Black Holes and SUSY

BND School 2025

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10 September 2025

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Black Holes

10 April 2019

12 May 2022

https://eventhorizontelescope.org/

Black Holes?

Forbes Billionaires Innovation Leadership Money Business Small Business Lifestyle Lists

Mar 11, 2016, 10:46am EST

Could The Large Hadron Collider Make An Earth-Killing Black Hole?

Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group
Science
The Universe is out there, waiting for you to discover it.

This article is more than 4 years old.

Image credit: CERN.

Every time we push the frontiers of knowledge, it comes with a risk, and it comes with the prospect of a reward. The risks are many: failure to find anything new, futility of the experiment to function as designed, and even the possibility of damage and destruction if things go awry. But the rewards can be tremendous, including the unlocking of new knowledge, the development of new technologies, and the advancement of the entire human enterprise of science.

Black-hole themed Spotify playlist: https://open.spotify.com/playlist/6JXkGkPwiBOksHnbYGEvvS?si=cba2e97e1d704639

In General Relativity

- A black hole (BH) can be formed when a large mass M is confined within a radius smaller than the Schwarzschild radius R_S:

$$R_S = \frac{2MG_N}{c^2}$$

- Naively, a BH would only grow, by attracting more mass. However, taking quantum effects into account, a BH behaves like a thermal blackbody with the Hawking temperature:

$$k_B T_H = \frac{1}{4\pi R_S} \hbar c$$

where k_B is the Boltzmann constant. In natural units, $G_N = c = \hbar = k_B = 1$ and $R_S T_H = (4\pi)^{-1}$

➡ BH evaporate and emit photons, or massive particles if T_H is high

- Conversely, two energetic particles collide with impact parameter smaller than R_S, a BH can be formed with subsequent decay to particles
  - ➡ $\sigma(E) \sim \pi {R_S}^2$
- In LED scenarios, the Schwarzschild radius could be large. Let's estimate it using classical mechanics:
  - ➡ Equate the kinetic energy of a particle travelling at the speed of light with gravitational potential energy in 4+δ dimensions:

$$\frac{mc^2}{2} \sim \frac{G_D\ m\ M_{BH}}{R_S^{(1+\delta)}}$$

  - ➡ Using the relation (from previous module):

$$G_N = 1/M_{Pl}^2 \quad \text{and} \quad G_D = 1/M_D^{(2+\delta)}$$

$$R_S^{(1+d)} \sim G_D\, M_{BH} \sim \frac{M_{BH}}{M_D^{2+\delta}}$$

$$R_S \sim \left(\frac{M_{BH}}{M_D.M_D^{1+\delta}}\right)^{\frac{1}{1+\delta}} \quad \Rightarrow \quad R_S \sim \frac{1}{M_D}\left(\frac{M_{BH}}{M_D}\right)^{\frac{1}{1+\delta}}$$

- Now let's compare this to the exact solution solving the General Relativity equations for a flat spacetime in 4+δ dimensions:

$$R_{\mathrm{S}} = \frac{k(\delta)}{M_{\mathrm{D}}}\left[\frac{M_{\mathrm{BH}}}{M_{\mathrm{D}}}\right]^{\frac{1}{(\delta+1)}}, \qquad k(\delta) = \left(2^{\delta}\pi^{\frac{\delta-3}{2}}\frac{\Gamma\left(\frac{\delta+3}{2}\right)}{\delta+2}\right)^{\frac{1}{(\delta+1)}}$$

The mass M_{BH} would roughly correspond to the total energy in a collision. If $M_D = 1$ TeV, where σ is the BH production cross section per partons and s the total energy of the partons participating in the collision. This would mean one BH per second of the LHC.

- A BH at ~TeV scale will also have ~TeV temperature, and it's lifetime will be 10^{-27} - 10^{-25} s.
- If decay is approximately that of a classical black hole, it will thermally radiate with Hawking temperature of:

$$T_H = \frac{(\delta + 1)}{4\pi R_S}$$

Evaporating isotropically and democratically into SM particles. The multiplicity of particles emitted by the BH evaporation is given by:

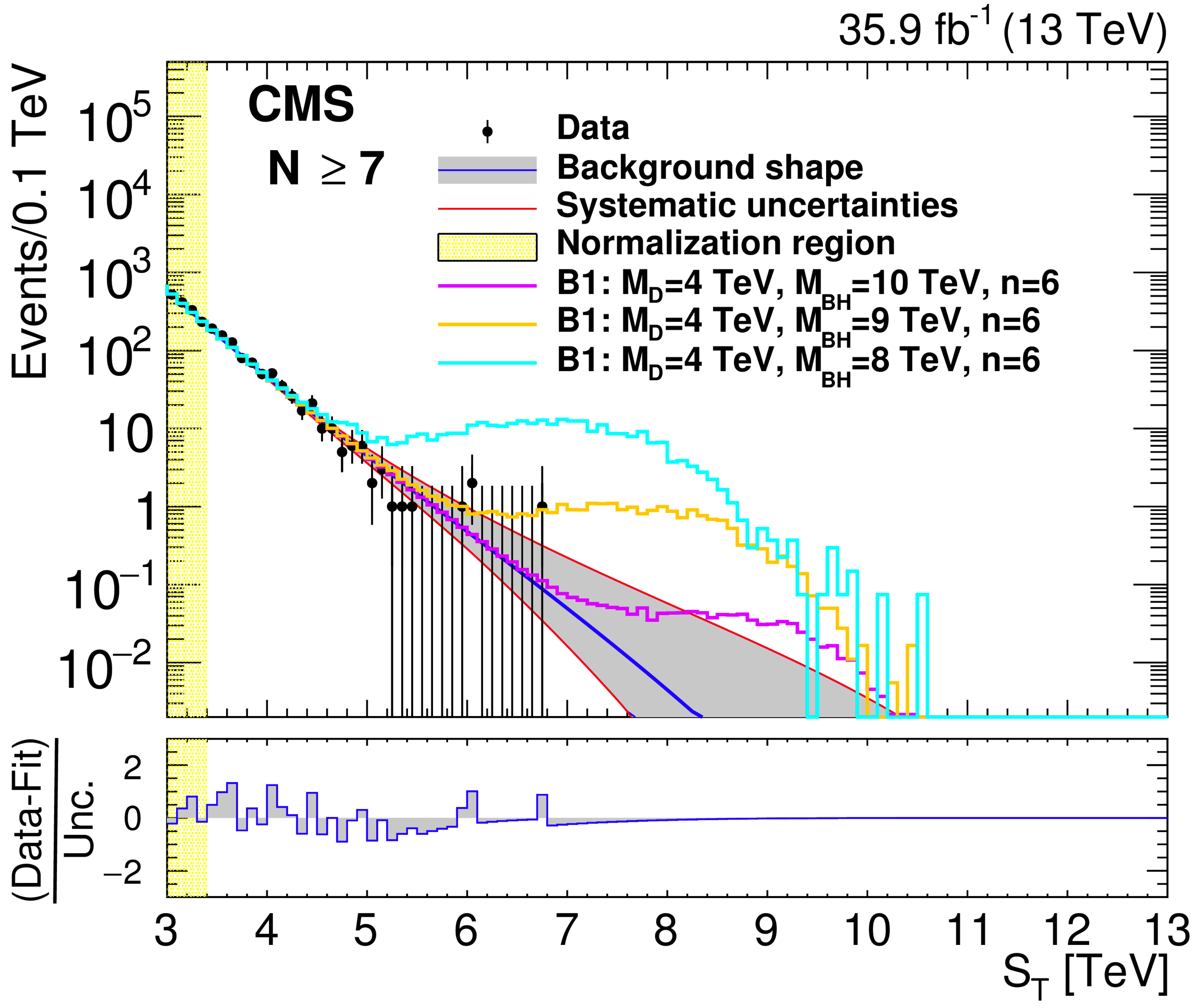
$$< N_{BH} >= \left\langle \frac{M_{BH}}{2E_{\text{particle}}} \right\rangle \sim \left\langle \frac{M_{BH}}{2T_H} \right\rangle$$

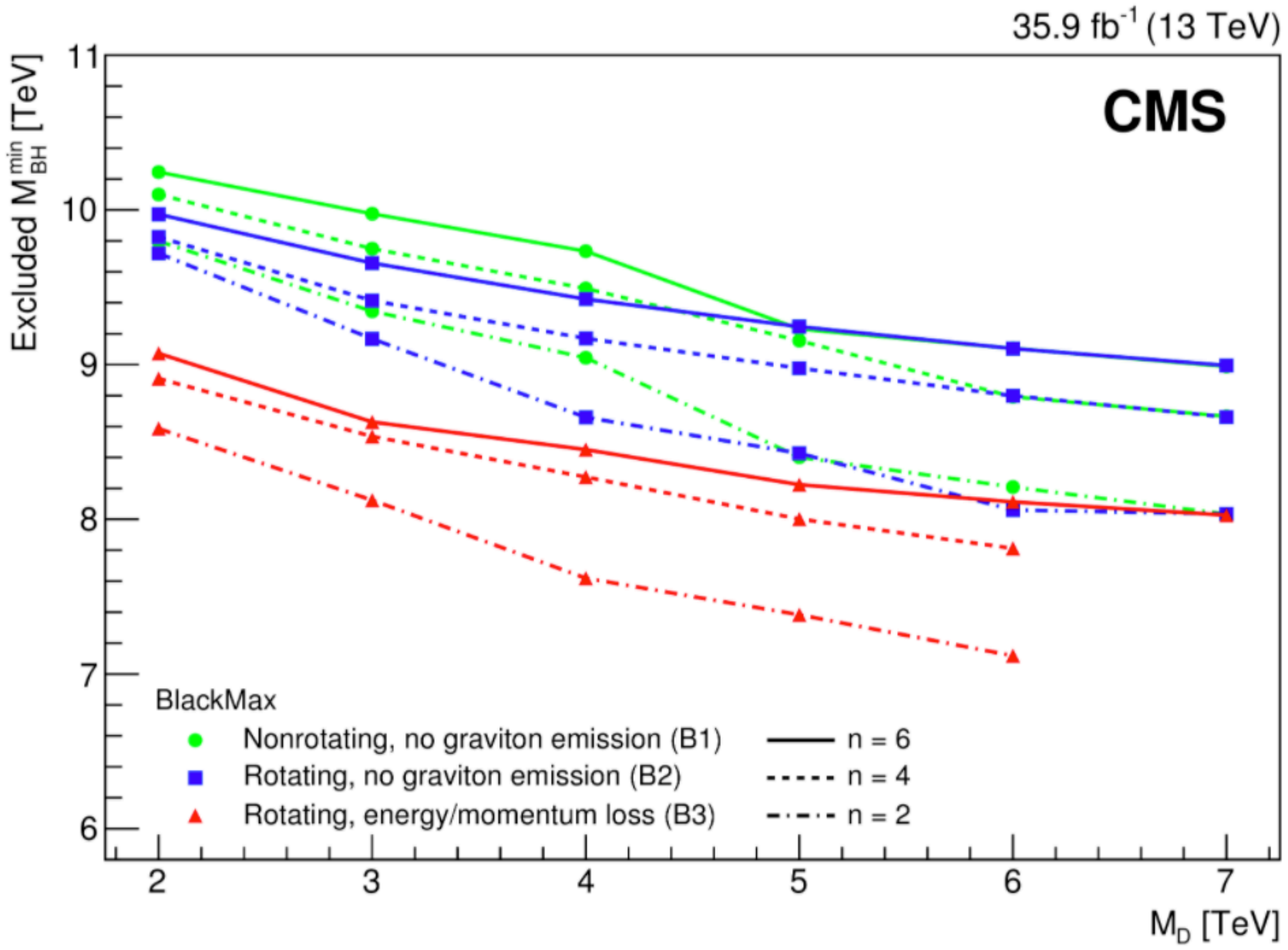
- The most stringent limits on microscopic black holes arise from LHC searches in high-multiplicity final states.

High Multiplicity Searches

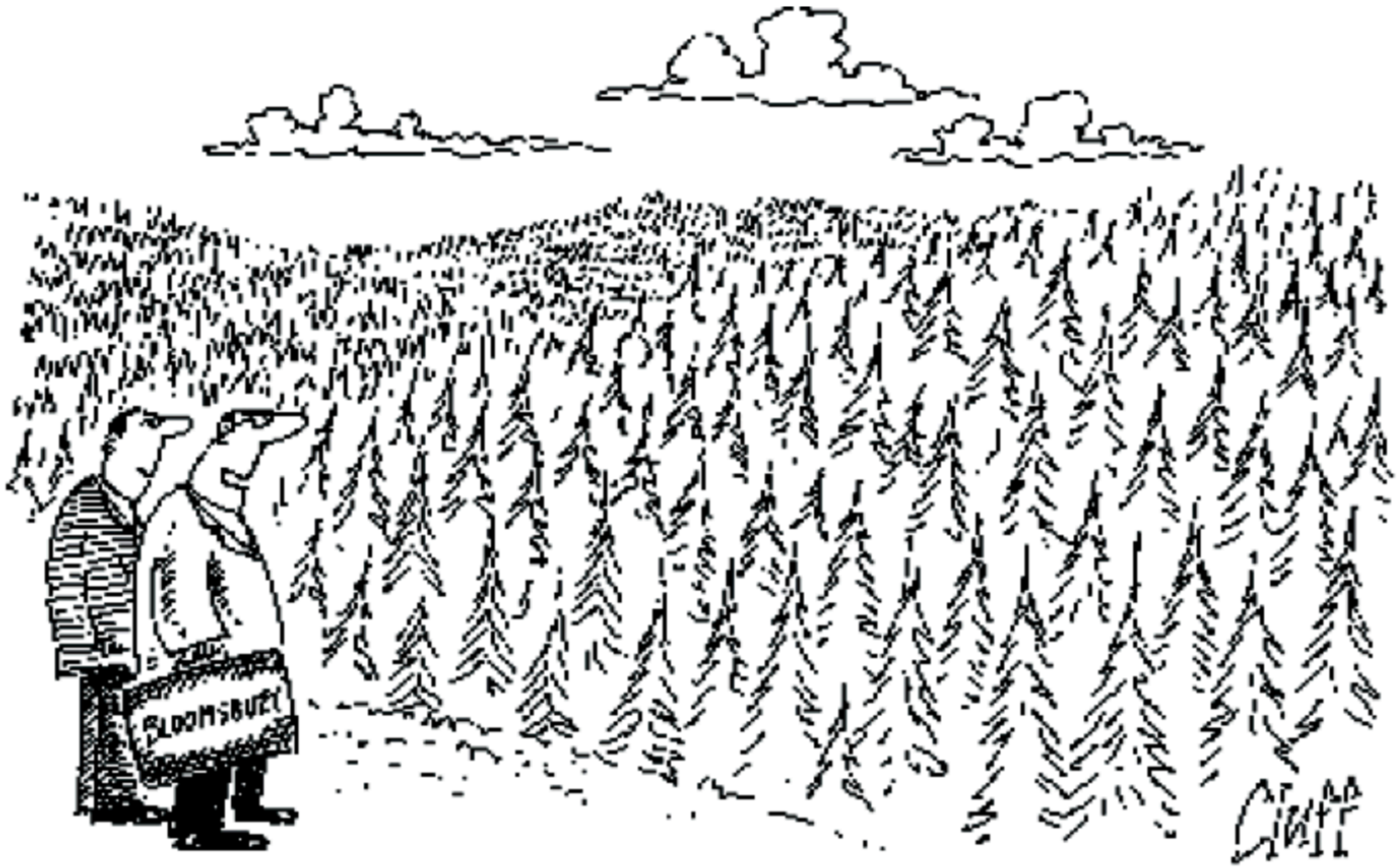
- Simulated samples of semi-classical black holes in different scenarios:
  - ➡ Non-rotating BHs
  - ➡ Rotating BHs
  - ➡ Rotating BHs with mass loss
- For each model, investigate M_D 2-9 TeV, δ=2,4,6
- M_D+1 TeV < M_{BH} < 11 TeV
- Discriminant variable: $S_T = p_T^{\text{miss}} + \sum_{i=1}^{N} p_T^i$
  - ➡ Scalar sum of p_T of all N energetic objects in an event (jets, electrons, muons, and photons with p_T above a given threshold), plus p_T^{miss} in the event, if it exceeds the same threshold
- Look into object multiplicities between ≥3 and ≥11

- No excess above the SM expectation found
  - ➡ Excludes MBH < 10.1 TeV (MD = 2, δ = 6)
  - ➡ Similar ATLAS analysis with multi-jets excludes between MBH < 9.0 - 9.7 TeV depending on MD, for δ = 6





Supersymmetry

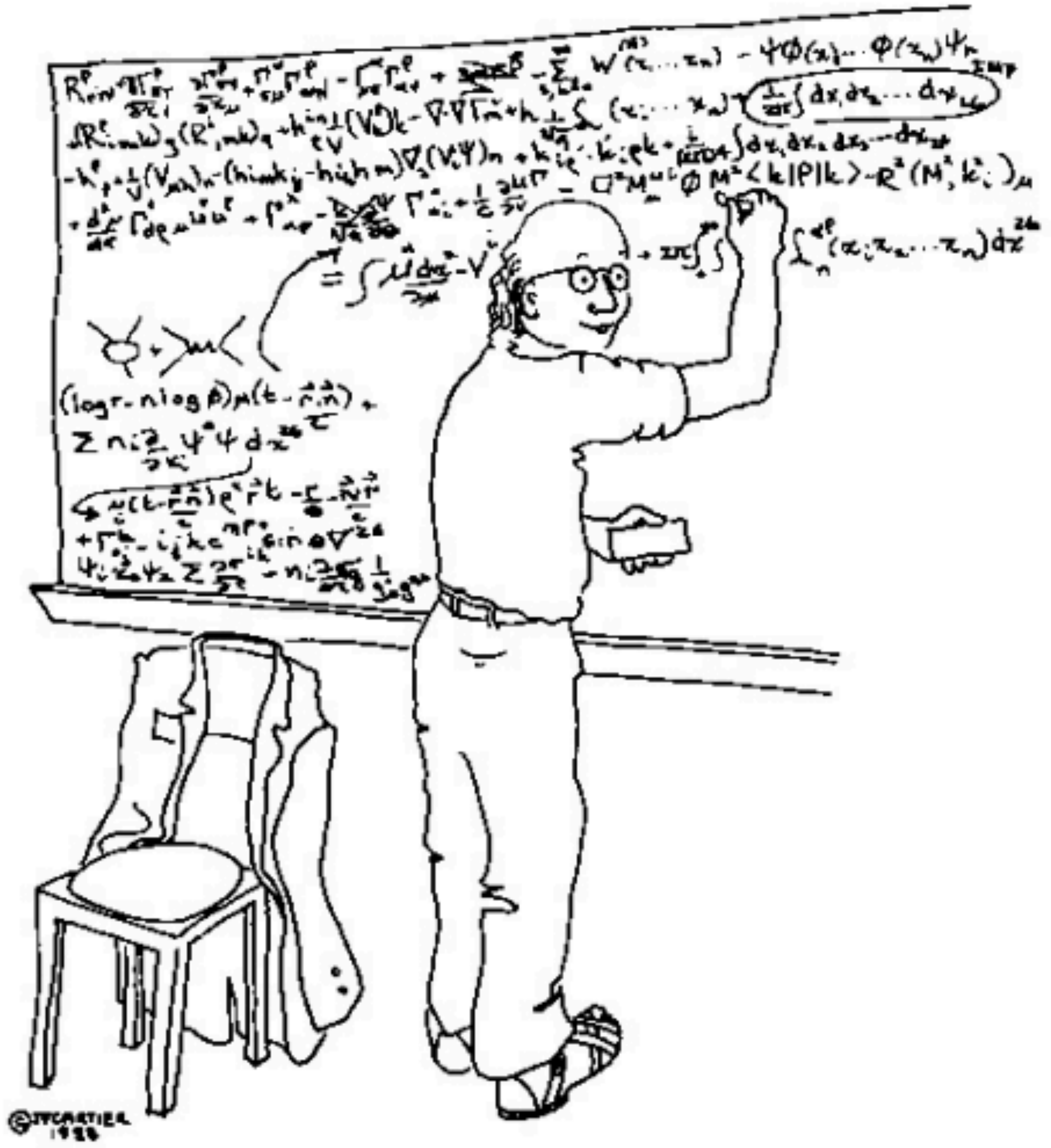


"One day, all of these will be supersymmetric phenomenology papers."

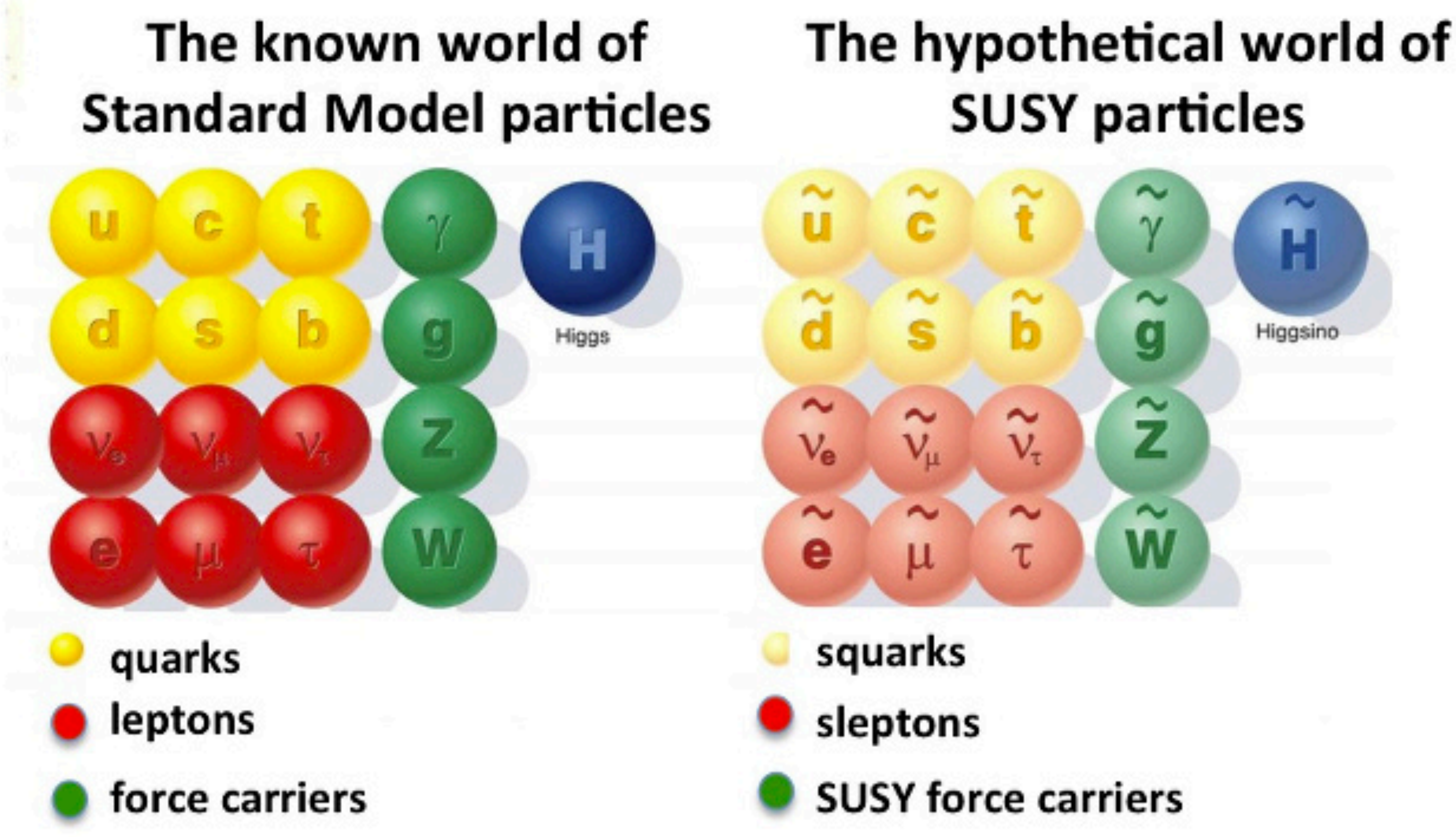
~10.000 papers since 1990

What is SUSY?

- Spacetime symmetry between bosons-fermions
  - ➡ Make equations of force and matter similar
  - ➡ Each particles gets a *superpartner* **same mass/quantum numbers**
    - Electron —> selectron (scalar electron)
    - Gluon —> gluino



"At this point we notice that this equation is beautifully simplified if we assume that space–time has 92 dimensions."


The known world of
Standard Model particles
u
c
t
γ
H
Higgs
d
s
b
g
ν_e
ν_μ
ν_τ
Z
e
μ
τ
W
quarks
leptons
force carriers
The hypothetical world of
SUSY particles
$\tilde{u}$
$\tilde{c}$
$\tilde{t}$
$\tilde{\gamma}$
$\tilde{H}$
Higgsino
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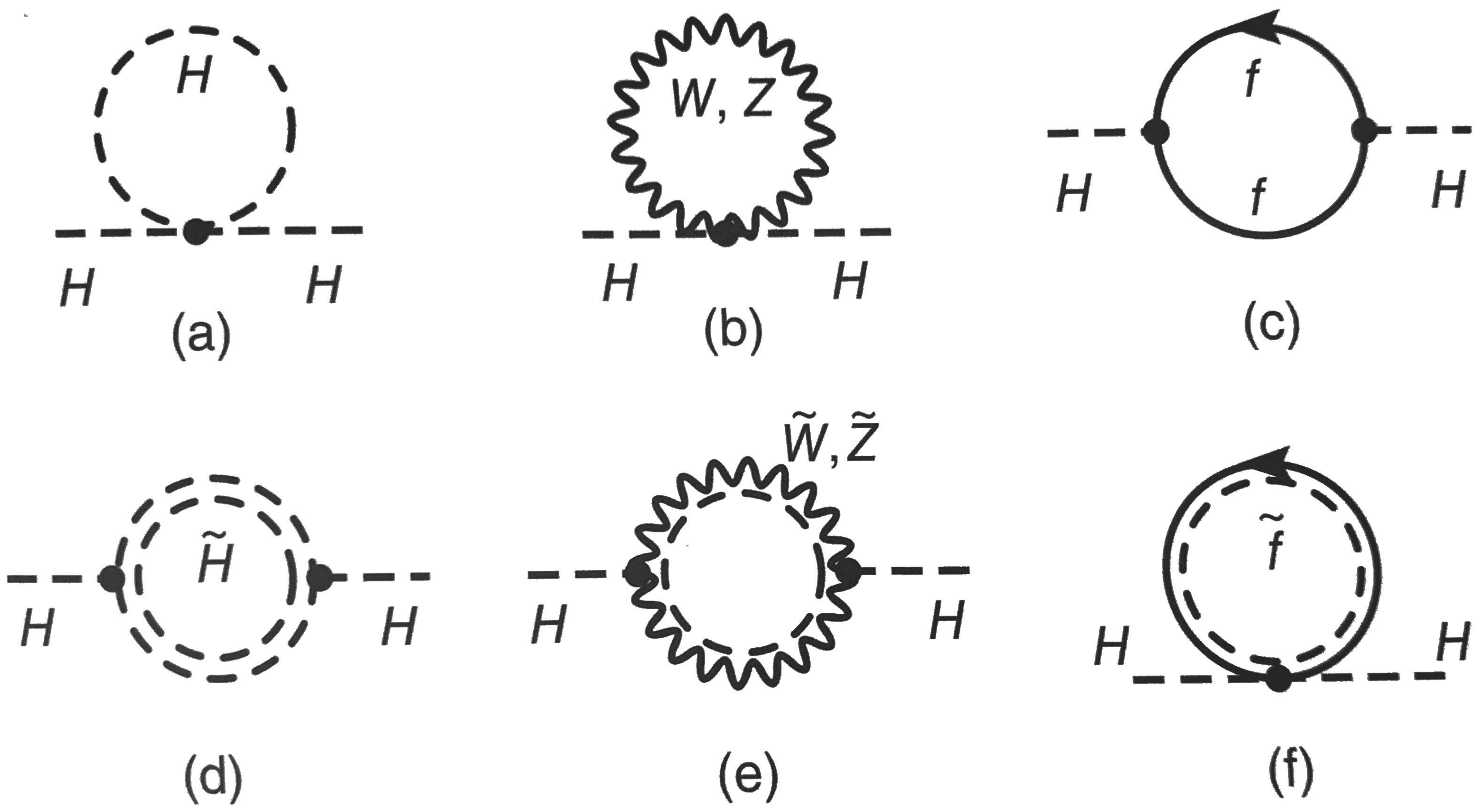
$\tilde{\nu}_\tau$
$\tilde{Z}$
$\tilde{e}$
$\tilde{\mu}$
$\tilde{\tau}$
$\tilde{W}$
squarks
sleptons
SUSY force carriers

Why is SUSY?

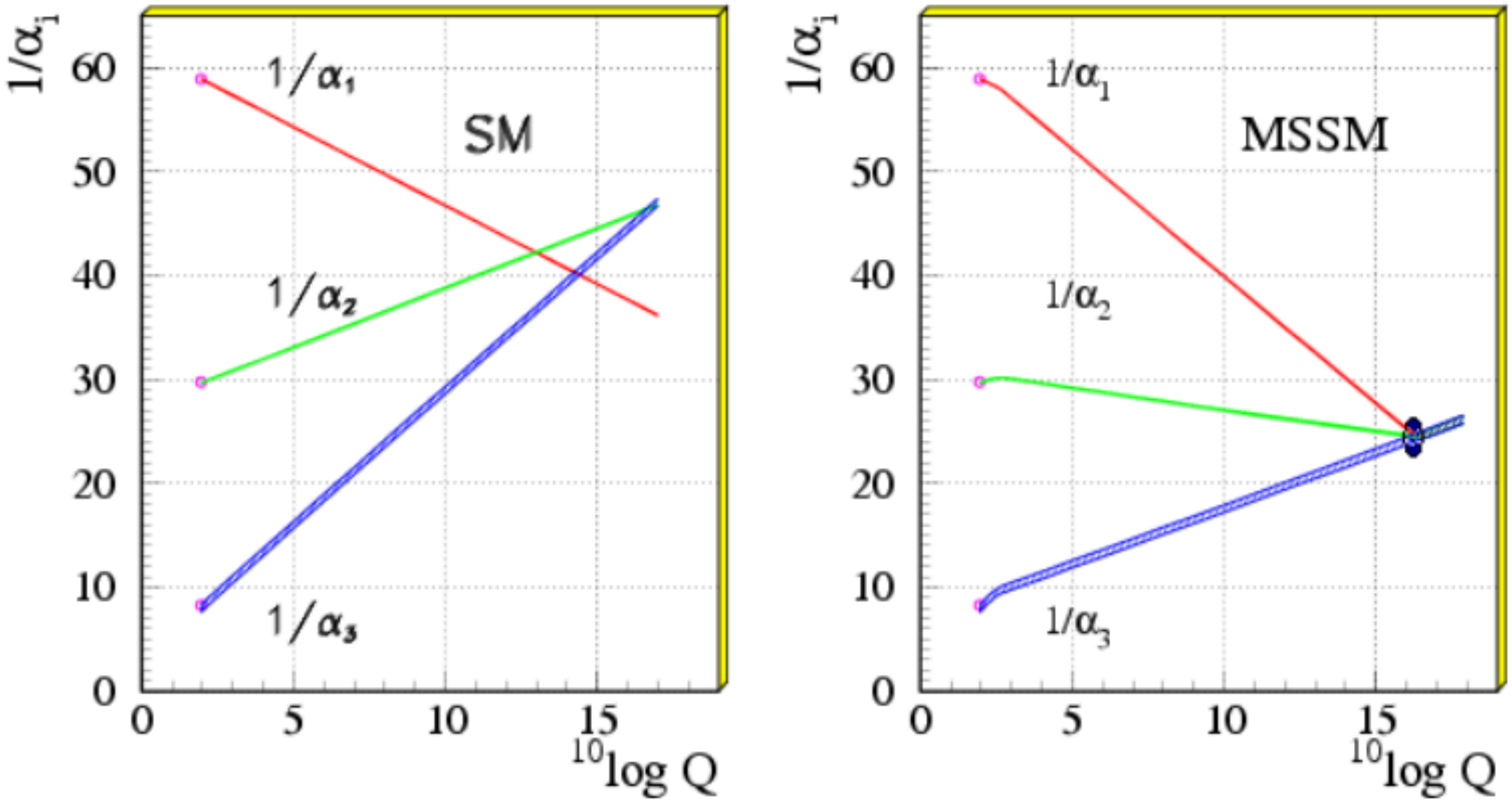
- Naturalness

➡ Radiative corrections by fermion loops have opposite signs to those by boson (Fermi-Dirac statistics)

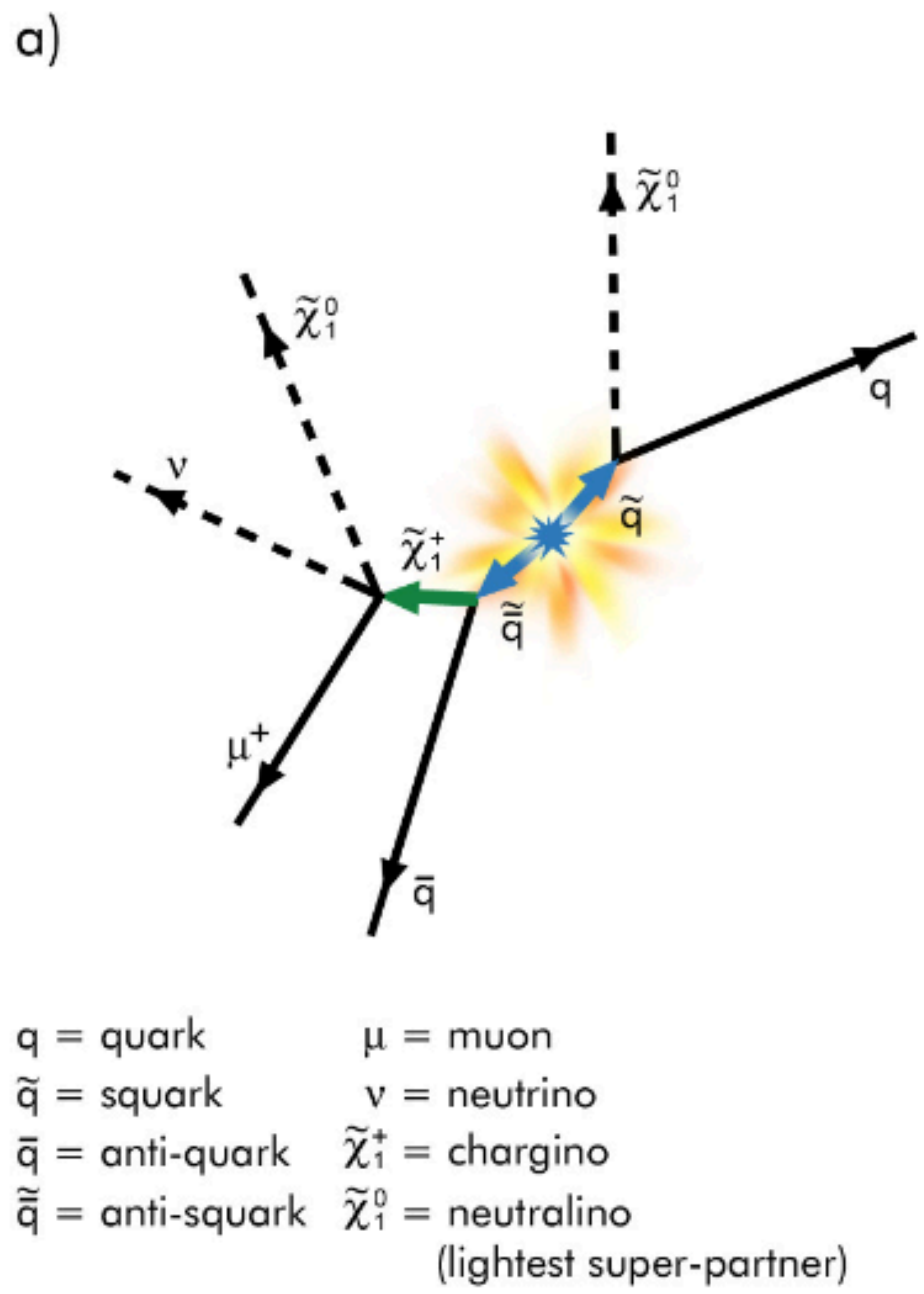
- New fermions corresponding to known bosons with same mass and same coupling could cancel exactly the boson loop
- SM fermion loop compensated by a corresponding scalar boson
- If supersymmetry is broken (not exactly the same mass), can still solve fine tuning provided that mass difference of partners remain ≤1 TeV

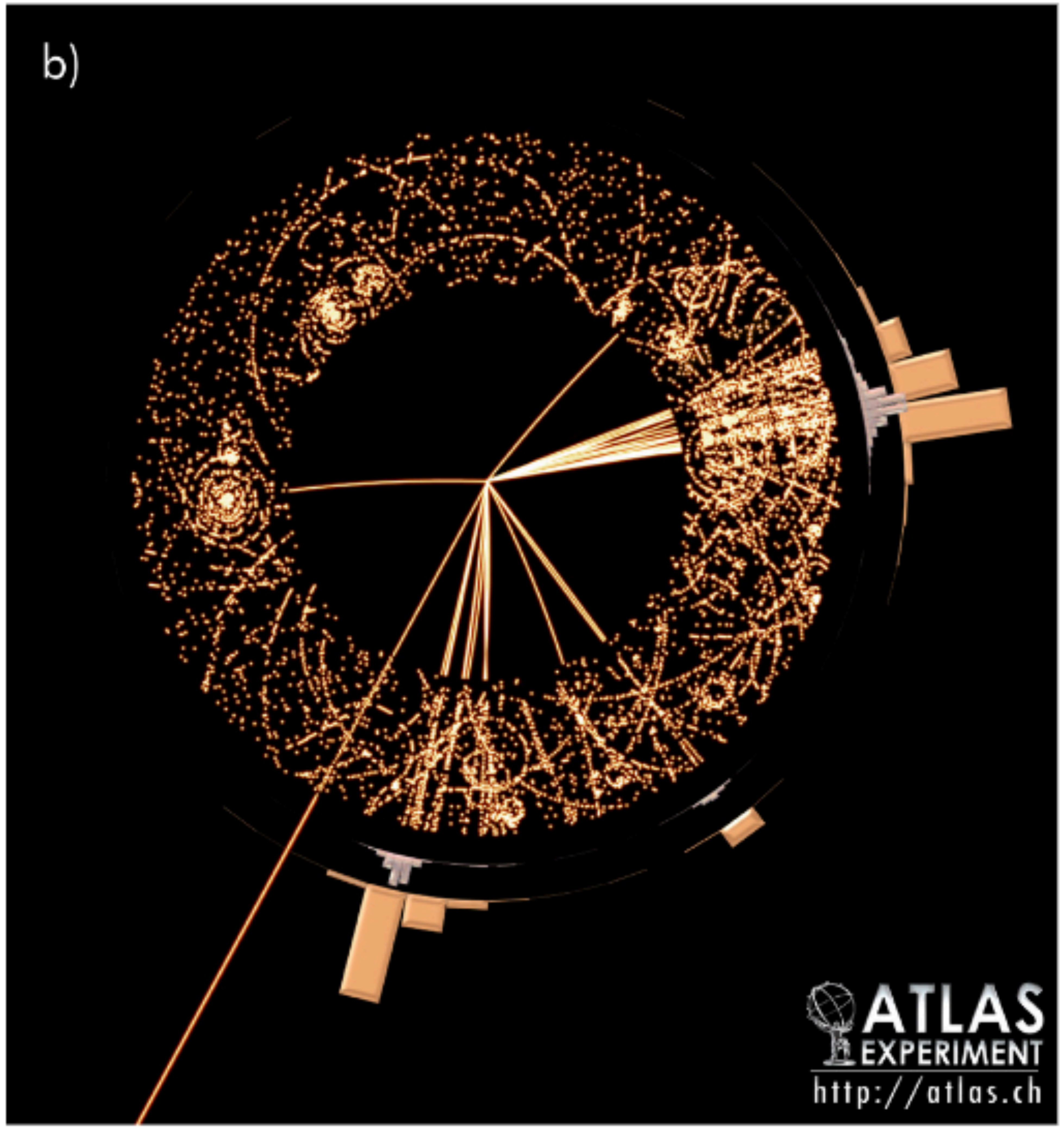


- Gauge-coupling unification



- Dark matter candidate





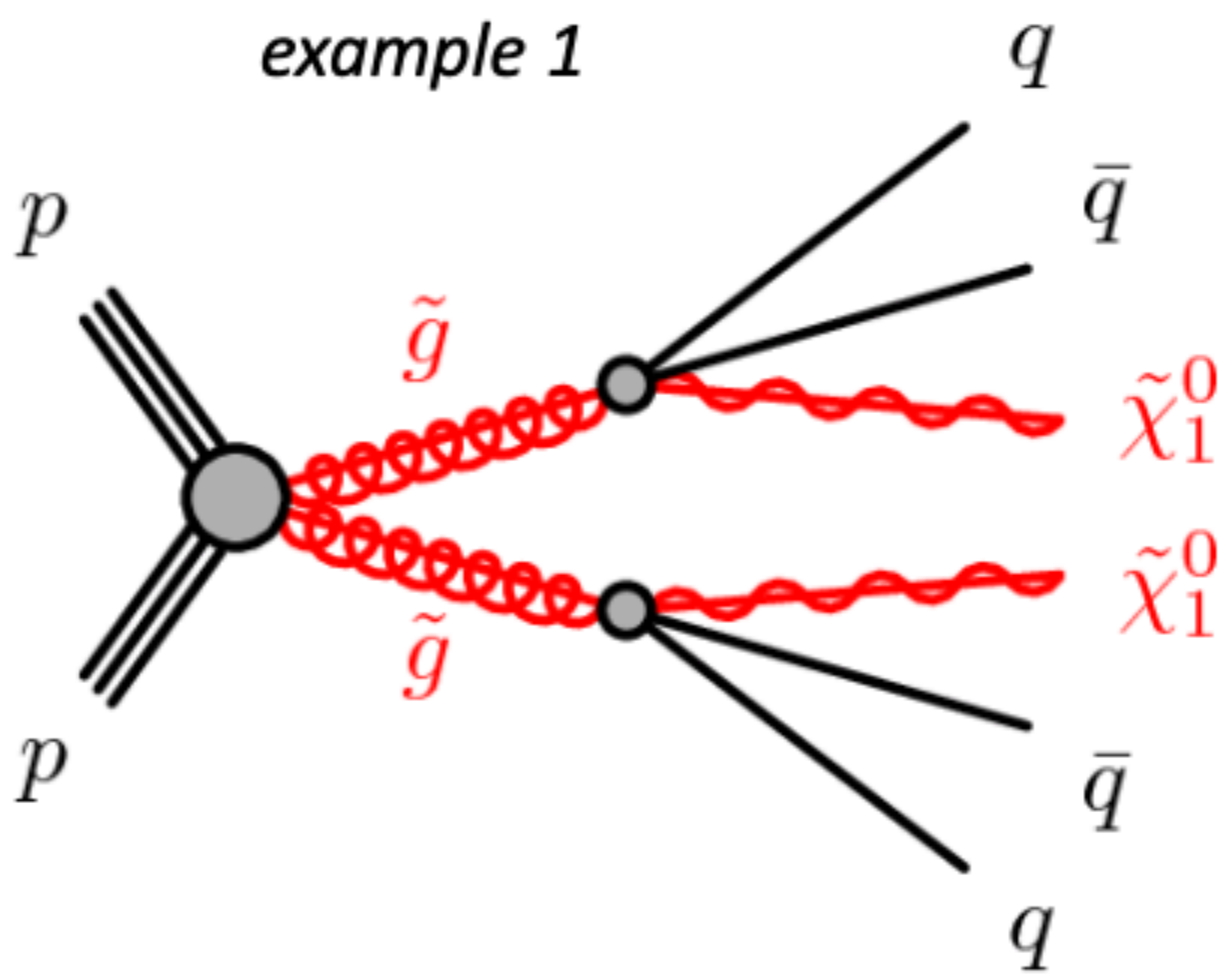
Not everything is shiny though…

- Large number of new, free parameters (and particles!)
- Too heavy SUSY does not solve hierarchy!
  - ➡ Ad-hoc SUSY breaking mechanisms
- Lack of experimental evidence
  - ➡ Effects on precision observables
  - ➡ On-shell SUSY particle production
  - ➡ Cosmological implications

SUSY Phenomenology

- MSSM: Minimal Supersymmetric Standard Model
  - ➡ LHC: squarks and gluinos (strongly interacting); lightest SUSY particle (neutralinos);
- Too many free parameters in MSSM
  - ➡ Simplified models:
    - ➡ Set of basis: complicated SUSY spectrum can be decomposed in a set of simplified models
    - ➡ Scan of masses, to exclude cross sections
    - ➡ Combined results to draw conclusion about a more complicated model

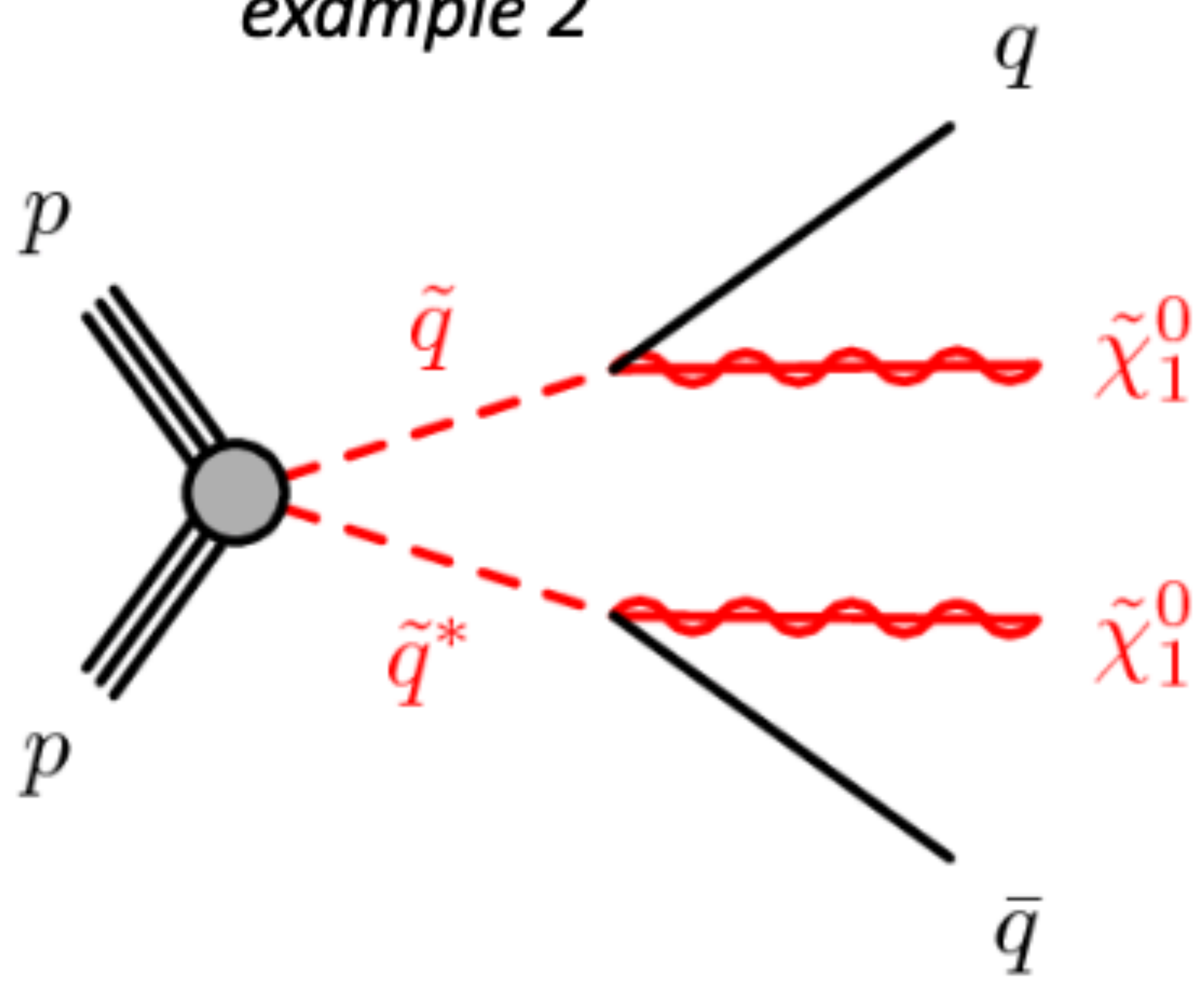
example 1



Assume: only gluino and neutralino1 light
all other susy particles very massive
(so gluino → squark quark not possible)

Scan all gluino and neutralino1 masses
Assume 100% branching fraction

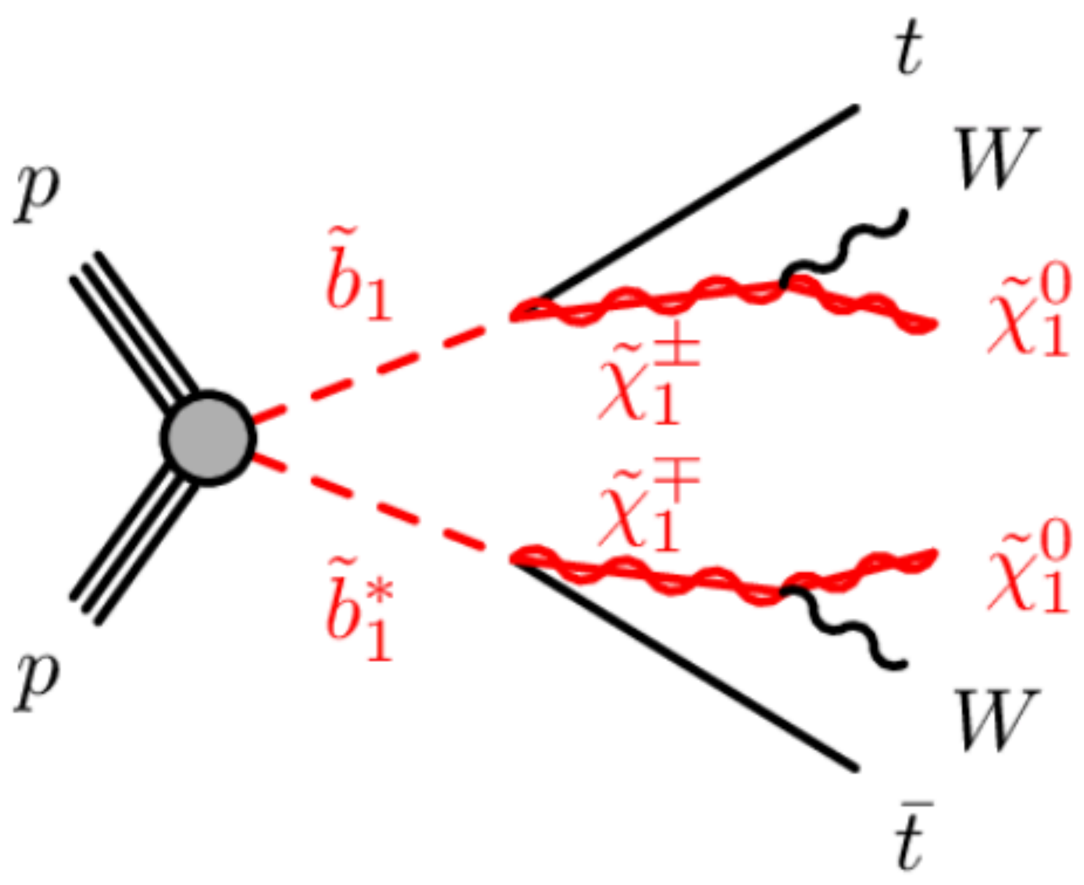
example 2

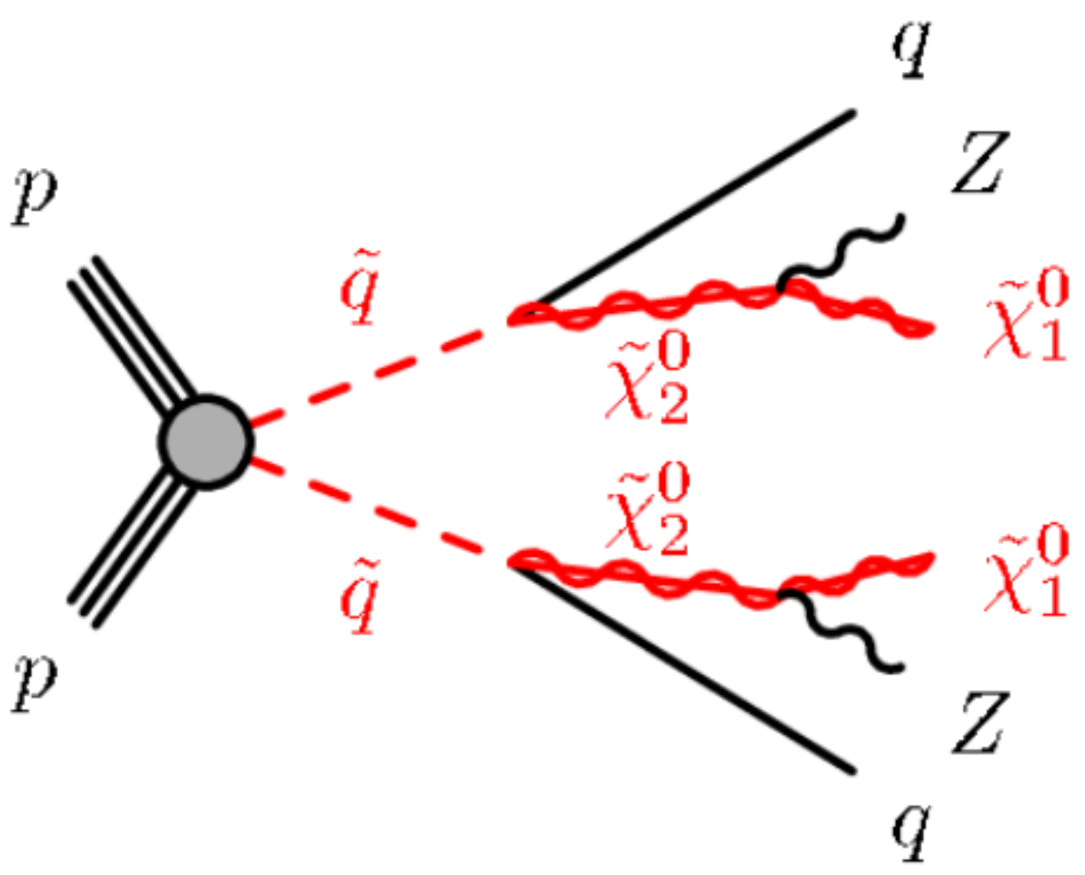


Assume: only squark and neutralino1 light
all other susy particles very massive
(so squark → gluino quark not possible)

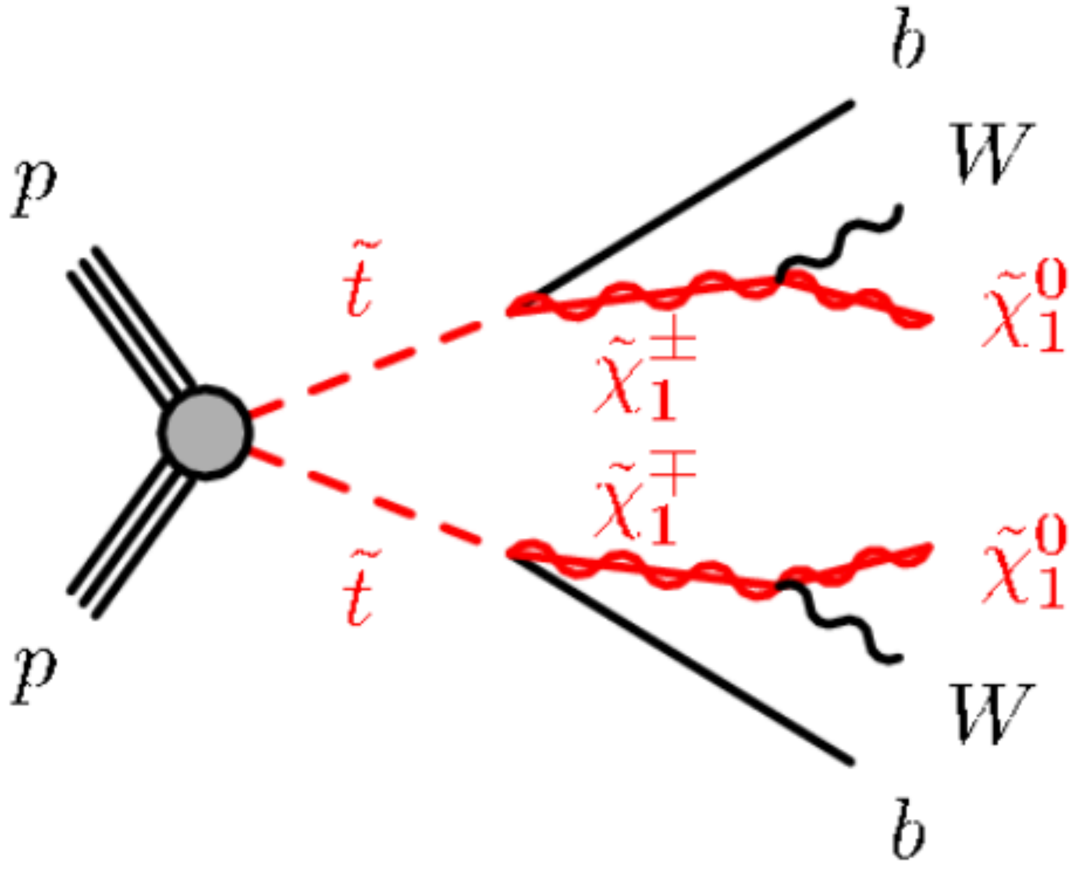
Scan all squark and neutralino1 masses
Assume 100% branching fraction

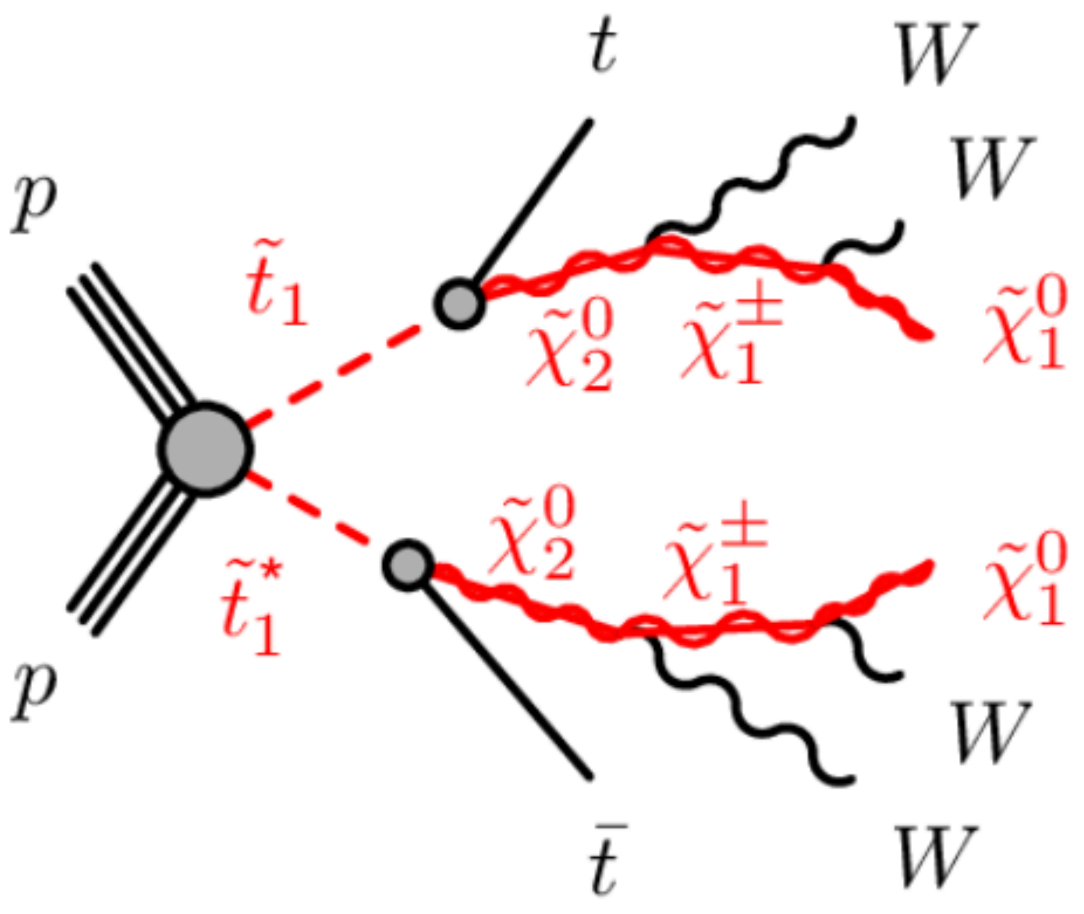
More complicated simplified models



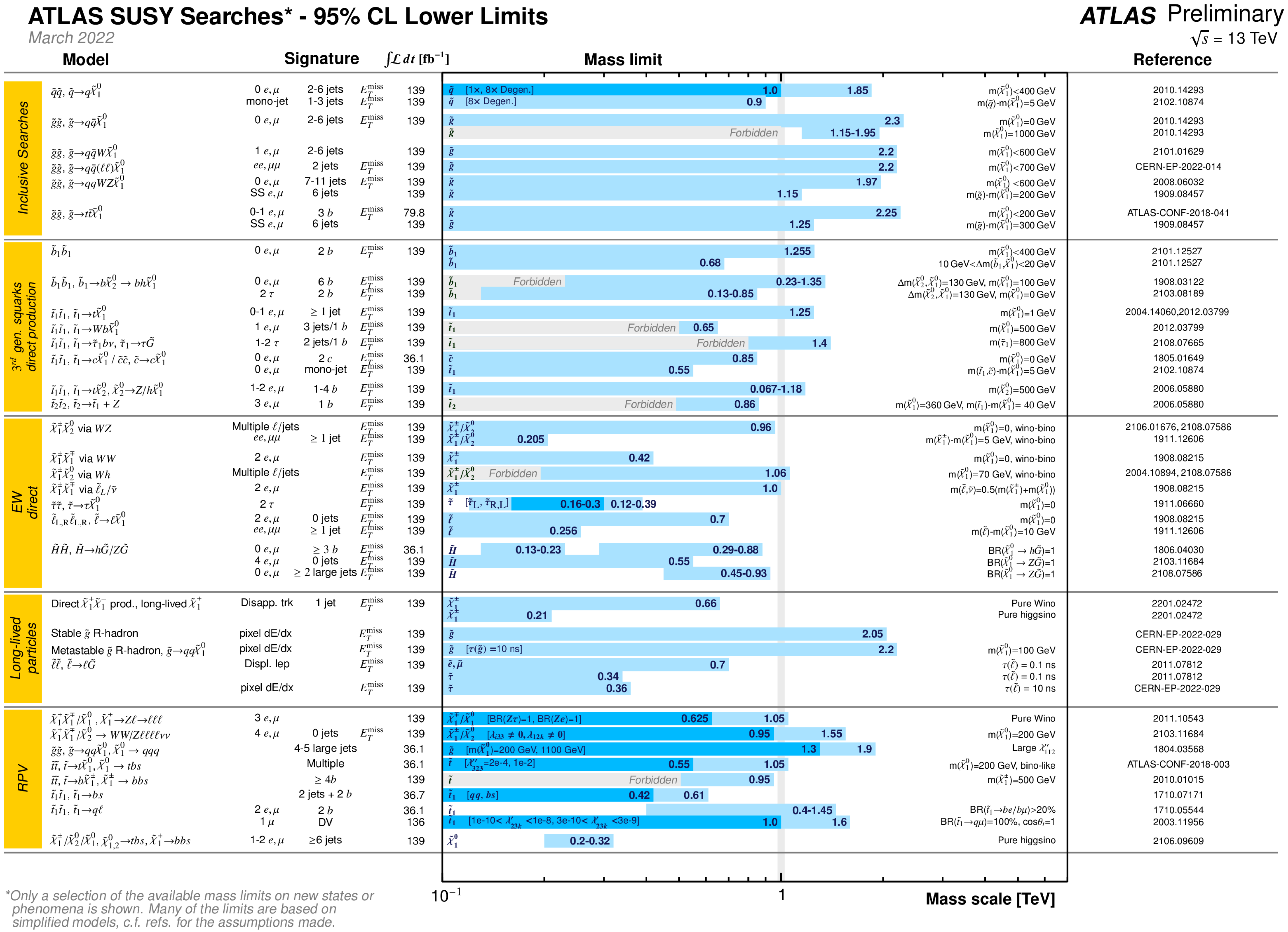


2 → 3 or 4 free masses

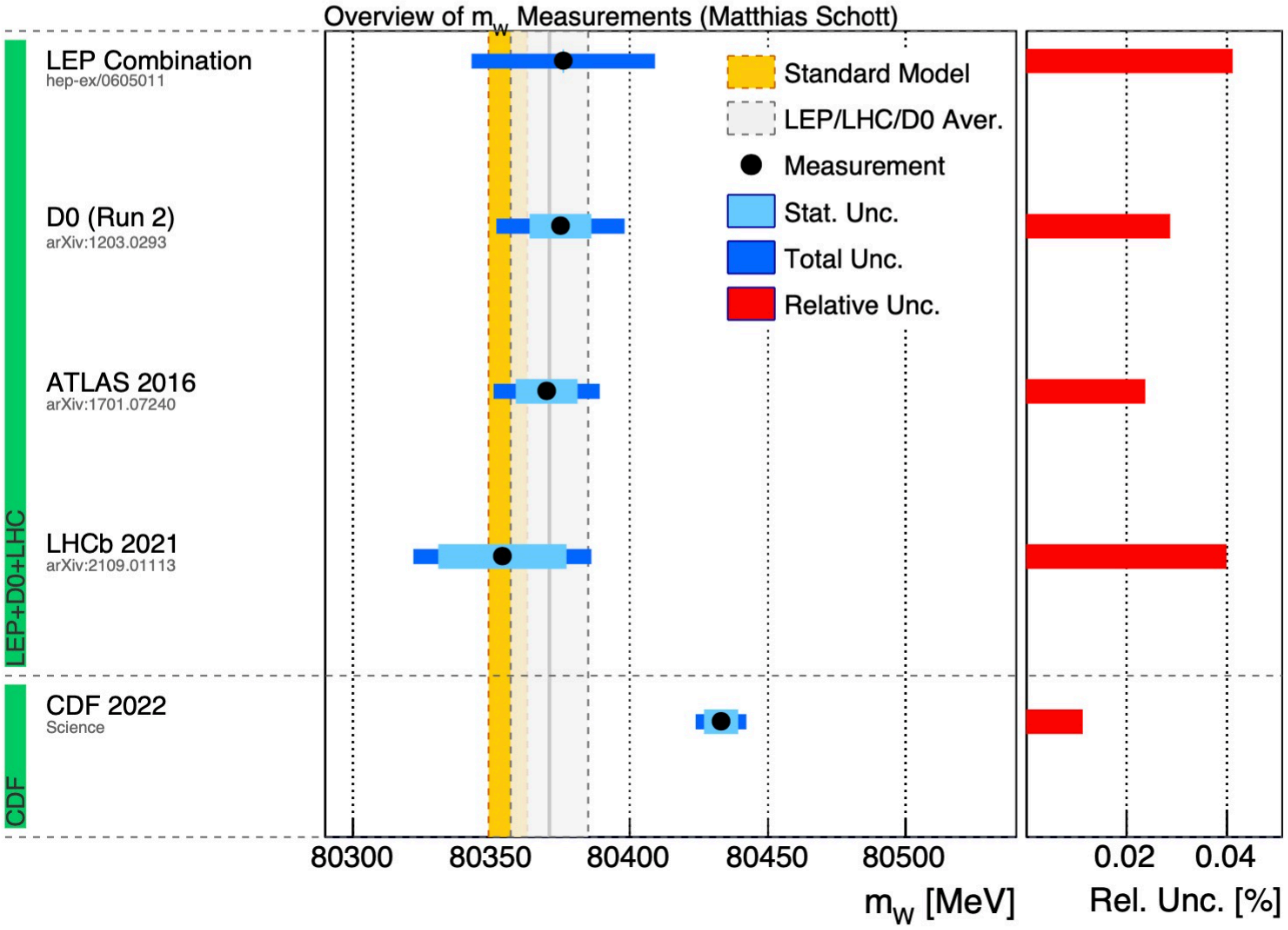




SUSY searches: Still not there…



W Mass

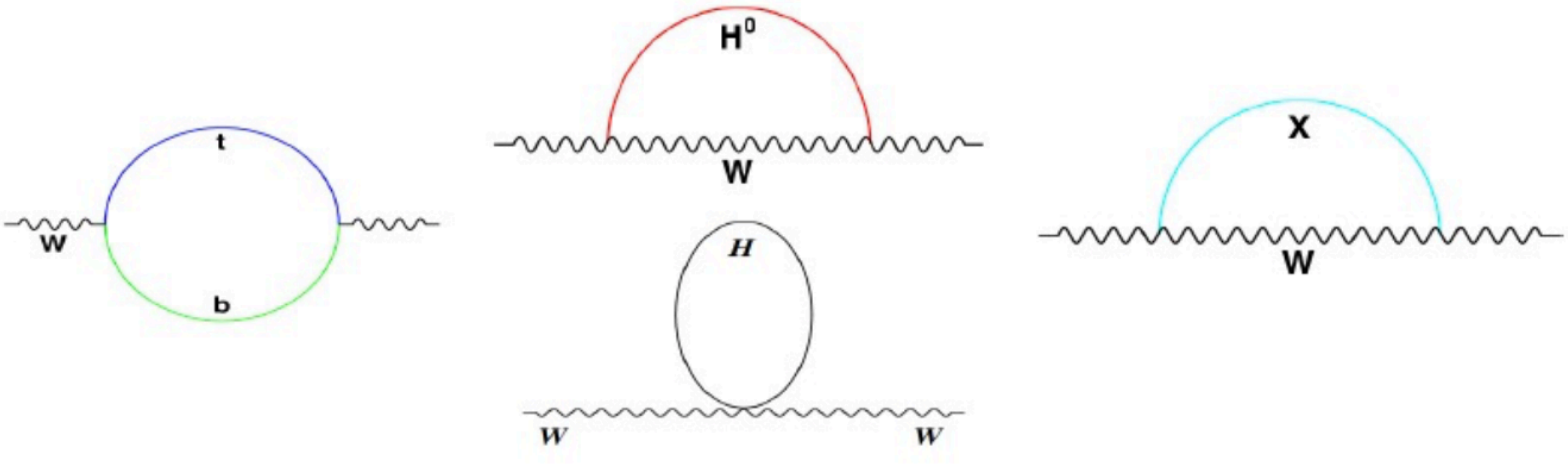


EW Fit: 80354 ± 7 (w.o.)
80357 ± 6 (w. M_W)

CDF 80433.5 ± 9.4

(+ 7 sigma)

- Affected by radiative corrections due to heavy quarks, Higgs, potentially undiscovered particles



- SUSY particles could run in the loop and change the value of W mass (or new Higgs bosons, new strong interactions, …)

Summary

- (microscopic) Black Holes could potentially be created in colliders if we have extra spatial dimensions
  - ➡ Searches for semi-classical (high multiplicity) and quantum (2->2) black holes part of LHC programme
- Supersymmetry could lead to interesting solutions to some of the open questions in physics
  - ➡ But unfortunately, it has not yet been seen by the LHC