The Quest for phenomena Beyond the Standard Model at ATLAS

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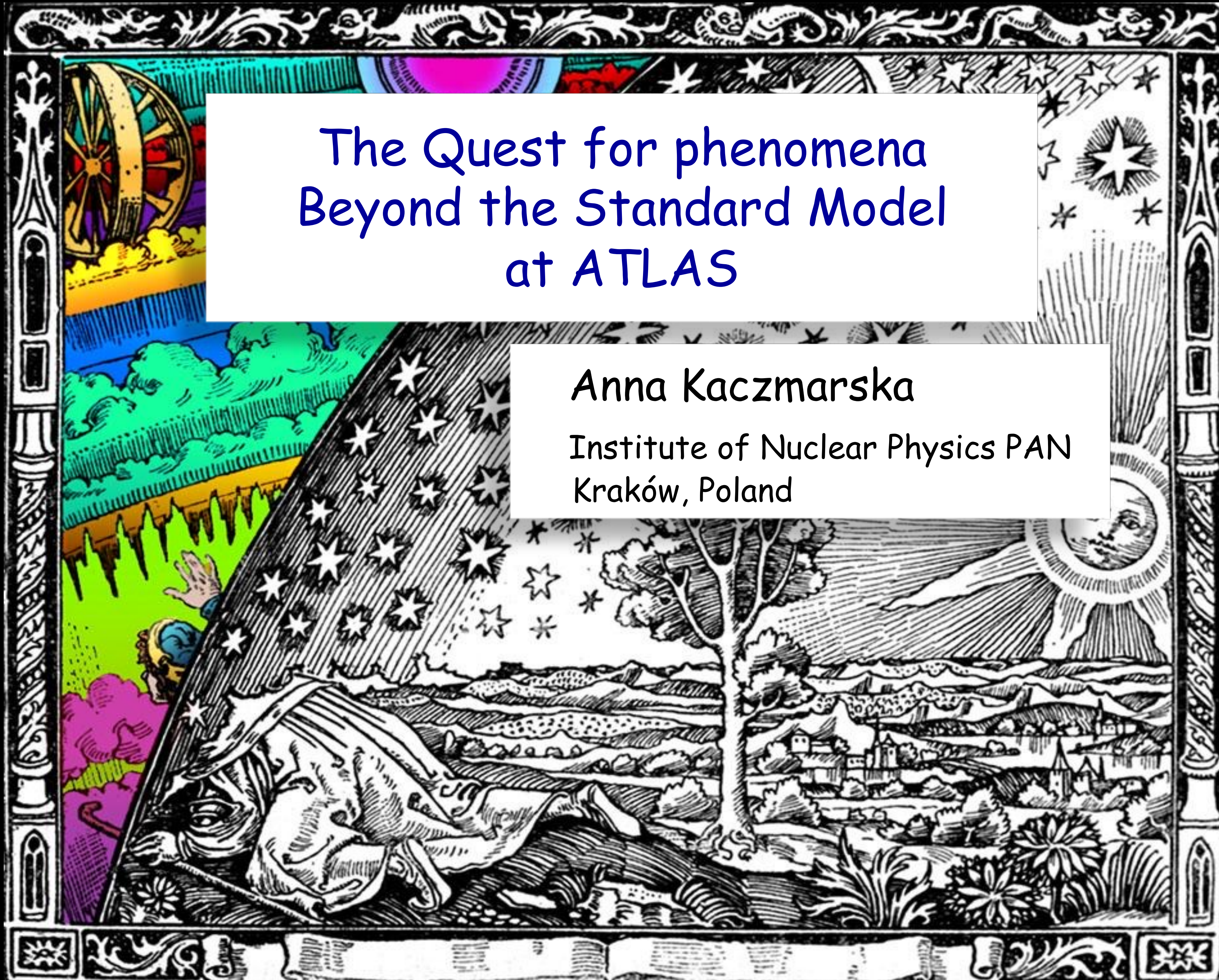
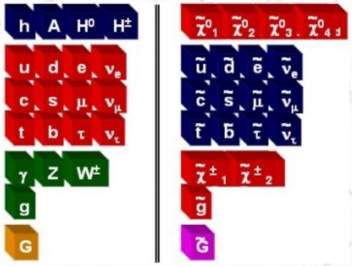


Thanks to Greg Landsberg for his lectures and healthy approach to BSM searches

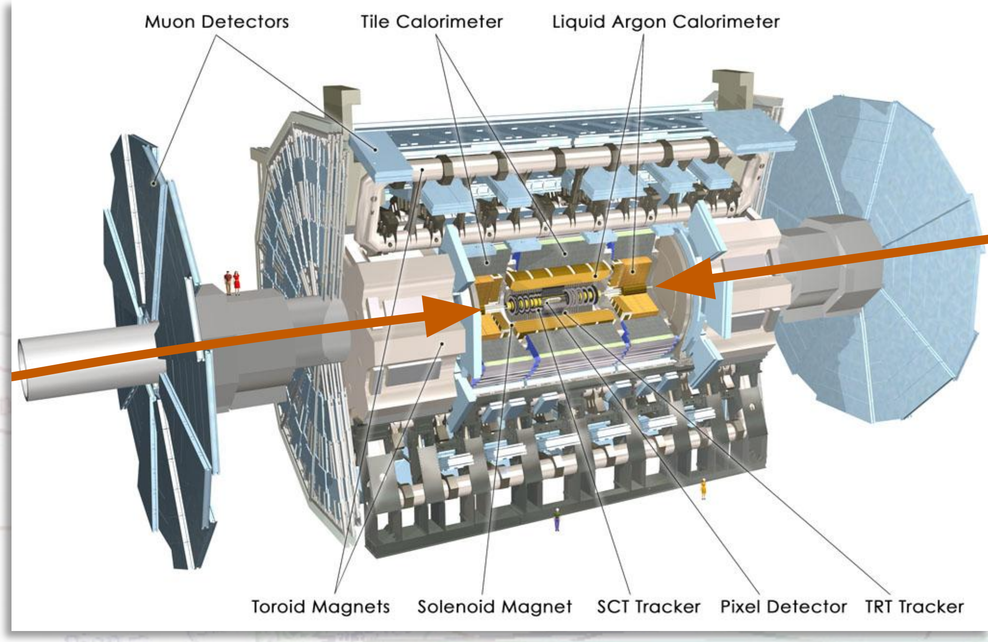
How to find a black cat in a dark room
Especially when there is no cat

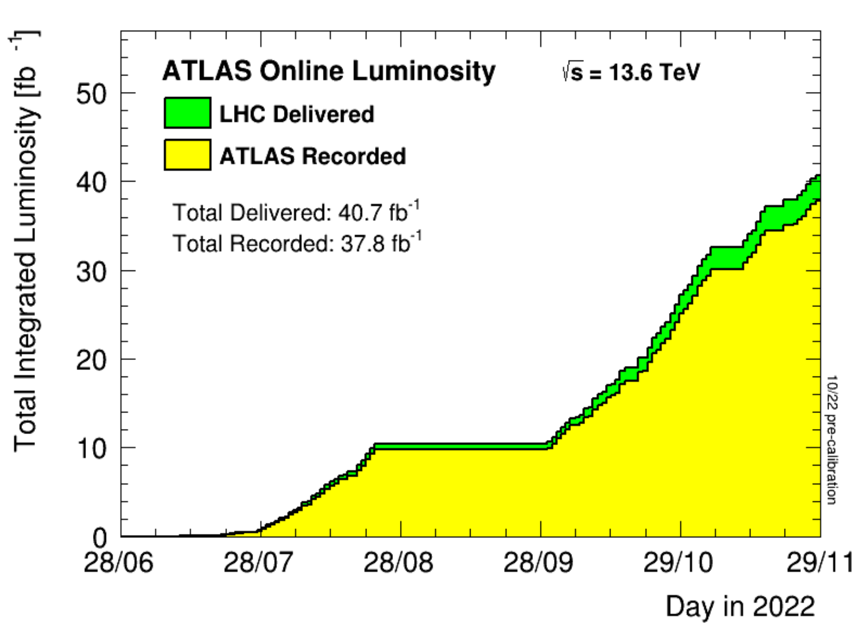
- Quest for new physics is not for wimps
  - A lot of searches performed by ATLAS so far, and all came empty-handed
  - A likelihood for any given search to find something interesting seems to be very small…
  - … yet, the only way to find something is to keep looking!
- And we are quite well motivated

- The SM is our best tool to understand nature but it's not the ultimate one!
  - Hierarchy problem? Dark matter? Neutrino masses? Matter/anti-matter asymmetry….
  - Tention from SM predictions in B-physics measurements, muon g-2 anomaly etc.
- Shift of paradigm: from searches of the highest masses, and low background to searches experimentally challenging, with low couplings, low masses etc.
- This talk will present **a few** of the most recent ATLAS results from the full Run-II data



ATLAS detector – Run 2 and Run 3





Run 2 2015 – 2018

- completed very successfully
- delivered total 156 fb^{-1} of proton–proton collisions at $\sqrt{s}$=13 TeV
- **'good for physics' data set 139 fb^{-1}**
- peak luminosity: 2.1×10^{34} $cm^{-2}s^{-1}$, average number of interactions per bunch crossing: 33.7

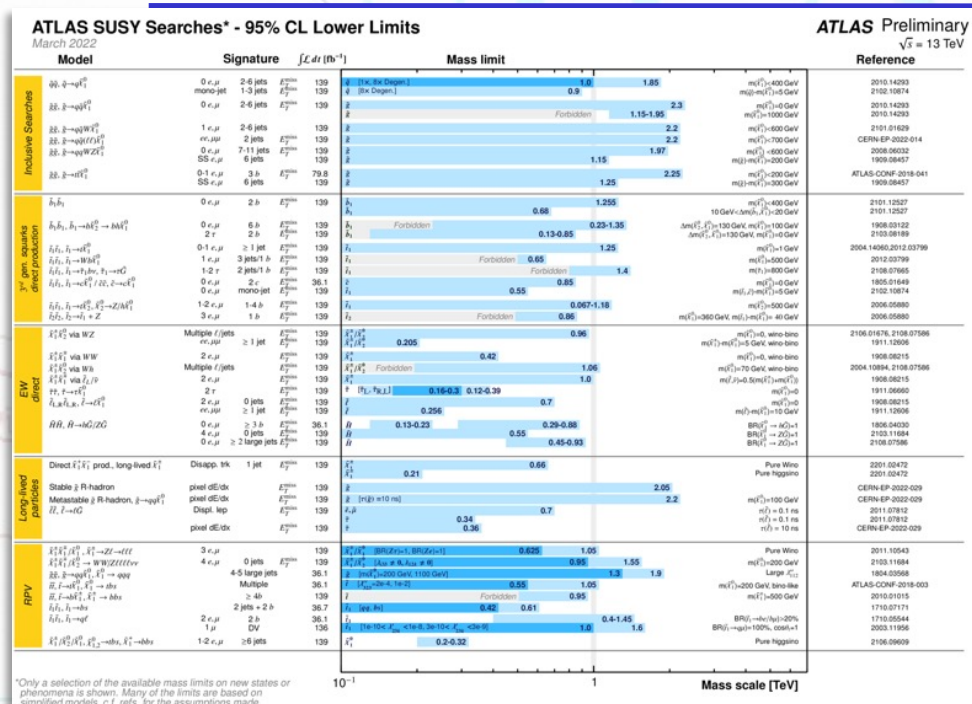
Run 3 2022 – 2025

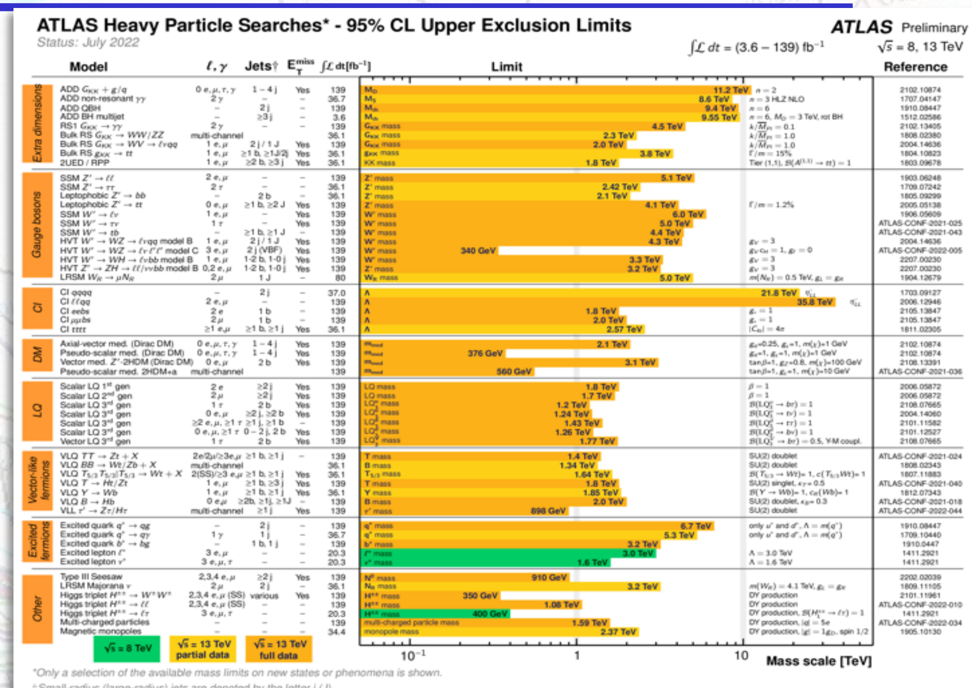
- **~40 fb^{-1} already delivered in 2022**
- expect to double Run 2 dataset until 2025

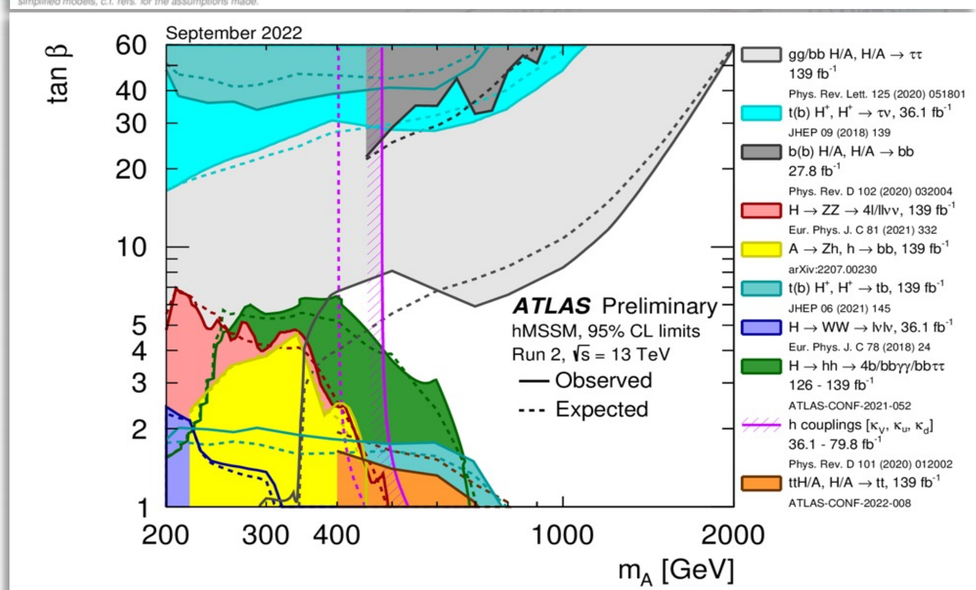
Extensive Run 2 analysis program in both ATLAS & CMS advancing well

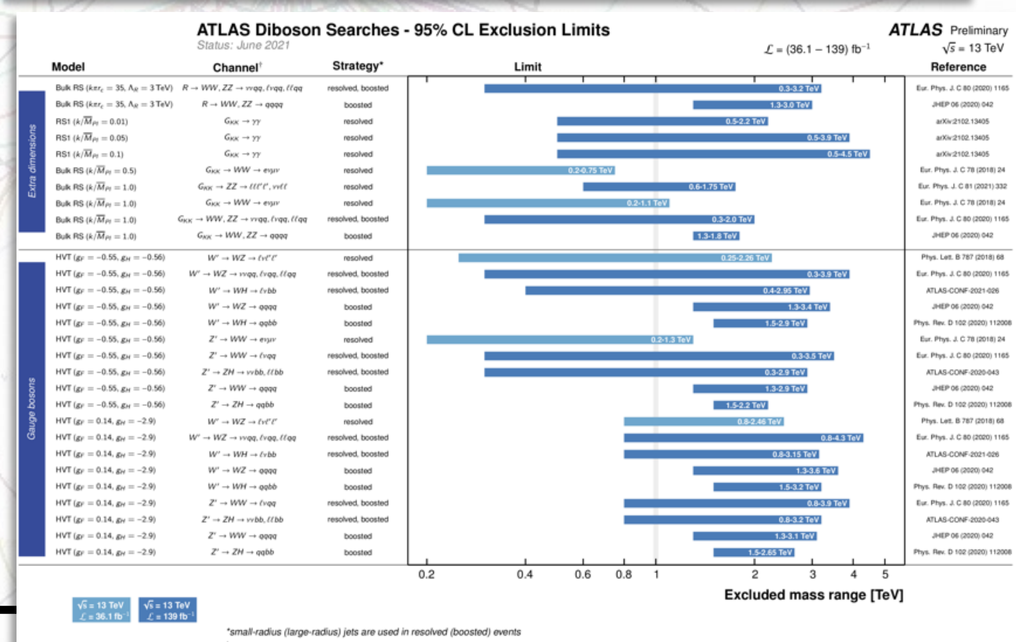
- more than 400 papers submitted each and O(300) in progress

The Landscape ("the wailing wall")









Extended scalar sector

- So far Higgs boson (125) looks like from SM, but consistent with SM ≠ incompatible with BSM

- Extended scalar sector appears in many extensions of the SM (e.g. SUSY)
- They allow for SM-like light Higgs phenomenology and bring additional Higgs bosons
- Searches often interpreted in the contest of 2HDM (MSSM)
- Rich phenomenology and final states -> also exotic Higgs decays
- Wide range of masses to be tested

SM Higgs doublet + Additional Field	=	Additional Higgs Bosons
EWS: Additional EW Singlet Model SM + one scaler EW singlet	=	Neutral CP Even: h, H
2HDM: Two Higgs Doublet Model SM + another Higgs doublet (MSSM)	=	Neutral CP Even: h, H; CP Odd: A; Charged: $H^{\pm}$
2HDM + Singlet (complex) Model SM + doublet & singlet (NMSSM)	=	Neutral CP Even: s; CP Odd: a; + 2HDM Higgses
Higgs Triplet Model SM + triplet	=	Double Charged: $H^{\pm\pm}$; + 2HDM Higgses

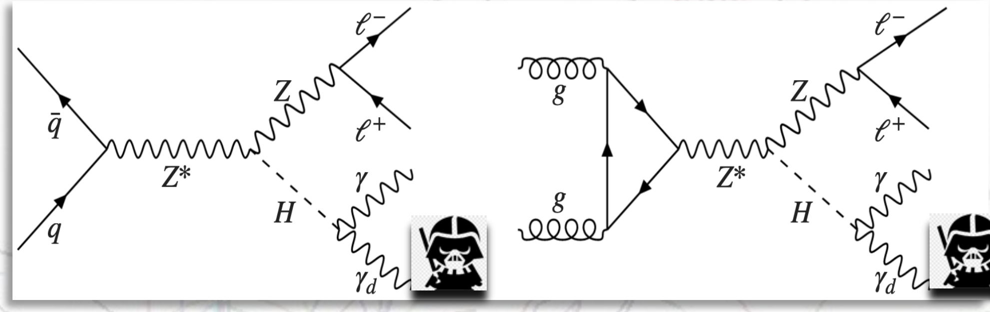
7

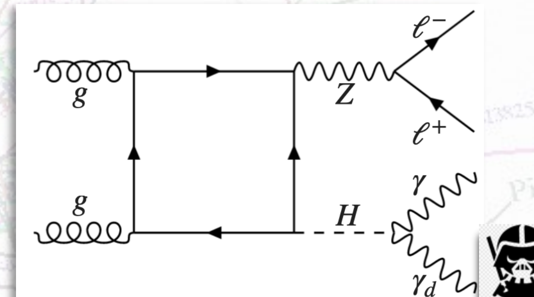
courtesy of N. Ilic

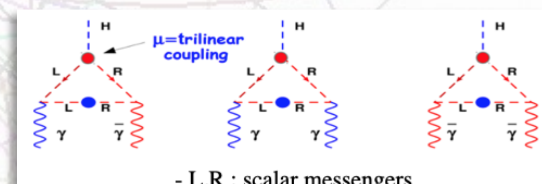
Dark photons from Higgs boson decays via ZH production

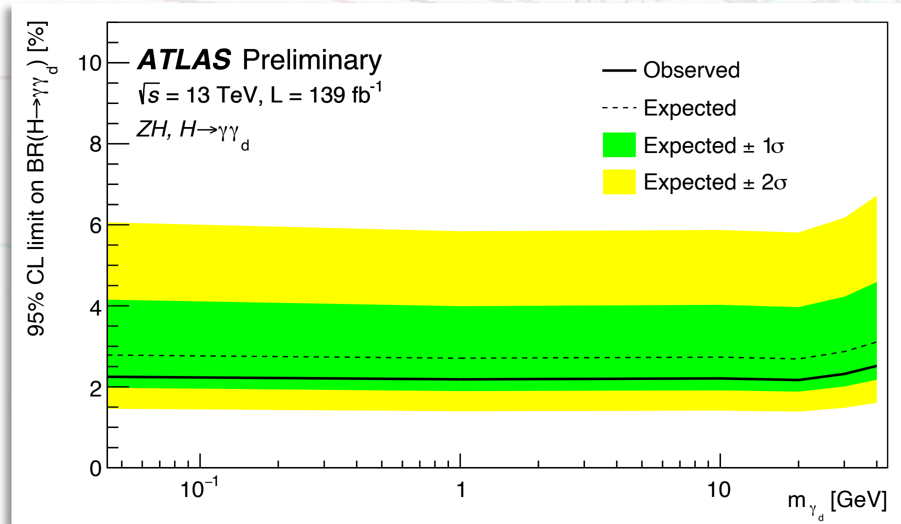
ATLAS-CONF-2022-064

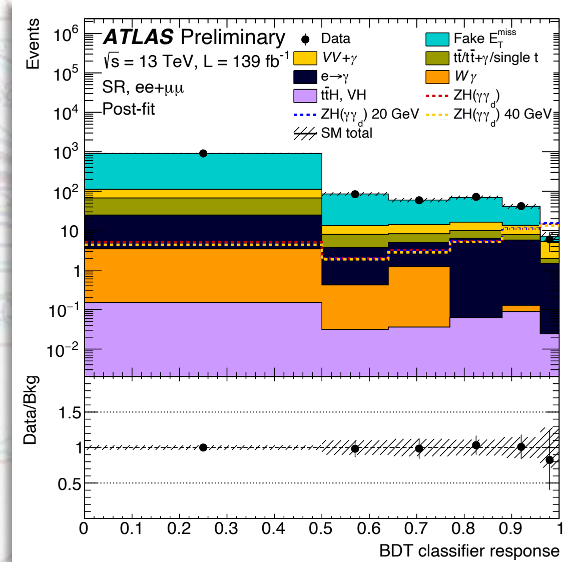
- **Dark photon:** predicted in hidden-sector models with an unbroken dark $U(1)_d$ gauge symmetry
- *Model independent analysis*
- Massless and light dark-photon (up to 40 GeV)
- Clean final state: l^+l^-(trigger) $\gamma\ \gamma_{dark}$ (MET)











- No excess observed, limit set on BR($H \rightarrow \gamma\gamma_{dark}$)
- For massless γ_{dark} , BR($H\rightarrow \gamma\gamma_{dark}$) of 2.28% at 95% CL

Improvement by factor 2 wrt previous (CMS) result

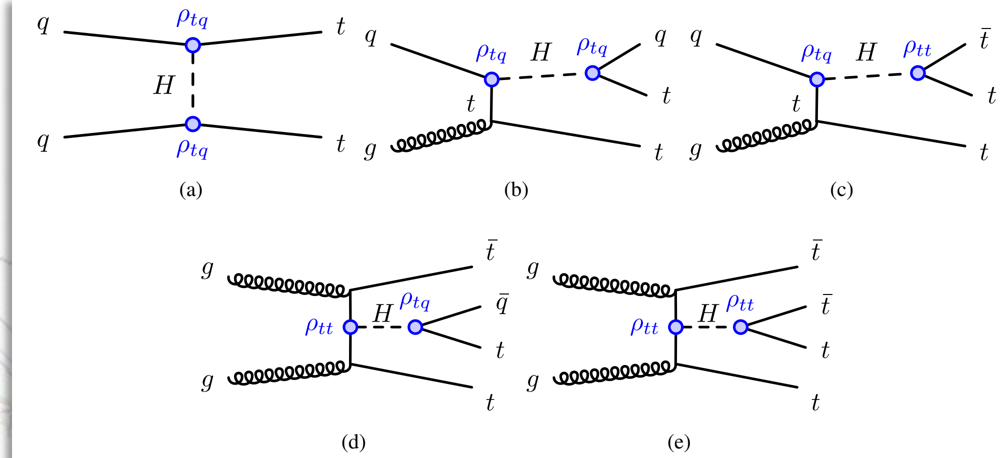
The BDT classifier output is used as discriminant for the final statistical analysis

$\sigma_{E_T^{miss}}$, $m_T(p_T^{\gamma}, E_T^{miss})$, $m_{\ell\ell}$, $m_{\ell\ell\gamma}$, p_T^{γ}, $\frac{|\vec{E}_T^{miss}+\vec{p}_T^{\gamma}|-p_T^{\ell\ell}}{p_T^{\ell\ell}}$

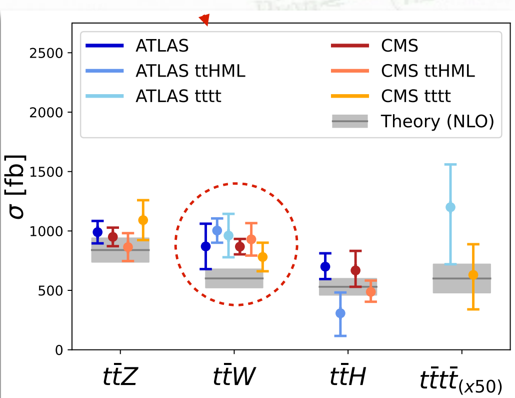
Heavy scalars with FV decays in final states with multiple leptons and b-jets

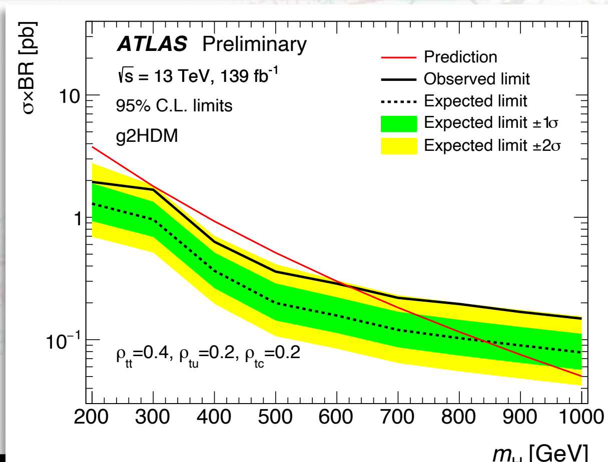
ATLAS-CONF-2022-039

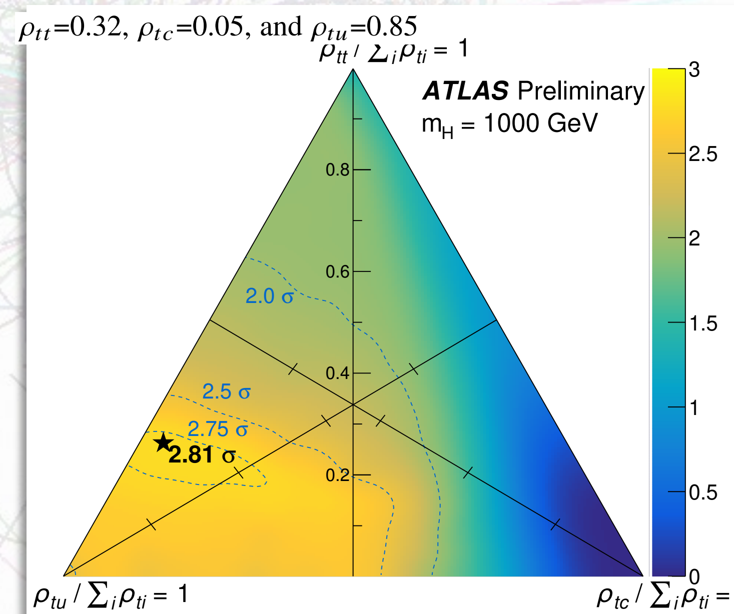
- Search for heavy scalar H from general 2HDM without Z_2 symmetry
- The first search targeting 3 top BSM production and first with 2HDM with flavour violation
  - only couplings involving top quarks considered: $\rho_{tt}, \rho_{tu}, \rho_{tc}$ - parameters of the model
  - m_H = [200 GeV, 1 TeV]
- Final state with multiple leptons (e,mu) and b-jets
  - 2lSS, 3l, 4l final states considered



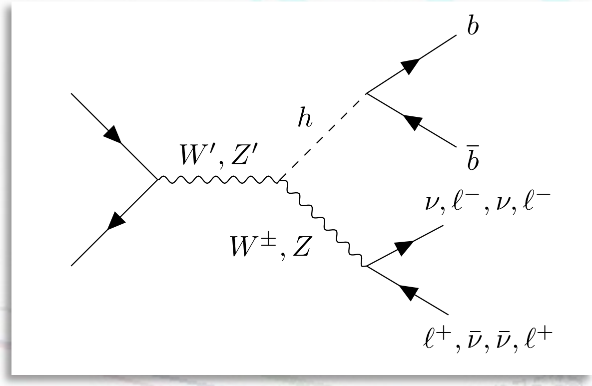
- 17 Signal Regions (DNN trained to classify the different signal channels) + 10 Control Regions => 27 analysis regions
- DNN trained over each SR region to separate signal and background
- Main backgrounds: ttW, ttZ, VV – from MC with normalisation during the fit

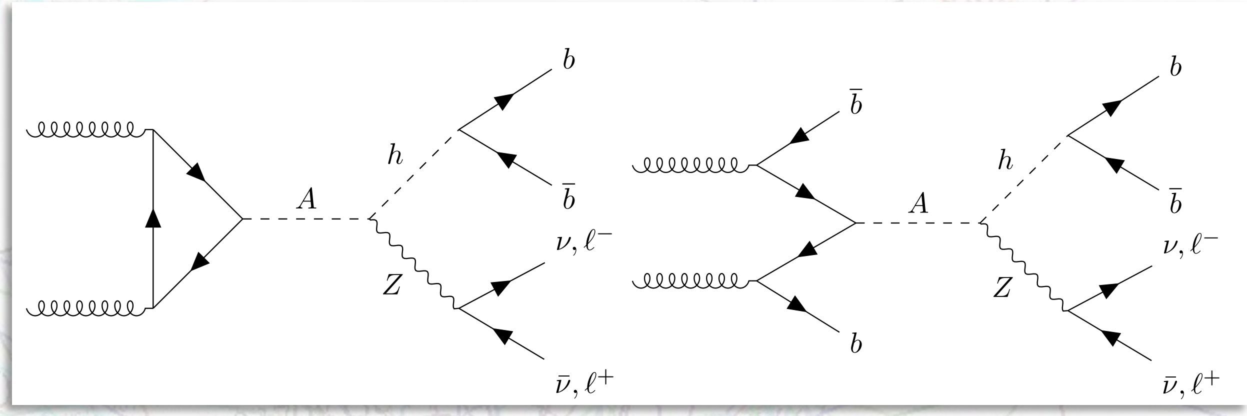




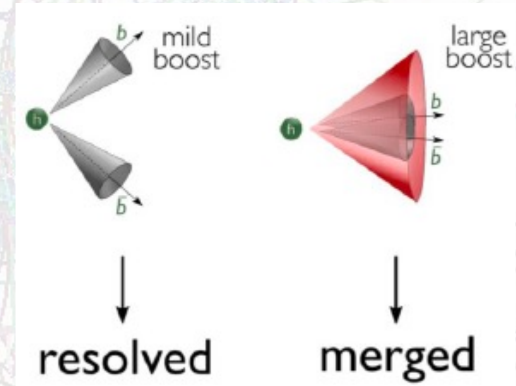


Most significant deviation observed at m_H=1TeV with local significance of 2.81 σ arXiv:2207.00230





- Search for heavy pseudoscalar A or new vector boson decaying to Z/W boson and SM Higgs
  - Heavy Vector Triplet W'/Z'
  - 2HDM
- Resonance mass tested
  - A: 220 GeV – 2 TeV
  - W',Z' : 220 GeV – 5 TeV

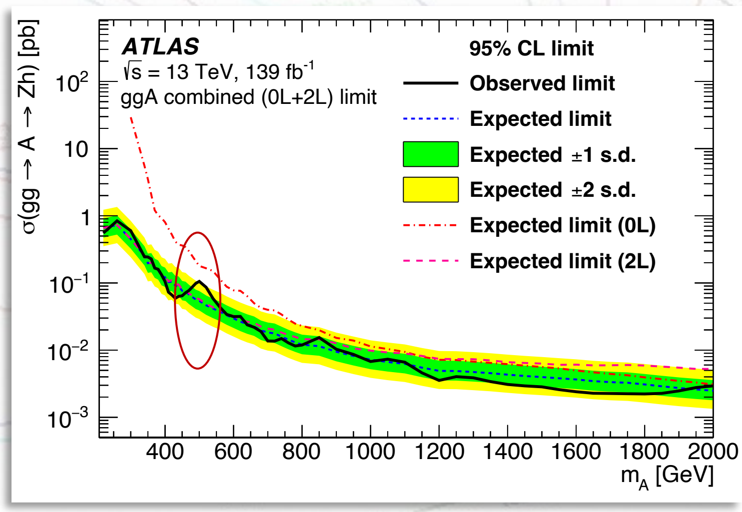


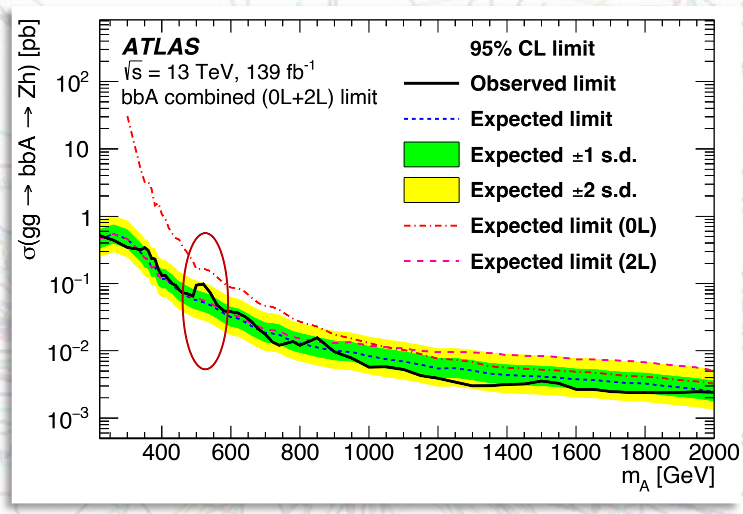
- Signal regions according to 0L/1L/2L and b-jet multiplicity
- MET/lepton trigger
- Two event categories depending on p_T^h: resolved and merged
  - dedicated jet reconstruction in merged case (large-R jets)
- Discrimination variable Vh resonance mass (0L->m_T^{Vh})
- Dominant backgrounds (depending on number of leptons): ttbar, Z/W+jets
- Backgrounds from MC with normalisation from fit to data, small QCD background data-driven

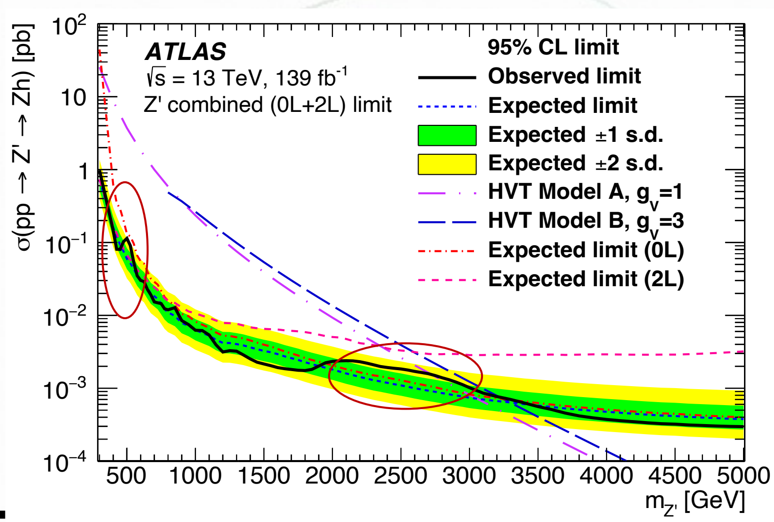
Heavy resonances into Z/W and Higgs boson in final states with leptons and b-jets

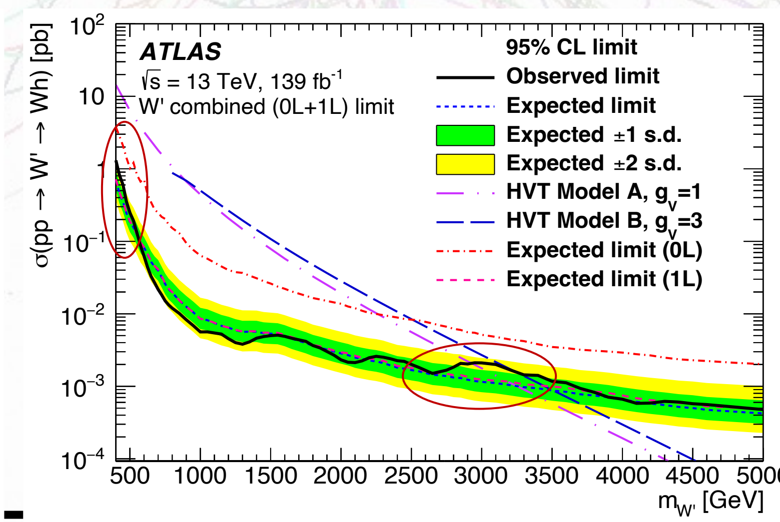
arXiv:2207.00230

- No significant excess observed
- Largest deviation from the SM expectation found at 500 GeV in ggA and Z′, corresponding to significance of ~2σ
- Similar excess in bbA - 1.6σ

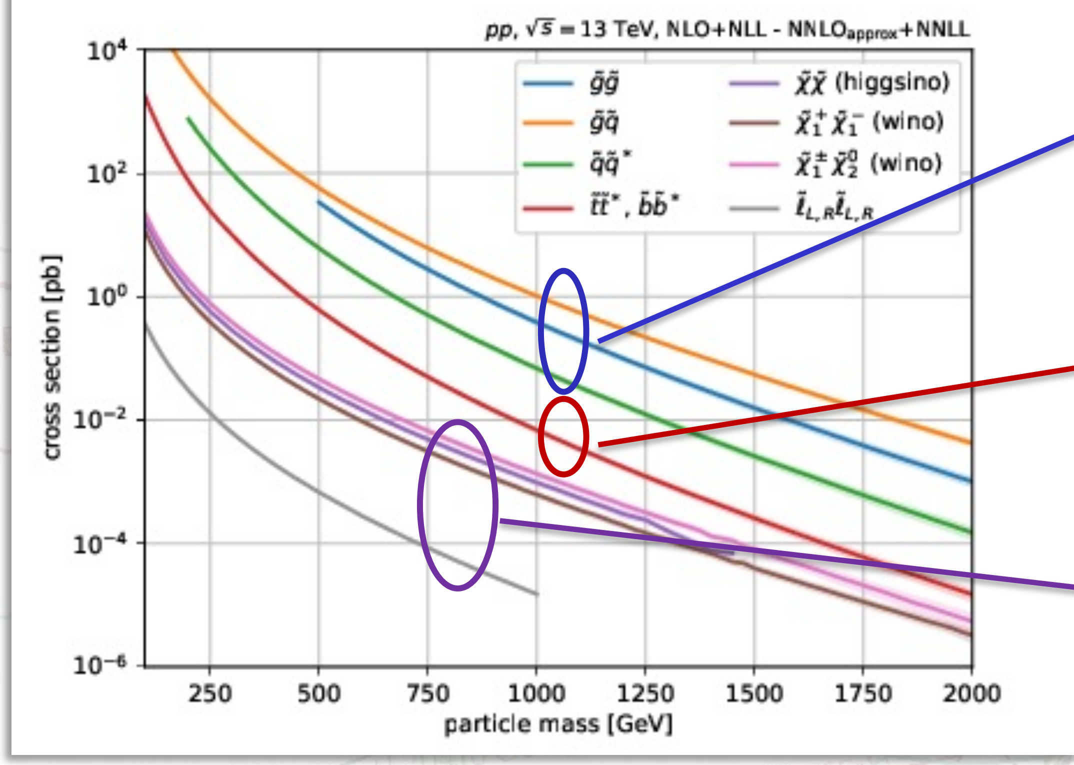








SUSY searches strategy



Strong production
- **Copious production**
- **Large MET in final state**

Third-generation sparticles
- Naturalness -> mass of ~O(TeV)
- Lighter than other squarks

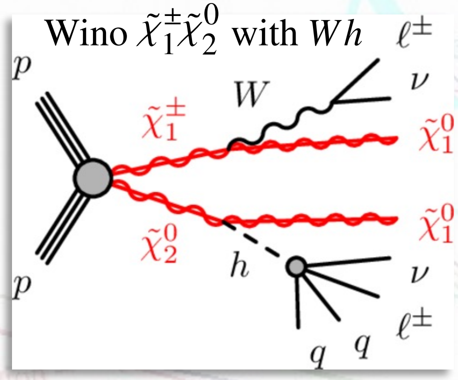
Electroweak production
- Coloured spartners too heavy
- Direct gaugino/higgsino/slepton production

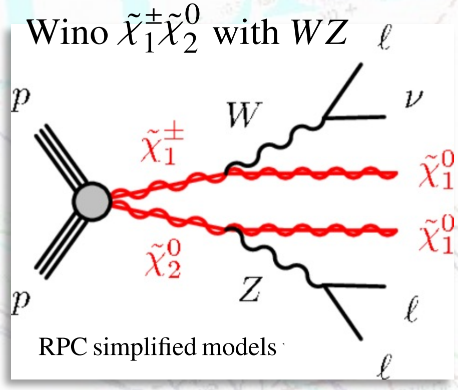
R-parity conservation vs R-parity violation (RPV)
- RPC – large MET from weakly interacting LSPs
- RPV - more leptons/jets and less or no MET
- RPV – prompt or delayed LSP decay

Long lived/metastable sparticles
- Supressed (effective) coupling
- Lack of phase space, e.g.mass degeneraces (compressed searches)
- May induce non-trivial signals in detectors
  - displaced vertices
  - disappearing tracks etc.

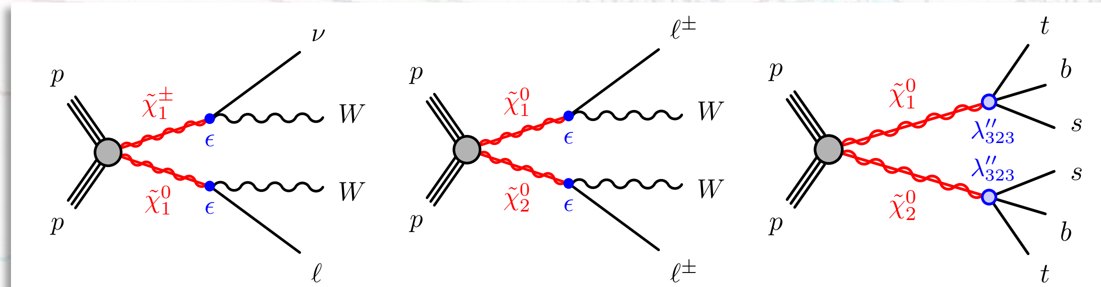
Same-sign 2L/3L from direct production of winos and higgsinos

ATLAS-CONF-2022-057



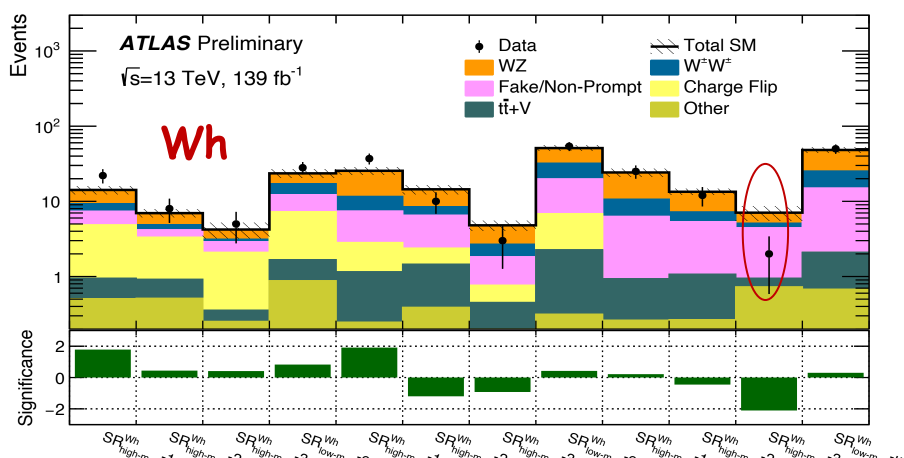


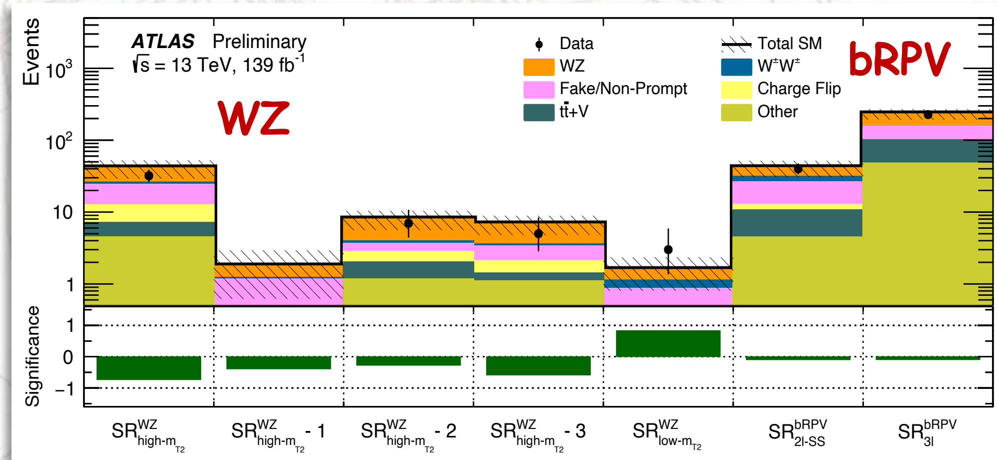
- Direct production of winos and higgsinos
  Models with and without R-parity conservation, and with different RPV origin (L or B violating terms)
- Final states considered: 2L SS (e/μ) or 3L



(a) Higgsino $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0$ bRPV (b) Higgsino $\tilde{\chi}_1^0\tilde{\chi}_2^0$ bRPV (c) Higgsino $\tilde{\chi}_1^0\tilde{\chi}_2^0$ UDD RPV

- Backgrounds mainly data-driven (fake leptons, charge misID, WZ/WW)
- The observed data are compatible with the SM prediction (mild deficit)

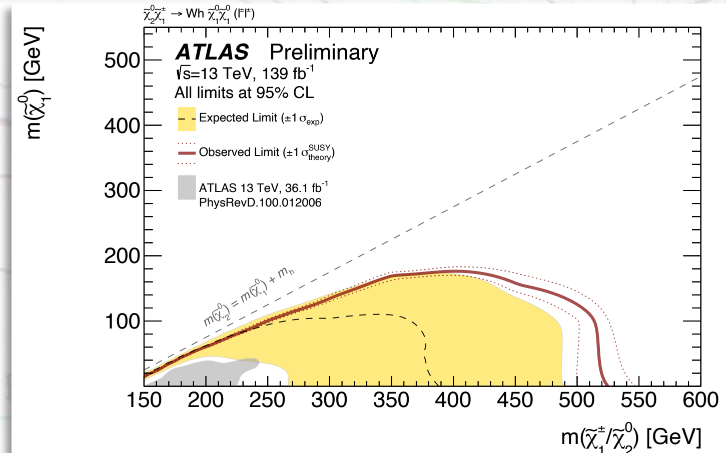


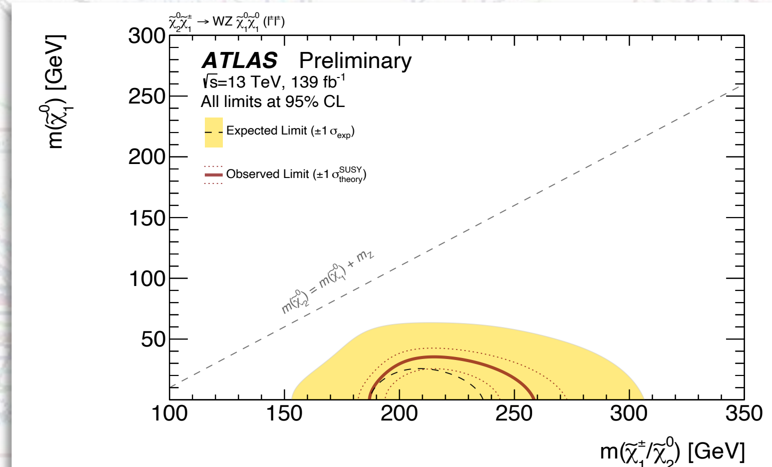


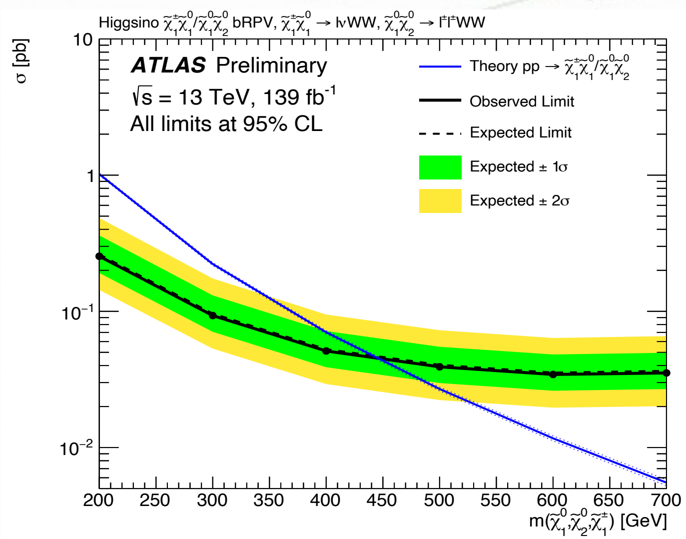
Same-sign 2L/3L from direct production of winos and higgsinos

ATLAS-CONF-2022-057

- The number of observed events and the background expectation in each SR are used to set an upper limit on the number of events from any BSM physics scenario.
- For intermediate states including Wh (WZ), wino masses up to 525 GeV (260 GeV) are excluded, for a bino of vanishing mass







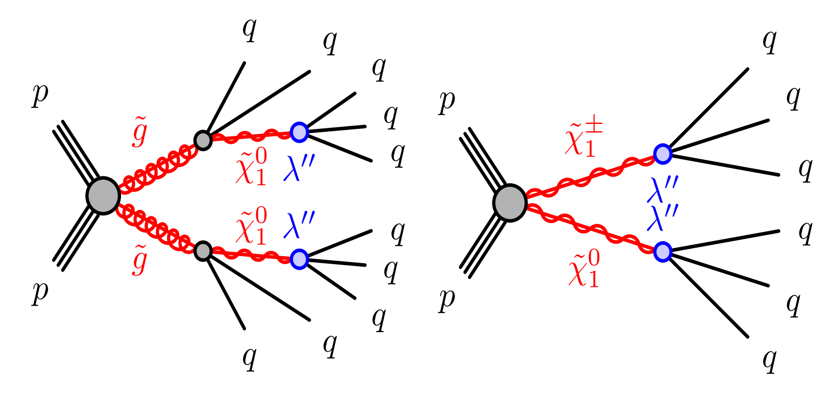
Higgsino masses smaller than 440 GeV are excluded in bRPV

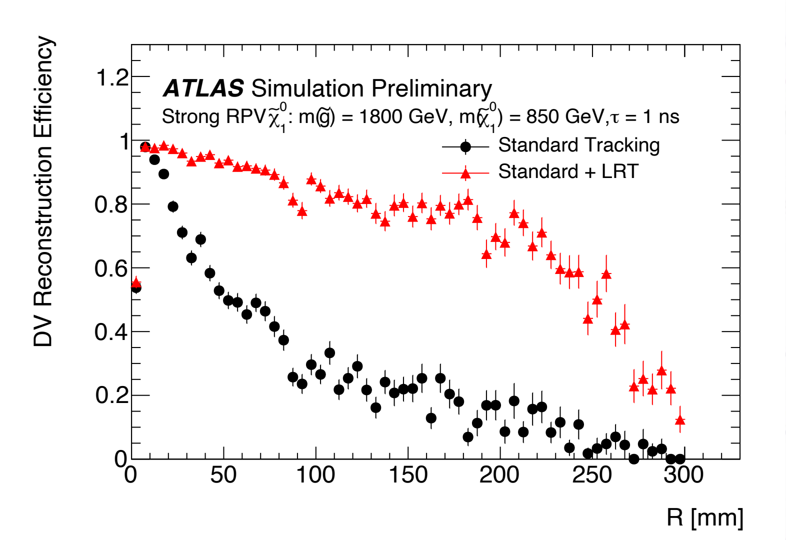
The first experimental constraint on bRPV models with degenerate higgsino masses

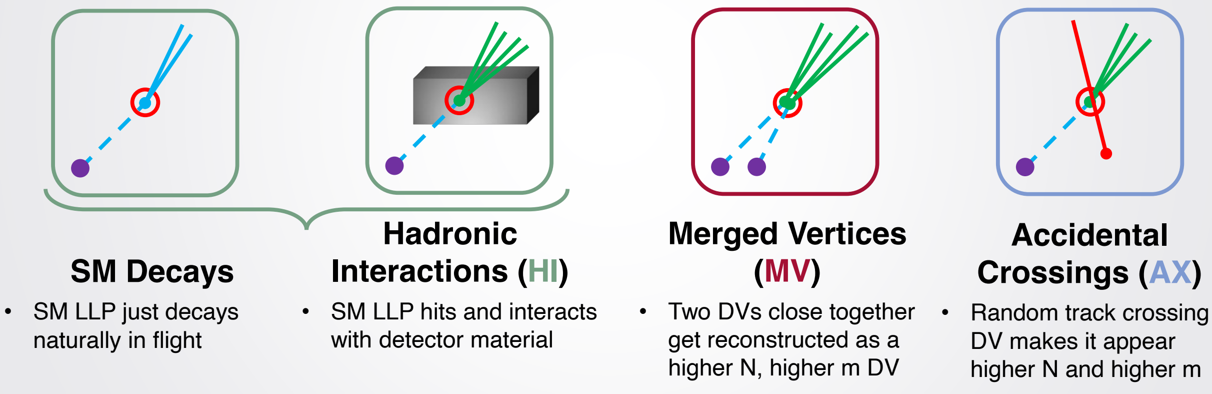
Displaced vertices + jets

ATLAS-CONF-2022-054

- General search for heavy LLPs decaying in hadrons
  - B-number violating RPV, gaugino->qqq, Λ'' **small coupling**
  - Lifetime O(10) ns – decaying in the ID **creating displaced verices (DV) with high mass and large track multiplicity**
- DV reconstruction possible up to 300 mm thanks to dedicted track reconstruction – Large Radius Tracking
  - Uses left-over hits after standard tracking with looser impact parameters constrains
  - Computationally expensive, run only on events passing high-pT jets and "trackless jets" filters
- Dedicated secondary-vertex reconstruction algorithm
- 2 SRs: high-pT jet and trackless jet
- Nearly background-free search
  - Small backgrounds from hadronic interactions and instrumental effects
  - Data-driven inclusive estimation







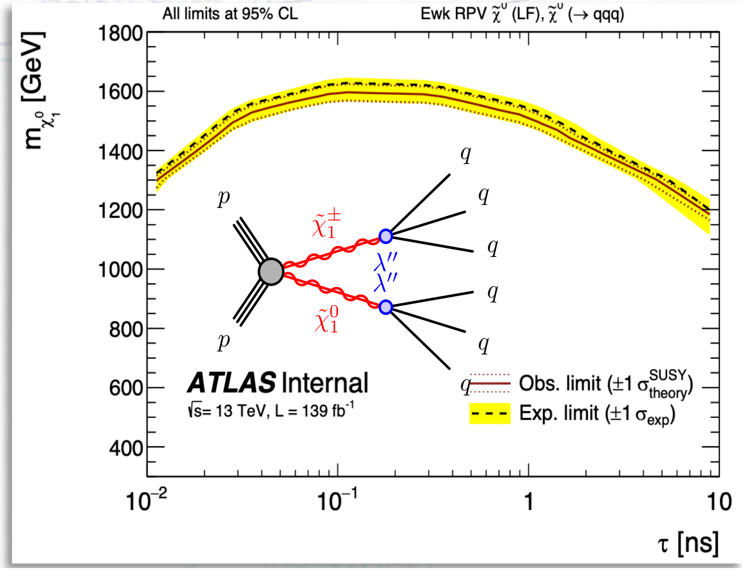
Displaced vertices + jets

ATLAS-CONF-2022-054

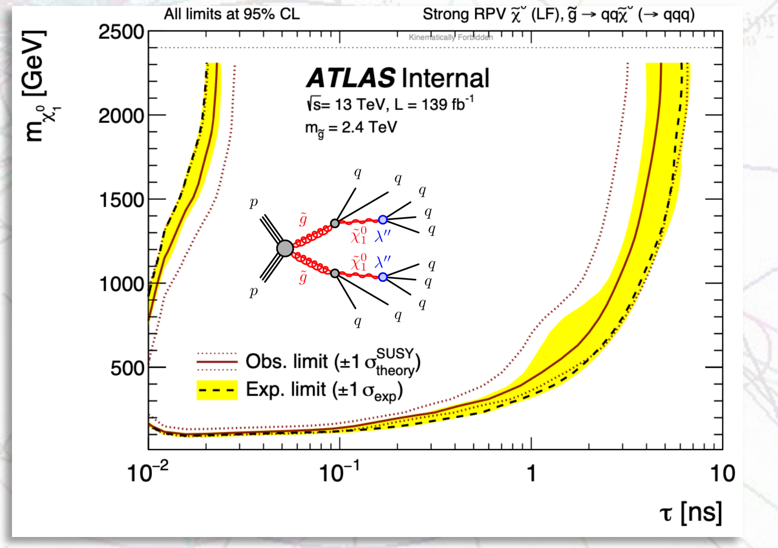
Signal Region	Observed	Expected
High-p_T jet SR	1	$0.46^{+0.27}_{-0.30}$
Trackless jet SR	0	$0.83^{+0.51}_{-0.53}$

- No events are observed in the Trackless jet SR, while a single event is observed in the High-pT jet SR
- The observed event yields are in good agreement with the background-only expectations
- The single event observed in the High-pT jet SR contains 7 selected jets with p_T above 90.8 GeV, and 1 selected DVs. The DV has 5 tracks, m_{DV} = 32.6 GeV, and net electric charge of $-1e$.

The predicted backgrounds and observed yields in the two signal regions are used simultaneously to set exclusion limits on the BSM signal models of interest



Observed limit above 1.5 TeV for lifetimes between 0.03 ns and 1 ns



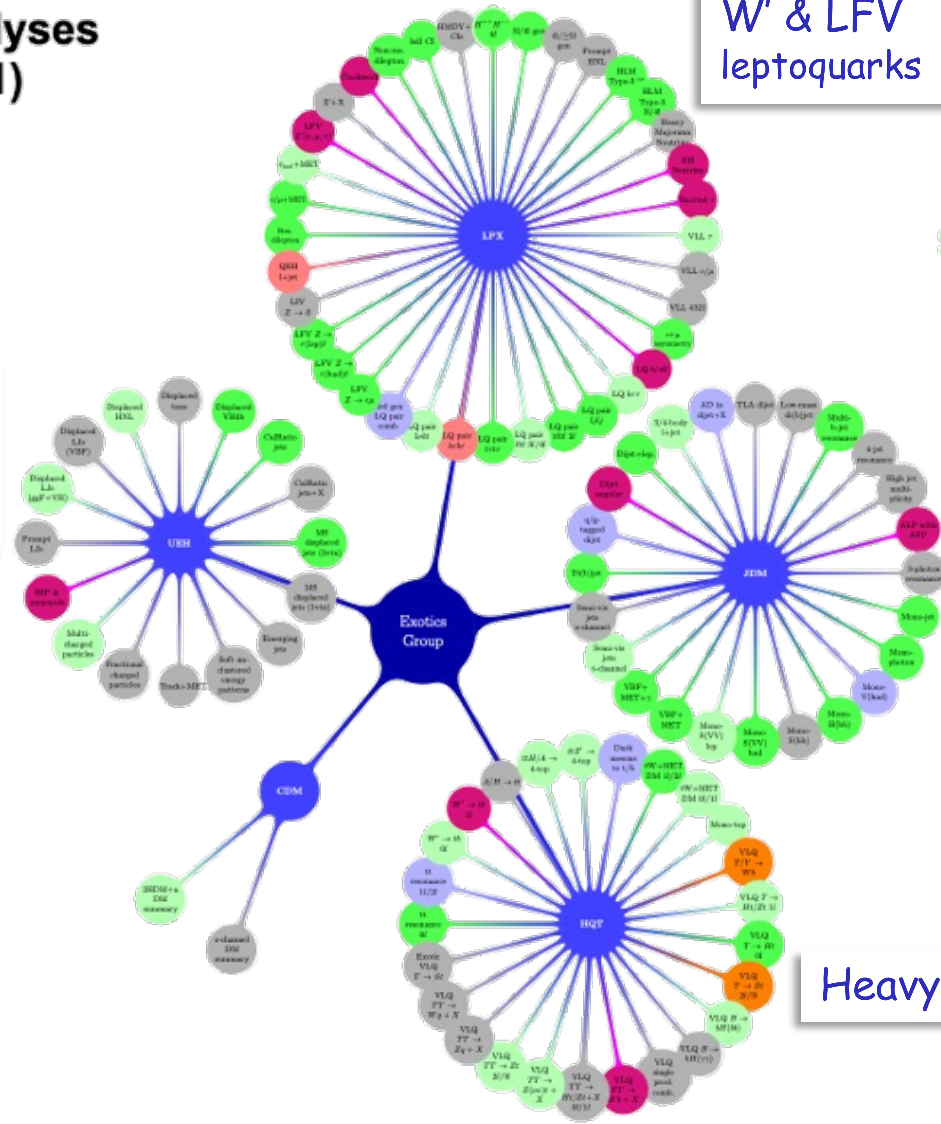
Stronger limits in strong production model

Exotics (non-SUSY)

Full Run 2 analyses (Release 21)

September 2022

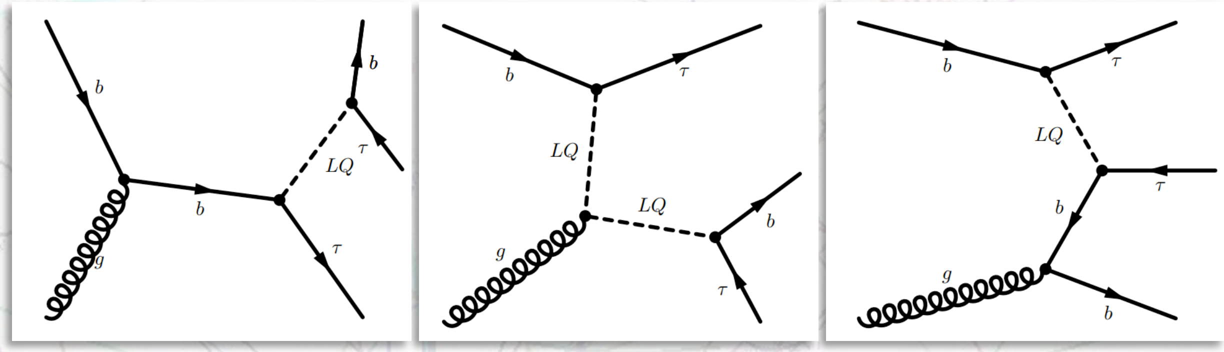
Kicked-off
With EB
In SG approval
In group approval
ATLAS circulation
Submitted / CONF-conv
Accepted / Published



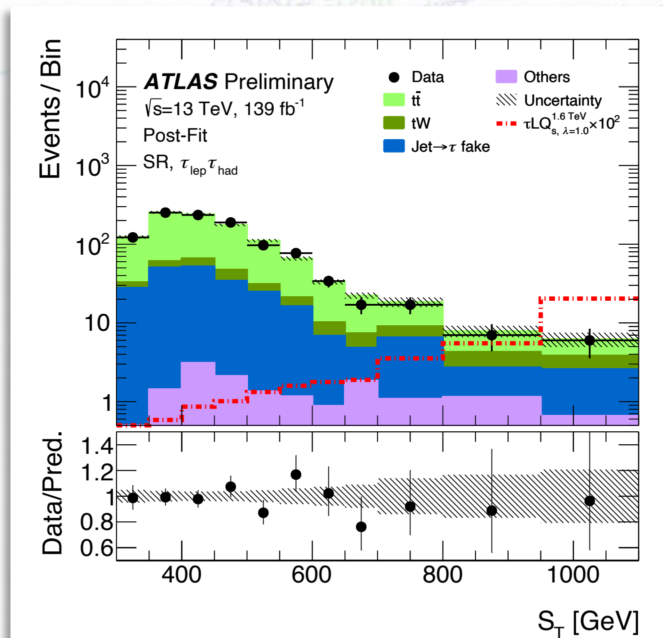
Scalar leptoquarks in bττ final state

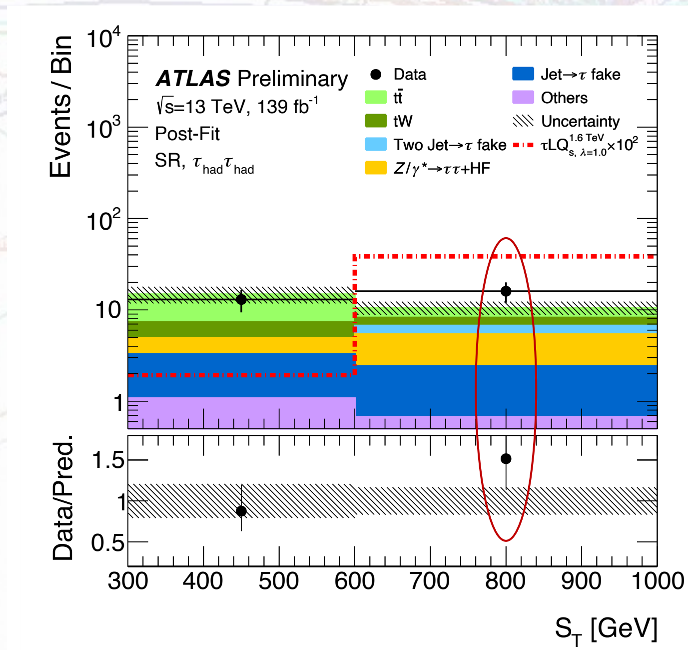
ATLAS-CONF-2022-037

- Single scalar leptoquark (LQ) production model (+4/3e, F=3B+L = −2)
  - observed LFU deviations can be explained by LQs
- Decays into 3rd generation: $b\tau$
- Final state: τ τ b
- First ATLAS result for such a search
- Parameters: m_{LQ} 0.4-2.4 TeV, λ 0.5-2.5



- Two channels $\tau_{lep}\tau_{had}$ (single lepton trigger) and $\tau_{had}\tau_{had}$ (single τ_{had} trigger)
- Discriminant variable: S_T-scalar p_T sum of the two τ's and the leading-p_T b-jet





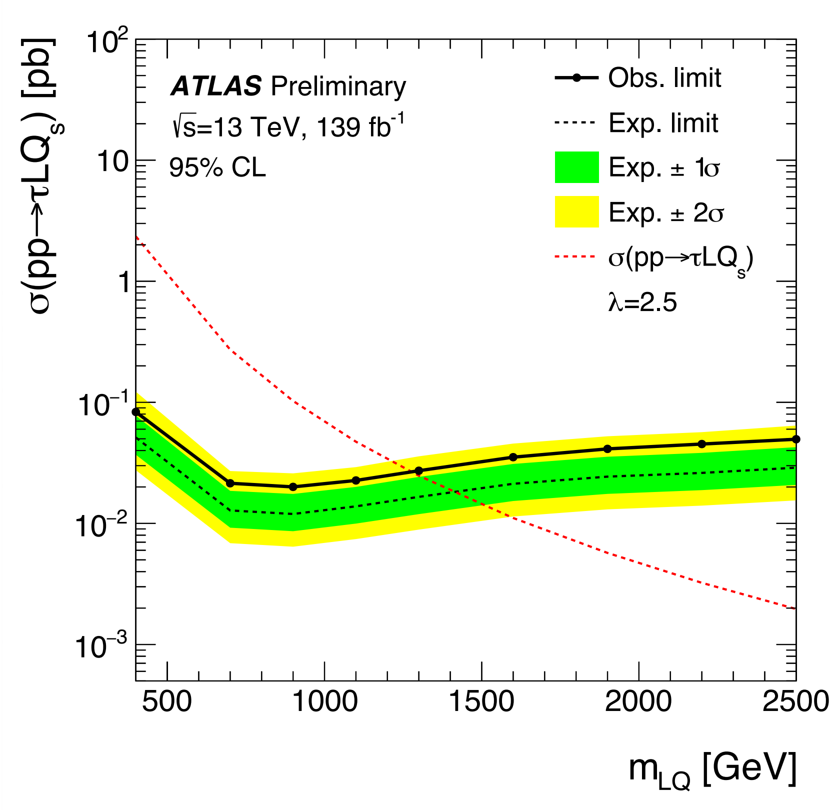
Backgrounds:

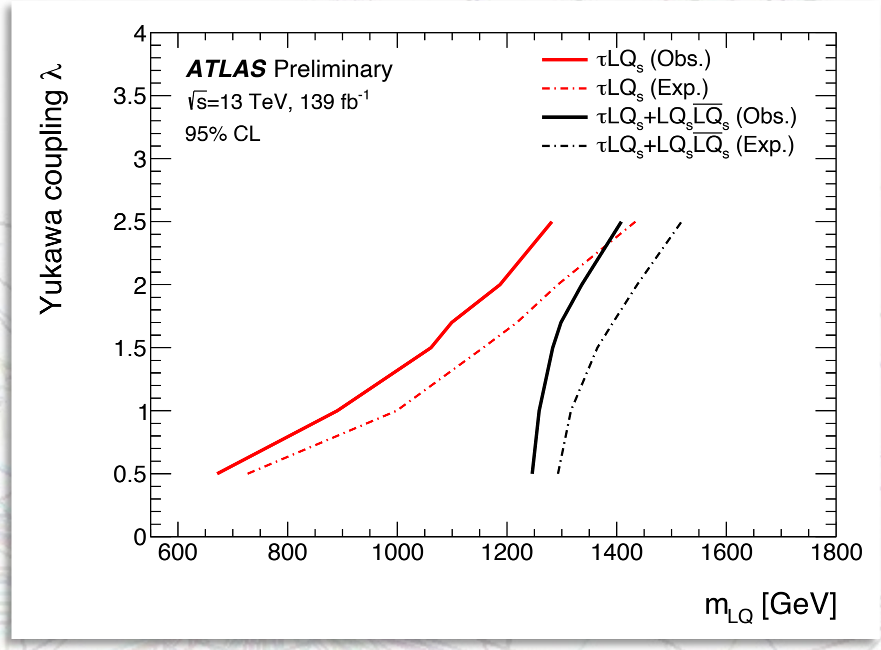
- ttbar, single top - MC with correction (SF=f(ST))
- Fake τ - MC with correction
- Multi-jet events: data-driven method
- Z+jets - MC with normalization correction
- W+jets and Diboson – MC

- No significant excess observed in data

Scalar leptoquarks in bττ final state

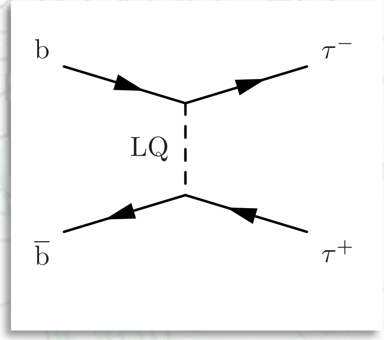
ATLAS-CONF-2022-037





CMS has excess in similar analysis CMS-PAS-EXO-19-016 => 3.4σ for LQ mass of 2 TeV and λ =2.5 but including t-channel

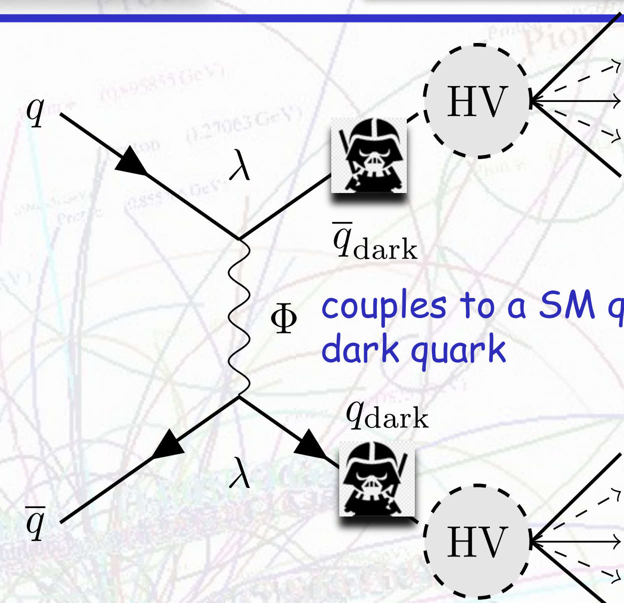
No excess:
$m(LQ)$ < 1.26 TeV, 1.30 TeV and 1.41 TeV are excluded for Yukawa coupling to *b*τ of 1.0, 1.7 and 2.5, respectively
For the chosen LQ model, masses below 1.25 TeV are excluded for all λ above 0.5.



Semi-visible jets, t-channel

ATLAS-CONF-2022-038

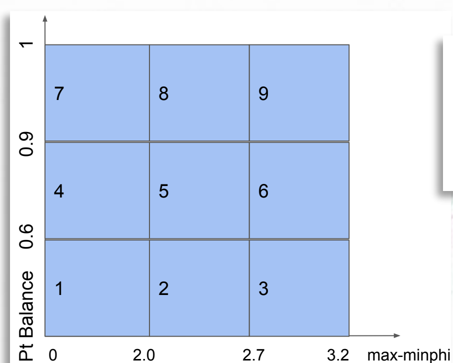
- Sensitive to strongly coupled dark sector
- Scalar mediator (Φ) acts as portal
- Focus on t-channel (non-resonant)
  - first for both experiments
- The ratio of the rate of stable dark hadrons over the total number of hadrons in the event => R_{inv} (free parameter of the model)
- Reconstructed jets geometrically encompassing the dark hadrons => semi-visible jets (SVJ)



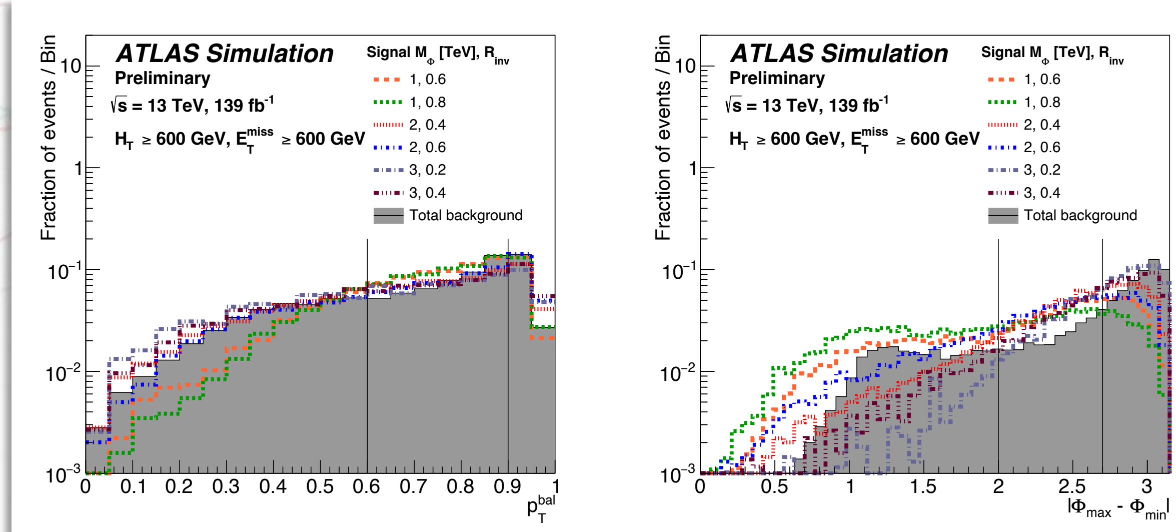
Φ couples to a SM quark and a dark quark

final state consisting of SM hadrons and dark hadrons, governed by the R_{inv} fraction

- MET trigger
- Key variables: MET, **Scalar jet p_T sum (H_T)**, DeltaPhi (closest jet, MET) , p_T balance (between closest and farthest jet from MET), difference in azimutal angle between those two jets
- Signal region MET and HT >600 GeV

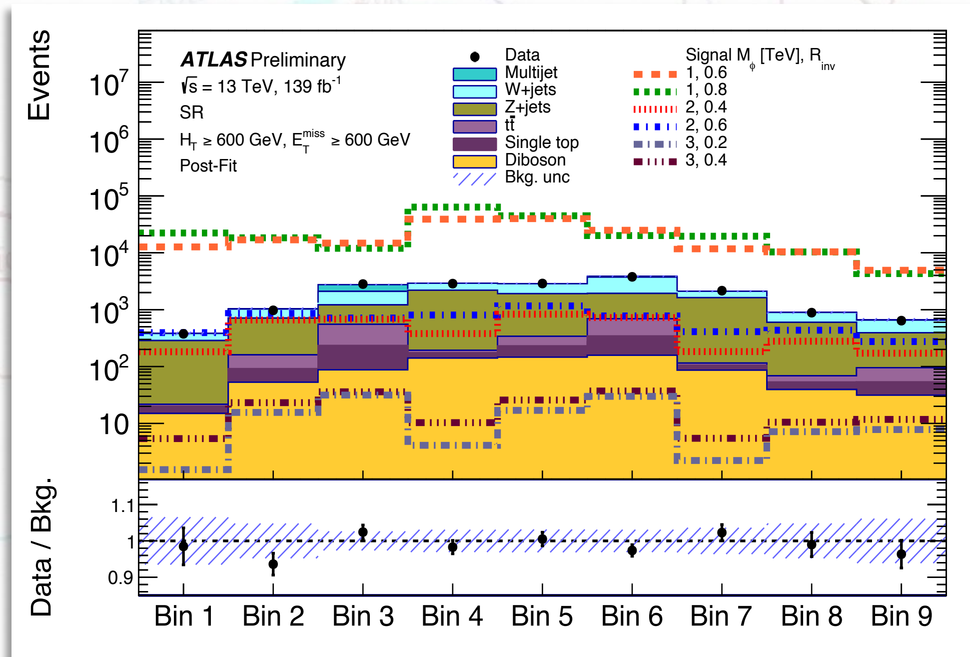


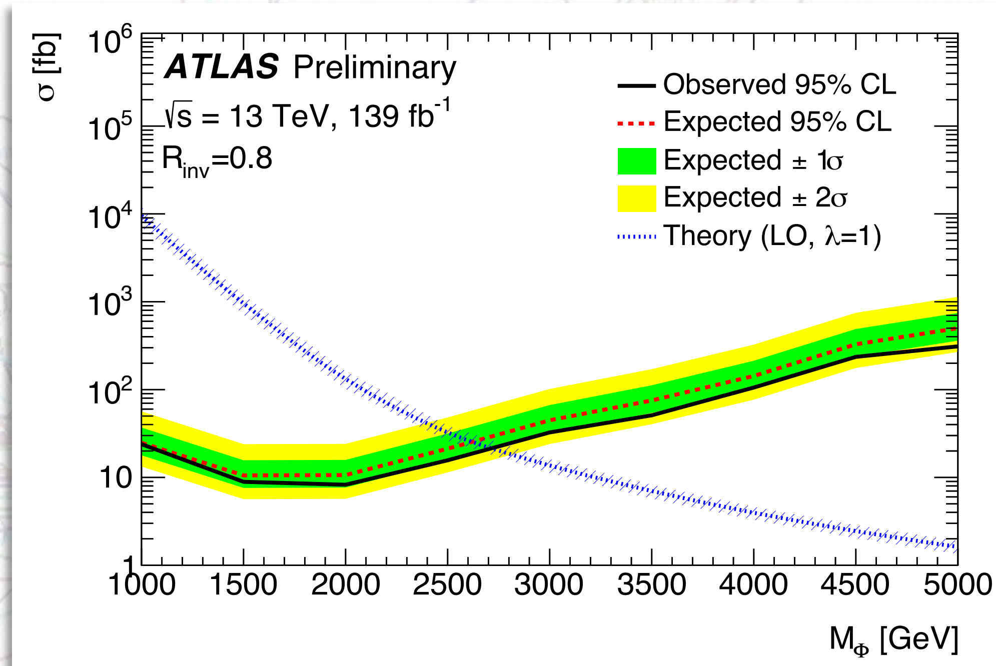
Yields in 9 bins in SR used for statistical analysis



Semi-visible jets, t-channel

ATLAS-CONF-2022-038





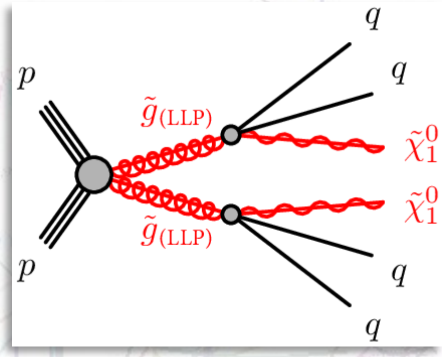
- The first limits on the SVJ *t*-channel production for mediator masses ranging from 1–5 TeV, and for R_{inv} of 0.2–0.8.
- The observed limits increase from 2.4 TeV for R_{inv} = 0.2 to 2.7 TeV for R_{inv} = 0.8

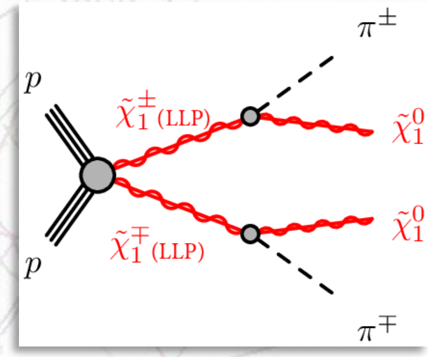
Heavy, long-lived, charged particles with large ionisation energy loss

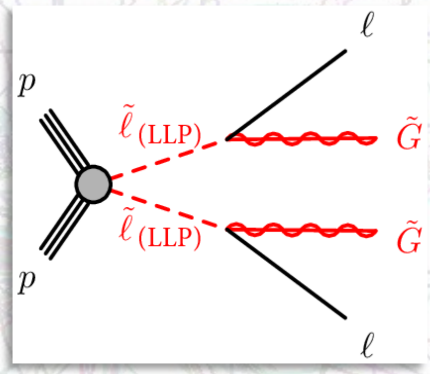
arXiv:2205.06013

Long lived particle particles (LLPs) are predicted by e.g. certain SUSY models:

- **Gluinos:** form R-Hadrons when R-parity conserved and squark mass scale very high (split-SUSY)
- **Charginos:** the mass splitting between the neutralino counterpart is highly degenerate
- **Sleptons** : the quasi-massless gravitino is assumed to be LSP and the coupling between the slepton and gravitino is very week



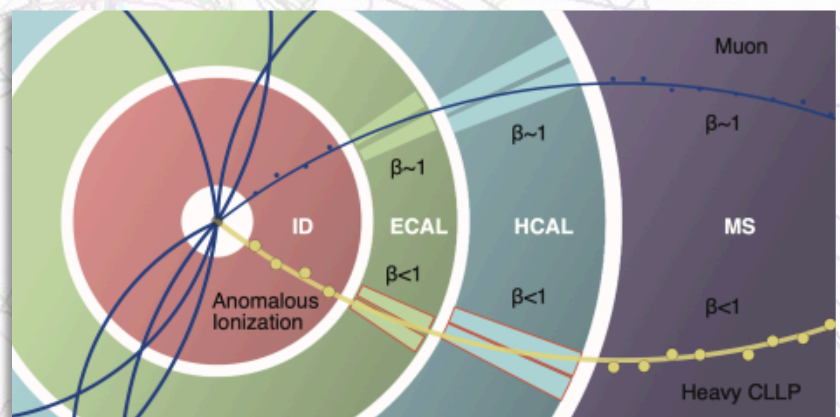




Unique opportunity to observe a SUSY particle directly!

- Charged particles crossing the detectors => ionisation losses (dE/dx) along their paths
- Charged **heavy** (slow) particles => significantly higher ionisation
- The pixel detector can measure dE/dx for R<13 cm
  - identify LLPs with lifetime of O(1) ns
- Using dE/dx => extraction of $\beta\gamma$ of the particle in the range [0.3-0.9] => derive the mass of the particle

- This method does not depend on the way the LLP interacts in the calorimeters or on the LLP decay mode
  - no dependence on the specific models

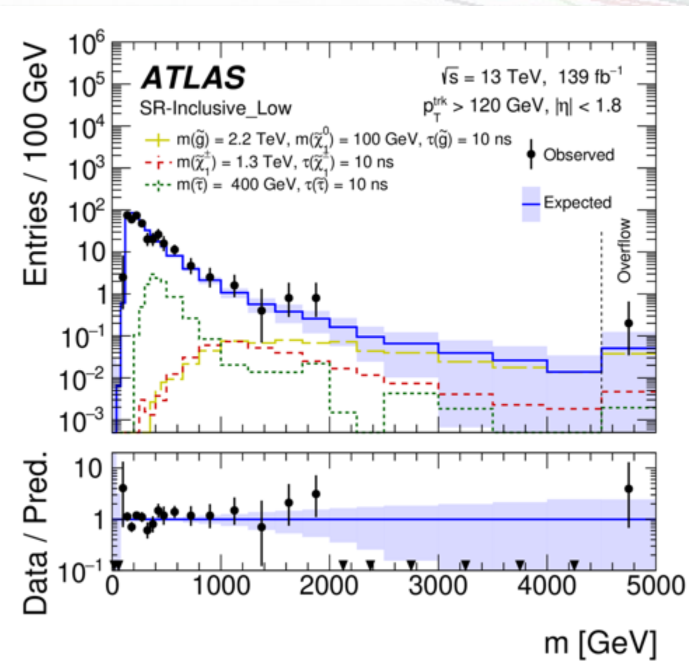


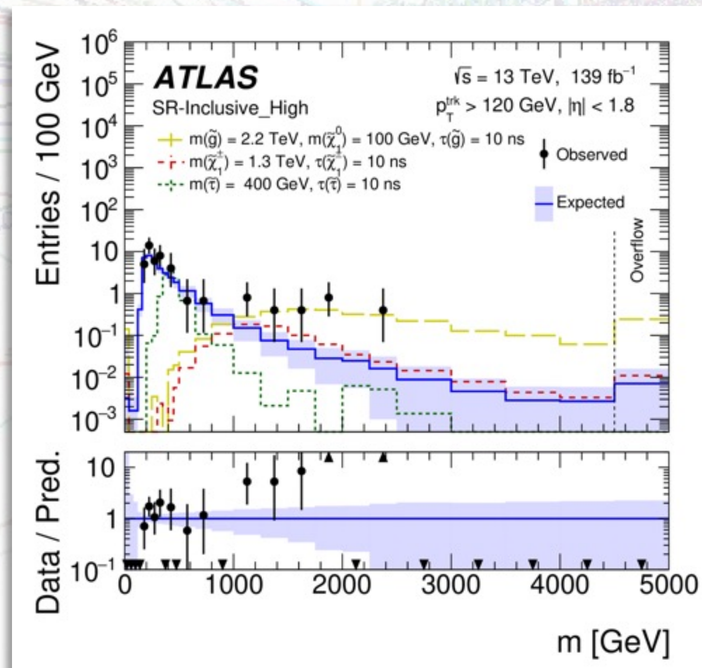
- MET trigger
- Isolated tracks with high p_T and large ionisation
  - only central tracks ($|\eta|$ < 1.8) are used to reduce background events

Heavy, long-lived, charged particles with large ionisation energy loss

arXiv:2205.06013

- Two SRs depending on presence of IBL overflow (signal outside IBL dynamic range)
- Background estimated using data-driven method
  - generate bkg tracks from measured events (1/pT and dE/dx) in CRs inverting cuts (where each CR accurately reproduces pT or dE/dx of the SR)
  - Normalize obtained mass distribution to data in low mass CR
  - validate in dedicated regions: low track pT ([50, 100] GeV) and high η ([1.8, 2.5])
- Identify mass windows containing 70% of the expected signal and set limits or find excesses in those windows





Observed excess in the SR-Inclusive-High for m>1 TeV

- observed 7 events where 0.7±0.4 were expected
- local significance 3.6σ, global significance of 3.3σ

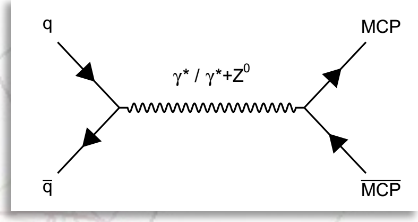
Cross-check with timing variables show that candidate tracks have β≈1, which does not support a heavy LLP signal-like interpretation of the excess

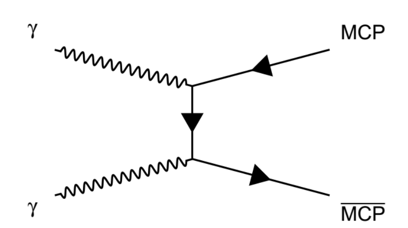
Follow up analysis under way including additional detector information

Long-lived highly ionizing heavy muon-like particles with high electric charges

ATLAS-CONF-2022-034

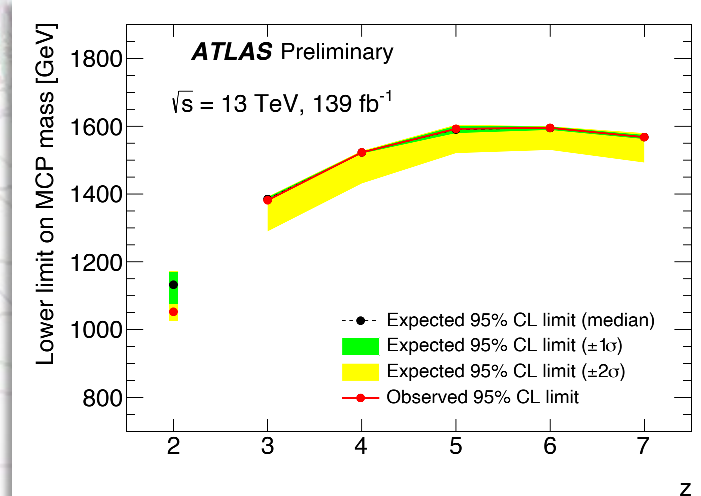
- "Blue-sky" search, but some models in fact predict new particles with charges > 1:
  - almost commutative geometry model (AC-leptons), walking technicolor model (techni-leptons), left-right symmetric model (doubly charged H)
- Signature is a muon-like object with high ionisation losses in both ID and MS
  - dE/dx measured in Pixel, TRT and MS – **dE/dx ~ z^2**
- High mass → low β → muon-trigger-timing window can be too short for these particles
  - dedicated late-muon trigger in addition to standard muon and MET triggers
- Background: detector occupancy and noise
  - estimated using an ABCD method
- **Results consistent with the expectations within ±2σ**





Selection	$N_{\text{data}}^{\text{A observed}}$	$N_{\text{data}}^{\text{B observed}}$	$N_{\text{data}}^{\text{C observed}}$	$N_{\text{data}}^{\text{D expected}}$	$N_{\text{data}}^{\text{D observed}}$
$z = 2$	24 294	4039	9	1.5 ± 0.5 (stat.) ± 0.5 (syst.)	4
$z > 2$	192 036 934	15 004	441	0.034 ± 0.002 (stat.) ± 0.004 (syst.)	0

- ***MCP analysis sees 2 from 7 excess events from pixel dE/dx analysis***
  - they are compatible with those satisfying the $z = 2$ tight-selection requirement in MCP analysis, but not ending up in the corresponding signal region
  - these events have good enough dE/dx in pixel, but sufficient dE/dx in TRT or MDT



Summary

- Several highlights presented from a broad ATLAS program searching for Physics Beyond the Standard Model:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HDBSPublicResults
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

- So far we haven't discovered any Beyond the SM Physics yet
- ATLAS (and CMS) analyses showed a couple of small excesses being followed up
  - need more statistics - but for small excesses Run3 data set only brings small improvement to significance
  - already started to work on
    - more sophisticated reconstruction and analysis techniques
    - characterizing searches by final state instead of specific BSM model
    - new ideas being explored

- Stay tuned for reinterpretations, combinations, less model dependent scans - many Run2 analyses still going to be published and first Run3 data at 13.6 TeV is coming in

Beyond the Standard Slides

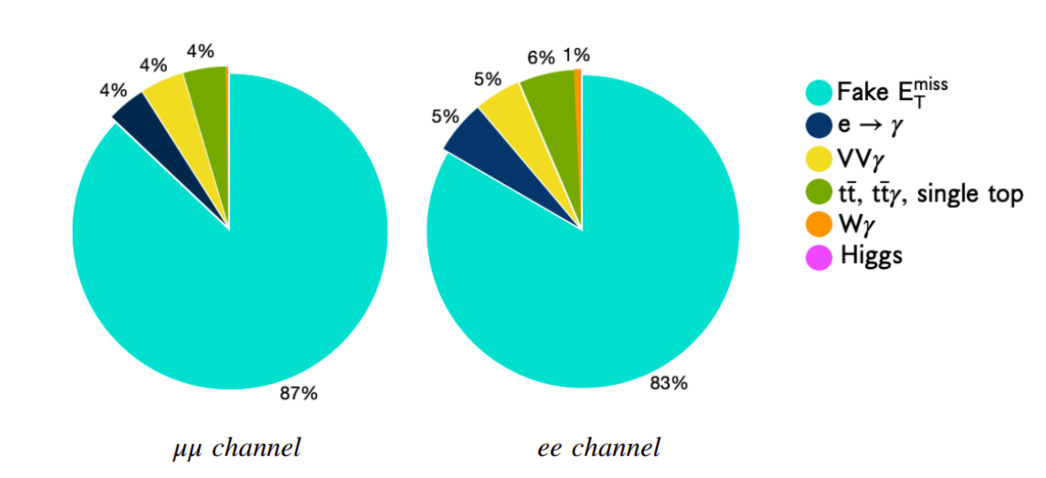
Courtesy of J. Keller

Dark photons from Higgs boson decays via ZH production

ATLAS-CONF-2022-064

Table 3: Optimised kinematic selections defining the signal region for $\ell^+\ell^-\gamma + E_T^{miss}$.

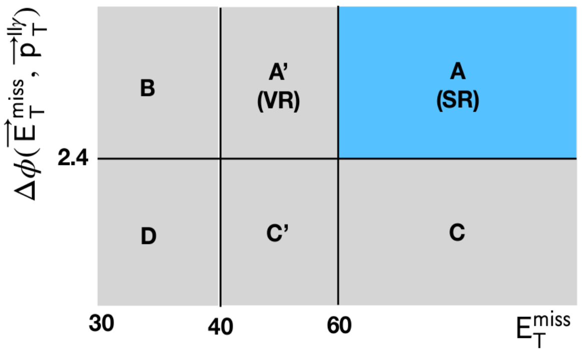
Two same flavour, opposite sign, medium ID and loose isolated leptons, with leading p_T > 27 GeV, sub-leading p_T > 20 GeV
Veto events with additional lepton(s) with loose ID and p_T > 10 GeV
76 GeV < $m_{\ell\ell}$ < 116 GeV
Only one tight ID, tight isolated photon with E_T^γ > 25 GeV
E_T^{miss} > 60 GeV with $\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{\ell\ell\gamma})$ > 2.4 rad
$m_{\ell\ell\gamma}$ > 100 GeV
$N_{jet} \leq 2$, with p_T^{jet} > 30 GeV, $\lvert\eta\rvert$ < 4.5
Veto events with b-jet(s)



- **ABCD method**, based on E_T^{miss} and $\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{\ell\ell\gamma})$ variables:

$$N_A^{fakeMET} = R\frac{N_B N_C}{N_D} \quad , \quad R = \frac{N_{A+A'}^{MC} N_D^{MC}}{N_{C+C'}^{MC} N_B^{MC}}$$

  - R takes into account possible correlation between the 2 variables
  - N_X is number observed data in region X, after subtraction of the contribution from non fake E_T^{miss} backgrounds



Heavy scalars with FV decays in final states with multiple leptons and b-jets

ATLAS-CONF-2022-039

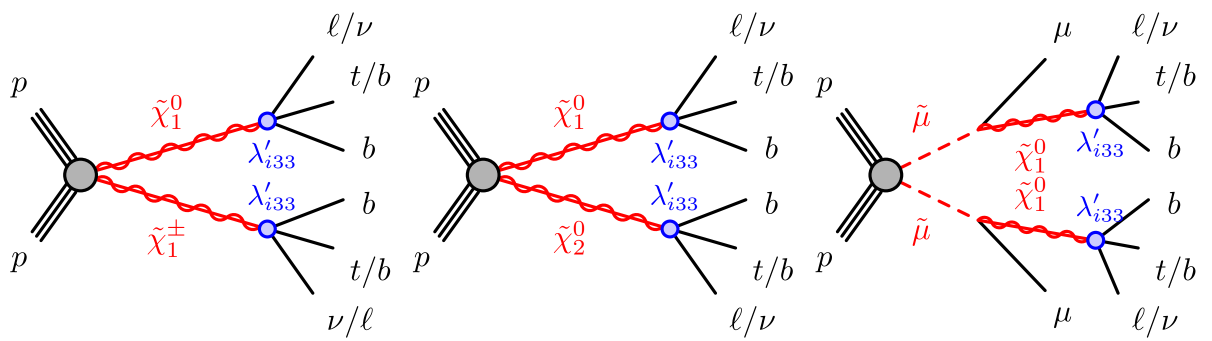


Figure 2: Signal diagrams for the RPV SUSY signals used as additional interpretation in the analysis. The subsequent decay can lead to a final state with high multiplicity of leptons and b-jets which is targeted by the search.

Table 5: Input variables to the training of the DNN^{cat} and DNN^{SB} discriminants.

Variable	DNN^{cat}	DNN^{SB}
Number of jets (N_{jets})	✓	✓
Sum of pseudo-continuous b-tagging scores of jets	✓	✓
Pseudo-continuous b-tagging score of 1st, 2nd, 3rd leading jet in p_{T}	✓	✓
Sum of p_{T} of the jets and leptons ($H_{T,jets}$, $H_{T,lep}$)	✓	✓
Angular distance of leptons (sum in the case of 3ℓ and 4ℓ)	✓	✓
Missing transverse energy	✓	✓
Leading transverse momentum of jet	-	✓
Invariant mass of leading lepton and missing transverse energy	-	✓
Di/tri/quad-lepton type variable (associated to the number of electrons/muons in event)	-	✓

Heavy scalars with FV decays in final states with multiple leptons and b-jets

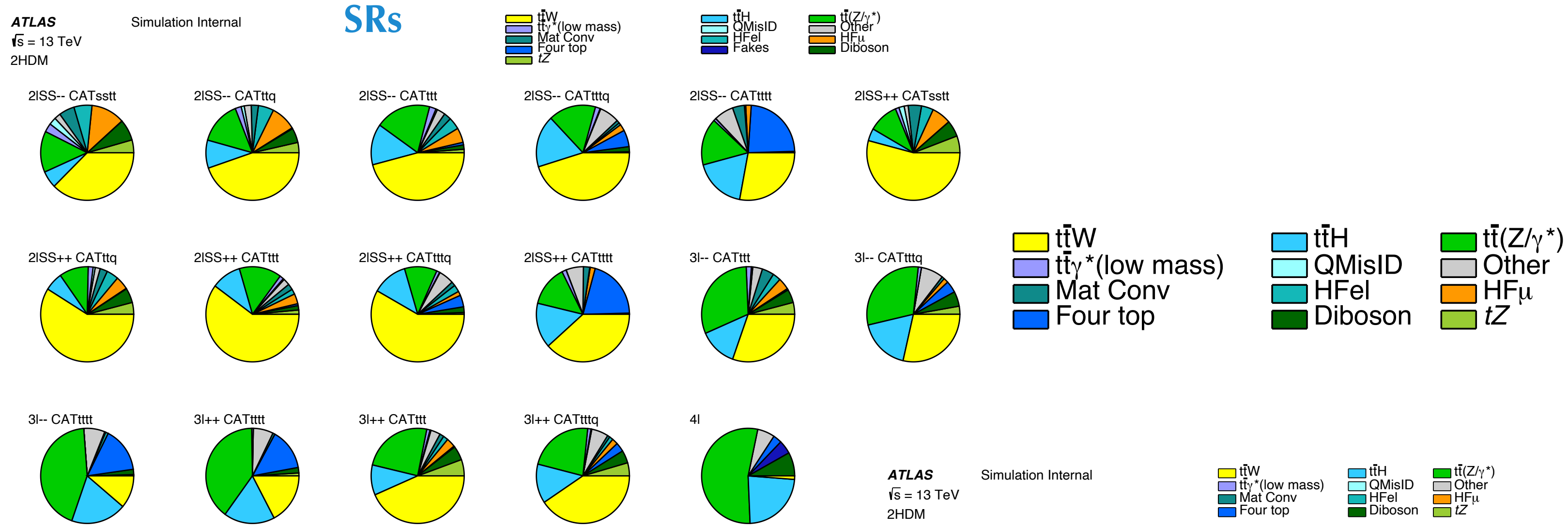
ATLAS-CONF-2022-039

Table 3: Event selection summary in the signal regions. Leptons are ordered by p_T in the 2ℓSS and 4ℓ regions. In the 3ℓ regions the lepton with opposite-sign charge is taken first, followed by the two same-sign leptons in p_T order. In the lepton selection, *T, M, L* stand for Tight, Medium and Loose lepton definitions. In the region naming, the "CAT ttX" denotes the category based on the DNN^{cat} output enriched in the signal process "ttX". Each of these regions is split according to the lepton charge of the same-sign lepton pair ("++" or "- -").

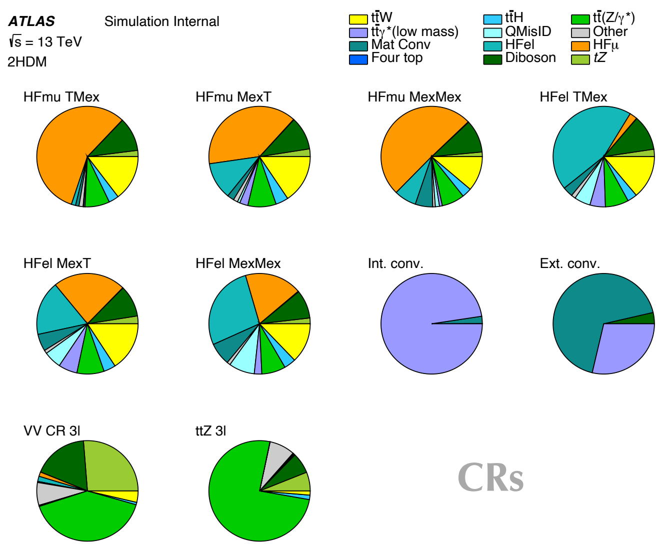
Lepton category	2ℓSS	3ℓ	4ℓ
Lepton definition	(T,T) with $\geq 1\ b^{60\%}$ || (T,M) with $\geq 2\ b^{77\%}$	(L,T,M) with $\geq 1\ b^{60\%}$ || (L,M,M) with $\geq 2\ b^{77\%}$	(L,L,L,L)
Lepton p_T [GeV]	(20, 20)	(10, 20, 20)	(10, 10, 10, 10)
$m_{\ell^+\ell^-}^{OS-SF}$ [GeV]	–	>12	
$\lvert m_{\ell^+\ell^-}^{OS-SF} - m_Z\rvert$ [GeV]	–	>10	
N_{jets}	≥ 2		
$N_{b-\text{jets}}$	$\geq 1\ b^{60\%}$ || $\geq 2\ b^{77\%}$		
Region split	(sstt, ttq, ttt, tttq, tttt) $\times$ (Q^{++}, Q^{--})	(ttt, tttq, tttt) $\times$ (Q^{+}, Q^{-})	–
Region naming	2ℓSS ++ CAT sstt	3ℓ ++ CAT ttt	4ℓ
	2ℓSS ++ CAT ttq	3ℓ ++ CAT tttq	
	2ℓSS ++ CAT ttt	3ℓ ++ CAT tttt	
	2ℓSS ++ CAT tttq	3ℓ −− CAT ttt	
	2ℓSS ++ CAT tttt	3ℓ −− CAT tttq	
	2ℓSS −− CAT sstt	3ℓ −− CAT tttt	
	2ℓSS −− CAT ttq		
	2ℓSS −− CAT ttt		
	2ℓSS −− CAT tttq		
	2ℓSS −− CAT tttt		

Background contributions

SRs



- Important contribution from tt̄W, tt̄Z, VV and 4tops in SRs
- ~50% purity in HF non-prompt leptons in dedicated CRs



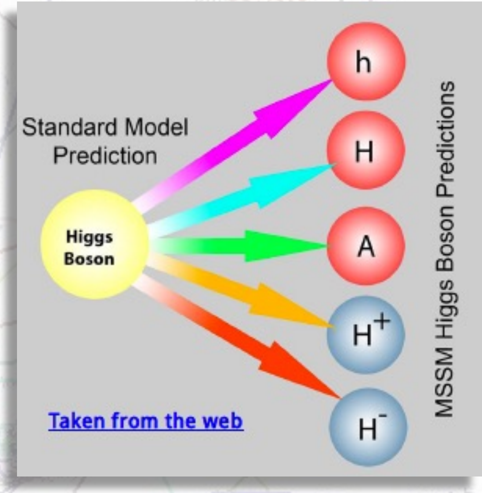
CRs

Table 2: Topological and kinematic selections for each channel and category as described in the text. (*) Applies in the case of only two central jets. (**) Applied only for the W' search. (†) A higher threshold (80 GeV) is used for the single-electron channel. (††) Applied only for $m_{Vh} > 320$ GeV. (‡‡) Only the two leading VR track-jets matched by ghost-association to the large-R jet are considered when classifying events into b-tag categories. Events are further classified according to the number of b-tagged jets in the events.

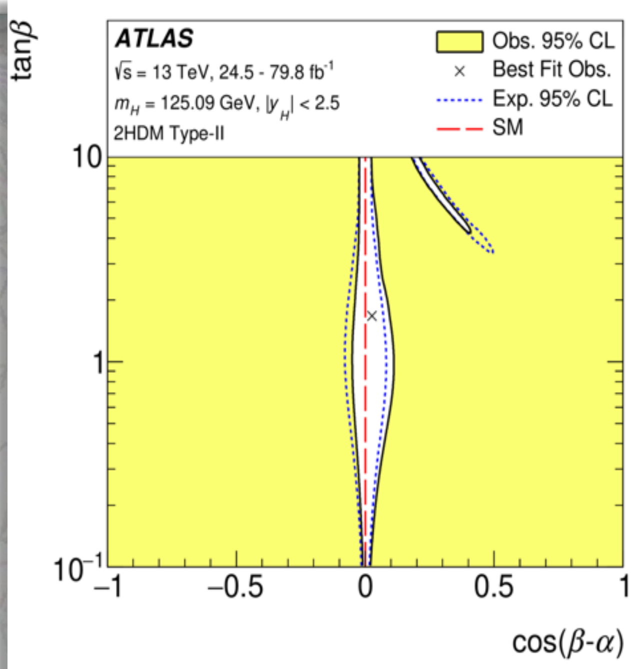
Variable	Resolved	Merged
Common selection		
Number of jets	$\geq$2 small-R jets (0, 2-lep.) 2 or 3 small-R jets (1-lep.)	$\geq$1 large-R jet $\geq$ 1 VR track-jets (matched to leading large-R jet)‡‡
Leading jet p_T [GeV]	> 45	> 250
m_h [GeV]	110–140 (0,1-lep.), 100–145 (2-lep.)	75–145
0-lepton selection		
E_T^{miss} [GeV]	> 150	> 200
S_T [GeV]	> 150 (120^*)	–
$\Delta\phi_{jj}$	$< 7\pi/9$	–
p_T^{miss} [GeV]	> 60 (both)	
$\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{miss})$	$< \pi/2$ (both)	
$\Delta\phi(\vec{E}_T^{miss}, h)$	$> 2\pi/3$ (both)	
$\min\left[\Delta\phi(\vec{E}_T^{miss}, \text{small-}R\text{ jet})\right]$	$> \pi/9$ (2 or 3 jets), $> \pi/6$ (≥ 4 jets) (both)	
$N_{\tau_{had}}$	0 ($\leq 1^{**}$) (both)	
E_T^{miss} significance $\mathcal{S}$	$\begin{cases} > 9 & \text{if } m_{Vh} < 240\,\text{GeV}, \\ > 6.6 + 0.01 \cdot m_{Vh} & \text{if } 240\,\text{GeV} \leq m_{Vh} < 700\,\text{GeV}, \\ > 13.6 & \text{if } m_{Vh} > 700\,\text{GeV}, \end{cases}$ (both)	
1-lepton selection		
Leading lepton p_T [GeV]	> 27	> 27
E_T^{miss} [GeV]	> 40 ($80^\dagger$)	> 100
$p_{T,W}$ [GeV]	$> \max\left[150,\ 710 - (3.3 \cdot 10^5\ \text{GeV})/m_{Vh}\right]$	$> \max\left[150,\ 394 \cdot \log(m_{Vh}/(1\ \text{GeV})) - 2350\right]$
$m_{T,W}$ [GeV]	< 300 (both)	
$\Delta R(\ell, h)$	> 2.0 (both)	
2-lepton selection		
Leading lepton p_T [GeV]	> 27	> 27
Subleading lepton p_T [GeV]	> 20	> 25
$E_T^{miss}/\sqrt{H_T}$ [$\sqrt{\text{GeV}}$]	$< 1.15 + 8 \times 10^{-3} \cdot m_{Vh}/(1\ \text{GeV})$ (both)	
$p_{T,\ell\ell}$ [GeV]	$> 20 + 9 \cdot \sqrt{m_{Vh}/(1\ \text{GeV}) - 320}^{\dagger\dagger}$ (both)	
$m_{\ell\ell}$ [GeV]	$\in \left[\max\left[40,\ 87 - 0.030 \cdot m_{Vh}/(1\ \text{GeV})\right],\ 97 + 0.013 \cdot m_{Vh}/(1\ \text{GeV})\right]$ (both)	

Two Higgs Doublet Model (2HDM)

- Generic class with second Higgs doublet. Four variants to couple SM fermions to the 2HDs (no FCNCs):
  - Type I: all quarks and leptons couple to only one doublet
  - Type II: one doublet couples to up-type quarks, the other to down-type quarks and leptons: „MSSM-like"
  - Lepton-specific: couplings to quarks as in the Type I model and to leptons as in Type II
  - Flipped: couplings to quarks as in the Type II model and to leptons as in Type I



Phys. Rev. D 101 (2020) 012002



- 5 Higgs bosons: h, H, A, H^+, H^-
- Free parameters: tanβ (ratio between the vevs of the doublets), α (mixing angle between h and H) and m_A
- Minimal Supersymmetric SM (MSSM) is a special case of 2HDM:
  - "type II" with fixed α
  - numerous benchmark models: hMSSM, m_h^{mod+}, etc.

- SM Higgs results give big constraints on 2HDM. Data prefers alignment limit: cos(β- α)=0 – h recovers properties of the SM Higgs

Analysis strategy: SRs definitions

Wino/Bino WZ on-shell

	SR-WZonshell1	SR-WZonshell2
$N_{Comb}(l)$	=2	
$N_{BL}(l)$	=2	
$N_{Sig}(l)$	=2	
Charge(l)	Same-Sign	
$p_T(l)$	≥25 GeV	
$N_{jets}(p_T > 25$ GeV)	≥1	
N_{b-jets}	=0	
m_{jj}	≤350 GeV	
m_T2	≥100 GeV	≤100 GeV
m_T^{min}	≥100 GeV	≥130 GeV
E_T^{miss}	≥100 GeV	≥140 GeV
m_{eff}	-	≤600 GeV
$\Delta R(\ell^\pm, \ell^\pm)$	-	≤3
Bins	Sig(E_T^{miss}): [0-10], Spread(Φ) ≥2.2	-
	Sig(E_T^{miss}): [10-13]	
	Sig(E_T^{miss}): [13-∞], $\Delta R(\ell^\pm, \ell^\pm)$ ≥1	

Wino/Bino Wh-SS on-shell

	Wh-SS pre-selection		
	$e^\pm e^\pm$	$e^\pm\mu^\pm$	$\mu^\pm\mu^\pm$
$N_{Comb}(\ell)$	= 2		
$N_{BL}(\ell)$	= 2		
$N_{Sig}(\ell)$	= 2		
Charge(ℓ)	same-sign		
$p_T(\ell)$	≥ 25 GeV		
n_{b-jets}	= 0		
E_T^{miss}	≥ 50 GeV		
n_{jets}	≥ 1		
ECIDS	97% WP		-

+

	SR1			SR2		
	$e^\pm e^\pm$	$e^\pm\mu^\pm$	$\mu^\pm\mu^\pm$	$e^\pm e^\pm$	$e^\pm\mu^\pm$	$\mu^\pm\mu^\pm$
m_{jj}	< 350 GeV					
m_{T2}	≥ 80 GeV			< 80 GeV		
m_T^{min}	-			≥ 100 GeV		
Sig(E_T^{miss})	≥ 7			≥ 6		
E_T^{miss}	≥ 75 GeV			≥ 50 GeV		
E_T^{miss} binning[a]	SR1a: ∈ [75, 125)			-		
	SR1b: ∈ [125, 175)					
	SR1c: ∈ [175, +∞)					

[a] The E_T^{miss} binning applies separately to each flavour channel of SR1.

Higgsino bRPV

Variables	Two leptons final state	Three leptons final state
$N_{Sig}(\ell)$	= 2	= 3
isSameSign	Yes	-
leading lepton p_T	20 GeV	20 GeV
subleading lepton p_T	20 GeV	20 GeV
third lepton p_T	-	10 GeV
E_T^{miss}	≥ 100 GeV	≥ 120 GeV
m_{eff}	-	≥ 350 GeV
m_{T2}	≥ 60 GeV	≥ 80 GeV
$N_{b-jets}(p_T > 20$ GeV)	= 0	-
$N_{jets}(p_T > 25$ GeV)	≥ 1	≥ 1
$N_{jets}(p_T > 40$ GeV)	≥ 4	-
$M_{ee}/M_{\mu\mu}$ SFOS pairs	-	< 81 or > 101 GeV

Higgsino RPV UDD

N_{lept}^{signal} (N_{lept}^{base}), p_T > 25 GeV	N_{b-jets} [20 GeV]	N_{jets} [25 GeV]	E_T^{miss} [GeV]
= 2 (= 2)	= 1	≥ 1 and ≤ 6	> 50

SR name	N_{jets} [25 GeV]	$\sum p_T^{b-jet}/\sum p_T^{jet}$	$\sum p_T$ (jet) [GeV]	$\Delta R(\ell_1, jet)$	E_T^{miss} [GeV]	$\sum p_T$ (lept)	$\Delta R(\ell_1, \ell_2)$
Rpv2L1bL	≤ 2	> 0.70	> 120	< 1.2	> 100	> 100	> 2.0
Rpv2L1bM	= 2 or = 3	> 0.45	> 400	< 1.0	–	> 100	> 2.5

N_{lept}^{signal} (N_{lept}^{base}), p_T > 25 GeV	N_{b-jets} [20 GeV]	N_{jets} [25 GeV]	E_T^{miss}
= 2 (= 2)	= 2	≥ 1 and ≤ 6	> 80

SR name	N_{jets} [25 GeV]	$\sum p_T^{b-jet}/\sum p_T^{jet}$	$\sum p_T$ (jet) [GeV]	$\Delta R(\ell_1, jet)$	$\Delta R(\ell_1, \ell_2)$
Rpv2L2bL	≤ 3	> 0.90	> 300	< 1.0	> 2.5
Rpv2L2bM	= 3 or = 4	> 0.75	> 420	< 1.0	> 2.5
Rpv2L2bH	≥ 5	–	> 420	< 1.0	> 2.0

N_{lept}^{signal} (N_{lept}^{base}), p_T > 25 GeV	N_{b-jets} [20 GeV]	N_{jets} [25 GeV]	E_T^{miss} [GeV]
= 2 (= 2)	≥ 3	≥ 1 and ≤ 6	> 20

SR name	N_{jets} [25 GeV]	$\sum p_T^{b-jet}/\sum p_T^{jet}$	$\sum p_T$ (jet) [GeV]	$\Delta R(\ell_1, \ell_2)$	$\Delta R(\ell_1, jet)$
Rpv2L3bL	≤ 3	> 0.8	–	> 2.0	< 1.5
Rpv2L3bM	≤ 3	> 0.8	–	–	–
Rpv2L3bH	≤ 6	> 0.5	> 350	> 2.0	< 1.0

- For **Exclusion** fit:
  - **WZ:** orthogonal SRs with SR-WZonshell1 split in Sig(MET) bins → simultaneous fit
  - **Wh:** 12 orthogonal SRs: SR1 and SR2 split in flavour bins (ee, eμ, μμ), SR1 further split in three MET bins → simultaneous fit
  - **bRPV:** 2 orthogonal SRs → simultaneous fit
  - **RPV UDD:** 1b, 2b, 3b SRs defined in low, medium, high mass region → simple OR
- For **Discovery** fit:
  - **WZ:** use SR-WZonshell1 with merged Sig(MET) bins
  - **Wh:** merged MET and flavour bins → SR1_Disc & SR2_Disc
  - **bRPV & RPV UDD:** use the same regions

Same-sign 2L/3L from direct production of winos and higgsinos

ATLAS-CONF-2022-057

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

$$m_T(\mathbf{p}_T, \mathbf{q}_T) = \sqrt{2(p_T q_T - \mathbf{p}_T \cdot \mathbf{q}_T)}.$$

Background Type	Wino Wh	non-Wh
Irreducible	1. CR/VR defined for WZ[1] and $W^{\pm}W^{\pm}$	1. CR/VR defined for WZ[1] and VR for $t\bar{t}V$
	2. Other small backgrounds are estimated using full Monte-Carlo samples	
Reducible	3. Charge flip rates are estimated in MC and corrected using the Egamma SFs	
	4. Fakes: using Fake Factor Method	4. Fakes: using Matrix Method and MCTemplate method as a cross-check

[1]. Note that the WZ would be normalised in the respective CR in Wh and non-Wh.

Table 7: Model-independent statistical analysis for SRs optimised for the Wh, WZ and bRPV models: 95% CL upper limits on the visible cross section, $\langle\epsilon\sigma\rangle^{95}_{obs}$, and on the number of signal events S^{95}_{obs}. The S^{95}_{exp} is the expected 95% CL upper limit on the number of signal events, given the the expectation (and $\pm 1\sigma$ variations) of background events. The last two columns report the CL_b value for the background-only hypothesis, the one-sided p_0-value and the local significance Z (the number of equivalent Gaussian standard deviations).

Signal channel	$\langle\epsilon\sigma\rangle^{95}_{obs}$ [fb]	S^{95}_{obs}	S^{95}_{exp}	CL_b	p_0 (Z)
$SR^{Wh}_{high-m_{T2}}$	0.28	39.3	$33.9^{+14.3}_{-10.0}$	0.66	0.34 (0.41)
$SR^{Wh}_{low-m_{T2}}$	0.24	33.0	$29.5^{+11.7}_{-8.8}$	0.63	0.33 (0.43)
$SR^{WZ}_{high-m_{T2}}$	0.13	18.7	$24.4^{+6.8}_{-5.0}$	0.12	0.50 (0.00)
$SR^{WZ}_{low-m_{T2}}$	0.04	5.9	$4.4^{+1.8}_{-0.8}$	0.81	0.22 (0.76)
$SR^{bRPV}_{2\ell-SS}$	0.16	22.6	$25.8^{+7.9}_{-5.8}$	0.29	0.50 (0.00)
$SR^{bRPV}_{3\ell}$	0.44	61.4	$93.0^{+56.0}_{-20.3}$	0.02	0.50 (0.00)

Displaced vertices + jets

Table 2: Summary of the signal region selections. The x in the $n^{x}_{\text{jet/trackless jet}}$ notation refers to the jet p_{T} threshold in GeV. All jets are required to have $|\eta| < 2.5$.

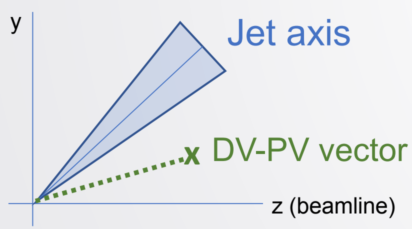
Signal Region	High-p_{T} jet SR	Trackless jet SR
Jet selection	$n^{250}_{\text{jet}} \geq 4$ or $n^{195}_{\text{jet}} \geq 5$ or $n^{116}_{\text{jet}} \geq 6$ or $n^{90}_{\text{jet}} \geq 7$	Fail high-p_{T} jet selection, $n^{137}_{\text{jet}} \geq 4$ or $n^{101}_{\text{jet}} \geq 5$ or $n^{83}_{\text{jet}} \geq 6$ or $n^{55}_{\text{jet}} \geq 7$, $n^{70}_{\text{trackless jet}} \geq 1$ or $n^{50}_{\text{trackless jet}} \geq 2$
DV pre-selection	$R_{\text{DV}} < 300$ mm, $\lvert z_{\text{DV}} \rvert < 300$ mm, $\min(\lvert\vec{r}_{DV} - \vec{r}_{PV}\rvert) > 4$ mm, $\chi^2/n_{\text{DoF}} < 5$, $n^{\text{DV}}_{\text{Selected tracks}} \geq 2$, pass material map veto	
$n^{\text{DV}}_{\text{Tracks}}$ m_{DV}	≥ 5 >10 GeV	

Inclusive Estimate Procedure (1)

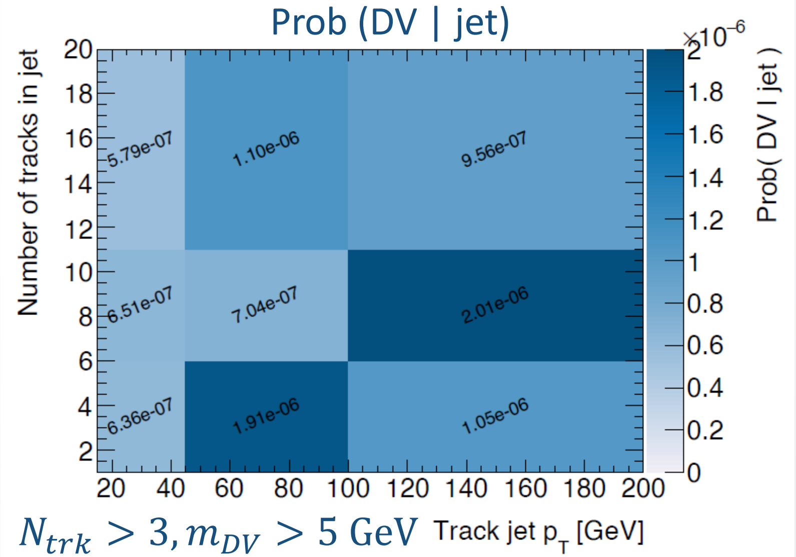
1. Measure jet-DV correlations in low n-jet control region of data (single photon trigger, fail jet requirements of SR)

In control region of data, match each DV to closest track jet:

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$



Calculate Prob(DV | track jet) as a function of track jet properties



$$P = \frac{N_{DV}}{N_j}$$

Number of jets matched to a DV (N_{DV})

Number of jets (N_j)

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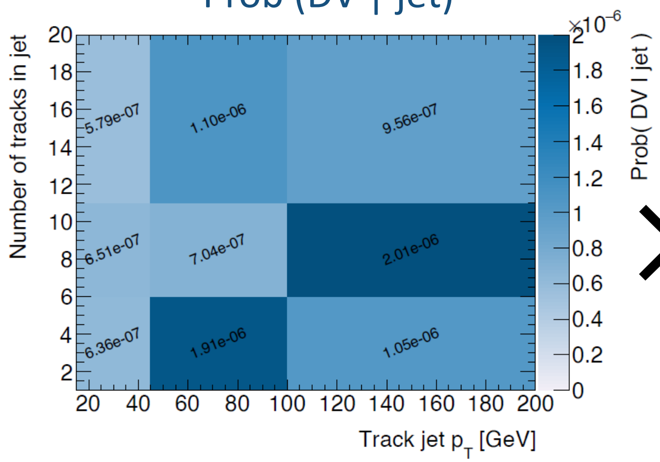
Inclusive Estimate Procedure (2)

1. Measure jet-DV correlations in low n-jet control region of data (single photon trigger, fail jet requirements of SR)
2. Use track jets in events passing SR jet requirements to estimate expected background:

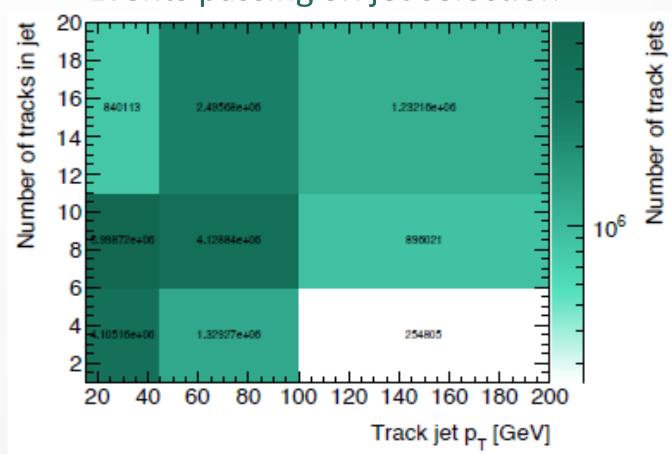
Prob (DV | jet)



$N_{trk} > 3, m_{DV} > 5$ GeV

×

Events passing SR jet selection



$N_{trk} > 4, m_{DV} > 10$ GeV

(Trackless SR shown)

$$N_{DV}^{SR} = f \cdot \sum_{bins} P(DV|jet) \cdot N_{jets,bin}$$

$$f = \frac{N_{\text{Event}}(m > 10\text{ GeV}, N_{\text{track}} > 4)}{N_{\text{Event}}(m > 5\text{ GeV}, N_{\text{track}} > 3)} \text{ in CR}$$

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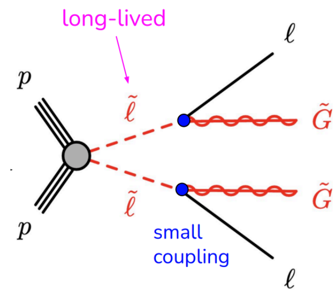
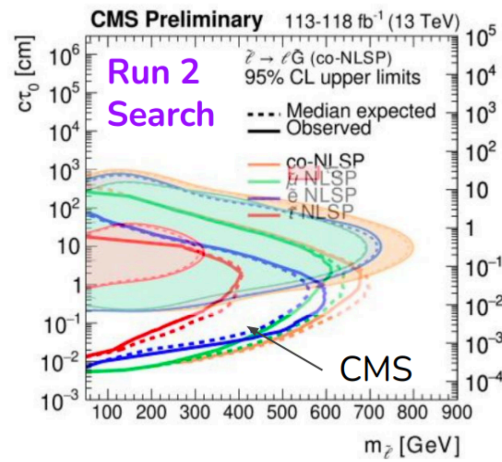
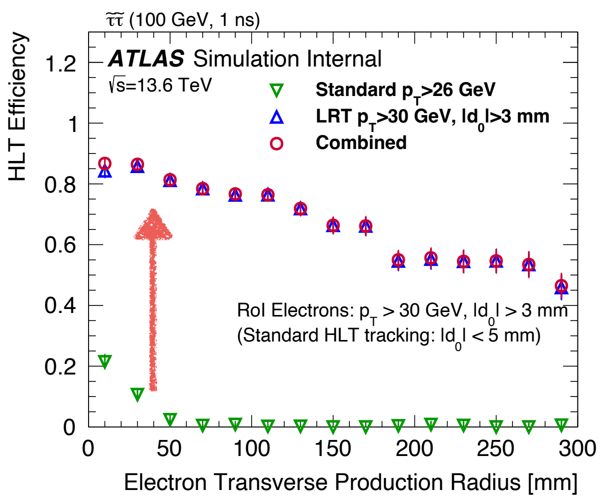
Displaced Leptons and New Triggers

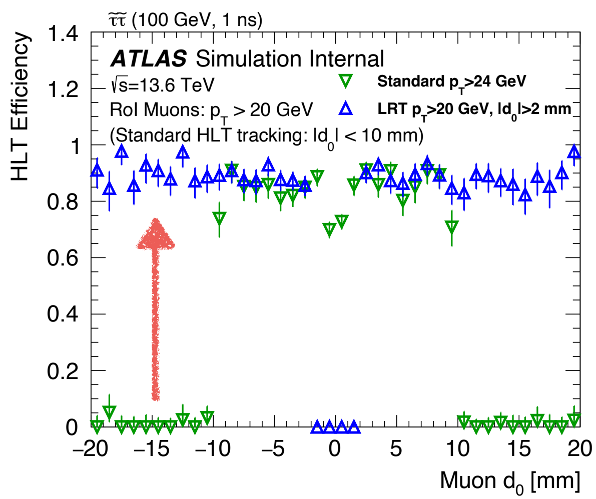
- New triggers deployed in Run 3 to target a variety of unconventional tracking (twiki)
  - Displaced leptons, displaced taus, emerging jets, displaced jets, displaced vertex, disappearing tracks, isolated high-pt tracks, large dE/dx
- New opportunities for LLP searches
- Several expression of interests at LLP Forum focussed on early-Run3 searches
- Publications with these new triggers expected soon as proof of principle of the reach of the new analyses and as documentation of the performance of such triggers

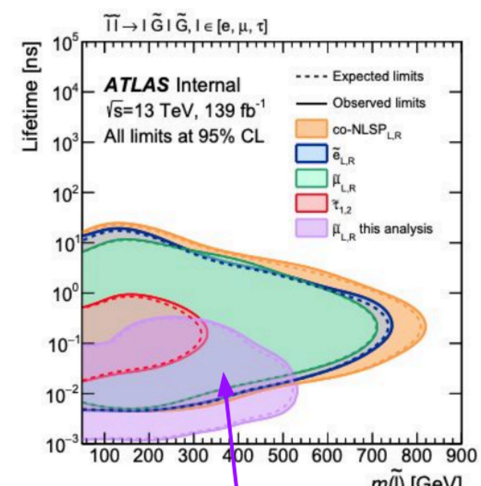


Yumeng Cao









Micro-displaced leptons

D. Zanz

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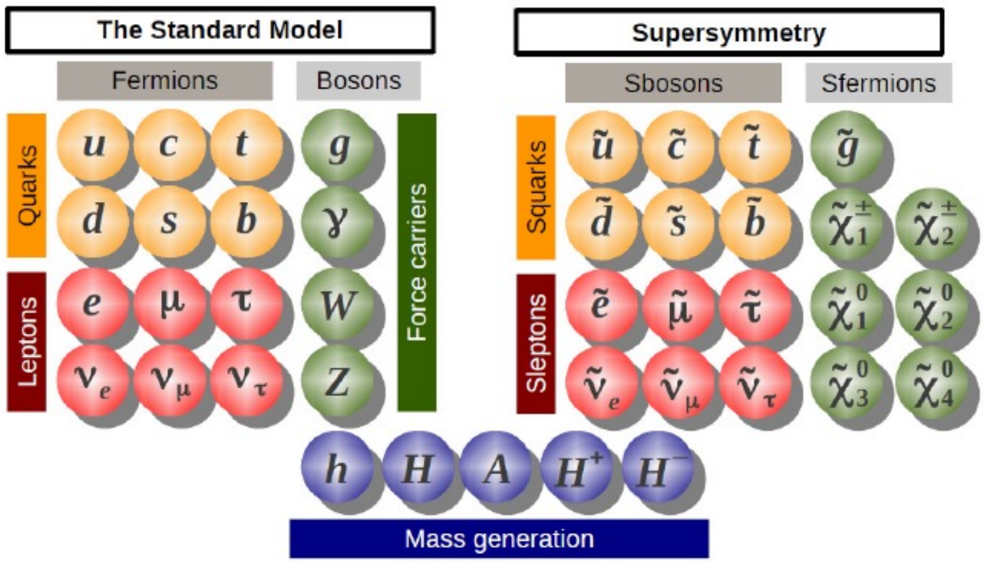
Supersymmetric Family



$$\text{SM}: \; W^{\pm},\; W^0,\; B \xrightarrow{\text{mixing}} W^{\pm},\; Z,\; \gamma$$

$$\text{SUSY}: \; \tilde{H}_u^0,\; \tilde{H}_d^0,\; \tilde{W}^0,\; \tilde{B}^0 \xrightarrow{\text{mixing}} \tilde{\chi}_1^0,\; \tilde{\chi}_2^0,\; \tilde{\chi}_3^0,\; \tilde{\chi}_4^0$$

neutralinos

$$\tilde{H}_u^+,\; \tilde{H}_d^-,\; \tilde{W}^+,\; \tilde{W}^- \xrightarrow{\text{mixing}} \tilde{\chi}_1^{\pm},\; \tilde{\chi}_2^{\pm}$$

charginos

- New quantum number => R-parity

$$R_p = (-1)^{3(B-L)+2S} \qquad \text{S: Spin}$$

- SM particles R=+1
- SUSY particles R=-1
- Multiplicative number
- Two important consequences if R-parity is preserved:
  - Superpartners are pair-produced
  - Lightest superpartner is stable (LSP)
  - Proton is stable (in general SUSY allows for non conservation of L and B)

Event selections

- Single lepton trigger
- Isolated and trigger-matched lepton + τ passing medium RNN τ ID
- $p_T(l)$> 30 GeV, $p_T(\tau)$ > 50 GeV
- Opposite-sign charge between l and τ
- At least one b-jet, 70% b-tagging WP of DL1r
- $p_T(bjet)$ > 200 GeV — To avoid contribution from non-resonant LQ production at lower b-jet pt which has interference with SM diagrams such as those from Z+jets
- $m_{vis}(l,\tau)$ > 100 GeV — Against Z->tautau bkg
- $\Delta\phi\left(l, E_T^{miss}\right)$ < 1.5 — Against top, ttba bkg
- S_T > 300 GeV

$\tau_{lep}\tau_{had}$

- Single τ trigger (80, 125, 160 GeV)
- Leading τ: trigger-matched, pT > (trigger threshold + 5 GeV), pass medium RNN τ ID
- Sub-leading τ: pT > 65 GeV, pass loose RNN τ ID
- Opposite-sign charge between τ and τ
- Veto electrons or muons
- At least one b-jet, 70% b-tagging WP of DL1r
- $p_T(bjet)$ > 200 GeV
- $m_{vis}(\tau,\tau)$ > 100 GeV
- S_T > 300 GeV

$\tau_{had}\tau_{had}$

- The discriminant variable: $S_T = p_T^{\tau} + p_T^{\tau} + p_T^{bjet}$

Other discriminant variables were tested. See backups.

Scalar leptoquarks in bττ final state

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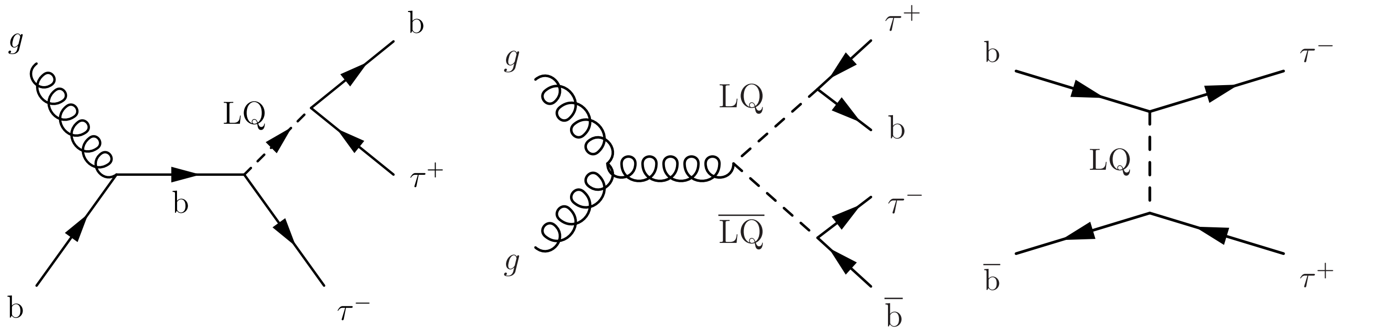
Table 3: Definition of signal, control and fakes regions used in the τ_{lep} τ_{had} channel. The symbol ℓ represents the selected electron or muon candidate and τ_1 represents the leading $\tau_{had\text{-}vis}$ candidate.

	Selection	
Signal Region	ℓ (trigger, isolated), τ_{had} (medium), $q(\ell) \times q(\tau) < 0$, $\Delta\phi(\ell, E_T^{miss}) < 1.5$, $m_{vis}(\ell, \tau_{had}) > 100$ GeV, $S_T > 300$ GeV, at least one b-jet, lead b-jet $p_T > 200$ GeV	
Control/Validation Region	**Selection**	**Notes**
Multijet-CR	ℓ (trigger, pass or fail offline isolation), $m_T(\ell, E_T^{miss}) < 30$ GeV, one b-jet, RNN τ ID score < 0.01, $E_T^{miss} < 50$ GeV	Measure lepton fake factor
Top-CR	Pass SR except: remove S_T and lead b-jet p_T cuts, $\Delta\phi(\ell, E_T^{miss}) > 2.5$	Derive top correction
SS-CR	Pass SR except: remove $\Delta\phi(\ell, E_T^{miss})$ and S_T cut, $q(\ell) \times q(\tau) > 0$	Correct fake modeling
VR	Pass SR except: $1.5 < \Delta\phi(\ell, E_T^{miss}) < 2.5$, 300 GeV $< S_T <$ 600 GeV	Background modeling
b-tag Z-CR	Pass SR except: remove S_T and 45 GeV $< m_{vis} <$ 80 GeV and $p_T(\ell)/p_T(b\text{-jet}) > 0.8$ and $\lvert\Delta\phi(\ell, \tau)\rvert > 2.4$	Z+HF normalisation factor

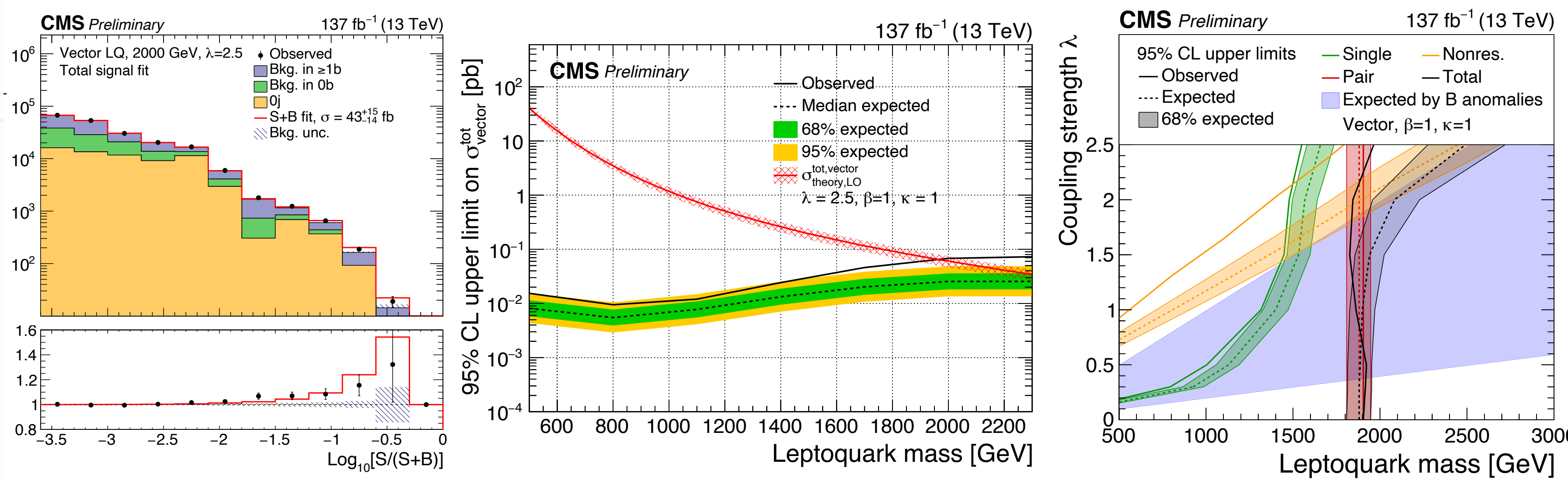
Table 4: Definition of signal, control and fakes regions used in the $\tau_{had}\tau_{had}$ channel. The symbol τ_1 (τ_2) represents the leading (sub-leading) τ_{had} candidate.

	Selection	
Signal Region	$\tau_{had,1}$ (trigger, med.), $\tau_{had,2}$ (loose), $q(\tau_{had,1}) \times q(\tau_{had,2}) < 0$, $m_{vis}(\tau_{had,1}, \tau_{had,2}) > 100$ GeV, $S_T > 300$ GeV, at least one b-jet, lead b-jet $p_T > 200$ GeV	
Control/Validation Region	**Selection**	**Notes**
DJ-FR	Jet trigger, τ_1+τ_2 (very loose ID), $q(\tau_1) \times q(\tau_2) < 0$	Measure τ_{had} fake factor
CR-1	Pass SR except: τ_2 (fail loose)	Apply τ_{had} fake factor
SS-VR	Pass SR except: $q(\tau_1) \times q(\tau_2) == 1$	Multijet modeling check
Z+LF VR	Pass SR except: 0 b-jets, $\Delta\phi(\tau_{had}, \tau_{had}) > 0.25$, $m_{vis} < 100$ GeV, $E_T^{miss} > 60$ GeV	Z+light jets modeling

Leptoquark in $b\tau$ in $s-$ and $t-$channels CMS-PAS-EXO-19-016



- LQ$\rightarrow b\tau$ in events w/ τ and ≥ 1 b-jets
- Range of coupling strengths and masses tested



- Significant 3.4σ excess for a LQ mass of 2 TeV and $\lambda = 2.5$

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Analysis preselections

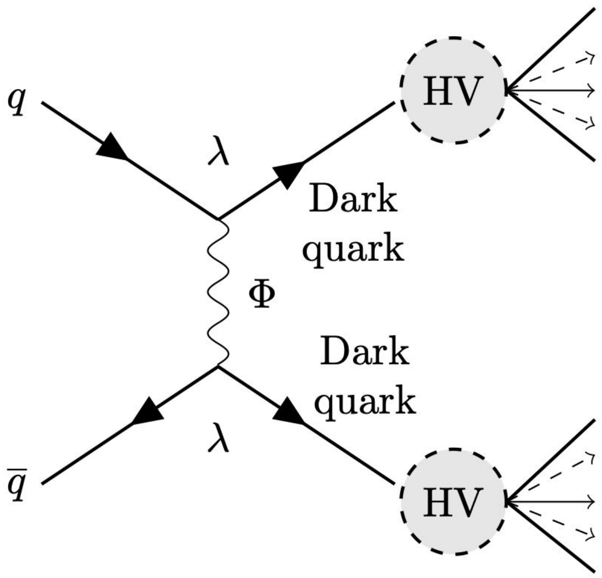
1. No electrons / muons (p_T > 7 GeV)
2. Looking at events with MET trigger (trigger is fully efficient, tests in backup slide), MET > 200 GeV
3. At least 2 jets with leading jet p_T > 250 GeV, other jet p_T > 30 GeV and |eta| < 2.8, jet cleaning LooseBad (also TightBad selection applied on data leading jet, for NCB treatment)
4. Dead-tile correction, LAr, SCT error veto
5. DeltaPhi(closest jet, MET) < 2.0
6. B-tagged jets < 2
7. Tau jets (p_T > 20 GeV) < 1

Key variables for this analysis:

- MET
- Scalar jet pT sum, HT
- DeltaPhi (closest jet, MET)
- p_T balance (between closest and farthest jet from MET)

$$\Delta_{\rm rel} p_{\rm T}(j_1, j_2) = \frac{|\vec{p_{\rm T}}(j_1) + \vec{p_{\rm T}}(j_2)|}{|\vec{p_{\rm T}}(j_1)| + |\vec{p_{\rm T}}(j_2)|}$$

- Maxminphi |Δϕ(farthest jet, MET) - Δϕ(closest jet, MET)|



The resultant MET direction is aligned along one of the jets.

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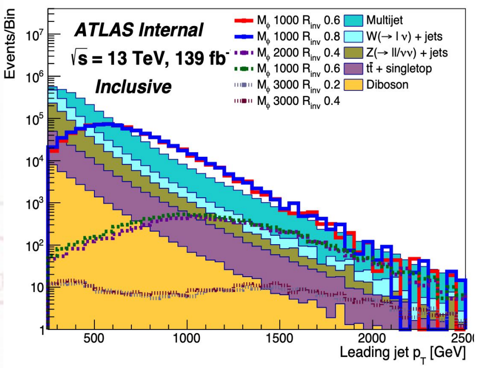
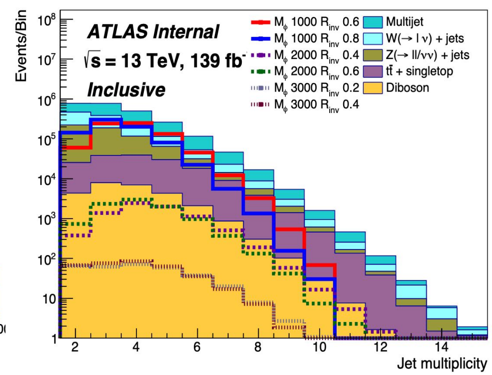
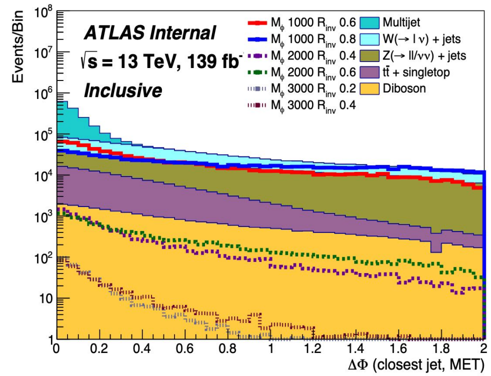
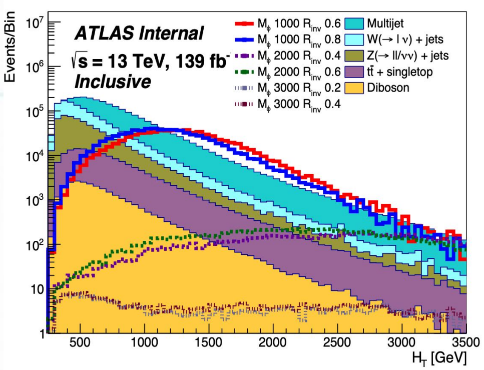
The region with MET>600 GeV and HT> 600 GeV after the pre-selection is defined as the SR.

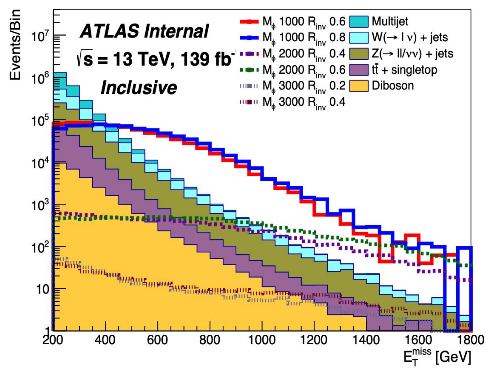
Key kinematic variables











Other signal mass points show similar trend.

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Table 2: Scale factors for each background processes obtained from simultaneous fit using SR, 1L CR, 1L1B CR and 2L CR. Top processes denotes merged contributions from $t\bar{t}$ and single top processes.

Process	k_i^{SF}
Z+jets	1.18 ± 0.05
W+jets	1.09 ± 0.04
Top processes	0.64 ± 0.04
Multijet	1.10 ± 0.04

dE/dx Measurement

- When charged particles pass through the inner detector layer multiple pixel hits across a pixel layer are recorded.
  - The charge deposited on a cluster of hits is calculated by summing the charges over all pixels in a cluster.
  - In the IBL layer, If the deposited charge exceeds the dynamic range of a pixel (~2MIPs), an overflow bit is set. The tracks that use these energy deposits with overflows are referred in this paper as IBL overflow tracks (OF_{IBL}). All other pixel layers have much larger dynamic range (~10 MIPs), but no overflow bits
- The dE/dx measurement of an individual track is calculated by averaging the individual clusters that are associated with the tracks.
  - It's expected that the energy deposited by an individual track on a cluster should follow a Landau distribution.
  - To estimate the most probable dE/dx value for a track from the limited number of the dE/dx measurements associated to it a truncated mean method is used. The most probable dE/dx value is represented by $< dE/dx >_{\text{trunc}}$

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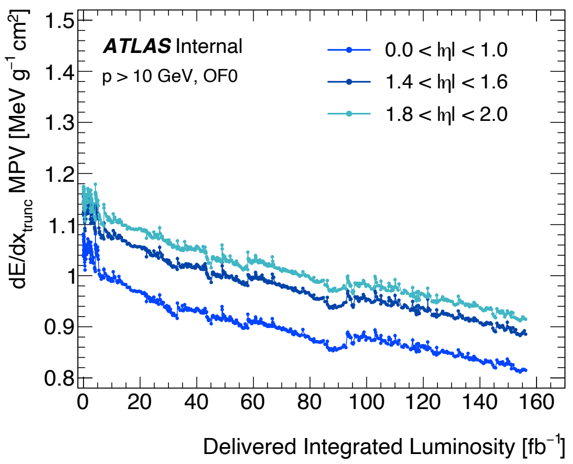
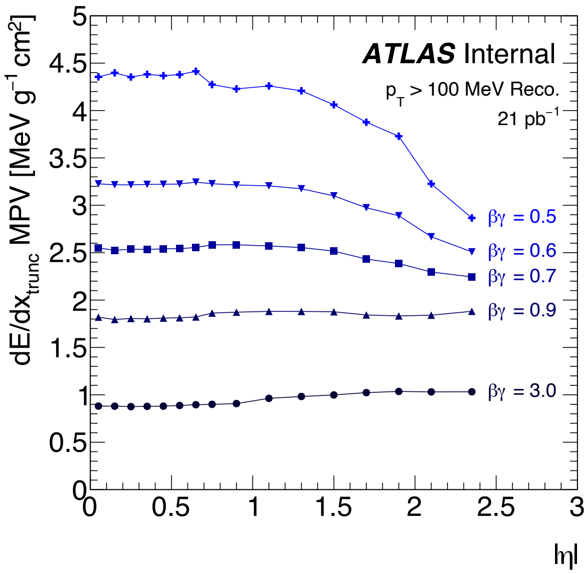
SR name	Discovery	Limit setting	Track category	IBL overflow	dE/dx [MeV g^{-1}cm^2]
SR-Inclusive_Low	✓		inclusive	yes or no	[1.8, 2.4]
SR-Inclusive_High	✓				> 2.4
SR-Trk-IBL0_Low		✓	track	no	[1.8, 2.4]
SR-Trk-IBL0_High		✓		no	> 2.4
SR-Trk-IBL1		✓		yes	> 1.8
SR-Mu-IBL0_Low		✓	muon tracks	no	[1.8, 2.4]
SR-Mu-IBL0_High		✓		no	> 2.4
SR-Mu-IBL1		✓		yes	> 1.8

dE/dx Corrections

- The measured $< dE/dx >_{\text{trunc}}$ changes with data-period due to detector conditions as well as radiation damage.
  - $|\eta|$ dependence can be observed in the plots.
- To correct for these effects each run
  - Each run is corrected to a reference run as a function of $|\eta|$, OF_{IBL}
  - After run dependent corrections, $|\eta|$ corrections are done separately for tracks with/with IBL overflow.
- The resulting corrected dE/dx value is referred to as $< dE/dx >_{\text{corr}}$





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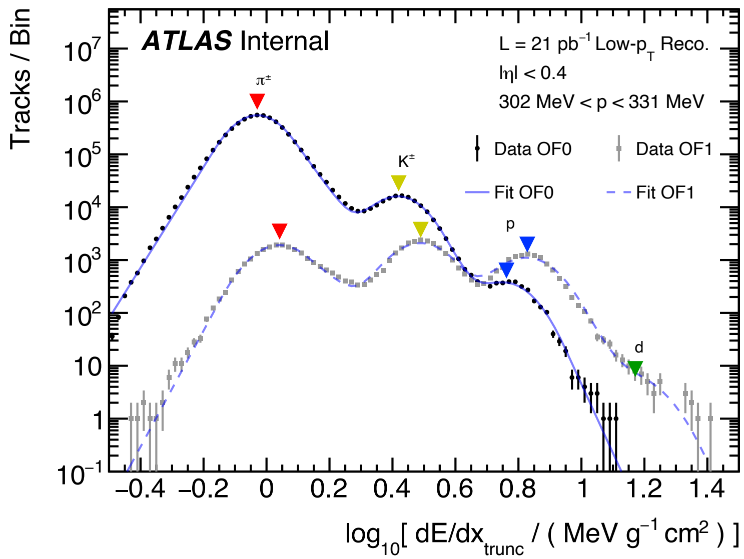
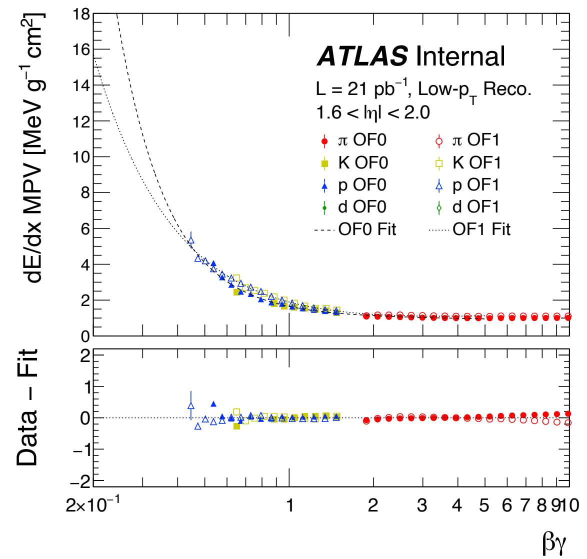
Mass Calibrations





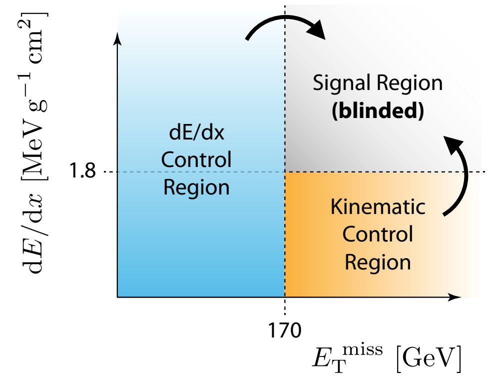
- The $< dE/dx >_{\text{corr}}$ to $\beta\gamma$ mapping is done using the low pile-up runs taken in 2017 with a luminosity of 21 pb^{-1} with low momentum reconstructed tracks.
  - Similar to dE/dx energy calibration, IBL overflow is treated separately.
- In the low pile-up runs, tracks as low as 100 MeV are used to measure the Bethe-Bloch curve.
- **This is done by plotting the dE/dx curves in eta and momentum slices.**
- Template fitting these slices to separate the pion, Kaon and proton contributions.
  - This way the most probable dE/dx value for a given momentum for each of these particle types is obtained, which can be converted in to the seen $\beta\gamma$ function.

Definition of Control and Validation Regions

Table 3: Definitions of the control and validation regions.

Region	p_T [GeV]	$\|\eta\|$	E_T^{miss} [GeV]	dE/dx [MeV g^{-1}cm^2]
SR	> 120	< 1.8	> 170	> 1.8
CR-kin			> 170	< 1.8
CR-dEdx			< 170	> 0
VR-LowPt	[50, 110]	< 1.8	> 170	> 1.8
CR-LowPt-kin			> 170	< 1.8
CR-LowPt-dEdx			< 170	> 0
VR-HiEta	> 50	[1.8, 2.5]	> 170	> 1.6
CR-HiEta-kin			> 170	< 1.6
CR-HiEta-dEdx			< 170	> 0

*Figure from outside of the paper.



- 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.

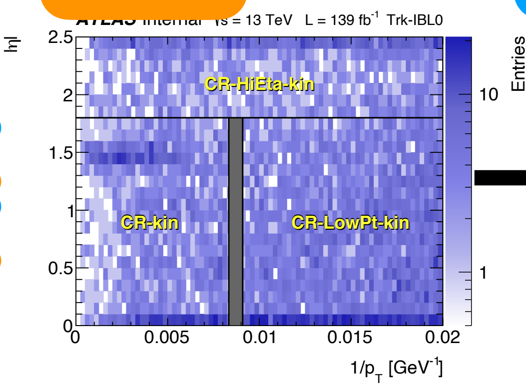
- In addition two control regions have been defined for every signal and validation region for background generation
  - Kinematic CR : dE/dx cut of >1.8 is reverted to <1.8 (1.6 for Hi-Eta VR)
  - dE/dx CR: MET cut of >170 GeV is reverted to <170 GeV and dE/dx cut is removed

Background Estimation

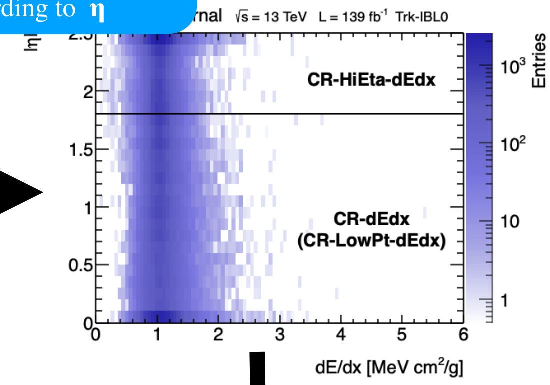
Table 3: Definitions of the control and validation regions.

Region	p_T [GeV]	$\|\eta\|$	E_T^{miss} [GeV]	dE/dx [MeV $g^{-1}cm^2$]
SR			> 170	> 1.8
CR-kin	> 120	< 1.8	> 170	< 1.8
CR-dEdx			< 170	> 0
VR-LowPt			> 170	> 1.8
CR-LowPt-kin	[50, 110]	< 1.8	> 170	< 1.8
CR-LowPt-dEdx			< 170	> 0
VR-HiEta			> 170	> 1.6
CR-HiEta-kin	> 50	[1.8, 2.5]	> 170	< 1.6
CR-HiEta-dEdx			< 170	> 0

Select a $(1/p_T, \eta)$



Select a dE/dx value according to η



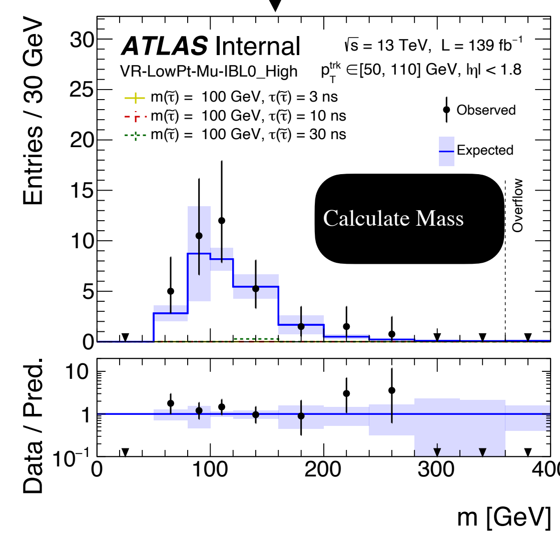
- The analysis employs a fully data-driven background estimation that uses toys.
- The principle idea is to generate random toy tracks following the procedure below:

(1) Sample **$(1/p_T, \eta)$** values from kinematic CR

(2) Sample **dE/dx** value from corresponding dE/dx CR (binned in η)

(3) Calculate mass of toy track from selected values **$(m = p/\beta\gamma)$**

Calculate Mass



- This method is repeated 10 M (40 M times for dE/dx>2.4) for each category generating a mass distribution.
- The mass distribution is normalized to match the data on the low mass region. (M<160) where the signal contamination is negligible.
- Then a dE/dx cut is applied to the generated distribution and a new mass distribution is obtained that satisfies the new dE/dx cut.

Event selection and bkg. estimation

- at least one combined muon
- triggers: single muon, E_T^{miss}, late-muon trigger
- at least 6 ‘good’ TRT hits
- ID track not in close proximity with another track
- additional tight selection for z = 2 candidates

ABCD parameters

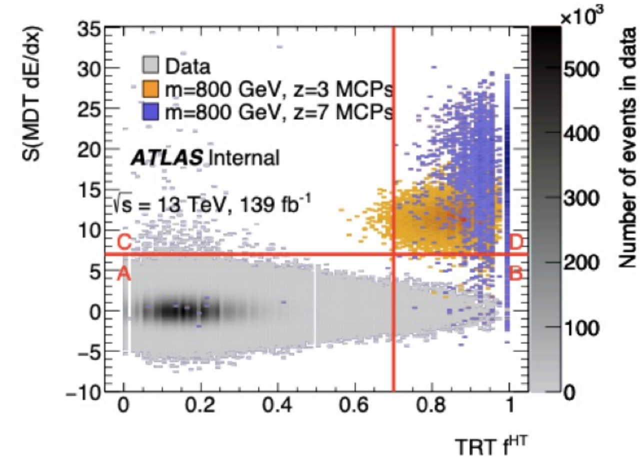
z = 2

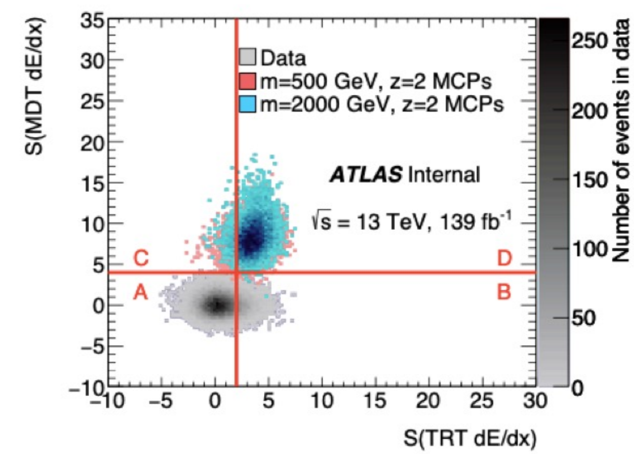
$S(TRT\ dE/dx) \geq 2.0,\ S(MDT\ dE/dx) \geq 4.0$

$$S(dE/dx) = \frac{dE/dx - \langle dE/dx \rangle_{\mu}}{\sigma(dE/dx)_{\mu}}$$

z > 2

$TRT\ f^{HT} \geq 0.7,\ S(MDT\ dE/dx) \geq 7.0$





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