Towards Model-Independence in New Physics Searches

Philip Schuster
SLAC Theory Group

Outline

- What is Model-Independence?
- Topological Approaches for BSM Searches
  - Crucial Details: Matrix Elements and Event Generation

    hep-ph/0703088: Arkani-Hamed et al w/ PS
- Characterizing New Physics Signals
  - a tractable collection of SUSY-like topologies

    Simplified Models: (0810.3921 Alwall, PS, Natalia Toro)

For additional information, see:
http://indico.cern.ch/conferenceDisplay.py?confId=94910
and
www.lhcnewphysics.org

BSM Problems For the LHC Era

(besides understanding detector and Standard Model)

1. Search in all the Right Places

2. Present search results so that useful limits can be extracted

3. If new physics is seen, characterize it as much as possible, describe **observed properties** of New Physics with minimal reliance on **untested assumptions**

Any scheme to characterize data, with a model or otherwise, should make these tasks easier.

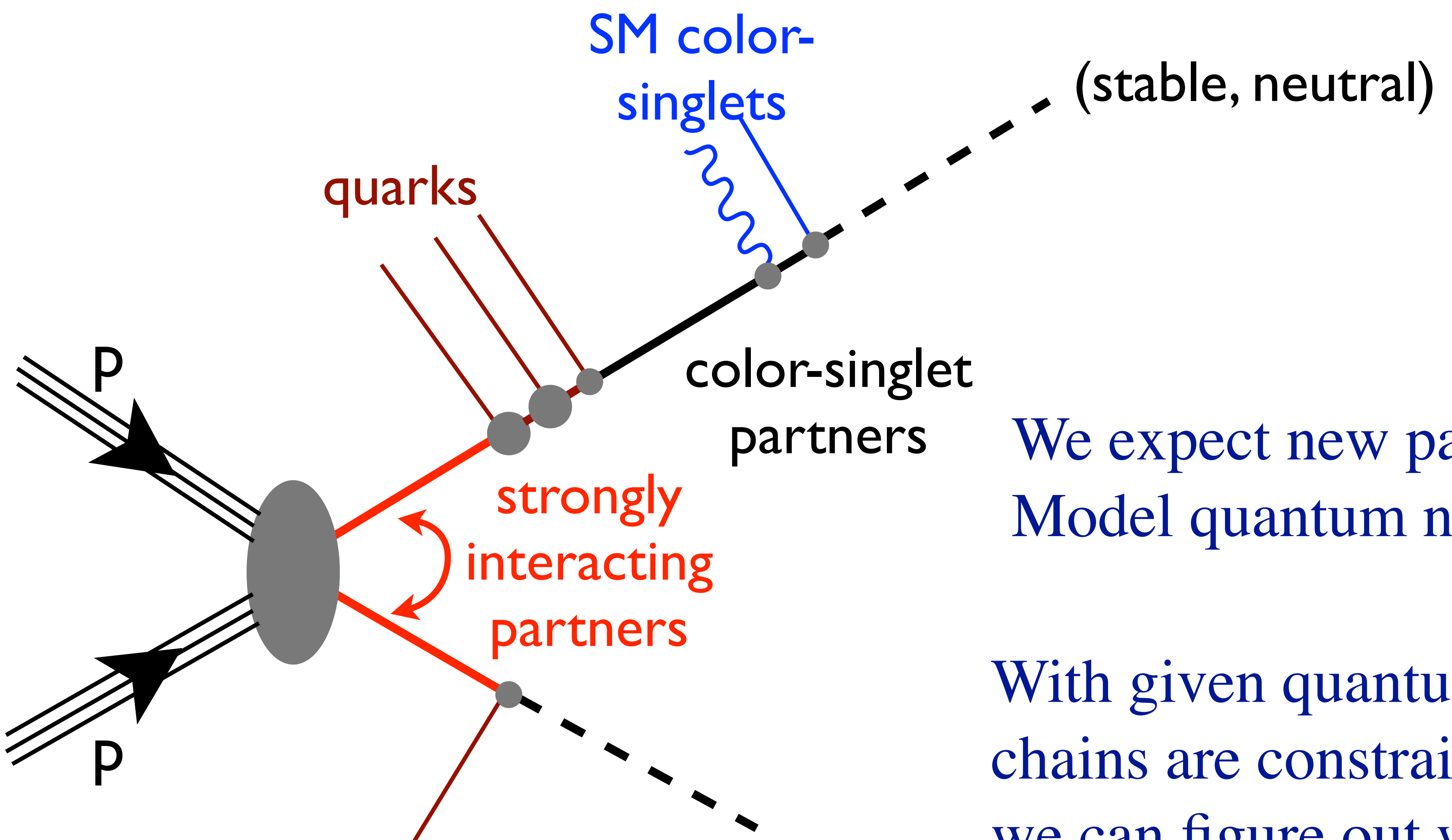
Model Independence?

- What's in a model?
  New particles
  Masses
  Couplings $\Rightarrow$ σ, BR formulas
  Relations between masses

- We need to simulate new physics to understand search sensitivity, so full "model-independence" is clearly not possible
- We can still remove as many unnecessary/untested assumptions as possible… what and how?

Building Blocks

Topologies are the basic building blocks of models.



We expect new particles with Standard Model quantum numbers

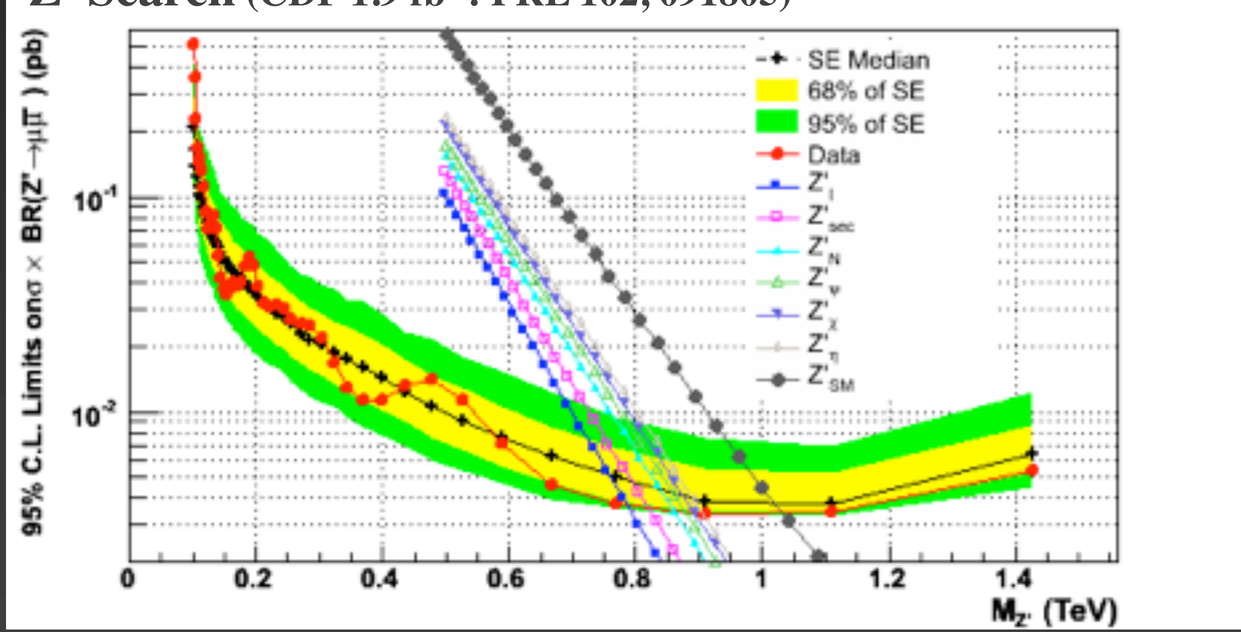
With given quantum numbers, decay chains are constrained by symmetry, so we can figure out what's reasonable without knowing much about the model.

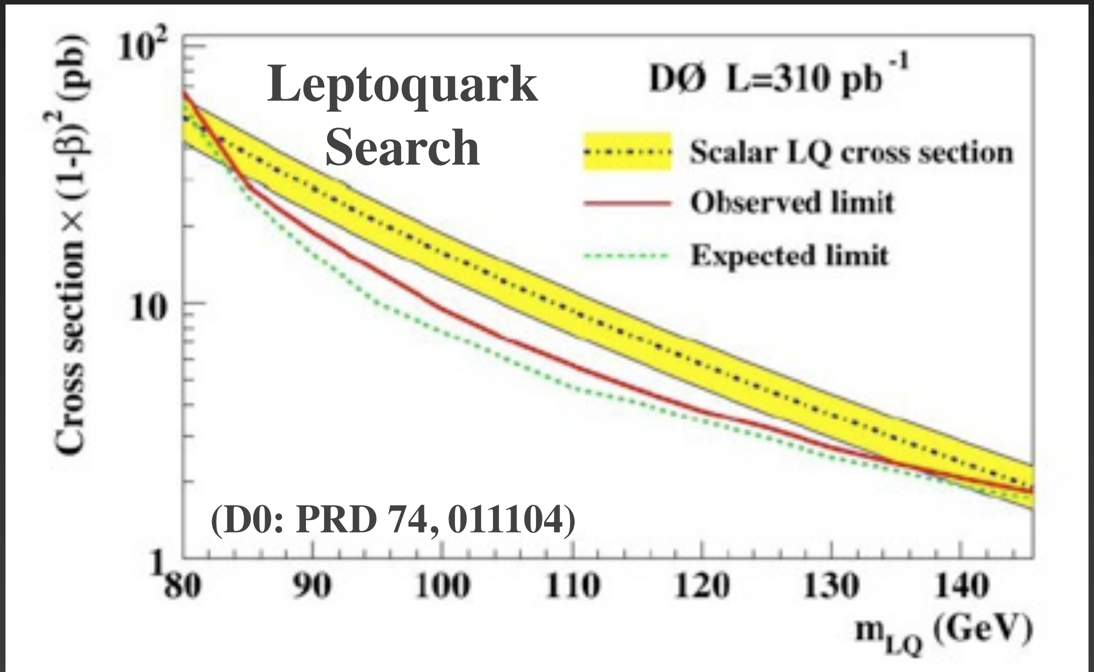
Detailed cross-sections and branching ratios are very **model-dependent**, not easy to motivate using symmetry arguments…

Search/Characterization Approaches

- Resonance searches, e.g. higgs,Z′: σ x Br limits, as function of mass, in many decay channels (challenge is searching in every channel)
- Many exotics searches likewise tailored to particular event topology (e.g. b′→ tW): mass-dependent limit on σ overlaid w/ prediction
- Top physics

Z′ Search (CDF 1.9 fb^{-1}: PRL 102, 091805)





Search/Characterization Approaches

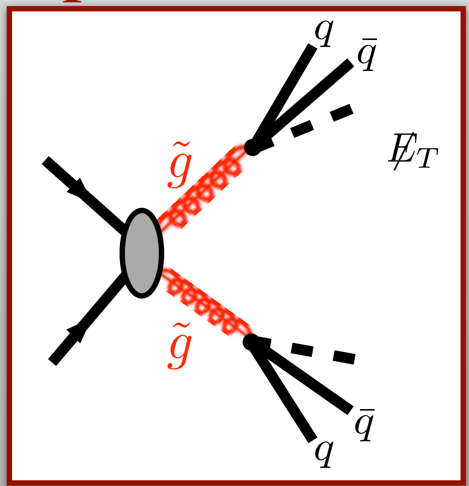
- Resonance searches, e.g. higgs,Z′: σ x Br limits, as function of mass, in many decay channels (challenge is searching in every channel)
- Many exotics searches likewise tailored to particular event topology (e.g. b′→ tW): mass-dependent limit on σ overlaid w/ prediction
- Top physics

- **Much harder** for rich (e.g. SUSY-like) new physics
  - Practical: Each search is sensitive to variety of topologies; hard to classify these because there are so many
  - Technical: 2→2 process kinematics depends on matrix element involving many unknown parameters
- Instead, focus on raw distributions & specific model exclusions/fits
- But determining topologies is **crucial**
  - Directs program of measurements
  - Decipher structure (e.g. SUSY: light stop, neutralino hierarchy, …)

Topology-Based Searches

Plenitude of models **and** of signals (topologies)

topology = pattern of production & decay



- Determine kinematics & efficiency
  ⇒ figure of merit for robustness
- Common building blocks repeated in many models
  ⇒ broad impact

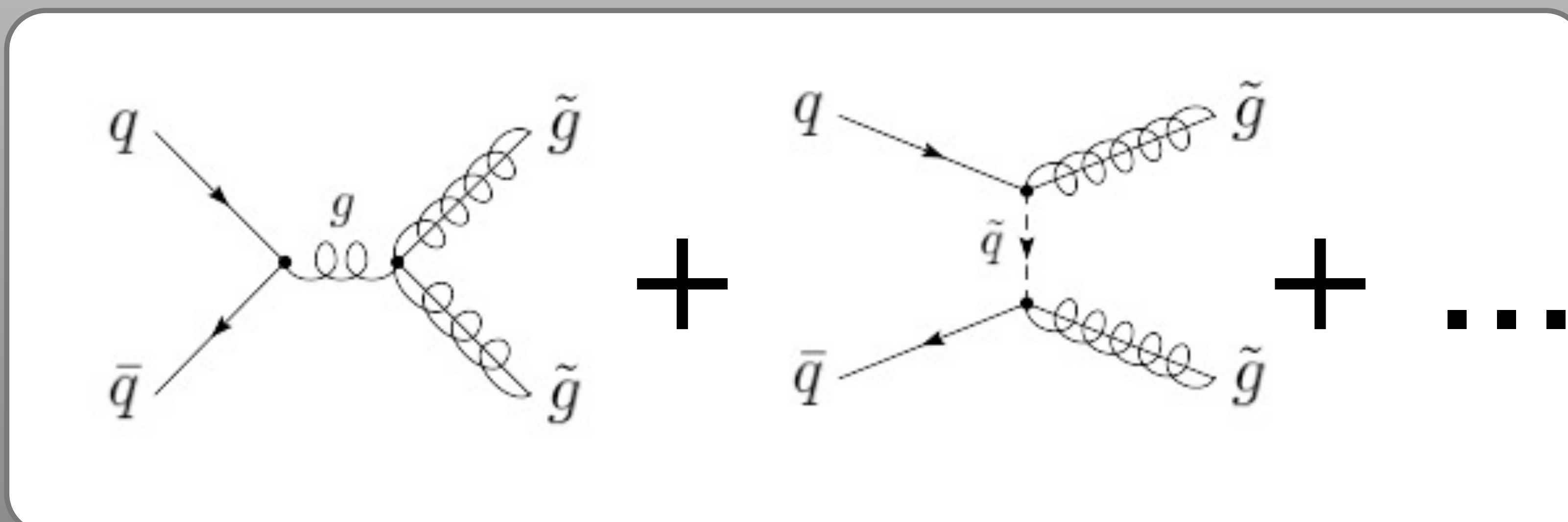
*Raw limit (counts, distributions, etc.) even broader – but detector-dependent interpretation

Plots follow to illustrate these points.

First, we need to address the issue of simulating events.

Matrix Elements and Event Generation

Stick figures suffice for **talking** about topologies, but **generating events** introduces new subtleties:

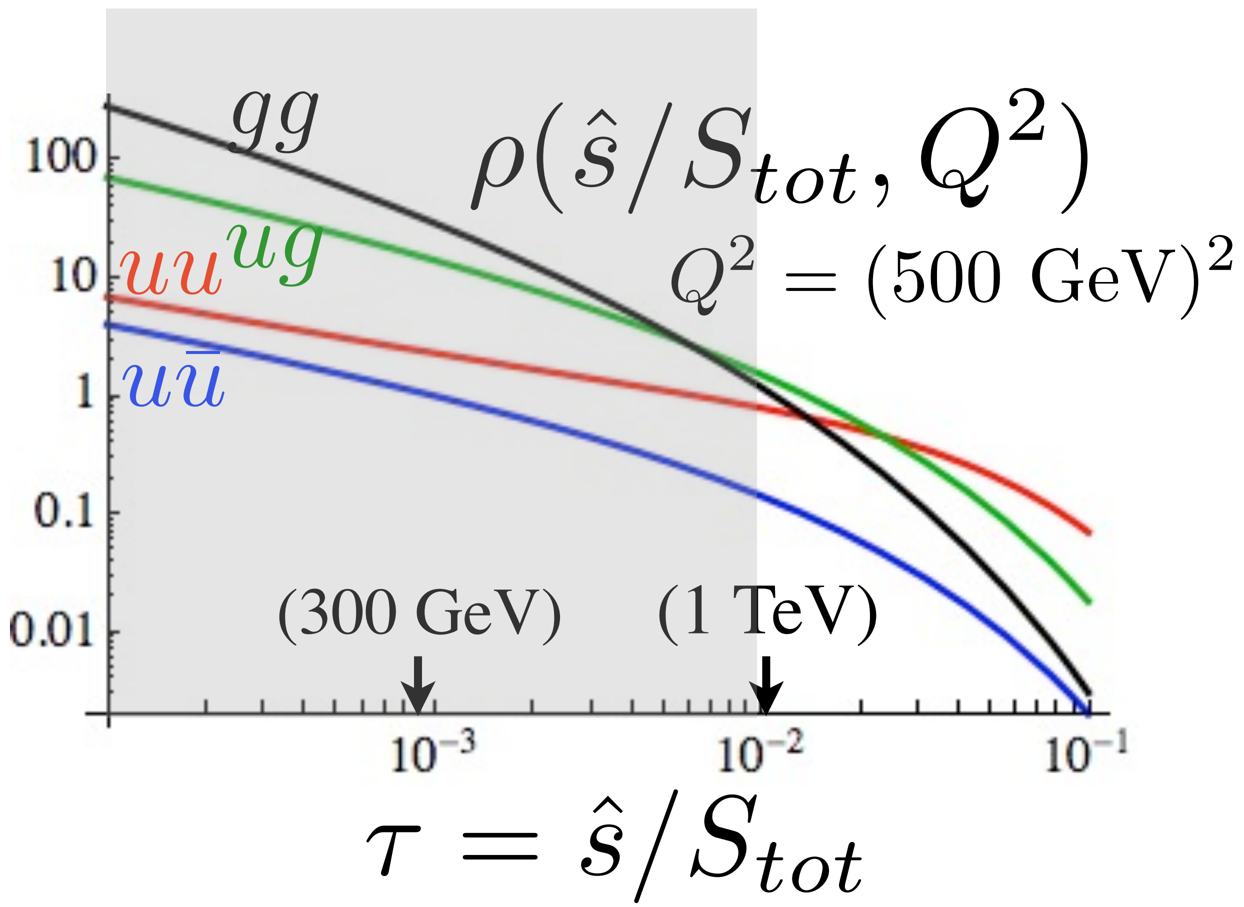


$$|\mathcal{M}|^2 = \frac{\pi\alpha_s^2}{s^2}\left(\frac{4}{9}\frac{m_{\tilde{g}}^2 - \ t}{s} + \frac{\left[(m_{\tilde{g}}^2 - t)s + 2m_{\tilde{g}}^2(m_{\tilde{q}}^2 - t)\right]}{(t - m_{\tilde{g}}^2)^2} \quad +u + st + su + tu \quad \text{channels}\right)$$

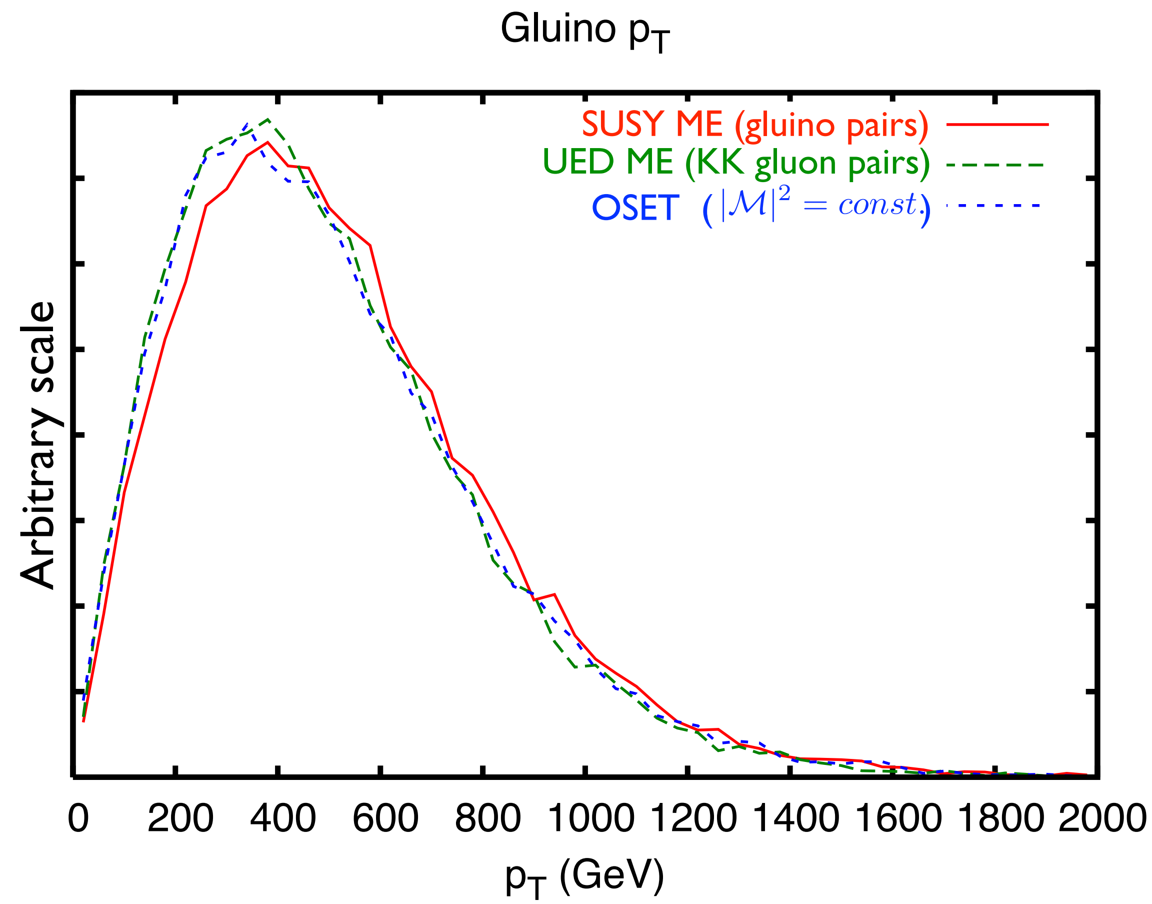
Depend on **unknown** spins, and on masses of other particles. Measure/limit cross-section, but what about distributions?

Are we forced to assume one model or another?

Shape Invariance



$\Rightarrow$



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.

Implication

Can get by with (almost any) ansatz matrix elements

– assume SUSY spins, QCD production modes

– $|M|^2$=const. (parametrized corrections for *p*-wave)

– …

Methodology I've discussed isn't premised on any one choice!

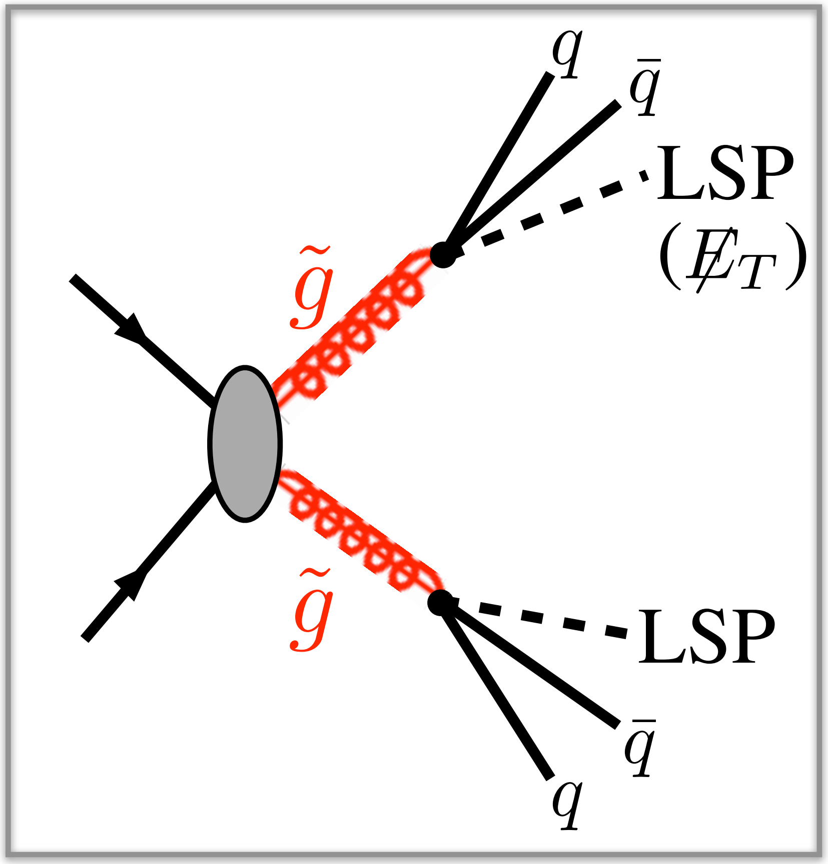
Valuable to have multiple tools

– test systematic effect of M.E. on analysis (being careful to allow for biases between the true mass and best-fit mass)

[See Meade and Reece, Phys.Rev.D74:015010 for one good example of why this is crucial]

– test for impact of initial-state radiation, etc.

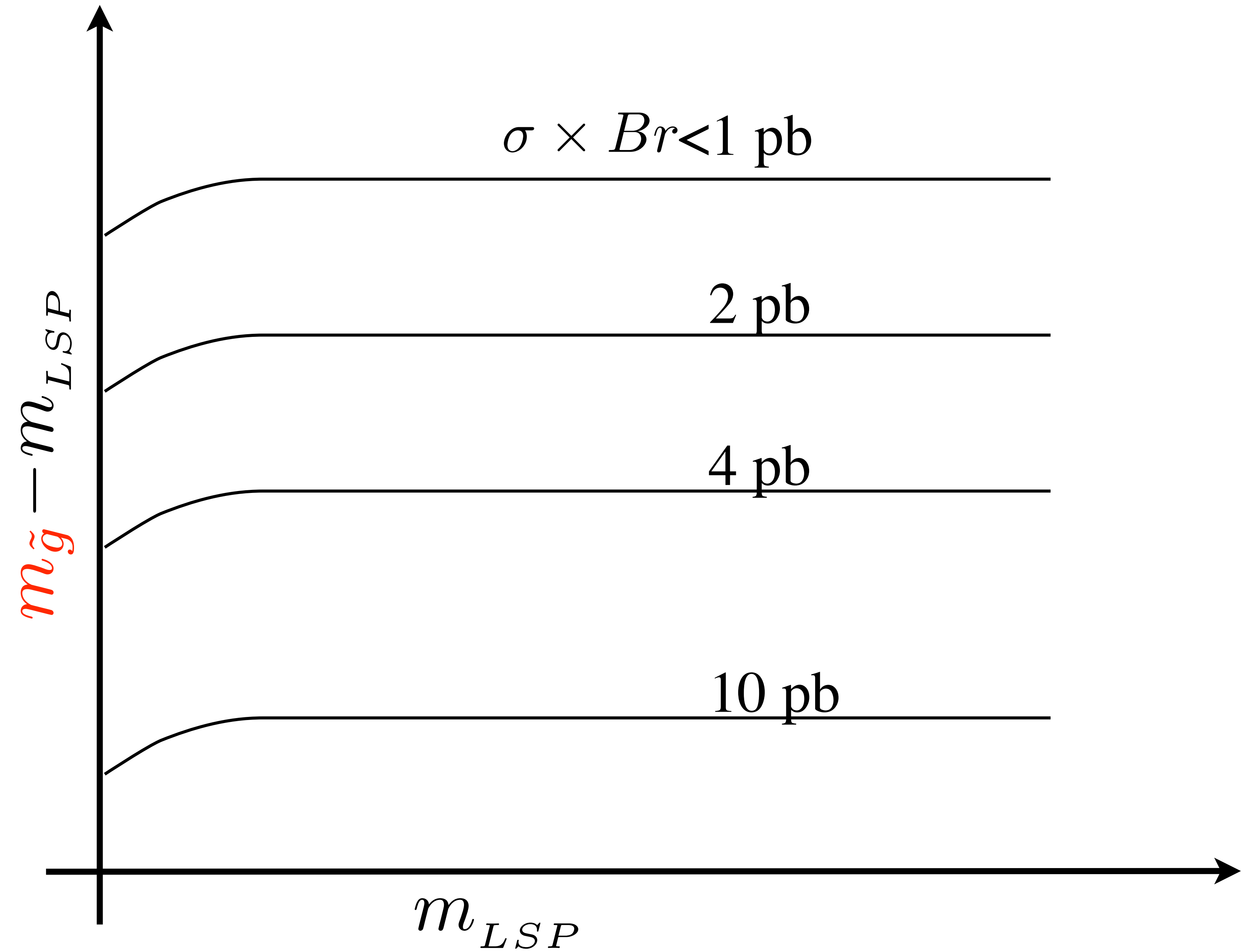
Tools and theory support for several Monte Carlo approaches exists: see www.lhcnewphysics.org



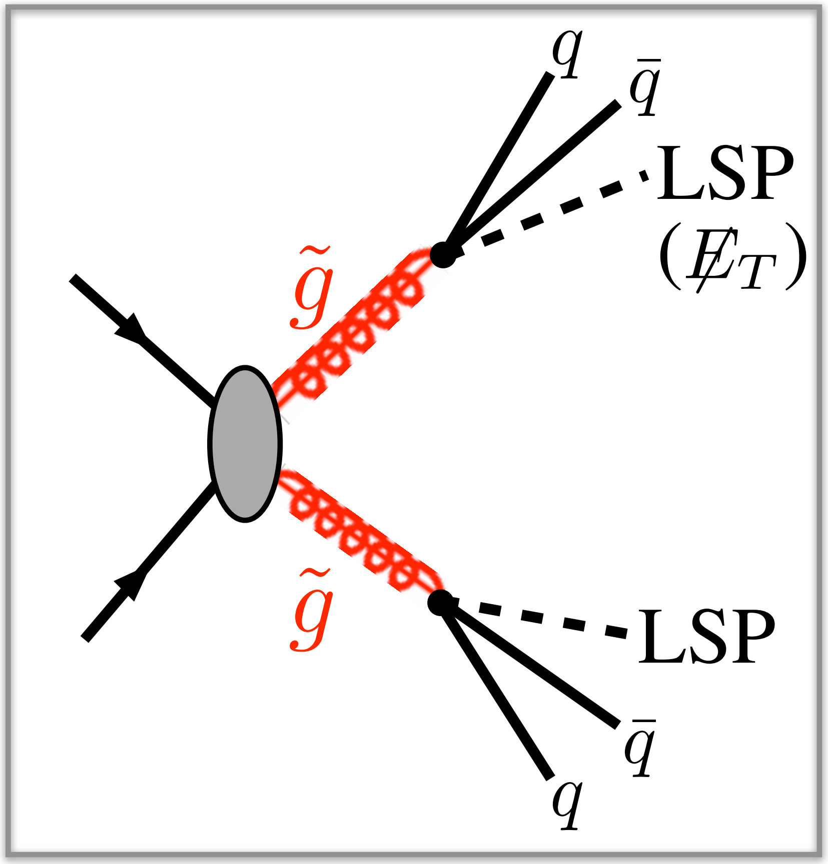
Parameters:

- 2 masses
  $m_{\tilde{g}}$
  m_{LSP}
- $\sigma \times Br$

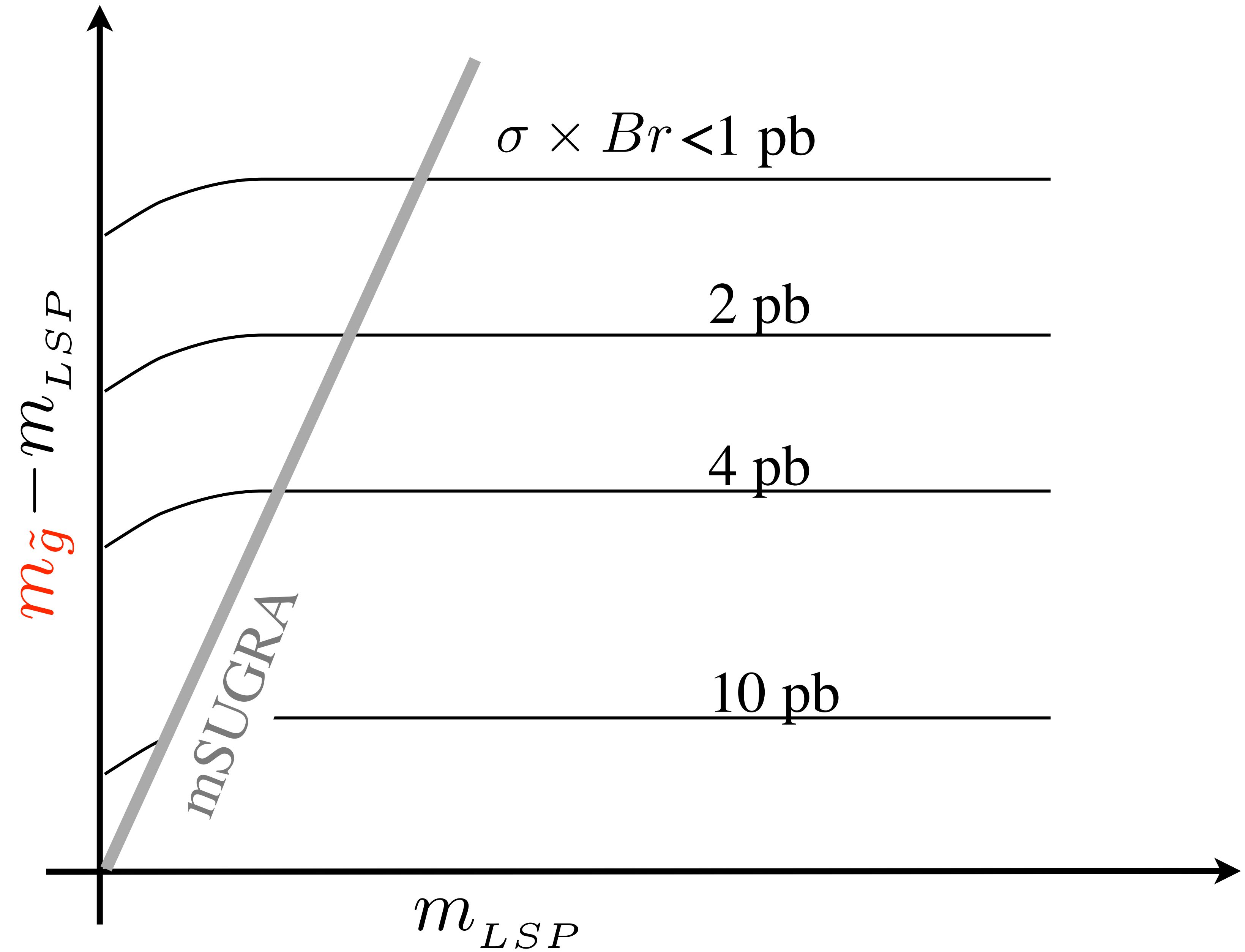
Limit on (Cross-section)x(Branching ratio) as function of mass parameters



Efficiency for multi-jet+MET search cuts decreases for small mass difference $\Rightarrow$ weaker cross-section limits
Approximately independent of m_{LSP}, except at low masses.



Limit on (Cross-section)x(Branching ratio) as function of mass parameters

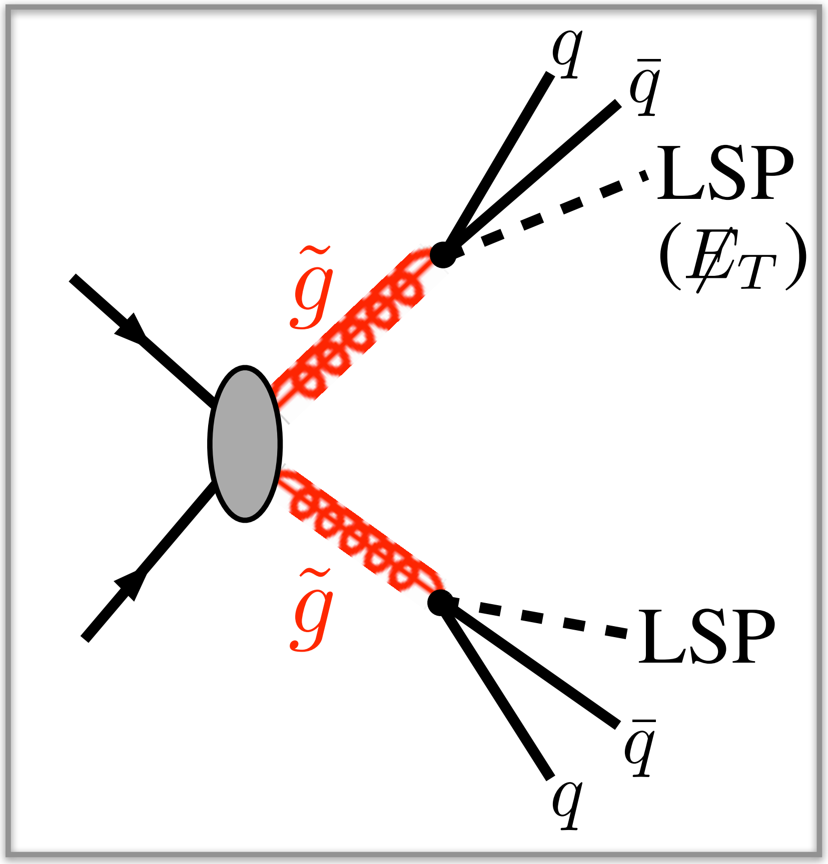


Parameters:

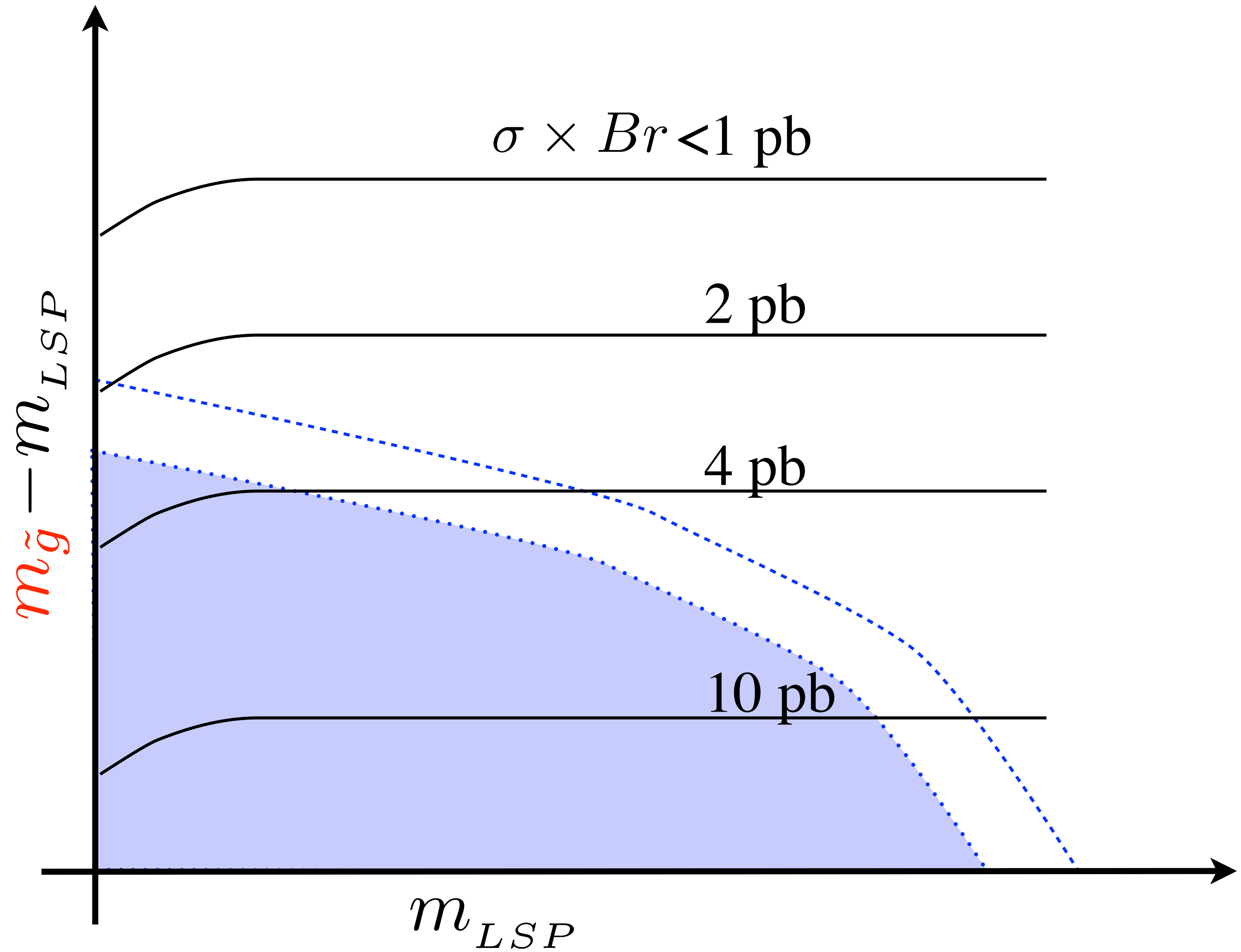
- 2 masses
  $m_{\tilde{g}}$
  m_{LSP}
- $\sigma \times Br$

In mSUGRA, ratio of gluino and LSP masses is approximately fixed (~7 to 1), so mSUGRA only explores a line on this plane.

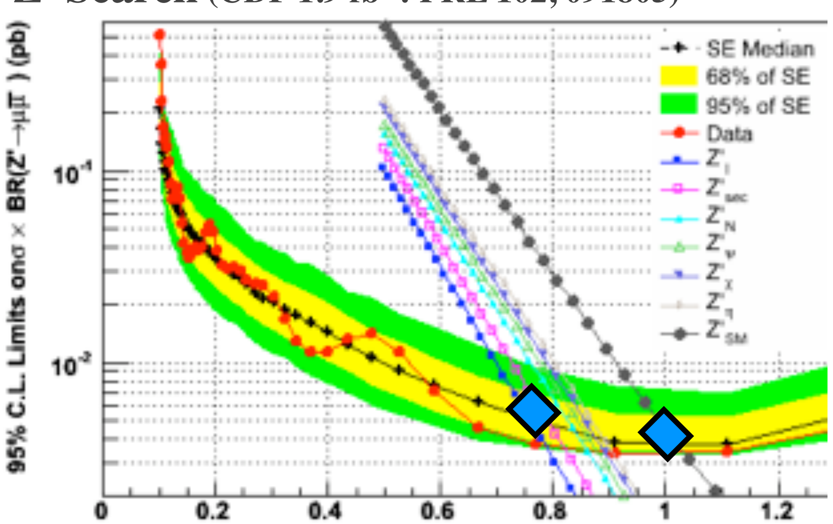
Needlessly narrow!



Limit on (Cross-section)x(Branching ratio) as function of mass parameters



Z′ Search (CDF 1.9 fb-1: PRL 102, 091805)

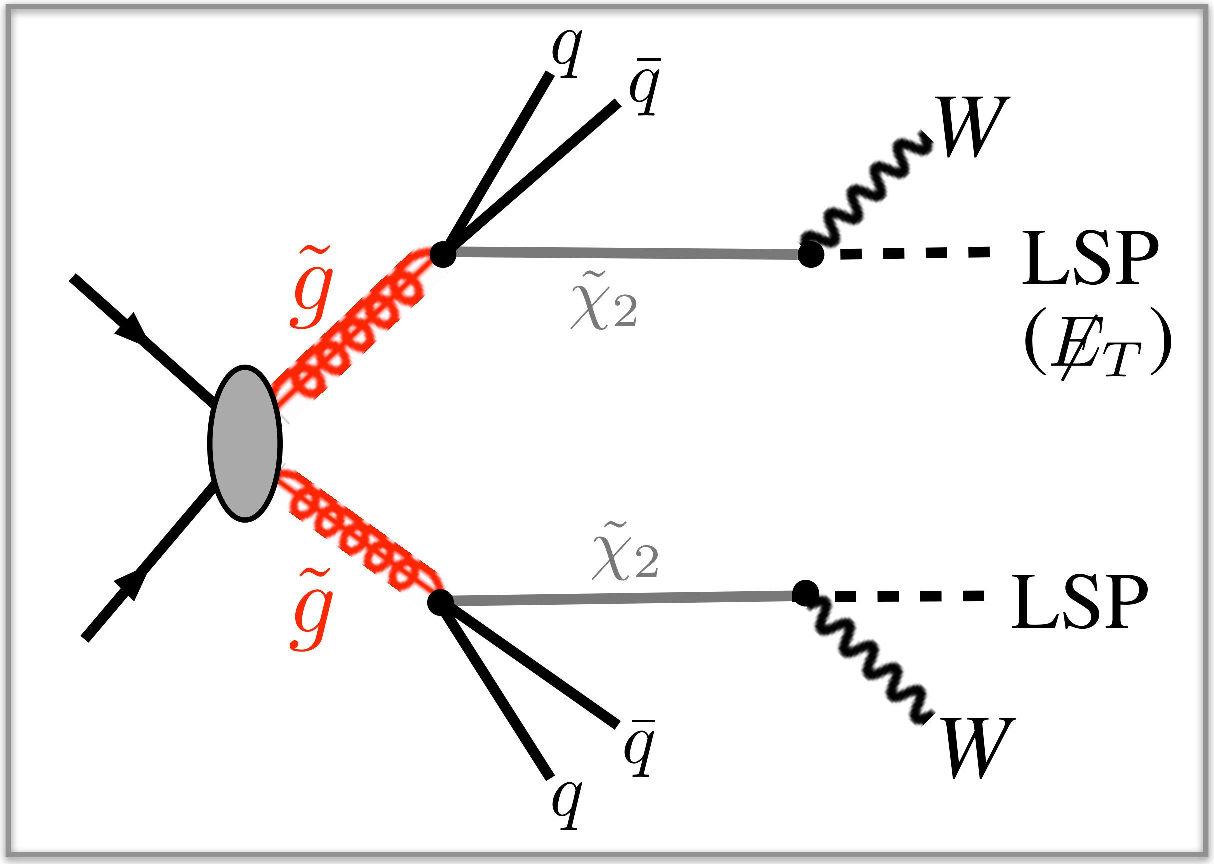


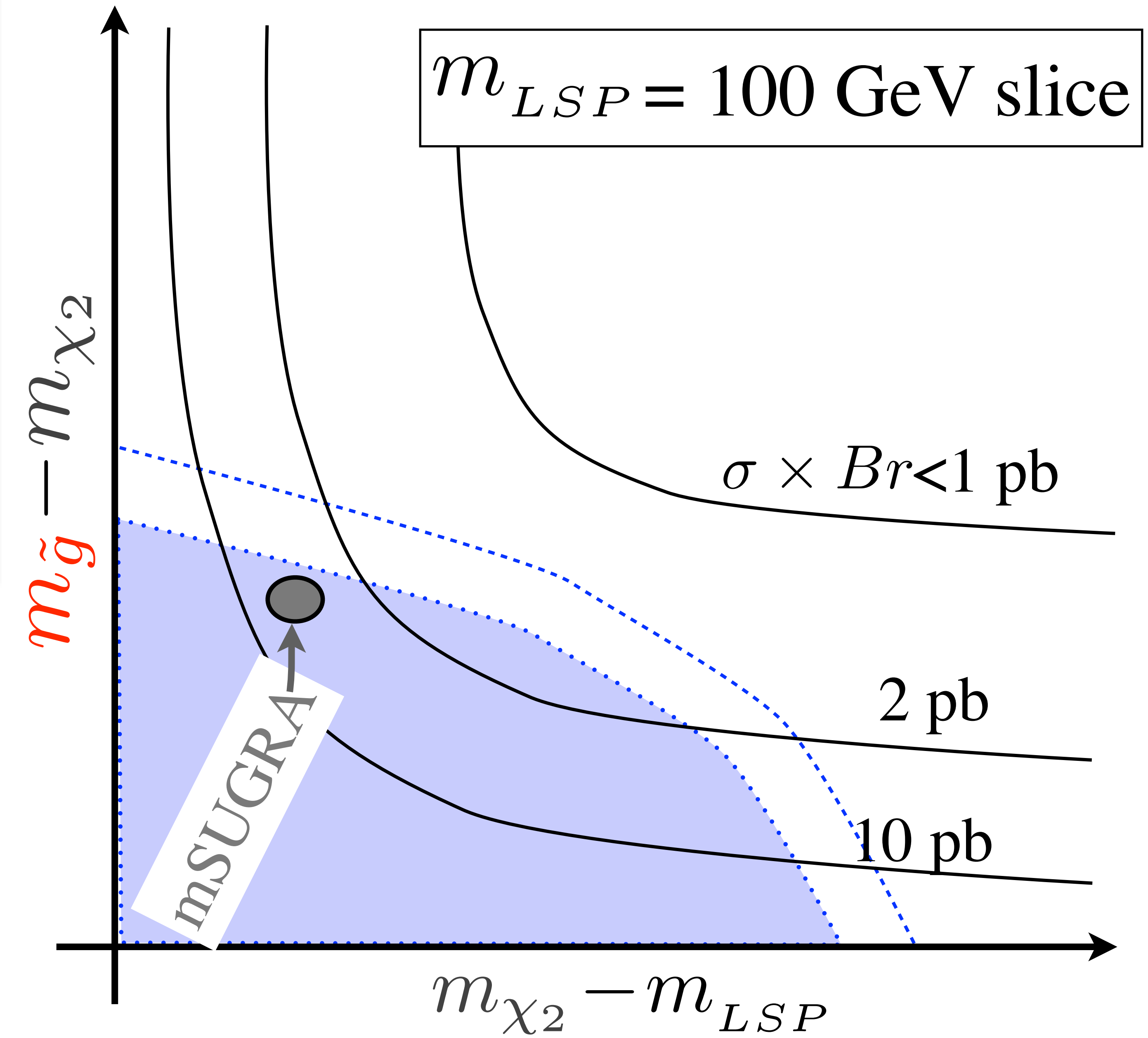
Different models (e.g. spins, squark mass) imply different mass–(σ x Br) relations.

Blue curves: exclusions on models, i.e. contours where **expected** cross-section equals maximum allowed cross-section (region below curves provides approximate exclusion).

A more complex example

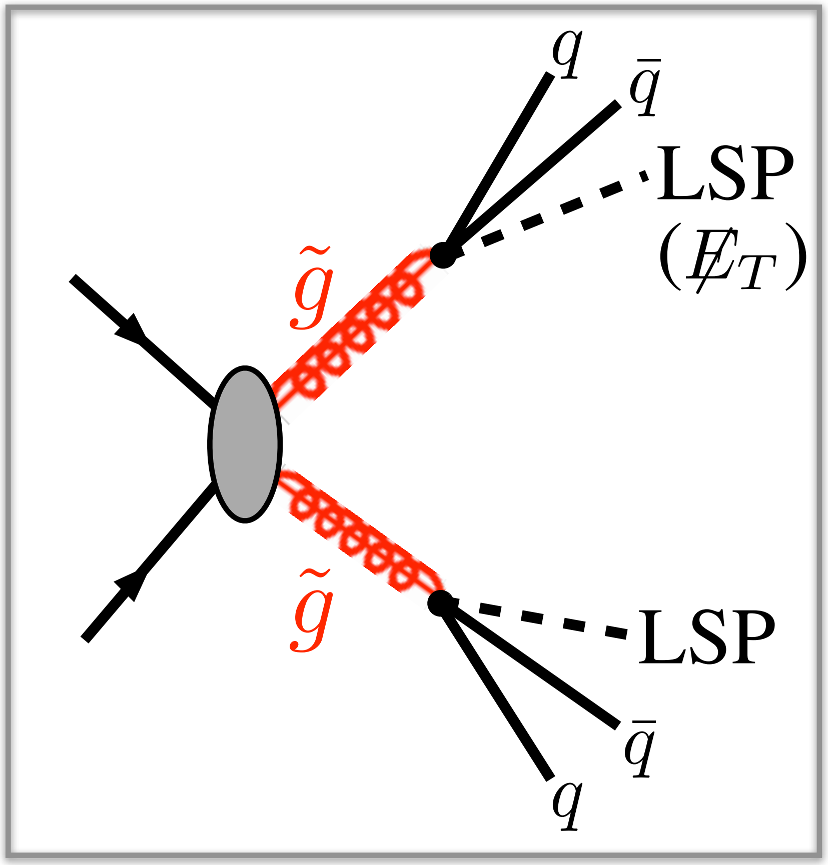
As before, efficiencies (and hence cross-section limits) depend most strongly on mass **differences –** plot one or more slices

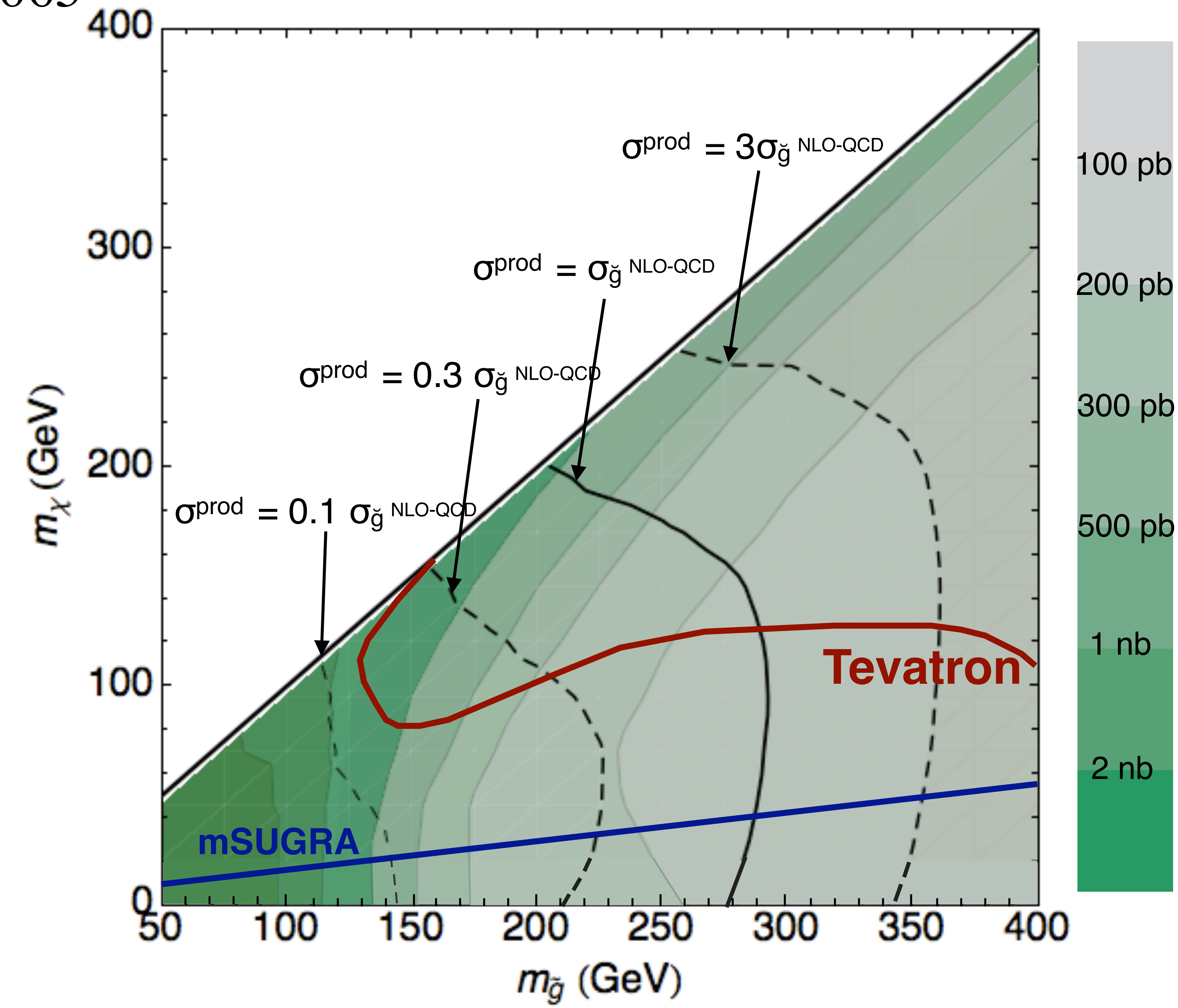




Estimated sensitivity for ATLAS

using ATLAS-CONF-2010-065





Parameters:

- 2 masses

  $m_{\tilde{g}}$

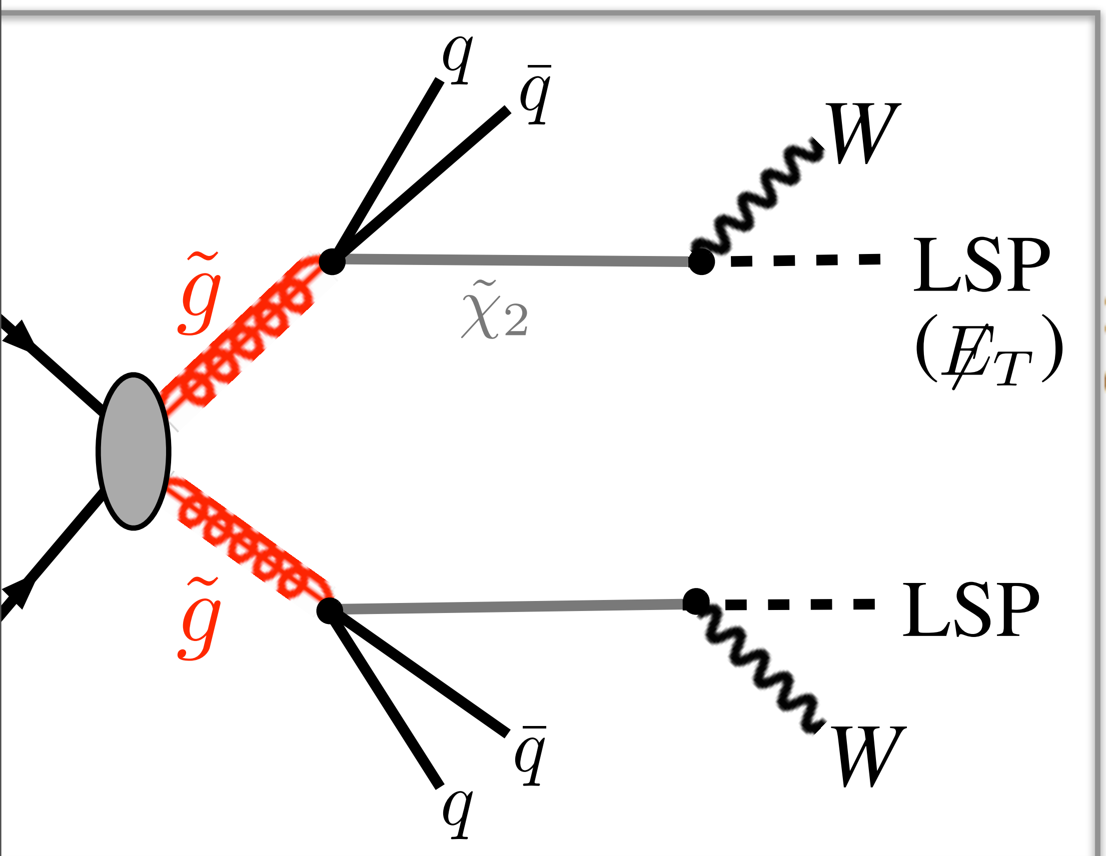
  m_{LSP}

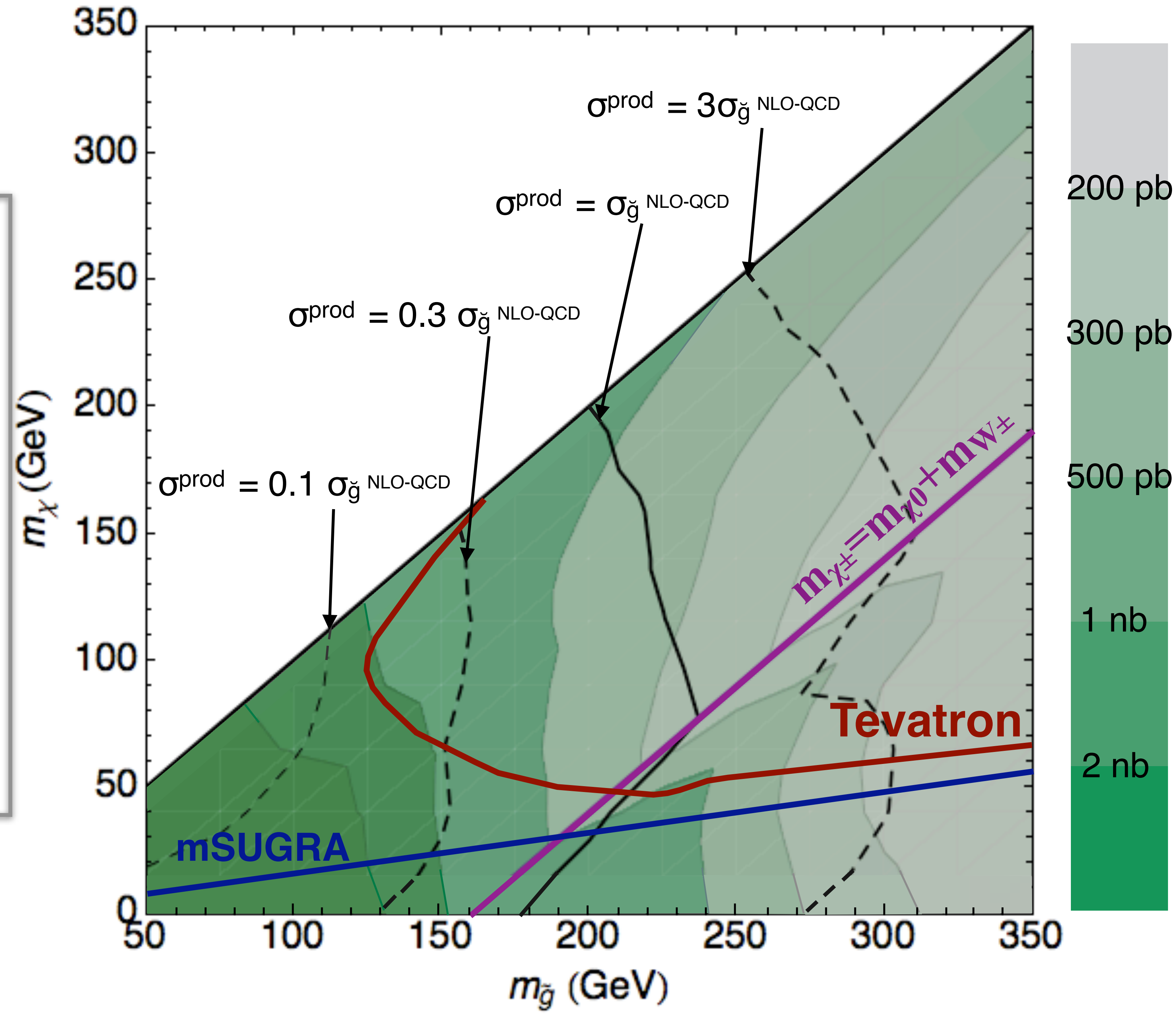
- $\sigma \times Br$

Alves, Izaguirre, Wacker

http://arxiv.org/abs/1008.0407

A 1-stage cascade:





Alves, Izaguirre, Wacker
http://arxiv.org/abs/1008.0407

Topology-Based Searches

Plentitude of models **and** of signals (topologies)

- Determine kinematics & efficiency
  ⇒ figure of merit for robustness
- Common building blocks repeated in many models
  ⇒ broad impact

Subtleties from Overlap:

*** Multiple topologies in a search**
(e.g. Jets+MET sensitive to both example topologies)

*** Multiple searches sensitive to each topology**
(e.g. W topo. in Jets+MET+0,1,2)

*** Multiple topologies in a model**
(can weight topo. limits to find model limit)

Reflect complication inherent in large model parameter spaces (but obscured in mSUGRA)

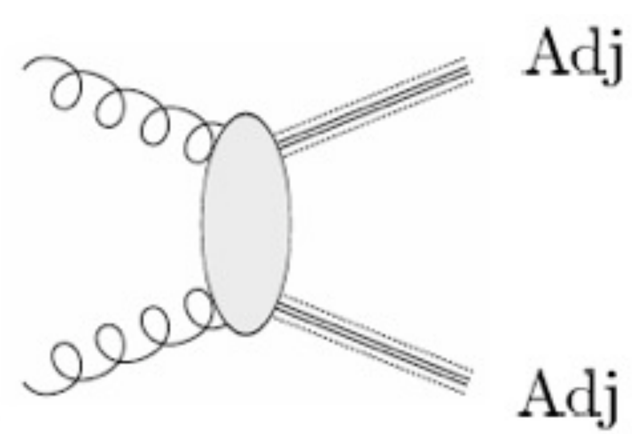
Weighting much simpler than replicating search!, accurate enough for most purposes

Topologies and Topology-Sets

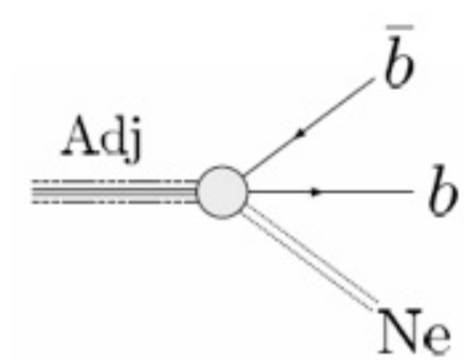
- Null results are naturally cast as limits on <u>individual</u> topologies (even if search is sensitive to several of them)

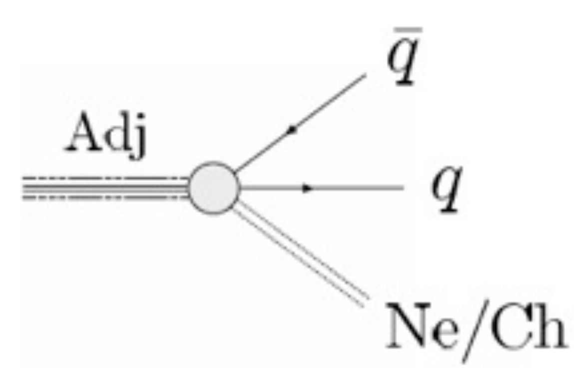
- To characterize a positive signal, must consider multiple decays of each particle ⇒ correlations (e.g. top: hadronic, leptonic, semi-leptonic)
  - The appropriate language is a "topology set": production modes and decay modes for each particle:

<u>Production</u>

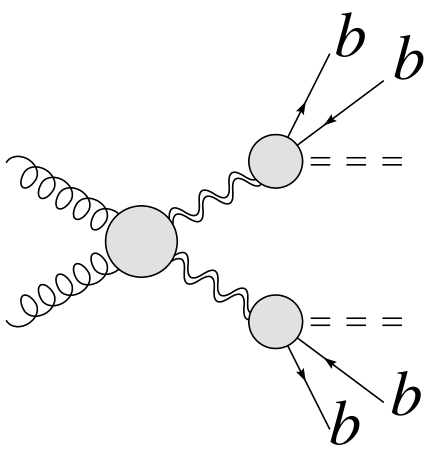


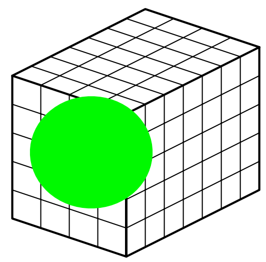
<u>Decays</u>



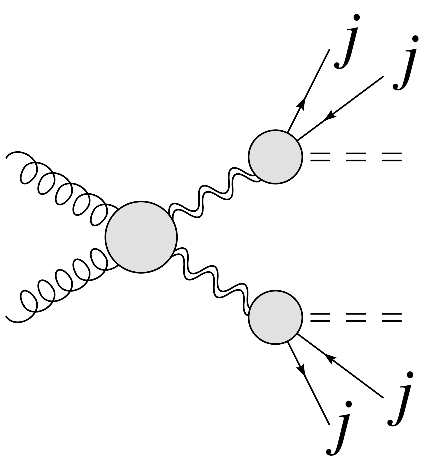


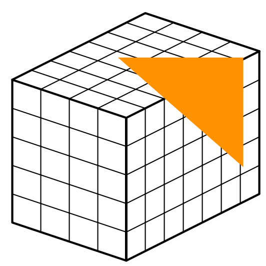
Organizing Process Sets



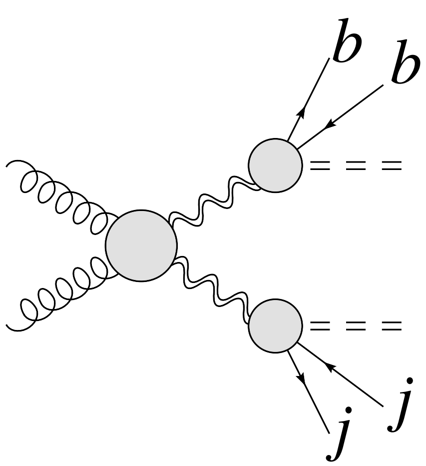
$=$  $\times\, \sigma_1 \times \mathrm{Br}_{1a} \times \mathrm{Br}_{1b}$

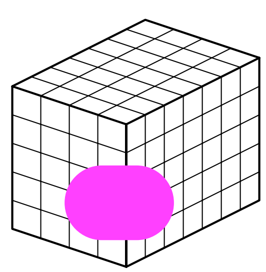
topo 1



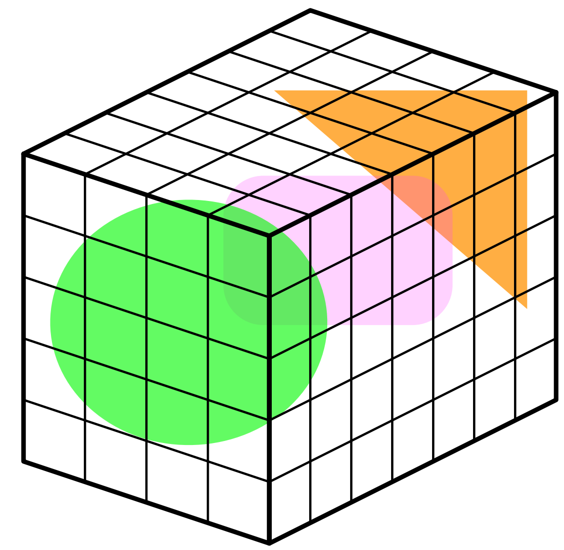
$=$  $\times\, \sigma_2 \times \mathrm{Br}_{2a} \times \mathrm{Br}_{2b}$

topo 2



$=$  $\times\, \sigma_3 \times \mathrm{Br}_{3a} \times \mathrm{Br}_{3b}$

topo 3



distributions

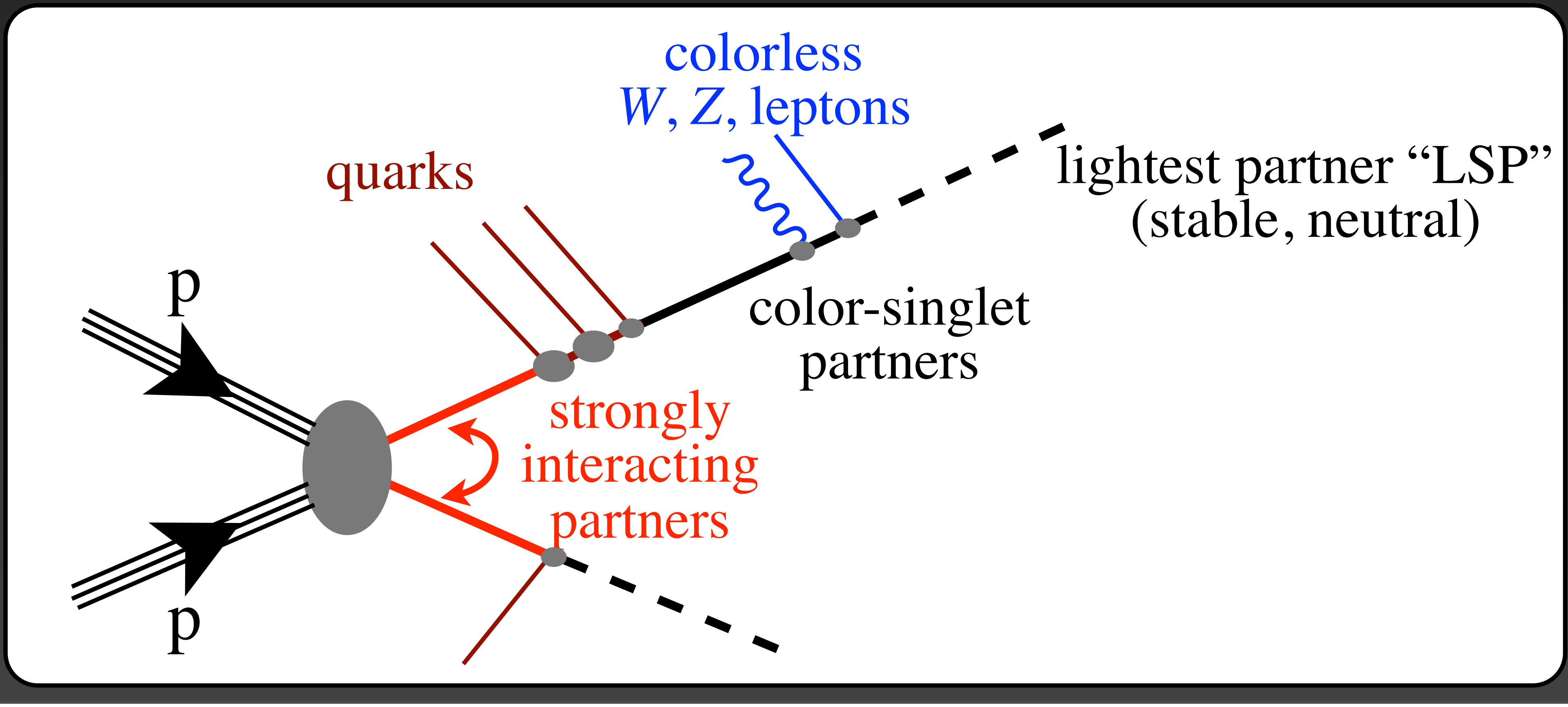
→ most invariant correlations predictive power!

Parameters are masses, cross-sections, and branching ratios

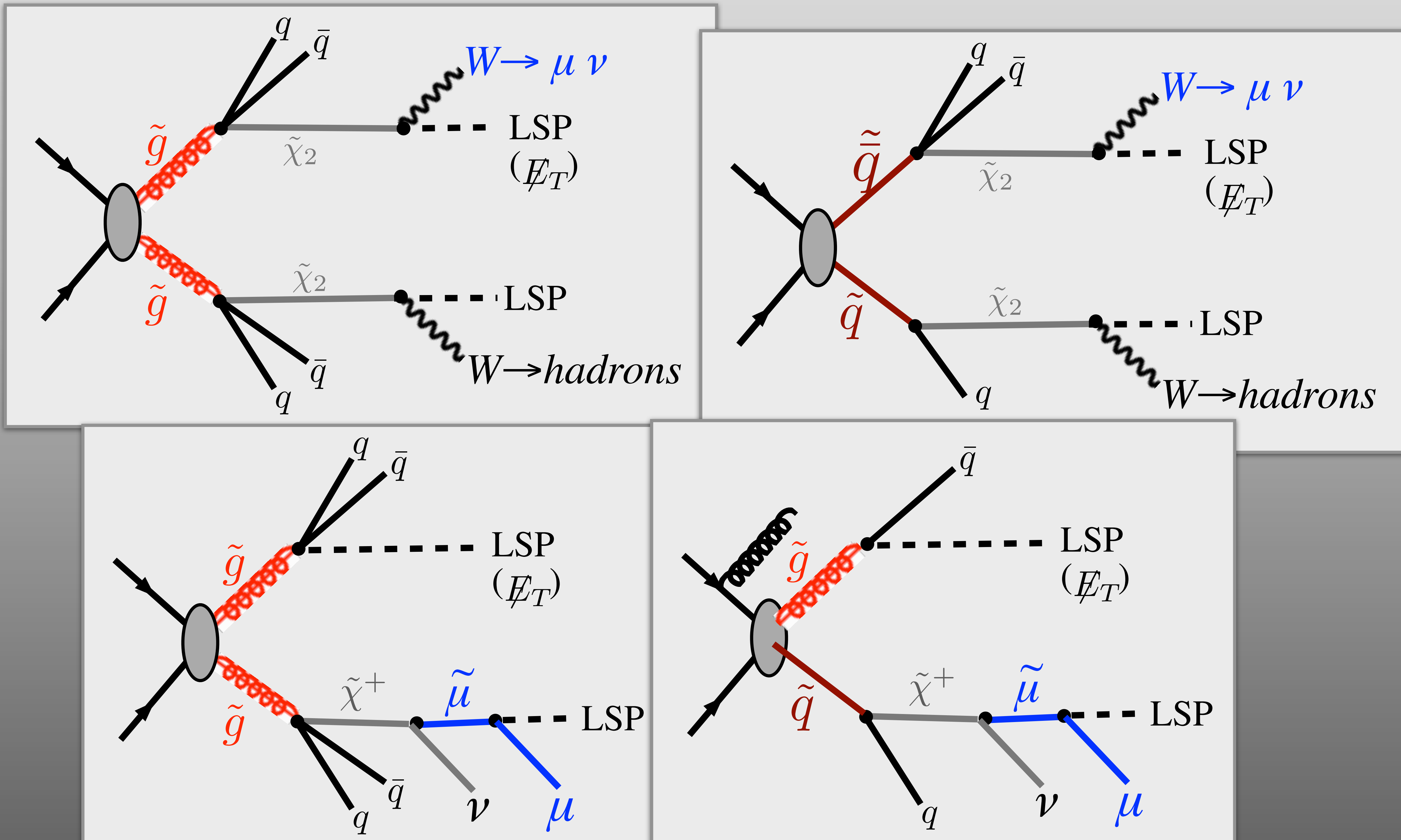
→ can be varied by reweighting events

Condensing Topologies for SUSY-Like New Physics

- **Partners** with same quantum numbers & couplings as SM particles
  - Large $\alpha_3 \Rightarrow$ Strongly interacting quark and gluon partners dominate production
- New **Parity** (exact or approximate) under which new particles are odd $\Rightarrow$ produced in pairs, conserved partner number.



This basic rule allows huge multiplicity of topologies (e.g. huge multiplicity even restricting to ≥4 jets + 1μ + MET)

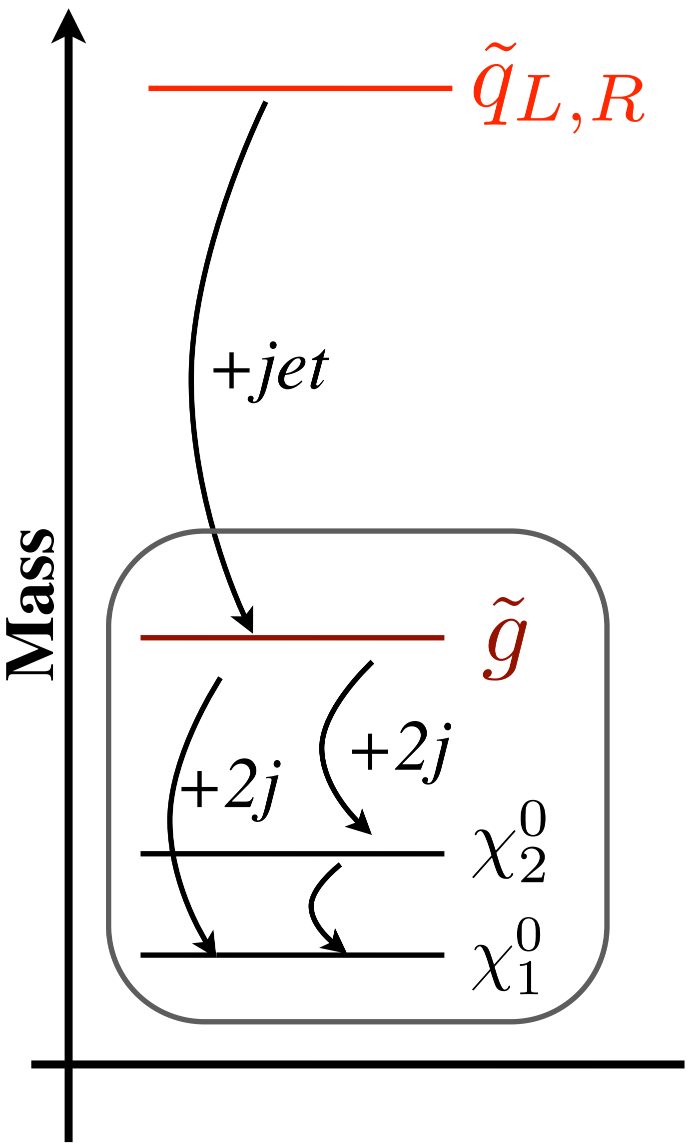


⇒ Further organization, reduction required!

* Hard(er)-to-distinguish topologies
* Target specific spectrum questions

} → Simplified Models (Alwall, Schuster, NT)

Simple Limits of Strong Production

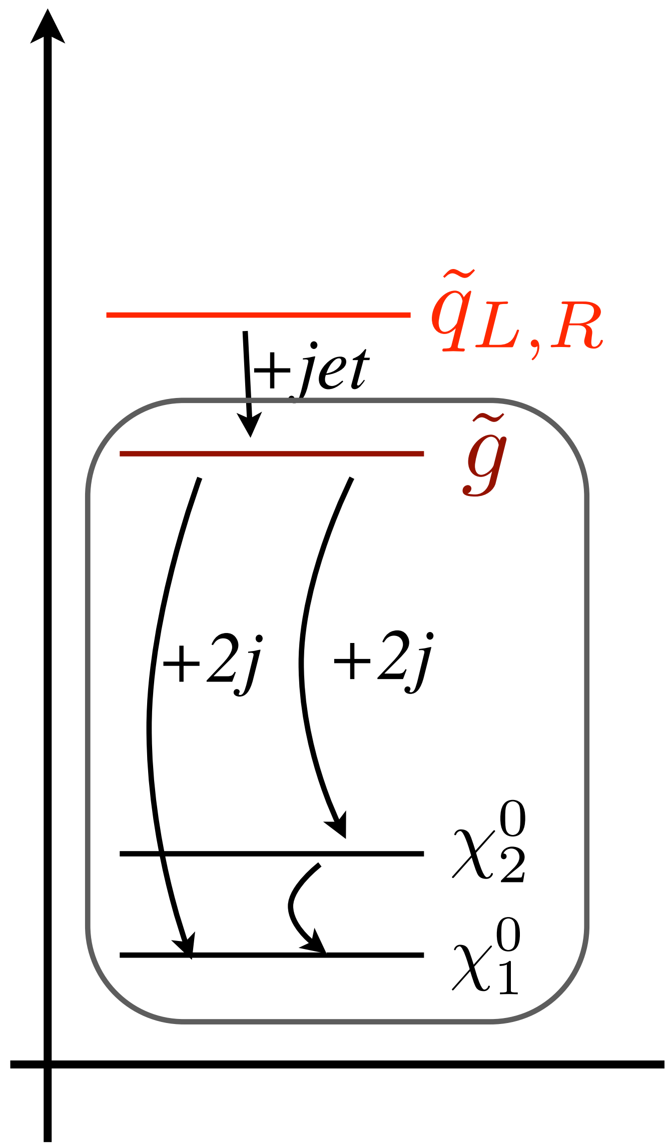


$m_{\tilde{q}} - m_{\tilde{g}} \gg m_{\tilde{g}}$

$\Downarrow$

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

can ignore squarks



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

$\Downarrow$

jet from squark decay **very soft**

can ignore squarks

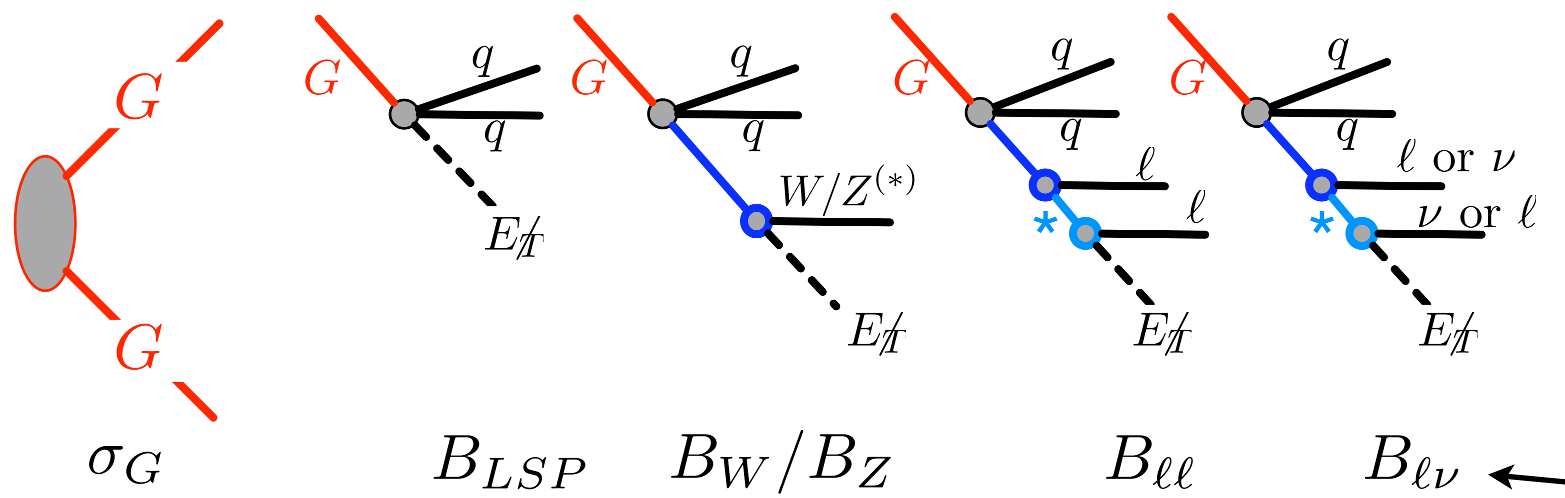
Extreme spectra well described by fewer particles –> *squark role is subdominant* in these cases

[PRD 79:075020 (0810.3921): Alwall, PS, Natalia Toro]

Simplified Models

- Aimed at **characterizing** a new physics signal as simply as possible

For lepton studies



*on or off-shell

Masses

M_G

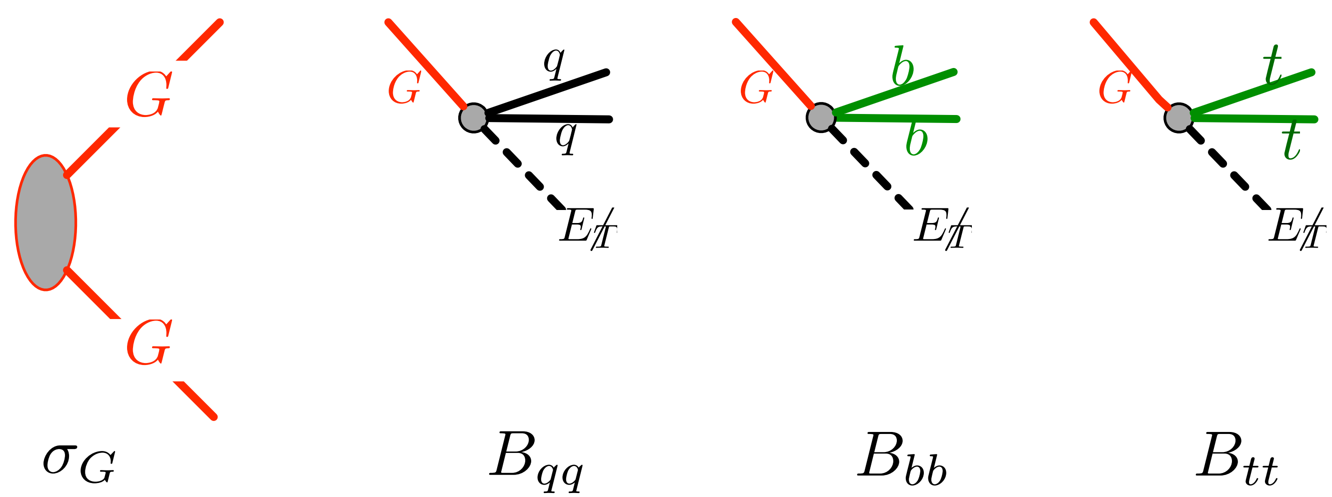
M_I

(M_L)

M_{LSP}

physical parameters **directly** connected to *observables* (*rates, kinematics, efficiencies*).

For b-tag studies



Masses

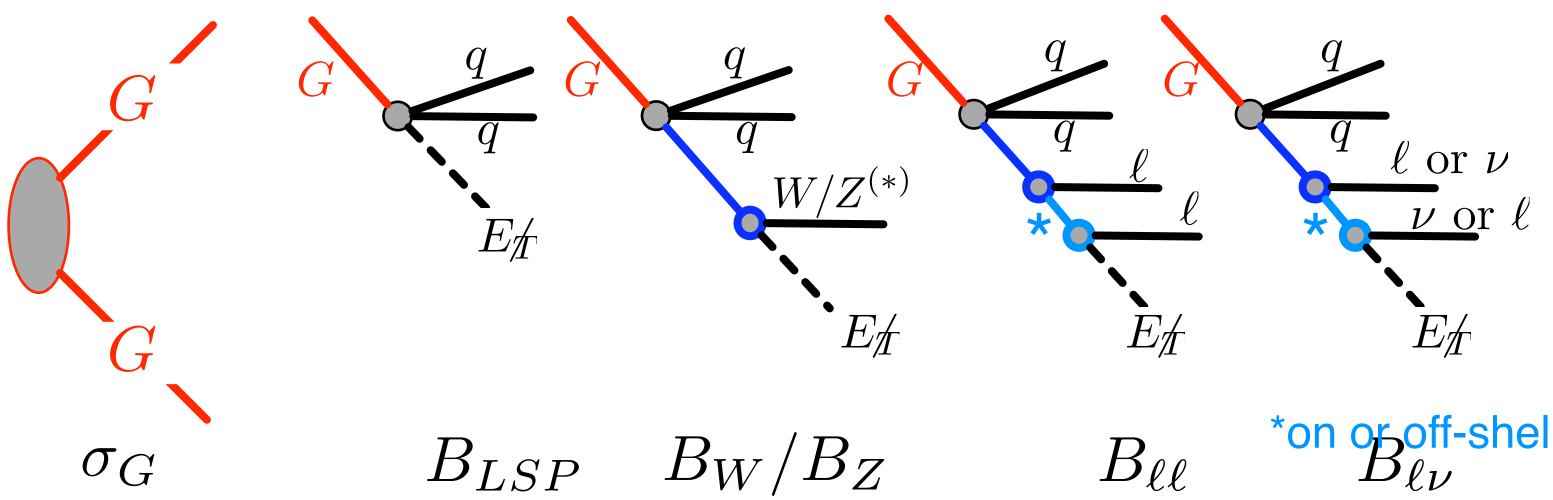
M_G

M_{LSP}

(similarly, two models for quark-partner production)

Topologies from simplified models are good search templates:

e.g. from gluon partner:



Masses

M_G

M_I

(M_L)

M_{LSP}

...*etc*.

Contained topologies hit many searches:

jets+MET+0, 1, 2, ≥3 leptons; bjets

...and many signatures:

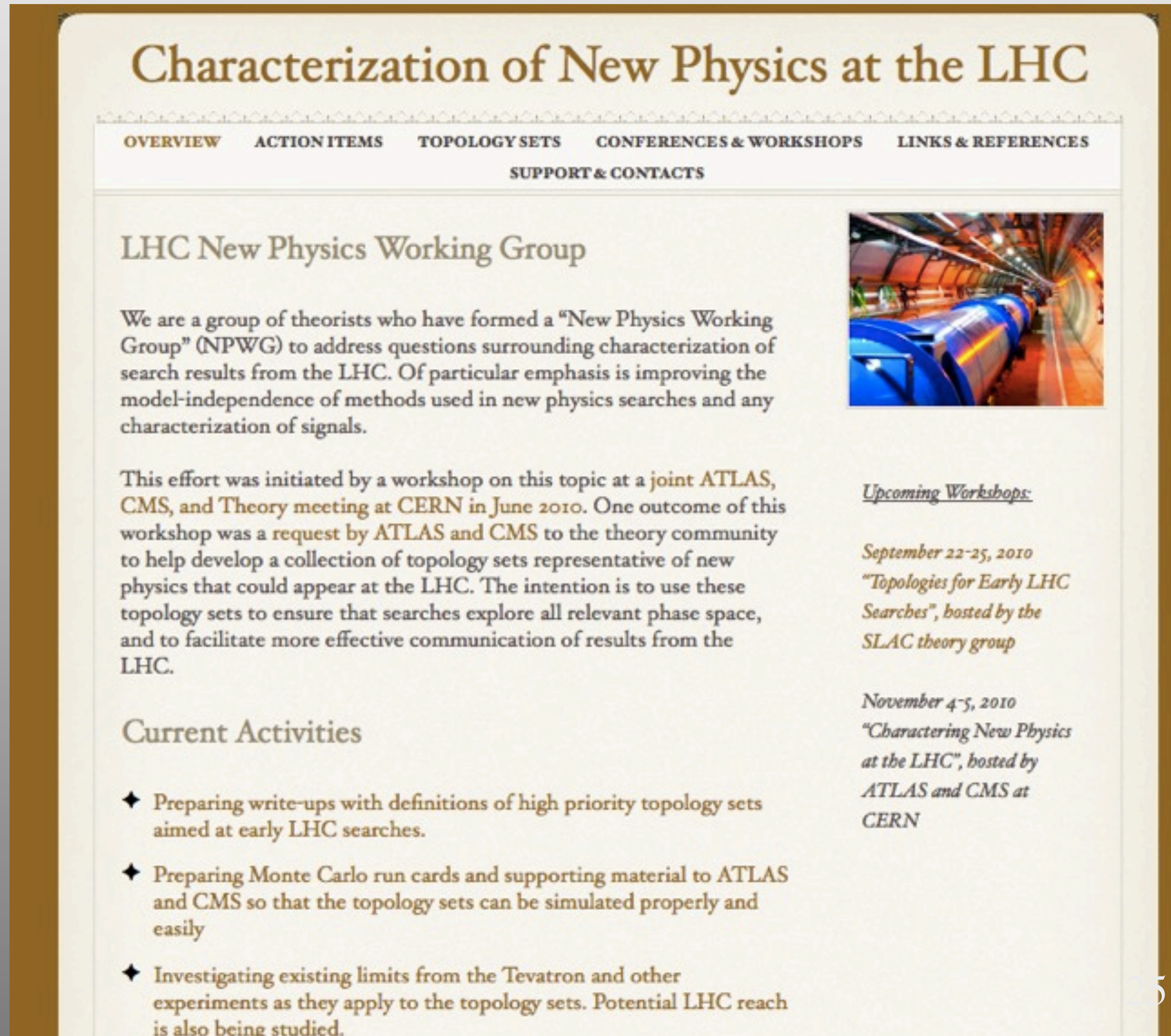
edges, endpoints, lepton sign & flavor correlations, btag–lepton correlations (top)...

Proposals and Tools for Model-Independent Studies

Theory support @:
www.lhcnewphysics.org

Various topology sets provided and supported
(notes and MC implementation)

Workshops at:
SLAC in September
CERN in November

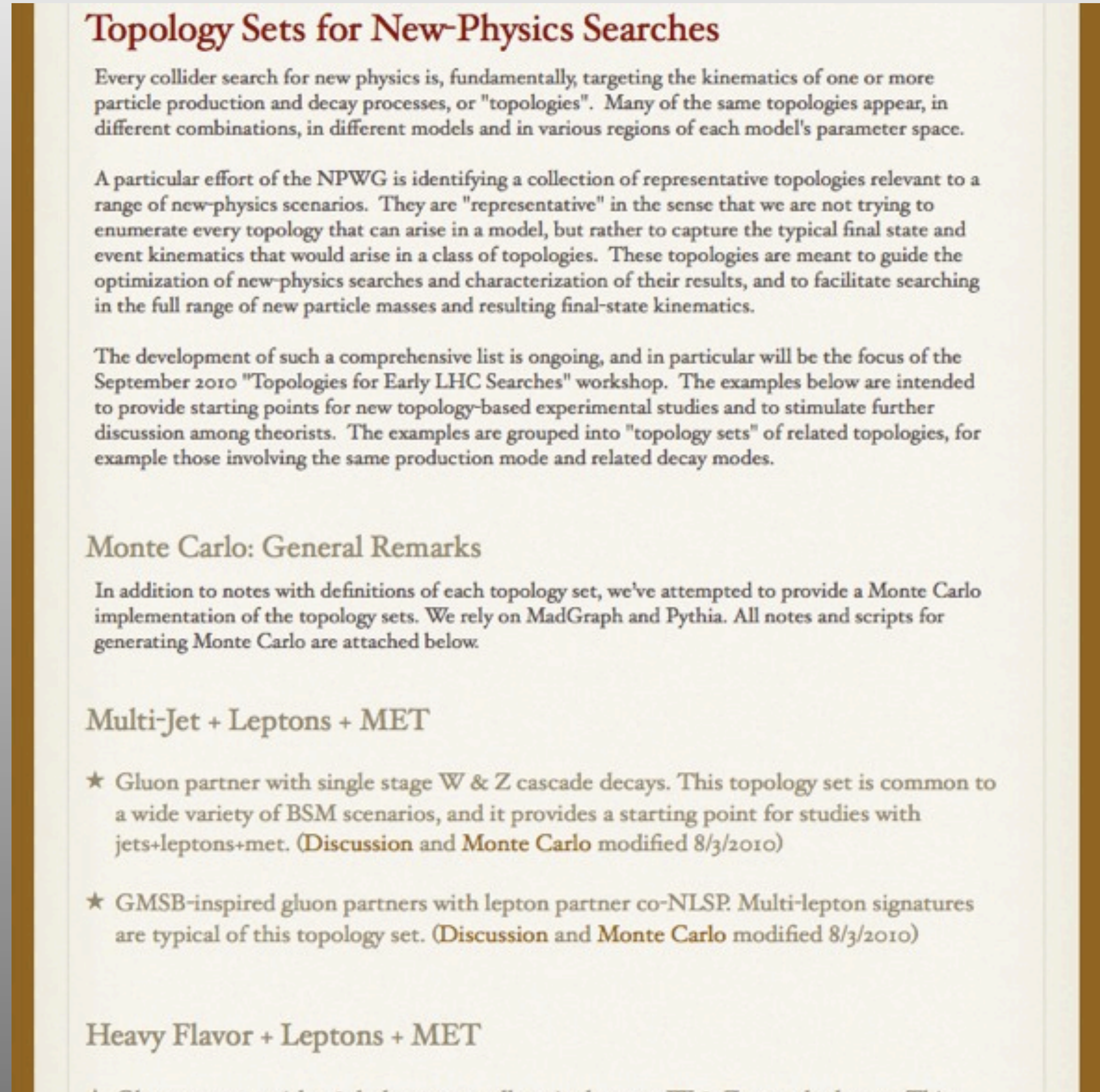


Proposals and Tools for Model-Independent Studies

Theory support @:
www.lhcnewphysics.org

Various topology sets provided and supported
(notes and MC implementation)

Workshops at:
SLAC in September
CERN in November



Topology Sets for New-Physics Searches

Every collider search for new physics is, fundamentally, targeting the kinematics of one or more particle production and decay processes, or "topologies". Many of the same topologies appear, in different combinations, in different models and in various regions of each model's parameter space.

A particular effort of the NPWG is identifying a collection of representative topologies relevant to a range of new-physics scenarios. They are "representative" in the sense that we are not trying to enumerate every topology that can arise in a model, but rather to capture the typical final state and event kinematics that would arise in a class of topologies. These topologies are meant to guide the optimization of new-physics searches and characterization of their results, and to facilitate searching in the full range of new particle masses and resulting final-state kinematics.

The development of such a comprehensive list is ongoing, and in particular will be the focus of the September 2010 "Topologies for Early LHC Searches" workshop. The examples below are intended to provide starting points for new topology-based experimental studies and to stimulate further discussion among theorists. The examples are grouped into "topology sets" of related topologies, for example those involving the same production mode and related decay modes.

Monte Carlo: General Remarks

In addition to notes with definitions of each topology set, we've attempted to provide a Monte Carlo implementation of the topology sets. We rely on MadGraph and Pythia. All notes and scripts for generating Monte Carlo are attached below.

Multi-Jet + Leptons + MET

- ★ Gluon partner with single stage W & Z cascade decays. This topology set is common to a wide variety of BSM scenarios, and it provides a starting point for studies with jets+leptons+met. (Discussion and Monte Carlo modified 8/3/2010)
- ★ GMSB-inspired gluon partners with lepton partner co-NLSP. Multi-lepton signatures are typical of this topology set. (Discussion and Monte Carlo modified 8/3/2010)

Heavy Flavor + Leptons + MET

- ★ Gluon partner with t & b decays as well as single stage W & Z cascade decays. This

Proposals and Tools for Model-Independent Studies

Theory support @:
www.lhcnewphysics.org

Various topology sets provided and supported
(notes and MC implementation)

Workshops at:
SLAC in September
CERN in November

Summary

- Model independence is useful for ensuring search robustness and for characterizing data in a simple and physical manner.
- Role of “spectroscopic”/ topological description:
  - Ensure search robustness by studying production/ decay topologies (and present results this way)
  - Characterize new physics in same language as key step to further understanding it
- Many possibilities → Coarse-grain topologies
- A matrix element ansatz is necessary (many options, only mild sensitivity)
- Many proofs of concept exist! Ready to apply to data.