New Physics in the LHC Era

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$\tilde{B}$

$\widetilde{W}$

Pheno 2011

May 9, 2011

$\tilde{g}$

with M. Lisanti, J. Alwall, M-P Le, E. Izaguirre, M. Manhart, D. Alves, R. Essig & J. Kaplan

arXiv: 0803.0019, 0809.3264, 1003.3886, 1008.0407, 1102.5338, 1105.XXX

Outline

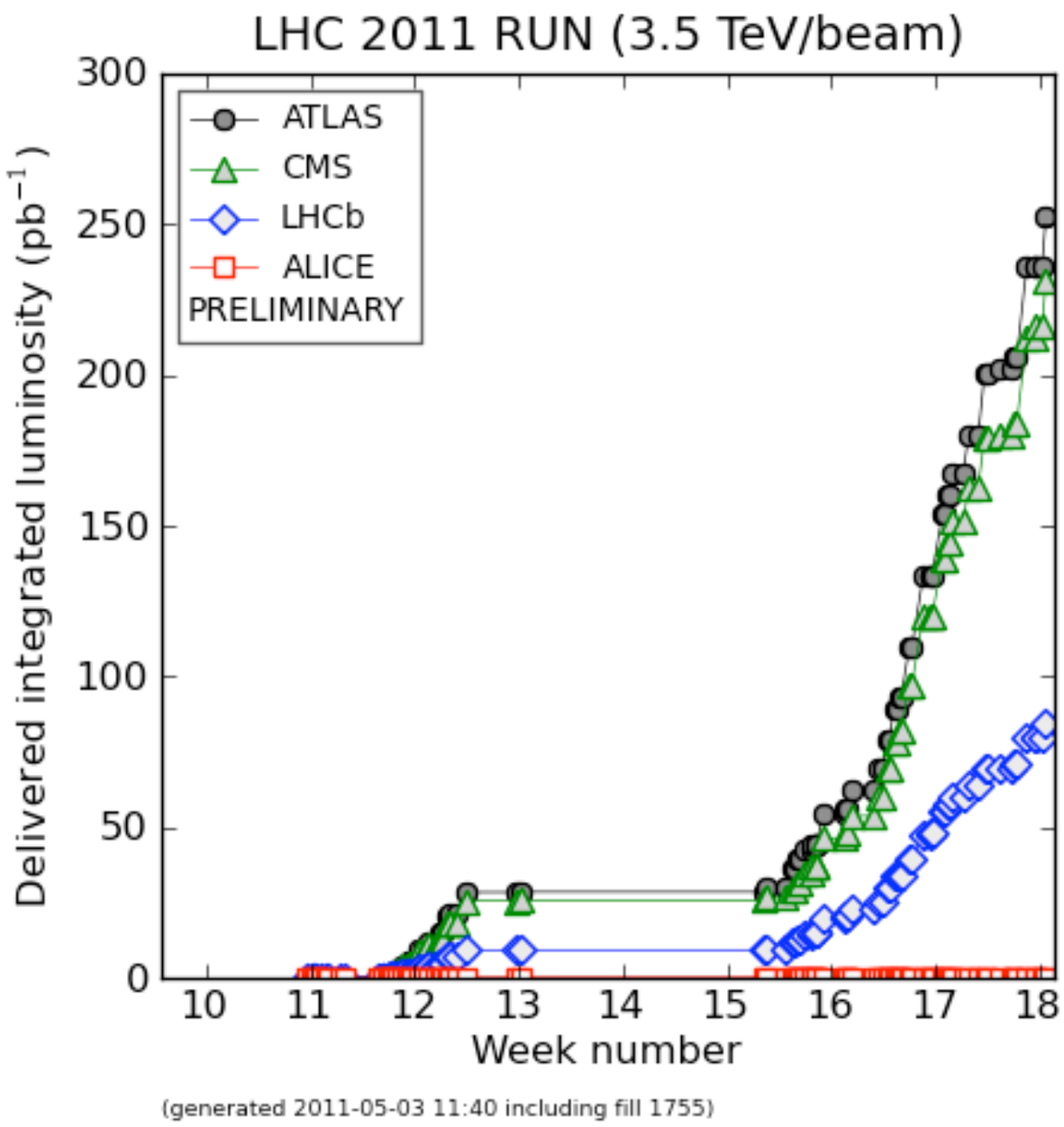
The Discovery Era

Simplified Models

Using Simplified Models

We're entering the Inverse Femtobarn Era!

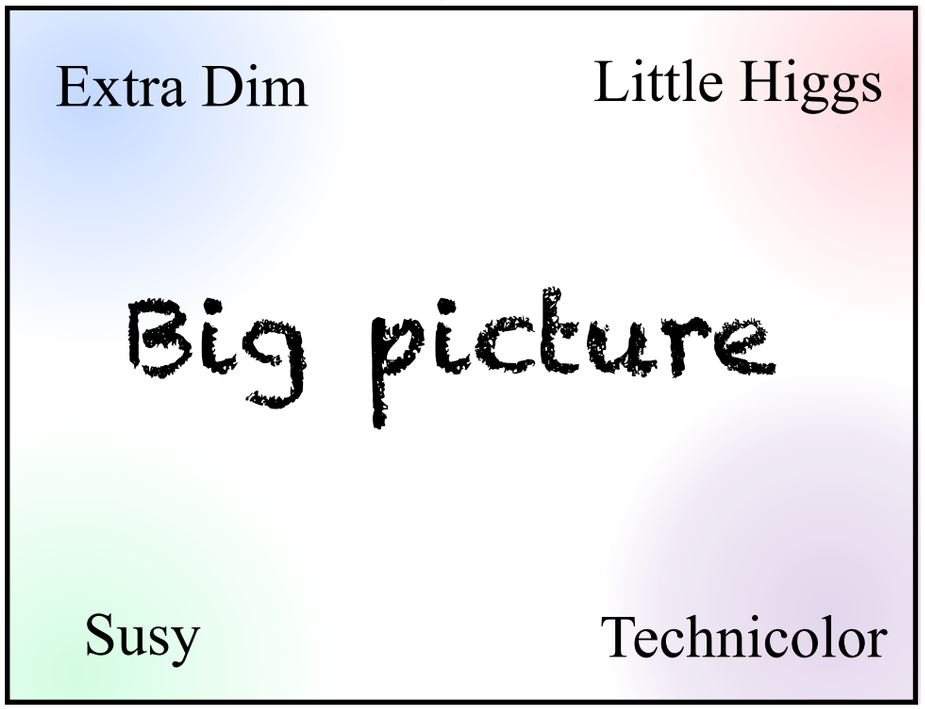
40/pb let the LHC push pass the Tevatron,
1/fb will rewrite the what we know about BSM theories



It's Discovery Time!

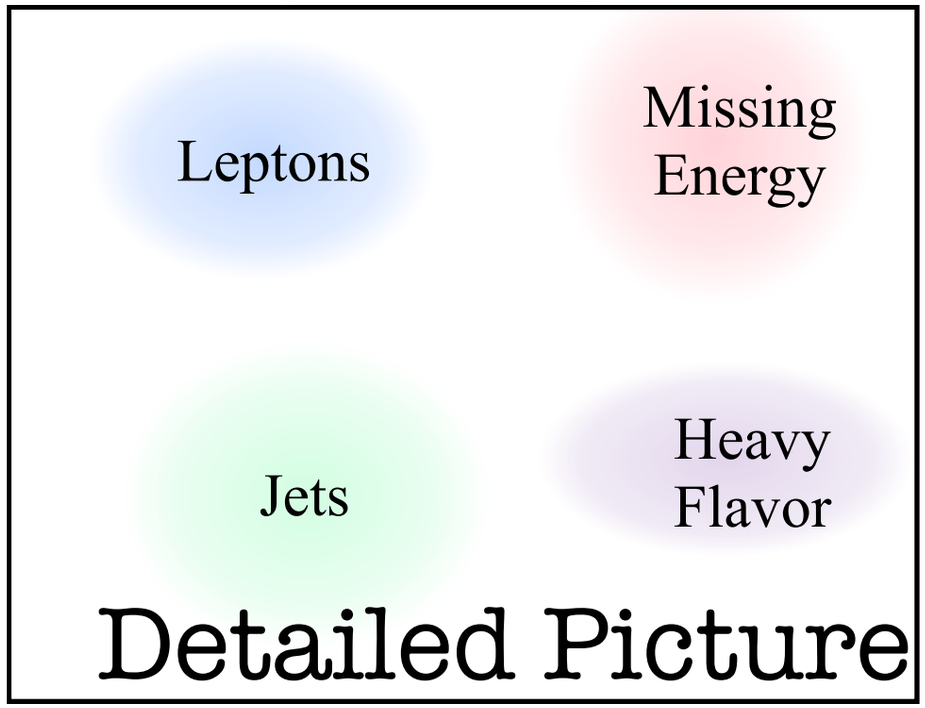
How to make sure that no stone is unturned?

Theory Space



Constructing Signature Space
from Theory Space
not easy/efficient

Signature Space



Need axes for
Theory Space to map into
Signature Space

Supersymmetry as an example

Too many parameters so we make an ansatz

$$m_{\frac{1}{2}}, m_0^2, A_0, B_\mu, \mu$$

$$B_\mu, \mu \to v_{\rm EW} = 246 \text{ GeV}, \tan\beta$$

Gaugino Masses

$$\frac{d}{dt} M_a = \frac{1}{8\pi^2} b_a g_a^2 M_a$$

Scalar Masses

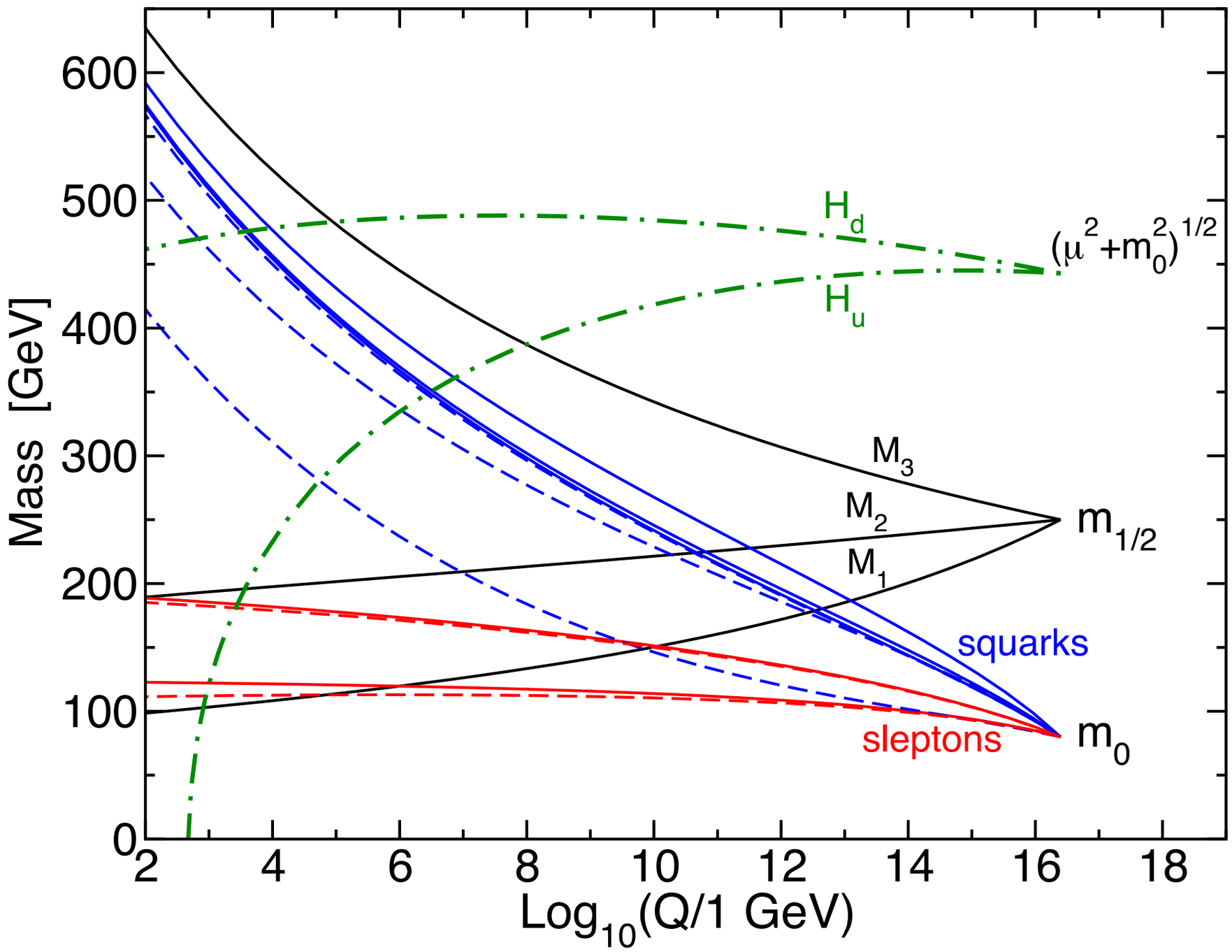
$$\begin{aligned} 16\pi^2 \frac{d}{dt} m_{Q_3}^2 &= X_t + X_b \\ &- \frac{32}{3} g_3^2 |M_3|^2 - 6 g_2^2 |M_2|^2 \\ &- \frac{2}{15} g_1^2 |M_1|^2 + \frac{1}{5} g_1^2 S, \end{aligned}$$

Gauge interactions make particles heavier

Yukawa interactions make particles lighter

Typical mSUGRA Spectrum

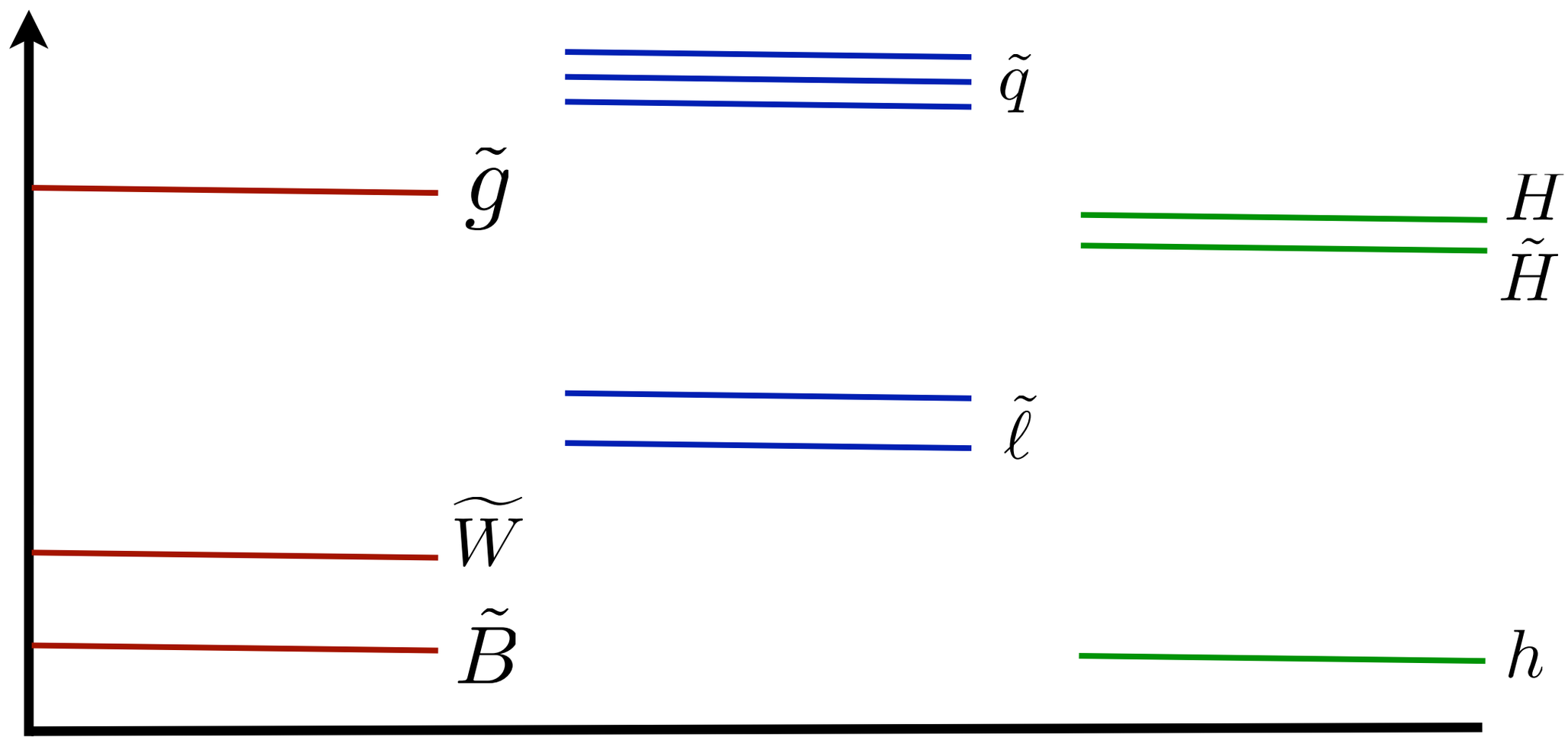
	Principle	Fine	HyperFine
Structure:	$SU(3)_c$ Charged	$SU(2)_L$ Charged	3rd Generation
	Heavier	Heavier	Lighter



mSugra and "Gaugino Mass Unification"

$$m_{\tilde{g}} : m_{\tilde{W}} : m_{\tilde{B}} = \alpha_3 : \alpha_2 : \alpha_1 \simeq 6 : 2 : 1$$

Most models look like this



Diversity is whether squarks & Higgsinos are lighter than gluinos and sleptons are lighter than the winos

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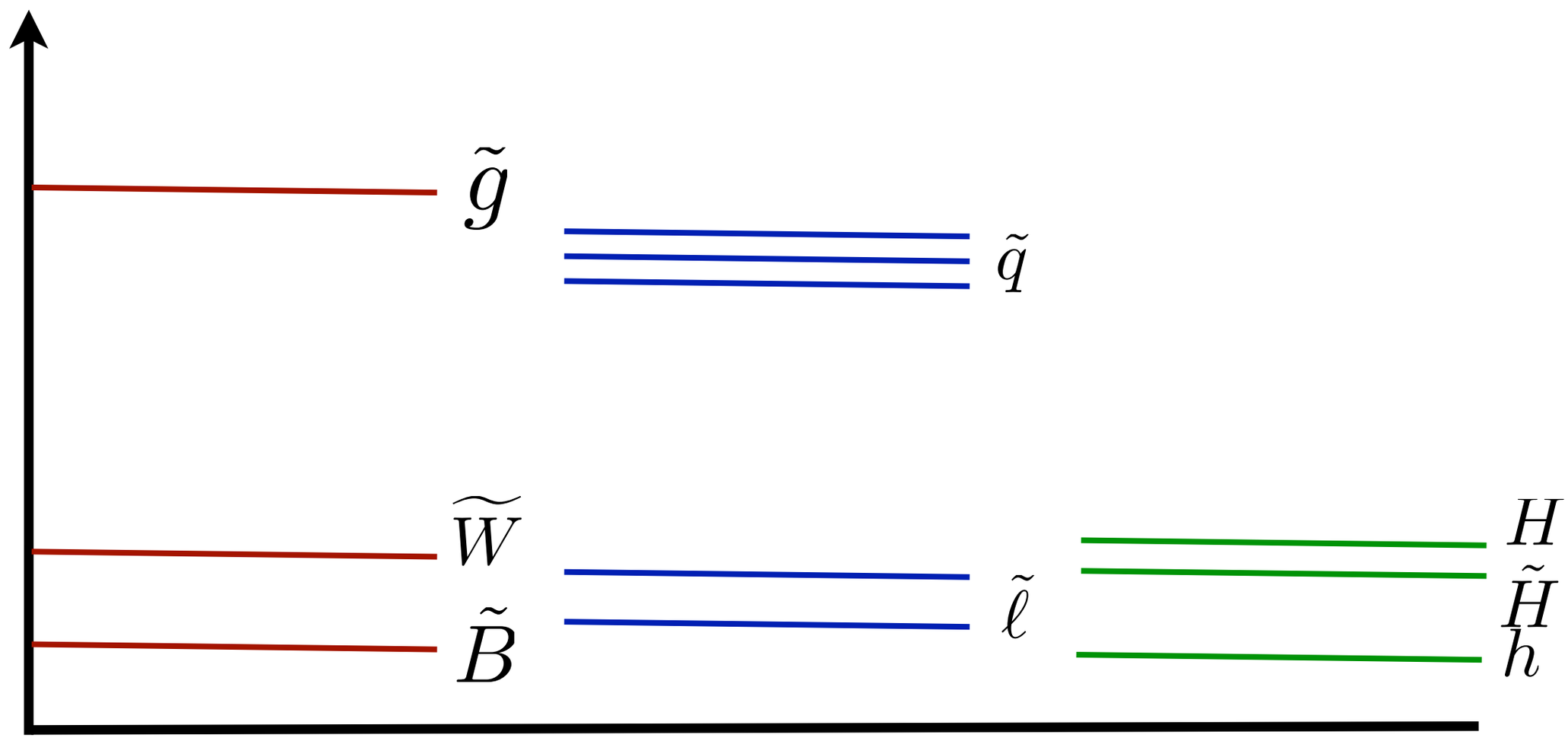

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The Phenomenological MSSM

The part of parameter space that was allowed circa 1981

$m^2_{\tilde{q}}, m^2_{\tilde{u}^c}, m^2_{\tilde{d}^c}, m^2_{\tilde{\ell}}, m^2_{\tilde{e}^c}$ — 5 for 1st 2 Generations
5 for 3rd Generations

$m_{\tilde{g}}, m_{\tilde{W}}, m_{\tilde{B}}, \mu$ — 4 for *-ino masses

A_t, A_b, A_τ — 3 for A-terms

$m^2_{h_u}, m^2_{h_d}, B_\mu$ — 3-1 for Higgs Sector

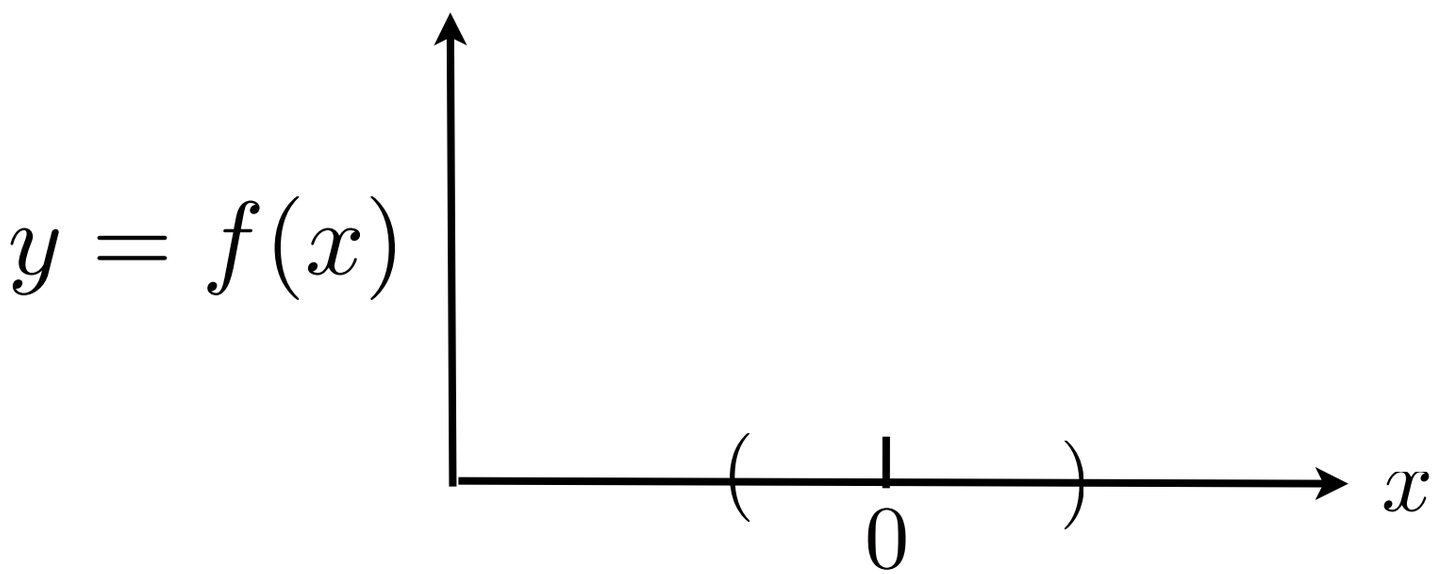
19 Dimensional Parameter Space

Challenging to explore in detail: $2^{19} \sim 0.5$ Million

Berger, Gainer, Hewett, Rizzo

Imagine a simpler world...

Theory of nature is a one parameter function, *y=f(x),*
Can only do measurements of *y* near *x=0* that we don't know



A very complicated space to explore!

∞-dimensional

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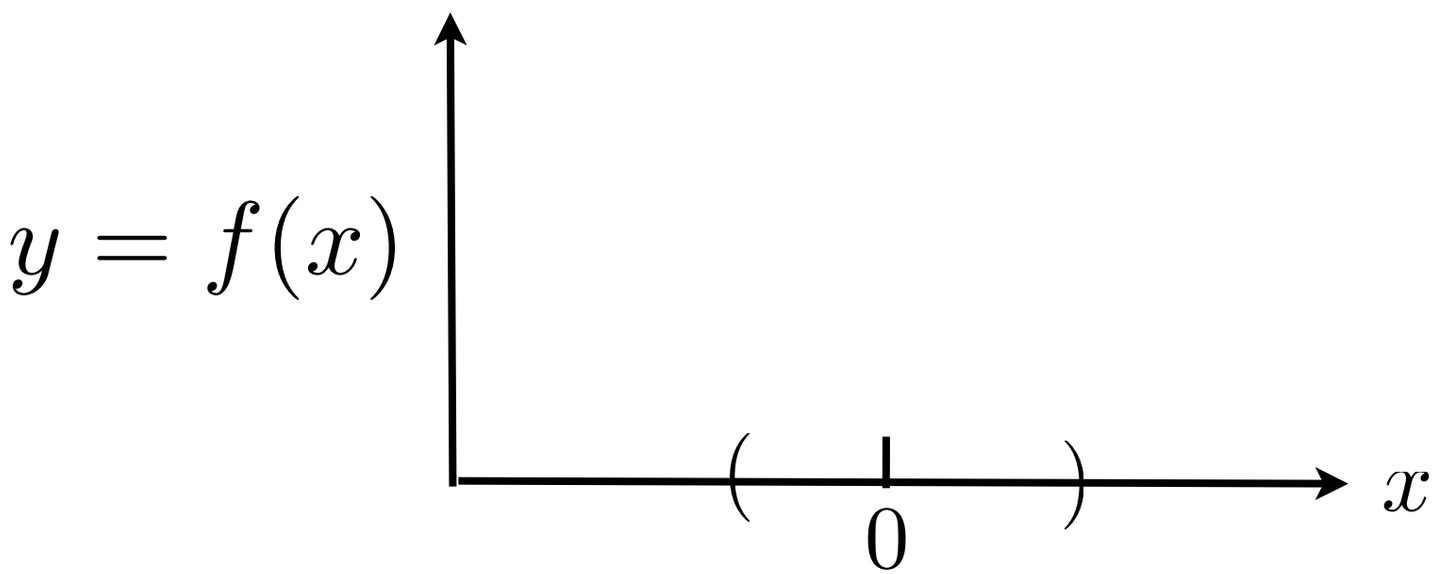

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∞-dimensional

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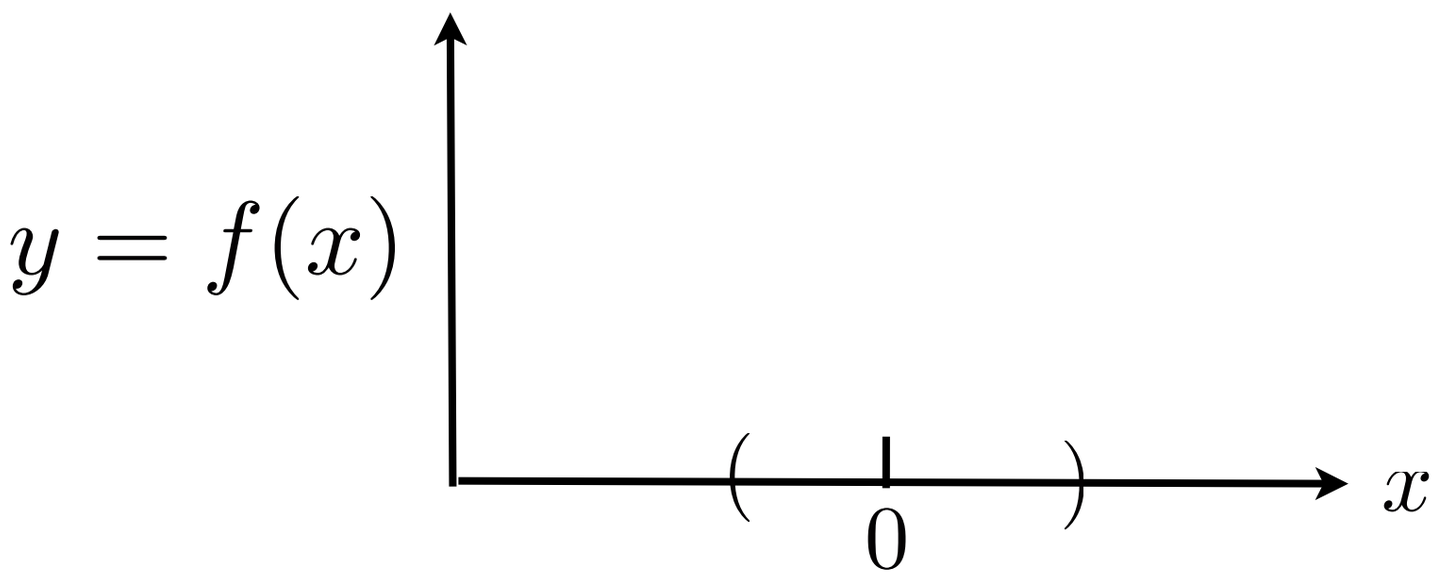

A very complicated space to explore!

∞-dimensional

In this world, the leading theory is $f(x) = e^{\alpha(x-x_0)}$

Could design a measurement strategy to discover

$$f(x) \neq 0,\ \alpha,\ x_0$$

Problem with this strategy

What happens if we're wrong about
our theoretical assumption?

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$$f(x) = -e^{\alpha(x-x_0)}$$

f(x) is negative

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f(x) is negative

$$f(x) = \sinh(x)$$

f(x) vanishes at 0

Problem with this strategy

What happens if we're wrong about
our theoretical assumption?

$f(x) = -e^{\alpha(x-x_0)}$	*f(x)* is negative
$f(x) = \sinh(x)$	*f(x)* vanishes at 0
$f(x) = \cos(x)$	Doesn't grow asymptotically

Problem with this strategy

What happens if we're wrong about
our theoretical assumption?

$$f(x) = -e^{\alpha(x-x_0)}$$ *f(x)* is negative

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$$f(x) = \cos(x)$$ Doesn't grow asymptotically

Could enumerate all possibilities

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$$f(x) = \sinh(x)$$ *f(x)* vanishes at 0

$$f(x) = \cos(x)$$ Doesn't grow asymptotically

Could enumerate all possibilities

<u>A better strategy</u>

$$f(x) = a_0 + a_1 x + a_2 x^2 + \cdots$$

Easy to identify special cases

Not a cure-all

Still infinite dimensional

But there is some notion of simplicity

$f(x) = -x^6 + x^{12}$ less likely than $f(x) = 1$

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There could be technicalities:

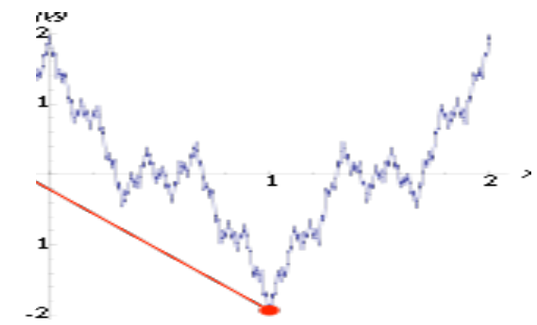
Radius of convergence problems

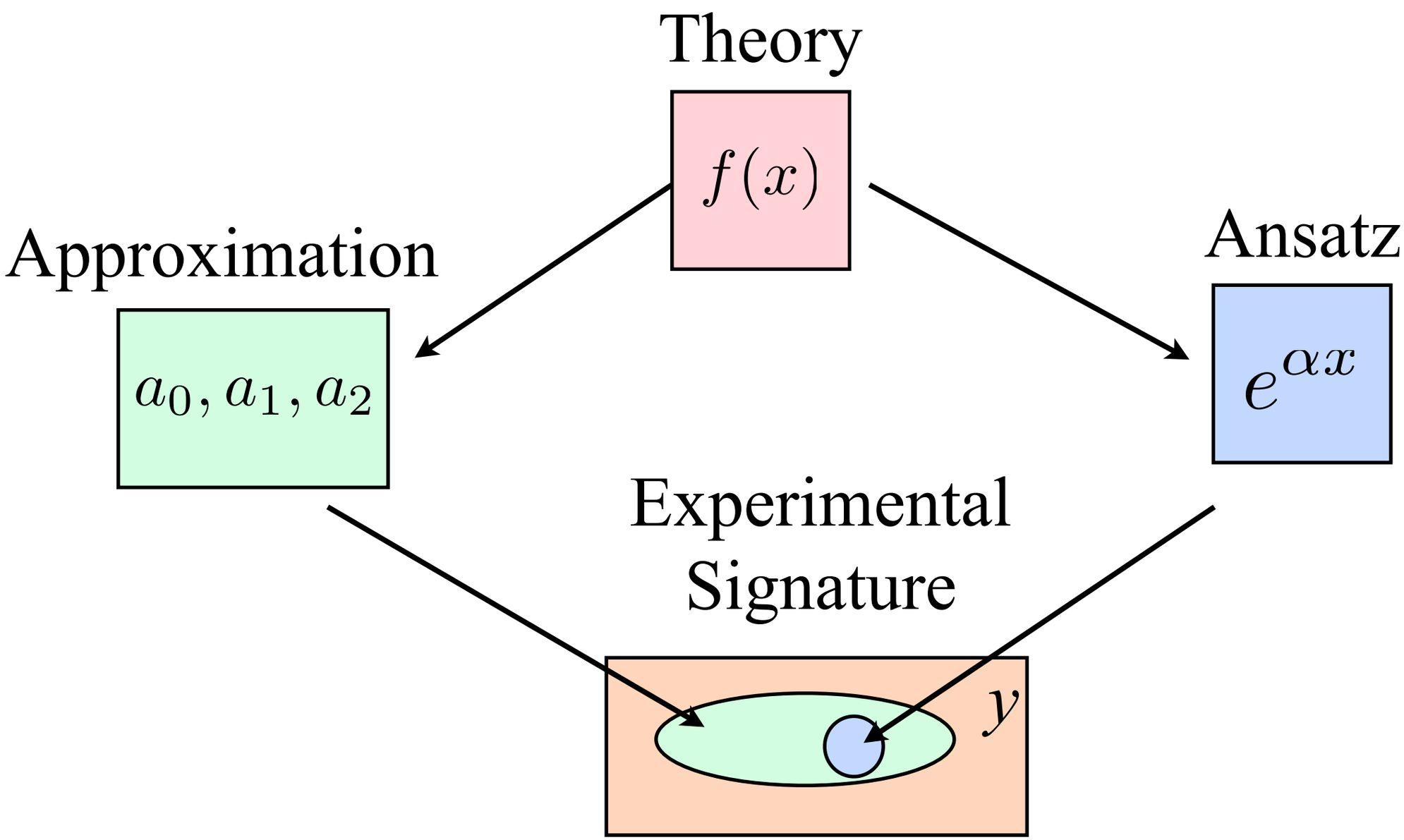
$$f(x) = \log(1 + x)$$

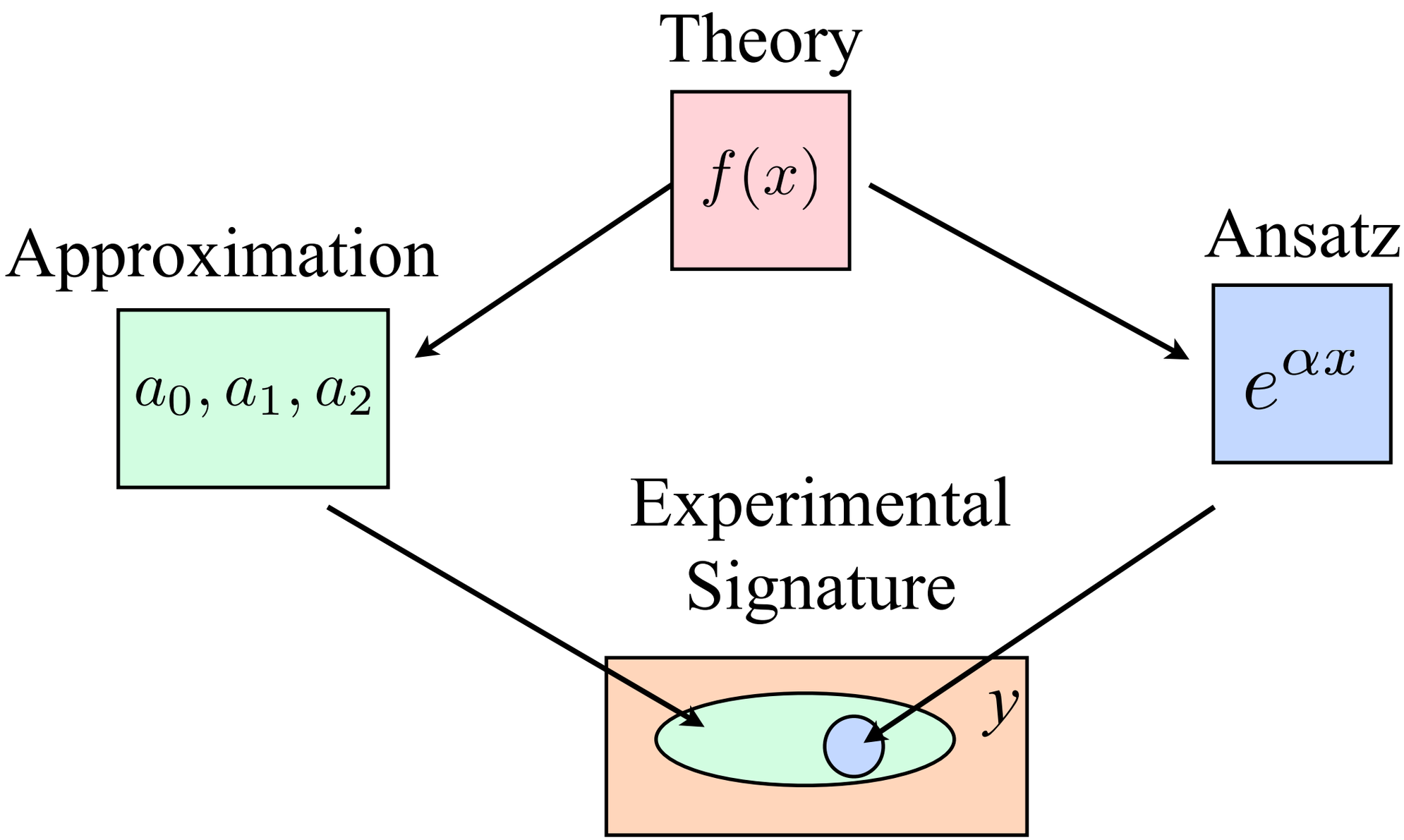
Assumes the function is continuous/differentiable

$$f(x) = \Theta(x)$$

$$f(x) = \sum_{n=0}^{\infty} a^n \cos(b^n \pi x)$$



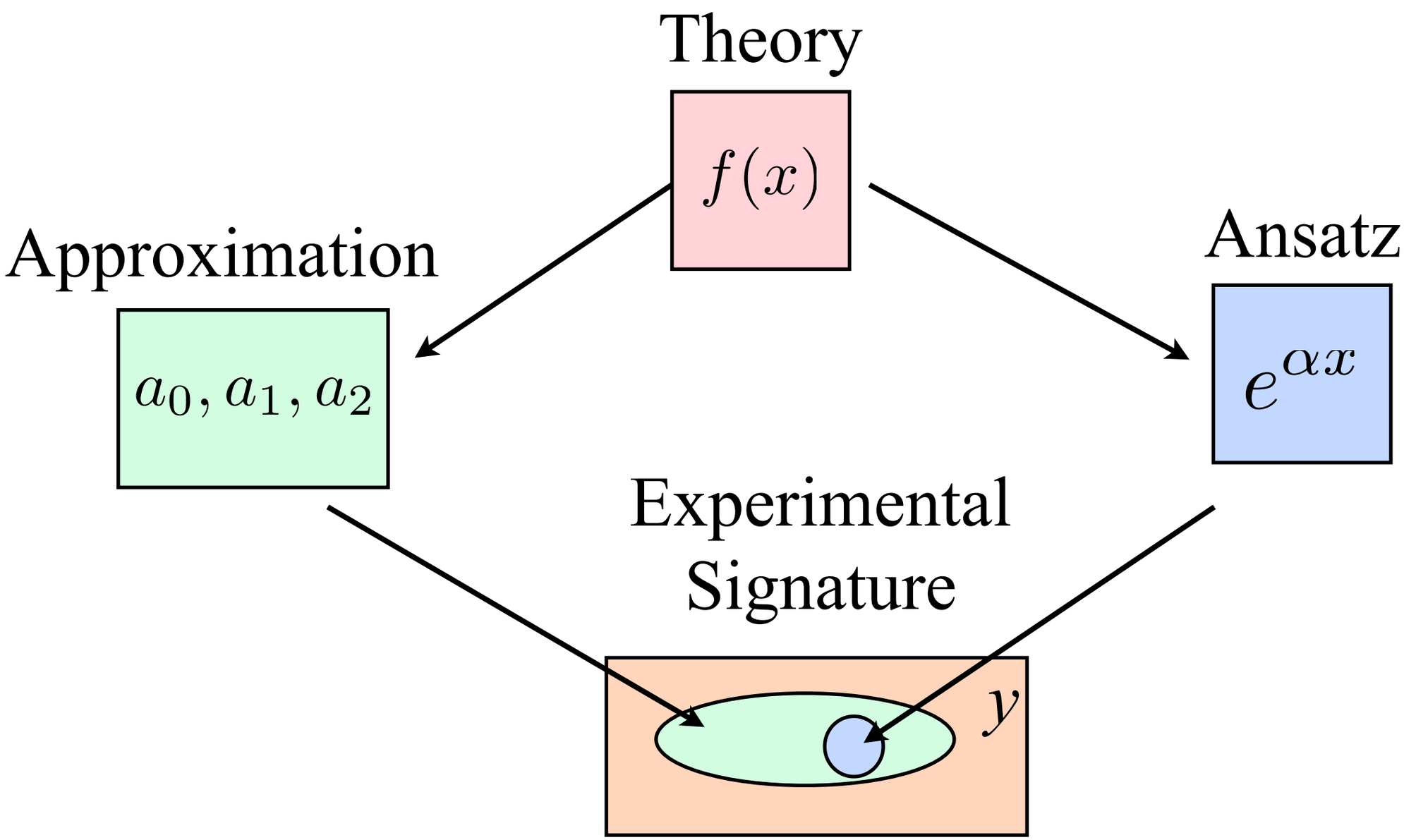

Theory
$f(x)$
Approximation
a_0, a_1, a_2
Ansatz
$e^{\alpha x}$
Experimental Signature
y



f(x) = All theories beyond the Standard Model

e^x= mSUGRA

y = A typical LHC observable, *e.g.* Missing Energy



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What is the systematic approximation?

Outline

The Discovery Era

Simplified Models

Using Simplified Models

Simplified Models

(Effective Field Theories for Collider Physics)

Limits of specific theories

Only keep particles and couplings relevant for searches

A full Lagrangian description

Removes superfluous model parameters

Masses, Cross Sections, Branching Ratios

Add in relevant modification to models (*e.g.* singlets)

Not fully model independent, but greatly reduce model dependence

Captures specific models

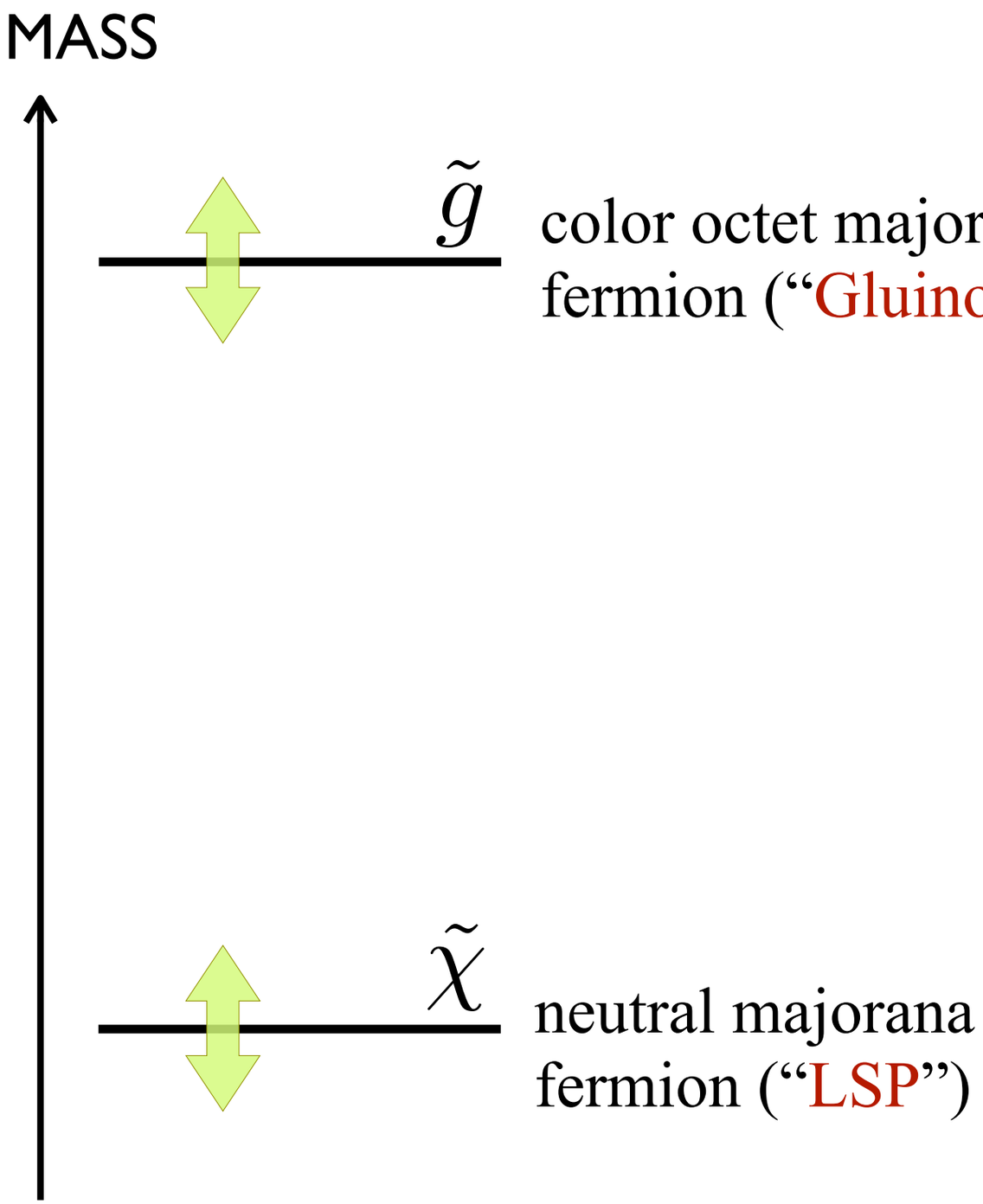
Including ones that aren't explicitly proposed

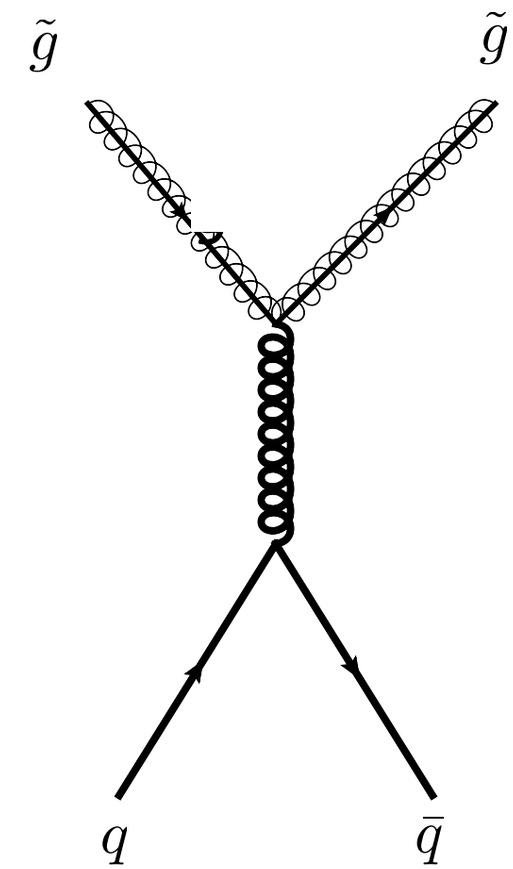
Easy to explore

Example Simplified Model

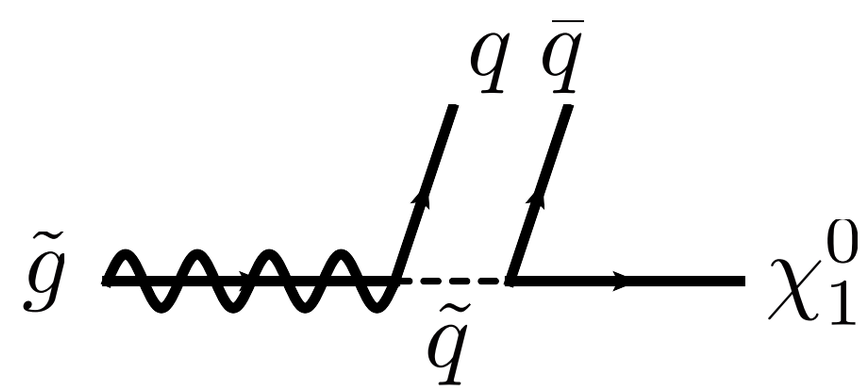
$$f(x) = a_0$$

Direct Decays





Three-Body Decay

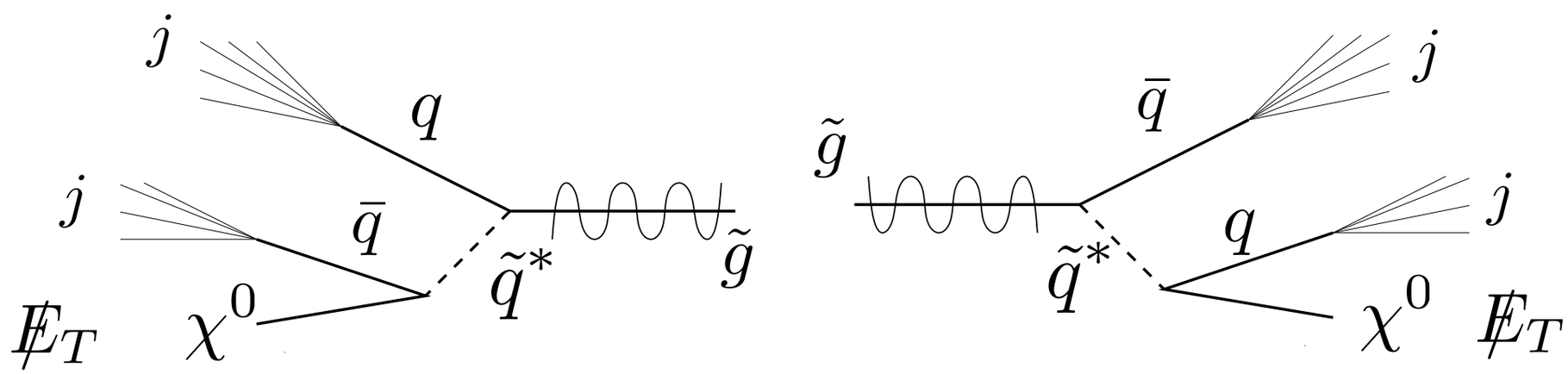


(off-shell squark that is too heavy to be seen)

Directly Decaying Gluino

Keep masses and total cross section free

$$m_{\tilde{g}} \qquad m_{\chi^0} \qquad \sigma(pp \to \tilde{g}\tilde{g}X)$$

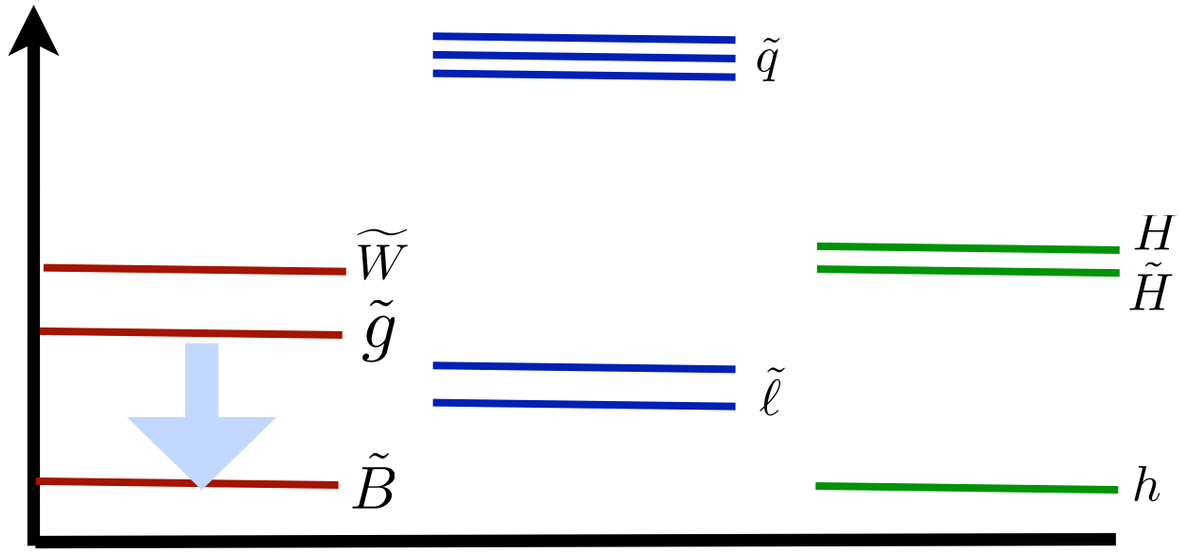


Typical signature is 4 jets plus missing energy

Directly Decaying Gluino

Study one decay mode $\tilde{g} \to q\bar{q}\tilde{\chi}^0$

Sometimes this is the exact theory



$\mathrm{Br} = 100\%$

Directly Decaying Gluino

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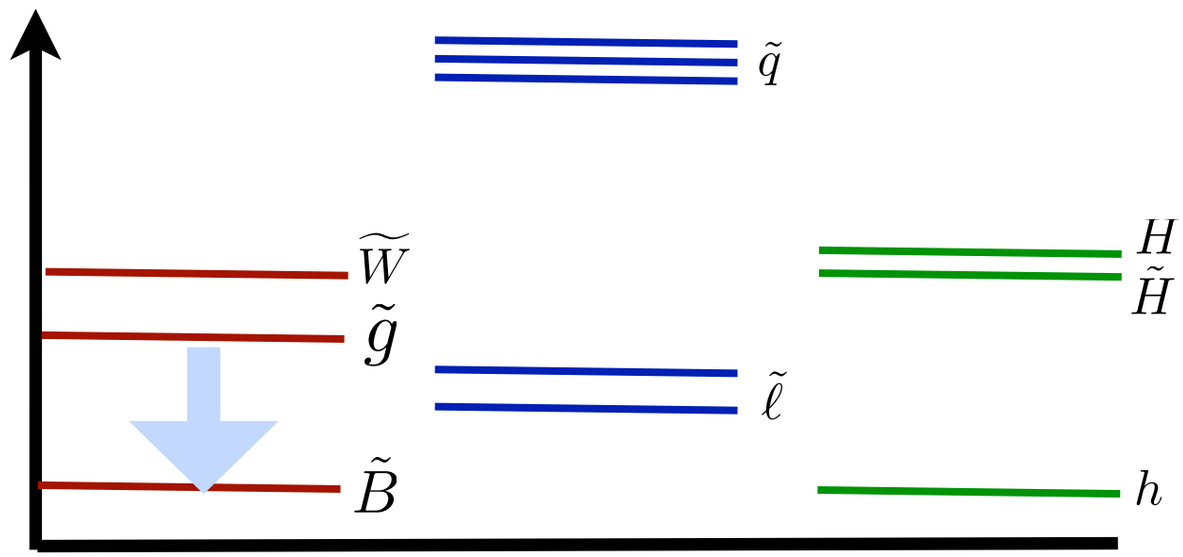
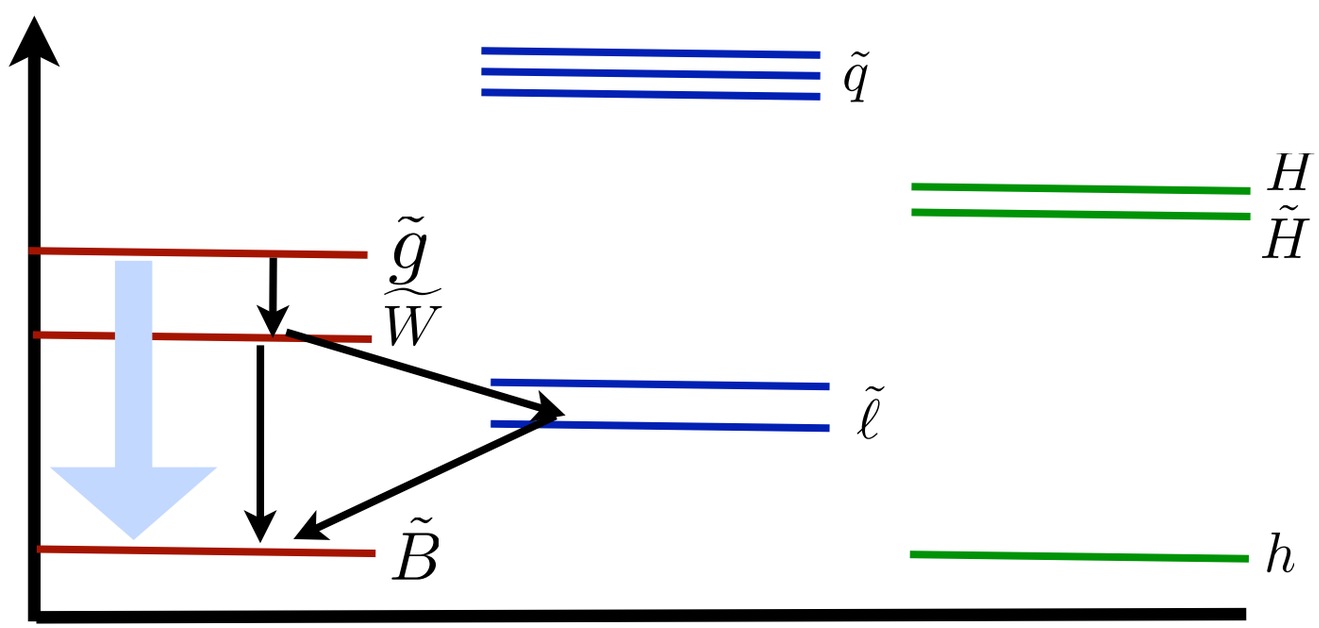


$\mathrm{Br} = 100\%$

Other times this is a subdominant branching ratio



$\mathrm{Br} \sim 10\%$

New Spectra to Consider

Imagine having a 400 GeV Gluino

mSUGRA would predict LSP is 50 GeV

4 jets of 120 GeV
130 GeV of Missing Energy

Hard to miss

LSP could have mass of 370 GeV

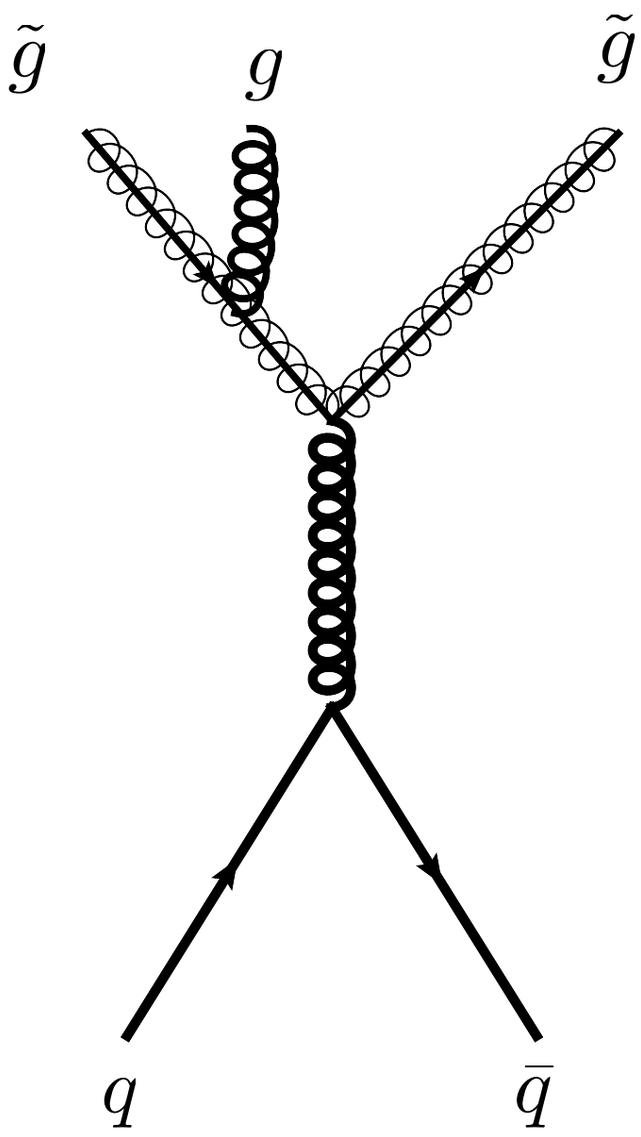
4 jets of 8 GeV
15 GeV of Missing Energy

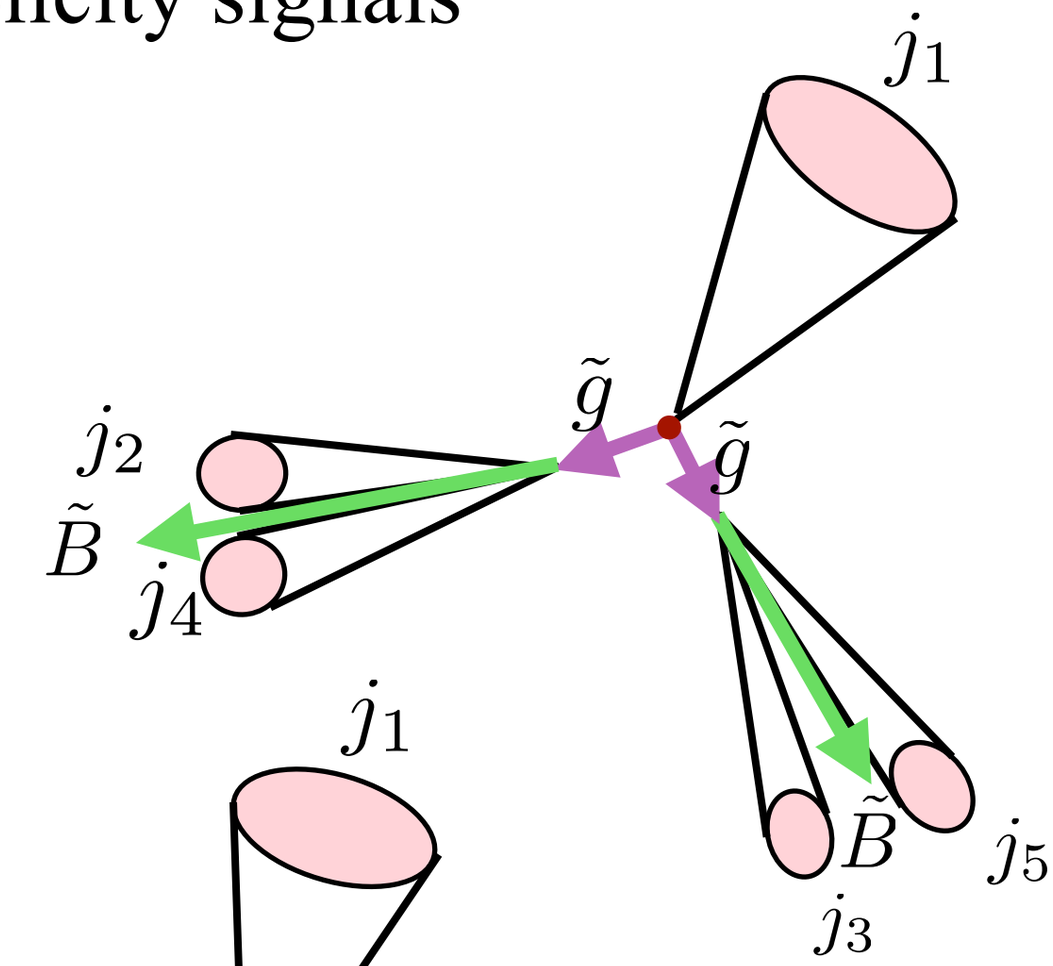
Nearly impossible to see!

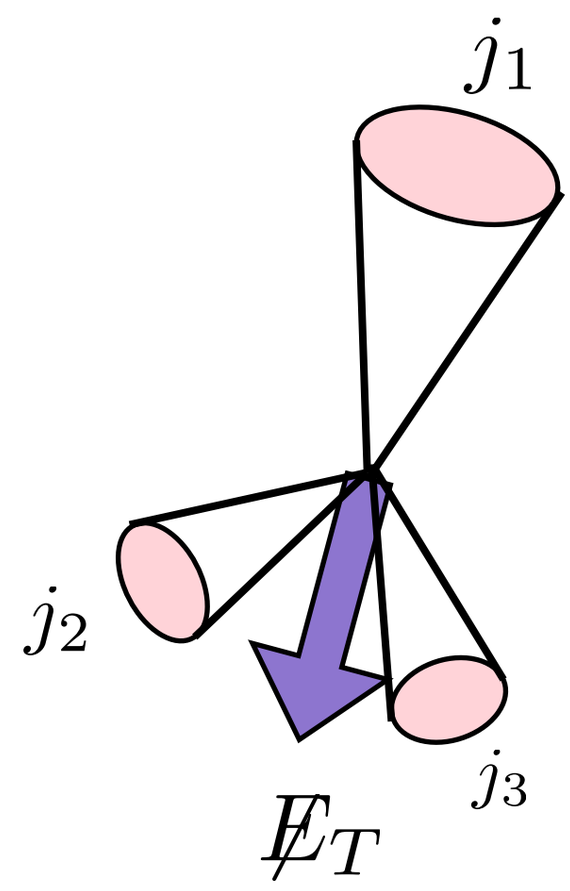
Compressed Spectra have different kinematics

Visible events use ISR/FSR

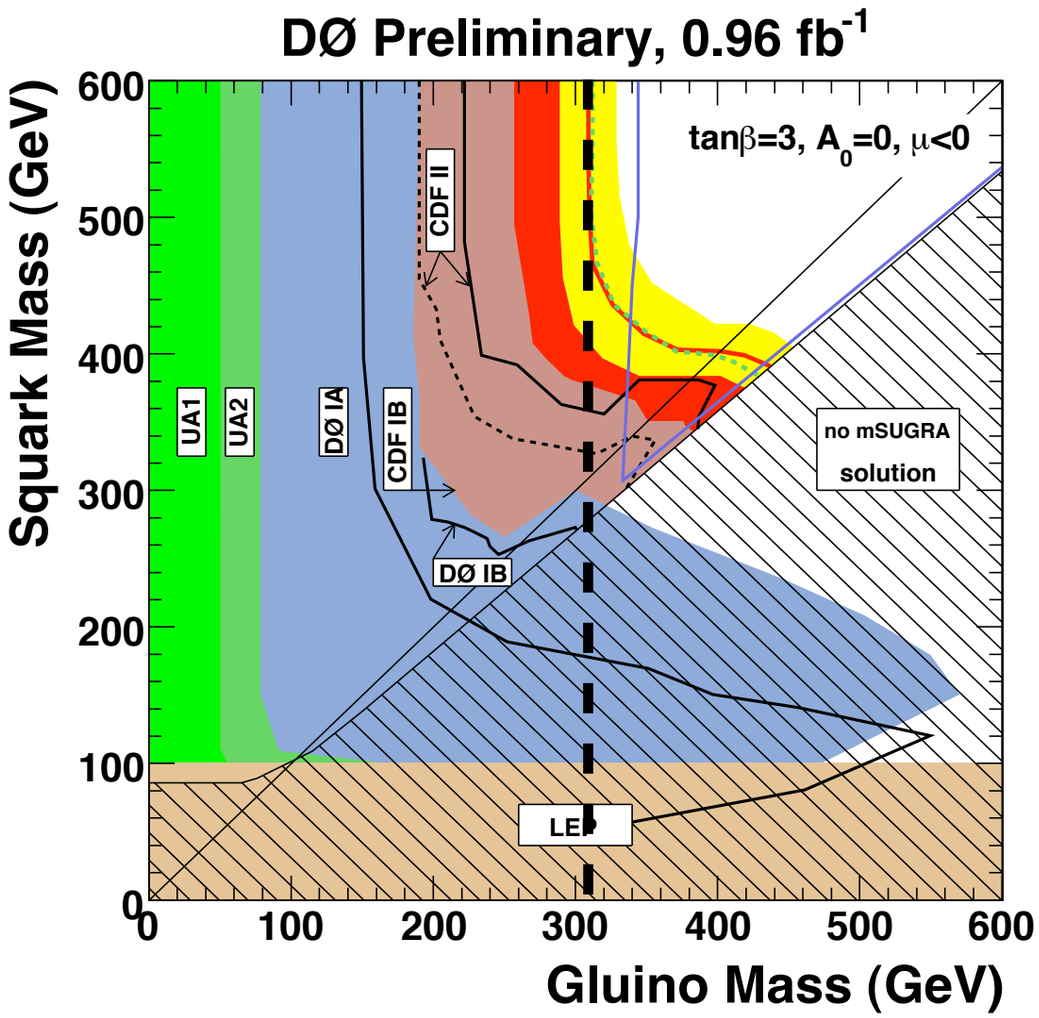
Low jet multiplicity signals

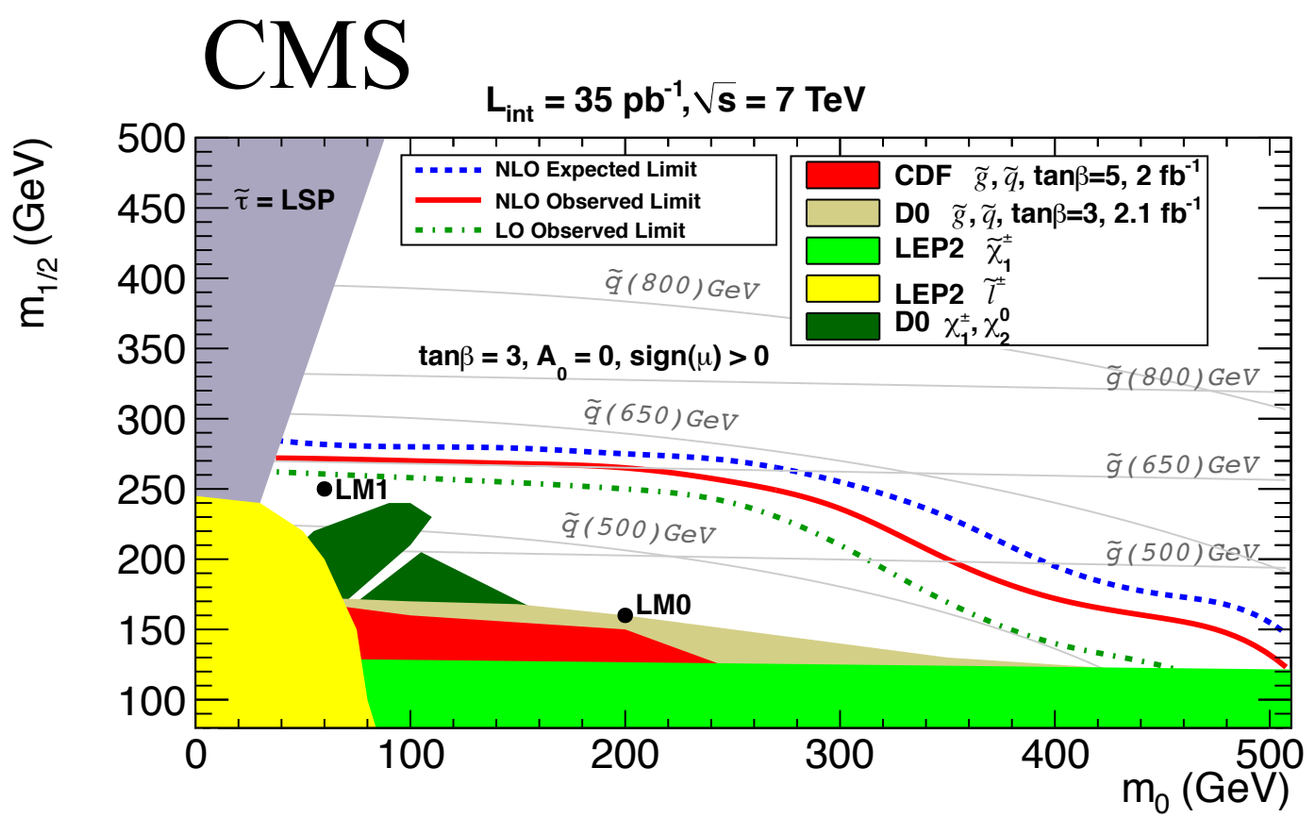






How do you interpret mSUGRA Results





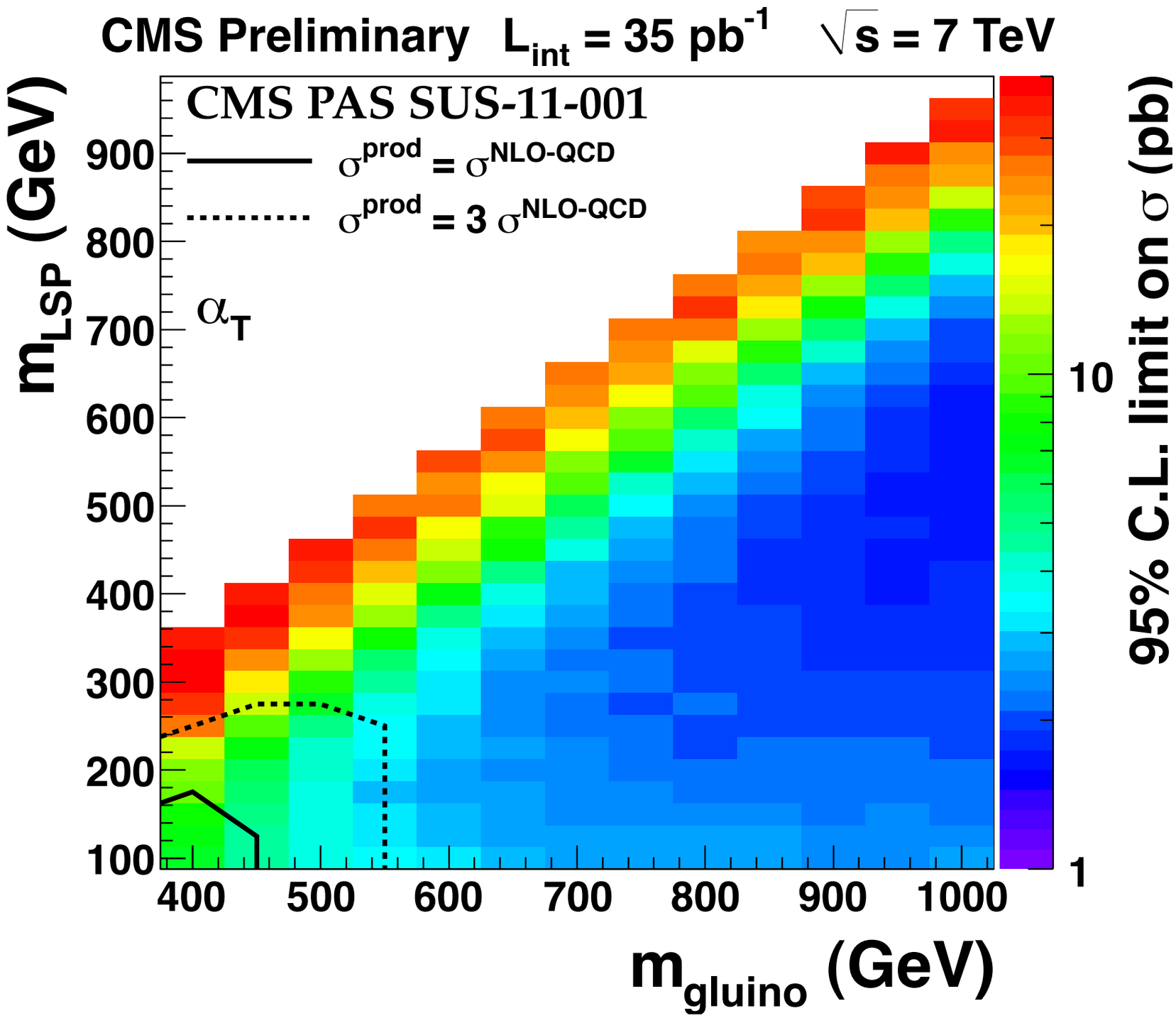
There is no way of getting anything close to

a 300 GeV Gluino & a 270 GeV LSP

Much easier to interpret!

$m_{\tilde{g}} = 400$ GeV $\quad m_{\chi^0} = 50$ GeV $\quad \sigma \times \mathrm{Br} \leq 8$ pb

$m_{\tilde{g}} = 400$ GeV $\quad m_{\chi^0} = 370$ GeV $\quad \sigma \times \mathrm{Br} \leq 30$ pb



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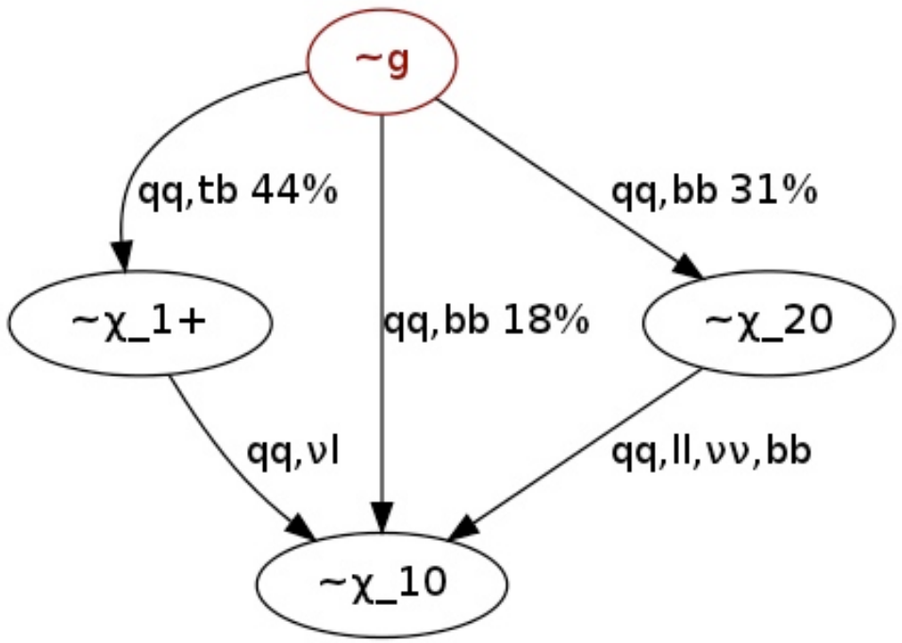
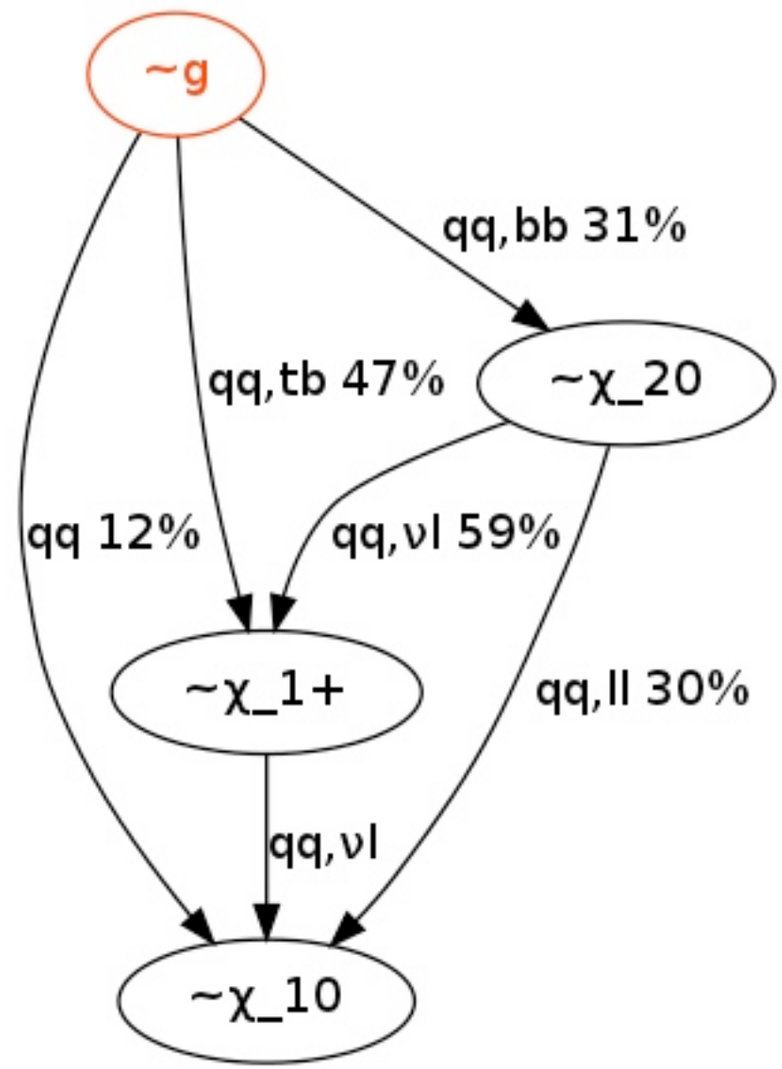
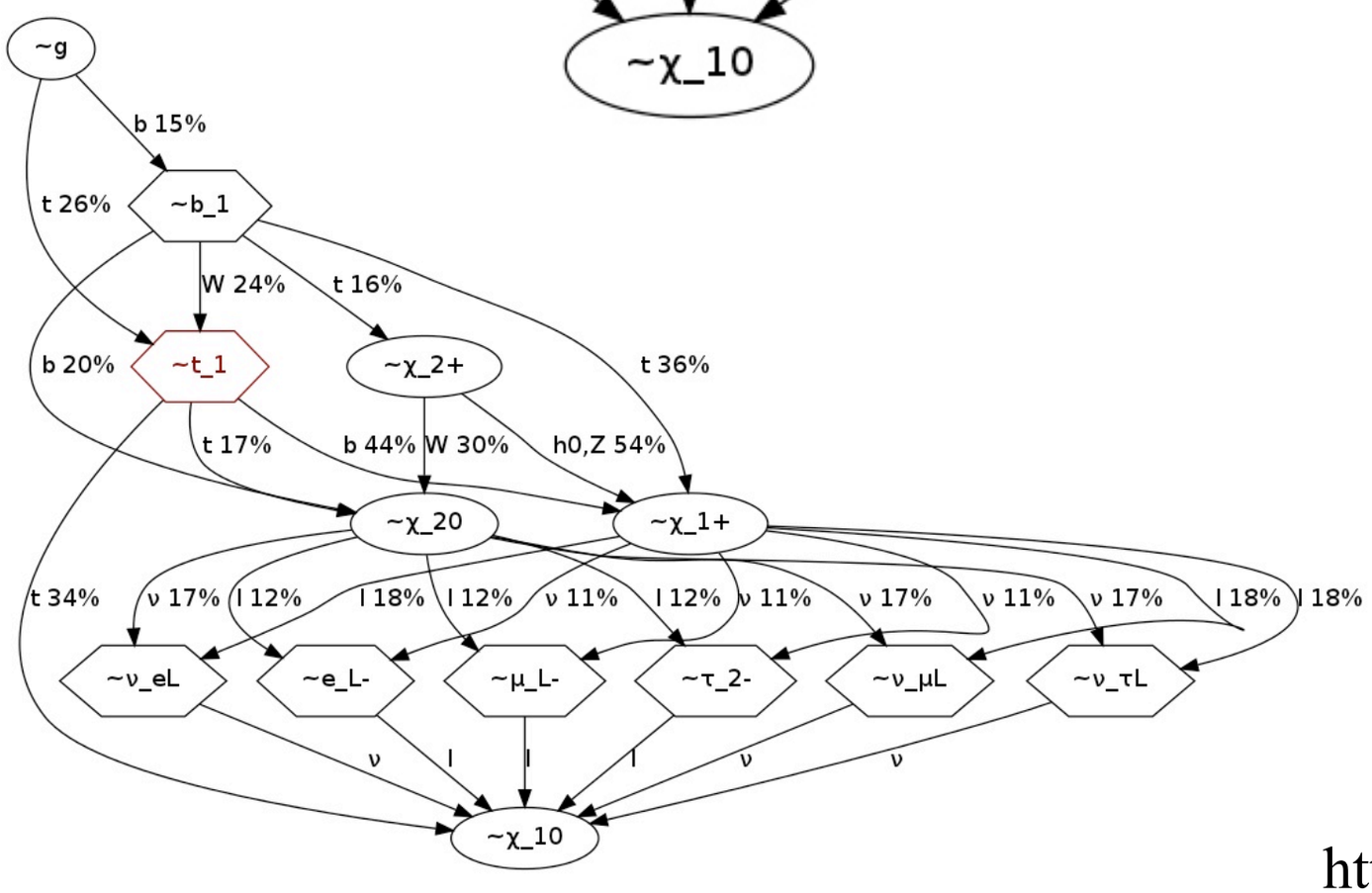
Using Simplified Models to improve searches

mSUGRA designs are usually based on averaging over a huge number of topologies







http://www.hephy.at/user/walten/msugra

Want to ensure discovery isn't an accident

7 Decay Topologies:

2 Body Decay

$$\tilde{g} \to \chi_1^0 + g$$

3 Body Direct Decay

$$\tilde{g} \to \chi_1^0 + q\bar{q}$$

1 Step Cascade Decay

$$\tilde{g} \to \chi_1^\pm + q\bar{q}$$
$$\chi_1^\pm \to \chi_1^0 + W^\pm$$

2 Step Cascade Decay

$$\tilde{g} \to \chi_1^\pm + q\bar{q}$$
$$\chi_1^\pm \to \chi_2^0 + W^\pm$$
$$\chi_2^0 \to \chi_1^0 + Z^0$$

3 Body Decay to bottoms

$$\tilde{g} \to \chi_1^0 + b\bar{b}$$

3 Body Decay to tops

$$\tilde{g} \to \chi_1^0 + t\bar{t}$$

3 Body Decay to top bottom

$$\tilde{g} \to \chi_1^\pm + t\bar{b}$$
$$\chi_1^\pm \to \chi_1^0 + W^\pm$$

Multiple Search Regions

Need a set of search regions
when combined has universal coverage

(for all masses and decay topologies)

Number of search regions depends on desired "Efficacy"

$$\mathcal{E}(\mathcal{M},\mathcal{S}) = \frac{\sigma_{\rm lim}(\mathcal{M},\mathcal{S})}{\sigma_{\rm lim}^{\rm best}(\mathcal{M})} \geq 1$$

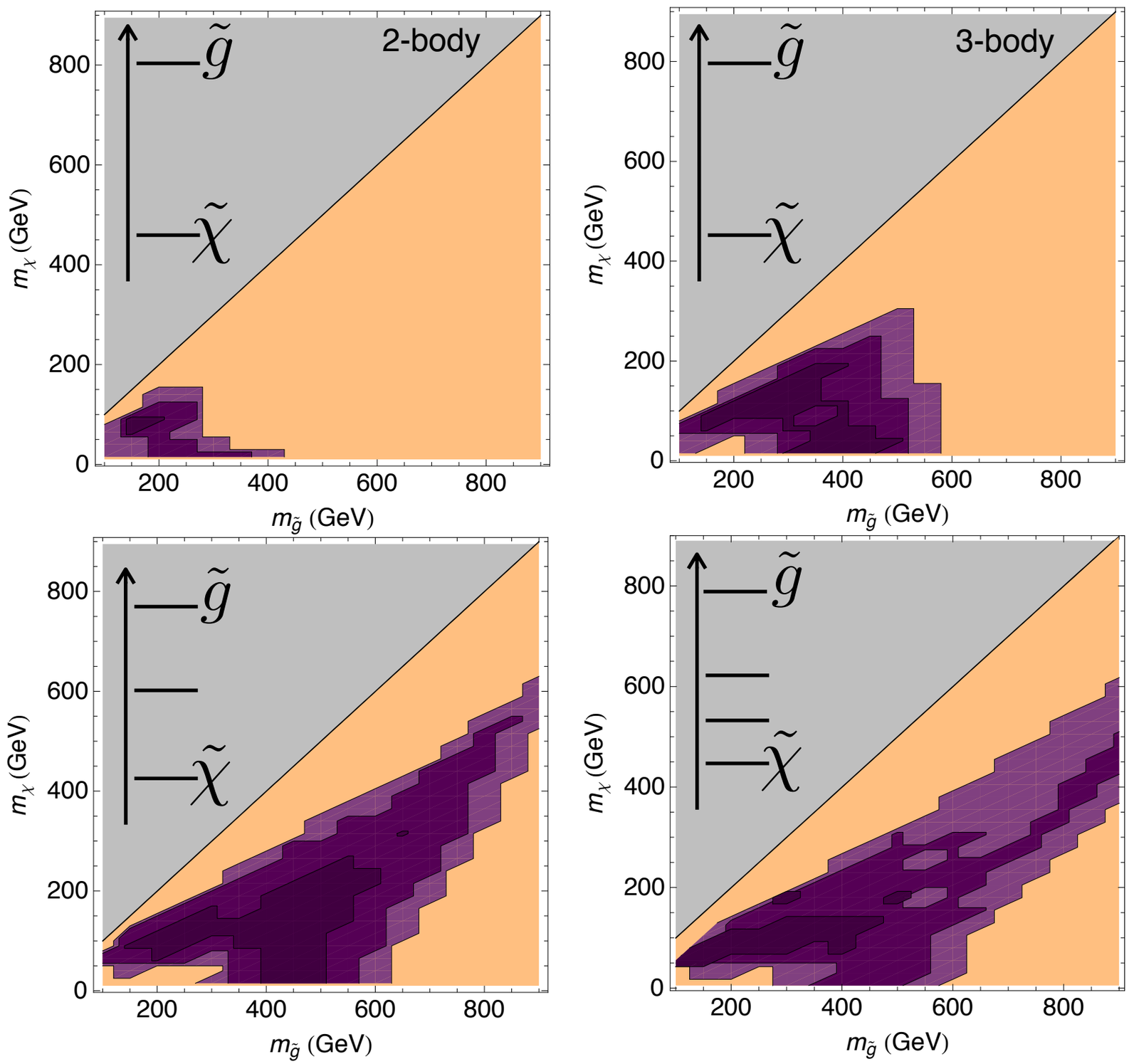
$\mathcal{M} =$ Model
$\mathcal{S} =$ Search Region

Keep $\mathcal{E} \leq \mathcal{E}_{\rm crit}$ for all theories

Hunting for Optimal Cuts

E.g.,
reach of the search region

$$\begin{cases} \not{E}_T \geq 150 \text{ GeV} \\ H_T \geq 750 \text{ GeV} \end{cases}$$



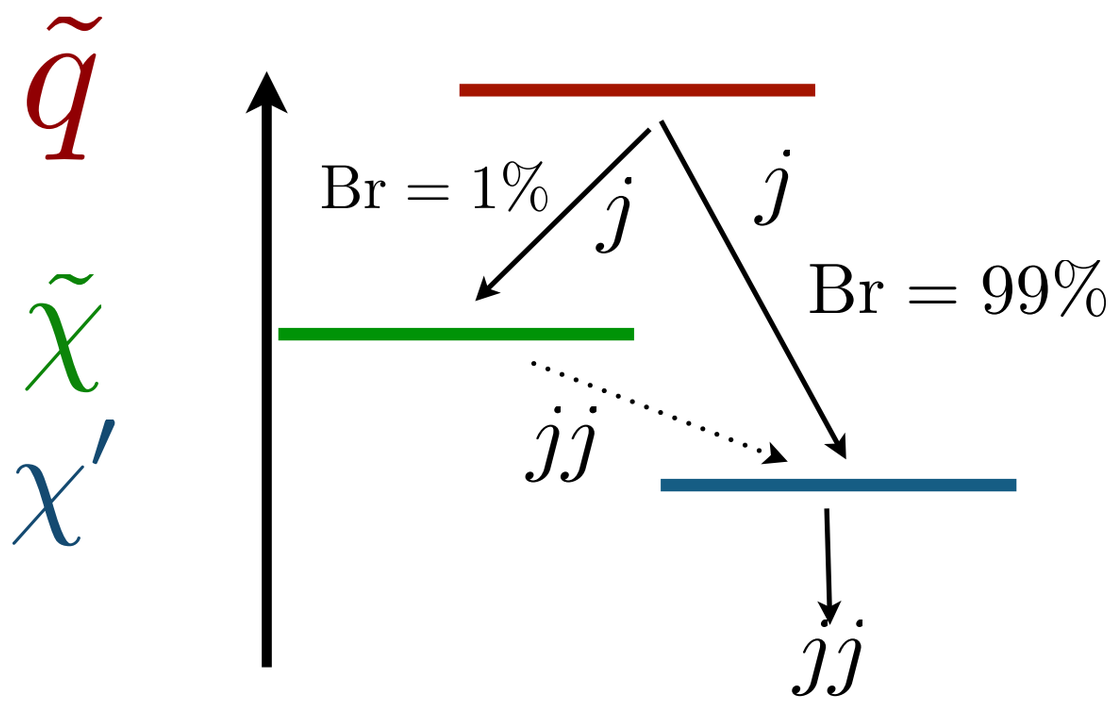
within 10% of optimal

within 20% of optimal

within 30% of optimal

Continued improvement at low masses

$$\sigma_{\tilde{g}\tilde{g}}\ \mathrm{Br}(\tilde{g} \to \not{E}_T\ )^2 \ll \sigma_{\tilde{g}\tilde{g}\ \mathrm{QCD}}$$



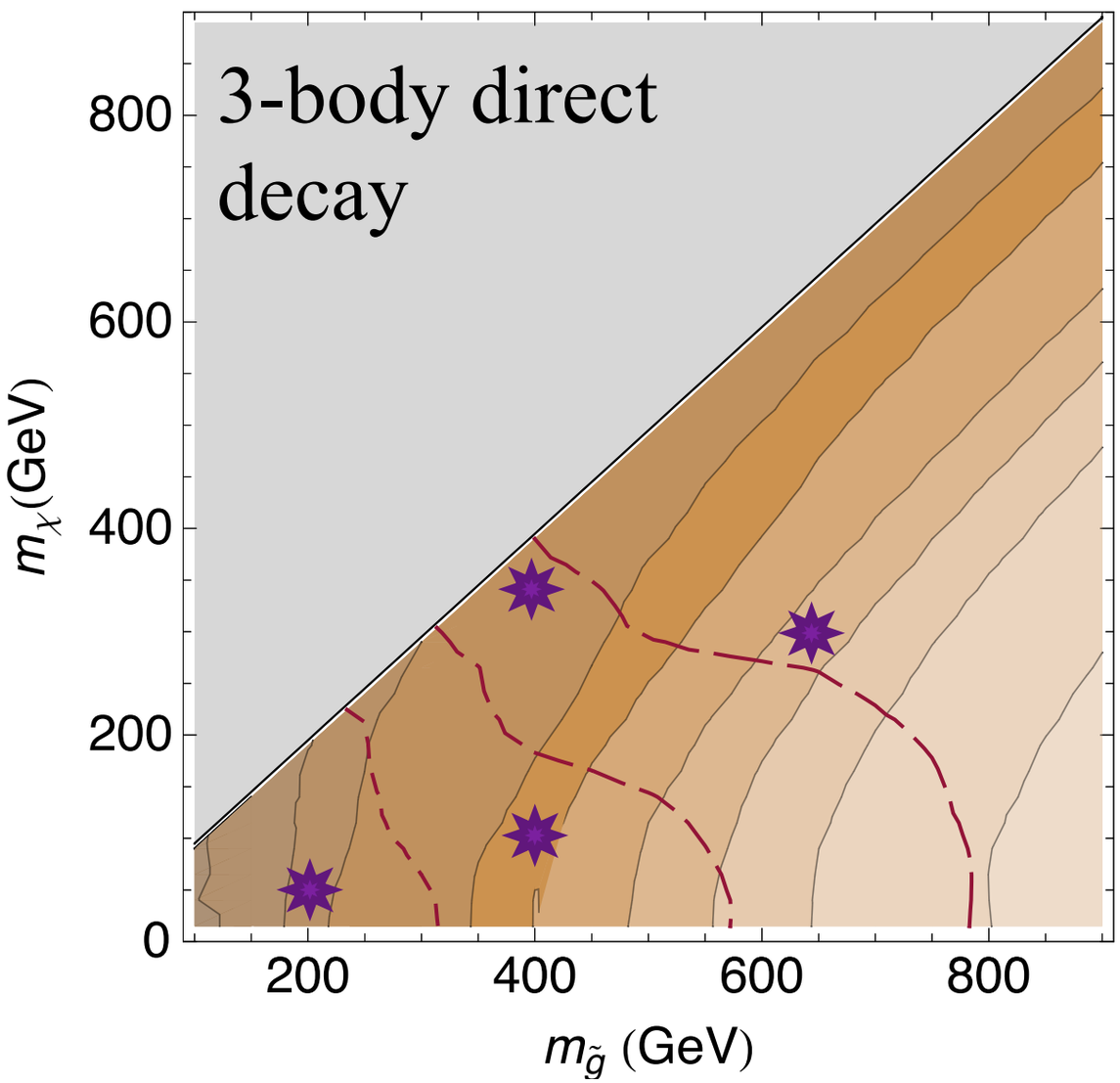
$$\Gamma(\tilde{\chi} \to \chi' + jj) \sim 1\ \mathrm{km}^{-1}$$

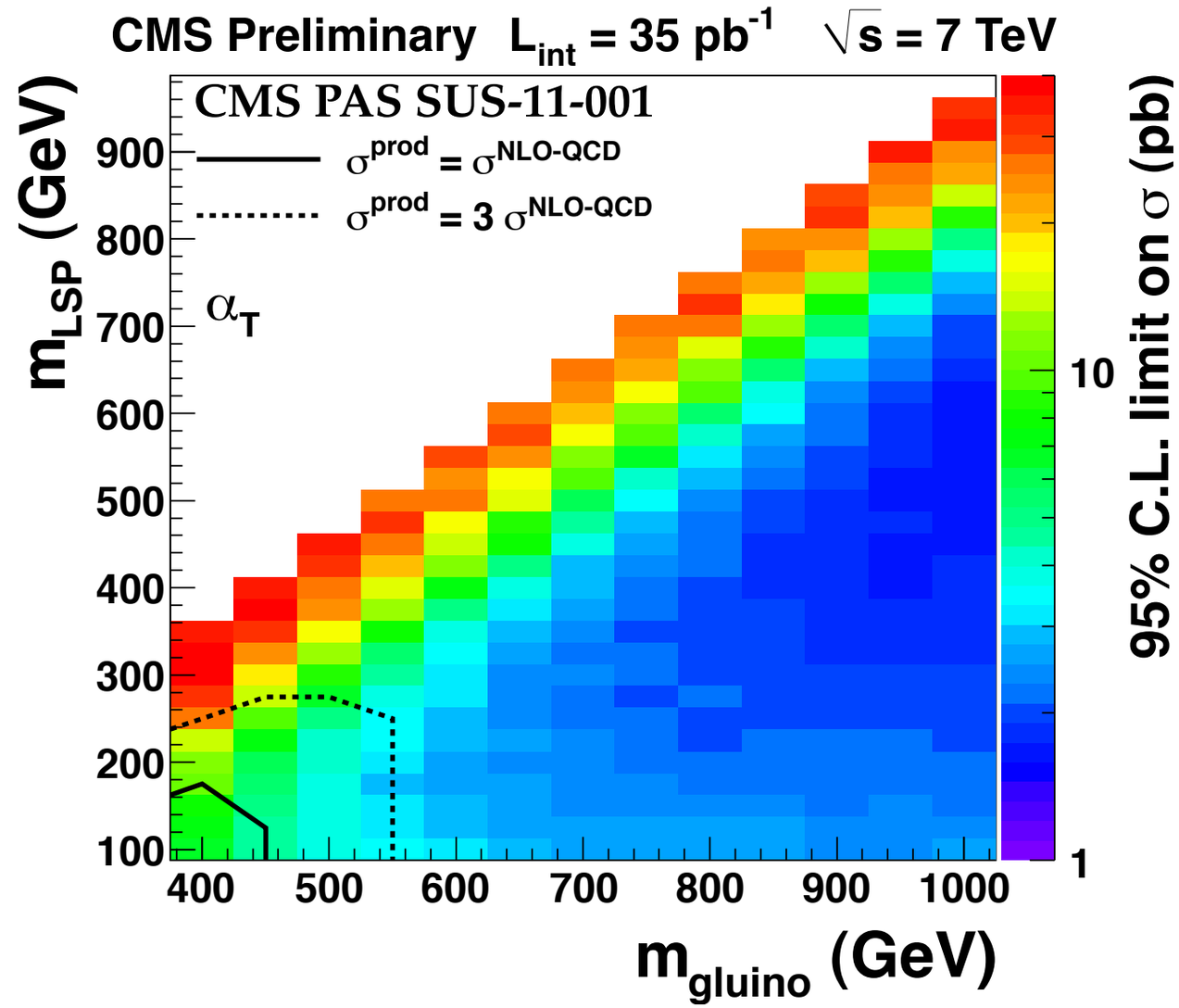
Only a small fraction of events are visible in Jets + MET

mSUGRA designed searches

can be extremely non-optimal $\mathcal{E} \sim 5$

Cost 125 GeV in reach

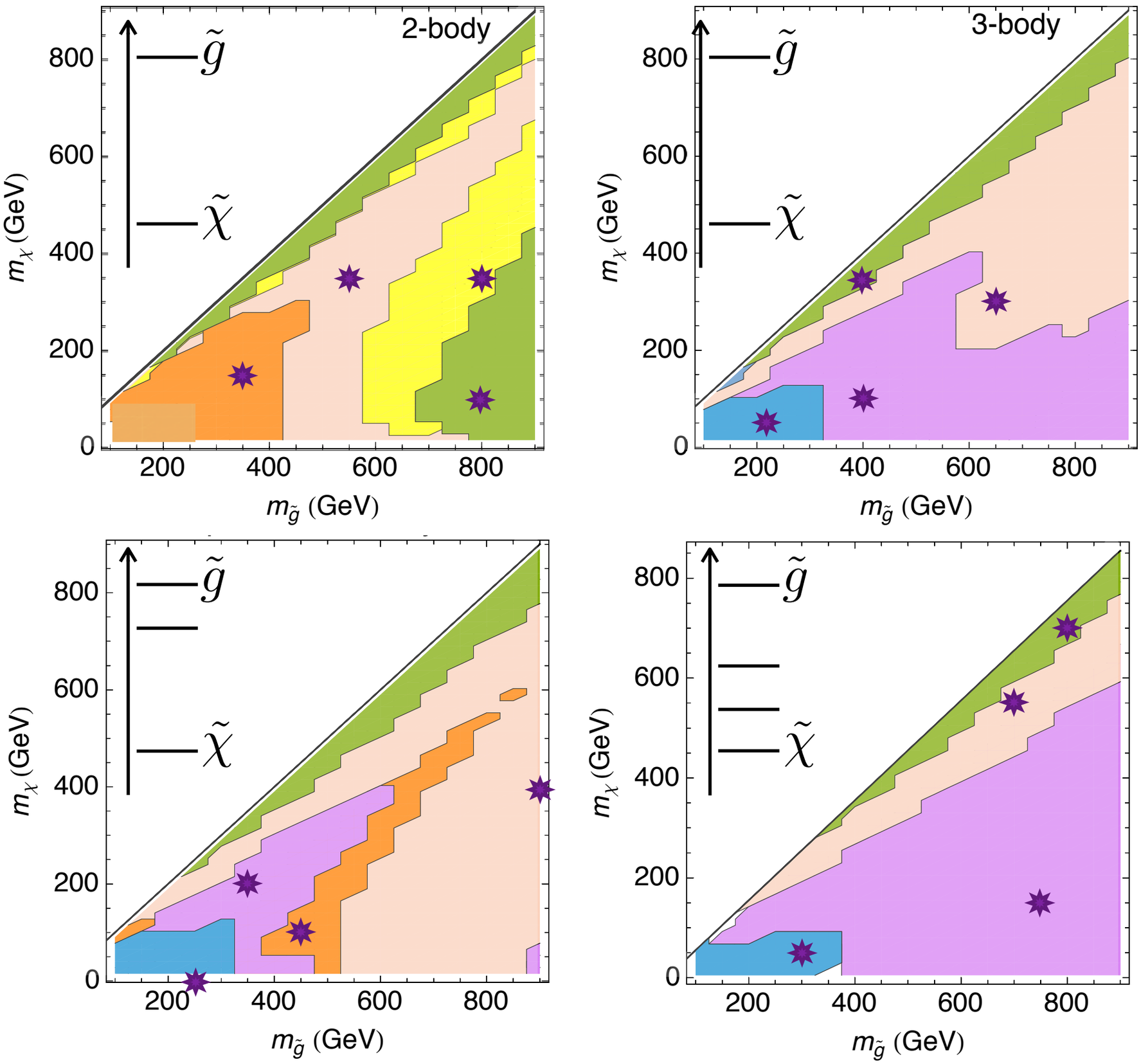




ATLAS Simplified Model based searches sometimes outperform on mSUGRA models!

Multiple Search Regions for light flavors

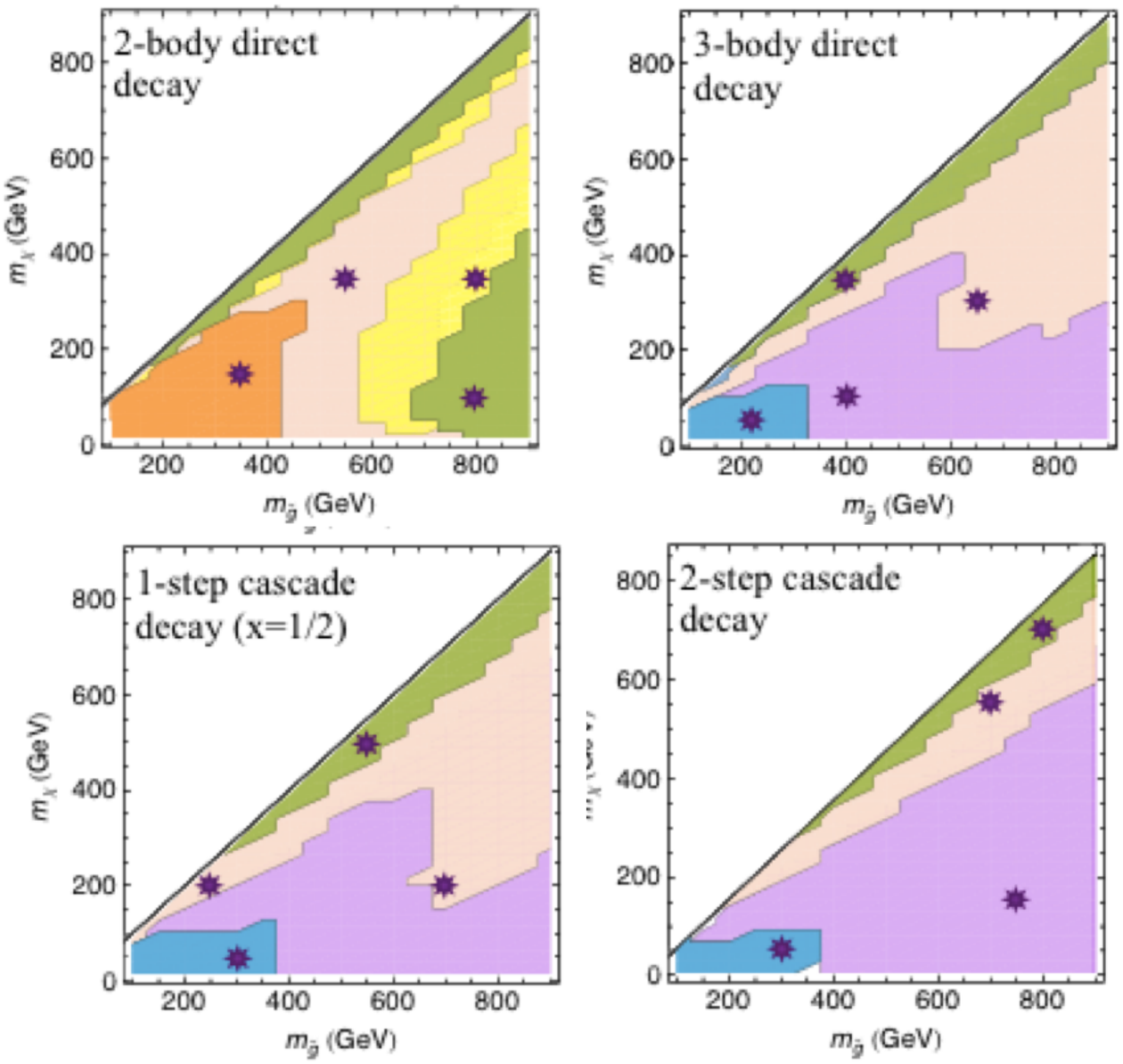
Not necessarily complicated $\mathcal{E} \leq 1.3$



cut	ch	MET	H_T
	2^+j	500	750
	3^+j	450	500
	4^+j	100	450
	4^+j	150	950
	4^+j	250	300
	4^+j	350	600

Designing Optimal Regions

- Choice of multiple search regions depends upon
  - backgrounds
  - detector efficiencies & acceptances
  - how good is good enough
  - etc
- Not something a theorist should be designing too closely
- Scans are expensive for experiments, providing benchmark theories saves effort
- We've done rough exploration of corners of parameter space looking for



Benchmark Models

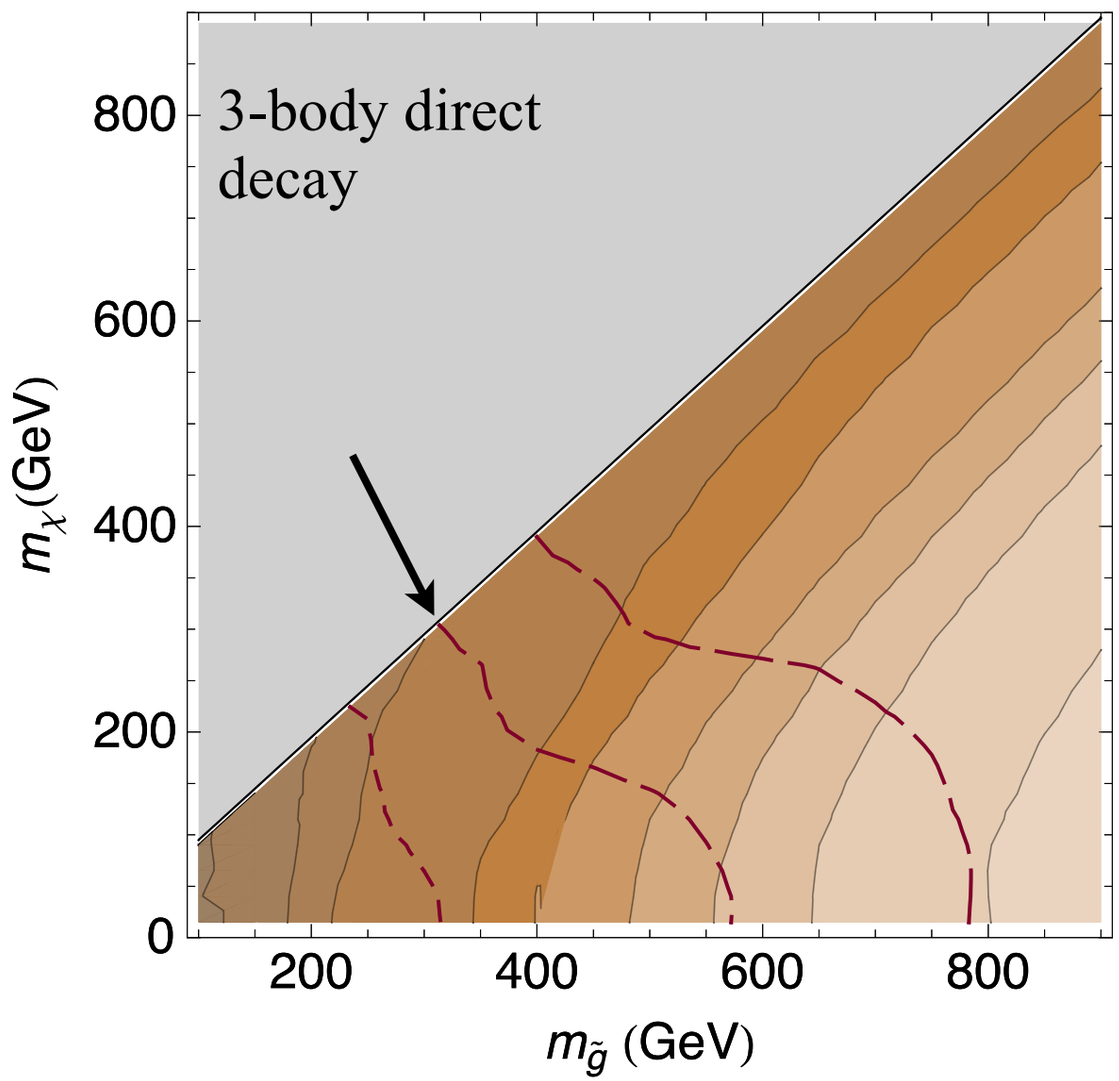
- Chosen to maximize differences in how they appear in given searches
- Simple and easy to define
- Consistent theories on their own

Name	$m_{\tilde{g}}$ (GeV)	$m_{\tilde{\chi}^0}$ (GeV)	Decay
$\mathcal{M}_1$	800	100	direct 2-body
$\mathcal{M}_2$	800	350	direct 2-body
$\mathcal{M}_3$	550	300	direct 2-body
$\mathcal{M}_4$	350	150	direct 2-body
$\mathcal{M}_5$	250	50	direct 3-body
$\mathcal{M}_6$	400	100	direct 3-body
$\mathcal{M}_7$	400	350	direct 3-body
$\mathcal{M}_8$	650	300	direct 3-body
$\mathcal{M}_9$	150	50	1-step cascade (x=1/4)
$\mathcal{M}_{10}$	400	80	1-step cascade (x=1/4)
$\mathcal{M}_{11}$	450	350	1-step cascade (x=1/4)
$\mathcal{M}_{12}$	600	200	1-step cascade (x=1/4)
$\mathcal{M}_{13}$	250	200	1-step cascade (x=1/2)
$\mathcal{M}_{14}$	300	50	1-step cascade (x=1/2)
$\mathcal{M}_{15}$	550	500	1-step cascade (x=1/2)
$\mathcal{M}_{16}$	700	200	1-step cascade (x=1/2)
$\mathcal{M}_{17}$	250	0	1-step cascade (x=3/4)
$\mathcal{M}_{18}$	350	200	1-step cascade (x=3/4)
$\mathcal{M}_{19}$	450	100	1-step cascade (x=3/4)
$\mathcal{M}_{20}$	900	400	1-step cascade (x=3/4)
$\mathcal{M}_{21}$	300	50	2-step cascade
$\mathcal{M}_{22}$	750	150	2-step cascade
$\mathcal{M}_{23}$	750	550	2-step cascade
$\mathcal{M}_{24}$	800	750	2-step cascade

$$m_{\chi^\pm} = m_{\chi^0} + x(m_{\tilde{g}} - m_{\chi^0})$$

Expectations for Full 2010 & 2011 Data Sets

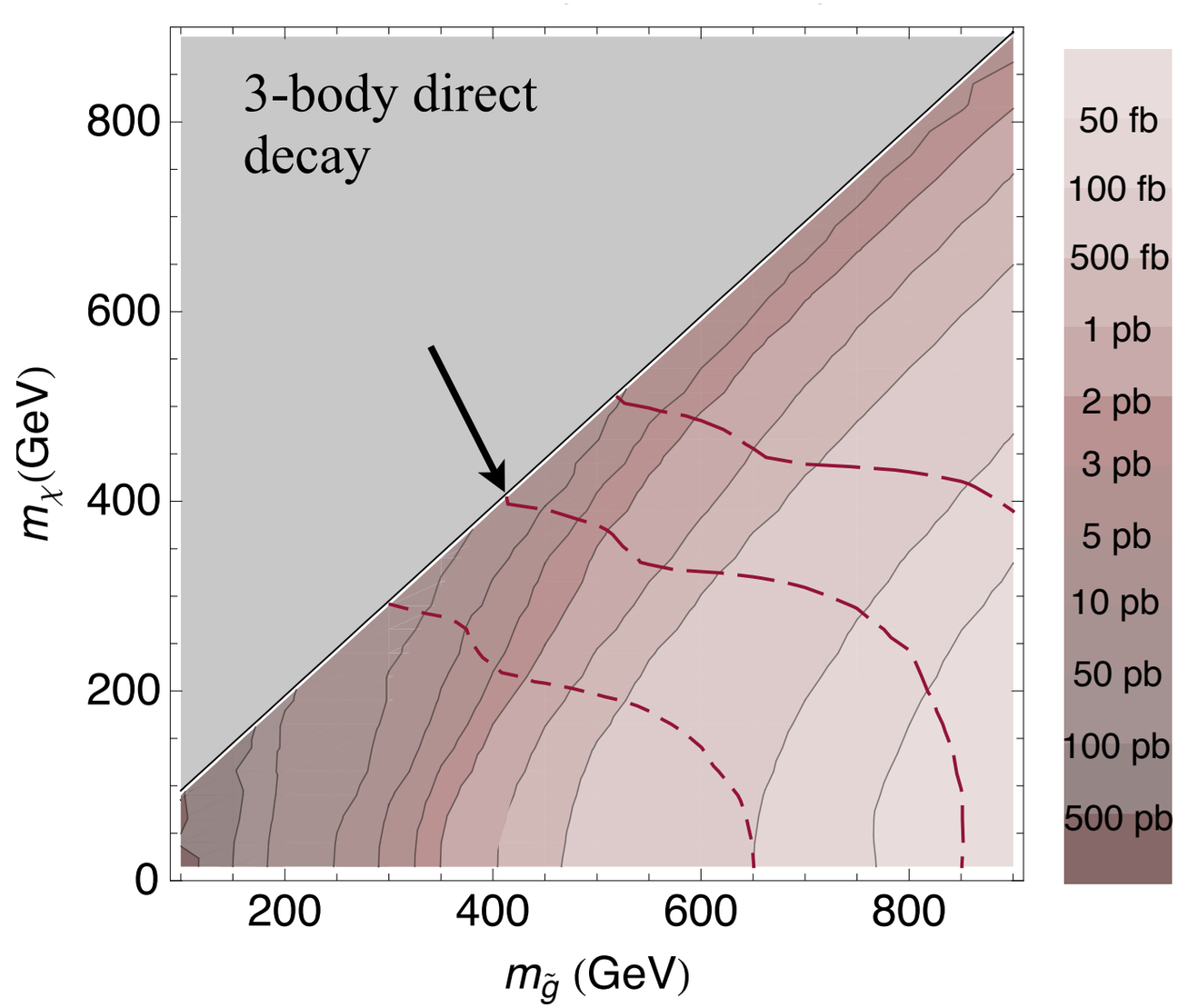
45 pb^{-1}



Full Coverage up to 300 GeV

Reach up to 575 GeV

1000 pb^{-1}



Full Coverage up to 375 GeV

Reach up to 850 GeV

Alves, Izaguirre, JW

Results based on Simplified Models

Before first anomaly appears:

Easier to interpret what is being missed

Do searches miss compressed spectra?

After first anomaly appears:

How well a simplified model fits
is important piece of information

Is the anomaly fit with only 2 particles?

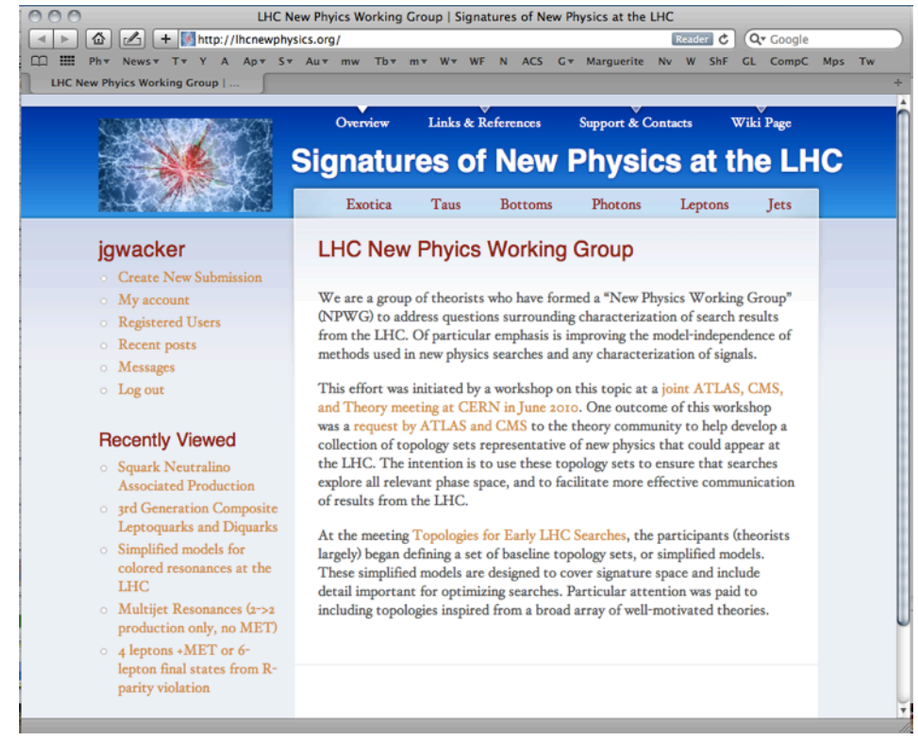
After many anomalies:

Will allow test models without unnecessary priors

How do we confirm that there are 4 neutralinos?

Keeping a repository of Simplified Models

http://LHCNewPhysics.org



Now approaching a fully featured website with supplemental information:

Definitions of Models, Model files,
LHE Files, Presentations,
Refereeing, Discussions

ATLAS & CMS are using for
for many upcoming analyses

Many Simplified Models have not been studied