

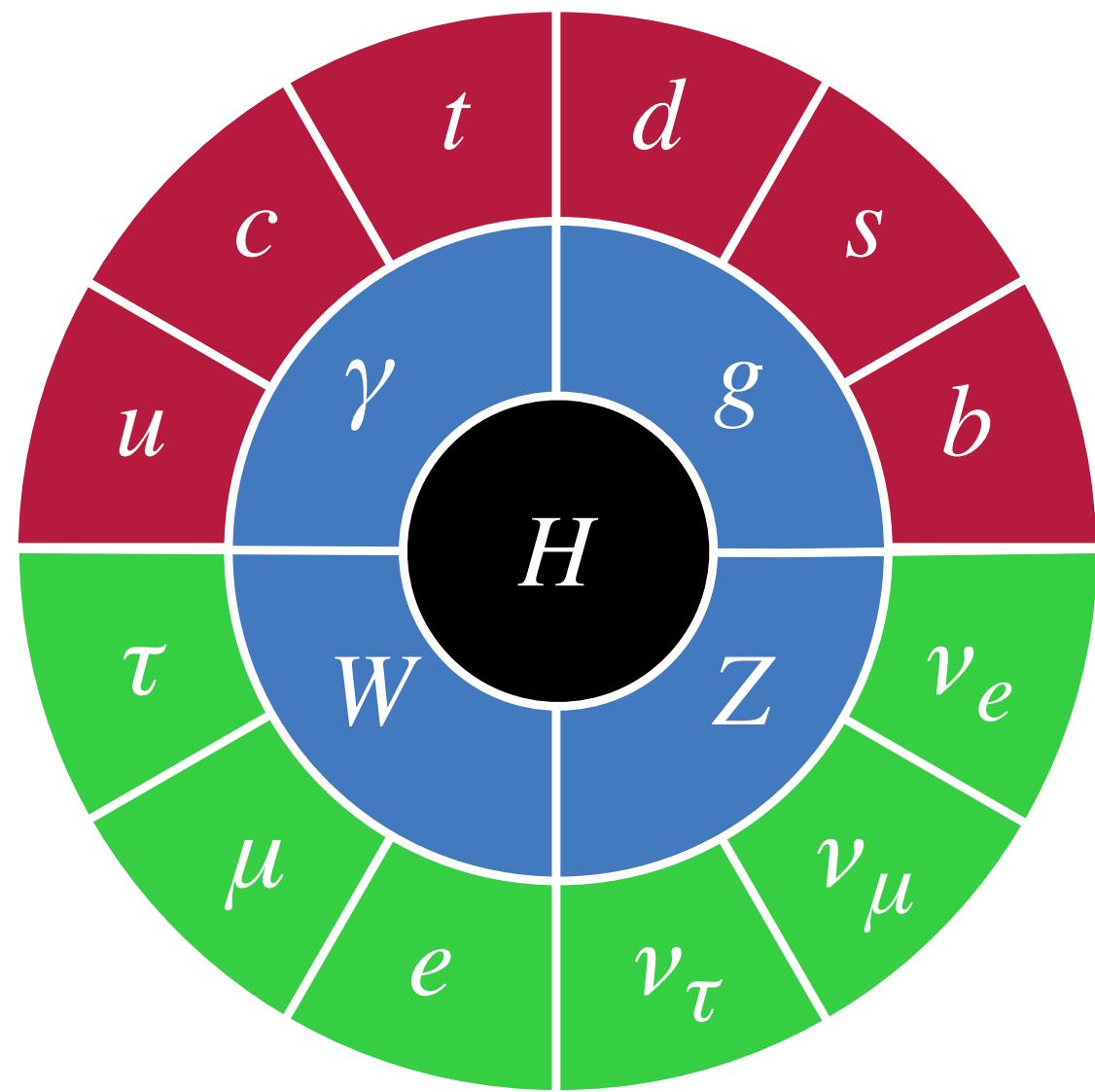
Python for Data Science 2

Lecture 16- SUSY at LHC

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PARTICLE PHYSICS: 19 PARAMETERS

$$\mathcal{L}_{SM} = \underbrace{\frac{1}{4}\mathbf{W}_{\mu\nu} \cdot \mathbf{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu}}_{\text{kinetic energies and self-interactions of the gauge bosons}} + \underbrace{\bar{L}\gamma^\mu(i\partial_\mu - \frac{1}{2}g\tau \cdot \mathbf{W}_\mu - \frac{1}{2}g'YB_\mu)L + \bar{R}\gamma^\mu(i\partial_\mu - \frac{1}{2}g'YB_\mu)R}_{\text{kinetic energies and electroweak interactions of fermions}} + \underbrace{\frac{1}{2}|(i\partial_\mu - \frac{1}{2}g\tau \cdot \mathbf{W}_\mu - \frac{1}{2}g'YB_\mu)\phi|^2 - V(\phi)}_{W^\pm, Z, \gamma, \text{and Higgs masses and couplings}} + \underbrace{g''(\bar{q}\gamma^\mu T_a q)G_\mu^a}_{\text{interactions between quarks and gluons}} + \underbrace{(G_1\bar{L}\phi R + G_2\bar{L}\phi_c R + h.c.)}_{\text{fermion masses and couplings to Higgs}}$$



Symbol	Description	Value
m_e	Electron mass	511 keV
m_μ	Muon mass	105.7 MeV
m_τ	Tau mass	1.78 GeV
m_u	Up quark mass	1.9 MeV
m_d	Down quark mass	4.4 MeV
m_s	Strange quark mass	87 MeV
m_c	Charm quark mass	1.32 GeV
m_b	Bottom quark mass	4.24 GeV
m_t	Top quark mass	172.7 GeV
θ_{12}	CKM 12-mixing angle	13.1°
θ_{23}	CKM 23-mixing angle	2.4°
θ_{13}	CKM 13-mixing angle	0.2°
δ	CKM CP-violating Phase	0.995
g_1	U(1) gauge coupling	0.357
g_2	SU(2) gauge coupling	0.652
g_3	SU(3) gauge coupling	1.221
θ_{QCD}	QCD vacuum angle	~0
v	Higgs vacuum expectation value	246 GeV
m_H	Higgs mass	125 GeV

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Flavor	Mass GeV/c ²	Electric charge	Approx. Mass GeV/c ²	Electric charge
ν_e electron neutrino	<0.08	0	0.000511	-1
e electron	0.000511	-1	d down	0.006
ν_μ muon neutrino	<0.0002	0	c charm	1.3
μ muon	0.106	2/3	s strange	1.75
ν_τ tau neutrino	<0.02	0	t top	175
τ tau	1.7771	2/3	b bottom	4.3

Spin is the intrinsic angular momentum of particles. Spin is given in units of \hbar , which is the quantum unit of angular momentum, where $\hbar = h/e = 6.58 \times 10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of e. The proton has a positive charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. Masses are given in GeV/c² (remember $E = mc^2$), where 1 GeV = 10^9 eV = 10^{30} joule. The mass of the photon is 0.938 GeV/c² = 1.67×10^{-27} kg.

- Why Look Beyond the Standard Model?

- Takes 19 parameters (eg Masses)... Why these values?

- Still looking for the Higgs particle.

- Gravity not included! Why gravity is so much weaker than everything else?

- Misses a lot of the Universe: No Dark matter candidate. Can't explain Dark Energy.

- Doesn't have enough asymmetry between matter/anti-matter to explain why we exist!

- At ~ 1 TeV of energy, some of the SM predictions don't make sense. So something **new** has to happen at 1 TeV.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c ²	Electric charge
γ	0	0
W^-	80.4	-1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c ²	Electric charge
g gluon	0	0

Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons
The quarks in an atom are confined in hadrons. The hadrons are formed from quarks and gluons. As the energy of the hadron increases, the energy in the color-force field between the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: mesons $q\bar{q}$ and baryons qqq .

Residual Strong Interaction
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interaction between their color-charged constituents. It is similar to the residual electromagnetic interaction between neutral atoms. It is responsible for the stability of atoms and molecules. It can also be

PROPERTIES OF THE INTERACTIONS

Baryons qqq and Antibaryons q-q-q					
Baryons are fermionic hadrons.					
There are about 120 types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c ²	Spin
p	proton	uud	+1	0.938	1/2
\bar{p}	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
n	neutron	udd	0	0.941	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	-1	1.672	3/2

Matter and Antimatter
For every particle type there is a corresponding anti-particle type, denoted by a bar over the particle symbol. Particle and anti-particle have identical masses and charges. Some electrically neutral bosons (e.g., Z^0 , γ , and η_c = ψ) are their own antiparticles.

Figures
These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and \bar{B}^0 mesons via a virtual Z boson or a virtual photon.

Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

Mesons q-q-bar					
Mesons are bosonic hadrons.					
There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c ²	Spin
K ⁻	kaon	s \bar{u}	-1	0.494	0
ρ^+	rho	u \bar{d}	+1	0.770	1
B ⁰	B-zero	d \bar{b}	0	5.279	0
η_c	eta-c	c \bar{c}	0	3.980	0

Visit the award-winning web feature The Particle Adventure at <http://ParticleAdventure.org>

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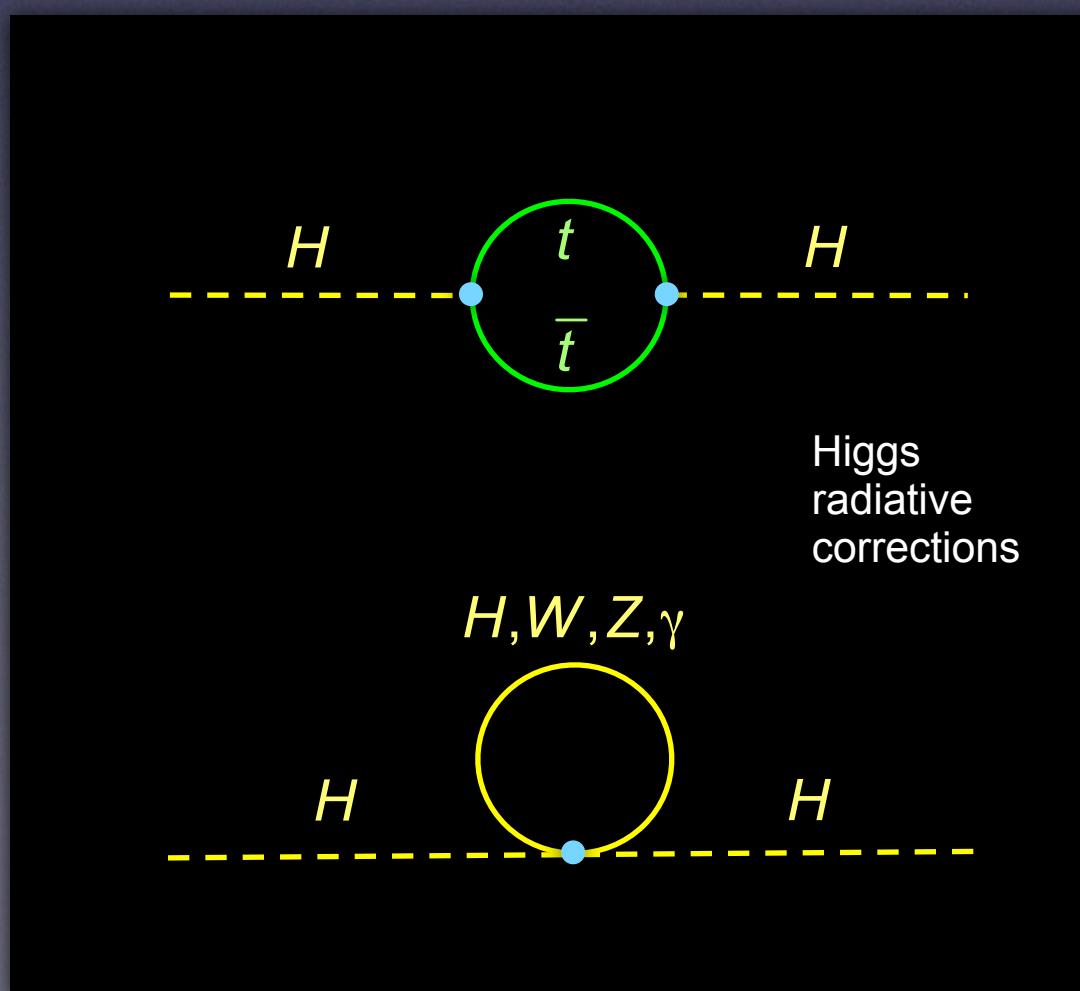
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Hierarchy Problem

m_H =Higgs Mass
~ EW Symmetry
Breaking

m_H Calculation:
Radiative Corrections

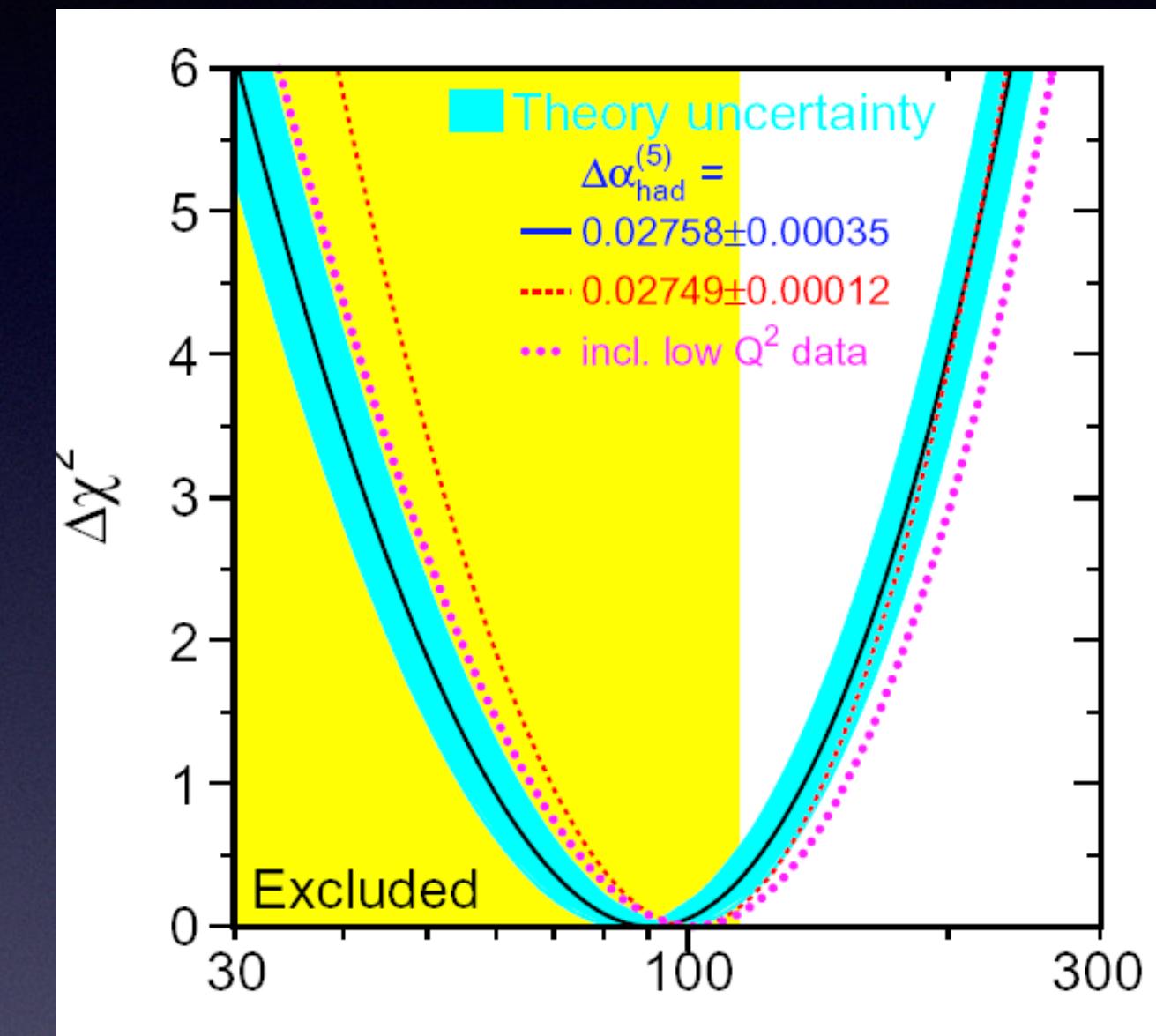
Cut-off Scale (Λ)



GUT Scale
Planck Scale

Quadratic Divergence
 $m_H \sim m_{\text{GUT}}$ or m_{Pl}

Measurements: Electroweak
 $m_H < 1 \text{ TeV}$



Naturalness

$$m_H^2 = m_0^2 + \delta m_0^2$$

Measured = Bare + Correction

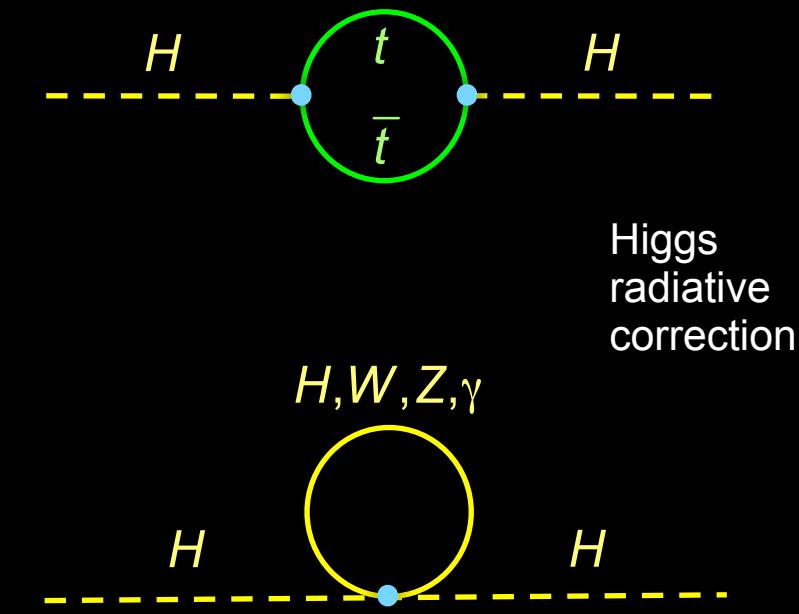
We input Bare

But $\delta m_H^2 \sim \Lambda^2$ (ie large)

m_H (Measured) 125 GeV,
but $\delta m_0 \sim m_{\text{GUT}}$ or m_{Pl}

Need in part in 10^{16} cancellation
between $m_0^2 + \delta m_H^2$

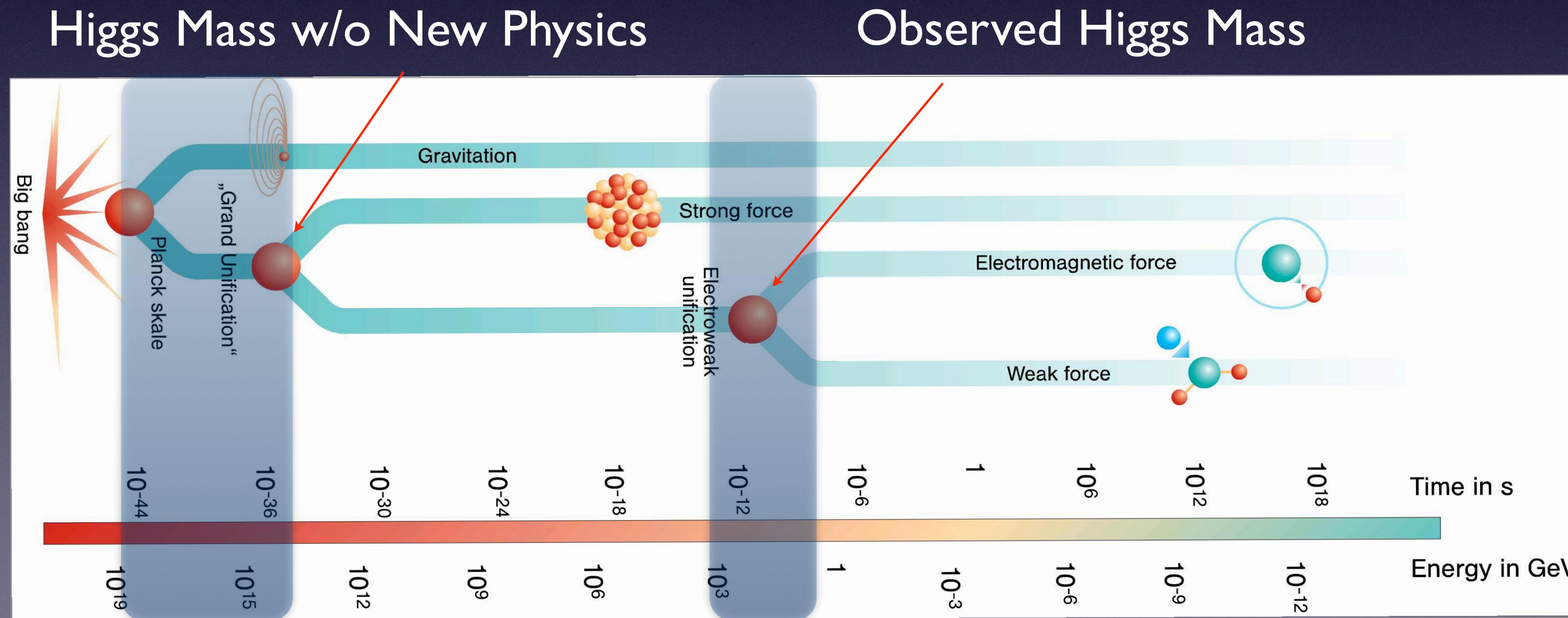
So we must fine-tune the value of bare



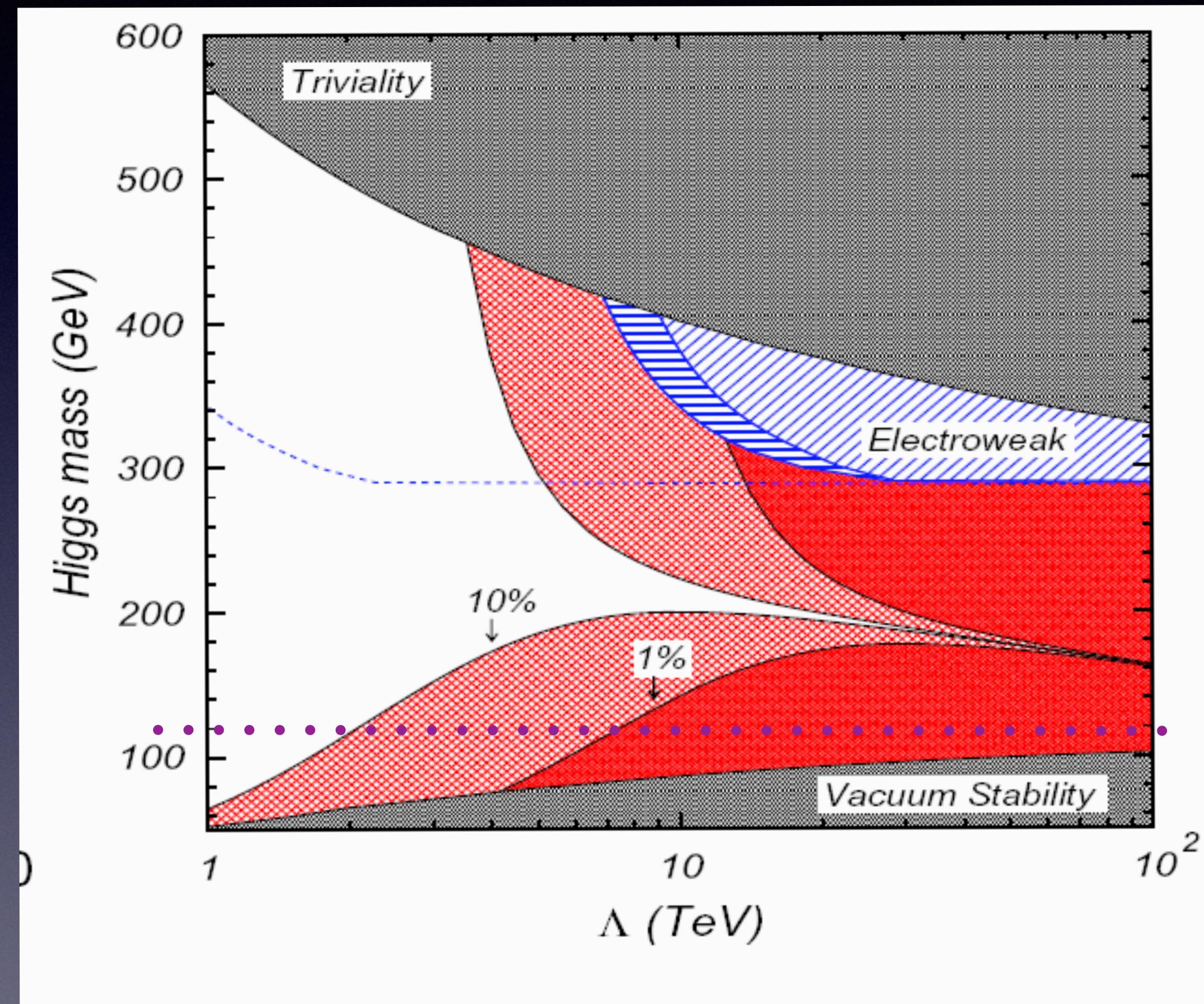
$$\delta m_H^2 \propto \int_0^\infty d^4 k \frac{k^2 + m_f^2}{(k^2 + m_f^2)^2} + \dots \xrightarrow{\text{cut-off}} \int_0^{\Lambda_{\text{cut-off}}} (\dots) \propto \Lambda_{\text{cut-off}}^2$$

Hierarchy Problem

- At the heart of the Standard Model is a particle called the Higgs (which we haven't seen yet...)
- For the SM to work, the Higgs mass has to be $< 1 \text{ TeV}$
- But the SM predicts the Higgs mass to be around the mass where something new happens.
- So for SM to work... something new has to happen $\sim 1 \text{ TeV}$



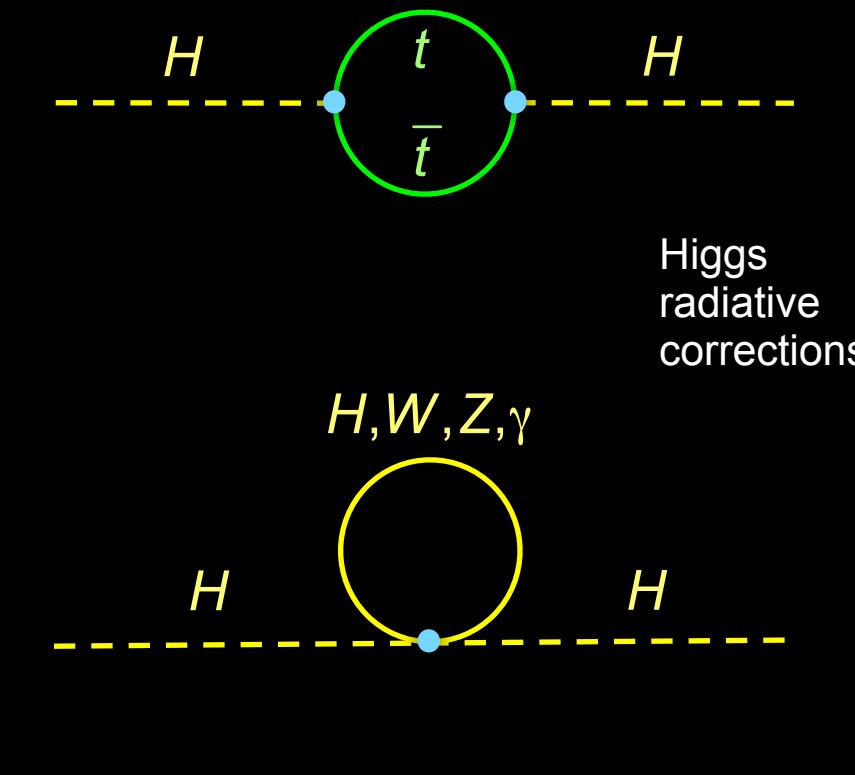
Naturalness/Fine-tuning



3 Solutions to The Hierarchy problem

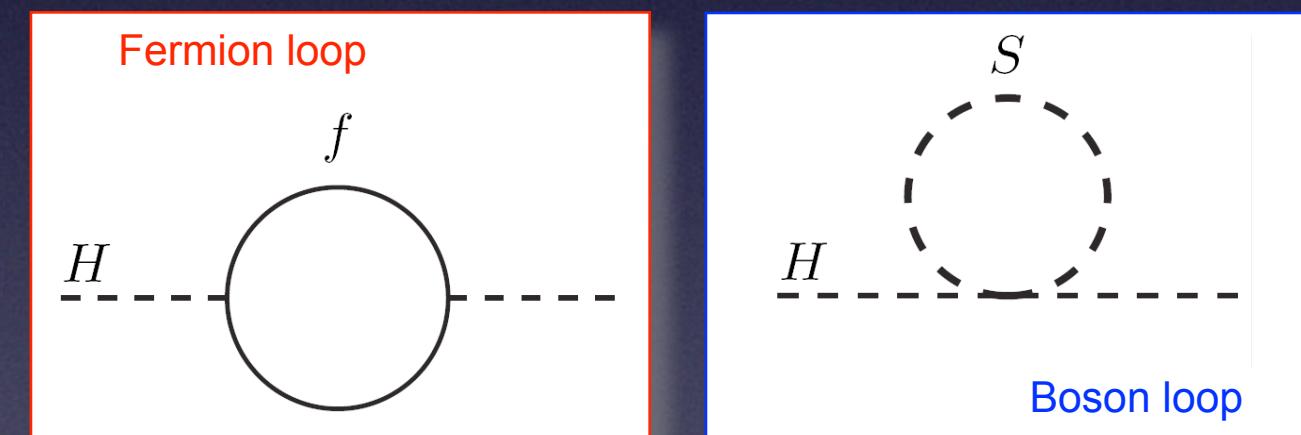
- Something new should show up around $\sim 1 \text{ TeV}$
- 3 classes of suggested possibilities:
 - Supersymmetry
 - Extra-dimensions
 - Additional sub-structure
- All predict new particles... usually partners to the Standard Model particles

SUSY and Hierarchy Problem



- Recall the mass of the Higgs is M_{GUT} or M_{PL} , because of “infinite” radiative corrections (ie loop diagrams) that are quadratic in cut-off Λ .

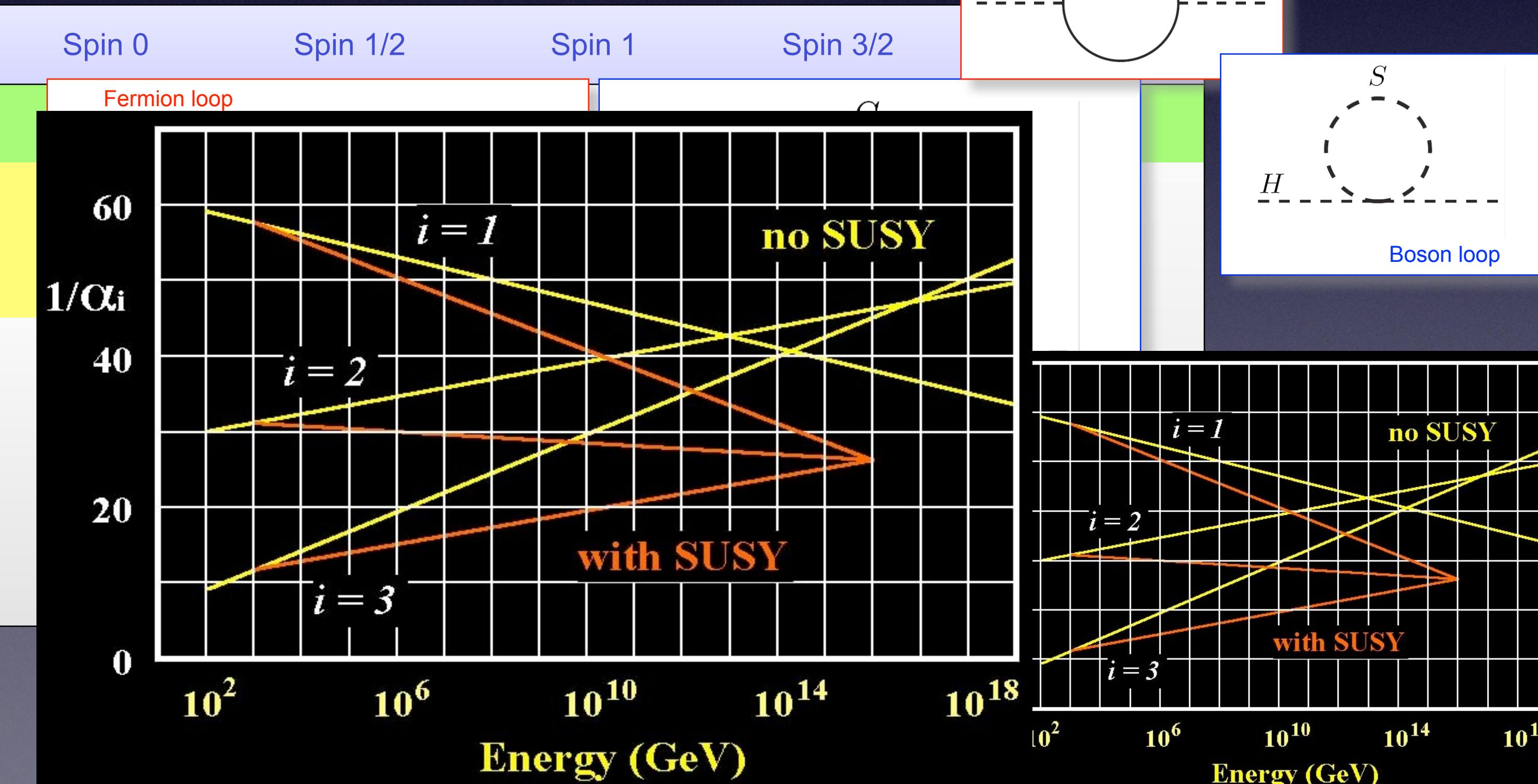
- What if for every such diagram, there existed another diagram, with opposite sign?
- Bosons/Fermions come with different signs
- A new space-time symmetry (extension of Poincare Group) results in a new boson for every fermion and visa-versa
- particle \rightarrow sparticle, gauge boson \rightarrow gaugino
- No scalar electron partner \Rightarrow SUSY broken
- Still keeps the Higgs mass low



u	d	e	ν_e
c	s	μ	ν_μ
t	b	τ	ν_τ
g	W	B	
H_1	H_2		
\tilde{u}_e	\tilde{e}	\tilde{d}	$\tilde{\nu}_e$
\tilde{d}_μ	$\tilde{\mu}$	\tilde{s}	$\tilde{\nu}_\mu$
\tilde{d}_τ	$\tilde{\tau}$	\tilde{b}	$\tilde{\nu}_\tau$
\tilde{B}	\tilde{W}	\tilde{g}	
\tilde{H}_2	\tilde{H}_1		

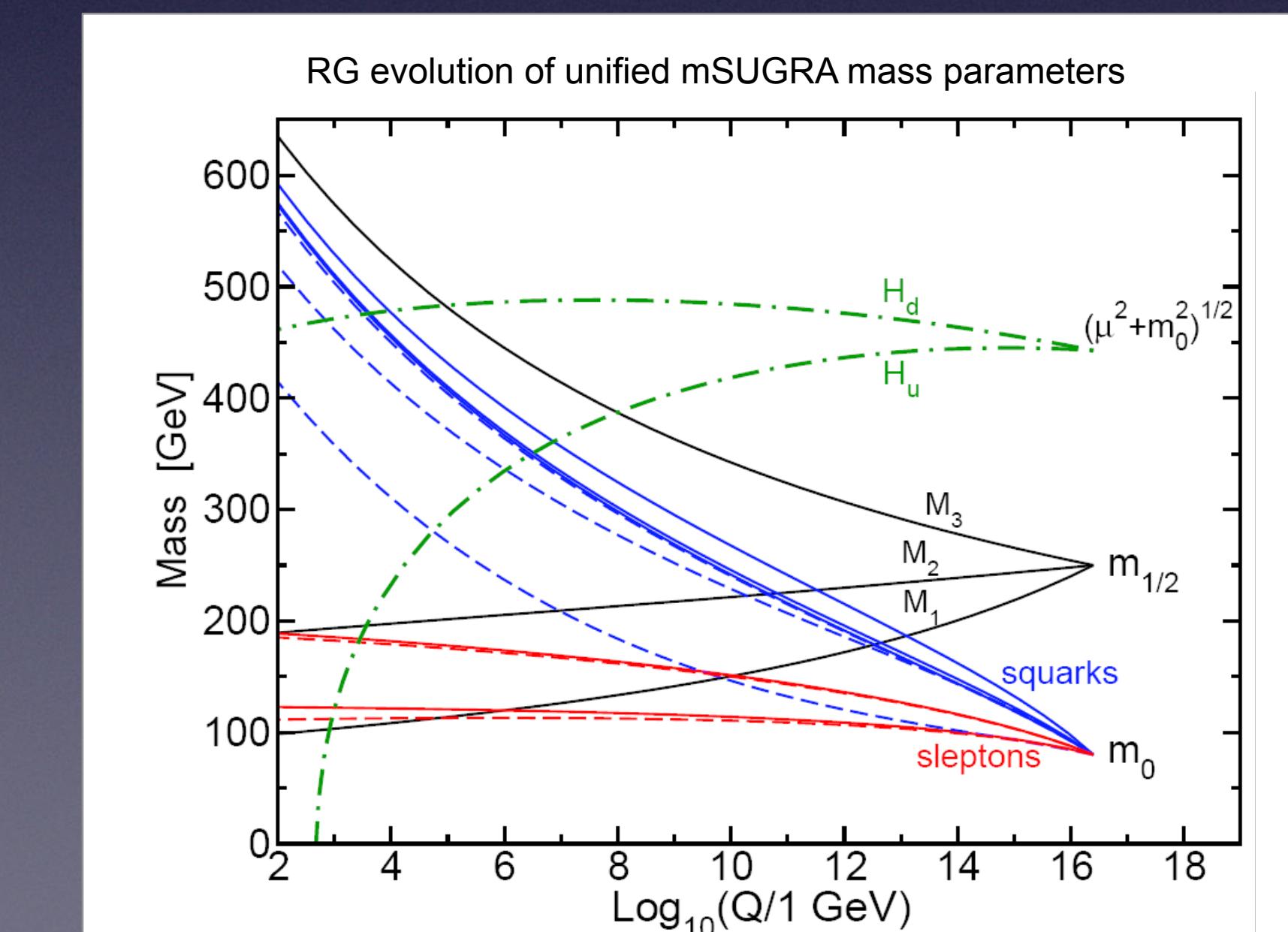
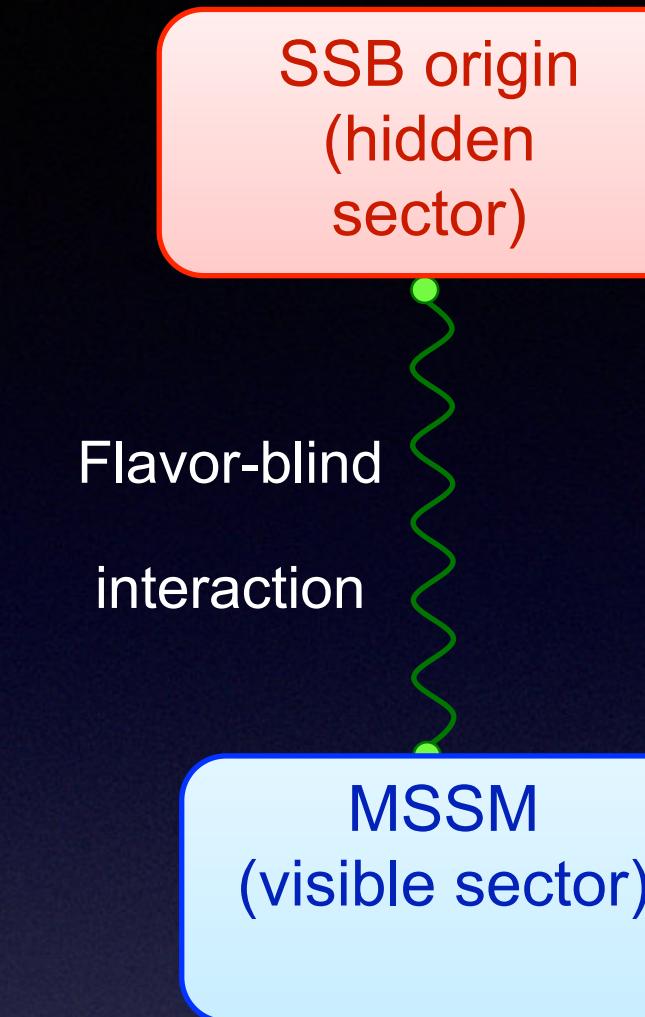
SUSY Motivation

- Aesthetic: new space-time symmetry
 - Leads to new partners for every SM particle.
 - Removes \rightarrow Resolves Higgs problem
 - Gauge unification
 - Has Gravitino
 - Dark matter can be a helion



SUSY Phenomenology

- No scalar electron partner \Rightarrow SUSY broken
- If want SUSY to preserve EW naturalness \Rightarrow SUSY broken in hidden sector at scale $F < M_{Pl}$
- SUSY has 105 parameters...
- Some SUSY Breaking Models take parameters to a practical handful, example:
 - Minimal Gravity Mediated (mSUGRA): m_0 , $m_{1/2}$, $\text{sig}(\mu)$, $\tan \beta$, A_0
 - \rightarrow Just a useful framework for searches
- R-Parity = +|-(-) for SM (SUSY) particles
 - RPC: no proton decay, dark matter (LSP), SUSY produced in pairs
 - RPV: Lose MET signature... wide-array of couplings (production) in different models

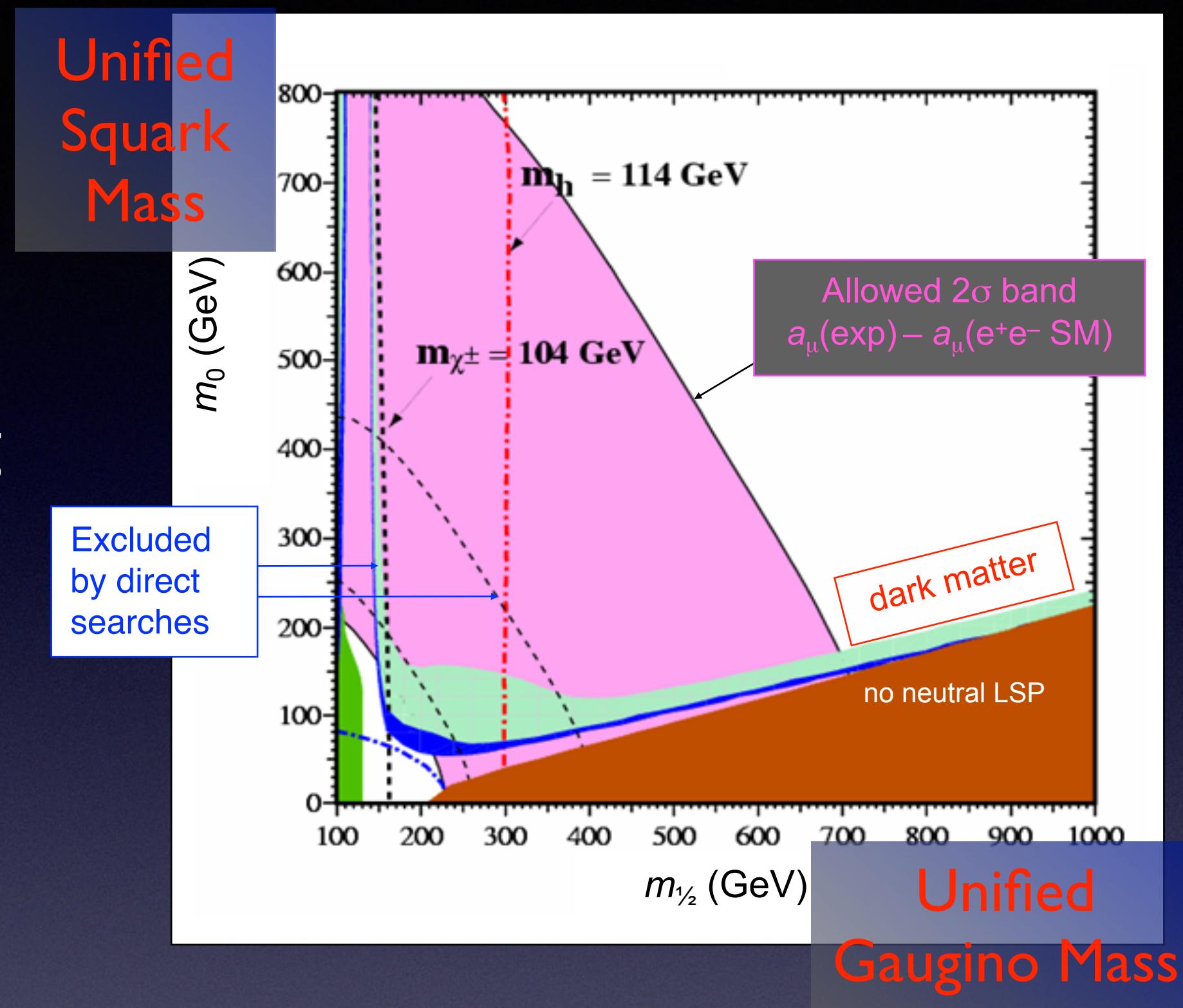


SUSY Models

- Many, many models of what SUSY could look like.
- Most common models focus on big signals at early LHC.
- 3 Typical Assumptions
 1. In any process, the number of superpartners can only change by an even number
 2. The lightest superpartner [which is stable, by assumption 1] is a superpartner of a particle we know (eg neutralino which is the partner of photon/Z)
 3. The superpartners that are affected by the strong nuclear force are significantly heavier than the other superpartners of known particles

Looking for SUSY

- Constraints on SUSY come from:
 - From cosmology: cold dark matter density
 - Direct Accelerator Searches: looking for sparticles
 - Indirect Accelerator Searches:
 - Precision Electroweak: W mass, weak mixing angle
 - Anomalous magnetic moment of muon ($g-2$)
 - Studying flavor-changing neutral currents: eg $b \rightarrow s\gamma$
 - mSUGRA's five parameters are very constraining...

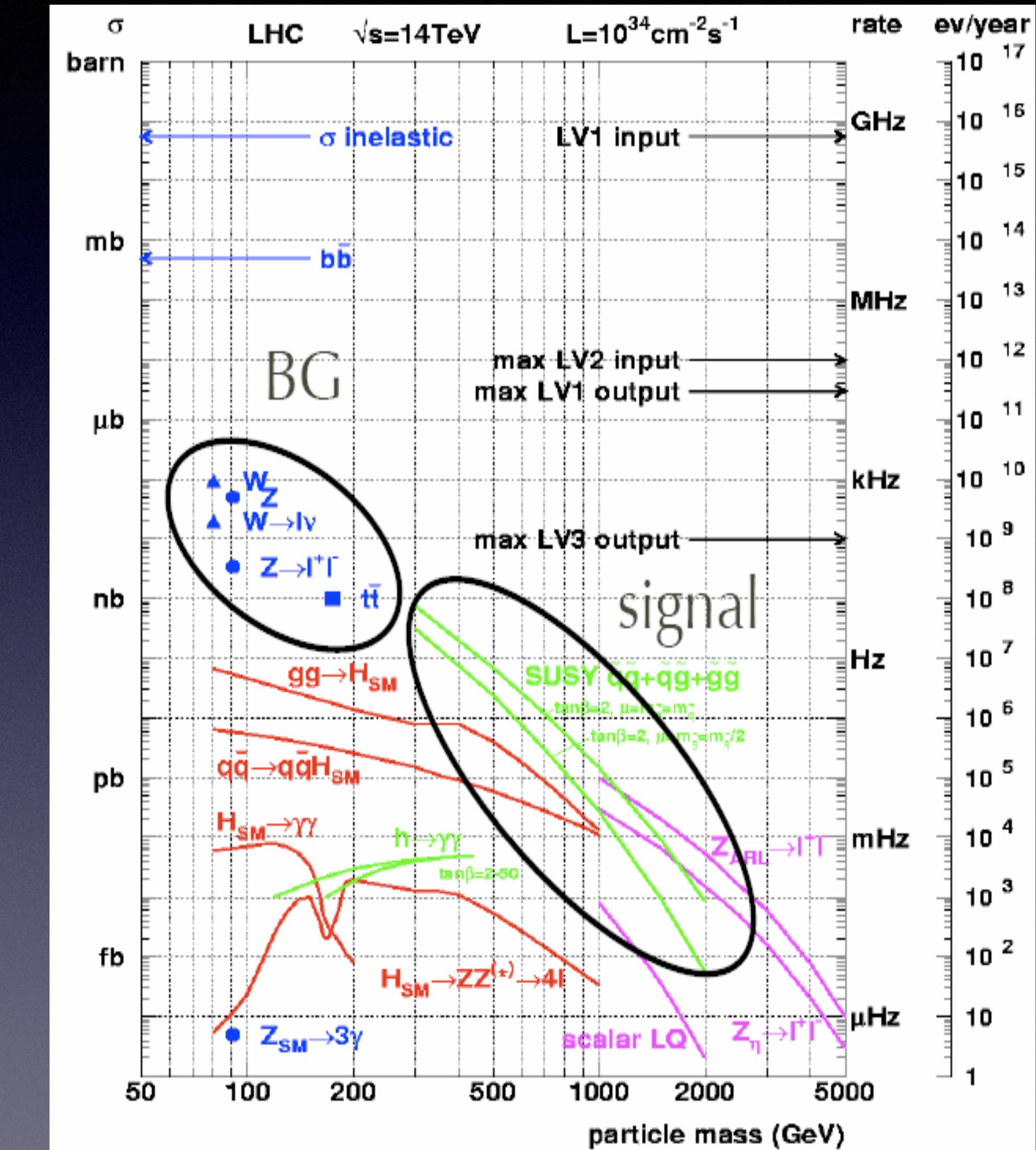


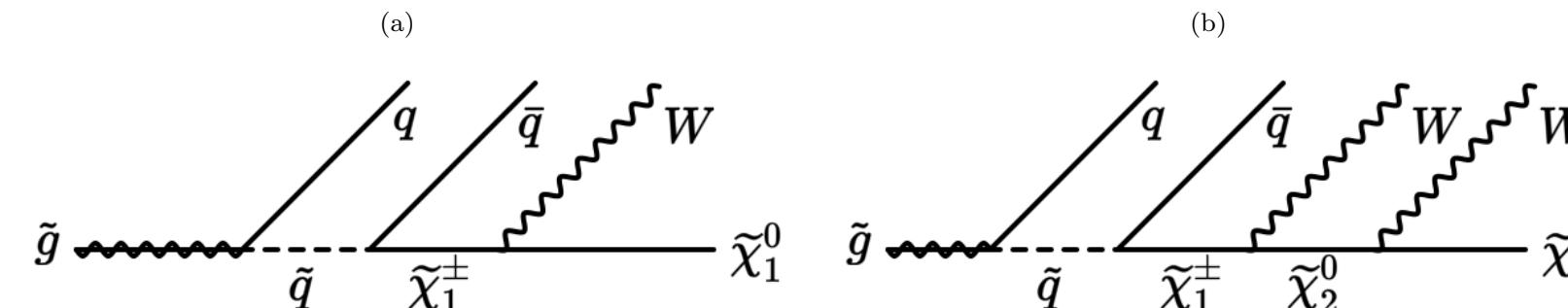
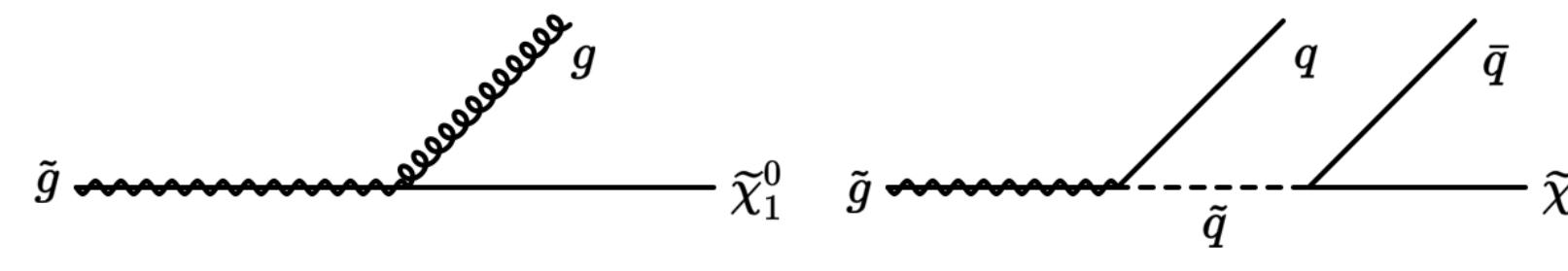
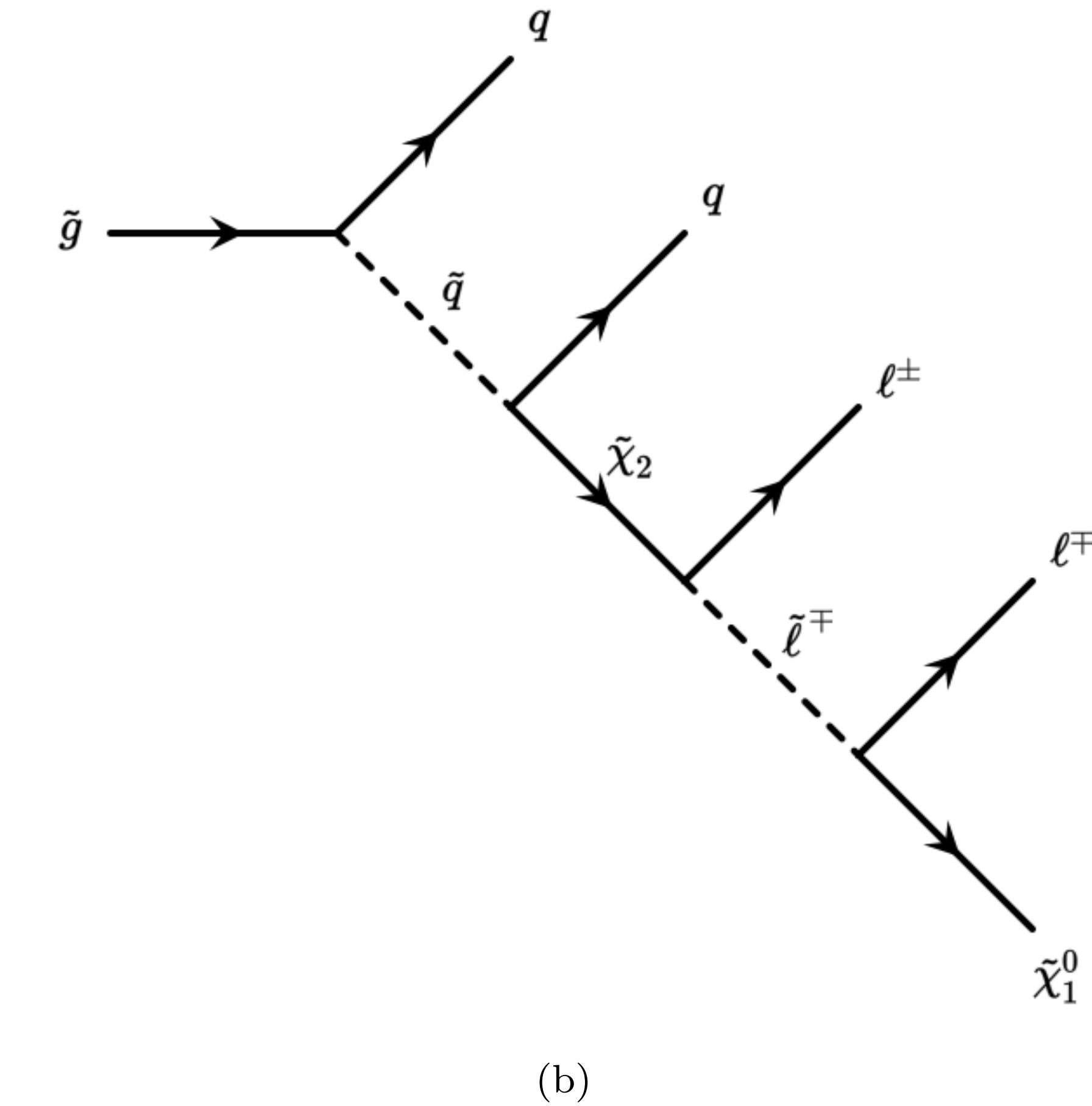
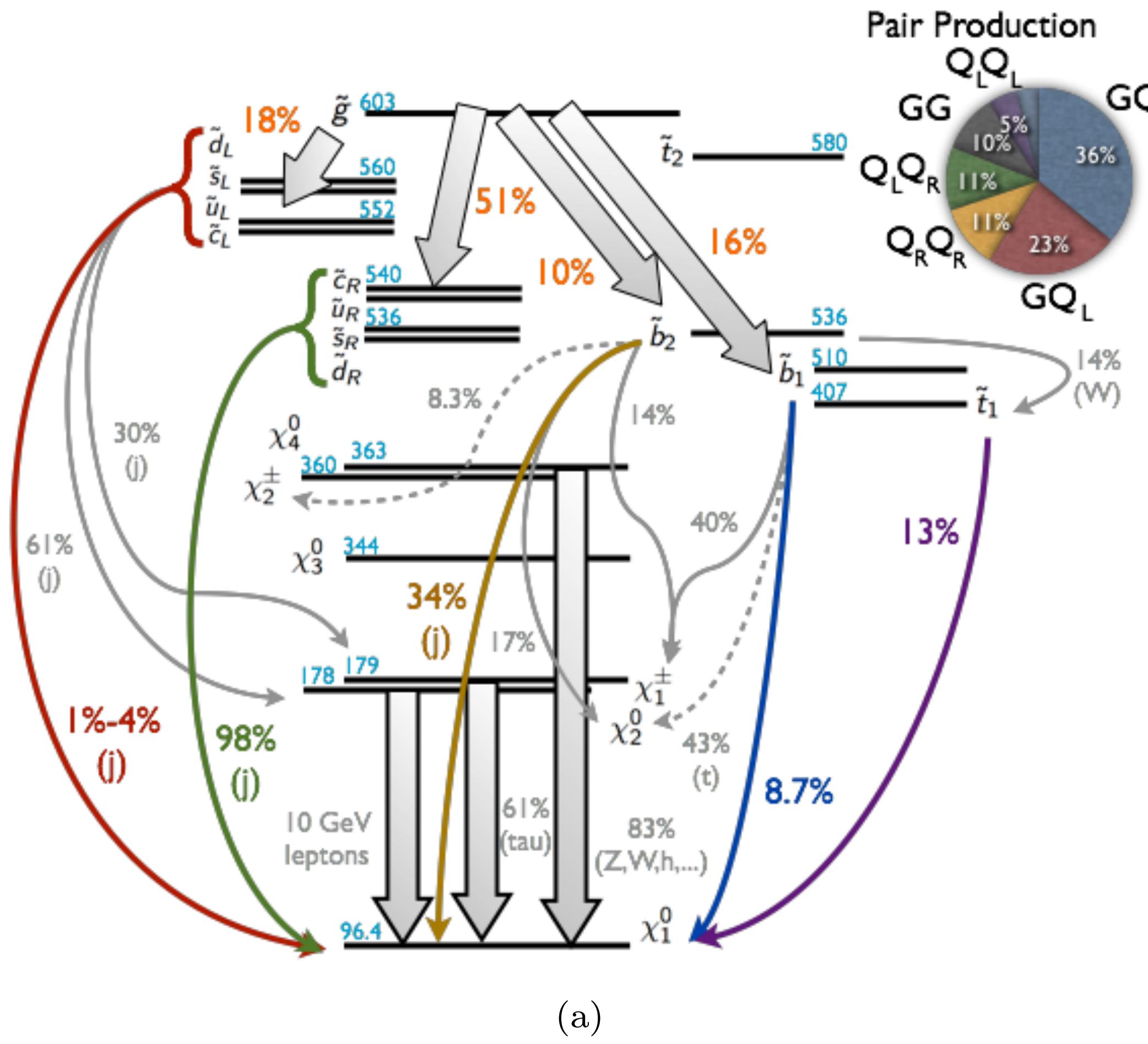
Looking for SUSY

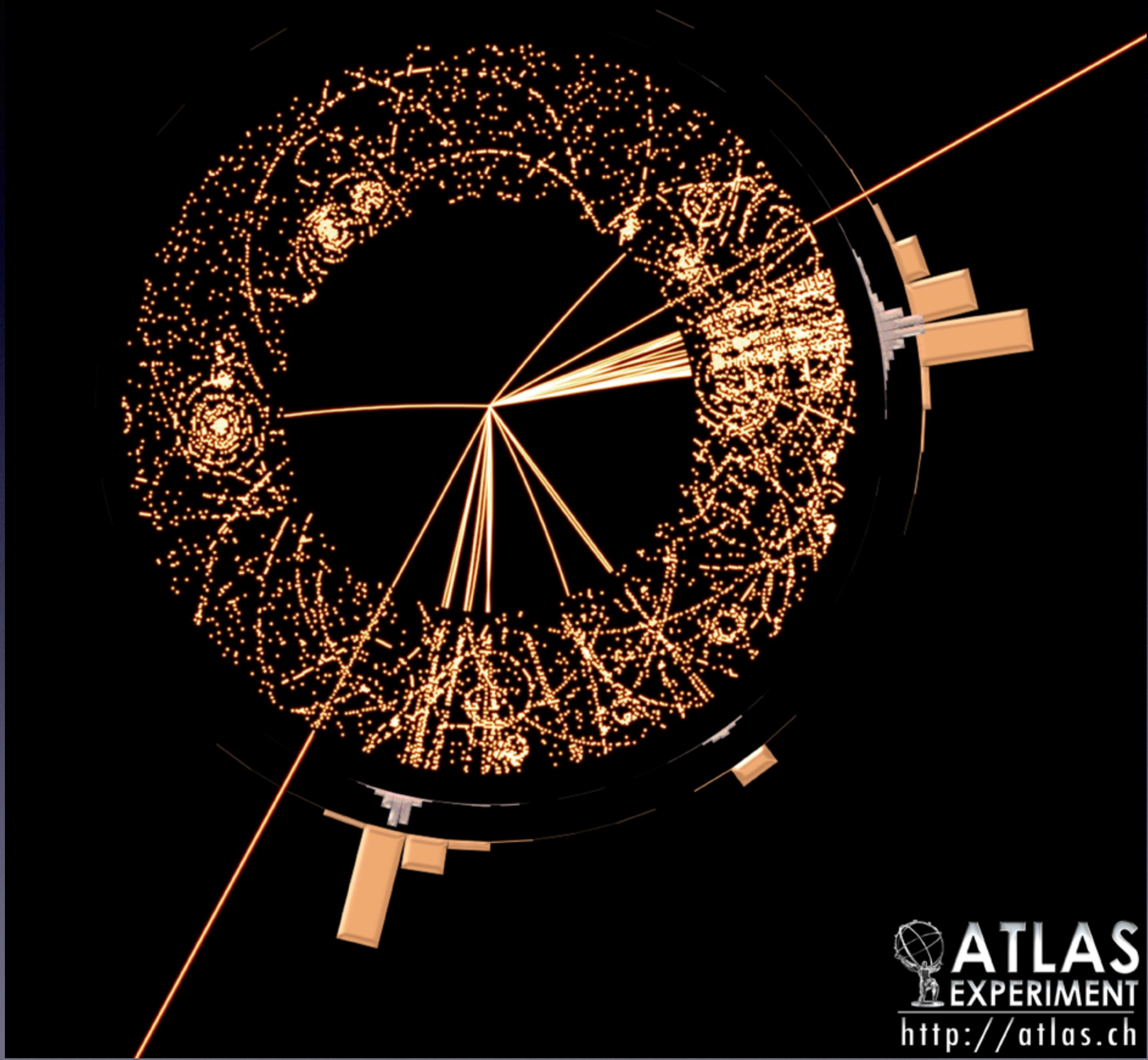


Signal vs Background

- 40 Million collisions a second
- 50 interactions per collision
- Interesting stuff (signal) is ~ 1 in a trillion
- The rest is background



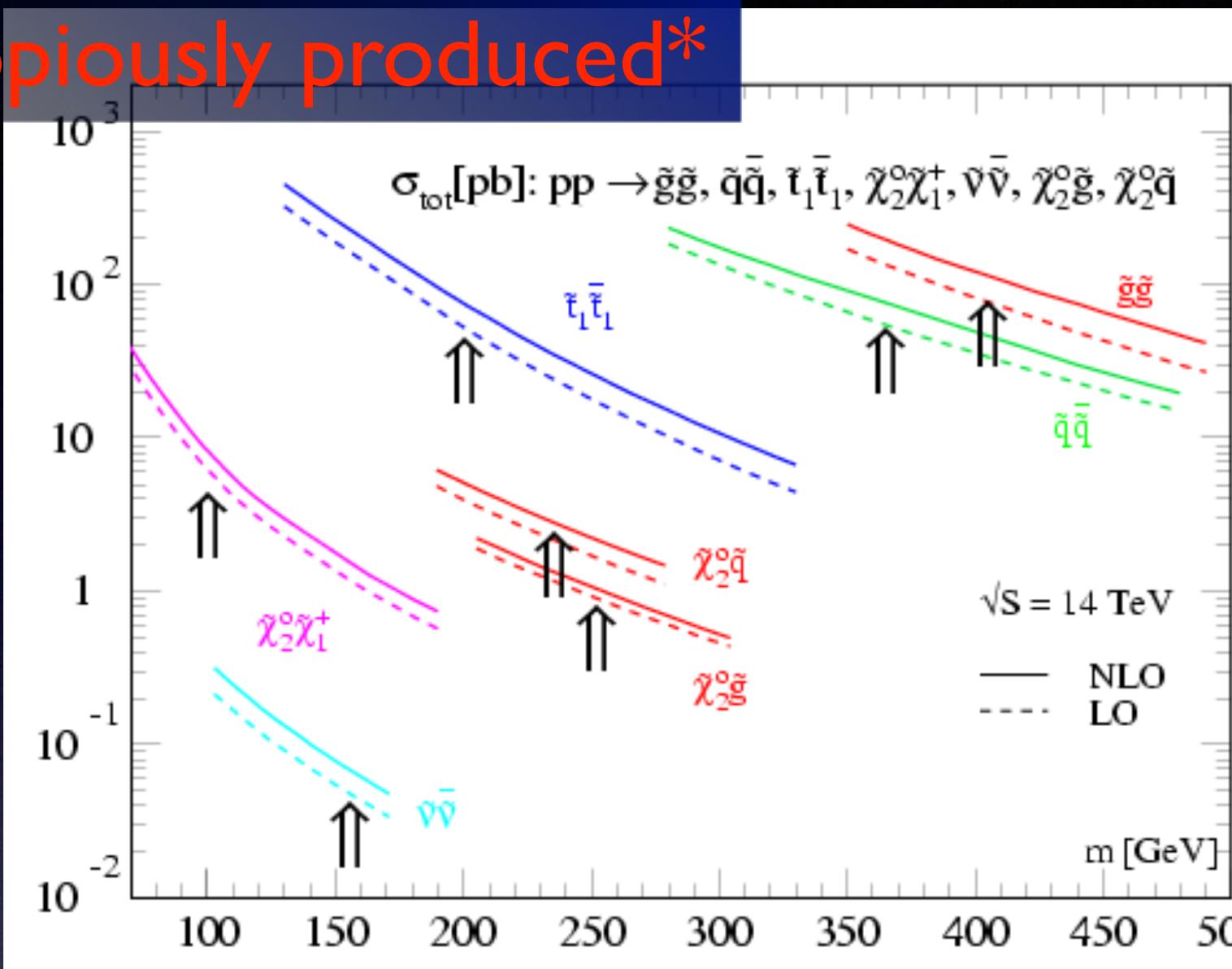




 **ATLAS**
EXPERIMENT
<http://atlas.ch>

SUSY at LHC

Gluinos and squarks
copiously produced*



GMSB

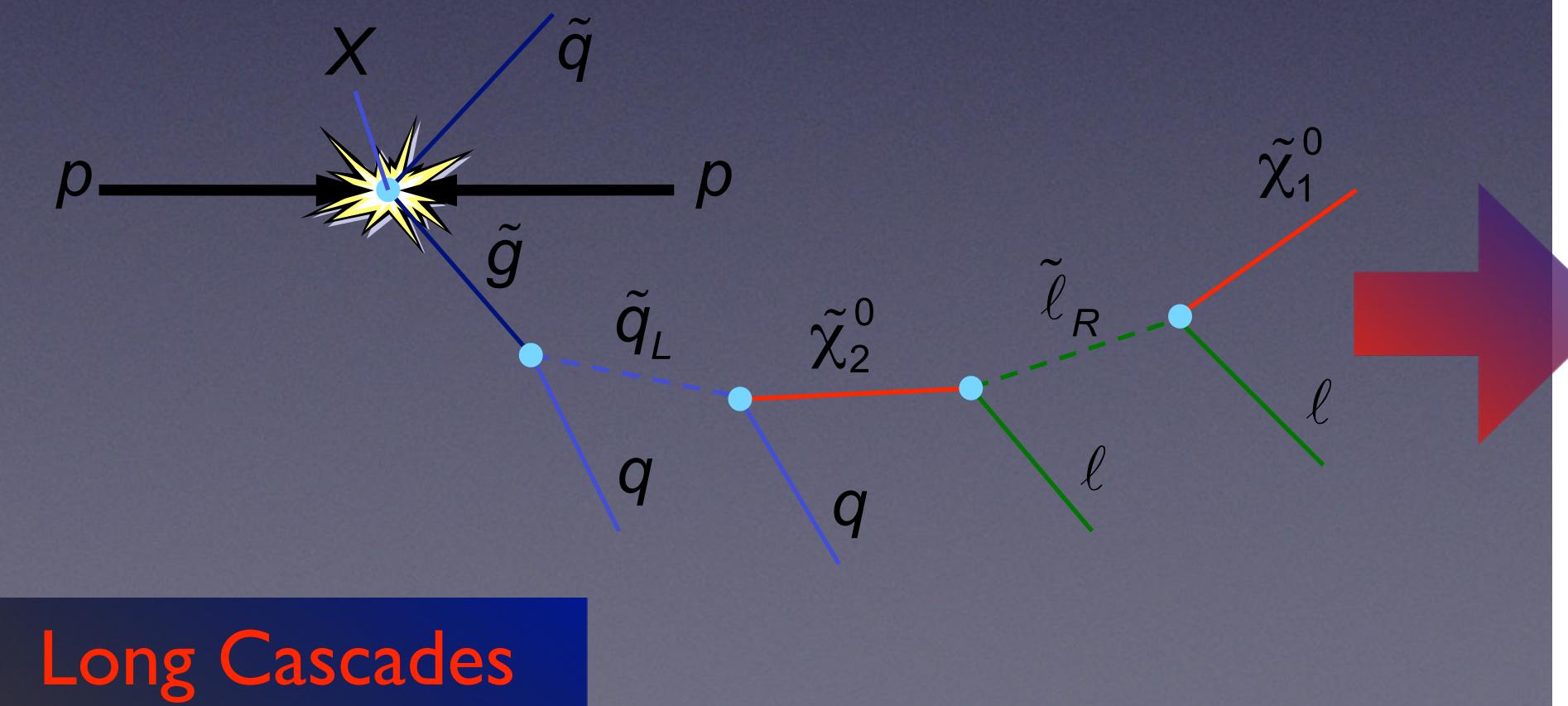
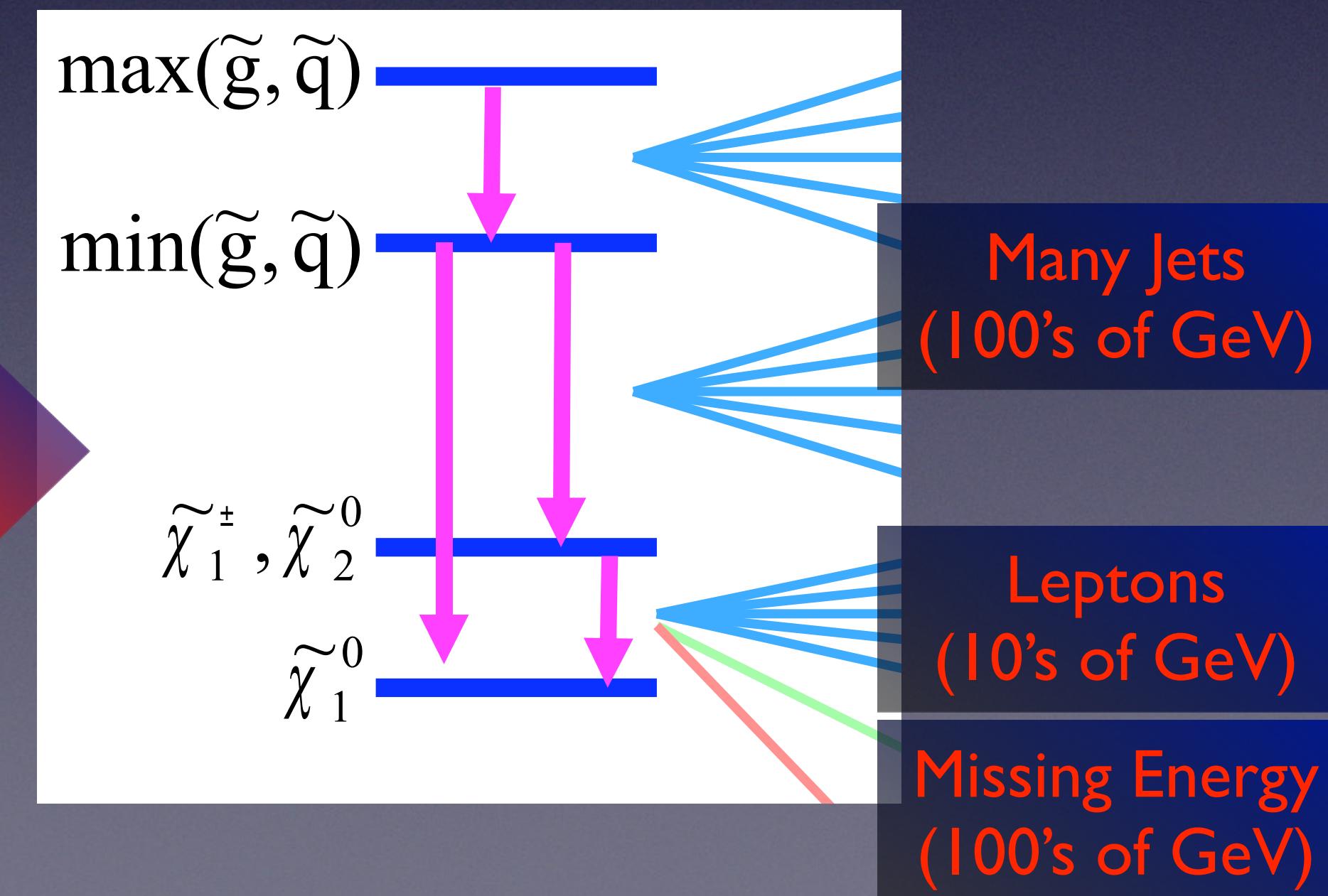
AMSB

$$\frac{H^\pm}{H^0 A^0} = \frac{\tilde{N}_4}{\tilde{N}_3} = \frac{\tilde{C}_2}{\tilde{C}_1}$$

mSUGRA

$$\frac{H^\pm}{H^0 A^0} = \frac{\tilde{N}_4}{\tilde{N}_3} = \frac{\tilde{N}_4}{\tilde{N}_2} = \frac{\tilde{N}_4}{\tilde{N}_1}$$

Gluinos and squarks
heavier than charginos/
neutralinos



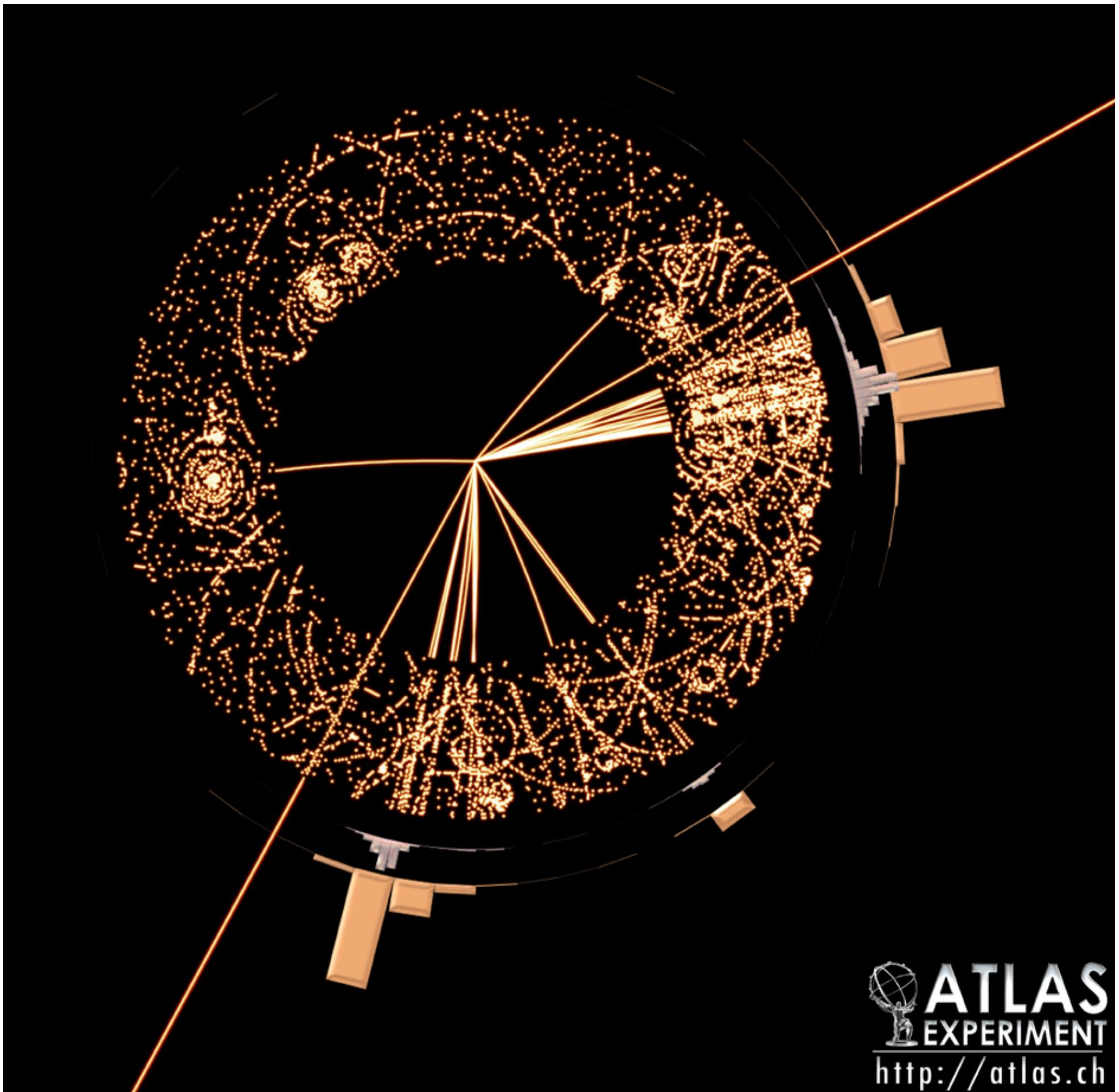
Inclusive Signatures

Signature	Motivating Model(s)	Comments
1 Jet + 0 Lepton + MET	<ul style="list-style-type: none"> • Large Extra Dim (ExoGraviton) <ul style="list-style-type: none"> • strong qG production, G propagate in extra Dim • Planck Scale is MD in 4+δ dim • Normal Gravity $\gg R$ • SUSY <ul style="list-style-type: none"> • $qg \rightarrow \text{ISR} + 2 \text{ Neutralino or squark} + \text{Neutralino}$ 	<ul style="list-style-type: none"> • Not primary discovery channel for SUGRA, GMSB, AMSB... but helps in characterization • Possible leading discovery for neutralino NLSP with nearly degenerate gluino
2,3,4 [b]-Jet + 0 Lepton + MET	<ul style="list-style-type: none"> • Squark/gluino production • squark $\rightarrow q + \text{LSP}$, gluino $\rightarrow q + \text{squark} + \text{LSP}$ 	<ul style="list-style-type: none"> • Possible leading squark/gluino discovery channel • Must manage QCD bkg
2,3,4 [b]-Jet + 1 Lepton + MET	<ul style="list-style-type: none"> • squark/gluino production with cascades which include electroweak (or partner) decays • high $\tan \beta$ leads to more b/t/T's 	<ul style="list-style-type: none"> • Lepton requirement suppresses QCD • T's partially covered by e/μ
2 lepton + MET	<ul style="list-style-type: none"> • Same sign: gluino cascade can have either sign lepton... squark/gluino prod can produce same sign. • Opposite sign: squark/gluino decay mediated by Z (or partner) • Same flavor: 2 leptons from same sparticle cascade must be same flavor 	<ul style="list-style-type: none"> • Reduced SM backgrounds for same sign • Opposite Sign-Flavor Subtraction
3 lepton + MET	<ul style="list-style-type: none"> • SUSY events ending in Chargino/neutralino pair decays • Weak Chargino/Neutralino production • Exotic sources 	<ul style="list-style-type: none"> • Low SM bkg
2 photon + MET	<ul style="list-style-type: none"> • GMSB models with gravitino LSP and neutralino or stau NLSP • UED- each KK partons cascade to LKP which decays to graviton + γ 	<ul style="list-style-type: none"> • No SUSY limit (not sensitive at the time)

SUSY/Higgs Data

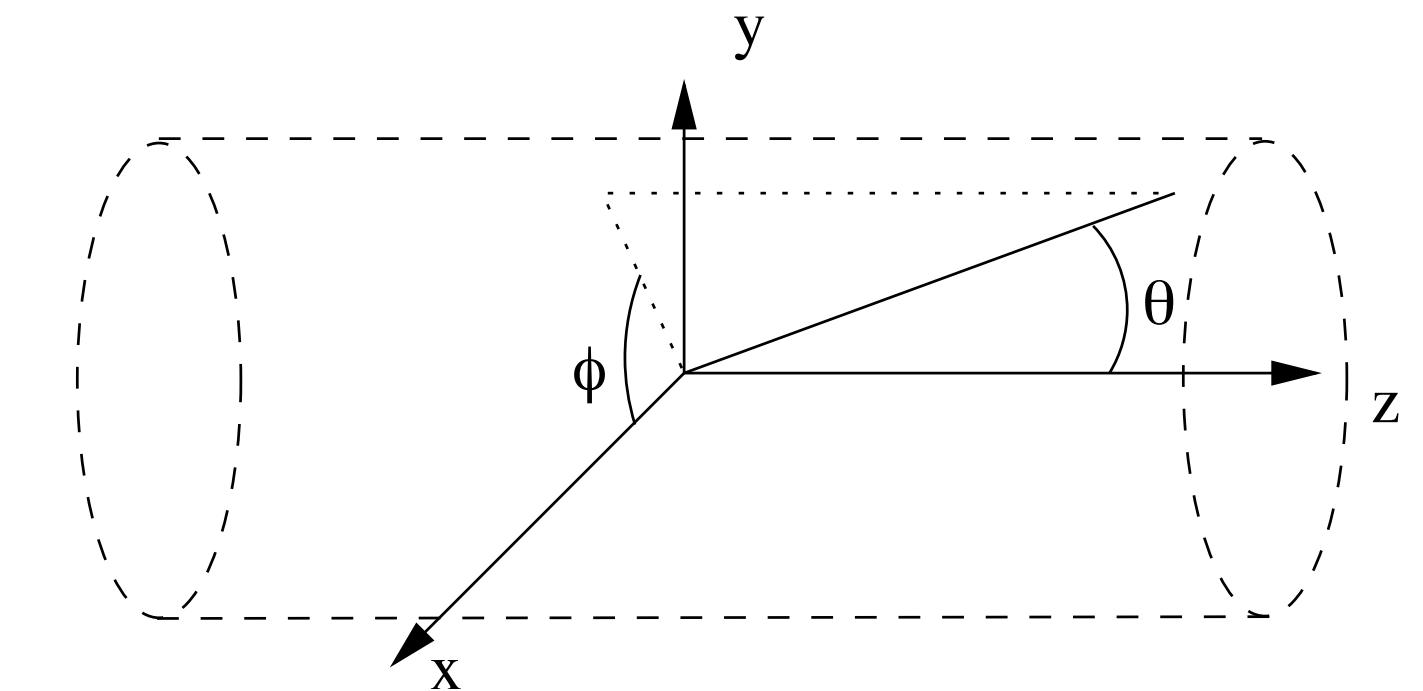
LHC Event

- The trigger LHC data is reconstructed into particle candidates.
 - Reconstruction algorithms try to find, identify, and measure particles
 - Typically there is one set of algorithms for each type of particle (corresponding to unique way the particle interacts with detector). For example:
 - *electron / photon*: Look tight deposits of energy in Electromagnetic Calorimeter. If a charged track points to it → electron otherwise photon.
 - *muon*: find track segment in inner detector and outer muon tracker.
 - *jets*: Look for broad deposits of energy in the Hadronic Calorimeter.
 - Not exclusive: Most electrons get also reconstructed as jet.
 - A process of Particle Identification and Overlap removal attempts to associate energy deposits in the detector with one unique hypothesis (as best as possible).
- Therefore the data and simulated data for an analysis will be processed up to a level where every event consists of:
 - List of particle candidates, each with their momenta: electrons, photons, muons, jets (+ b-tagging), tau-jets, ...
 - Event level quantities: missing energy



LHC Events

- Candidate variables:
 - For each candidate, we measure it's 3-vector in a coordinate system best suited for Hadron Colliders.
 - Reflects the fact that not all of energy of beam goes into collision → can only apply energy conservation transverse to the beam.
 - $(p_x, p_y, p_z) \rightarrow (p_T, \eta, \phi)$
 - Once you choose what to call a particle, then you can assume a mass and turn your 3-vector → 4-vector
 - Event Variables: Missing transverse energy (magnitude and direction in transverse plane (ϕ))
 - In this context, by raw features we mean these 4-vector and event variables.



$$p_T^2 \equiv p_x^2 + p_y^2$$
$$\vec{p}_T \equiv \vec{p} \sin \theta$$
$$\eta \equiv \frac{1}{2} \ln \frac{1 + \cos \theta}{1 - \cos \theta}$$
$$= -\ln \left(\tan \frac{\theta}{2} \right)$$

$$E_T^2 \equiv p_T^2 + m^2$$
$$= E^2 - p_z^2$$

Data Sample

- SUSY Data: (Selected events with only 2 leptons)
 - “signal”: The truth. 1 = signal. 0 = background.
 - 2 leptons: "l_1_pT", "l_1_eta", "l_1_phi", "l_2_pT", "l_2_eta", "l_2_phi"
 - Missing energy: "MET", "MET_phi"
 - Features: "MET_rel", "axial_MET", "M_R", "M_TR_2", "R", "MT2", "S_R", "M_Delta_R", "dPhi_r_b", "cos_theta_r1"
- Higgs Data: (Selected events with 1 lepton and 4 jets)
 - lepton pT, lepton eta, lepton phi
 - missing energy magnitude, missing energy phi,
 - jet 1 pt, jet 1 eta, jet 1 phi, jet 1 b-tag,
 - jet 2 pt, jet 2 eta, jet 2 phi, jet 2 b-tag,
 - jet 3 pt, jet 3 eta, jet 3 phi, jet 3 b-tag,
 - jet 4 pt, jet 4 eta, jet 4 phi, jet 4 b-tag,
 - Features: m_jj, m_jjj, m_lv, m_jlv, m_bb, m_wbb, m_wwbb.

High Level Features

- In this context, high-level features mean observables that are calculable from the 4-vectors.
 - Generally motivated by physics.
- For example: if you are expecting your signal and/or background events to include particles that are the decay products of a heavy particle,
 - you can attempt to identify the decay products and compute the mass of the heavy particle.
 - W bosons decays to 2 jets (m_{jj}), 3 jets (m_{jjj}), lepton+neutrino ($m_{l\nu}$), lepton+jet+neutrino ($m_{j\nu l}$), or 2 b-jets (m_{bb})
 - Top quark decays into $W + 2$ b-jets (m_{wbb})
 - These are an attempt to *exclusively* reconstruct W and top particles.
 - Exclusive: look for a specific particle by pull together *all* of the decay particles
- Another example: if you expect your signal and/or background events to consist of various types of particles with common traits,
 - you can attempt to construct features that capture the trait:
 - SUSY particles are heavy, therefore sum of the momenta of their decay products is large.
 - In SUSY, the last particle in the decay chain is not detected → large missing energy that isn't a fluctuation (e.g. same direction as a jet).
 - particles in SUSY events are more broadly distributed → “spherical” rather than “jetty” events.

$$H_T(n) \equiv \sum_{i=1}^n p_{ji,T} \quad M_{eff} \equiv H_T(4) + \sum_{k=1}^m p_{\ell k,T} + E_T^{miss}$$