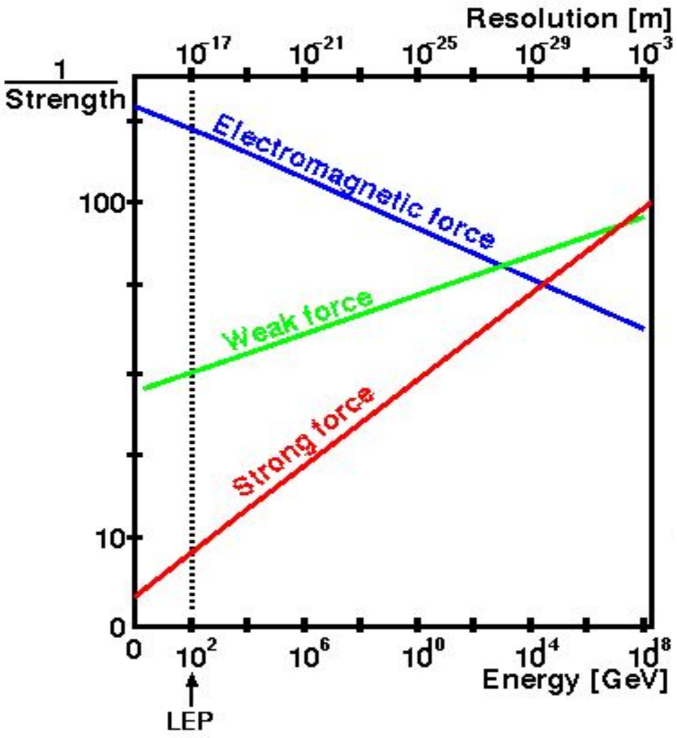
Beyond the SM

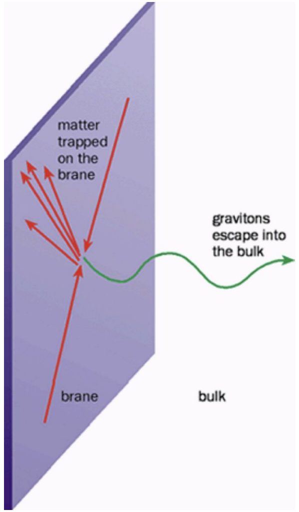
Limitations of the SM

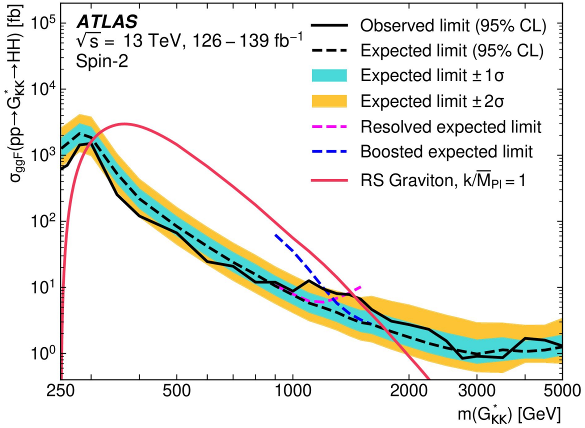
- The SM has numerous limitations
- Theoretical limitations:
  - Gravity
  - Hierarchy problem
  - Neutrino masses
  - Strong CP problem
  - Unification of forces
- Unexplained phenomena:
  - Flavor anomaly
  - Identity of dark matter



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 γγ, top/anti-top, HH, etc.





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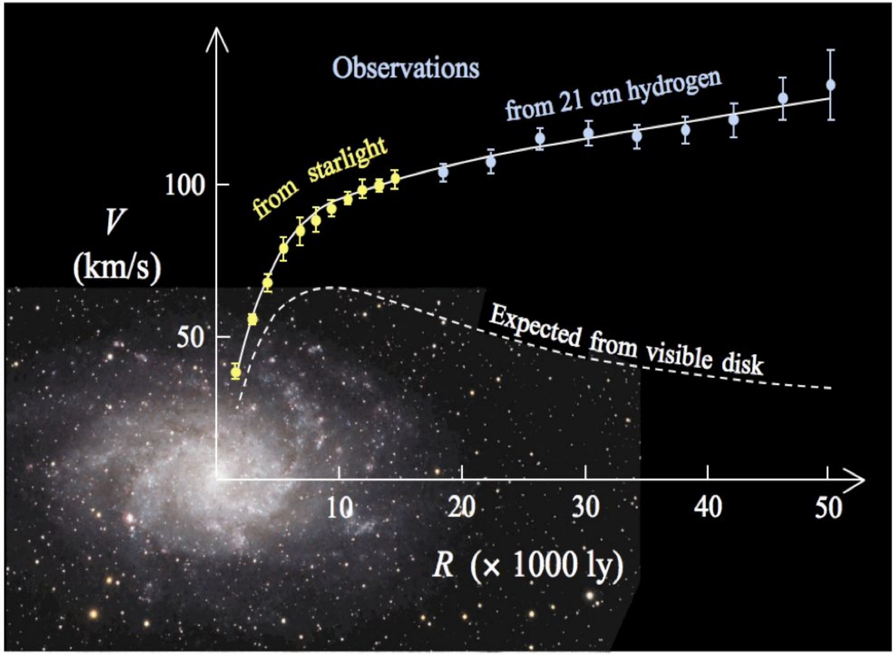
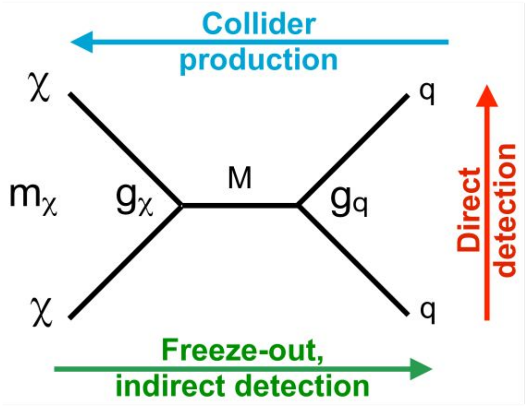
Dark Matter

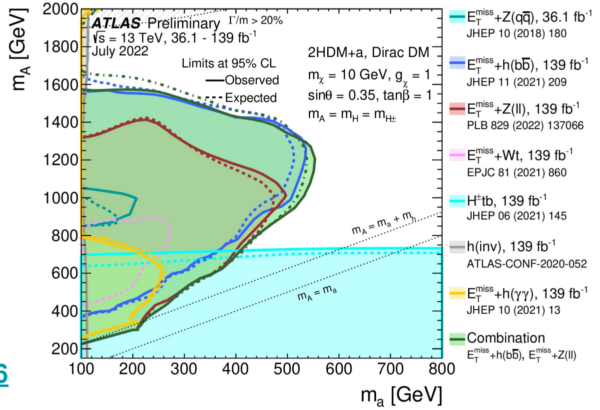
- Dark Matter is hypothetical matter that does not interact through EM
- Various arguments for DM have been made since the 19th century
- Studies in the 60s and 70s showed that galaxy rotation curves could not be explained by visible matter
- Many other observational results support its existence



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 - γγ, 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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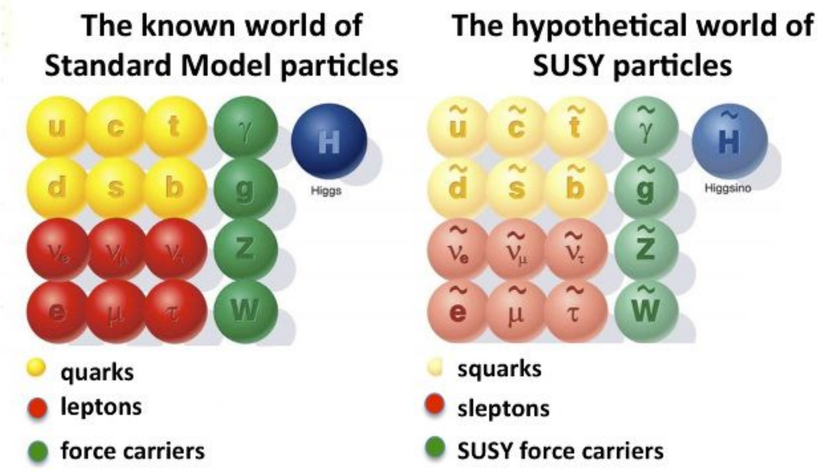
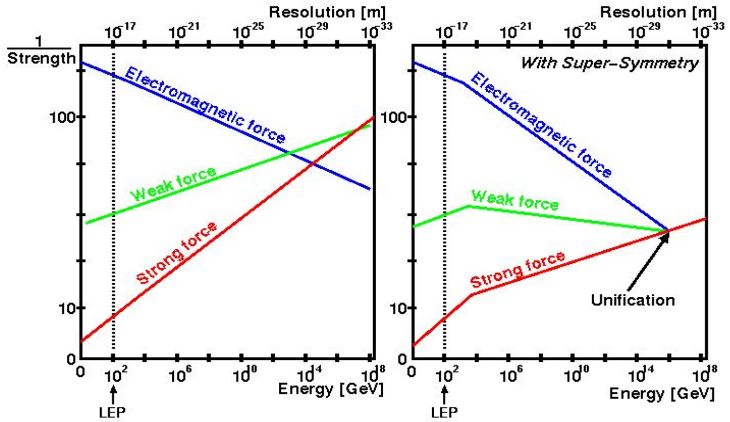
Supersymmetry

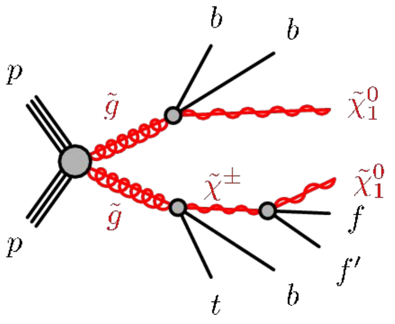
- SUSY is a model that could resolve the hierarchy and unification problems
- Introduction of superpartners
  - Fermion ↔ bosons
  - Superpartners have large masses
- Introduction of R-parity
  - R-parity conserving models have DM candidate
- Huge number of free parameters
  - MSSM is one of the most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



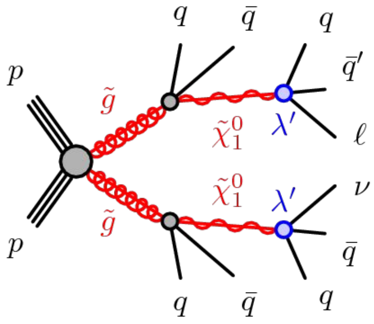


Supersymmetry searches

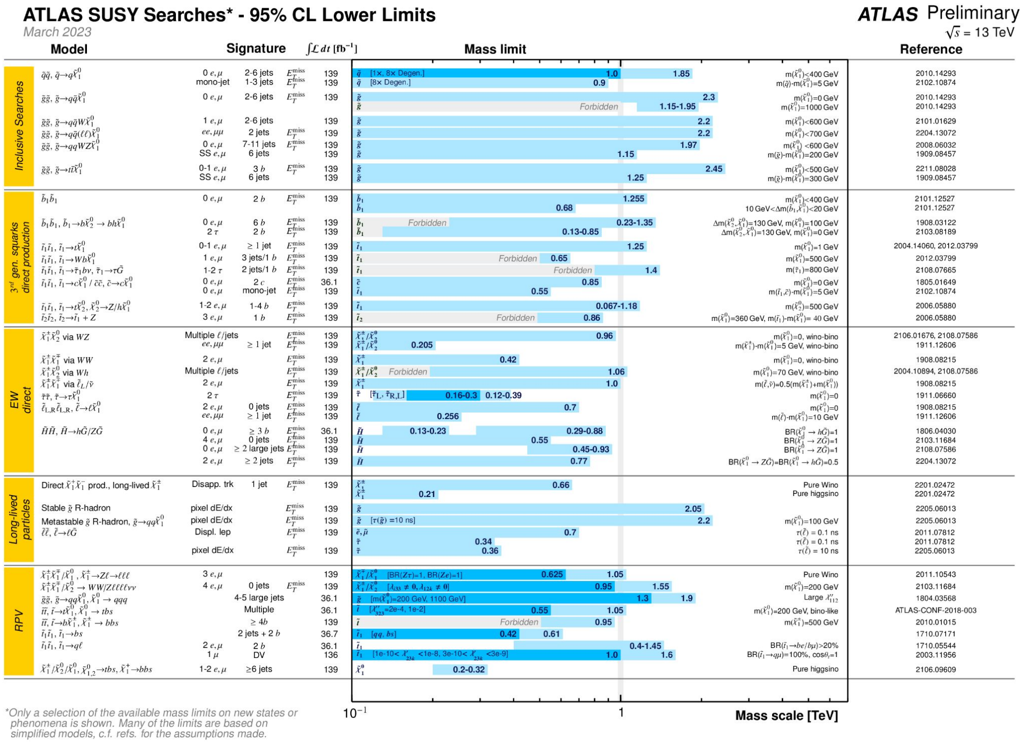
- Wide range of ongoing searches
- Generally complex signatures
- RPC - large missing energy
- RPV - resonance search



RPC



RPV

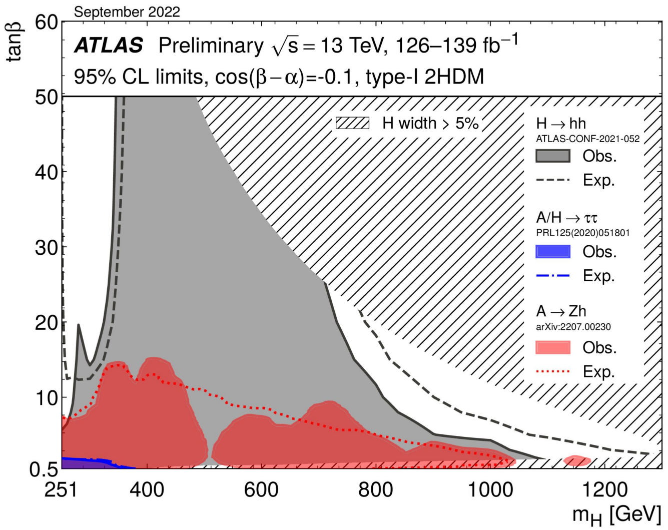


EPJ Web Conf. 18 (2018) 20212

ATL-PHYS-PUB-2023-005

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 tanβ
  - Other additions of singlets and triplets are popular
- 4 new d.o.f. → 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



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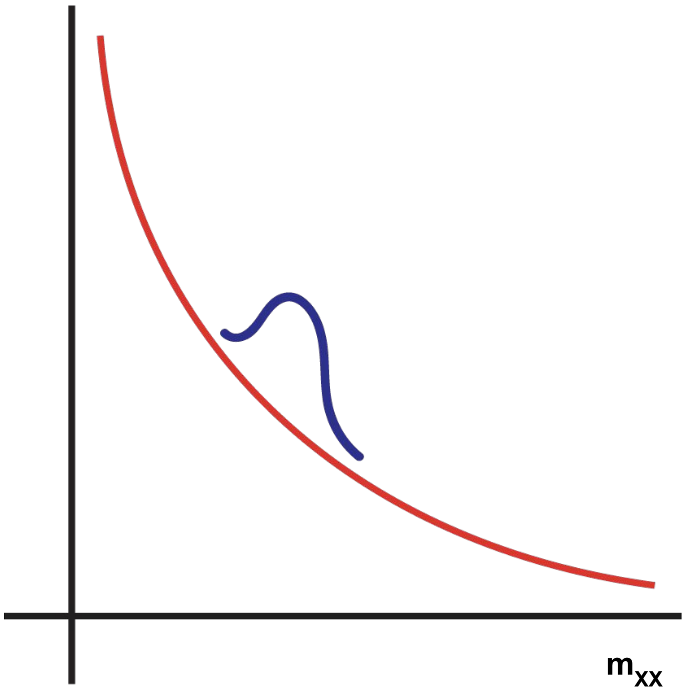
Many other BSM models available

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

Resonance searches

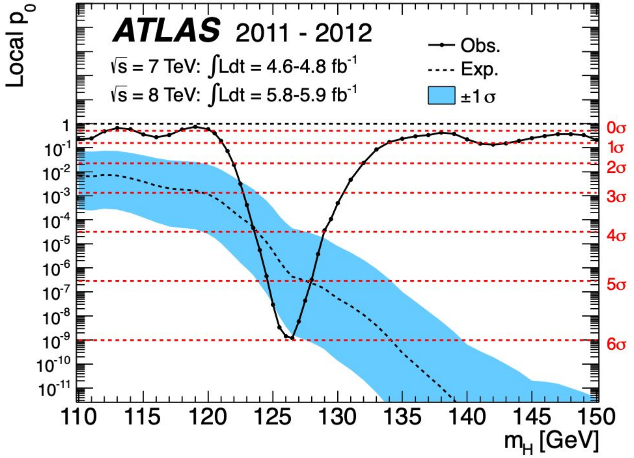
- Search for localized excesses in data
- Typically in an invariant mass distribution
  - Other kinematic distributions can be used
- Direct access to new particles
- Correlating searches in multiple decay channels can help identify new particles
  - Or constrain models



Discovery

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

- 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

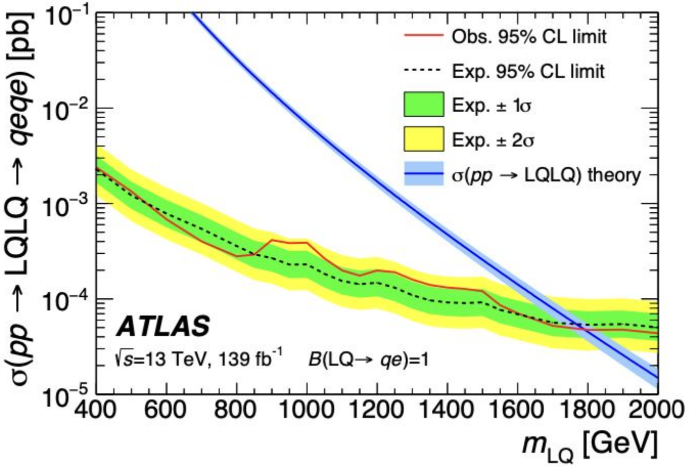


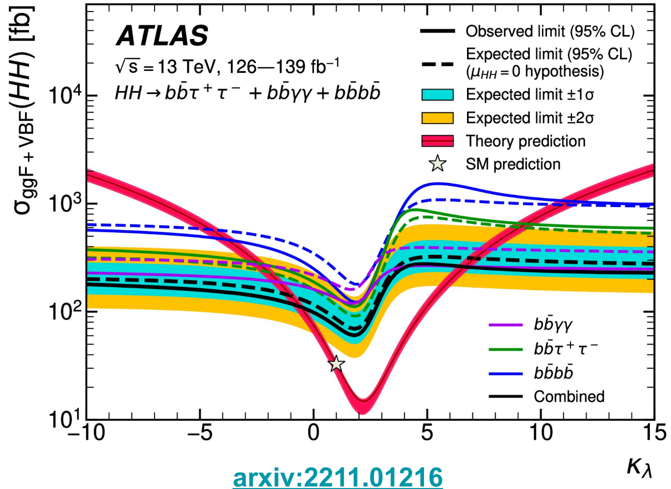
[Science Vol. 338 no. 6114 pp. 1576-1582](#)

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

JHEP 10 (2020) 112





arxiv:2211.01216

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

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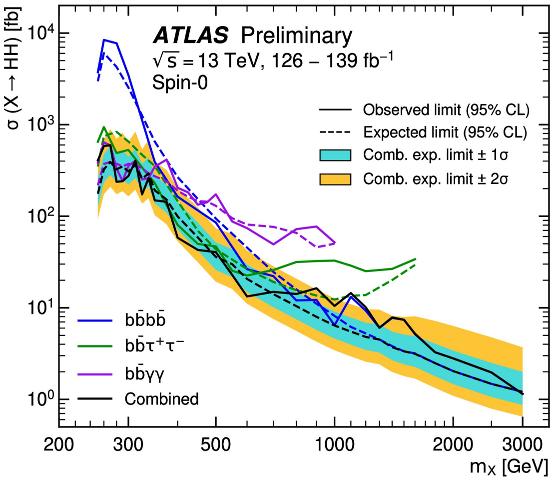

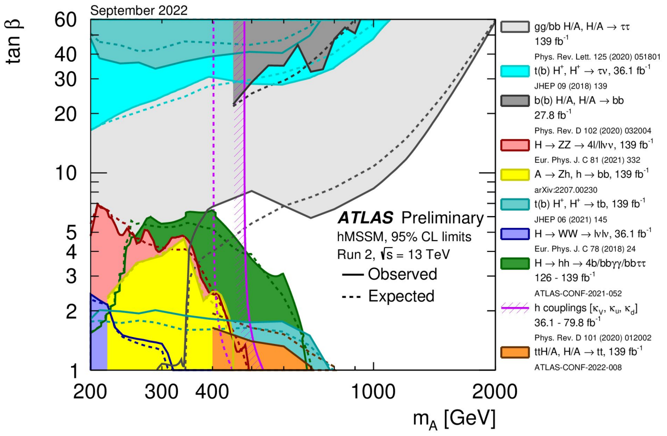

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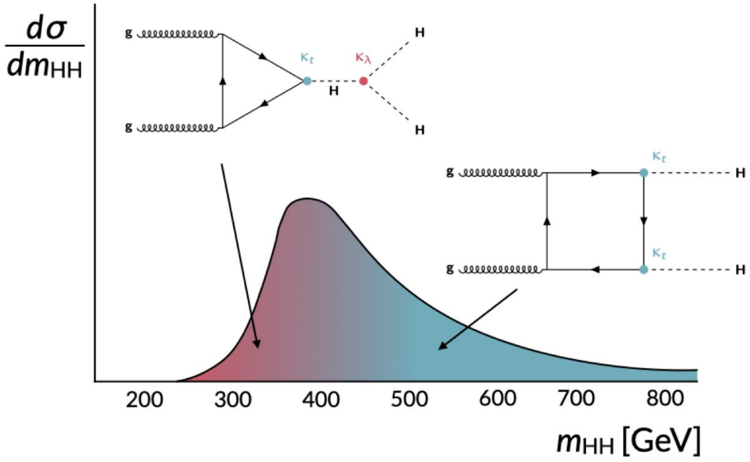
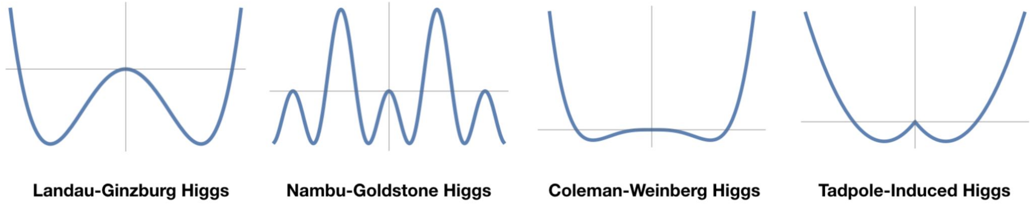
Precision measurements

- 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

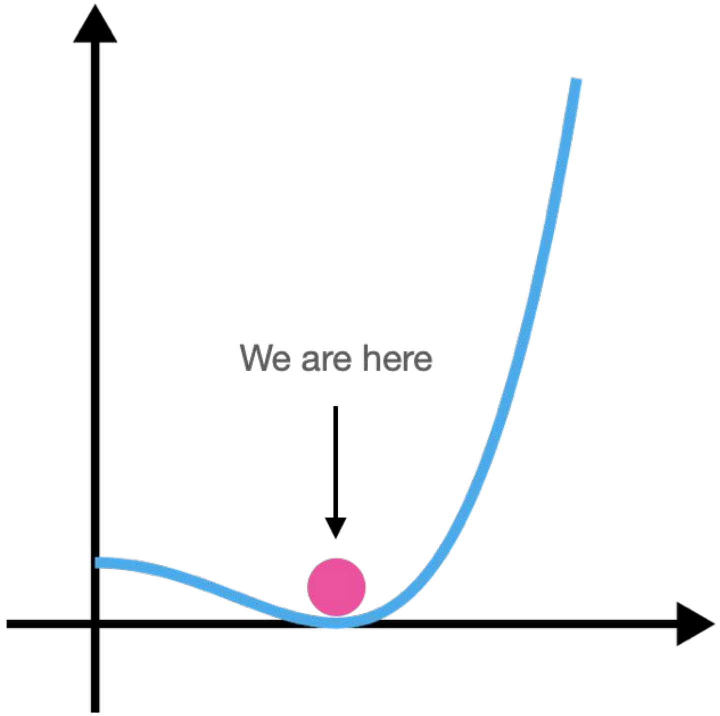
- The Higgs potential parameter λ could indicate new physics
- Possibly related vacuum stability or electroweak baryogenesis
- Measured through Higgs boson pair production
  - Cross-section and m_{HH} distribution could indicate BSM modifications



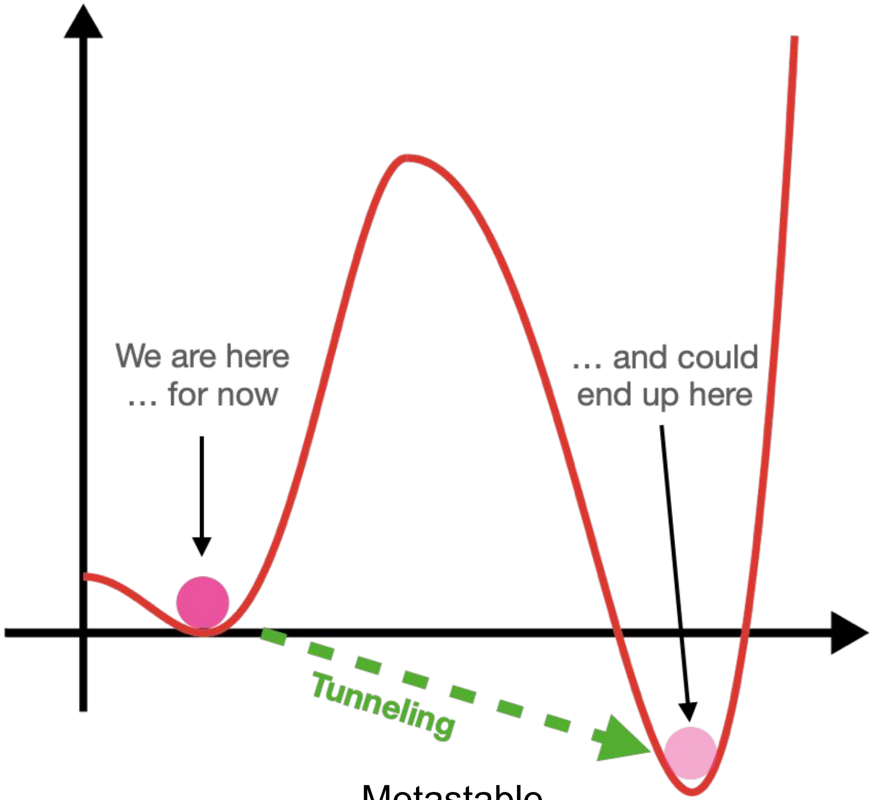


Phys. Rev. D 101, 075023 (2020)

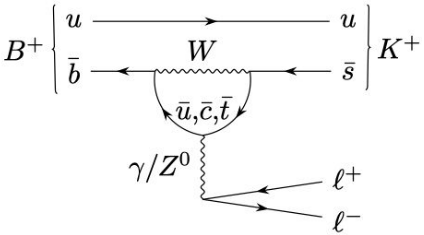
Vacuum stability



Stable



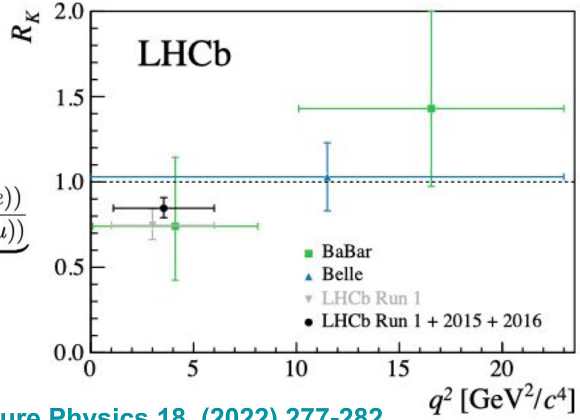
Metastable



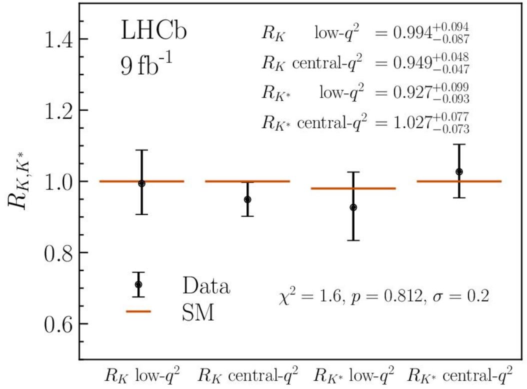
Flavor anomalies

- 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

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



Nature Physics 18, (2022) 277-282

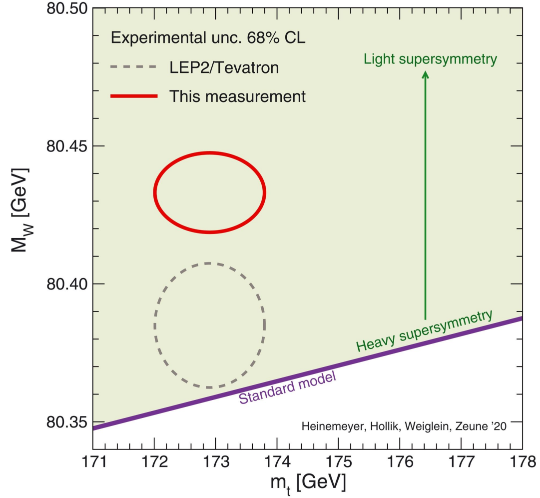


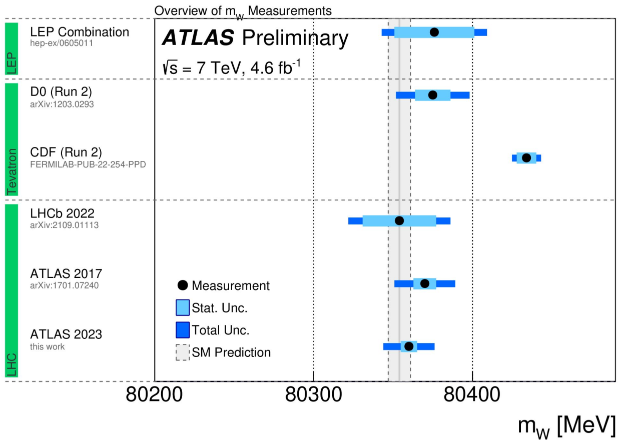
arxiv:2212.09153

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

Science 376 (2022) 6589, 170-176





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