Python for Data Science 2

Lab 5- SUSY at LHC

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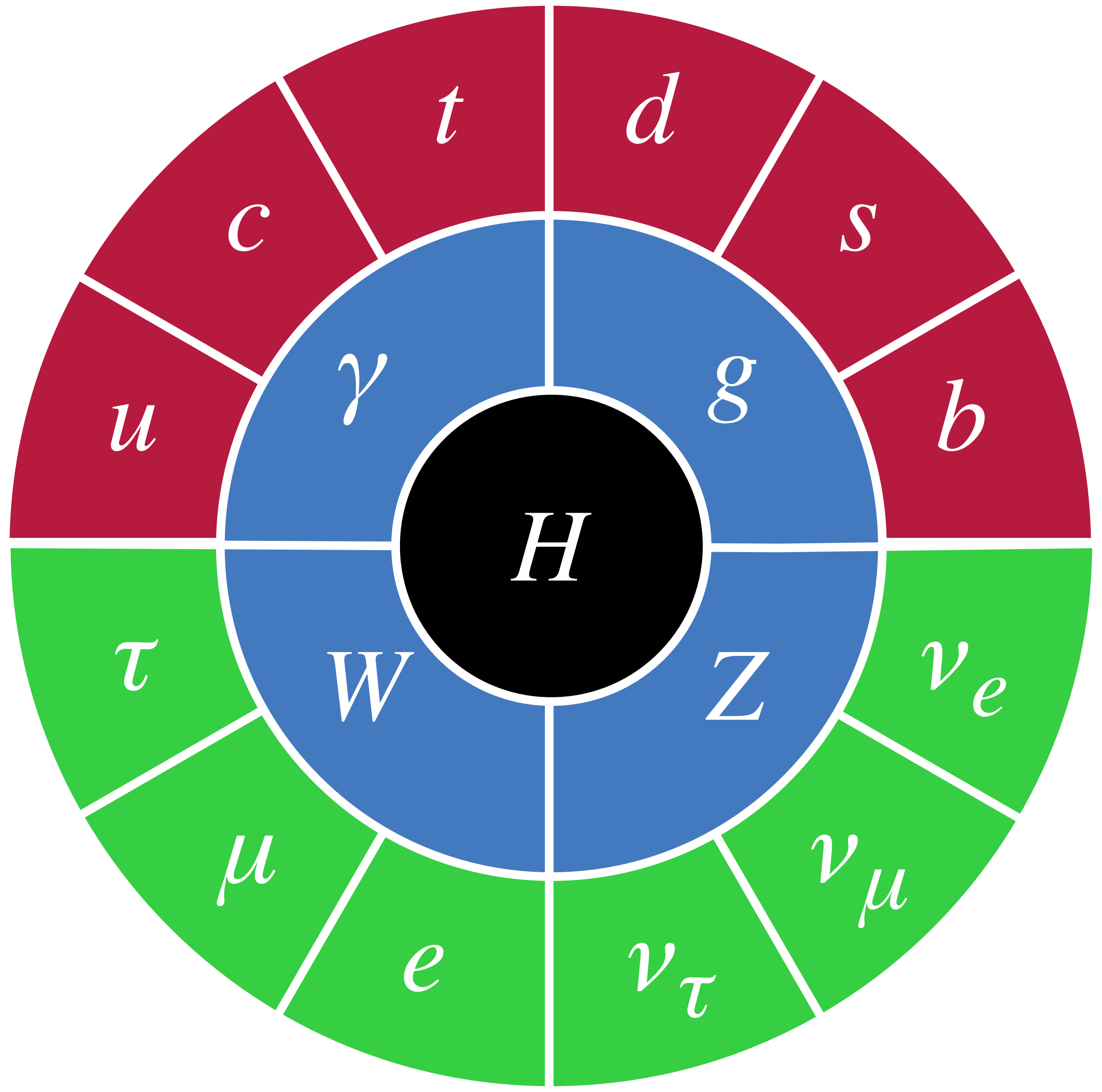
PARTICLE PHYSICS: 19 PARAMETERS

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



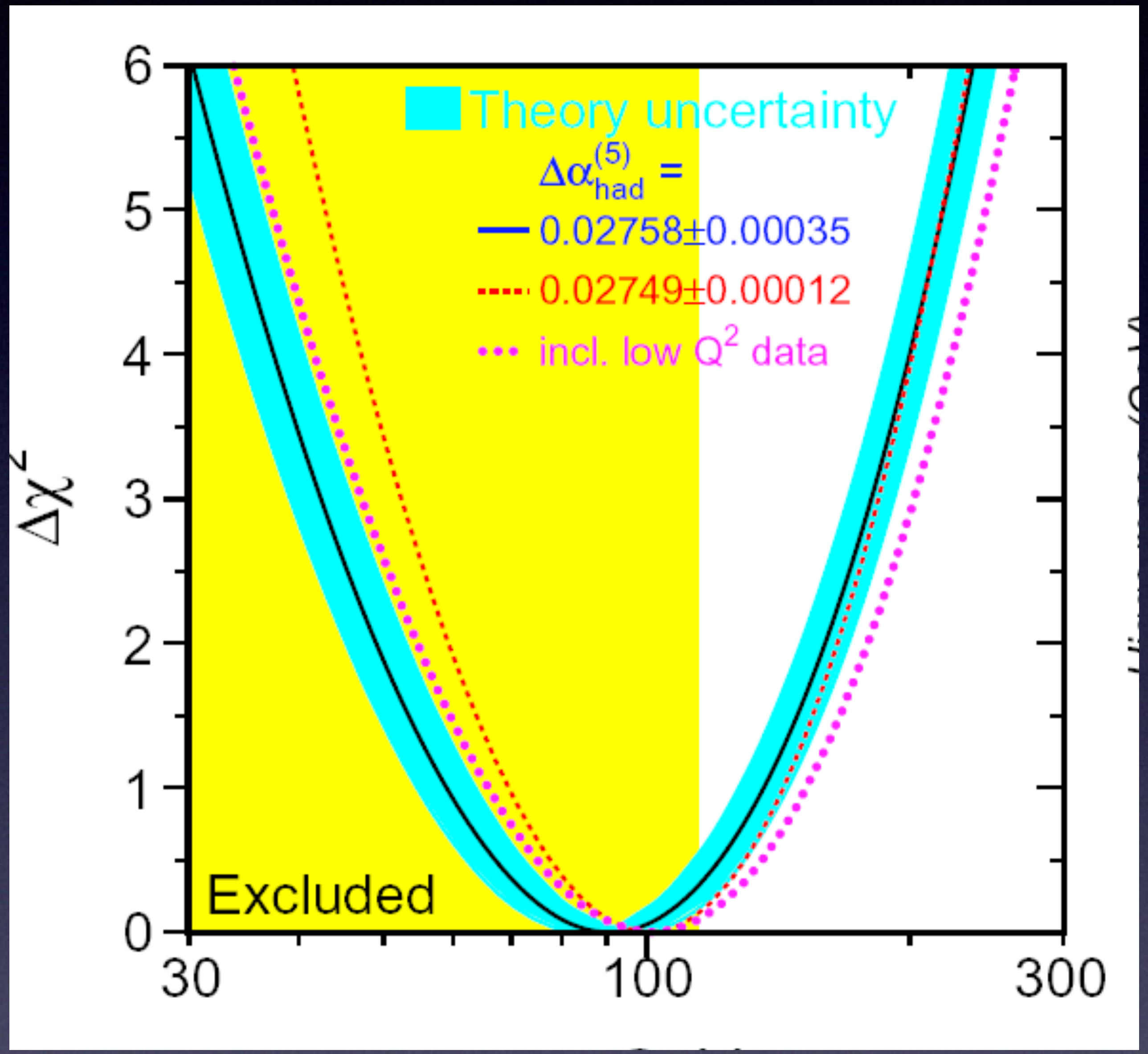
Symbol	Description	Value
m_e	Electron mass	511 keV
m_μ	Muon mass	105.7 MeV
m_τ	Tau mass	1.78 GeV
m_u	Up quark mass	1.9 MeV
m_d	Down quark mass	4.4 MeV
m_s	Strange quark mass	87 MeV
m_c	Charm quark mass	1.32 GeV
m_b	Bottom quark mass	4.24 GeV
m_t	Top quark mass	172.7 GeV
θ_{12}	CKM 12-mixing angle	13.1°
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

- 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.

Hierarchy Problem

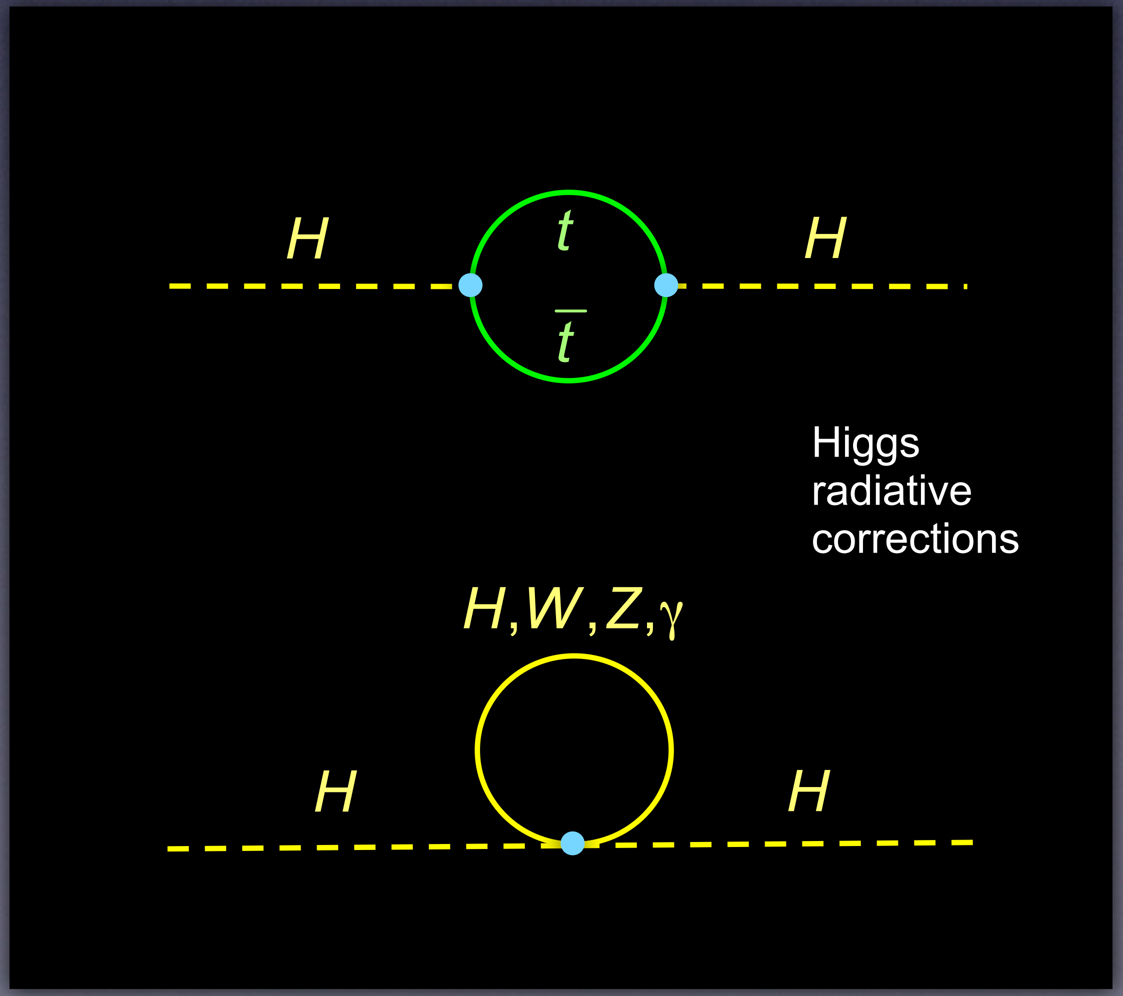
m_H=Higgs Mass
~ EW Symmetry
Breaking

Measurements: Electroweak
m_H < 1 TeV



m_H Calculation:
Radiative Corrections

Cut-off Scale (Λ)



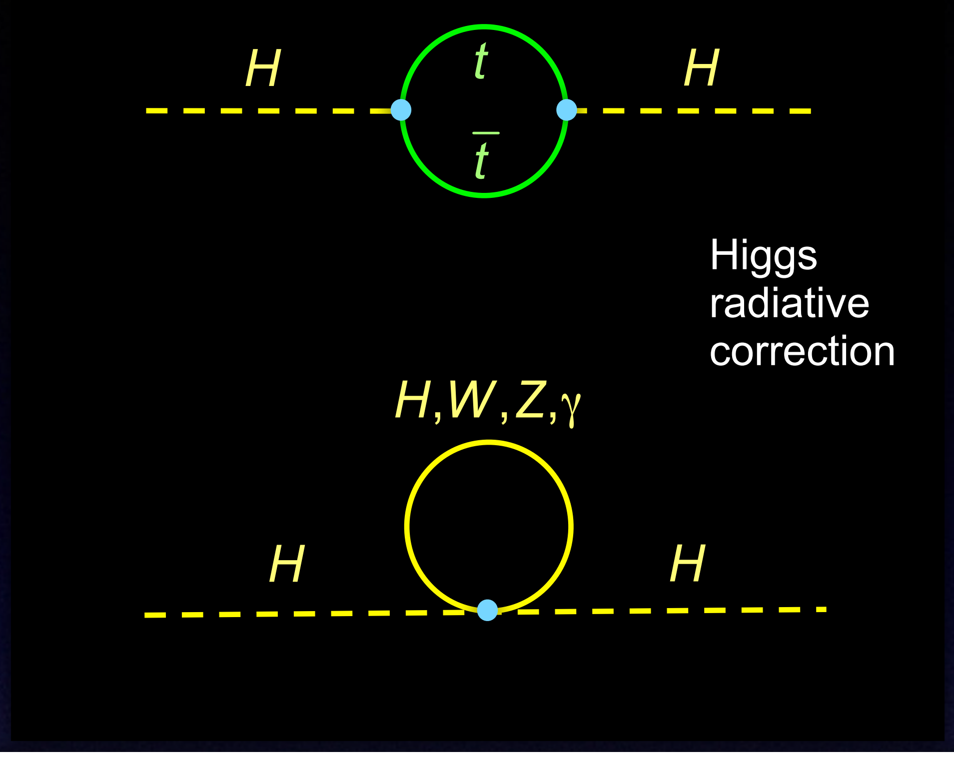
GUT Scale
Planck Scale

Quadratic Divergence
$m_H \sim m_{GUT}$ or m_{pl}

Naturalness

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

Measured = Bare + Correction



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

We input Bare

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

m_H(Measured) 125 GeV,

but $\delta m_0 \sim m_{GUT}$ or m_{pl}

Need in part in 10^{16} cancellation

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

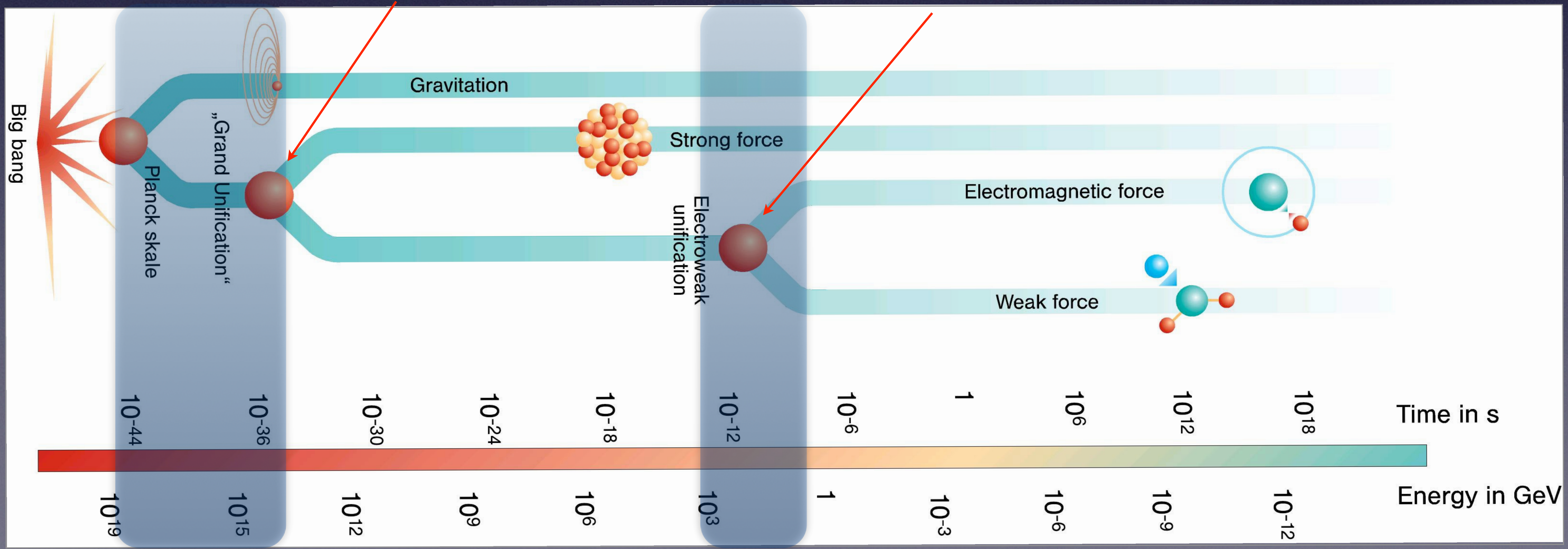
So we must fine-tune the value of bare

Hierarchy Problem

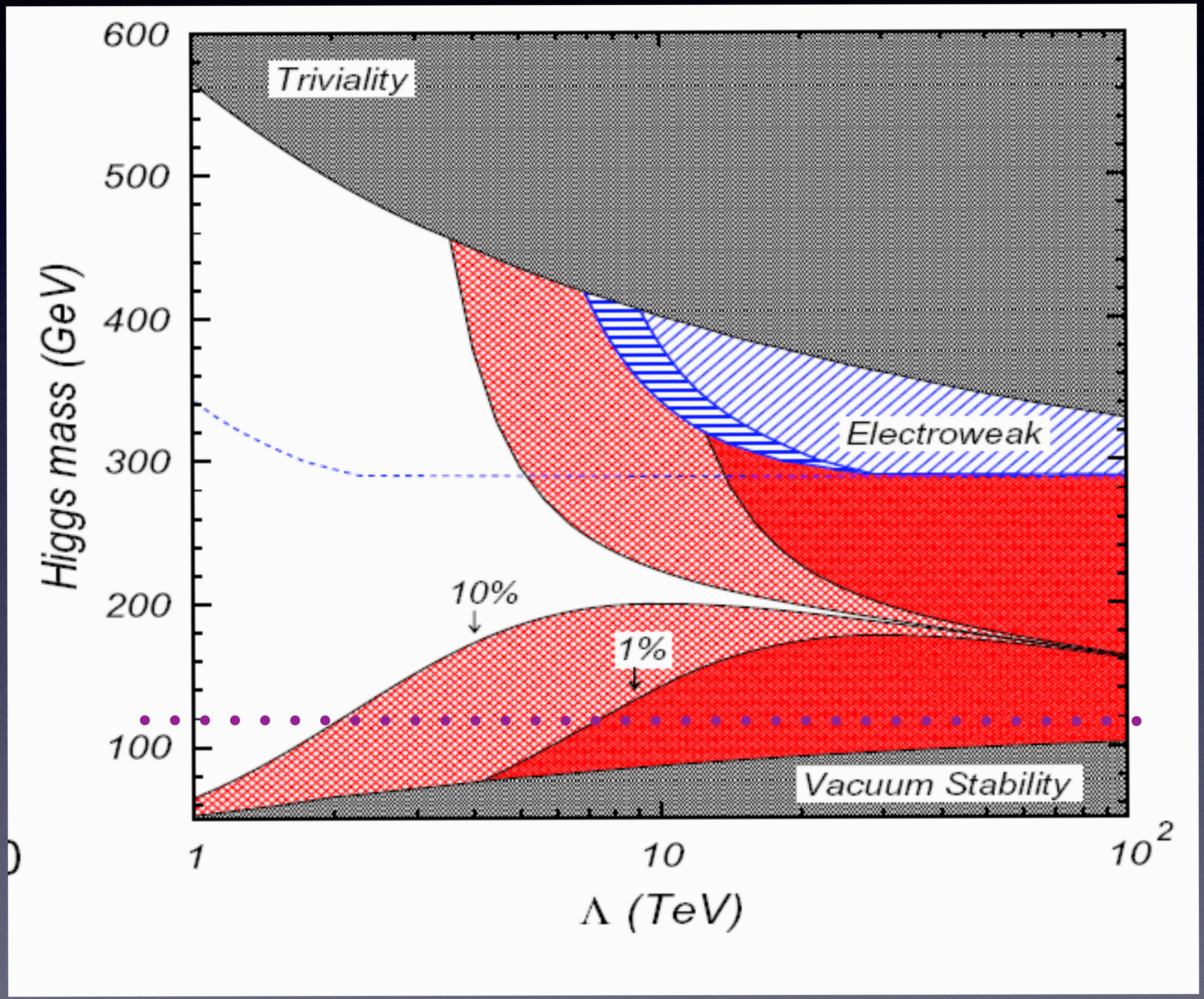
- At the heart of the Standard Model is a particle called the Higgs (which we haven't seen yet...)
  - For the SM to work, the Higgs mass has to be < 1 TeV
  - But the SM predicts the Higgs mass to be around the mass where something new happens.
  - So for SM to work... something new has to happen ~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

Higgs Mass w/o New Physics

Observed Higgs Mass



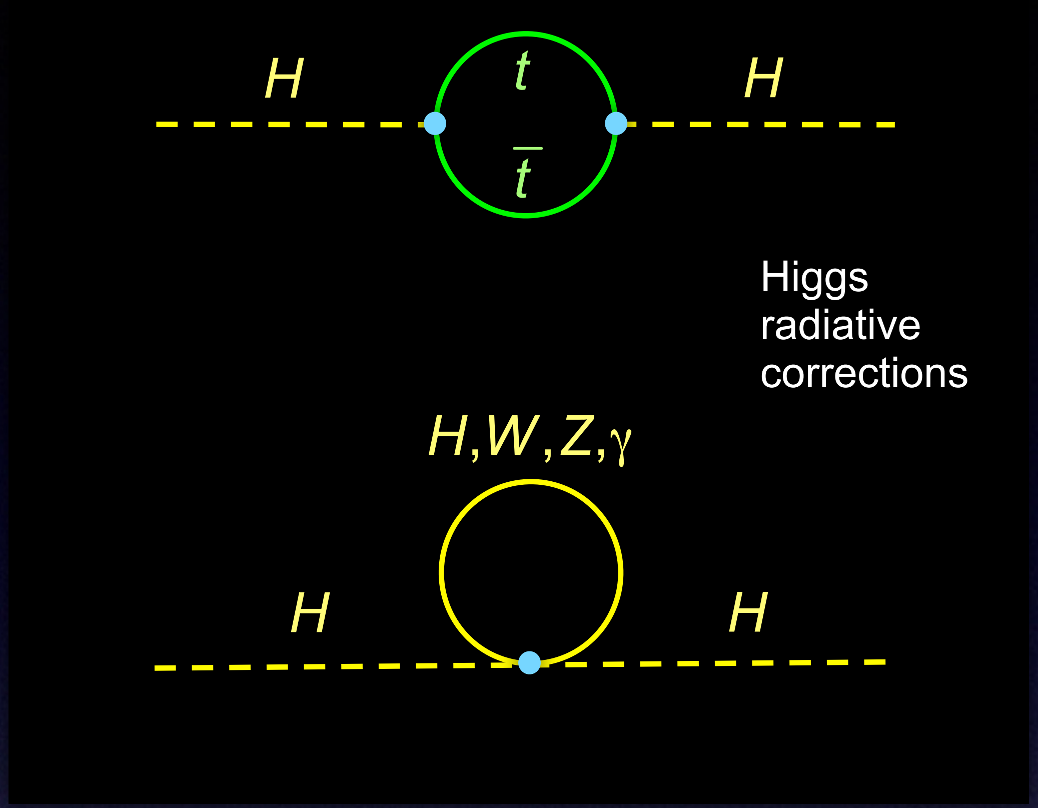
Naturalness/Fine-tuning



3 Solutions to The Hierarchy problem

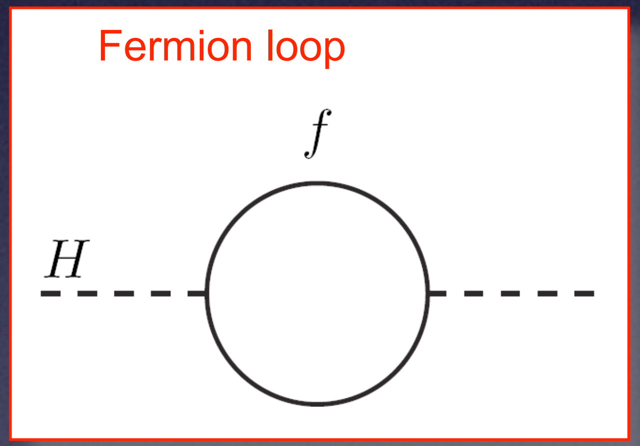
- Something new should show up around ~1 TeV
- 3 classes of suggested possibilities:
  - Supersymmetry
  - Extra-dimensions
  - Additional sub-structure
- All predict new particles... usually partners to the Standard Model particles

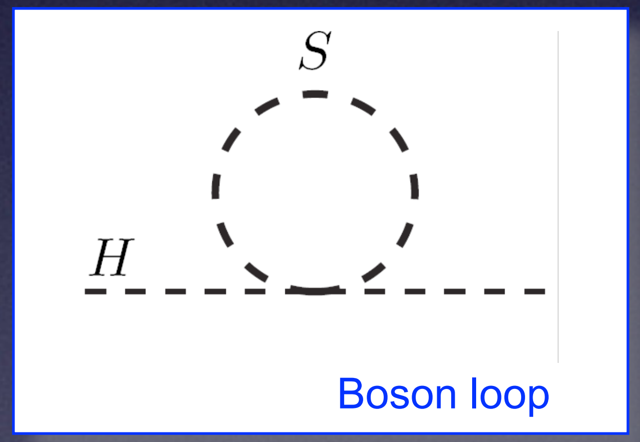
SUSY and Hierarchy Problem

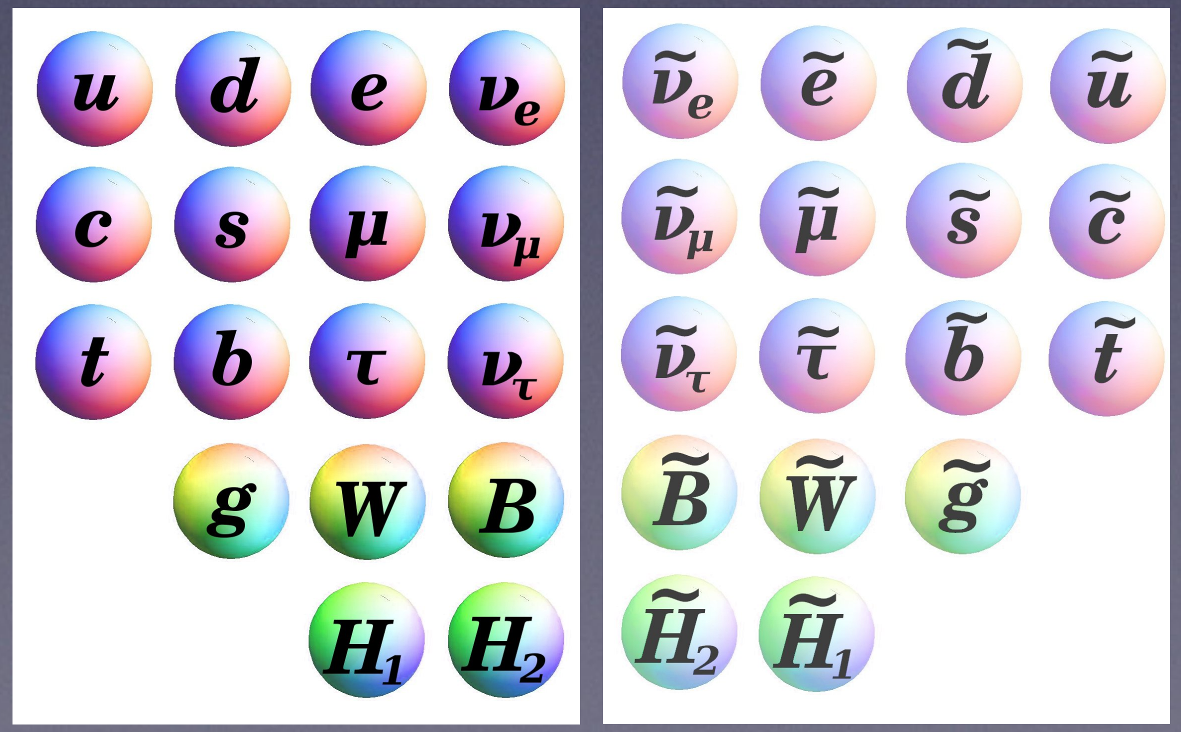


- Recall the mass of the Higgs is M_{GUT} or M_{PL}, because of "infinite" radiative corrections (ie loop diagrams) that are quadratic in cut-off Λ.

- 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 → sparticle, gauge boson → gaugino
- No scalar electron partner ⇒ SUSY broken
  - Still keeps the Higgs mass low



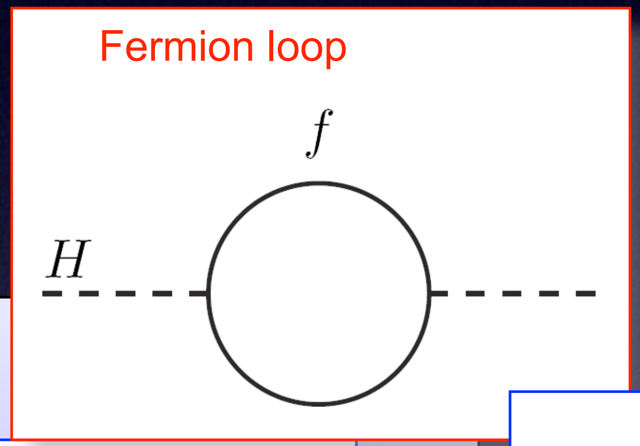


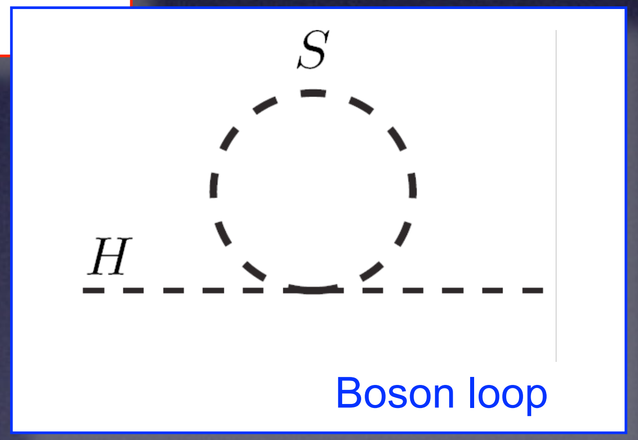


SUSY Motivation

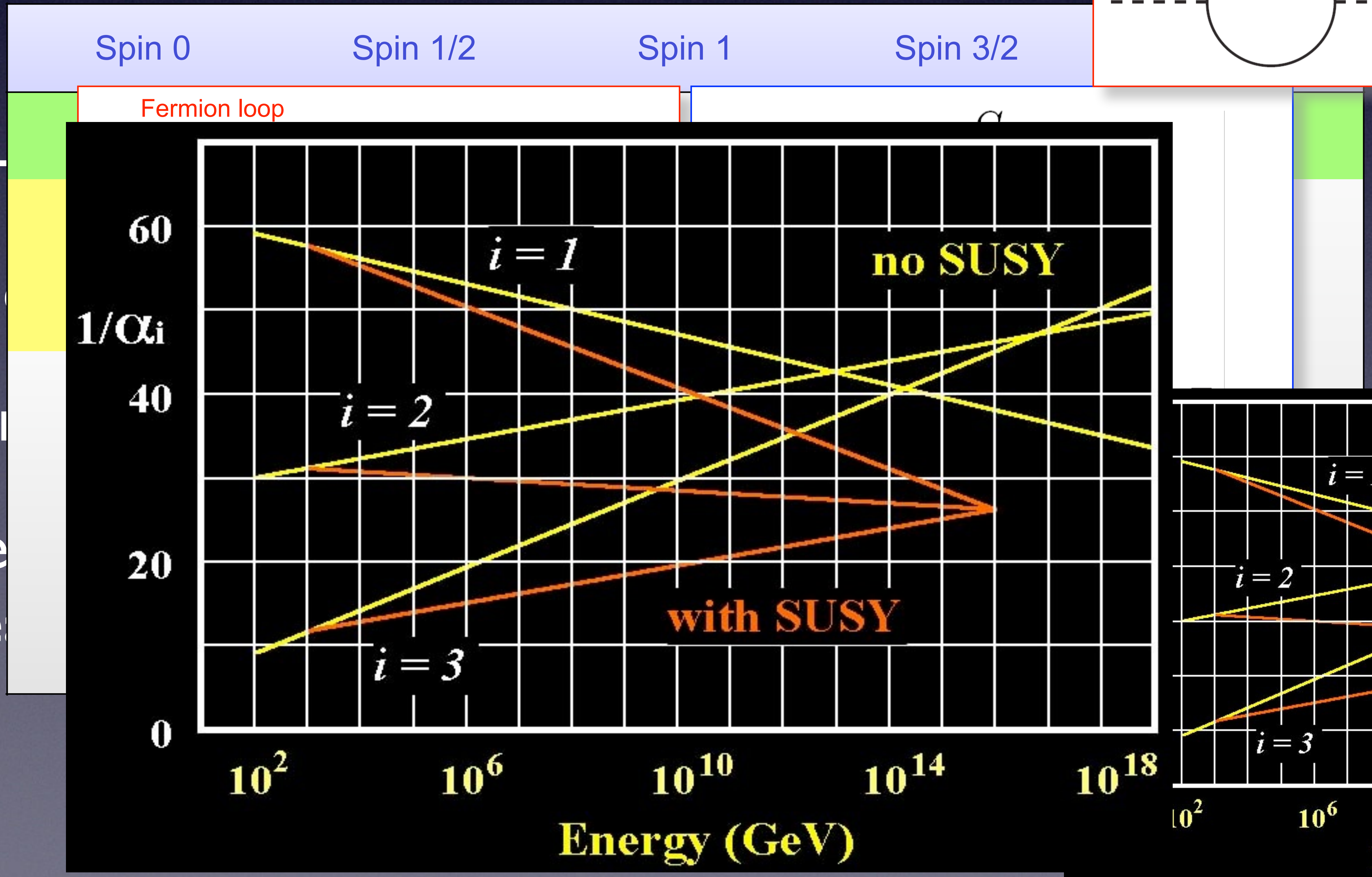
Spin 0	Spin 1/2	Spin 1	Spin 3/2	Spin 0
Higgs	Higgsino		Gravitino	Graviton
sLepton	Lepton			
sQuark	Quark			
	Gluino	Gluon		
	Photino	Photon		
	Zino	Z		
	Wino	W		

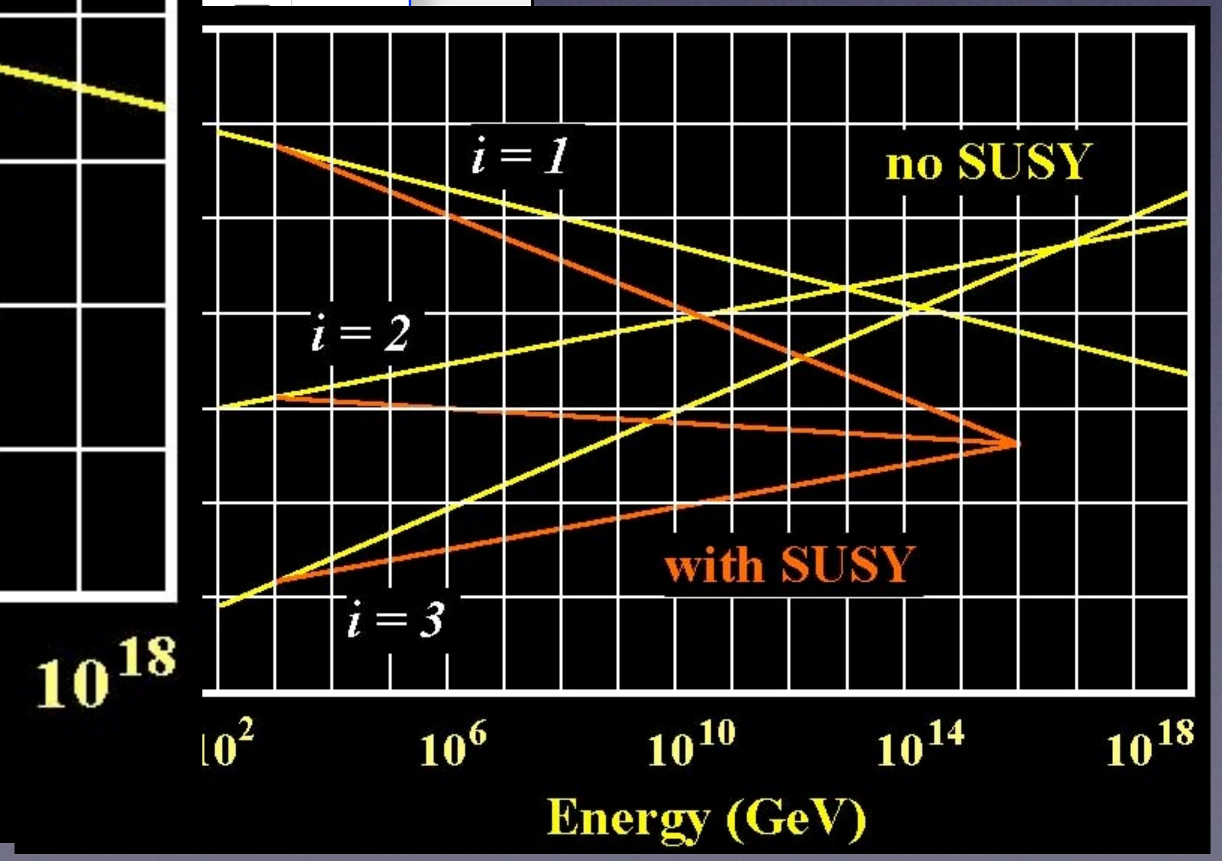
SM
SUSY





- Aesthetic: new space-time symmetry
  - Leads to new partners for every SM particle.
  - Removes
- ➡ Resolves H
- Gauge unifi
- Has Gavitor
- Dark matte
  can be a he



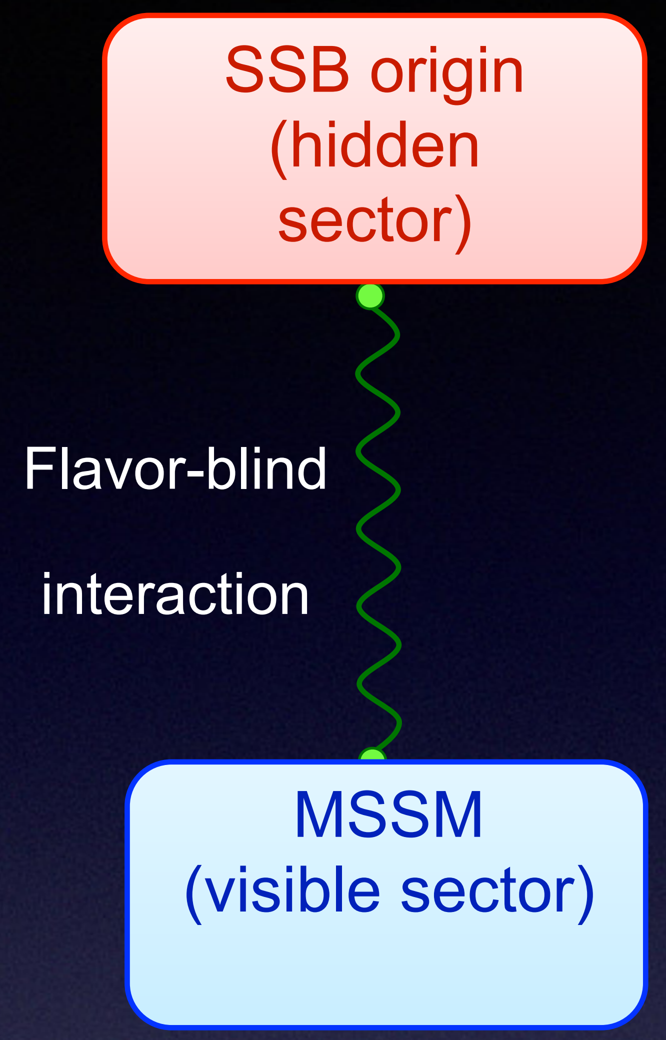


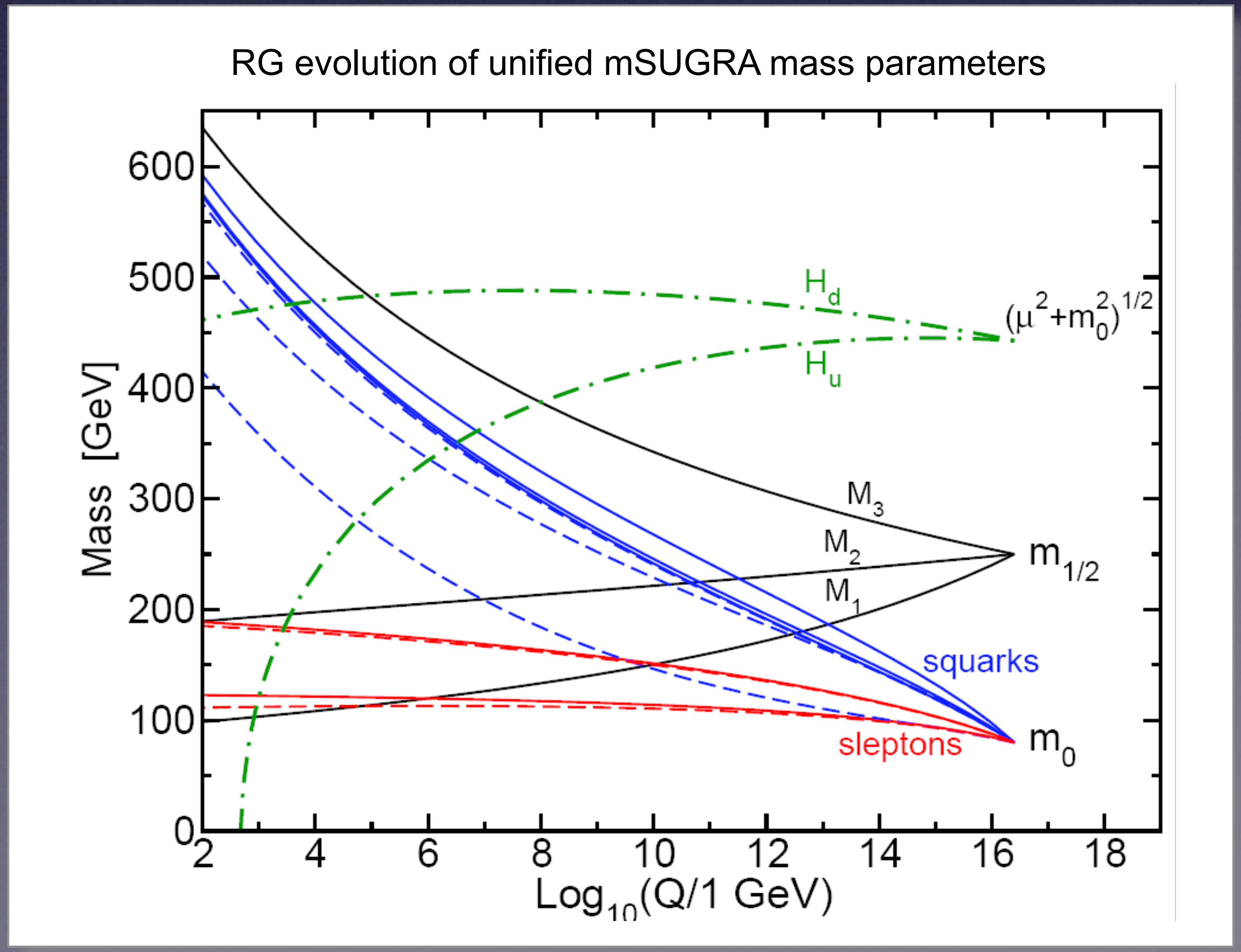
SUSY Phenomenology

- No scalar electron partner ⇒ SUSY broken
- If want SUSY to preserve EW naturalness ⇒ 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, $m_{1/2}$, sig(μ), tan β, A_0

➡ 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





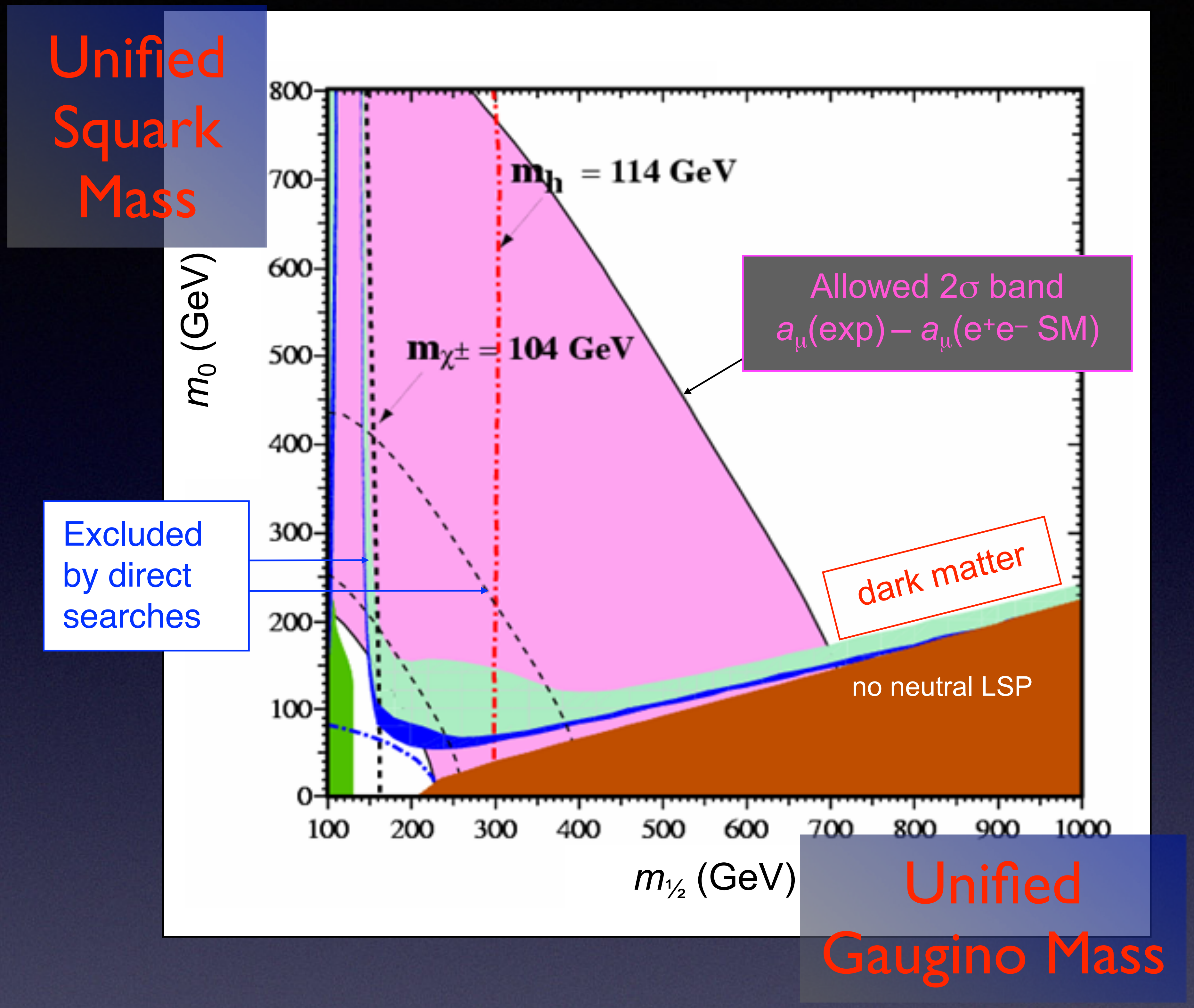
SUSY Models

- 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

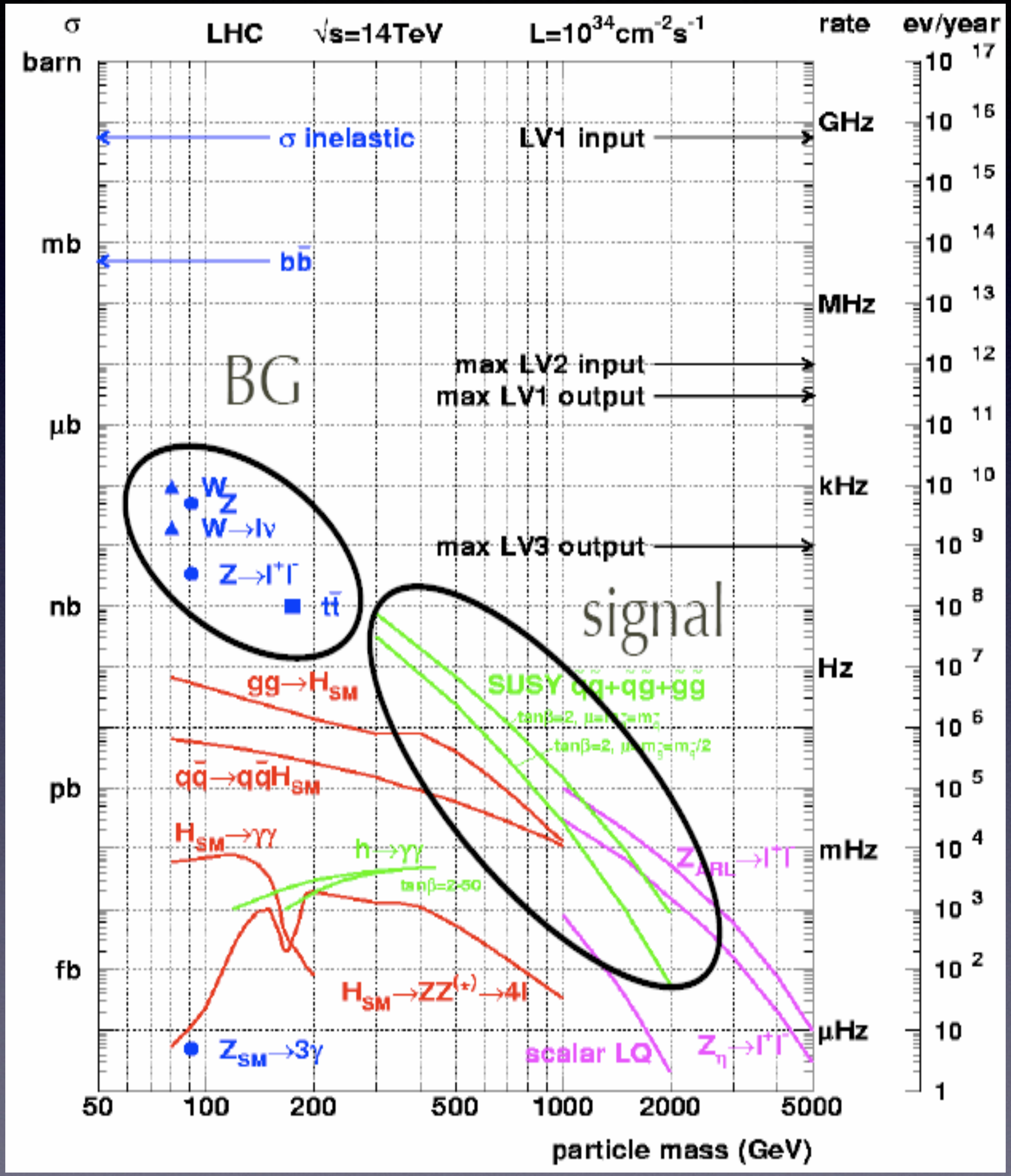
- Constrains on SUSY come from:
  - From cosmology: cold dark matter density
  - Direct Accelerator Searches: looking for sparticles
  - Indirect Accelerator Searches:
    - Precision Electroweak: W mass, weak mixing angle
    - Anomalous magnetic moment of muon (g-2)
    - Studying flavor-changing neutral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

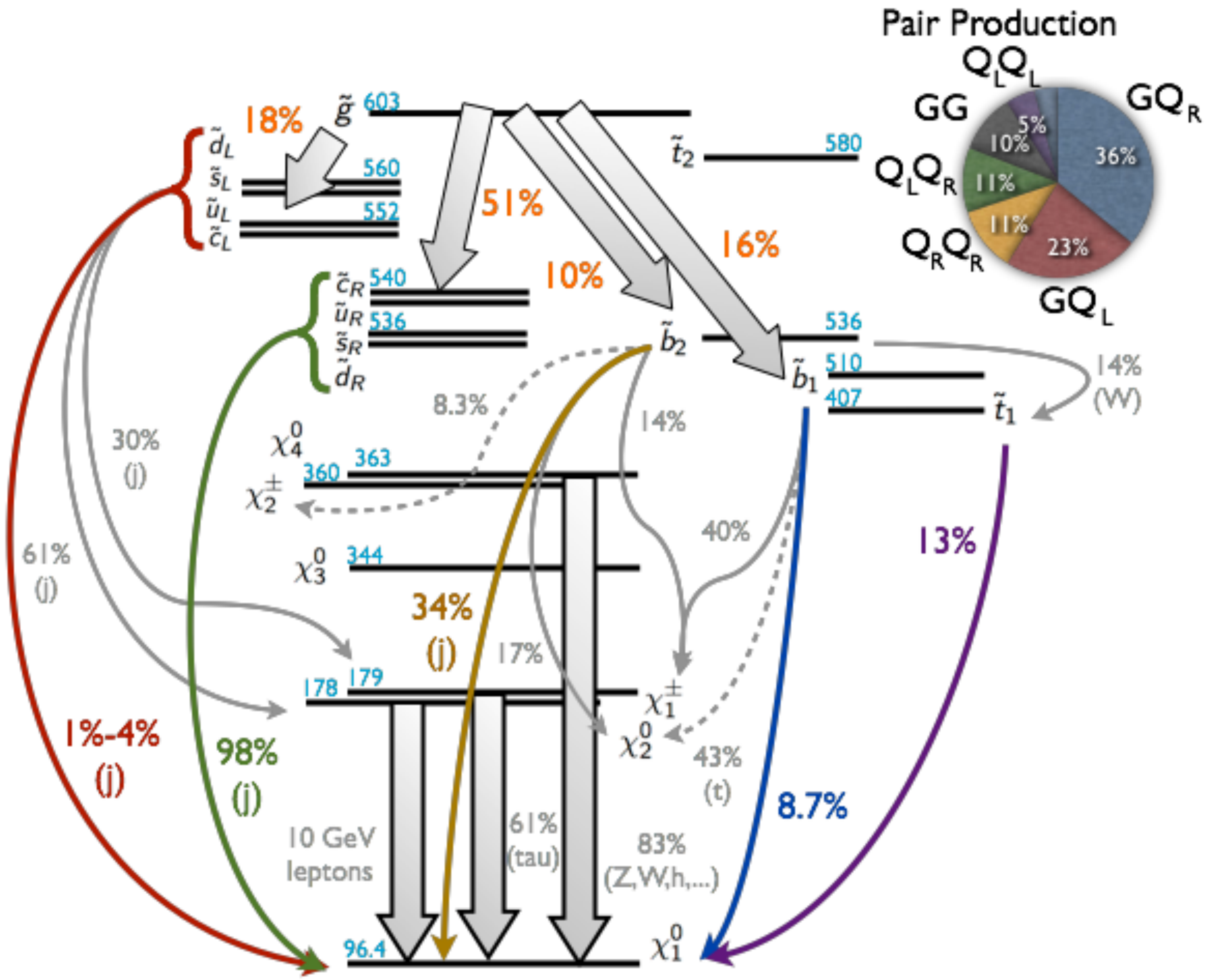


Looking for SUSY

Signal vs Background

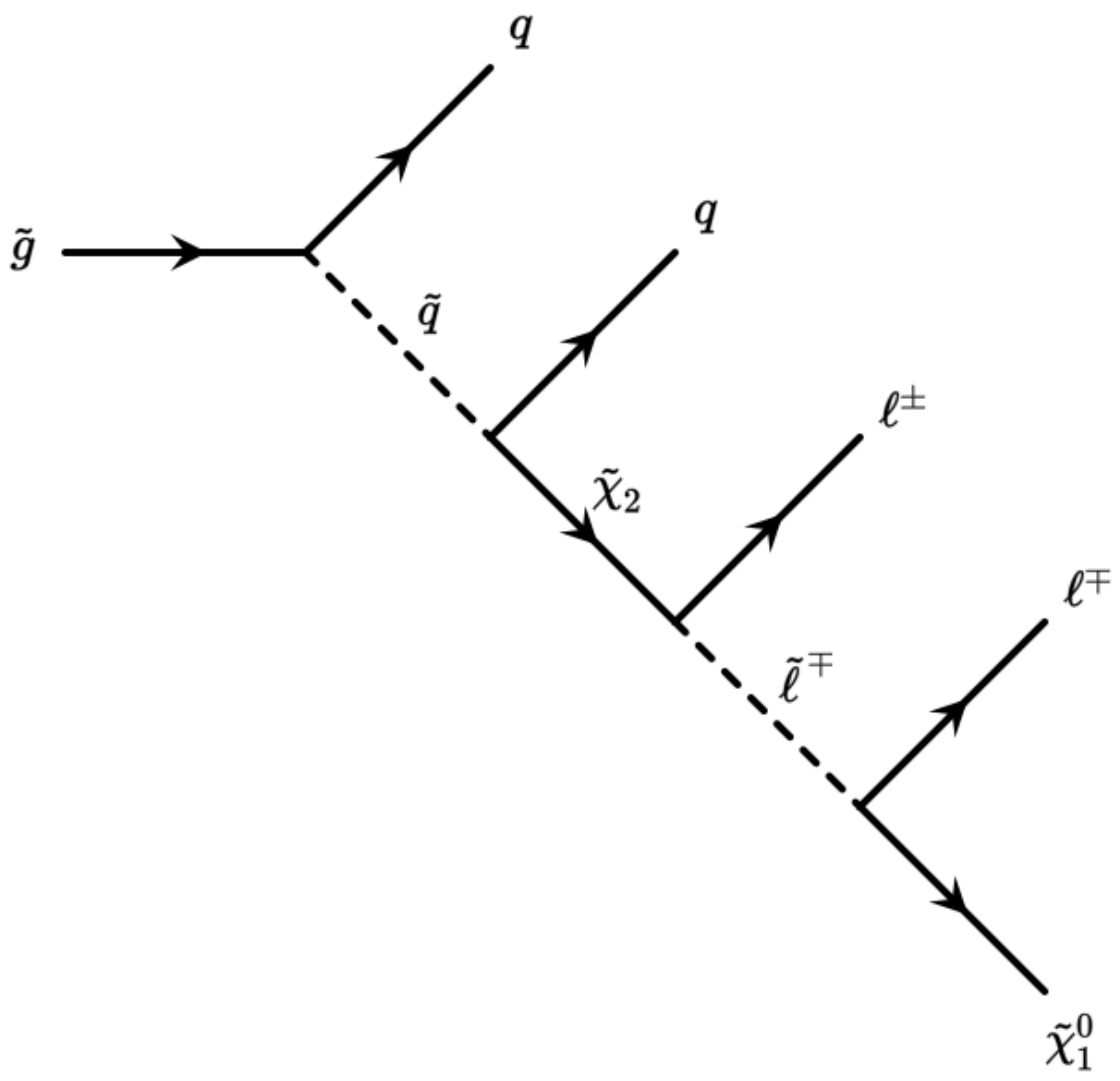
- 40 Million collisions a second
  - 50 interactions per collision
- Interesting stuff (signal) is ~ 1 in a trillion
  - The rest is background





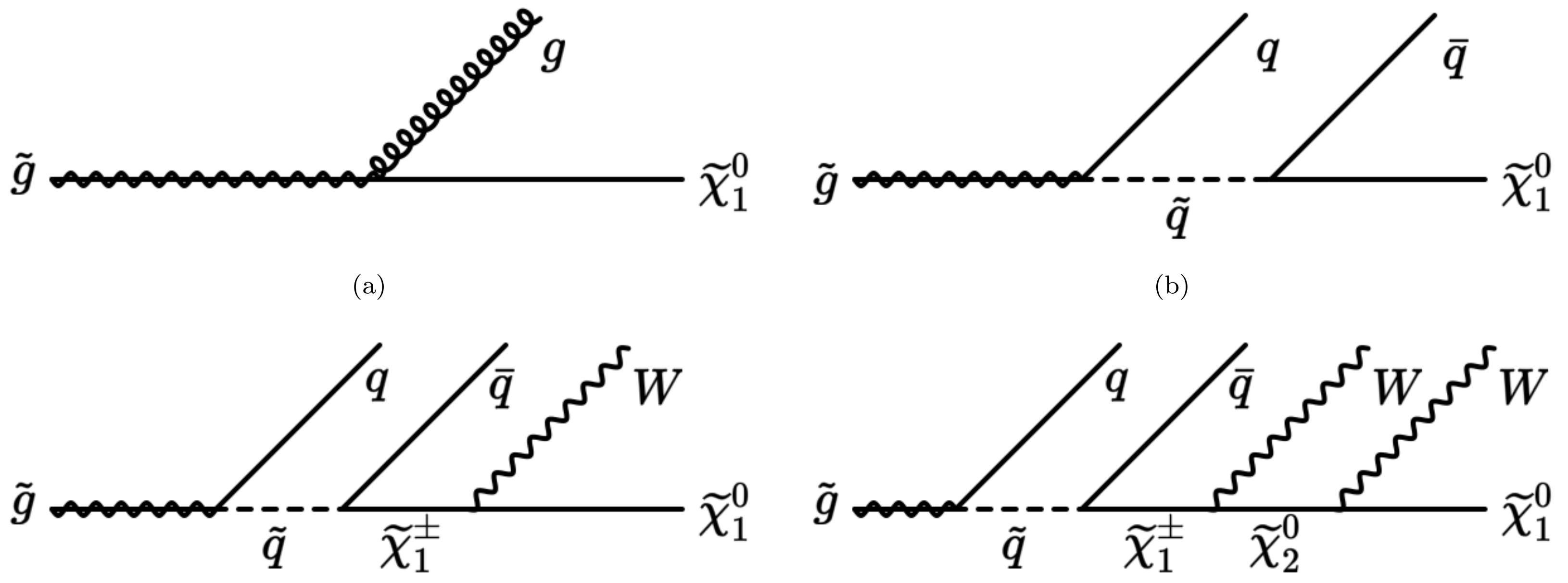
Pair Production
Q_LQ_L
GG
GQ_R
Q_LQ_R
Q_RQ_R
GQ_L
5%
10%
11%
11%
36%
23%
$\tilde{g}$ 603
$\tilde{t}_2$ 580
$\tilde{d}_L$
$\tilde{s}_L$ 560
$\tilde{u}_L$ 552
$\tilde{c}_L$
$\tilde{c}_R$ 540
$\tilde{u}_R$ 536
$\tilde{s}_R$
$\tilde{d}_R$
$\tilde{b}_2$ 536
$\tilde{b}_1$ 510
407 $\tilde{t}_1$
χ_4^0 363
$\chi_2^\pm$ 360
χ_3^0 344
$\chi_1^\pm$ 179
χ_2^0 178
χ_1^0 96.4
18%
51%
10%
16%
8.3%
14%
14% (W)
30% (j)
61% (j)
40%
34% (j)
17%
13%
43% (t)
1%-4% (j)
98% (j)
8.7%
10 GeV leptons
61% (tau)
83% (Z,W,h,...)

(a)

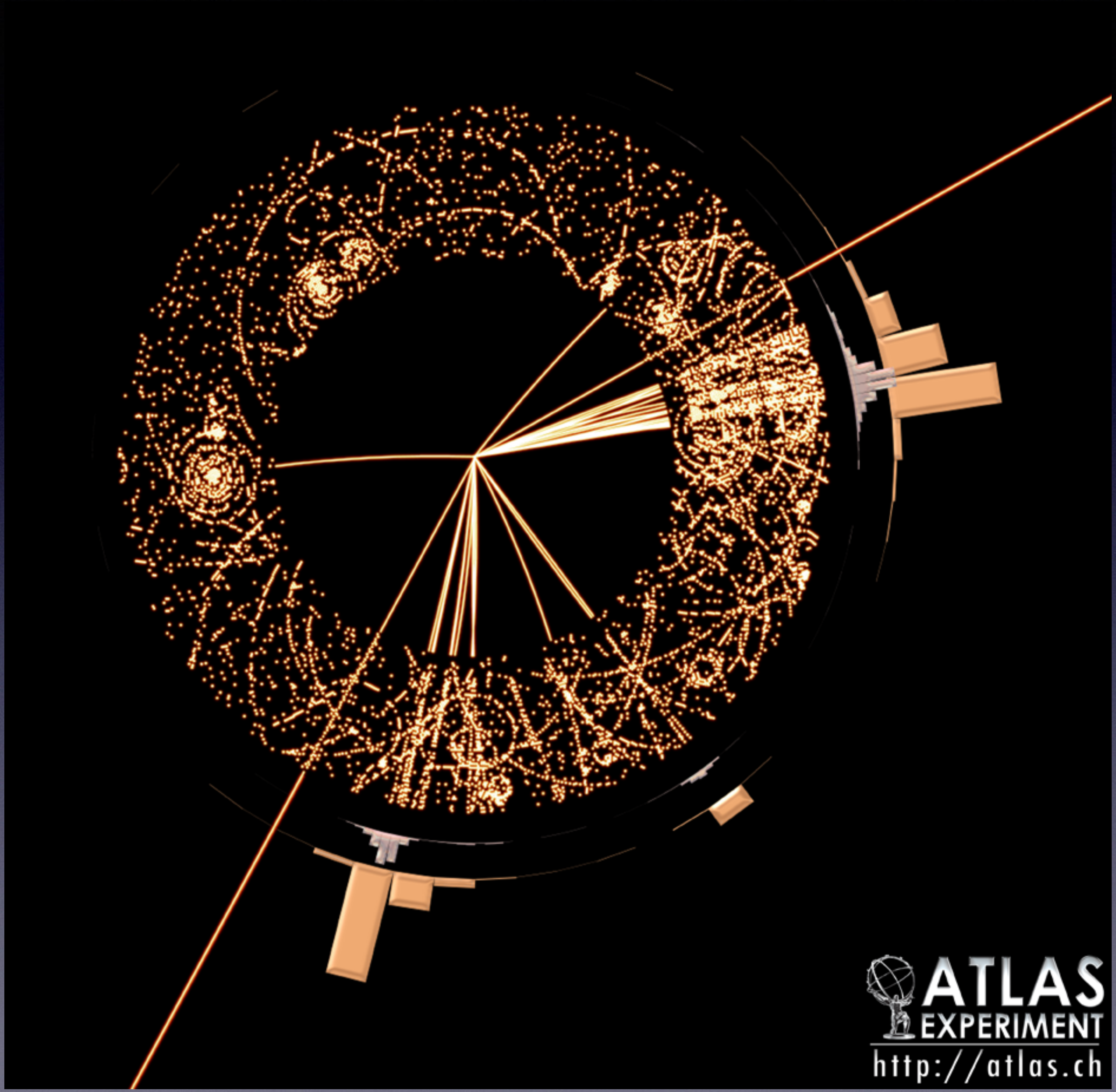


$\tilde{g}$
q
q
$\tilde{q}$
$\tilde{\chi}_2$
$\ell^\pm$
$\ell^\mp$
$\tilde{\ell}^\mp$
$\tilde{\chi}_1^0$

(b)

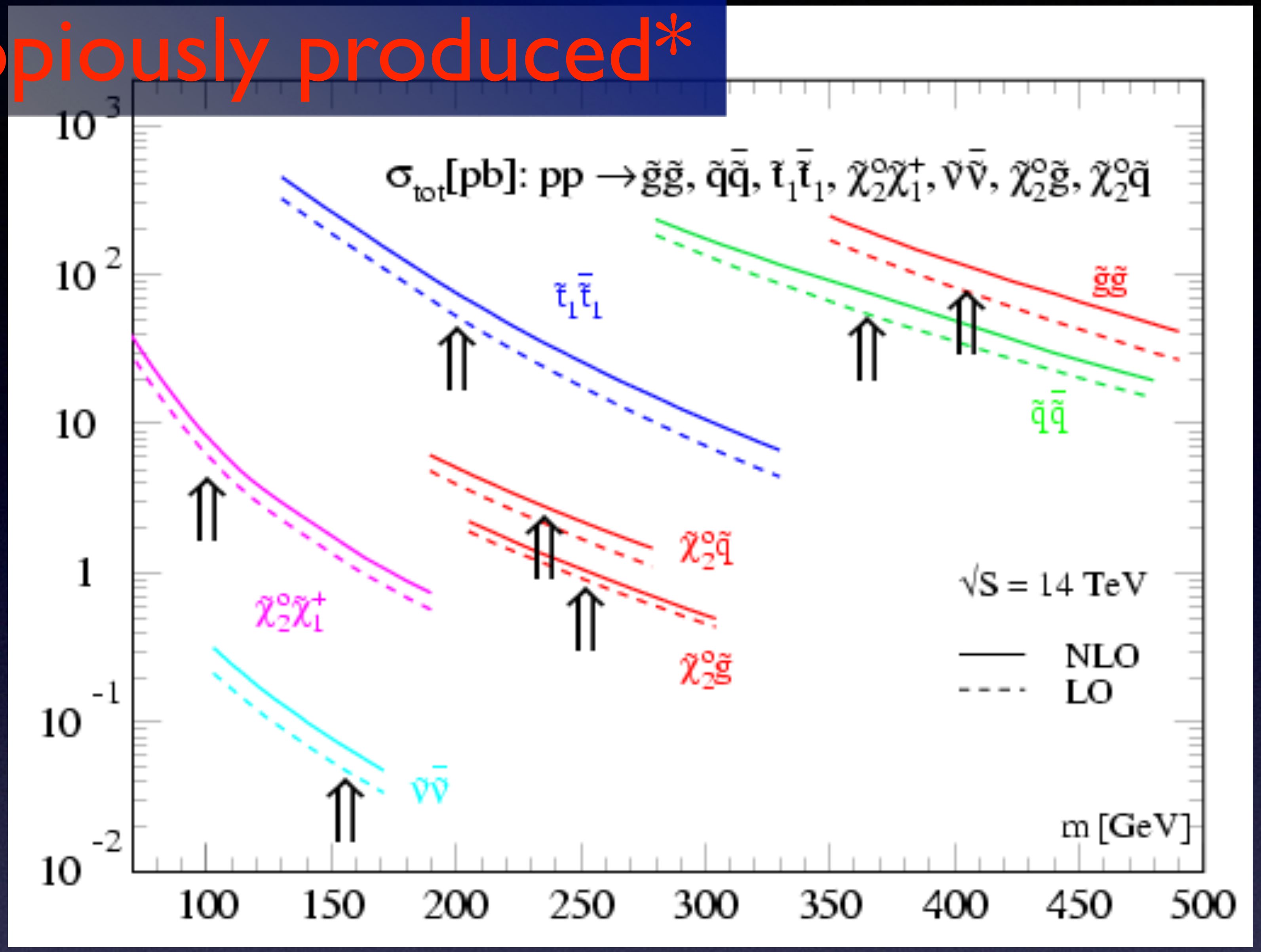


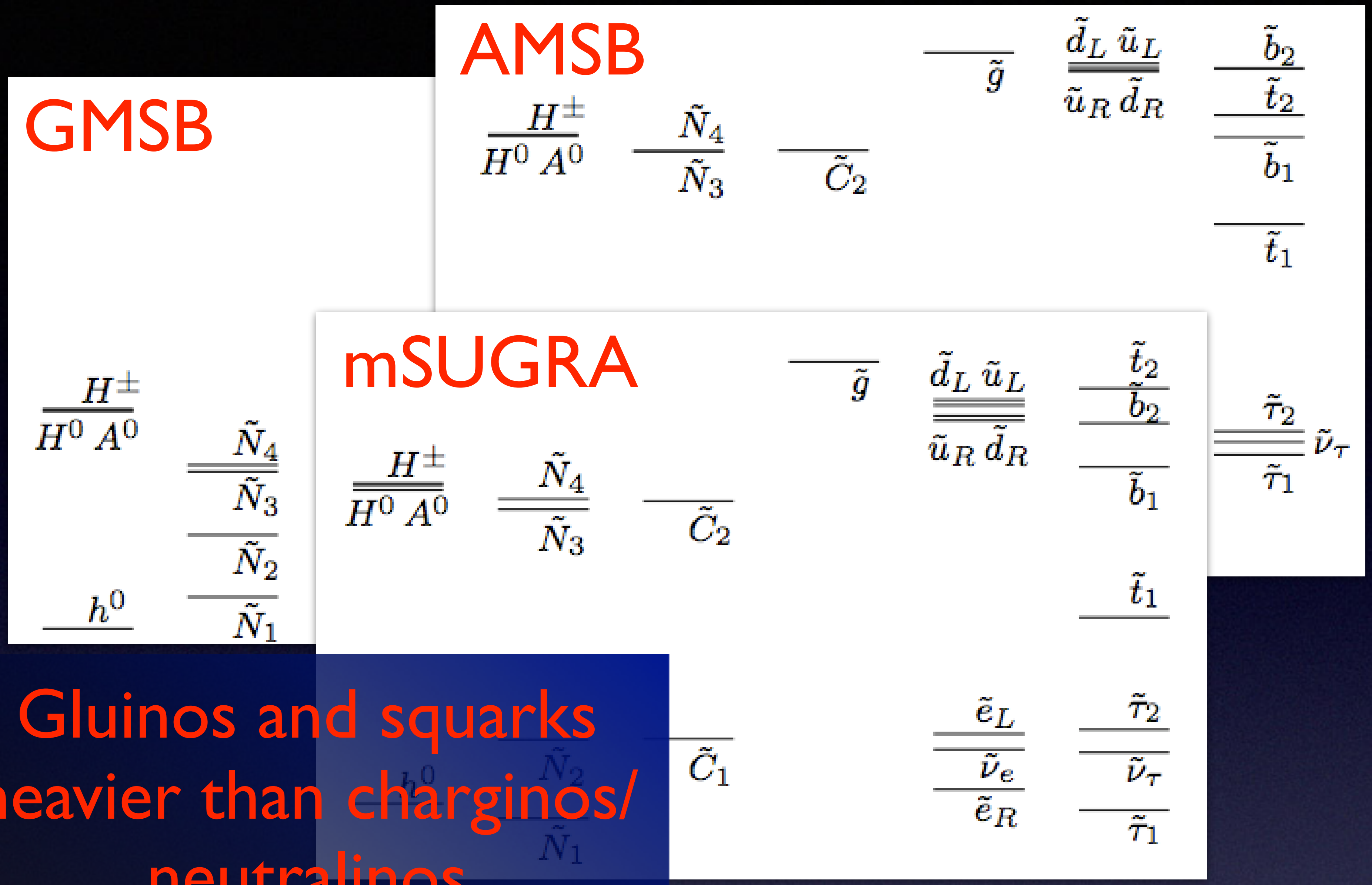
$\tilde{g}$
g
$\tilde{\chi}_1^0$
(a)
$\tilde{g}$
q
$\bar{q}$
$\tilde{q}$
$\tilde{\chi}_1^0$
(b)
$\tilde{g}$
q
$\bar{q}$
W
$\tilde{q}$
$\tilde{\chi}_1^\pm$
$\tilde{\chi}_1^0$
$\tilde{g}$
q
$\bar{q}$
W
W
$\tilde{q}$
$\tilde{\chi}_1^\pm$
$\tilde{\chi}_2^0$
$\tilde{\chi}_1^0$


ATLAS
EXPERIMENT
http://atlas.ch

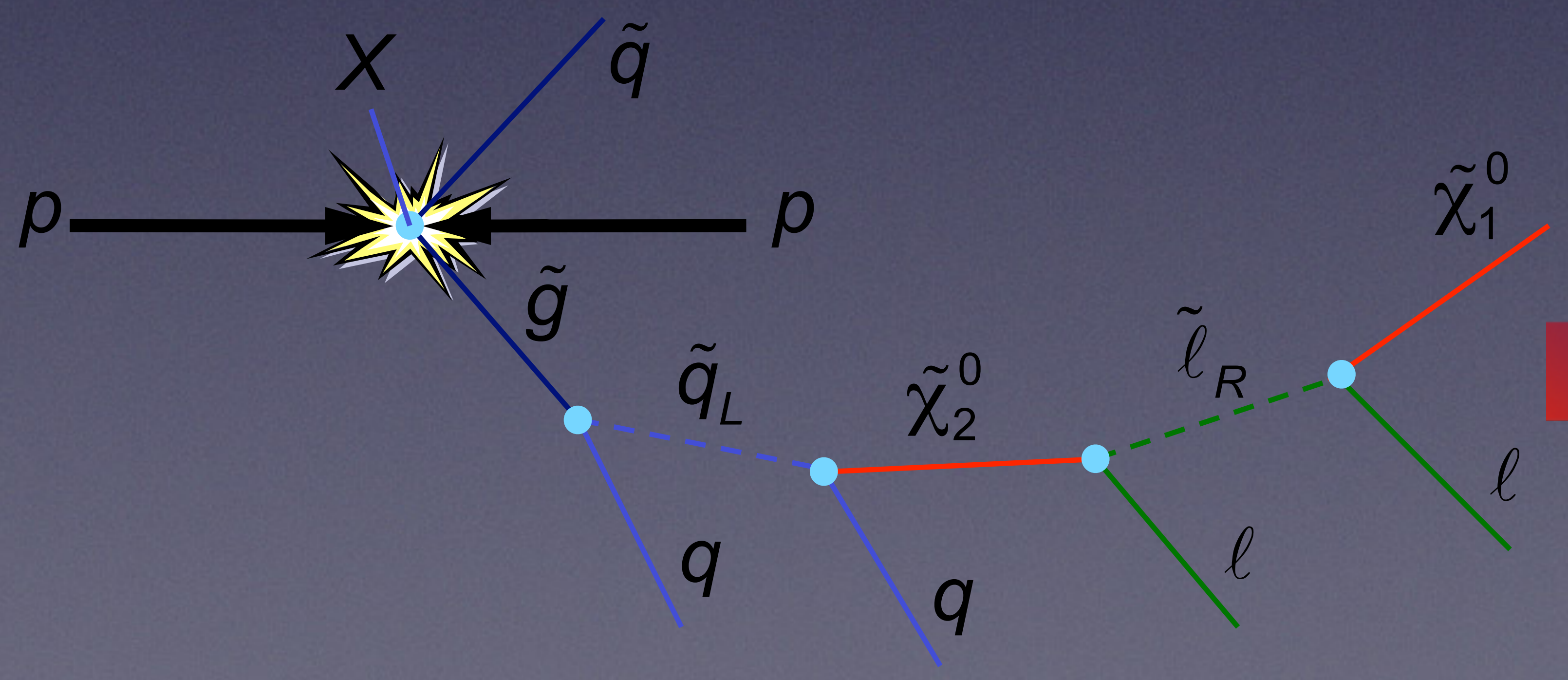
SUSY at LHC

Gluinos and squarks copiously produced*

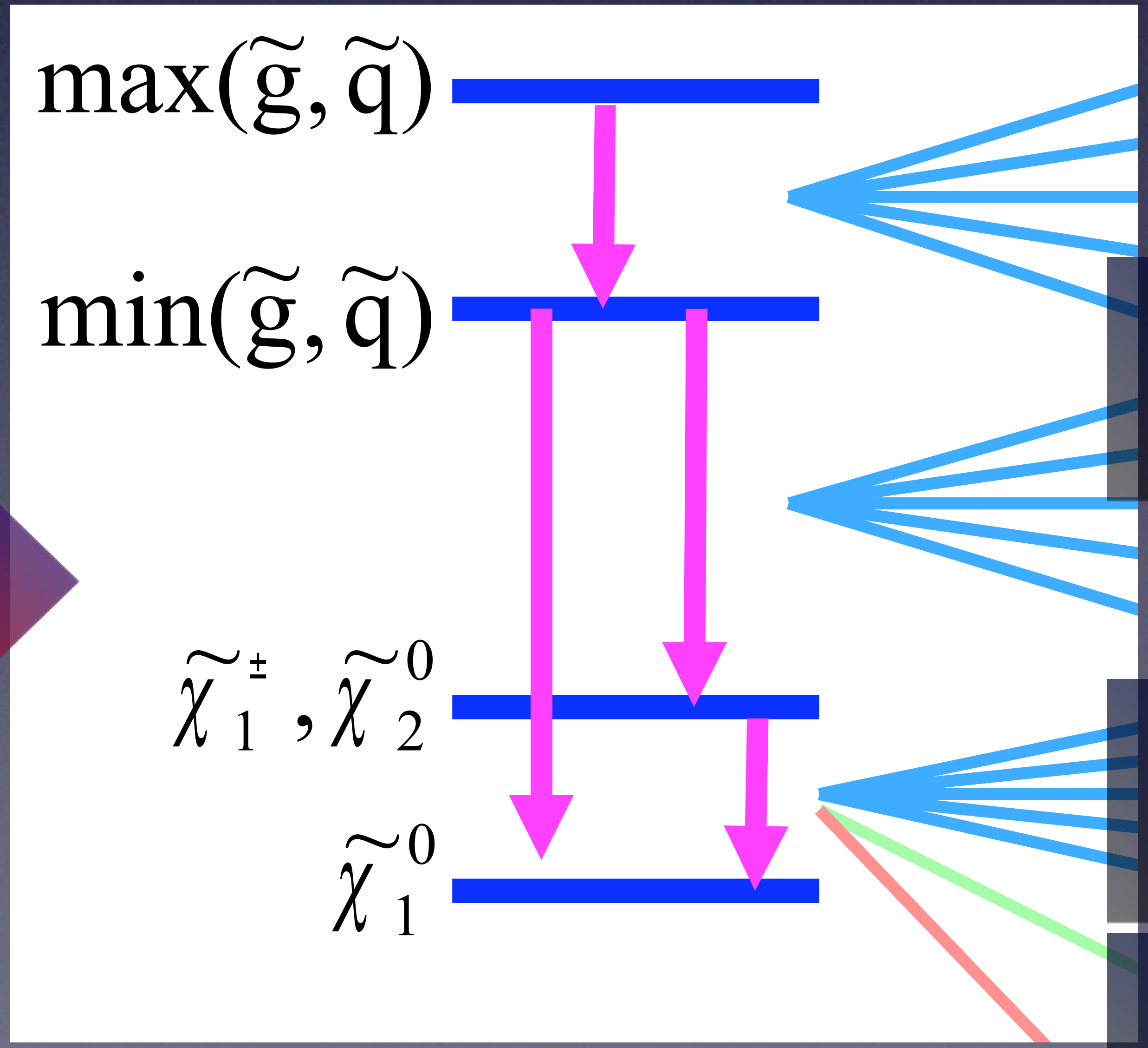




Gluinos and squarks heavier than charginos/ neutralinos



Long Cascades



Many Jets (100’s of GeV)

Leptons (10’s of GeV)

Missing Energy (100’s of GeV)

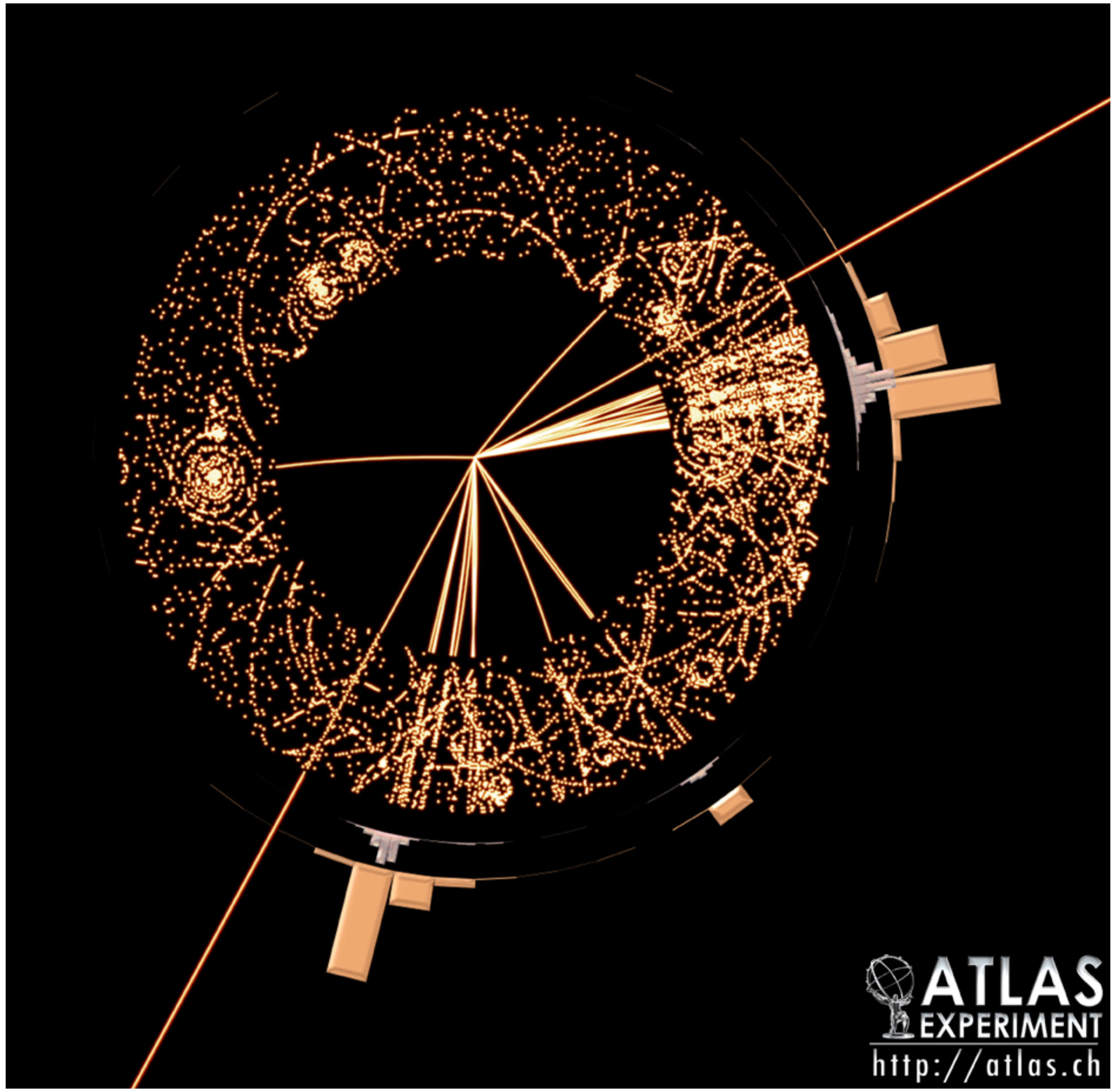
Inclusive Signatures

Signature	Motivating Model(s)	Comments
1 Jet + 0 Lepton + MET	• Large Extra Dim (ExoGraviton) • strong qG production, G propagate in extra Dim • Planck Scale is MD in 4+δ dim • Normal Gravity >> R • SUSY • qg→ISR + 2 Neutralino or squark + Neutralino	• 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	• Squark/gluino production • squark→q+LSP, gluino→q+squark+LSP	• Possible leading squark/gluino discovery channel • Must manage QCD bkg
2,3,4 [b]-Jet + 1 Lepton + MET	• squark/gluino production with cascades which include electroweak (or partner) decays • high tan β leads to more b/t/τ's	• Lepton requirement suppresses QCD • τ's partially covered by e/μ
2 lepton + MET	• 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	• Reduced SM backgrounds for same sign • Opposite Sign-Flavor Subtraction
3 lepton + MET	• SUSY events ending in Chargino/neutralino pair decays • Weak Chargino/Neutralino production • Exotic sources	• Low SM bkgs
2 photon + MET	• GMSB models with gravitino LSP and neutralino or stau NLSP • UED- each KK partons cascade to LKP which decays to graviton + γ	• No SUSY limit (not sensitive at the time)

SUSY/Higgs Data

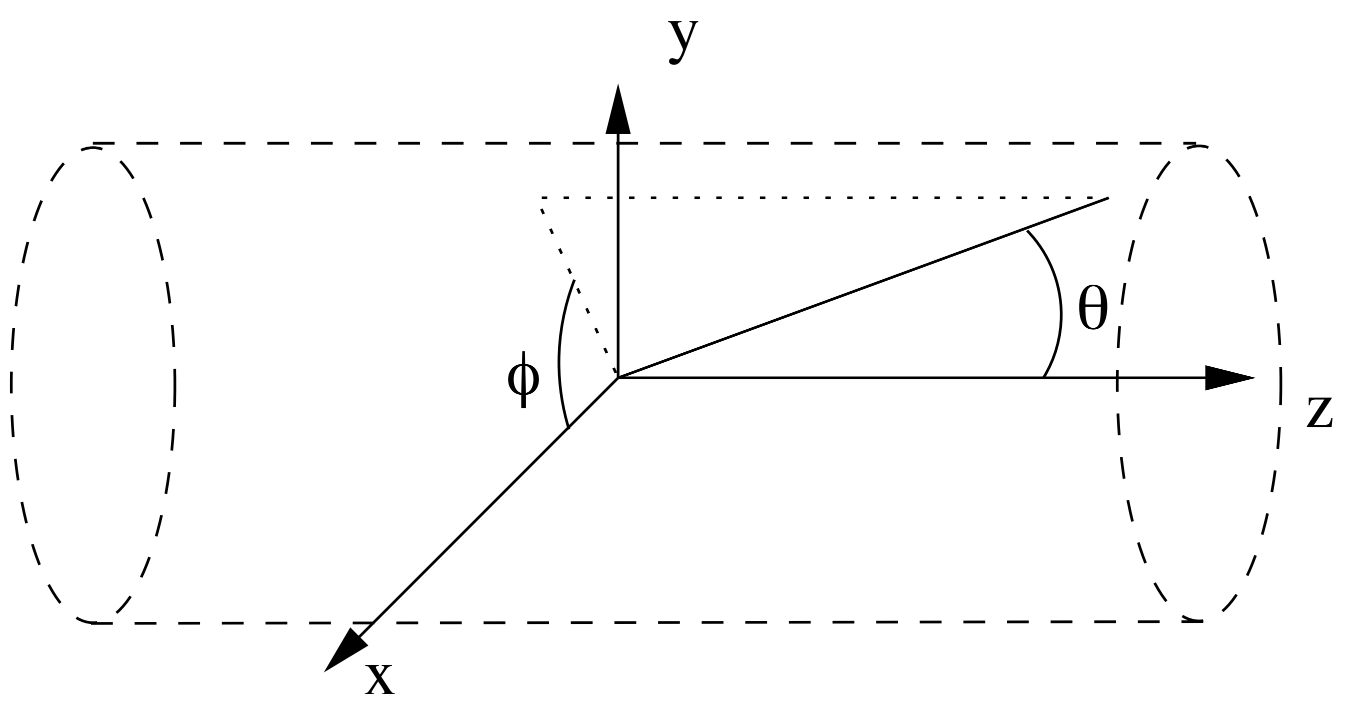
LHC Event

- 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 process up to a level where every event consists of:
  - List of particle candidates, each with their momenta: electrons, photons, muons, electrons, 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,
  - Feaures: 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_lv), lepton+jet+neutrino (m_jlv), 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.

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

    - 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.