ATLAS results and prospects with focus on BSM

Lucia Masetti - JGU Mainz

on behalf of the ATLAS collaboration

7th workshop on Theory, Phenomenology and Experiments in Flavour Physics and the future of BSM physics Capri, 9/06/18 PRISMA





- Impossible to cover all ATLAS results relevant for BSM searches (strictly speaking all SM measurements are indirect BSM searches too)
- Focus on a choice of direct searches and measurements interpreted as BSM limits and for which prospects are available
- Aim is to present experimental challenges and expectations
- Will NOT list all models being considered, but discuss interpretation restrictions where relevant





Outline

- Introduction
- Direct BSM searches
 - SUSY → 3rd generation squarks, EW, long-lived particles
 - All the rest → resonances, dark matter
- Indirect BSM searches
 - Very rare decays → limits on anomalous couplings
 - Higgs and top couplings → EFT interpretations
- Conclusion







BSM: why and how?

• Open questions in the SM

- Nature of Dark Matter
- Hierarchy problem
- Matter/antimatter asymmetry

• Experimental strategies at LHC

- High energy → sensitivity to heavy new particles
- High luminosity → sensitivity to rare processes
- Mostly model-independent searches with possibility to recast results



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BSM theories and models provide answers!

From LHC to HL-LHC

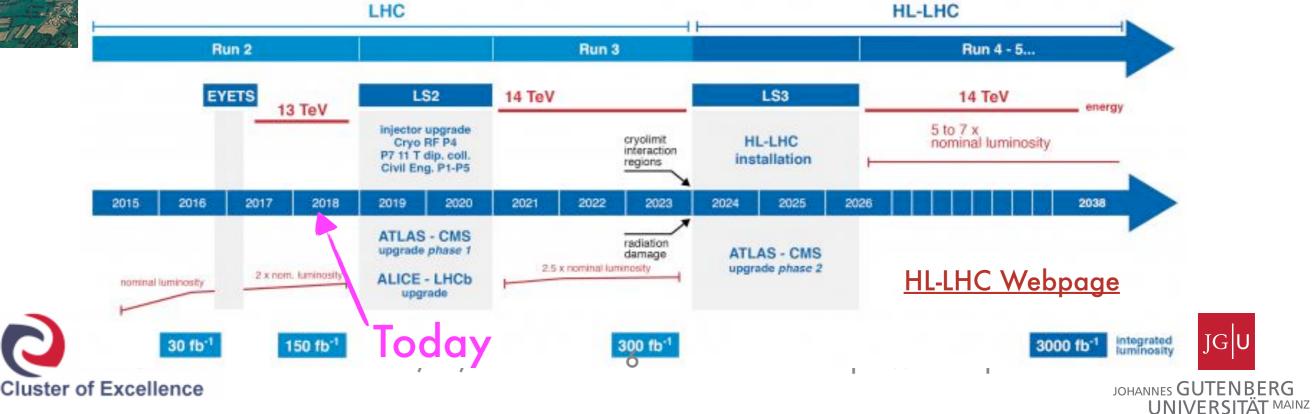


• Run 2

- integrated luminosity so far >100/fb
- results with up to 36/fb of data

• Run 3

- instantaneous luminosity >2.5x10³⁴cm⁻²s⁻¹
- integrated luminosity 300/fb
- Run 4
 - instantaneous luminosity >5x10³⁴cm⁻²s⁻¹
 - integrated luminosity 3000/fb

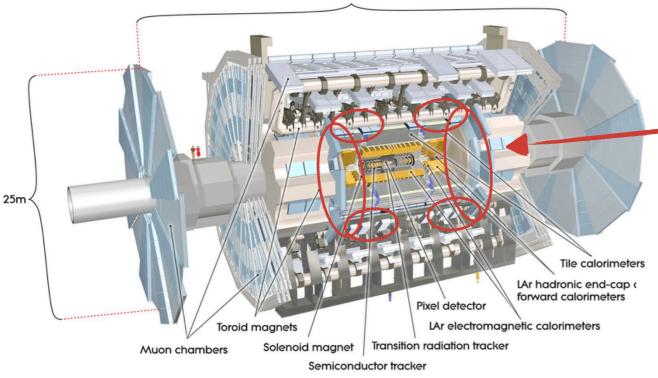


ATLAS upgrades



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Main challenges: trigger rate (runs 3 and 4) and pile-up (run 4)



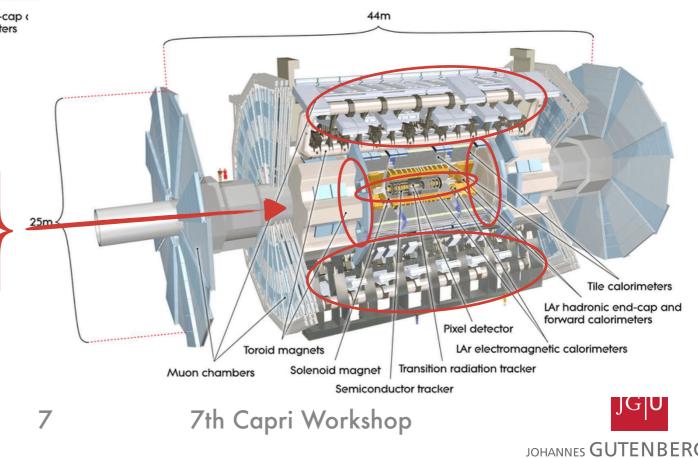
• Run 4

- silicon tracker up to $|\eta| < 4.0$
- new barrel muon chambers
- timing information in endcaps
- improved calorimeter readout
- new trigger electronics



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- Run 3
 - reduce muon fakes and improve trigger
 coverage
 - faster trigger off-detector electronics and tracking at trigger level

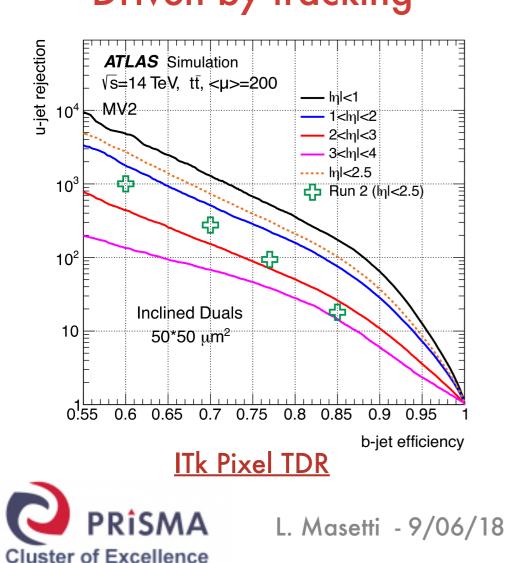


Performance

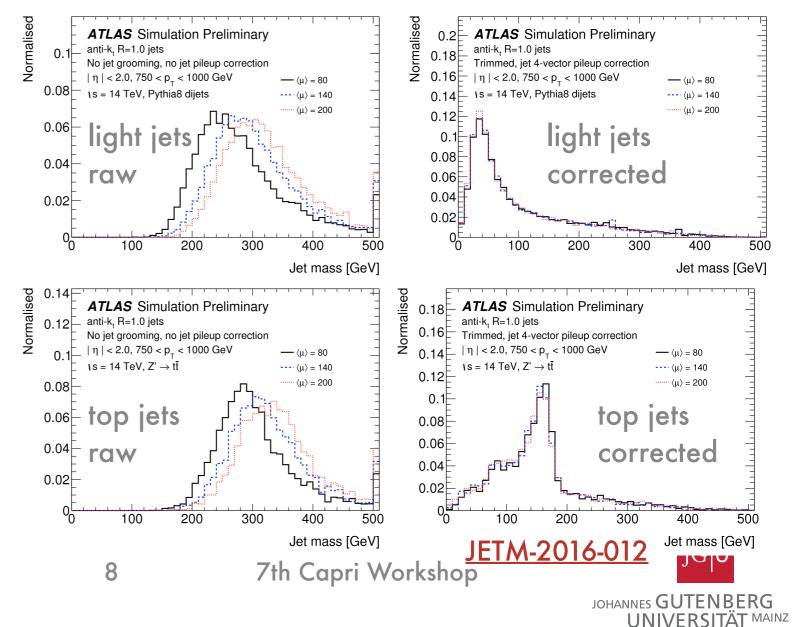


New hardware and new reconstruction techniques allow to recover or improve on run 2 performance in spite of much higher pile-up level

Example: b-tagging Driven by tracking



Example: jet mass - Driven by techniques



Direct BSM searches

SUSY 3rd gen squarks

- Many searches for stop pair production. Decay topology depends on masses of SUSY particles
- General strategy
 - Dedicated signal regions for different scenarios
 - Background estimate in control regions
 - Model-independent limits on number of events
 - Model-dependent mass limits (next slide)
- Limiting factors
 - Most signal regions limited by statistics
 - Background modelling uncertainties O(20%)
- Examples of recent results and techniques
 - stop to stau: BDT for hadronic tau ID [1803.10178]
 - stop to charm: c-jet tagging [1805.01649] -
 - RPV stop to jets: ΔR_{jets}∝m_{stop} [1710.07171]



[GeV]

 $m_{\tilde{t}_1} < m$

ATLAS

10³

10²

10

√s = 13 TeV, 36.1 fb⁻



 $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$

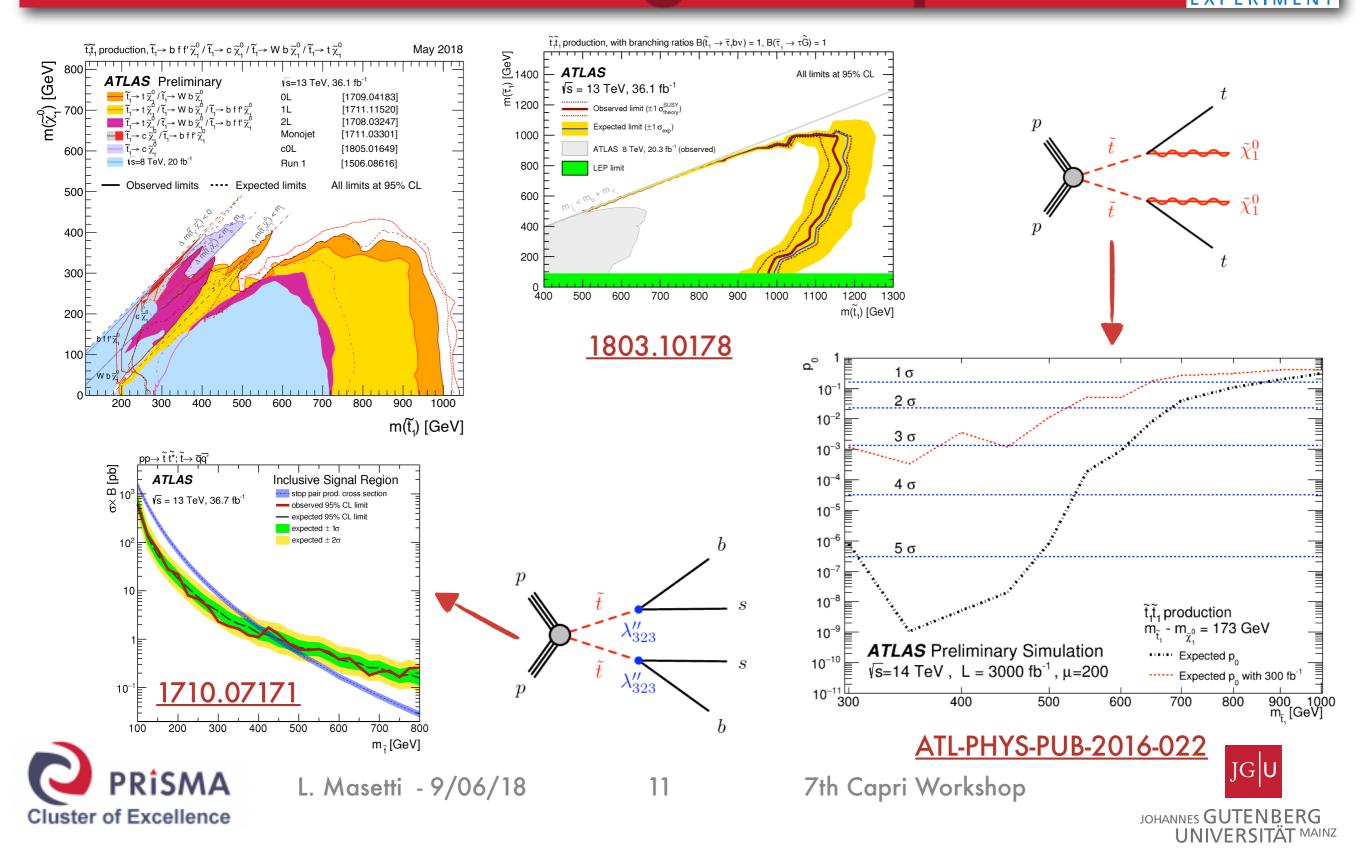
300

 $m_{\tilde{t}_{\star}}$ [GeV]

200

CRHH tE-take

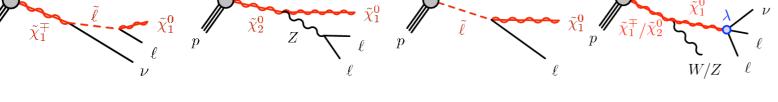
SUSY 3rd gen squarks



SUSY electroweak

Relative Uncertainty

Events

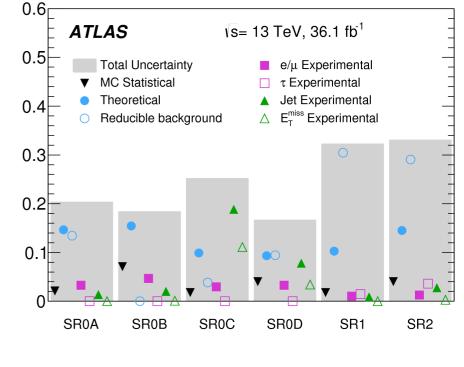


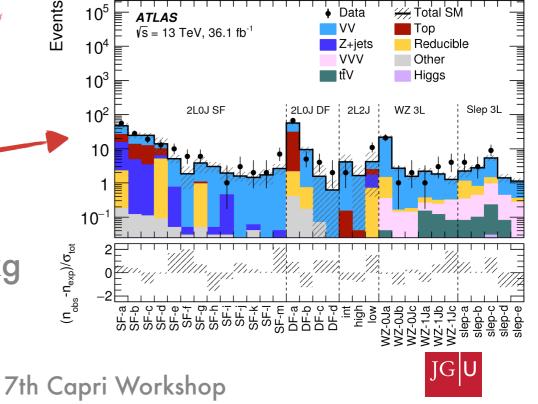
Very different processes with similar final states

- General strategy as for squark searches
- Limiting factors
 - Background estimate: statistics in control regions, data-driven estimates, diboson modelling
- Examples of recent results and techniques
 - 21 and 31 (RPC): Z+jets background with high MET in 21+jets regions estimated with γ +jets template [1803.02762]
 - 41 (RPV and RPC): includes taus, fake lepton bkg estimate with "fake factors" [1804.03602]

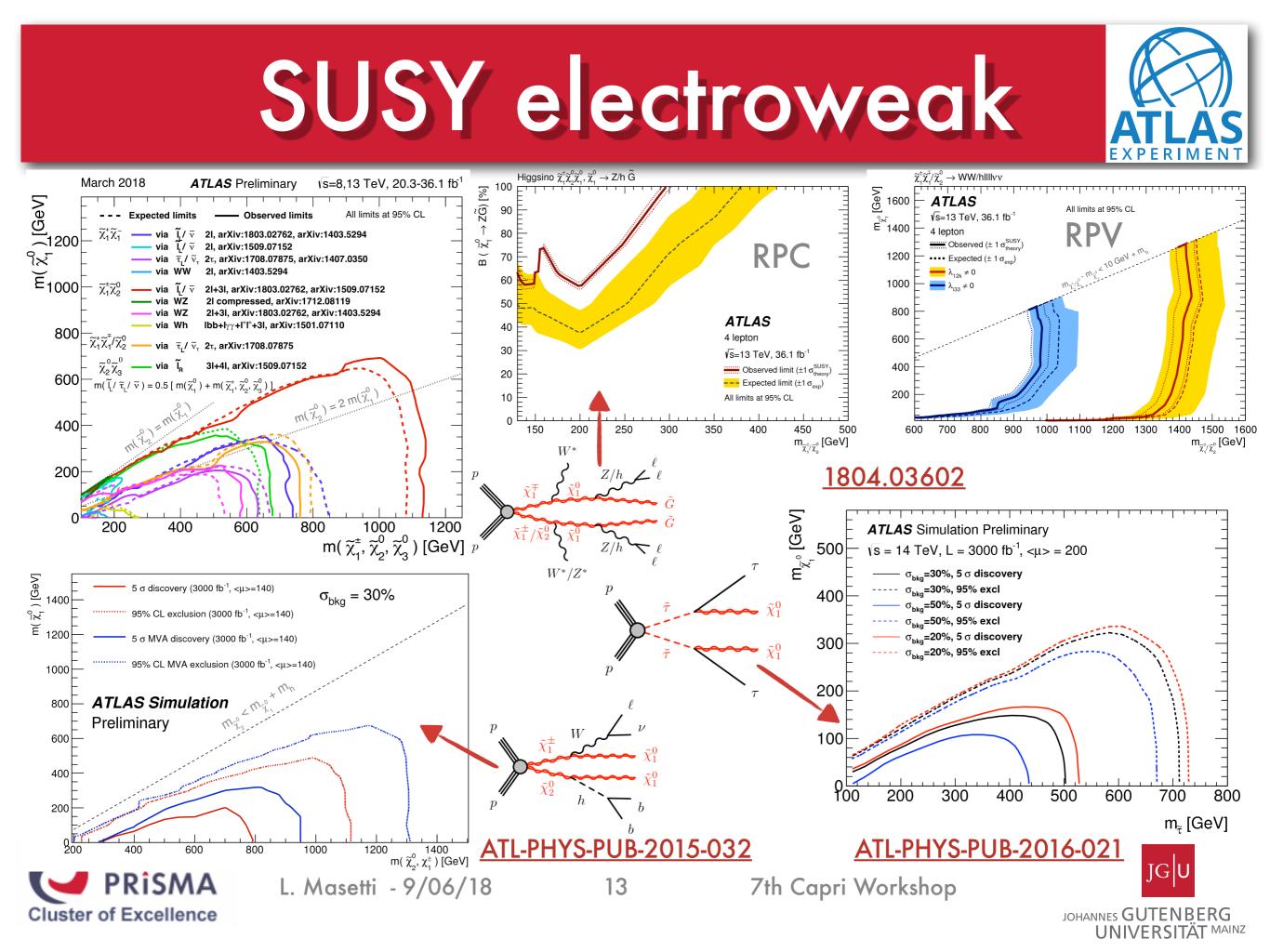


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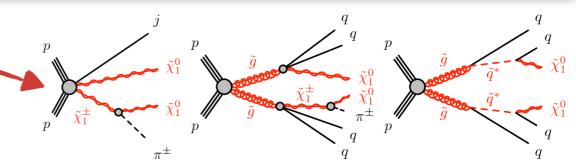


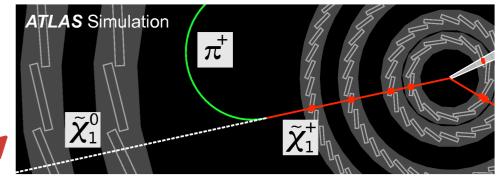
Long-lived particles

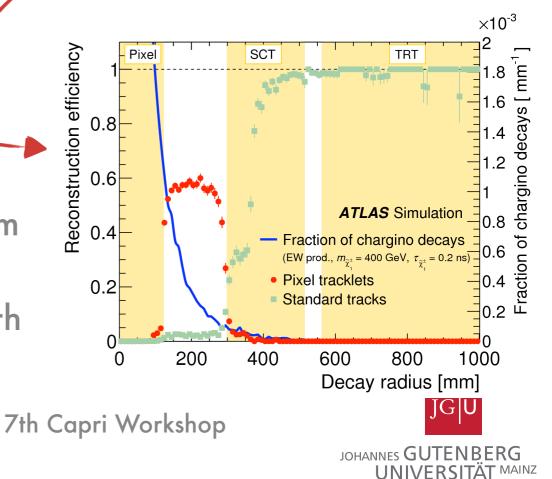


- Appear e.g. for mass-degenerate spectra, small couplings or highly virtual intermediate states
- Specific strategies
 - Dedicated reconstruction techniques
 - Limits on cross section vs. lifetime or only modeldependent
- Limiting factors
 - Statistics, background estimate
- Examples of recent results and techniques
 - Disappearing track: pixel-only tracklets [1712.02118]
 - Displaced vertex: large-radius tracking algorithm [1710.04901]
 - Reinterpretation: b-jet multiplicity correlation with lifetime [ATLAS-CONF-2018-003]

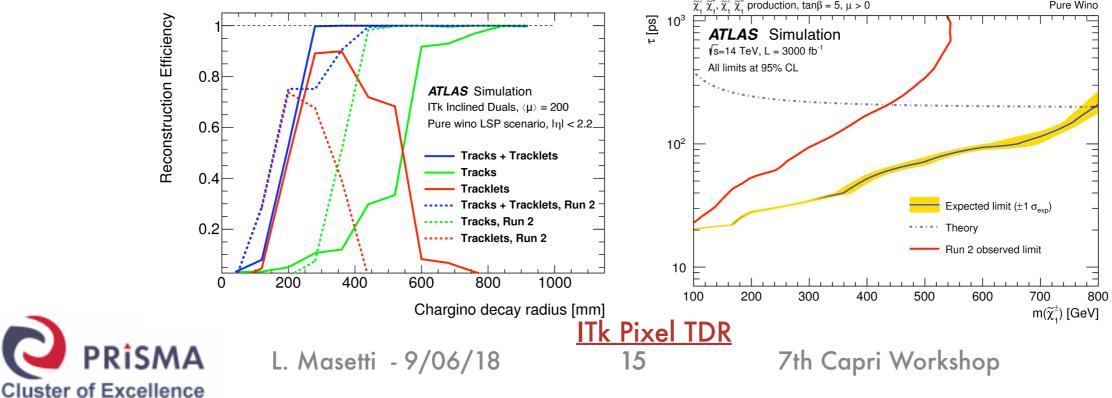








Long-lived particles $\widetilde{\chi}_{1}^{\pm}[\sim\widetilde{W}^{\pm}] \rightarrow \pi^{\pm} \widetilde{\chi}_{1}^{0}[\sim\widetilde{W}^{0}]$ on cross section [pb] Status: December 2017 \widetilde{g} (R-hadron) $\rightarrow qq \ \widetilde{\chi}_1^0$; m($\widetilde{\chi}_1^0$) = 100 GeV -----March 2018 36 fb⁻¹, √s=13 TeV Obs limit (m2=1.4 TeV) RPC 0L 2-6 jets arXiv:1712.02332 (√s=13 TeV, 36 fb⁻¹) RPC 0L 2-6 jets ATLAS-CONF-2018-003 (√s=13 TeV, 36 fb⁻¹) ATLAS Preliminary - - - Expected limits ATLAS isappearing track (pixel-only) arXiv:1712.02118 - - Expected Displaced vertices arXiv:1710.04901 (Vs=13 TeV, 33 fb⁻¹) Observed limits 10 √s=13 TeV, L=32.8 fb⁻¹ ---- Exp limit $(\pm 1, 2\sigma_{ovo})$ 18.4-20.3 fb⁻¹, √s=8 TeV Pixel dE/dx arXiv:1604.04520 (Vs=13 TeV, 3.2 fb⁻¹) --- Observed 95% CL limits. Stable charged arXiv:1606.05129 (Vs=13 TeV, 3.2 fb⁻¹ All limits at 95% CL • Pixel dE/dx arXiv:1506.05332 Obs limit (m₂=2.0 TeV) 800 2500 Stopped gluino arXiv:1310.6584 (vs=7,8 TeV, 5.0,23 fb⁻¹) $\sigma_{\text{theory}}^{\text{SUSY}}$ not included Stable charged arXiv:1411.6795 $\widetilde{g} \rightarrow qq \widetilde{\chi}_{1}^{0}, m_{10} = 100 \text{ GeV}$ Exp limit $(\pm 1, 2\sigma_{axn})$ limit on Disappearing track arXiv:1310.3675 700 ATLAS Preliminary 2000 Lower 600 -500 Upper limit o $\sigma_{NLO+NLL}(pp \rightarrow \tilde{g}\tilde{g}), m_{2}=1.4 \text{ TeV}$ 1500 400 300 1000 200 $\sigma_{NLO+NLL}(pp \rightarrow \tilde{g}\tilde{g}), m_{\tilde{z}}=2.0 \text{ TeV}$ 10-100 500 1.1.1.111 10⁻² 10² 10^{3} 10-10^{±1} 10⁴ 10 10! 1 τ [ns] 10 (r for $\eta=0, \beta\gamma=1$) Beampipe Inner Detector Calo MS (r for $\eta=0, \beta\gamma=1$) Inner Detector Calo MS $\mid \tau$ [ns] _____ لتتبيينا 10^{-3} 10^{-2} 10 10 10⁻³ 10 10^{-2} 10² 10^{3} 10 10 10⁴ 10⁻² 10-10 τ [ns] Cτ [m] Cτ [m] 1710.04901 $\overset{t}{\chi}$, $\tilde{\chi}^{\pm}_{,}$, $\tilde{\chi}^{\pm}_{,}$, $\tilde{\chi}^{0}_{,}$ production, tan β = 5, μ > 0 Pure Wino

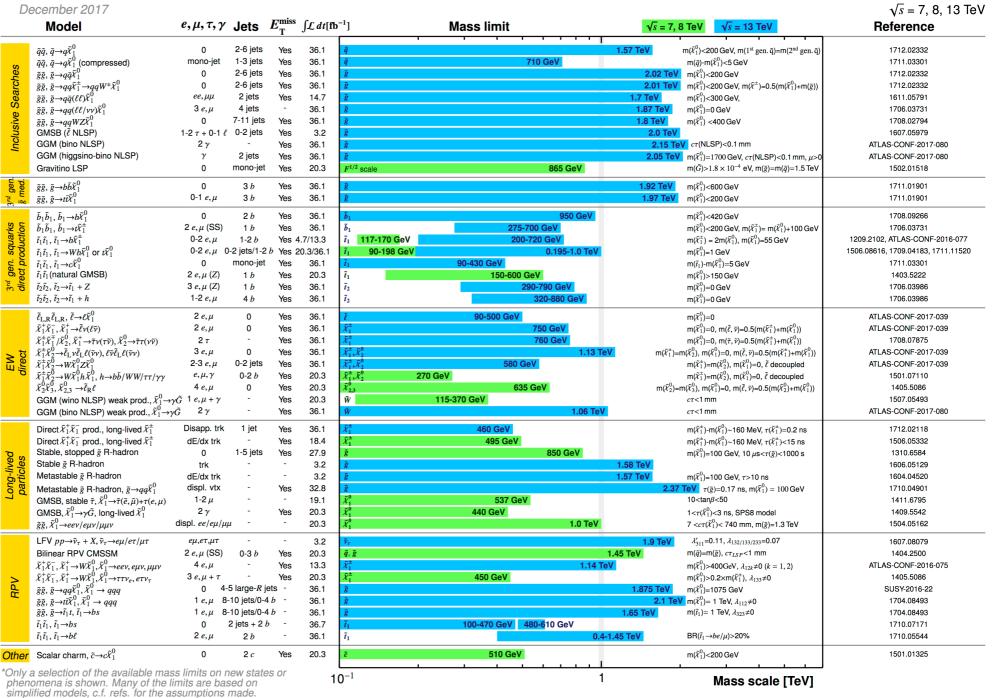


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SUSY summary

ATLAS SUSY Searches* - 95% CL Lower Limits

Many more searches have excluded SUSY particles up to the given masses and with the given assumptions Only a selection is shown here



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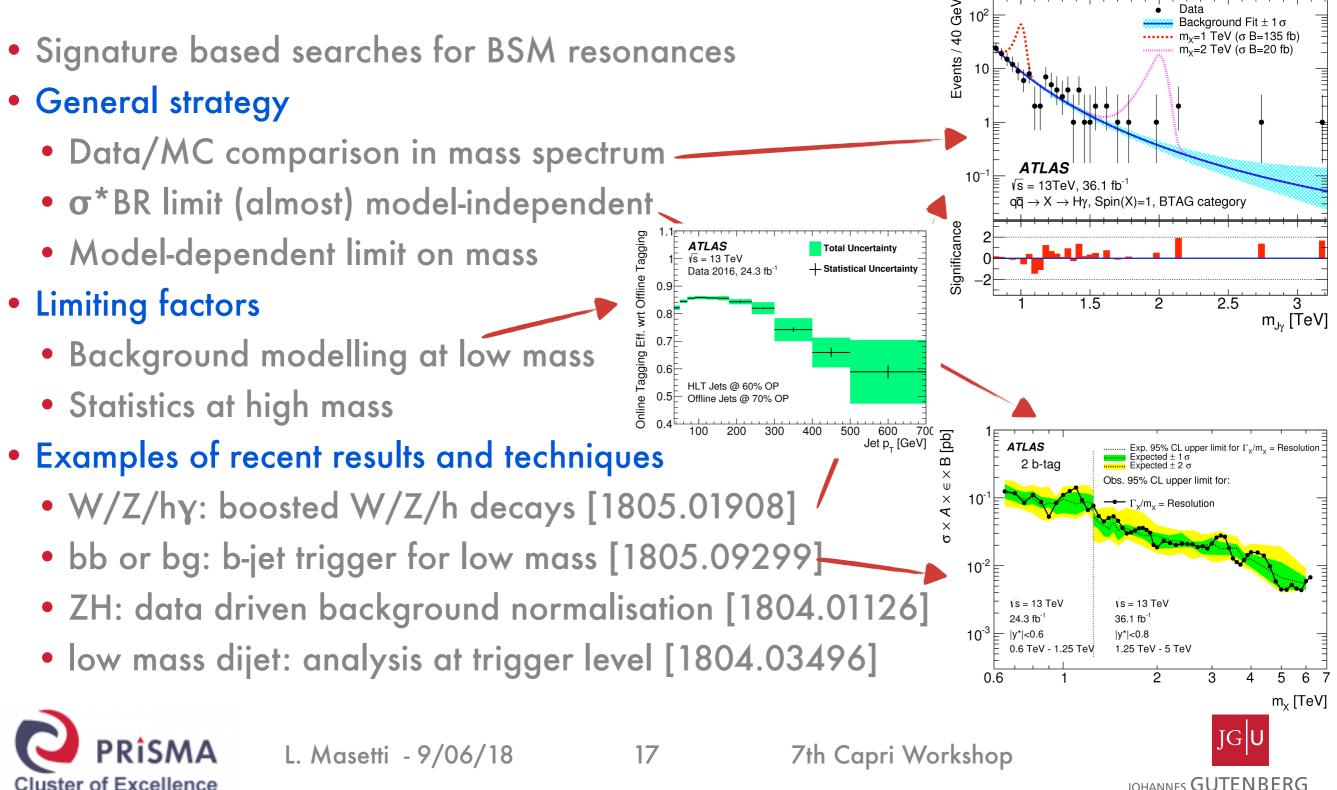
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ATLAS Preliminary

Resonances

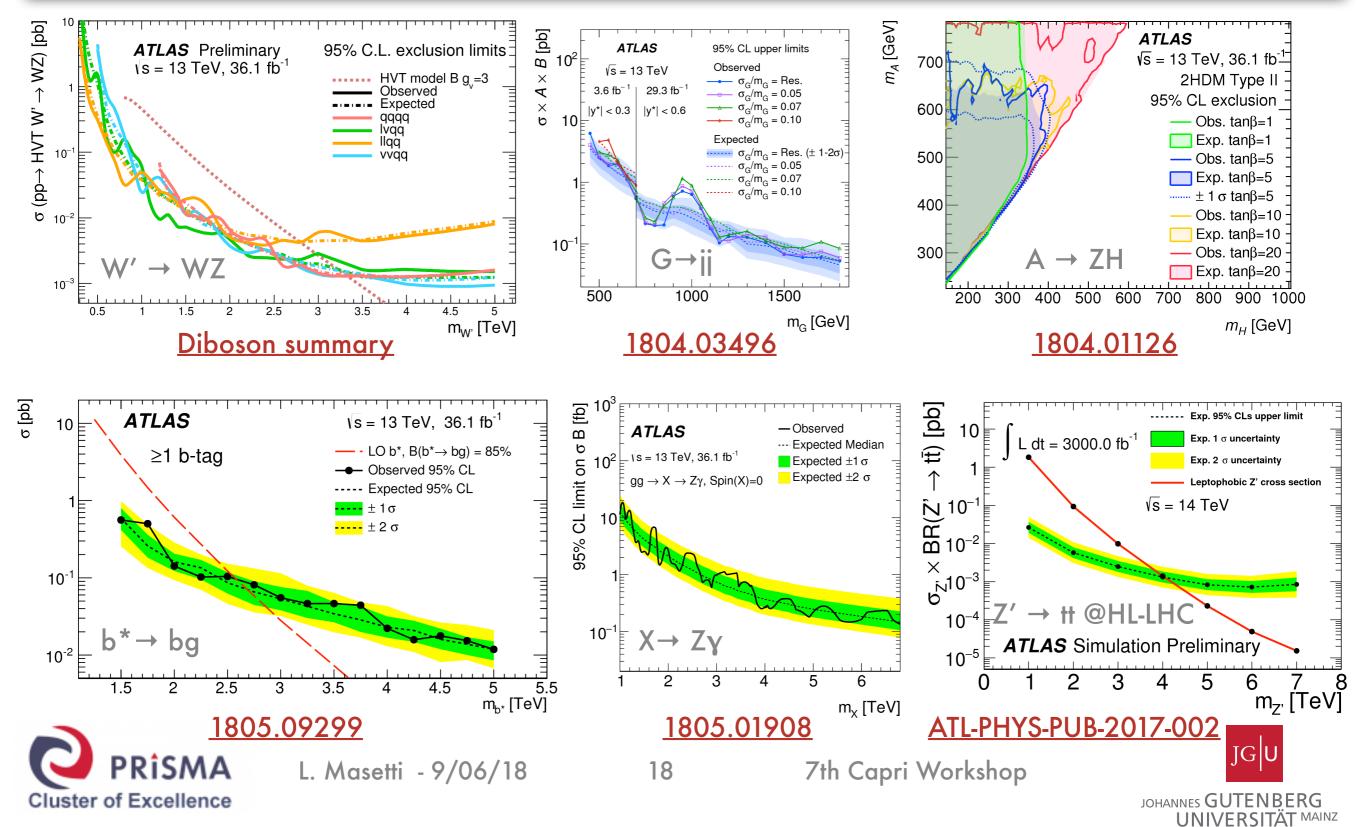




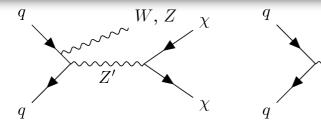
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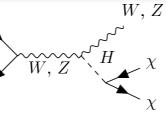
Resonances

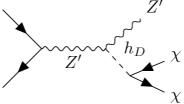


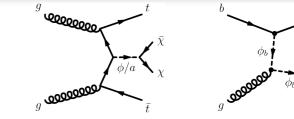


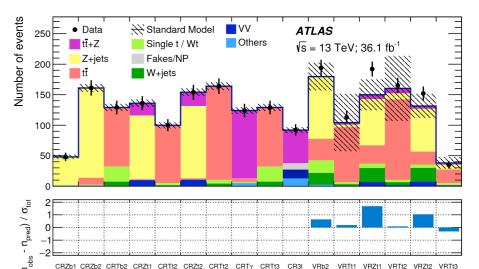
DM searches











• Limiting factor

• General strategy

• Very strong model dependence in the interpretation

• Mediators → reinterpretation of resonance searches

• Examples of recent results and techniques

Searches for DM candidates and mediators

DM candidates → high MET signature

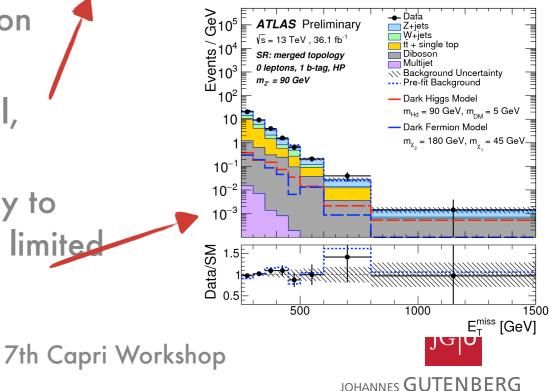
• All RPC SUSY searches are also DM searches

- t/b+MET: signal regions optimised for each model, similar strategy to SUSY searches [1710.11412]
- W/Z/Z'+MET: resolved or boosted W/Z/Z' decay to hadrons, large irreducible background, sensitivity limited by systematics [ATLAS-CONF-2018-005]



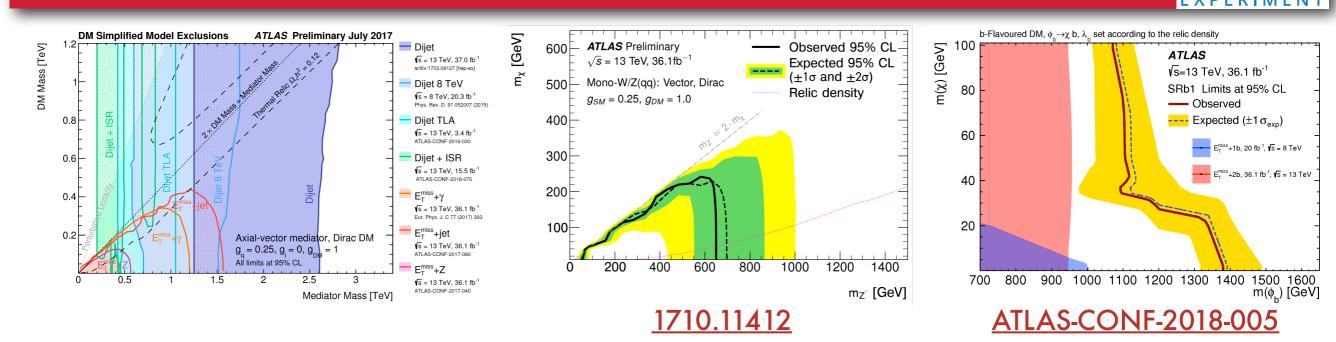
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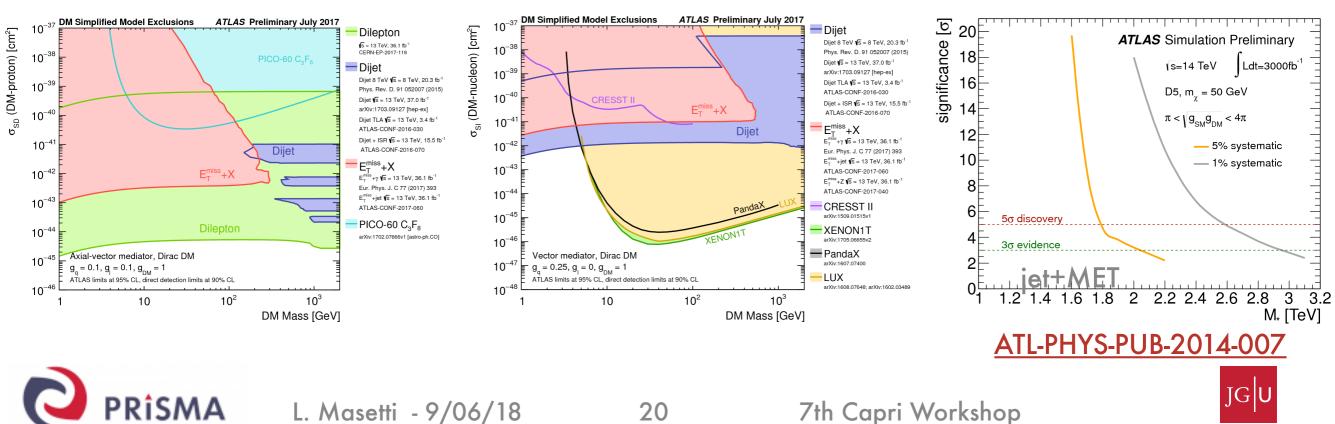
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DM searches





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Exotics summary

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits



ATLAS Preliminary

Many more searches have excluded exotic particles up to the given masses and with the given assumptions Only a selection is shown here

Status: July 2017 $\int \mathcal{L} dt = (3.2 - 37.0) \text{ fb}^{-1}$ $\sqrt{s} = 8, 13 \text{ TeV}$									
	Model	ℓ, γ Jet	s† E	miss T	∫£ dt[fb	o ⁻¹]	Limit	0.2 07.0710	Reference
Extra dimensions	ADD $G_{KK} + g/q$ ADD non-resonant $\gamma\gamma$ ADD QBH ADD BH high $\sum p_T$ ADD BH multijet RS1 $G_{KK} \rightarrow \gamma\gamma$ Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell v$ 2UED / RPP	$2\gamma - 2$ $\geq 1e, \mu \geq 2$ $- 2\gamma - 2$ $2\gamma - 1e, \mu = 1$	-4j - 2j 3j - J , ≥3j	Yes - - - Yes Yes	36.1 36.7 37.0 3.2 3.6 36.7 36.1 13.2	M _D M _S M _{th} M _{th} M _{th} G _{KK} mass G _{KK} mass	7.75 TeV 8.6 TeV 8.9 TeV 8.2 TeV 9.55 TeV 4.1 TeV 1.75 TeV 1.6 TeV	$\begin{split} n &= 2\\ n &= 3 \text{ HLZ NLO}\\ n &= 6\\ n &= 6, M_D = 3 \text{ TeV, rot BH}\\ n &= 6, M_D = 3 \text{ TeV, rot BH}\\ k/\overline{M}_{Pl} &= 0.1\\ k/\overline{M}_{Pl} &= 1.0\\ \text{Tier } (1,1), \mathcal{B}(A^{(1,1)} \rightarrow tt) = 1 \end{split}$	ATLAS-CONF-2017-060 CERN-EP-2017-132 1703.09217 1606.02265 1512.02586 CERN-EP-2017-132 ATLAS-CONF-2017-051 ATLAS-CONF-2016-104
Gauge bosons	$\begin{array}{l} \mathrm{SSM} \ Z' \to \ell\ell \\ \mathrm{SSM} \ Z' \to \tau\tau \\ \mathrm{Leptophobic} \ Z' \to bb \\ \mathrm{Leptophobic} \ Z' \to tt \\ \mathrm{SSM} \ W' \to \ell \nu \\ \mathrm{HVT} \ V' \to WV \to qqqq \ \mathrm{model} \\ \mathrm{HVT} \ V' \to WH/ZH \ \mathrm{model} \ \mathrm{B} \\ \mathrm{LRSM} \ W'_R \to tb \\ \mathrm{LRSM} \ W'_R \to tb \end{array}$	$\begin{array}{ccc} 1 \ e, \mu & \geq 1 \ b, \\ 1 \ e, \mu & \cdots \\ I \ B & 0 \ e, \mu & 2 \\ multi-channel \\ 1 \ e, \mu & 2 \ b, \end{array}$	- b ≥ 1J/2j - J 0-1 j o, 1 J	– – Yes – Yes –	36.1 36.1 3.2 3.2 36.1 36.7 36.1 20.3 20.3	Z' mass Z' mass Z' mass Z' mass W' mass V' mass W' mass W' mass	4.5 TeV 2.4 TeV 1.5 TeV 2.0 TeV 2.0 TeV 5.1 TeV 3.5 TeV 2.93 TeV 1.92 TeV 1.76 TeV	$\Gamma/m = 3\%$ $g_V = 3$ $g_V = 3$	ATLAS-CONF-2017-027 ATLAS-CONF-2017-050 1603.08791 ATLAS-CONF-2016-014 1706.04786 CERN-EP-2017-147 ATLAS-CONF-2017-055 1410.4103 1408.0886
CI	Cl qqqq Cl ℓℓqq Cl uutt	- 2 2 e,μ 2(SS)/≥3 e,μ ≥1 b	?j - , ≥1 j	– – Yes	37.0 36.1 20.3	Λ Λ Λ	4.9 TeV	21.8 TeV η _{LL} 40.1 TeV η _{LL} C _{RR} = 1	1703.09217 ATLAS-CONF-2017-027 1504.04605
MD	Axial-vector mediator (Dirac DM) Vector mediator (Dirac DM) $VV_{\chi\chi}$ EFT (Dirac DM)	$0 e, \mu, 1 \gamma \leq$	-4j 1j ≤1j	Yes Yes Yes	36.1 36.1 3.2	m _{med} m _{med} M _*	1.5 TeV 1.2 TeV 700 GeV	$\begin{array}{l} g_q{=}0.25,g_\chi{=}1.0,m(\chi)<400~{\rm GeV}\\ g_q{=}0.25,g_\chi{=}1.0,m(\chi)<480~{\rm GeV}\\ m(\chi)<150~{\rm GeV} \end{array}$	ATLAS-CONF-2017-060 1704.03848 1608.02372
ГØ	Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 rd gen	$2 \mu \geq$	2j 2j ,≥3j	– – Yes	3.2 3.2 20.3	LQ mass LQ mass LQ mass	1.1 TeV 1.05 TeV 640 GeV	$egin{array}{lll} eta = 1 \ eta = 1 \ eta = 1 \ eta = 0 \end{array}$	1605.06035 1605.06035 1508.04735
Heavy quarks	$ \begin{array}{l} VLQ TT \rightarrow Ht + X \\ VLQ TT \rightarrow Zt + X \\ VLQ TT \rightarrow Wb + X \\ VLQ BB \rightarrow Hb + X \\ VLQ BB \rightarrow Zb + X \\ VLQ BB \rightarrow Wt + X \\ VLQ QQ \rightarrow WqWq \end{array} $	$\begin{array}{l} 0 \text{ or } 1 \ e, \mu \ \geq 2 \ b \\ 1 \ e, \mu \ \geq 1 \ b \\ 1 \ e, \mu \ \geq 1 \ b \\ 1 \ e, \mu \ \geq 2 \ b \\ 2 / \geq 3 \ e, \mu \ \geq 2 / 2 \\ 1 \ e, \mu \ \geq 1 \ b \\ 1 \ e, \mu \ \geq 1 \ b \\ 1 \ e, \mu \ \geq 1 \ b \\ 1 \ e, \mu \ \geq 1 \ b \\ 1 \ e, \mu \ \geq 1 \ b \\ 1 \ e, \mu \ \geq 2 \end{pmatrix}$, ≥ 3 j ≥ 1J/2j , ≥ 3 j ≥1 b	Yes Yes Yes –	13.2 36.1 20.3 20.3 36.1 20.3	T mass T mass T mass B mass B mass B mass Q mass	1.2 TeV 1.16 TeV 1.35 TeV 700 GeV 790 GeV 1.25 TeV 690 GeV	$\begin{split} \mathcal{B}(T \to Ht) &= 1\\ \mathcal{B}(T \to Zt) &= 1\\ \mathcal{B}(T \to Wb) &= 1\\ \mathcal{B}(B \to Hb) &= 1\\ \mathcal{B}(B \to Zb) &= 1\\ \mathcal{B}(B \to Wt) &= 1 \end{split}$	ATLAS-CONF-2016-104 1705.10751 CERN-EP-2017-094 1505.04306 1409.5500 CERN-EP-2017-094 1509.04261
Excited fermions	Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $b^* \rightarrow bg$ Excited quark $b^* \rightarrow Wt$ Excited lepton ℓ^* Excited lepton ν^*	1γ 1 – 1b	?j j , 1 j 2-0 j -	- - Yes -	37.0 36.7 13.3 20.3 20.3 20.3	q* massq* massb* massb* masst* masst* massv* mass	6.0 TeV 5.3 TeV 2.3 TeV 1.5 TeV 3.0 TeV 1.6 TeV	only u^* and d^* , $\Lambda = m(q^*)$ only u^* and d^* , $\Lambda = m(q^*)$ $f_g = f_L = f_R = 1$ $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$	1703.09127 CERN-EP-2017-148 ATLAS-CONF-2016-060 1510.02664 1411.2921 1411.2921
Other	LRSM Majorana ν Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ Monotop (non-res prod) Multi-charged particles Magnetic monopoles	2,3,4 e, μ (SS) 3 e, μ, τ 1 e, μ 1 - -	:j - - - - - - -	- - Yes -	20.3 36.1 20.3 20.3 20.3 7.0	multi-charged monopole mas		$\begin{split} m(W_{\mathcal{R}}) &= 2.4 \text{ TeV, no mixing} \\ \text{DY production} \\ \text{DY production}, \ \mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1 \\ a_{\text{non-res}} &= 0.2 \\ \text{DY production}, \ q &= 5e \\ \text{DY production}, \ g &= 1g_D, \ \text{spin } 1/2 \end{split}$	1506.06020 ATLAS-CONF-2017-053 1411.2921 1410.5404 1504.04188 1509.08059
		√s = 8 TeV √s	= 13	iev		10	$)^{-1}$ 1 1	⁰ Mass scale [TeV]	

*Only a selection of the available mass limits on new states or phenomena is shown. †Small-radius (large-radius) jets are denoted by the letter j (J).

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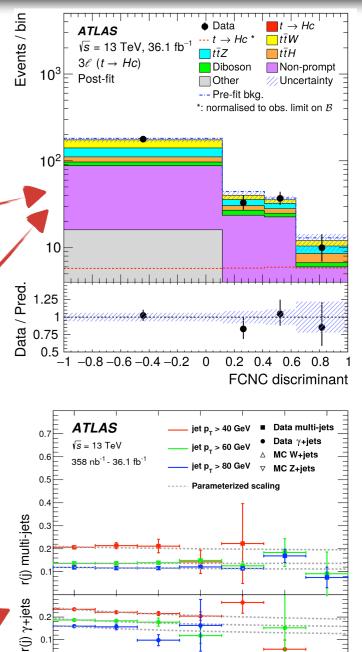
Indirect BSM searches

Very rare processes



- Processes expected in the SM with very low probability, well beyond sensitivity
- Searches for enhancement as predicted by many BSM models
- Strategies
 - Template fit of discriminant distribution
- Limiting factor: Statistics
- Examples of latest results and techniques
 - FCNC t→Hq: 2 same-sign or 3 leptons, boosted decision trees for background suppression [1805.03483]
 - hh→bbyy: data-driven continuum diphoton background fit [paper in preparation]
 - tttt: high multiplicity jet and b-jet signal regions, jetscaling parametrisation [1704.08493]





(j) W+jets

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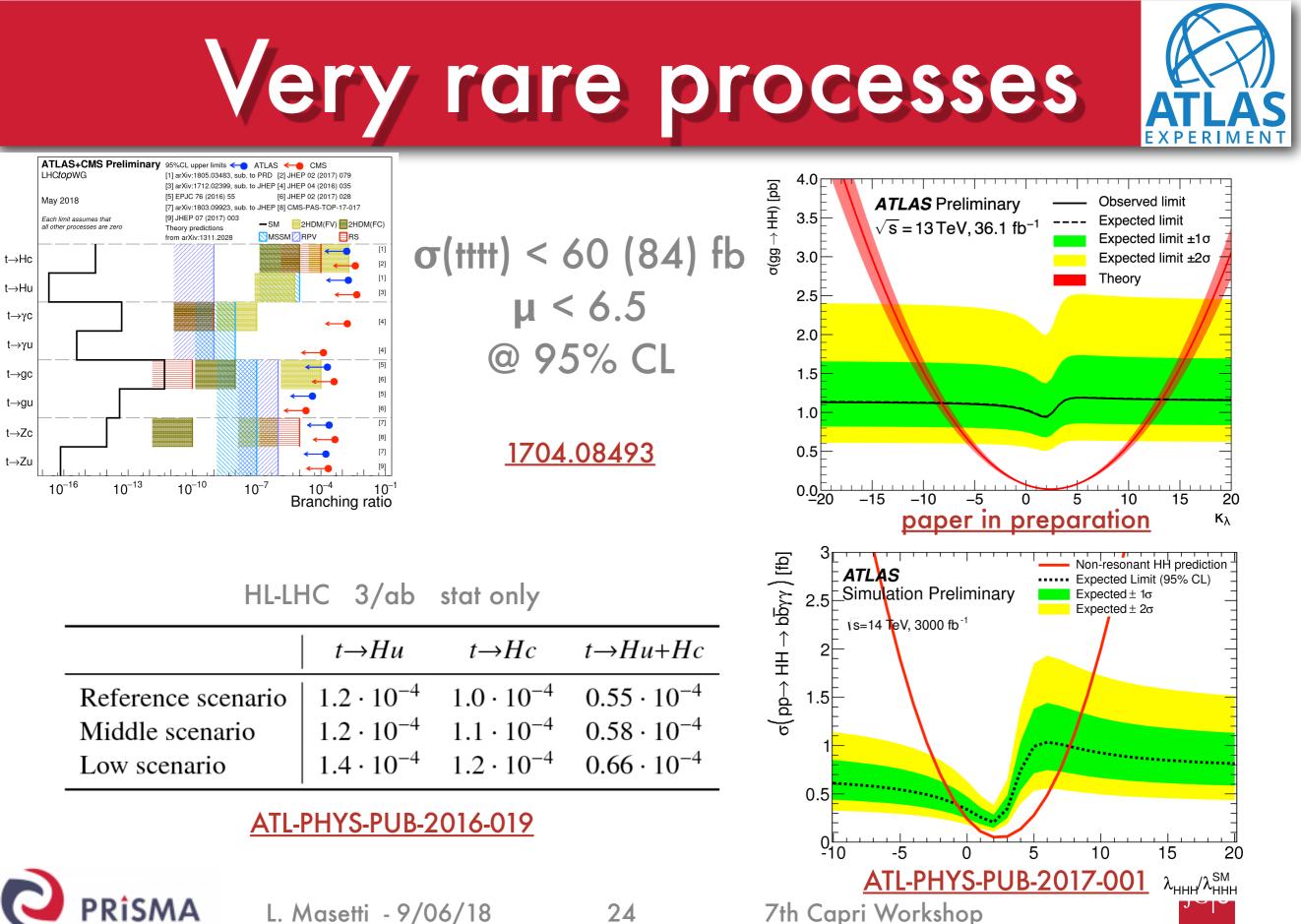
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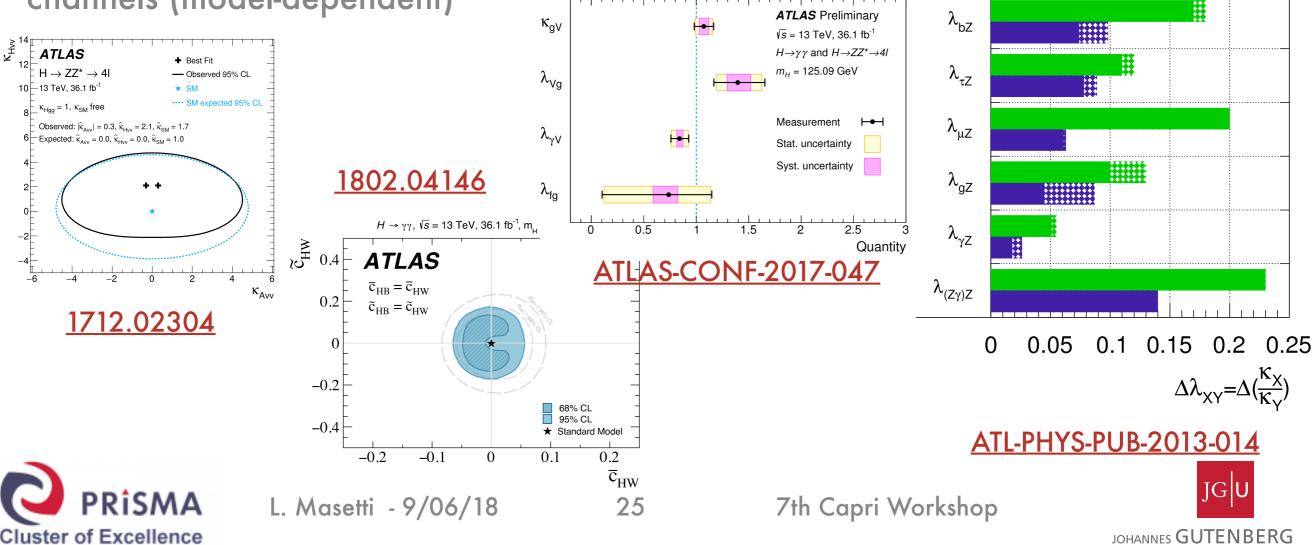
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Higgs couplings

- First EFT interpretations of SM Higgs boson cross section measurements (inclusive and differential)
 → limits on anomalous couplings
- Kappa framework used in the past

 → fit of couplings from several decay and production
 channels (model-dependent)



ATLAS EXPERIMENT

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ATLAS Simulation Preliminary

 $\sqrt{s} = 14 \text{ TeV}: \int Ldt = 300 \text{ fb}^{-1}; \int Ldt = 3000 \text{ fb}^{-1}$

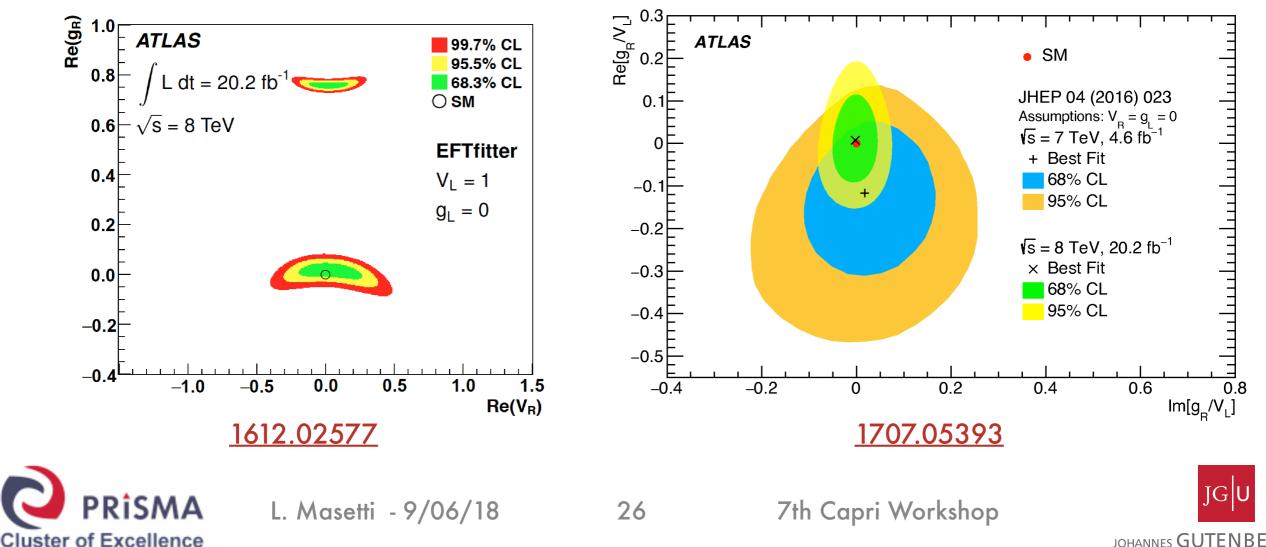
 κ_{gZ}

 λ_{WZ}

 $\lambda_{t\! o}$

Top couplings

- Some 8 TeV results interpreted in EFT
 - Wtb from single top production
 - W helicity in top pair production
- More expected in the future, e.g. from associated production with Z or $\boldsymbol{\gamma}$



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Summary

- Extensive programme of direct BSM searches carried out at ATLAS
 - Large variety of strategies
 - Many ingenuous analysis methods
 - See full list of results for <u>SUSY</u> and <u>exotics</u>
- More and more SM measurements being interpreted as limits on anomalous couplings
 - Very rare processes being searched for long before sensitivity at SM level is reached
 - Higgs and top cross section and property measurements interpreted in EFT





Outlook

 Strongly improved detector, slightly higher energy and 3/ab of data expected at HL-LHC

- Big improvement for all statistically limited searches
- Background estimate can profit from more populated control regions, better measurements and calculations
- Much higher pile-up requires improved analysis techniques
 - Non-trivial reconstruction e.g. of boosted W/Z/h and top decays used extensively in searches for heavy particles
 - Lots of very promising ideas in collaboration between experimentalists and theorists





