Search for new physics in the $t\bar{t}+E_T^{miss}$ (1L) and $tc+E_T^{miss}$ (0L) final states

Simran Gurdasani
on behalf of the ATLAS Collaboration

LHC Top WG 2023 @ CERN

November 30, 2023

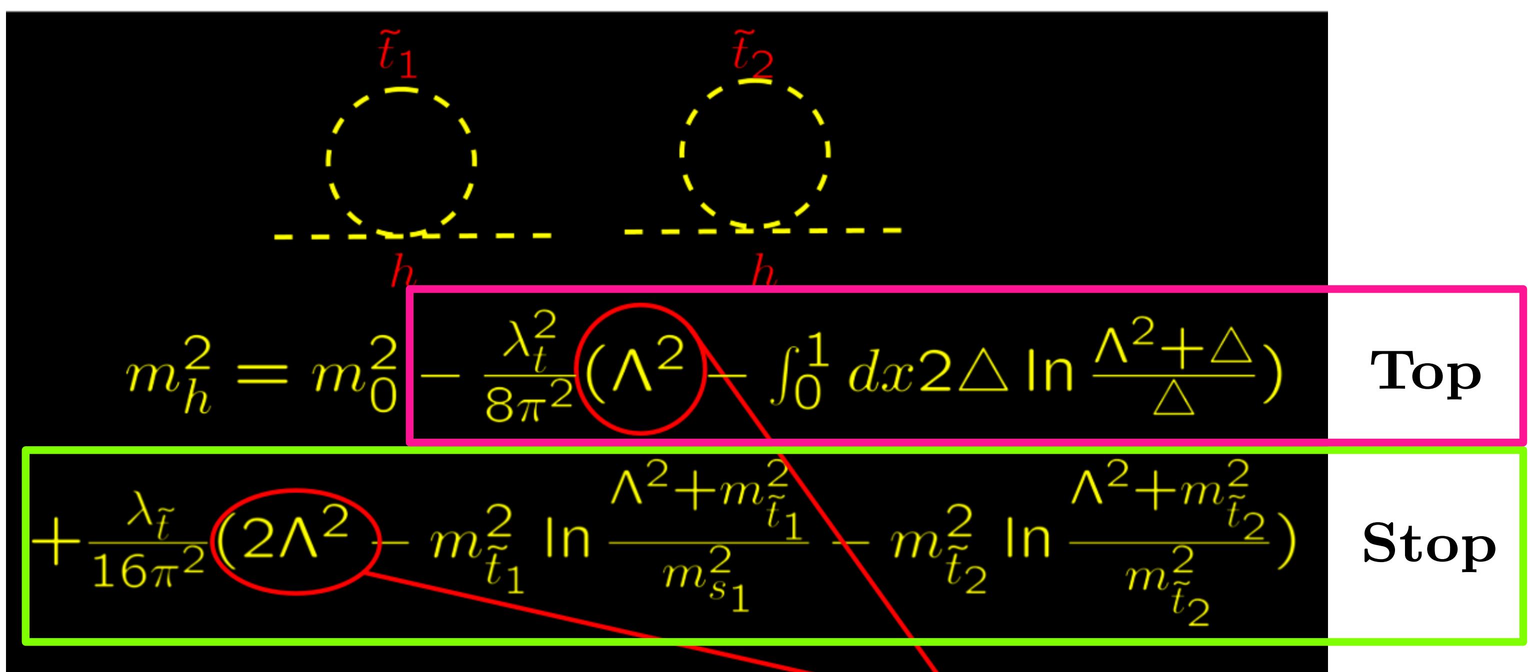
Motivation – SUSY (stop pair production)

Solution to the Hierarchy problem

One of the strong motivations of SUSY is that it provides a viable solution to the Hierarchy problem.

In SUSY, the stop can cancel quadratic quantum corrections to the Higgs mass from the top quark → explaining the low mass of the Higgs without fine tuning

⇒ Two scalar superpartners for each fermion



In SUSY $\lambda_{\tilde{t}} = \lambda_t^2$

Quadratic divergences cancelled!

⇒ No Fine Tuning?

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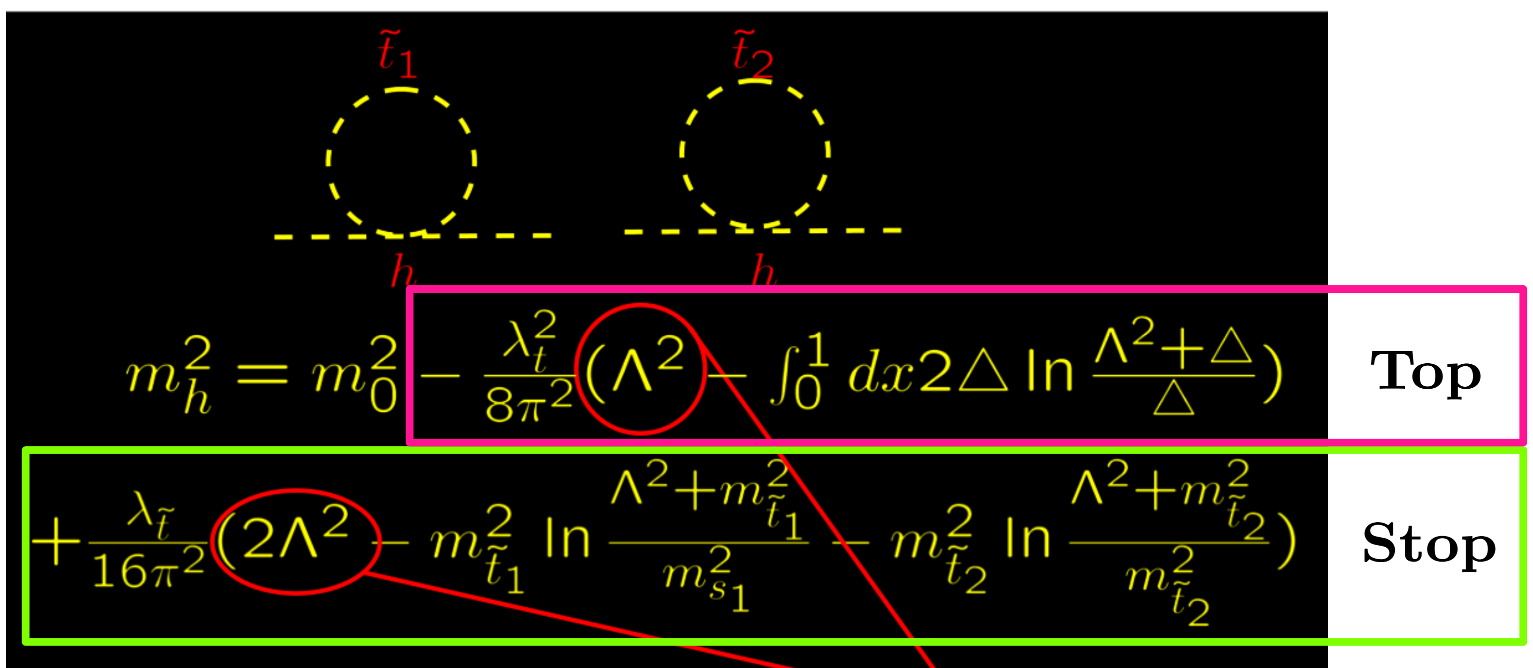

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R-parity conserving MSSM

Since SUSY can have a huge number of free parameters, often simplified models are probed → here R-parity conserving MSSM

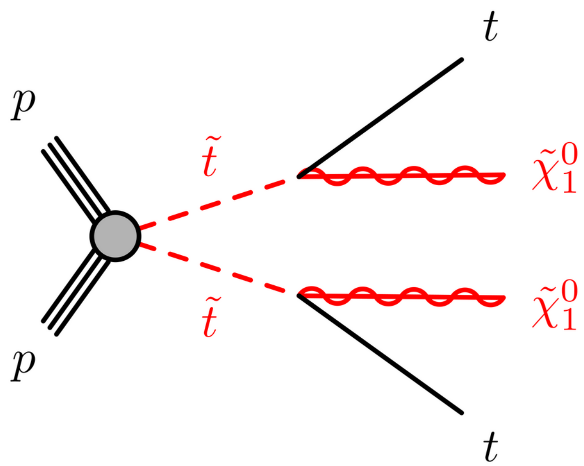
R-parity $= (-1)^{3(B-L)+2S}$
in SM, R = +1
in SUSY, R = -1

allows the accidental conservation of Baryon and Lepton number in the Standard Model without explicitly enforcing it.

Consequences of R-parity conserving MSSM:

- Provides a dark matter candidate to be part of the MSSM called the LSP or lighest supersymmetric particle. This particle is stable and all other sparticles must eventually decay to it.
- R-parity conversion also means that sparticles are produced in pairs → Pair Production

Motivation

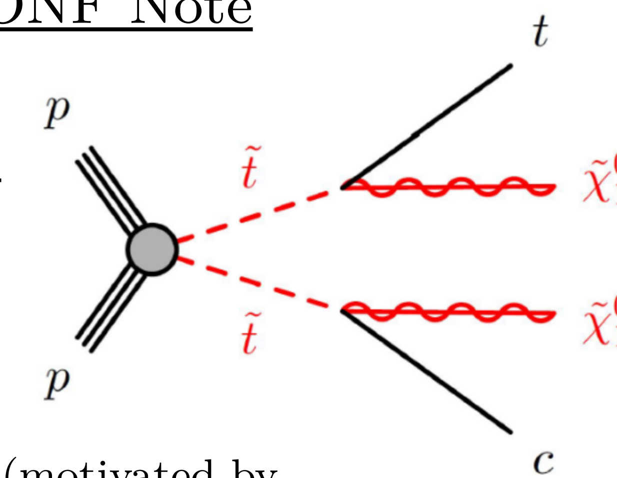


$t\bar{t}+E_T^{miss}$ (1L) CONF Note

$tc+E_T^{miss}$ (0L) CONF Note

Both searches target stop pair production

- Stop is considered to decay to the top in 100% of cases.



- 2^{nd} and 3^{rd} generation squarks are allowed to mix (motivated by non-minimal flavor violation extended MSSM)

Reference to this model

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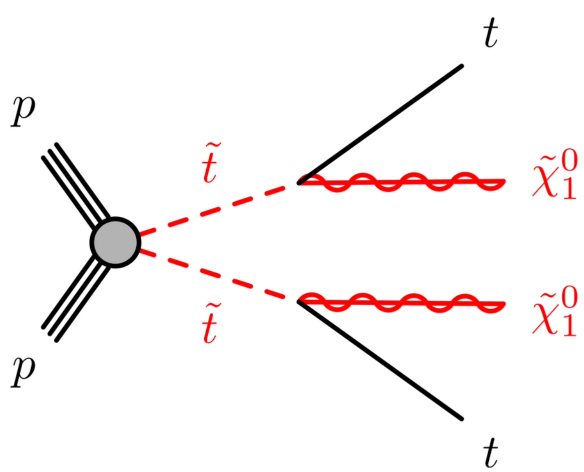

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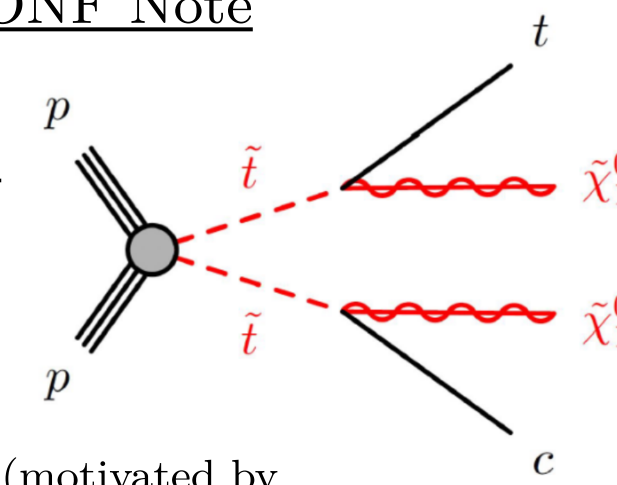

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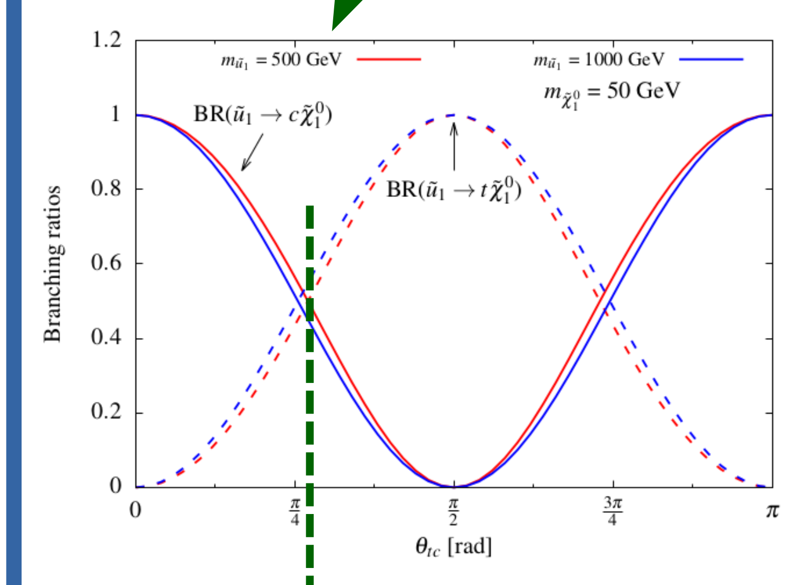

Maximal mixing scenario considered:

- BR(tcMET) = 50%
- BR(ttMET) = 25%
- BR(ccMET) = 25%

Followed by a scan on varying branching ratios

This signature is probed for the first time ever at the LHC → made possible by advancements in c-tagging

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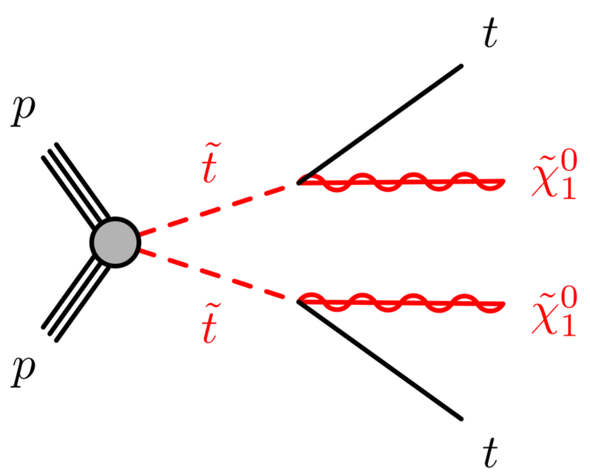

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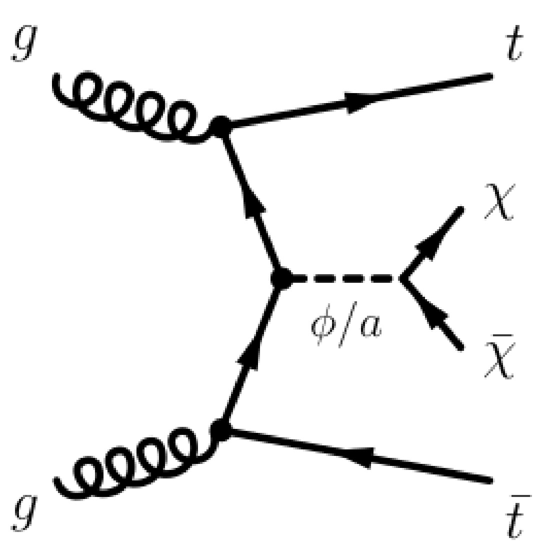
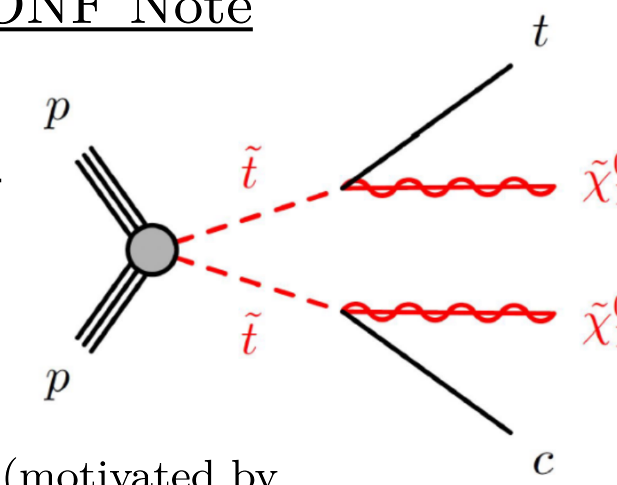


The same final state is also used to probe dark matter produced with top quarks

→ probing fermionic DM candidates that interact with SM via Higgs like scalar(pseudscalor) mediators

This is a 2nd wave attempt on the previous 1L result using an improved analysis strategy

$tc+E_T^{miss}$ (0L) CONF Note



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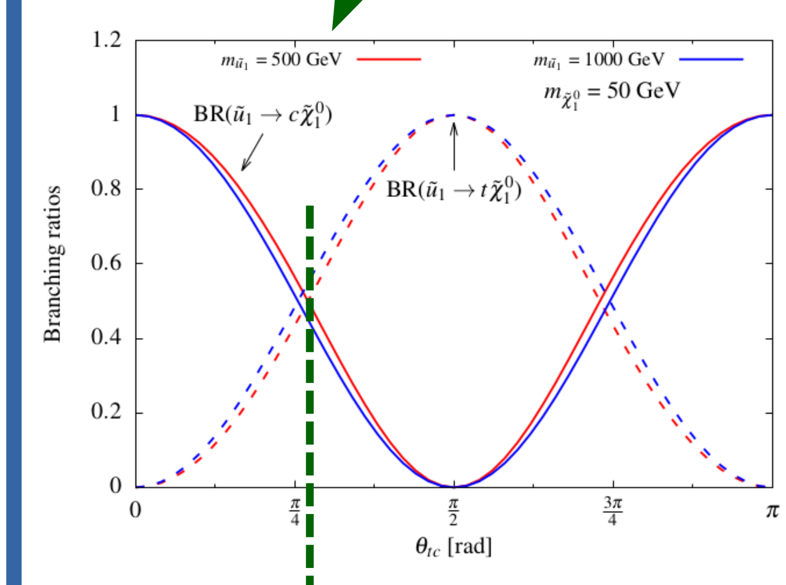

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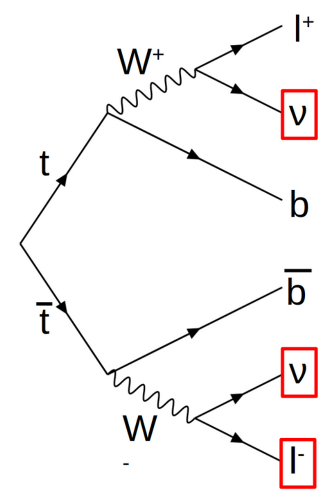
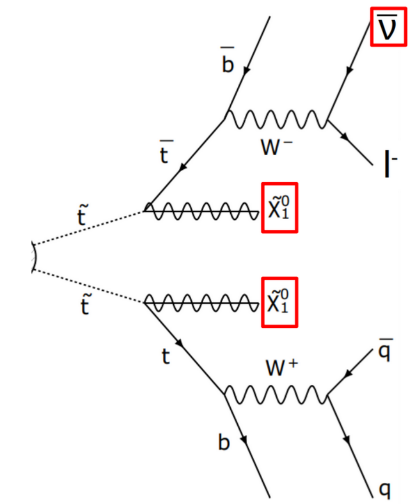
Search Strategy

- For a given signature that is used to probe a specific new physics process, SM processes are present with the same signature.

“Bkg”
ttbar 2L (missed lepton)



“Signal”
Stop – pair (1L decay)

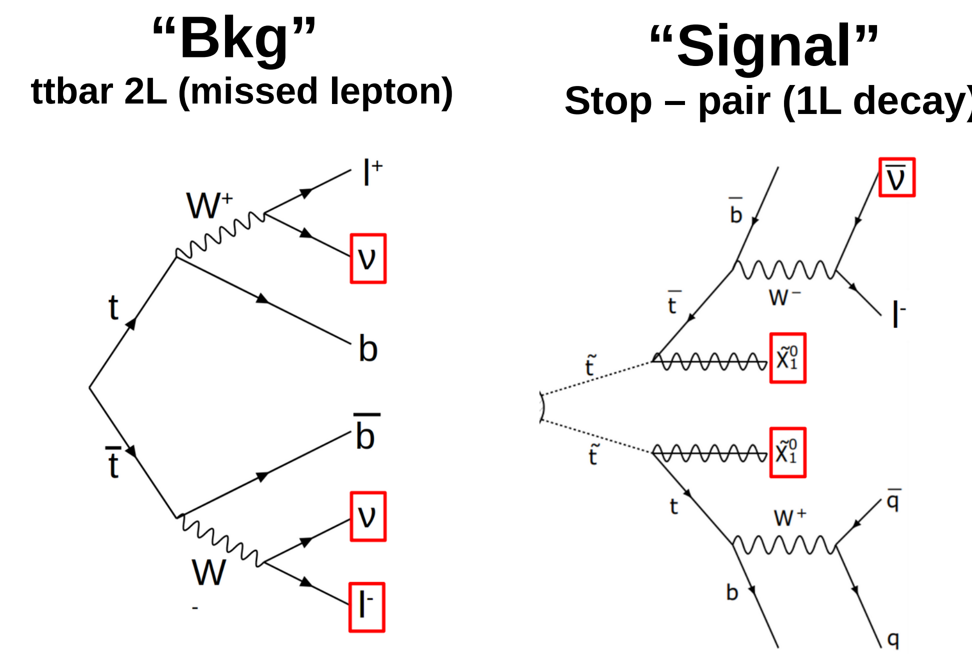


Search Strategy

- For a given signature that is used to probe a specific new physics process, SM processes are present with the same signature.

- Define **<u>"Signal Regions":</u>** enhanced in signal events while reducing SM processes with the same signature.
  - cannot be fully "cleaned" $\rightarrow$ generally have some remaining SM processes.
  - By design away from Standard Model physics and with significant MC mis-modeling.

- Corresponding **<u>"Control Regions":</u>** devoid of signal events but enhanced in the dominating background(s)
  - data driven estimate of backgrounds can be extracted.
  - This extraction is then extrapolated to Signal Regions.



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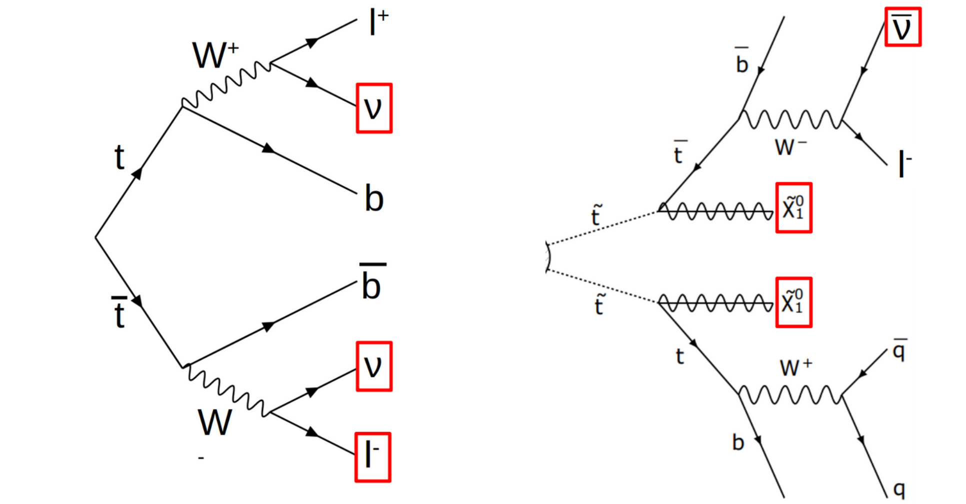
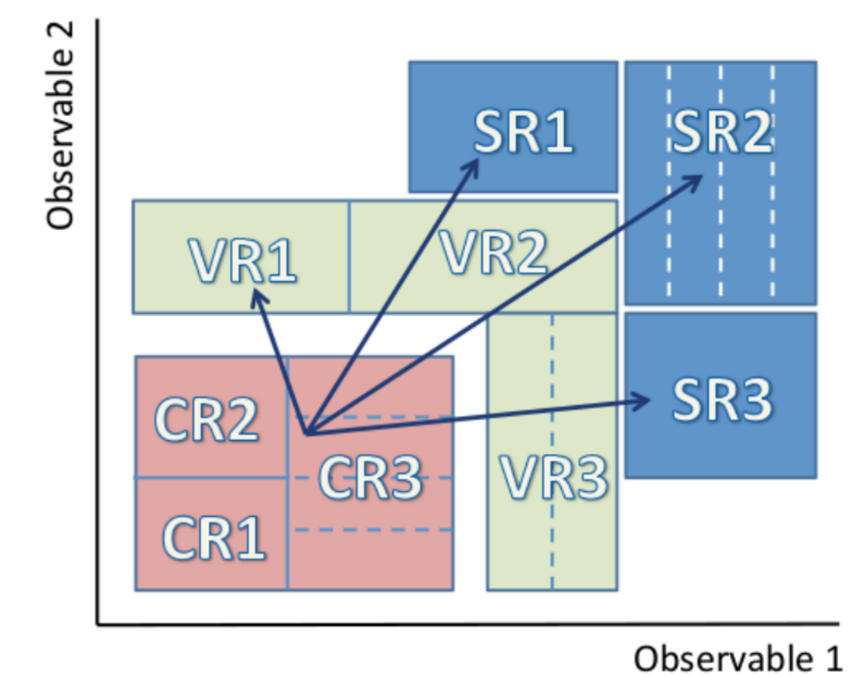
- **"Validation Regions":** in between SR and CR to validate extraction of data-driven estimate

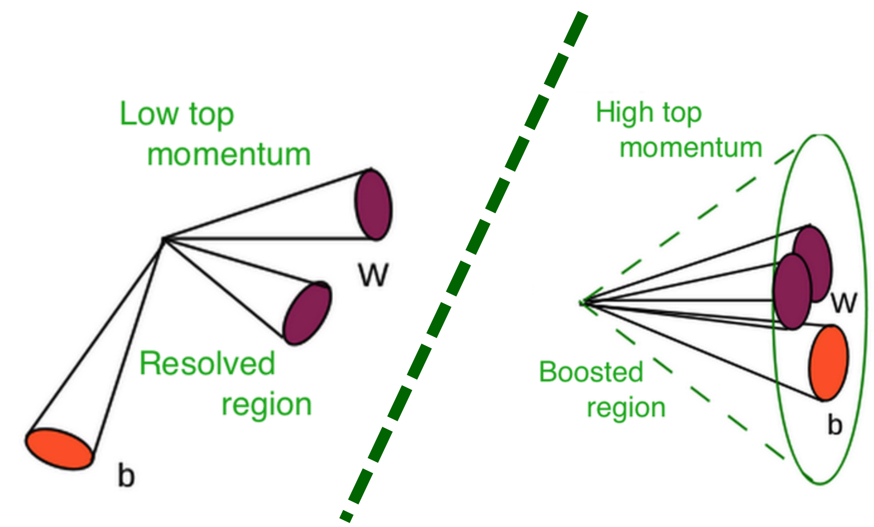
"Bkg"
ttbar 2L (missed lepton)

"Signal"
Stop – pair (1L decay)

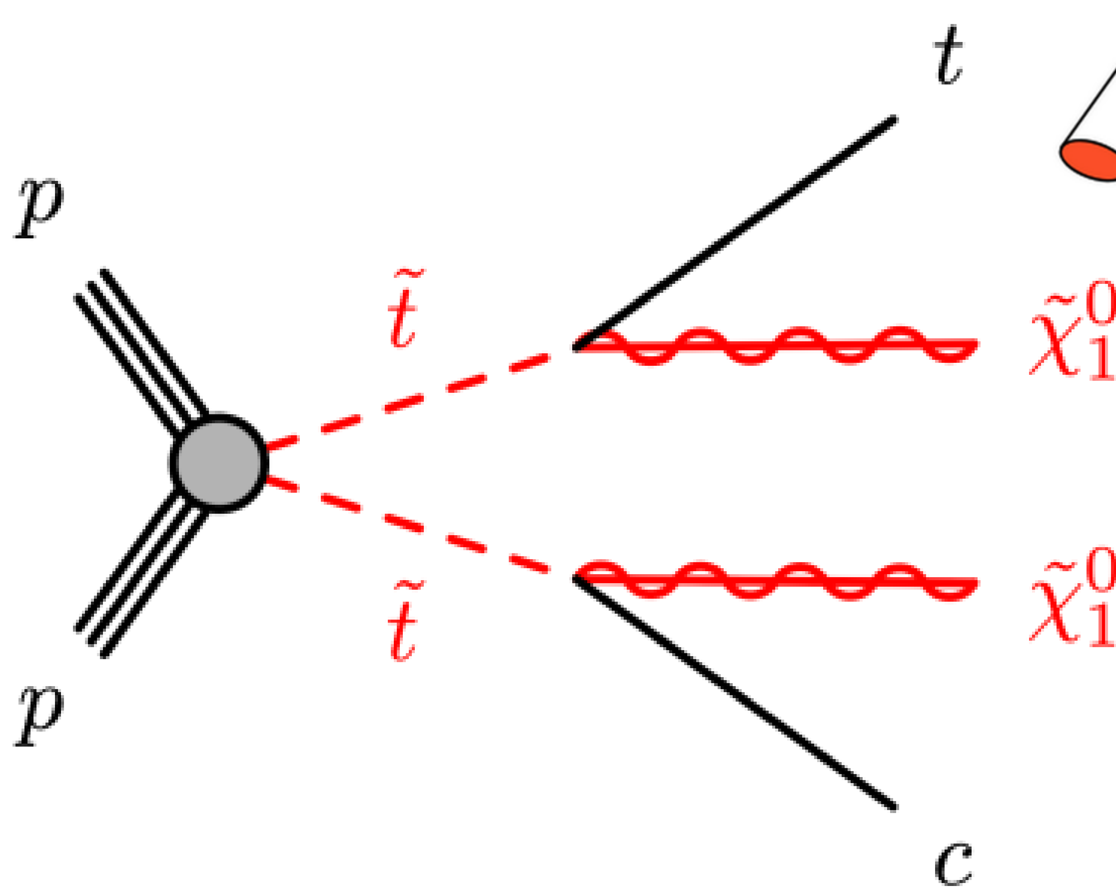




$\mathbf{tc+E_T^{miss}}$ (0L)



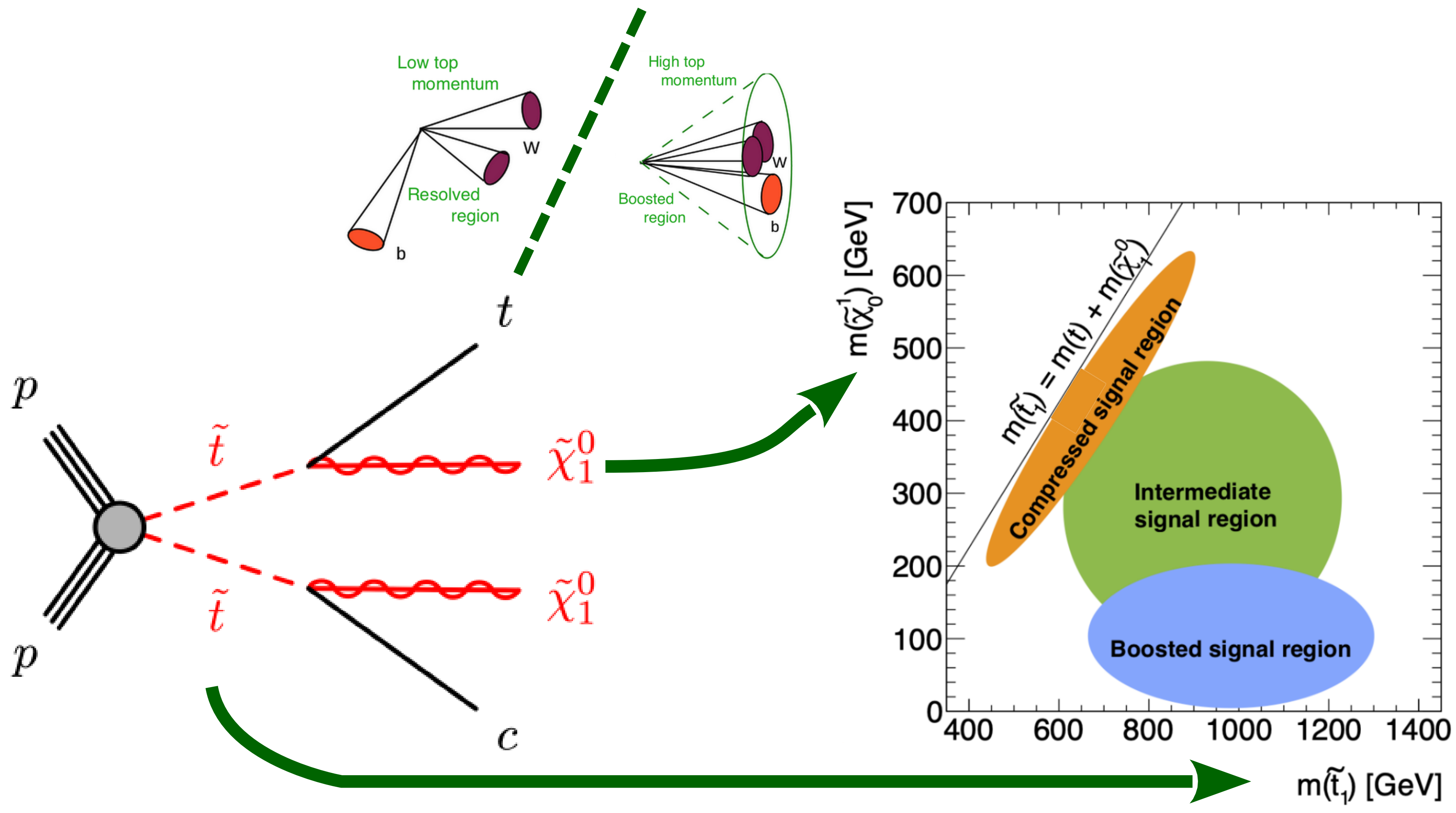
t(0L)



Large $\mathbf{E_T^{miss}}$

Isolated c-jet

Target Scenario



- $tc+E_T^{miss}$ signature → probed for the 1st time ever at the LHC
- 0L channel targeted – final state with many jets, large MET and c-jet

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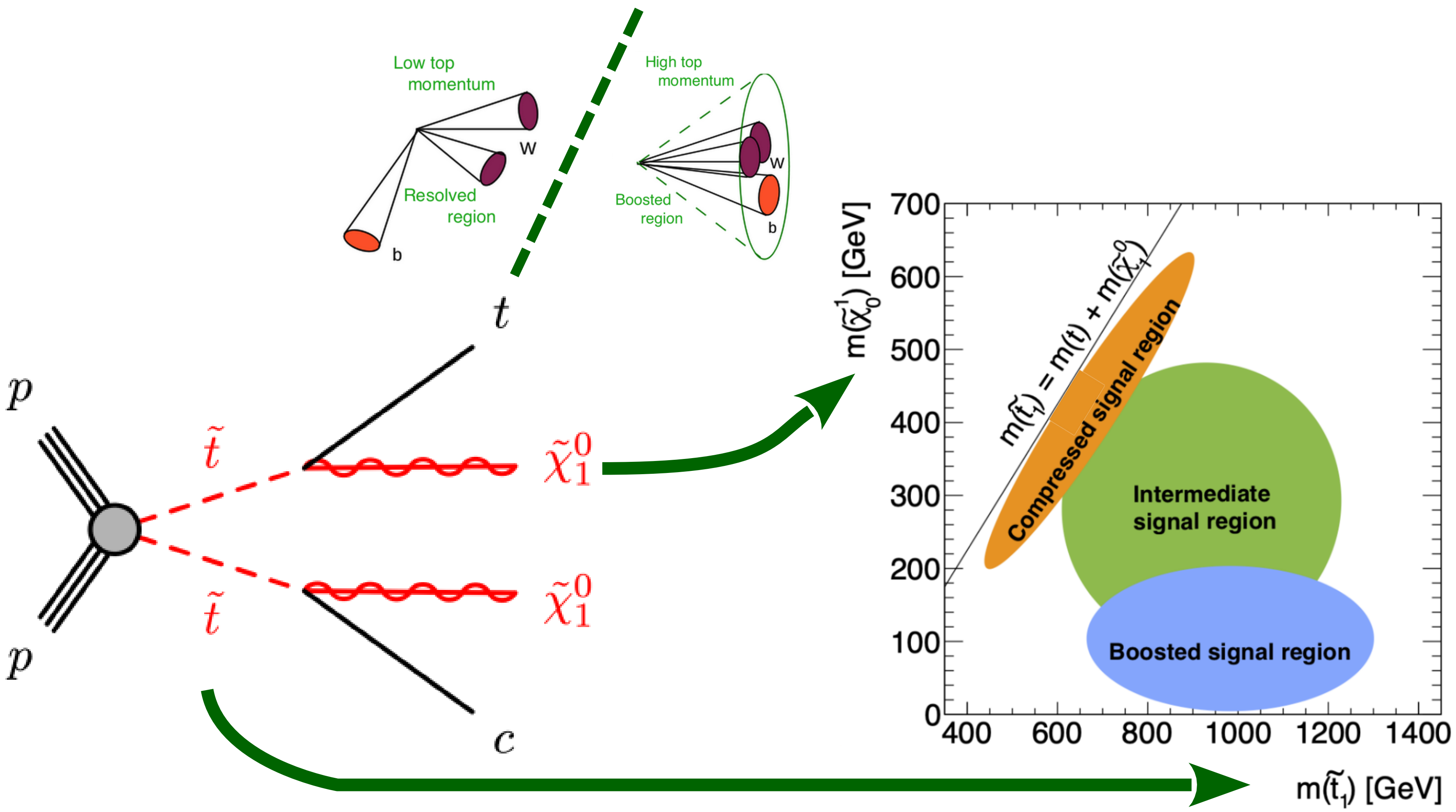

- $tc+E_T^{miss}$ signature → probed for the 1st time ever at the LHC
- 0L channel targeted – final state with many jets, large MET and c-jet
- Special multi-class DNN optimization for compressed region!
  - The diagonal represents where m(stop) = m(top) + m(LSP) → these events are very close to SM top events
- Top tagging also used → DNN for boosted tops
- Special c-tagging developed for the analysis!

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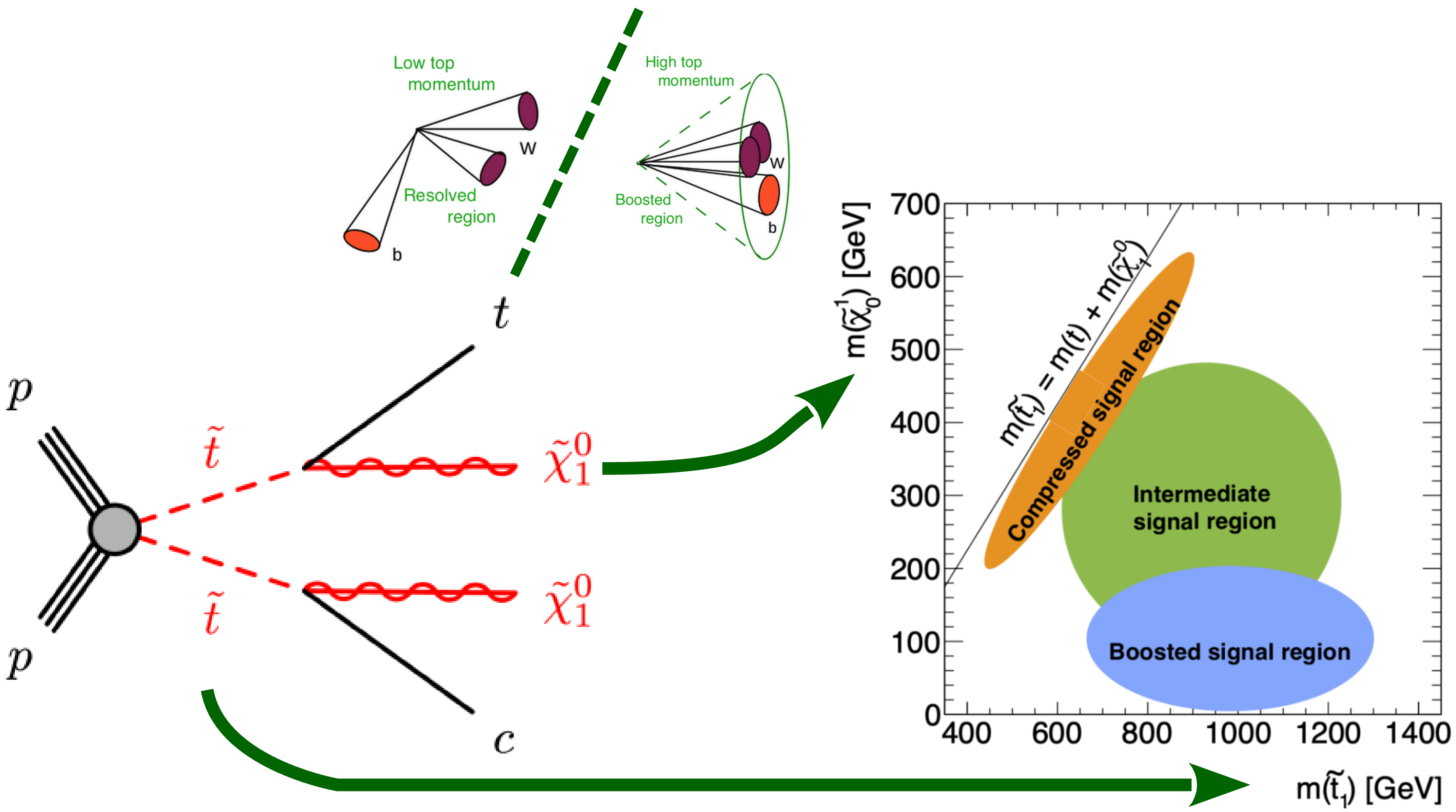

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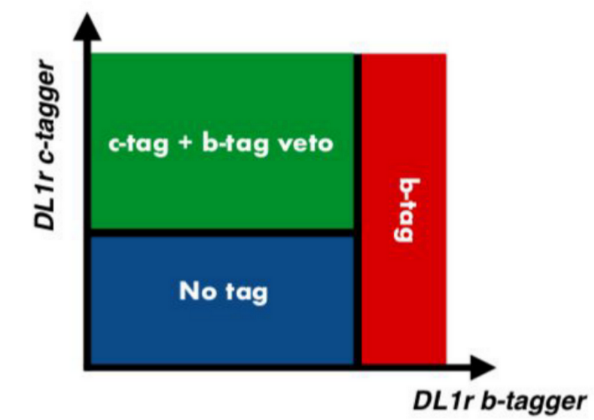
Improved c-tagging

c-tagging with b-veto technique

Step 1: DL1r → b-tagging algorithm

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



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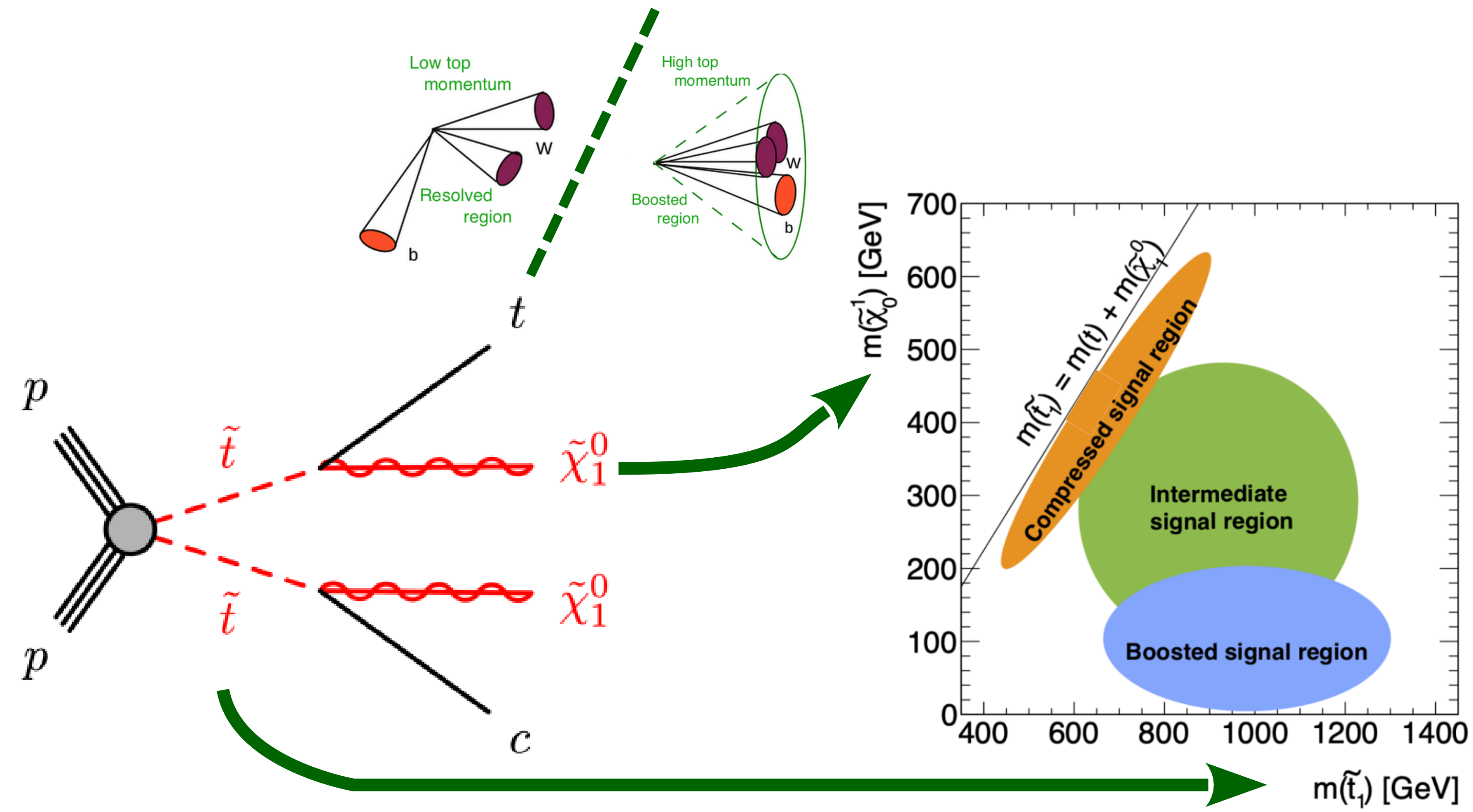

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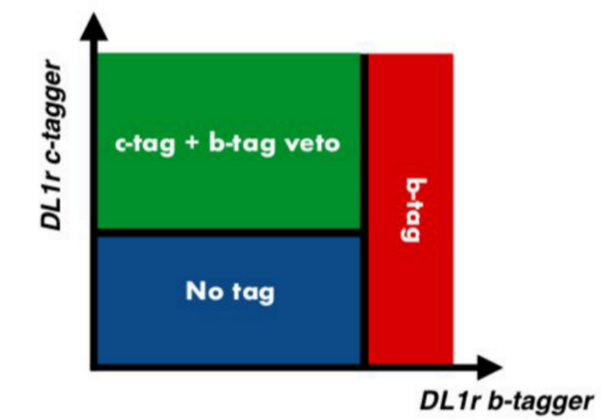
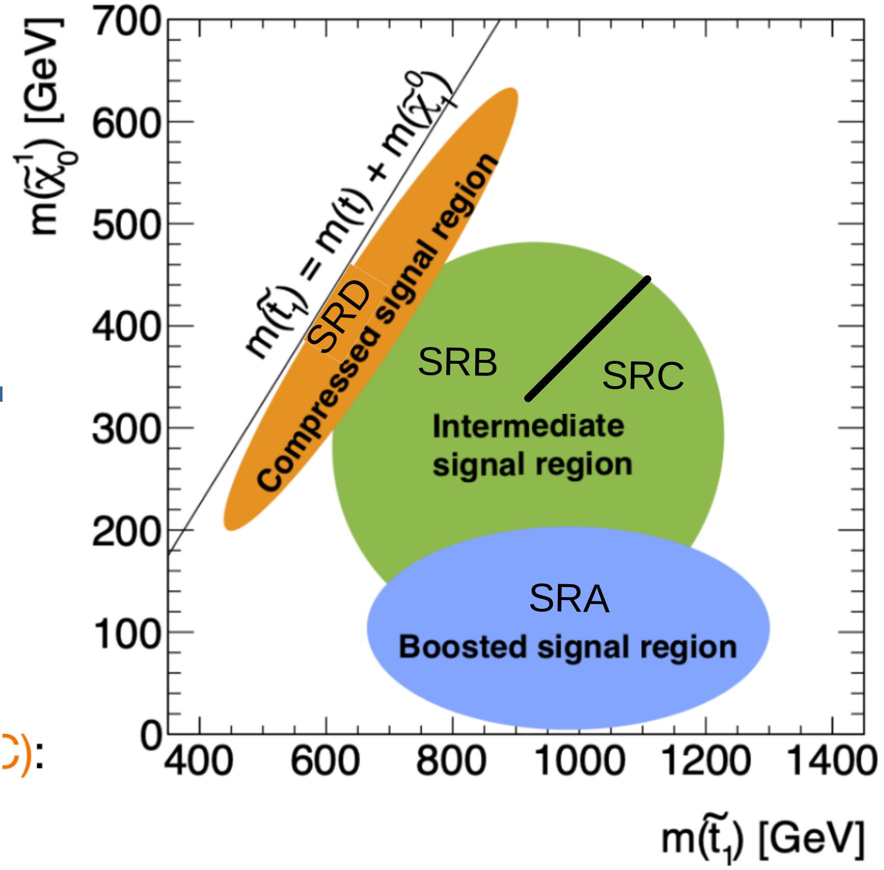
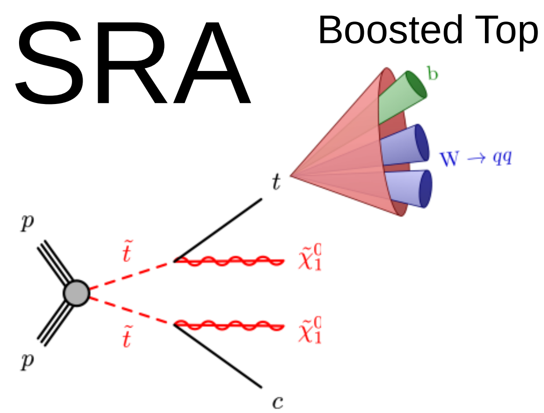
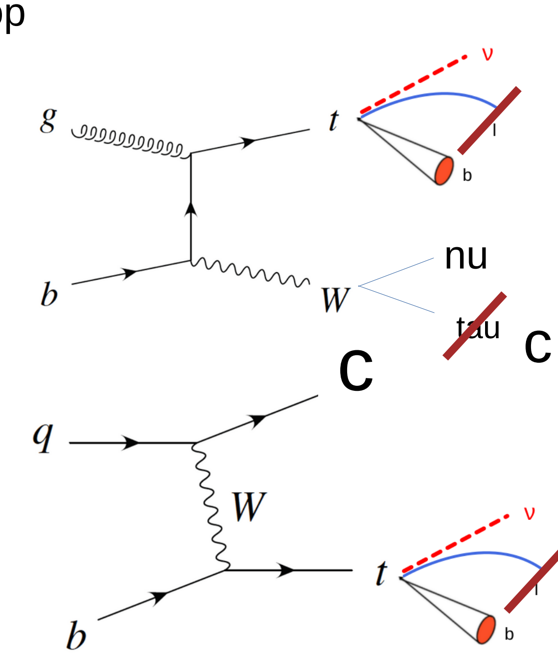


- very helpful to avoid a large rate of b-jets misidentified as c-jets
- DL1r (b-tagger) is used at the 77% working point which corresponds to 20% fake c-tags.
- Overall algorithm yields → 20% c-jet efficiency, with rejection factors of 29 for b-jets and 5 for light-jets
- What remains is a high rate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

Event Phase Space



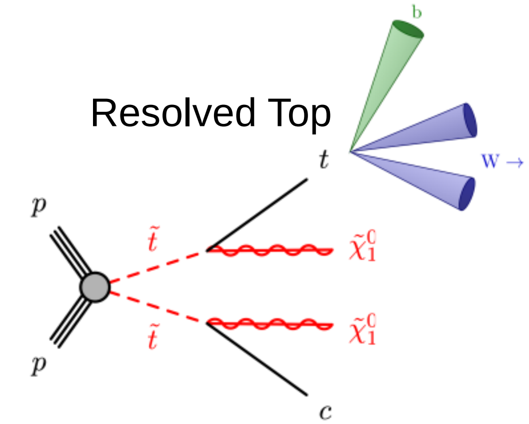




- **Main Backgrounds:**
  - Zjets where Z decays to neutrinos
  - Singletop [tW(tau → c)], [t-chan (t+j)]
- Orthogonality: MT2 > 450 GeV

Event Phase Space

SRB



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  - Without a top tag, mainly V+jets remain where b and c jets are present
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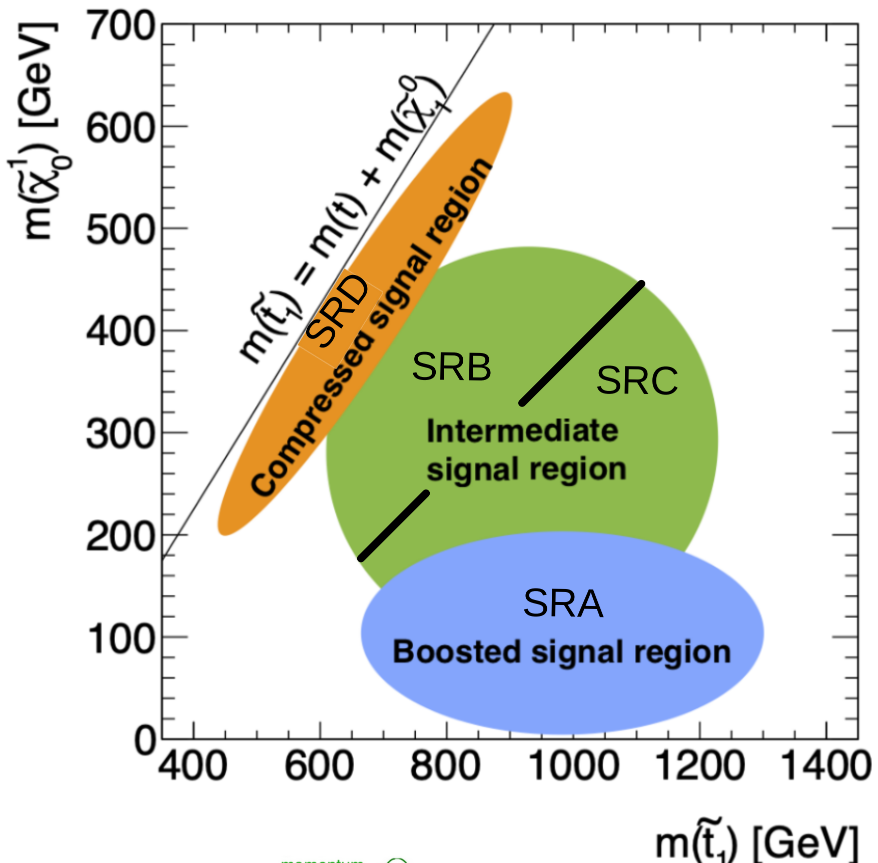

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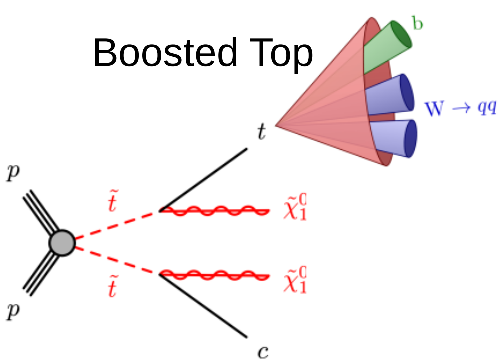

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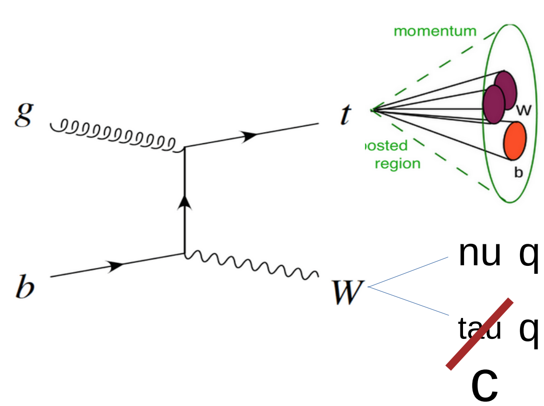
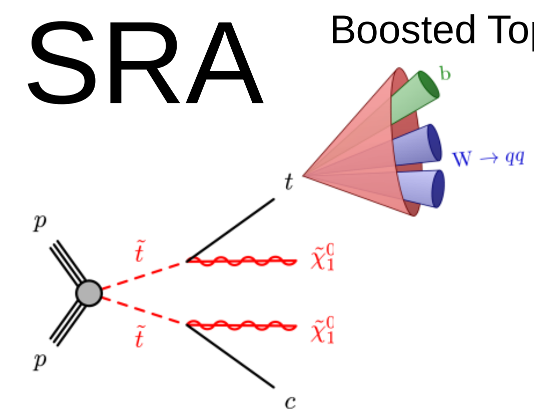
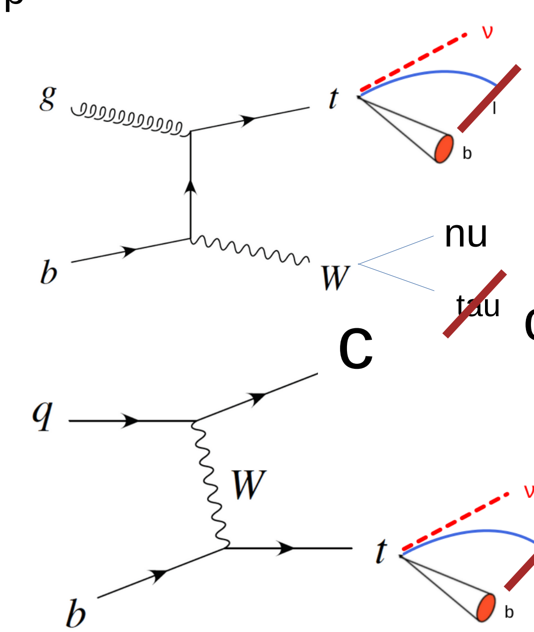


SRA





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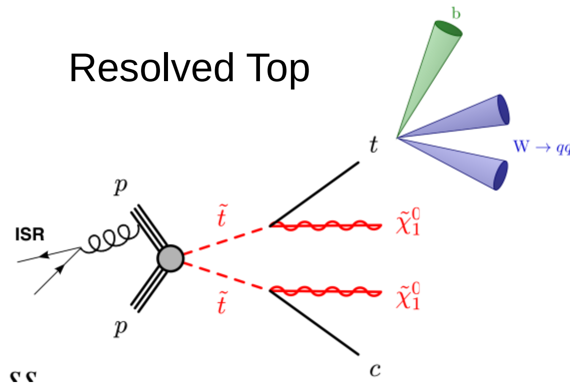
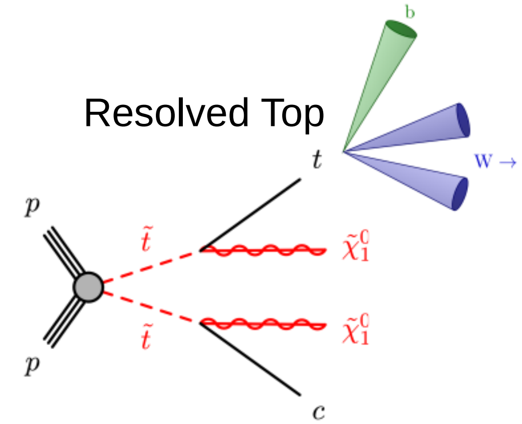
Event Phase Space

SRD



- **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)

SRB



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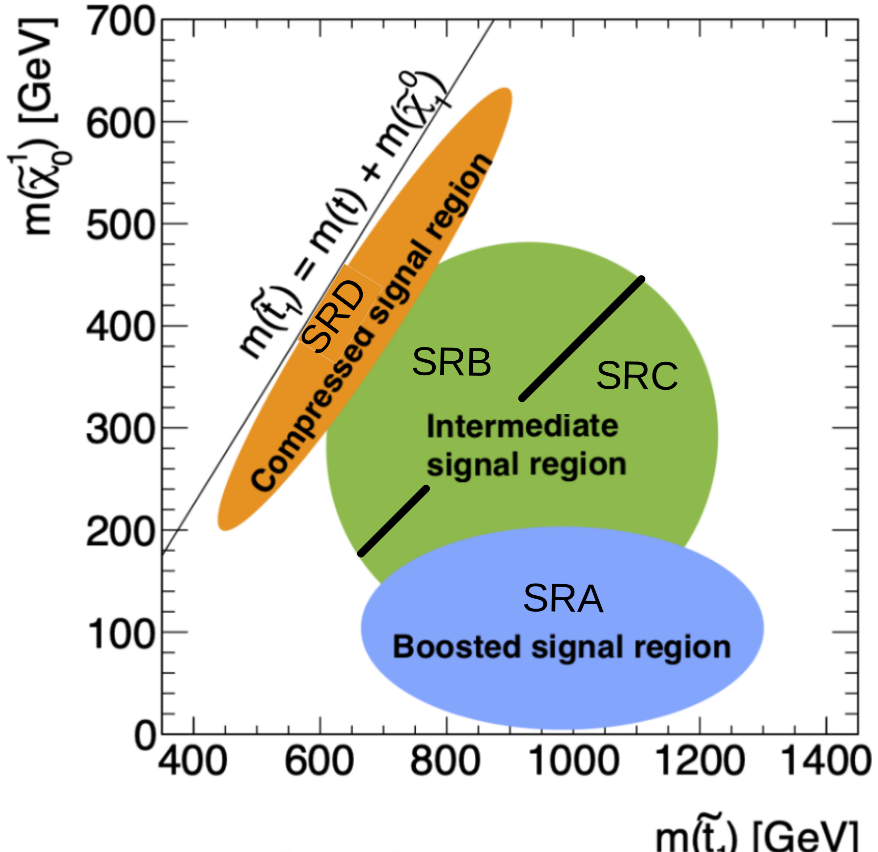

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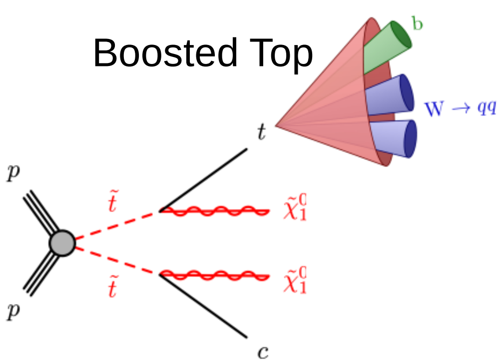

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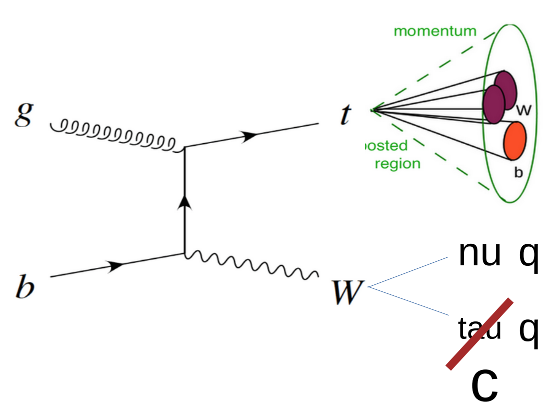

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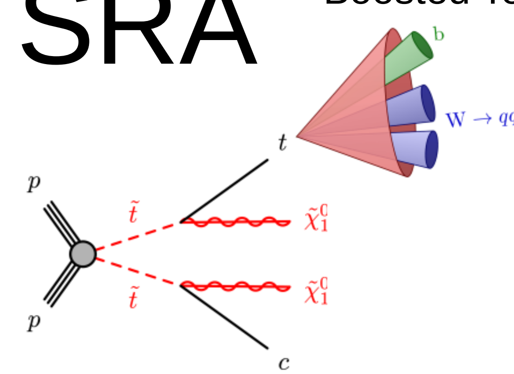

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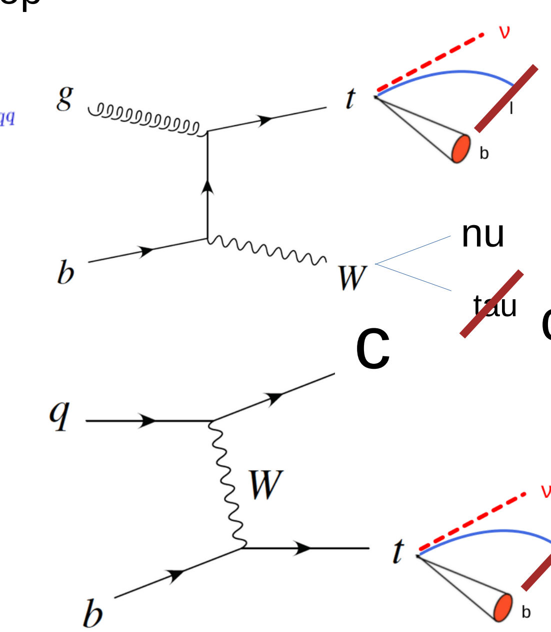
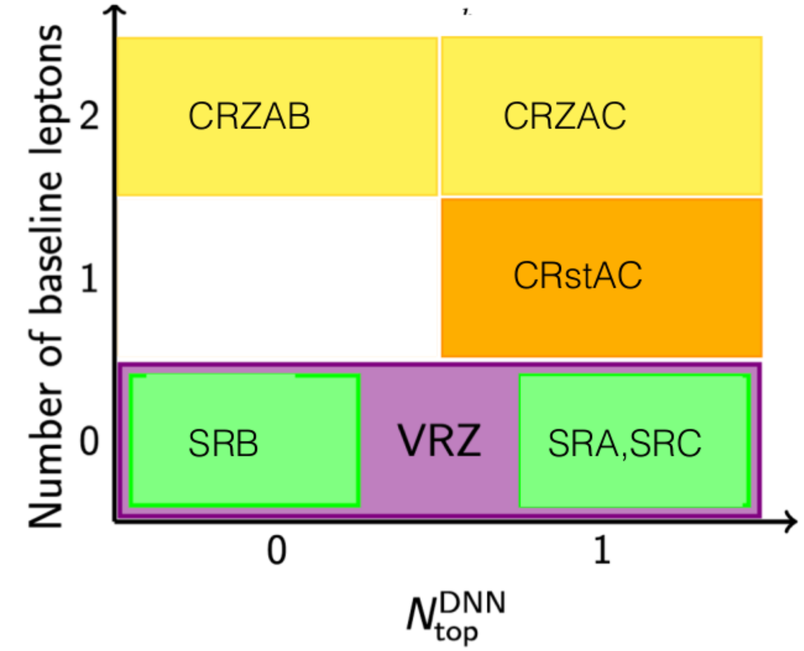


Background Estimation – Regions ABC



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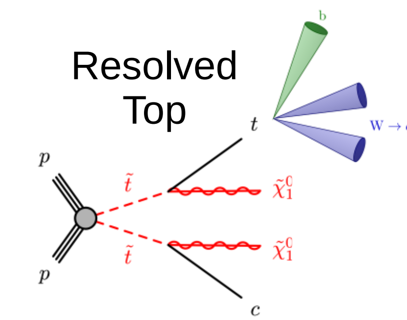

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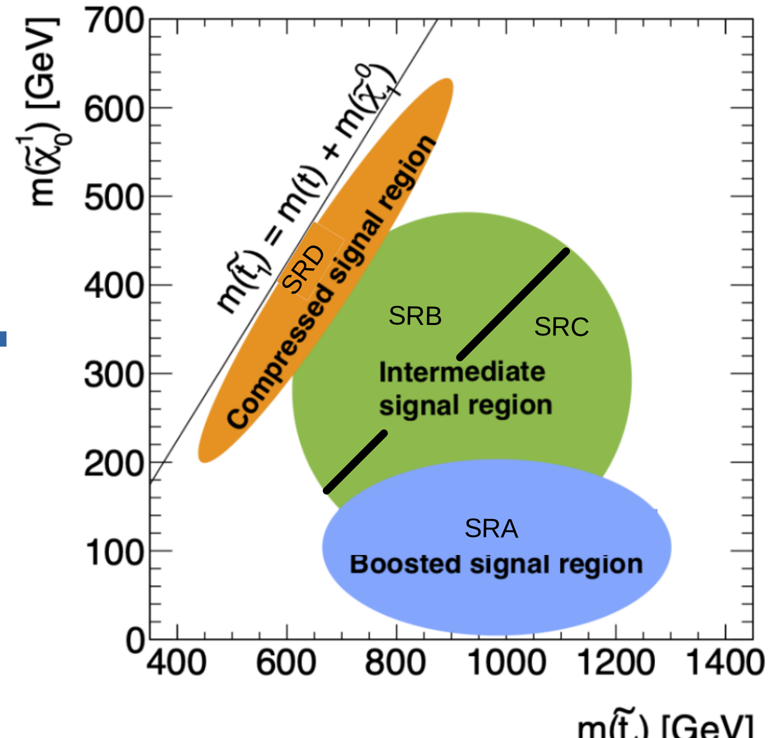

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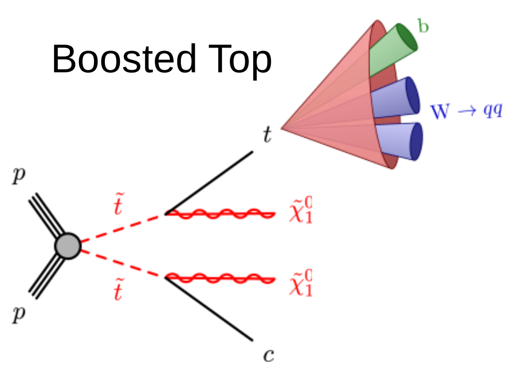

- **Main Backgrounds:** Z+jets, singletop
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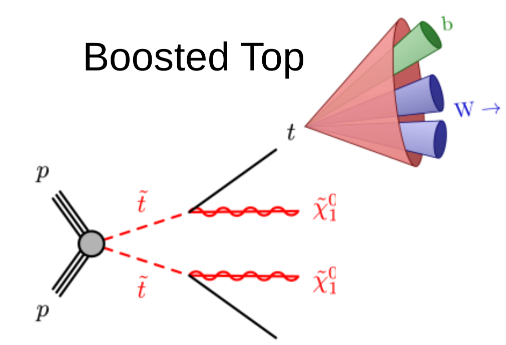

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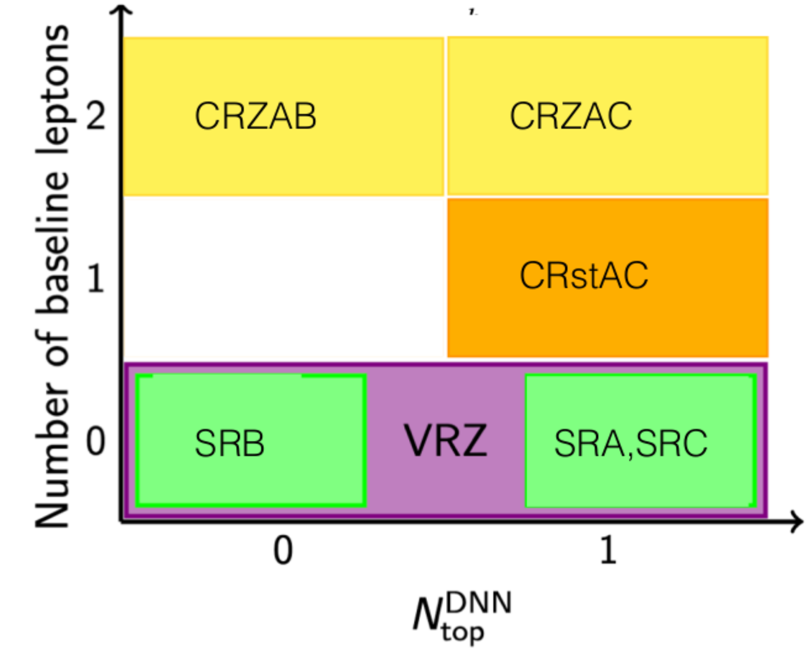
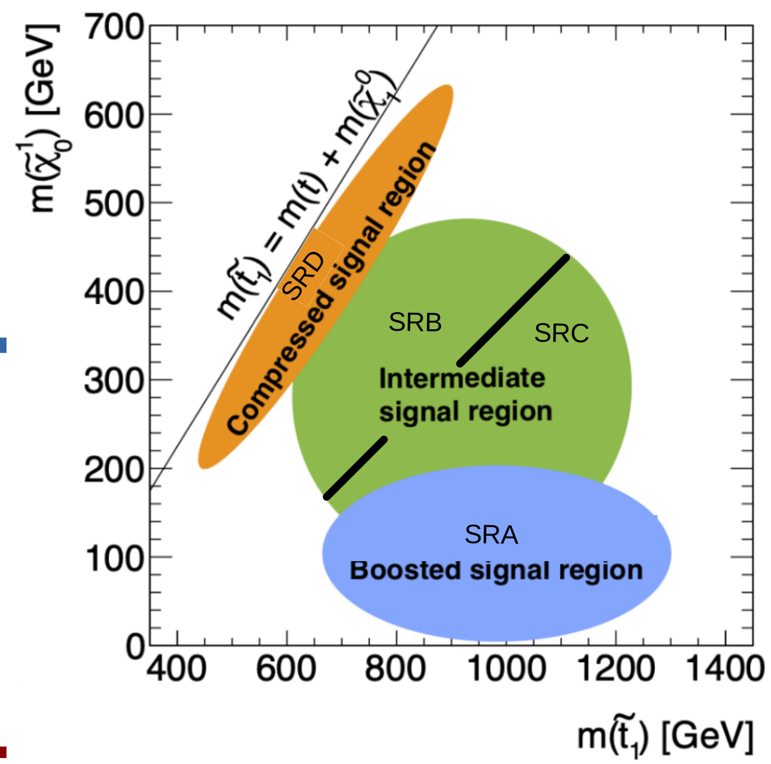
Background Estimation – Regions ABC

- Common control regions for SRA and SRC – events with a boosted top + same SM backgrounds:
  - singletop: CRstAC (1L events) + Zjets: CRZAC (2L events)





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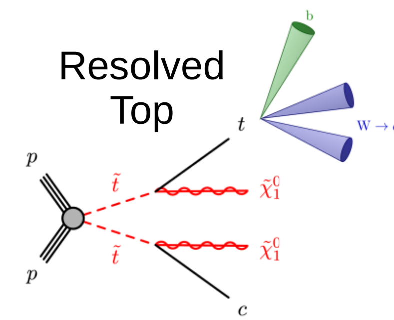

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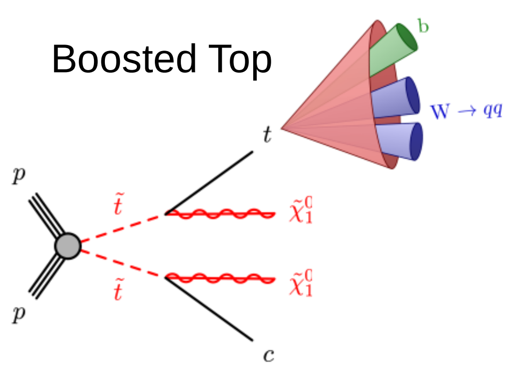

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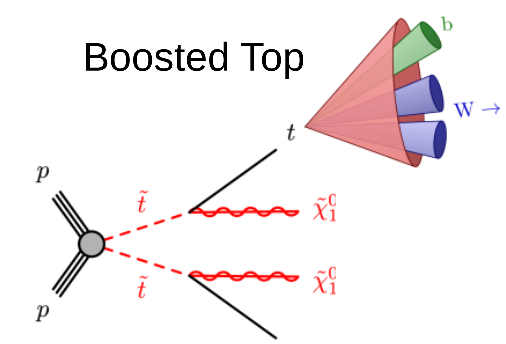

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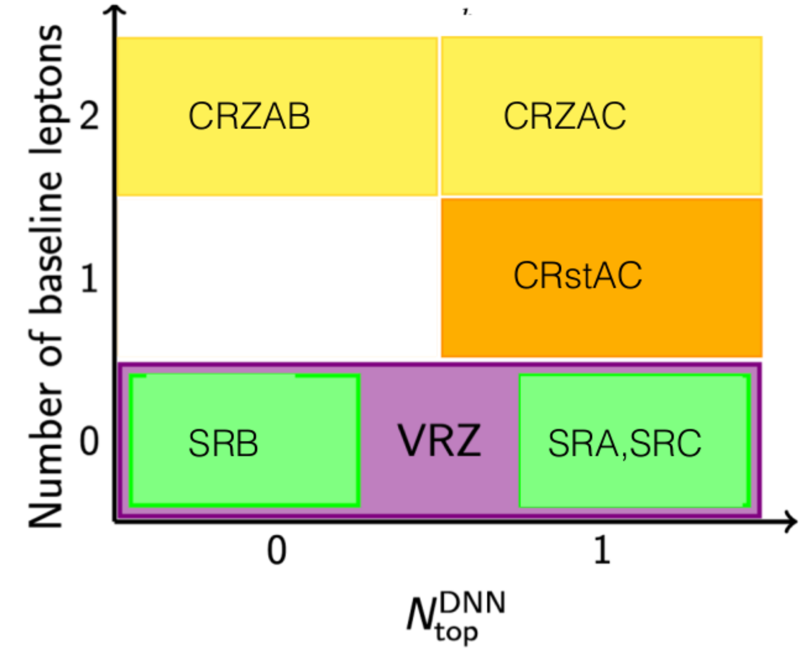
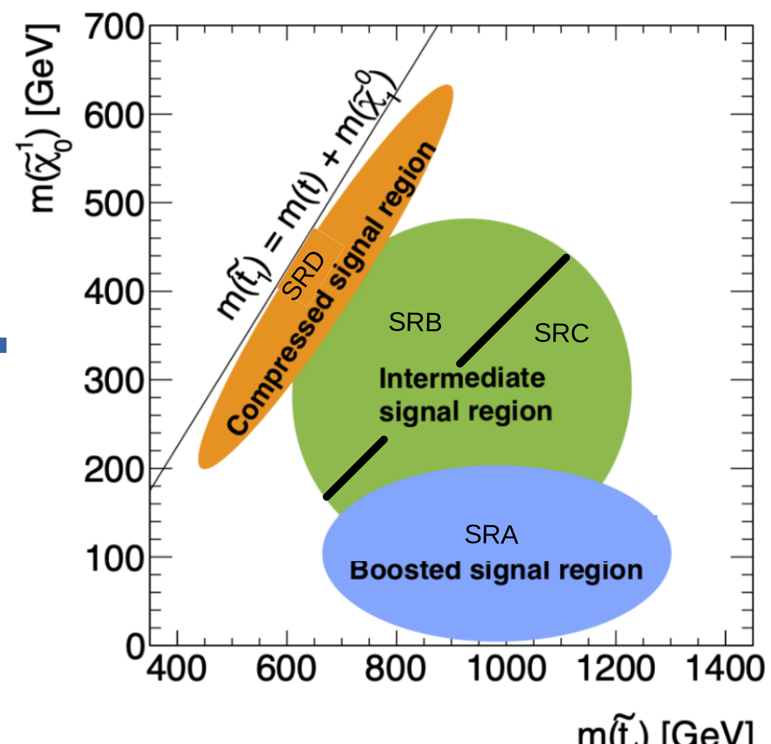
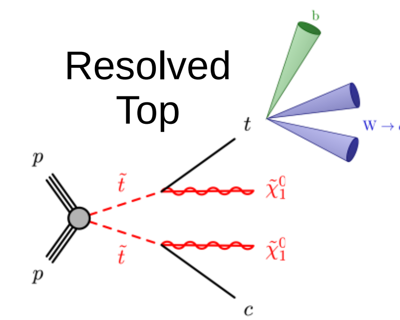
- Control regions for SRB – events without boosted top:
  - Z+jets: CRZB (2L events)

- One validation region for SRA, SRB, SRC
  - Z+jets: VRZABC (0L events)



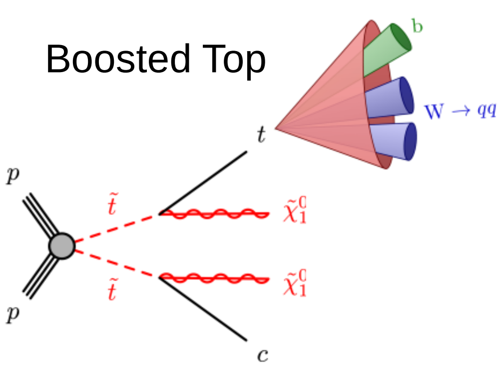


SRB



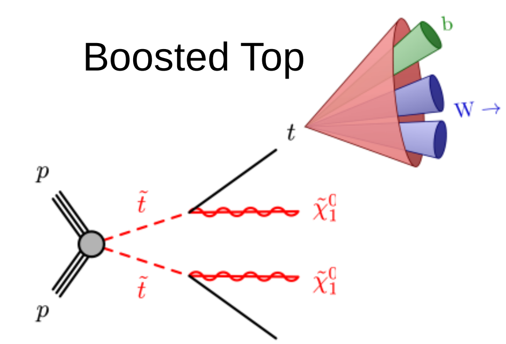
- **Main Backgrounds:** Z+jets, W+jets

SRC



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

SRA



- **Main Backgrounds:** Z+jets, singletop
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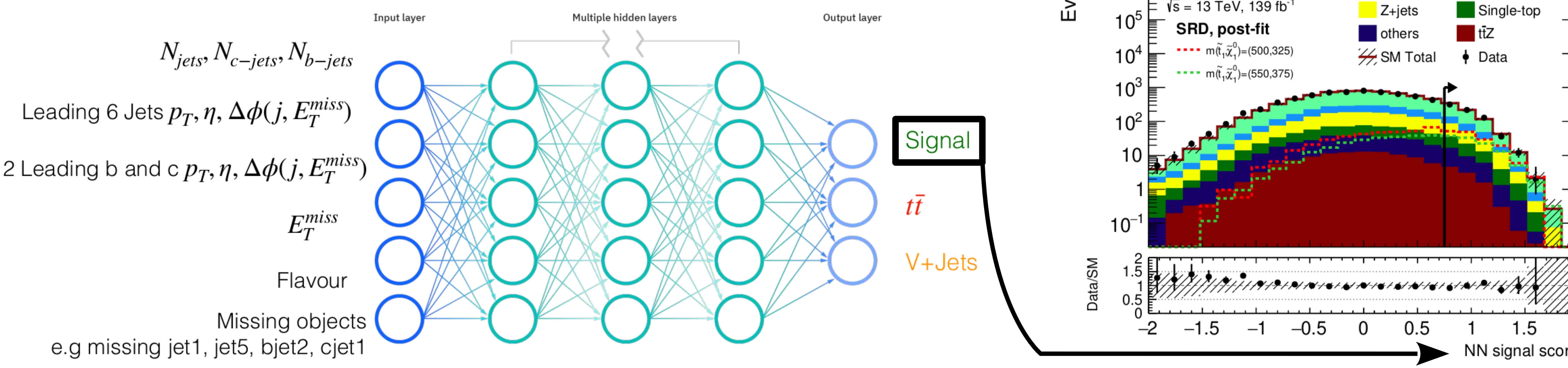
Analysis Strategy – Region D

Uses a multi-classifier DNN



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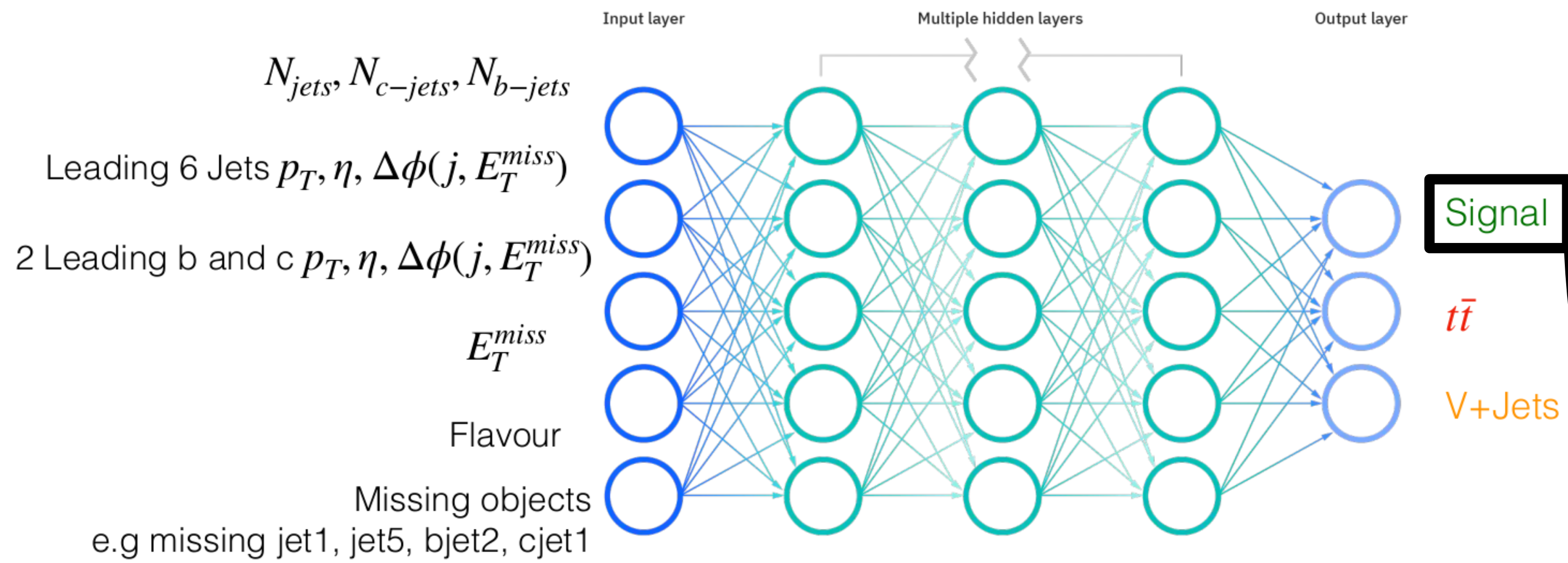
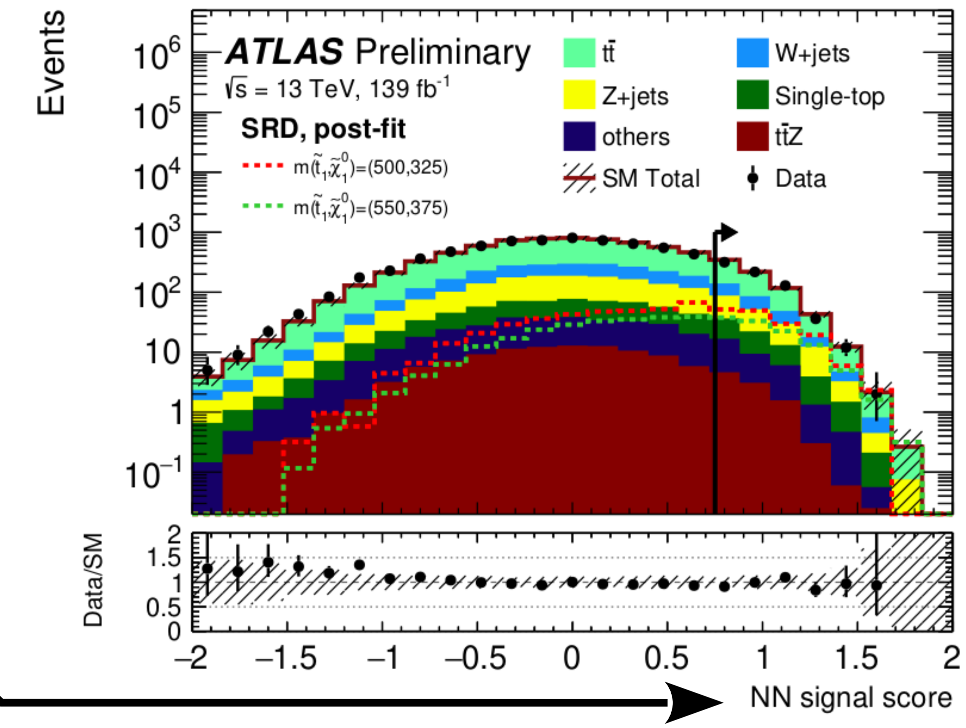
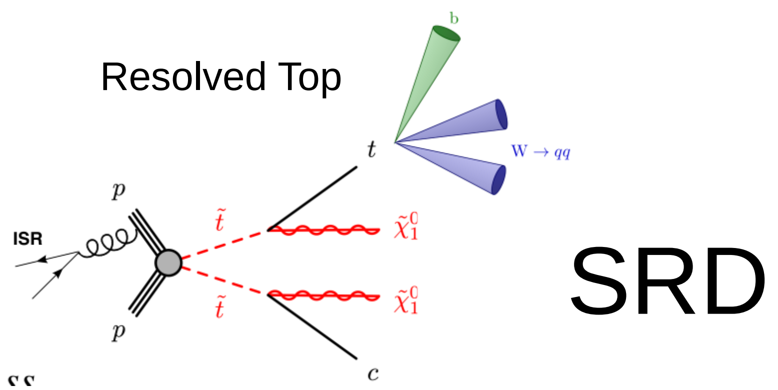




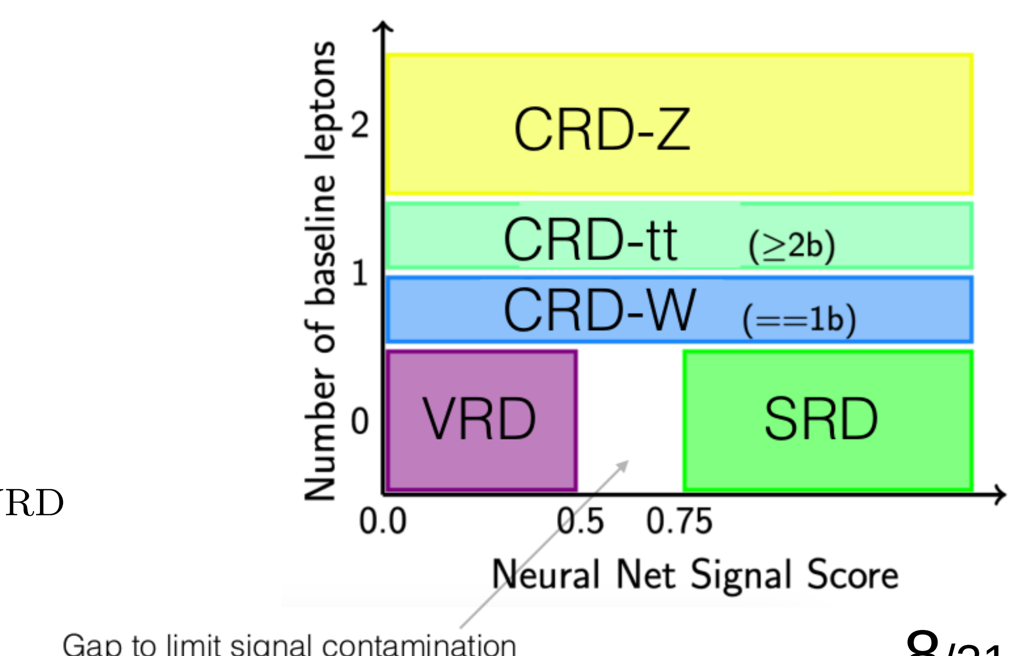


- **Main Backgrounds:** ttbar, Z+jets, W+jets

Each backgorund gets a CR:

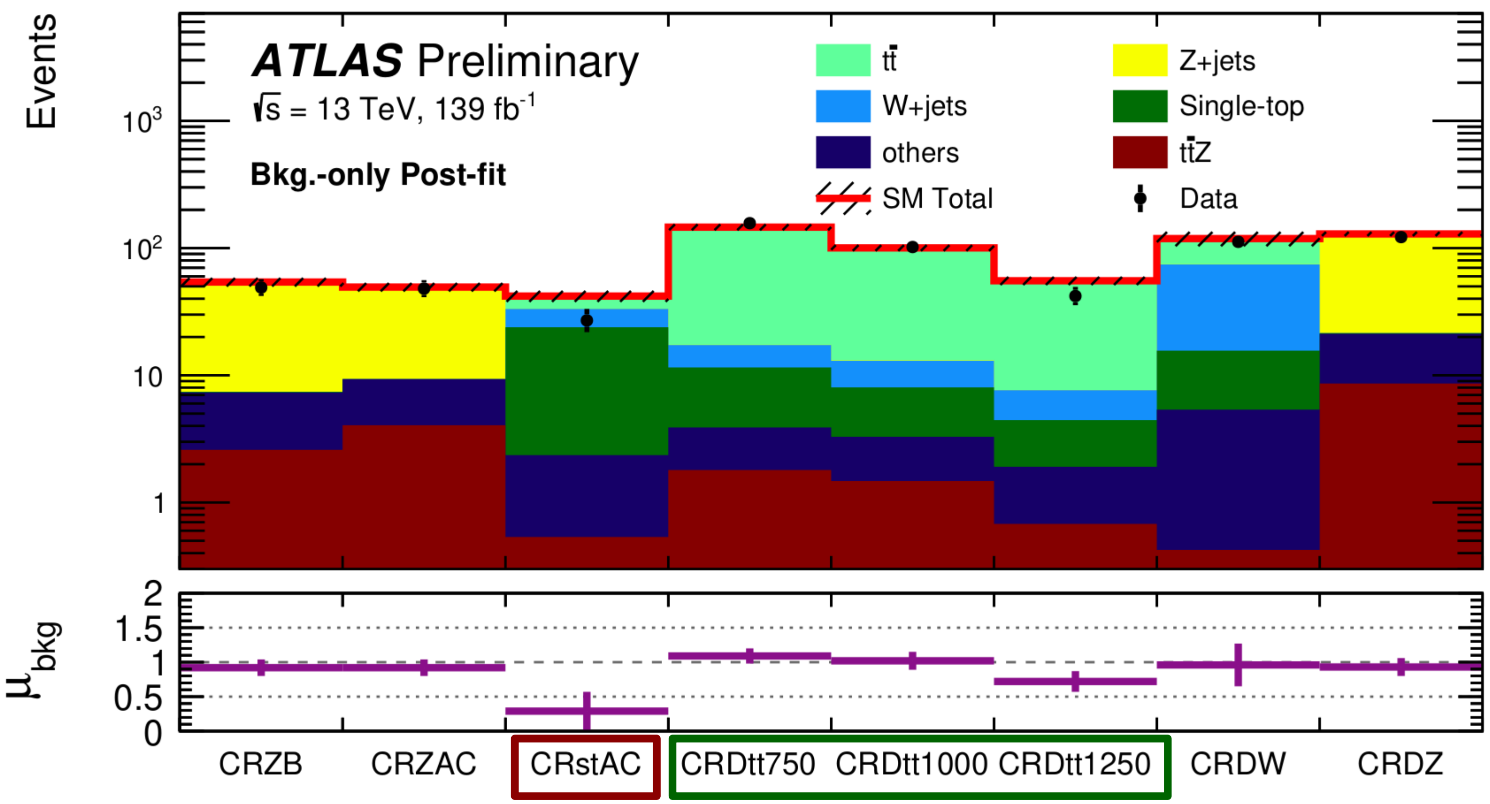
- Zjets CR for SRD (2L events)
- Ttbar CR for SRD (1L events) + (>=2b)
- Wjets CR for SRD (1L events) + (==1b)

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



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
- Data agrees well with SM prediction.

Results – Bkg-Only Fit

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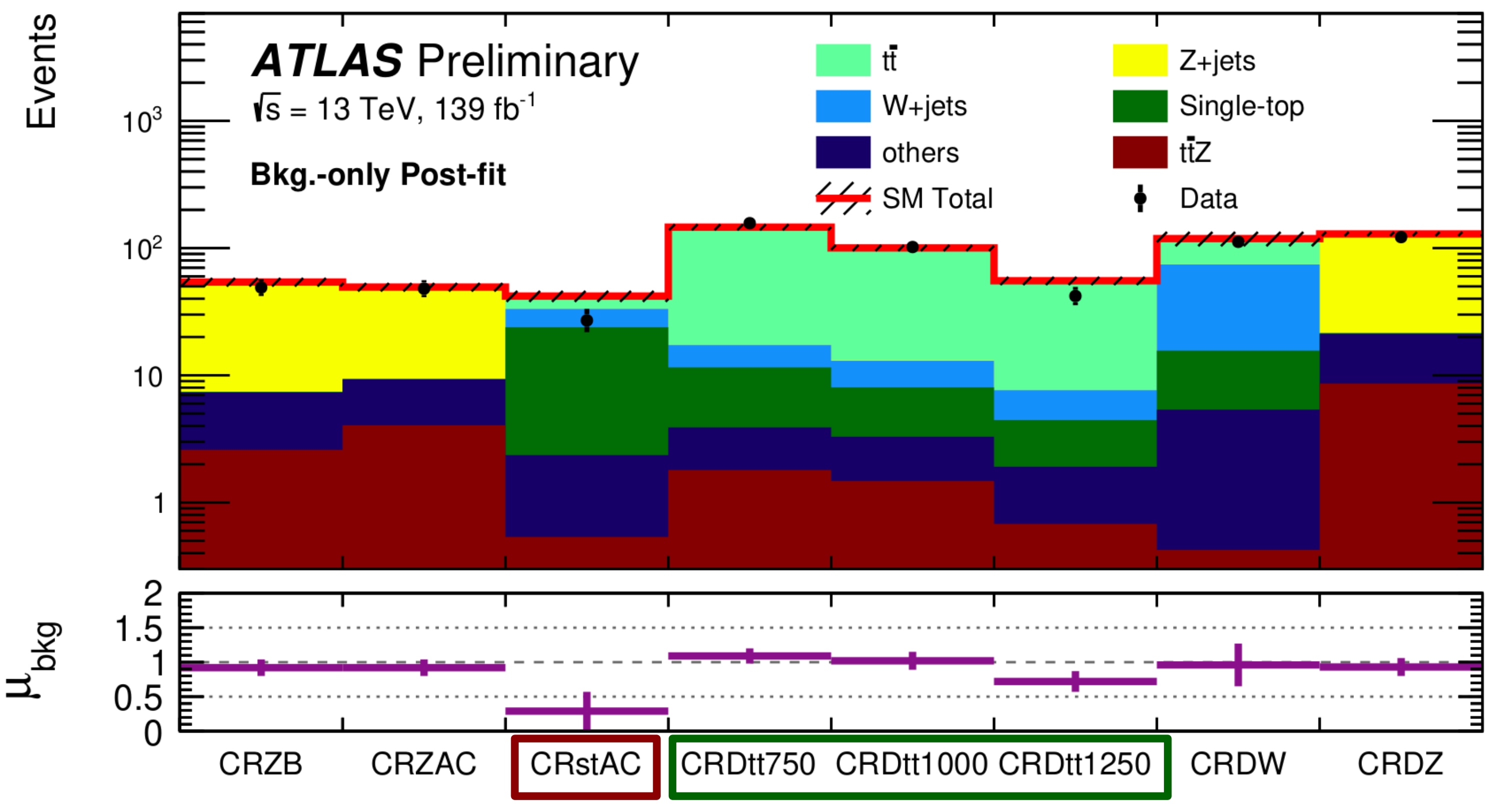
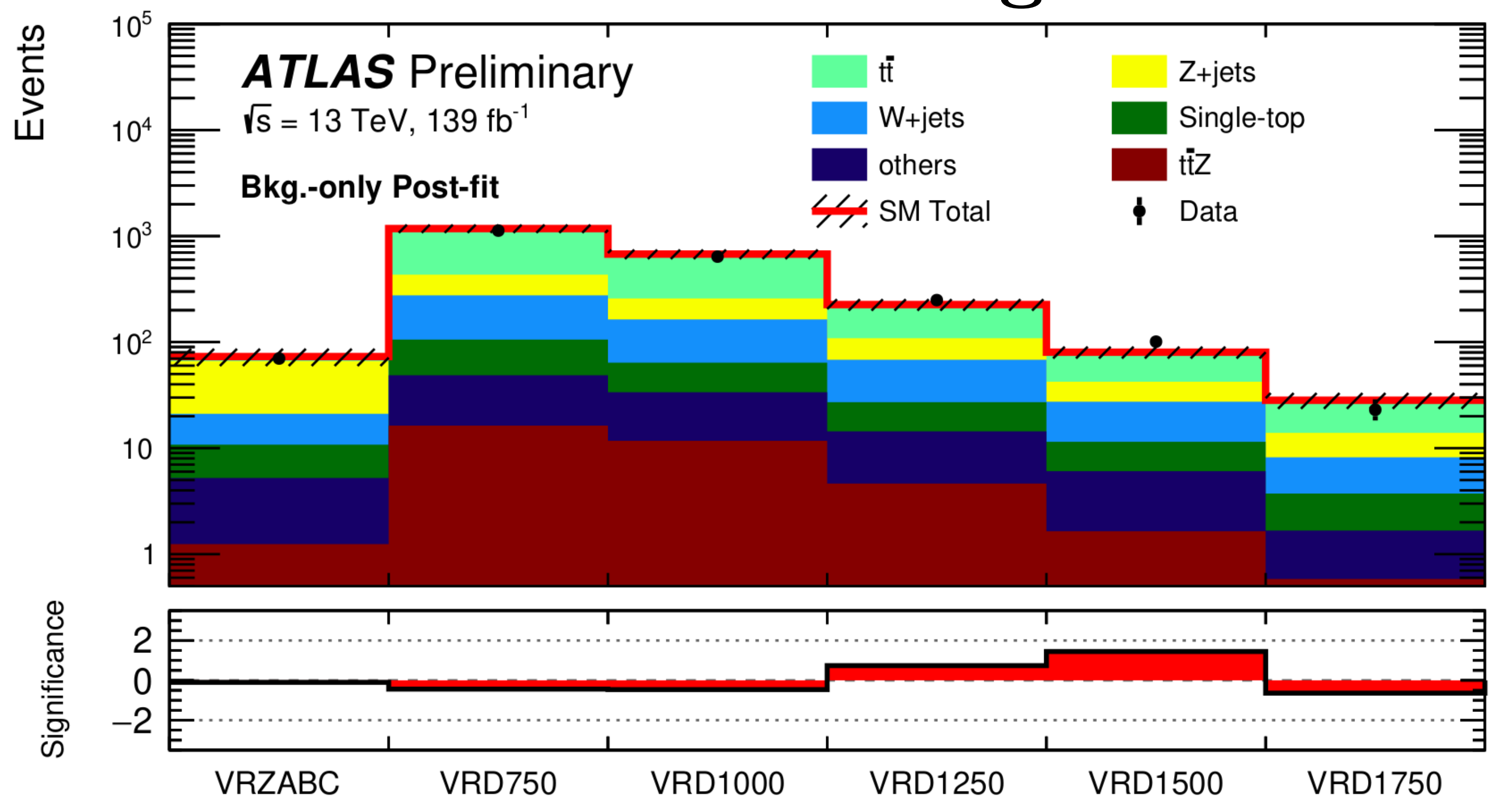


Validation Regions



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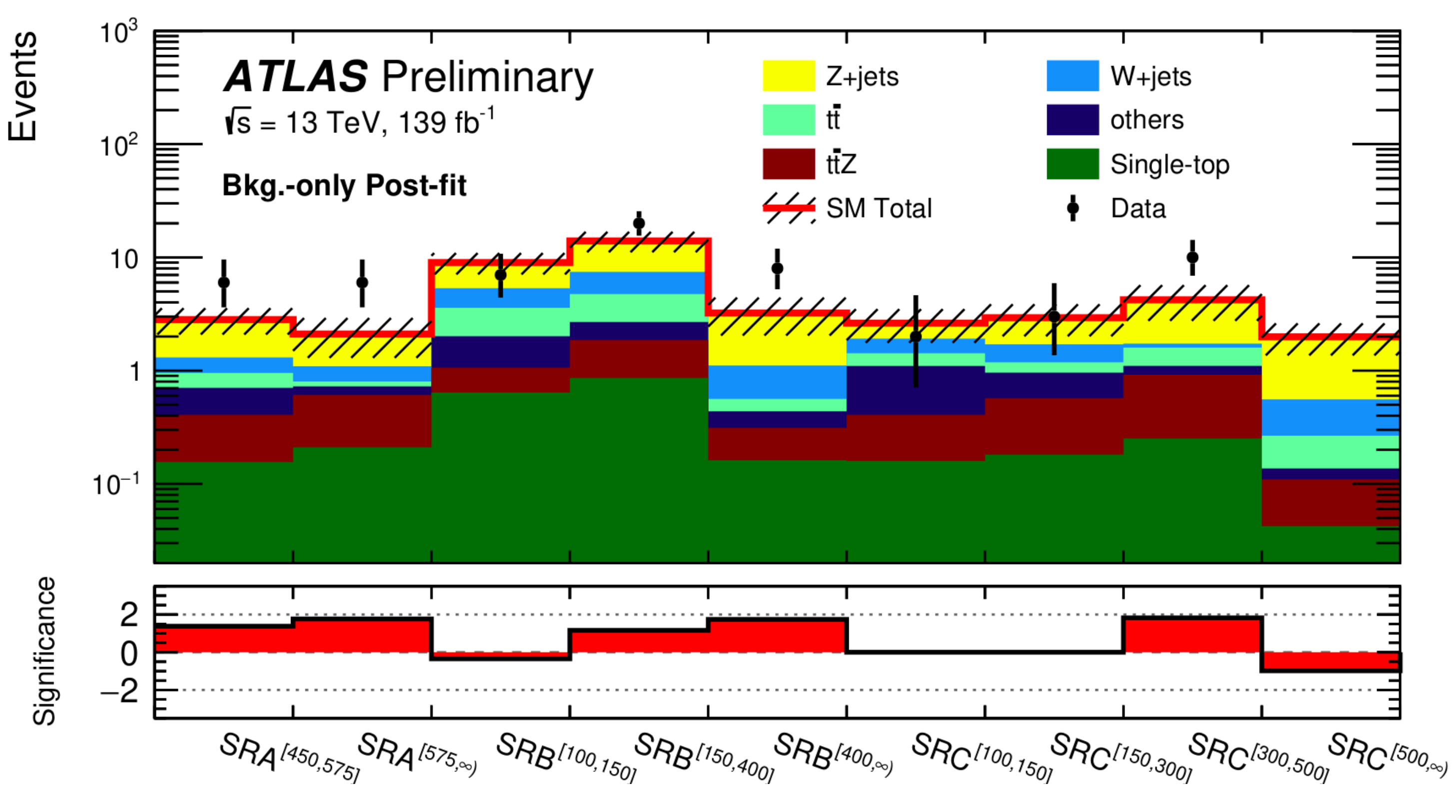
    - Highly correlated with increasing pT ttbar events → need increasing correction
- Data agrees well with SM prediction.

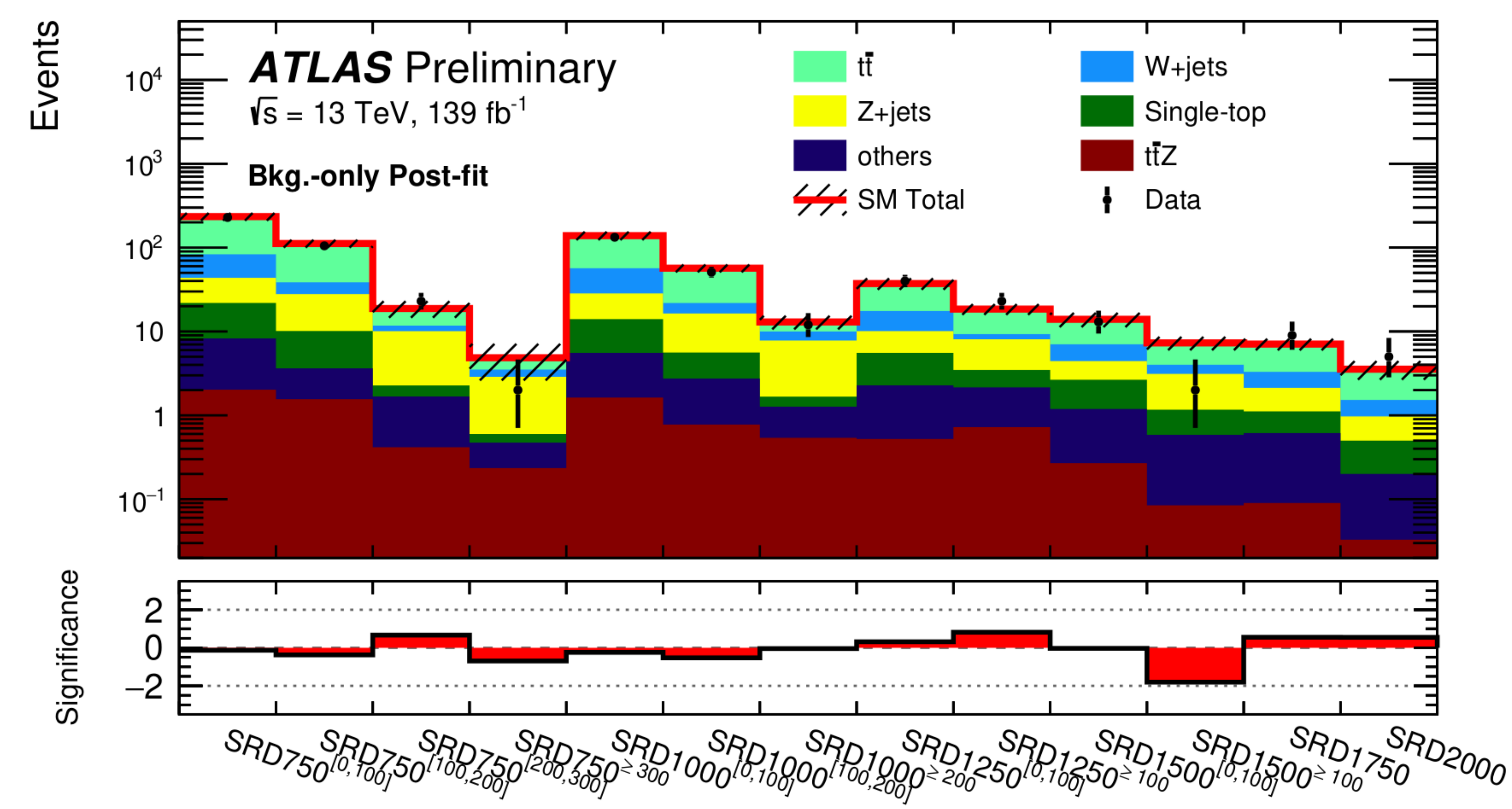
- Normalization factors (to correct the different background processes) from Control Regions extracted to corresponding Validation Regions
- Post-fit excesses in VRs < 2 sigma
- These are not used in the fit, they are used to validate the profile-likelihood fit in Control Regions

Results – Bkg-Only Fit

Signal Regions - ABC



Signal Regions - D

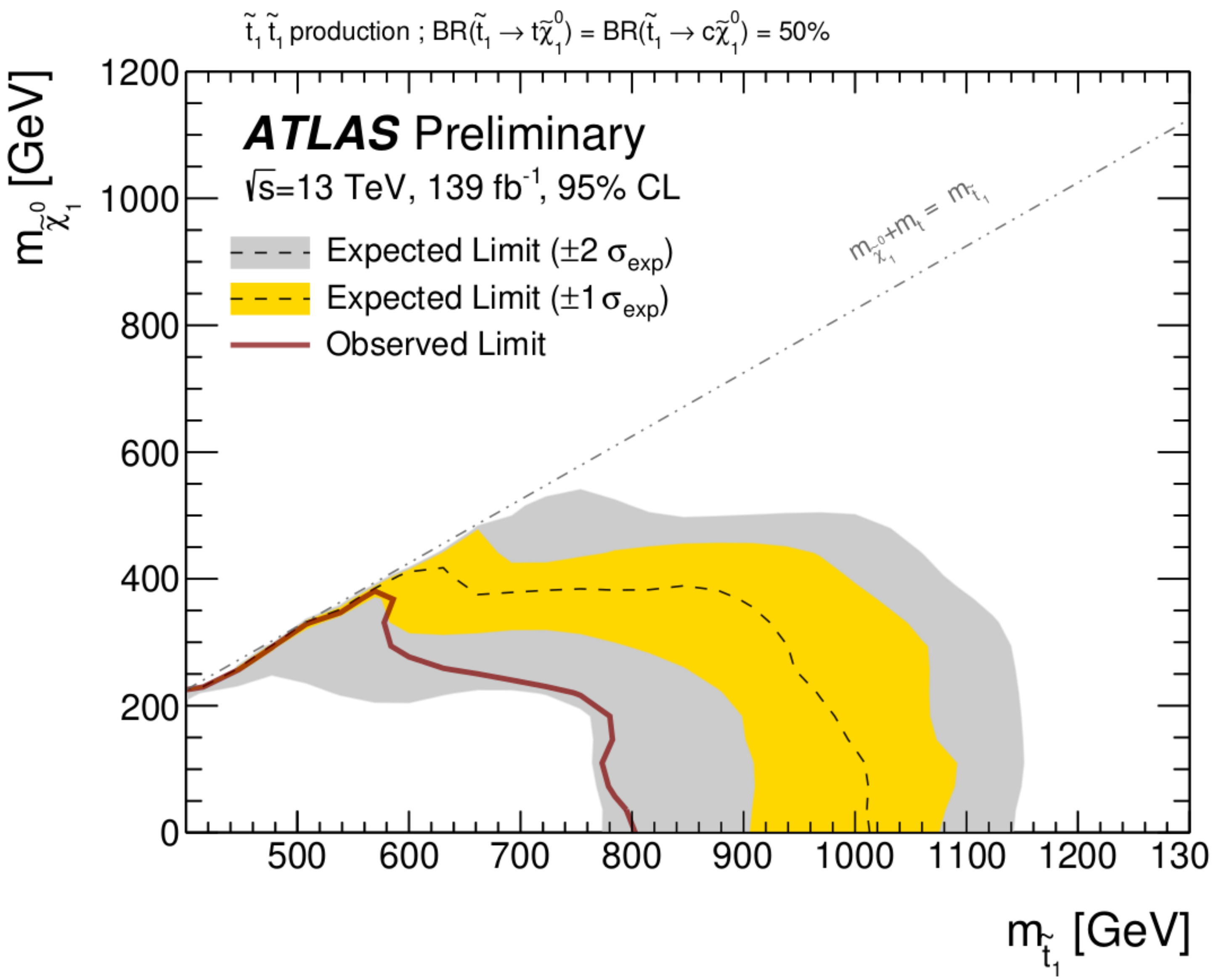


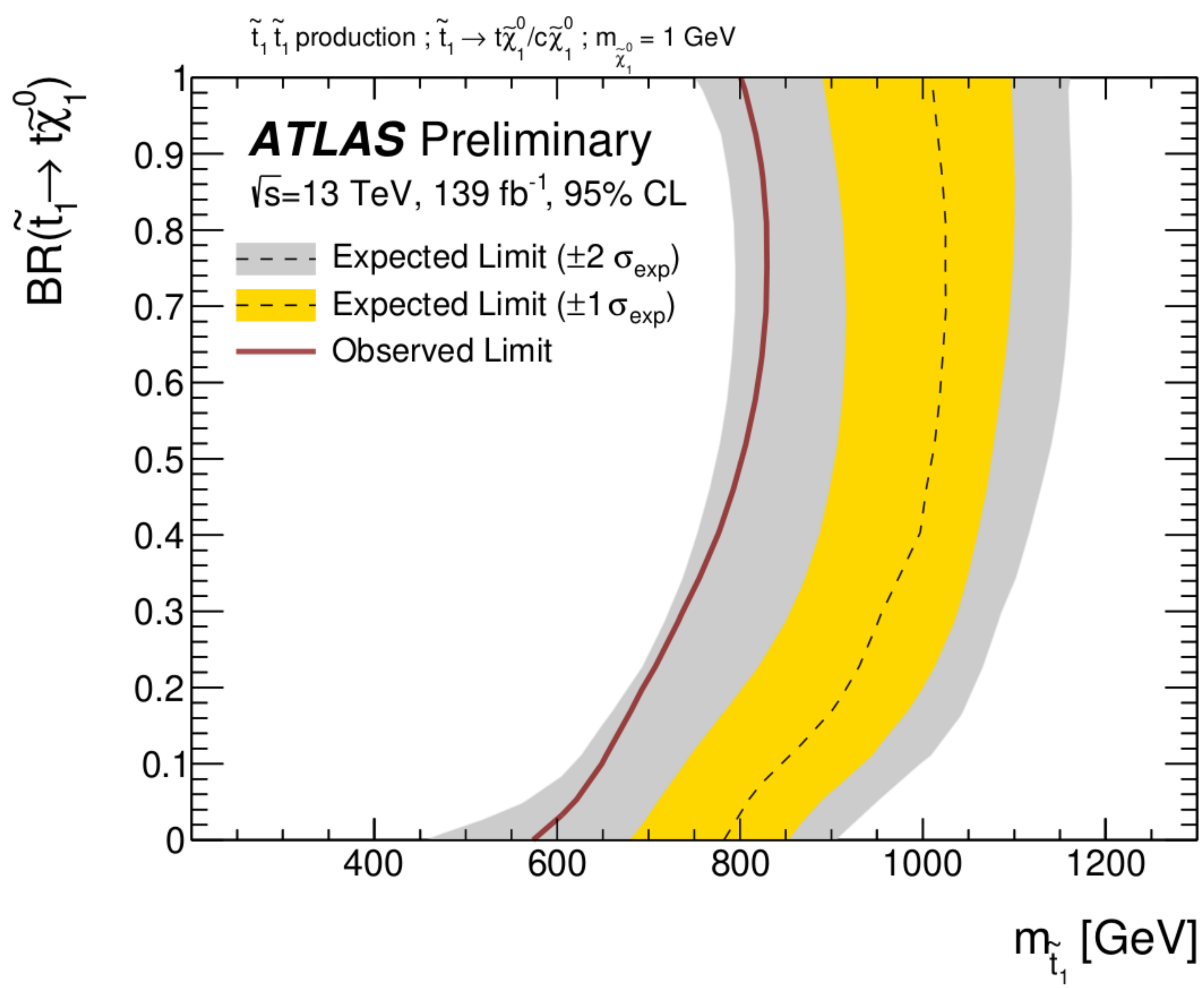
Each signal region is binned to increase sensitivity

- SRA, SRB and SRCs have excesses but within 2 sigma.

- Data agrees well with SM prediction.
  - Largest deficit in SRD1500_[0,100] ~ 1.8 sigma

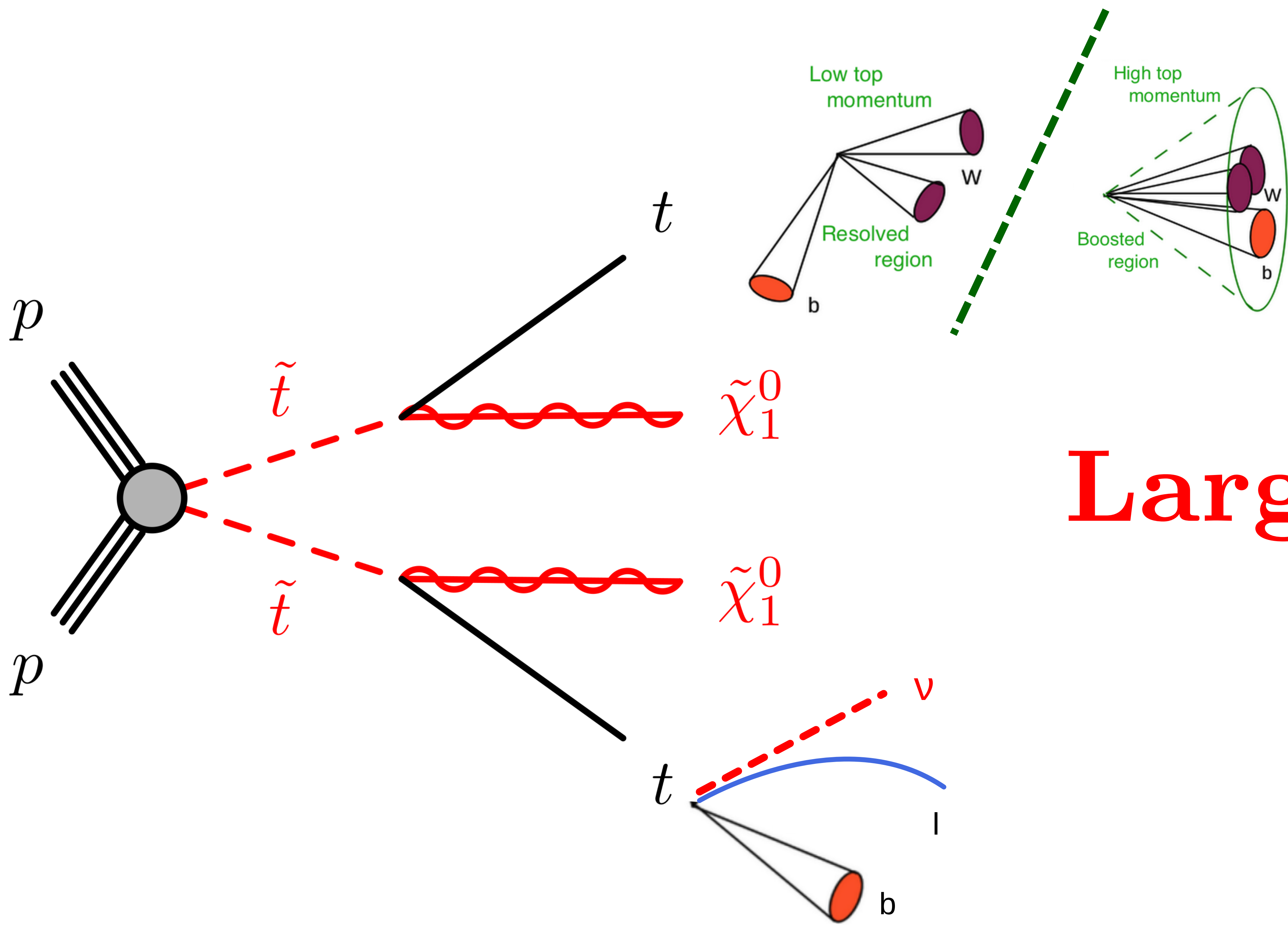
Results – Model Dependent Fit (Exclusion)





- Excess causes a weaker observed limit as compared to expected
- Good sensitivity retained even with varying BR

$\mathbf{t\bar{t}+E_T^{miss}}$ (1L)



t(0L)

Large $\mathbf{E_T^{miss}}$

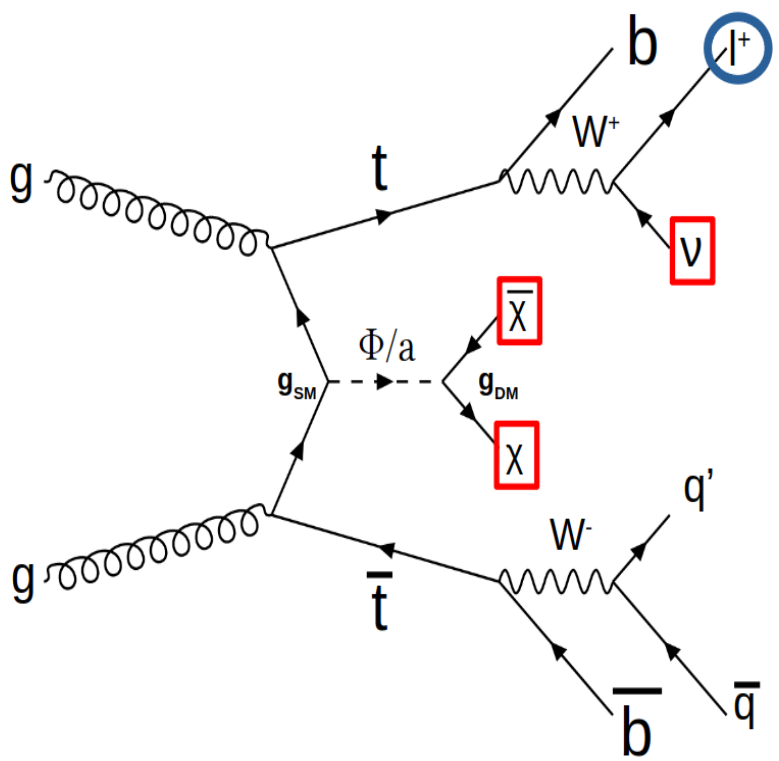
t(1L)

Target Scenarios

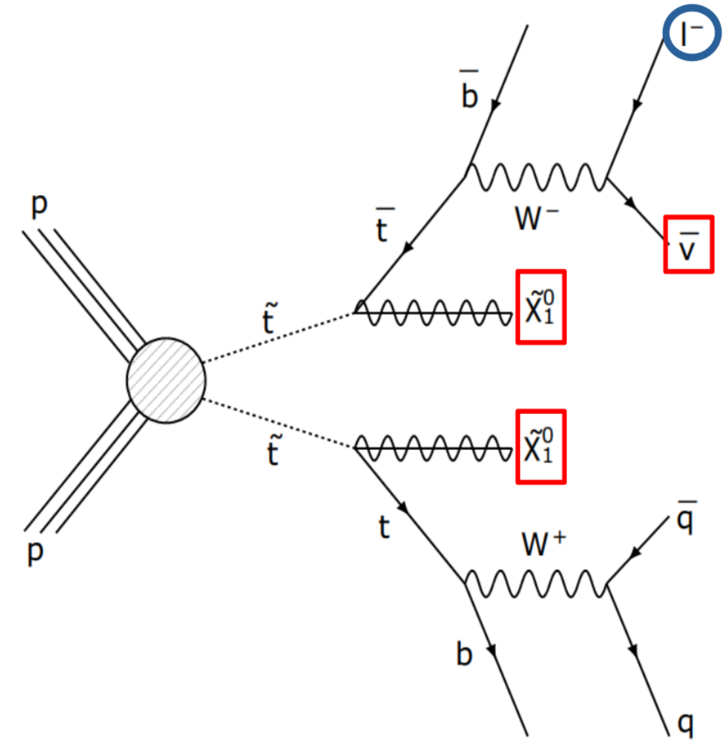
Specifically target production of:

Dark Matter

In association with two top quarks



Stop Pair Production



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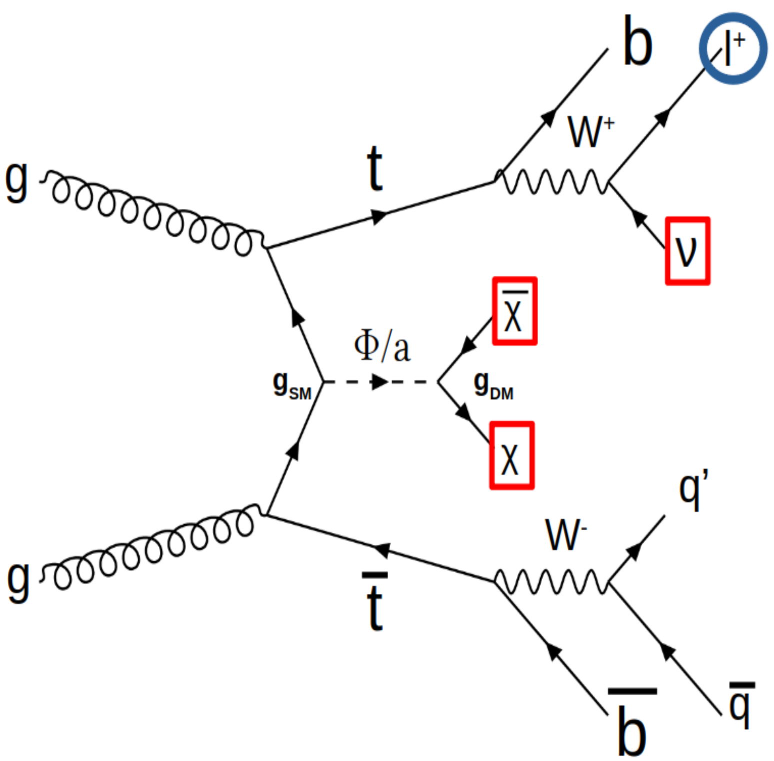

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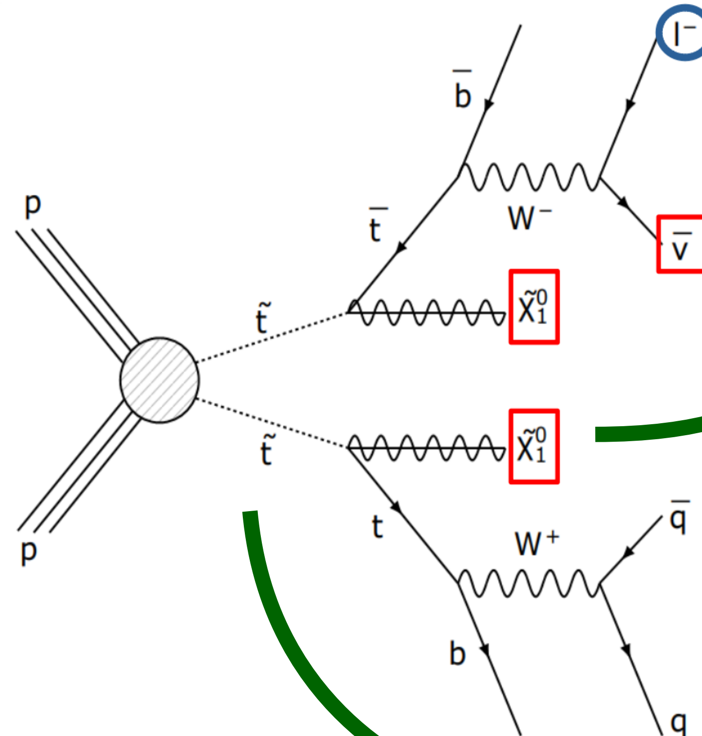
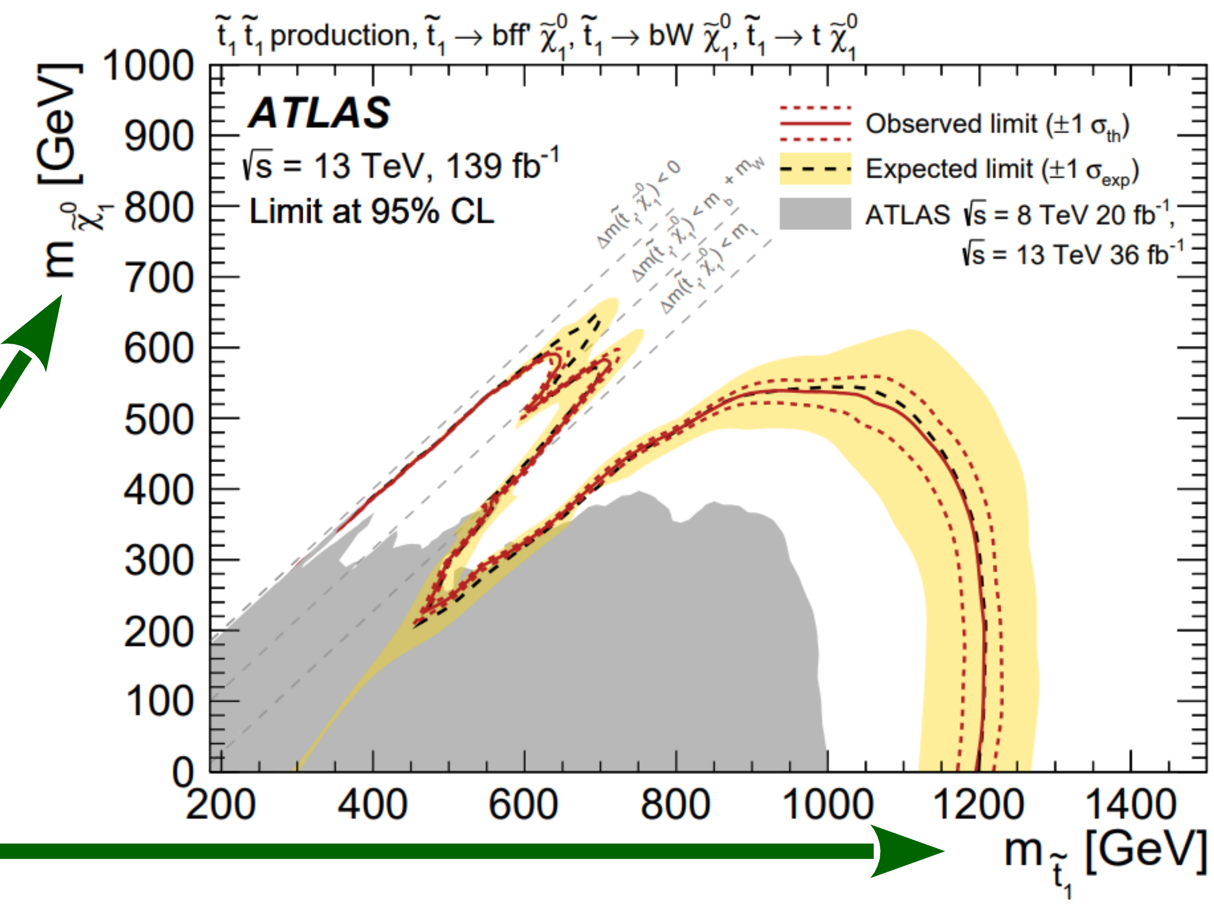


Previous Run-II 1L result



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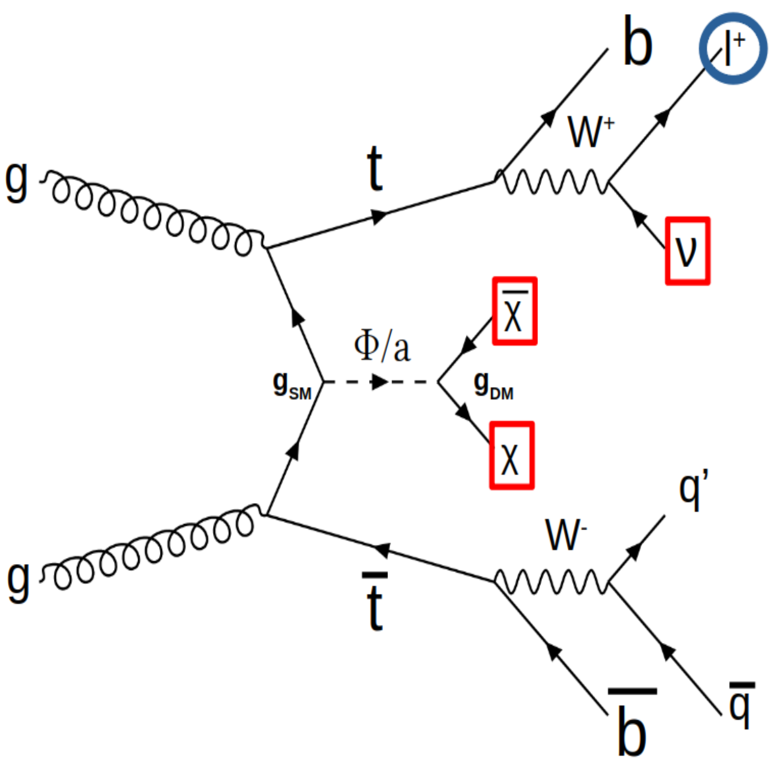

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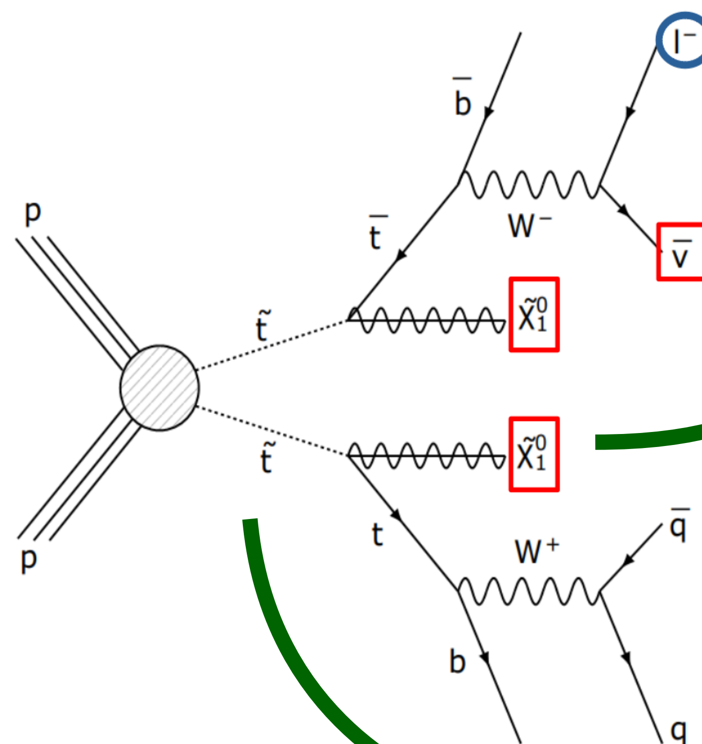

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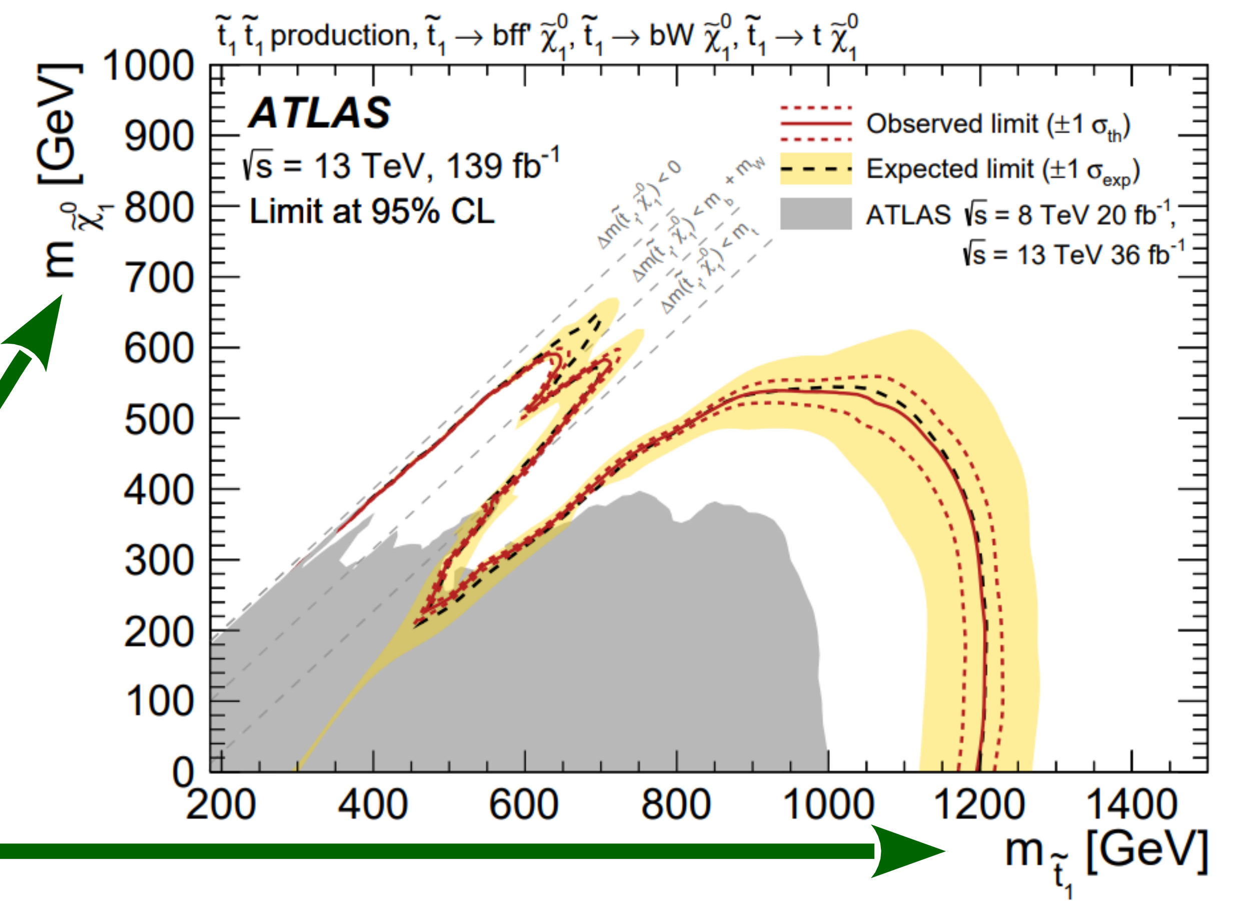
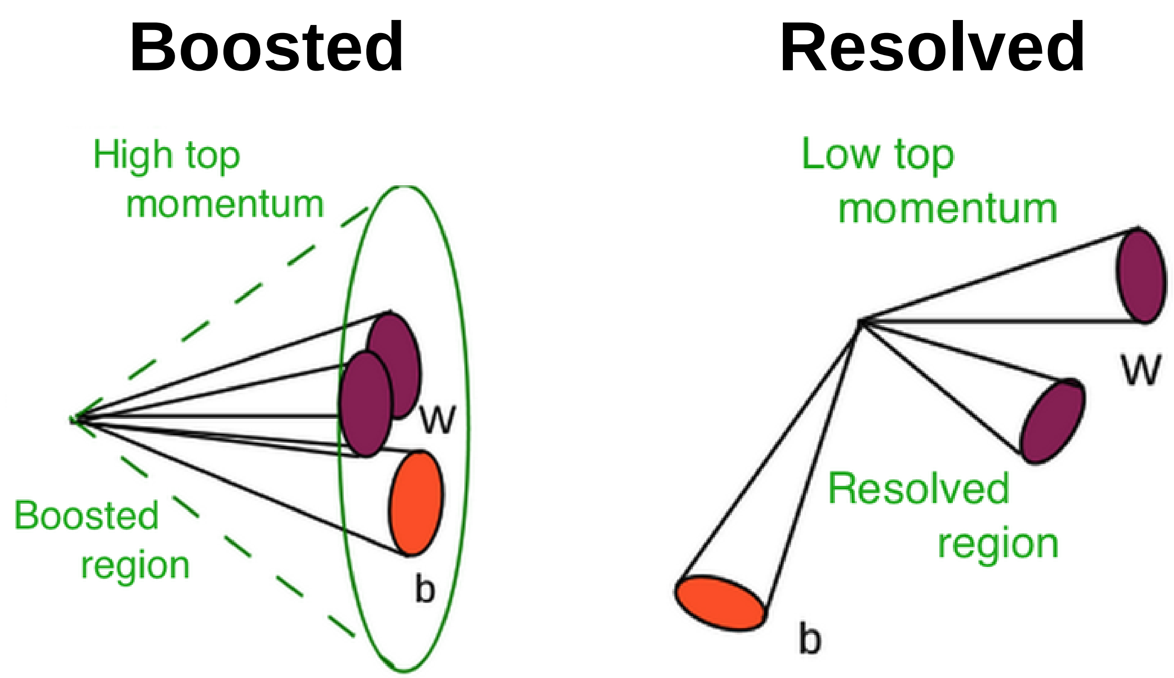


- ► Scan a range of masses for both DM and SUSY models
- ► Focus on the **1L final state** where the lepton is either an electron or muon.
- ► Using an improved analysis strategy (inclusive event categories and Neural Networks), aim to improve upon the 1[st] wave results while using the same dataset (full Run-II).

Neural Net Strategy

1. Top reconstruction with DNN

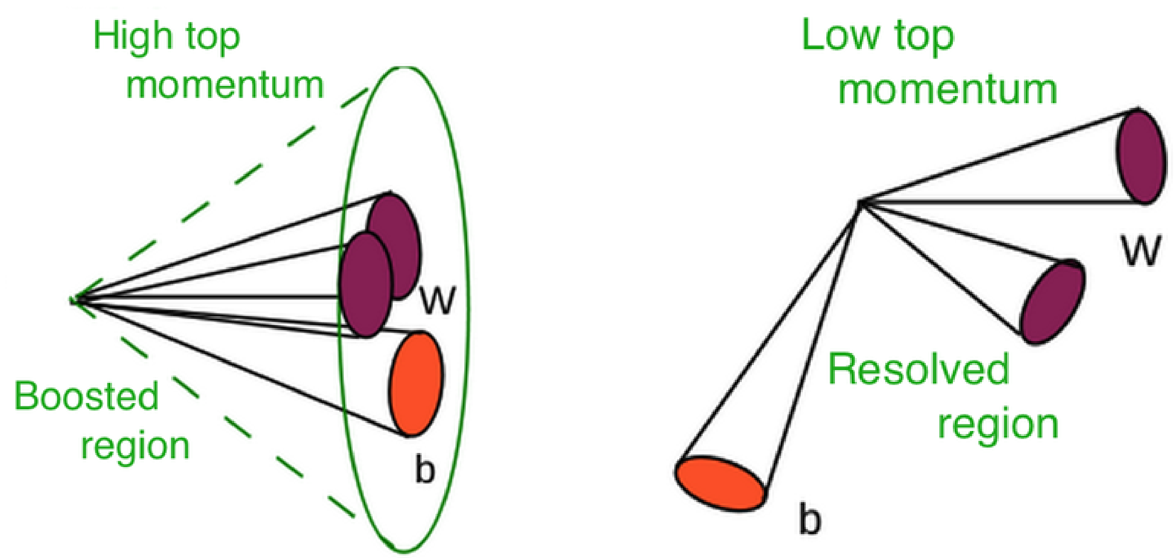


- For **boosted** (high pT) tops, large-R jets are selected and a DNN developed by the jet group is used to tag these jets as tops.
- For **resolved** (mid pT) tops, a dedicated NN is developed to reconstruct the top pair from 3 leading jets (2 b-tagged) and 1 leading lepton in the event.

Neural Net Strategy

1. Top reconstruction with DNN

Boosted **Resolved**



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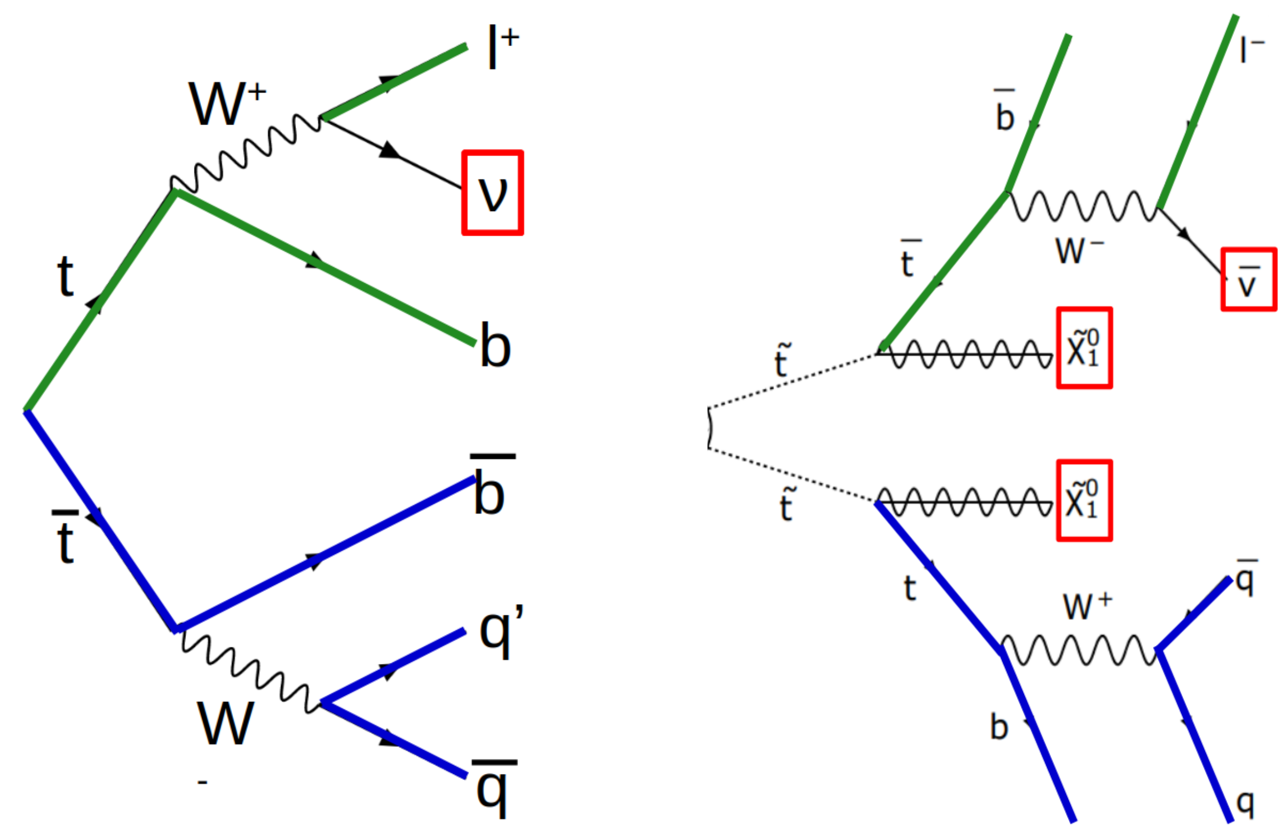
- For **resolved** (mid pT) tops, a dedicated NN is developed to reconstruct the top pair from 3 leading jets (2 b-tagged) and 1 leading lepton in the event.

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.

"Bkg" **"Signal" - Stop**



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

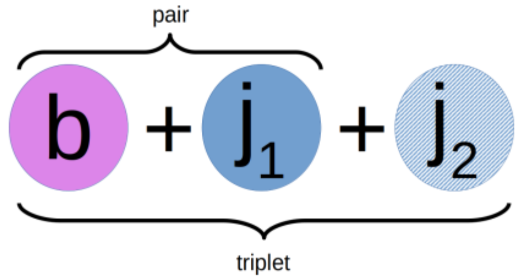
Resolved Top Reconstruction

Goal:

- To reconstruct hadronic top decays in the mid-pt range

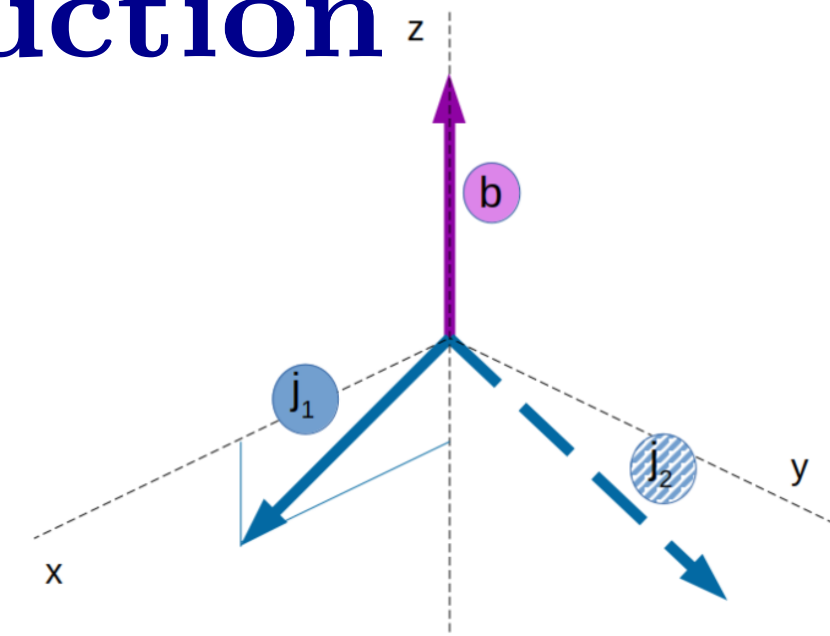
Pre-processing of Inputs:

- In each event, we take combinations of up to 6 jets and make pairs/triplets.
  - 2 leading b-tagged jets
  - 4 leading light jets



- All jets require pT above 20 GeV and the pairs/triplets require the first jet to be a b-jet.

Resolved Top Reconstruction



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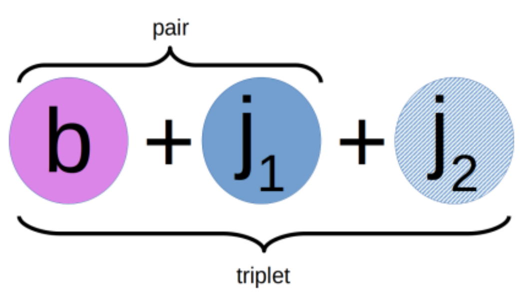


- All jets require pT above 20 GeV and the pairs/triplets require the first jet to be a b-jet.
- The multiplet is then:
  - boosted into its rest frame to remove Lorentz-boost symmetries and reduce dependence on top momentum.
  - rotated to remove rotational symmetries.
- Multiplet ("top") pt, "flattened" so that pairs at low- and high-pt can be distinguished but no discrimination based on solely top pt

Note: This is beneficial in reducing the complexity of the training so that we can work with smaller networks.

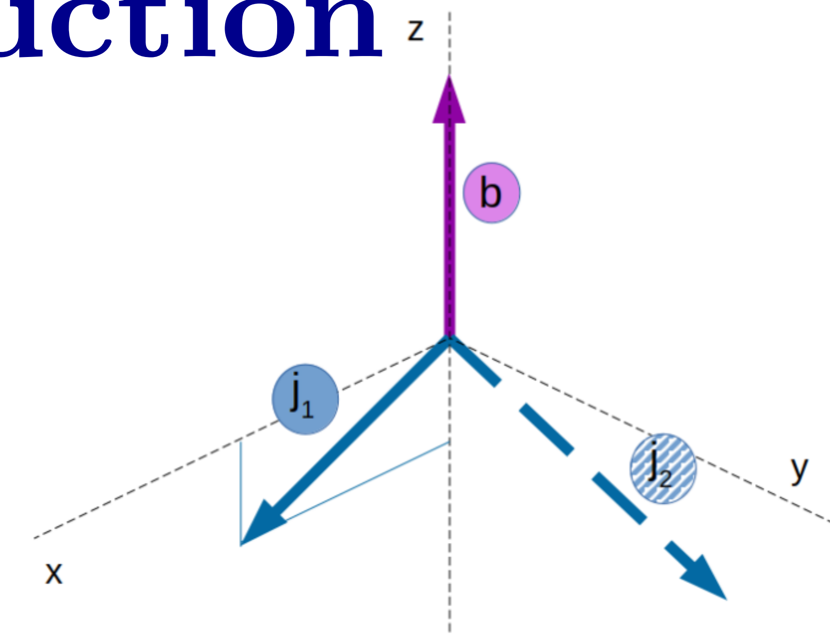
	b	j_1	j_2
E	*	*	*
P_x	0	a	-a
P_y	0	0	0
P_z	-b-c	b	c

- red - from rotation
- green - conservation in rest frame

Leftover 6 non-trivial parameters:

- b.E
- j1.E, j1.Px, j1.Pz
- j2,E, j2.Pz

Resolved Top Reconstruction



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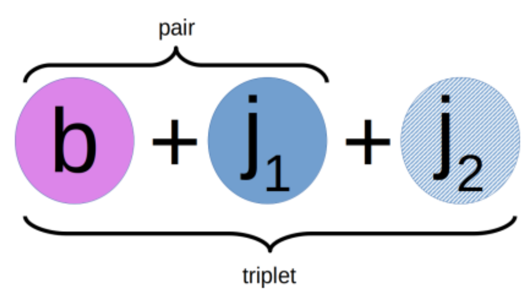

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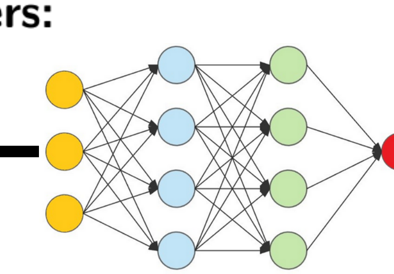
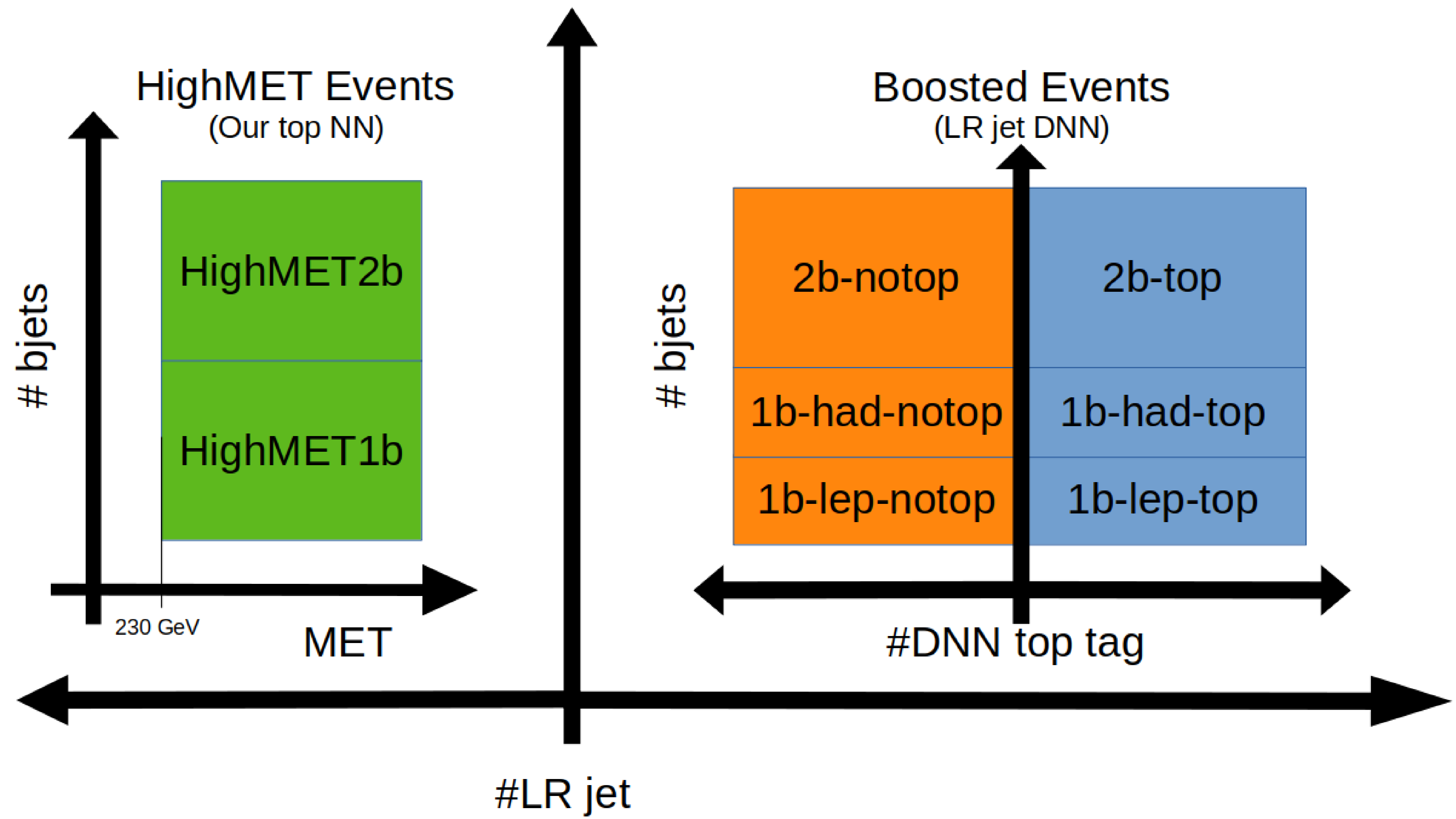


Score to define if a multiplet is a top

In each event, each multiplet is evaluated and the one with highest score used

Event Phase Space

Now, split (a very loose pre-selection) into different kinematic categories



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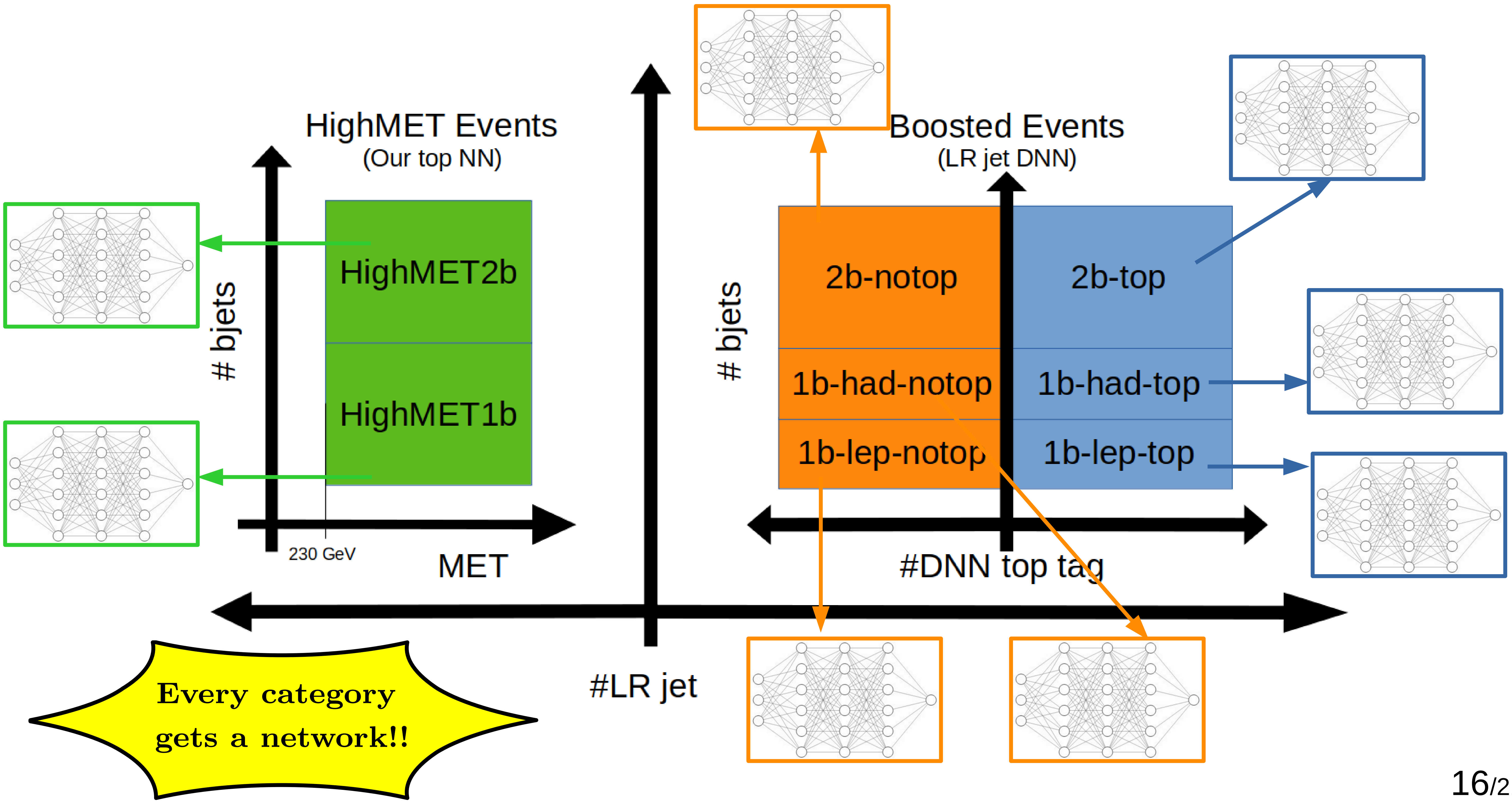
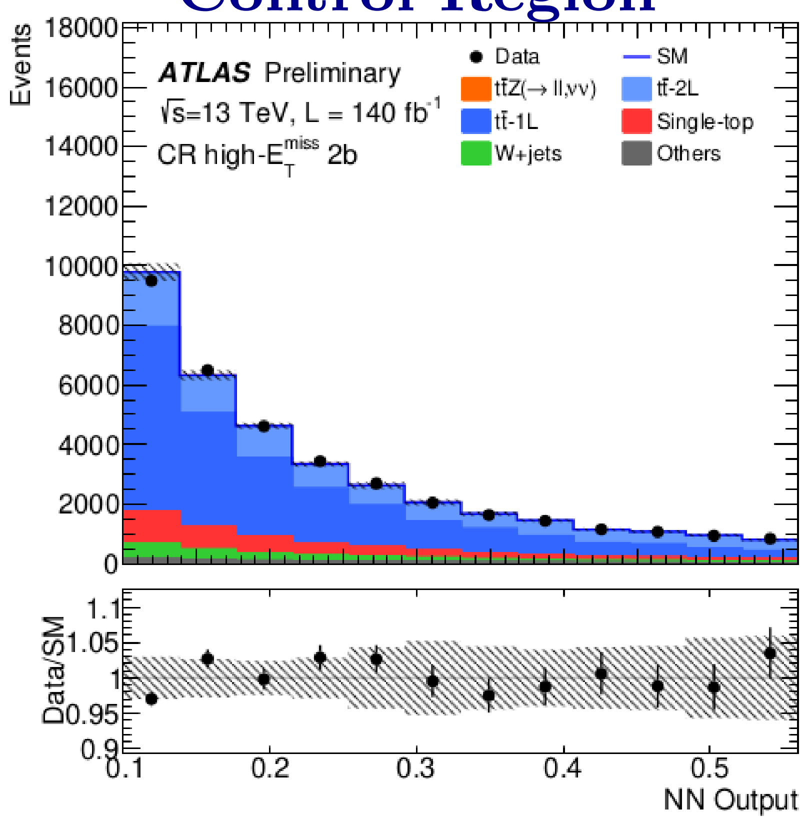


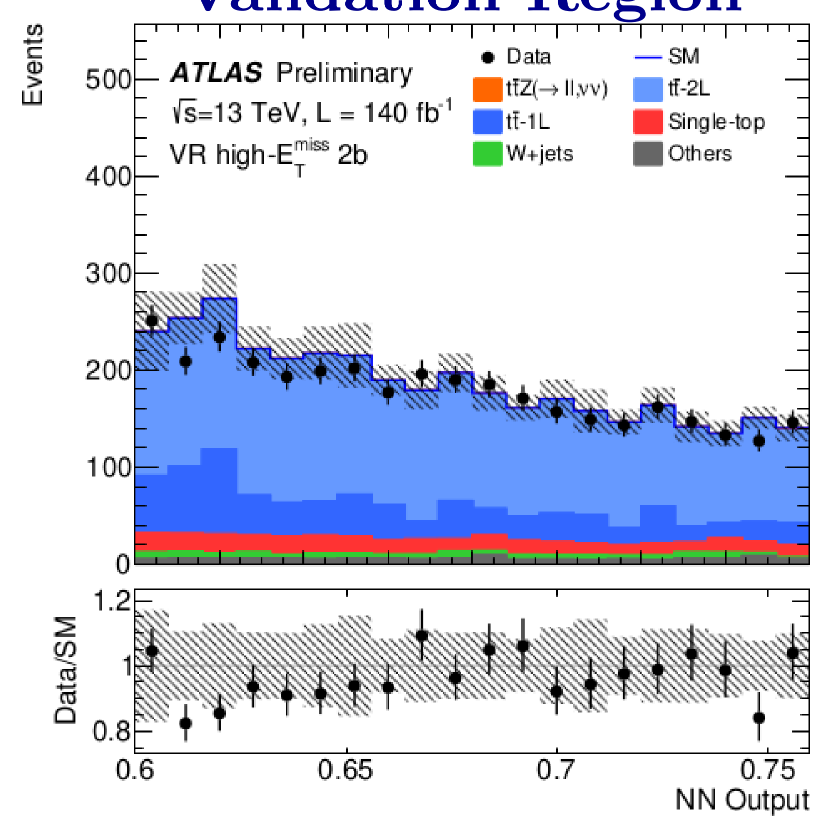
CR-VR-SR Strategy

- Using the NN output score, Control, Validation and Signal Regions are defined.
- Main Backgrounds:
  - ttbar (1L) with a hard ISR to boost MET
  - ttbar (2L) – missed lepton looking like MET
  - Wjets / singletop – sub-domninant backgrounds.
  - TtZnunu – irreducible background (exactly same signature as signal)

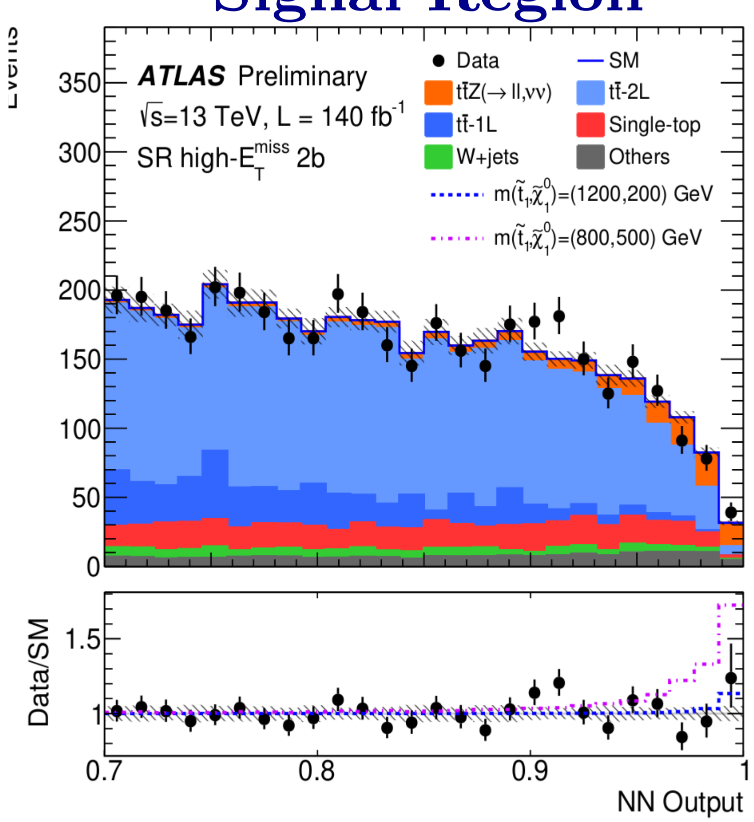
Control Region



Validation Region



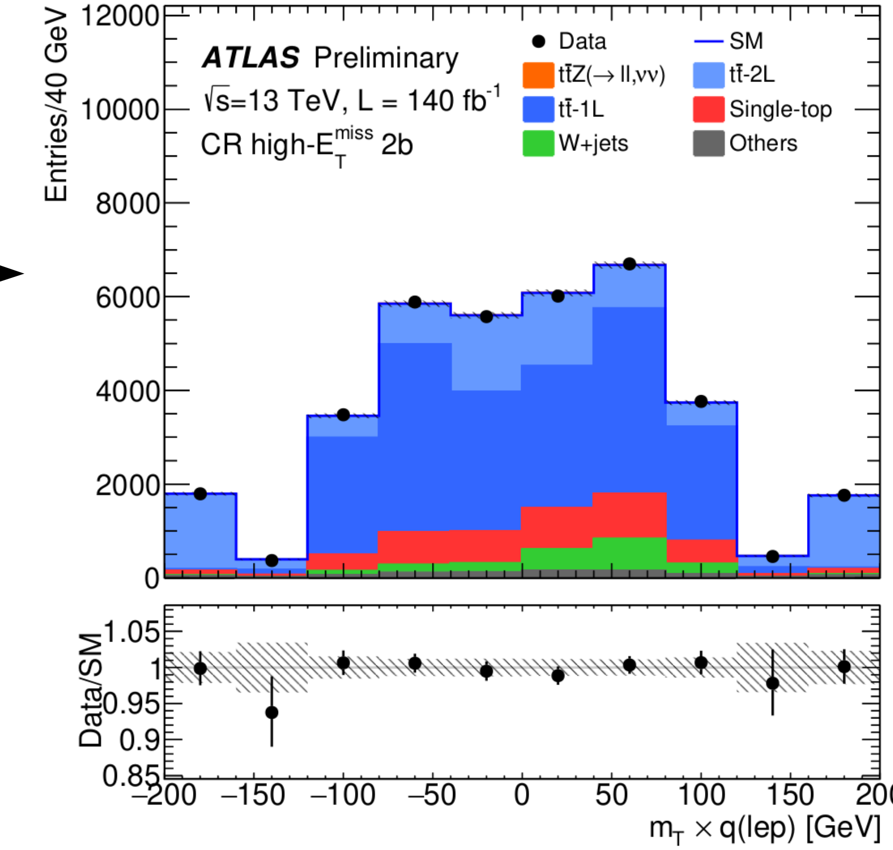
Signal Region

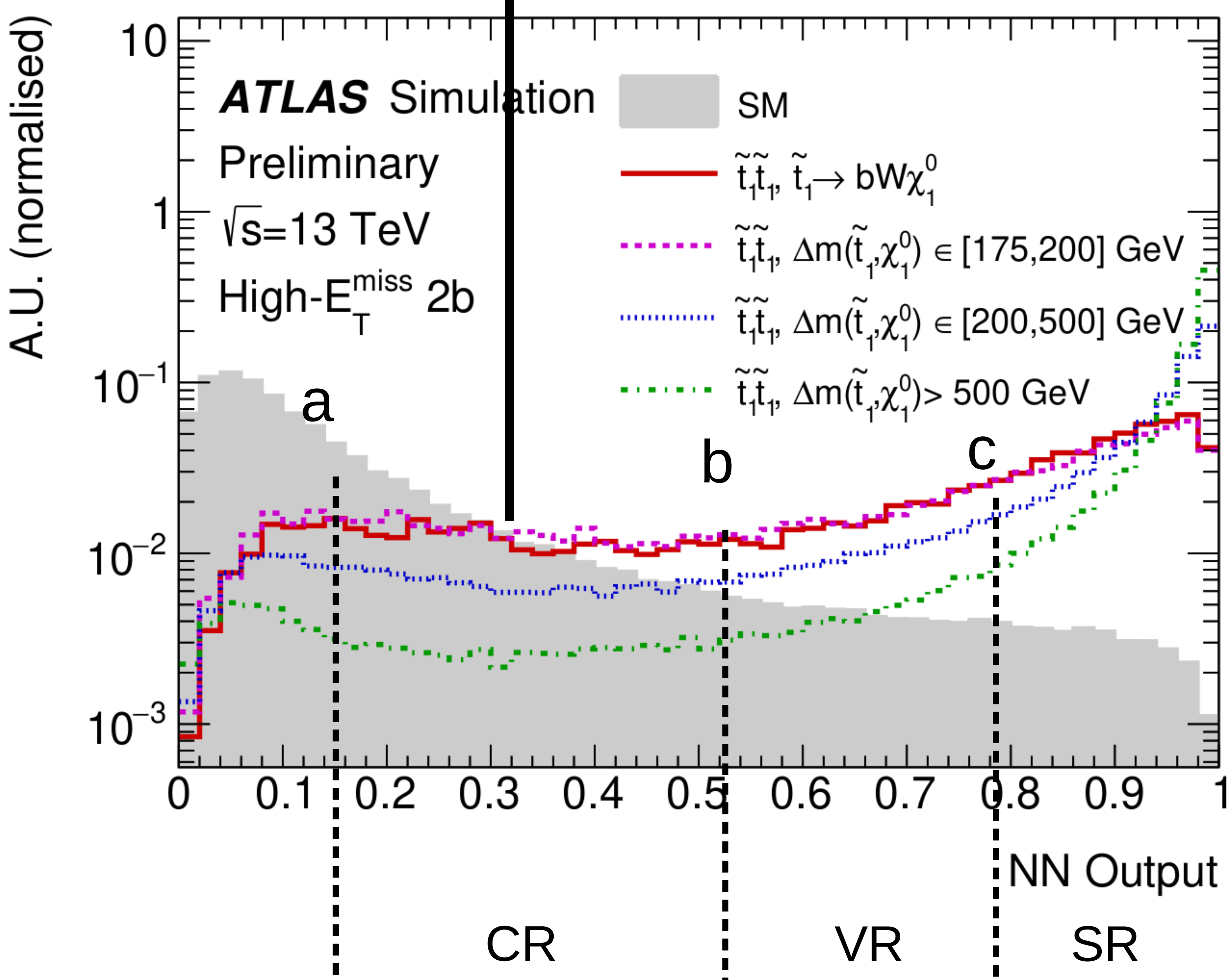


Fit Strategy (per category)

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

Used for the background fit





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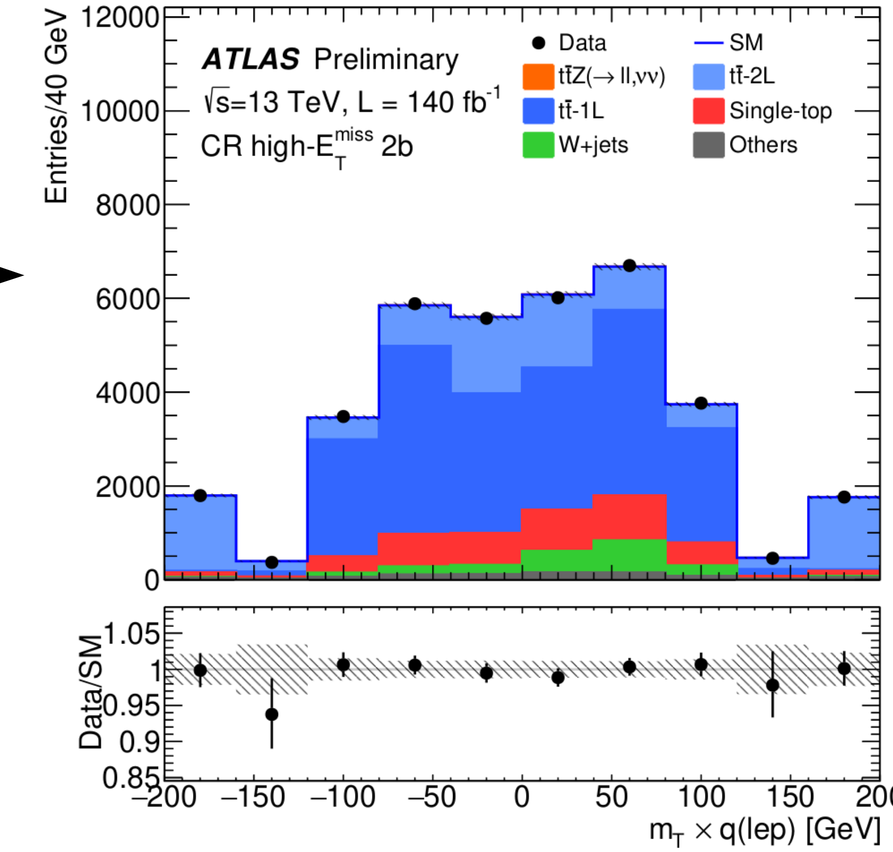
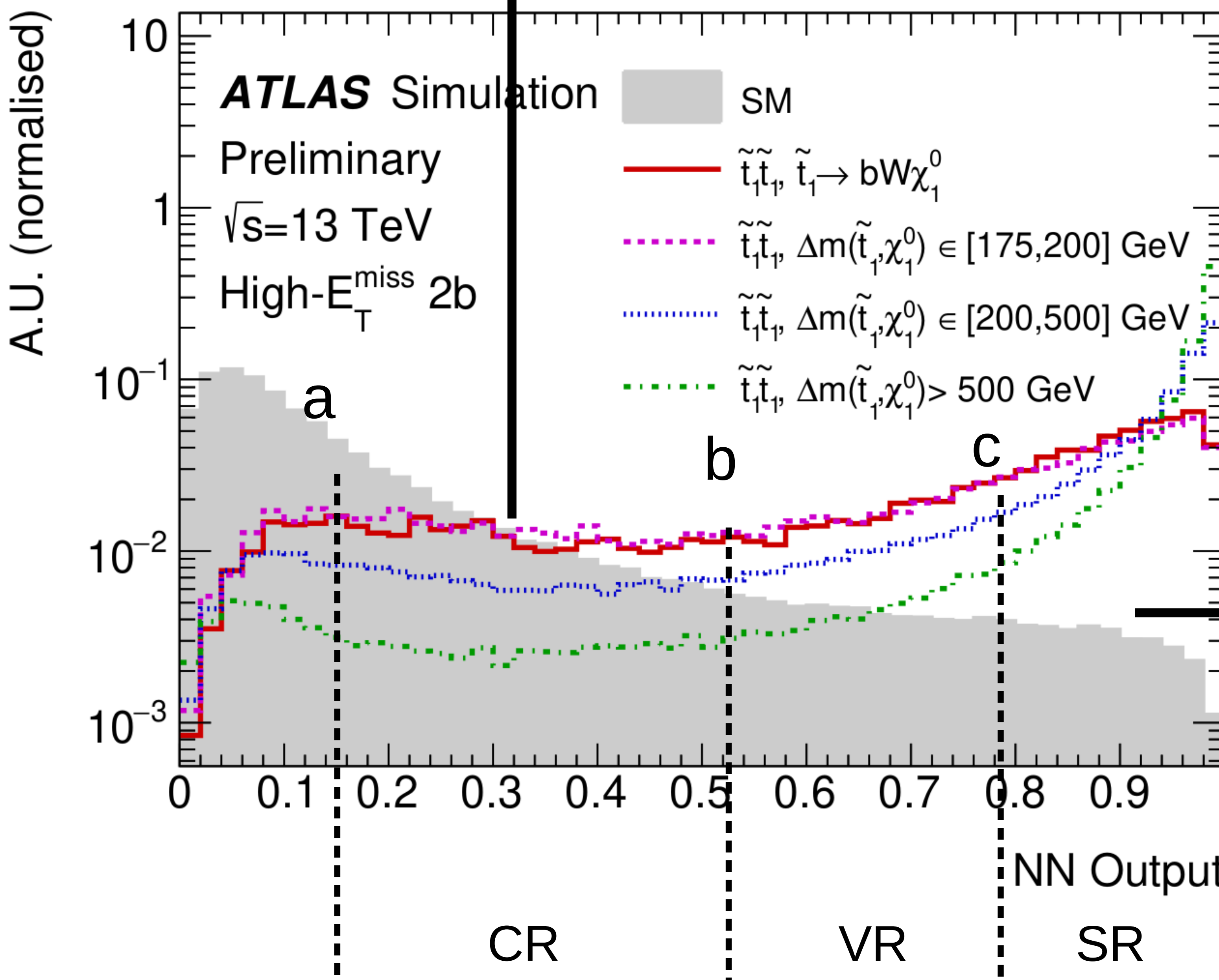
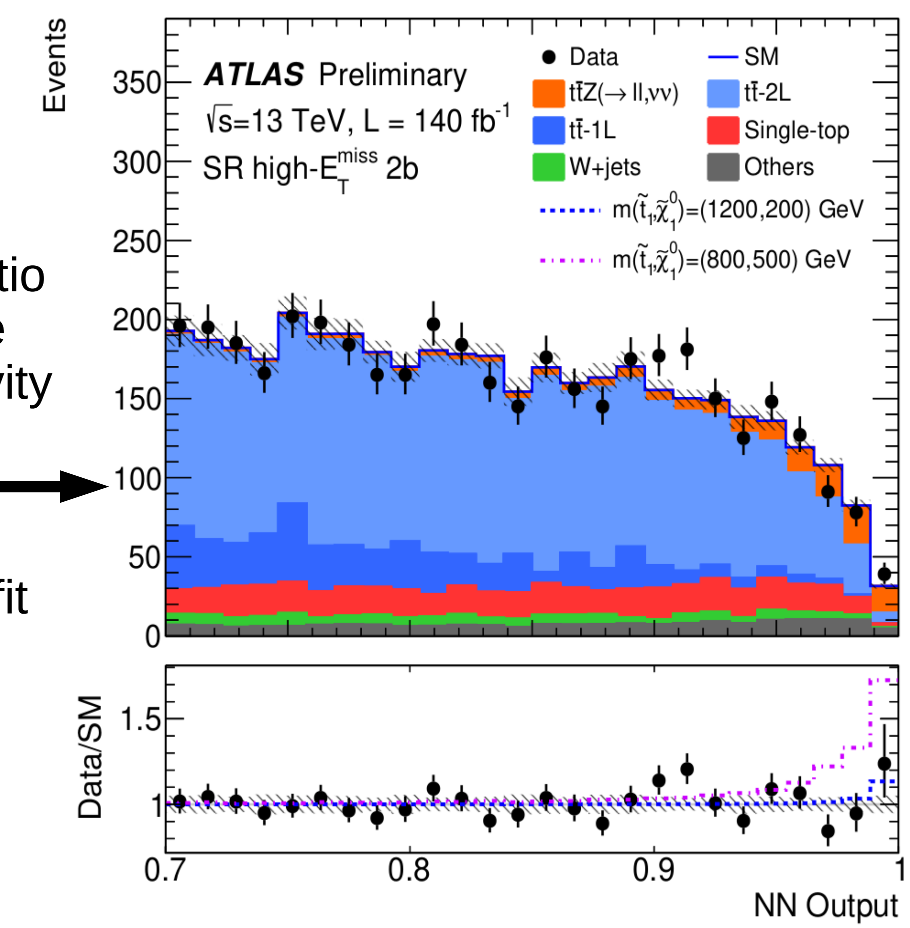




Changing S/B ratio used to achieve maximum sensitivity

With a multi-bin fit



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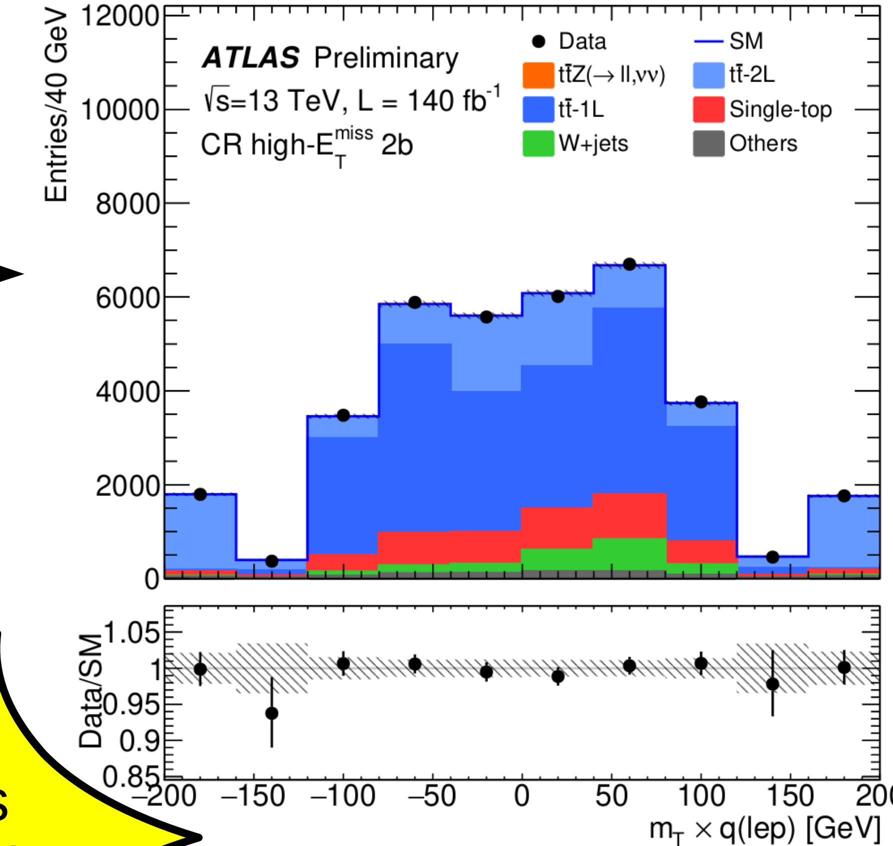
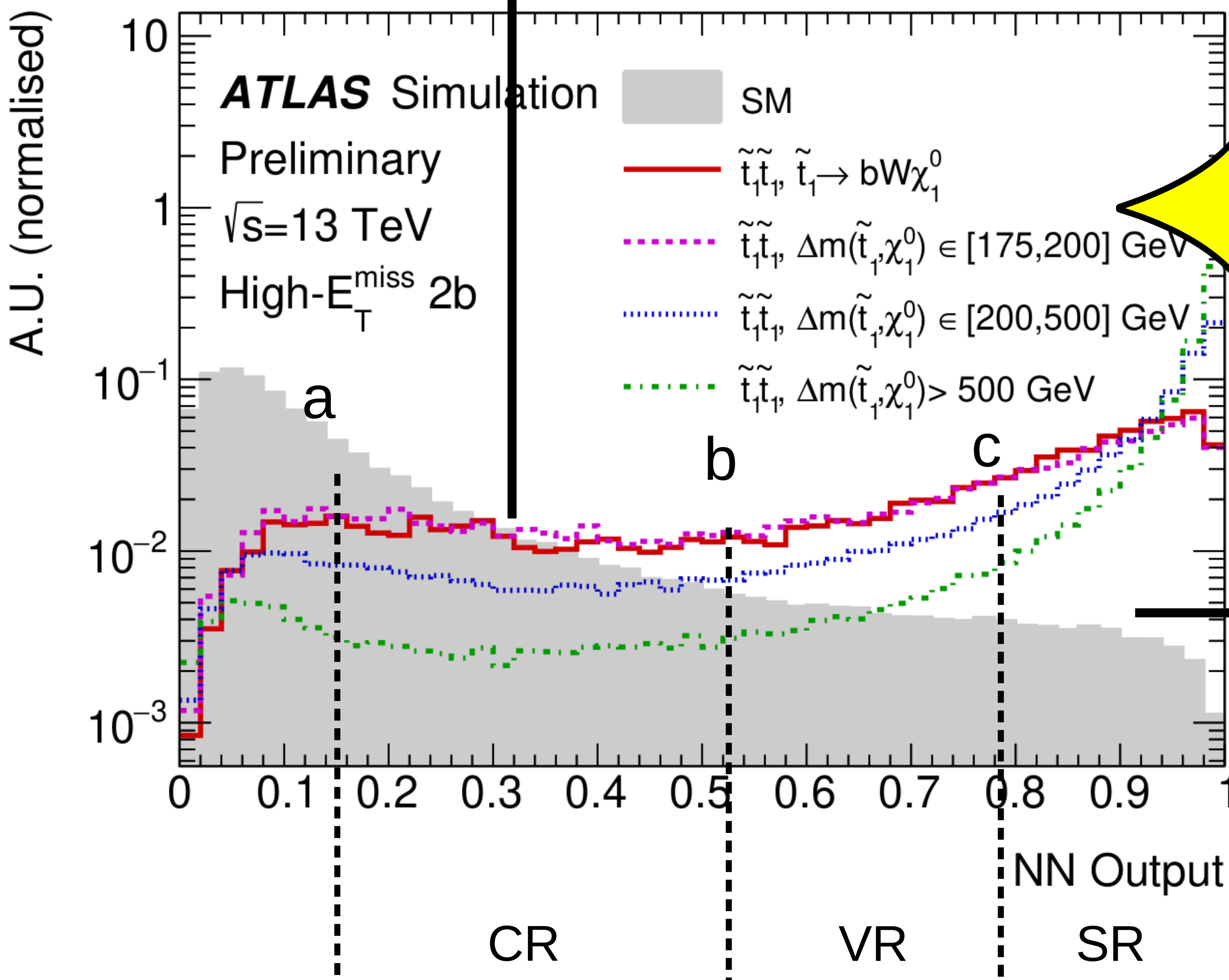
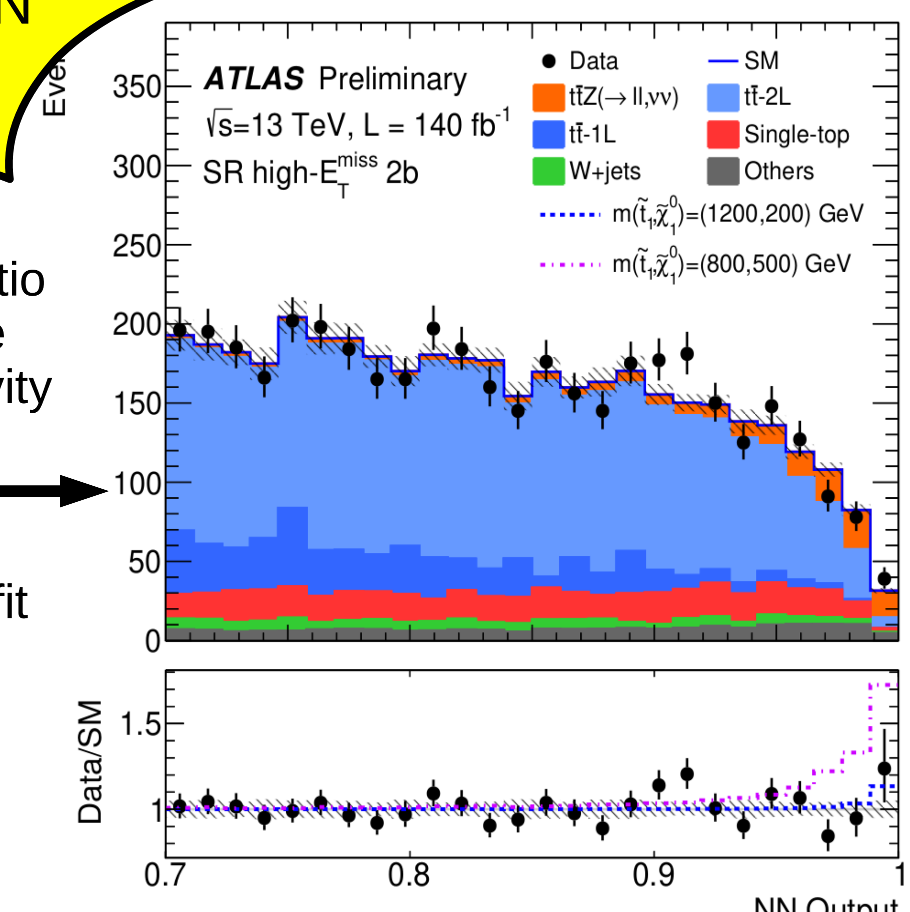




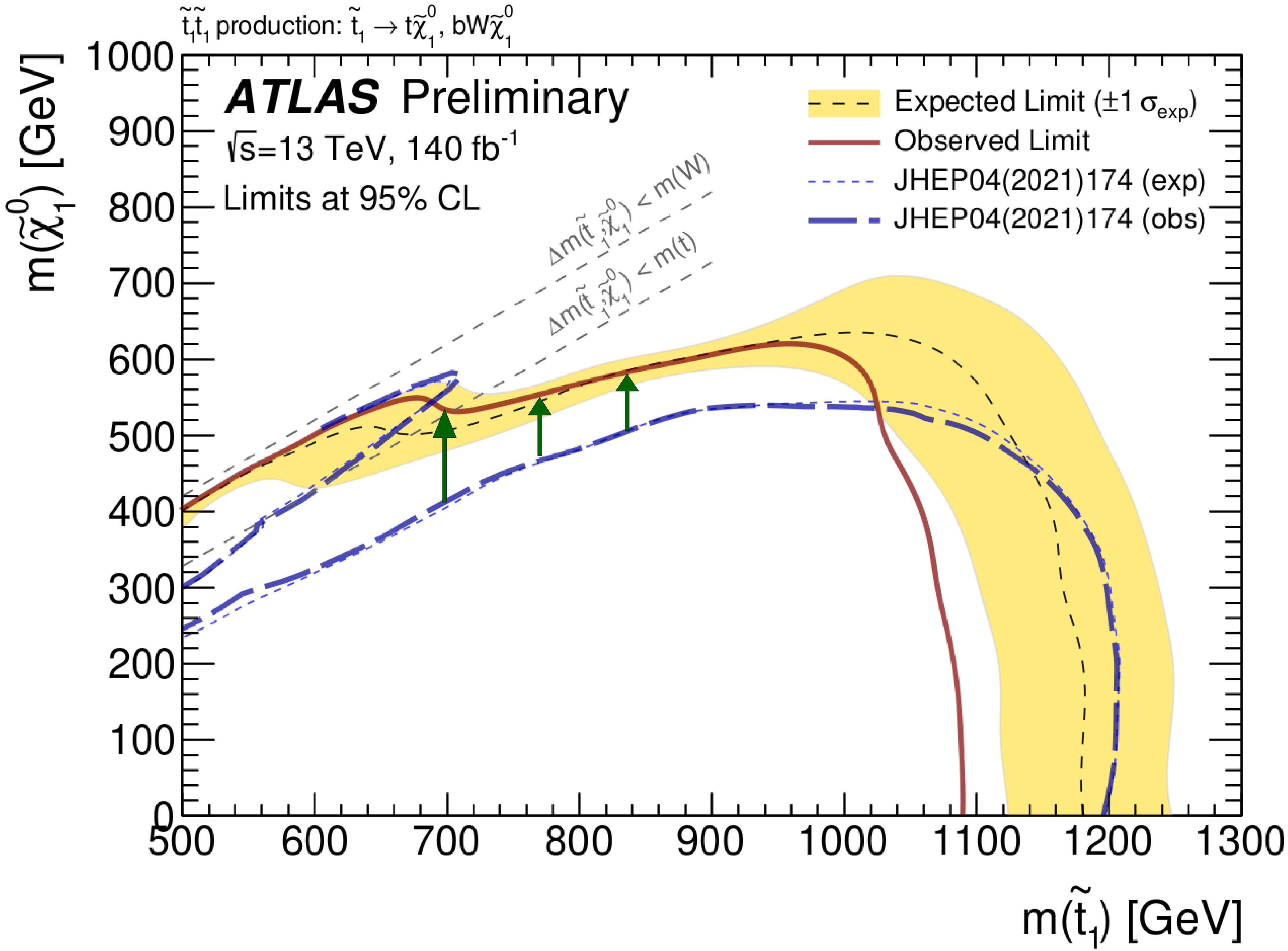
Sensitive to different signals with different NN distributions

Changing S/B ratio used to achieve maximum sensitivity

With a multi-bin fit



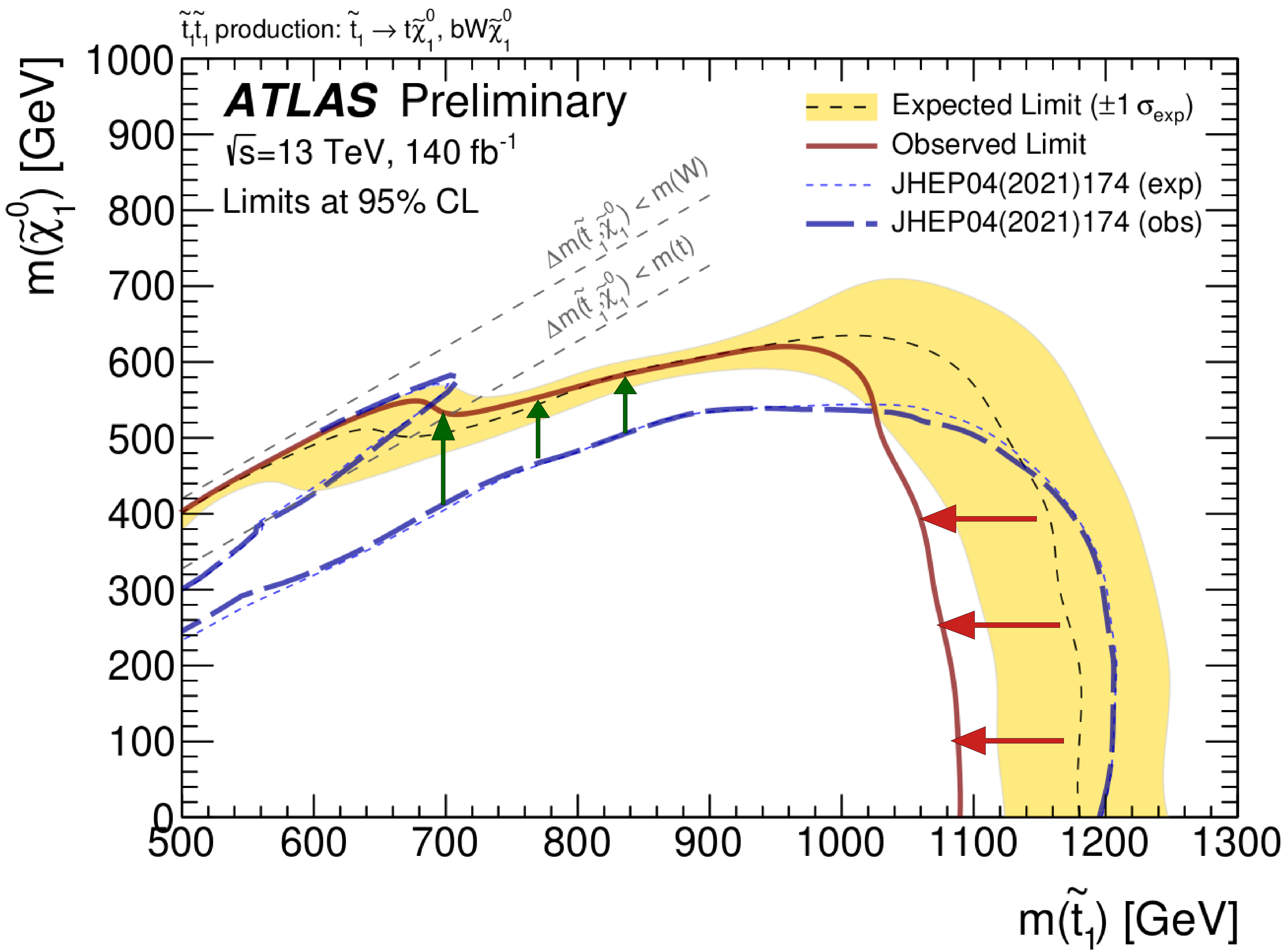
Results – SUSY Exclusion Plot



Multi-bin CRs and SRs used per region in all 8 regions

- Able to exclude the valley and even sensitive to the 3-body region (these models were not used in training).

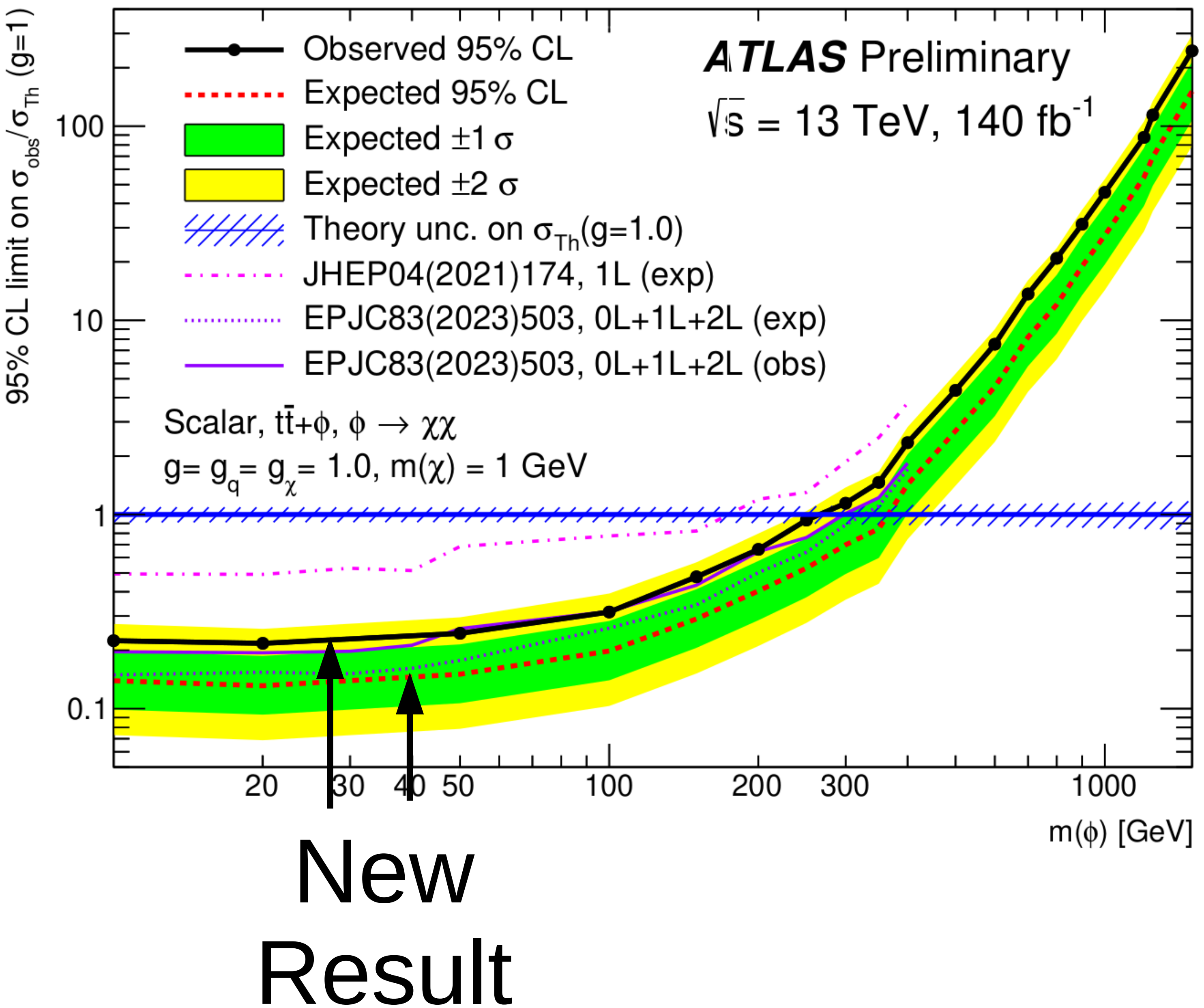
Results – SUSY Exclusion Plot

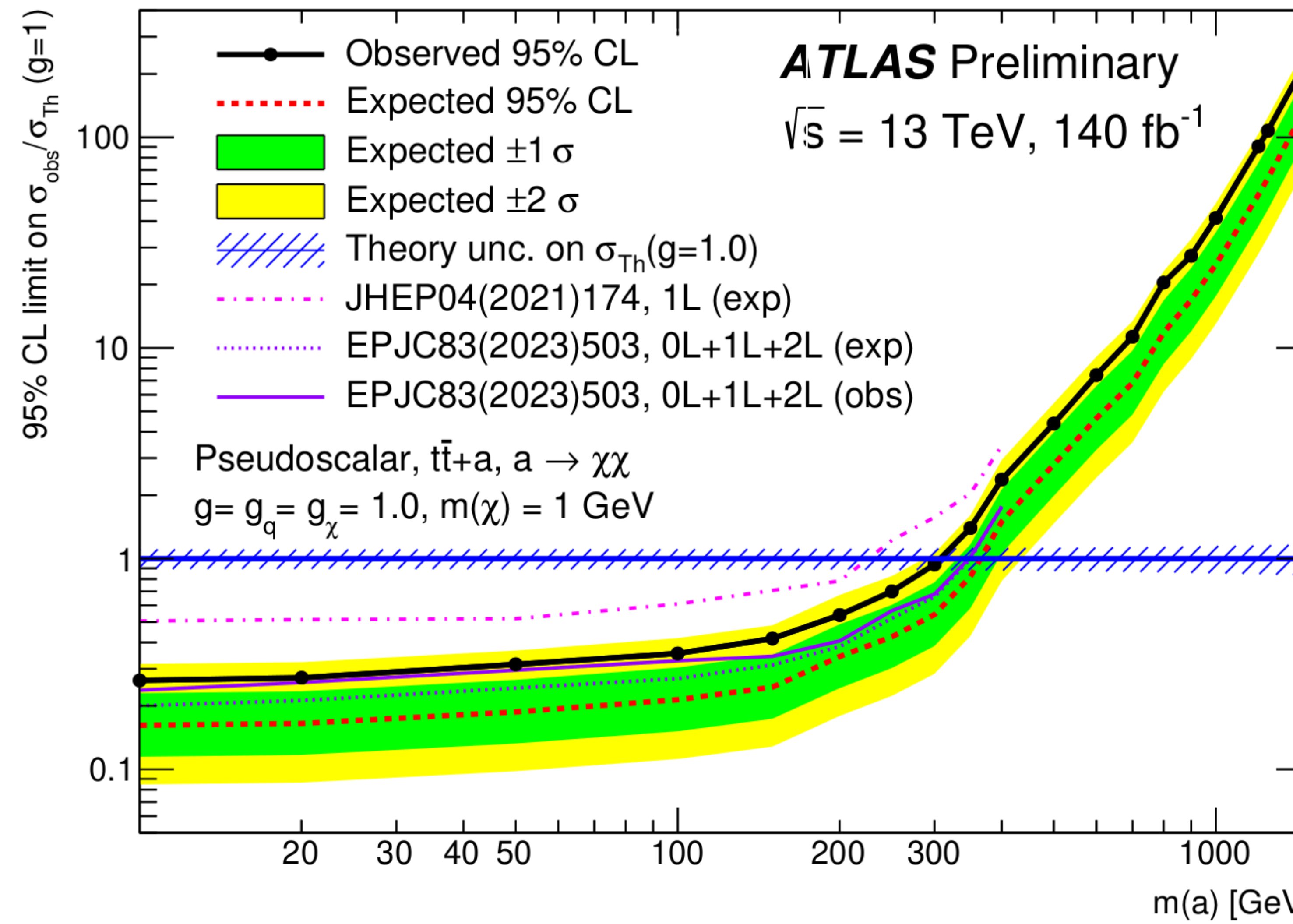


Multi-bin CRs and SRs used per region in all 8 regions

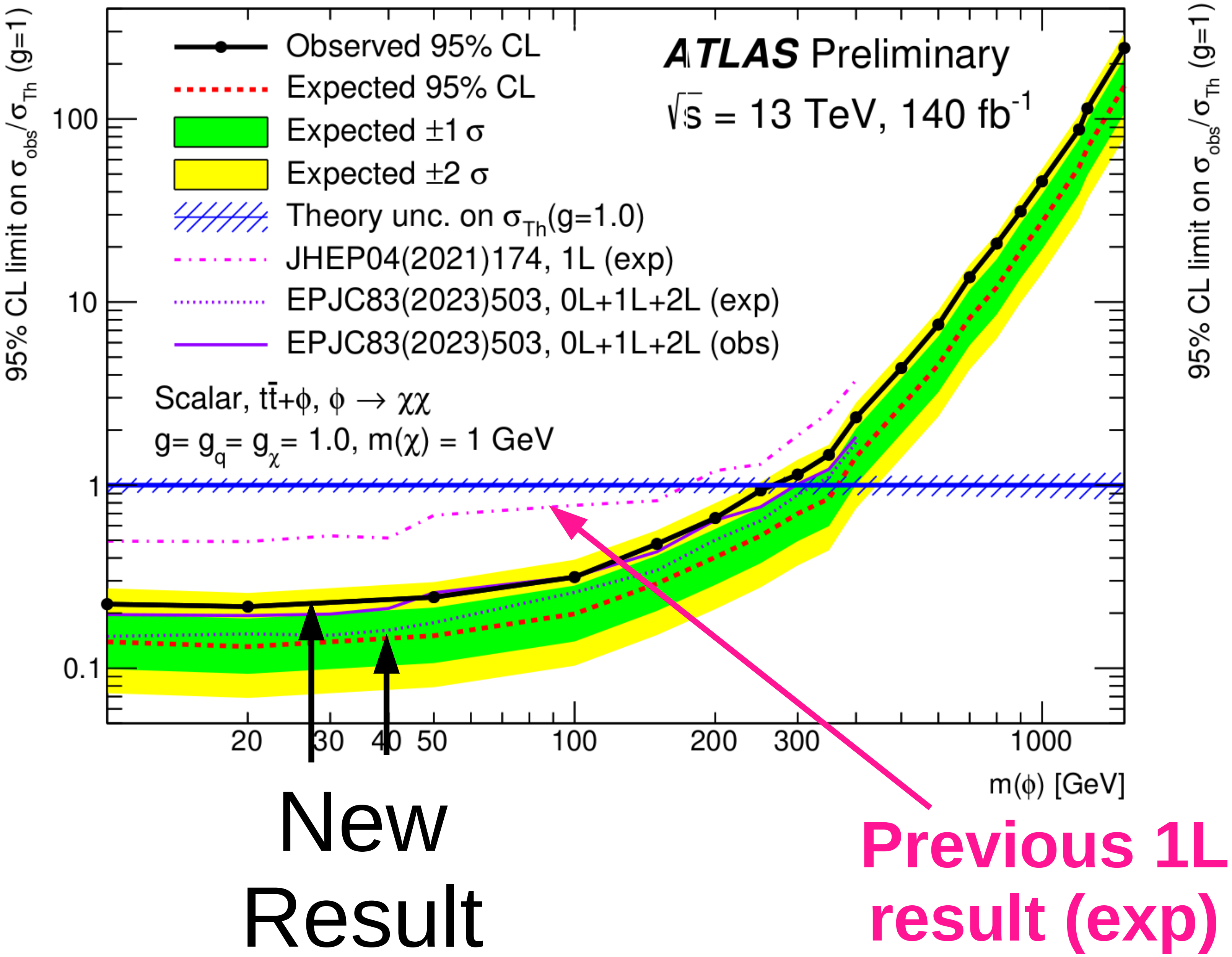
- Able to exclude the valley and even sensitive to the 3-body region (these models were not used in training).
- The difference between the observed and the expected limits at high stop mass is due to the excess of events in data at high NN output values in the highMET2b and boosted2b regions

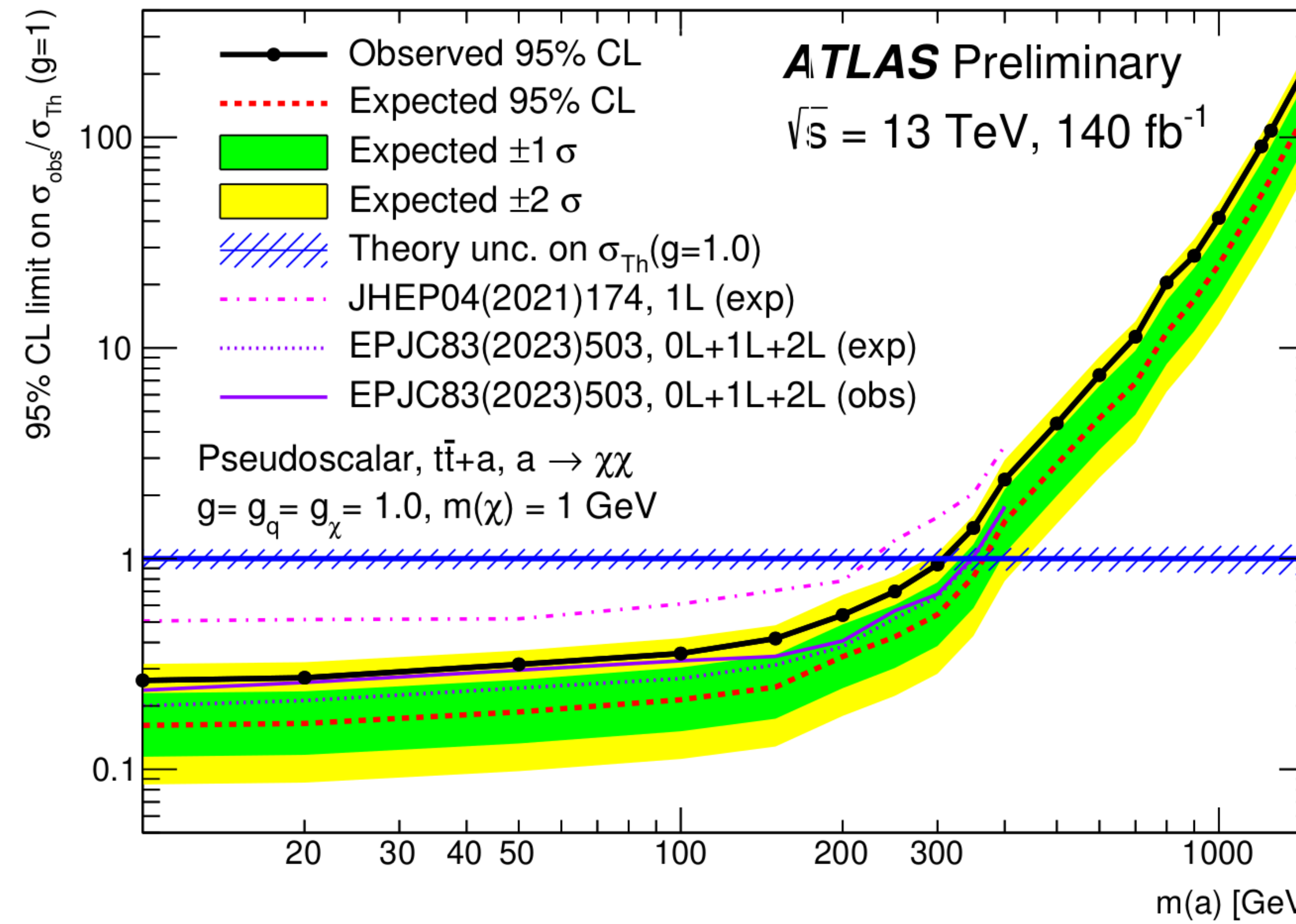
Results – Dark Matter Exclusion Plot



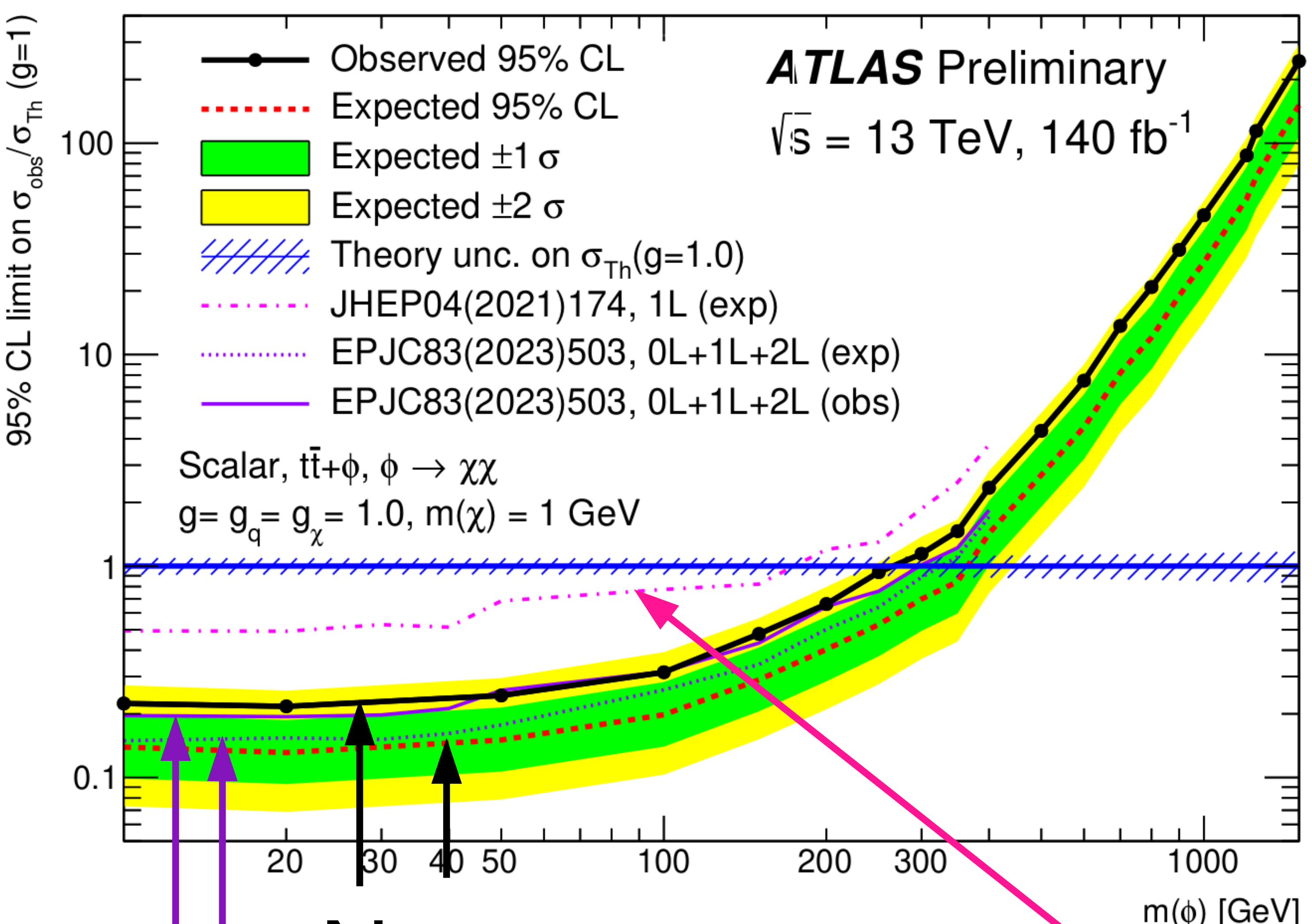


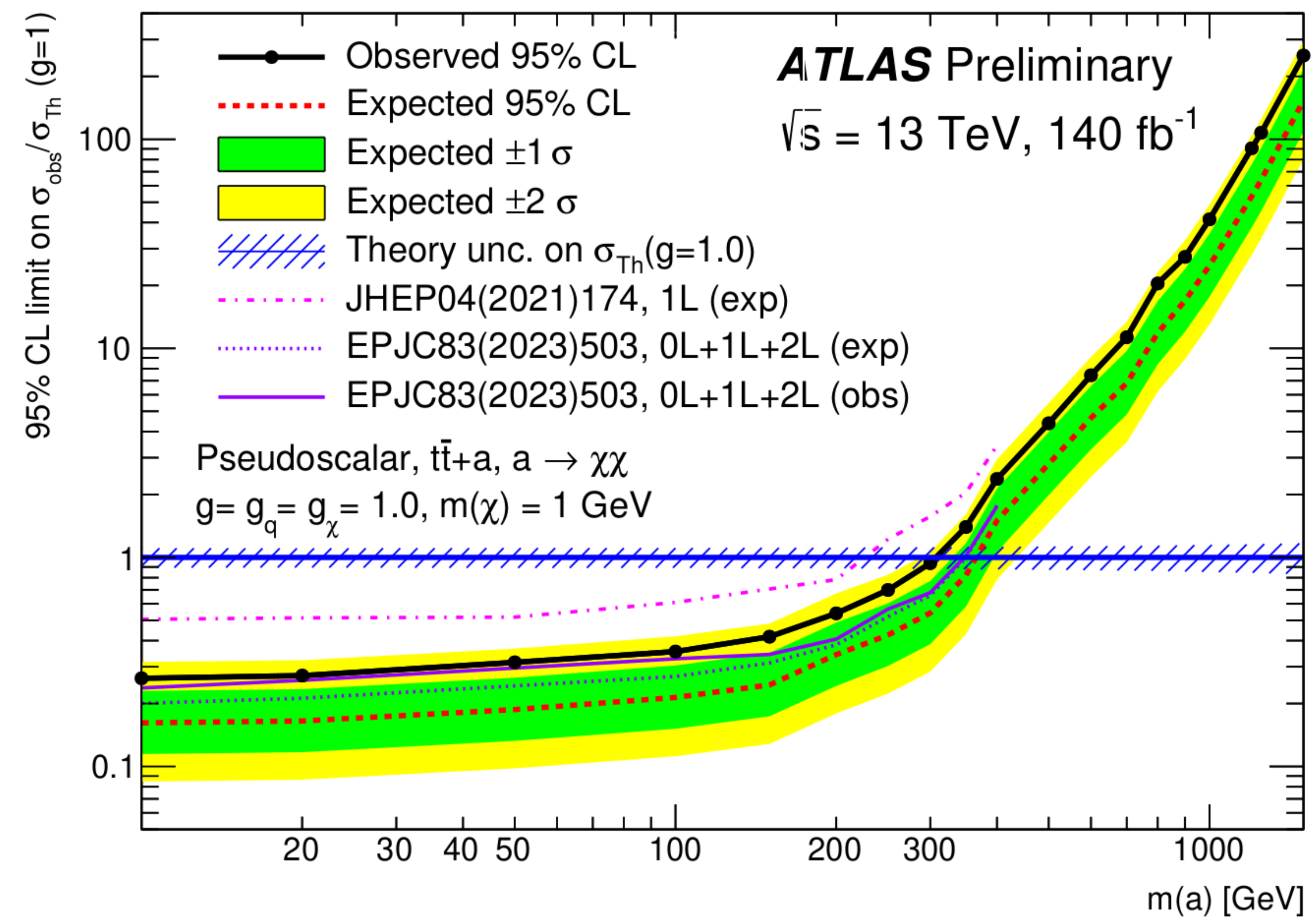
Results – Dark Matter Exclusion Plot





Results – Dark Matter Exclusion Plot





New Result

Previous 1L result (exp)

Previous DMtt (0L-1L-2L) combination

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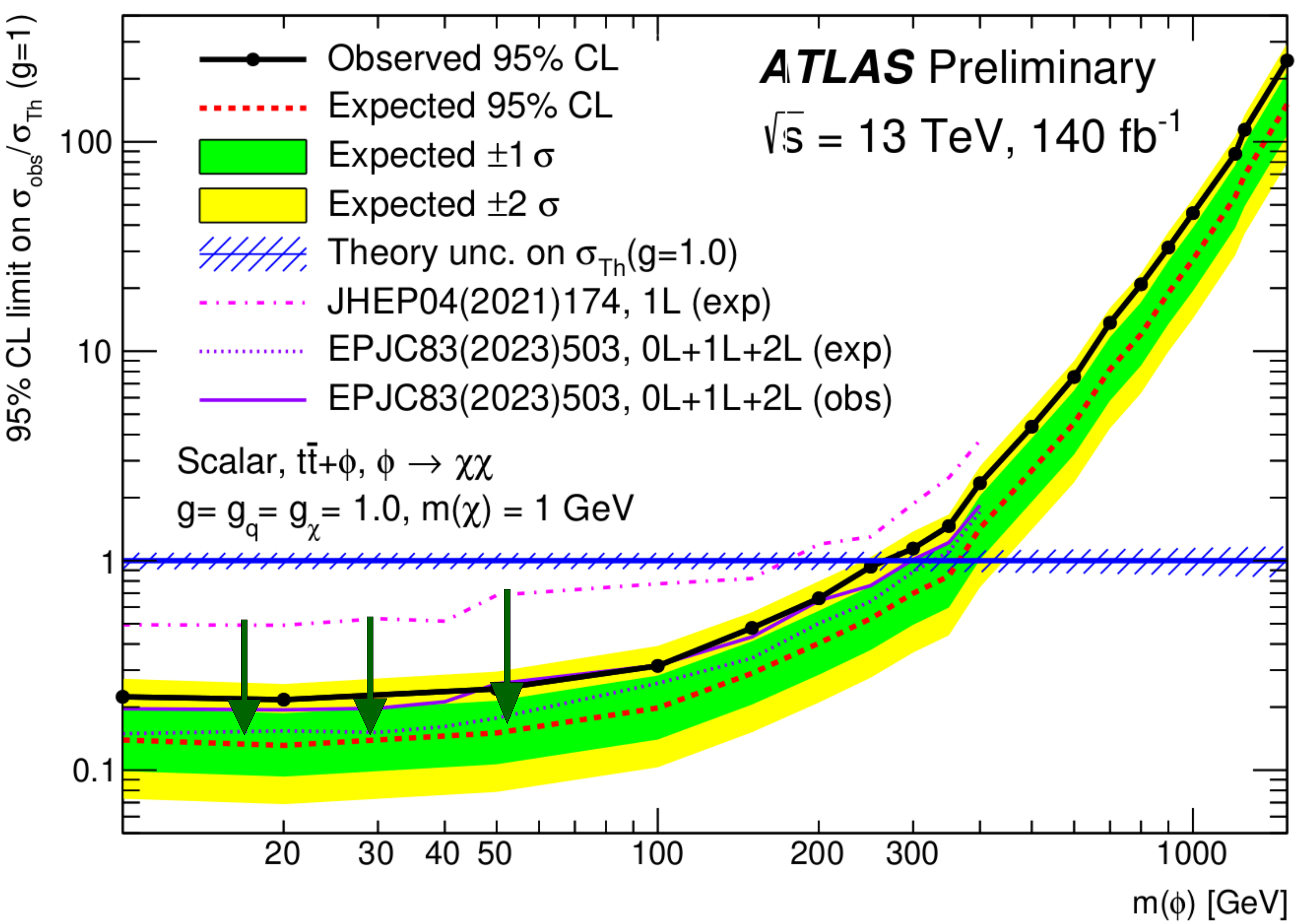

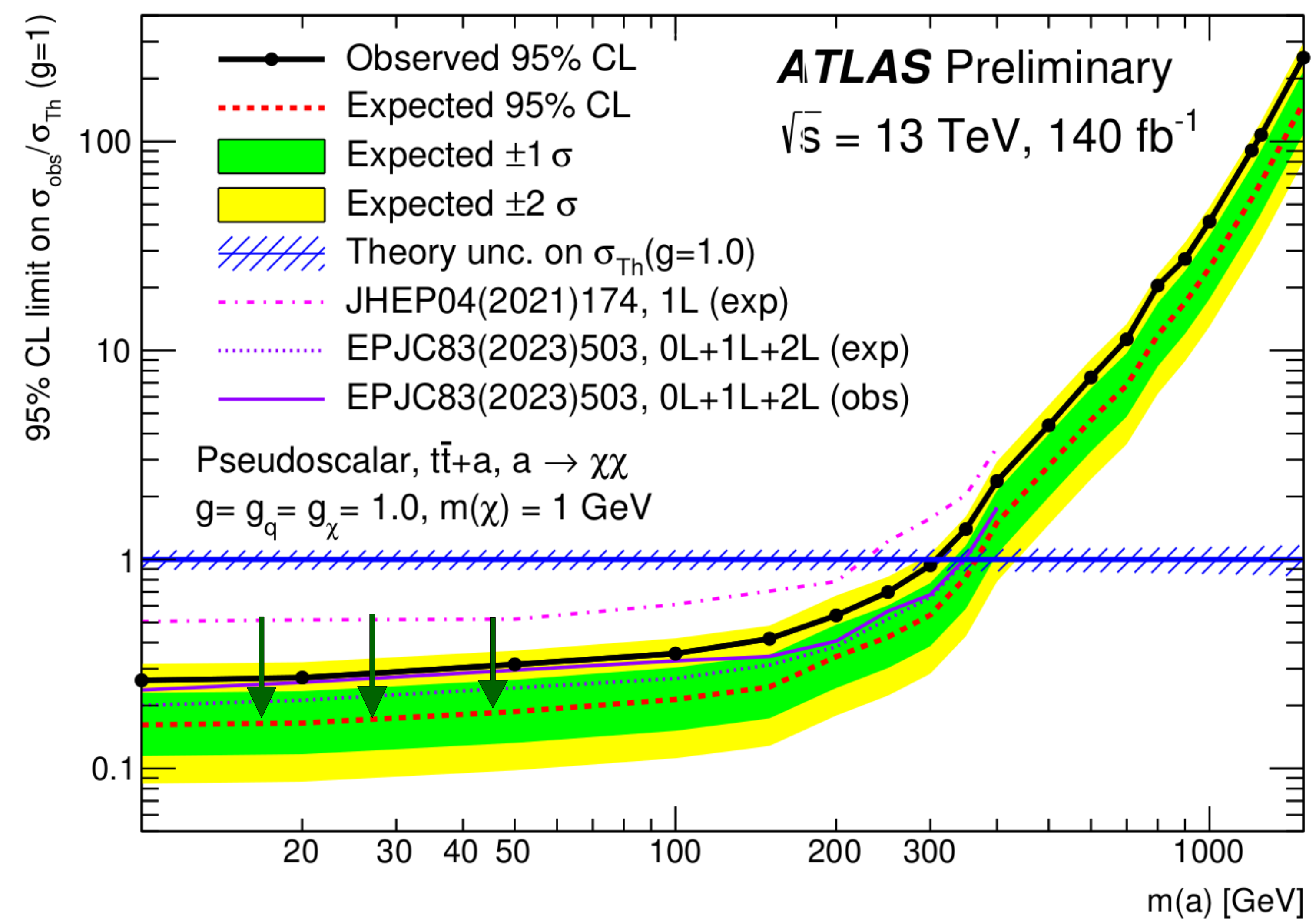

- **Expected Result: The 2nd wave expected 1L result is much improved compared to the 1st wave expected 1L combination result**

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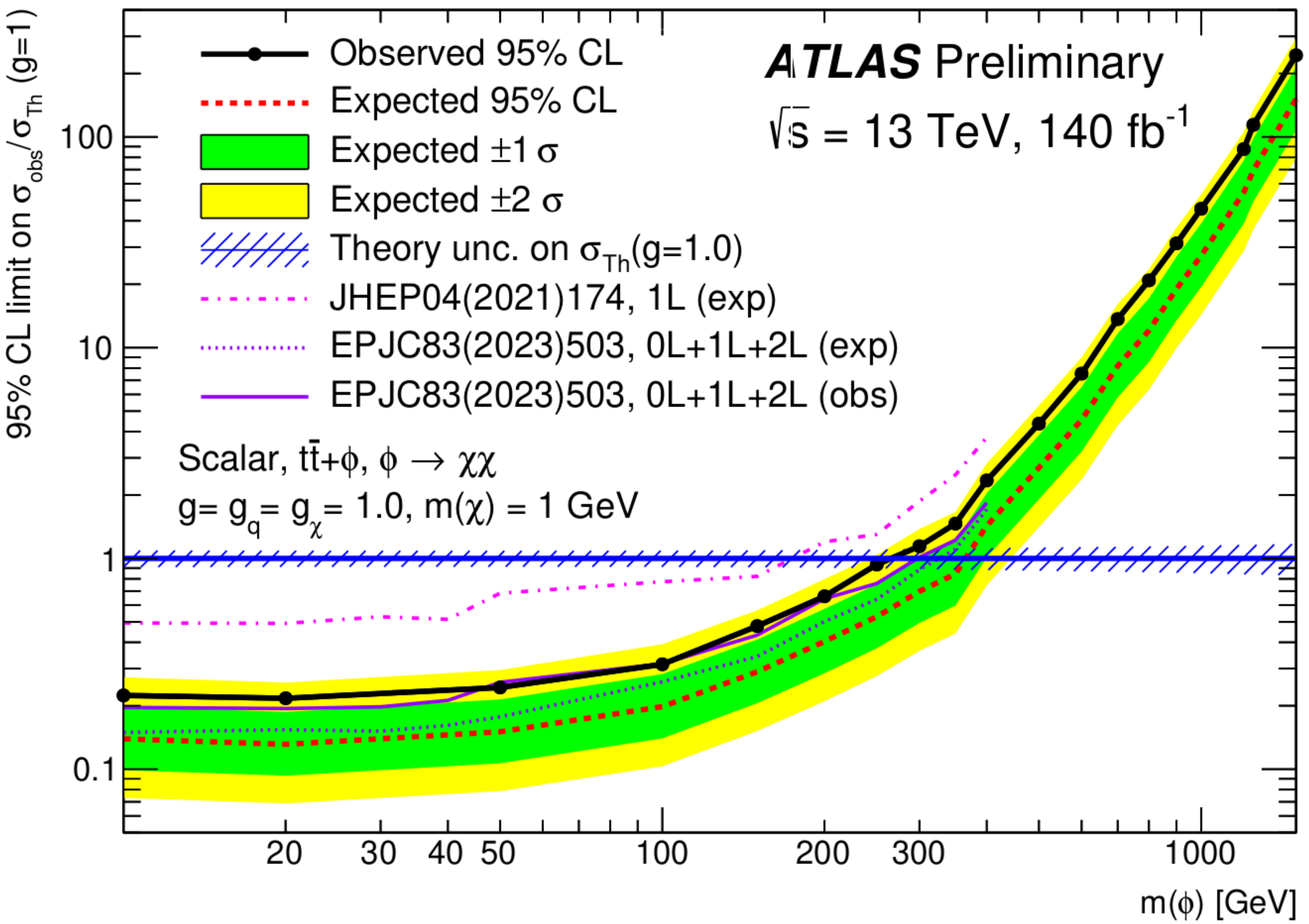

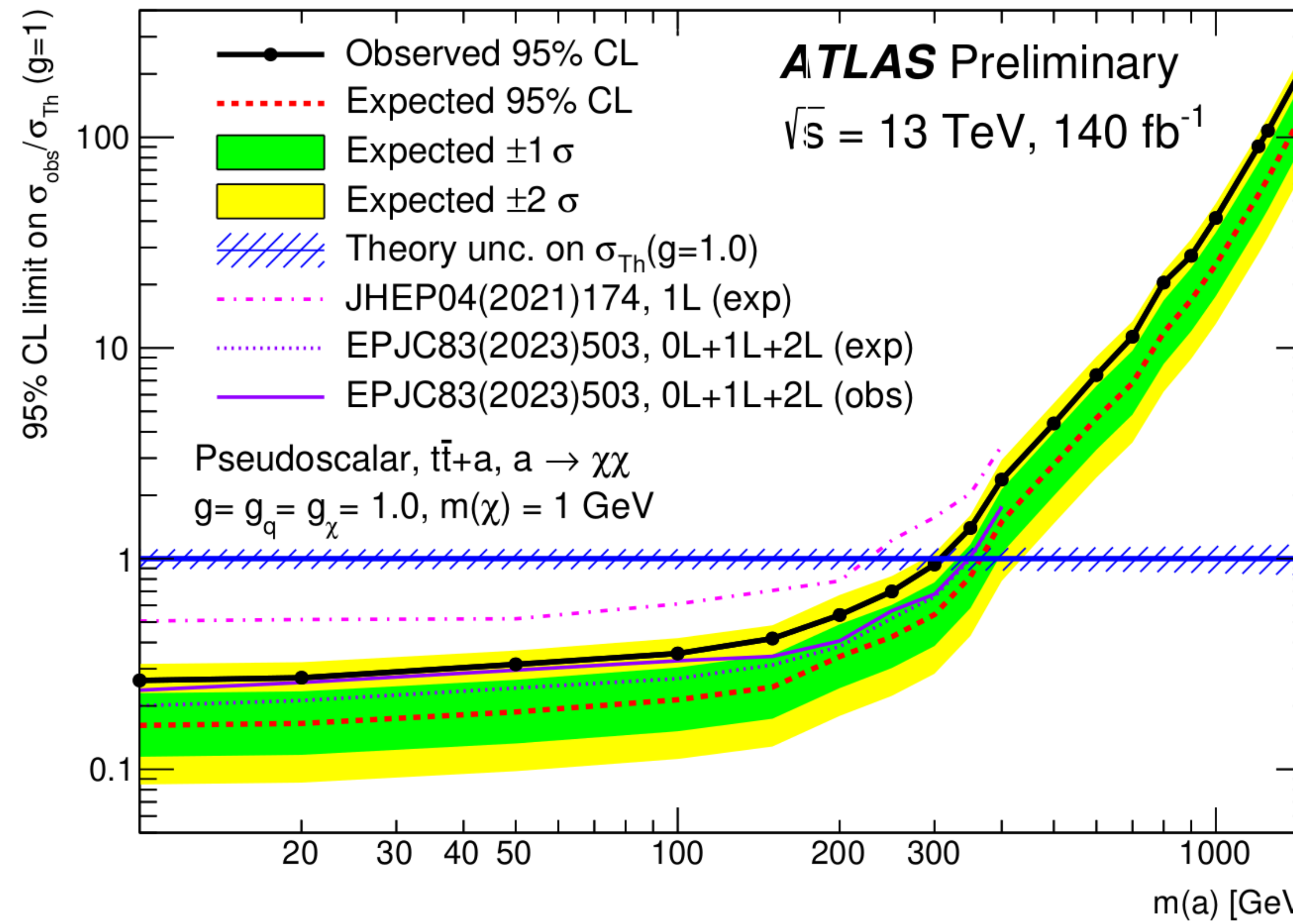

- **Expected Result: The 2nd wave expected 1L result is much improved compared to the 1st wave expected 1L combination result**
- **Observed Result: Our 2nd wave 1L observed result coincides with the 0L+1L+2L combination from the 1st wave analysis**

Conclusion

$t\bar{t}+E_T^{miss}$ (1L)

A **New and Improved!** search for new phenomena with top quark pairs in final states with 1L (electron or muon), jets, and large missing transverse momentum is performed.

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- Inclusive event categories
- Simple DNN!!
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SUSY

Sensitivity to stop pair production for in "valley" region is significantly improved.

DM

The sensitivity to spin-0 mediators decaying to dark matter is also improved across all the parameter space

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$tc+E_T^{miss}$ (0L) A **First time ever!** search for new mixed final states with top and charm quarks is performed.

- Dedicated c-tagging strategy
- DNN for compressed signals
- DNN for boosted tops
- Multi-bin optimized SRs

→

1st time limits are set for stop and neutralino masses for maximal mixing in a nMFV MSSM scenario

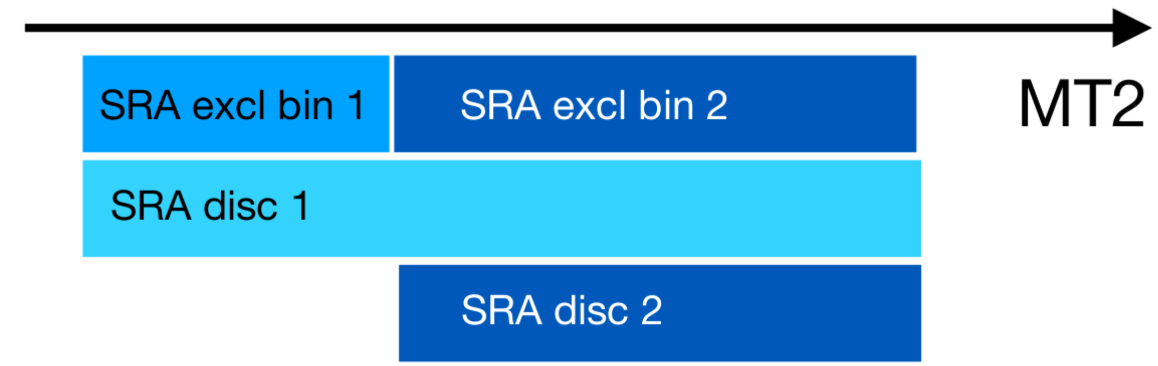
The largest deviation reaches a significance of 1.8σ in the SRs targeting the bulk and intermediate region of phase space.

Thank You!

Backup

Results – Model independent Fit

- Discovery Regions are built from SR bins
  - For each bin in SR, lower cut is retained and upper-cut removed → corresponding discovery region (1 bin)



Signal channel	$\langle\epsilon\sigma\rangle_{obs}^{95}$[fb]	S_{obs}^{95}	S_{exp}^{95}	CL_B	$p(s=0)$ (Z)
SRA ($m_{T2}(j^b_{R=1.0}, c) \geq 450$ GeV)	0.10	14	$8.4^{+3.5}_{-1.9}$	0.94	0.02 (2.1)
SRA ($m_{T2}(j^b_{R=1.0}, c) \geq 575$ GeV)	0.07	9	$5.8^{+2.9}_{-1.2}$	0.89	0.04 (1.7)
SRB ($m_T(j, E_T^{miss})_{close} \geq 100$ GeV)	0.17	24	$16.8^{+7.0}_{-5.2}$	0.85	0.09 (1.3)
SRB ($m_T(j, E_T^{miss})_{close} \geq 150$ GeV)	0.16	23	$13.2^{+5.5}_{-3.6}$	0.95	0.03 (1.9)
SRB ($m_T(j, E_T^{miss})_{close} \geq 400$ GeV)	0.08	11	$6.5^{+3.1}_{-1.6}$	0.92	0.04 (1.8)
SRC ($m_T(j, E_T^{miss})_{close} \geq 100$ GeV)	0.09	13	$9.6^{+4.2}_{-2.1}$	0.76	0.22 (0.76)
SRC ($m_T(j, E_T^{miss})_{close} \geq 150$ GeV)	0.09	12	$8.7^{+3.9}_{-1.9}$	0.81	0.15 (1.0)
SRC ($m_T(j, E_T^{miss})_{close} \geq 300$ GeV)	0.08	11	$7.8^{+3.6}_{-1.7}$	0.83	0.13 (1.1)
SRC ($m_T(j, E_T^{miss})_{close} \geq 500$ GeV)	0.02	3	$4.0^{+2.4}_{-1.4}$	0.13	0.50 (0.00)
SRD ($m_{eff} \geq 750$ GeV, $m_T(j, E_T^{miss})_{close} \geq 200$ GeV)	0.15	20	$18.5^{+8.4}_{-5.1}$	0.58	0.50 (0.00)
SRD ($m_{eff} \geq 1000$ GeV, $m_T(j, E_T^{miss})_{close} \geq 200$ GeV)	0.10	14	$13.7^{+3.5}_{-5.7}$	0.52	0.50 (0.00)
SRD ($m_{eff} \geq 1250$ GeV)	0.30	41	37^{+12}_{-11}	0.60	0.50 (0.00)
SRD ($m_{eff} \geq 1500$ GeV)	0.09	13	$14.6^{+6.3}_{-4.1}$	0.36	0.50 (0.00)
SRD ($m_{eff} \geq 1750$ GeV)	0.09	12	$9.1^{+3.9}_{-1.9}$	0.77	0.20 (0.84)
SRD ($m_{eff} \geq 2000$ GeV)	0.05	7	$5.6^{+3.0}_{-1.2}$	0.70	0.26 (0.64)

Largest Differences between data and SM

Compressed scenario very consistent with SM prediction