Searches for strong production of supersymmetric particles with the ATLAS detector

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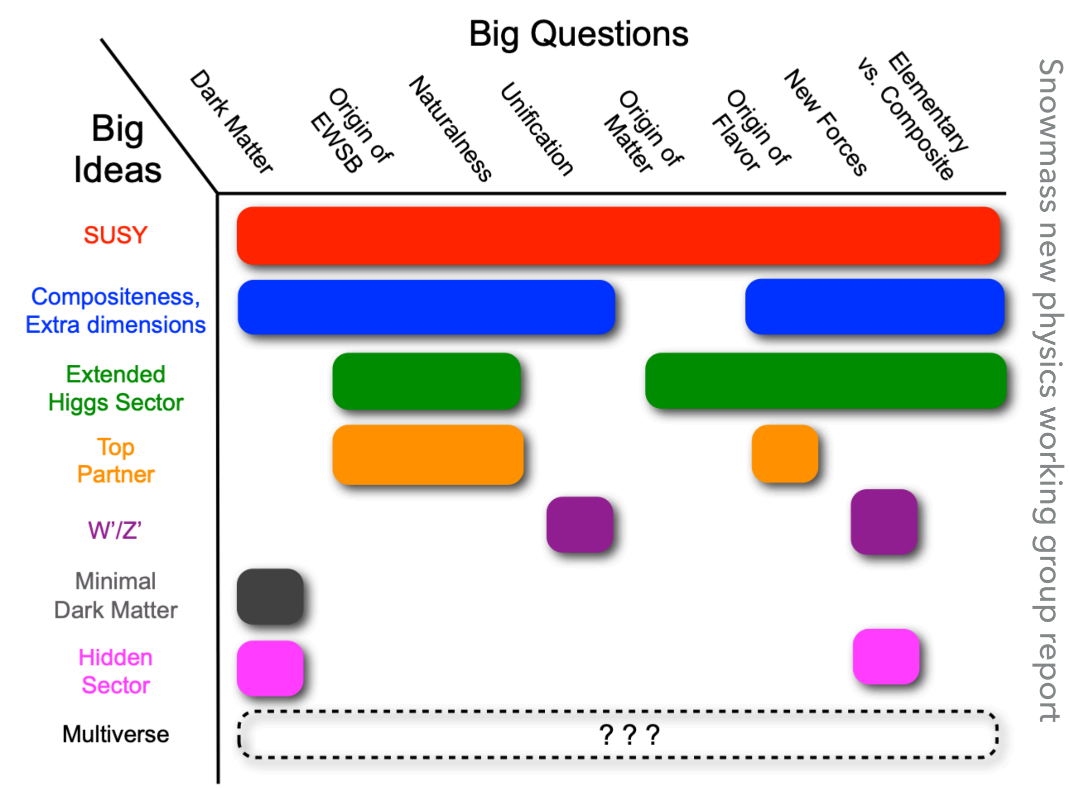
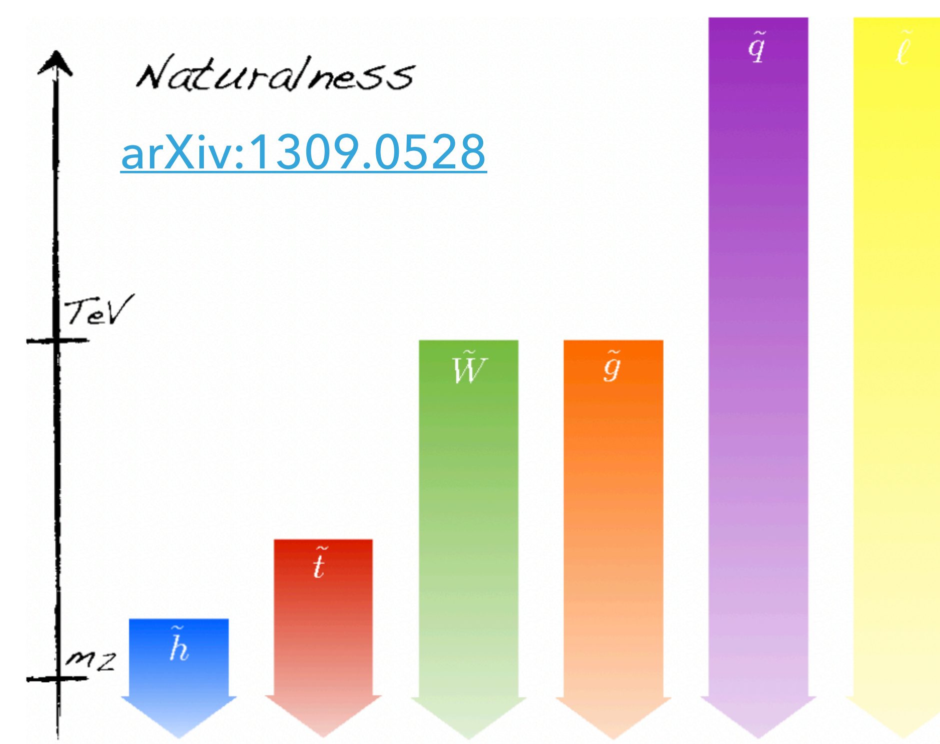
Motivation:

- Despite the huge success of the SM theory, physics beyond SM is strongly motivated:
    - hierarchy problem, dark matter, quantum description of gravity, the GUT e.t.c…
- Supersymmetry (SUSY) extend the SM and connect SM Fermions & Bosons with their super partner into a set of super-multiplets
    - Solving hierarchy problem if only soft breaking of supersymmetry (mass constraint within TeV scale, could be produced in the LHC)
    - Provide stable DM candidate (Lightest-SUSY-Particle) if R-parity is conserved (RPC)

$$P_R = (-1)^{3B+L+2S}$$

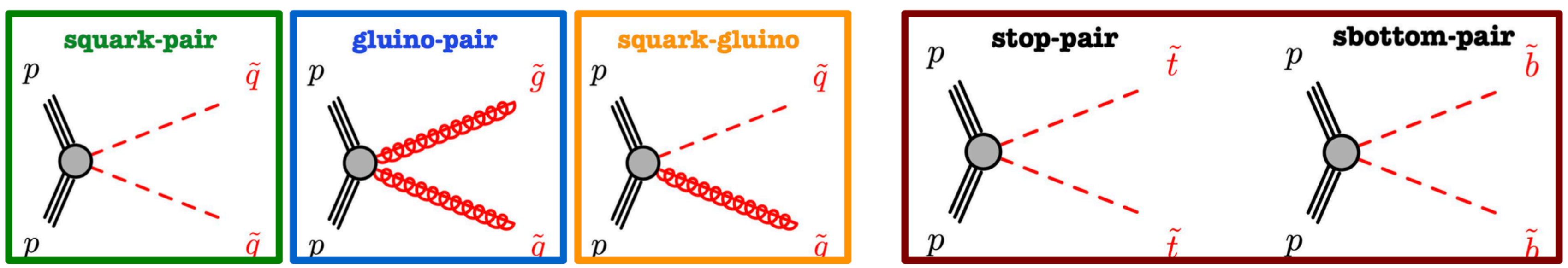
    - Including graviton & gravitino needed for the GUT…

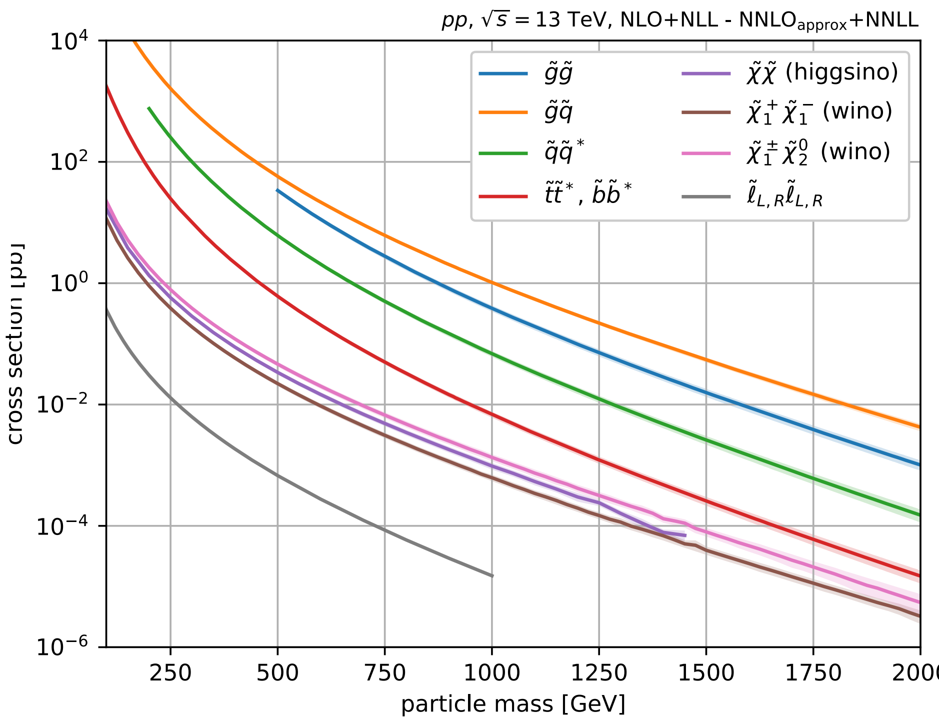




Status of SUSY search in ATLAS:

- ~40 analysis teams covering all aspects of SUSY scenarios and models including **Strongly produced SUSY**, EWK produced SUSY, RPC, RPV and LLP…
  - This talk will only cover the latest **searches of strong production** of gluino or squark^{3rd} in RPC or RPV scenarios
  - SUSY searches in EWK productions will be covered by Takuya's talk
- Four main strong production mechanisms at LHC:





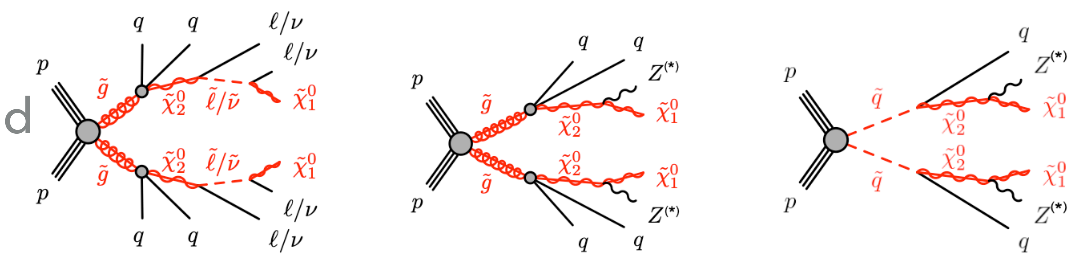
- Strong production of SUSY has relatively large production cross-sections which could probe higher mass regions but comes with more bkg contamination
- Only simplified models are used considering a few particles and decoupling the other to higher scale

Status of Strong SUSY search in ATLAS:

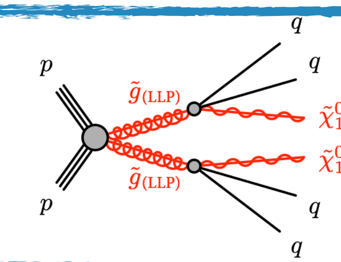
- With R-parity conserved, the LSP is stable and only interacting weakly with other SM particles, providing a suitable candidate of DM (WIMP) and large E_T^{miss} as signature
- With R-parity violated, the LSP could decay to SM particles via RPV sector leading to a final state with only SM particles:

$$W = W_{MSSM} + W_R;\ W_R = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_iL_iH_2$$

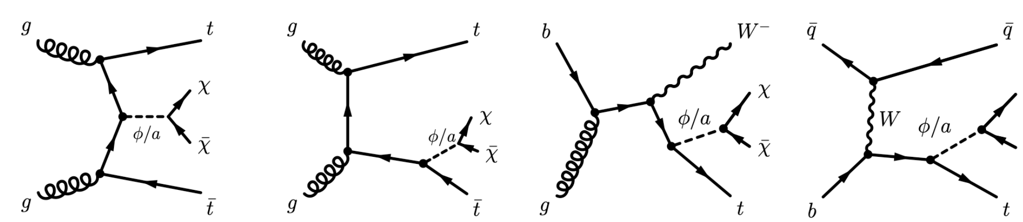
- In this talk will cover:
  - Searches for new phenomena in events with two leptons, jets, and missing transverse momentum in 139 fb^{-1} of $\sqrt{s} = 13$ TeV pp collision in the ATLAS detector [2L2J]



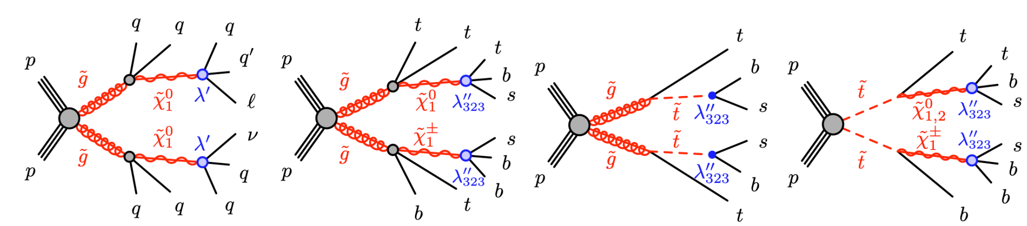
  - Search for heavy, long-lived, charged particles with large ionization energy loss in pp collision at $\sqrt{s} = 13$ TeV using the ATLAS experiment and the full Run 2 dataset [Pixel dE/dX]



  - Constraints on spin-0 dark matter mediators and invisible Higgs decays using ATLAS 13 TeV pp collision data with two top quarks and missing energy in the final state [DM_tt combination]

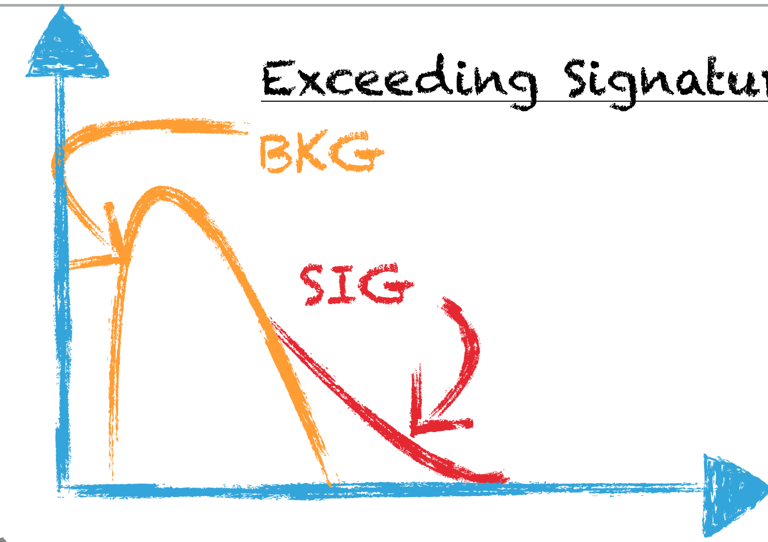


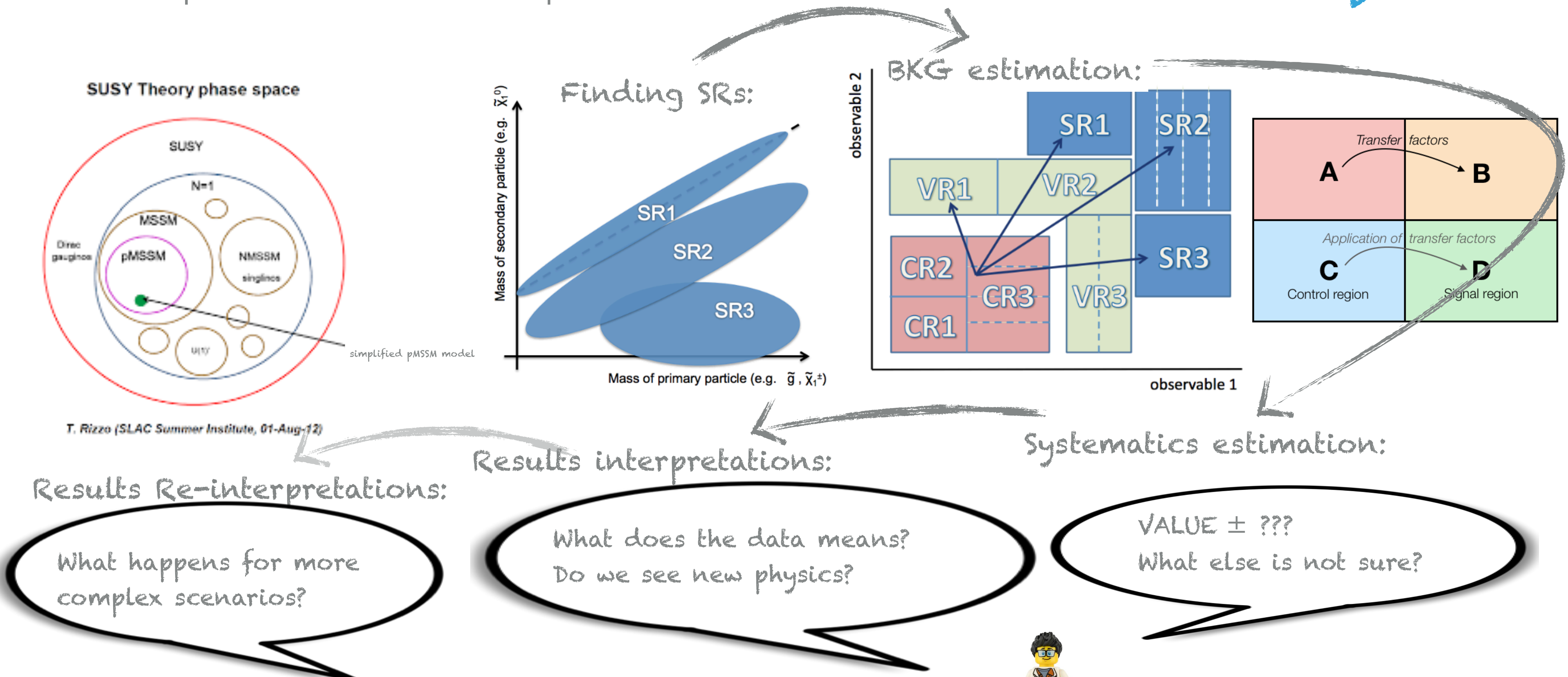
  - [BackUP] Search for R-parity-violating supersymmetry in a final state containing leptons and many jets with the ATLAS experiment using $\sqrt{s} = 13$ TeV proton-proton collision data [Rpv1L]



General strategy on Strong SUSY searches:

- SUSY is an exceeding signature
- Find SUSY at the tail of the sensitive observables
- Search with simplified SUSY models:
  - Relevant parameters are varied only
  - Decoupled with all the other SUSY particles

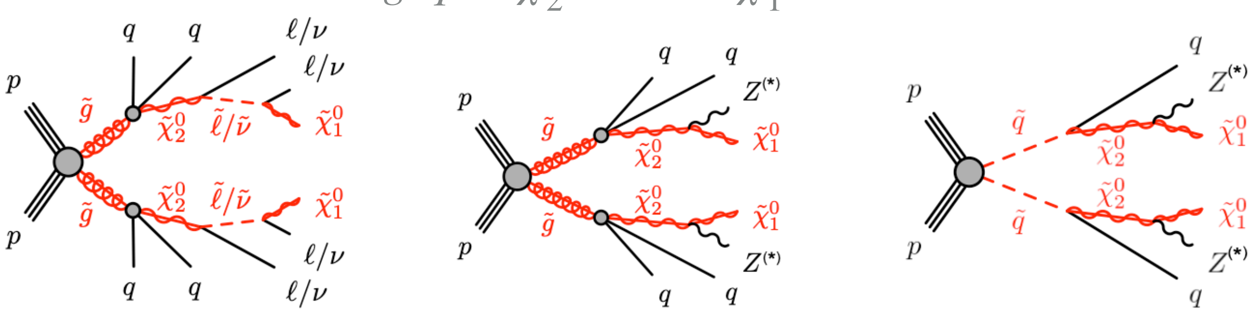




ATLAS EXPERIMENT

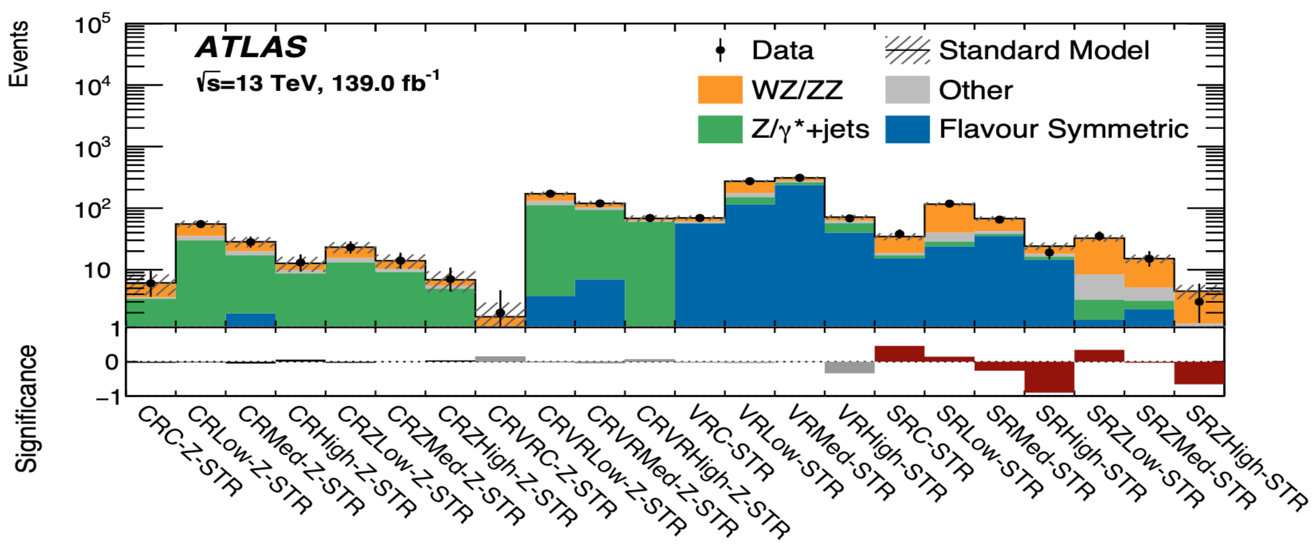
2L2J:

$\tilde{g}/\tilde{q} \rightarrow \tilde{\chi}_2^0 \rightarrow \ell^+\ell^-\tilde{\chi}_1^0$

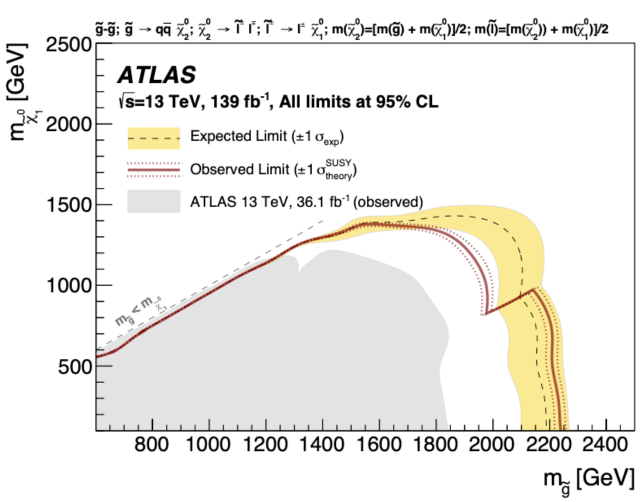


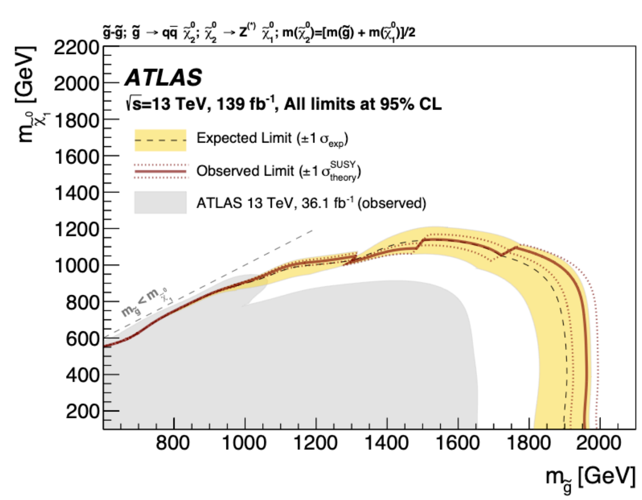
[arXiv: 2204.13072 (sub to JHEP)](arXiv: 2204.13072)

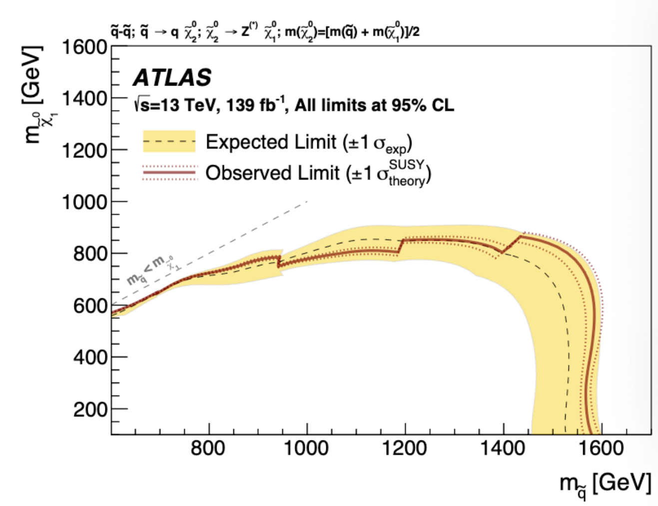
Process	Z/γ^* + jets and Drell–Yan	Top	Diboson	FNP	VVV	Other Top	Higgs
Strong	CR	DD	MC/DD	DD	MC	MC	MC



- **Signal regions:**
  - 4 inclusive SRs defined targeting different $\tilde{g} - \tilde{\chi}_1^0$ mass splitting
  - SRs are then further binned with $m_{\ell^\pm\ell^\mp}$ due to the kinematic endpoint of the target signal
- **BKG estimation:**
  - Z/γ^*+jets: normalized in CRs defined by inverting the $\Delta\phi(jet_{1,2}, E_T^{miss})$
  - Flavour-Symmetric process ($t\bar{t}$, $W^\pm W^\mp$): Using $e\mu$ data in CRs and corrected by the divergence between $e\mu$ and $ee/\mu\mu$
  - FNP: estimated via MxM

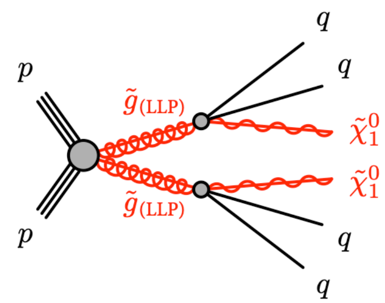






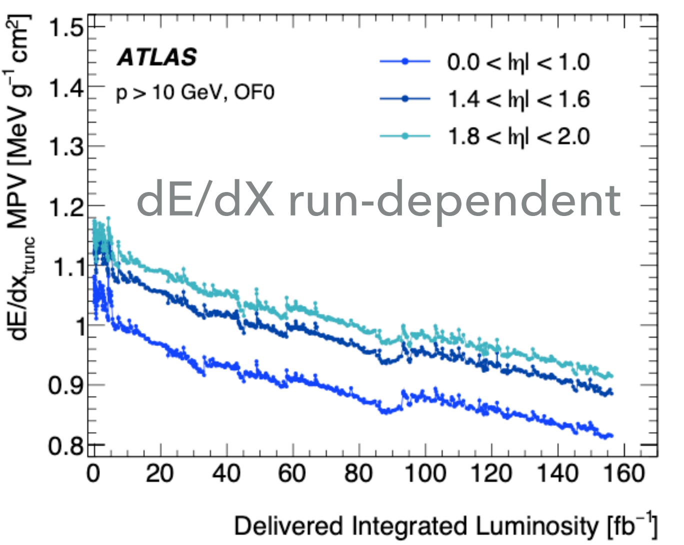
- No significant excess observed
- $m(\tilde{g})/m(\tilde{q})$ up to 2250/1550 GeV got excluded
- Got 400/300 GeV improvement compared to previous results

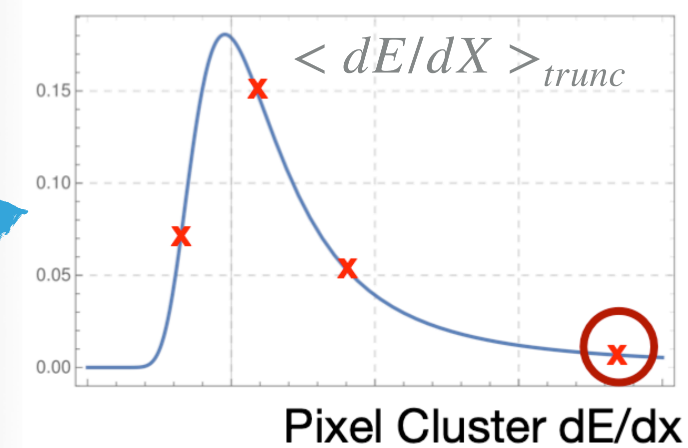
Pixel dE/dX:

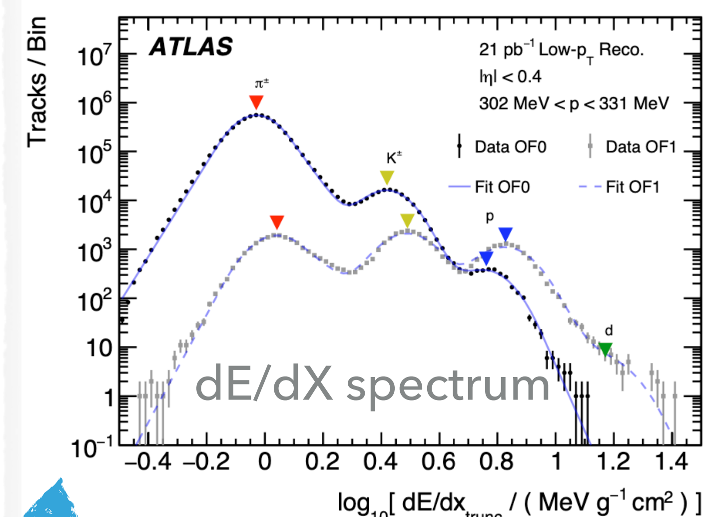


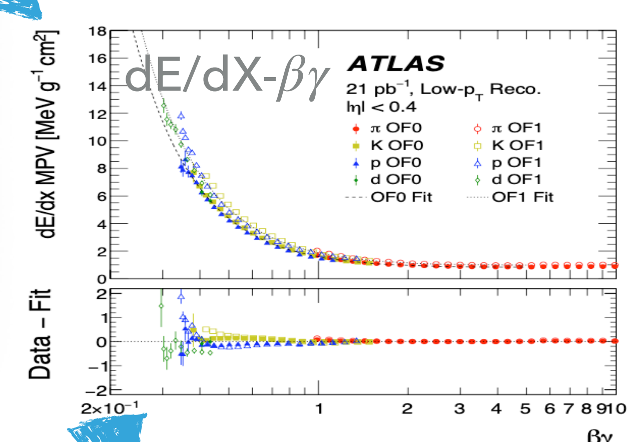
[arXiv: 2205.06013 (sub to JHEP)](https://arxiv.org/abs/2205.06013)

- **Signal model:** Long-lived $\tilde{g}$ formed into a charged R-hardon
- **General approach:**
  - Bethe-Bloch relation:
    - Connected the dE/dX with $\beta\gamma$ of one particle
    - With $\overrightarrow{p}$ known, mass can be derived from the measurement of the dE/dX
  - Extracting the dE/dX: $< dE/dX >_{trunc}$, averaging of the dE/dX along the tracks with the highest one excluded
  - dE/dX calibration: $< dE/dX >_{corr}$
    - calibrate tracks at different $|\eta|$ and times to the reference run due to the detector geometry and the radiation damage
  - dE/dX-$\beta\gamma$ calibration:
    - performed in the range $0.3 < \beta\gamma < 5$, special low-pile-up dataset
    - in a narrow low momentum slice, dE/dX spectrum can be resolved
    - use template fitting to known particles in individual p/eta slices to get a function that translates dE/dX to $\beta\gamma$



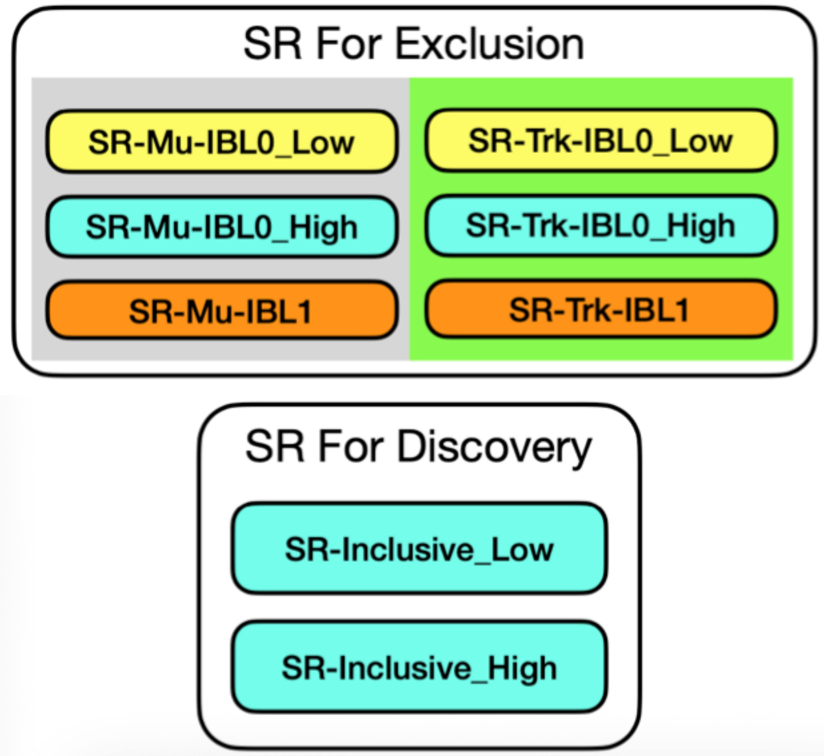


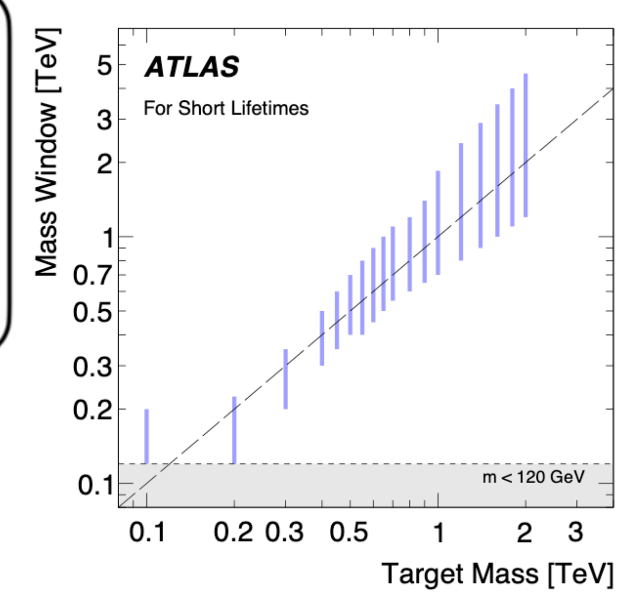




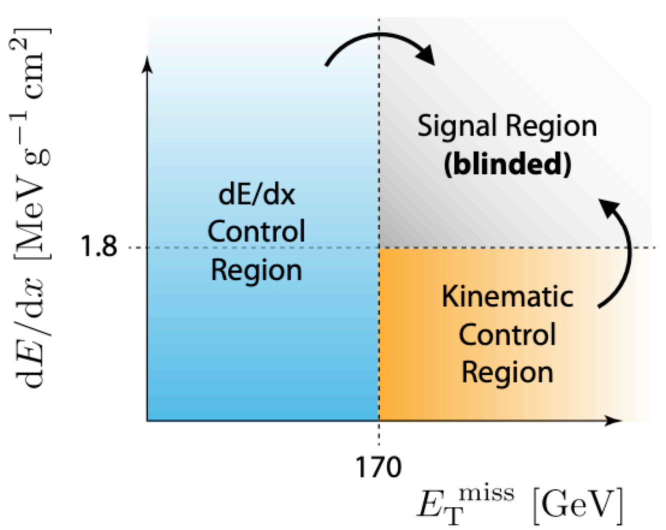
Pixel dE/dX:

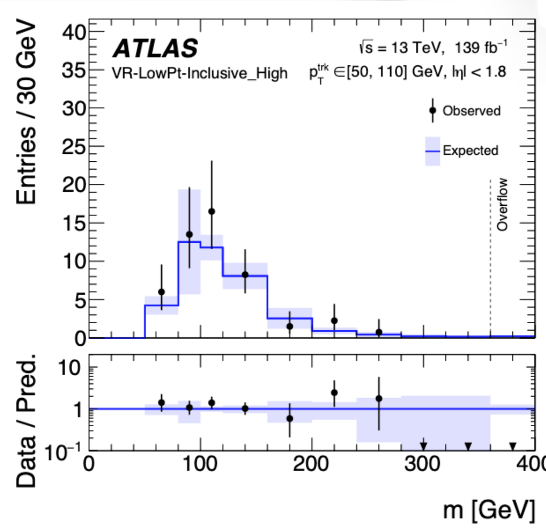
- **Signal regions:** split by dE/dX
  - Exclusion SRs: binned by Mu/track (track identified as a mu or no) and IBL0/IBL1 (overflow bit of the IBL)
    - SR-Mu: sensitive to stable signal events
    - SR-Track: lower bkg
    - SR-IBL1: lower bkg
    - Mass Window:
      - defined for signals with short and long life to optimized the sensitivity
- **BKG estimation:**
  - fully data-driven method applied
    - Sample (pT, η) value from the kinematic template
    - Sample dE/dX value from the corresponding dE/dX template
    - Calculate mass of "toy" track m=p/$\beta\gamma$
  - Validated in corresponding VRs

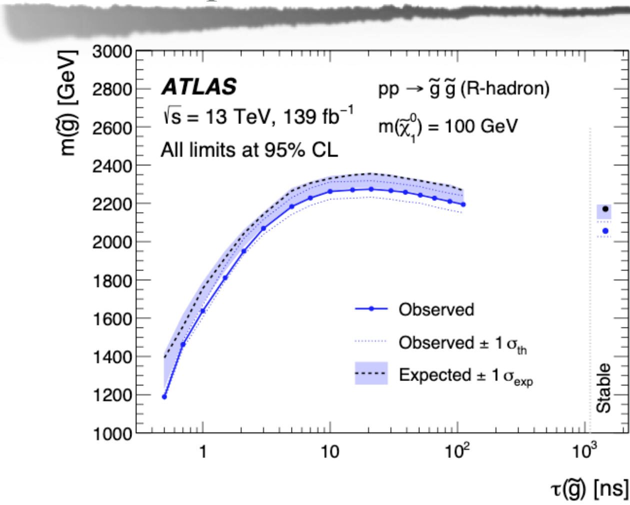


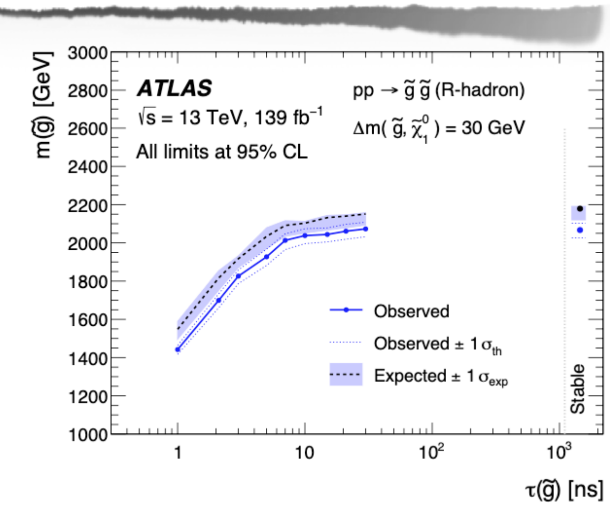


- $m(\tilde{g}) < 2.27$ TeV got excluded with $\tau = 20\ ns$ and $m(\tilde{\chi}_1^0) = 100\ GeV$
- $m(\tilde{g}) < 2.06$ TeV got excluded with $\tau = 30\ ns$ and $\Delta m(\tilde{g}, \tilde{\chi}_1^0) = 30\ GeV$





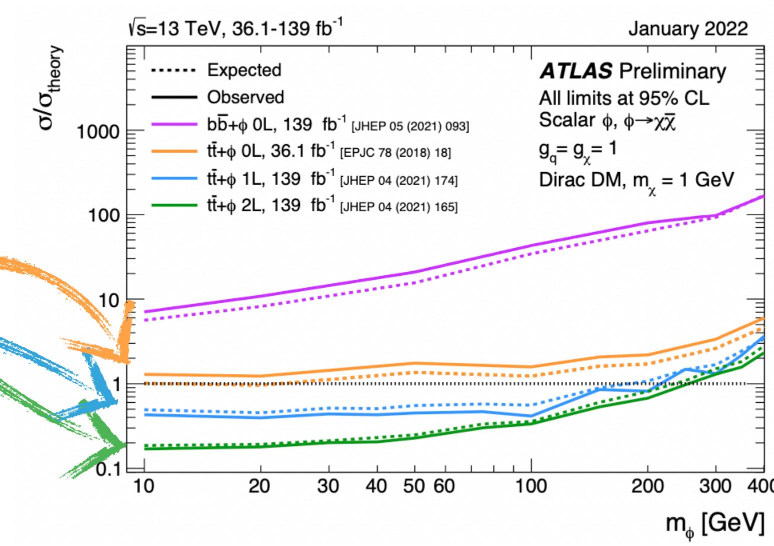


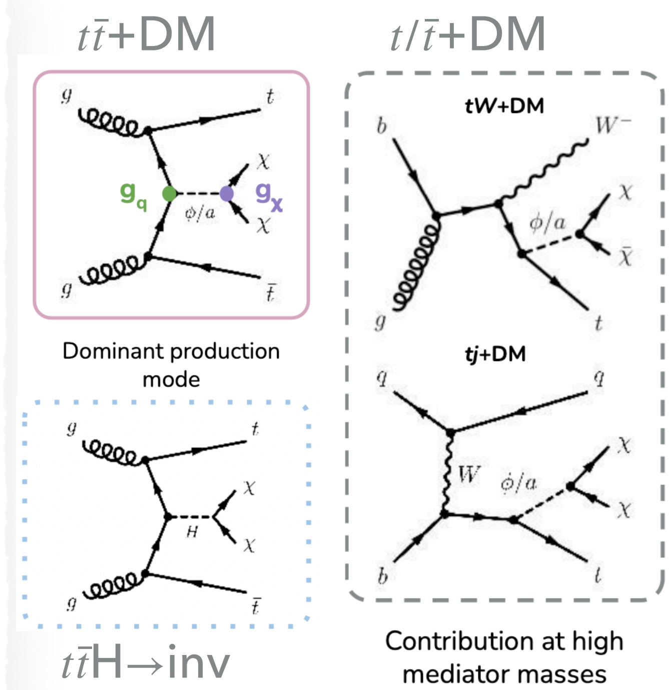


ATLAS EXPERIMENT

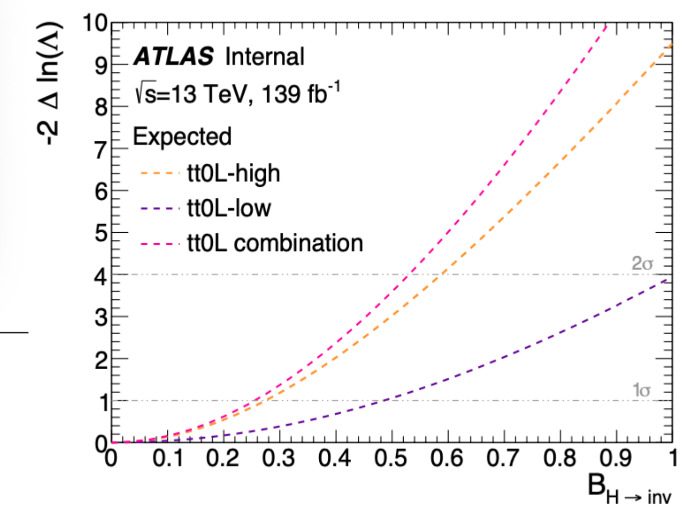
DM_tt combination:

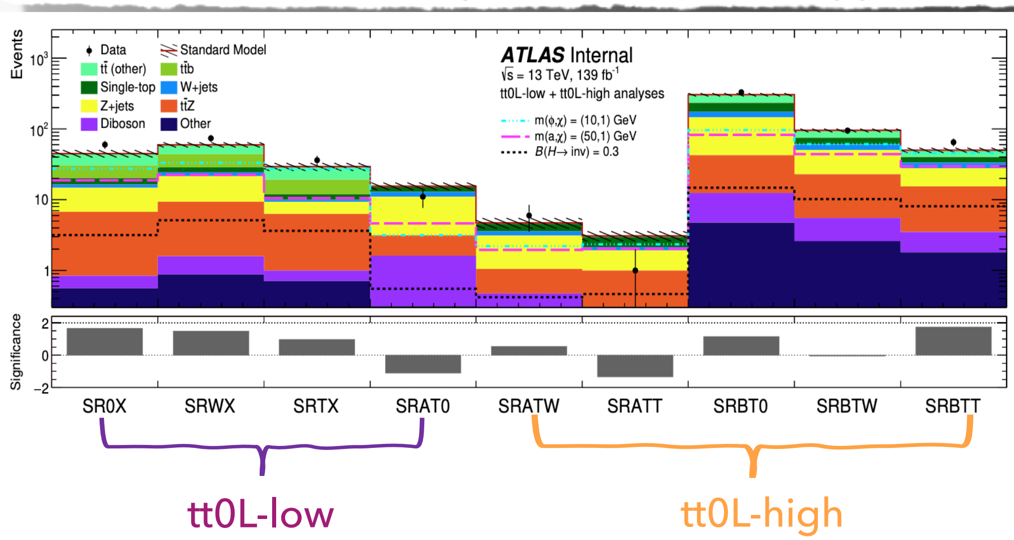
- **Signal models:**
  - WIMPs, Dirac fermion DM candidate (χ), scalar (ϕ)/pseudoscalar (a) mediator
  - Free parameter $m_{\chi'}$, $m_{\phi'}$, benchmark $g_q = g_\chi = 1$ (couplings between ϕ/a with quark is Yukawa-like and with multiplicative factors g_q)
  - Special case → SM 125 GeV Higgs is the mediator
- **Final states:**
  - tt2L: JHEP 04 (2021) 165
  - tt1L: JHEP 04 (2021) 174
  - tt0L -> tt0L-high MET: EPJC 80 (2020) 737
  - tt0L-low MET (newly designed):
    - tt0L extended and improved:
      - sensitivity for low mediator models
        - Improvements up to ~15%(5%) for scalar(pseudo scalar) mediator masses
      - Low improvement at the Higgs mass

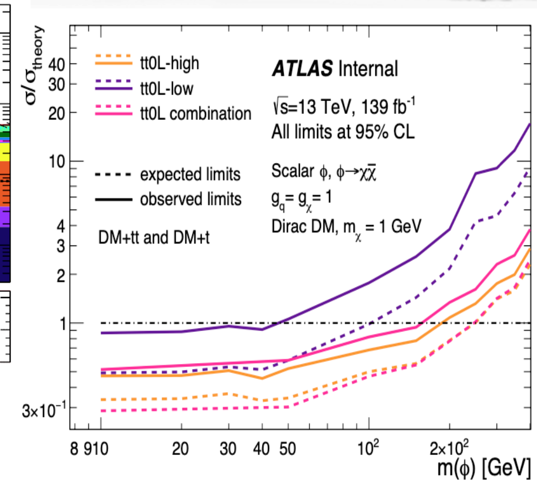


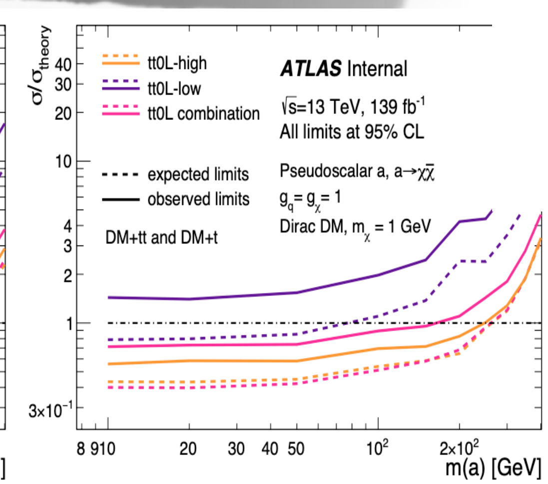


ATLAS-CONF-2022-007



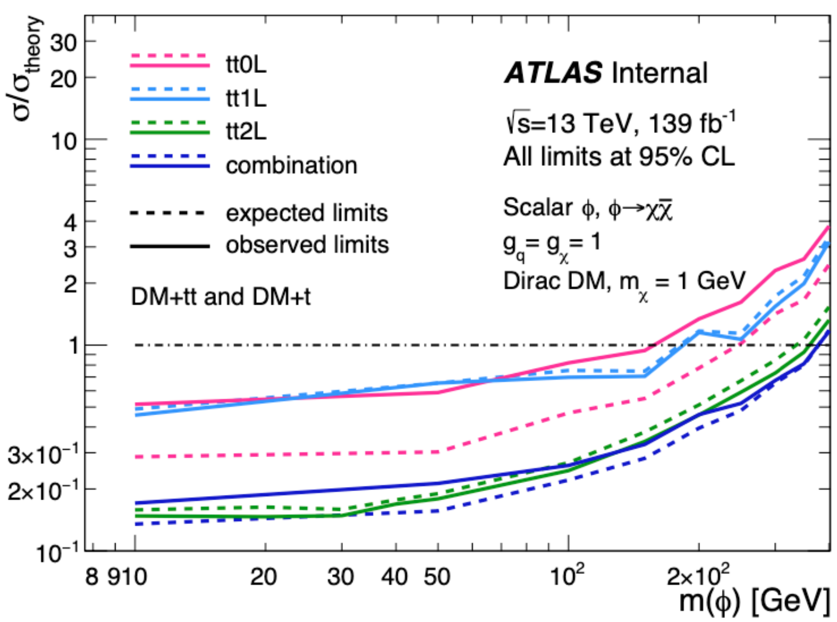


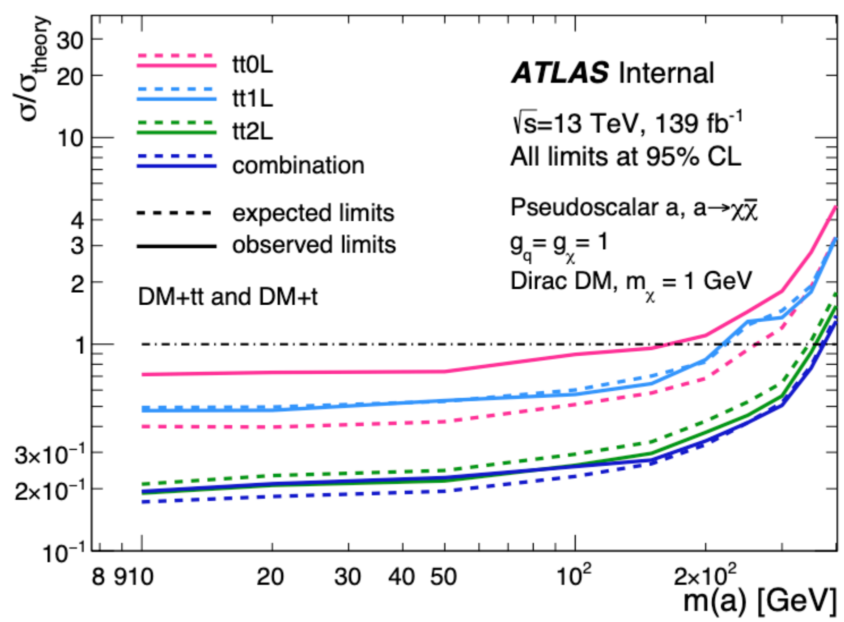


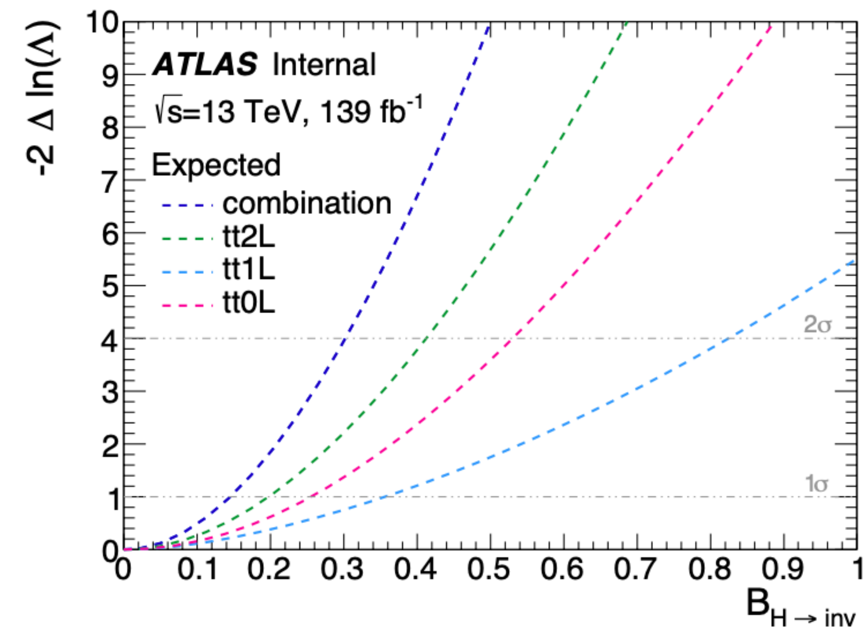


DM_tt combination:

- **Results on mediator masses:**
  - For scalar(pseudoscalar) dark matter models,
  - excluded mass range extended by 100(30) GeV wrt the best of the individual channels (= tt2L)
    - excluding mediator masses up to 370 GeV for unitary couplings assumptions
- **Results on B(H→inv):**
  - Combined best fit value consistent with the SM prediction (=0.12%)

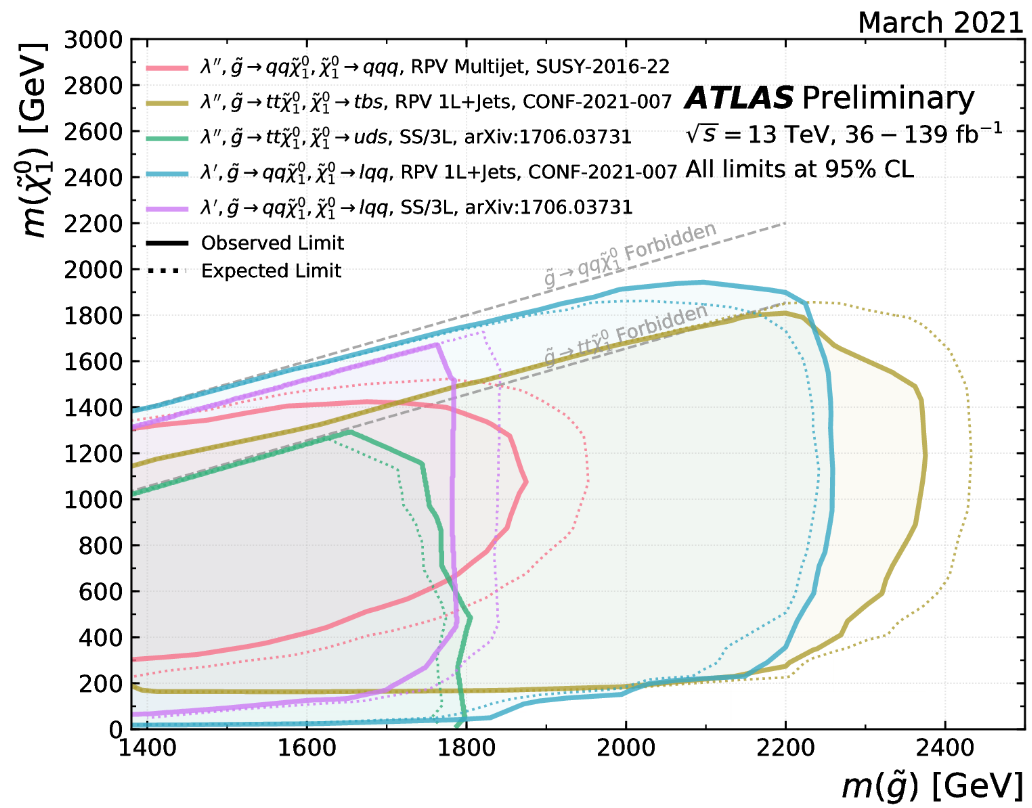


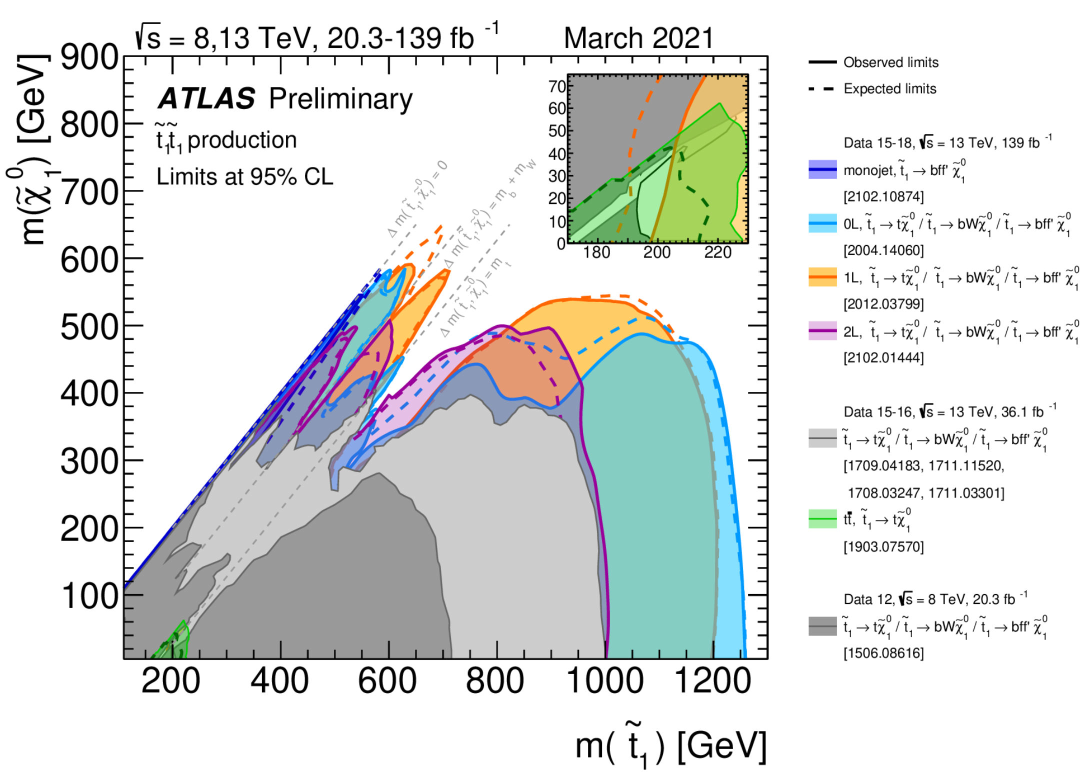


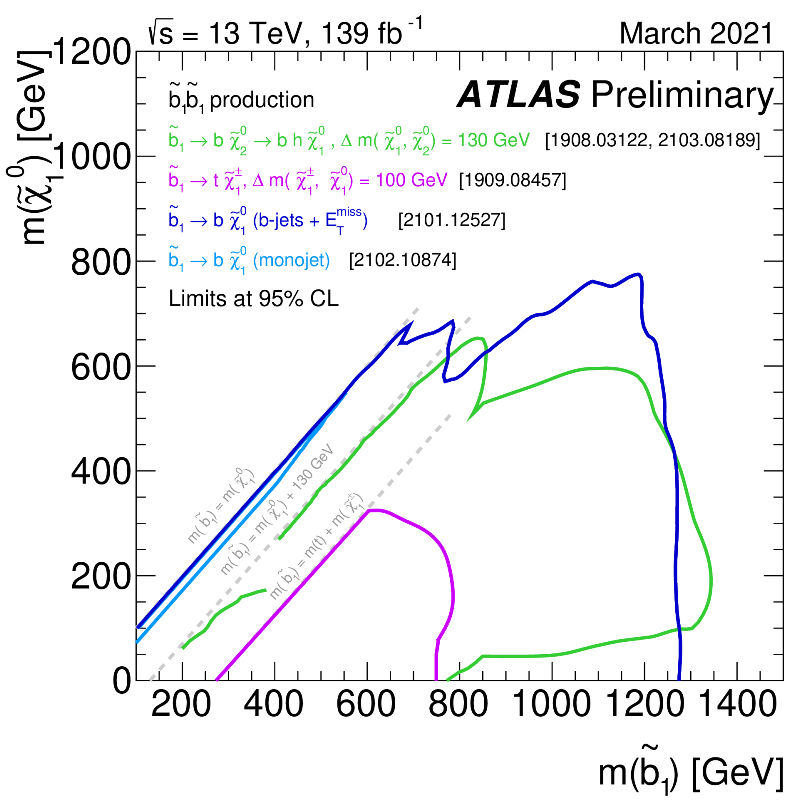


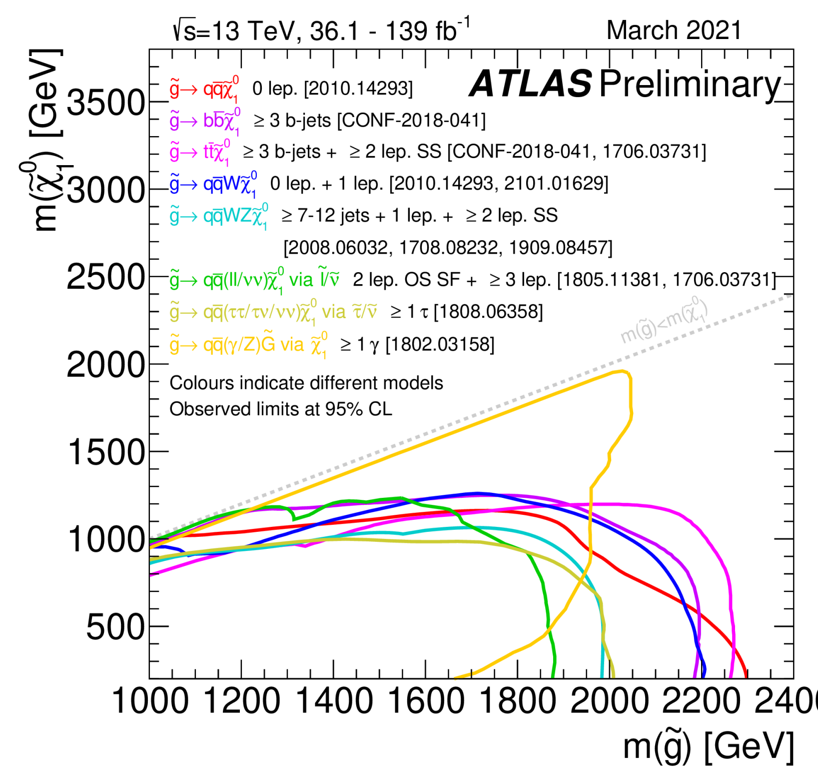
Conclusion:

- Strong SUSY searches in ATLAS have covered wide range of scenarios including both RPC and RPV and also long-lived gluino and squarks
- Lots of results coming out recently from searching for squark and gluino for direct decay or cascade decay in multiple channels
- Unfortunately, no significant excess observed yet
- Greatly extends the sensitivity to gluino and squarks under many different decay modes and assumptions
- Some "warp-up Run-2 results" activities are ongoing like the combination search and interpretations on pMSSM efforts









THE END

Rpv1L:

- No fundamental theoretical reason for strict R-parity conservation
- Signal model:
  - $B(\tilde{t} \rightarrow t\tilde{\chi}^0_{1,2})$ and $B(\tilde{g} \rightarrow t\bar{t}\tilde{\chi}^0_1)$ are varied according to LSP's type (pure wino, bino or higgsino)
  - RPV couplings: Strong enough to decay promptly, weak enough to disentangled with RPC mixture
    - λ''_{323}: dominant under the minimal flavor violation hypothesis
    - λ': to be complementary for light-quark case

arXiv: 2106.09609 (sub to EPJC)

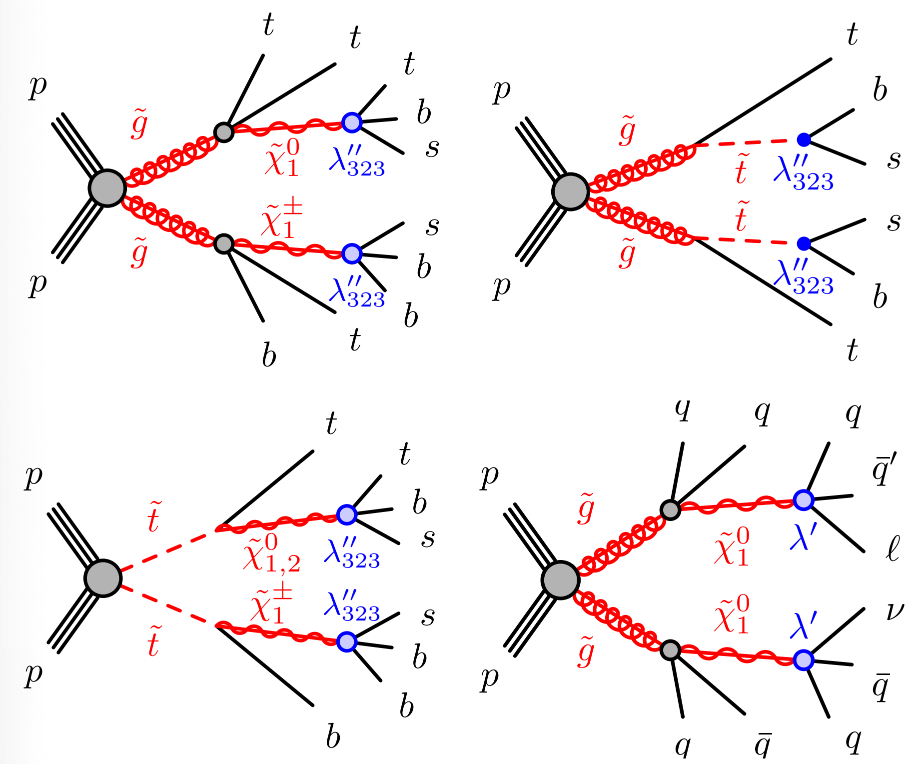


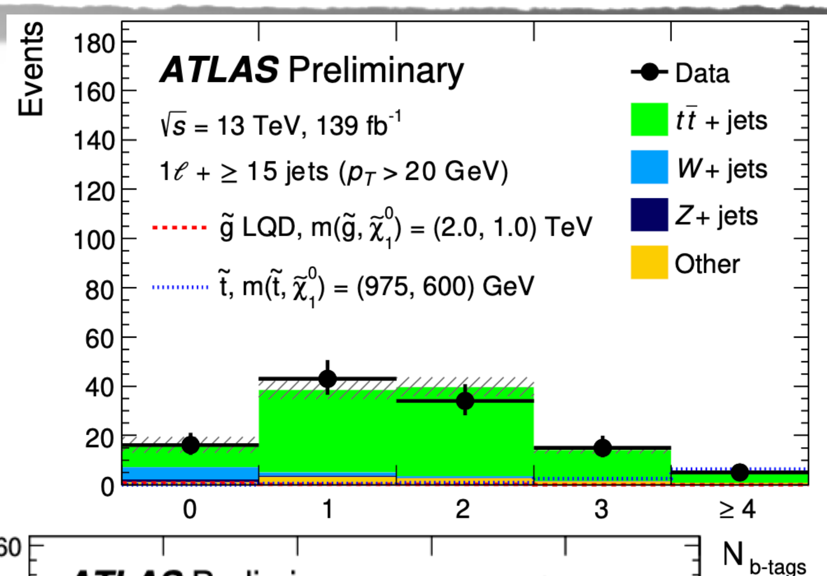
Table 3: Summary of regions considered in the jet counting analysis. The notation Nb is used to indicate a requirement on the b-jet multiplicity. The highest jet multiplicity considered (N_{last}) depends on the jet p_{T} threshold and the lepton category. In the 1ℓ category it corresponds to 15, 12, 11, 10, and 8 jets for the different jet p_{T} thresholds in increasing order. In the $2\ell^{\mathrm{sc}}$category it corresponds to 10, 8, 7, 7, and 6 jets respectively.

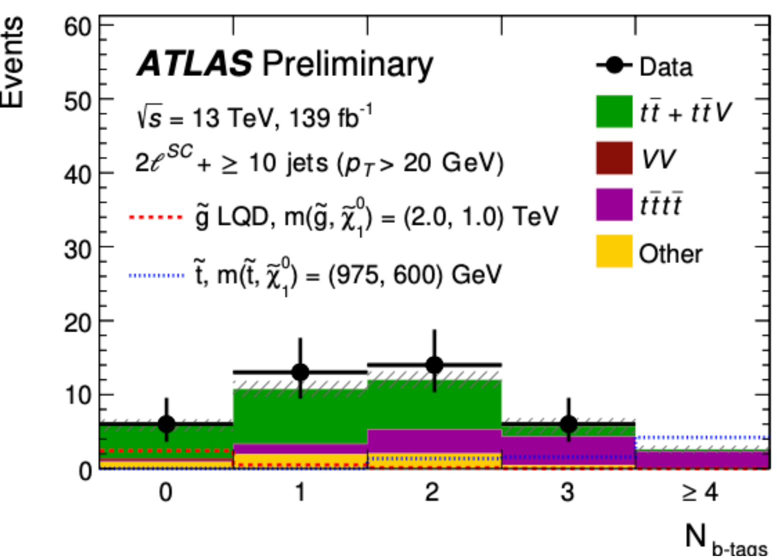
Lepton category	Jet multiplicity	Analysis regions
1ℓ category	$4 \ldots 7$ jets	$0b\ \ell^-$, $0b\ \ell^+$, $0b\ m_{\ell\ell}$, $1b$, $2b$, $3b$, $\geq 4b$
	$8 \ldots \geq N^{1\ell}_{\mathrm{last}}$ jets	$0b$, $1b$, $2b$, $3b$, $\geq 4b$
$2\ell^{\mathrm{sc}}$category	$4 \ldots \geq N^{2\ell^{\mathrm{sc}}}_{\mathrm{last}}$ jets	$0b\ 3\ell$, $0b$, $1b$, $2b$, $3b$, $\geq 4b$

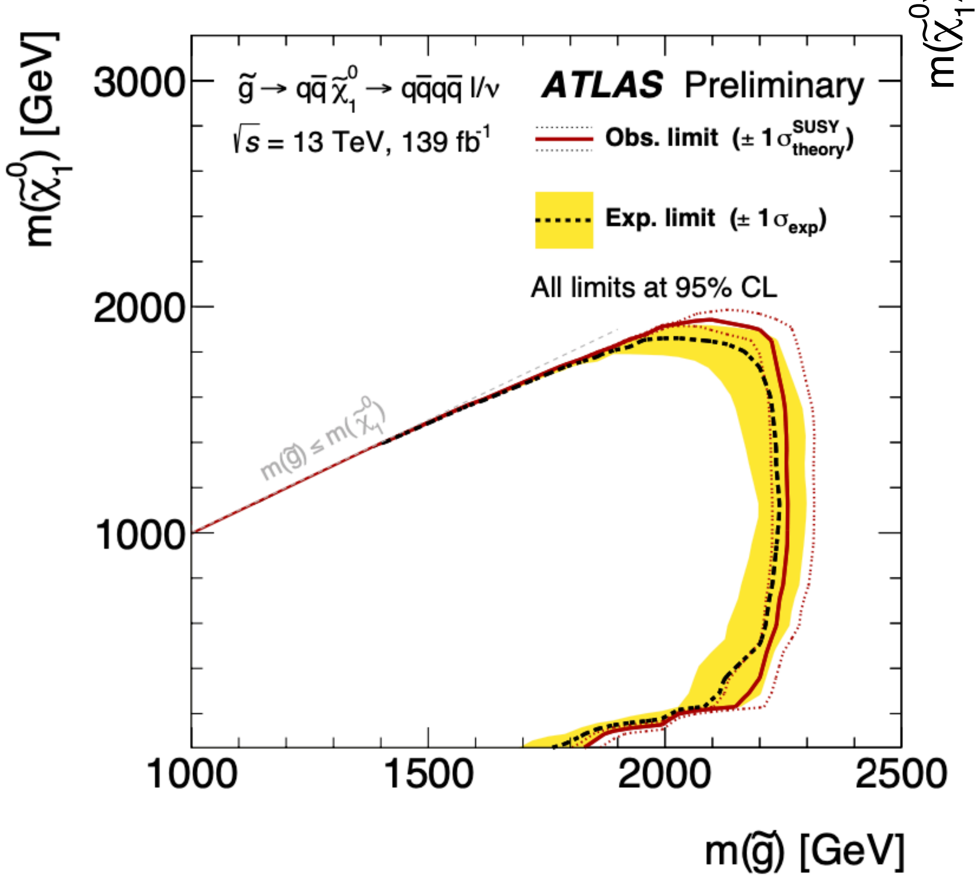
- Events are split into 2LSS case ($2l^{SC}$) and other case (1ℓ dominated)
- SRs are defined according to the jet pT threshold (20,40,60,80 GeV) and $2l^{SC}$ /1ℓ separately
- Binned with N_j and N_b formed as $N_{j,b}$ slices

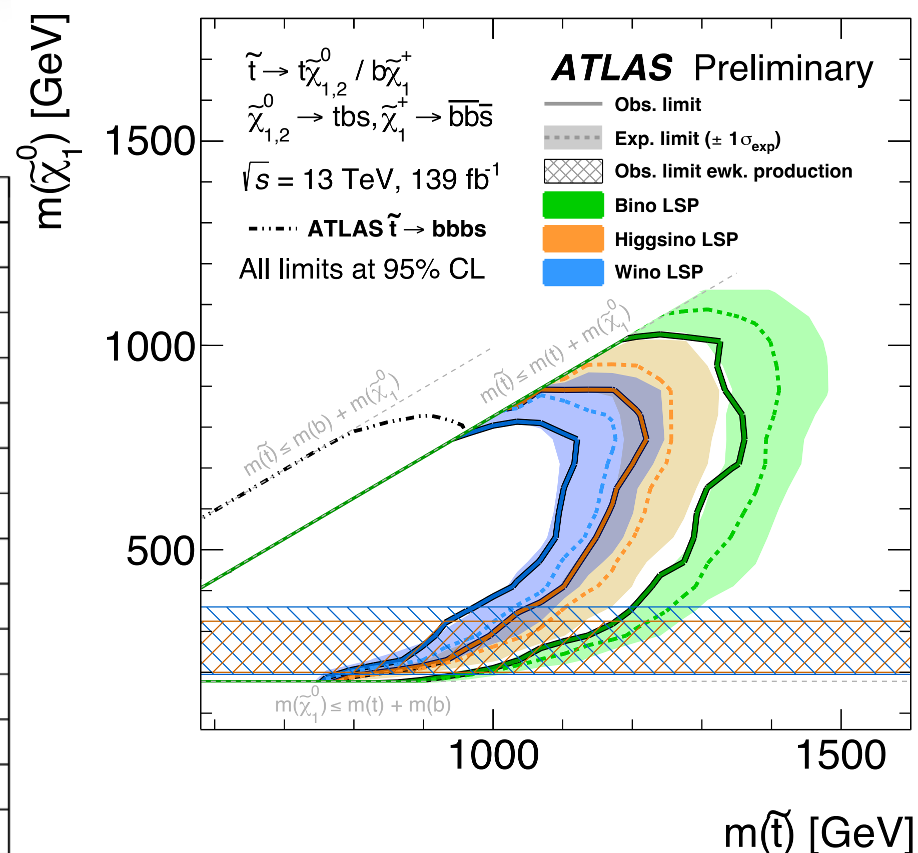
Rpv1L:

- BKG estimation:
  - $W/Z + jets$ dominant for bVeto and $t\bar{t}$ for b-jet required regions for $1l$ category
  - VV dominant for bVeto and $t\bar{t}X^{SC}$ for b-jet required regions for $2l^{SC}$ category
  - Large uncertainties for high jet multiplicity, $N_{j,b}^{process}$ estimated from low-jet case which is corrected by data
  - FNP: Matrix Method for $1l$ category, covered by $t\bar{t}X^{SC}$ in $2l^{SC}$ category
  - Other minor bkg estimated via MC simulation directly





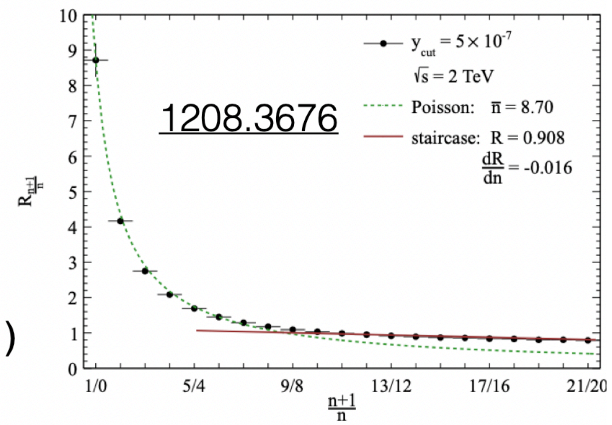




Rpv1L

W/Z/VV+jets estimation

- The V(V)+jets **Njet** distribution is parameterized making use of known jet scaling regimes
  - $r(j) = N_{j+1}/N_j$
  - $r(j) = c_0$ for very high jet multiplicities (staircase)
  - $r(j) = c_1/(j+1)$ for low jet multiplicities (Poisson)



- We use $r(j) = c_0 + c_1/(j+1)$ to cover the whole range
- Fit one normalization (N_4) and two parameters (c_0, c_1)
- This fully determines the prediction in all Njet bins:
  - $N_5 = N_4 * r(4)$
  - $N_8 = N_4 * r(4) * r(5) * r(6) * r(7)$

$$N_j = N_4 \cdot \prod_{j'=4}^{j'=j-1} r(j')$$

- Fit separate normalizations for W/Z, but common scaling parameters
- All parameters are independent for VV
- The V(V)+jets **Nbjet** distribution is taken from MC with large uncertainties

$$N_j = N_4 \cdot \prod_{j'=4}^{j'=j-1} r(j')$$

$$N_{j,b} = N_j \cdot f_{j,b}^{MC}$$

- $f_{j,b}^{MC}$ is the fraction of events that contain *b* b-tags in the *j* jet-slice, as predicted by MC
- No impact on the sensitivity from assigning large uncertainties to the fraction

ttbar estimation

- The ttbar **Njet** distribution is parameterized in a similar way as V+jets
- b-jets are pair produced, therefore some correlation is expected. Add a factor ρ_{11} to all terms with x_1*x_1
- The production of extra jets lead to, on average, higher-p_T events, and b-jets that were below p_T threshold can enter acceptance. Add a term with x_2

$$f_{j+1,b} = f_{j,b} \cdot x_0 + f_{j,b-1} \cdot x_1 + f_{j,b-2} \cdot x_2$$

- Can fit to data the initial fractions $f_{4,b}$, and x_1, and predict the b-tag fractions for any jet multiplicity

tt+X SS channel

- The leading backgrounds in the b-tagged regions of 2LSS are ttW (2/3) and ttbar + fake lepton (1/3)
- Both are **merged** and estimated simultaneously with the same method as ttbar in the 1-lepton channel
  - Njet prediction via jet scaling, using **independent** fit parameters
  - Nbjet prediction via additional heavy-flavour model, using **same** fit parameters

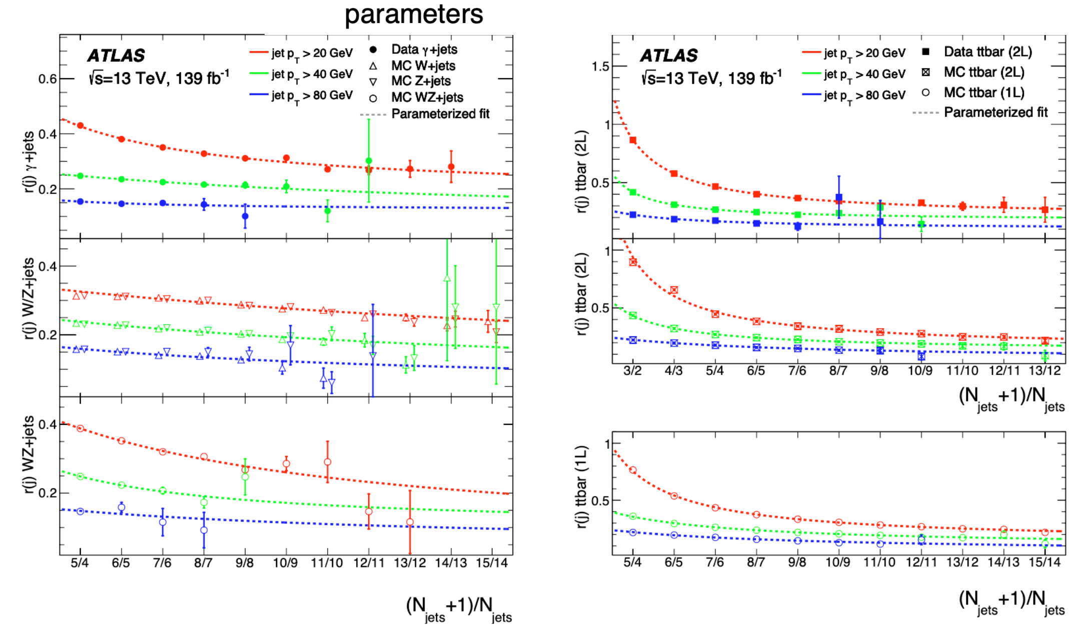


Figure 3: The ratio of the number of events with $(j + 1)$ jets to the number with j jets in various event samples (details in the legend), used to validate the jet-scaling parameterization. In the MC samples of *W*/*Z*/*WZ*+jets the vector bosons are forced to decay to leptons. Each panel shows the ratio for data or MC simulation with the fitted parameterization overlaid as a dashed line. The uncertainties shown are statistical.

2L2J:

- SRC-STR: 12, 31, 46, 61, 71, 81, 101, 201;
- SRLow-STR: 12, 41, 61, 81, 101, 141, 201, 301, 501;
- SRMed-STR: 12, 81, 101, 201, 301, 601;
- SRHigh-STR: 12, 101, 301, 1001.

$$N^{\text{est}} = \frac{1}{2} \cdot \left[\sum_{i}^{N_{e\mu}^{\text{data}}} \left(k_e(p_{\text{T}}^{i,\mu}, \eta^{i,\mu}) + k_\mu(p_{\text{T}}^{i,e}, \eta^{i,e}) \right) \cdot \alpha(p_{\text{T}}^{i,\ell_1}, \eta^{i,\ell_1}) - \sum_{i}^{N_{e\mu}^{\text{MC}}} \left(k_e(p_{\text{T}}^{i,\mu}, \eta^{i,\mu}) + k_\mu(p_{\text{T}}^{i,e}, \eta^{i,e}) \right) \cdot \alpha(p_{\text{T}}^{i,\ell_1}, \eta^{i,\ell_1}) \right],$$

$$k_e(p_{\text{T}}, \eta) = \sqrt{\frac{N_{ee}^{\text{meas}}(p_{\text{T}}, \eta)}{N_{\mu\mu}^{\text{meas}}(p_{\text{T}}, \eta)}},$$

$$k_\mu(p_{\text{T}}, \eta) = \sqrt{\frac{N_{\mu\mu}^{\text{meas}}(p_{\text{T}}, \eta)}{N_{ee}^{\text{meas}}(p_{\text{T}}, \eta)}},$$

$$\alpha(p_{\text{T}}, \eta) = \frac{\sqrt{\epsilon_{ee}^{\text{trig}}(p_{\text{T}}^{\ell_1}, \eta^{\ell_1}) \times \epsilon_{\mu\mu}^{\text{trig}}(p_{\text{T}}^{\ell_1}, \eta^{\ell_1})}}{\epsilon_{e\mu}^{\text{trig}}(p_{\text{T}}^{\ell_1}, \eta^{\ell_1})},$$

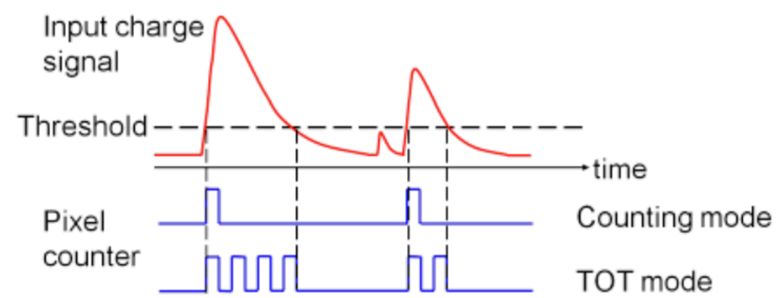
$$N_{\text{pass}}^{\text{FNP}} = \frac{N_{\text{fail}} - (1/\epsilon^{\text{real}} - 1) \times N_{\text{pass}}}{1/\epsilon^{\text{FNP}} - 1/\epsilon^{\text{real}}},$$

Region	n_{jets}	H_{T} [GeV]	$E_{\text{T}}^{\text{miss}}$ [GeV]	m_{T2} [GeV]	$\mathcal{S}(E_{\text{T}}^{\text{miss}})$	$p_{\text{T}}^{\ell\ell}$ [GeV]	$\Delta\phi(j_{1,2}, \vec{p}_{\text{T}}^{\text{miss}})$	SF/DF	$m_{\ell\ell}$ [GeV]
Signal regions									
SRC-STR	≥ 2	> 250	> 250	> 90	> 10	40–100	> 0.4	SF	> 12
SRLow-STR	≥ 2	> 250	> 250	> 100	–	40–500	> 0.4	SF	> 12
↪SRZLow-STR	≥ 4	> 250	> 250	> 100	–	40–500	> 0.4	SF	81–101
SRMed-STR	≥ 2	> 500	> 300	> 75	–	40–800	> 0.4	SF	> 12
↪SRZMed-STR	≥ 4	> 500	> 300	> 75	–	40–800	> 0.4	SF	81–101
SRHigh-STR	≥ 2	> 800	> 300	> 75	–	> 40	> 0.4	SF	> 12
↪SRZHigh-STR	≥ 4	> 800	> 300	> 75	–	> 40	> 0.4	SF	81–101
Control regions									
CRC-FS-STR	≥ 2	> 250	> 250	> 90	> 10	40–100	> 0.4	**DF**	> 12
CRLow-FS-STR	≥ 2	> 250	> 250	> 100	–	40–500	> 0.4	**DF**	> 12
↪CRZLow-FS-STR	≥ 4	> 250	> 250	> 100	–	40–500	> 0.4	**DF**	**61–121**
CRMed-FS-STR	≥ 2	> 500	> 300	> 75	–	40–800	> 0.4	**DF**	> 12
↪CRZMed-FS-STR	≥ 4	> 500	> 300	> 75	–	40–800	> 0.4	**DF**	**61–121**
CRHigh-FS-STR	≥ 2	> 800	> 300	> 75	–	> 40	> 0.4	**DF**	> 12
↪CRZHigh-FS-STR	≥ 4	> 800	> 300	> 75	–	> 40	> 0.4	**DF**	**61–121**
CRC-Z-STR	≥ 2	> 250	> 250	> 90	> 10	40–100	**< 0.4**	SF	**81–101**
CRLow-Z-STR	≥ 2	> 250	> 250	> 100	–	40–500	**< 0.4**	SF	**81–101**
↪CRZLow-Z-STR	≥ 4	> 250	> 250	> 100	–	40–500	**< 0.4**	SF	81–101
CRMed-Z-STR	≥ 2	> 500	> 300	> 75	–	40–800	**< 0.4**	SF	**81–101**
↪CRZMed-Z-STR	≥ 4	> 500	> 300	> 75	–	40–800	**< 0.4**	SF	81–101
CRHigh-Z-STR	≥ 2	> 800	> 300	> 75	–	> 40	**< 0.4**	SF	**81–101**
↪CRZHigh-Z-STR	≥ 4	> 800	> 300	> 75	–	> 40	**< 0.4**	SF	81–101
Validation regions									
VRC-STR	≥ 2	> 250	**150–250**	> 90	> 10	40–100	> 0.4	SF	> 12
VRLow-STR	≥ 2	> 250	**150–250**	> 100	–	40–500	> 0.4	SF	> 12
VRMed-STR	≥ 2	> 500	**150–250**	> 75	–	40–800	> 0.4	SF	> 12
VRHigh-STR	≥ 2	> 800	**150–250**	> 75	–	> 40	> 0.4	SF	> 12
VR3L-STR	≥ 2	> 250	**> 200**	> 100	–	> 40	> 0.4	**3L**	> 12

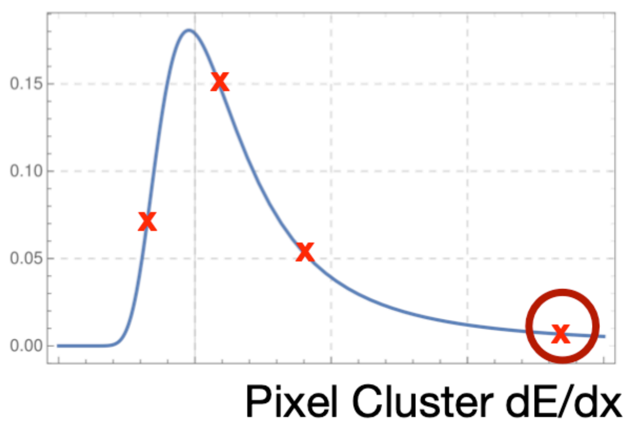
Pixel dE/dX:

Time over threshold measurements

- As charged particles traverse the detector, they deposit energy throughout the inner detector. This is converted into a 8-bit number proportional to the Time over Threshold (ToT) of the input charge signal. The ToT is proportional to the charge induced in each pixel.
  - IBL has different FE electronics w.r.t the other pixel layers - smaller dynamic range with an **overflow bit that triggers when the range is maxed out.** We call tracks that have triggered the overflow bit as **IBL Overflow track (IBL1).**



Extracting the dE/dx value



- As particles pass through the inner detector, they leave multiple energy deposits through out the inner detector.
  - The amount of deposited energy follows a Landau probability distribution.
- An example track could leave multiple dE/dx measurements (energy clusters along a track is marked in red).
  - To estiamte the most probable dE/dx value for a track from the limited number of the dE/dx measurements associated to it we have used a truncated mean method.
  - In this example we drop the highest energy measurment (circled in red) and take the average of the rest.
- Further details can be found in backups.

inspired by the original Bethe–Bloch formula

$$\mathrm{MPV}_{\mathrm{d}E/\mathrm{d}x}(\beta\gamma) = \frac{1+(\beta\gamma)^2}{(\beta\gamma)^2}\left(c_0 + c_1\log_{10}(\beta\gamma) + c_2\left[\log_{10}(\beta\gamma)\right]^2\right) \quad (1)$$

where c_0, c_1, and c_2 are free parameters of the fit. Inversion of the above function provides an estimate of the charged-particle $\beta\gamma$ from the measured $\mathrm{d}E/\mathrm{d}x$. Combined with the momentum measurement, the mass of the particle associated with the track can be calculated as $m_{\mathrm{d}E/\mathrm{d}x} \equiv p_{\mathrm{reco}}/\beta\gamma(\langle \mathrm{d}E/\mathrm{d}x\rangle_{\mathrm{corr}})$. This reconstructed mass is hereafter simply denoted by 'm'.

ATLAS EXPERIMENT

Pixel dE/dX:

SR For Exclusion

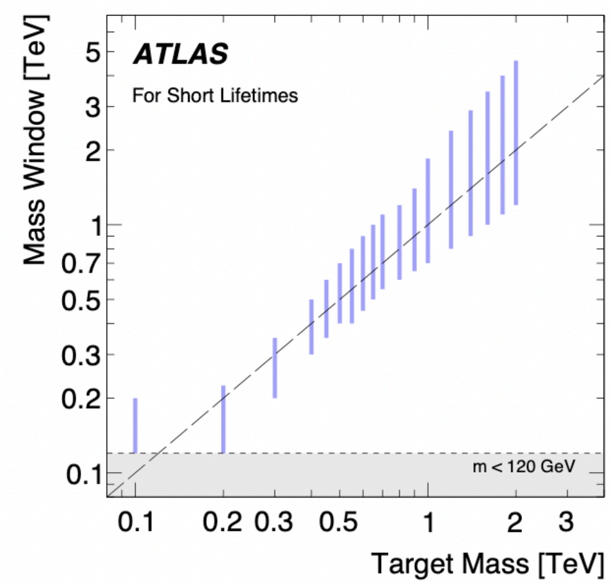
SR-Mu-IBL0_Low	SR-Trk-IBL0_Low
SR-Mu-IBL0_High	SR-Trk-IBL0_High
SR-Mu-IBL1	SR-Trk-IBL1

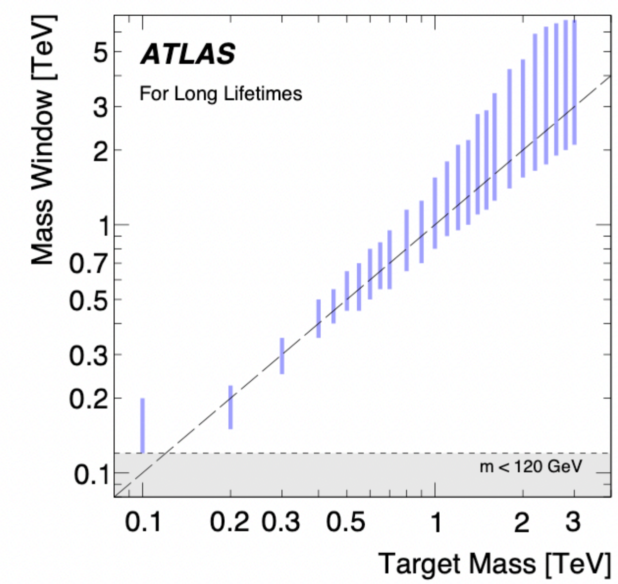
- When we going for exclusion limits the events are categorized according to the selected track properties:
  - Matched to a Muon (Mu) or Not (Trk)
  - dE/dx in (1.8, 2.4] (Low) or (2.4,∞] (High)
  - Has a hit with an IBL Overflow (IBL1) {dE/dx > 1.8}

SR For Discovery

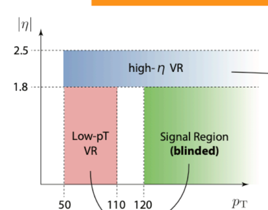
SR-Inclusive_Low
SR-Inclusive_High

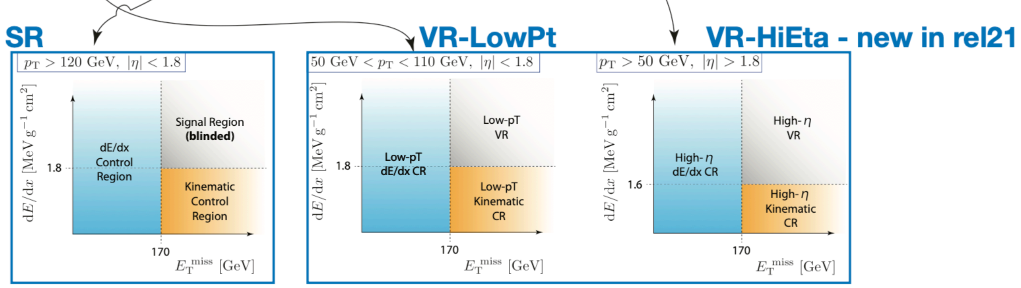
- Instead categorize tracks by
  - dE/dx in (1.8, 2.4] or (2.4,∞]
- **2 exclusive signal regions**
- Also easier for re-interpretation





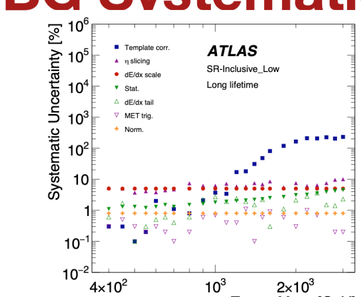
Validation Regions

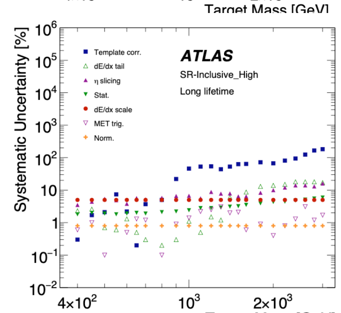




- In order to validate the generation background two separate VR has been designed:
  - **High-η VR:**
    - **SR:** $|\eta| < 1.8$ → **VR:** $1.8 < |\eta| < 2.5$
    - **SR:** $p_T > 120$ → **VR:** $p_T > 50$
    - **SR:** $dE/dx > 1.8$ → **VR:** $dE/dx > 1.6$
  - Shares a similar momentum spectrum with the SR but has a differentiated dE/dx spectrum due to eta differences.
  - **Low-pT VR:**
    - **SR:** $p_T > 120$ → **VR:** $50 < p_T < 110$
  - Shares identical dE/dx range and performance with SR but has a limited momentum range.
- Individual dE/dx CR and Kinematic CR are generated for each region to extract the kinematic templates.

BG Systematic Uncertainties





- Uncertainties are calculated **per each mass window** and the leading uncertainties are:
- **Template Corr:** Leading uncertainty. It evaluates the assumption that the kinematic and dE/dx templates can be drawn separately in the toy procedure
- **dE/dx Scale:** This uncertainty is introduced to cover the disagreement observed in the Low-pT VR - IBL0-Trk-Low.
  - The size of this additional systematic uncertainty is evaluated using VR-LowPt and VR-HiEta by making likelihood fit without other uncertainties.
- **dE/dx tail:** dE/dx tail statistical uncertainty estimated by using a fitted Crystal ball function instead of the raw template
- **η slicing** estimates the effect of the choice of η binning of the dE/dx templates

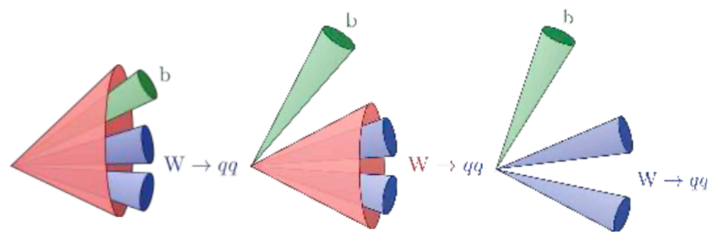
Signal Systematic Uncertainties

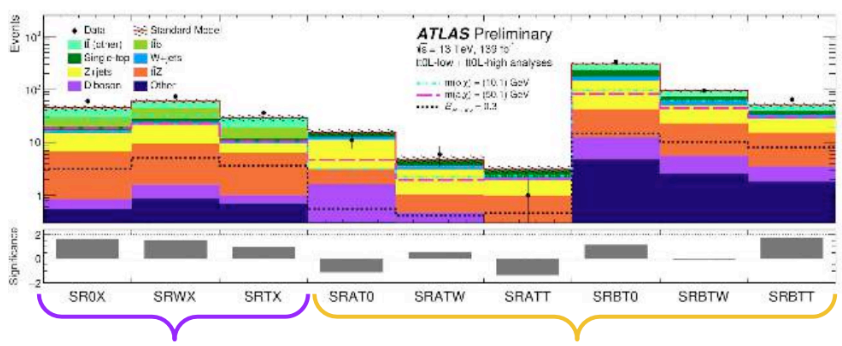
- Signal systematic uncertainties are computed for model dependent limits.
  - The dominant signal uncertainty depends on the signal model but overall the dominating uncertainties are:
    - Scale/ISR Uncertainties (py3c)
    - IBLSyst: IBL overflow fraction year dependence.
    - Track momentum and sagitta uncertainty
  - The remaining uncertainties are smaller and are grouped togethers (treating them as uncorrelated) to reduce the number of

ATLAS EXPERIMENT

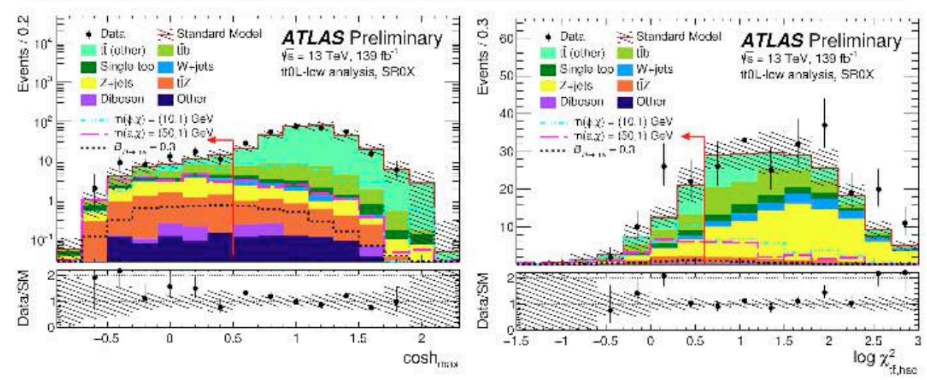
DM_tt combination:

tt0L-high MET - EPJC 80 (2020) 737
MET trigger
MET>250 GeV, MET significance $\mathcal{S}$>14, large-radius jet (R=1.2) → highly energetic top quark
SRs based on mass of subleading large-radius jet (R=1.2) → presence of m_t, m_W or *neither*





tt0L-low MET - this analysis	
MET trigger	*b*-jet trigger
MET>250 GeV but $\mathcal{S}$<14 OR no large-radius (R=1.2) jets → highly energetic top quark	MET∈[160,250] GeV
Discriminating variables	
$\cosh_{max}$ to reduce bkg with top quark + missing lepton	
$\chi^2_{t\bar{t},had}$ to identify events with fully hadronic top quark pairs	
SRs based on mass of the highest large-radius (R=1) jet → presence of m_t, m_W or *none*	



Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed upper limit	Expected upper limit
tt0L-low	$0.88^{+0.48}_{-0.46}$	1.80	$1.09^{+0.50}_{-0.26}$
tt0L-high	$0.27^{+0.28}_{-0.27}$	0.80	$0.59^{+0.29}_{-0.18}$
tt0L comb.	$0.48^{+0.27}_{-0.27}$	0.95	$0.52^{+0.23}_{-0.16}$

Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed upper limit	Expected upper limit
tt0L	$0.48^{+0.27}_{-0.27}$	0.95	$0.52^{+0.23}_{-0.16}$
tt1L	$-0.04^{+0.35}_{-0.29}$	0.74	$0.80^{+0.40}_{-0.26}$
tt2L	$-0.08^{+0.20}_{-0.19}$	0.36	$0.40^{+0.18}_{-0.12}$
$t\bar{t}H$ comb.	$0.08^{+0.15}_{-0.15}$	0.38	$0.30^{+0.13}_{-0.09}$

ATLAS EXPERIMENT