Characterizing Early LHC Data in Simple Terms

Recent Developments

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Early theory:

Alwall, Arkani-Hamed, Mrenna, Schuster, Thaler, NT, Wang hep-ph/0703088, 0810.3921
Alves, Alwall, Izaguirre, Le, Lisanti, Manhart, Wacker 0803.0019, 1003.3886, 1008.0407

Early Exp:

M. D'Alfonso, J. Incandela, S. Koay, R. Rossin (UCSB) W. Waltenberger (Vienna)
C. Horn, A. Schwartzman, et al (SLAC)

Example studies from CERN "Characterization of New Physics II" workshop:
http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=107769
SLAC "Topologies for LHC" Workshop:
http://www.lhcnewphysics.org/ and http://www-conf.slac.stanford.edu/topologies10/

Characterizing Early LHC Searches

Important questions to ask with the first (null) search results:

- What new-physics possibilities have been excluded?
- Are results from the two experiments compatible?

  An excess seen in some **other** search makes both questions more urgent.
- **Where else should we look? Are there models that slip through past searches, but could be seen by a different technique?**

Progress on each front requires mapping out the boundaries of sensitivity in the broad space of new-physics models, *and beyond the particular model (if any) that motivated the search*.

Inspired by Actual Conversations…

“Hey, I have a great model with 450 GeV gluinos!”

“Are you kidding? LM1 has gluinos at 600 GeV, and is excluded.”

“But my model is **nothing** like LM1. For starters, my squarks are heavy so there’s no associated production, which is really big for LM1.”

“But your gluinos are so light, they’d still produce tons of them.”

“That’s true, but my gluinos decay to several jets. The new search from CMS is best for di-jets. Do you know what its efficiency would be for my gluinos?”

“No. We could ask the people who did the analysis, but they’ve probably moved on.”

What can these two theorists do next?

First Steps

How do we understand search sensitivity to large class of models (even roughly), without expert knowledge of the detector/analysis?

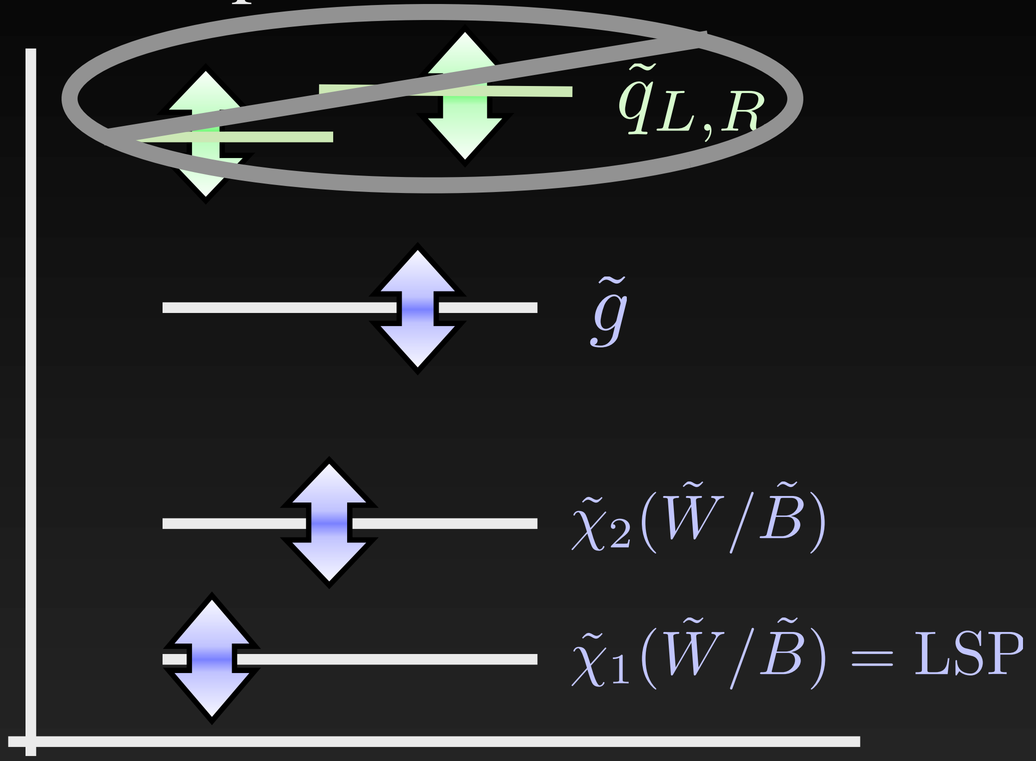
- Estimate sensitivity by running mock-up analysis on signal Monte Carlo (generator-level, PGS, …), but this is time-consuming, error-prone, not efficiently shared
- Best results can be applied easily & without expert knowledge

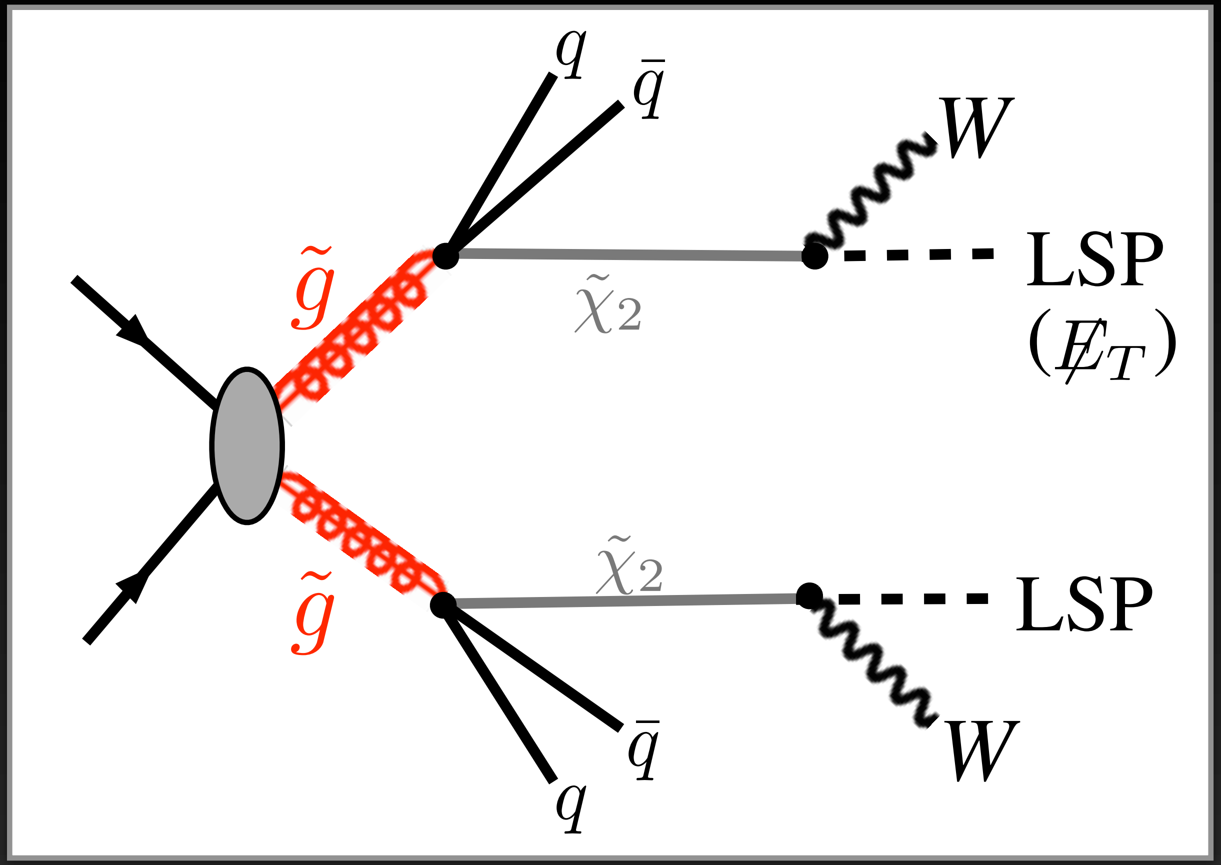
Partial, short-term solution: identify & study re-usable building blocks.

- ***Partial:*** Fully complete list is impossible
- ***Short-term:*** When one (or a few) tractable models are clearly preferred by data, use it to get precision results!
  …I expect this will take a while.

Processes: Re-Usable Building Blocks

Mass spectrum





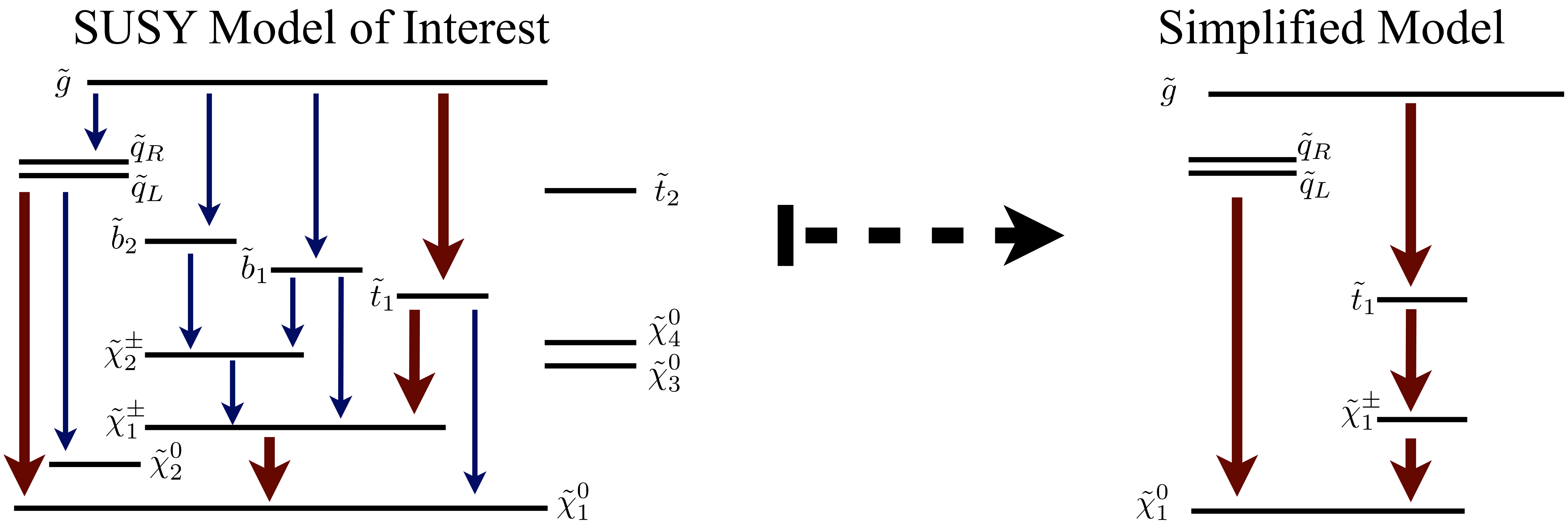
Masses of $\tilde{g}, \tilde{\chi}_2, \tilde{\chi}_1$ affect kinematics, search efficiency/optimization

Cross-section depends on unknowns (spins & masses of other particles), but scale is known (QCD gluino production)

These parameters are simply related to observables, **and** simple to calculate in given model.

Simplified Models

Example

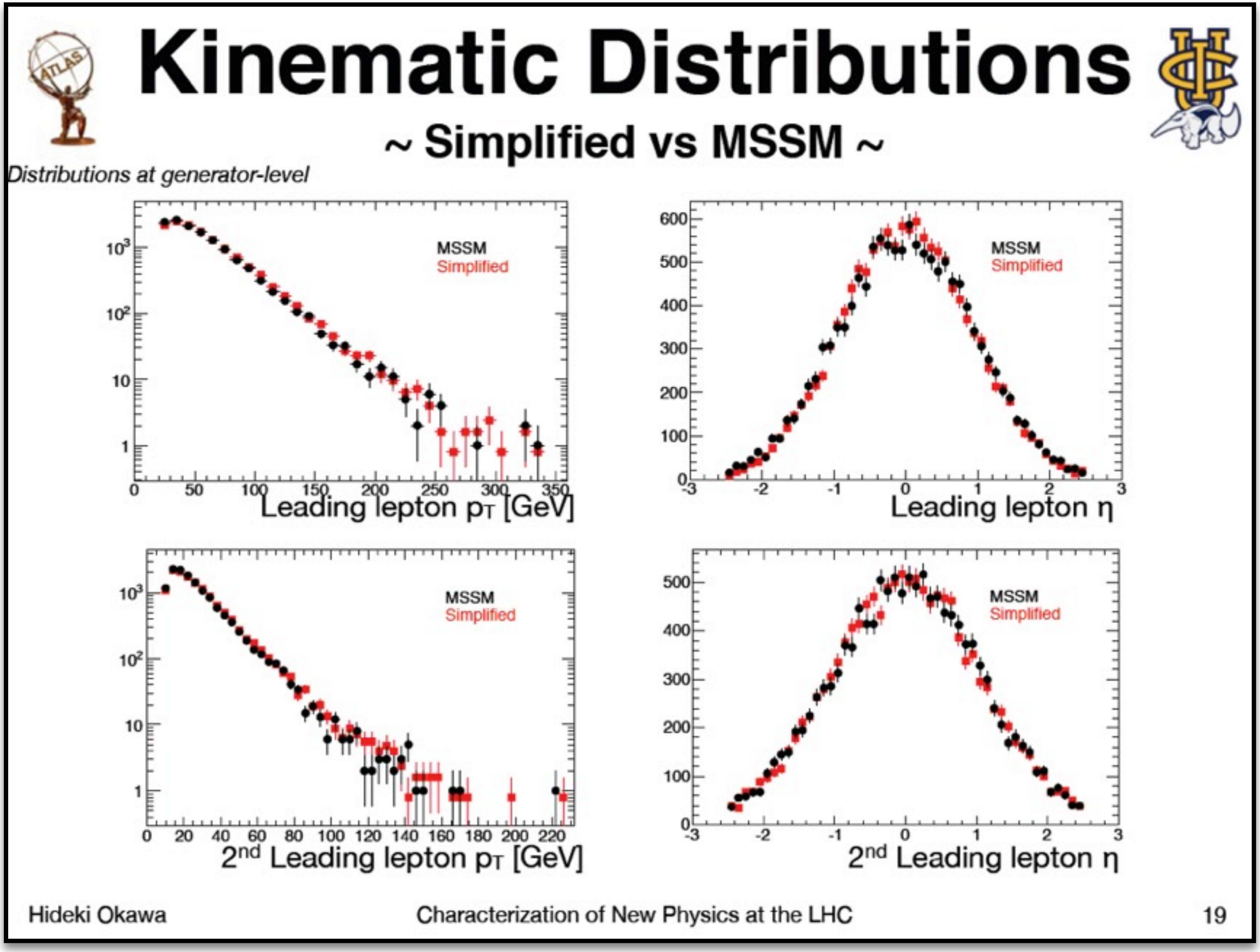


SUSY Model of Interest

Simplified Model

Most **Simplified Models** are perfectly valid models (this one is a limit of the MSSM), **built to emphasize features that matter in a collider search**

Slide from Hideki Okawa’s talk: http://indico.cern.ch/getFile.py/access?contribId=22&resId=0&materialId=slides&confId=107769



Kinematic Distributions

~ Simplified vs MSSM ~

Distributions at generator-level

Hideki Okawa Characterization of New Physics at the LHC 19

Outline

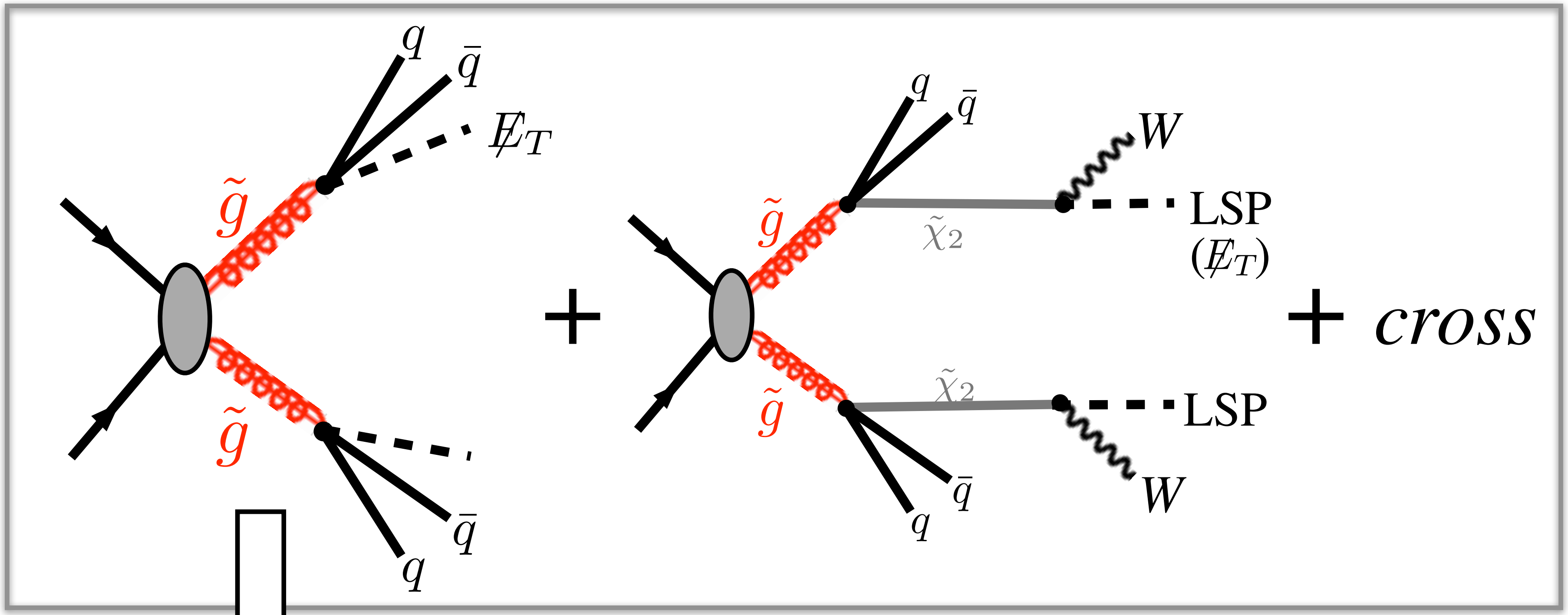
1. Example: Simplified Model Limits
   - What do they look like?
   - How are they used?

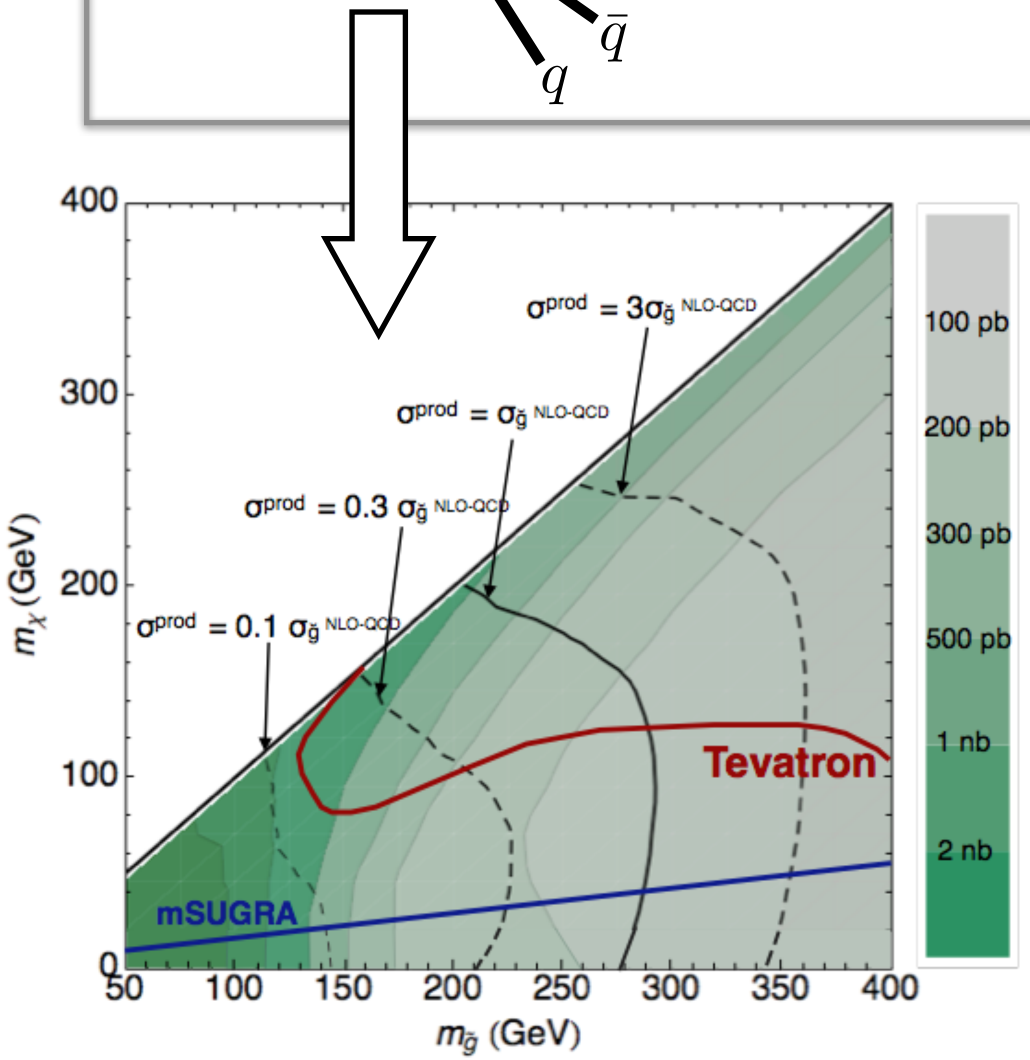
"What can we put in papers besides mSUGRA plots and raw distributions, to make them more useful?

2. Identifying and Using Simplified Models (SUSY Example)
   - What makes a good simplified model?
   - Simplified Models for 50 pb^{-1} SUSY Searches

3. A growing database of simplified models
   - SLAC Topologies Workshop (Enumeration)
   - http://lhcnewphysics.org (Implementation & Reference)

One-Stage "Gluino": Quoting Limits





Estimates of possible exclusion contours:

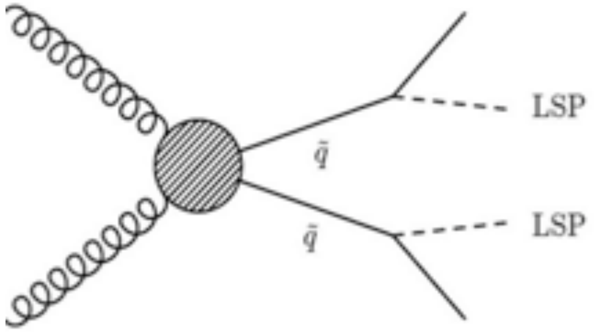
Green: contours of $\sigma_{max} = 1/(\varepsilon \bullet L)$

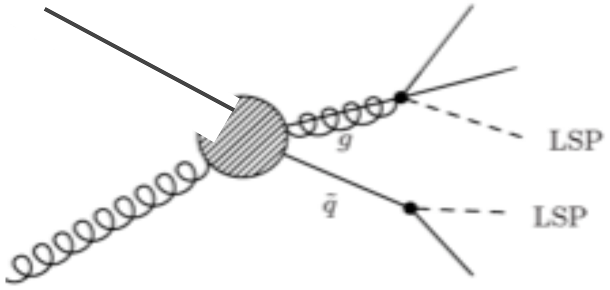
Black: estimated exclusions for different choices of reference cross-section: *numbers are appropriate for < 1 pb^{-1} exclusion reach.*

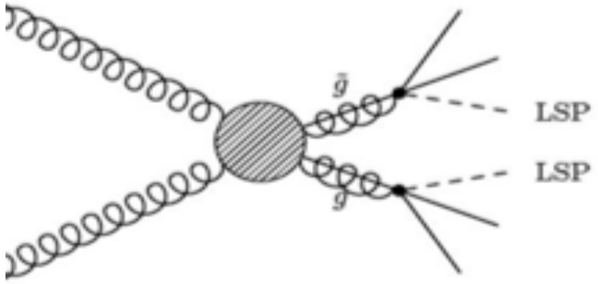
[Plots from Alvez, Izaguirre, Wacker; see also lhcnewphysics.org "Gluino One-Stage"]

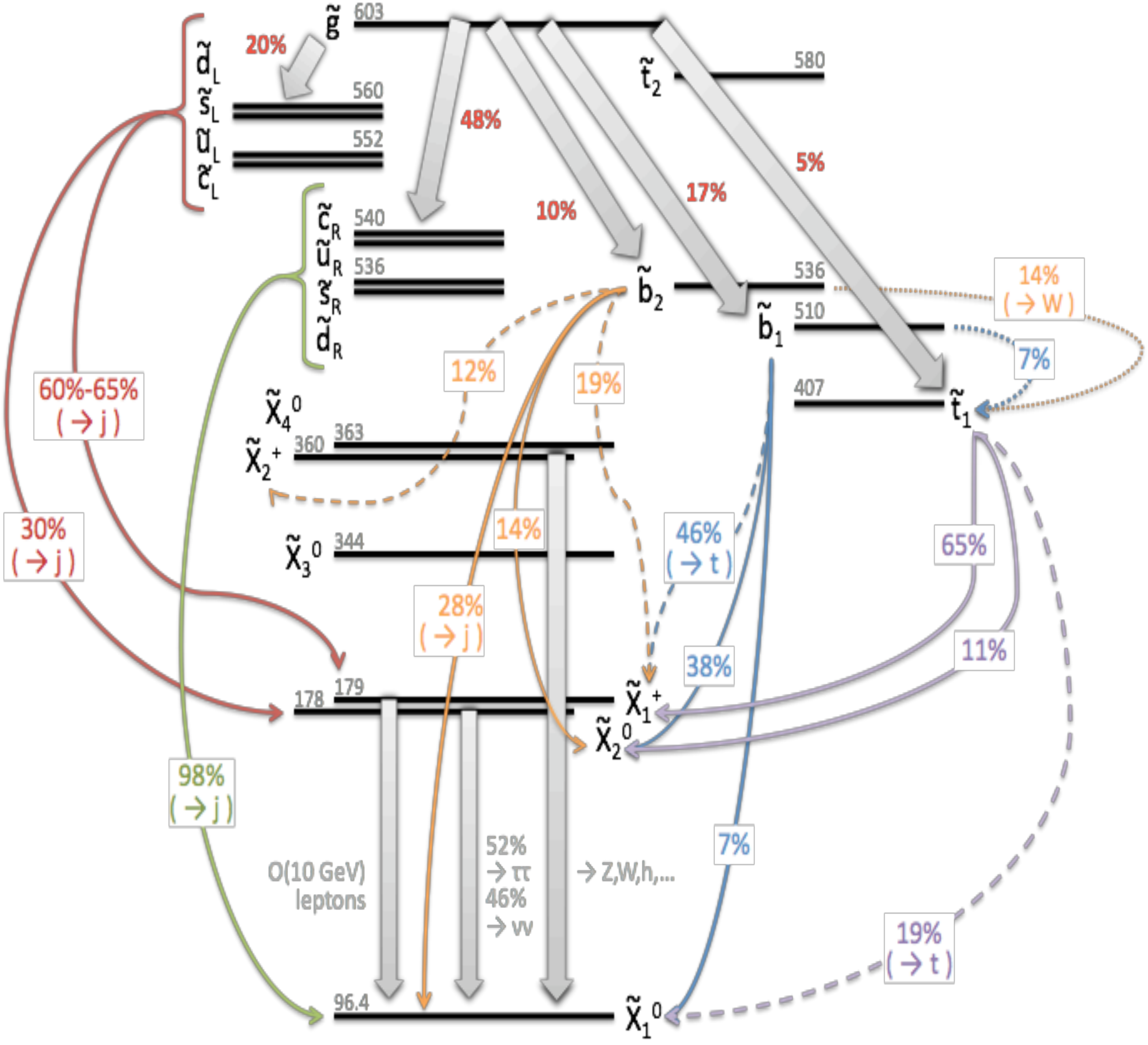
One-Stage "Gluino": Using Limits

simplified model:





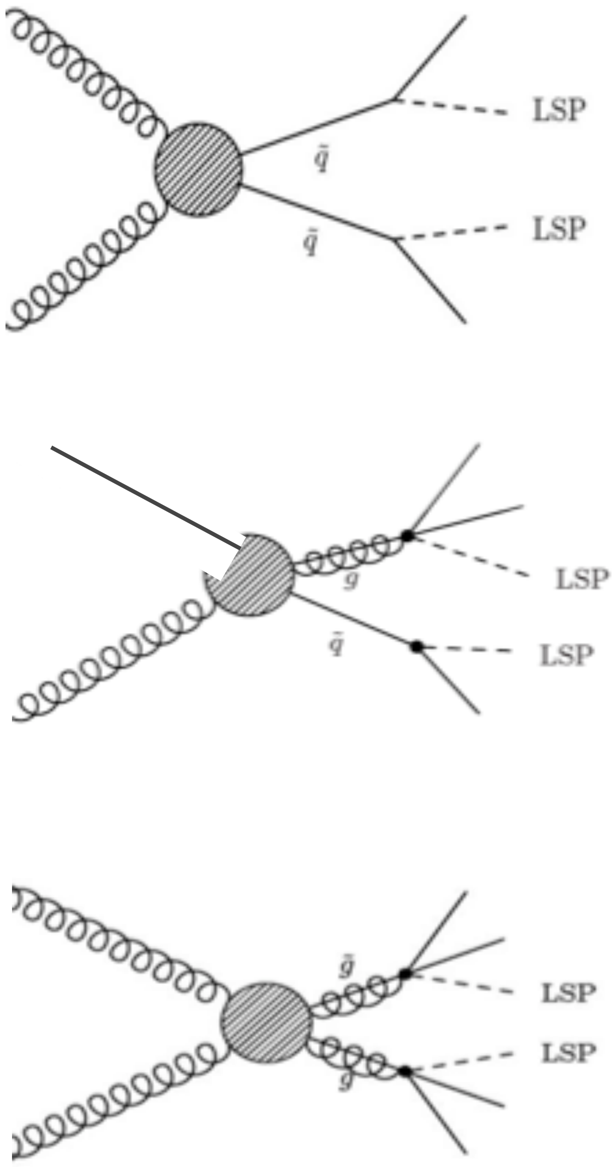


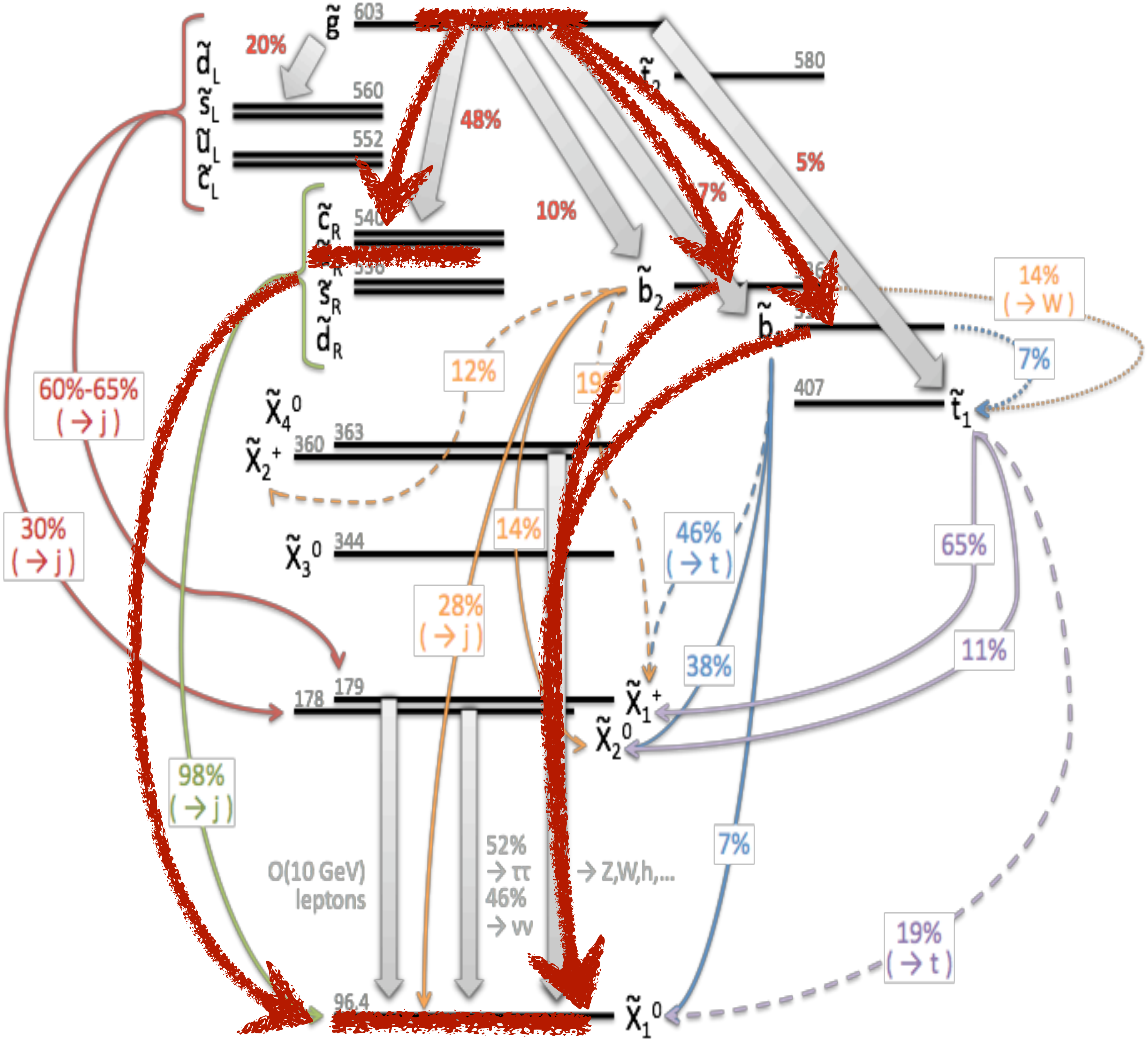


Is this model excluded? Depends on (cross-section) x (acceptance)

One-Stage "Gluino": Using Limits

simplified model:





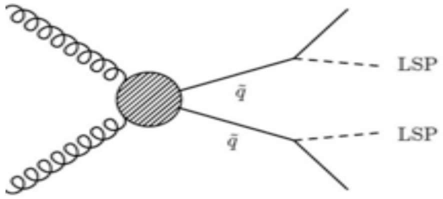
Is this model excluded? Depends on (cross-section) x (acceptance)

Approximate approach

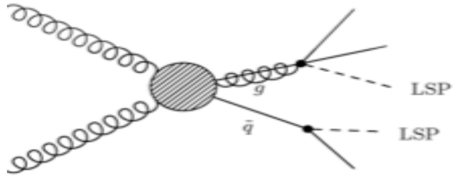
Nmax

theorist

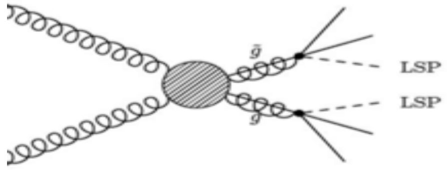
Experiments
(central value plus uncertainties)



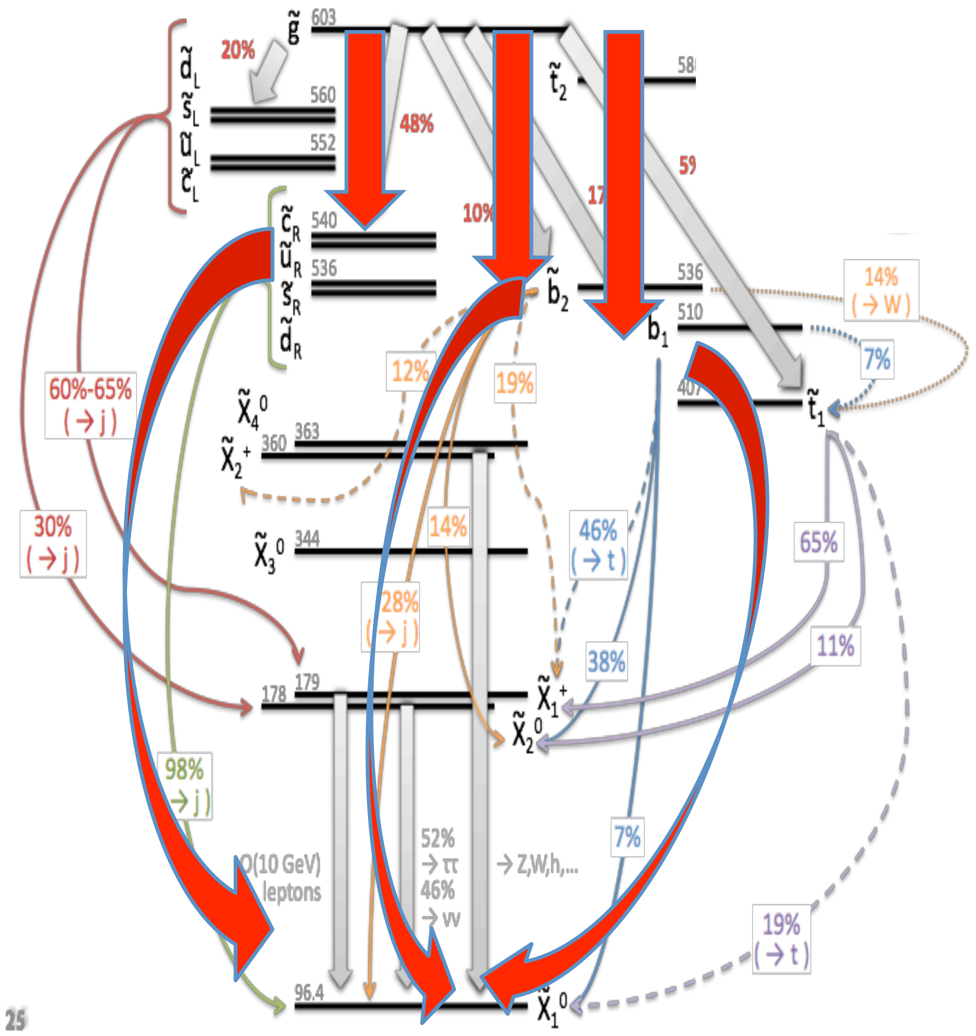
$(\sigma^*BR_{qq}/\sigma_{tot}) A^*\varepsilon_{qq}$



$(\sigma^*BR_{gq}/\sigma_{tot}) A^*\varepsilon_{gq}$



$(\sigma^*BR_{gg}/\sigma_{tot}) A^*\varepsilon_{gg}$



Approximate limit ~ $(\sigma^*BR_{qq}/\sigma_{tot} {}_{*}A^*\varepsilon_{qq} + \sigma^*BR_{qq}/\sigma_{tot}\ A^*\varepsilon_{qq} + \sigma^*BR_{gq}/\sigma_{tot}\ A^*\varepsilon_{qg})^{-1}$

~ 8.3 (moderateMET)
~ 12.5 (highMET)

Full blown LM1 limit ~ $1/(\sigma^*BR^*\varepsilon)$ ~ 6.6 (moderateMET)
~ 10 (highMET)

(use less info. → weaker limit by ~25%)

[M. D'Alfonso, CNP2 CERN]

Summary

- This is **one** of the ways that topology-level results are extremely useful to the rest of the world.
  - Complementary to what theorists already do – external mockups of analysis

    here, experimental details are all handled by experimental experts
  - Complementary to what experimentalists already do – parametrizing search impact in individual models

    less optimal limit, but vastly broader

- Valuable no matter how search is optimized/motivated – but offers natural language for theory-experiment collaboration on extending searches.

- Very useful way to build/convey intuition about search sensitivity.

- Why is simplified model limit only 20% worse, with limited information?
  - LM1 is easy case – “mostly” direct decays to LSP (80% of $\tilde{g}$ decays, 98% of $\tilde{q}_R$ decays
  - Search is more efficient for these decays than for cascades – leaving out ~40% of generated events cost only 25% in σ·acceptance

- Is search sensitive to models that go **dominantly** through cascade decays? Do these allow lighter superpartners?
  - Not addressed by LM search, **or** simplified model search unless it’s extended to include more topologies

    In particular, valuable to include **two-cascade** decay modes to study this case!

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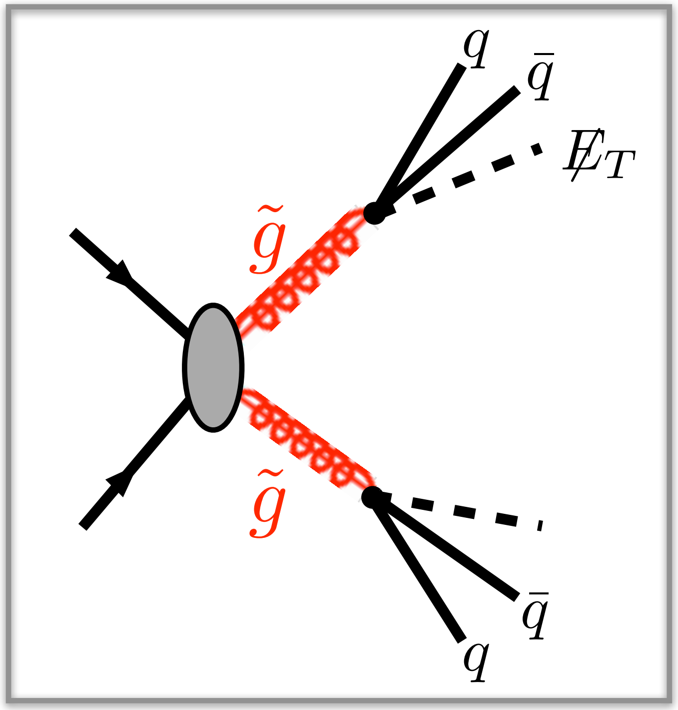
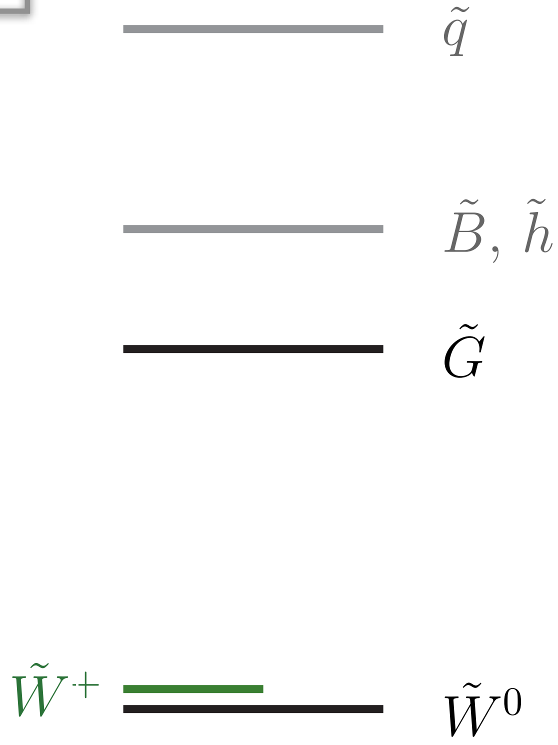
Hadronic SUSY



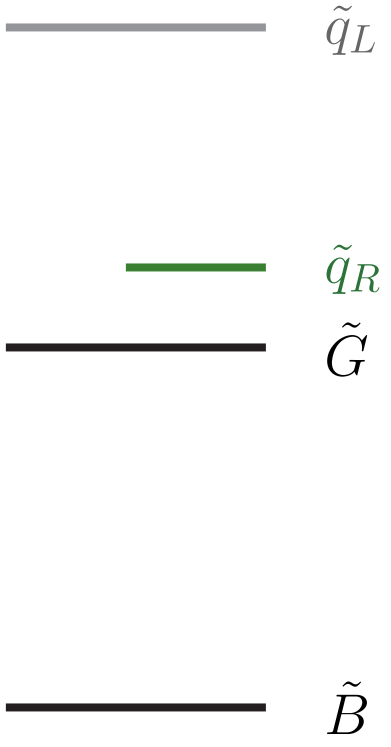
Ubiquitous production/decay mode for SUSY with neutralino LSP

For some MSSM spectra, this mode **dominates**

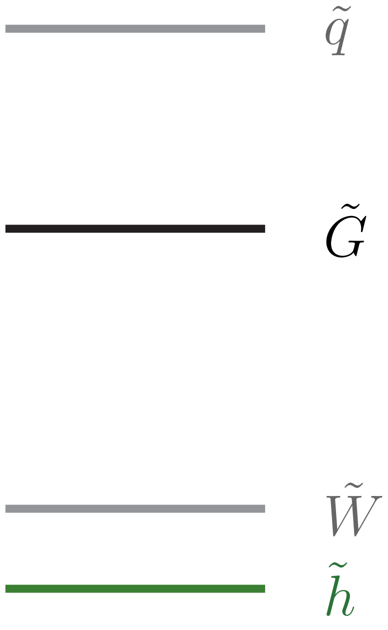
For others, it is a **good proxy for dominant modes**



soft chargino
decay products

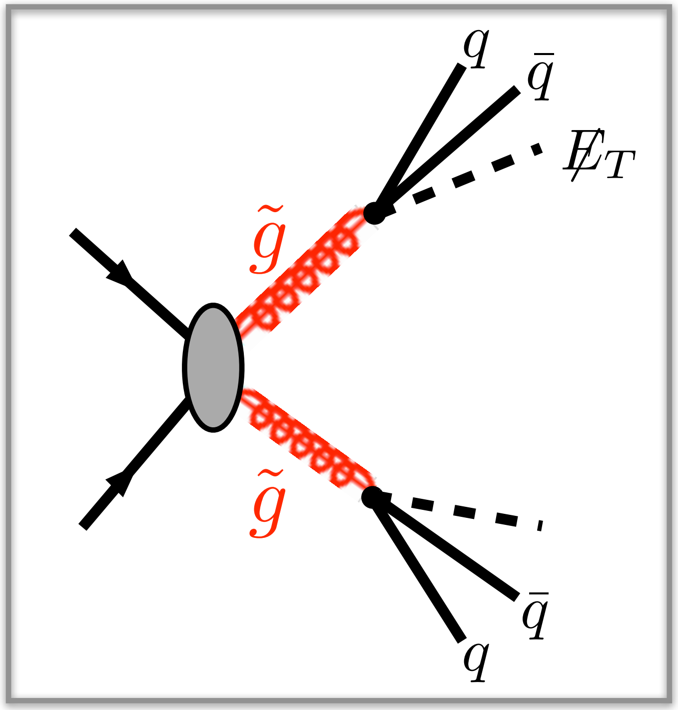


soft extra jet
from squark



heavy-flavor
(b) decays

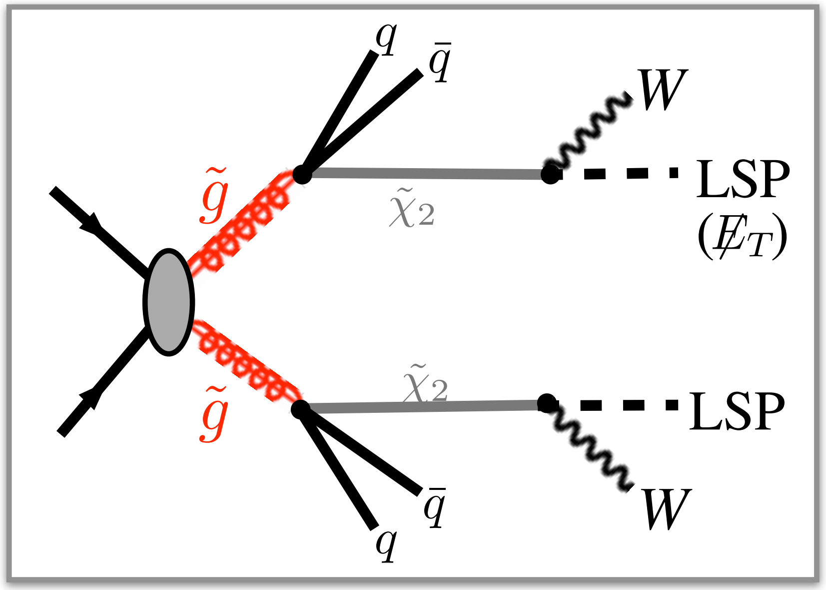
Hadronic SUSY



For some MSSM spectra, this mode **dominates**

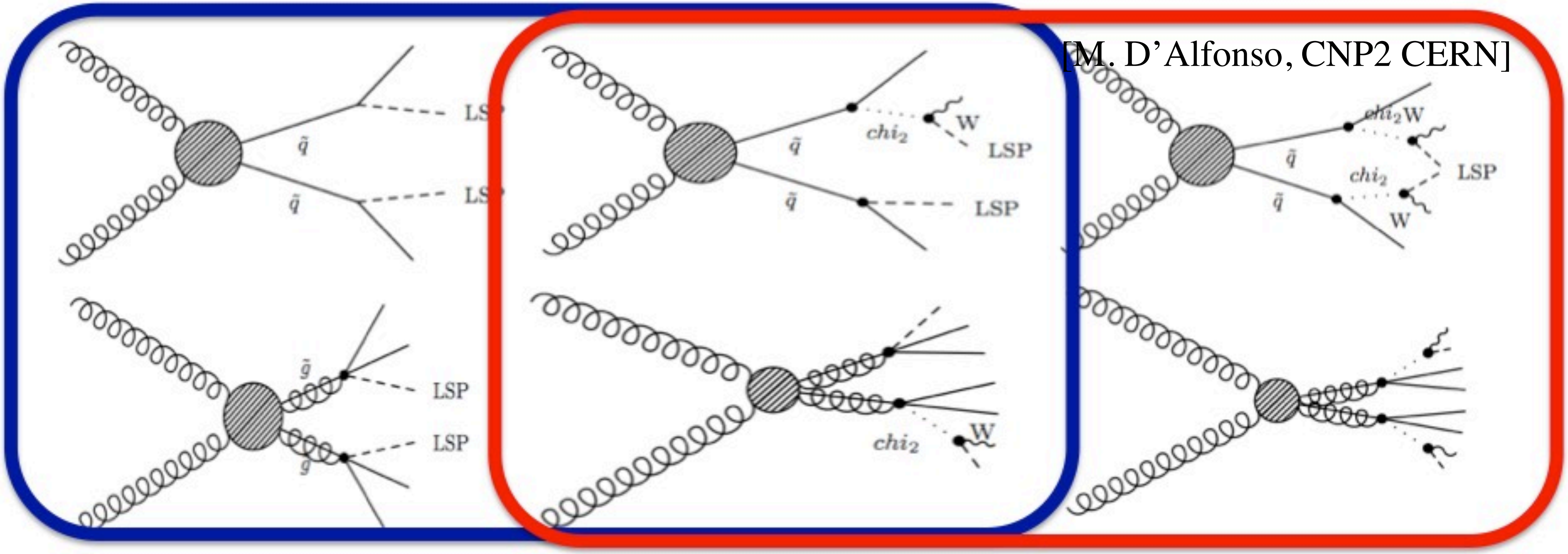
For others, it is a **good proxy for dominant modes**

For other spectra, **very different modes dominate**
– cascade decays



– squark production
– decays through top

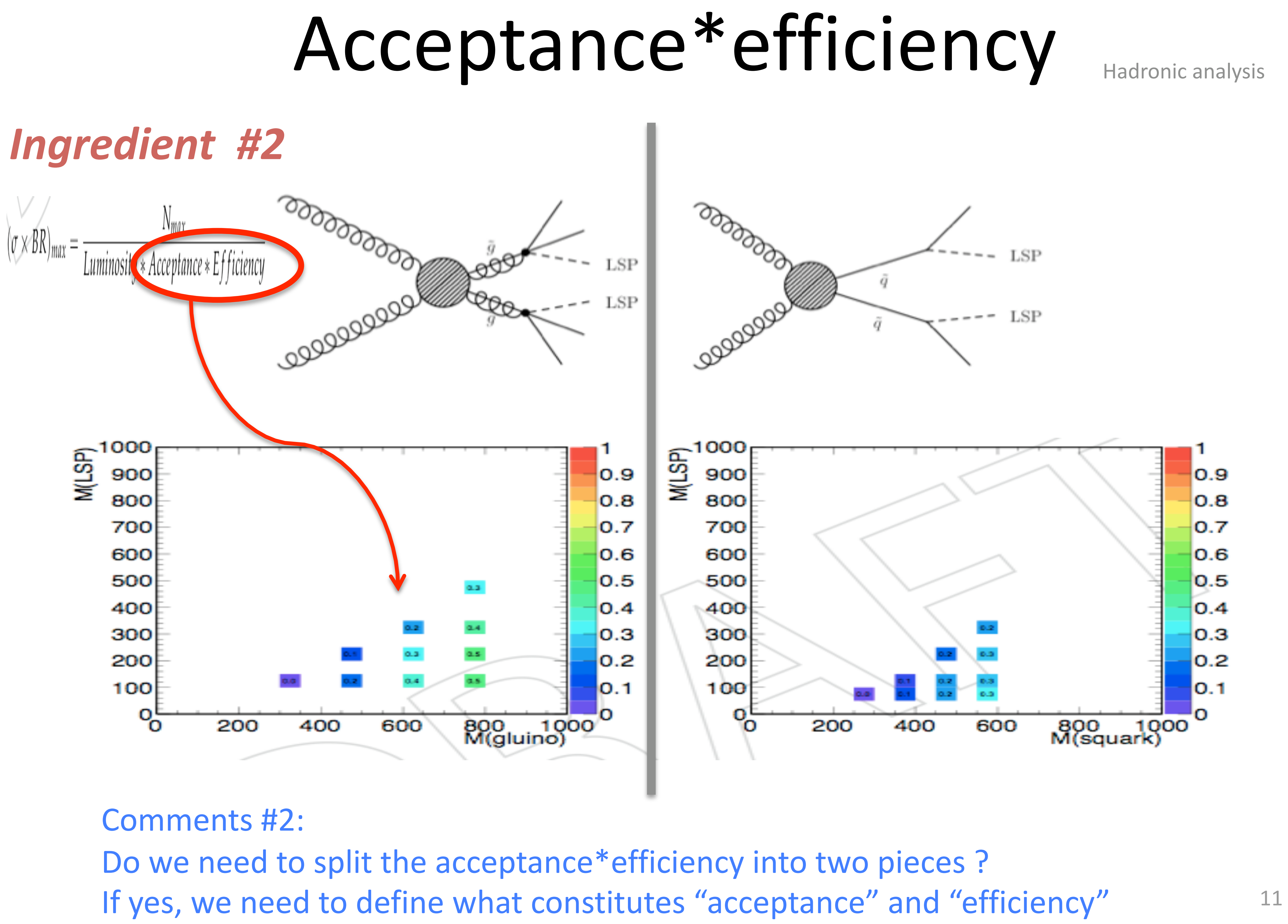
Simplified Model for SUSY with 0/1 leptons



[M. D'Alfonso, CNP2 CERN]

For hadronic search, consider hadronic W/Z in cascades
For 1-lepton search, consider leptonic W.

Parameters to scan for each topology: Gluino, LSP, χ_2



Acceptance*efficiency

Hadronic analysis

Ingredient #2

$$(\sigma \times BR)_{max} = \frac{N_{max}}{Luminosity * Acceptance * Efficiency}$$

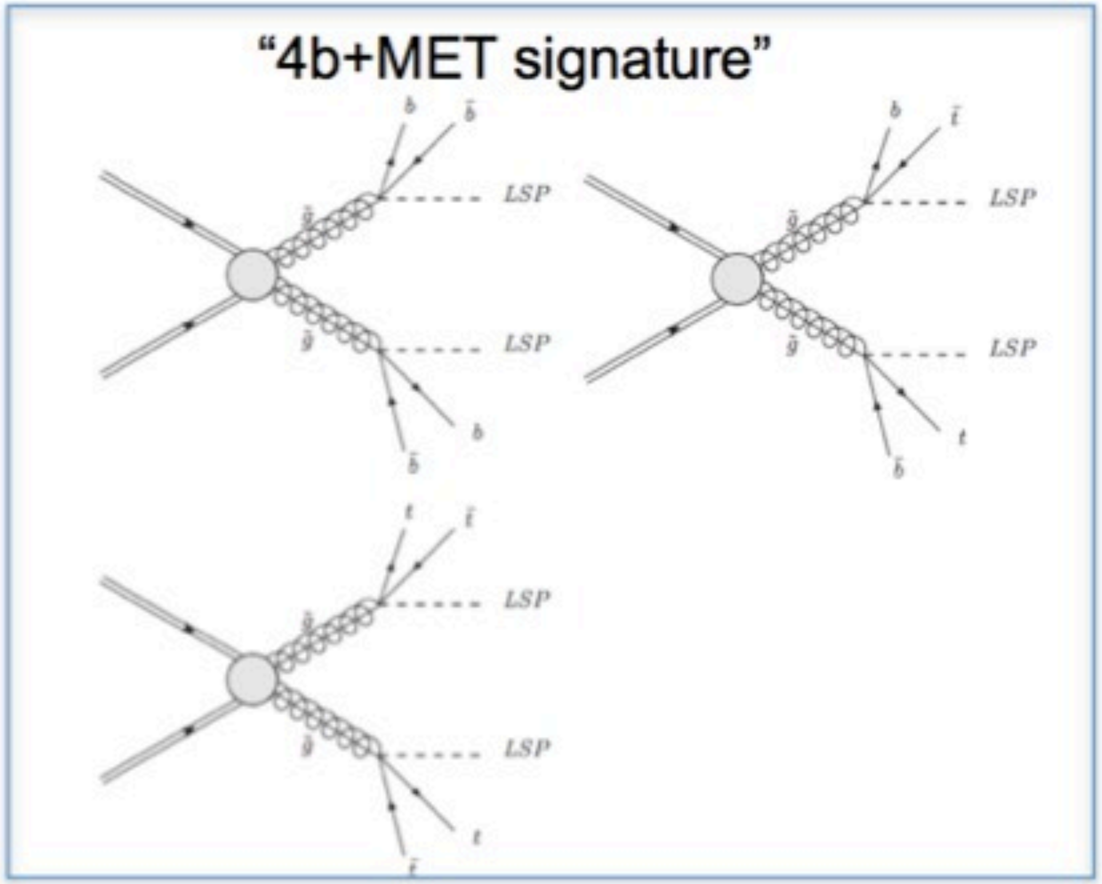
Comments #2:

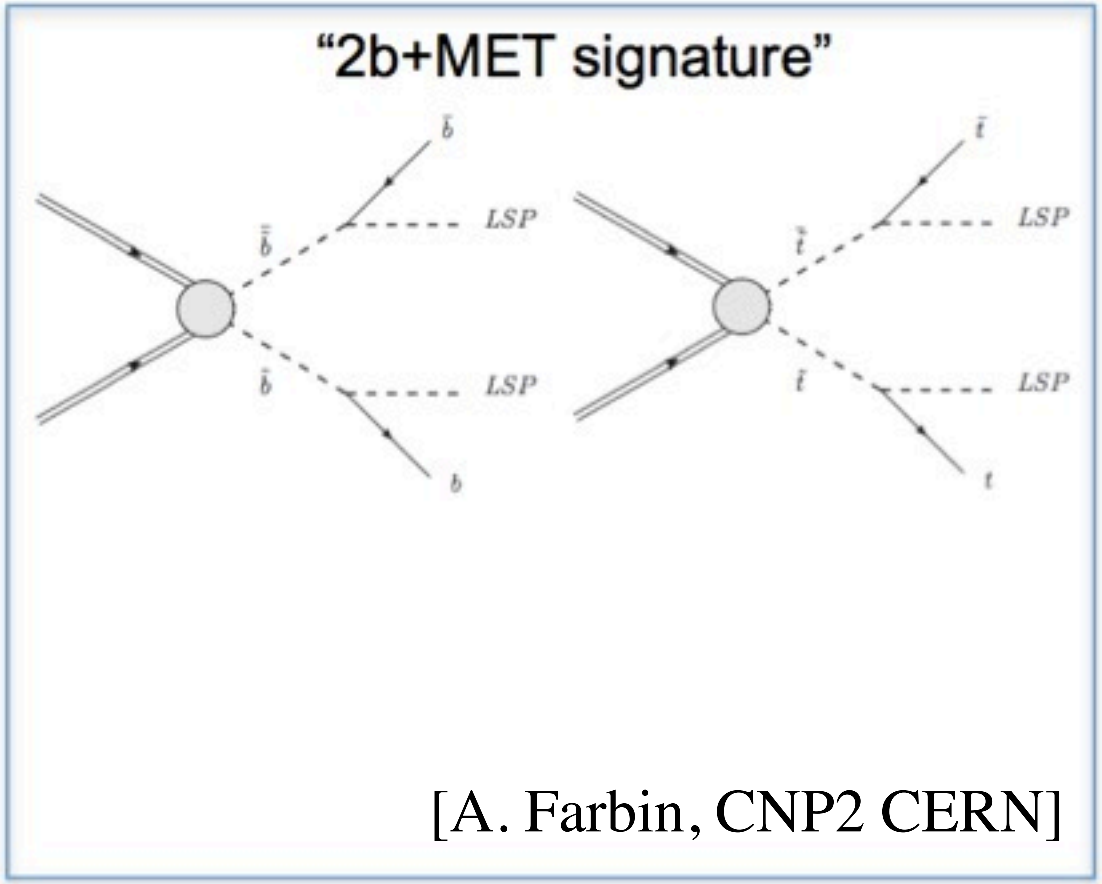
Do we need to split the acceptance*efficiency into two pieces ?

If yes, we need to define what constitutes "acceptance" and "efficiency"

[M. D'Alfonso (UCSB CMS), CNP2 CERN]

Heavy-Flavor Models





[A. Farbin, CNP2 CERN]

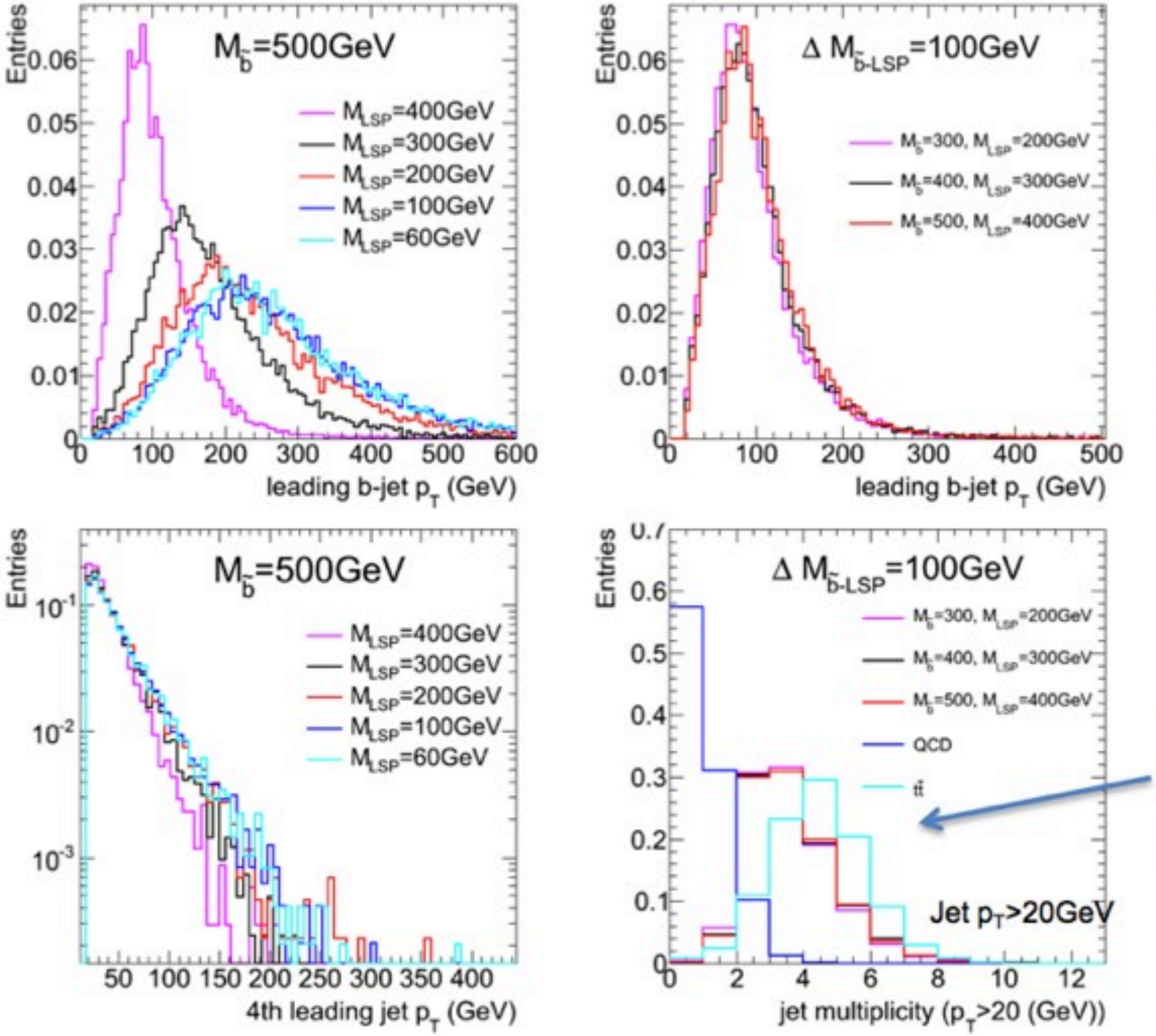
t-rich gluino decays ⇒ different jet kinematic distributions
b-rich gluino decays ⇒ alternate handle on SM backgrounds

Beautiful *b*-tagging in early LHC: opportunity to do this search soon!

High theoretical impact — *b*/*t*-rich decays dominate in direct mediation models (heavy *u*/*d*/*s*/*c* squarks), models w/ less fine-tuned m_Z!

Squark production: 2b+MET

(b-)jet kinematics



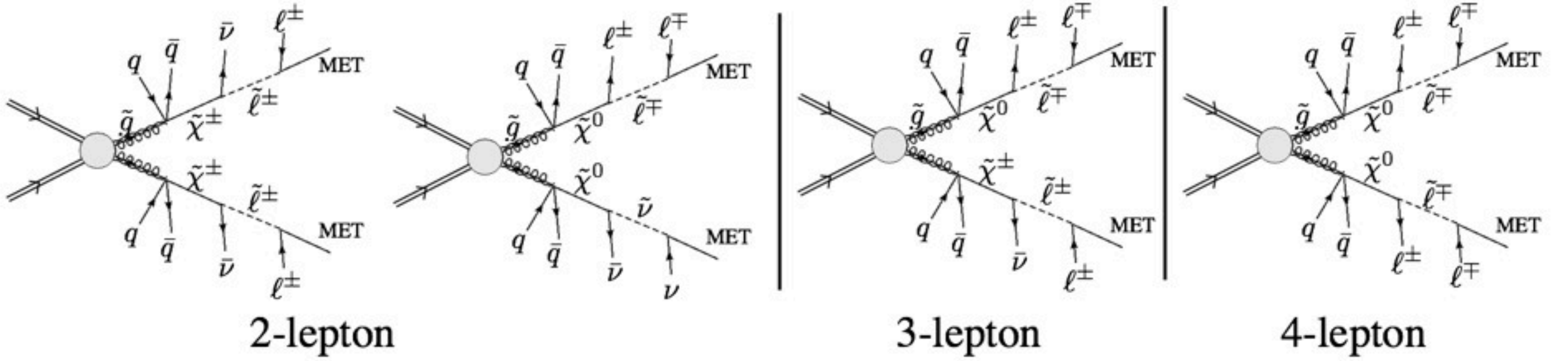
Two (b-)jets sensitive to mass difference

Additional light jets not sensitive to mass difference (see 4th leading jet p_T)

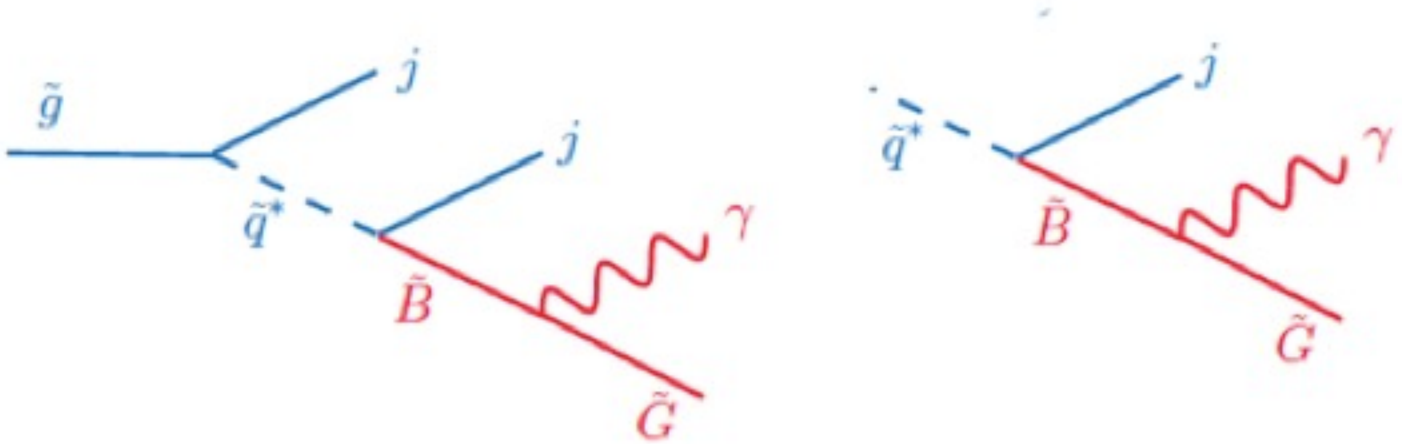
Low overall jet multiplicity: largely unaffected by mass difference

[P. de Jong (ATLAS) SLAC Topo Wkshop]

Multi-Leptons, Photons



Motivated by GMSB ($m_{MET} = 0$ gravitino) and models with $m_{3/2} \sim$ TeV ($m_{MET} \geq 50$ GeV neutralino)



Searches are typically much less sensitive to kinematics and jettiness of initial production!

New Physics vs. Simplified Models

Enough about exclusions!

How do simplified models help us if
there **is** new physics?

Caveats:

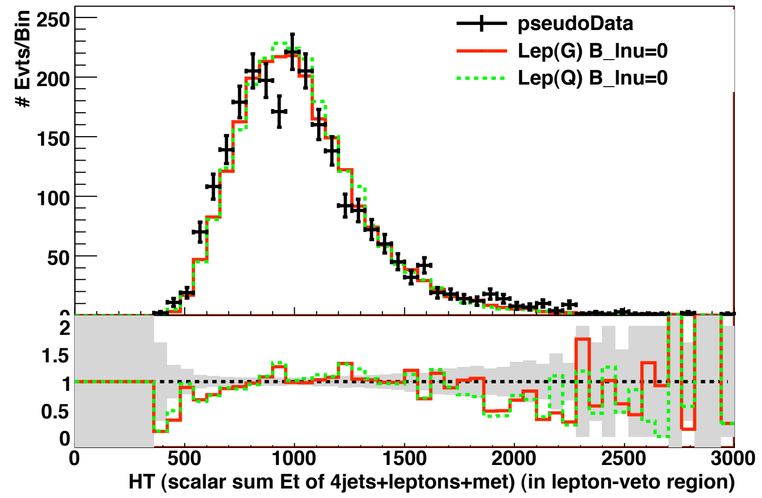
optimistic treatment – background subtracted w/o systematic errors to illustrate qualitative points.

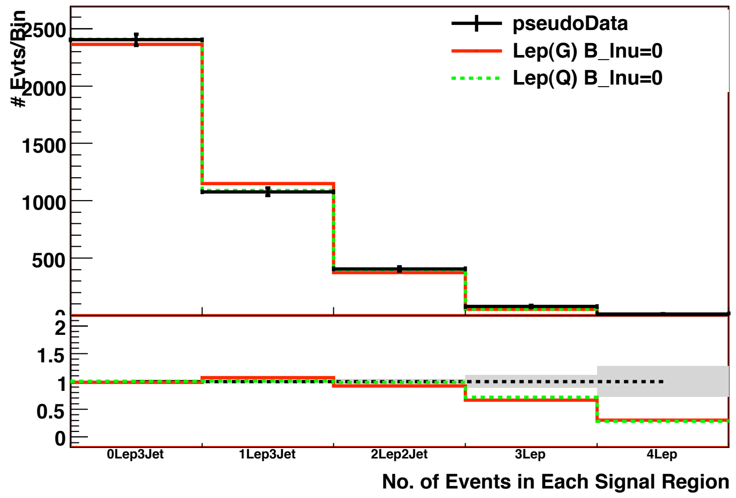
“true new physics” in this example was deliberately chosen to be complicated and **unlike** our simplified models

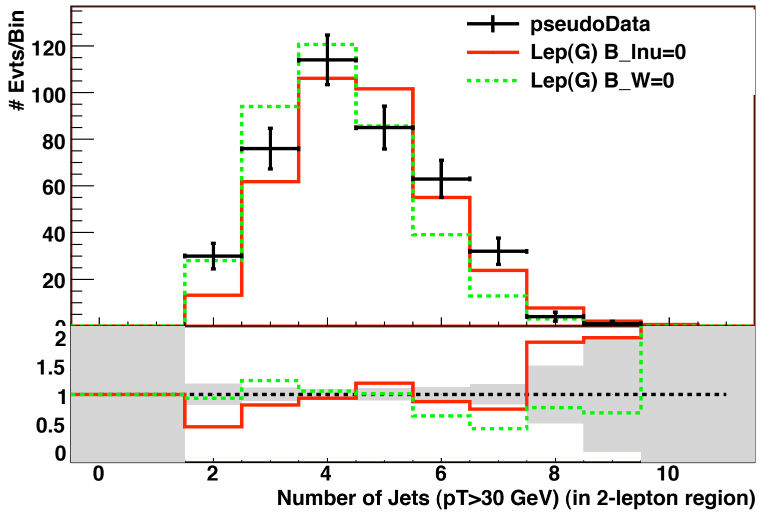
[uses simplified models from 0810.3921]

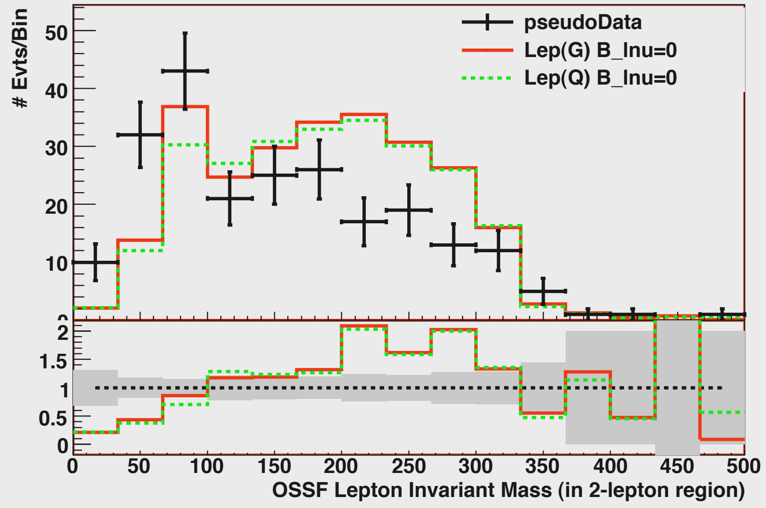
New Physics vs. Simplified Models

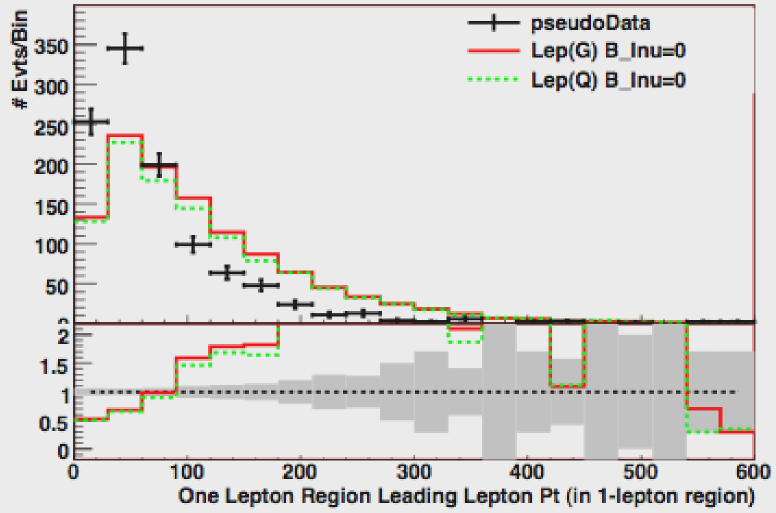
Leptonic



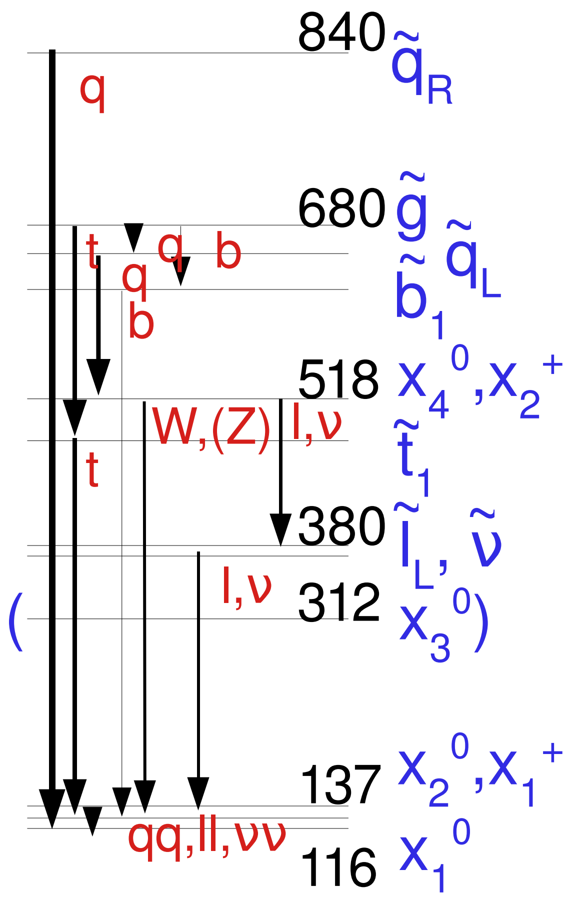








Example 2

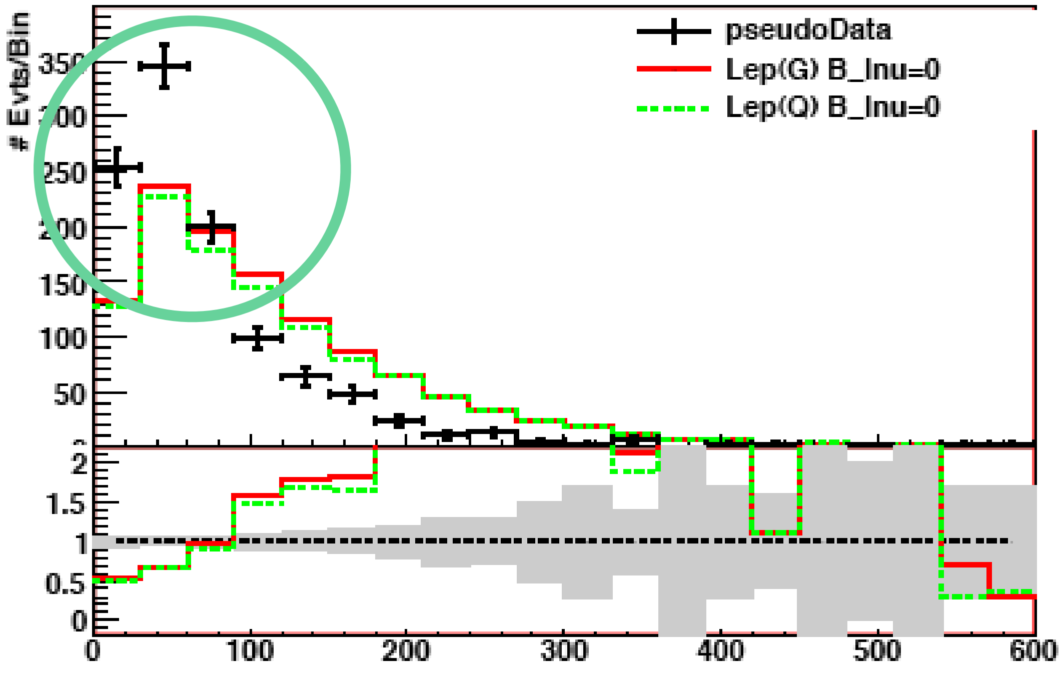


Good agreement in **many, not all** distributions & well-defined **best-fit parameters** –

Discrepancies hint at (specific!) additional structure, testable extensions

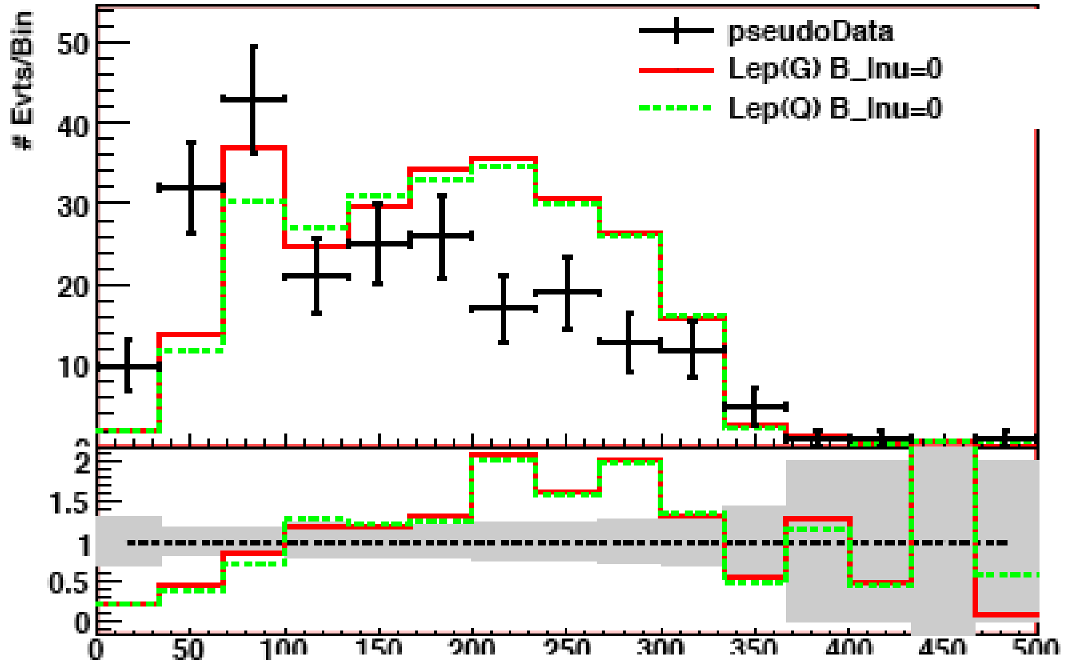
Inferring structure from simple characterization

(1-lepton plots)



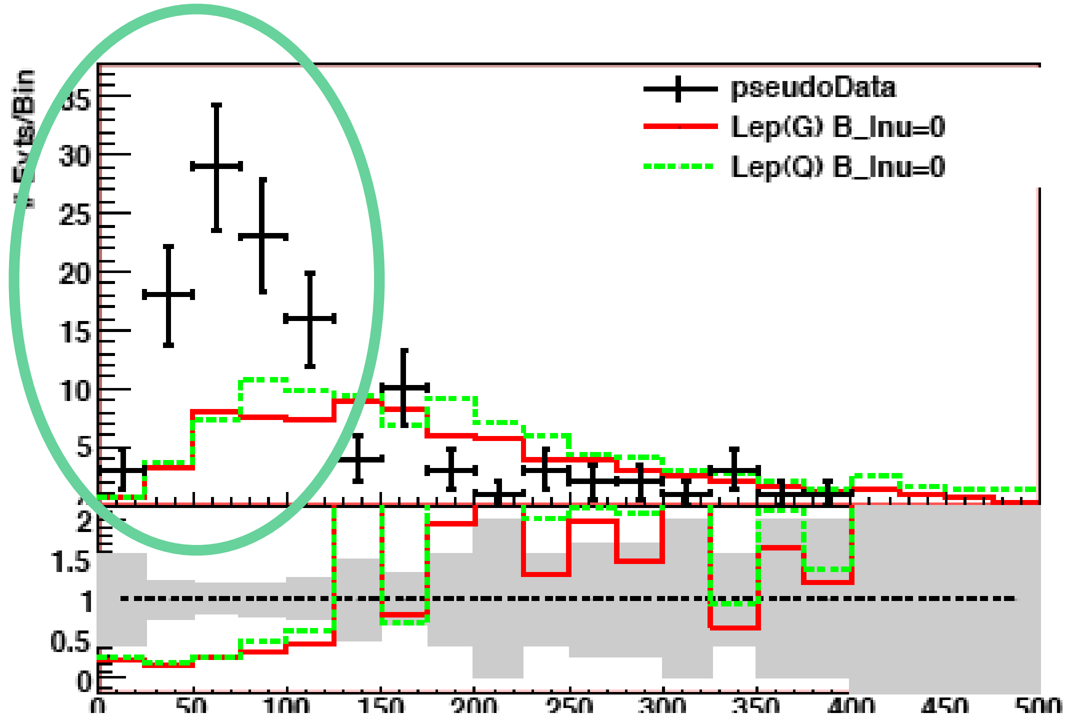
Lepton p_T

(2-lepton plots)

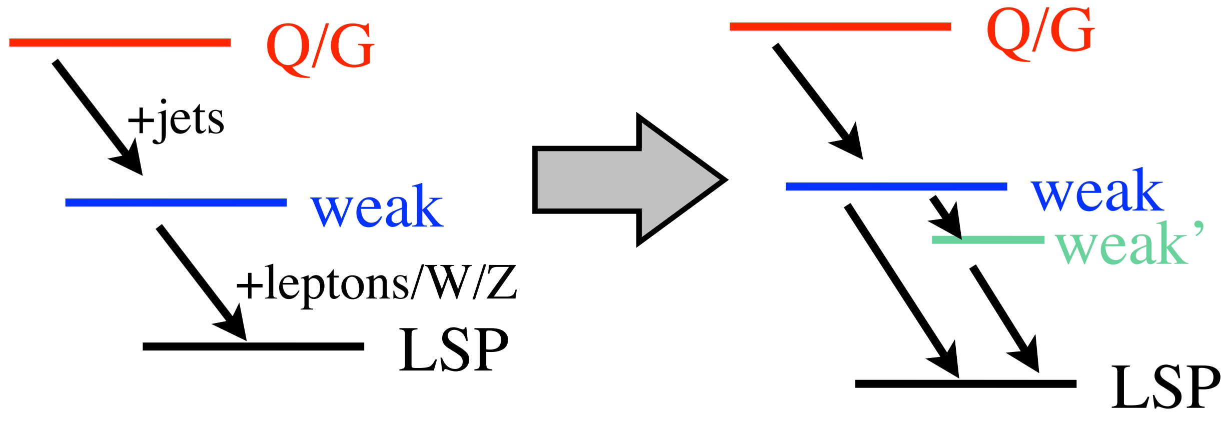


OSSF (e^+e^-) invariant mass

STRONG EVIDENCE for more complex source of **soft**, **flavor-uncorrelated** leptons.



Opposite-flavor ($e\mu$) invariant mass



Add and subtract intermediate particles to "prove" their existence!

Workshop on Topologies for Early LHC Searches

http://www.lhcnewphysics.org/
http://www-conf.slac.stanford.edu/topologies10/
Organizers: R. Essig, M. Lisanti, P. Schuster, T. Tait, N. Toro, J. Wacker

Over 100 theorists (mostly model builders) proposed a baseline set of simplified models for early LHC searches.

Working groups (subset of active contributors):

Leptons

S. Chang
W. Cho
J. Evans
E. Izaguirre
J. Kaplan
M. Lisanti
M. Luty
M. Nojiri
T. Okui
M. Park
M. Perelstein
J. Ruderman
V. Sanz
P. Schuster
D. Shih
S. Su
T. Tait
B. Thomas
N. Toro
J. Wacker
F. Yu

Hadrons

D. Alves
J. Gainer
M. Gomez
E. Izaguirre
C. Kilic
M. Nojiri
D. Krohn
M. Schwartz
J. Shelton
M. Spannowsky
M.Strassler
J. Wacker

Resonances

Y. Bai
H. Cheng
J. Evans
A. Freitas
T. Han
J. Hewett
T. Liu
V. Rentala
S. Su
T. Tait

Photons

P. Fox
R. Kitano
T. Okui
D. Shih
T. Roy
J. Ruderman

Exotic Objects

S. Chang
M. Baumgart
R. Essig
J. Hubisz
D. Krohn
P. Meade
D. Morrissey
M. Papucci
D. Phalen
J. Shao
T. Volansky
I. Yavin
K. Zurek

Heavy Flavor

M. Buckley
R.S. Chivukula
L. Fitzpatrick
R. Francescini
P. Fox
J. Kaplan
P. Ko
E. Kuflik
R. Lu
S. Mrenna
M. Peskin
K. Rehermann
M. Schmaltz
M. Schwartz
E. Simmons
C. Spethmann
M. Strassler
T. Tait
N. Toro
W. Waltenberger

Hadronic (Flavor-Blind) Simplified Models

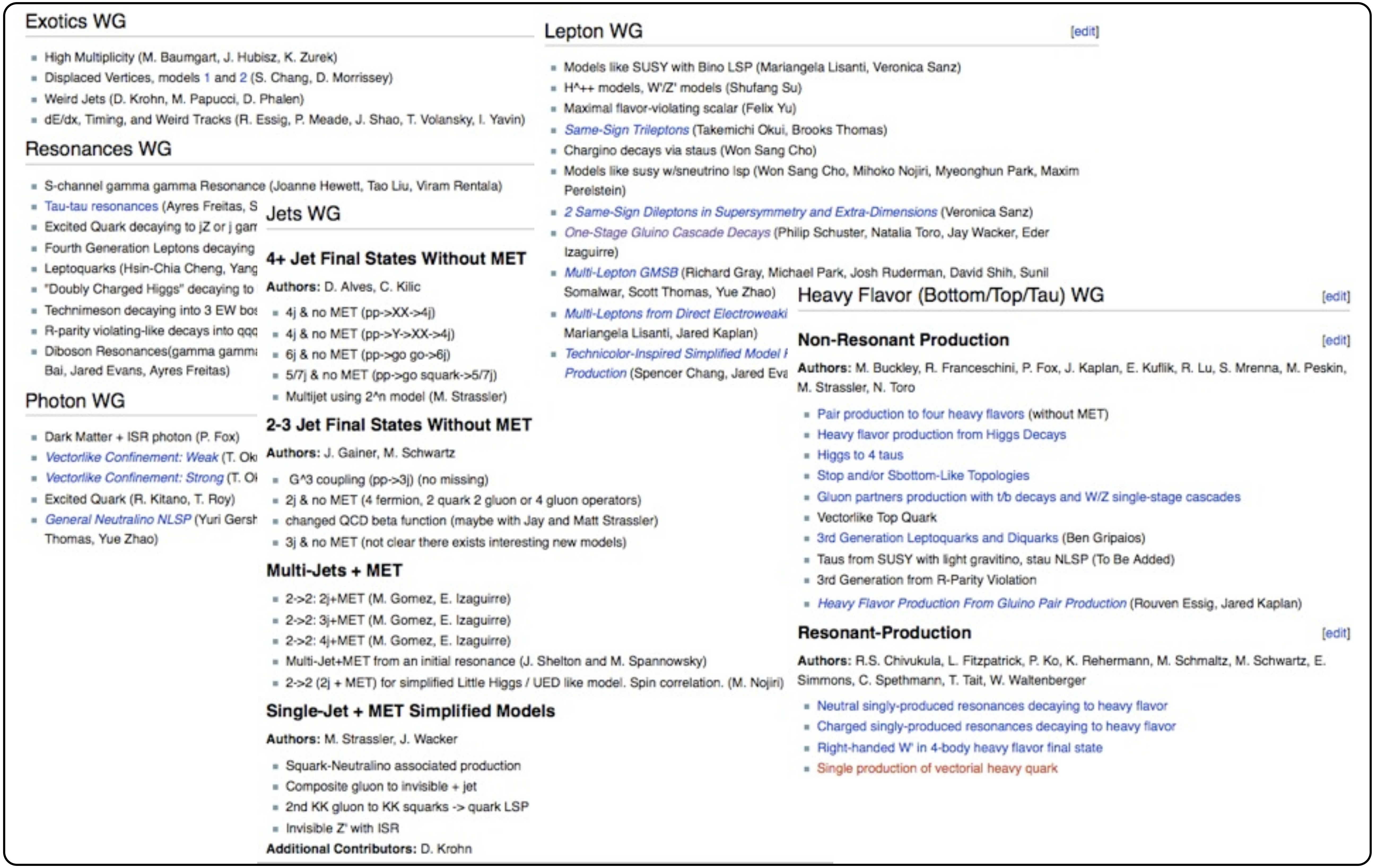
	With MET		No MET		
# jets	$2\to1$	$2\to2$	$2\to1$	$2\to2$	$2\to3$
1	Composite gluon: $pp\to g^* \to g\,\phi$(invis) KK gluon (2- or 3-body): $pp \to g_2 \to \gamma_1 g_1 \to g \gamma_1 \gamma_1$ $pp \to g_2 \to j\, \gamma_1\, \gamma_1$	ISR+invis. Z' ISR+invis. pair Squark+neutralino	–	–	–
2	Resonance $A\to B\phi$ $B\to$ jets $\phi\to$ invis.	KK quark or squark pair	dijet resonances	Compositeness, anomalous running of α_s	Anomalous $(G_{\mu\nu})^3$
3		Squark/ gluino pair			
≥ 4			Resonant coloron	Techni-π, RPV squark/ gluino	

Heavy-Flavor-Rich (t/b/τ) Simplified Models

	Source of b/τ's		
	Resonance	Pair	Cascade
Has flavor quantum no.	Vector-like heavy quark	Stop/sbottom $t' \rightarrow b/t + g/\gamma/W/Z$	stau NLSP 3rd-gen-rich RPV
Unflavored	Z', W' with enhanced 3rd gen. couplings	Gluino→heavy flavor Color-adjoint scalar Higgs cascades	$h \rightarrow \phi\,\phi \rightarrow 4b/\tau$ h→ bb in SUSY decay

Topologies '10 Progress

http://www.lhcnewphysics.org/ (improved searchable site in progress)



Exotics WG

- High Multiplicity (M. Baumgart, J. Hubisz, K. Zurek)
- Displaced Vertices, models 1 and 2 (S. Chang, D. Morrissey)
- Weird Jets (D. Krohn, M. Papucci, D. Phalen)
- dE/dx, Timing, and Weird Tracks (R. Essig, P. Meade, J. Shao, T. Volansky, I. Yavin)

Resonances WG

- S-channel gamma gamma Resonance (Joanne Hewett, Tao Liu, Viram Rentala)
- Tau-tau resonances (Ayres Freitas, S
- Excited Quark decaying to jZ or j gam
- Fourth Generation Leptons decaying
- Leptoquarks (Hsin-Chia Cheng, Yang
- "Doubly Charged Higgs" decaying to
- Technimeson decaying into 3 EW bos
- R-parity violating-like decays into qqq
- Diboson Resonances(gamma gamm Bai, Jared Evans, Ayres Freitas)

Photon WG

- Dark Matter + ISR photon (P. Fox)
- *Vectorlike Confinement: Weak* (T. Oki
- *Vectorlike Confinement: Strong* (T. Oi
- Excited Quark (R. Kitano, T. Roy)
- *General Neutralino NLSP* (Yuri Gersh Thomas, Yue Zhao)

Jets WG

4+ Jet Final States Without MET

Authors: D. Alves, C. Kilic

- 4j & no MET (pp->XX->4j)
- 4j & no MET (pp->Y->XX->4j)
- 6j & no MET (pp->go go->6j)
- 5/7j & no MET (pp->go squark->5/7j)
- Multijet using 2^n model (M. Strassler)

2-3 Jet Final States Without MET

Authors: J. Gainer, M. Schwartz

- G^3 coupling (pp->3j) (no missing)
- 2j & no MET (4 fermion, 2 quark 2 gluon or 4 gluon operators)
- changed QCD beta function (maybe with Jay and Matt Strassler)
- 3j & no MET (not clear there exists interesting new models)

Multi-Jets + MET

- 2->2: 2j+MET (M. Gomez, E. Izaguirre)
- 2->2: 3j+MET (M. Gomez, E. Izaguirre)
- 2->2: 4j+MET (M. Gomez, E. Izaguirre)
- Multi-Jet+MET from an initial resonance (J. Shelton and M. Spannowsky)
- 2->2 (2j + MET) for simplified Little Higgs / UED like model. Spin correlation. (M. Nojiri)

Single-Jet + MET Simplified Models

Authors: M. Strassler, J. Wacker

- Squark-Neutralino associated production
- Composite gluon to invisible + jet
- 2nd KK gluon to KK squarks -> quark LSP
- Invisible Z' with ISR

Additional Contributors: D. Krohn

Lepton WG [edit]

- Models like SUSY with Bino LSP (Mariangela Lisanti, Veronica Sanz)
- H^++ models, W'/Z' models (Shufang Su)
- Maximal flavor-violating scalar (Felix Yu)
- *Same-Sign Trileptons* (Takemichi Okui, Brooks Thomas)
- Chargino decays via staus (Won Sang Cho)
- Models like susy w/sneutrino lsp (Won Sang Cho, Mihoko Nojiri, Myeonghun Park, Maxim Perelstein)
- *2 Same-Sign Dileptons in Supersymmetry and Extra-Dimensions* (Veronica Sanz)
- *One-Stage Gluino Cascade Decays* (Philip Schuster, Natalia Toro, Jay Wacker, Eder Izaguirre)
- *Multi-Lepton GMSB* (Richard Gray, Michael Park, Josh Ruderman, David Shih, Sunil Somalwar, Scott Thomas, Yue Zhao)
- *Multi-Leptons from Direct Electroweaki* Mariangela Lisanti, Jared Kaplan)
- *Technicolor-Inspired Simplified Model f Production* (Spencer Chang, Jared Eva

Heavy Flavor (Bottom/Top/Tau) WG [edit]

Non-Resonant Production [edit]

Authors: M. Buckley, R. Franceschini, P. Fox, J. Kaplan, E. Kuflik, R. Lu, S. Mrenna, M. Peskin, M. Strassler, N. Toro

- Pair production to four heavy flavors (without MET)
- Heavy flavor production from Higgs Decays
- Higgs to 4 taus
- Stop and/or Sbottom-Like Topologies
- Gluon partners production with t/b decays and W/Z single-stage cascades
- Vectorlike Top Quark
- 3rd Generation Leptoquarks and Diquarks (Ben Gripaios)
- Taus from SUSY with light gravitino, stau NLSP (To Be Added)
- 3rd Generation from R-Parity Violation
- *Heavy Flavor Production From Gluino Pair Production* (Rouven Essig, Jared Kaplan)

Resonant-Production [edit]

Authors: R.S. Chivukula, L. Fitzpatrick, P. Ko, K. Rehermann, M. Schmaltz, M. Schwartz, E. Simmons, C. Spethmann, T. Tait, W. Waltenberger

- Neutral singly-produced resonances decaying to heavy flavor
- Charged singly-produced resonances decaying to heavy flavor
- Right-handed W' in 4-body heavy flavor final state
- Single production of vectorial heavy quark

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Writeups for simplified models including:

- Particle content & interactions
- Theoretical motivation
- MC generation tools & support
- Estimated past limits (when possible)
- Relevant variables/plots
  - Kinematic vars of interest
  - Parameter space for limits
- Estimated LHC reach, and possible challenges

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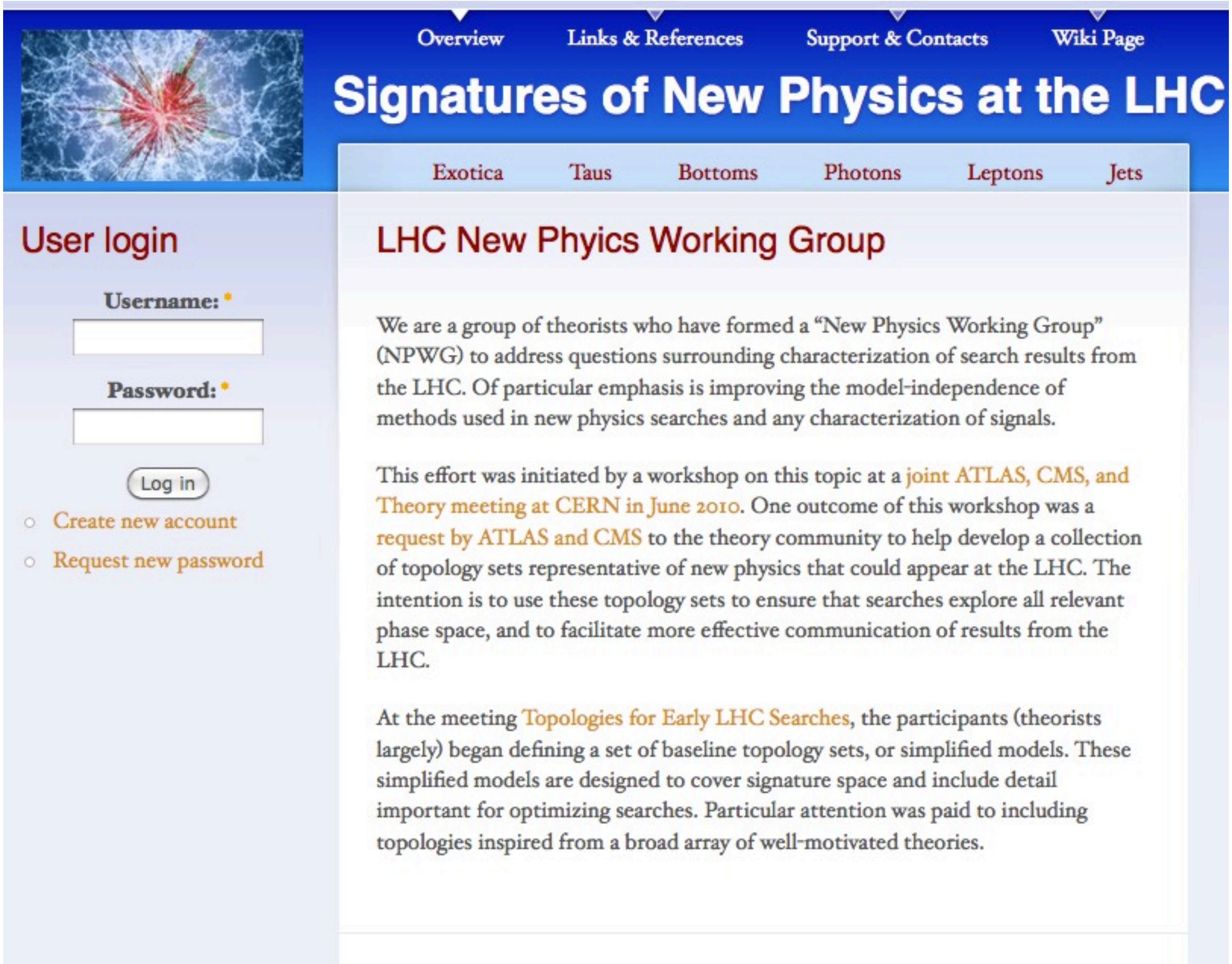

Signatures of New Physics at the LHC

LHC New Phyics Working Group

We are a group of theorists who have formed a "New Physics Working Group" (NPWG) to address questions surrounding characterization of search results from the LHC. Of particular emphasis is improving the model-independence of methods used in new physics searches and any characterization of signals.

This effort was initiated by a workshop on this topic at a joint ATLAS, CMS, and Theory meeting at CERN in June 2010. One outcome of this workshop was a request by ATLAS and CMS to the theory community to help develop a collection of topology sets representative of new physics that could appear at the LHC. The intention is to use these topology sets to ensure that searches explore all relevant phase space, and to facilitate more effective communication of results from the LHC.

At the meeting Topologies for Early LHC Searches, the participants (theorists largely) began defining a set of baseline topology sets, or simplified models. These simplified models are designed to cover signature space and include detail important for optimizing searches. Particular attention was paid to including topologies inspired from a broad array of well-motivated theories.

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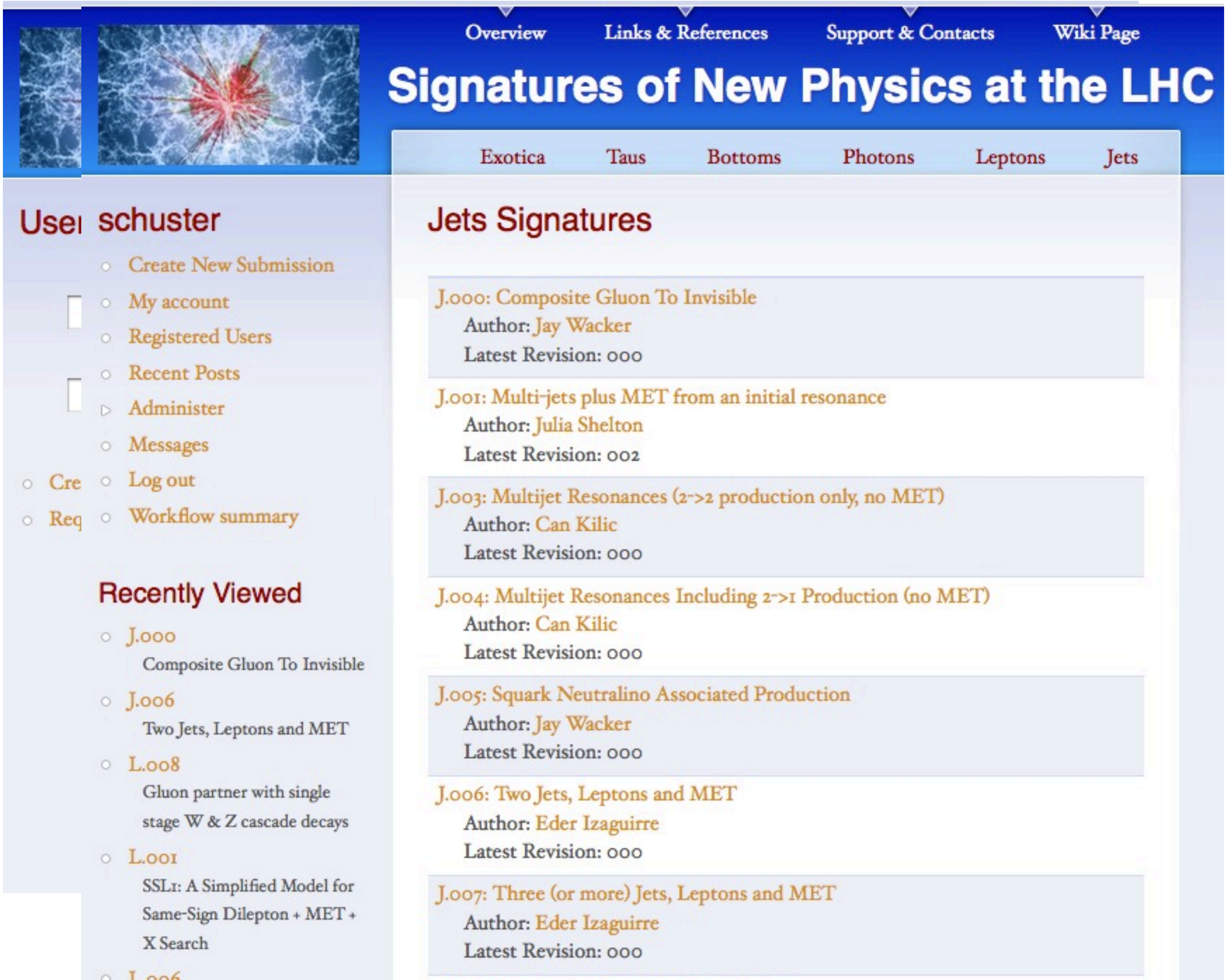

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- J.006
  Two Jets, Leptons and MET
- L.008
  Gluon partner with single stage W & Z cascade decays
- L.001
  SSL1: A Simplified Model for Same-Sign Dilepton + MET + X Search

Jets Signatures

J.000: Composite Gluon To Invisible
Author: Jay Wacker
Latest Revision: 000

J.001: Multi-jets plus MET from an initial resonance
Author: Julia Shelton
Latest Revision: 002

J.003: Multijet Resonances (2->2 production only, no MET)
Author: Can Kilic
Latest Revision: 000

J.004: Multijet Resonances Including 2->1 Production (no MET)
Author: Can Kilic
Latest Revision: 000

J.005: Squark Neutralino Associated Production
Author: Jay Wacker
Latest Revision: 000

J.006: Two Jets, Leptons and MET
Author: Eder Izaguirre
Latest Revision: 000

J.007: Three (or more) Jets, Leptons and MET
Author: Eder Izaguirre
Latest Revision: 000

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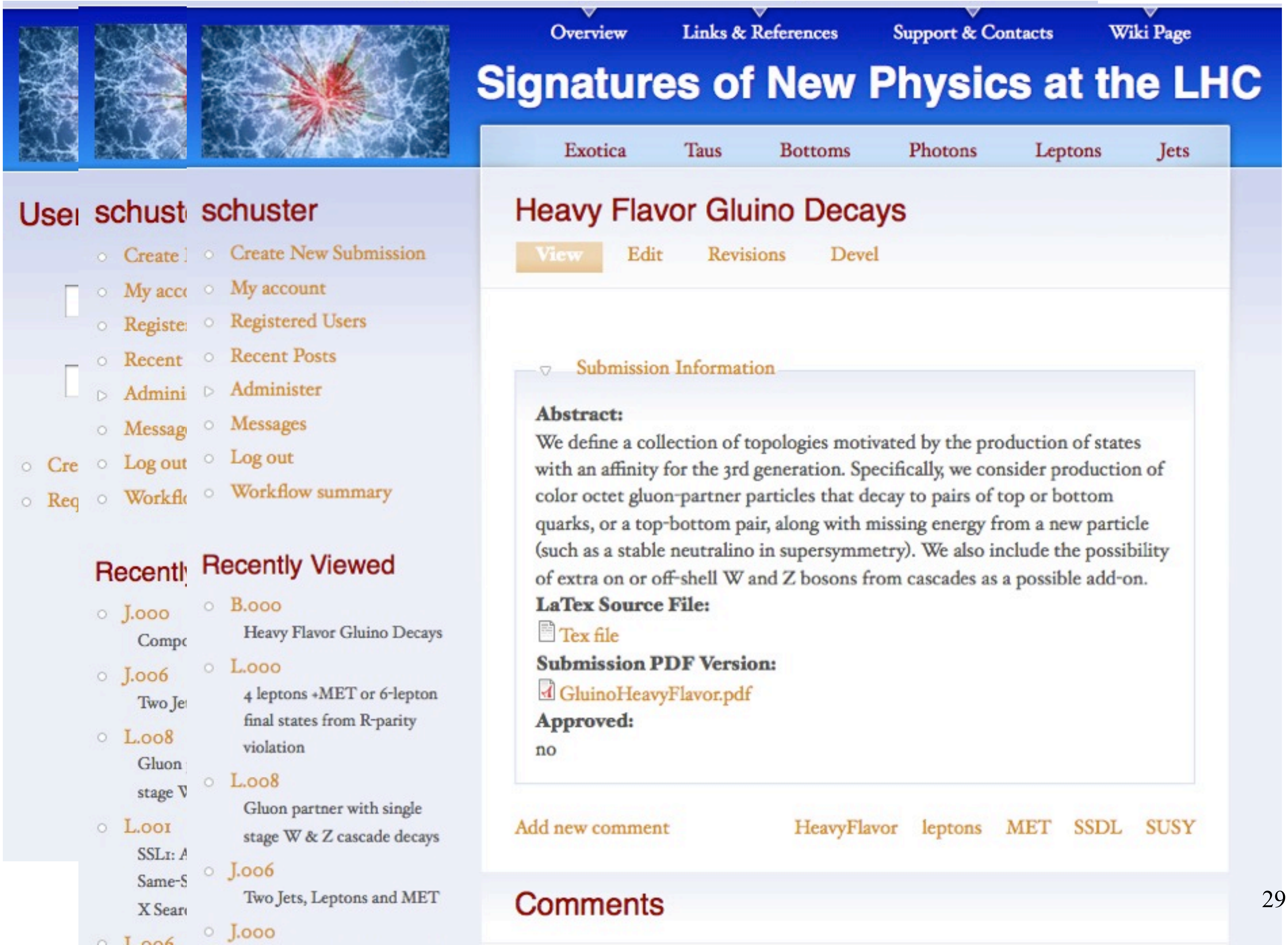

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  Two Jets, Leptons and MET
- J.000

Heavy Flavor Gluino Decays

Submission Information

Abstract:
We define a collection of topologies motivated by the production of states with an affinity for the 3rd generation. Specifically, we consider production of color octet gluon-partner particles that decay to pairs of top or bottom quarks, or a top-bottom pair, along with missing energy from a new particle (such as a stable neutralino in supersymmetry). We also include the possibility of extra on or off-shell W and Z bosons from cascades as a possible add-on.

LaTex Source File:
Tex file

Submission PDF Version:
GluinoHeavyFlavor.pdf

Approved:
no

Comments

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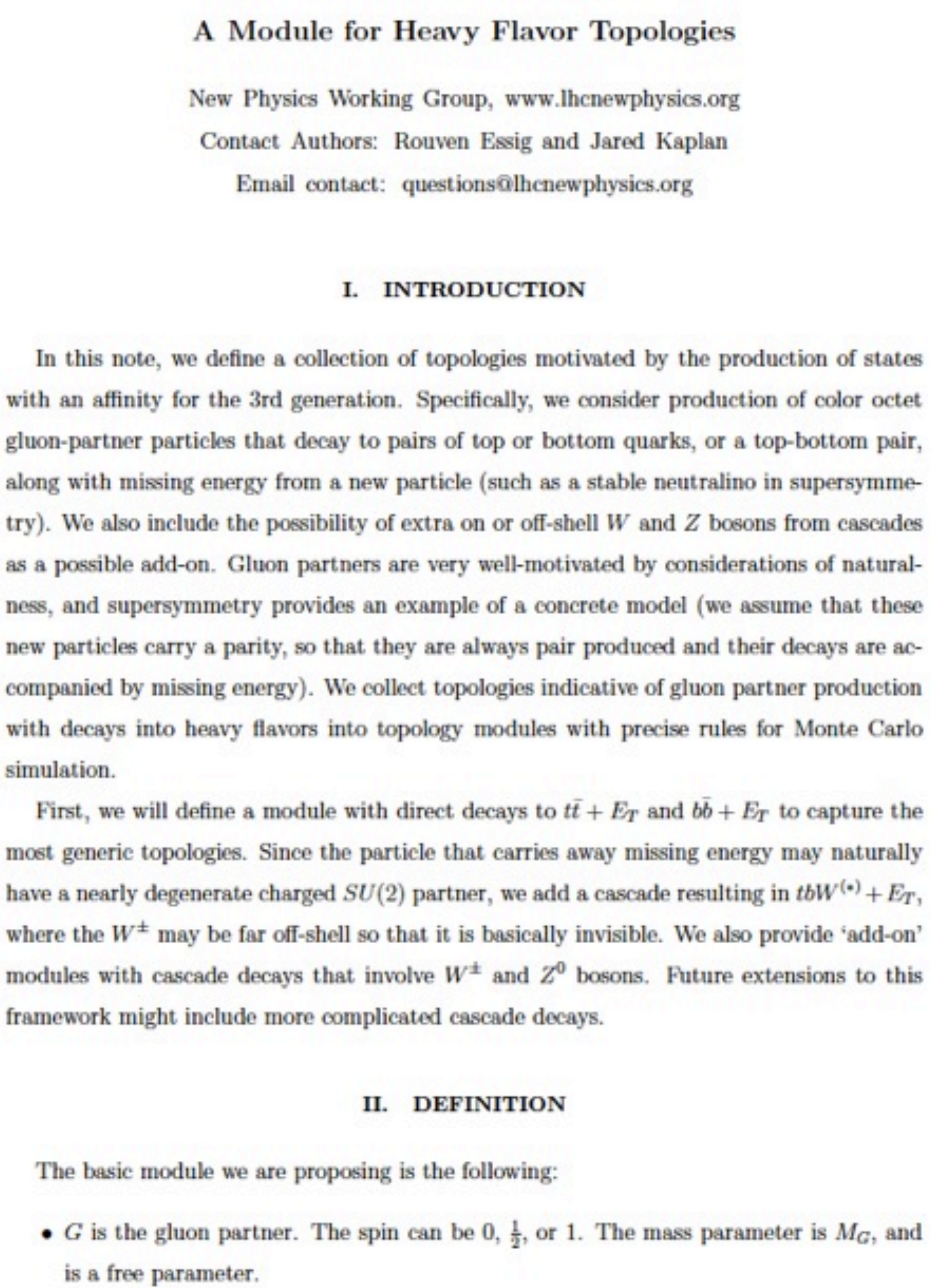


A Module for Heavy Flavor Topologies

New Physics Working Group, www.lhcnewphysics.org
Contact Authors: Rouven Essig and Jared Kaplan
Email contact: questions@lhcnewphysics.org

I. INTRODUCTION

In this note, we define a collection of topologies motivated by the production of states with an affinity for the 3rd generation. Specifically, we consider production of color octet gluon-partner particles that decay to pairs of top or bottom quarks, or a top-bottom pair, along with missing energy from a new particle (such as a stable neutralino in supersymmetry). We also include the possibility of extra on or off-shell W and Z bosons from cascades as a possible add-on. Gluon partners are very well-motivated by considerations of naturalness, and supersymmetry provides an example of a concrete model (we assume that these new particles carry a parity, so that they are always pair produced and their decays are accompanied by missing energy). We collect topologies indicative of gluon partner production with decays into heavy flavors into topology modules with precise rules for Monte Carlo simulation.

First, we will define a module with direct decays to $t\bar{t} + \not\!\!E_T$ and $b\bar{b} + \not\!\!E_T$ to capture the most generic topologies. Since the particle that carries away missing energy may naturally have a nearly degenerate charged $SU(2)$ partner, we add a cascade resulting in $tbW^{(*)} + \not\!\!E_T$, where the $W^{\pm}$ may be far off-shell so that it is basically invisible. We also provide 'add-on' modules with cascade decays that involve $W^{\pm}$ and Z^0 bosons. Future extensions to this framework might include more complicated cascade decays.

II. DEFINITION

The basic module we are proposing is the following:

- G is the gluon partner. The spin can be 0, $\frac{1}{2}$, or 1. The mass parameter is M_G, and is a free parameter.

Conclusion

- Search results can be made much more practically usable for studying TeV-scale physics, with (small) additional characterization.
- Simplified models organize production/decay topologies to
  - Allow almost-back-of-the-envelope study of search sensitivity to models
  - Easily parametrize ‘gaps’ in a search, where different approach is called for
- A broad list of simplified models inspired by **many** models and signatures is available.
  - Experimentalists: please use this resource in presenting results!
  - Th & Exp: Feel free to add/comment on the website http://www.lhcnewphysics.org

BACKUP

Simplified Model MC

- Pythia or MadGraph: take “simple spectrum” limit of an implemented model, e.g. SUSY, by decoupling unnecessary states – be careful, input masses aren’t always physical masses!

```
RMSS(1)=100 ! bino          RMSS(2)=1205 ! decouple wino
RMSS(3)=600 ! gluino        RMSS(6)=1000 ! decouple slepton-L
RMSS(8)=550 ! left-squark   RMSS(9)=1500 ! decouple squark-R
                            ...etc...
```

- Pythia: SLHA or native decay tables for ‘invented’ simplified model particles (can be automated using Marmoset)

```
DECAY 6000004  1.00           # gluino
          0.50000          2    -6000003      # → q    ~qbar
          0.50000         -2     6000003      # → qbar ~q
DECAY 6000003  1.00           # squark
          1.00000          2     1000022      # → q    LSP
```

- MadGraph/FeynRules: User models (assumed spin-dependent couplings of new-physics particles dictate matrix elements)

Differences:

- Treatment of initial-state radiation, decay matrix elements (can be important on tails, small elsewhere)
- Easy implementation of general models vs. generality

Limit Interpretation

- Highest-precision exclusion on a model is always dedicated analysis – but too many models of interest
- ***Approximate*** exclusions readily obtained from topology limits

$$(\sigma \times \varepsilon)_{\mathrm{model}} = \sum_{XY\to\mathcal{A}} \boxed{\sigma_{XY} \times \mathcal{B}_{\mathcal{A}}} \times \boxed{\varepsilon_{XY\to\mathcal{A}}}$$

Detector response to ***process***

Model-Specifics

For each search:

1) Simplified-model limits encode statistics & process efficiency

$$\sigma_{\max}(\mathcal{A}) = N_{\max}/(\varepsilon_{\mathcal{A}} \times \mathcal{L})$$

2) Calculate branching ratios for each process

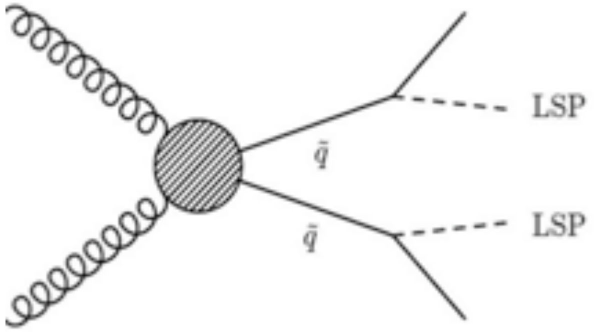
Require $$\sum_{XY\to\mathcal{A}} \sigma_{XY} \times \mathcal{B}_{\mathcal{A}} \times \frac{1}{\sigma_{\max}(\mathcal{A})} < 1$$

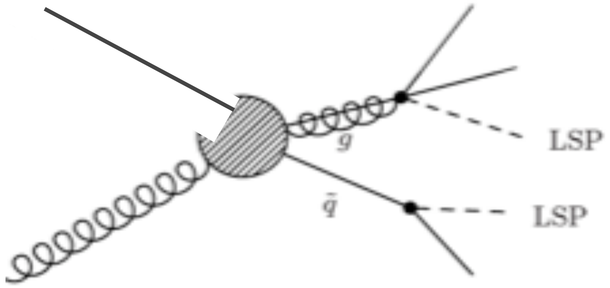
Simple: take strongest limit among different search channels

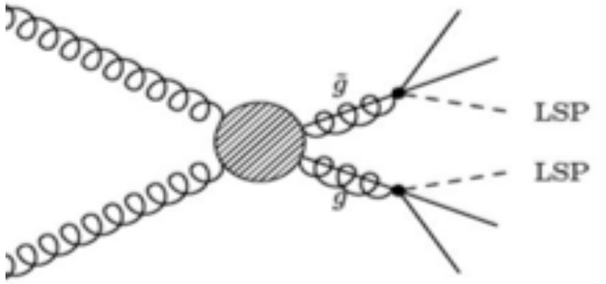
(More sophisticated: combine likelihoods… eventually?)

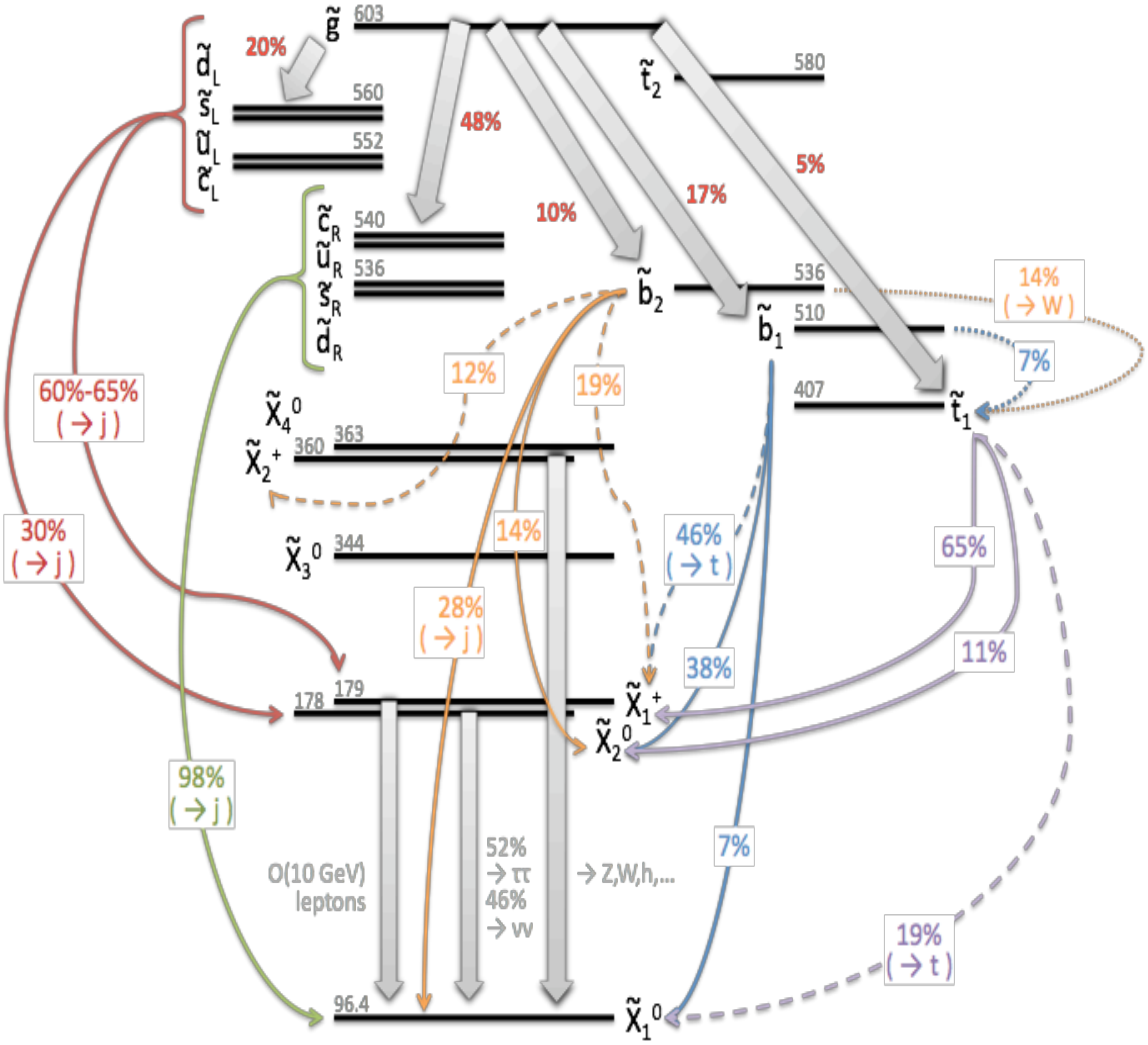
One-Stage "Gluino": Using Limits

simplified model:









One-Stage "Gluino": Using Limits

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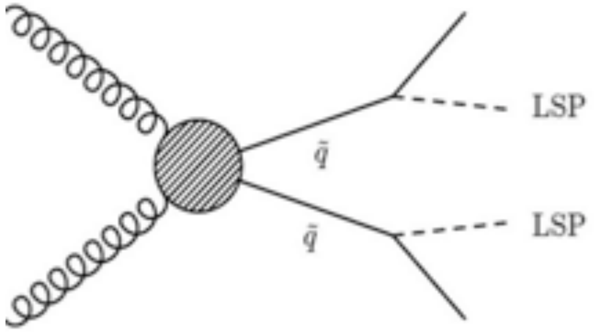

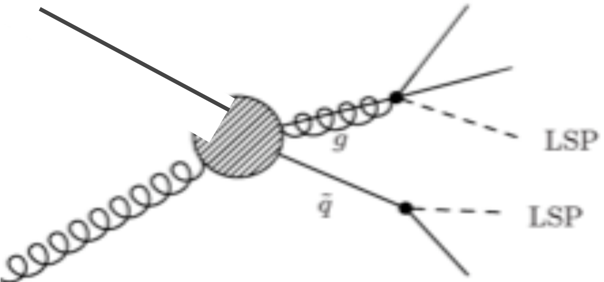

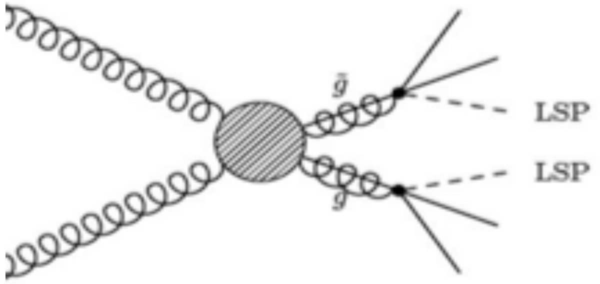

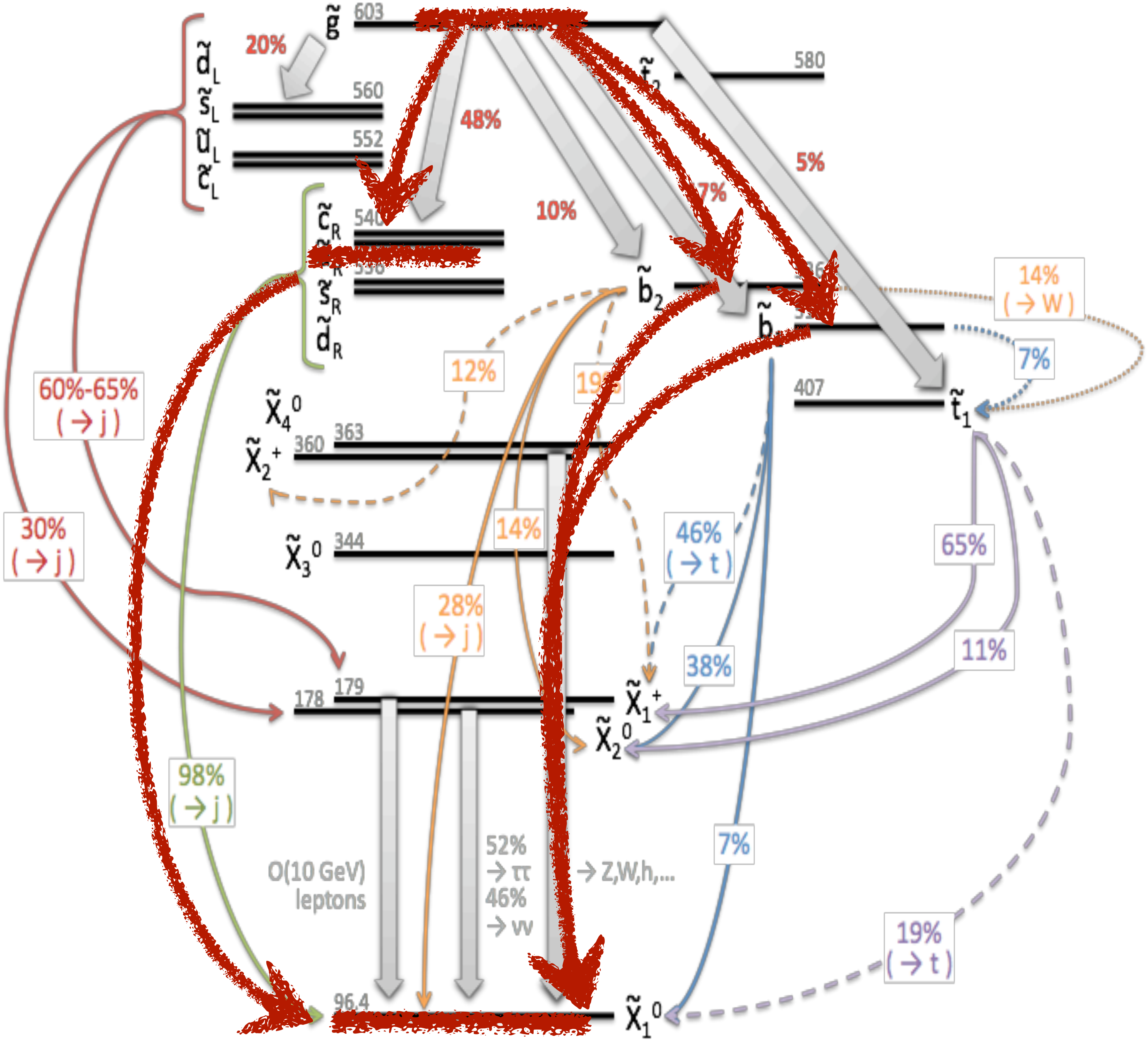

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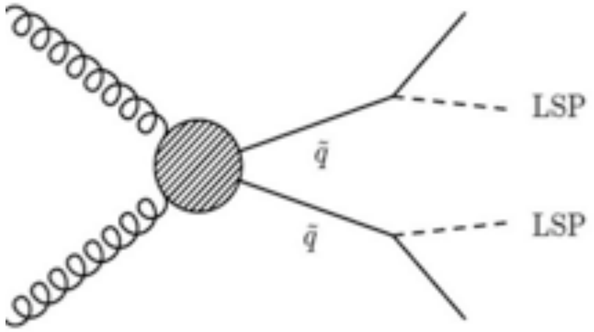
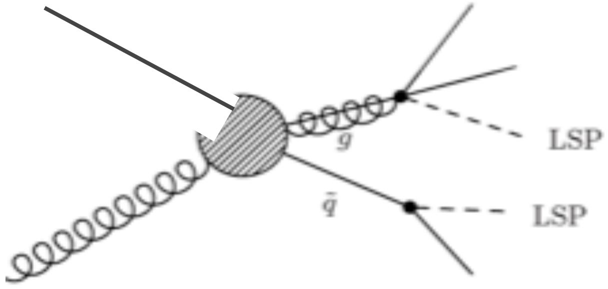
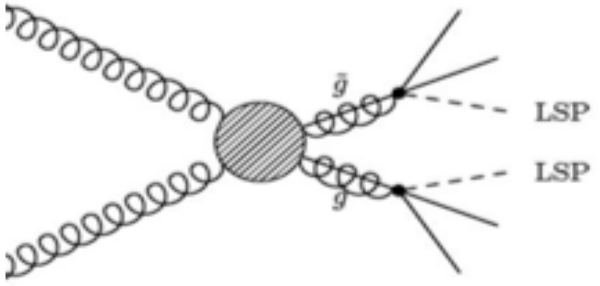
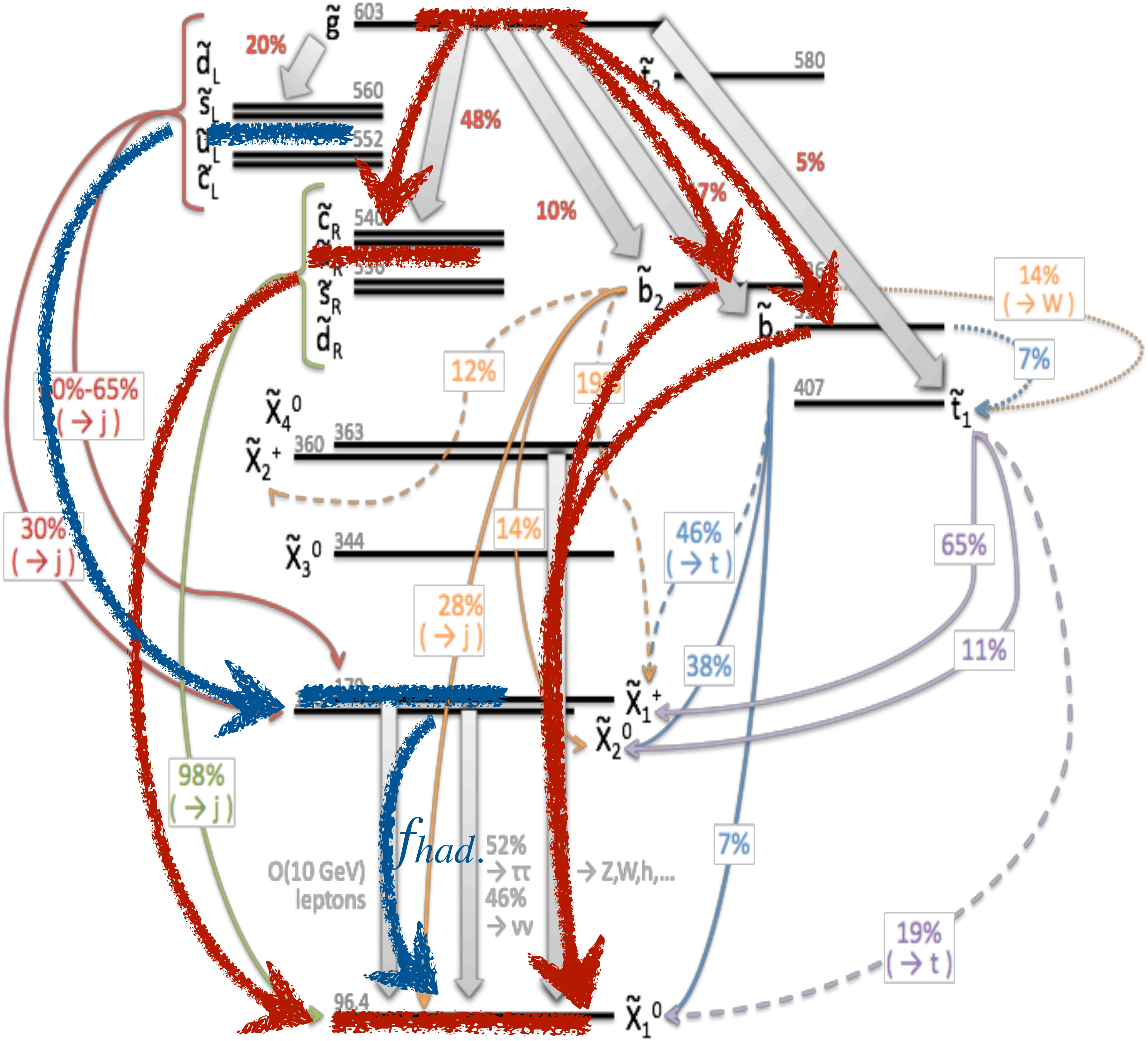
simplified model:







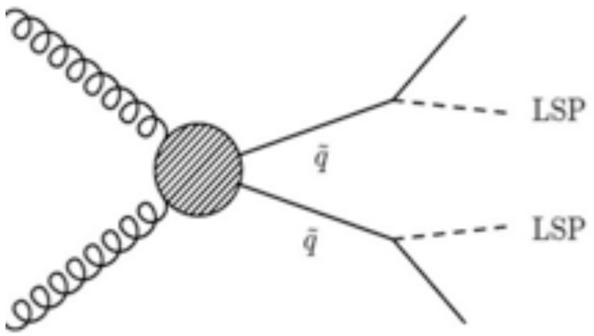
+hadronic W/Z cascades

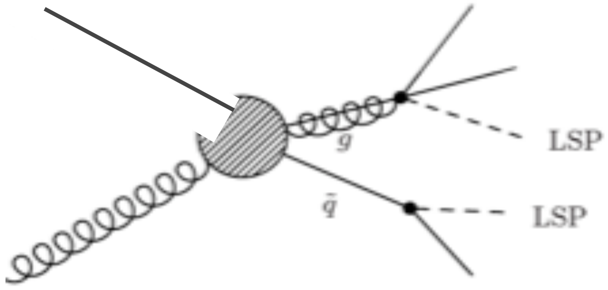


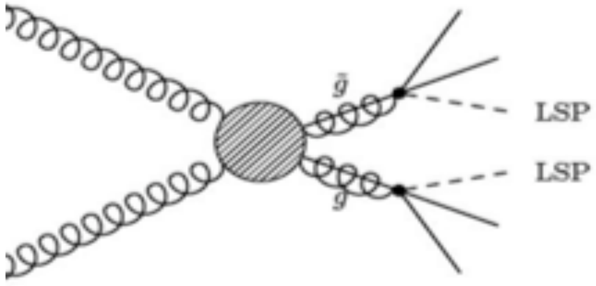
⇒ small simplified model encapsulates majority of production/ decay chains

One-Stage "Gluino": Using Limits

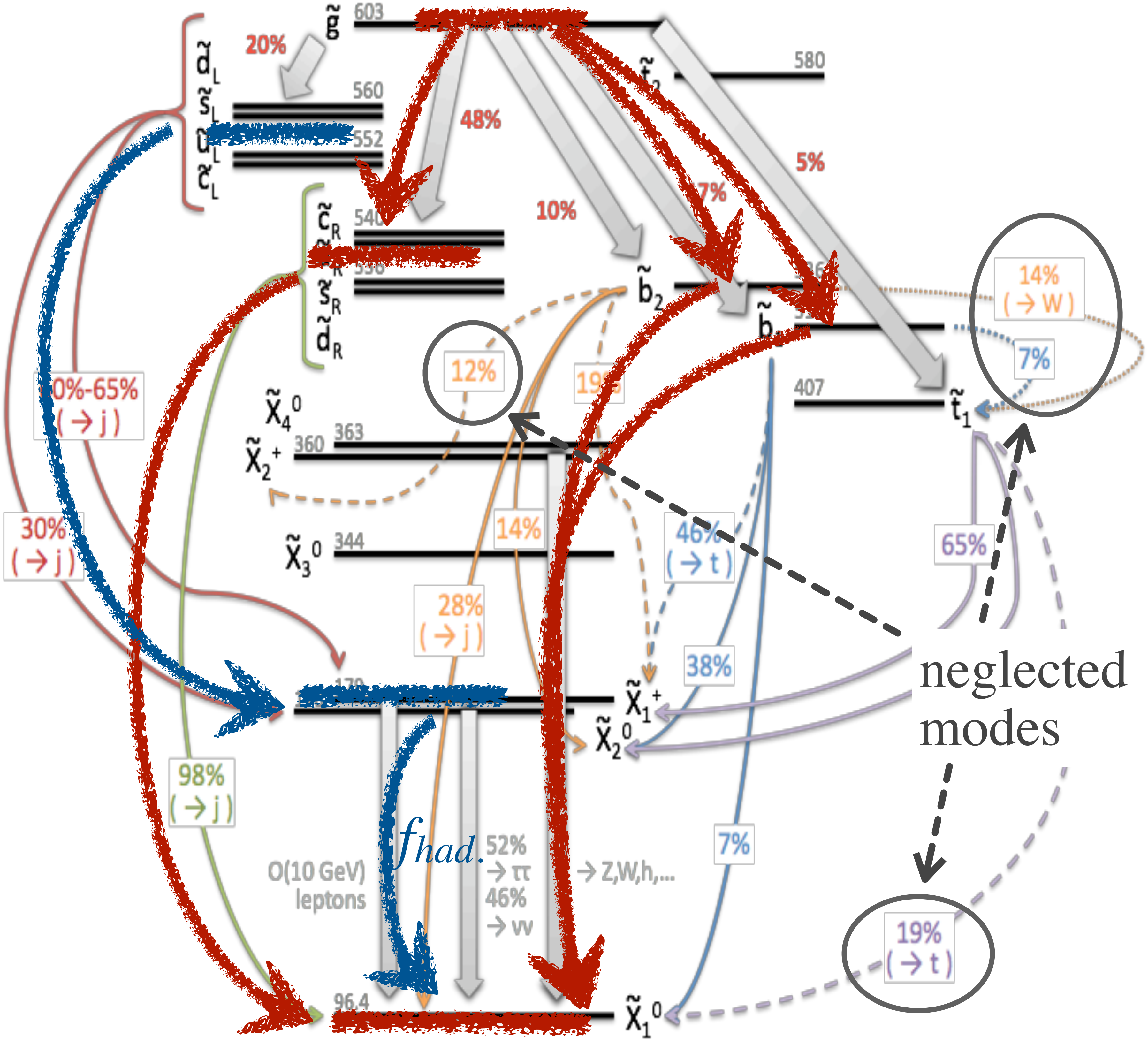
simplified model:





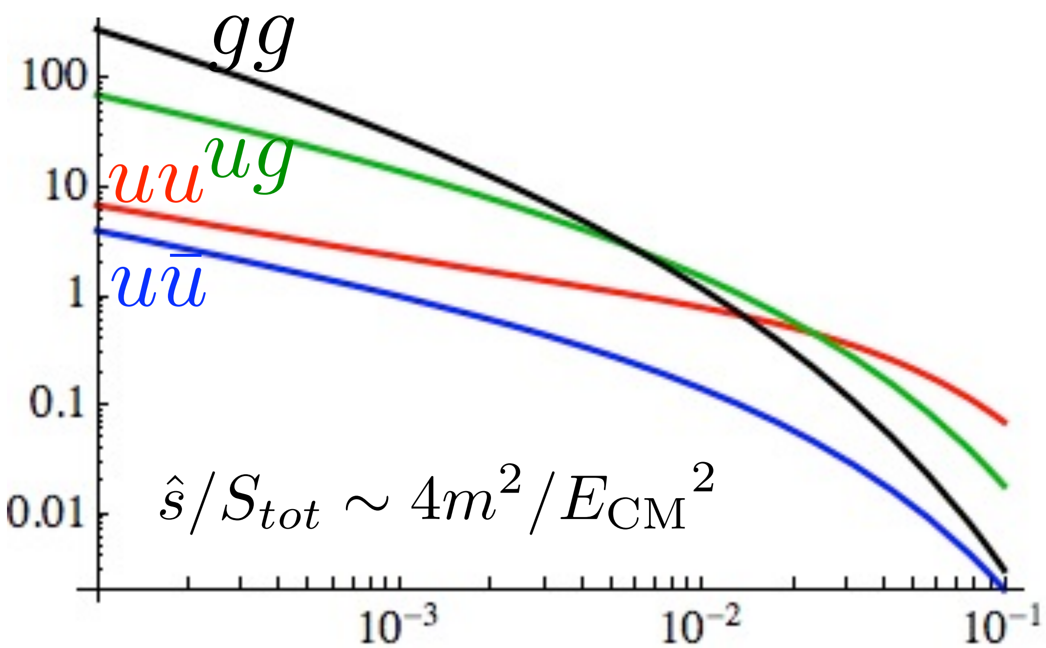


+hadronic W/Z cascades



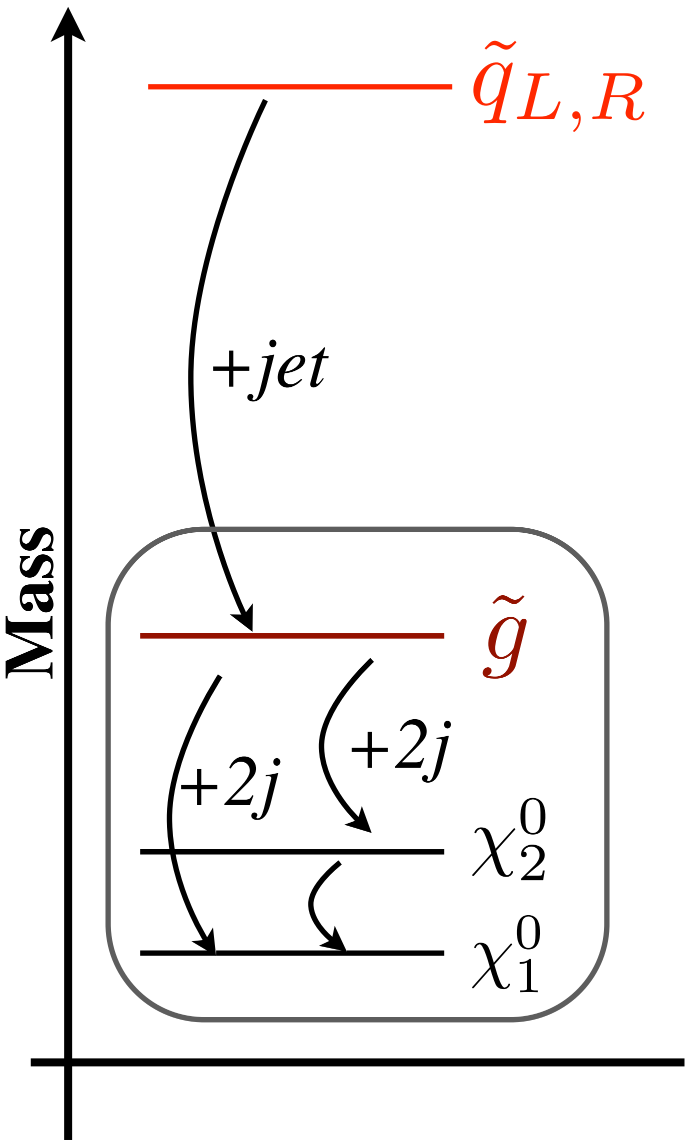
⇒ small simplified model encapsulates majority of production/ decay chains

Theoretical Simplification: Production



Parton luminosity falls steeply with mass ($m^{-5,6}$)

Electroweak production down by $(\alpha_2/\alpha_3)^2$, less visible energy



$$m_{\tilde{q}} - m_{\tilde{g}} \gg m_{\tilde{g}}$$

$$\Downarrow$$

$$\sigma_{\tilde{q}\tilde{q}}, \sigma_{\tilde{q}\tilde{g}} \ll \sigma_{\tilde{g}\tilde{g}}$$

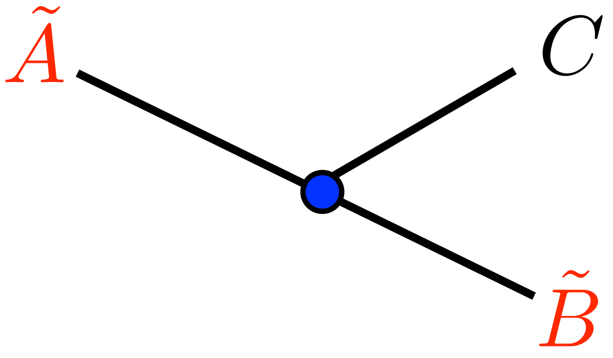
Mostly produce lightest (few) colored states

Theoretical Simplification: Decay

Feynman rules determined by Standard Model

2–body decays dominate over 3–body, if allowed.
(additional coupling & phase space suppression)

2–Body

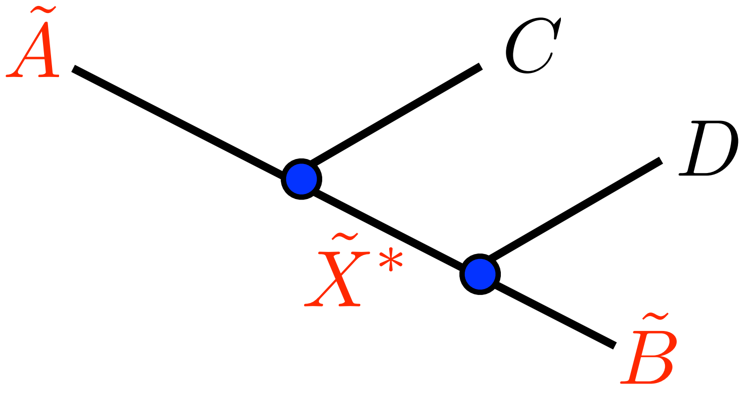


$\Gamma \propto \alpha$

$\alpha_t \gg \alpha_3 \gg \alpha_2 \gg \alpha_1$

Strongest coupling wins

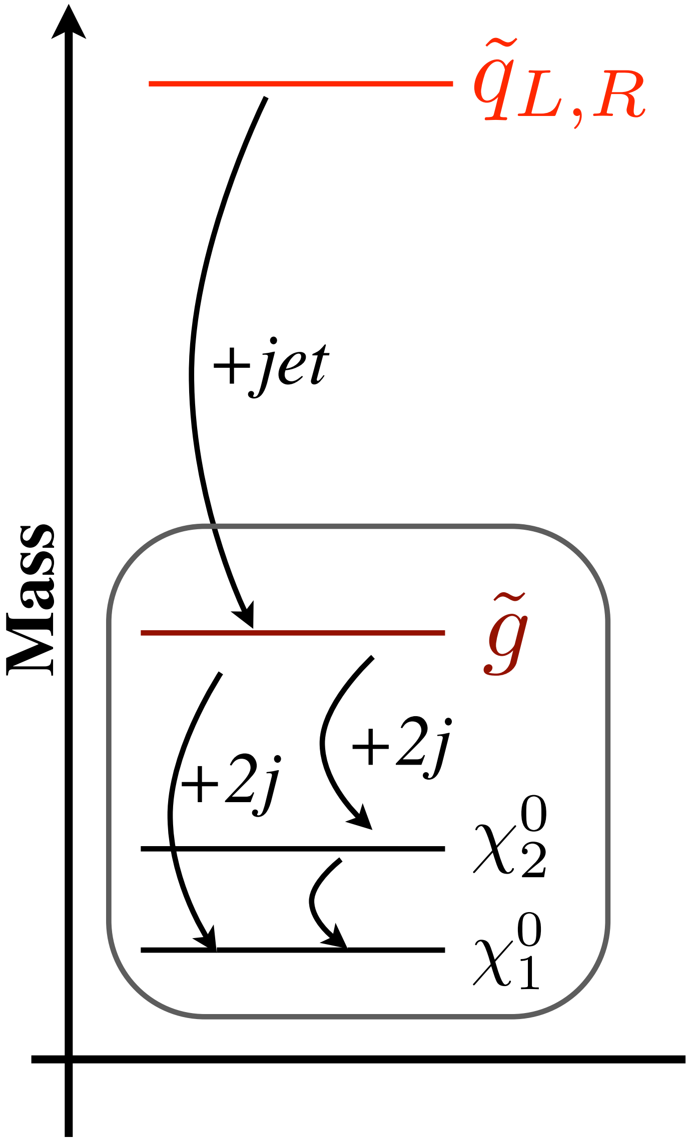
3–Body



$\Gamma \propto \alpha^2/m_{\tilde{X}}^4$

Significant suppression
by couplings **and**
intermediate mass

Experimental Simplification: Production

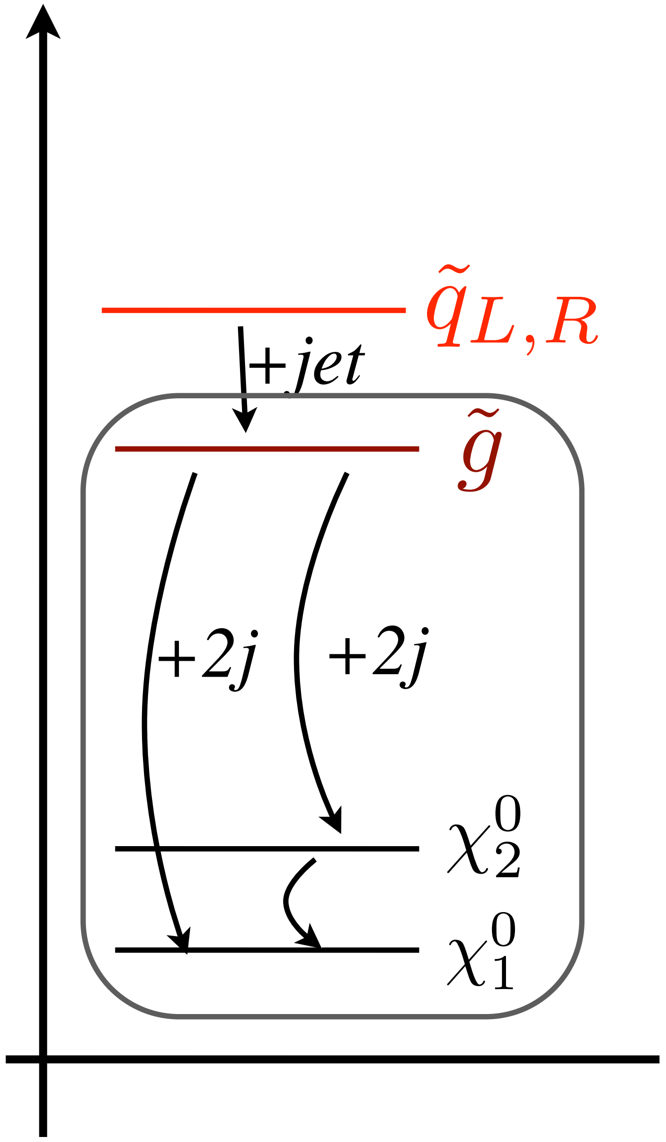


$$m_{\tilde{q}} - m_{\tilde{g}} \gg m_{\tilde{g}}$$

$$\Downarrow$$

$$\sigma_{\tilde{q}\tilde{q}}, \sigma_{\tilde{q}\tilde{g}} \ll \sigma_{\tilde{g}\tilde{g}}$$

can ignore squarks



$$m_{\tilde{q}} - m_{\tilde{g}} \ll m_{\tilde{g}}$$

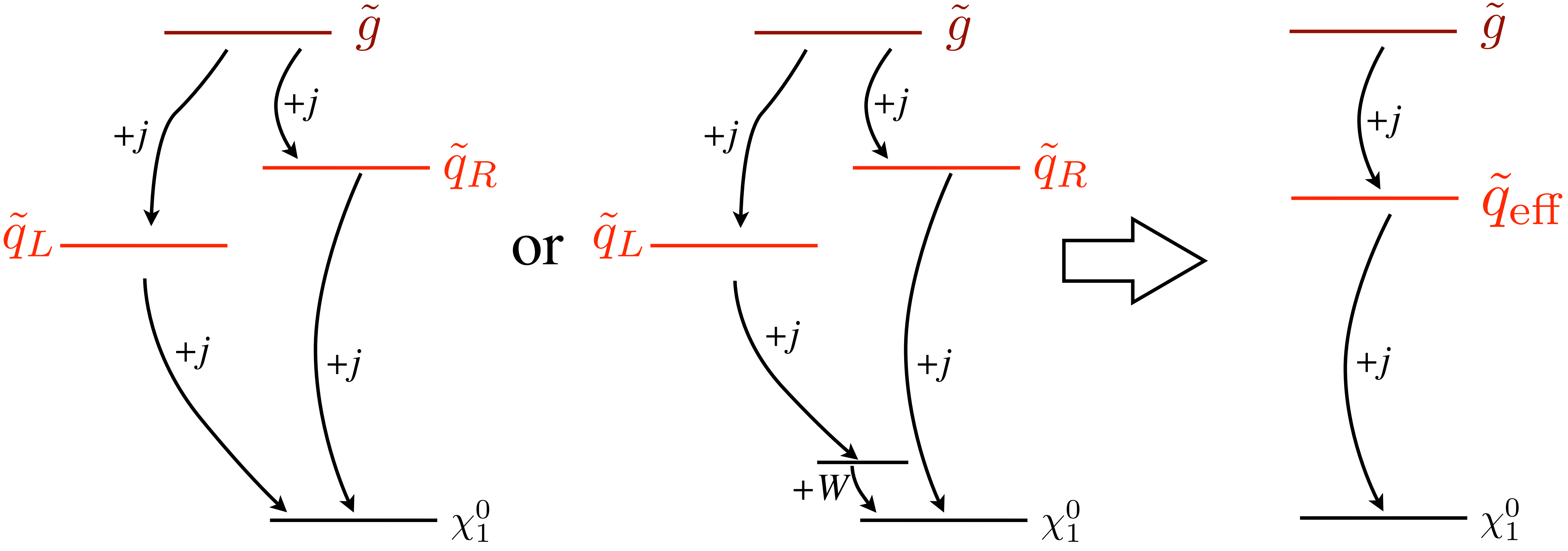
$$\Downarrow$$

jet from squark decay

very soft

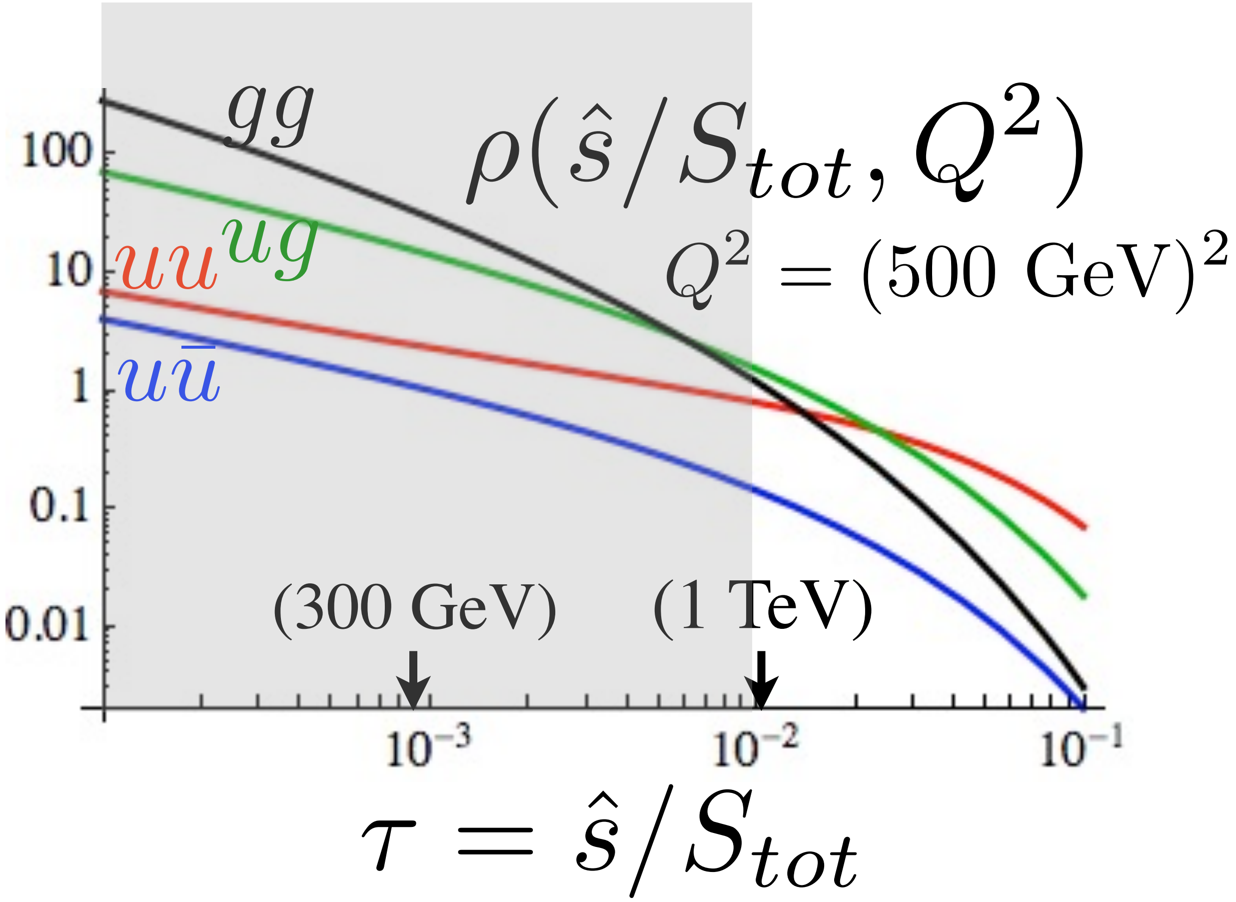
can ignore squarks

Experimental Simplification: Decay

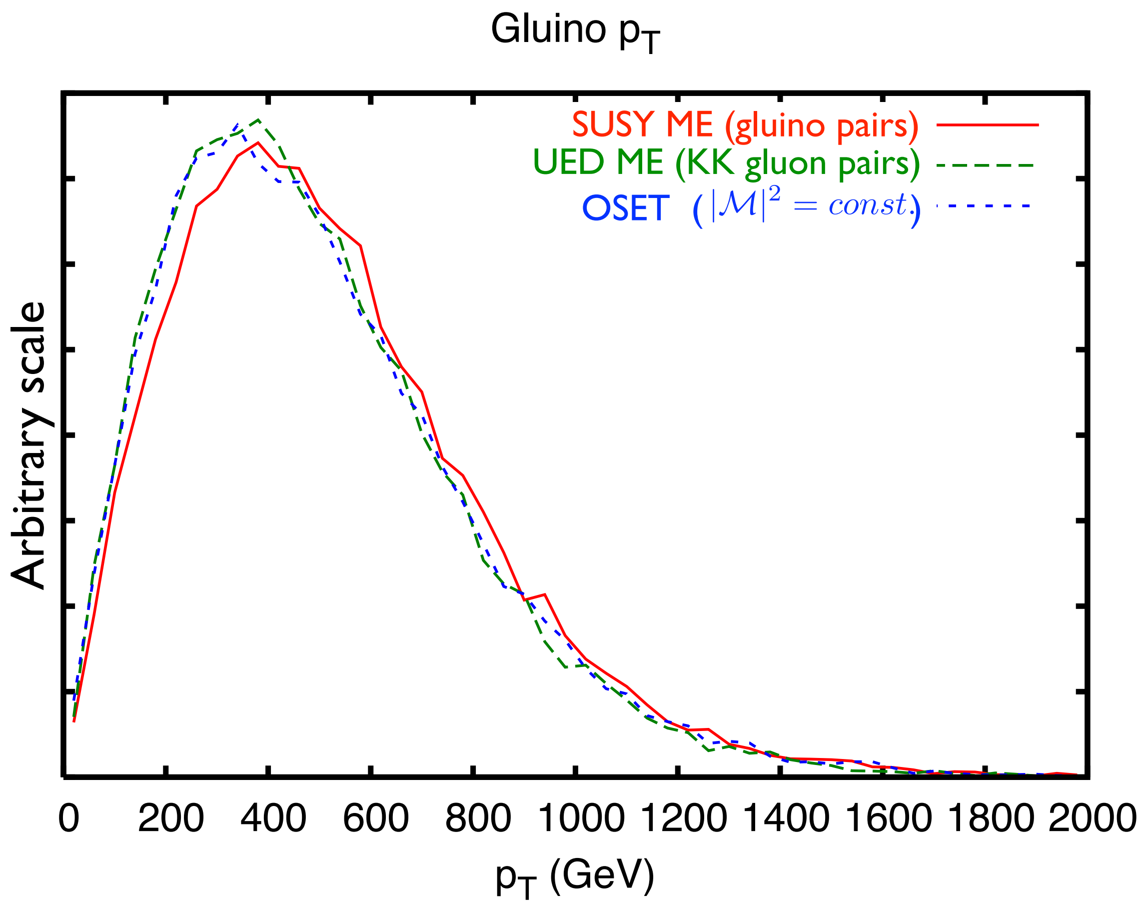


Similar intermediate states can be grouped together

Shape Invariance



$\Longrightarrow$



Final-state kinematics is ***mostly*** insensitive to the production matrix element.

This can be **justified analytically** (for object p_T's and rapidity) by approximating parton luminosities near threshold as a power-law.

Remaining dependence can be parametrized simply, and/or absorbed in a bias of the "masses" used to characterize data.

p_T Distributions

Simple and instructive to calculate p_T distribution for 2→2 product with general matrix element:

$$\frac{d\sigma_{inc}}{d\text{Vars}} = \int \underbrace{\frac{dx_1}{x_1}\frac{dx_2}{x_2}}_{= \frac{d\hat{s}}{\hat{s}}d\bar{y}} \underbrace{x_1 f_g(x_1, Q) x_2 f_q(x_2, Q)}_{\text{PDF's} \sim (1-x)^p x^{-q}} \underbrace{\frac{d\hat{\sigma}(qg \to AB)}{d\text{Vars}}}_{\text{parton cross-section}}$$

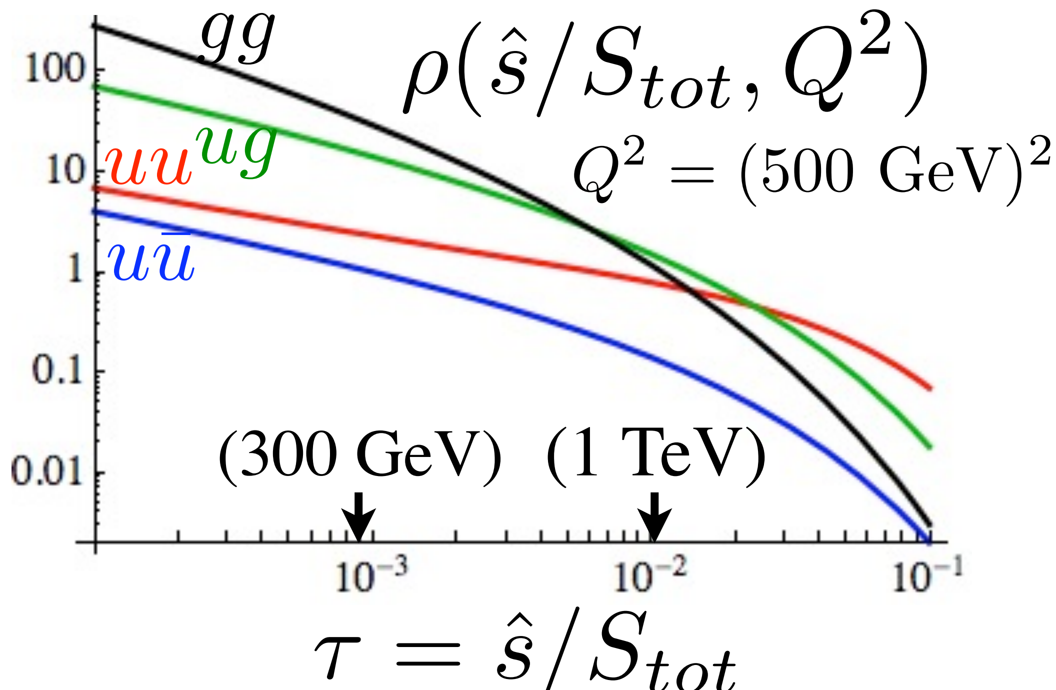
parton E^2_{cm} CM boost

$\int d\bar{y}$→parton luminosity

$$\rho(\hat{s}, Q^2) \propto (\hat{s}/S_{tot})^{-q} \qquad (q\text{~}1\text{–}1.5)$$

$$s_0^2 \frac{d\sigma}{d\hat{t}d\hat{s}} = \frac{1}{\hat{s}}\frac{s_0^2}{\hat{s}^2}\rho(\hat{s}, Q^2)\underbrace{\left(\hat{s}^2\frac{d\hat{\sigma}}{d\hat{t}}\right)}_{\frac{1}{8\pi}|\mathcal{M}(\hat{s},\hat{t})|^2}$$

($s_0 = 2M^2$: threshold s)



$\mathrm{p_T}$ Distributions

$$s_0^2 \frac{d\sigma}{d\hat{t}d\hat{s}} = \frac{1}{\hat{s}} \frac{s_0^2}{s^2} \rho(\hat{s}, Q^2) |\mathcal{M}|^2 \qquad \rho(\hat{s}, s_0) \approx A(\hat{s}/S_{tot})^{-q}$$

CM-frame Lorentz invariants: $\hat{s}$ & $\hat{t}$ **or** $\hat{s}$ & p_T^2 **or** $\hat{s}$ & ξ

related by: $\hat{t} = -\frac{1}{2}\left[\hat{s}(1-\xi) - s_0\right]$ $\qquad p_T^2 = \frac{\hat{t}\hat{u} - M^4}{\hat{s}} \Rightarrow dp_T^2 d\hat{s} = \xi d\hat{t} d\hat{s}$

$\xi \sim \beta \cos\theta_{CM}$:"pure angular" variable linearly related to

→ good variable for M.E. expansion

p_T Distributions

$$s_0^2 \frac{d\sigma}{dp_T^2} = \frac{1}{\xi}\int_{s_0 + 4p_T^2}^{S_{tot}} d\hat{s}\; s_0^2 \frac{d\sigma}{d\hat{t}\,d\hat{s}} = \int_{s_0 + 4p_T^2}^{S_{tot}} \frac{1}{\xi}\,\frac{d\hat{s}}{\hat{s}}\,\frac{s_0^2}{s^2}\,\rho(\hat{s}, Q^2)|\mathcal{M}|^2$$

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→ good variable for M.E. expansion

Expand $|\mathcal{M}|^2 = \sum C_{m,n}(\hat{s}/s_0)^m\xi^n$ near threshold (usually dominated by low m, n)

$$s_0^2\frac{d\sigma}{dp_T^2} = \left(\frac{s_0}{S_{tot}}\right)^{-q}\sum_{m,n} C_{m,n}\int_{s_0+4p_T^2}^{S_{tot}} \frac{d\hat{s}}{\xi\hat{s}}(\hat{s}/s_0)^{m-q-2}\xi^n$$

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$$= \left(\frac{s_0}{S_{tot}}\right)^{-q}\sum_{m,n} C_{m,n}\int_0^{\approx 1}\frac{2d\xi}{1-\xi^2}(1-\xi^2)^{-m+q+2}\xi^n \times (1+4p_T^2/s_0)^{m-q-2}$$

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shape independent of *n*

p_T Universality

pT variables are useful because they are simple, single-particle Lorentz invariants *and* insensitive to production matrix element!

$$\frac{d\sigma}{dp_T^2} \sim (1 + p_T^2/M^2)^{m-q-2} \qquad \text{for} \qquad |\mathcal{M}|^2 \sim (\hat{s}/s_0)^m \xi^n, \ \rho(\hat{s}) \sim \hat{s}^{-q}$$

Typical p_T~0.5 M

- Not ***completely*** universal
  - Depends on *m* (different for p-wave and contact operators)
  - Depends on *q* (sensitive to init. state)
  - Observable p_T's depend on decay M.E.
- **But** easy to get similar effects (after cuts) by changing s_0 – simple analysis can't distinguish
- Similarly, η distribution indep. of *m* – even different *n* convolved with $\bar{y}$ distribution have similar shape

"Shape invariance" Arkani-Hamed et al, hep-ph/0703....