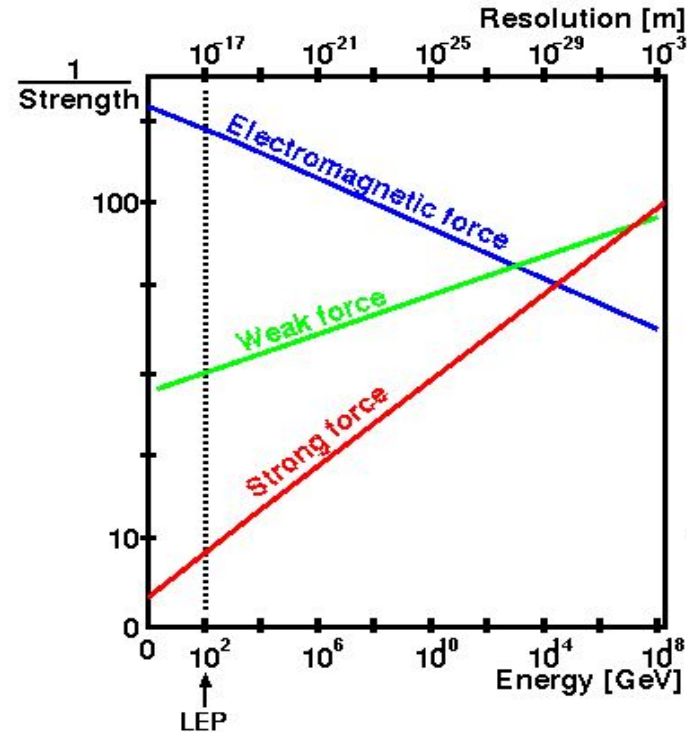


Beyond the SM

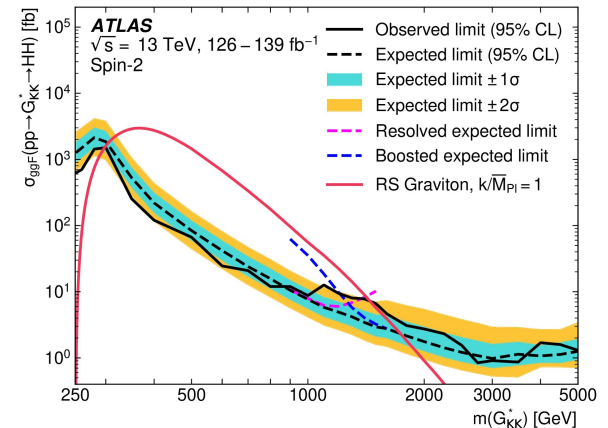
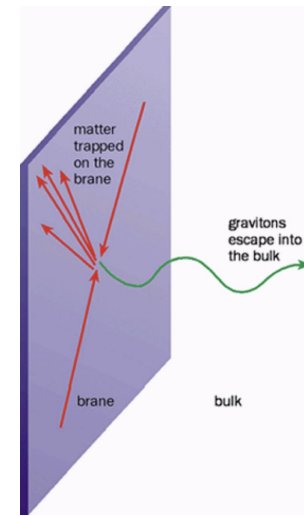
Limitations of the SM

- The SM has numerous limitations
- Theoretical limitations:
 - Gravity
 - Hierarchy problem
 - Neutrino masses
 - Strong CP problem
 - Unification of forces
- Unexplained phenomena:
 - Flavor anomaly
 - Identity of dark matter



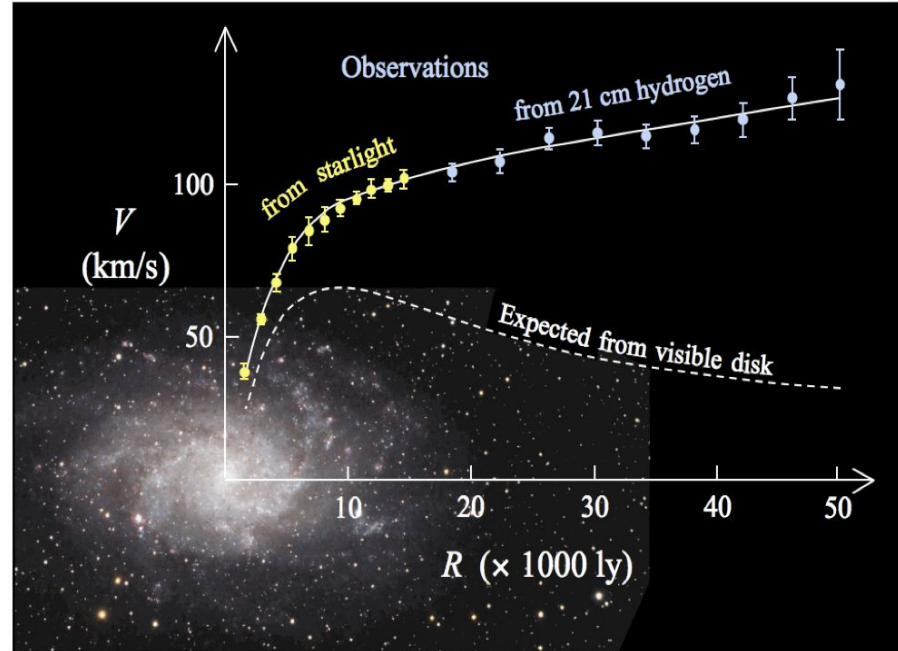
Gravity

- Gravity is currently not included in the Standard Model
- Quantization of gravity predicts graviton (G) as mediating particle
 - Neutral spin-2 boson
- Randall-Sundrum model of warped higher dimensions predicts a graviton
 - Favored model that is often used as a benchmark
- Numerous decay modes such as $\gamma\gamma$, top/anti-top, HH, etc.



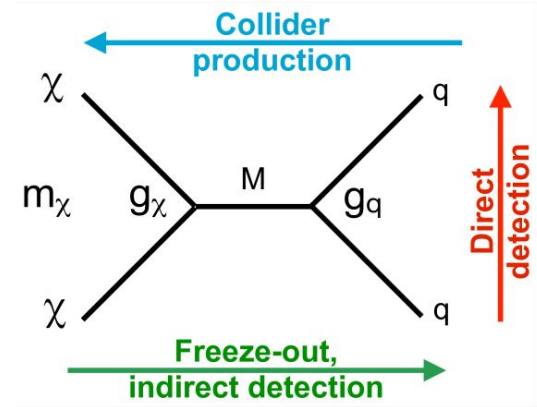
Dark Matter

- Dark Matter is hypothetical matter that does not interact through EM
- Various arguments for DM have been made since the 19th century
- Studies in the 60s and 70s showed that galaxy rotation curves could not be explained by visible matter
- Many other observational results support its existence

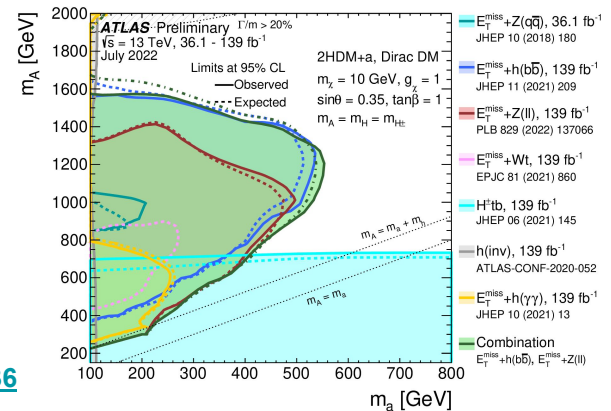


Dark Matter searches

- Direct detection:
 - Search for interactions between DM candidates and SM matter
 - Massive underground detectors sensitive to small energy deposits
- Indirect detection:
 - Search for DM decay products - $\gamma\gamma$, neutrinos or charged particles
 - Space- or ground-based detectors looking for decay products
- Collider searches:
 - Creation of DM particles from SM particle interactions
 - Search for missing energy scattering off of visible particles

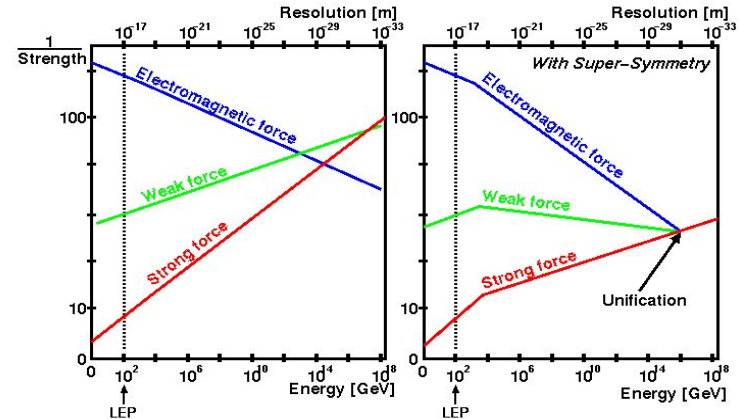
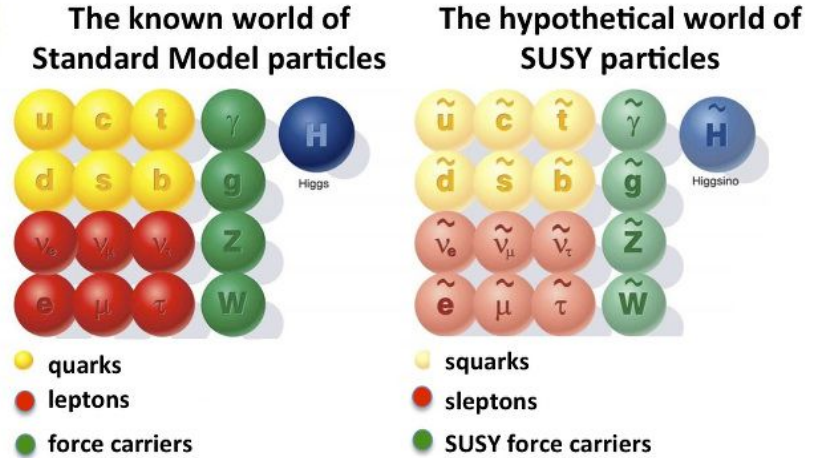


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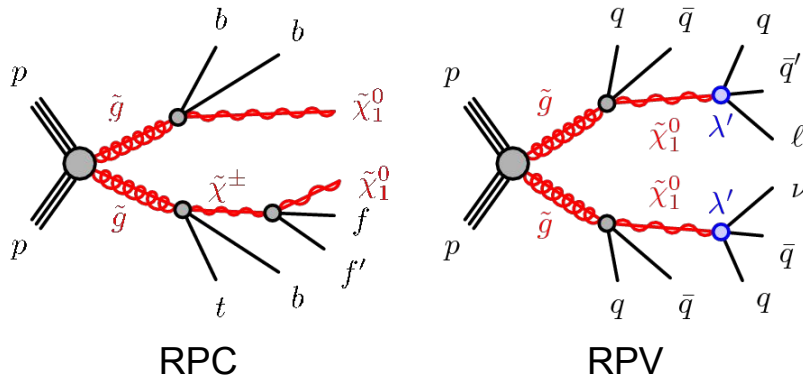
Supersymmetry

- SUSY is a model that could resolve the hierarchy and unification problems
- Introduction of superpartners
 - Fermion \leftrightarrow bosons
 - Superpartners have large masses
- Introduction of R-parity
 - R-parity conserving models have DM candidate
- Huge number of free parameters
 - MSSM is one of the most popular simplifications



Supersymmetry searches

- Wide range of ongoing searches
- Generally complex signatures
- RPC - large missing energy
- RPV - resonance search



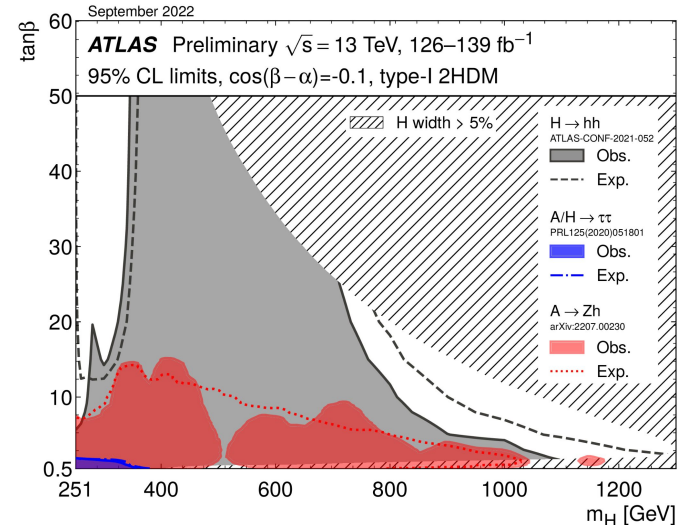
ATLAS SUSY Searches* - 95% CL Lower Limits
March 2023

Model	Signature	$[L dt (fb^{-1})]$	Mass limit	Reference							
Inclusive Searches	$\tilde{q}\tilde{q} \rightarrow q\tilde{q}\tilde{q}^0$	0 e, μ mono-jet	2-6 jets 1-3 jets	E_{T}^{miss} E_{T}^{miss}	139	0.9	1.85	$m(\tilde{t}_1) < 400$ GeV $m(\tilde{b}_1) < 450$ GeV	2010.14293 2102.10074		
	$\tilde{b}\tilde{b} \rightarrow b\tilde{q}\tilde{q}^0$	0 e, μ	2-6 jets	E_{T}^{miss}	139	Forbidden	1.15-1.95	2.3	$m(\tilde{t}_1) < 600$ GeV $m(\tilde{b}_1) < 700$ GeV	2010.14293 2101.01629	
	$\tilde{b}\tilde{b} \rightarrow q\tilde{q}W\tilde{Z}^0$	1 e, μ	2 jets	E_{T}^{miss}	139	2		2.2	$m(\tilde{t}_1) < 600$ GeV $m(\tilde{b}_1) < 700$ GeV	2204.13072	
	$\tilde{b}\tilde{b} \rightarrow q\tilde{q}Z\tilde{Z}^0$	0 e, μ	7-11 jets	E_{T}^{miss}	139	2		1.97	$m(\tilde{t}_1) < 600$ GeV $m(\tilde{b}_1) < 200$ GeV	2008.06032 1909.04547	
	$\tilde{b}\tilde{b} \rightarrow q\tilde{q}W\tilde{Z}^0$	0 e, μ	3 jets	E_{T}^{miss}	139	2	1.15		$m(\tilde{t}_1) < 500$ GeV $m(\tilde{b}_1) < 300$ GeV	2211.08206 1909.04547	
	$\tilde{b}\tilde{b} \rightarrow t\tilde{t}\tilde{Z}^0$	0.1 e, μ SS e, μ	6 jets	E_{T}^{miss}	139	2		1.25	2.45		
3 rd spin, squarks direct production	$\tilde{h}_1\tilde{h}_1$	0 e, μ	2 b	E_{T}^{miss}	139	A_1	0.68	1.255	$m(\tilde{t}_1) < 400$ GeV 10 GeV \rightarrow $\Delta m(\tilde{t}_1, \tilde{t}_2) < 20$ GeV	2101.12527 2101.12527	
	$\tilde{h}_1\tilde{h}_1, \tilde{b}_1 \rightarrow \tilde{h}_1\tilde{Z}^0 \rightarrow b\tilde{b}\tilde{Z}^0$	0 e, μ 2 τ	6 b 2 τ	E_{T}^{miss} E_{T}^{miss}	139	A_1 A_1	Forbidden	0.23-1.35	$\Delta m(\tilde{t}_1, \tilde{t}_2) < 130$ GeV, $m(\tilde{t}_1) < 100$ GeV $\Delta m(\tilde{t}_1, \tilde{t}_2) < 130$ GeV, $m(\tilde{t}_1) < 0$ GeV	1908.03122 2103.08189	
	$\tilde{h}_1\tilde{h}_1, \tilde{h}_1 \rightarrow \tilde{h}_1\tilde{Z}^0$	0.1 e, μ	≥ 1 jet	E_{T}^{miss}	139	F_1	Forbidden	0.65	1.25	$m(\tilde{t}_1) < 100$ GeV $m(\tilde{b}_1) < 500$ GeV	2004.14500, 2015.03799 2012.03799
	$\tilde{h}_1\tilde{h}_1, \tilde{h}_1 \rightarrow W\tilde{Z}^0$	1 e, μ	3 jets+1 b	E_{T}^{miss}	139	F_1	Forbidden	0.65	1.4	$m(\tilde{t}_1) < 800$ GeV $m(\tilde{b}_1) < 800$ GeV	2108.07665
	$\tilde{h}_1\tilde{h}_1, \tilde{h}_1 \rightarrow \tilde{h}_1 b, \tilde{t}_1 \rightarrow \tau\tilde{Z}^0$	1-2 τ	2 jets+1 b	E_{T}^{miss}	139	F_1	Forbidden	0.65	1.4	$m(\tilde{t}_1) < 100$ GeV $m(\tilde{b}_1) < 500$ GeV	1805.01649 2102.10074
	$\tilde{h}_1\tilde{h}_1, \tilde{h}_1 \rightarrow \tilde{h}_1\tilde{Z}^0 / \tilde{Z}^0, \tilde{t}_1 \rightarrow \tau\tilde{Z}^0$	0 e, μ 0 e, μ	2 τ mono-jet	E_{T}^{miss} E_{T}^{miss}	36.1 139	2 2	0.55	0.85	$m(\tilde{t}_1) < 90$ GeV $m(\tilde{b}_1) < 100$ GeV	2006.05880 2006.05880	
$\tilde{h}_1\tilde{h}_1, \tilde{h}_1 \rightarrow \tilde{h}_1\tilde{Z}^0, \tilde{t}_1 \rightarrow Z\tilde{h}_1^0$	1-2 e, μ	1-4 b	E_{T}^{miss}	139	F_2	Forbidden	0.067-1.18		$m(\tilde{t}_1) < 360$ GeV, $m(\tilde{b}_1) < 400$ GeV	2006.05880	
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{b}_1 Z$	3 e, μ	1 b	E_{T}^{miss}	139	F_2	Forbidden	0.86		$m(\tilde{t}_1) < 360$ GeV, $m(\tilde{b}_1) < 400$ GeV	2006.05880	
EW direct	$\tilde{t}_1\tilde{t}_1^*$ via WZ	Multiple t /jets cc, μ, τ	≥ 1 jet	E_{T}^{miss} E_{T}^{miss}	139	\tilde{t}_1^* \tilde{t}_1^*	0.205	0.96	$m(\tilde{t}_1) < 0$, wino-bino $m(\tilde{t}_1) < 5$ GeV, wino-bino	2106.01676, 2108.07586 1911.12606	
	$\tilde{t}_1\tilde{t}_1^*$ via WW	2 e, μ		E_{T}^{miss}	139	\tilde{t}_1^*	0.42		$m(\tilde{t}_1) < 0$, wino-bino	1908.08215	
	$\tilde{t}_1\tilde{t}_1^*$ via $W\tilde{Z}^0$	Multiple t /jets		E_{T}^{miss}	139	\tilde{t}_1^*	Forbidden	1.05	$m(\tilde{t}_1) < 0$ GeV, wino-bino	2004.10094, 2108.07586	
	$\tilde{t}_1\tilde{t}_1^*$ via $W\tilde{Z}^0$	2 e, μ		E_{T}^{miss}	139	\tilde{t}_1^*	Forbidden	1.0	$m(\tilde{t}_1) < 0$, wino-bino $m(\tilde{t}_1) < 500$ GeV	1908.08215 1911.06660	
	$\tilde{t}_1\tilde{t}_1^* \rightarrow \tau\tilde{t}_1, \tau \rightarrow \tau\tilde{Z}^0$	2 τ		E_{T}^{miss}	139	\tilde{t}_1^*	0.18-0.33	0.12-0.39	$m(\tilde{t}_1) < 0$	1908.08215	
	$\tilde{t}_1\tilde{t}_1^* \rightarrow \tau\tilde{t}_1, \tau \rightarrow \tau\tilde{Z}^0$	2 τ		E_{T}^{miss}	139	\tilde{t}_1^*	0.256	0.7	$m(\tilde{t}_1) < 0$	1908.08215	
Long-lived particles	$\tilde{h}_1\tilde{h}_1, \tilde{h}_1 \rightarrow h\tilde{Z}^0$	0 e, μ	0 jets	E_{T}^{miss}	139	\tilde{h}_1	0.256	0.7	$m(\tilde{t}_1) < 10$ GeV $m(\tilde{b}_1) < 10$ GeV	1806.04030	
	Direct $\tilde{t}_1\tilde{t}_1^*$ prod., long-lived \tilde{t}_1^*	Disapp. thr	1 jet	E_{T}^{miss}	139	\tilde{t}_1^*	0.21	0.66	$BR(\tilde{t}_1^* \rightarrow h\tilde{Z}^0) < 0.1$ $BR(\tilde{t}_1^* \rightarrow W\tilde{Z}^0) < 0.1$ $BR(\tilde{t}_1^* \rightarrow Z\tilde{h}_1^0) < 0.1$	2201.02472 2201.02472	
	Stable \tilde{t}_1 R-hadron	pixel dE/dx		E_{T}^{miss}	139	\tilde{t}_1		2.05	$m(\tilde{t}_1) < 100$ GeV	2205.00013	
	Metastable \tilde{t}_1 R-hadron, $\tilde{t}_1 \rightarrow q\tilde{q}\tilde{Z}^0$	pixel dE/dx		E_{T}^{miss}	139	\tilde{t}_1	$[R] < 10$ ns	2.05	$m(\tilde{t}_1) < 100$ GeV	2205.00013	
	$\tilde{t}_1, \tilde{t}_1 \rightarrow tG$	Disapp. lep		E_{T}^{miss}	139	e, μ		0.7	$\tau(\tilde{t}_1) < 0.1$ ns $\tau(\tilde{t}_1) < 0.1$ ns	2011.07812 2205.00013	
	$\tilde{t}_1, \tilde{t}_1 \rightarrow tG$	pixel dE/dx		E_{T}^{miss}	139	\tilde{t}_1	0.34 0.36		$\tau(\tilde{t}_1) < 10$ ns	2205.00013	
RPV	$\tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{t}_1\tilde{t}_1^* \rightarrow t\tilde{t} \rightarrow t\tilde{t} \rightarrow t\tilde{t}$	3 e, μ	0 jets	E_{T}^{miss}	139	\tilde{t}_1^*	0.625	1.05	Pure Wino	2011.10543	
	$\tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{t}_1\tilde{t}_1^* \rightarrow W\tilde{Z}^0(\nu\nu)$	4 e, μ	0 jets	E_{T}^{miss}	139	\tilde{t}_1^*	0.85	1.55	$m(\tilde{t}_1) < 200$ GeV	2103.11684	
	$\tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{t}_1\tilde{t}_1^* \rightarrow W\tilde{Z}^0(\nu\nu)$	Multiple	4-5 large jets	E_{T}^{miss}	36.1	\tilde{t}_1^*	$m(\tilde{t}_1) < 200$ GeV, $m(\tilde{b}_1) < 100$ GeV	1.3	1.9	Large \tilde{t}_1^*	1804.03568
	$\tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{t}_1\tilde{t}_1^* \rightarrow q\tilde{q}$	Multiple	$\geq 4b$	E_{T}^{miss}	139	\tilde{t}_1^*	0.55	1.05	$m(\tilde{t}_1) < 200$ GeV, wino-like $m(\tilde{t}_1) < 500$ GeV	ATLAS-COM-2010-003	
	$\tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{t}_1\tilde{t}_1^* \rightarrow b\tilde{b}$	Multiple	$\geq 4b$	E_{T}^{miss}	139	\tilde{t}_1^*	Forbidden	0.95		$m(\tilde{t}_1) < 200$ GeV, wino-like $m(\tilde{t}_1) < 500$ GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{t}_1\tilde{t}_1^* \rightarrow b\tilde{b}$	2 e, μ	2 jets + 2 b	E_{T}^{miss}	36.1	\tilde{t}_1^*	0.42	0.61	0.4-1.45	$BR(\tilde{t}_1^* \rightarrow b\tilde{b}) < 20\%$ $BR(\tilde{t}_1^* \rightarrow q\tilde{q}) < 100\%$, $0.05 < 1$	1710.07171 1710.05544
$\tilde{t}_1\tilde{t}_1^* \rightarrow \tilde{t}_1\tilde{t}_1^* \rightarrow b\tilde{b}$	1 e, μ	2 b	E_{T}^{miss}	136	\tilde{t}_1^*	0.2-0.32			2203.11956		

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Extended Higgs sector

- Numerous BSM theories extend the Higgs sector
 - Attempts to resolve various SM open questions
- One of the most favored extensions is the Two-Higgs-Doublet Model (2HDM)
- Add a second complex doublet
 - Mixing between doublets defined as $\tan\beta$
 - Other additions of singlets and triplets are popular
- 4 new d.o.f. \rightarrow 4 new Higgs bosons
 - H^0 (sometimes h^0), X^0 (sometimes H^0), A^0 , H^\pm
- Predicted by many SUSY models
 - Can exclude, but cannot confirm SUSY

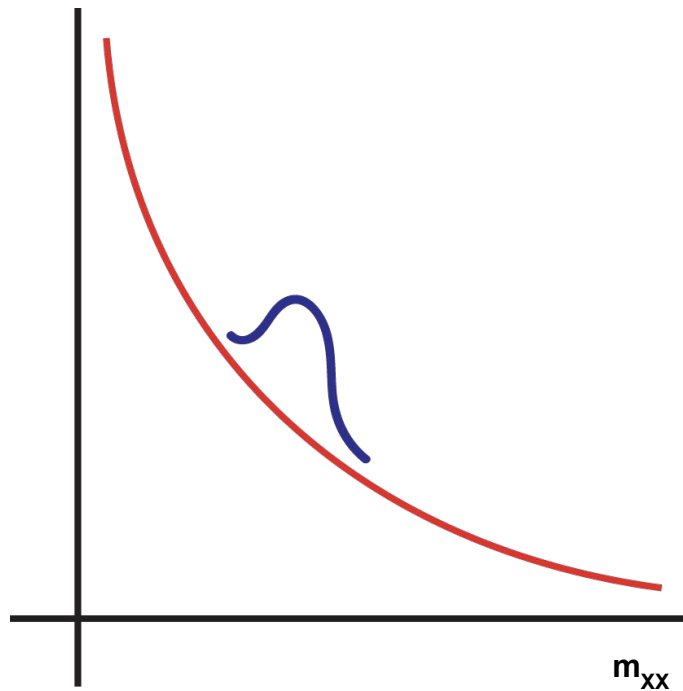


Many other BSM models available

- Axions
- Leptoquarks
- Quantum black holes
- Long-lived particles
- NMSSM
- Two Real Scalar Model
- Etc.

Resonance searches

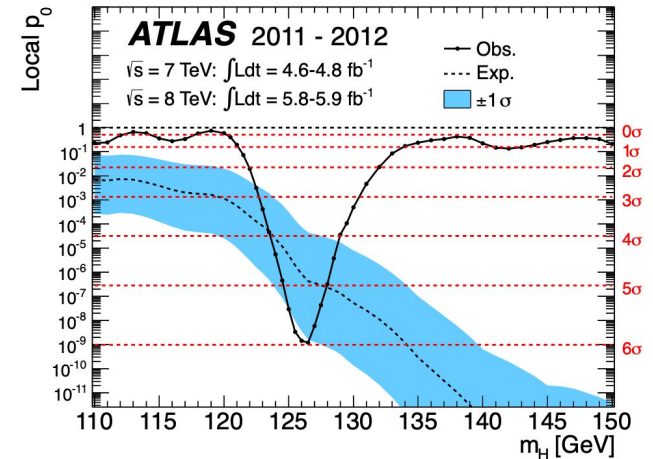
- Search for localized excesses in data
- Typically in an invariant mass distribution
 - Other kinematic distributions can be used
- Direct access to new particles
- Correlating searches in multiple decay channels can help identify new particles
 - Or constrain models



Discovery

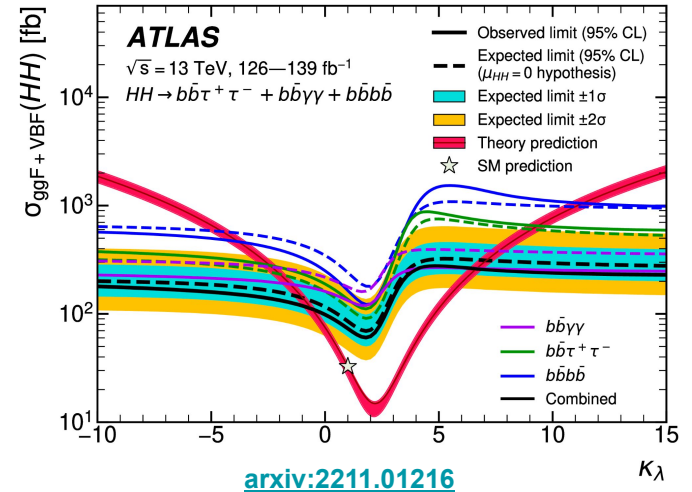
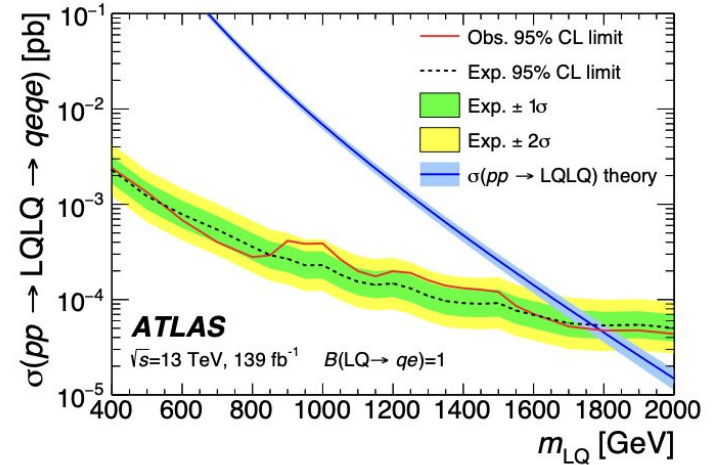
- If an excess is seen in data over predicted background, it may be a new particle
- Statistical significance calculated based on available data
 - How likely is it a real excess and not just a statistical fluctuation
- Calculate p-value for excesses in data
 - Probability that the background will fluctuate and fake the observed signal

Threshold	p-value	Significance
Fluctuation	0.045	2σ
Evidence	0.003	3σ
Discovery	3×10^{-7}	5σ



Limits

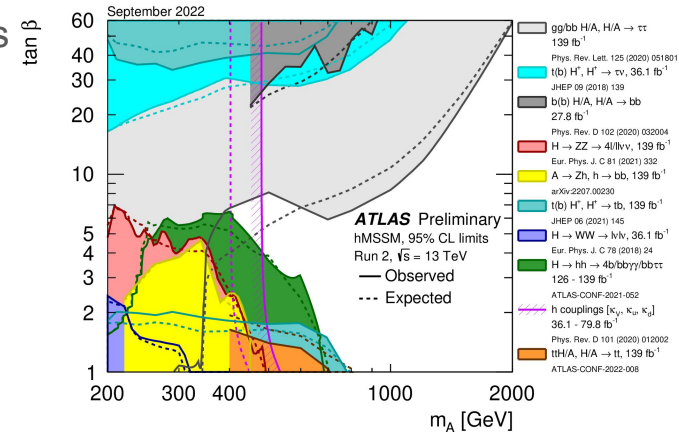
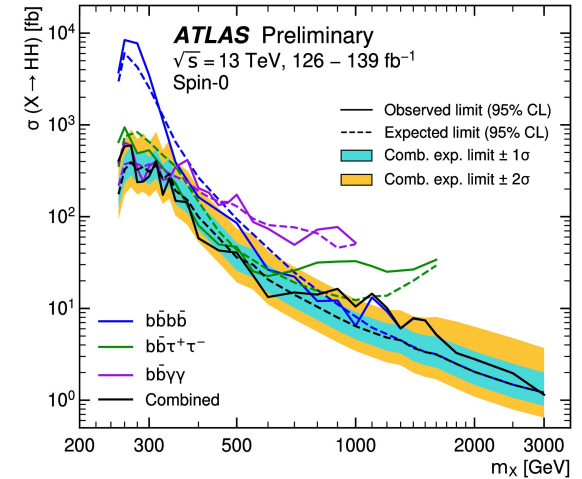
- What is the maximum cross-section a phenomena could have such that its existence would still be consistent with a lack of observation in the data
 - Statistical and systematic uncertainties
- Expected and observed limits
- Use simulated templates to set limits as a function of mass or other properties
- Comparison to theoretical predictions allows exclusion of model phase space
 - Important feedback to theorists



Combinations

- Searches for new physics are performed in dedicated channels
 - Optimize for a particular signature
- Each channel has different sensitivities to models
 - Cross-sections, branching ratios, experimental constraints
- Statistically combining multiple channels can increase sensitivity
 - Improved statistical power and phase-space coverage
 - Correlating channels can further exclude models

[ATLAS-CONF-2021-052](#)



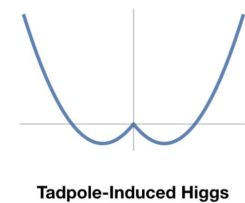
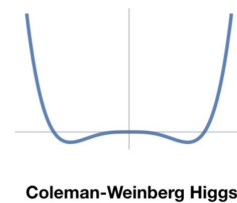
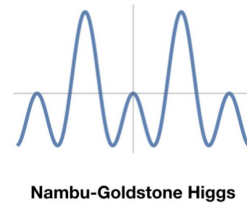
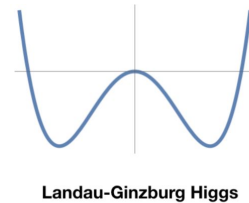
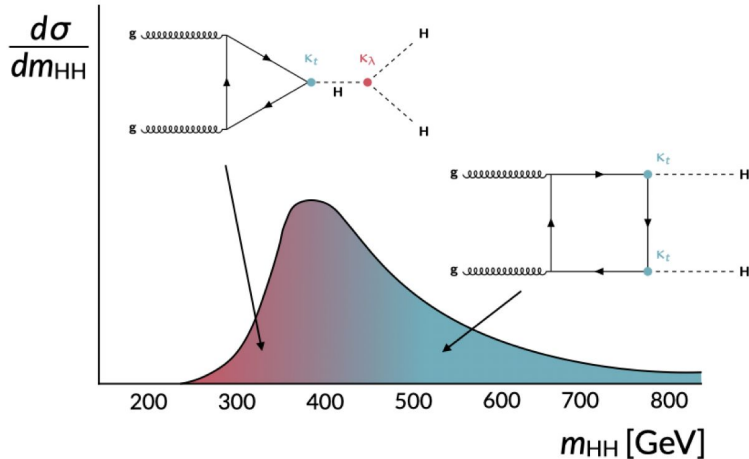
[ATL-PHYS-PUB-2022-043](#)

Precision measurements

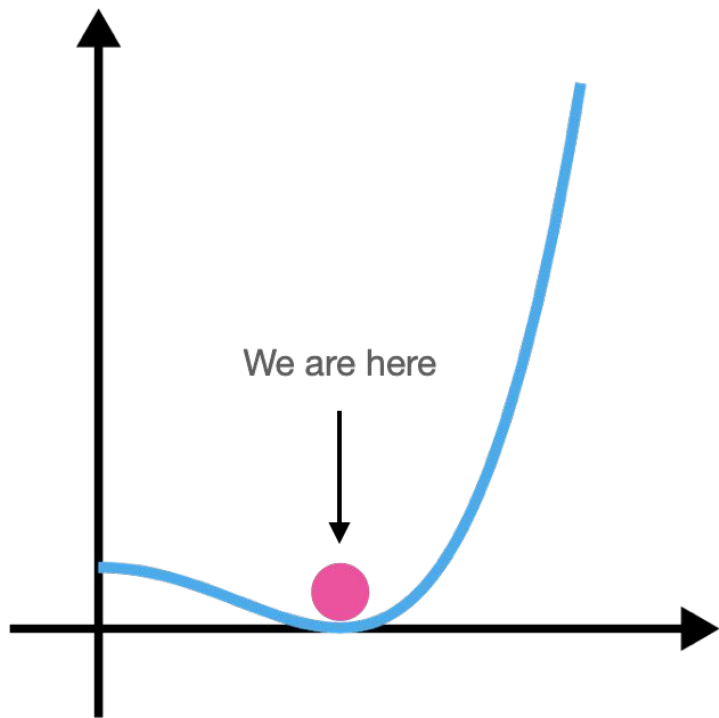
- BSM effects are also searched for through indirect methods
- Precision measurements of various parameters
 - Coupling strengths, kinematic distributions, etc.
- Can provide access to BSM physics at higher energy scales
- Typically slower analyses than resonance searches due to subtle signatures

Higgs boson self-coupling

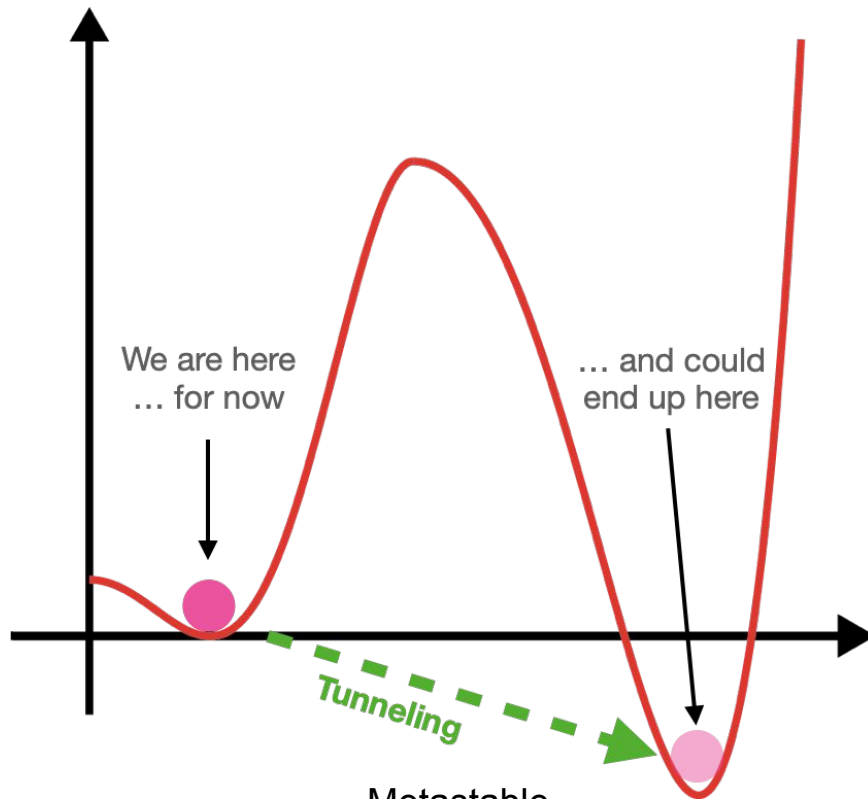
- The Higgs potential parameter λ could indicate new physics
- Possibly related vacuum stability or electroweak baryogenesis
- Measured through Higgs boson pair production
 - Cross-section and m_{HH} distribution could indicate BSM modifications



Vacuum stability

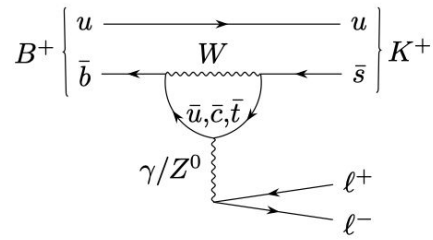


Stable



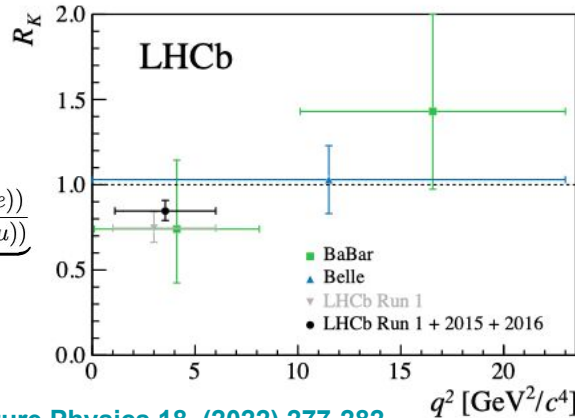
Metastable

Flavor anomalies

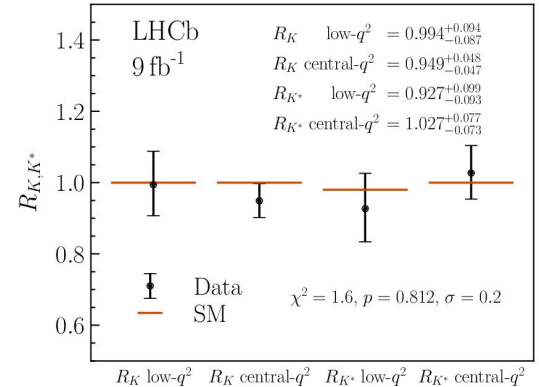


- The principle of lepton universality means many particles should decay into electrons and muons at equal rates
- Deviations from a ratio of 1 could indicate new physics
- LHCb observed a 3.1σ deviation from 1 in March 2021
- Newer result from late 2022 shows consistency with SM

$$R_K = \frac{N(K^+\mu\mu) \varepsilon(K^+ee)}{N(K^+ee) \varepsilon(K^+\mu\mu)} \bigg/ \underbrace{\frac{N(K^+J/\psi(\mu\mu)) \varepsilon(K^+J/\psi(ee))}{N(K^+J/\psi(ee)) \varepsilon(K^+J/\psi(\mu\mu))}}_{\tau_{J/\psi}}$$



[Nature Physics 18, \(2022\) 277-282](#)



[arxiv:2212.09153](#)

W boson mass measurement

- In 2022, the CDF collaboration published precision W boson mass measurement
 - Measured value incompatible with the SM prediction
 - Strong implications for existence of BSM physics
 - Controversial due to some missing systematic uncertainties
- Last week, ATLAS published results using 2011 data
 - Consistent with SM prediction
 - No significant evidence of BSM physics

