

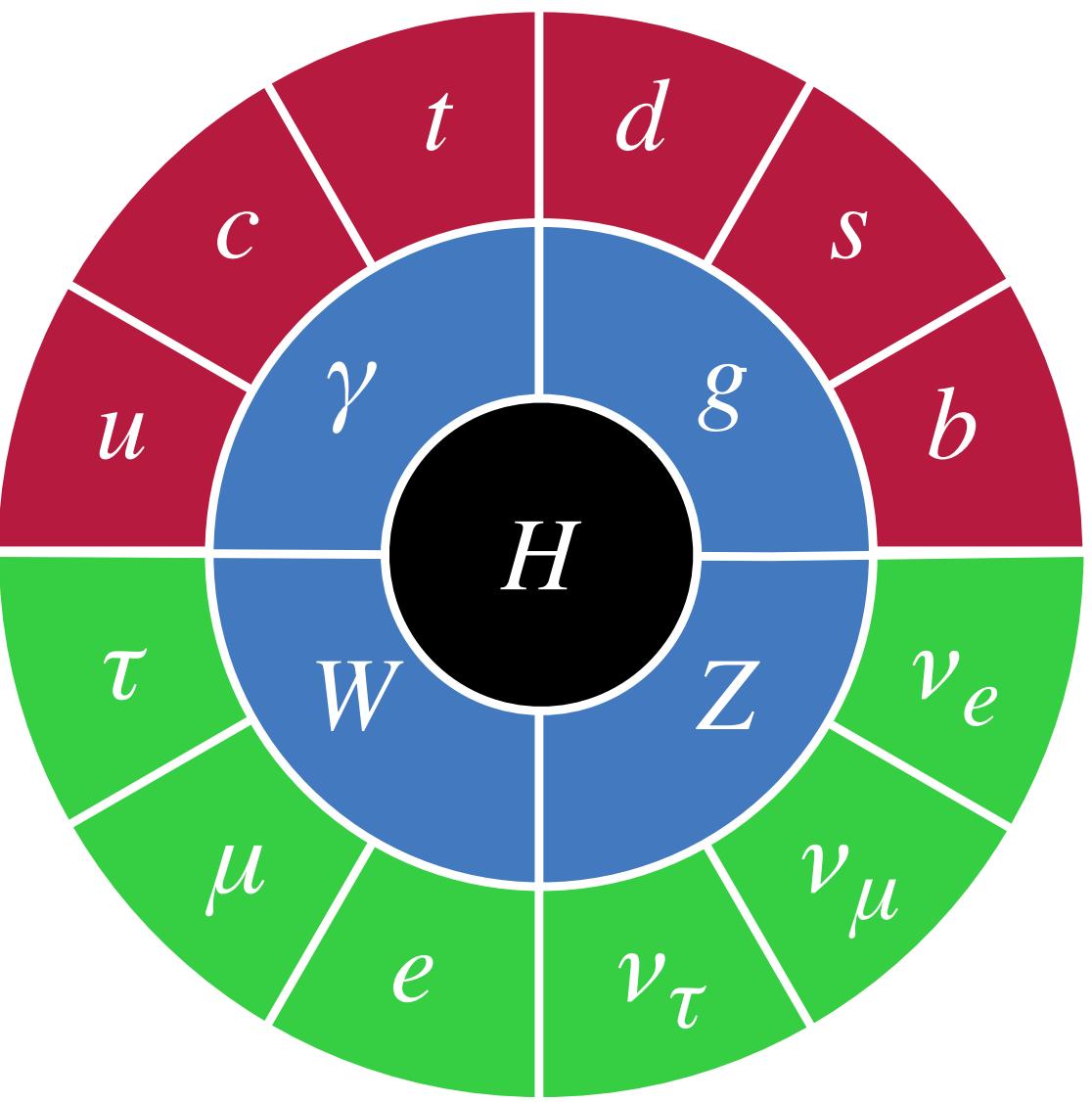
# **Python for Data Science 2**

**Lab 7- SUSY at LHC**

**Amir Farbin**

# 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
$m_\mu$	Muon mass	105.7 MeV
$m_\tau$	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
$\theta_{12}$	CKM 12-mixing angle	13.1°
$\theta_{23}$	CKM 23-mixing angle	2.4°
$\theta_{13}$	CKM 13-mixing angle	0.2°
$\delta$	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
$\theta_{QCD}$	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, ...

Leptons		spin = 1/2	
Flavor	Mass GeV/c <sup>2</sup>	Electric charge	Approx. Mass GeV/c <sup>2</sup>
$\nu_e$ electron neutrino	<1x10 <sup>-8</sup>	0	
e electron	0.000511	-1	
$\nu_\mu$ muon neutrino	<0.0002	0	
$\mu$ muon	0.106	-1	
$\nu_\tau$ tau neutrino	0.02	0	
$\tau$ tau	1.7771	-1	

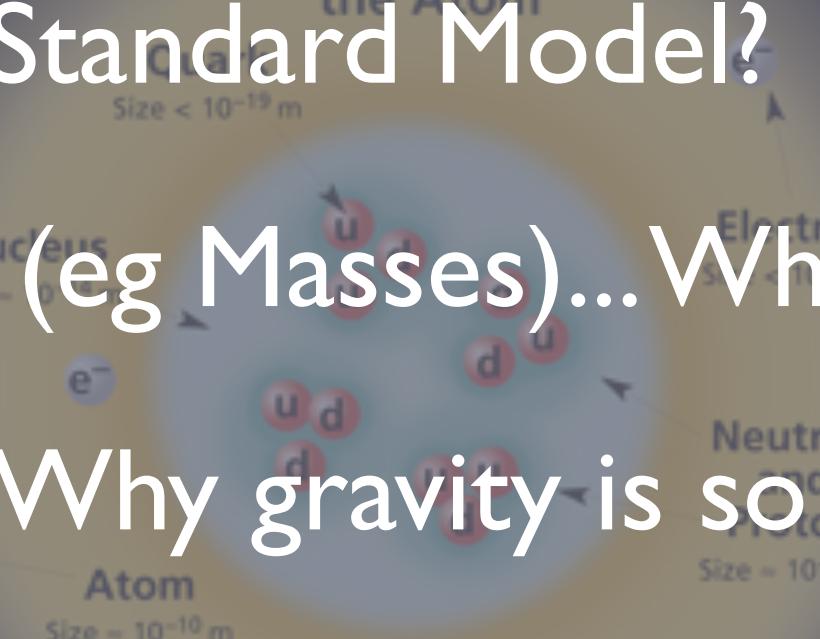
Spin is the intrinsic angular momentum of particles. Spin is given in units of  $\hbar$ , which is the quantum unit of angular momentum, where  $\hbar = h/2\pi = 6.58 \times 10^{-25}$  GeV s =  $1.05 \times 10^{-34}$  J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is  $1.60 \times 10^{-19}$  coulombs.

The energy unit of particle physics is the electron volt (eV), the energy gained by an electron in crossing a potential difference of one volt. Masses are given in GeV/c<sup>2</sup> (remember  $E = mc^2$ ), where 1 GeV =  $10^9$  eV =  $1.60 \times 10^{-10}$  joule. The mass of the proton is  $0.938$  GeV/c<sup>2</sup> =  $1.67 \times 10^{-27}$  kg.

- Why Look Beyond the Standard Model?
- Takes 19 parameters (eg Masses)... Why these values?
- 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.

## Structure within the Atom



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

## BOSONS

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

Unified Electroweak spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0
$W^+$	80.1	-1
$W^-$	80.4	+1
$Z^0$	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	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, and  $W$  and  $Z$  bosons.

Quarks Confined in Mesons and Baryons  
One cannot isolate quarks and gluons; they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among 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 interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

## PROPERTIES OF THE INTERACTIONS

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$			
Baryons are fermionic hadrons. There are about 120 types of baryons.			
Symbol	Name	Quark content	Electric charge
p	proton	uud	1
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1
n	neutron	udd	0
$\Lambda$	lambda	uds	1/2
$\Omega^-$	omega	sss	-1

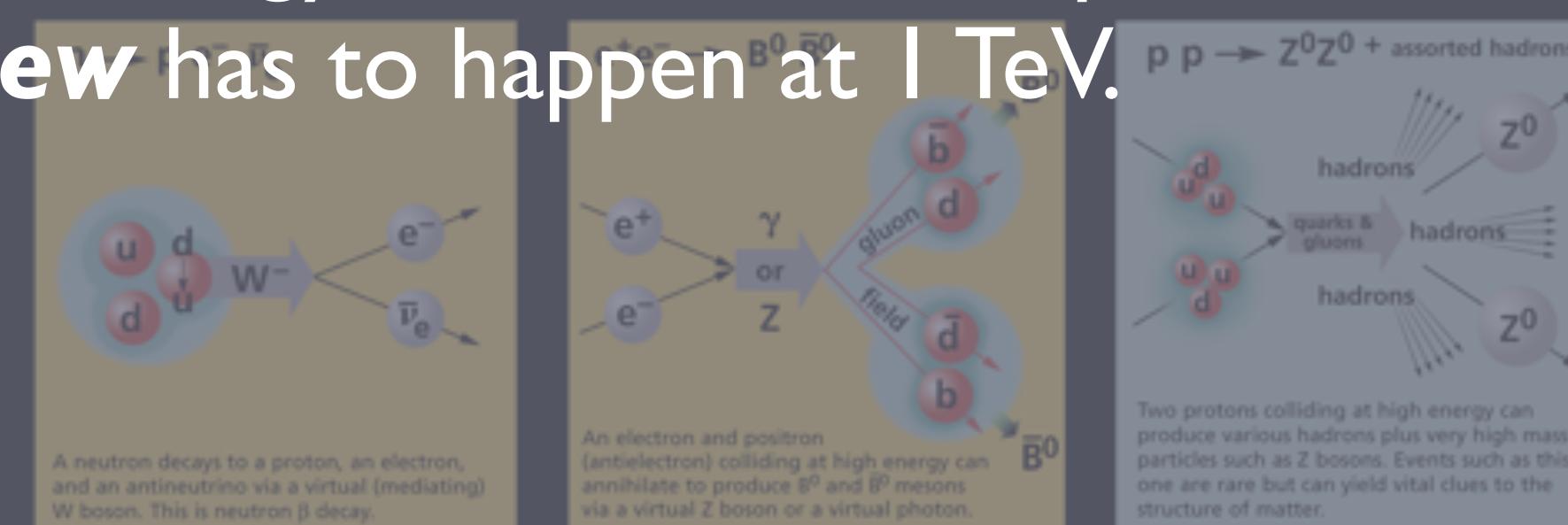
- Doesn't have enough asymmetry between matter/anti-matter to explain why we exist!

Matter and Antimatter  
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g.,  $Z^0$ ,  $\gamma$ , and  $\eta_c = cc\bar{s}$ , but not  $K^0 = d\bar{s}$ ) 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.

Interaction	Gravitational	Weak	Electromagnetic	Strong
Property	Action:	Flavor	Electric Charge	Color Charge
	Mass – Energy	Quarks, Leptons	Electrically charged	Quarks, Gluons
	Graviton (not yet observed)	$W^+$ $W^-$ $Z^0$	$\gamma$	Gluons
Particles experiencing:	All			Hadrons
Interactions involving:				Mesons
Strength relative to electromagnetism for two u quarks at:	$10^{-18}$ m	$10^{-41}$	0.8	25
for two d quarks at:	$3 \times 10^{-17}$ m	$10^{-41}$	1	60



Mesons q $\bar{q}$				
Mesons are bosonic hadrons. There are about 140 types of mesons.				
Symbol	Name	Quark content	Electric charge	Mass GeV/c <sup>2</sup>
$\pi^+$	pion	u $\bar{d}$	+1	0.140
$K^-$	kaon	s $\bar{u}$	-1	0.494
$\rho^+$	rho	u $\bar{d}$	+1	0.770
$\rho^0$	B	s $\bar{s}$	0	0.550
$\eta_c$	eta-c	c $\bar{c}$	0	2.980

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

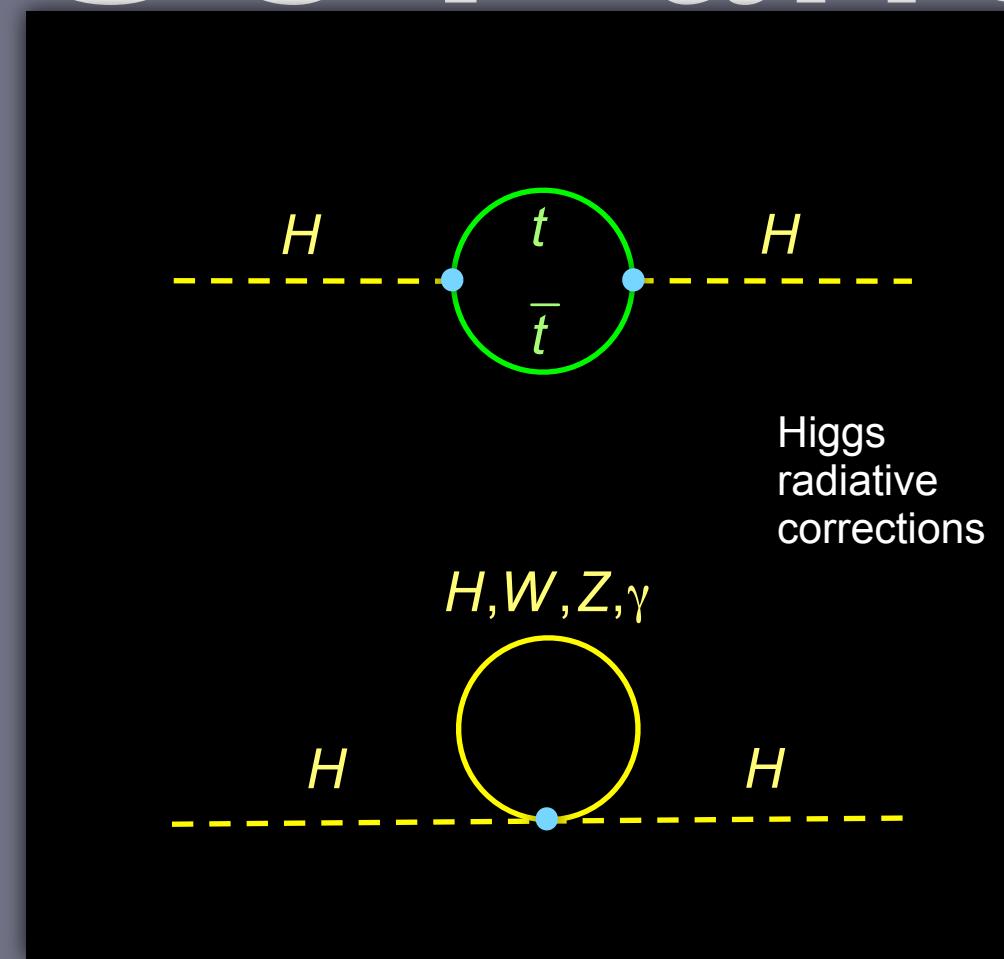
This chart has been made possible by the generous support of:  
U.S. Department of Energy  
U.S. National Science Foundation  
Lawrence Berkeley National Laboratory  
Stanford Linear Accelerator Center  
American Physical Society, Division of Particles and Fields  
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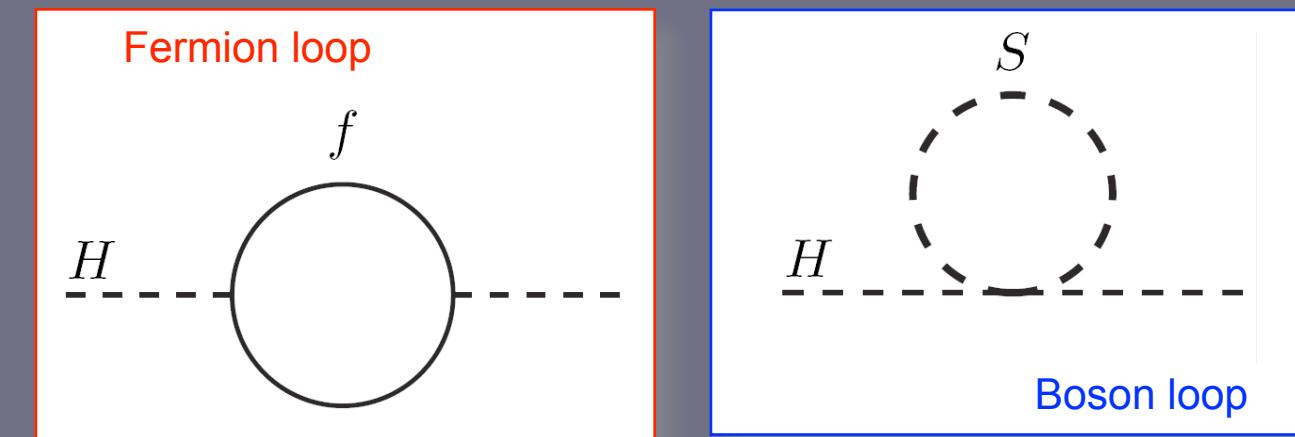
# Physics at the LHC

- Something new should show up around  $\sim 1$  TeV
  - Higgs, Higgs Mass Fine tuning, Dark Matter, Gauge Unification
- 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



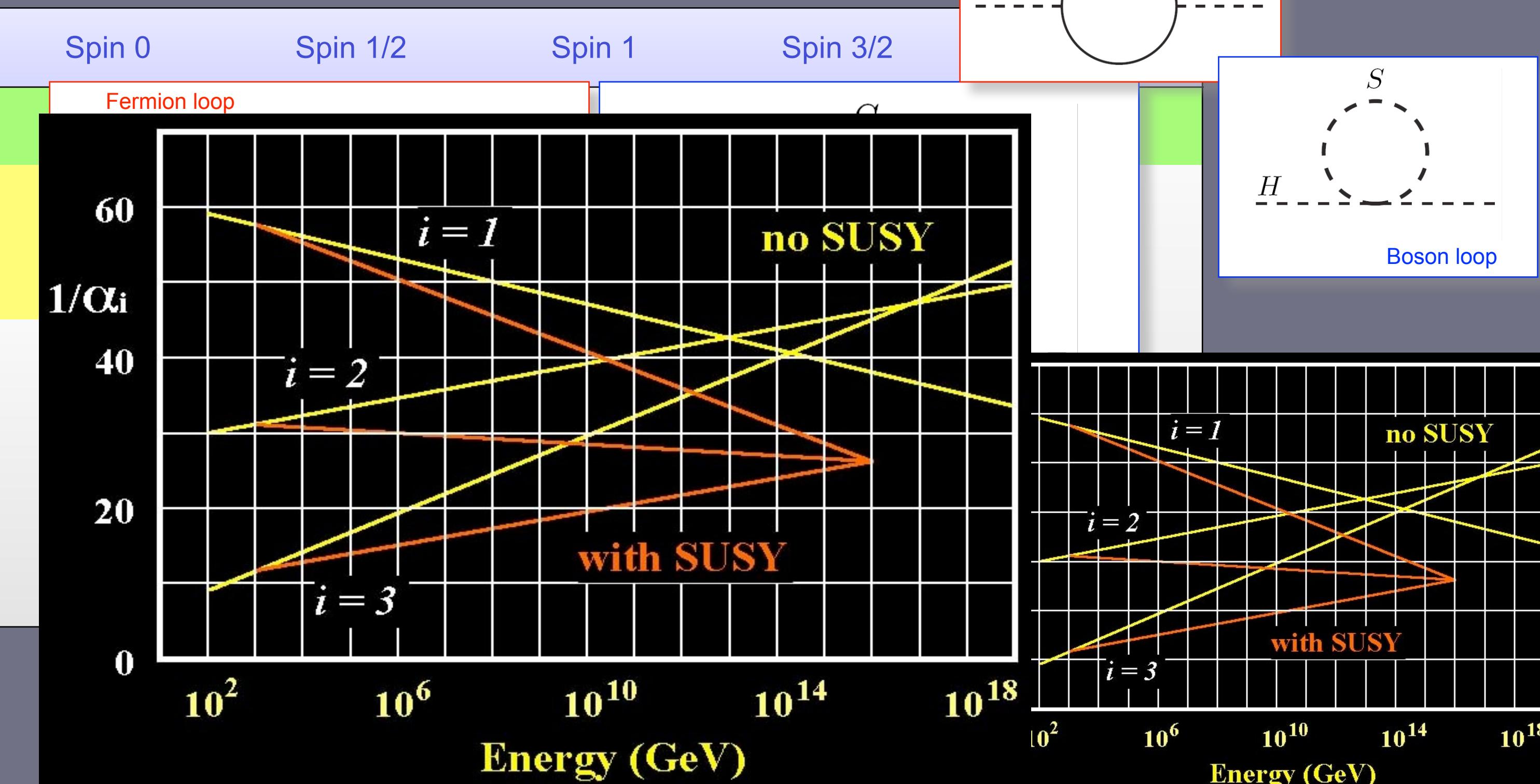
- Recall the mass of the Higgs is  $M_{\text{GUT}}$  or  $M_{\text{PL}}$ , because of “infinite” radiative corrections (ie loop diagrams) that are quadratic in cut-off  $\Lambda$ .
- What if for every such diagram, there existed another diagram, with opposite sign?
  - Bosons/Fermions come with different 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



$u$	$d$	$e$	$\nu_e$
$c$	$s$	$\mu$	$\nu_\mu$
$t$	$b$	$\tau$	$\nu_\tau$
$g$	$W$	$B$	
$H_1$	$H_2$		
$\tilde{u}_e$	$\tilde{e}$	$\tilde{d}$	$\tilde{\nu}_e$
$\tilde{d}_\mu$	$\tilde{\mu}$	$\tilde{s}$	$\tilde{c}$
$\tilde{b}_\tau$	$\tilde{\tau}$	$\tilde{b}$	$\tilde{t}$
$\tilde{B}$	$\tilde{W}$	$\tilde{g}$	
$\tilde{H}_2$	$\tilde{H}_1$		

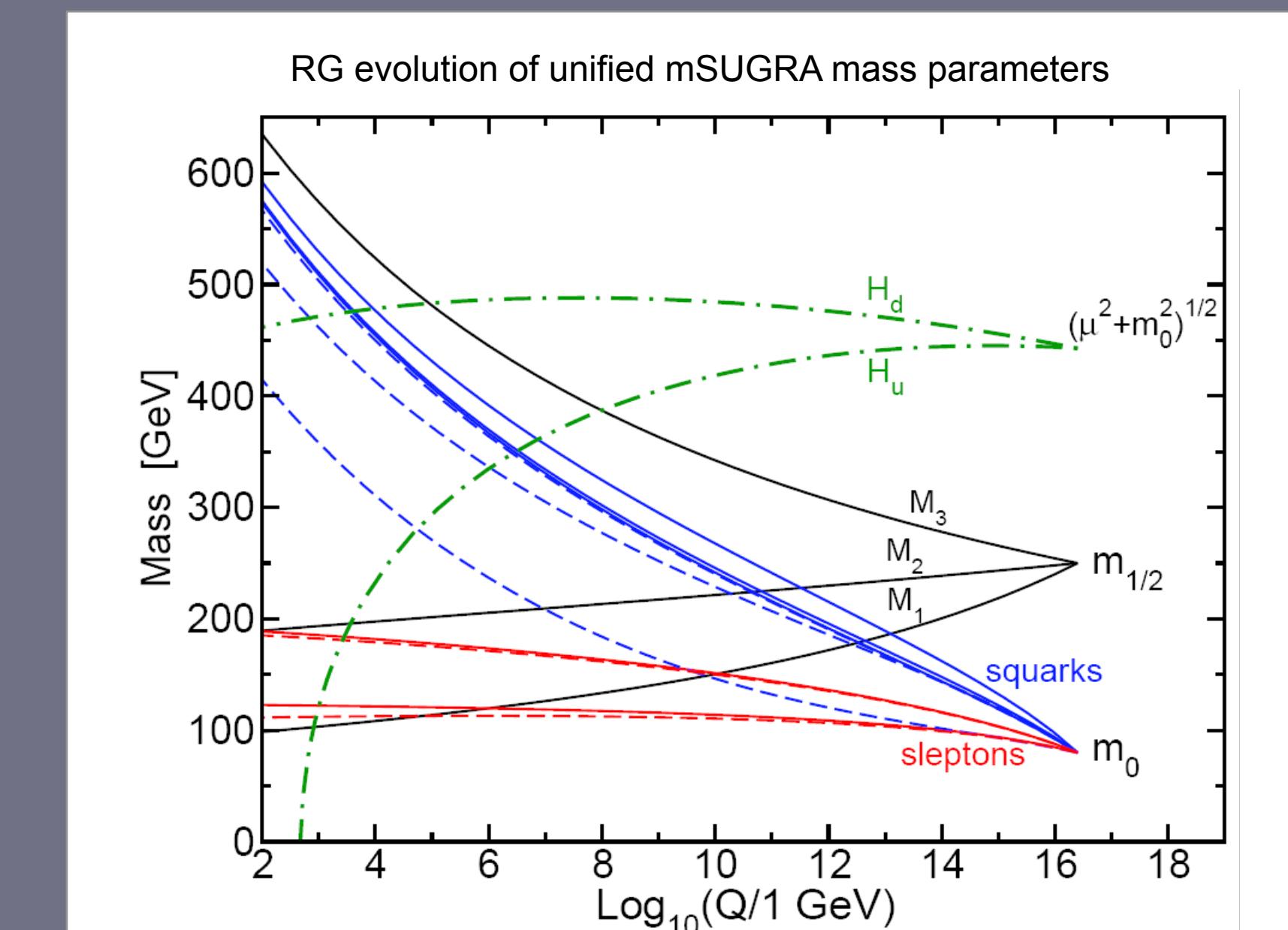
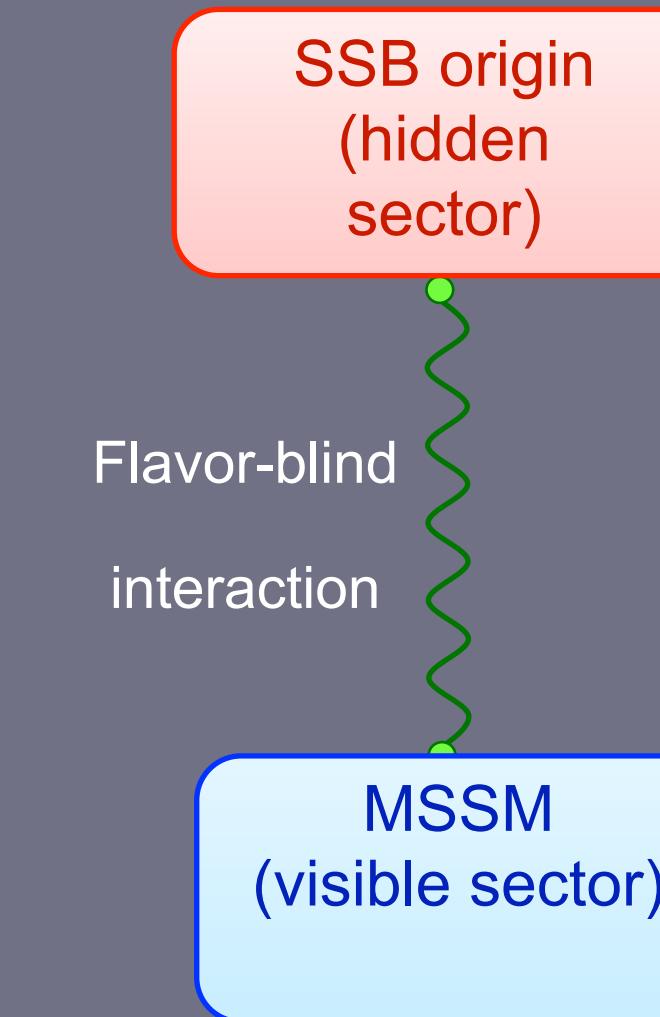
# SUSY Motivation

- Aesthetic: new space-time symmetry
  - Leads to new partners for every SM particle.
  - Removes  $\mu$
  - Resolves Higgs problem
  - Gauge unification
  - Has Graviton
  - 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 = +1 (-1) 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

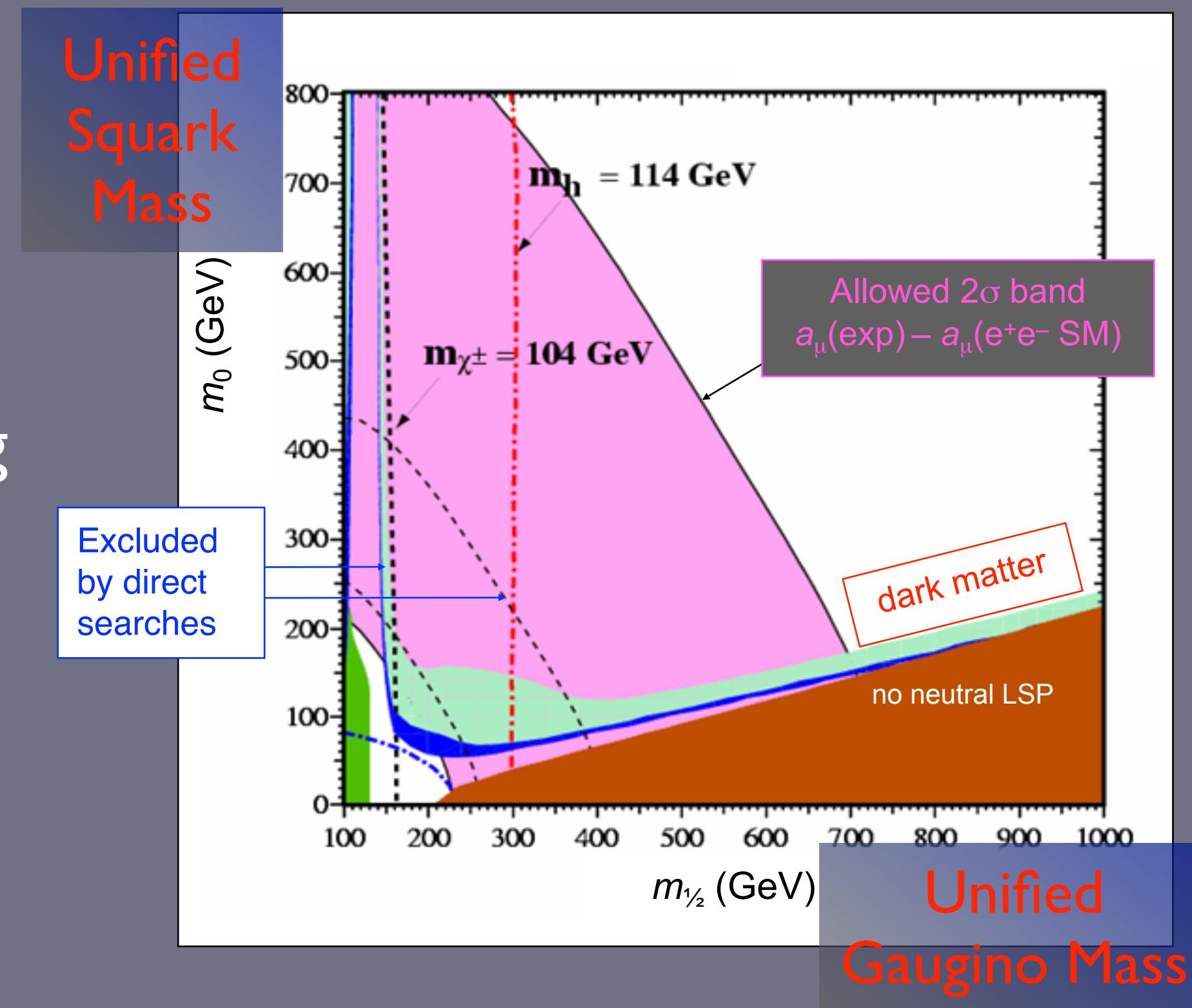


# SUSY Models

- 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...

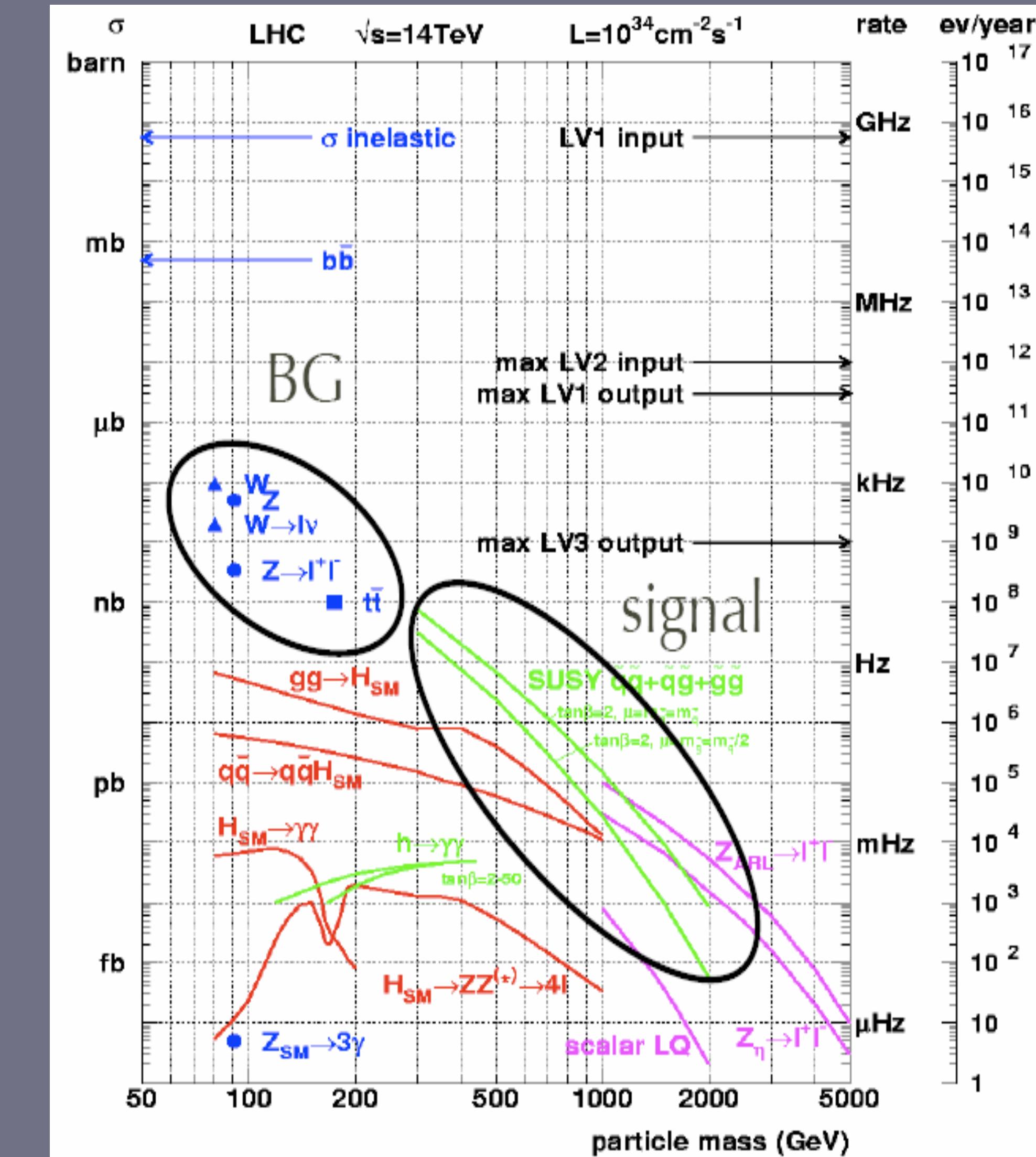


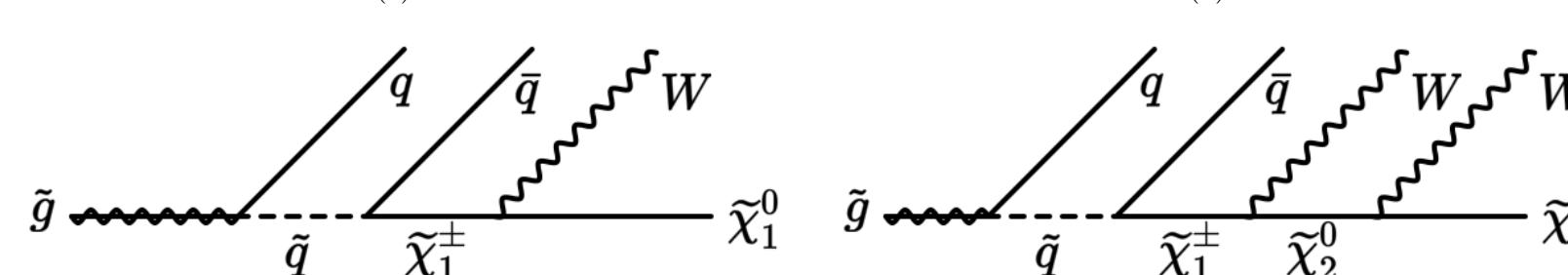
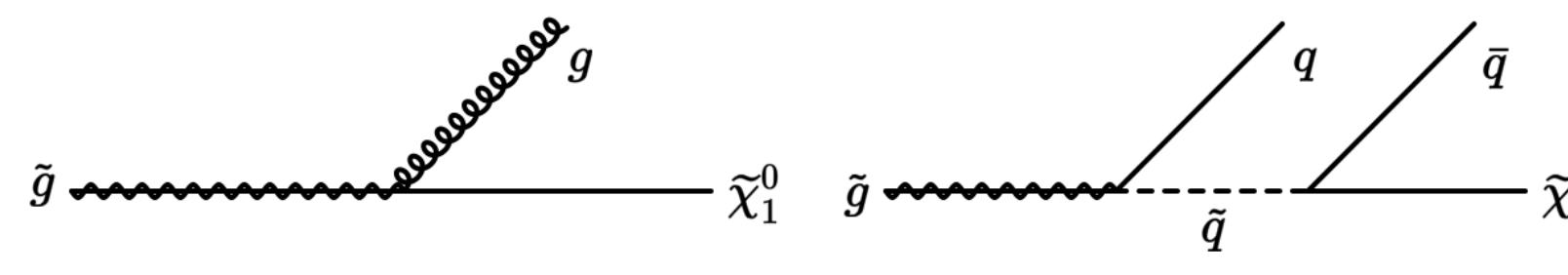
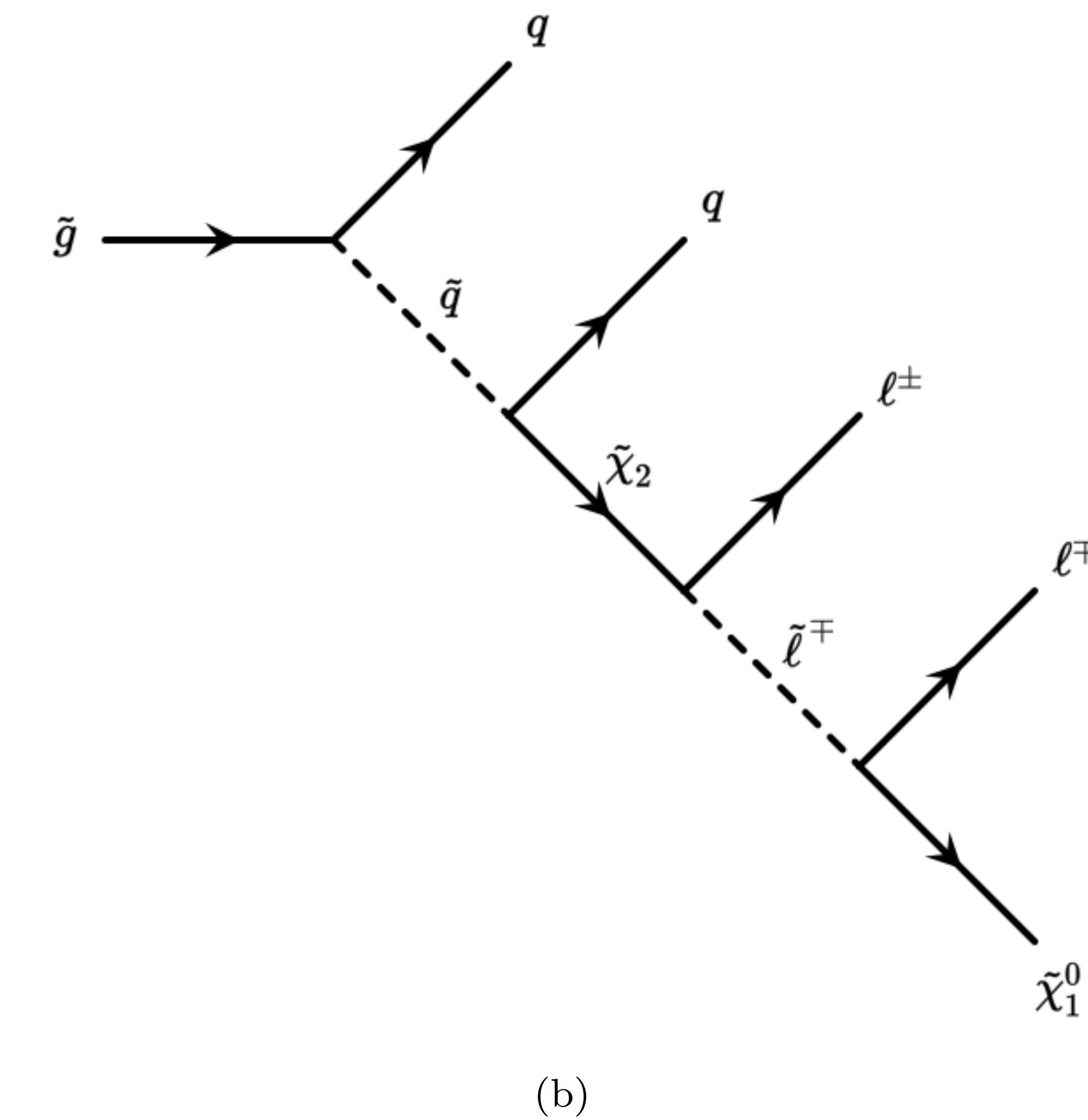
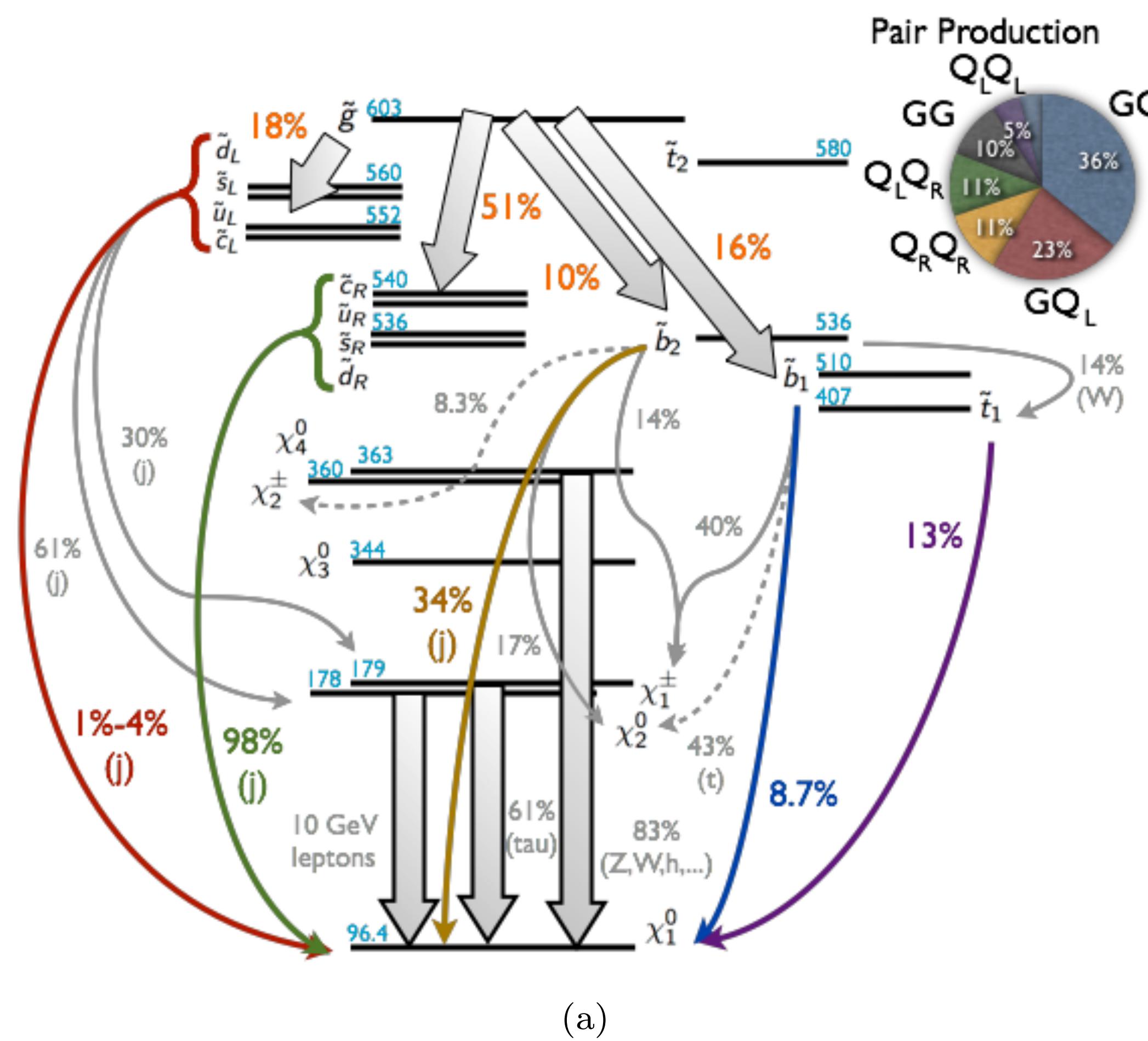
# Looking for SUSY

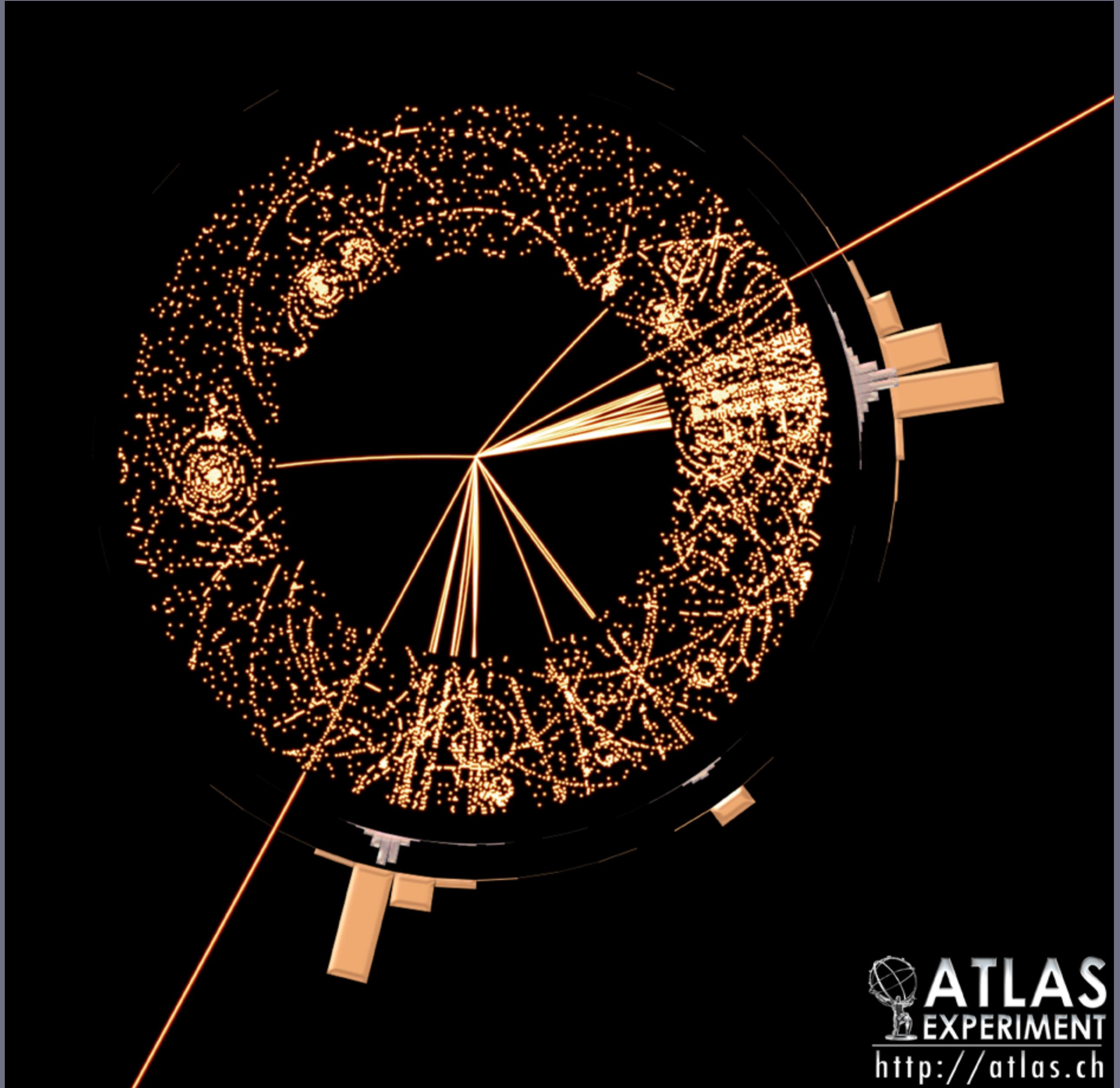


# Signal vs Background

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



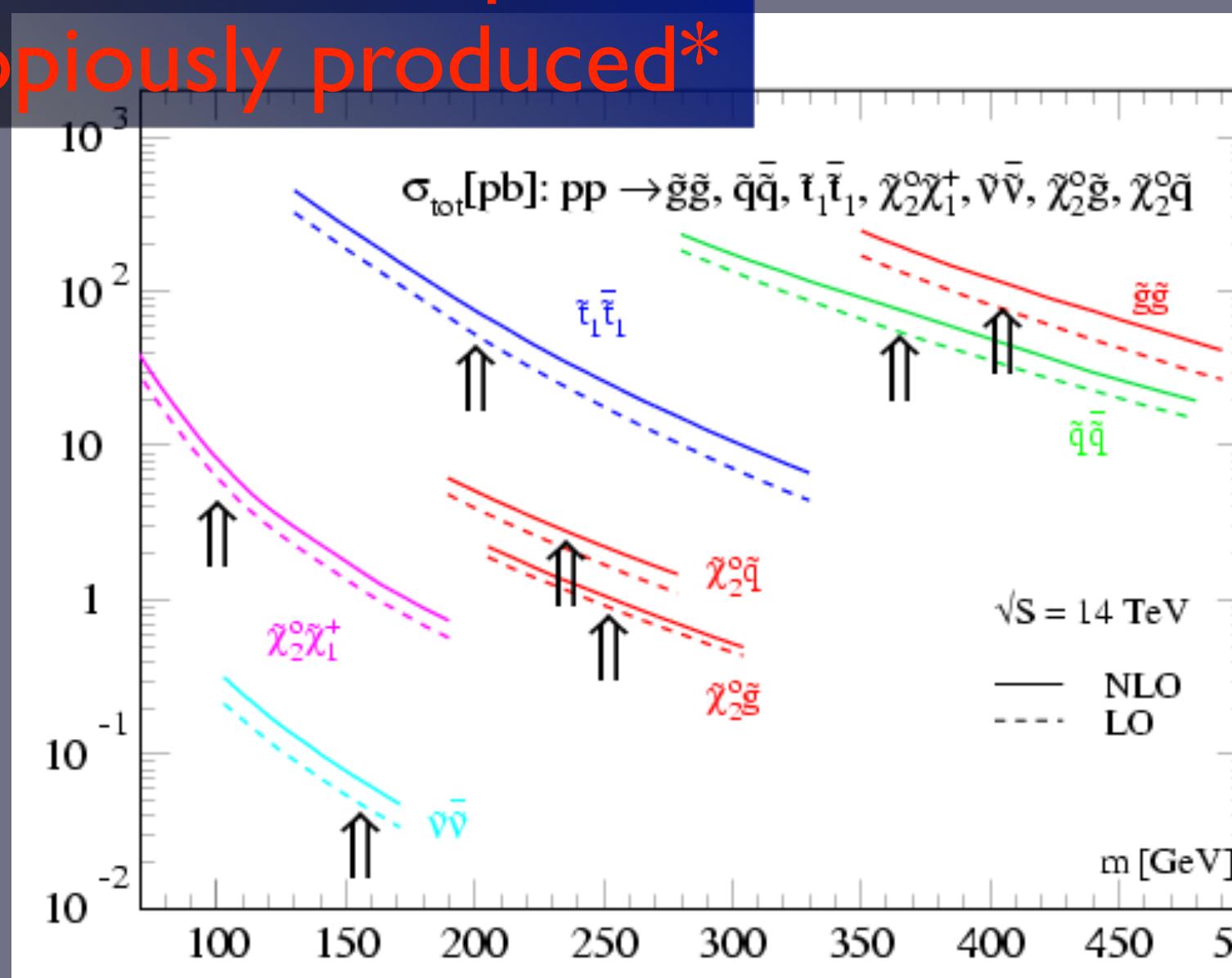




 **ATLAS**  
EXPERIMENT  
<http://atlas.ch>

# SUSY at LHC

Gluinos and squarks  
copiously produced\*

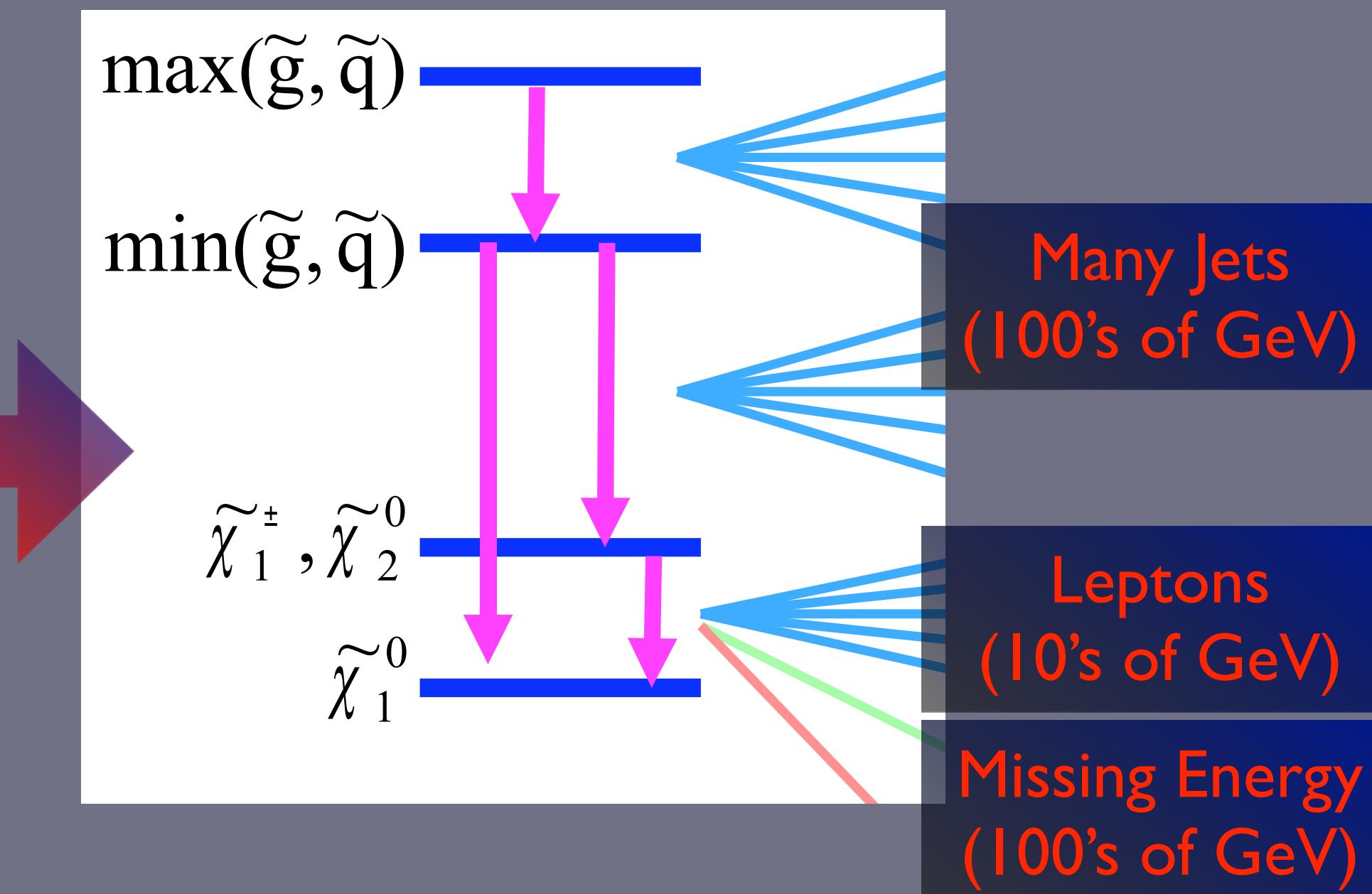
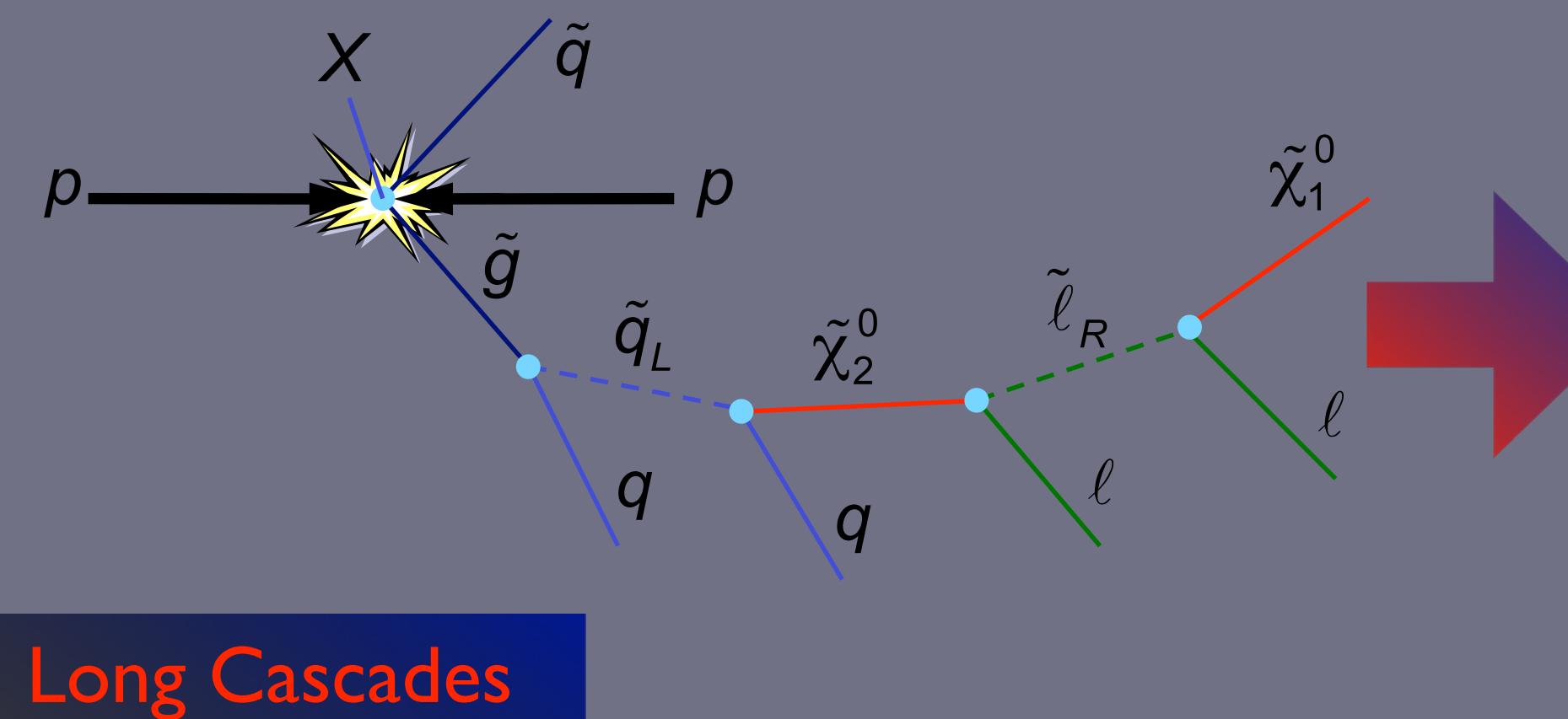


GMSB

AMSB

mSUGRA

Gluinos and squarks  
heavier than charginos/  
neutralinos



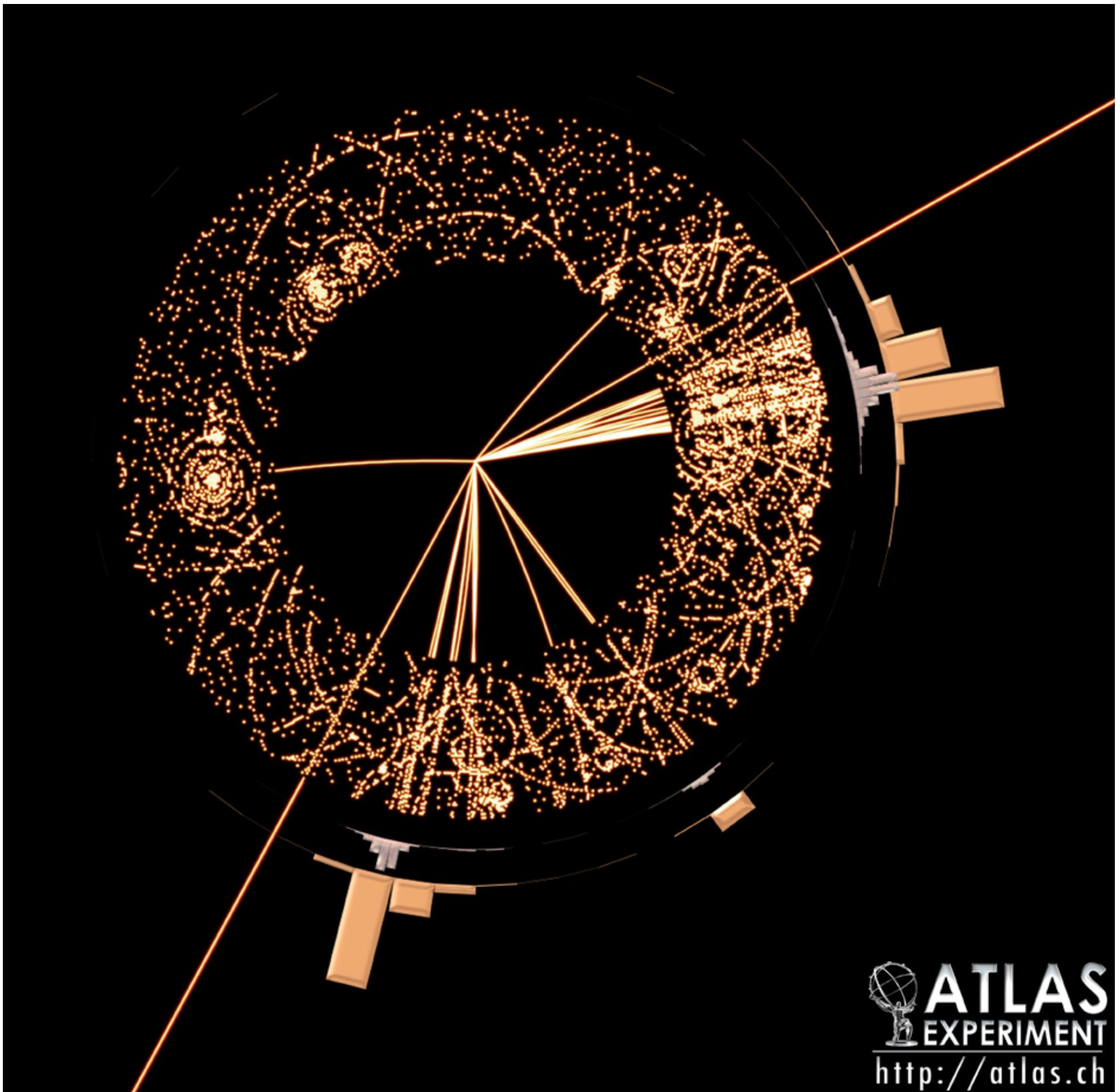
# Inclusive Signatures

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

# **SUSY/Higgs Data**

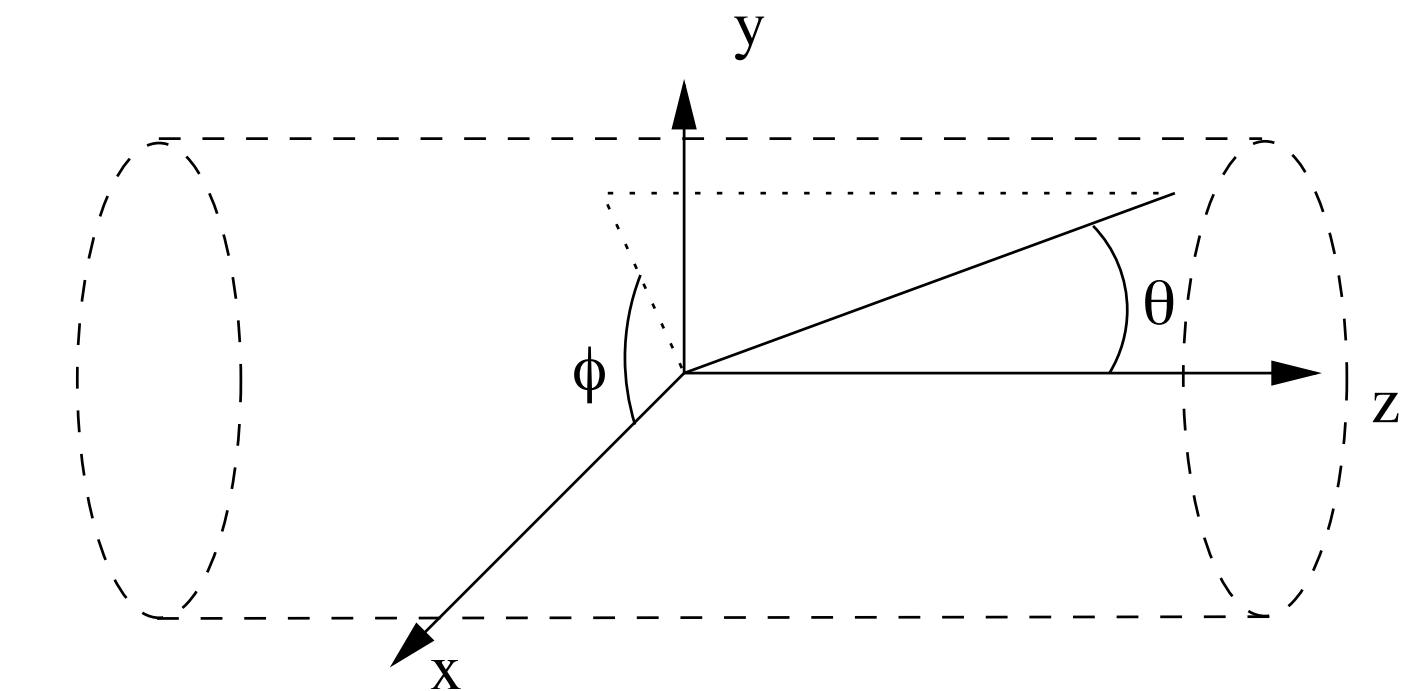
# LHC Event

- 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 ( $\phi$ ) )
  - 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.

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