Hunting New Physics with ATLAS

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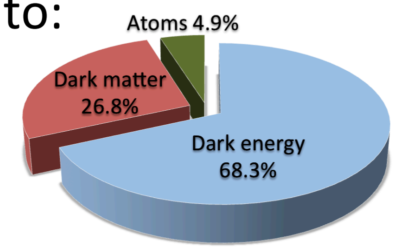
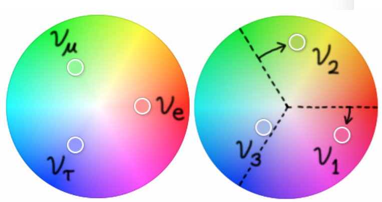
6th International Conference on New Frontiers in Physics
ICNFP 2017

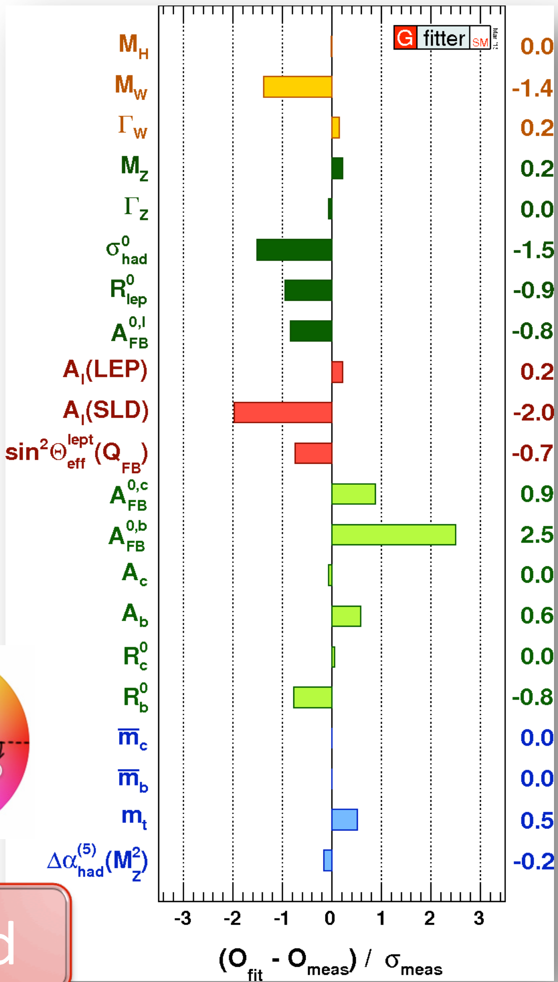
17 – 29 August 2017, Kolymbari, Crete, Greece

Why going beyond the Standard Model?

- SM provides an excellent description of the experimental data so far
  - QCD and hadronic structure
  - precision EW physics
  - top quark
  - flavour physics
- yet… it does not provide an answer to:
  - hierarchy / fine tuning problem
  - matter-antimatter asymmetry
  - dark matter & dark energy
  - neutrino masses
  - unification of EW interactions & QCD
  - gravitation
  - more than one fermion generation

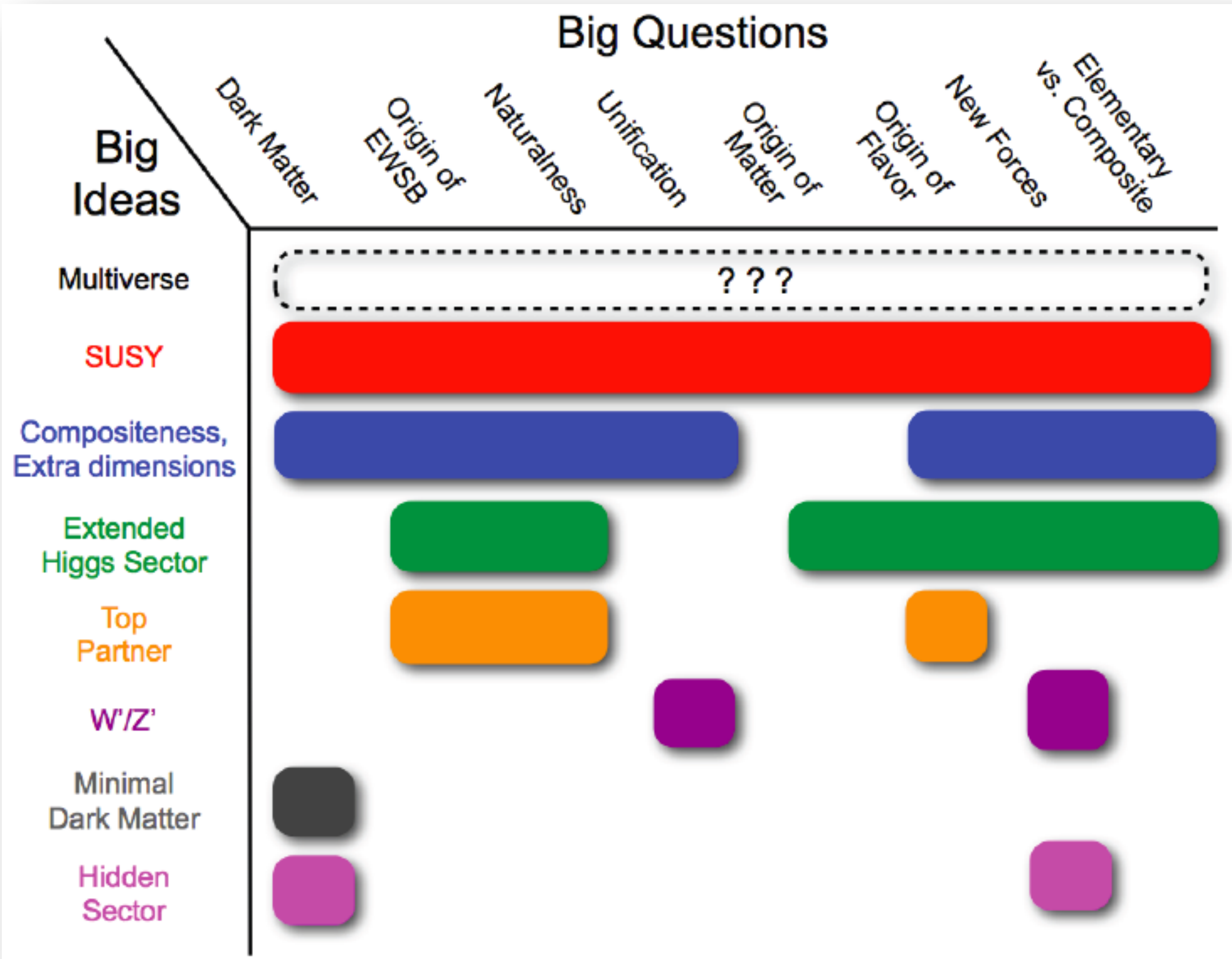






☛ An extension of the Standard Model is needed

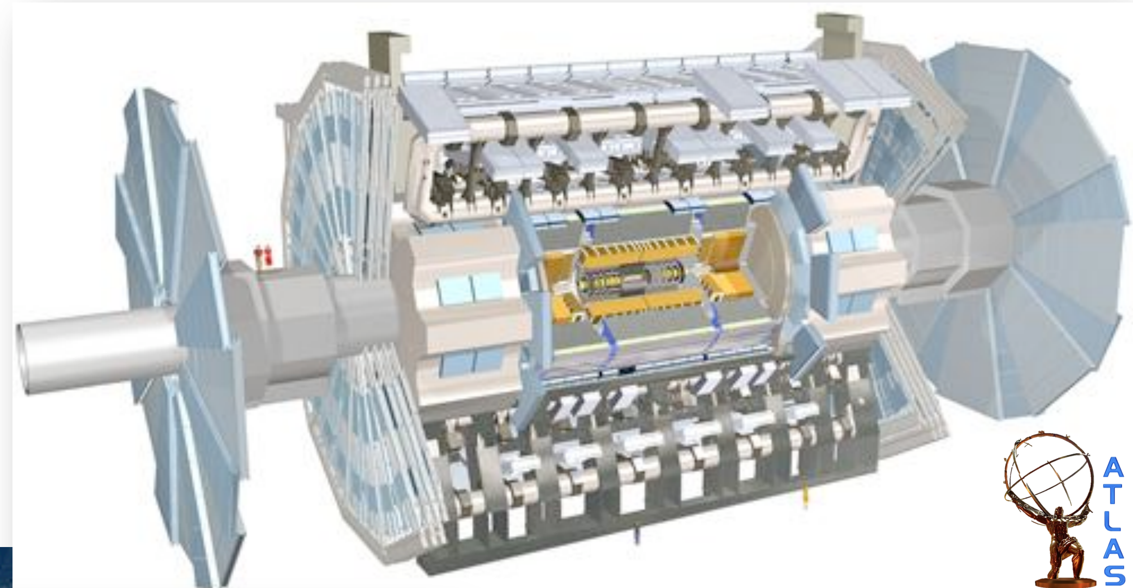
(some) ideas beyond Standard Model

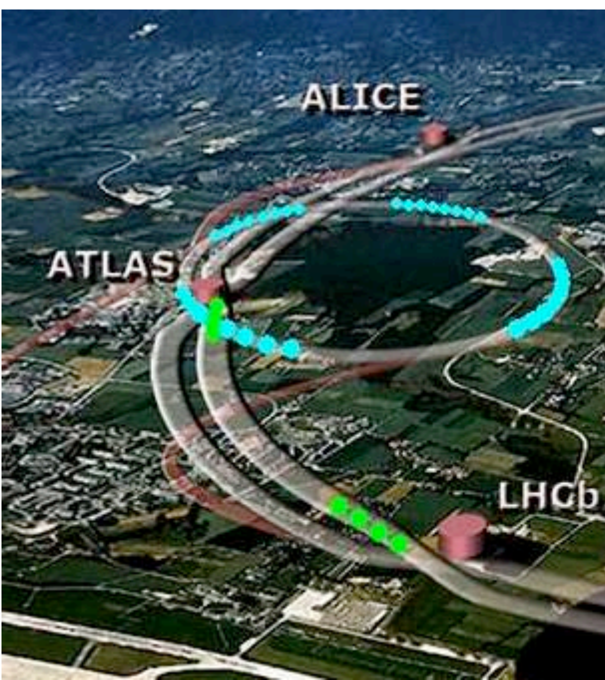


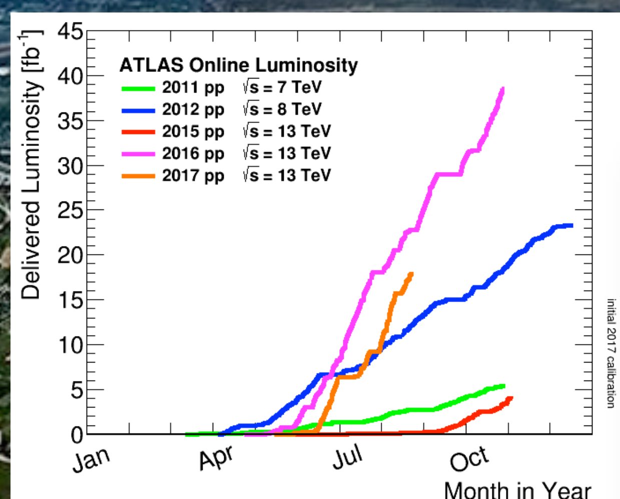
Snowmass 2013 Summary Paper

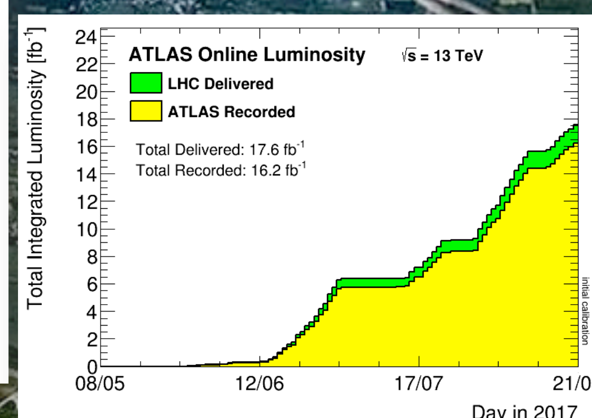
ATLAS at the LHC

- **Spectacular LHC performance**
- Run 2: 2015 – ongoing
  - **√s = 13 TeV**
  - 2015-2016: **~40 fb^{-1}** *pp* collisions recorded by ATLAS
  - 2017: **~16 fb^{-1}** recorded so far









Beyond-SM searches strategy

① Pursue signature-driven analyses:
- resonances: dileptons, jets, photons, ...
- non-resonant: tails in kinematic distributions
- special particles: slow-moving, long-lived, ...
- ...

② Search for excess of events over the expected SM background
- in one or more *Signal Regions (SRs)*

③ If no significant excess is observed
- set cross-section upper limits
- interpret in specific models to obtain limits on masses, couplings, ...

☛ Background estimate: data-driven techniques for main; MC for smaller
- measurement with data in *Control Regions (CRs)*, extrapolated to SRs
- method validated in *Validation Regions (VRs)*

☛ Blind analysis: first define and validate analysis, then open signal box

Signatures probing models

Emphasis on most recent results

- Resonances
  - dileptons: Z’ → ℓℓ, …
  - W’ → ℓν
  - dibosons: WW, WZ, γγ, …
  - top/bottom: VLQs
  - BSM Higgs, …
  - leptons+jets: leptoquarks, …
  - dijets
- Non-resonant final states
  - dileptons
  - leptons+jets
  - mono-X + E_T^{miss}, dark matter, …
  - …
- Long-lived particles
  - high ionisation
  - disappearing tracks
  - displaced lepton jets, vertices

Pawel Bruckman’s talk

Yoram Rozen’s talk

Cristiano Sebastiani ‘s poster

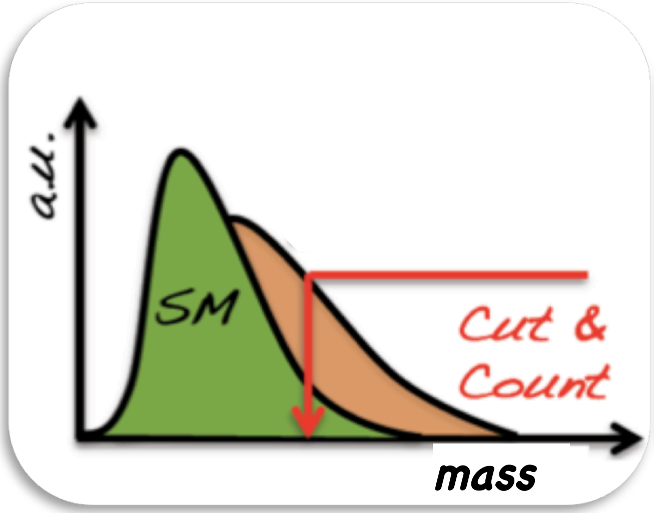
Signature-based searches cover multitude of theoretical scenarios

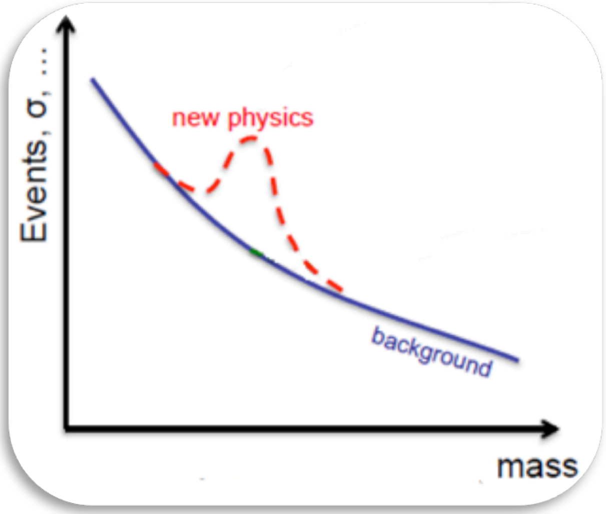
- SUSY-specific signatures: E_T^{miss} + X
  - strong production
  - 3rd-generation squarks
  - electroweak production
  - …

See talks by:
- *Andre Sopczak*
- *Shunsuke Adachi*
- *Nicolas Koehler*
- *Athina Kourkoumeli*

Looking for resonances & tails in distributions

- Non-SUSY searches only presented here
- Detailed reviews for SUSY in other talks



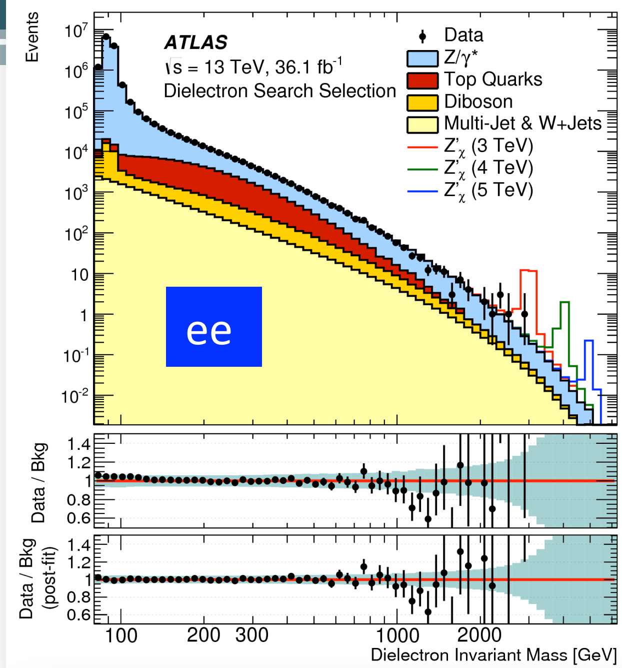


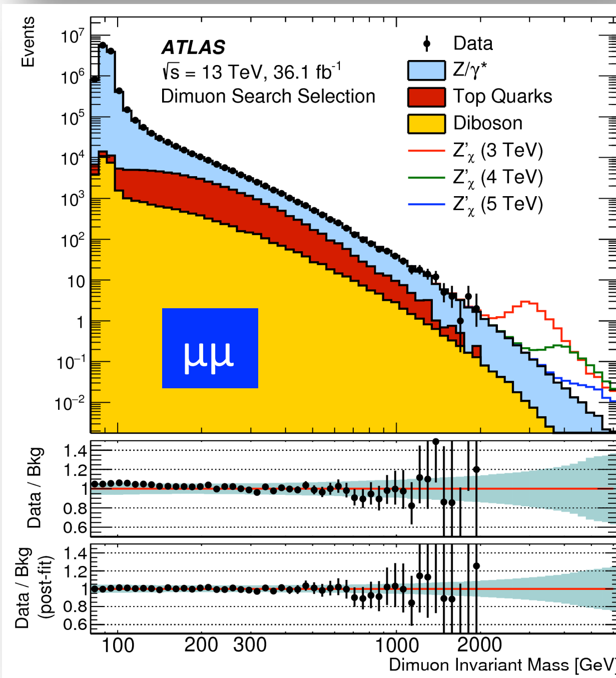
Dileptons (1/3)

36.1 fb^{-1} @ 13 TeV

- Selection
  - 2 opposite-sign (OS) isolated electrons OR muons with p_T > 30 GeV
- Background
  - Drell-Yan (DY), diboson, top (pair & single)
    - DY fitted to data at Z-peak
  - fakes (QCD jets & W+jets) → data-driven matrix method
- Reconstruction of dilepton invariant mass **$m_{\ell\ell}$**
- Looking for narrow resonances OR broad excesses in the invariant mass distribution

➡ Data consistent with SM expectation

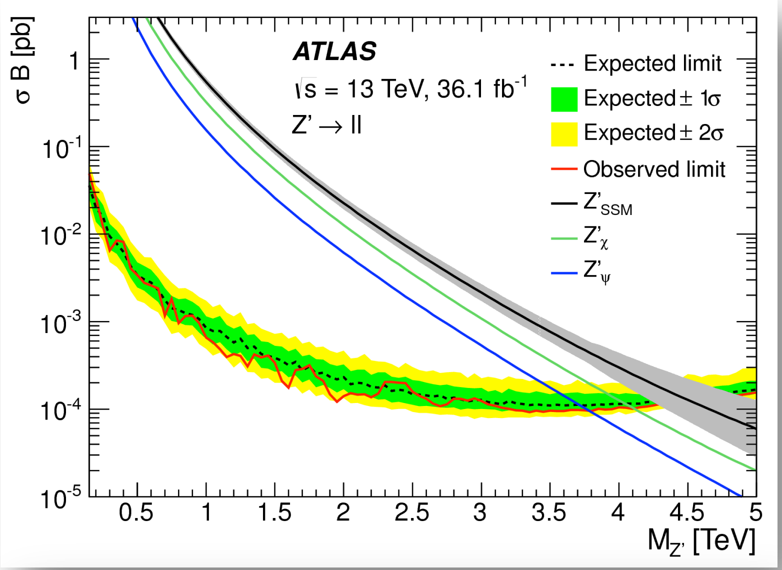




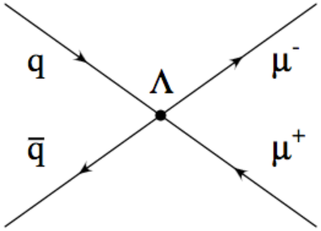
arXiv:1707.02424

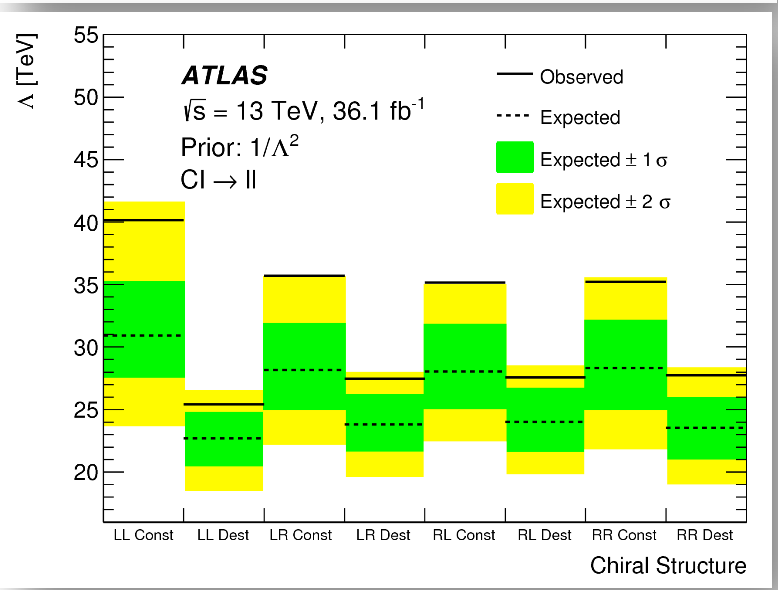
Dileptons (2/3)

- **Z' resonances**: spin-1 neutral gauge bosons
  - Sequential SM (SSM): Z' with same couplings as SM Z
  - GUT models based on E_6 gauge group predict two additional U(1) gauge fields: Z'_ψ, Z'_χ
  - observable as narrow resonances in dilepton invariant mass spectrum



- **Contact Interactions (CI)**
  - probes quark and lepton compositeness, with binding energy scale Λ
  - different chiral structures considered
  - detectable as broad excess in dilepton invariant mass spectrum





arXiv:1707.02424

36.1 fb^{-1} @ 13 TeV

Dileptons (3/3)

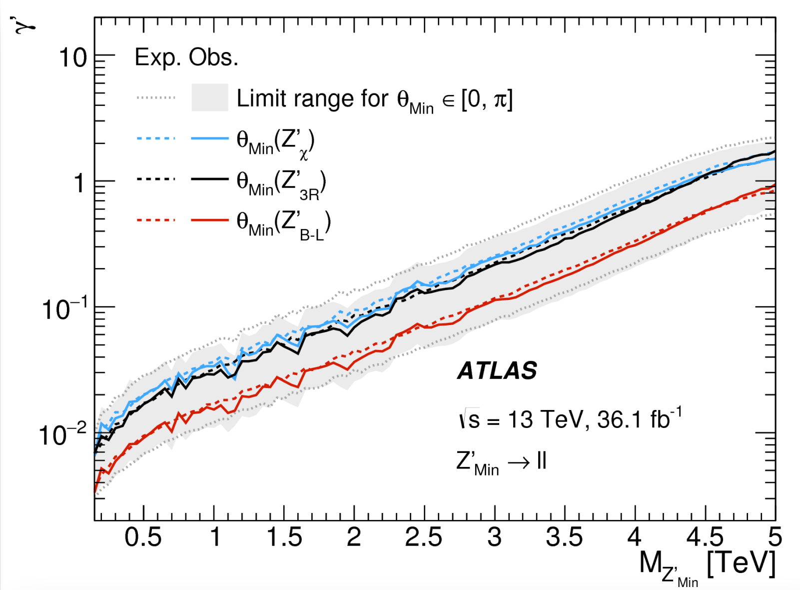
- **Minimal Z' models** are characterized by three parameters:
  - Z' boson mass
  - γ': strength of Z' boson coupling relative to SM Z
  - θ_{Min}: mixing angle between the generators of B-L (Baryon minus Lepton number) and the weak hypercharge gauge groups

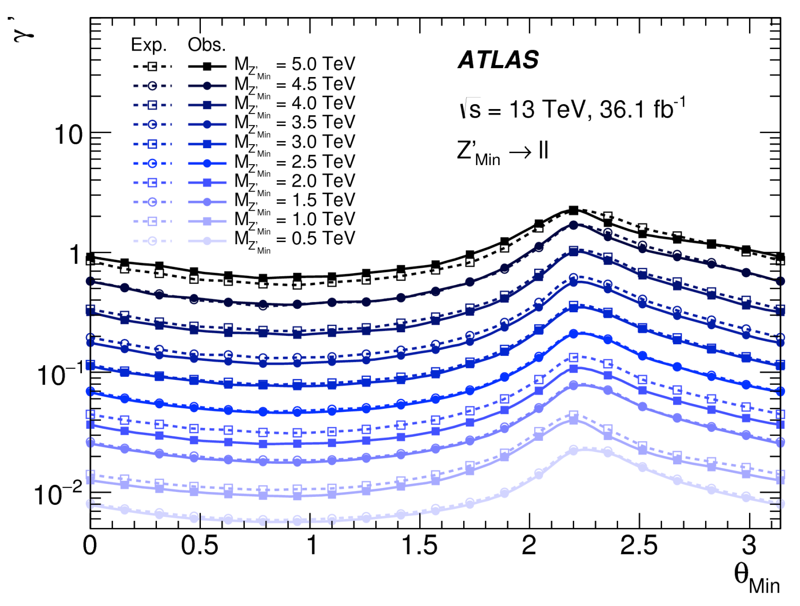
Model	γ'	$\tan\theta_{\rm Min}$	Lower limits on $M_{Z'_{\rm Min}}$ [TeV]					
			ee		$\mu\mu$		$\ell\ell$	
			Obs	Exp	Obs	Exp	Obs	Exp
Z'_χ	$\sqrt{\frac{41}{24}}\sin\theta_{\rm Min}$	$-\frac{4}{5}$	3.7	3.7	3.4	3.3	3.9	3.8
Z'_{3R}	$\sqrt{\frac{5}{8}}\sin\theta_{\rm Min}$	-2	4.0	3.9	3.6	3.6	4.1	4.1
Z'_{B-L}	$\sqrt{\frac{25}{12}}\sin\theta_{\rm Min}$	0	4.0	4.0	3.6	3.6	4.2	4.1

- Also obtained generic upper limits on visible σ in fiducial lepton p_T & η and mass-window for various widths *(not shown here)*

36.1 fb^{-1} @ 13 TeV

arXiv:1707.02424



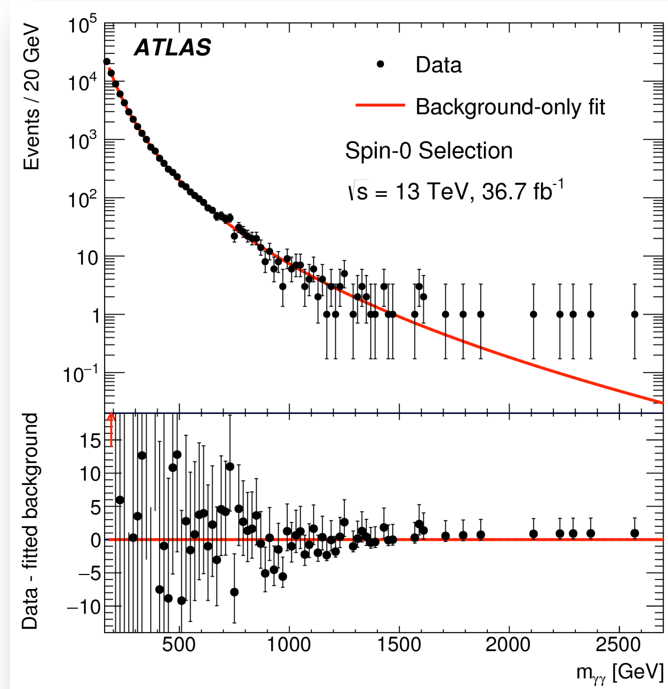


Diphotons

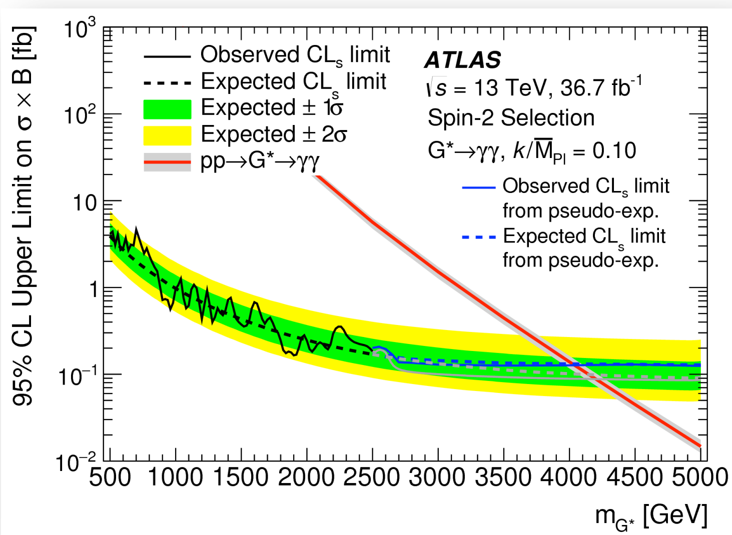
arXiv:1707.04147

- Search for heavy resonant and non-resonant BSM physics decaying into diphoton final states
- Event selection
  - ≥ 2 isolated photons with E_T > 40 GeV & 30 GeV
  - different kinematic selections applied for spin-0 vs. spin-2
  - narrow-width approximation (NWA) bump in $m_{\gamma\gamma}$
  - non-resonant: counting experiment for $m_{\gamma\gamma}$ > 2240 GeV

➡ No significance excess observed up to diphoton masses of 2.7 TeV



36.7 fb^{-1} @ 13 TeV

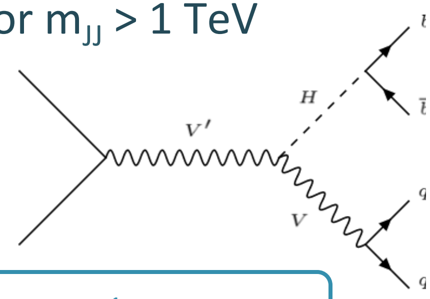


Limits set in various scenarios

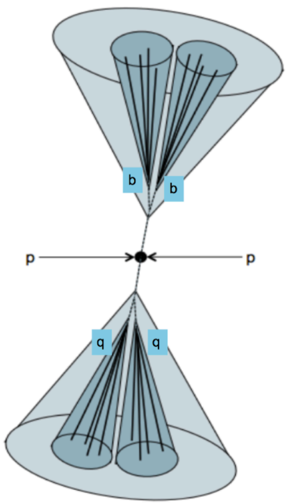
- Spin-0 resonance: exclusion limits for NWA signal σ×BR(γγ) range from **11.4 fb @200 GeV** to about **0.1 fb @ 2.7 TeV**
- Spin-2 resonance: Randall-Sundrum (RS) graviton with k/M_{Pl}=0.1 excluded below **m_{G*}=4.1 TeV**
- Spin-2 non-resonant: lower limit on M_S placed between **5.7 TeV** and **8.6 TeV** on ADD model depending on formalism used and number of extra dimension assumed

Dibosons: $V' \rightarrow VH \rightarrow q\bar{q}^{(\prime)}b\bar{b}$ (1/2)

- Search for boosted heavy resonances decaying to VH in all-hadronic channel
  - final state composed of two large-R jets, J
  - narrow-width bumps at di-jet (m_{JJ}) invariant mass for m_{JJ} > 1 TeV
- Event selection
  - lepton veto; E_T^{miss} veto
  - ≥ 2 large-R jets with p_T > 250 GeV; leading p_T > 450 GeV
  - larger mass is H-jet; smaller is V-jet
  - W/Z and H mass window
- Background estimated by side band and/or no-b-tag

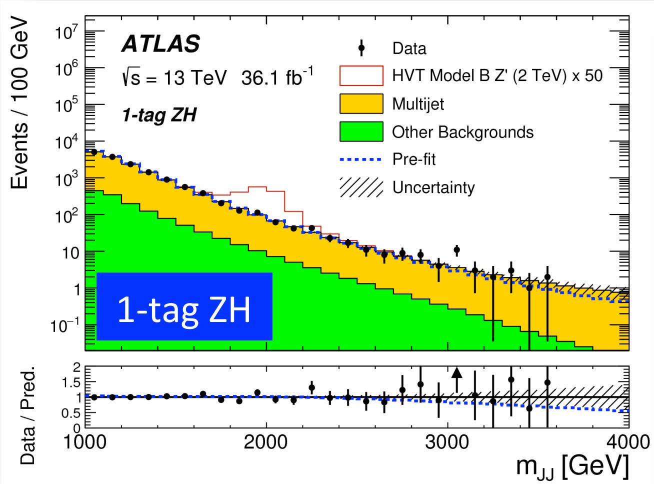


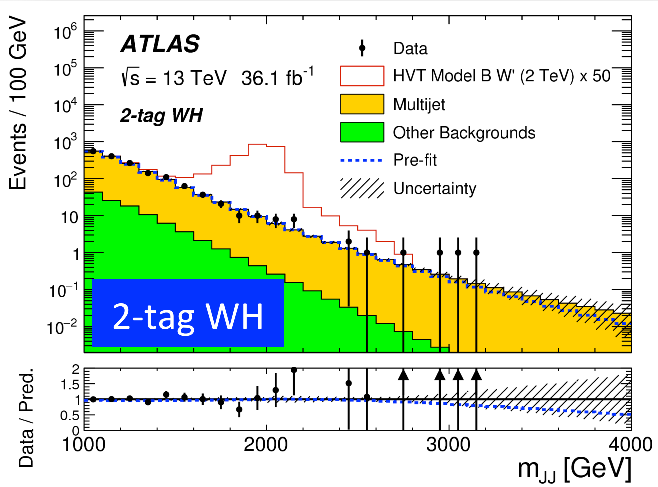
36.1 fb^{-1} @ 13 TeV



➡ Data compatible with SM hypothesis

Largest deviation in ZH channel at $m_{JJ} \approx 3$ TeV with local (global) significance of 3.3σ (2.1σ)



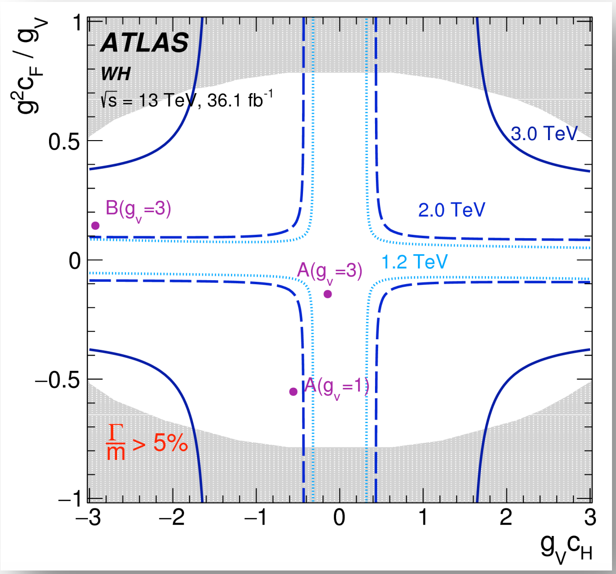


arXiv:1707.06958

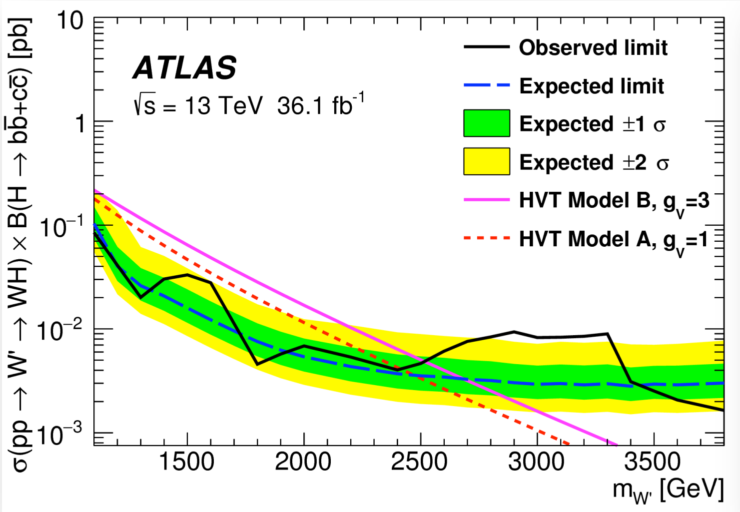
Dibosons: V’ → VH → $q\bar{q}^{(\prime)}b\bar{b}$ (2/2)

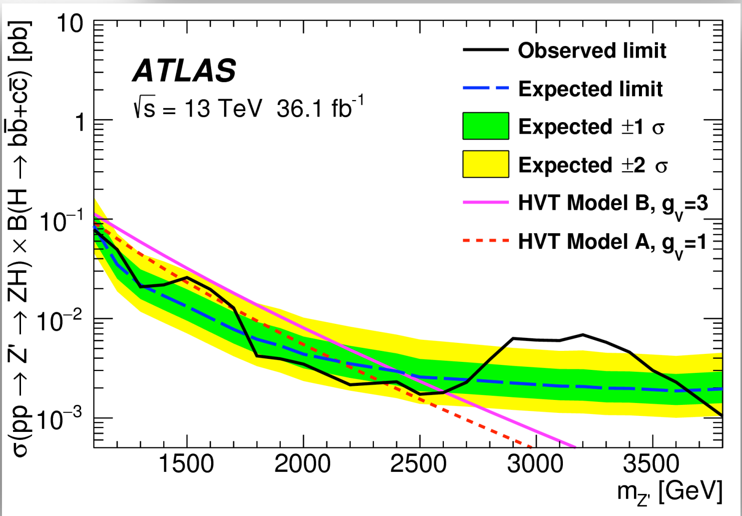
36.1 fb^{-1} @ 13 TeV

- Candidate signal models:
  - Heavy Vector Triplet (HVT) **W’ and Z’**
  - Model A: comparable BRs to fermions and gauge bosons
  - Model B: suppressed couplings to fermions
- Upper limits on σ×BR set for W’ and Z’ resonances:
  - HVT Model B resonances excluded in mass range 1100 - 2500 GeV for WH, and 1100 - 2600 GeV for ZH
  - HVT Model A resonances excluded in mass range 1100 - 2400 GeV for WH, and 1100 - 1480 GeV and 1700 - 2350 for ZH



Note: there is a ~60% overlap of data between the WH and ZH selections, for both 1-tag and 2-tag regions



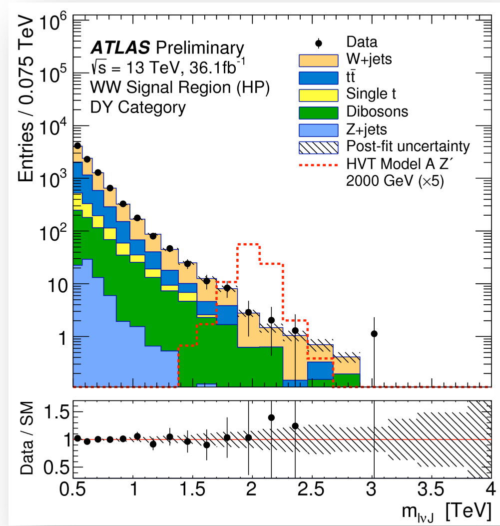


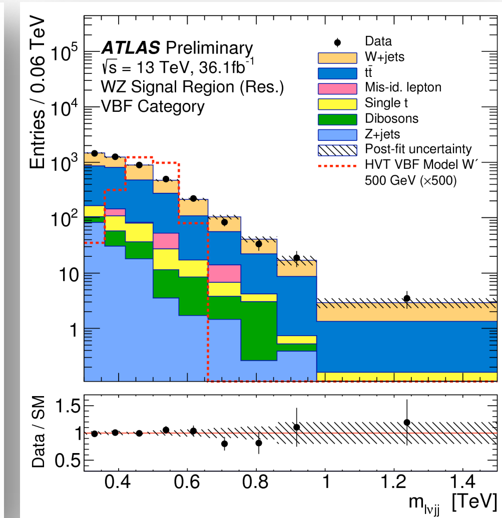
arXiv:1707.06958

Dibosons: X → WV → ℓνqq̄

36.1 fb^{-1} @ 13 TeV

- Motivation:
  - Spin 0: **Composite Higgs** (ggF or VBF)
  - Spin 1: **Heavy Vector Triplet** (qq̄ or VBF)
  - Spin 2: **RS graviton** (ggF production)
- Consider both resolved (jj) and "merged" (J), if highly boosted, dijet system
- Events categorisation:
  - VBF or DY (includes ggF & qq̄)
  - (i) merged high purity (HP); (ii) merged low purity (LP); (iii) resolved
  - WW or WZ (overlap)
- Search for bump in **m(ℓνjj)** or **m(ℓνJ)** distributions



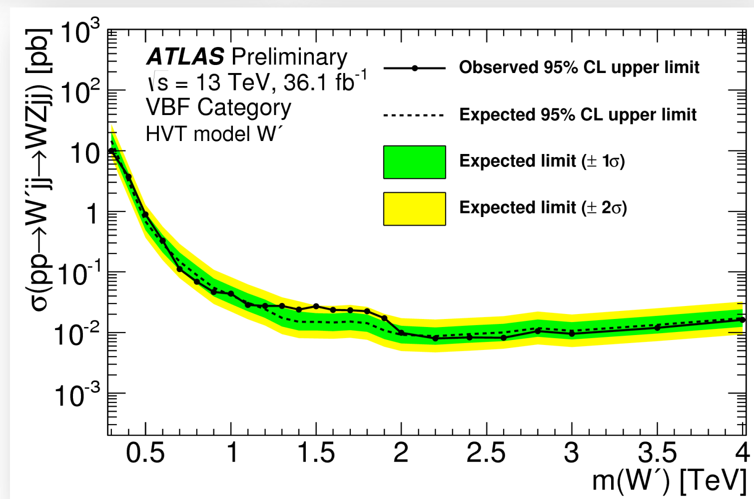


➡ No significance excess observed

⇒ limits set in resonance masses for considered models

WW Selection			
Excluded	HVT		RS G_{KK}
Masses	Model A	Model B	$k/\bar{M}_{Pl} = 1.0$
Observed	<2750 GeV	<3090 GeV	<1760 GeV
Expected	<2840 GeV	<3230 GeV	<1750 GeV

WZ Selection		
Excluded	HVT	
Masses	Model A	Model B
Observed	<2820 GeV	<2980 GeV
Expected	<2890 GeV	<3240 GeV



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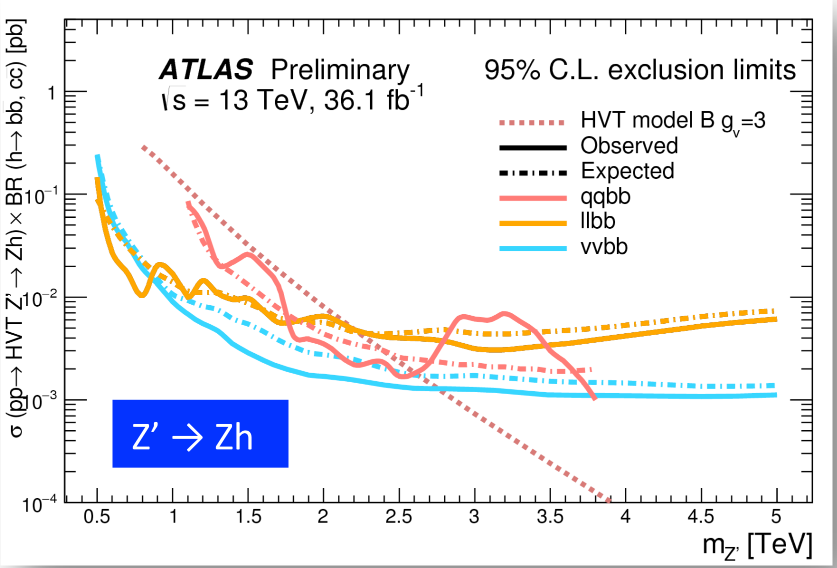
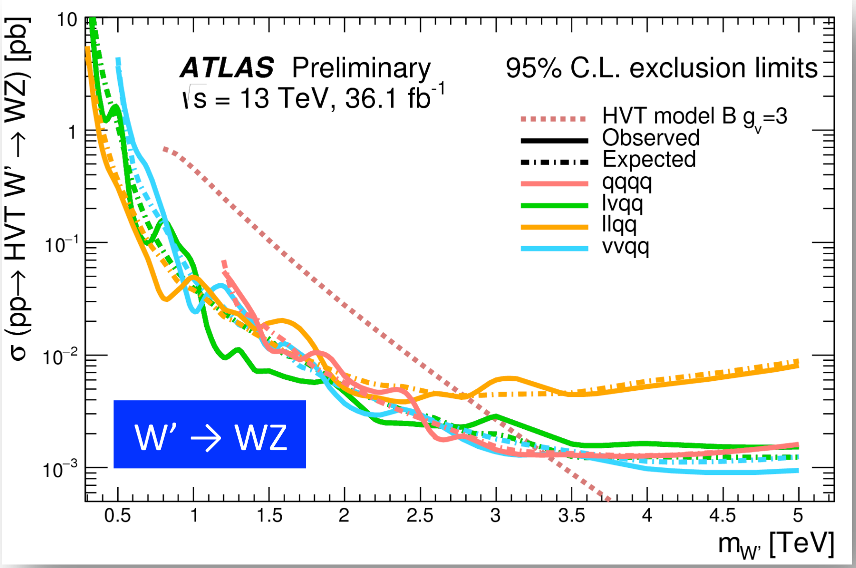
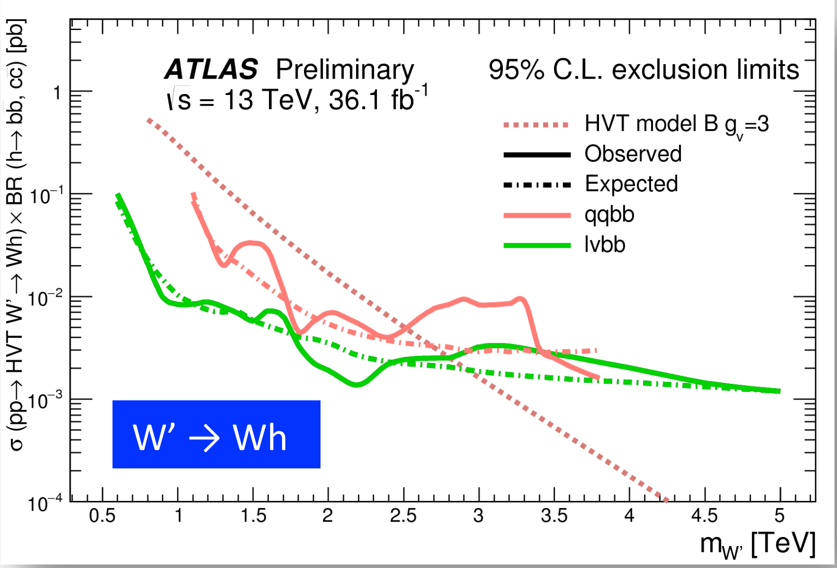
Dibosons – summary

σ×BR upper limits for Heavy Vector Triplets decaying to dibosons for different final states







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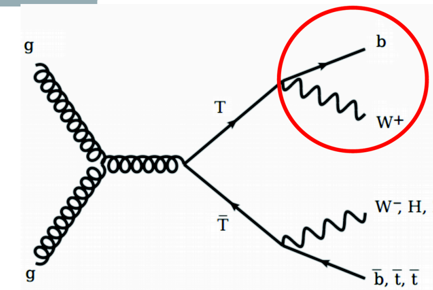
Vector-Like Quarks (VLQs): T→Wb



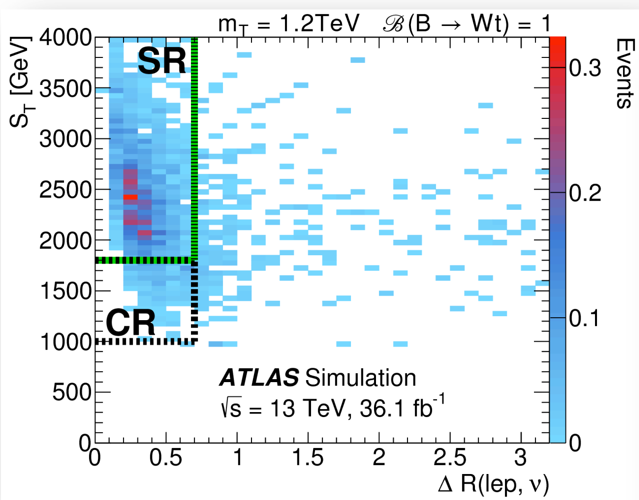
- VLQs proposed to cancel quadratic divergences in Higgs mass
- Predicted in Little/Composite Higgs
- Production: pair (QCD) or single (EW)
- Decays:
  - T→ Wb / Zt / Ht
  - B→ Wt / Zb / Hb

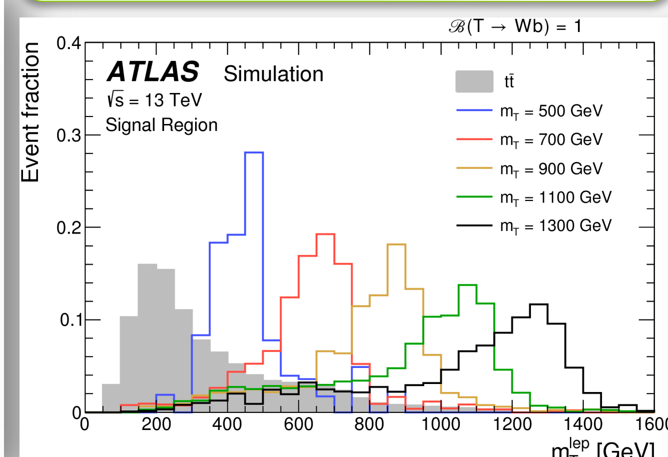
36.1 fb^{-1} @ 13 TeV

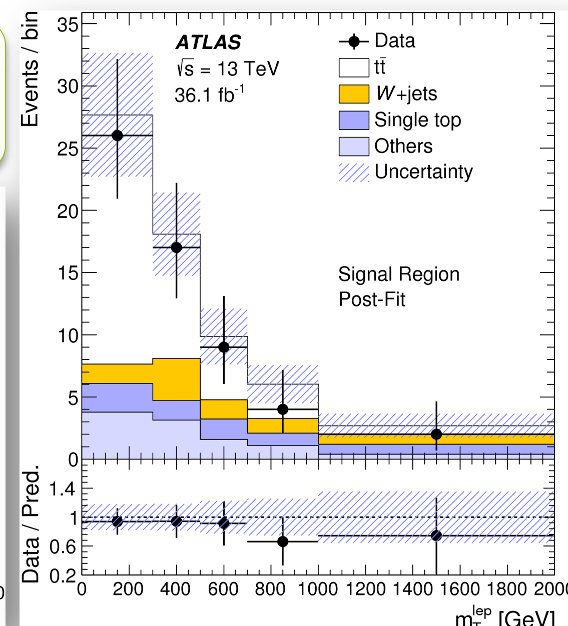
- **T→Wb** analysis
  - 1 lepton, MET, ≥ 3 jets, ≥ 1 b-jet
  - ≥ 1 W-tagged large-R jet, no overlap with b-jet
- Full event reconstruction by minimising **$|\Delta m_T|$**
- Profile likelihood fit to improve BG modelling
  - **$\Delta R(\ell,\nu)$** & **S_T** cut to define SR/CR
  - discriminating variable: **m_T^{lep}**

arXiv:1707.03347

No significant deviation from SM expectation is observed



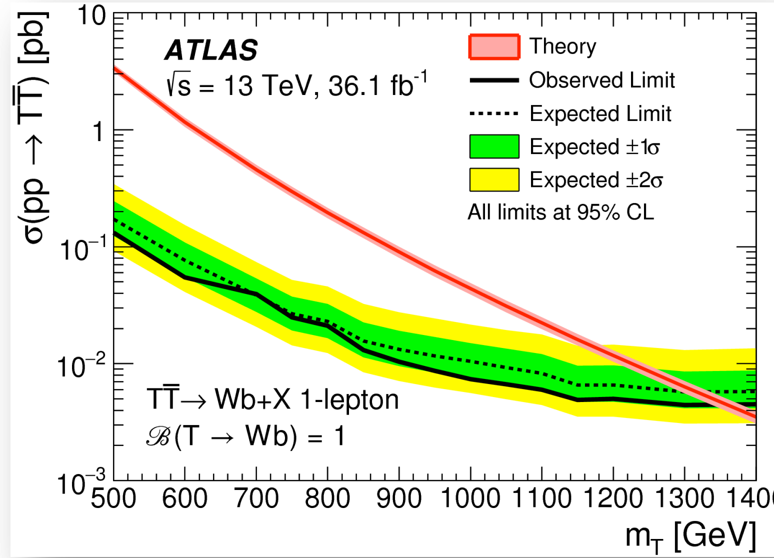




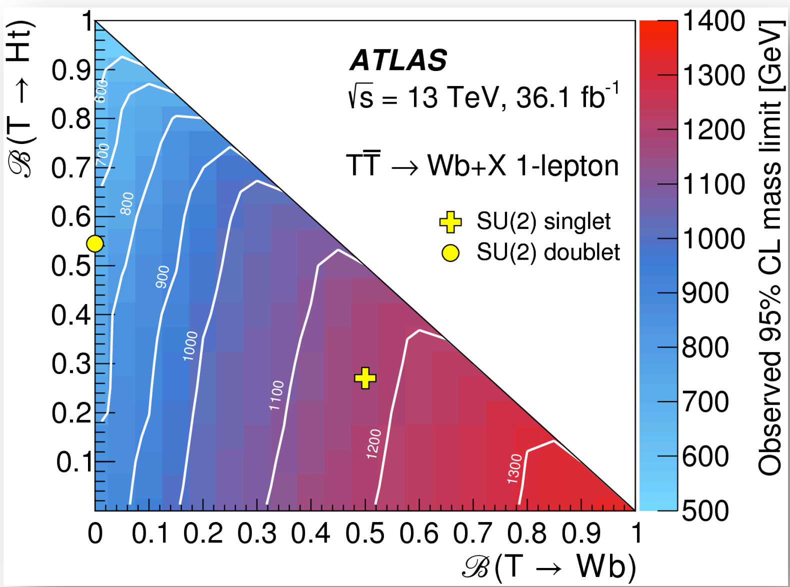
VLQs: T→Wb results

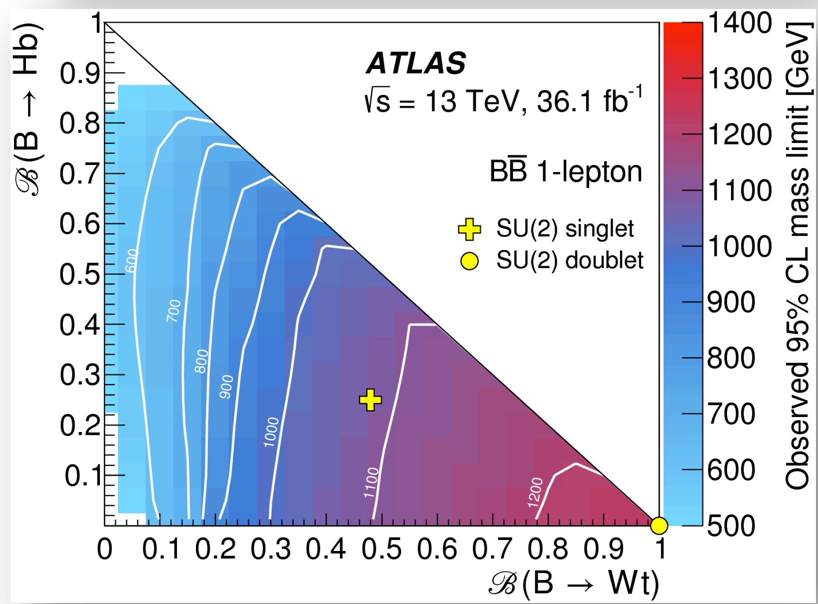
36.1 fb^{-1} @ 13 TeV

- Uncertainties
  - dominated by low statistics
  - main systematics: t & tt̄ modelling
- **Significantly improved limits w.r.t. Run I**
  - **$m_{T/Y}$ (BR_{Wb}=100%) > 1350 (782) GeV**
  - **m_T (singlet) > 1170 GeV**
  - **$m_{B/X}$ (BR_{Wt}=100%) > 1250 GeV**
  - **m_B (singlet) > 1180 GeV**



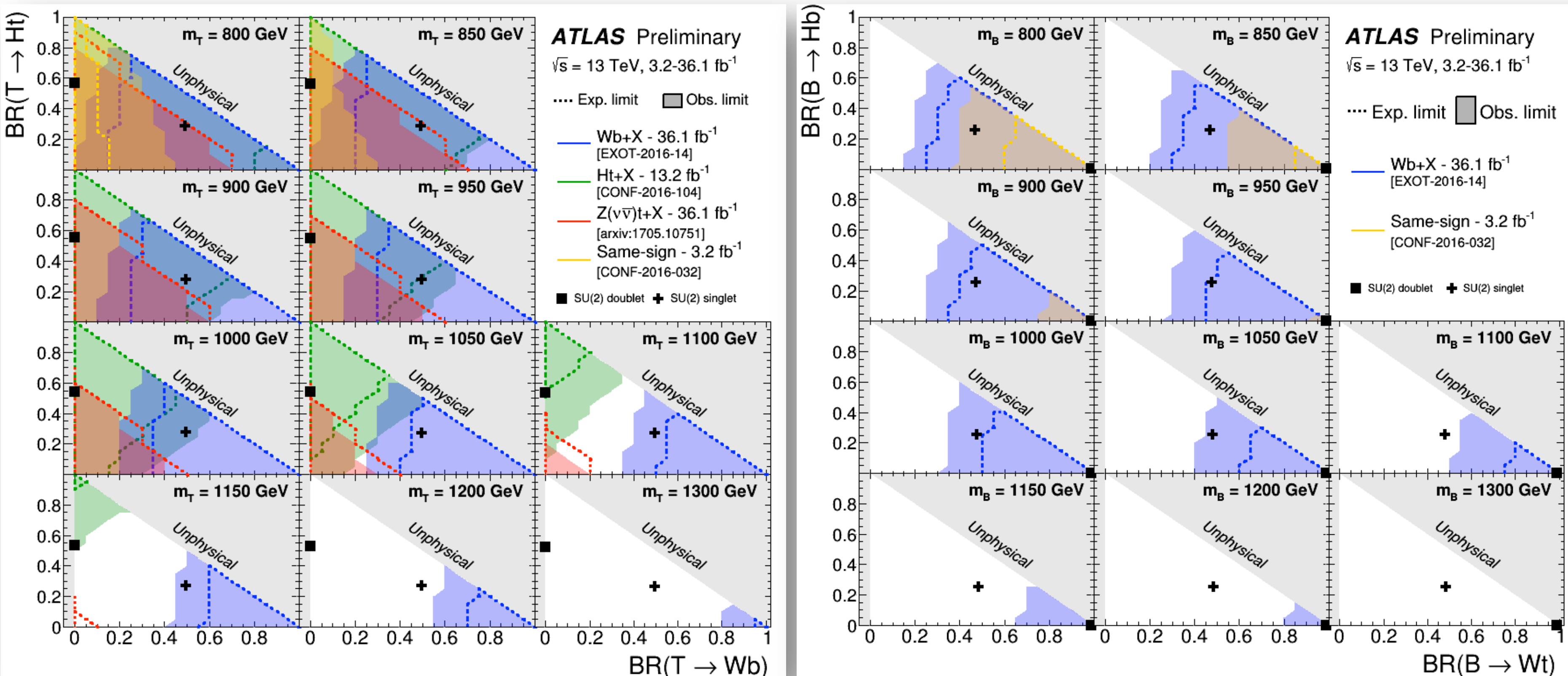
arXiv:1707.03347



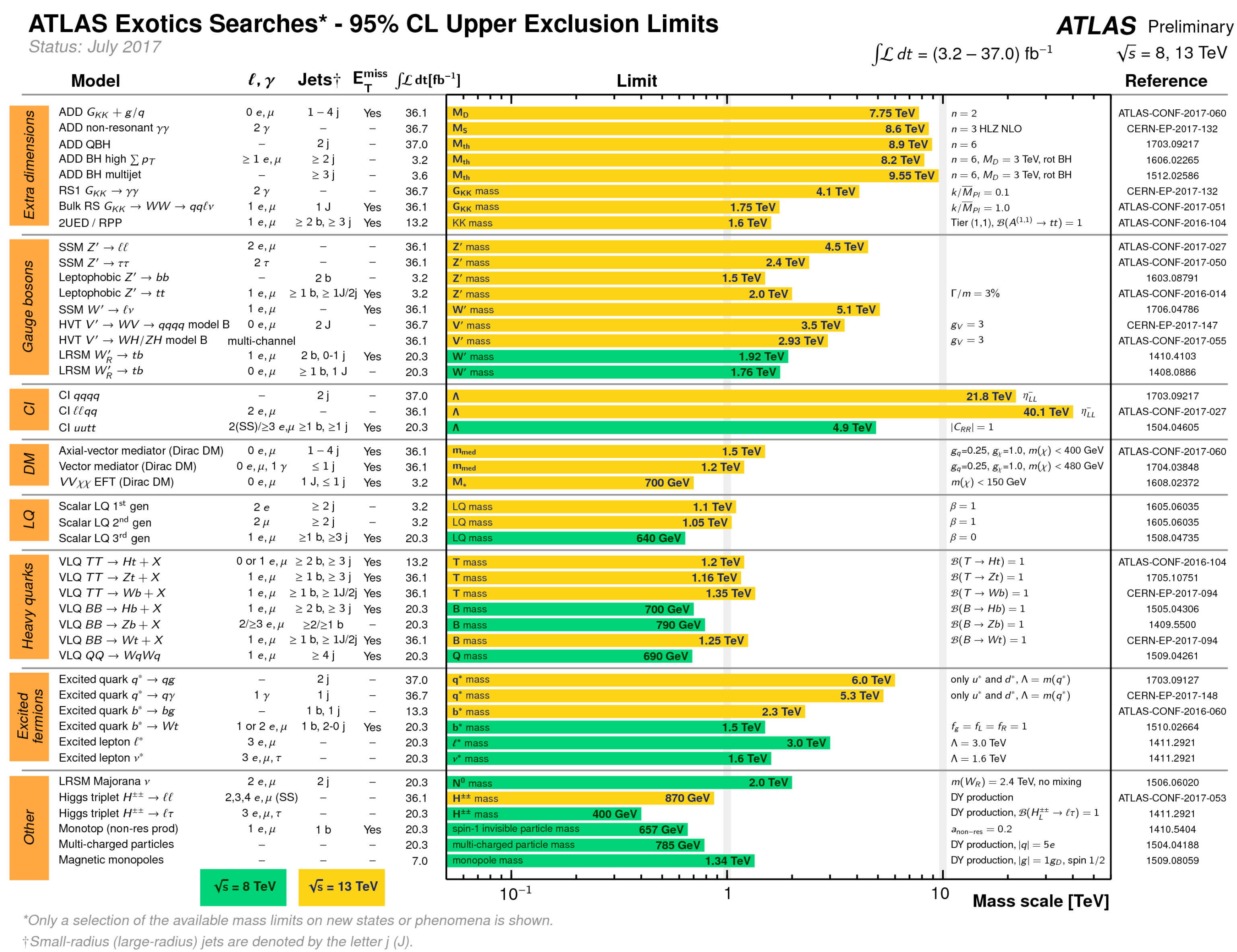


VLQ summary

- All decays of vector-like T quark considered: **Wb / Zt / Ht**
- Vector-like B decays not yet fully covered: only **Wt / Hb** included
- Analyses make use of boosted decays at 13 TeV



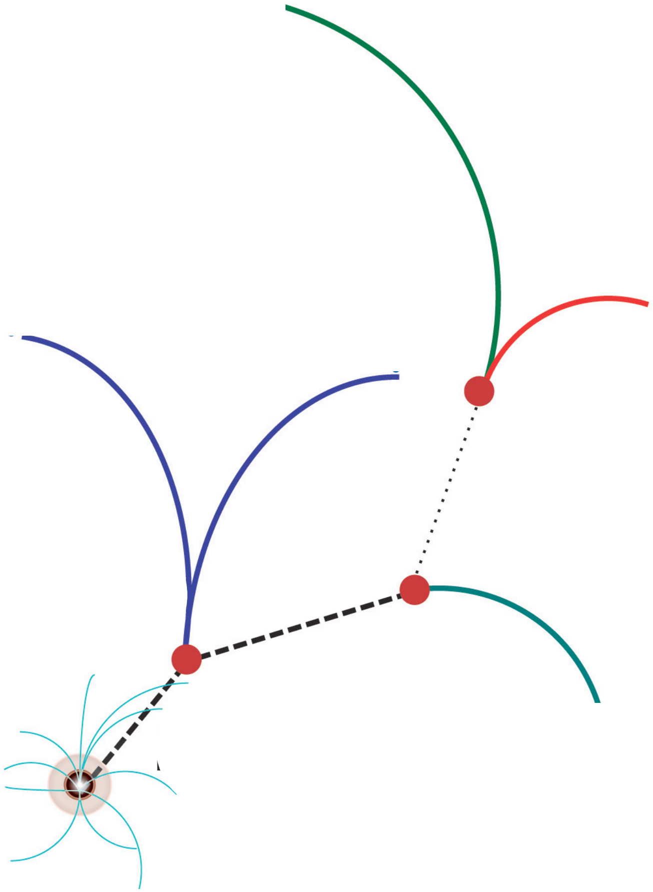
… in a nutshell



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/

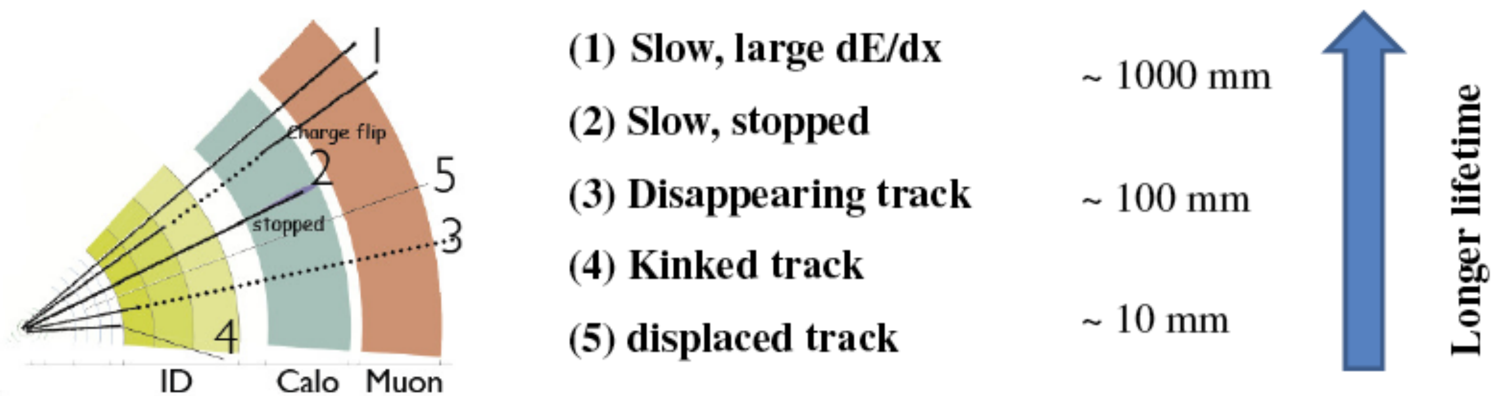
Long-lived particles

- Most recent results @ 13 TeV presented here
- Searches for supersymmetric particles
- Many more searches for non-SUSY are underway with 13 TeV data



Stable or metastable particles

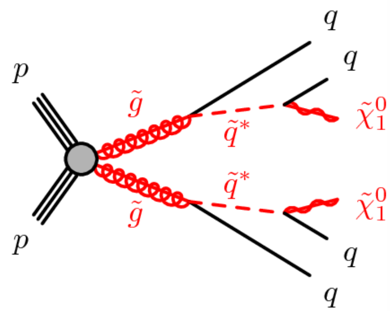
- Long-lived decays of spartners possible in several frameworks, including
  - nearly conserved symmetry
    - e.g. long lived gluinos or squarks that hadronise before decaying → R-hadrons in Split SUSY
  - low coupling between the particle and the final state
    - e.g. weak R-parity violating (RPV) couplings in SUSY
  - mass degeneracy between the particle and the final state
- Depending on the lifetime, different detection techniques involving various objects: tracks, photons, leptons, …



ATLAS-CONF-2017-026

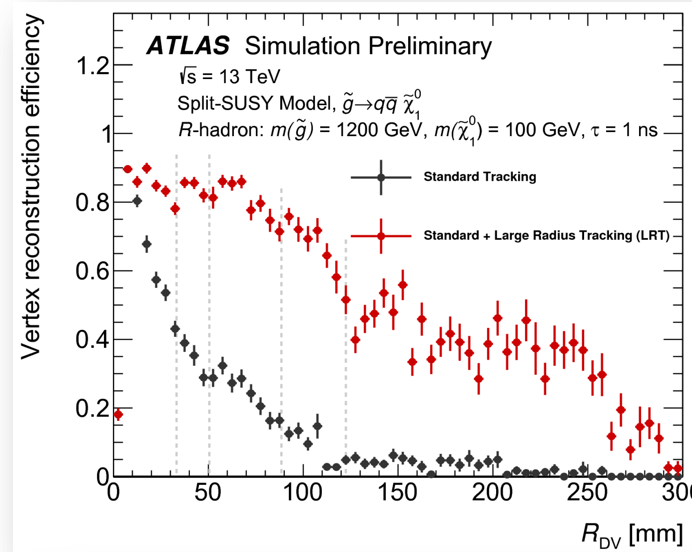
Displaced vertices (1/2)

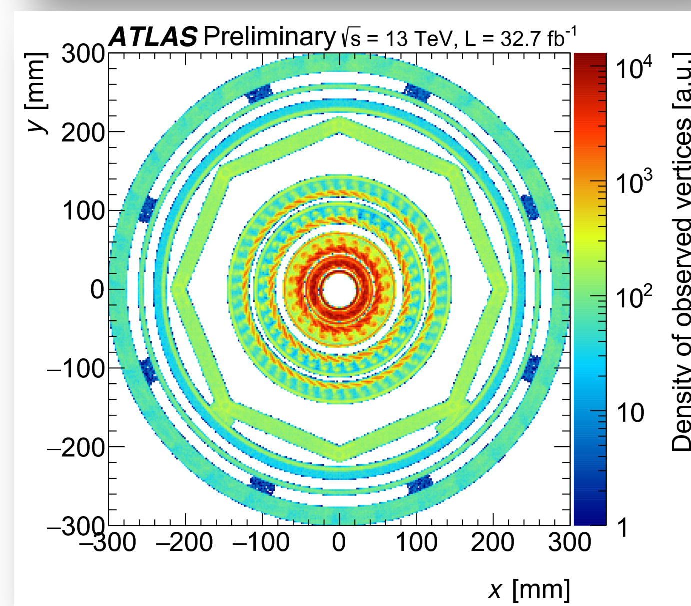
- Metastable particles decaying in the Inner Detector
  - predicted in models of RPV SUSY or split-SUSY
  - benchmark signal: gluino hadronising into an R-hadron



32.7 fb^{-1} @ 13 TeV

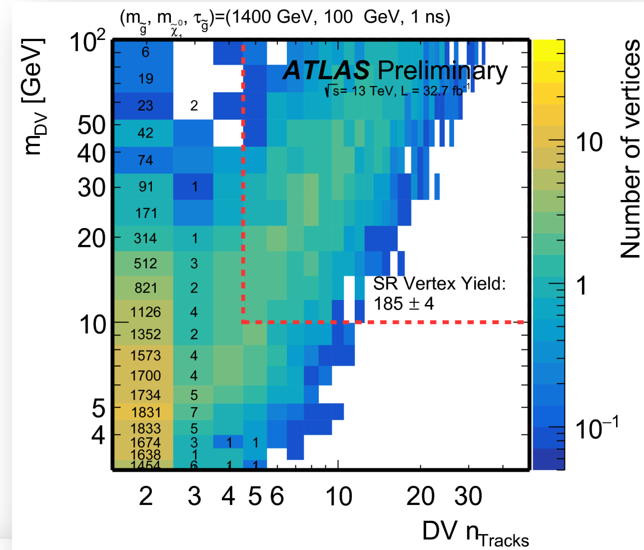
- Large-radius tracking: re-running standard track and vertex reconstruction improves signal efficiency at large radii
- Backgrounds: instrumental and estimated from data
  - high track multiplicity hadronic interactions
    - ➤ DV in regions with high material density vetoed
  - merged DV extrapolated from low-n_{trk} region
- Background estimate validated in signal-depleted regions

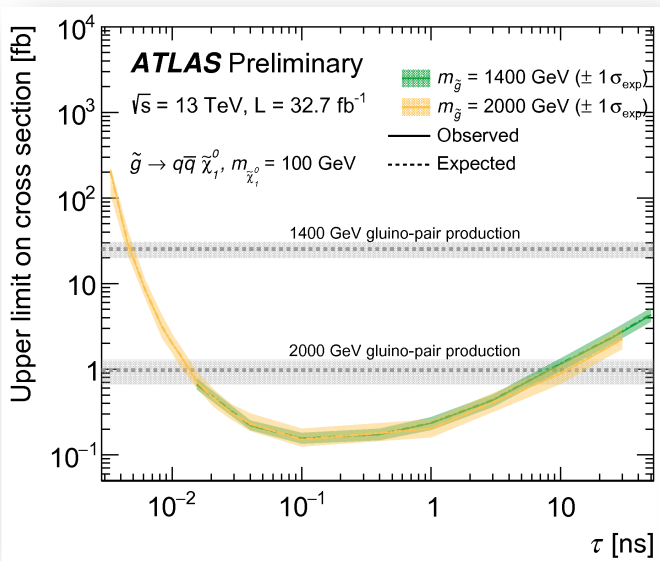


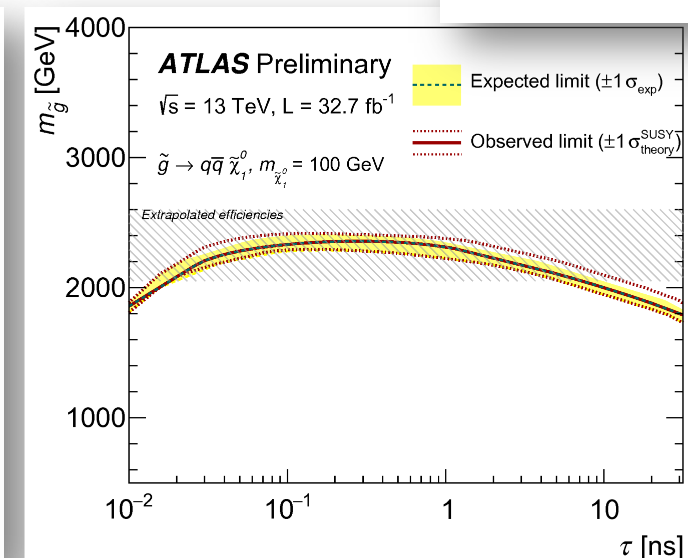


Displaced vertices (2/2)

- SR defined as a DV with mass > 10 GeV and high track multiplicity (> 5 tracks)
- **No event is observed in the SR, compatible with a bkg. expectation of 0.2±0.2 events**







32.7 fb^{-1} @ 13 TeV

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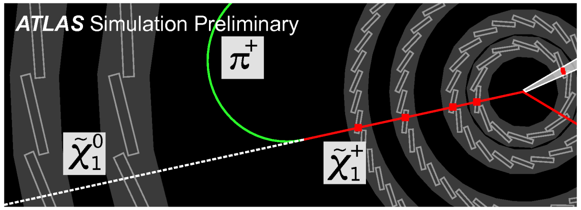
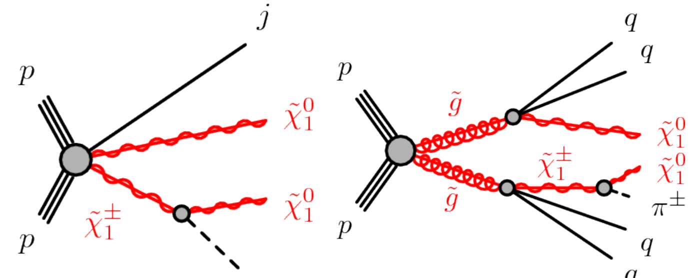
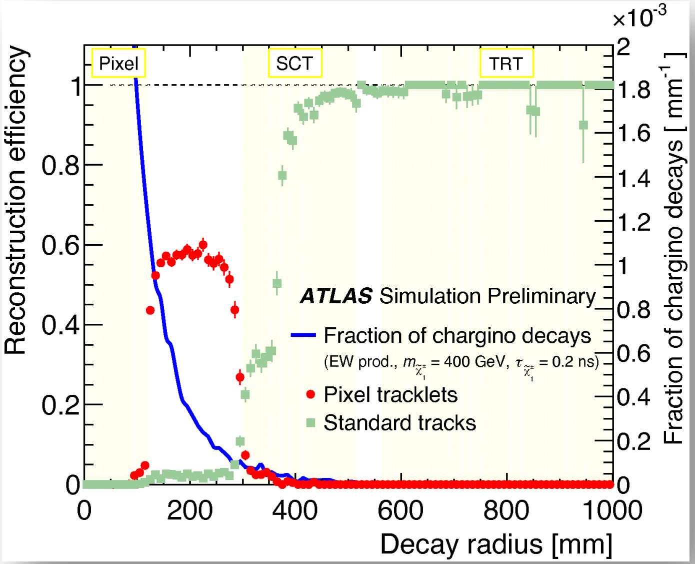
- Limits are set on gluino R-hadrons as a function of masses and lifetime
- For a lifetime of 1 ns, gluino masses up to 2.2 TeV are excluded

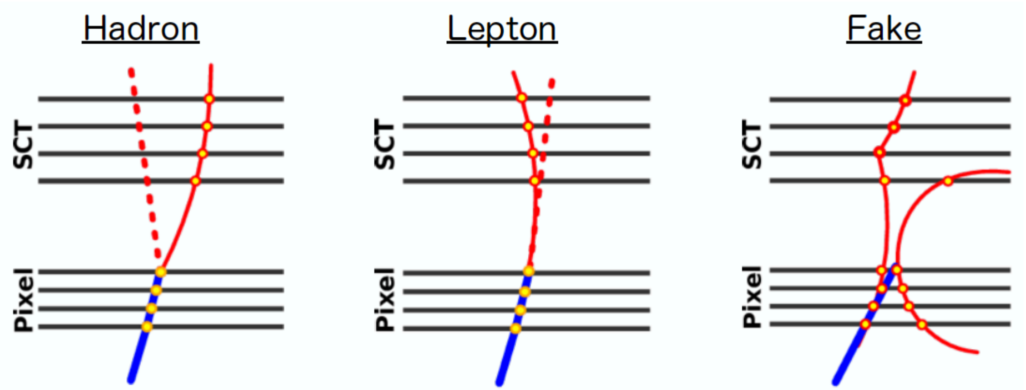
Disappearing track (1/2)

- Decays to invisible products in the Inner Detector
  - chargino and neutralino nearly degenerate, the soft pions in the decay are not reconstructed
  - for wino LSP generic prediction of ~160 MeV splittings, or lifetimes of ~0.2 ns ➤ 6 cm
- ***Pixel tracklets (≡ pixel-only tracks)***: 10× increase in acceptance over standard tracks for low lifetimes
- Backgrounds estimated by a simultaneous fit to the tracklet p_T distribution









Background configurations

36.1 fb^{-1} @ 13 TeV

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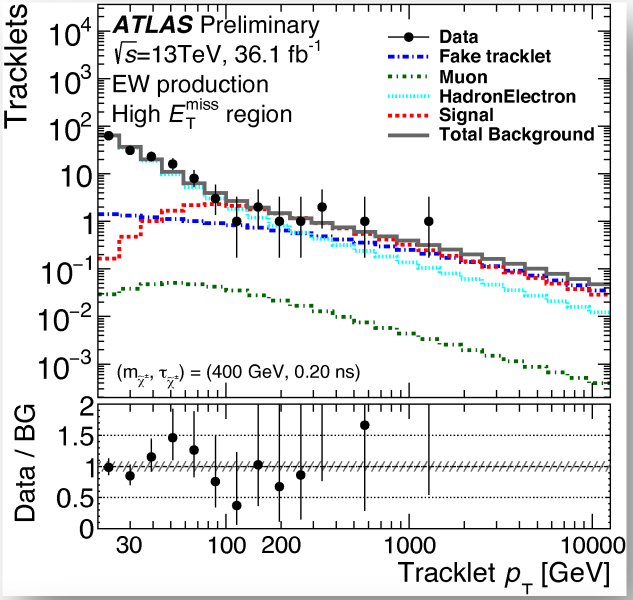
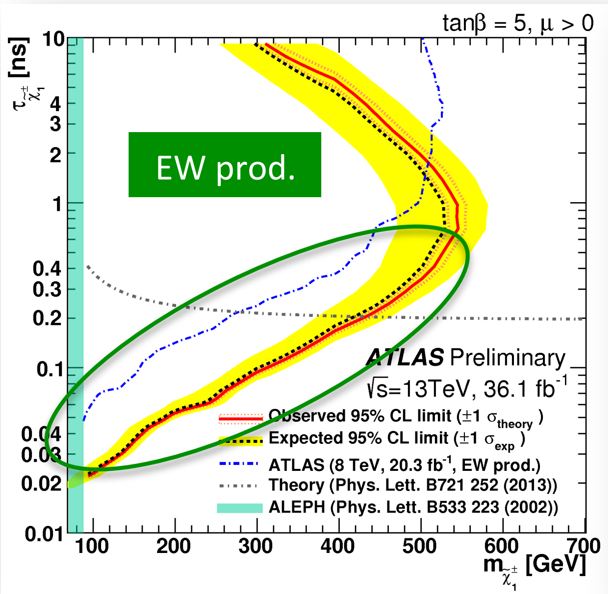
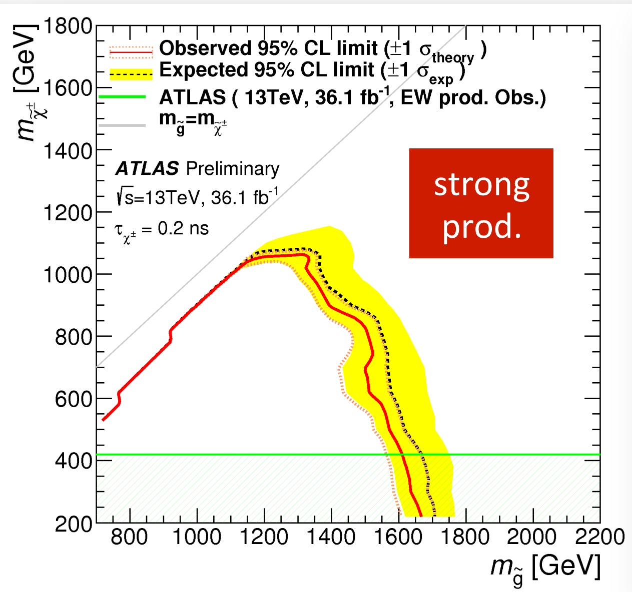
Disappearing track (2/2)

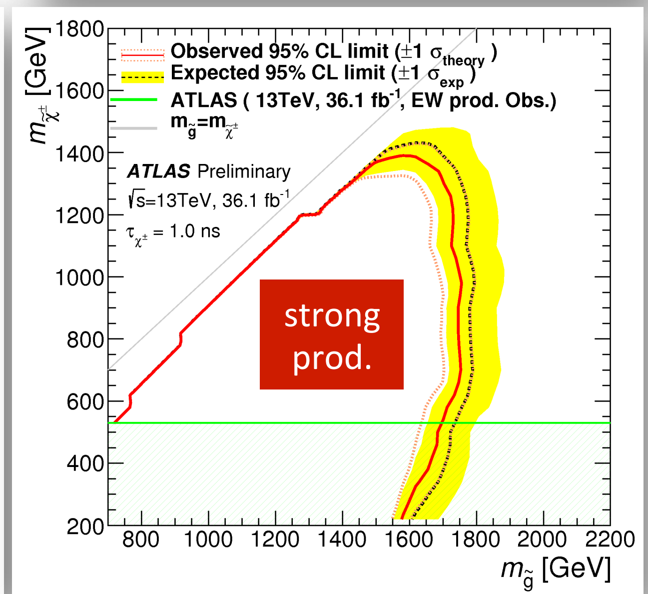
36.1 fb^{-1} @ 13 TeV

- No significant excess is observed
- **EWK production limits significantly improved at low lifetimes** ($c\tau \lesssim$ 12 cm)
  - thanks to new **insertable pixel B-layer (IBL)** installed during long shutdown (r ~ 3 cm)
- Strong production: reaching 1.4 (1.1) TeV in chargino mass for lifetimes of 1.0 (0.2) ns









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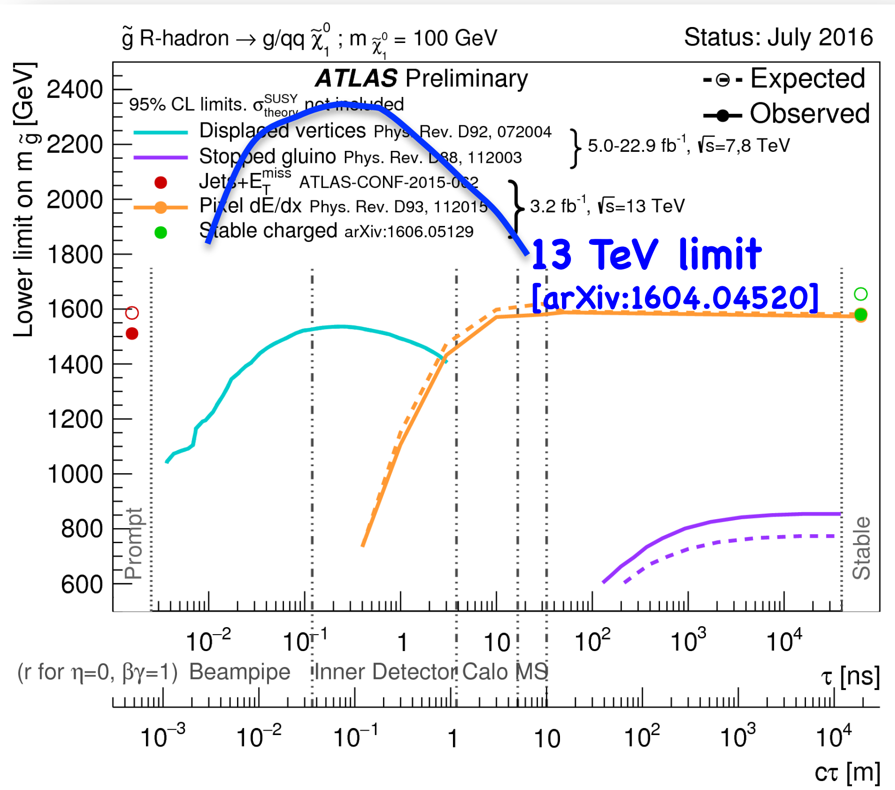
Long-lived particles in SUSY - summary

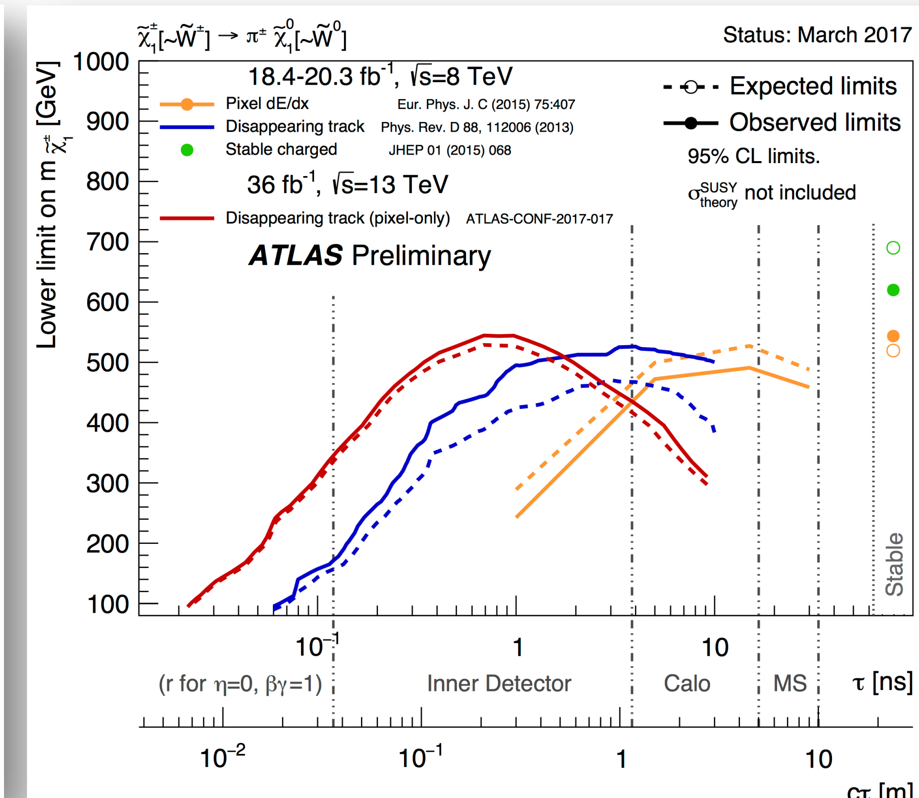
8-TeV results on R-hadrons

Split SUSY with metastable $\tilde{g} \rightarrow g/qq\ \tilde{\chi}_1^0$



Summary 8-TeV & 13 TeV on disappearing track

Long lived chargino, $\tilde{\chi}_1^{\pm} \rightarrow \pi^{\pm}\ \tilde{\chi}_1^0$



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/

Summary

- Standard Model limitations imperatively call for Physics beyond it, extending and complementing it
- ATLAS has searched for physics BSM at TeV scale in a variety of signatures inspired by a multitude of theoretical scenarios
- No significant deviation from SM expectations observed so far
- LHC Run 2 new data may reveal hints of New Physics
  - ATLAS is well-prepared to make the most of them
  - analysis continuously improved with new trigger and/or reconstruction techniques

... for 2017 run results

Continuously updated public results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Thank you for your attention!

Project supported by a 2017 Leonardo Grant for Researchers and Cultural Creators, BBVA Foundation