Jets and Missing at the LHC

Jay Wacker
SLAC

BSM: Results from the 7 TeV LHC

Nov. 9, 2011

w/ E. Izaguire
D. Alves
R. Essig
J.Kaplan
A. Hook
M. Lisanti

Outline

Simplified Models

Two Examples

Light Flavored Models

Heavy Flavored Models

Future Directions

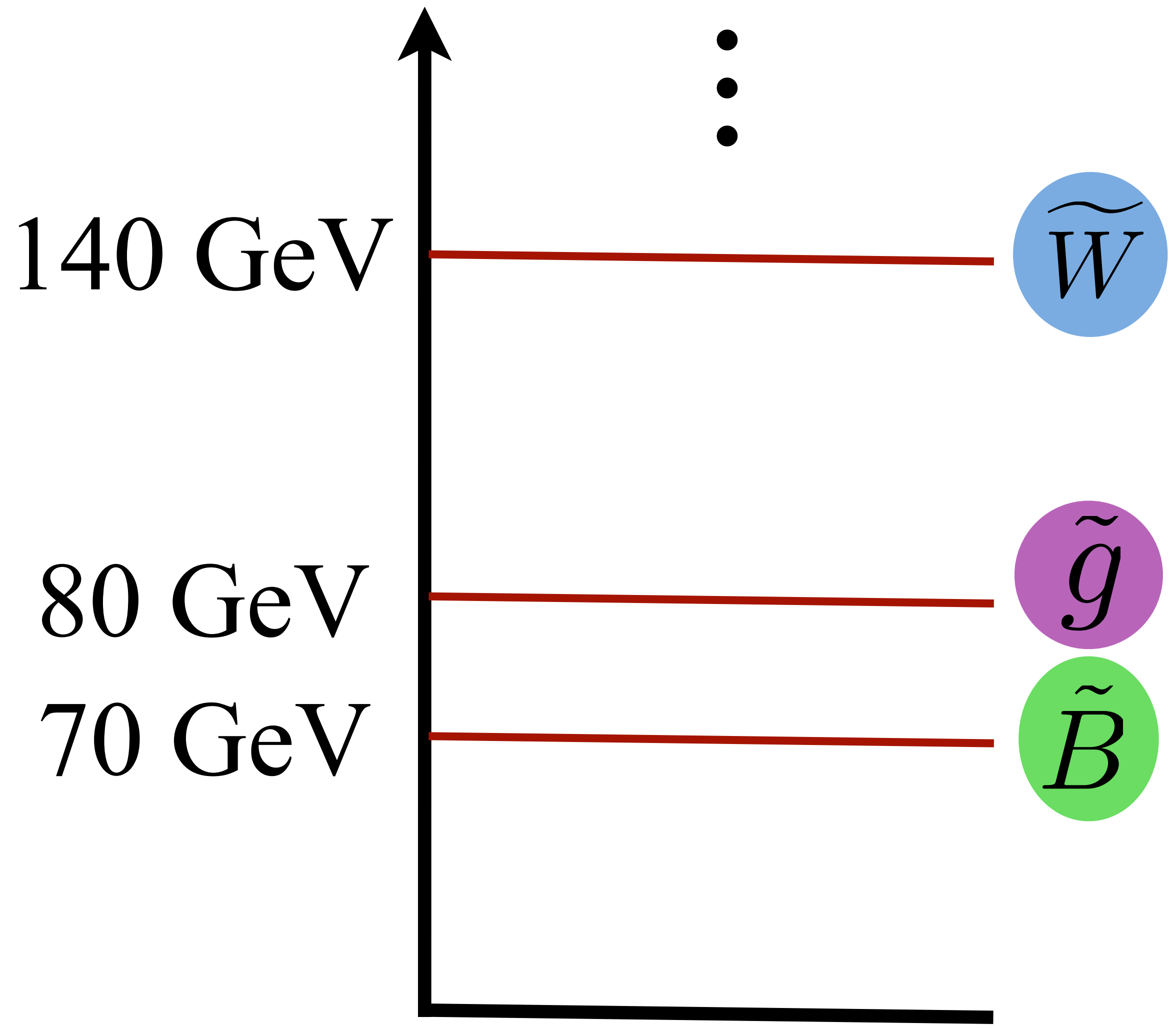
Stops

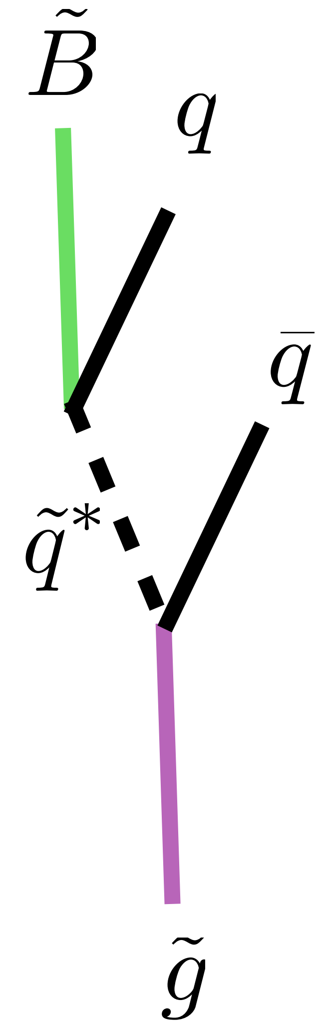
High Multiplicity Searches

Quark/Gluon Tagging

All started a few years back...

Had an MSSM model that predicted a spectrum





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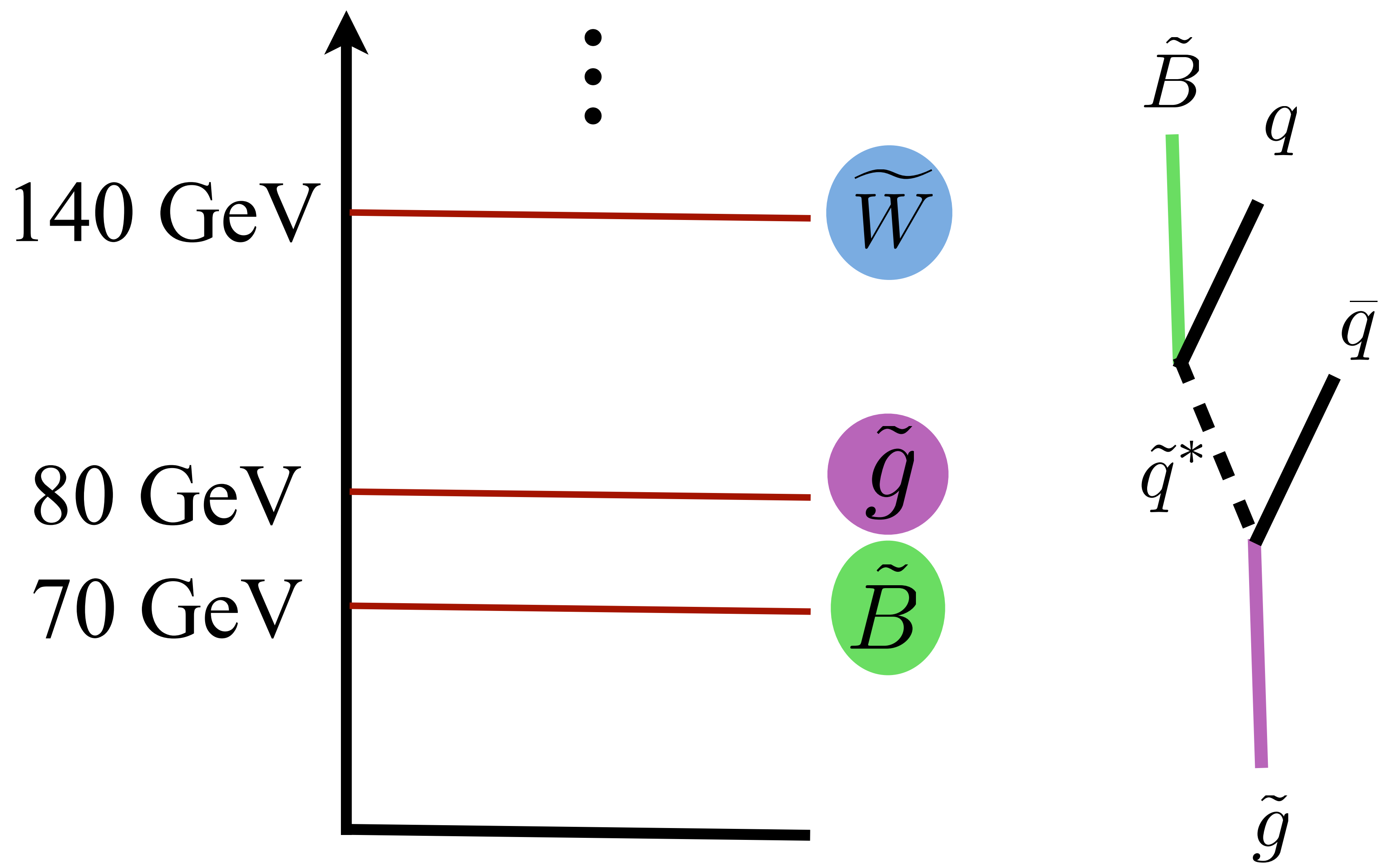


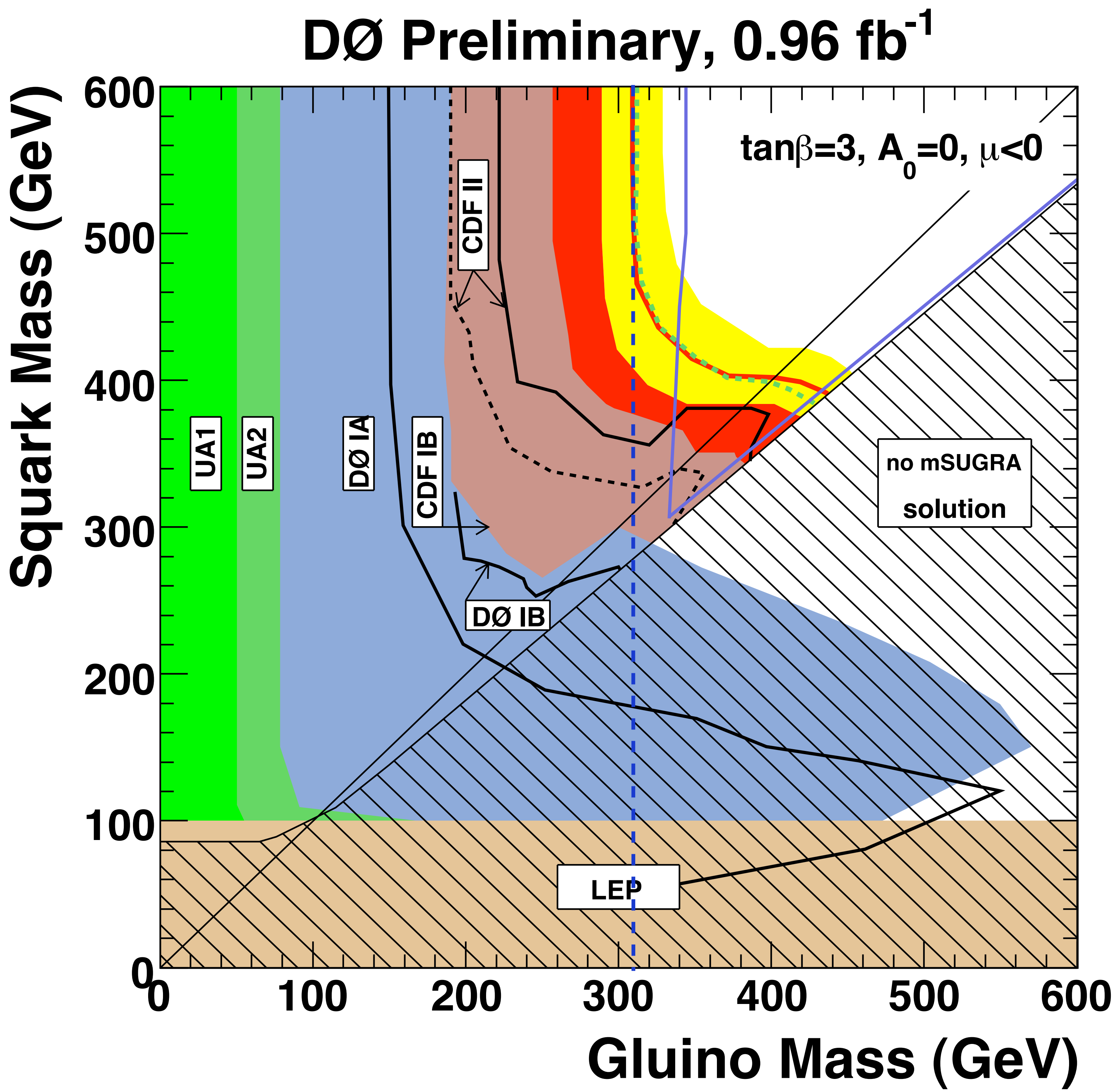
Surely this must be excluded!

The production cross section at the Tevatron is

$$\sigma(p\bar{p} \to \tilde{g}\tilde{g}) \simeq 2 \text{ nb}$$

I went through the 25 years of squark and gluino searches

They all came back to versions of this:



mSUGRA

(Five parameters to rule them all)

$m_{\frac{1}{2}}, m_0, A_0, \tan\beta, \text{sign}\ \mu$

$m_{\frac{1}{2}} \longrightarrow m_{\tilde{g}}$

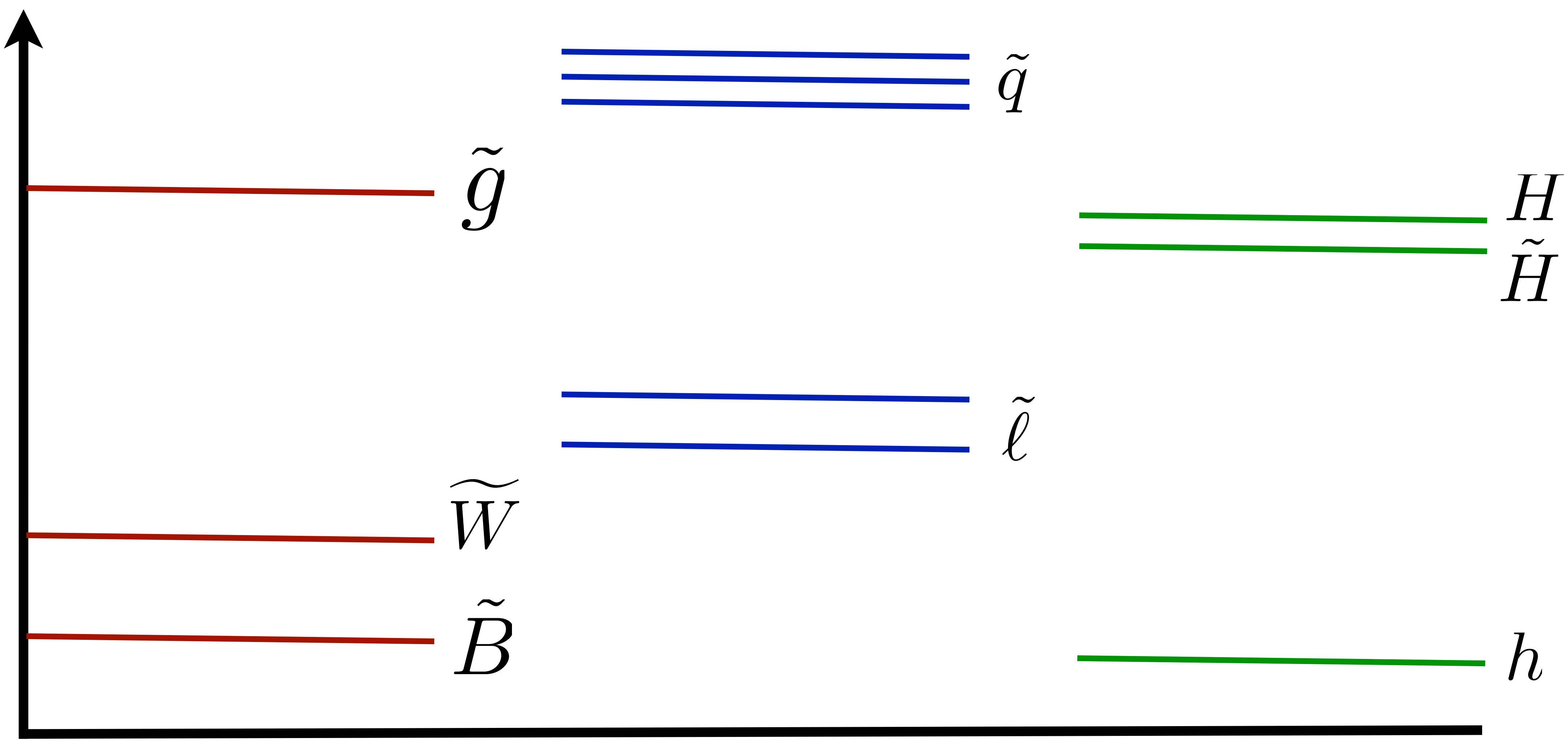
$m_0 \longrightarrow m_{\tilde{q}}$

but where is $m_{\tilde{B}}$?

mSugra has “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



A shocking lack of diversity (see the pMSSM)

Jets + MET

Solution to Hierarchy Problem

If the symmetry commutes with $SU(3)_C$,
new colored top partners

(note twin Higgs exception)

Dark Matter

Wimp Miracle: DM a thermal relic if
mass is 100 GeV to 1 TeV

Usually requires a dark sector,
frequently contains new colored particles

Fewest requirements on spectroscopy

Doesn't require squeezing in additional states to decay chains

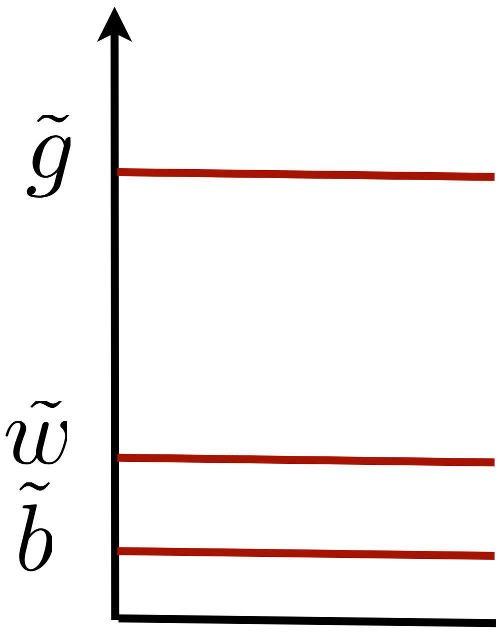
Spectrum in Different Theories

MSSM

High Cut-Off

Large Mass Splittings

$$\delta m = \frac{g^2}{16\pi^2}\, m\, \log\Lambda$$

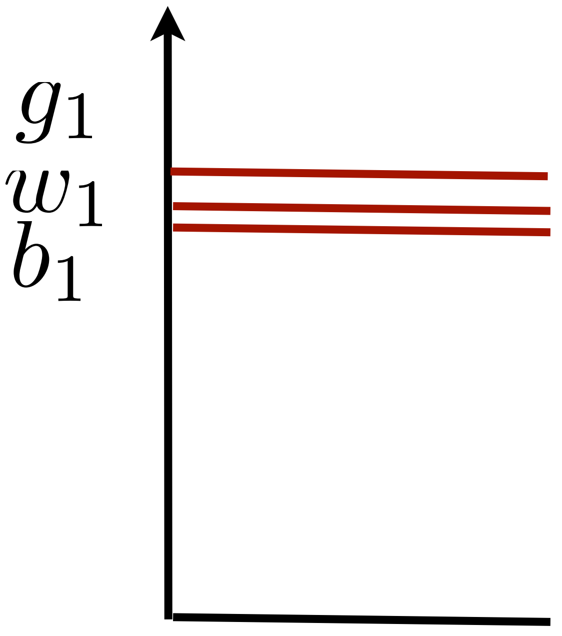


Universal Extra Dimensions

Low Cut-Off

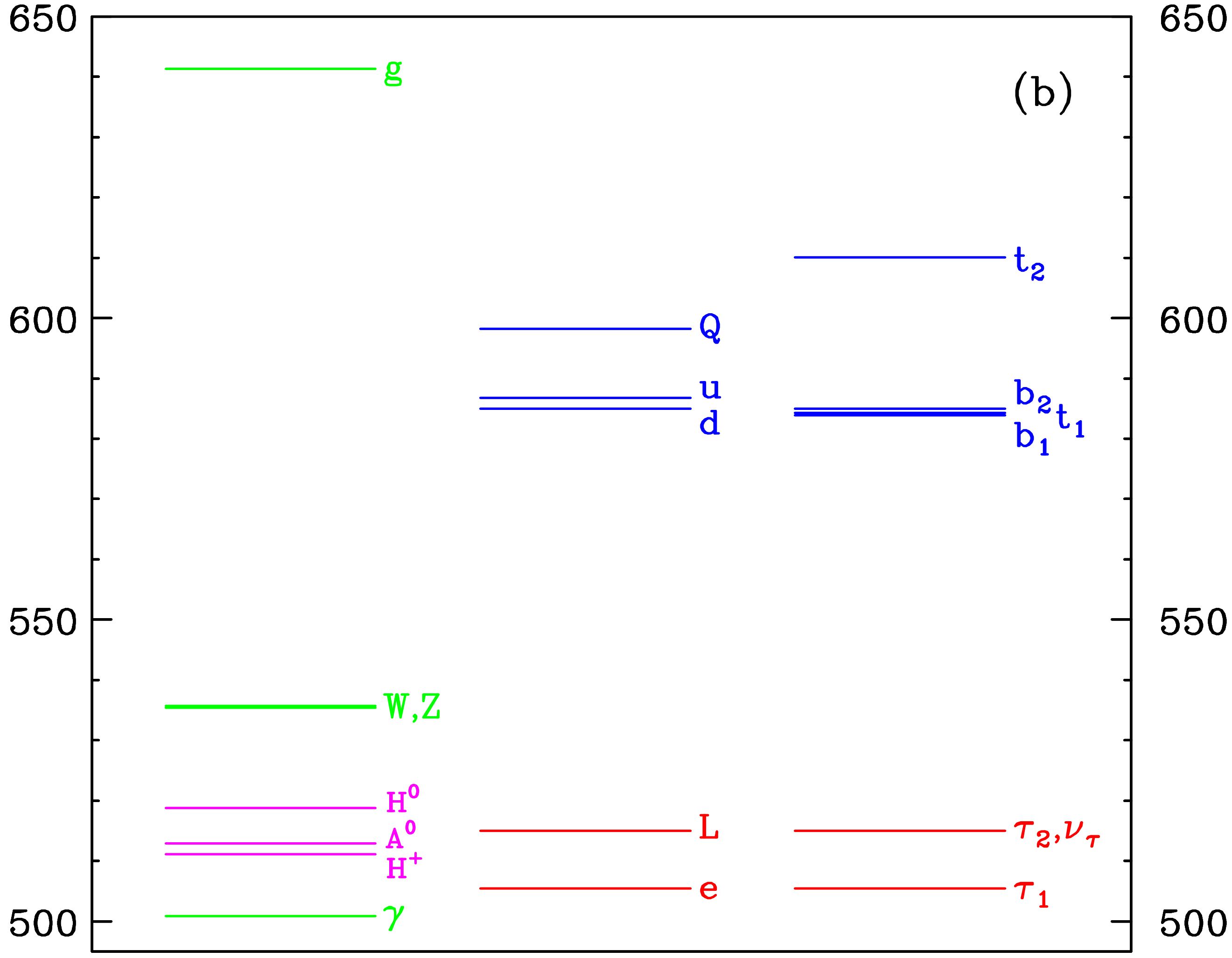
Small Mass Splittings

$$\delta m = \frac{g^2}{16\pi^2}\frac{\Lambda^2}{m}$$



Radiative Corrections to Kaluza-Klein Masses

Cheng, Matchev, Schmaltz (2002)



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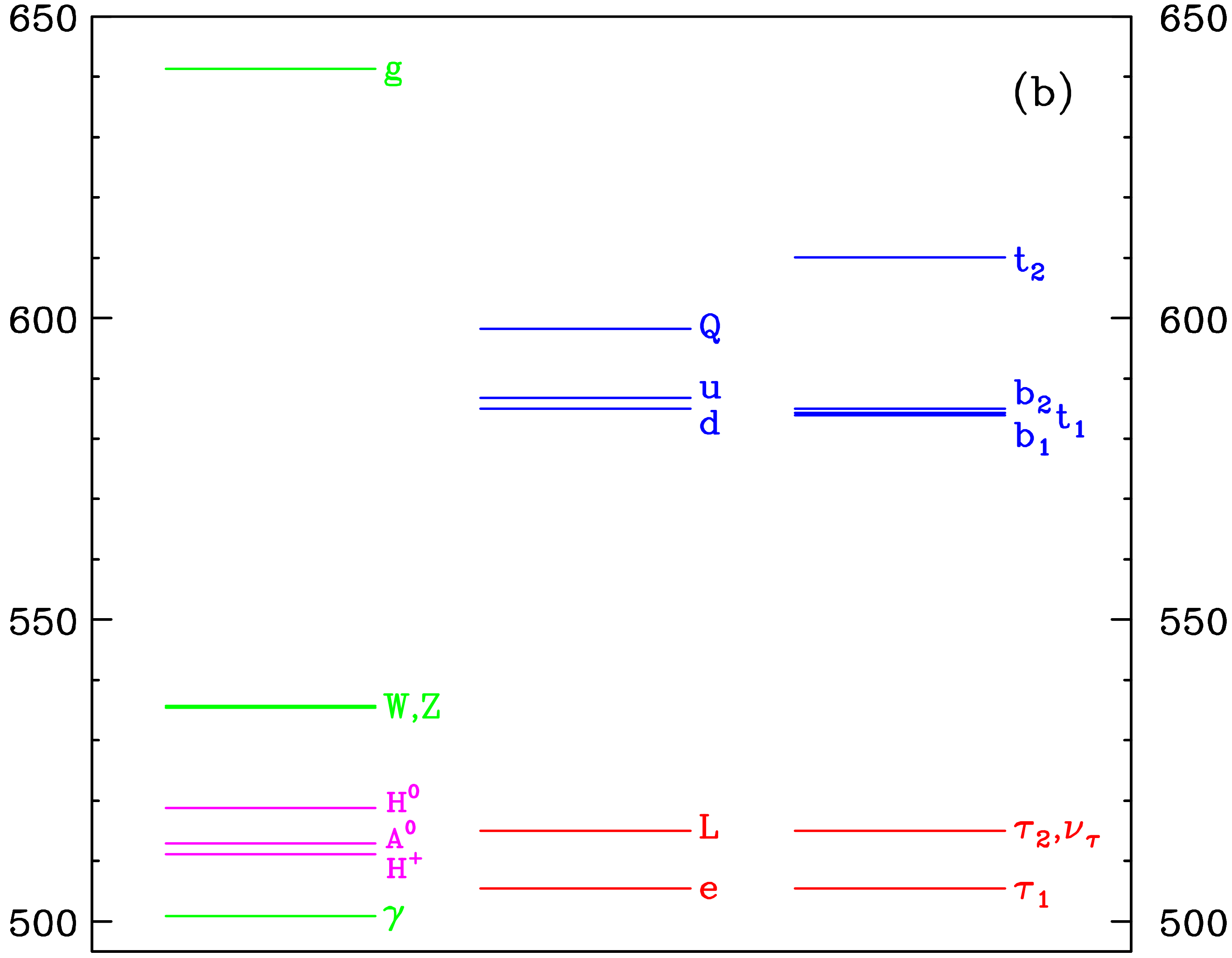
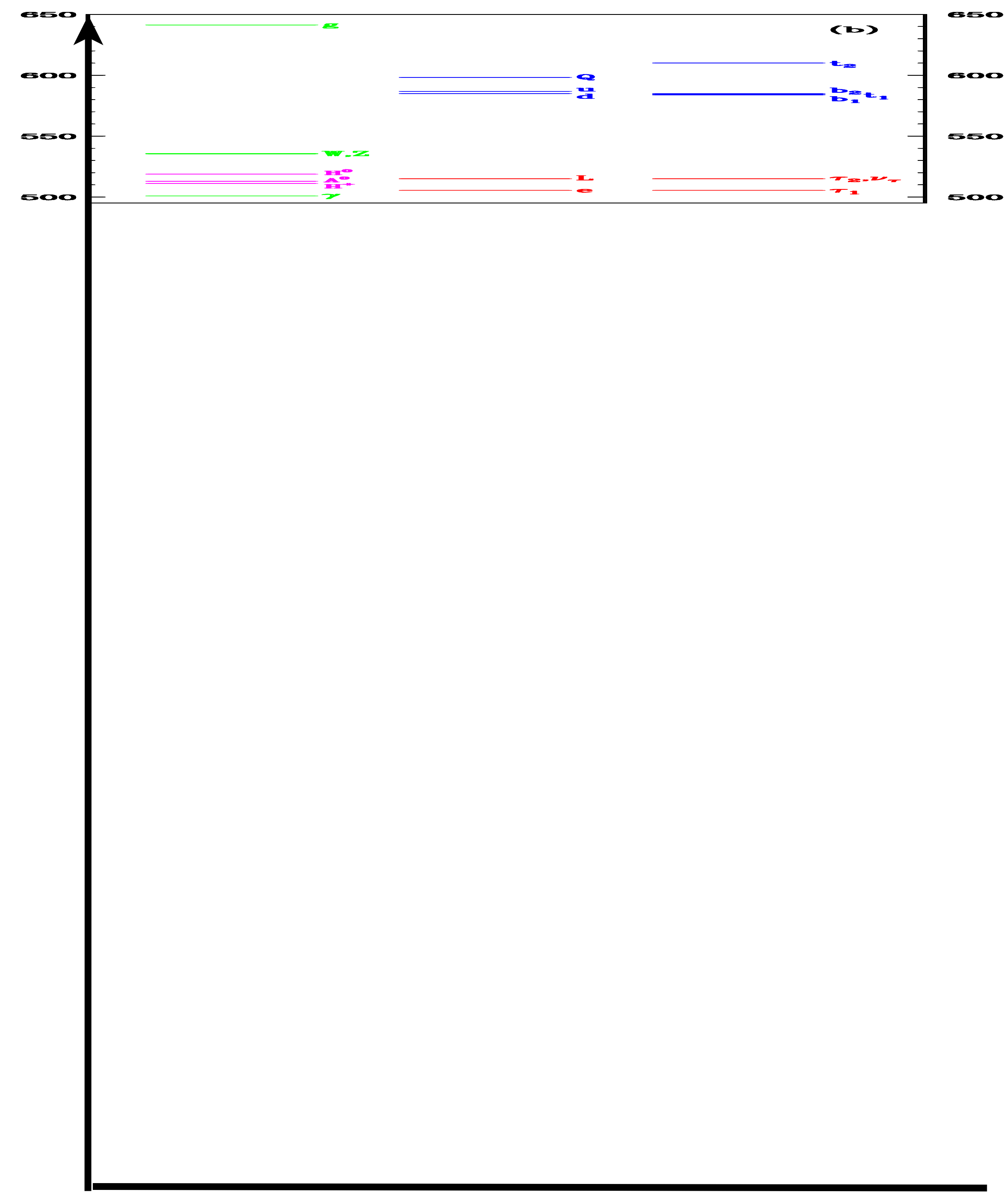




Simplified Models

Effective Field Theories for Collider Physics

Limits of specific theories

Only keep particles and couplings relevant for searches

Still a full Lagrangian description

Removes superfluous model parameters

Masses, Cross Sections, Branching Ratios (*e.g.* MARMOSET)

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 notice & explore kinematic limits

Simplified Models

When an anomaly appears,
we want evidence of discovery for each particle

We want to know that we need

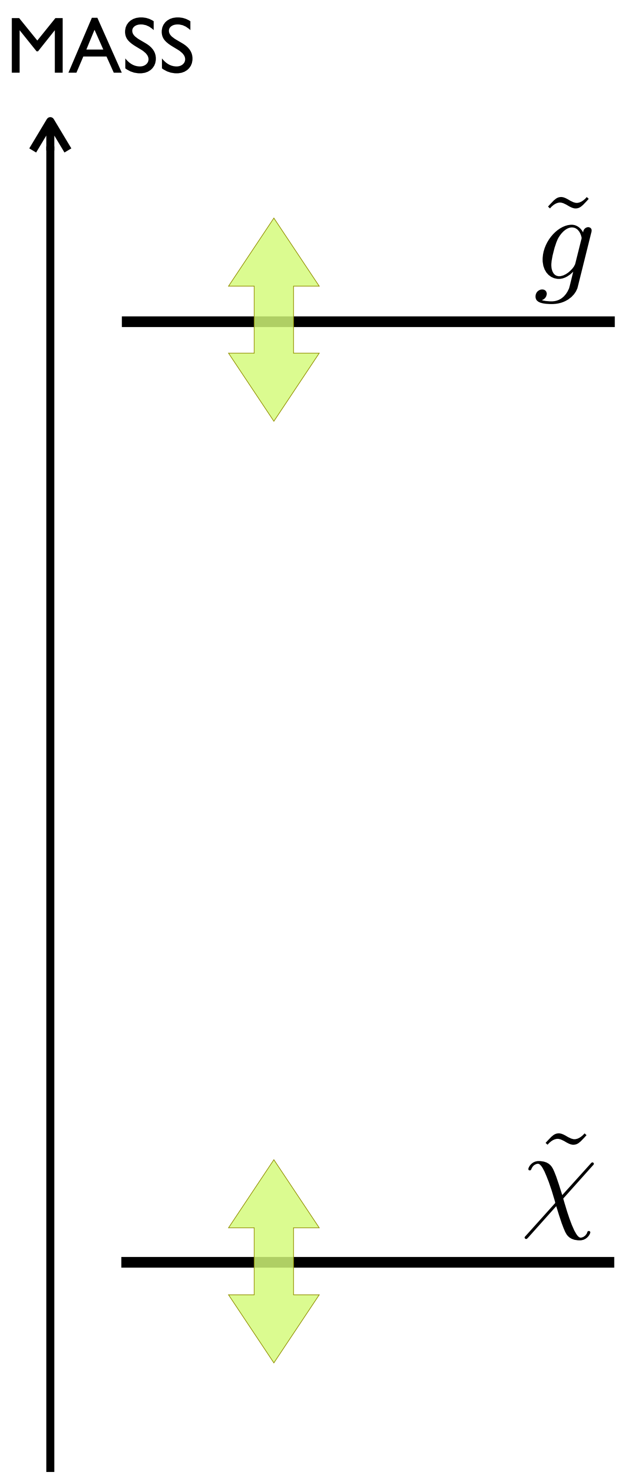
$$\tilde{g}, \tilde{\chi}^{\pm}, \chi^{0}$$

but nothing else to explain the anomaly

Then design searches to piece together
the rest of the spectrum

Simplified Models

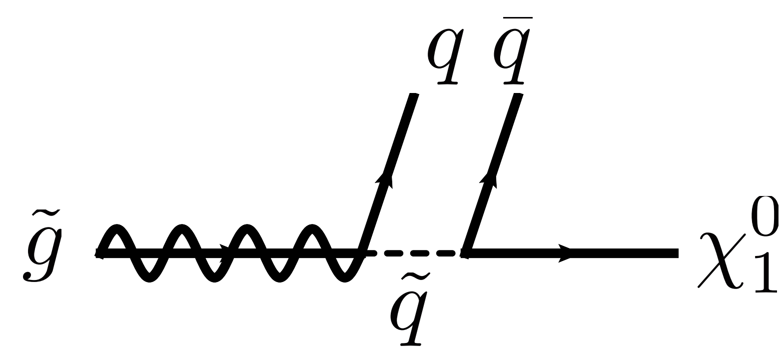
Direct Decays



color octet majorana fermion (“Gluino”)

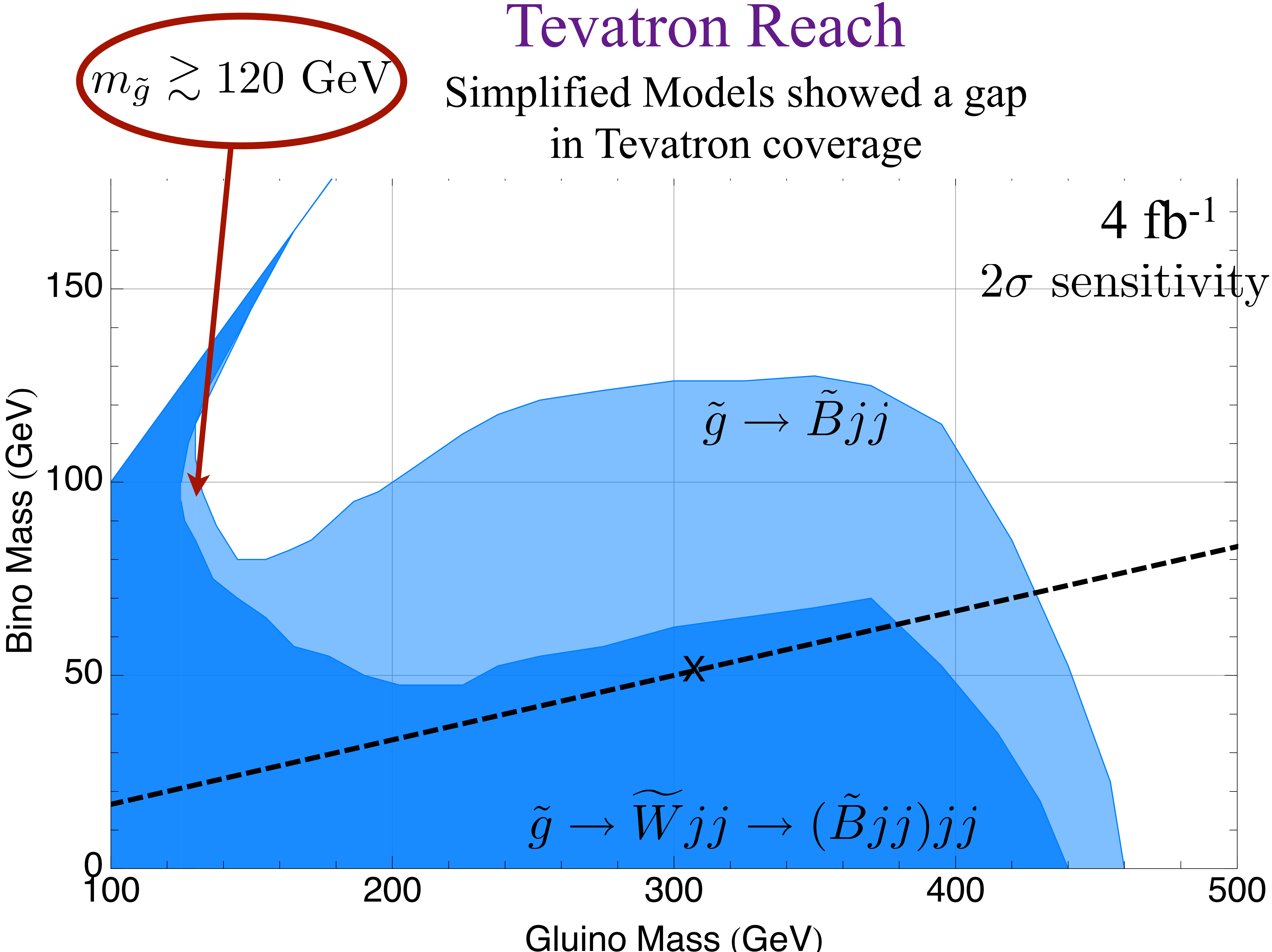
neutral majorana fermion (“LSP”)

THREE-BODY



Tevatron Reach

Simplified Models showed a gap in Tevatron coverage



Alwall, Le, Lisanti, Wacker 2008

Important to keep the cross section free

All searches at LHC are model dependent

Easy to dilute signal with small branching ratios

$$\text{Rate} \sim \quad \sigma \times (\mathrm{Br}(\tilde{g} \to X))^2$$

If $\mathrm{Br}(\tilde{g} \to X) \sim \frac{1}{3}$

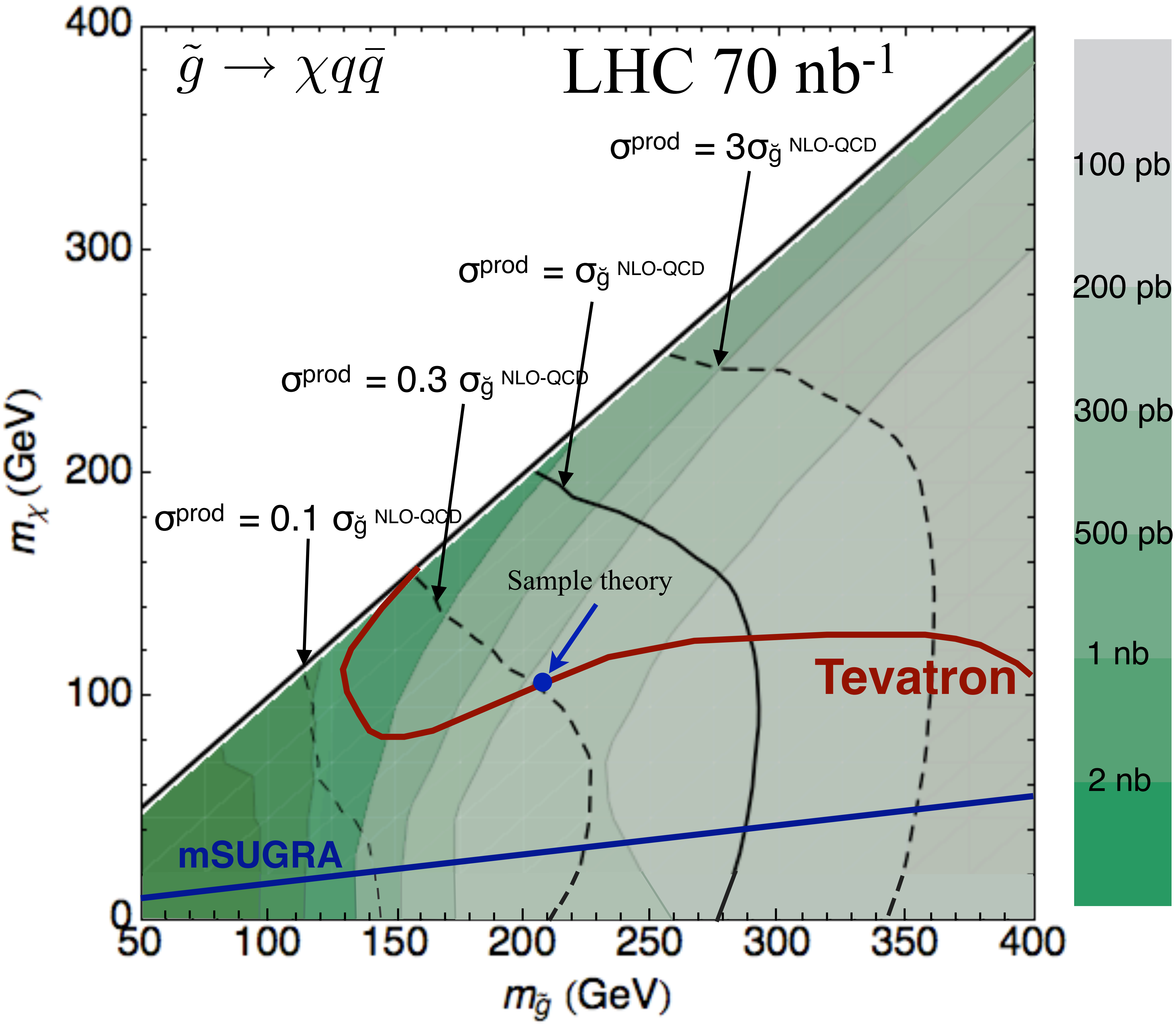
the rate drops by an order of magnitude

If $\tilde{g}$ is a scalar, σ drops by ~1/6

Dropping S/B by an order of magnitude
dramatically changes discovery prospects

Putting it all together

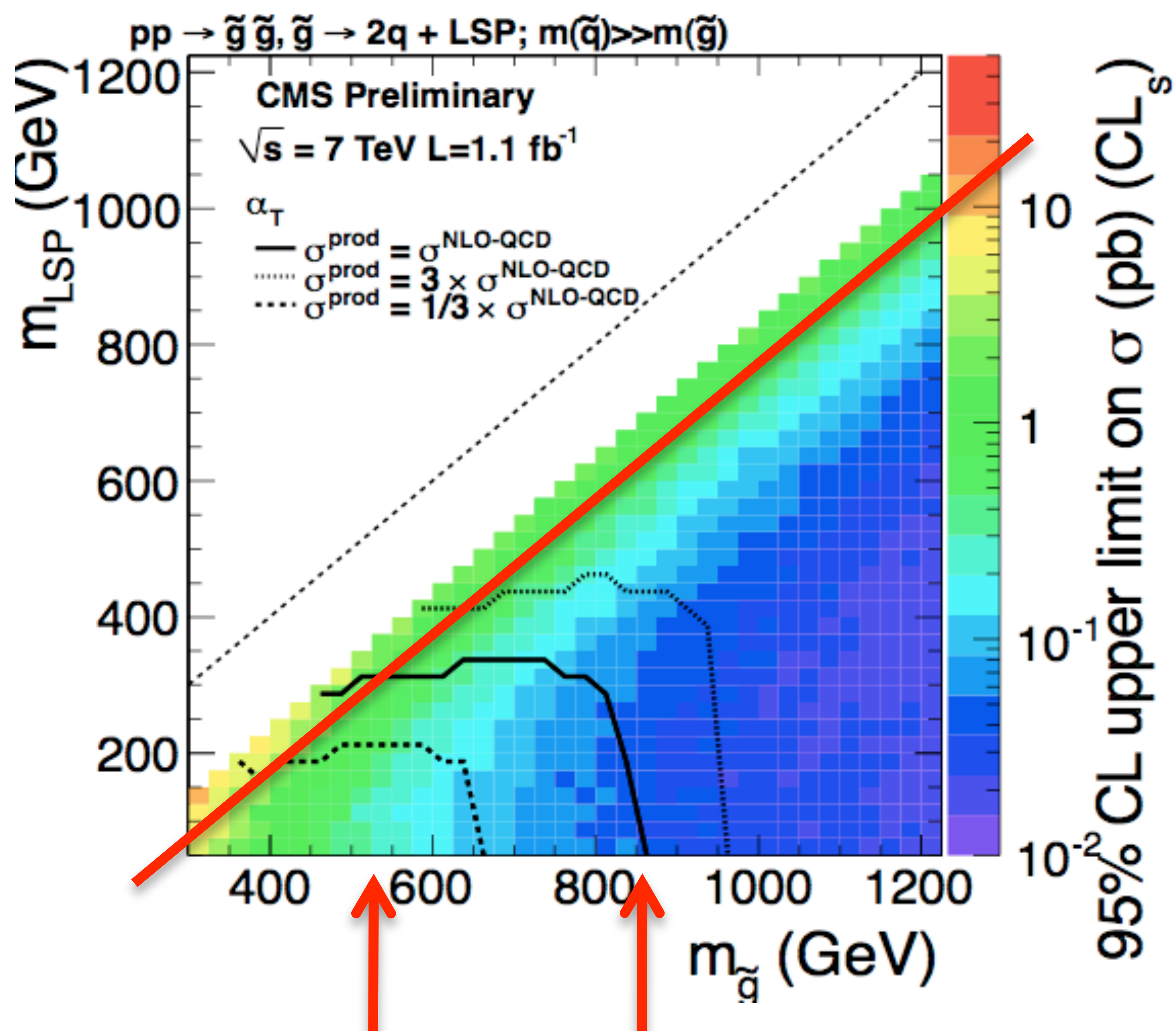
There could have been discoveries!



Much easier to interpret!

$m_{\tilde{g}} = 800$ GeV $\quad m_{\chi^0} = 50$ GeV $\quad \sigma \times \text{Br} \leq 20$ fb

$m_{\tilde{g}} = 800$ GeV $\quad m_{\chi^0} = 600$ GeV $\quad \sigma \times \text{Br} \leq 2$ pb



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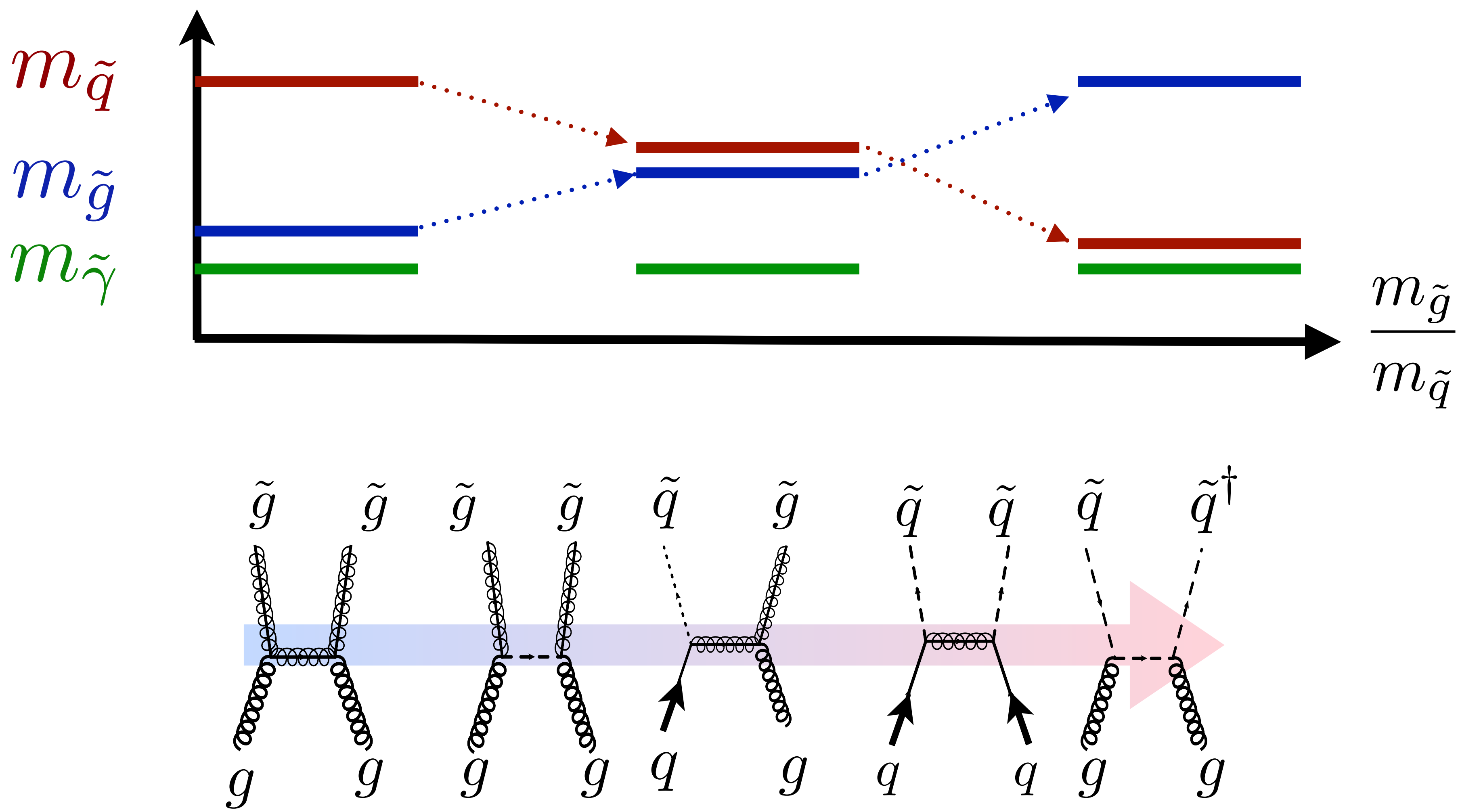
Light Flavored Simplified Models

4 Topologies Studied Based On Gluino Pair Production

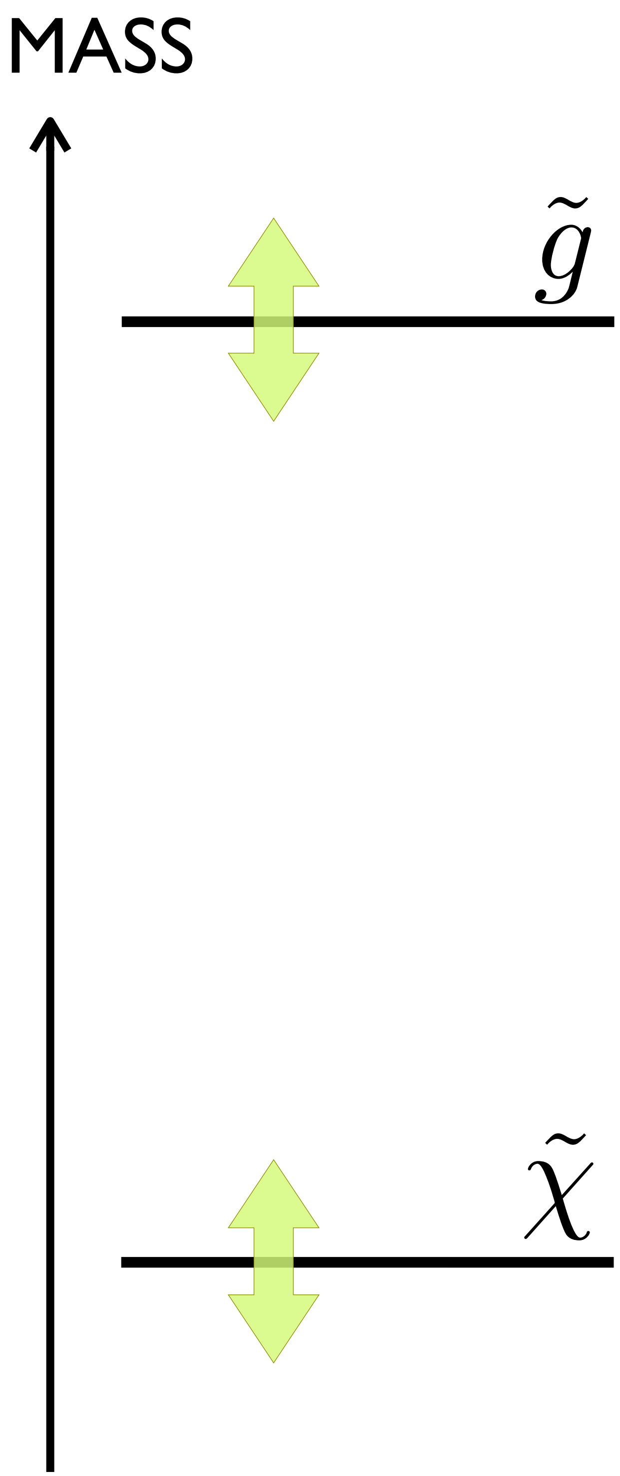
Light Flavored Squark Pair Production Not Studied Yet

Squark Gluino Associated Production Not Studied Yet



Simplified Models

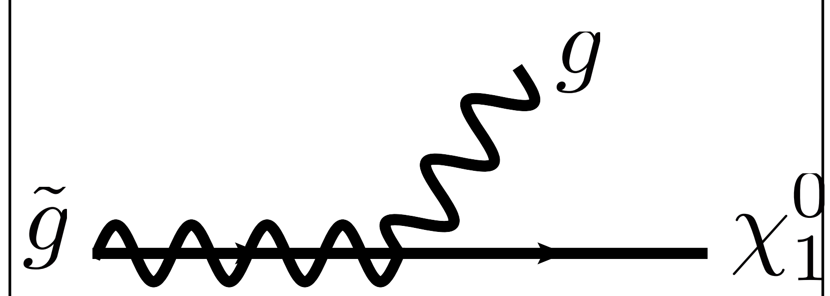
Direct Decays



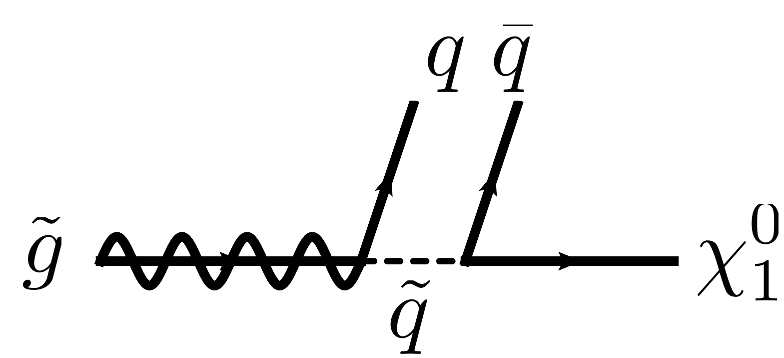
color octet majorana fermion ("Gluino")

neutral majorana fermion ("LSP")

TWO-BODY

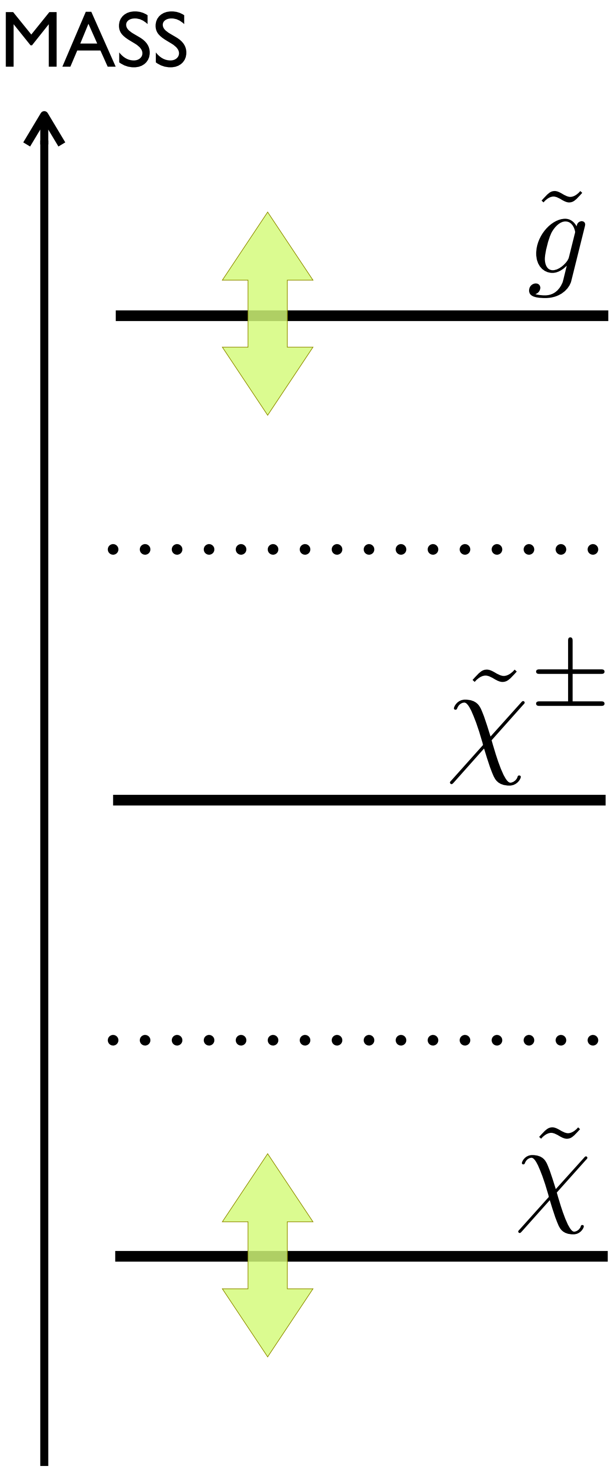


THREE-BODY



Simplified Models

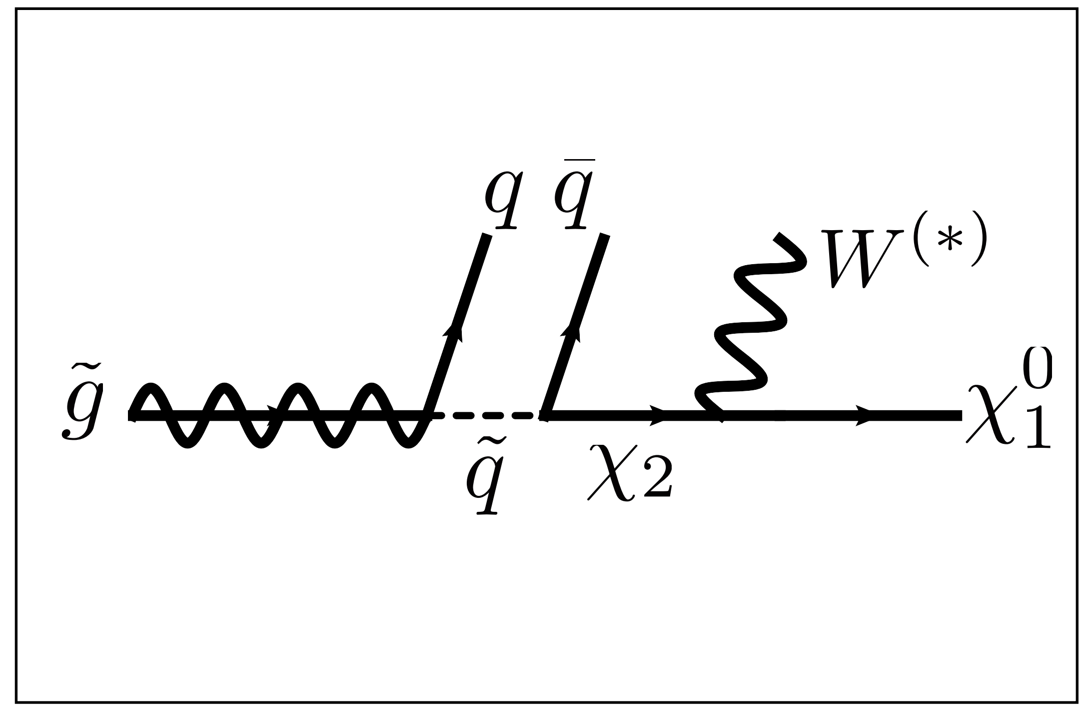
One-Step Cascade Decays



color octet majorana fermion ("Gluino")

electroweak majorana fermion ("Wino")

neutral majorana fermion ("LSP")

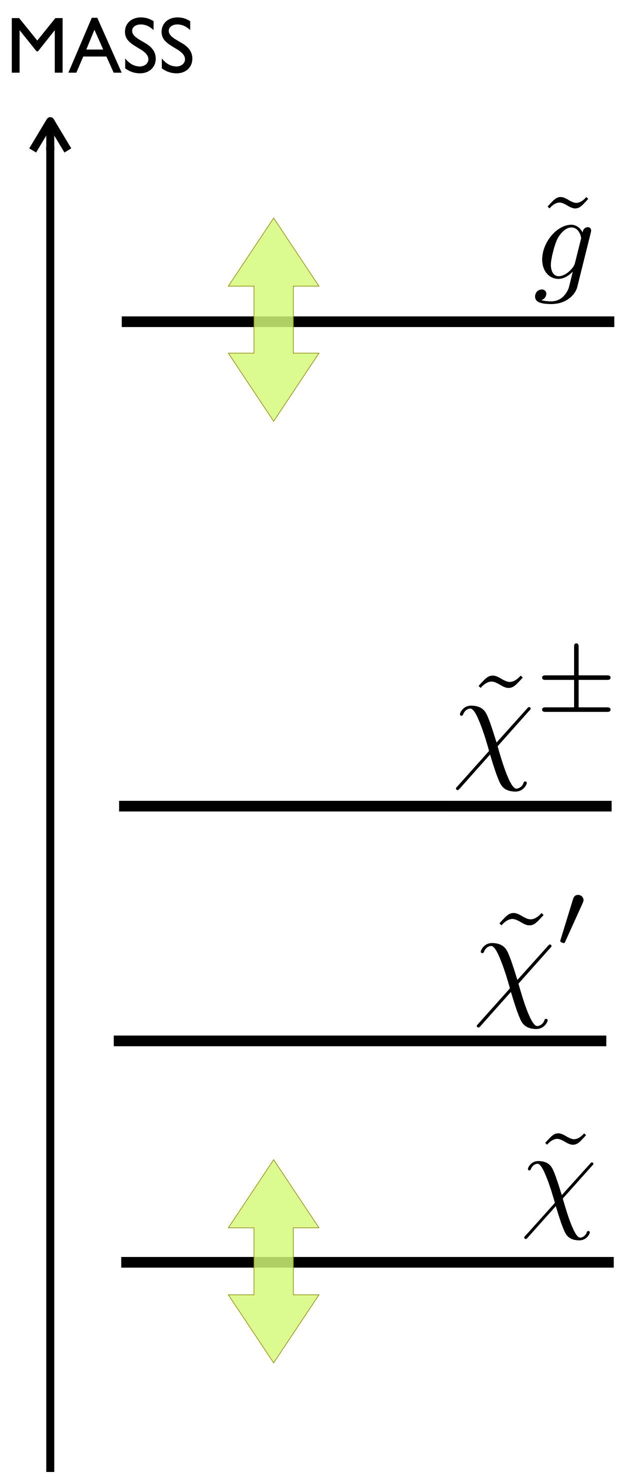


$$m_{\tilde{\chi}^{\pm}} = m_{\tilde{\chi}} + r\,(m_{\tilde{g}} - m_{\tilde{\chi}})$$

$$r = \frac{1}{4}, \frac{1}{2}, \frac{3}{4}$$

Simplified Models

Two-Step Cascade Decays

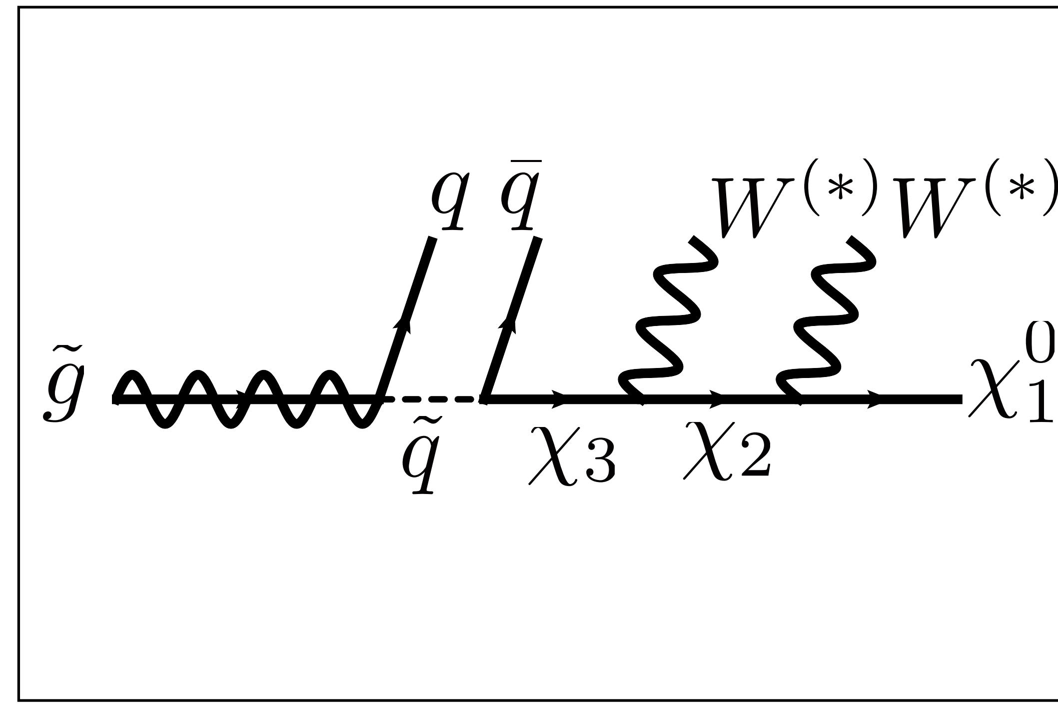


color octet majorana fermion ("Gluino")

electroweak majorana fermion ("Wino")

neutral majorana fermion ("Higgsino")

neutral majorana fermion ("LSP")



$$m_{\tilde{\chi}^{\pm}} = m_{\tilde{\chi}} + \frac{1}{2}(m_{\tilde{g}} - m_{\tilde{\chi}})$$

$$m_{\tilde{\chi}'} = m_{\tilde{\chi}} + \frac{1}{2}(m_{\tilde{\chi}^{\pm}} - m_{\tilde{\chi}})$$

Hunting for Optimal Cuts

Want to have good coverage
for all these models
for all kinematic ranges

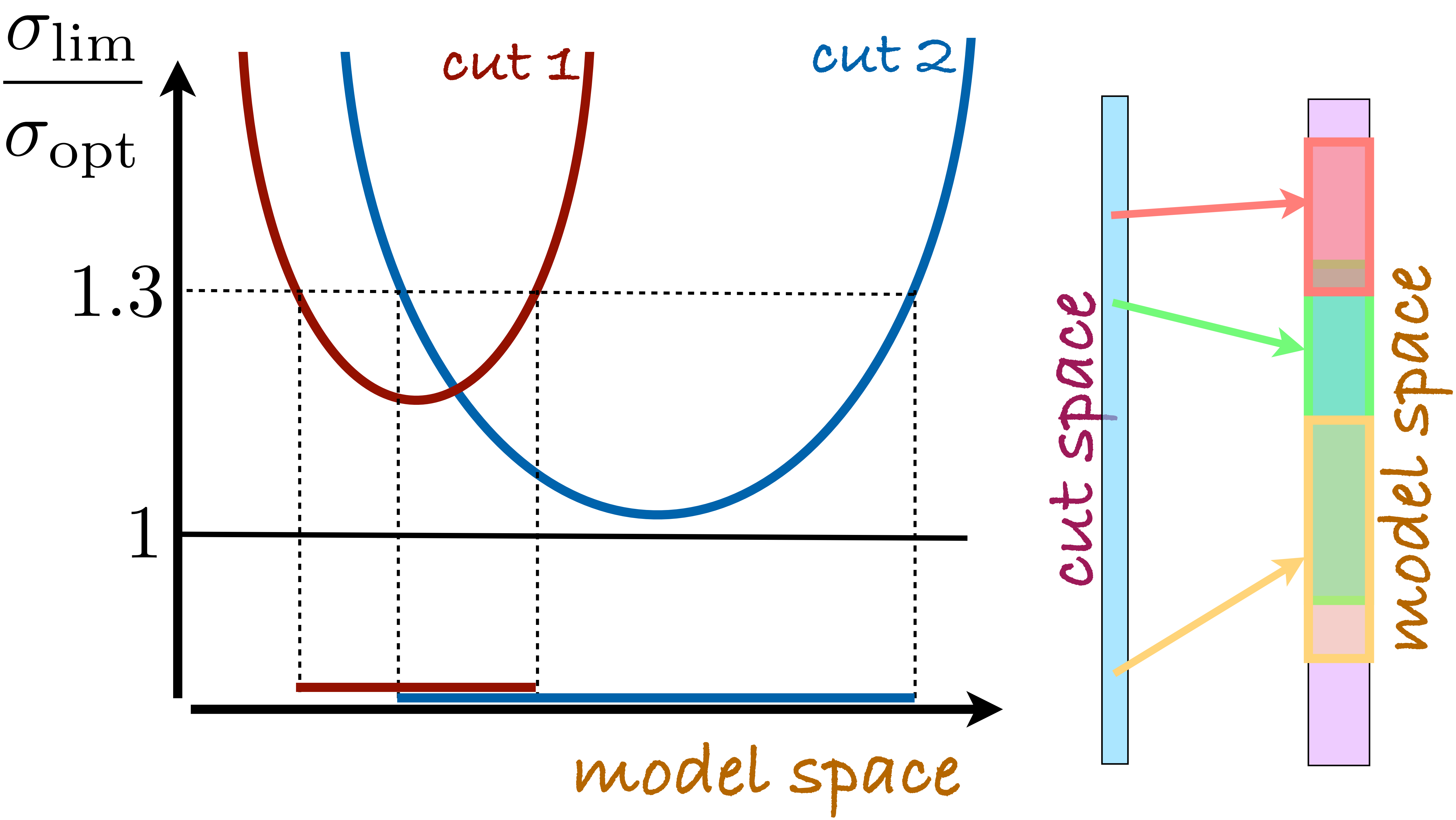
Want to minimize: $$\frac{\sigma_{\rm lim}(\rm cut)}{\sigma_{\rm optimal\ lim}}$$

QUESTION: Is there a single cut whose sensitivity is close to optimal for all masses and decay modes?

ANSWER: No

Hunting for Optimal Cuts

TASK: Find the *minimum* set of cuts on MET and H_T whose *combined* reach is close to optimal (within a given accuracy) for all models.



Hunting for Optimal Cuts

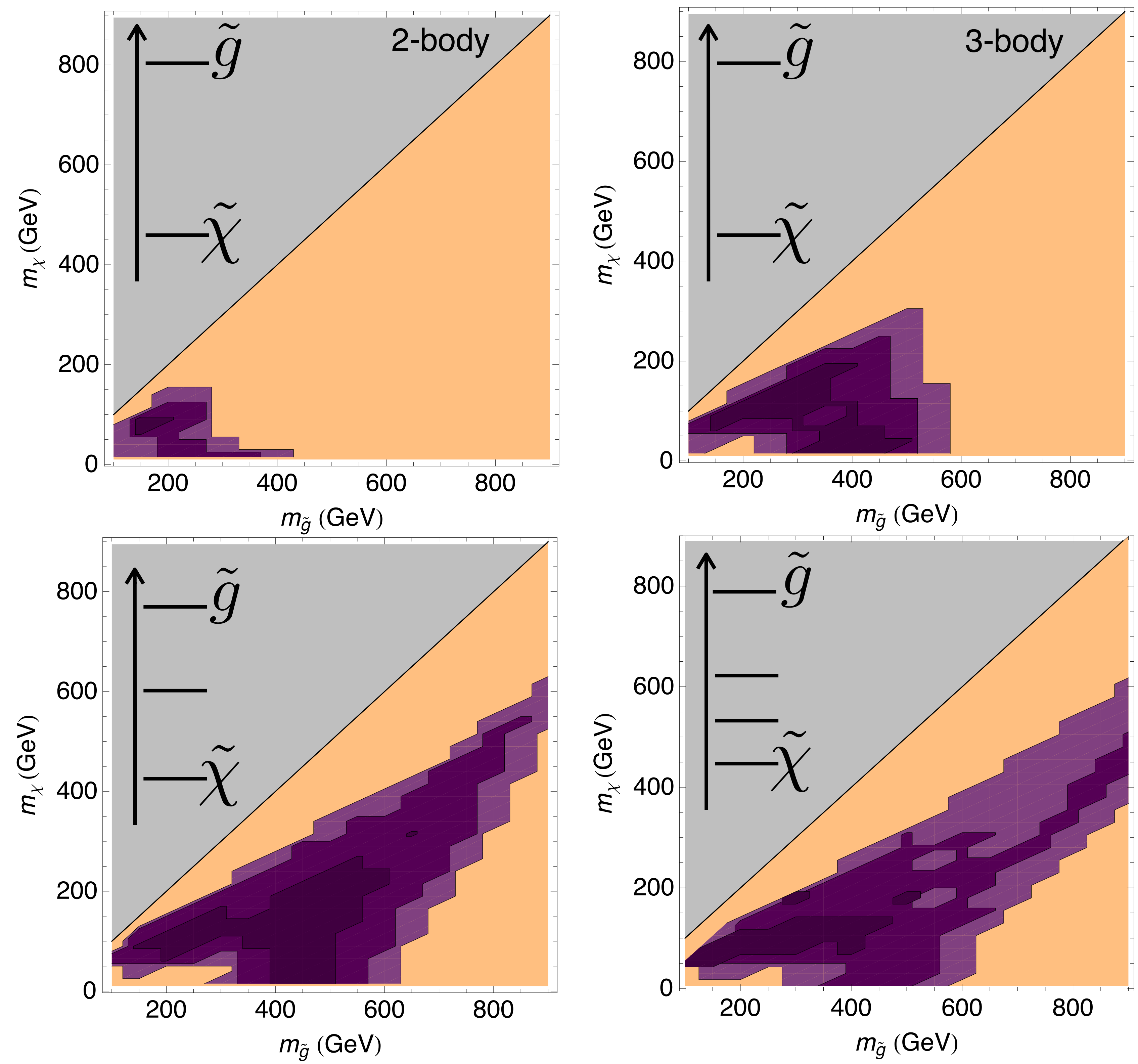
E.g.,
reach of the search region

$$\left\{ \begin{array}{l} \not{E}_T \geq 150 \text{ GeV} \\ H_T \geq 750 \text{ GeV} \end{array} \right.$$

within 10% of optimal

within 20% of optimal

within 30% of optimal



Multiple Search Regions

- minimal set of cuts (*multiple search regions*) whose combined reach is within optimal to a given accuracy

→ for all masses and decay modes

Set up a genetic algorithm to optimize search strategies

- size of the set depends on the optimal accuracy
  - 5% → $\mathcal{O}$(30 cuts)
  - 10% → $\mathcal{O}$(16 cuts)
  - 30% → $\mathcal{O}$(6 cuts)
  - 50% → $\mathcal{O}$(4 cuts)
- not sensitive to exact values of the cuts
- only *comprehensive* when *combined*

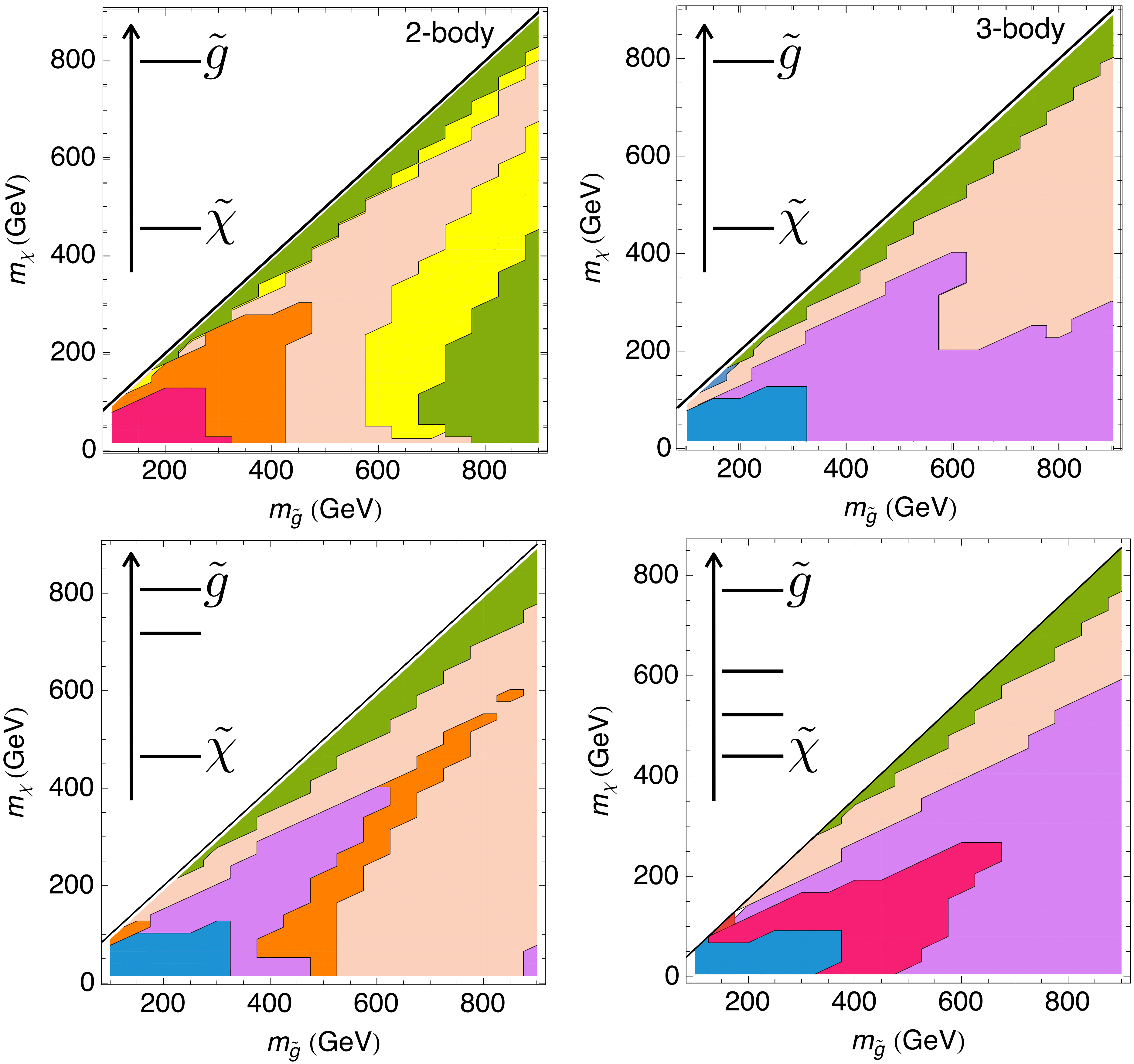
Multiple Search Regions

combined reach within 30% of optimal

- 6 search regions necessary:

Dijet high MET	$\not{E}_T > 500$ GeV, $H_T > 750$ GeV
Trijet high MET	$\not{E}_T > 450$ GeV, $H_T > 500$ GeV
Multijet low MET	$\not{E}_T > 100$ GeV, $H_T > 450$ GeV
Multijet very high H_T	$\not{E}_T > 150$ GeV, $H_T > 950$ GeV
Multijet moderate MET	$\not{E}_T > 250$ GeV, $H_T > 300$ GeV
Multijet high MET	$\not{E}_T > 350$ GeV, $H_T > 600$ GeV

Multiple Search Regions



Multijet high MET

cut	ch	MET	H_T
(green)	2^+j	500	750
(yellow)	3^+j	450	500
(blue)	4^+j	100	450
(pink)	4^+j	100	650
(violet)	4^+j	150	950
(orange)	4^+j	250	300
(peach)	4^+j	350	600

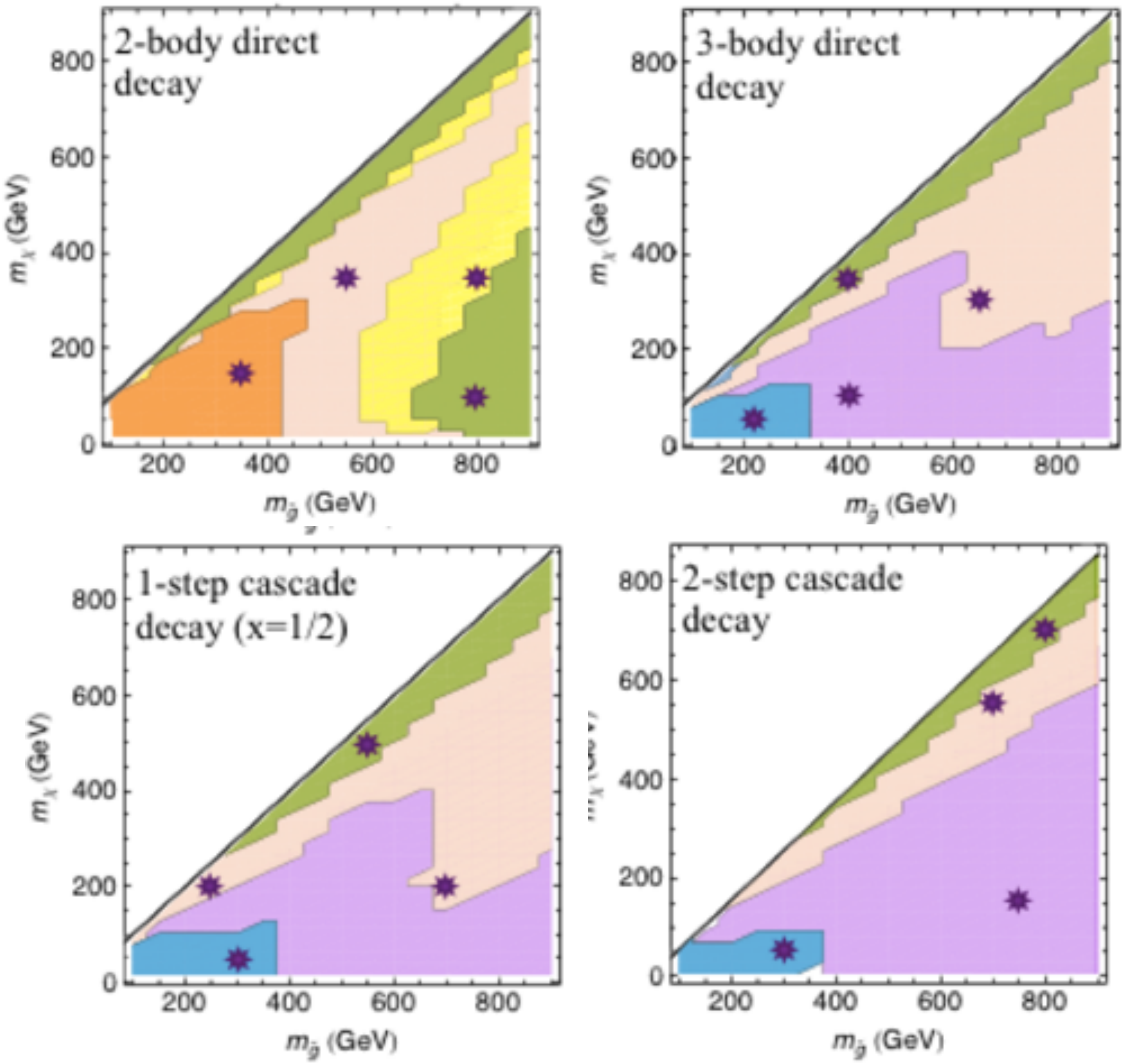
Designing Optimal Regions

- 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



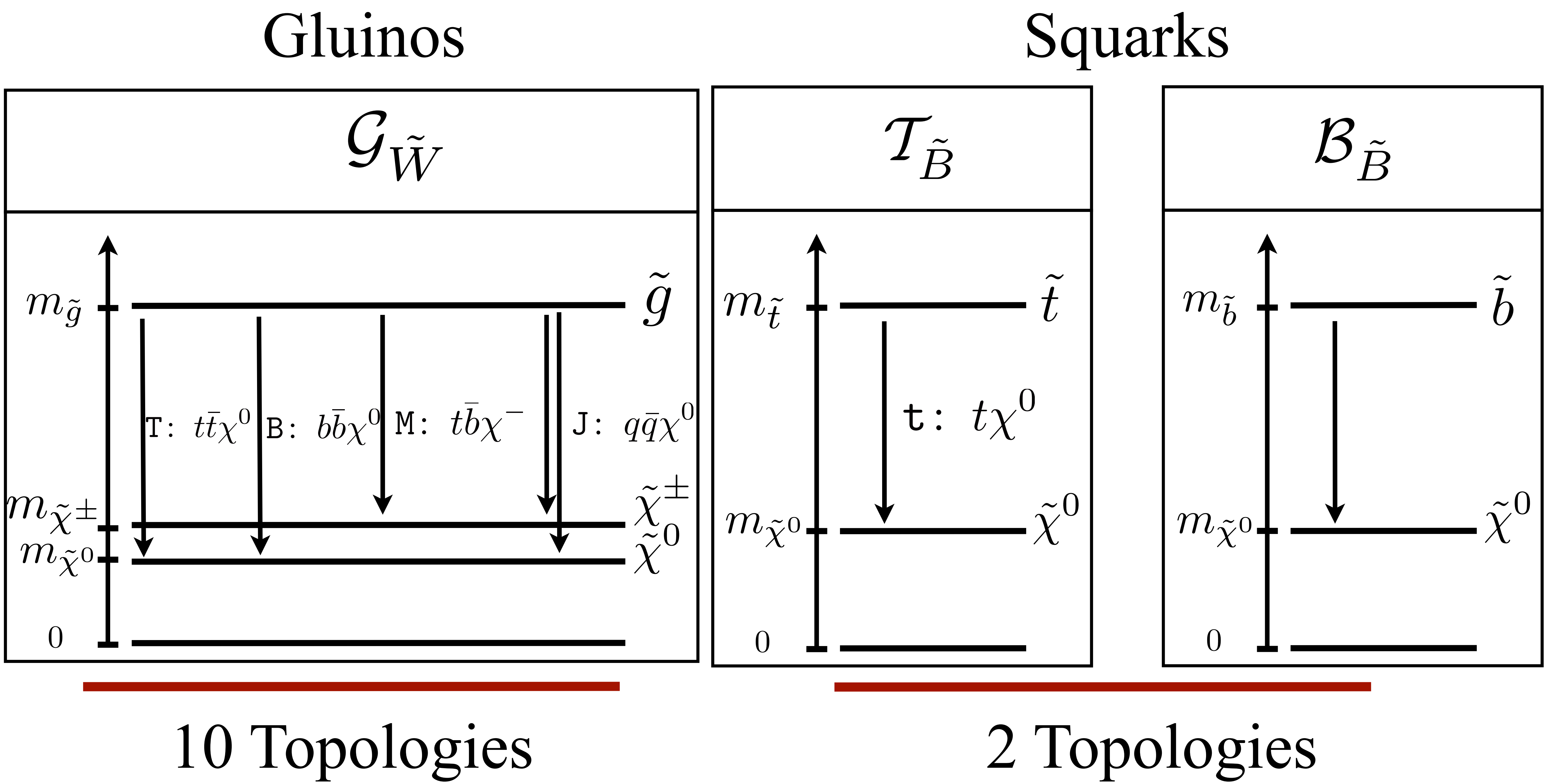
List of Benchmark Models

- 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

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

Heavy Flavor Susy Jets+MET



Have 3 Free Parameters in Each Topology

2 Masses & Cross Section x BR

What are these searches?

(searches useful for 1/fb)

	Search Region	N_j	N_ℓ	$N_{\rm bjet}$	$\not{E}_T$	H_T
High HT	1	2^+	0	0	300	700
High MET	2	4^+	0	0	500	900
1 b Low multiplicity	3	2^+	0	1^+	300	400
1 b High HT	4	4^+	0	1^+	300	600
3 b	8	4^+	0	3^+	150	400
b SSDL	9	2^+	SSDL	1^+	0	200

2 Normal Light Flavor

2 Normal Heavy Flavor

2 Low BG Heavy Flavor

Not surprising, not unique

Benchmarks Distributed Over 10 Topologies

Name	$m_{\tilde{g}}$ (GeV)	m_{χ^0} (GeV)	$\sigma^{\rm reach}_{1\ \rm fb^{-1}}$ (fb)	$\sigma^{\rm reach}_{5\ \rm fb^{-1}}$ (fb)	$\sigma^{\rm reach}_{15\ \rm fb^{-1}}$ (fb)	$\sigma^{\rm QCD}_{\rm prod}$ (fb)
$\mathcal{G}^{\rm TT}_{\tilde{B}}$	500	115	592	129	44	2310
$\mathcal{G}^{\rm TT}_{\tilde{B}}$	500	40	428	95	32	2310
$\mathcal{G}^{\rm TT}_{\tilde{B}}$	650	40	139	65	26	335
$\mathcal{G}^{\rm TT}_{\tilde{B}}$	800	415	469	129	44	61
$\mathcal{G}^{\rm TT}_{\tilde{B}}$	800	40	92	27	13	61
$\mathcal{G}^{\rm BB}_{\tilde{B}}$	100	40	353000	265000	226000	21.2×10^6
$\mathcal{G}^{\rm BB}_{\tilde{B}}$	200	15	17800	11400	10400	625000
$\mathcal{G}^{\rm BB}_{\tilde{B}}$	200	165	3360	3230	3210	625000
$\mathcal{G}^{\rm BB}_{\tilde{B}}$	350	165	875	591	373	24200
$\mathcal{G}^{\rm BB}_{\tilde{B}}$	500	40	94	37	24	2310
$\mathcal{G}^{\rm BB}_{\tilde{B}}$	600	365	236	112	70	617
$\mathcal{G}^{\rm BB}_{\tilde{B}}$	700	265	57	20	11	186
$\mathcal{G}^{\rm BB}_{\tilde{B}}$	750	490	153	62	41	106
$\mathcal{G}^{\rm BB}_{\tilde{B}}$	800	765	4056	1840	1490	61
$\mathcal{G}^{\rm BB}_{\tilde{B}}$	800	40	42	11	5.2	61
$\mathcal{G}^{\rm BB}_{\tilde{B}}$	900	540	65	23	13	21

Name	$m_{\tilde{g}}$ (GeV)	m_{χ^0} (GeV)	$\sigma^{\rm reach}_{1\ \rm fb^{-1}}$ (fb)	$\sigma^{\rm reach}_{5\ \rm fb^{-1}}$ (fb)	$\sigma^{\rm reach}_{15\ \rm fb^{-1}}$ (fb)	$\sigma^{\rm QCD}_{\rm prod}$ (fb)
$\mathcal{G}^{\rm TB}_{\tilde{B}}$	500	115	239	146	92	2310
$\mathcal{G}^{\rm TB}_{\tilde{B}}$	500	40	175	100	63	2310
$\mathcal{G}^{\rm TB}_{\tilde{B}}$	650	40	88	29	14	335
$\mathcal{G}^{\rm TB}_{\tilde{B}}$	800	415	152	59	37	61
$\mathcal{G}^{\rm TB}_{\tilde{B}}$	800	40	66	17	8.3	61
$\mathcal{G}^{\rm TJ}_{\tilde{B}}$	450	65	1680	1320	1080	4760
$\mathcal{G}^{\rm TJ}_{\tilde{B}}$	550	140	653	470	354	1170
$\mathcal{G}^{\rm TJ}_{\tilde{B}}$	650	40	177	102	83	335
$\mathcal{G}^{\rm TJ}_{\tilde{B}}$	800	415	349	234	183	61
$\mathcal{G}^{\rm TJ}_{\tilde{B}}$	800	40	79	39	24	61
$\mathcal{G}^{\rm BJ}_{\tilde{B}}$	200	165	25000	17900	13000	625000
$\mathcal{G}^{\rm BJ}_{\tilde{B}}$	200	40	35100	25400	11800	625000
$\mathcal{G}^{\rm BJ}_{\tilde{B}}$	500	40	311	197	179	2310
$\mathcal{G}^{\rm BJ}_{\tilde{B}}$	800	765	4120	2960	2510	61
$\mathcal{G}^{\rm BJ}_{\tilde{B}}$	800	40	58	29	17	61

Name	$m_{\tilde{g}}$ (GeV)	m_{χ^0} (GeV)	$\sigma^{\rm reach}_{1\ \rm fb^{-1}}$ (fb)	$\sigma^{\rm reach}_{5\ \rm fb^{-1}}$ (fb)	$\sigma^{\rm reach}_{15\ \rm fb^{-1}}$ (fb)	$\sigma^{\rm QCD}_{\rm prod}$ (fb)
$\mathcal{G}^{\rm TM}_{\tilde{W}}$	500	115	422	184	63	2310
$\mathcal{G}^{\rm TM}_{\tilde{W}}$	500	40	324	126	44	2310
$\mathcal{G}^{\rm TM}_{\tilde{W}}$	650	40	115	52	25	335
$\mathcal{G}^{\rm TM}_{\tilde{W}}$	800	415	243	130	66	61
$\mathcal{G}^{\rm TM}_{\tilde{W}}$	800	40	81	25	12	61
$\mathcal{G}^{\rm BM}_{\tilde{W}}$	300	45	1370	1180	1010	62100
$\mathcal{G}^{\rm BM}_{\tilde{W}}$	400	220	2660	1300	619	10400
$\mathcal{G}^{\rm BM}_{\tilde{W}}$	600	170	113	40	25	617
$\mathcal{G}^{\rm BM}_{\tilde{W}}$	800	595	1160	452	240	61
$\mathcal{G}^{\rm BM}_{\tilde{W}}$	800	45	55	15	6.9	61
$\mathcal{G}^{\rm MM}_{\tilde{W}}$	300	45	3230	695	272	62100
$\mathcal{G}^{\rm MM}_{\tilde{W}}$	450	270	3190	1530	674	4760
$\mathcal{G}^{\rm MM}_{\tilde{W}}$	550	45	150	86	51	1170
$\mathcal{G}^{\rm MM}_{\tilde{W}}$	800	595	1290	727	413	61
$\mathcal{G}^{\rm MM}_{\tilde{W}}$	800	45	69	21	10	61

Name	$m_{\tilde{g}}$ (GeV)	m_{χ^0} (GeV)	$\sigma^{\rm reach}_{1\ \rm fb^{-1}}$ (fb)	$\sigma^{\rm reach}_{5\ \rm fb^{-1}}$ (fb)	$\sigma^{\rm reach}_{15\ \rm fb^{-1}}$ (fb)	$\sigma^{\rm QCD}_{\rm prod}$ (fb)
$\mathcal{T}_{\tilde{B}}$	250	0	15100	9960	5980	180000
$\mathcal{T}_{\tilde{B}}$	350	50	1970	1500	1104	24200
$\mathcal{T}_{\tilde{B}}$	500	200	536	349	289	2310
$\mathcal{T}_{\tilde{B}}$	500	50	240	124	104	2310
$\mathcal{T}_{\tilde{B}}$	650	350	321	178	144	335
$\mathcal{T}_{\tilde{B}}$	650	50	96	49	32	335
$\mathcal{B}_{\tilde{B}}$	100	0	219000	203000	124000	21.2×10^6
$\mathcal{B}_{\tilde{B}}$	200	50	11200	8620	5370	625000
$\mathcal{B}_{\tilde{B}}$	350	200	2260	1680	1260	24200
$\mathcal{B}_{\tilde{B}}$	350	50	481	438	427	24200
$\mathcal{B}_{\tilde{B}}$	400	50	263	209	171	10400
$\mathcal{B}_{\tilde{B}}$	450	150	230	168	133	4760
$\mathcal{B}_{\tilde{B}}$	500	350	989	586	348	2310
$\mathcal{B}_{\tilde{B}}$	500	50	142	71	54	2310
$\mathcal{B}_{\tilde{B}}$	550	0	121	65	45	1170
$\mathcal{B}_{\tilde{B}}$	600	350	233	153	120	617

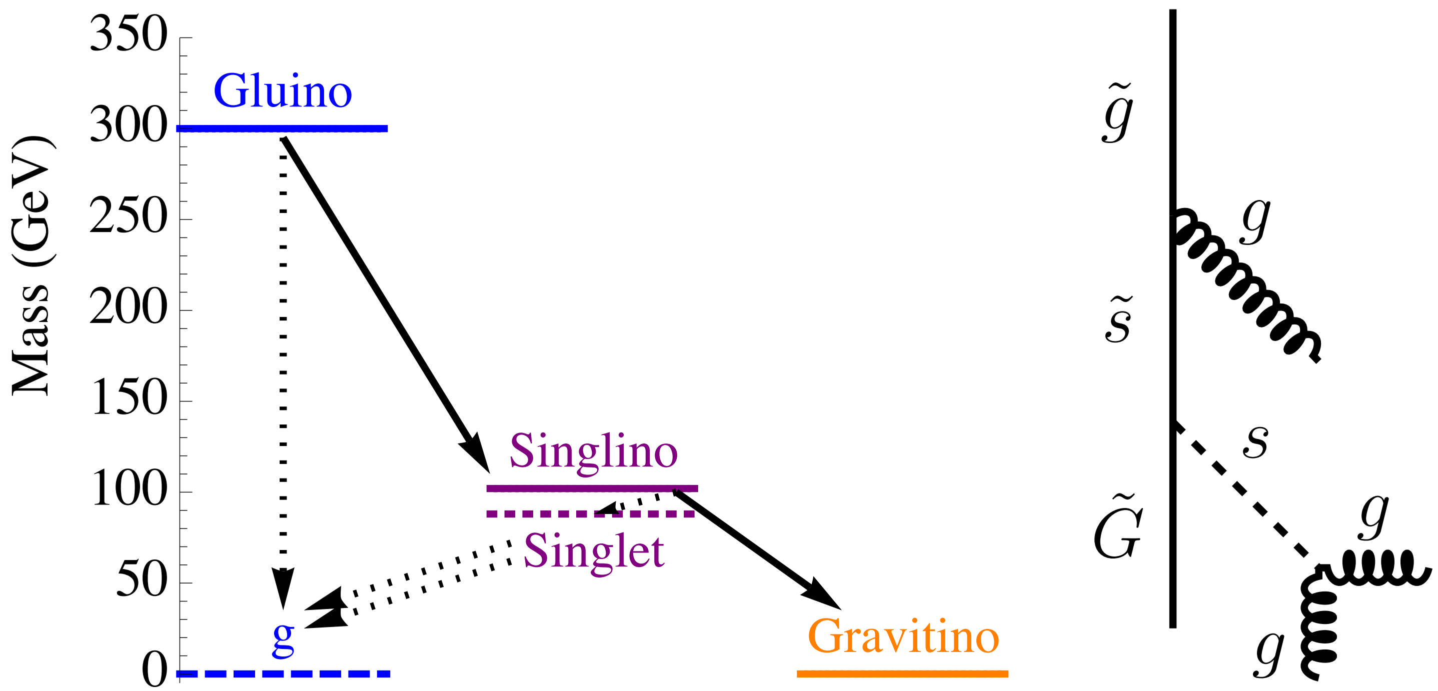
More Novel Simplified Models Being Discovered

Gluino-Squark-LSP Simplified Model not studied

Stealth Susy

Fan, Reece, Ruderman

Eviscerates MET even with stable LSP



$$\not{E}_T \sim \frac{m_{\tilde{g}}}{2m_{\tilde{S}}}(m_{\tilde{G}} \oplus \delta m_{S\tilde{S}})$$

Outline

Simplified Models

Two Examples

Light Flavored Models

Heavy Flavored Models

Future Directions

Stops

High Multiplicity Searches

Quark/Gluon Tagging

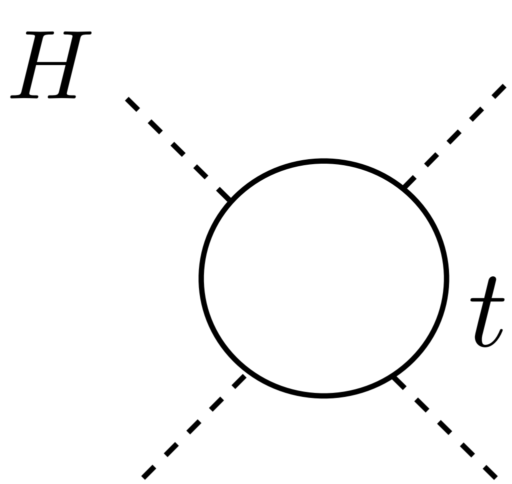
Stops

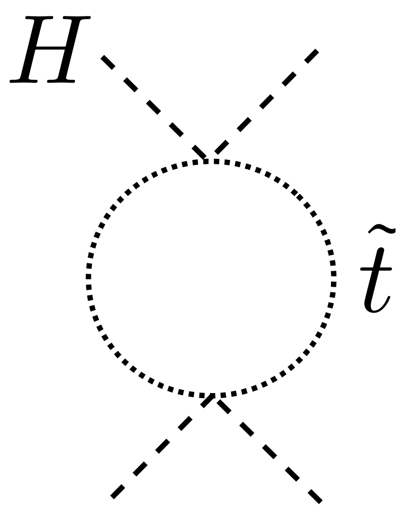
Critical for understanding naturalness

$$m_{h^0}^2 = 2\lambda v^2 = -2\mu^2$$

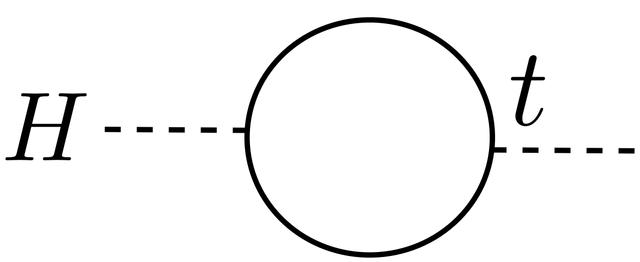
$$\lambda_{\text{susy}} = \frac{1}{8}\left(g^2 + g'^2\right)\cos^2 2\beta$$

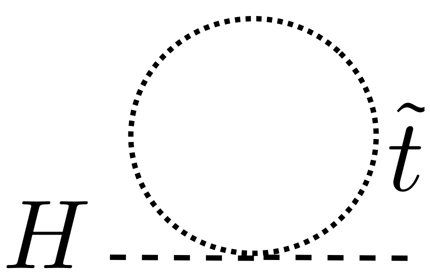
$$m_{h^0} \le M_{Z^0}$$





$$\delta\lambda = \frac{3y_{\text{top}}^4}{8\pi^2}\log\frac{m_{\text{stop}}}{m_{\text{top}}} + \frac{3a^2 y_{\text{top}}^4}{8\pi^2}\left(1 - \frac{a^2}{12}\right)$$





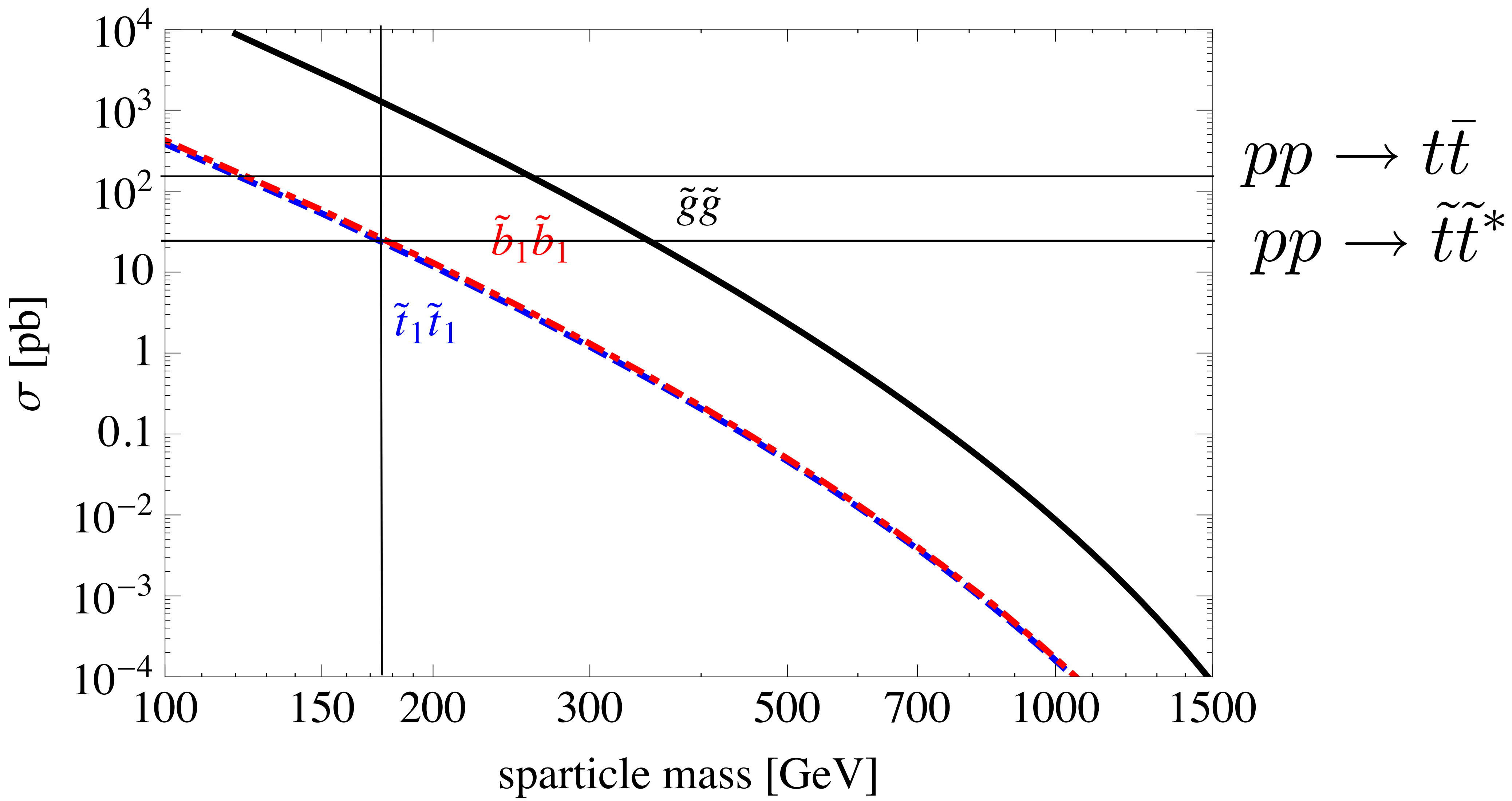
$$\delta\mu^2 = -\frac{3y_{\text{top}}^2}{8\pi^2} m_{\text{stop}}^2$$

Stop Searches

$$\tilde{t} \to t\chi^0$$

Stops look remarkably similar to tops

But with a low cross section

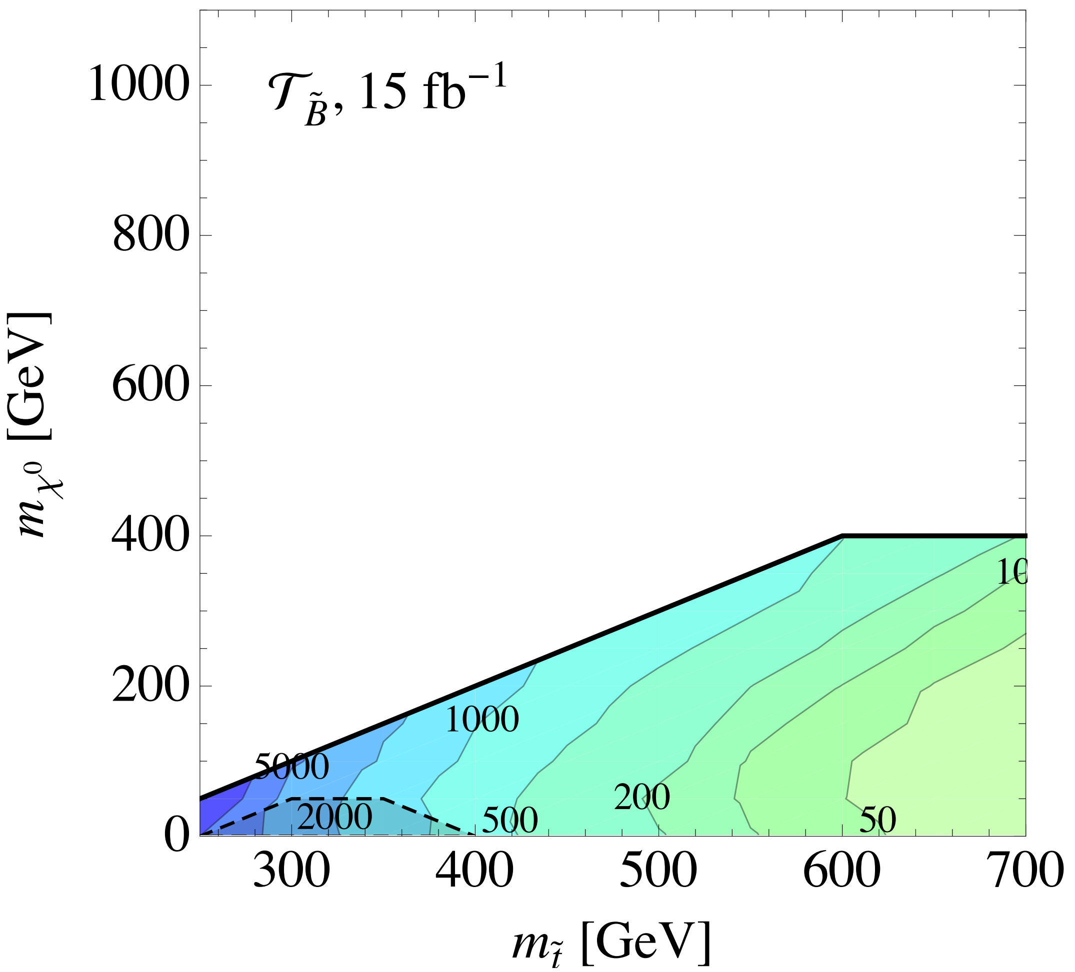


Cut-and-Count not sufficient

Stop Searches

$$\tilde{t} \rightarrow t\chi^0$$

It's not clear whether this simplified model will be effectively explored at the 7TeV LHC



Working groups are attempting multivariate analyses

Reconstructing tops

High Multiplicity Final States

Multi-Top Final States (4 tops ~ 12 jets)

Long Cascades (2 Step Cascade ~ 12 jets)

UDD R-Parity Violation (~ 10 jets)

Lowers Missing Energy

Can't Calculate Backgrounds

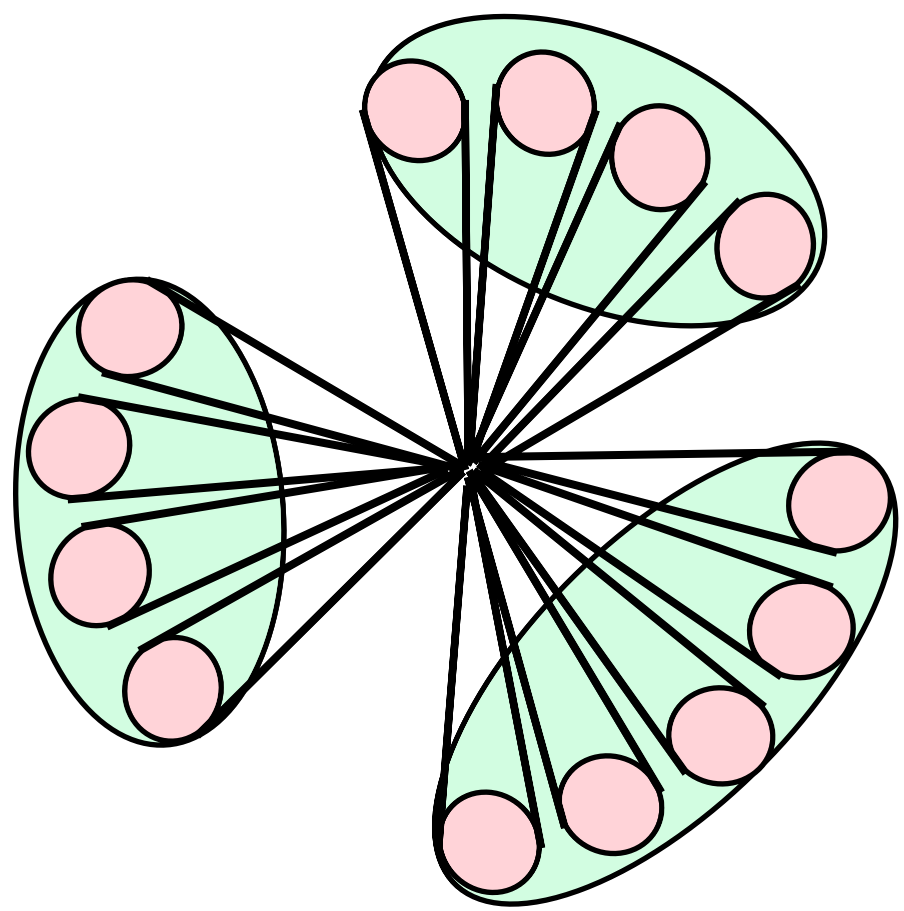
$$d\sigma(12j) \sim (\alpha_s(\mu))^{12}$$

Data-Driven Backgrounds have Large errors

Change Approach

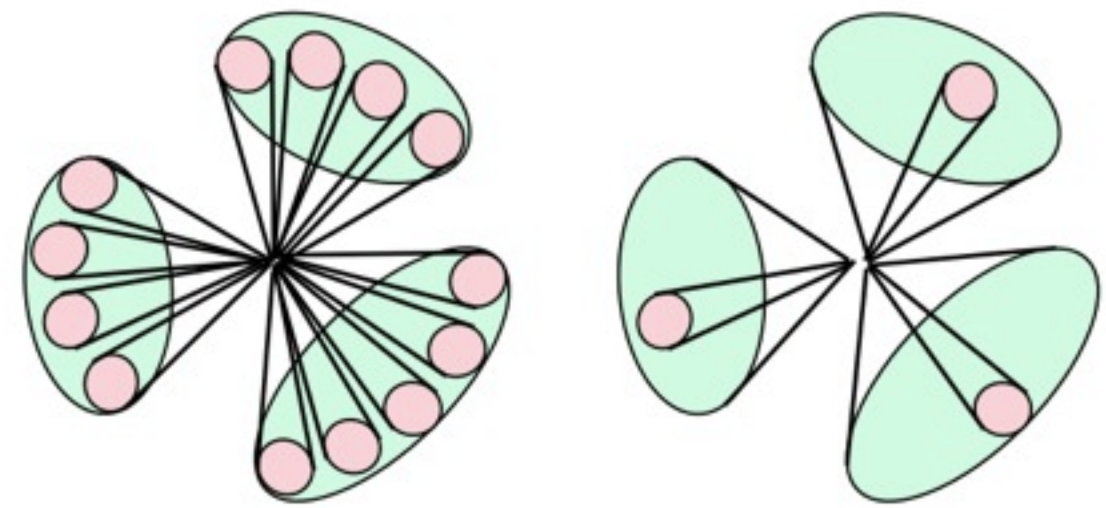
Use Large Cone Jets   e.g. CA w/ R =1.2

High Multiplicity Event
Turns into a Small Multiplicity Event



Grouping doesn’t necessarily represent topology

How to Distinguish



Jet Mass

Jet Masses are now becoming standard tools

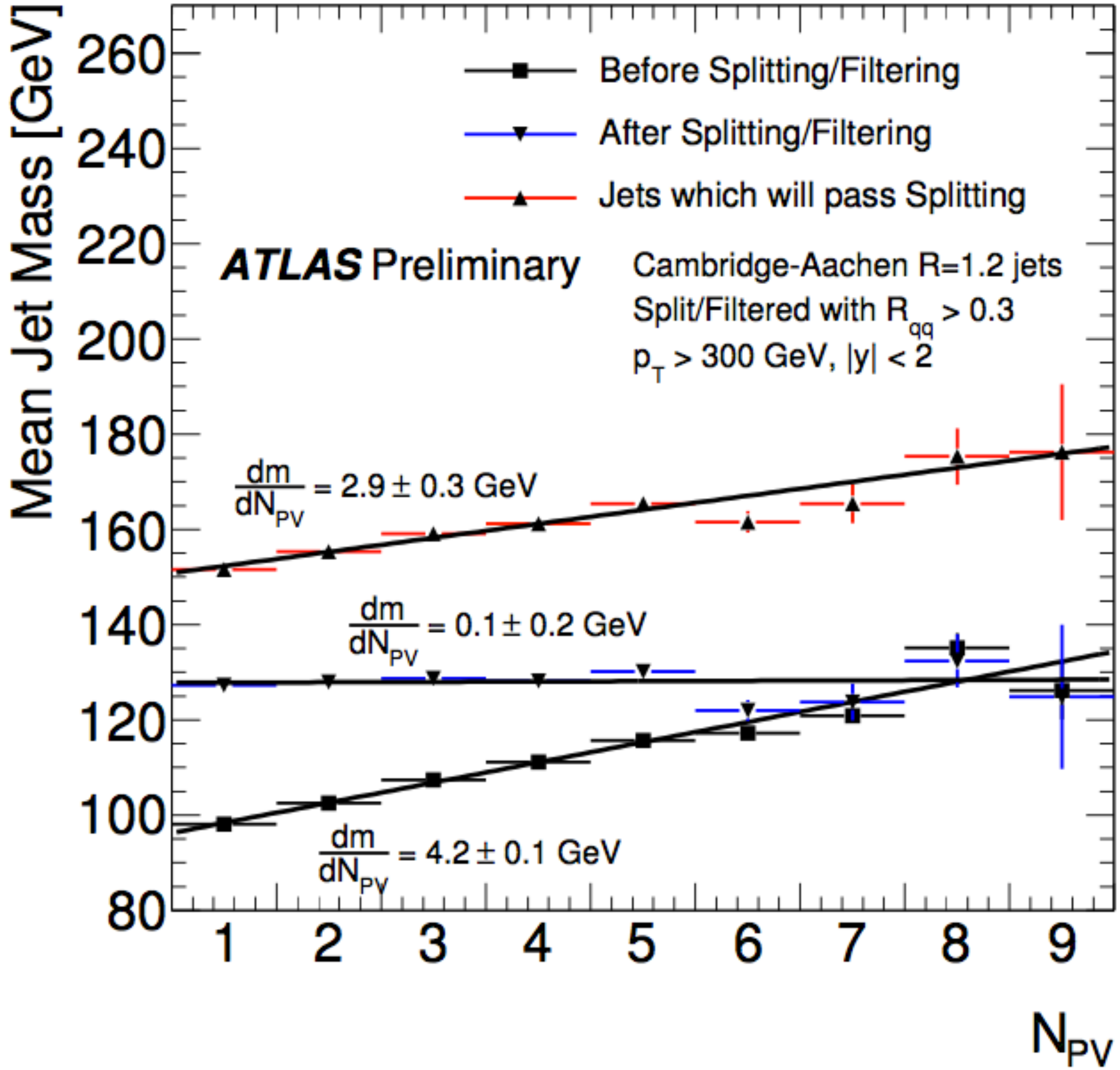
Historically not used because of UE/PU sensitivity

Stray radiation changes jet mass

Different methods for removing stray radiation

Jet Filtering/Pruning/Trimming Solves Problem

Jet Filtering at ATLAS

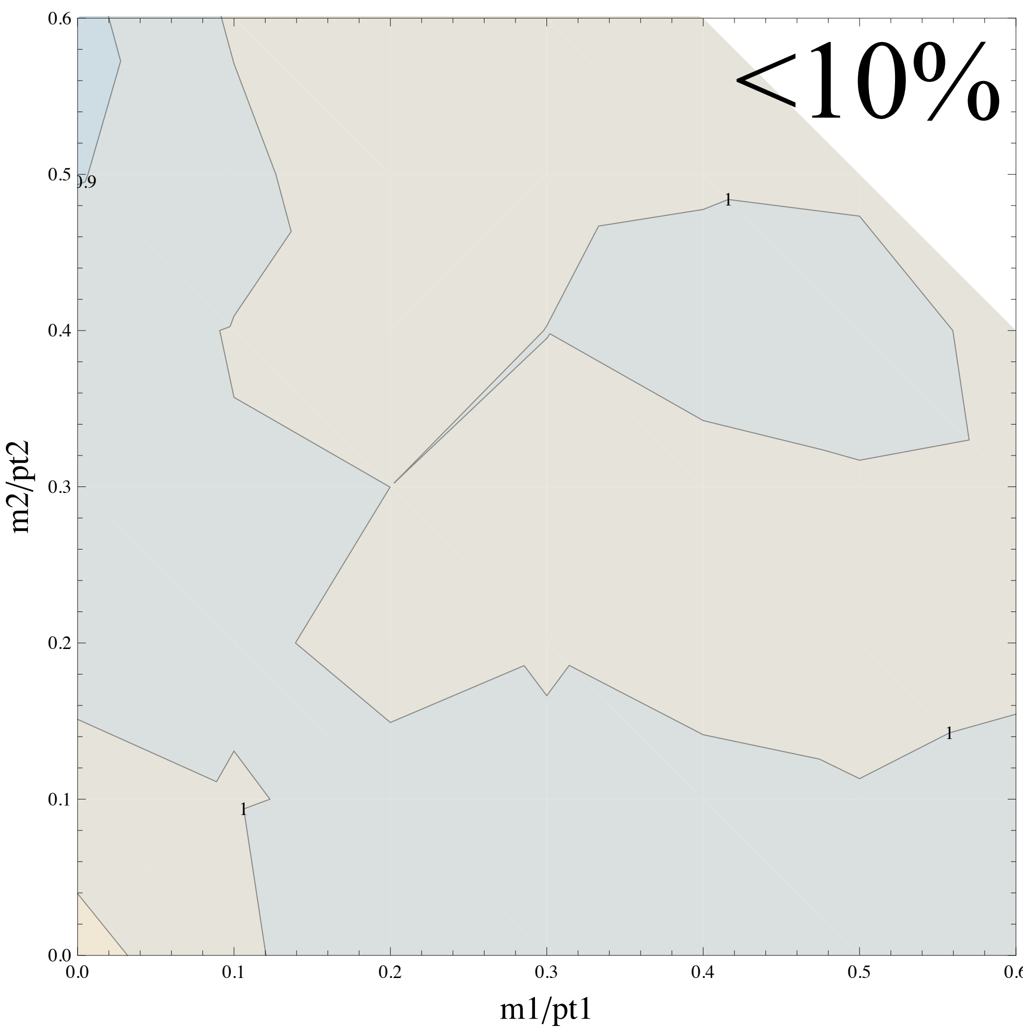


Jet Masses are (mostly) Uncorrelated

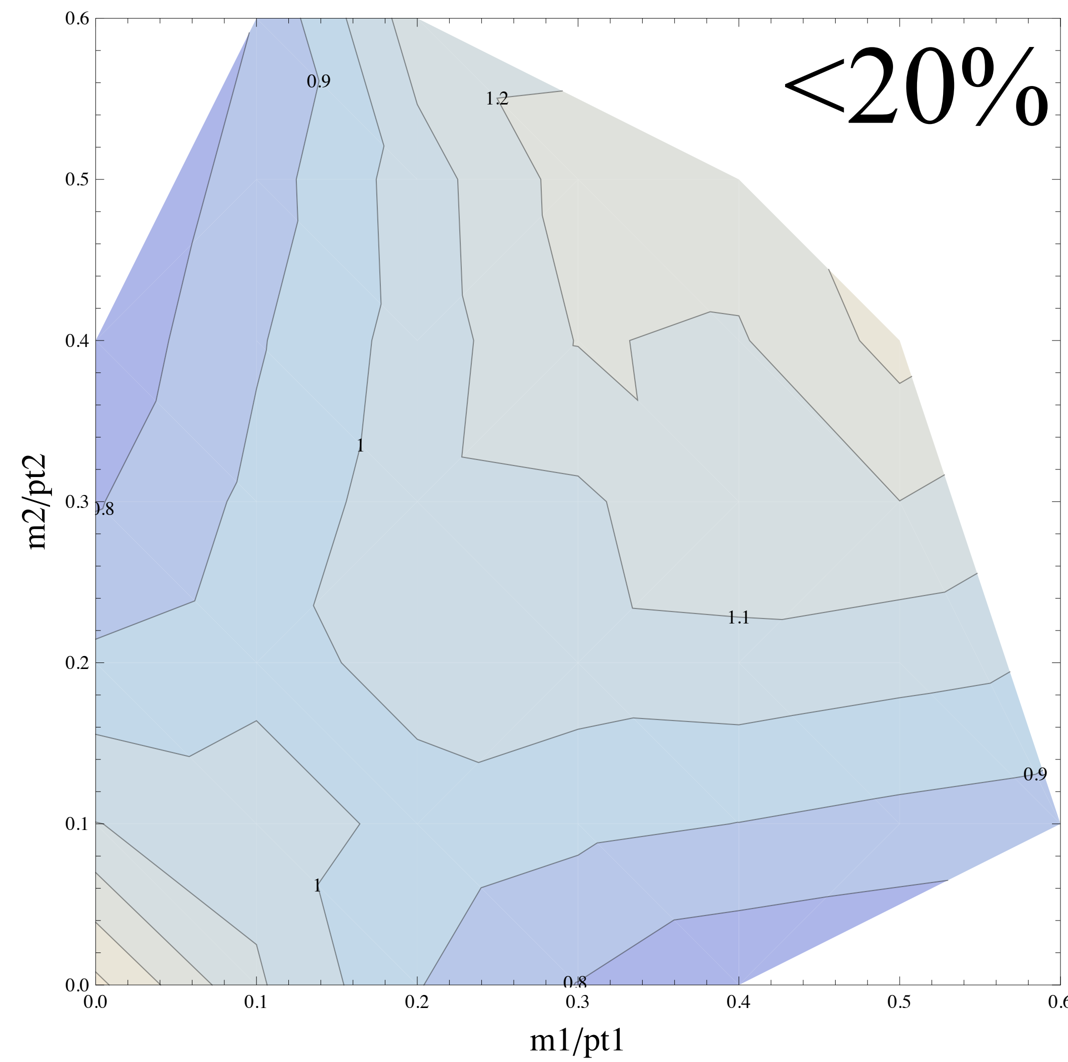
The probability of getting 1st anomalously massive jet nearly unrelated to getting the 2nd anomalously massive jet

10% to 20% correlations in MC between jet masses

$\Delta R_{j_1 j_2} > 3$



$1 < \Delta R_{j_1 j_2} < 2$

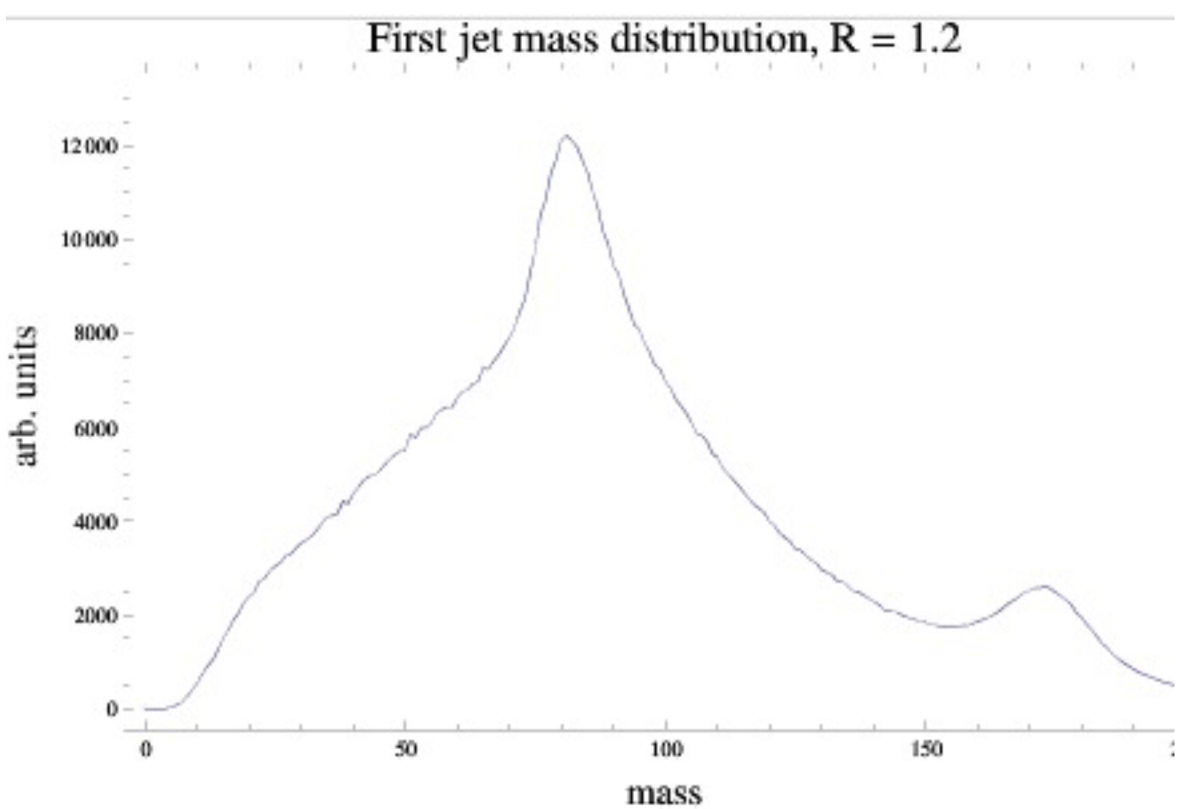


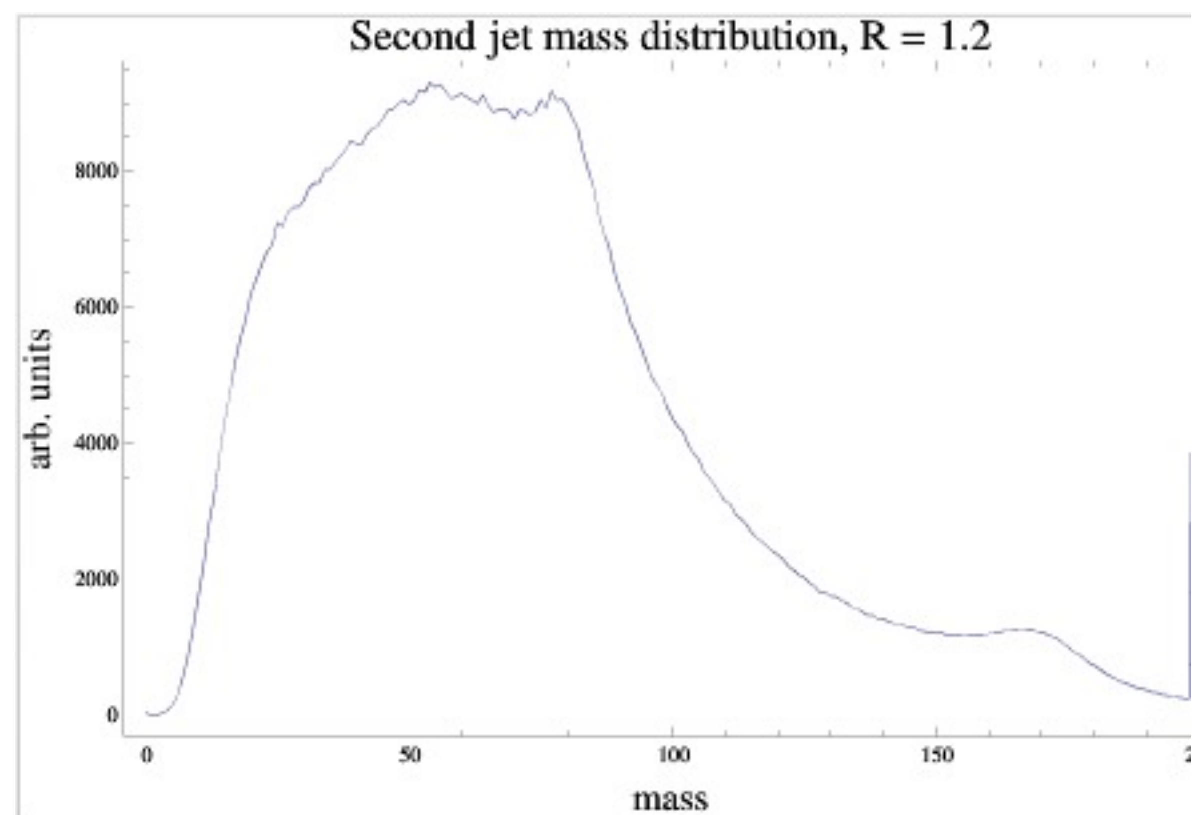
Can do data driven estimates of BGs

Perform searches requiring several jets with anomalously large mass/pTs

Top events have few events with $m_j > 180$ GeV

$m_{j1} > 200$ GeV removes 95%



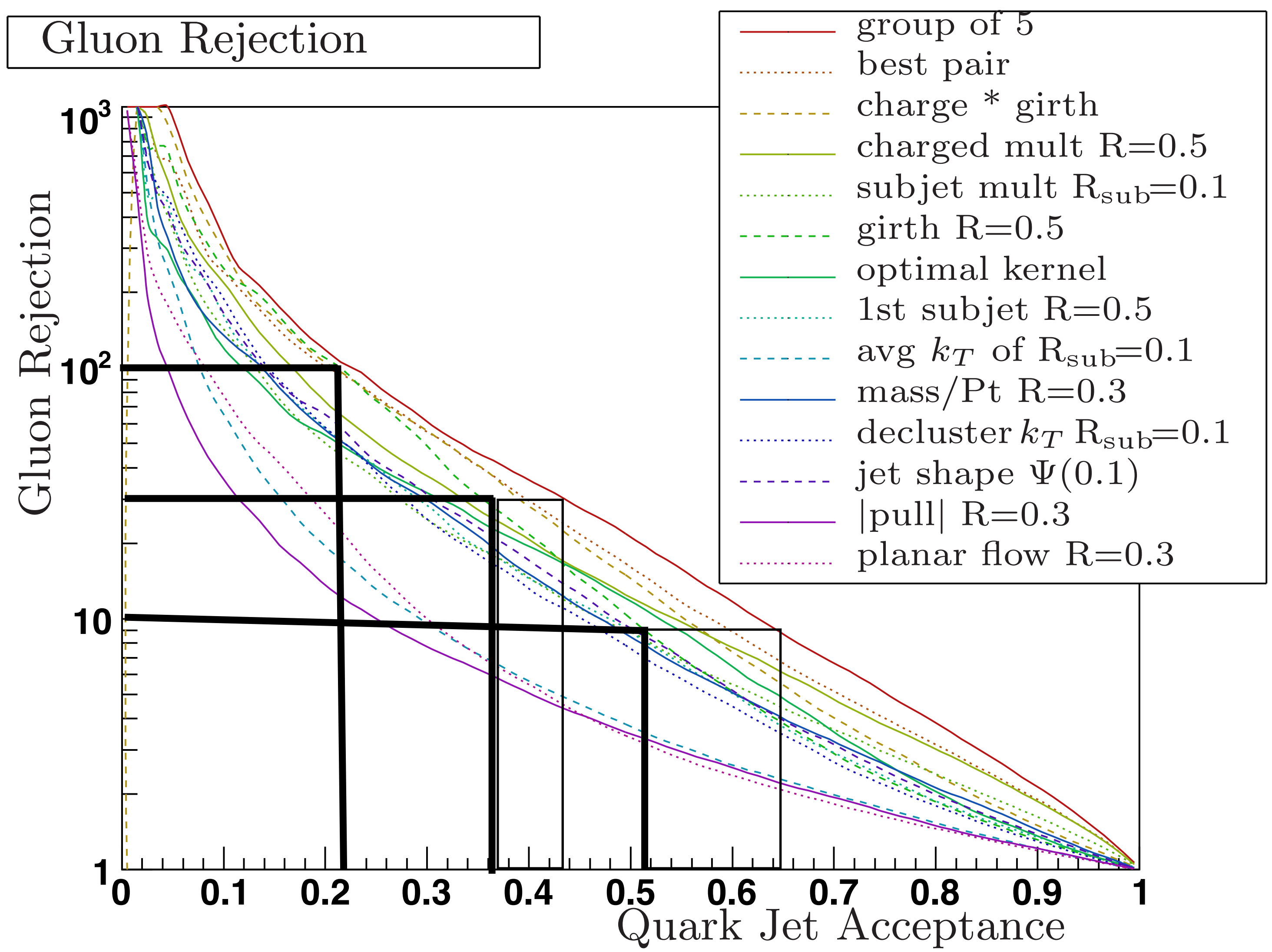


Preliminarily looks like sizable gains in significance are possible

Quark/Gluon Tagging

Recent work by Schwartz & Gallicchio

$$g = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^{jet}} |r_i|$$



R	A_g	A_{bdt}
100	22%	23%
30	36%	43%
10	51%	65%

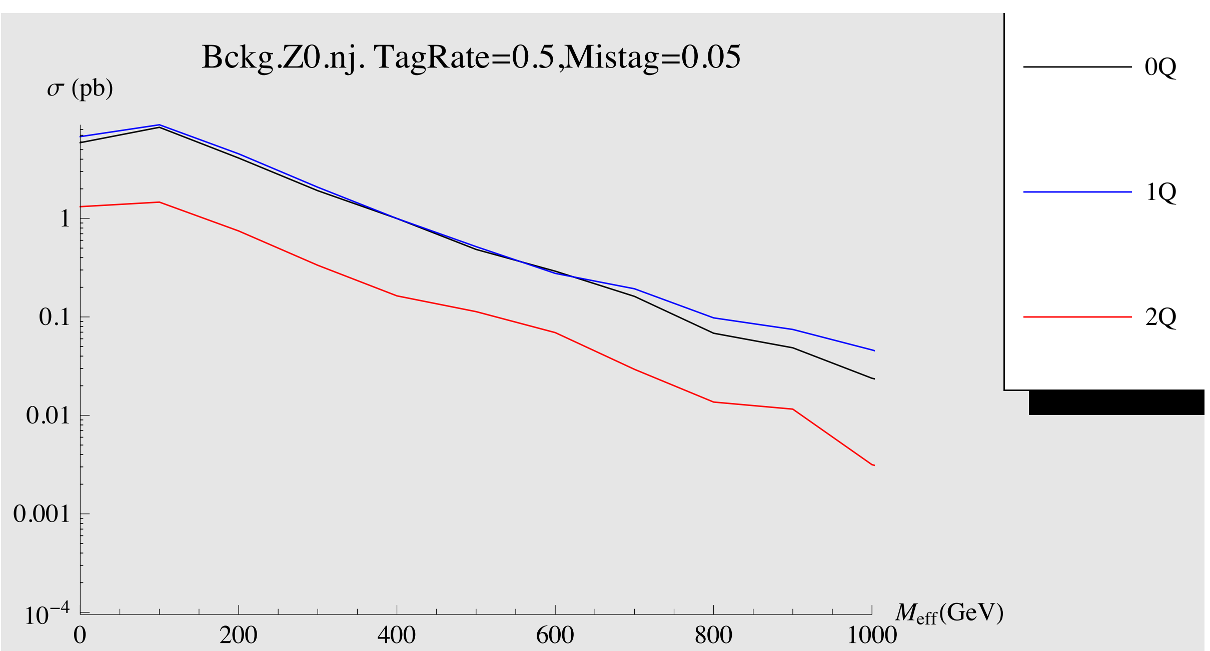
BSM Physics Produces Mostly Quark Jets

Tops Mostly Quarks

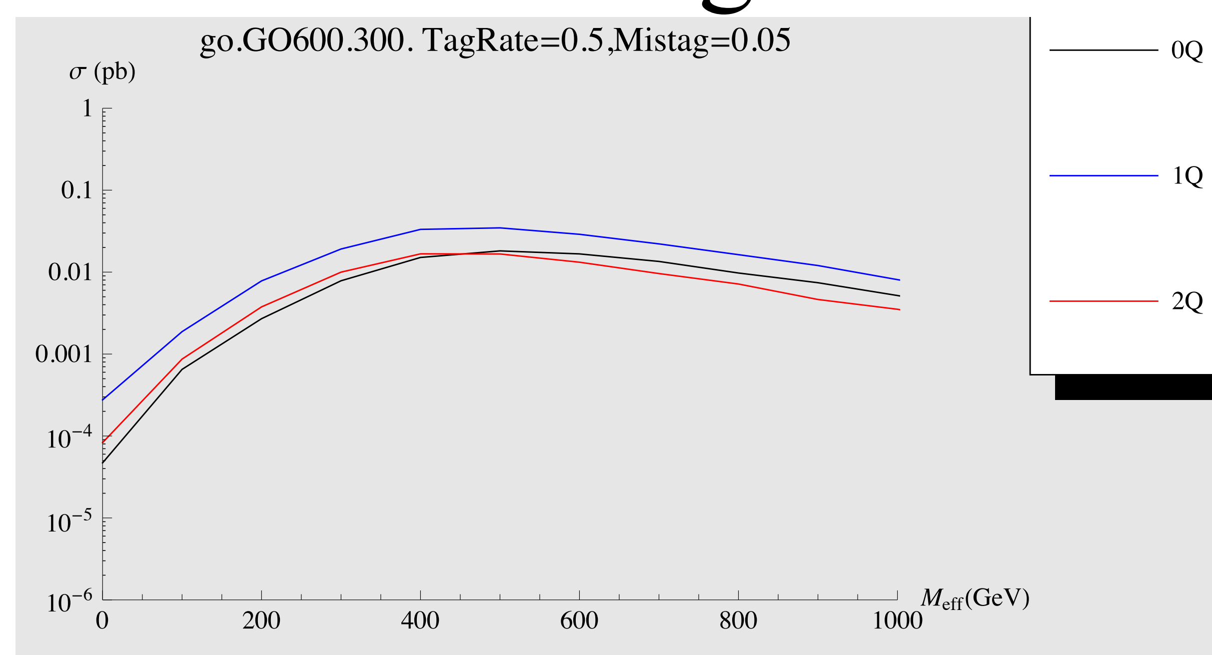
Z/W+jets Mostly Gluons

QCD Mostly Gluons

Z+jets



Gluino Signal



Can enhance S/B by a factor of 5 by requiring double Quark tags

Outlook

We're rapidly increasing our knowledge of the TeV scale

We don't have a target to aim at

New physics can be subtle and hidden under backgrounds

Lots of new techniques to use

Joint Theory-Experiment effort to ensure we're not letting physics hide