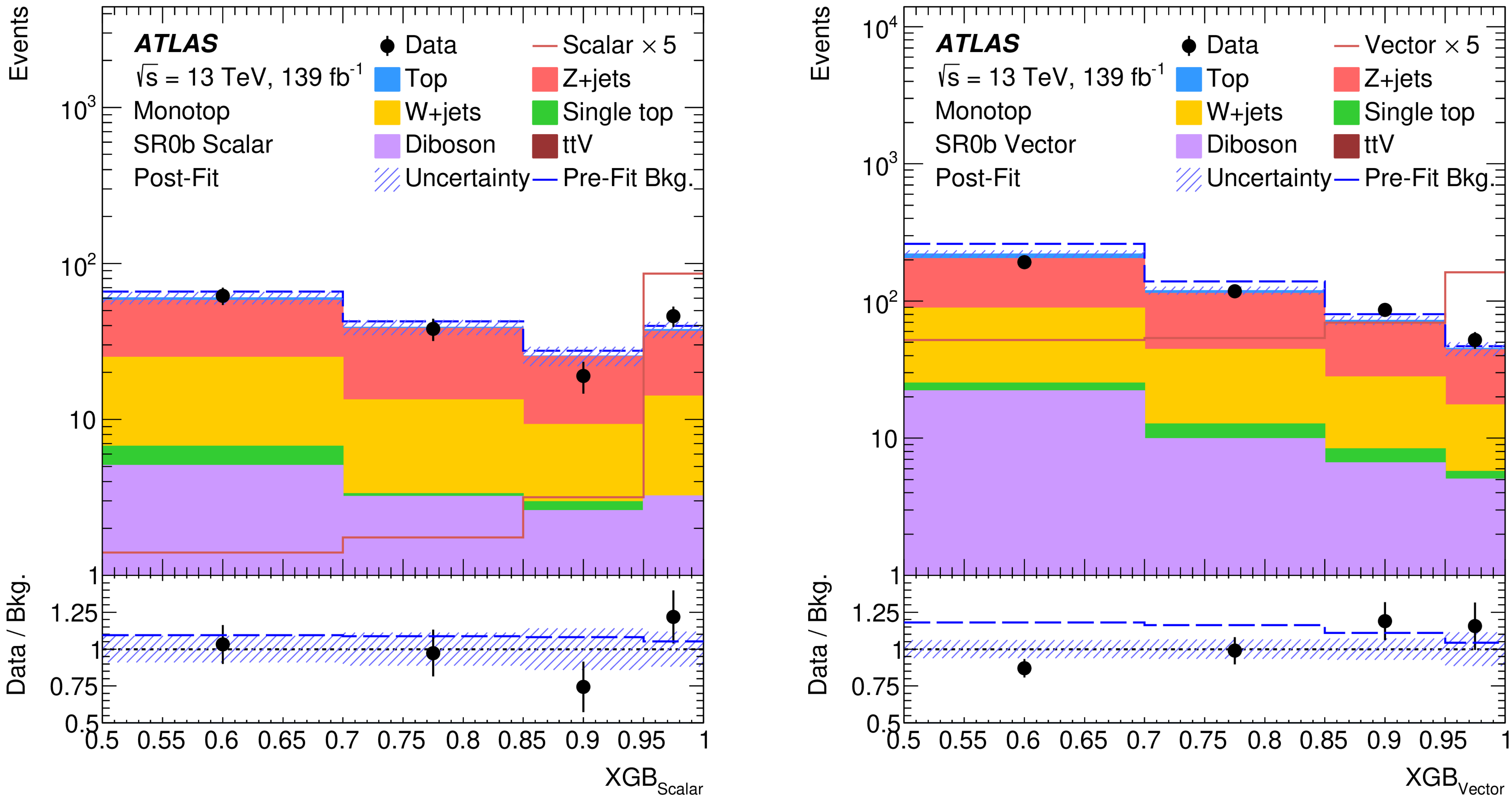
$$w^i_{\text{rw}} = \overbrace{\frac{\epsilon_{\text{target}}}{\epsilon_{\text{reference}}}}^{\text{Acceptance}} \times \overbrace{\frac{\sigma_{\text{target}}}{\sigma_{\text{reference}}}}^{\text{Cross-section}} \times \overbrace{\frac{y^i_{\text{target}}}{y^i_{\text{reference}}}}^{\text{Shapes}}$$







Mono-top – BDT Score Fit



W' → tb resonance