First Characterization of New Physics at the LHC

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arXiv:0810.3921 with J. Alwall, P. Schuster

Outline

Assumption: A **robust** jets+MET excess has been seen at the LHC

Why a model-independent characterization of new physics is valuable.

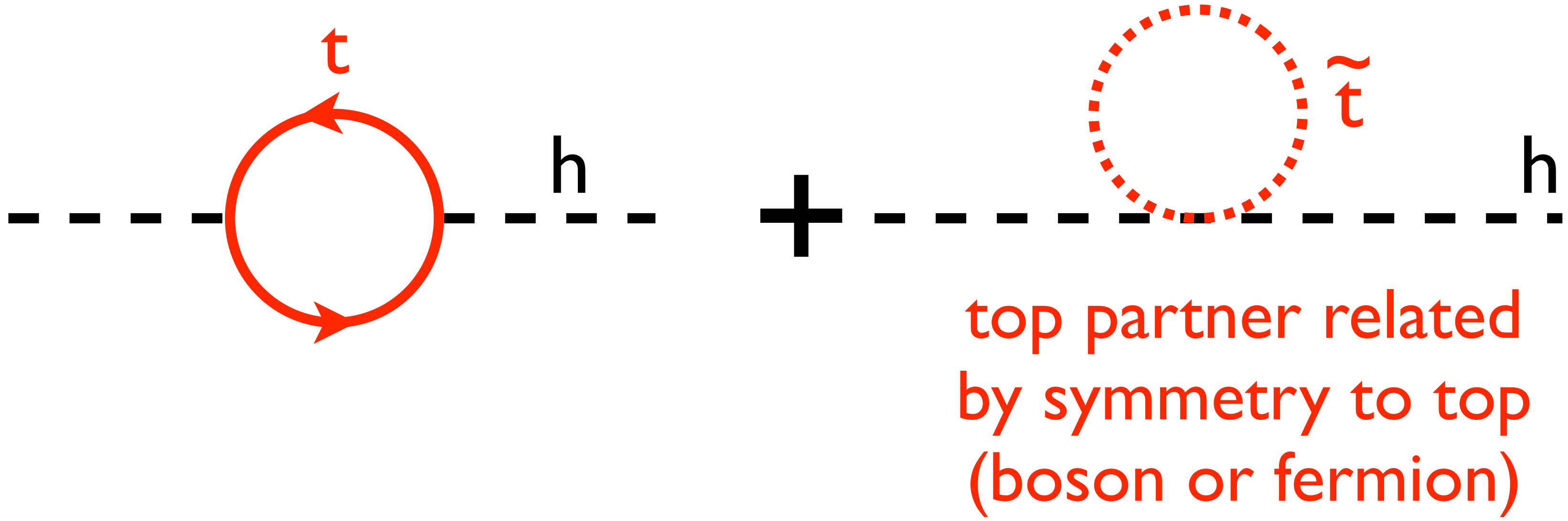
The first three questions to ask about the new physics

Four "simplified models" to frame and answer these questions

How the simplified models are constrained, and how to use them

Why new physics?

- **Hierarchy problem**: What cancels top contribution to Higgs mass?

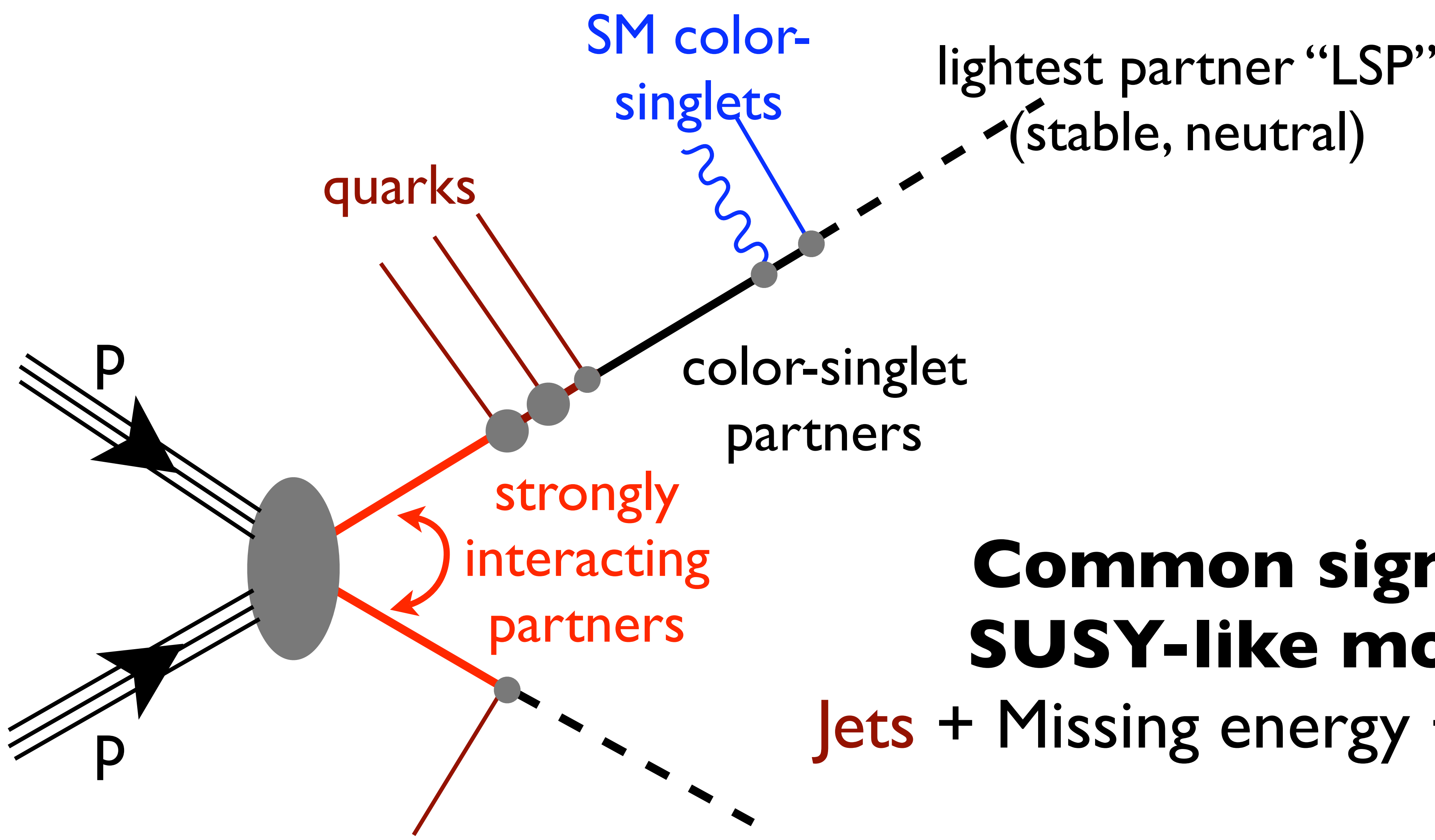


- Symmetry ⇒ "partners" with same 3-2-1 quantum numbers as Standard Model particles.
- Minimal: top, SU(2)xU(1) gauge boson partners – top partner is colored, will be produced (if light enough)
- SUSY, Randall-Sundrum, or Universal Extra Dimensions: Spacetime symmetry → partners for **all** SM particles

Why new physics?

- **Hierarchy Problem** → partners
- **TeV-scale Dark matter?** → parity
  - If partner states are odd under a new parity, lightest parity-odd particle is stable and a DM candidate (also helps guarantee proton stability)
  - Two consequences for LHC searches
    - *new particles produced in pairs*
    - *some collision energy in lost to invisible particles (2 of them)*
- We'll call models with partners *and* parity "SUSY-like": e.g. weak-scale supersymmetry, universal extra dimensions, and "theory space" models (e.g. Little Higgs) w/ T-parity

Well-Motivated Signature



Common signal of SUSY-like models:

Jets + Missing energy + (leptons?)

If jets+MET+leptons excess(es) are seen, it's reasonable to assume SUSY-like physics interpretation!

Jets+MET excess is evidence for SUSY-like new physics

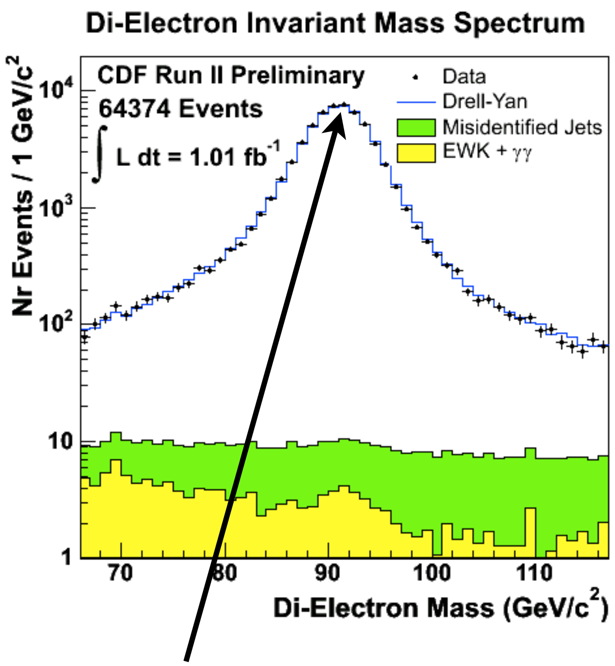
.....how do we learn more about it?

Focus on questions that (within SUSY-like framework) are **almost guaranteed** to be relevant and **accessible in the first few years of the LHC** (really 1-10x discovery luminosities).

Preliminary Interpretation

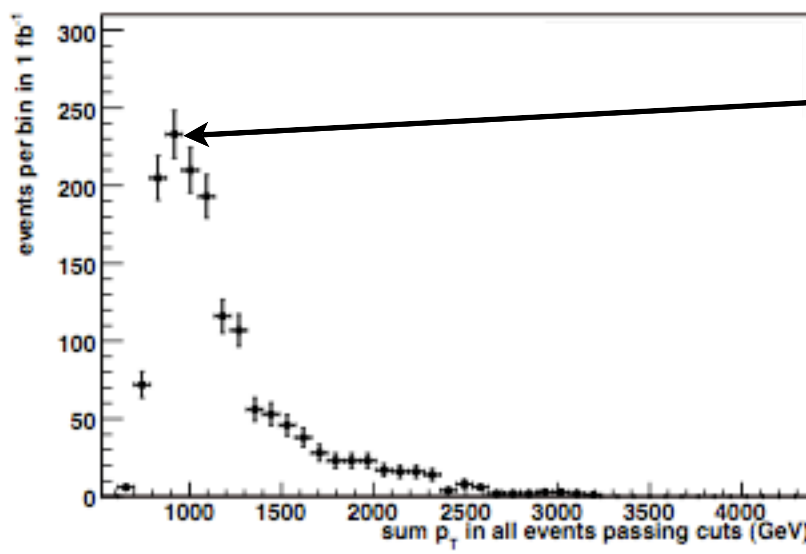
When we do get distributions, there will be a lot we can do

Easy Cases:

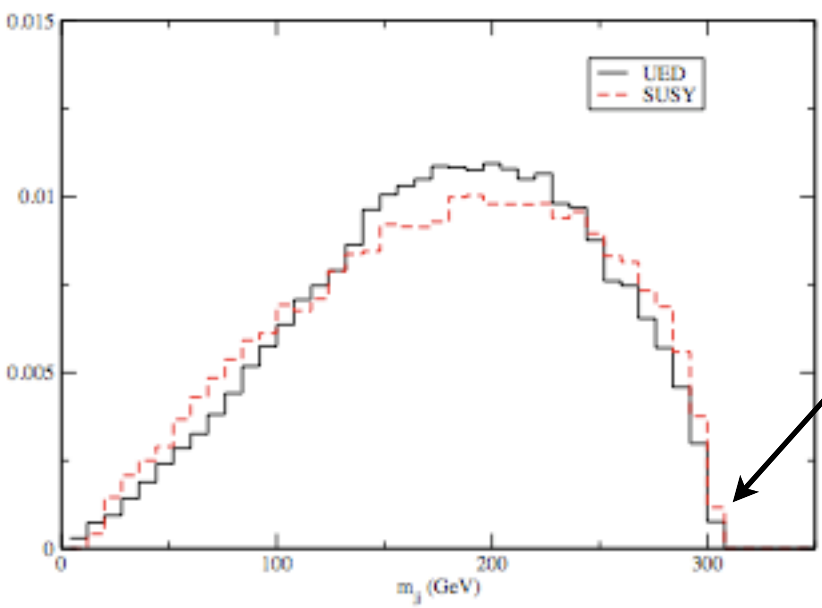


Self-calibrating signal, like a mass peak

HT observable

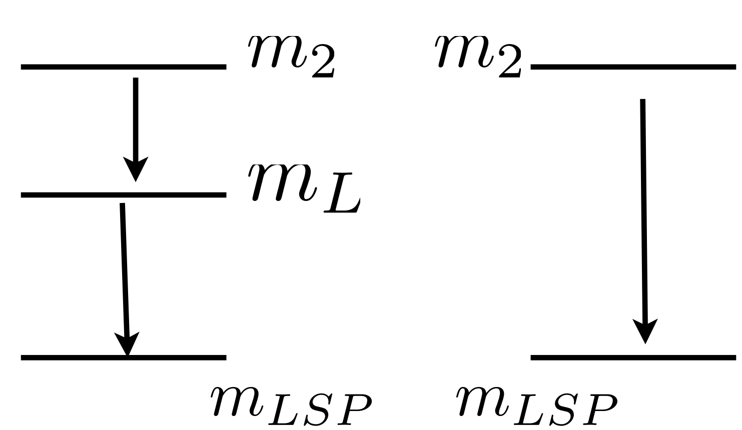


peak~1.7*Mass difference (depending on decay chain) is roughly encoded



$$m_{edge} = \frac{\sqrt{(m_2^2 - m_L^2)(m_L^2 - m_{LSP}^2)}}{m_L}, \quad \text{or } m_{end} = m_2 - m_{LSP}.$$

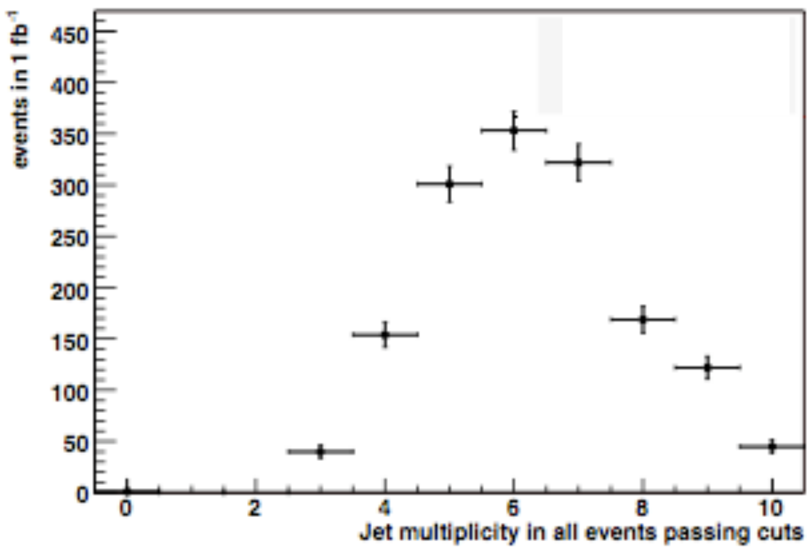
di-object mass can have distinctive phase space cutoff, giving a constraint on decay chain mass difference



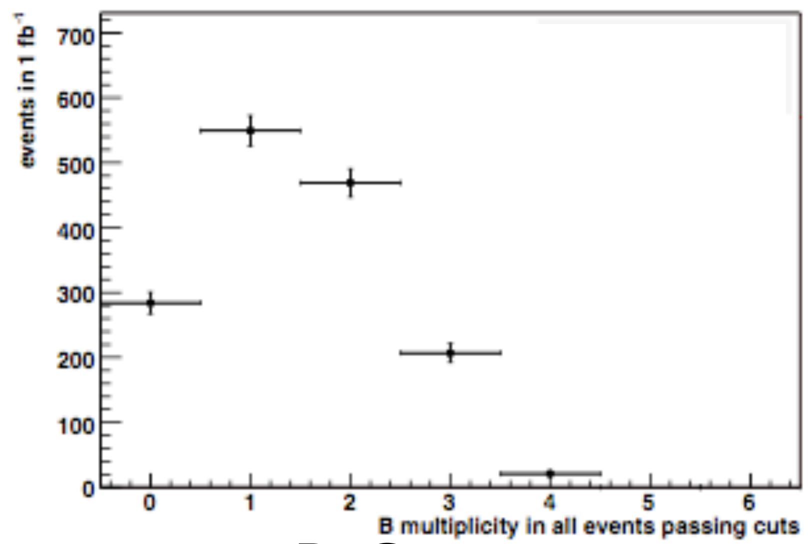
(this slide + several others "borrowed" from P. Schuster and J. Alwall)

Preliminary Interpretation

What about less kinematically sharp distributions?

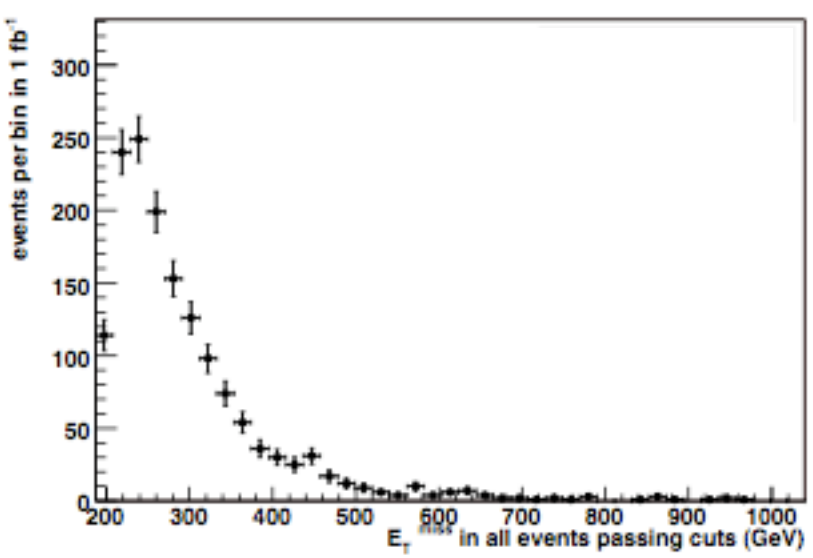


Jet Count

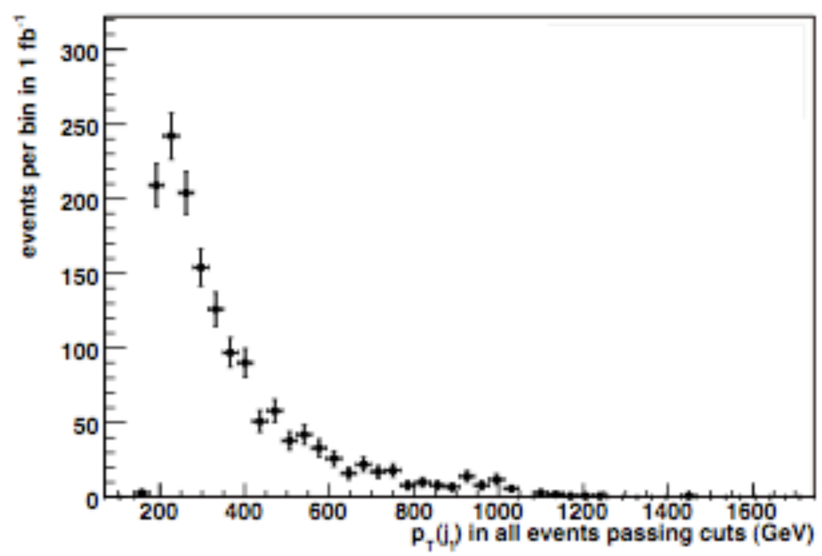


B Count

even in principle, distributions not narrow



Jet ET

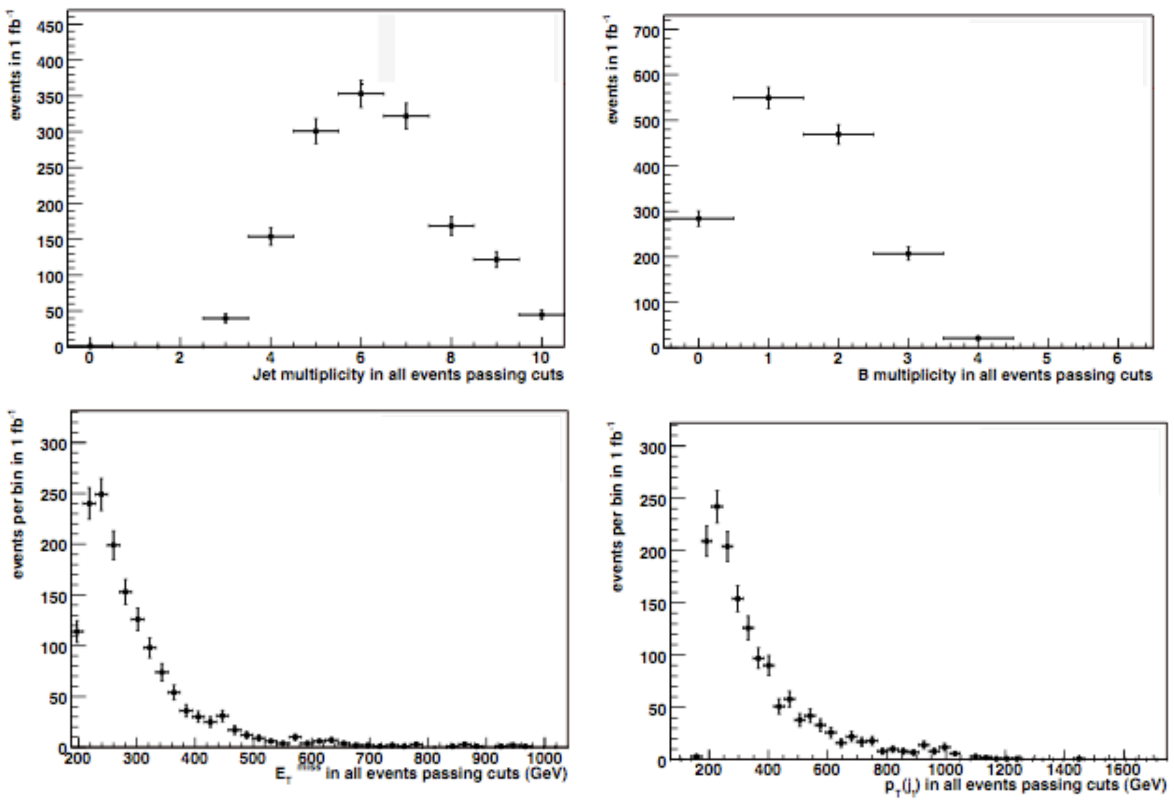


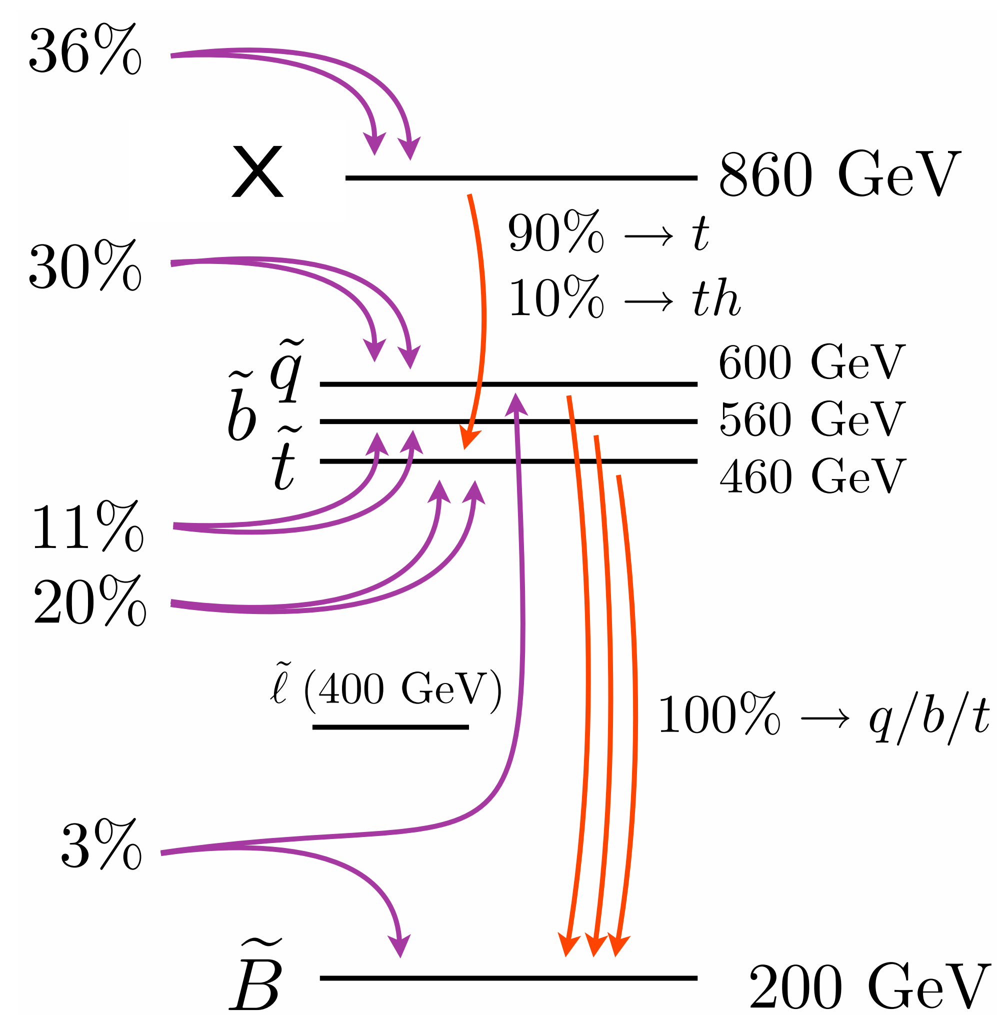
Lepton ET

further smeared by detector

Easy to compare to well-simulated guesses...much harder to turn out physical quantities (masses, branching ratios, cross sections ...or even “detector-corrected” distributions)

Goals for Early Characterization





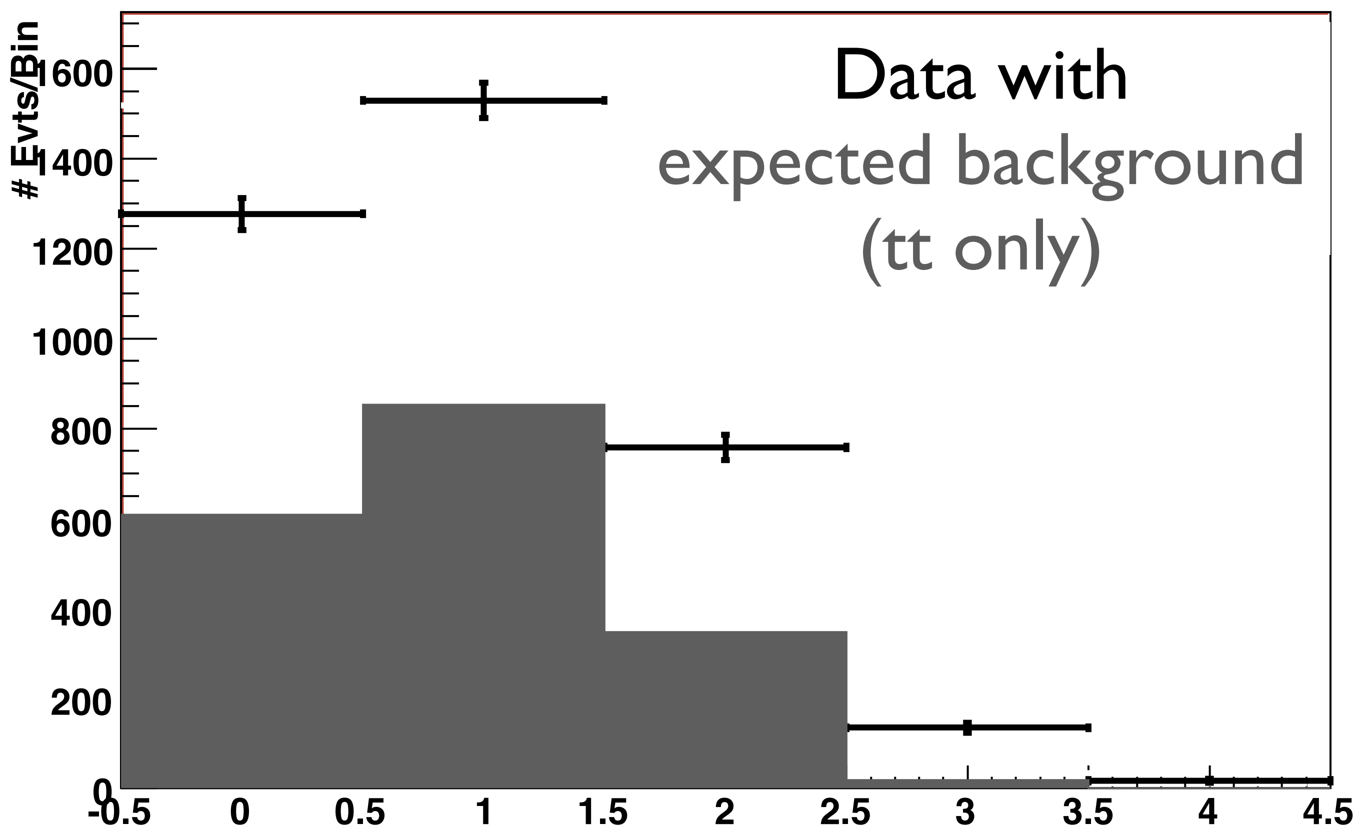
Obstacles to assembling hard-to-read distributions into physical results:

- distributions with no sharp features
- many possible models
- many regions of parameter space to consider in each model

cross sections
branching ratios
masses

Example

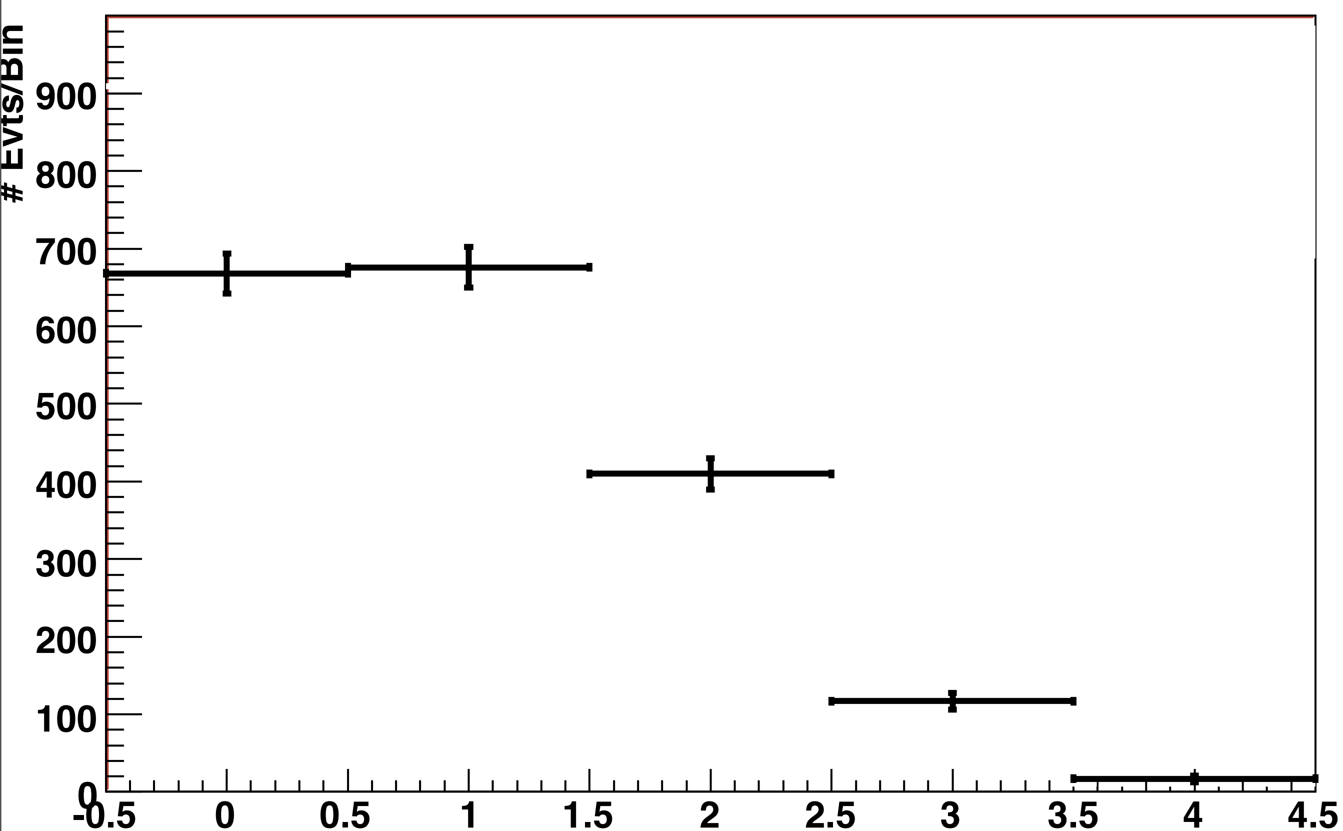
lepton-inclusive signal region (3 jets, pT>75 GeV, HT> 350, MET > 100)



# of b-tagged jets
(transverse momentum > 30 GeV)

Assume experimentalists have understood and subtract backgrounds
(we'll make life easy: ignore them completely!)

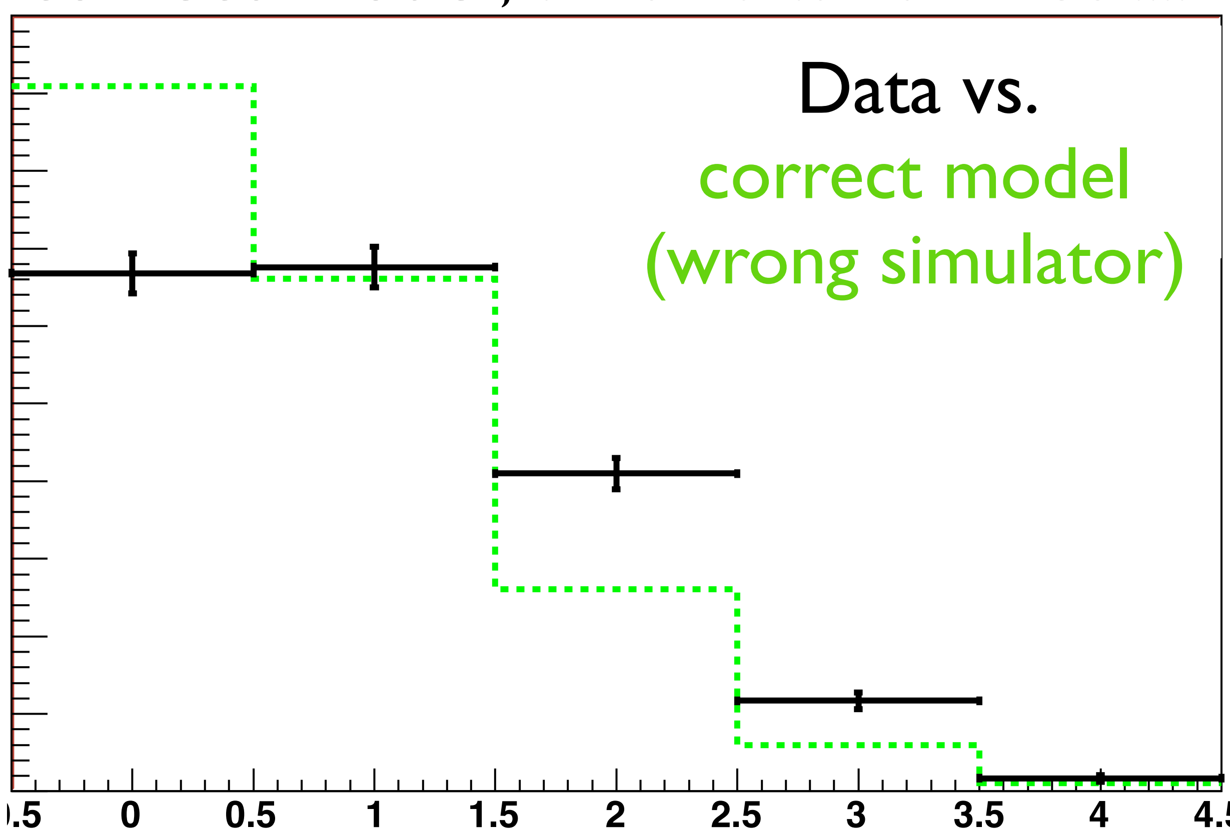
Example



# of b-tags
(backgrounds subtracted)

(I have used one version of PGS as my "detector" and "experimentalist's simulator", and a different version as my "theorist's simulator")

Suppose a theorist were to guess **the correct model**, and simulate it in PGS ....

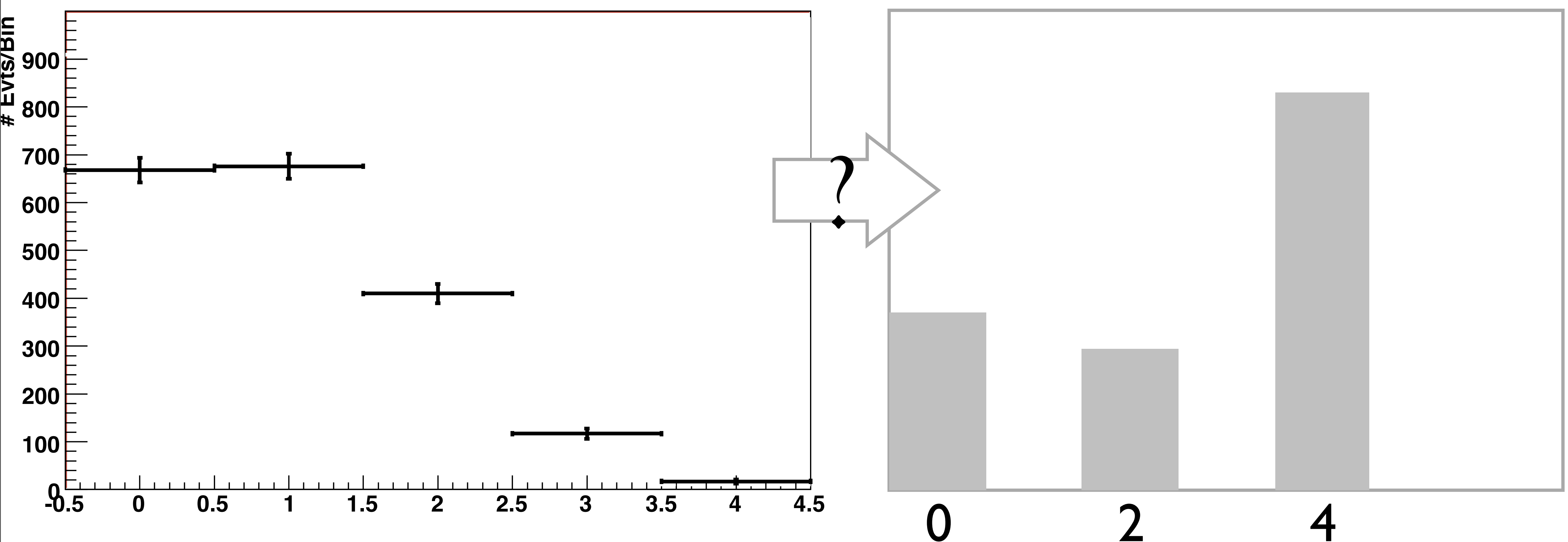


b-counts off by almost 50% in some bins!

Limited by accuracy of **model-builder's description of detector**

Example

lepton-inclusive signal region (3 jets, pT>75 GeV, HT> 350, MET > 100)



# of b-tags

inferred # of b-jets

Could make RHS plot by “inverting” efficiencies based on # of jets, pT’s, and etas in each event

(I’ve never seen it done, seems very hard)

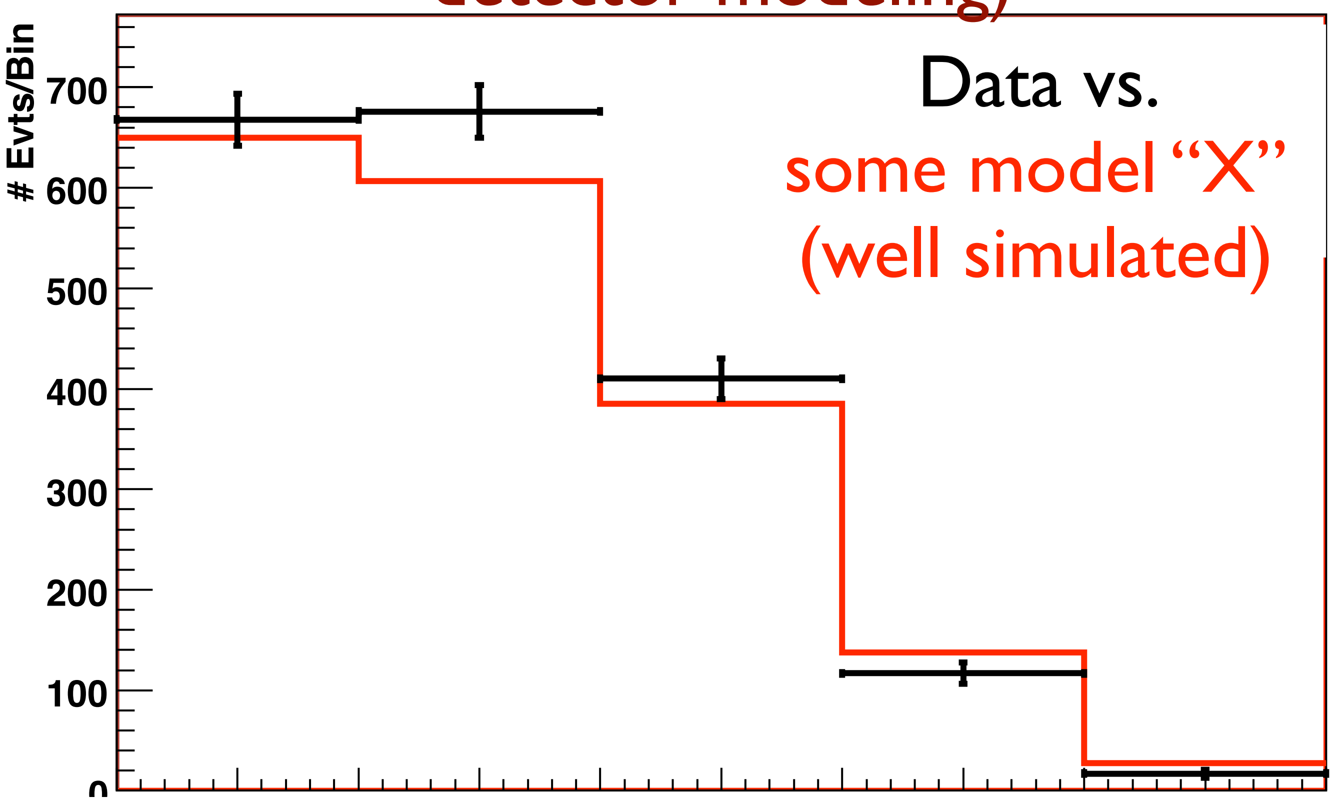
Alternative Approach

Experimenter's comparison

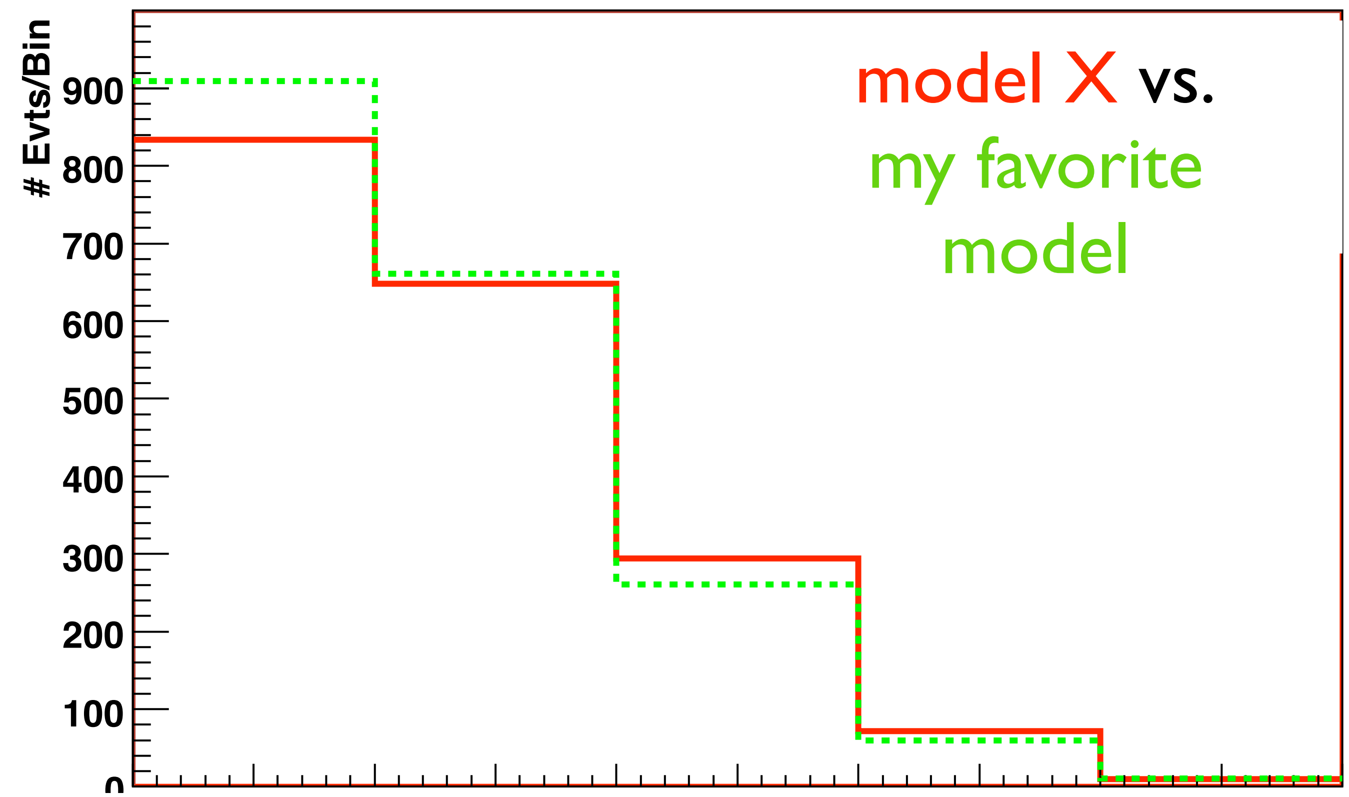
Red line: model X with gluon-partner pair production, 32% → qq LSP, 68% → tt LSP

(limited by **experimental collaboration**'s detector modeling)

Instead of comparing their model to data, any theorist can simulate their model **and** model X in PGS



# of b-tags

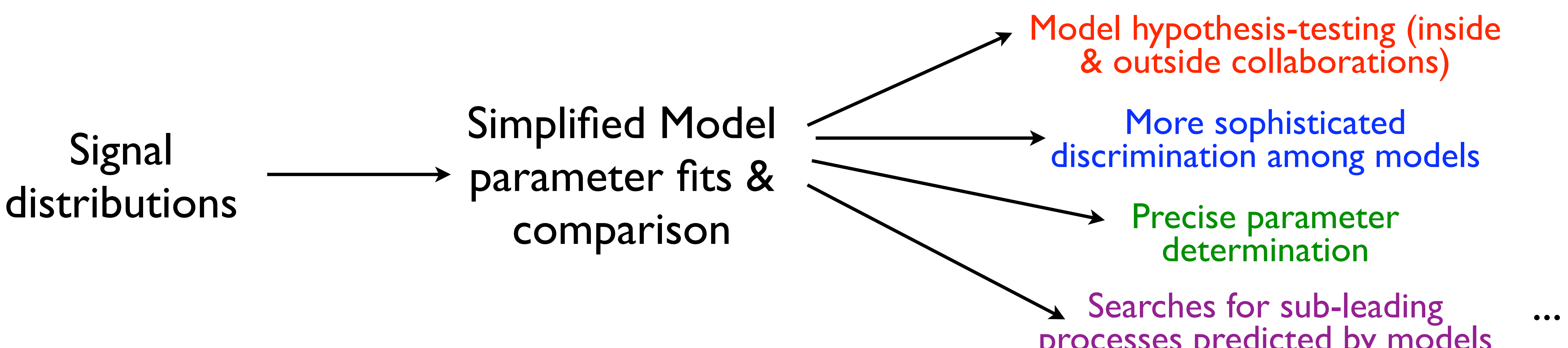


# of b-tags (PGS)

(There ***are*** systematic errors in this procedure — e.g. if model X mis-models kinematics **and** PGS mis-models efficiencies but they are partially corrected)

How do we get physics out?

- Choose our battles:
    - Specific, well-posed phenomenology questions (motivated by theoretical interest)
- How much of the model structure can we resolve?
    - Choose small parameter spaces that span resolvable structure efficiently (Simplified Models)
- Once there's robust evidence for new physics:



The First Three Questions

Very simple questions for a broad-brush characterization of SUSY-like data

1) Which colored particles dominate production?

2) What color-singlet decay channels are present, and in what fractions?

3) How b-rich are the events?

Why are these interesting theoretically?

(1) Dark Matter & Cosmology

Can the LSP (SUSY or not) account for most of the dark matter in the universe? Is a thermal freeze-out scenario consistent with direct nuclear recoil DM searches?

Low production cross-section for weakly interacting states at LHC, and they're (nearly) invisible.

→ can't expect to measure DM couplings directly

(1) Dark Matter

Can get clues about LSP couplings, SU(2) multiplet, nearby states from decay chains!

Consistent DM scenarios in MSSM:

best discovery scenarios

Wino ~1 TeV

Higgsino ~2 TeV

Bino <100 GeV

B/W or B/H mixture 100-1000 GeV

annihilates through t-channel slepton at ~100 GeV

10-20% mass splitting, large mixing and/or coannihilation

Within a model, LHC data may suffice to exclude LSP thermal dark matter within particular models, or to predict annihilation channel.

(2) Hierarchy Questions

How heavy is the top partner? Is it lighter than the other quark partners, or heavier? Are LH and RH stops very split? Is there mixing/large A-terms?

Like LSP, first sign of top-partner may not be direct production (no top PDF, no N_f), but role in gluino decay chain.

First question (pheno): what is the dominant source of heavy flavor in the new physics? Is it correlated with leptonic cascades? With *W*'s?

Second: What spectra and interactions are consistent with this? And what are their implications for model-building?

(3) SUSY Mediation to SM

What is the ordering and splitting of gaugino/partner masses?

Many models make specific predictions for M1 : M2 : M3 –

mSUGRA or Gauge mediation – 1:2:6

Anomaly mediation – 2:1:6

Minimal UED – 1:1:1 + corrections

...

Constraints on ordering and splitting from decay chains place tight constraints on underlying physics!

The First Three Questions

1) Which colored particles dominate production?

2) What color-singlet decay channels are present, and in what fractions?

3) How b-rich are the events?

Easiest to frame quantitative questions in terms of sharply specified models – what models should we choose, to have a good chance of fitting any jets+MET+leptons signal from SUSY-like physics?

Most Familiar Models

(CMS and ATLAS are prepared to use these)

Benchmarks : Good for designing searches – most production & decay topologies of interest are in a benchmark, but most ***combinations*** of topologies are not.

mSUGRA (or similar constrained frameworks) : Fixed mass ratios still prohibit qualitative changes to spectrum; need many different frameworks to cover phenomenology.

MSSM (and other many-parameter models) : Technically challenging to optimize, very hard to present and interpret globally (e.g. if >1 region of parameter space is consistent with data)

Four Simplified Models

1) Which colored particles dominate production?

Either Gluon partner G or Quark partner Q

study each in a <u>separate</u> model

2) What color-singlet decay channels are present, and in what fractions?

Models with ***one*** produced species, ***one***-stage cascade decay (produced species either G or Q).

3) How b-rich are the events?

G: Produce gluon partners that decay to $q\bar{q}$, $b\bar{b}$, or $t\bar{t}$ +LSP

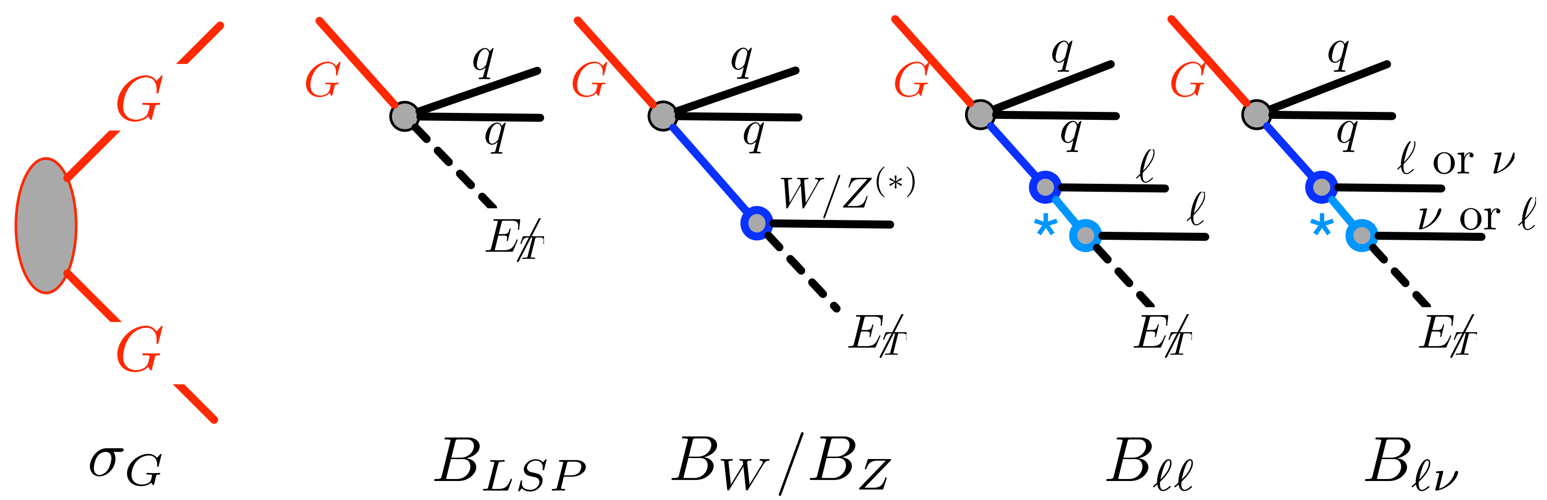
Q: Pair-produce parters of q_{12}, b, and t

➡ Total of four models

GOAL: As simple as possible to answer these three questions
+ fit ANY new physics in SUSY-like class well

Simplified Models of Lepton Cascades

From gluon partner:



*on or off-shell

Masses

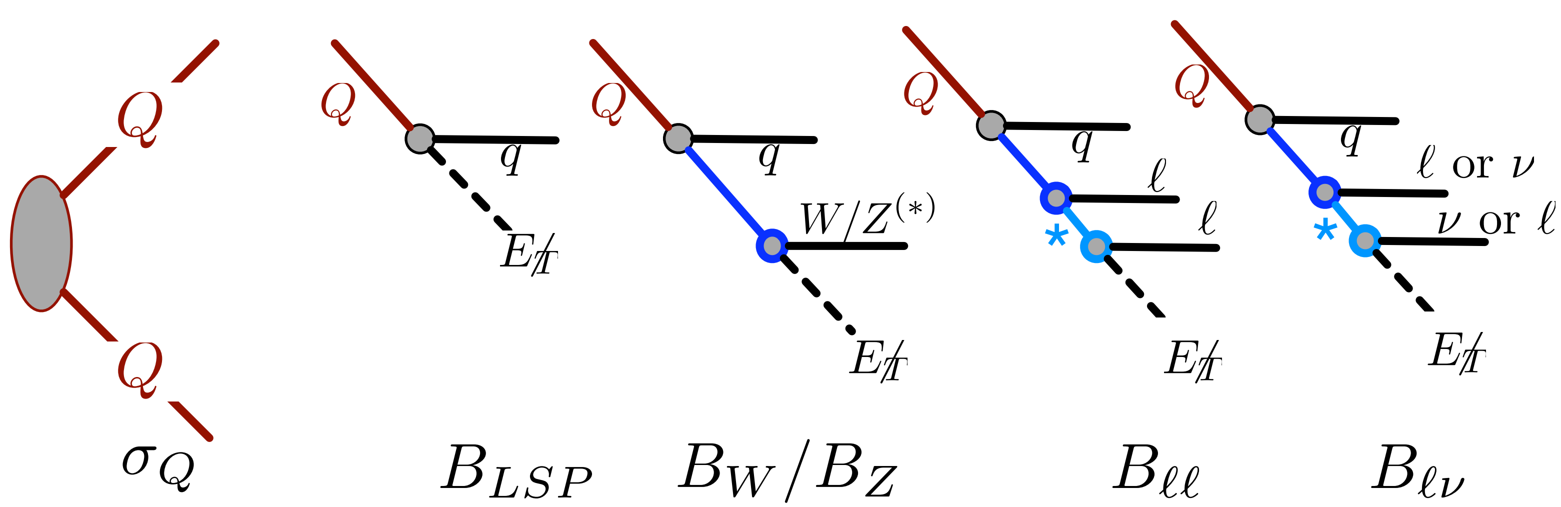
M_G

M_I

(M_L)

M_{LSP}

From quark partner:



Masses

M_Q

M_I

(M_L)

M_{LSP}

Simplified models don't include all possible SUSY-like behavior in models:

- Quark-partner and gluon-partner production
- Different decay modes for LH and RH quark partners
- Multiple cascades

etc...

But our goal is to answer the three questions – additional structure can often be guessed from comparisons of data distributions to those predicted by simplified models.

Trying to match too much at once → larger parameter space, less constrained and harder to present. No **in-principle** reason not to extend the models, but important to understand what we can do with simplest models.

Simplified Models of Lepton Cascades

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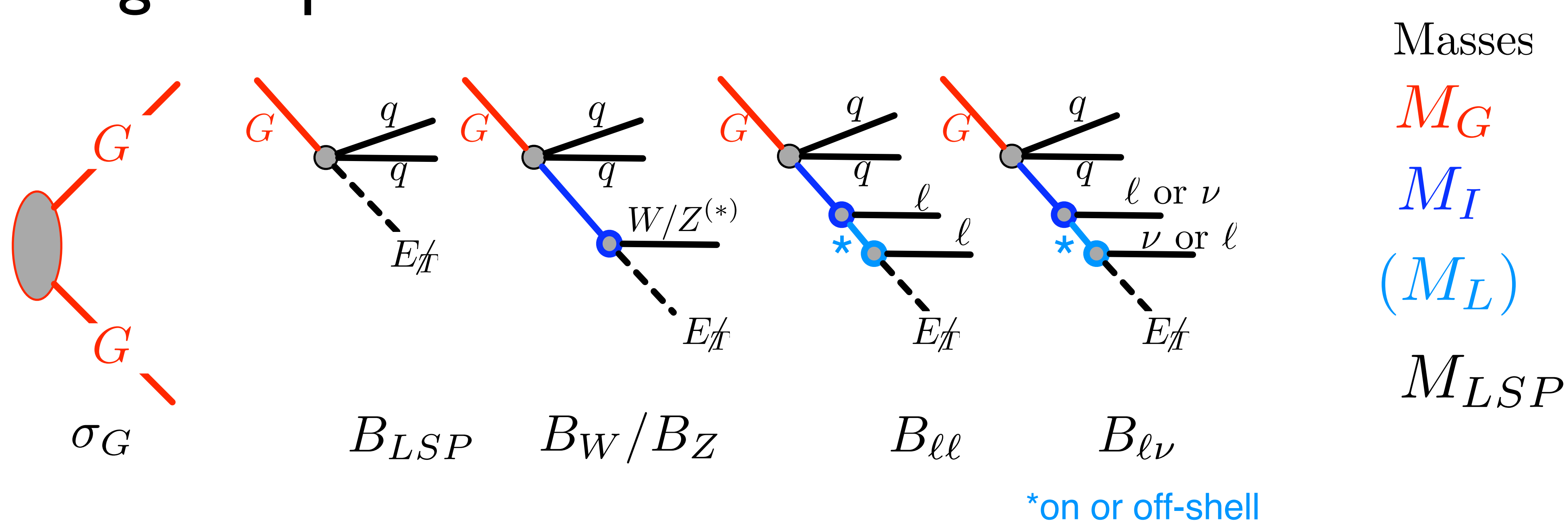
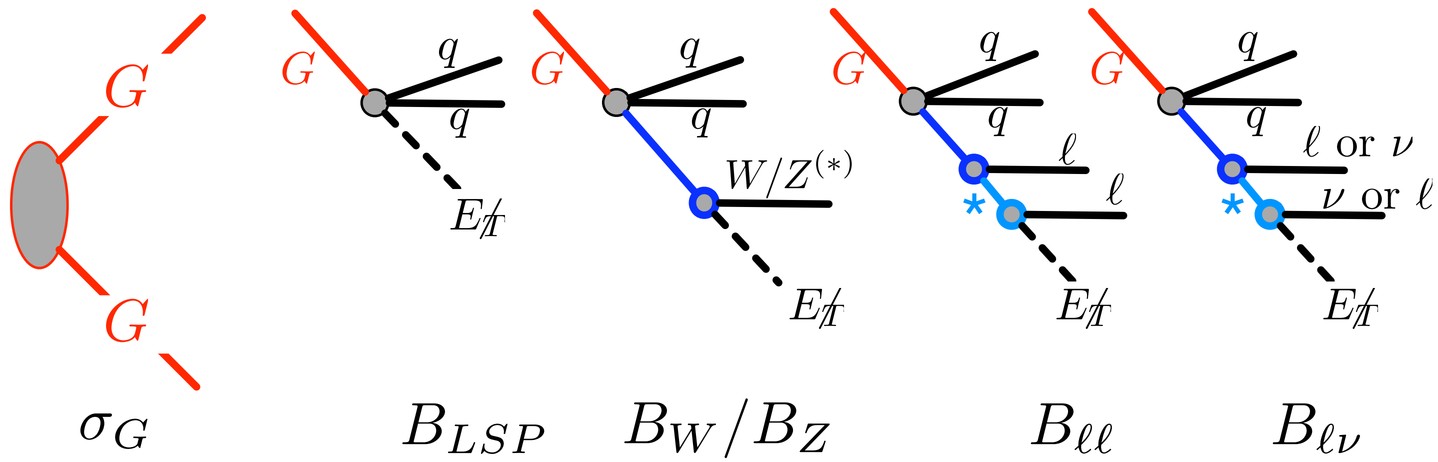


Parameters:

- One total production cross-section
- Five branching fractions (sum to 1); three easy
- Three masses (four if slepton on-shell)

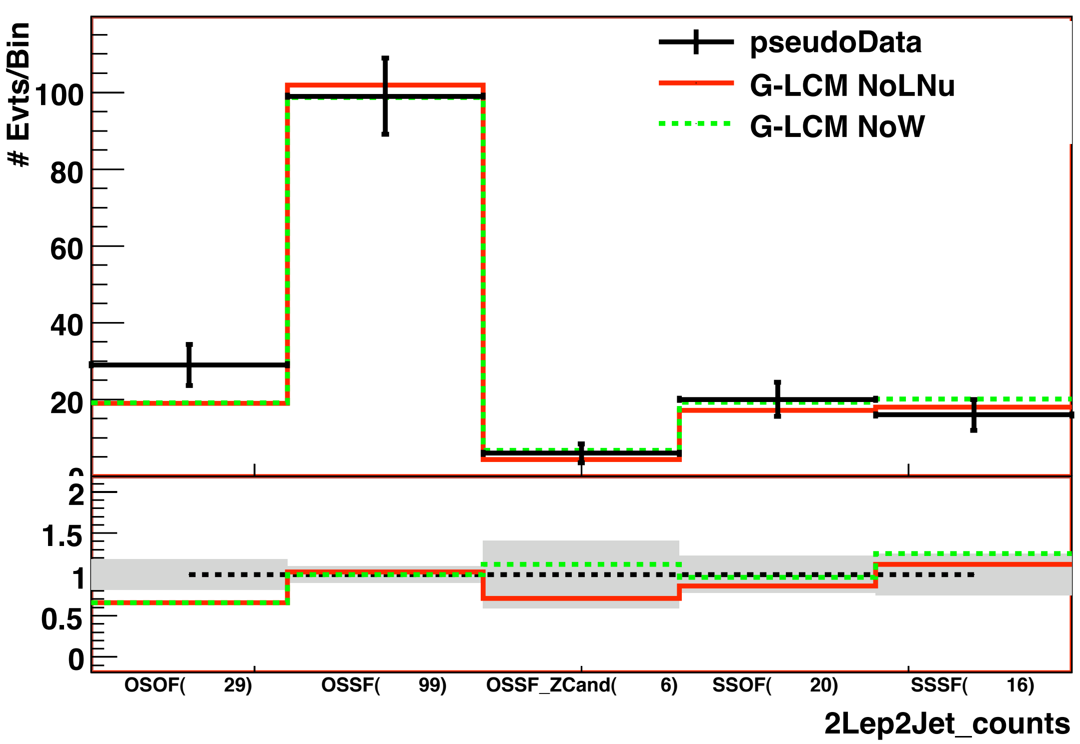
Can be constrained in data (2 parameters harder)

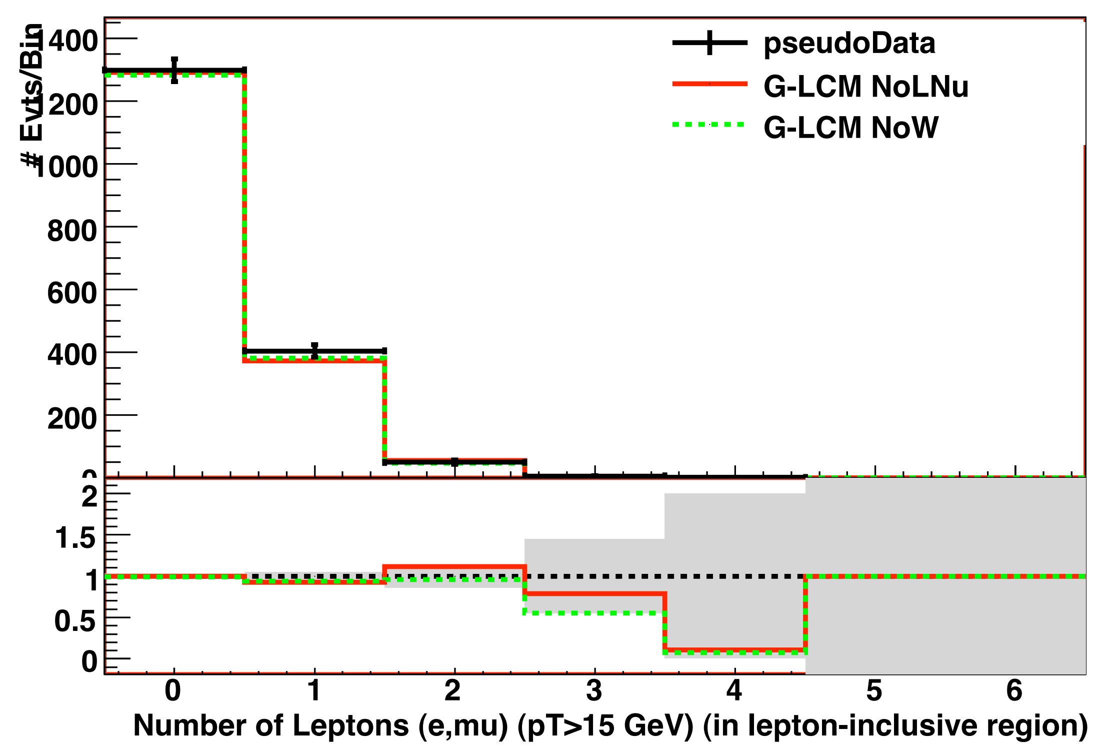
Constraining σ and BR's



Signatures quite distinctive (dilepton pairs on Z peak, opposite-flavor leptons, ...) *except* B_W looks like $B_{l\nu}$ x 0.32 + B_{LSP} x 0.68.

Study extreme limits, e.g. B_W=0, or $B_{l\nu}$=0





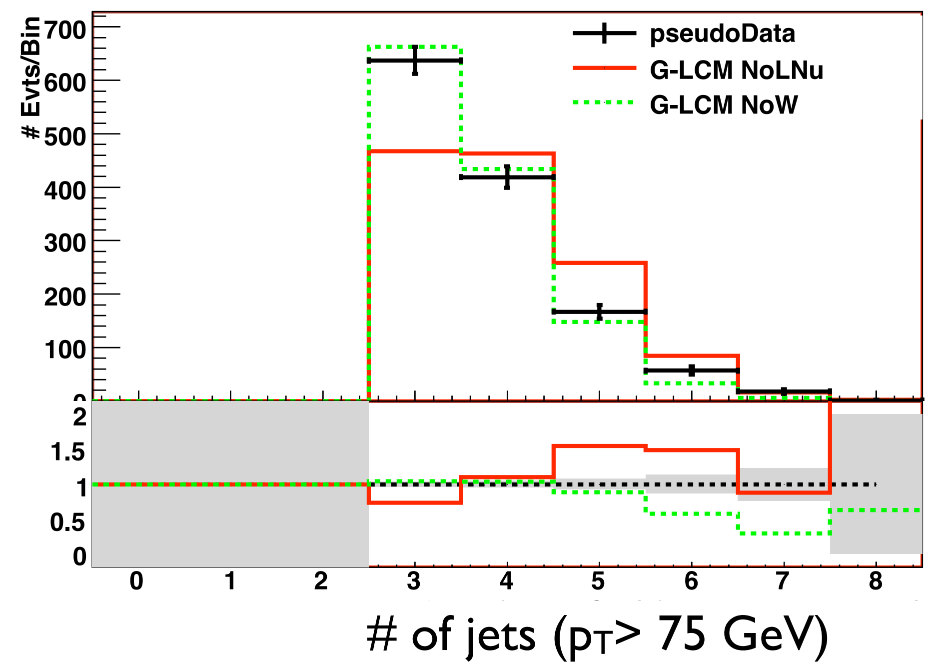
Additional constraints

Exchanging W↔(lν+direct)

changes jet multiplicities, and correlation with lepton counts.

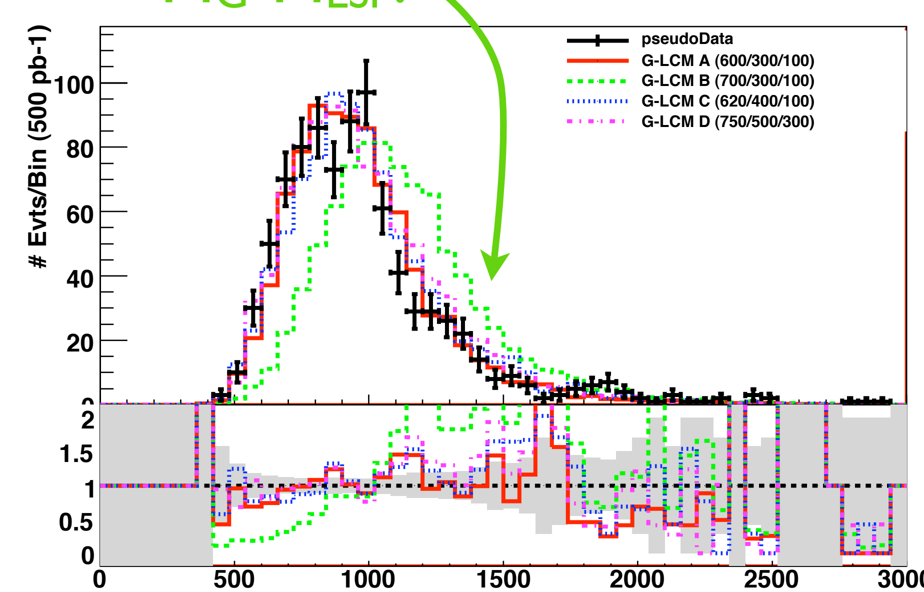
Choosing gluon/squark partner also changes jet multiplicities.

Lepton-veto region



Varying particle masses changes kinematic distributions

M_G-M_{LSP}:



$H_T=\sum p_T$ (GeV)

(sum over up to 4 jets + leptons + missing ET)

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✔ 2) What color-singlet decay channels are present, and in what fractions?

study each in a <u>separate</u> model

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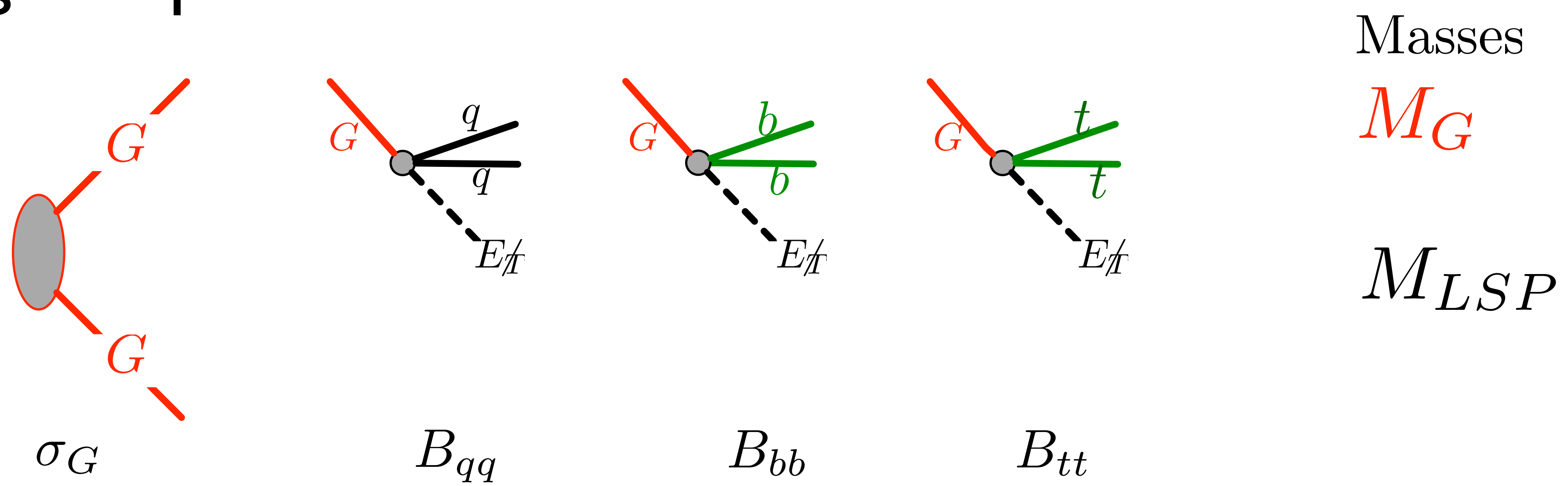
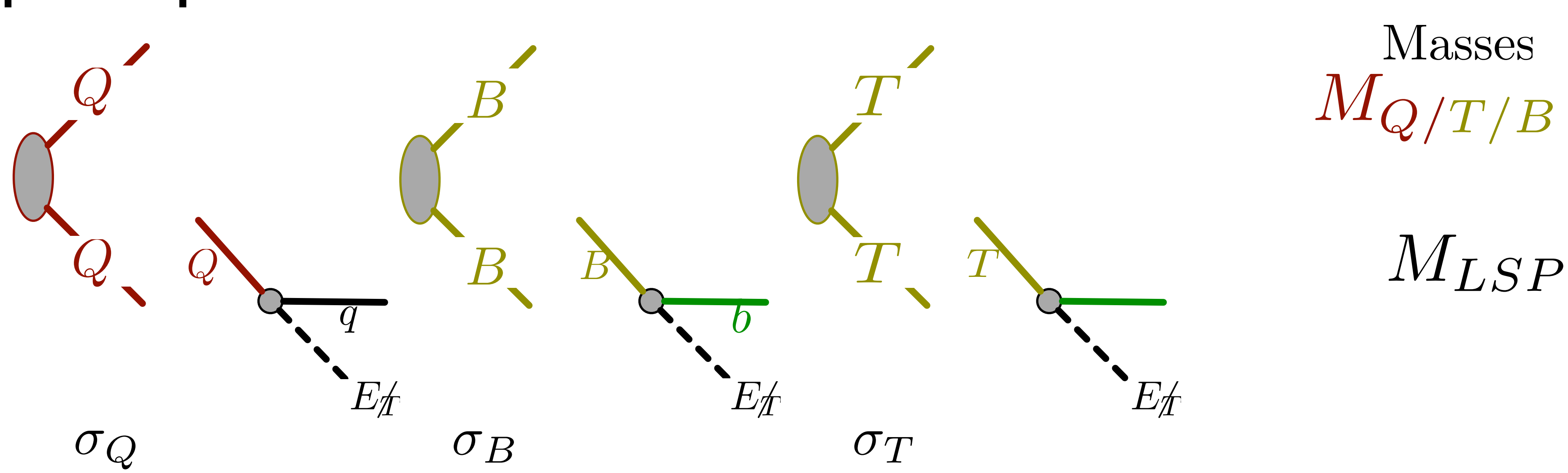
➡ Total of four models

Heavy Flavor Models

From gluon partner:

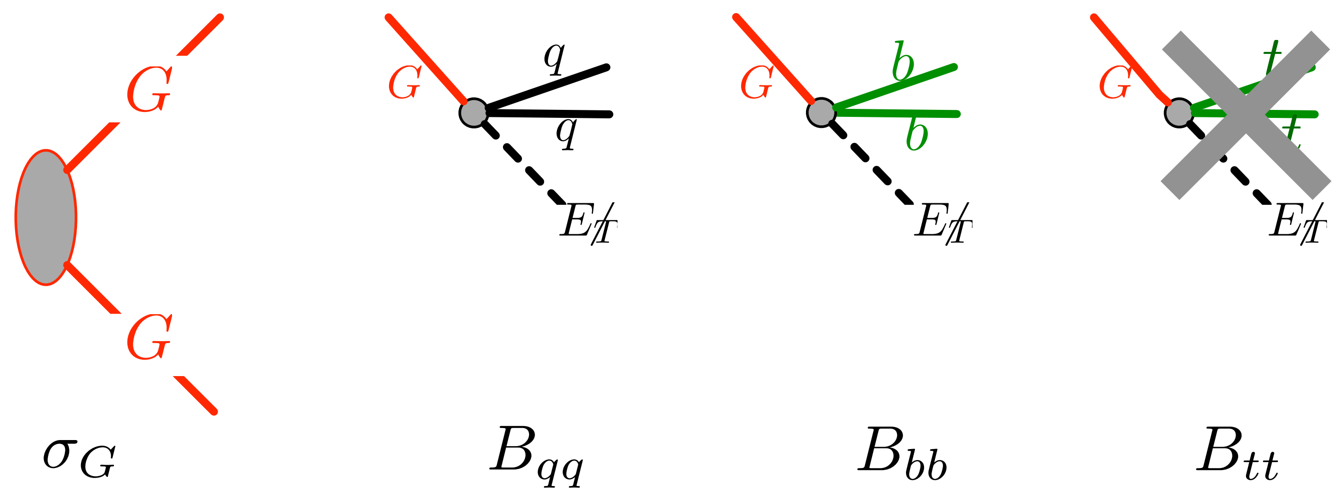


From quark partner:



Different structures / <u>different patterns</u> of b-tag multiplicity

Gluon Heavy Flavor Model: Top/Bottom Fractions



(1) fit using only b-jet counts, and no tt mode:

- detector-independent characterization of b-jet fraction
- check consistency with <u>one</u> source of b-jet pairs

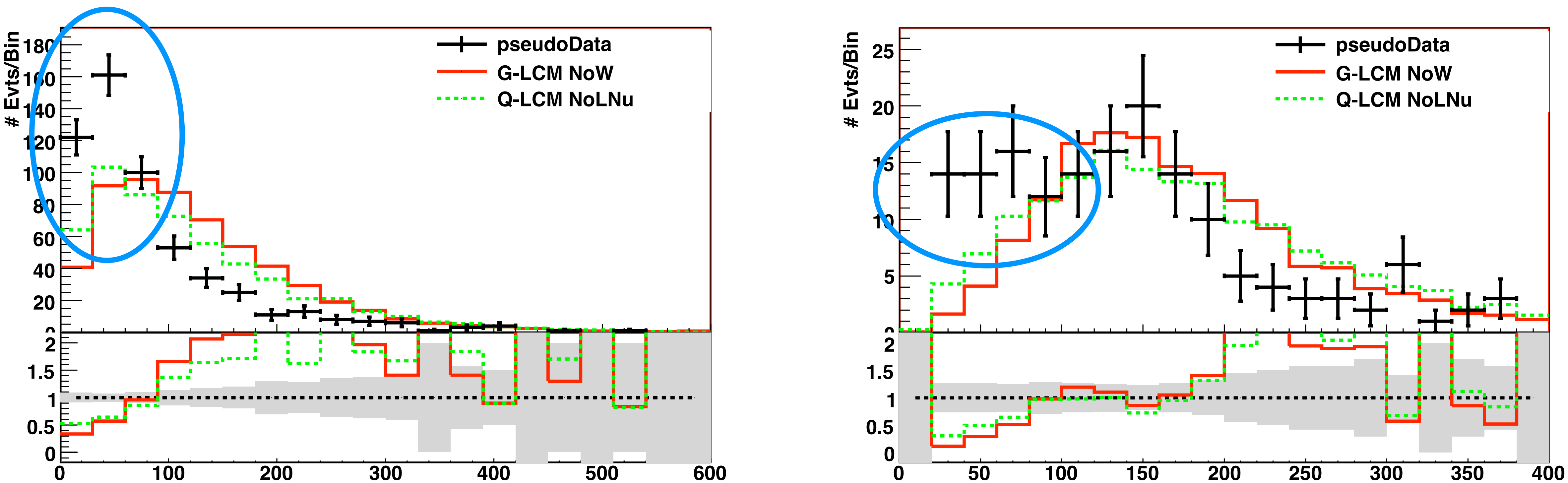
(2) include tt, lepton counts

- is it consistent for all leptons come from tops?
- check kinematics, too

Note the omission of lepton cascades here!

Another kind of information

Distributions that cannot be explained without adding structure beyond simplified models



Lepton p_T (one-lepton region)   Leading lepton p_T (two-lepton region)

Softer lepton source in signal than simplified models: can't match while keeping invarinat mass distribution agreement – indicative of multiple cascades

Using Simplified Model Fits

Important to see several kinds of results

- Simplified model best fit
- Parameter uncertainties, particularly careful treatment of weakly constrained parameters
- Comparisons of the data to expectations for best-fit simplified model — both for distributions used in the fit and for diagnostics

Back-of-the-envelope analysis

- "Good fit" suggests what regions of parameter space to study in model-building
- "Bad fit" suggestive of additional structure (multiple species production, multiple cascades in decays, etc...)

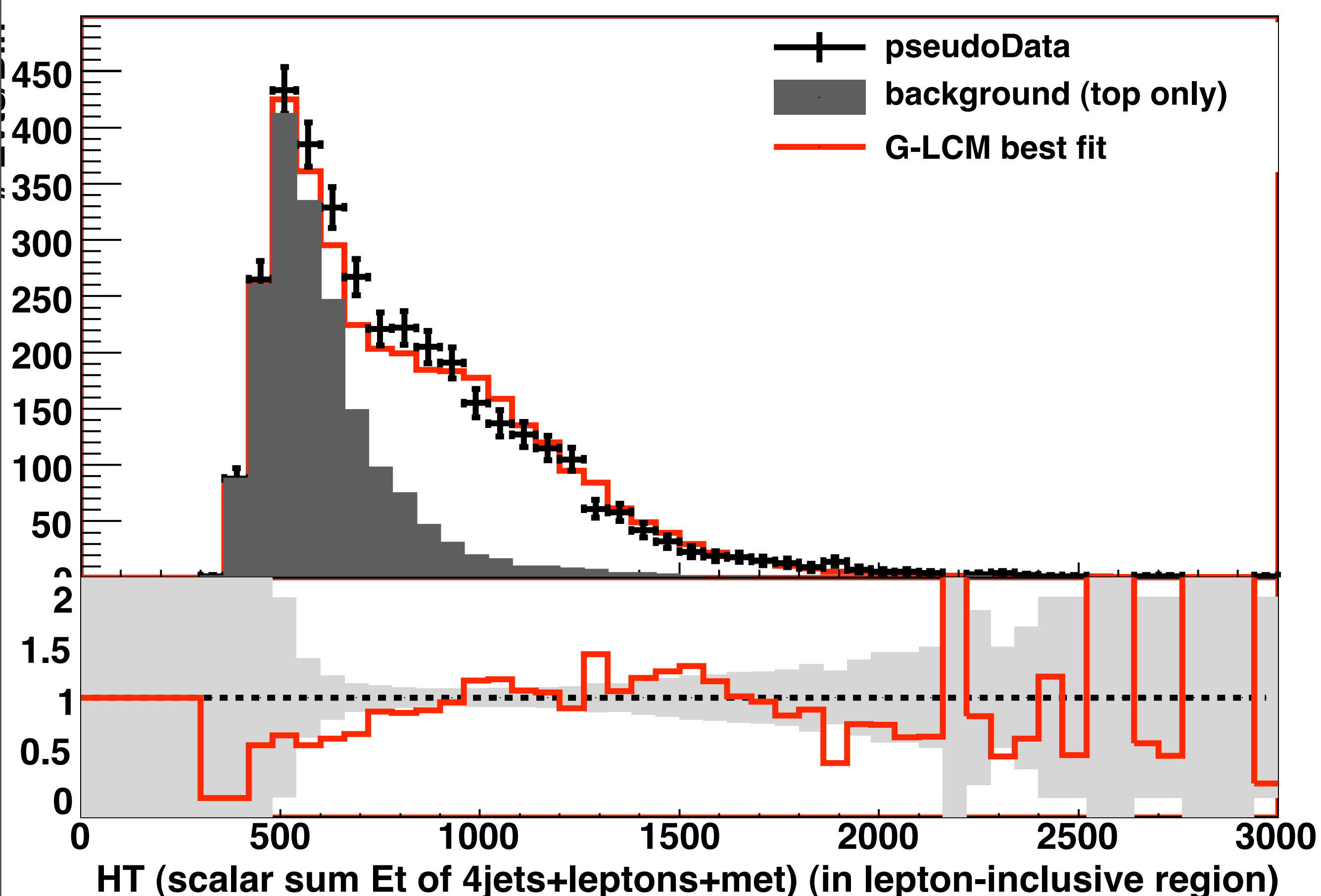
Quantitative comparison

- Can compare predictions of any model to simplified model predictions (e.g. in PGS) to gauge consistency with data.

Building Models from Simplified Models

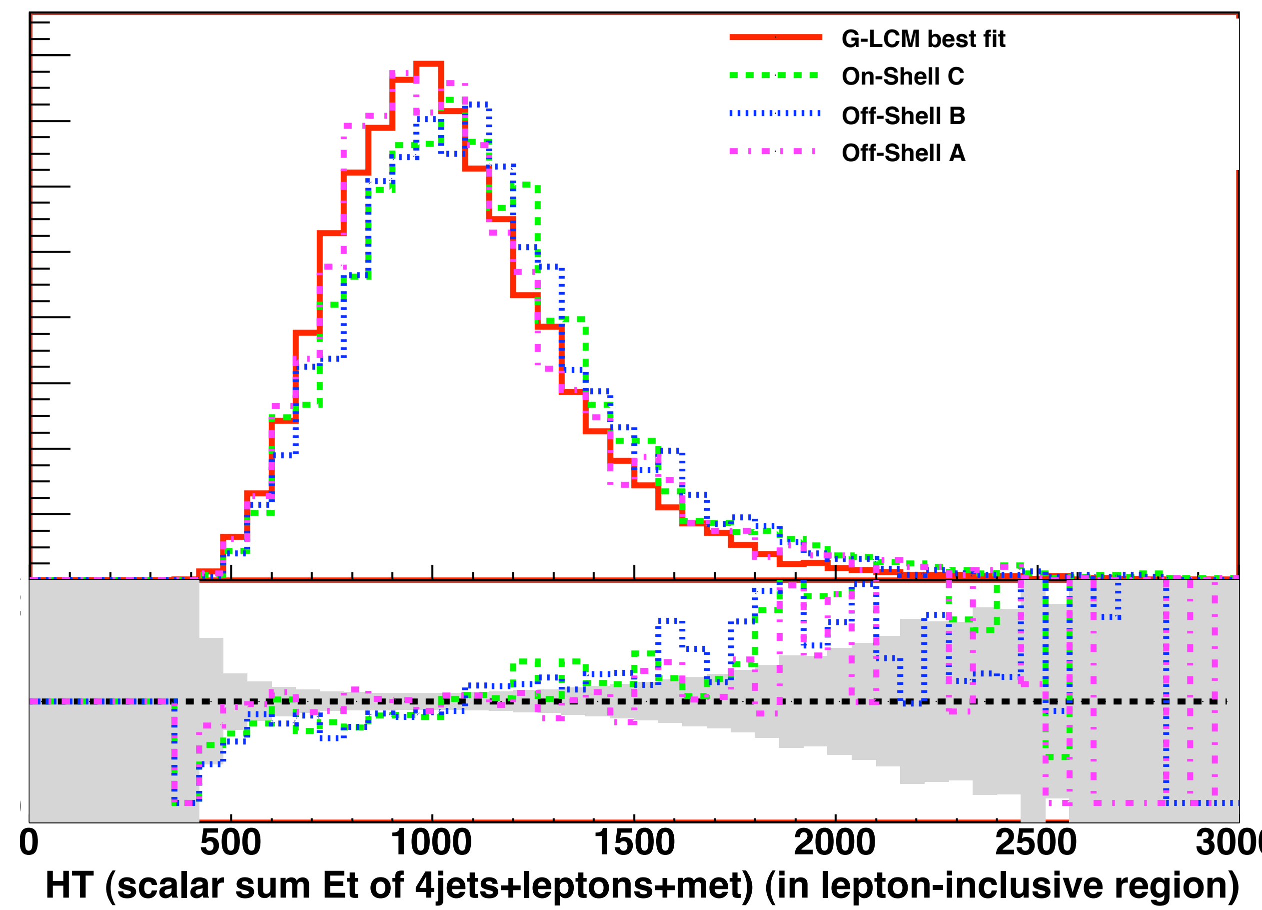
Experimental comparison:

Simplified Model (Leptons)
vs. Data
(shown over ttbar background)



Theorist's comparison

Simplified Model
vs. 3 SUSY models



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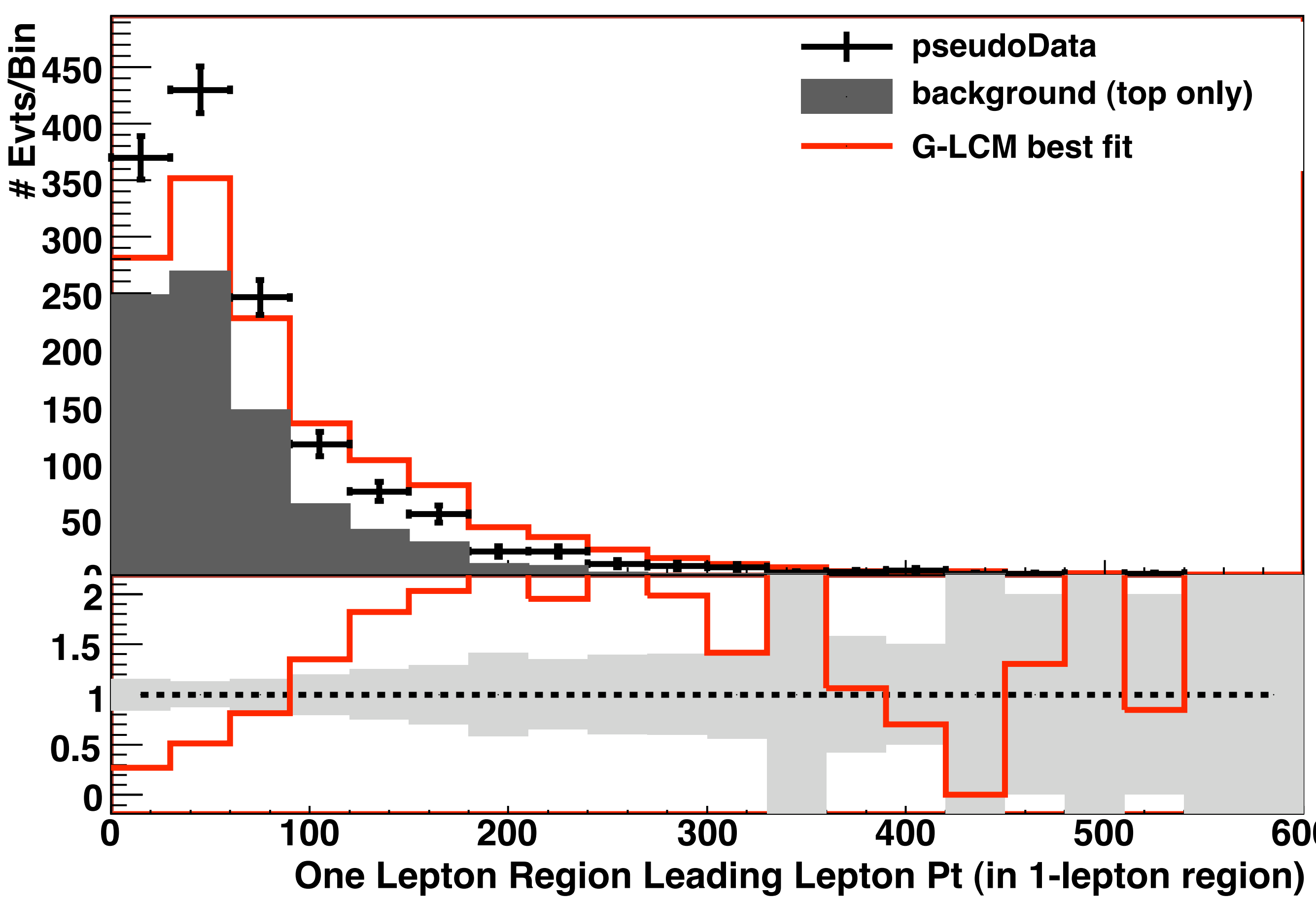

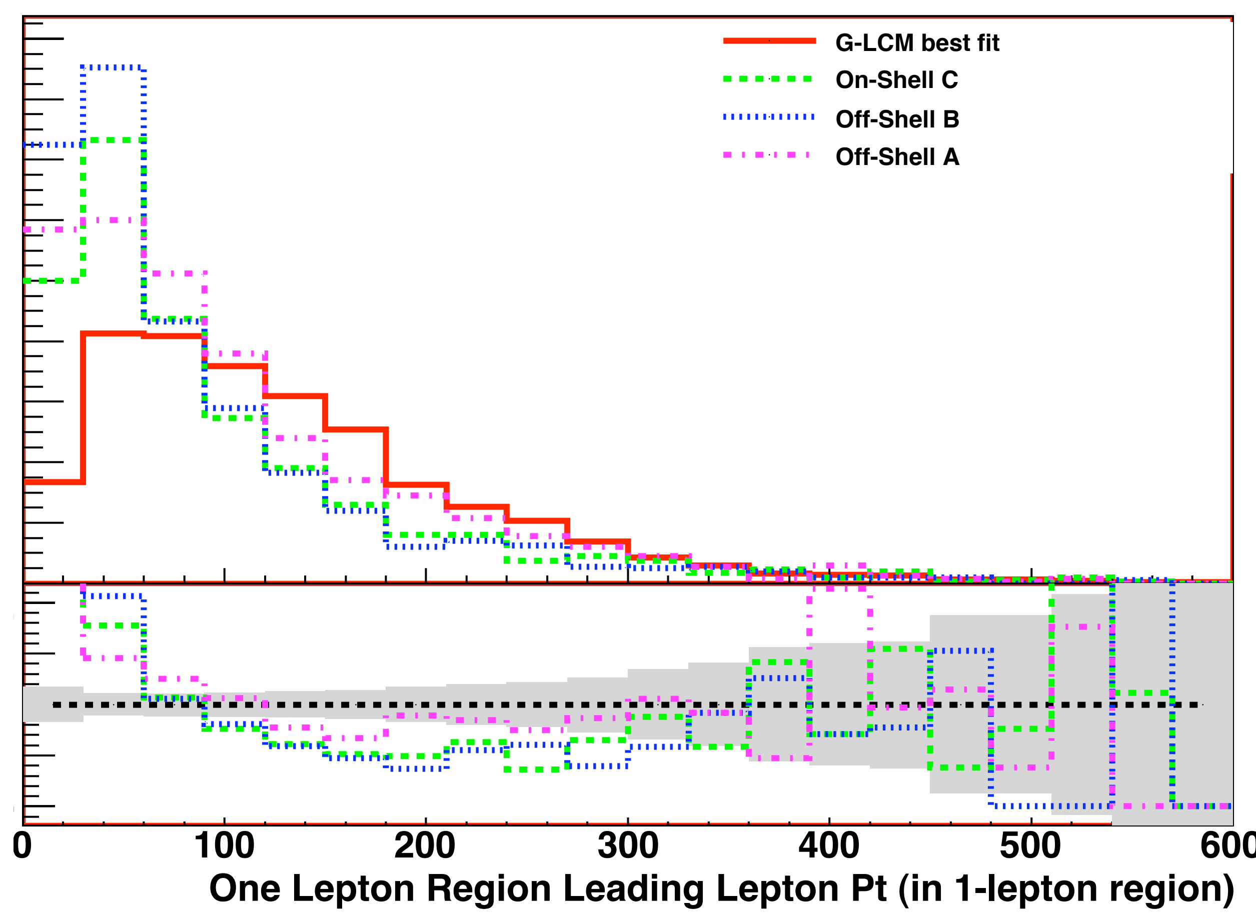

Conclusions

Many kinds of new physics could be visible at the LHC in jets+missing energy searches

- How to characterize them to maximize theory returns?
- And in a detector-independent way?

Simplified models are a concrete proposal:

- 2 models for leptonic cascades, 2 models for heavy flavors
- Few, simple parameters – easy to fit and easy to interpret

Fits of simplified models to data facilitate qualitative and quantitative comparisons to data by theorists outside collaborations

Building Models from Simplified Models

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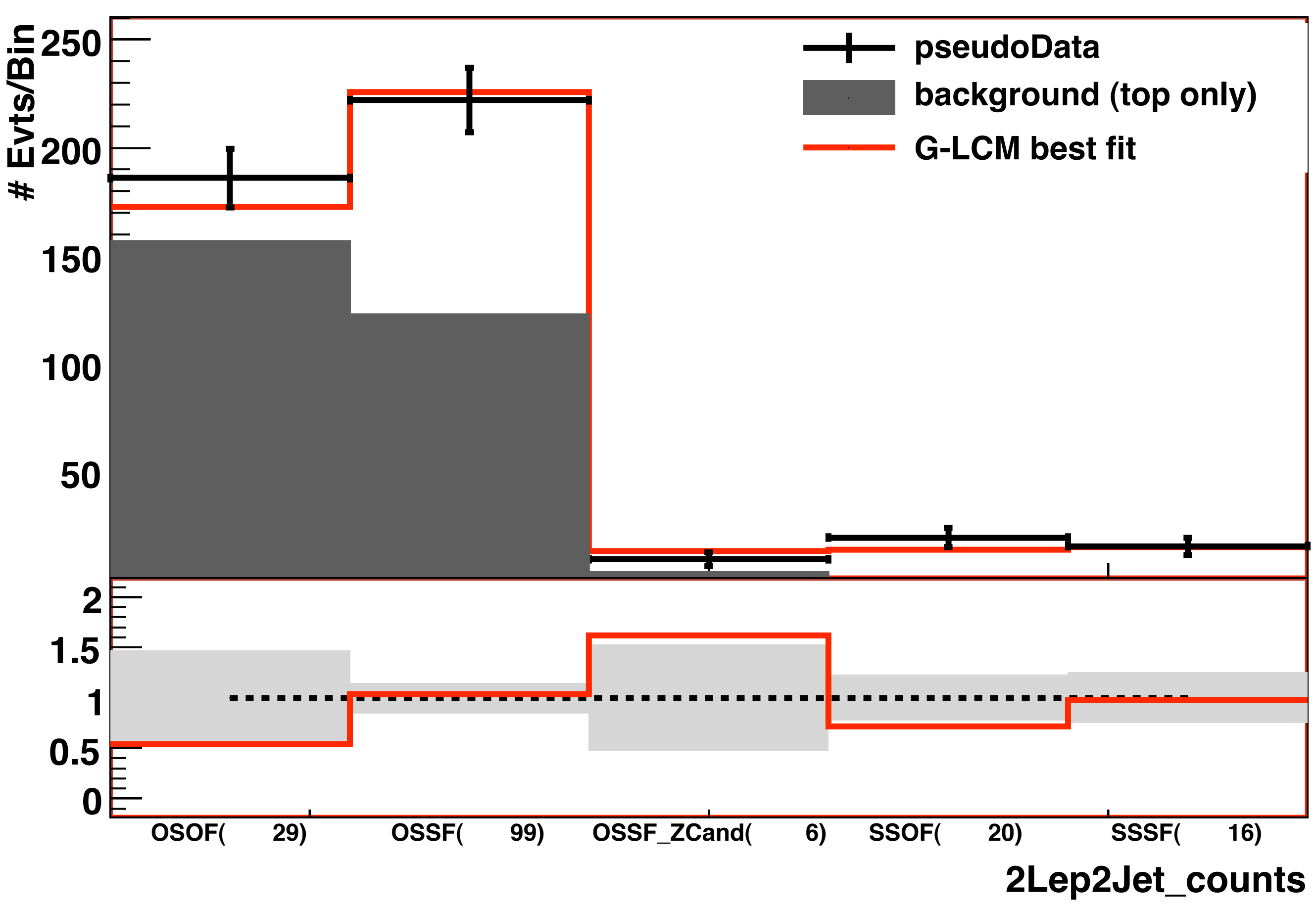
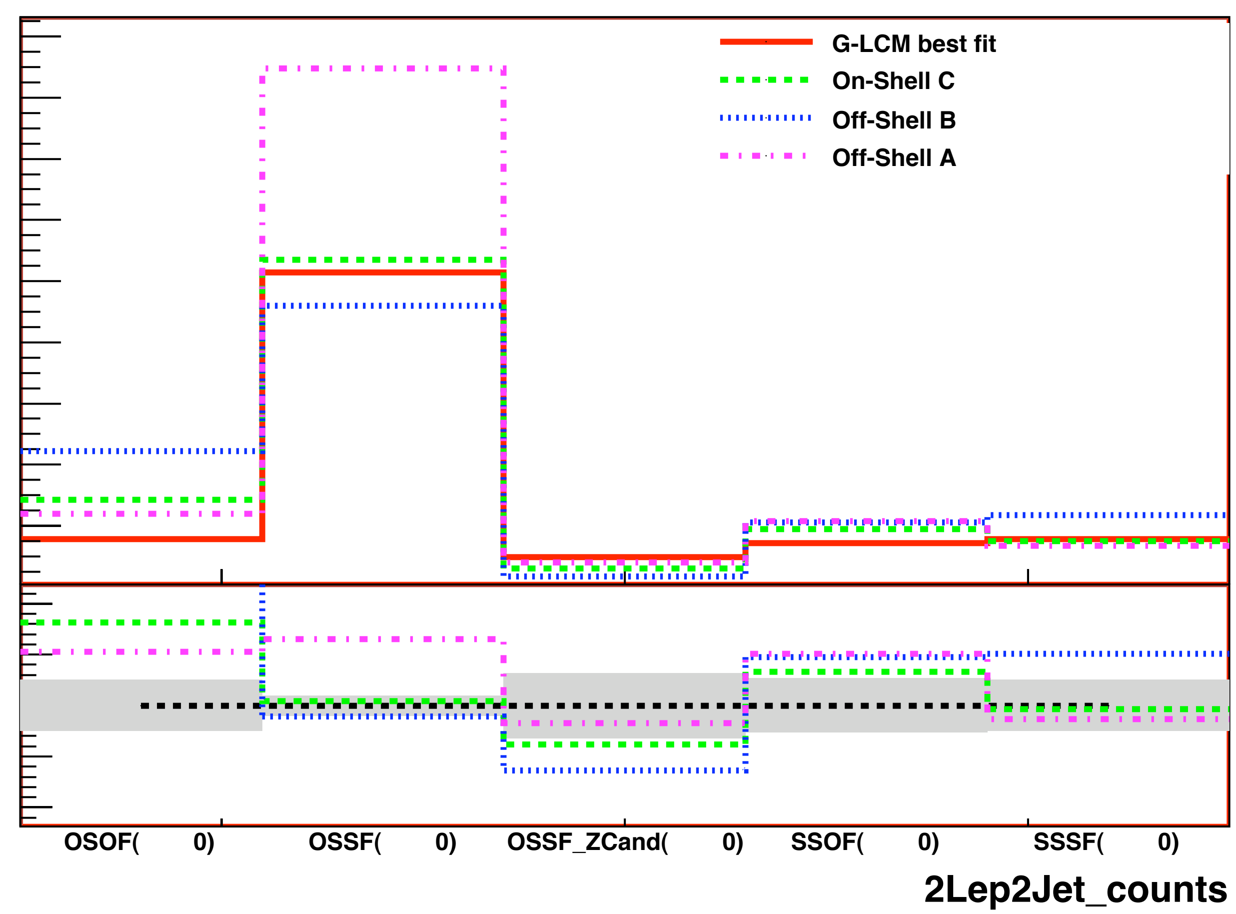




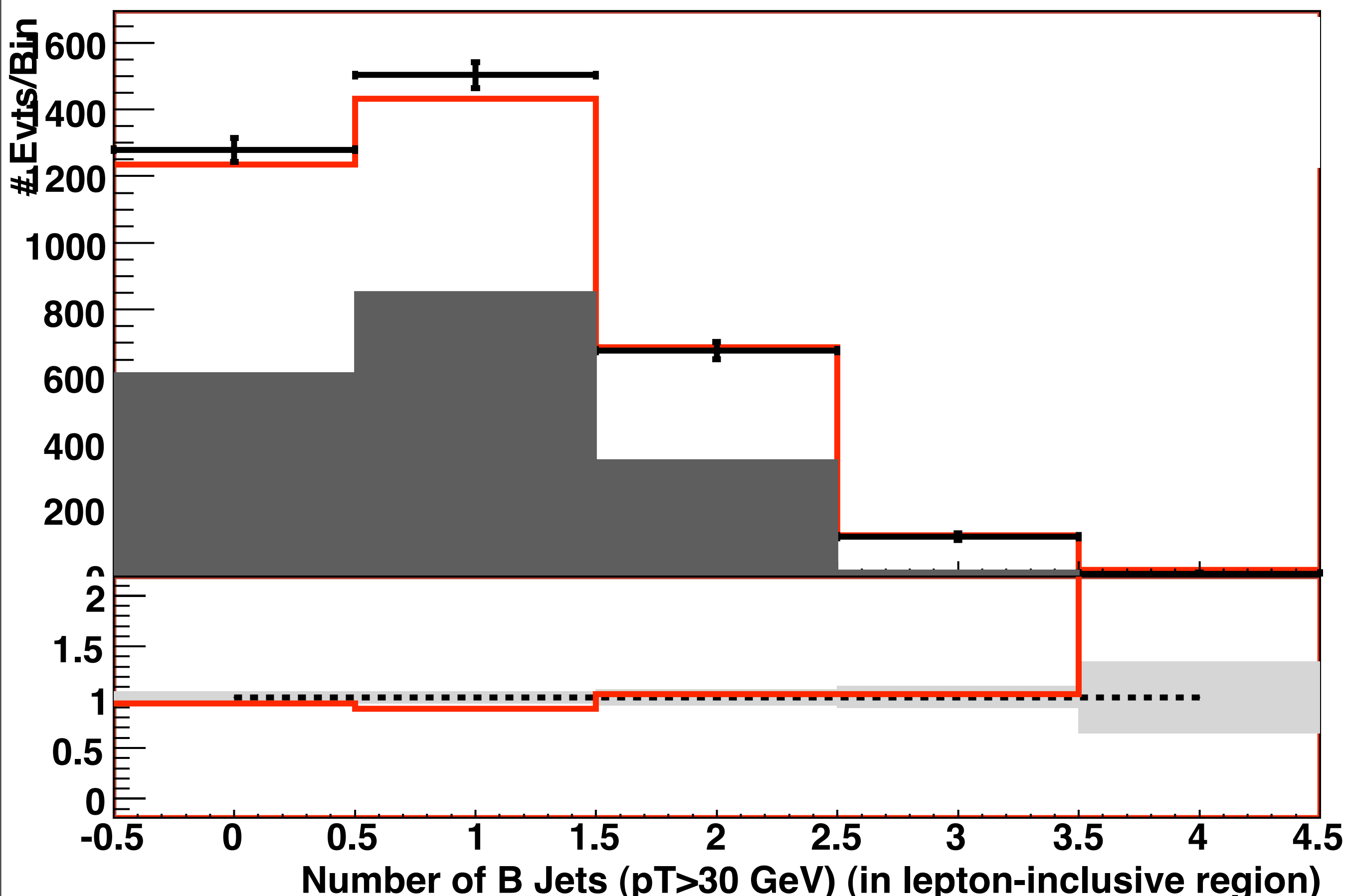
Building Models from Simplified Models

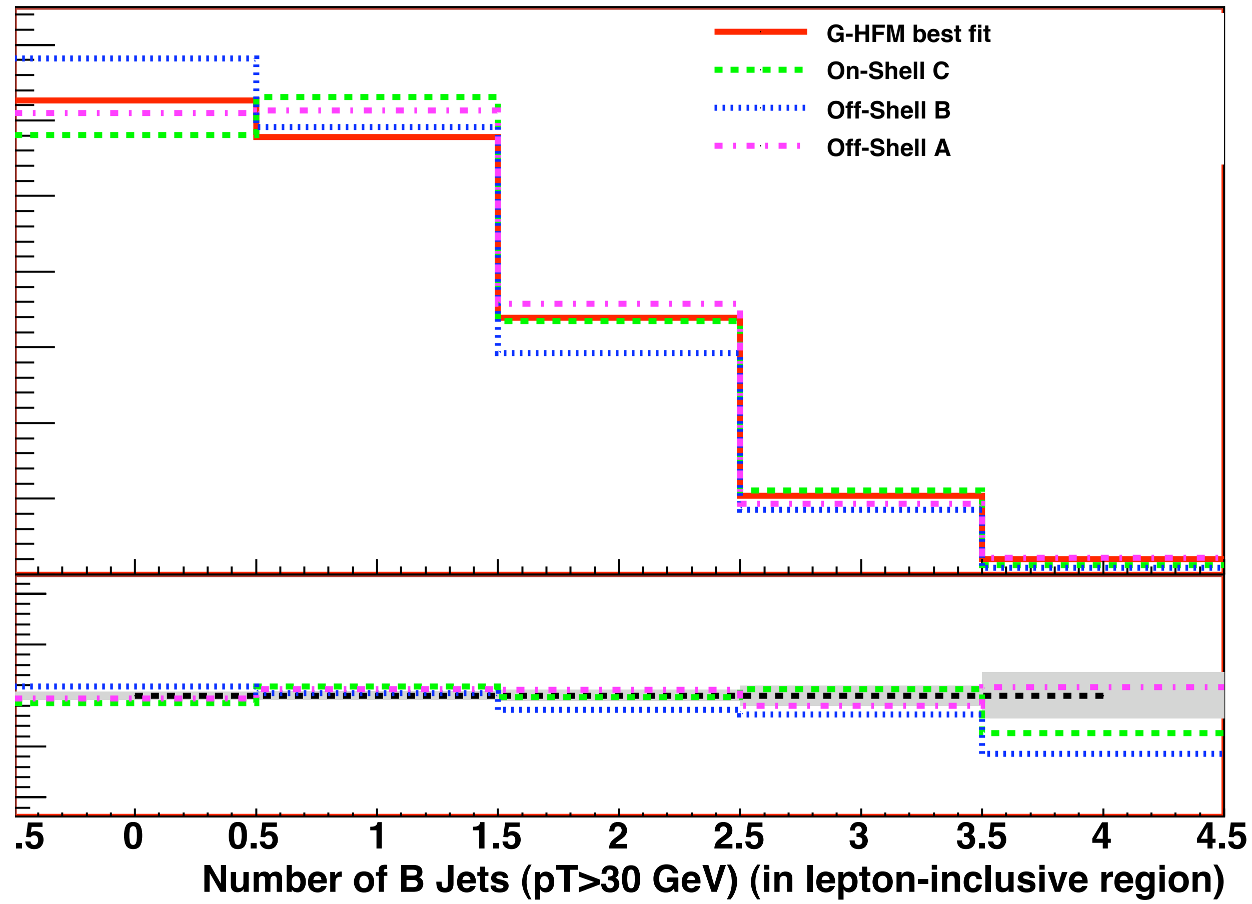
Experimental comparison:

Simplified Model (Heavy flavor)
vs. Data
(shown over ttbar background)

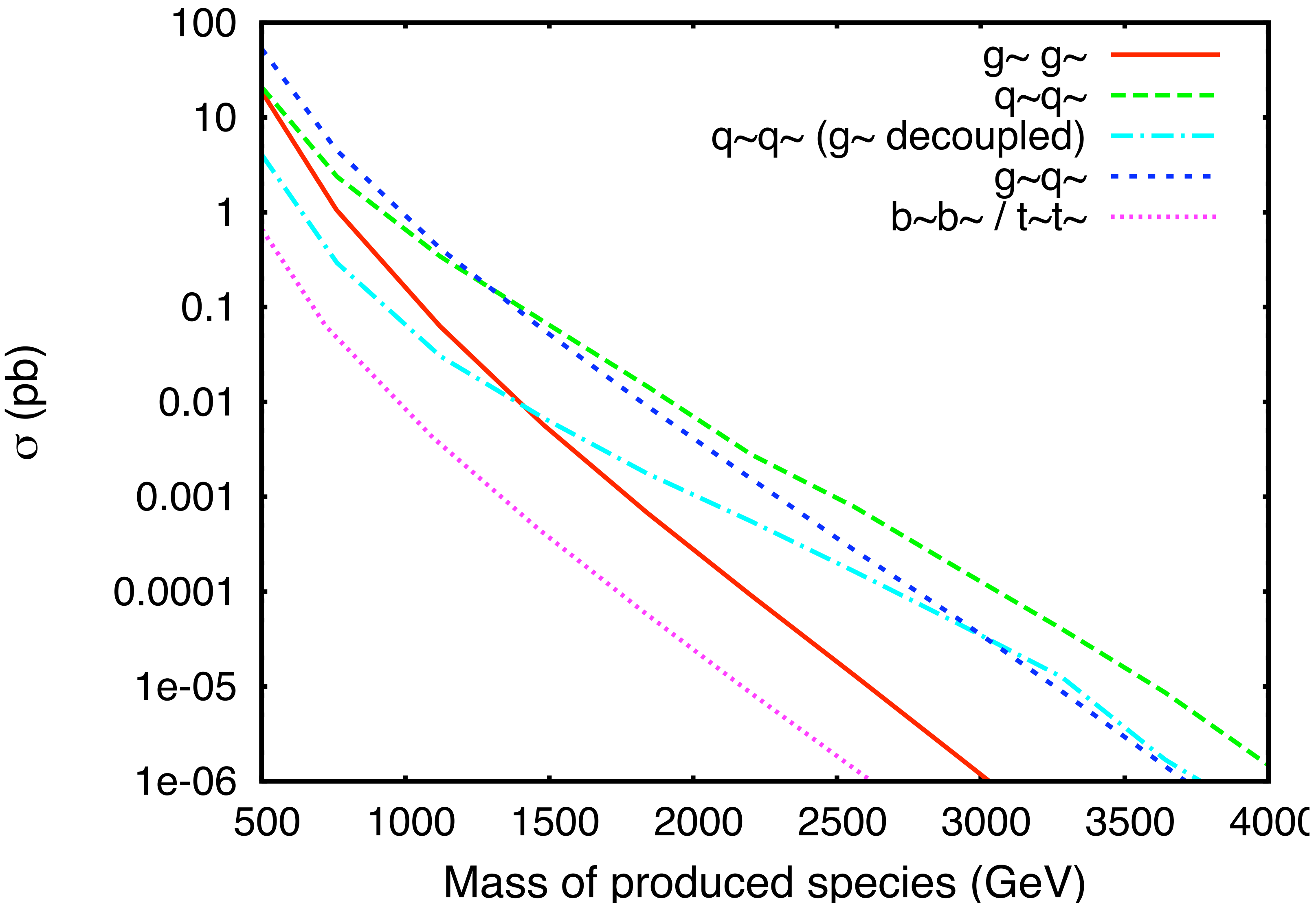
Theorist's comparison

Simplified Model
vs. 3 SUSY models





Will we see it?



We're kind of prepared

Let's look at what CMS and ATLAS are prepared to use:

Benchmarks : Good for designing searches – most production & decay topologies of interest are in a benchmark, but most ***combinations*** of topologies are not.

mSUGRA (or similar constrained frameworks) : Fixed mass ratios still prohibit qualitative changes to spectrum; need many different frameworks to cover phenomenology.

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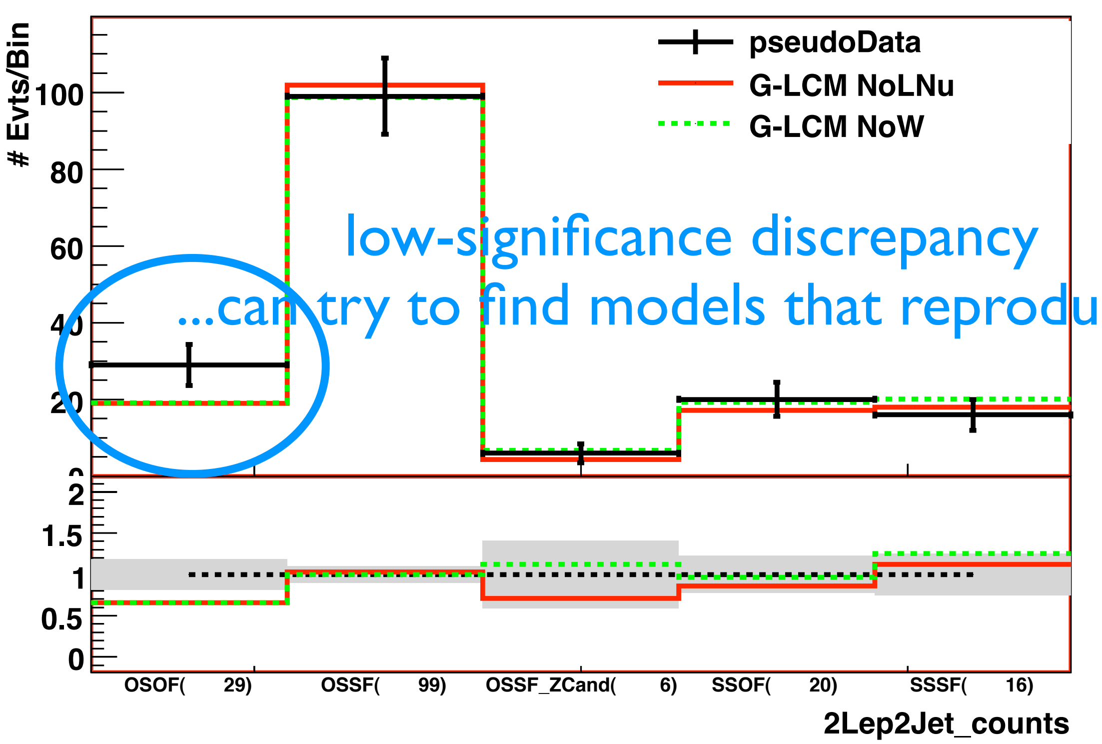
Constraining σ and BR’s

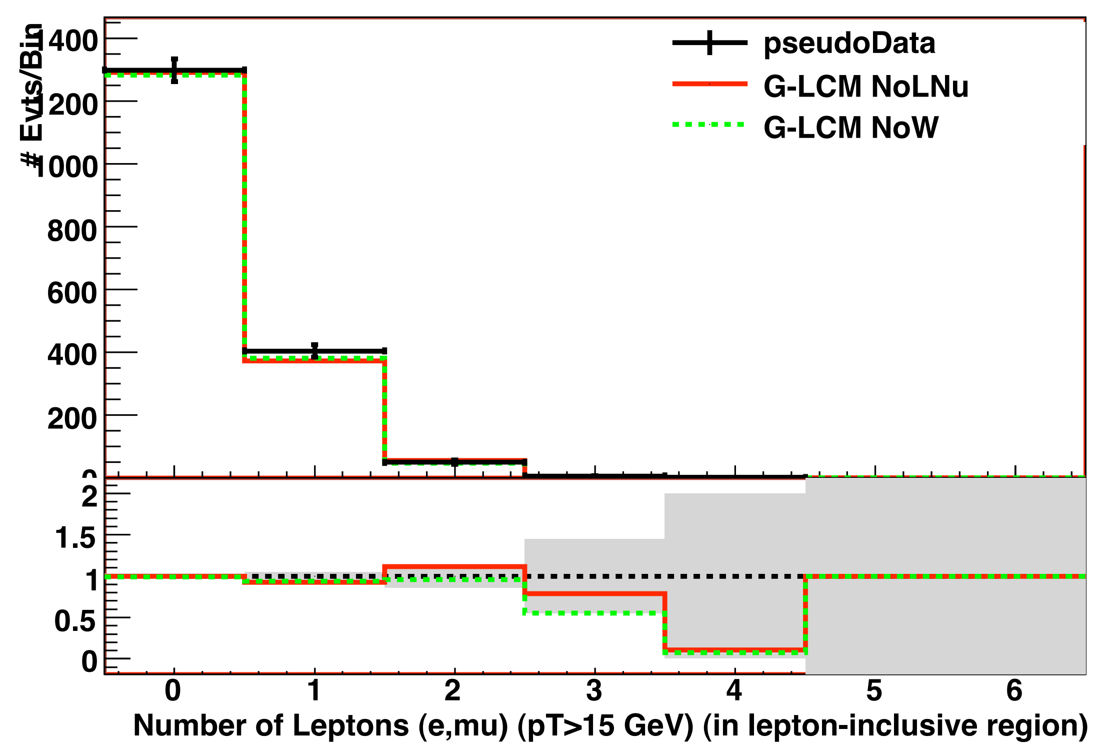
Branching ratios well constrained by these counts (aside from the W/Lnu ambiguity):

	σ (pb)	B_{LSP}	B_W	B_Z	B_{ll}	$B_{l\nu}$
Red	11.3	0.0	0.914	0.02	0.063	—
Green	13.1	0.613	—	0.03	0.052	0.30
± (**)	0.1	0.04	0.05	0.02	0.005	0.01

Masses:
Best fit to kinematics, with LSP fixed at 100 GeV

** Don’t take these errors too seriously!! No backgrounds, etc.





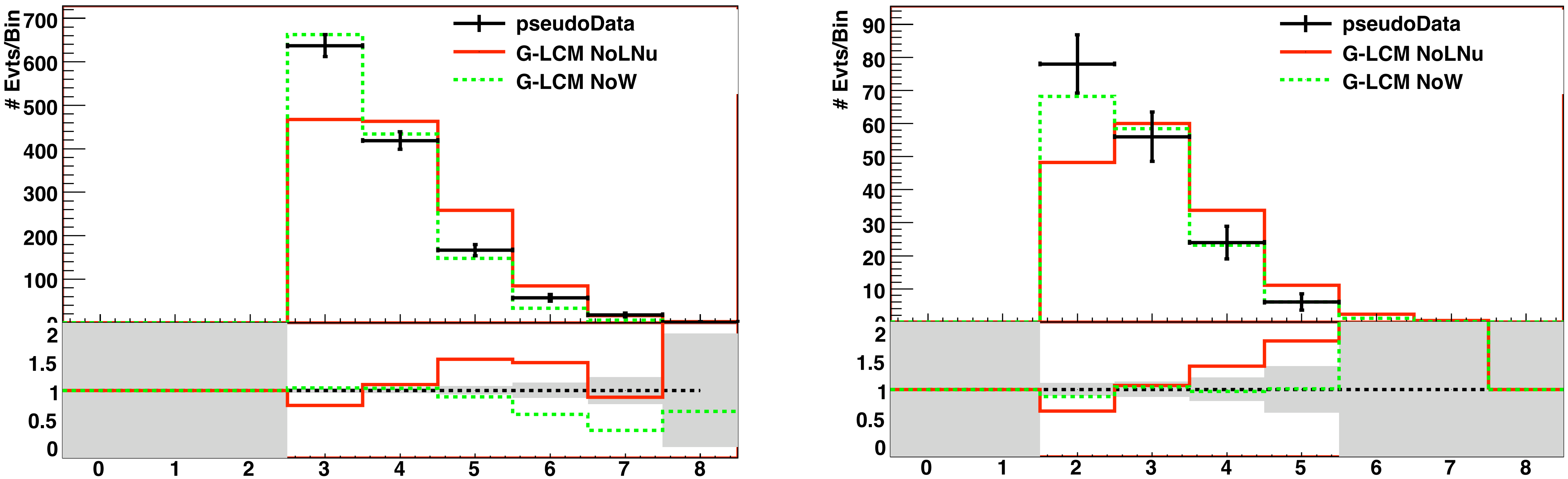
W vs lnu Modes

Within each of the two models (quark-partner or gluon-partner initiated), W↔(lν+direct) changes jet multiplicities, and

correlation with lepton counts.

Lepton-veto region

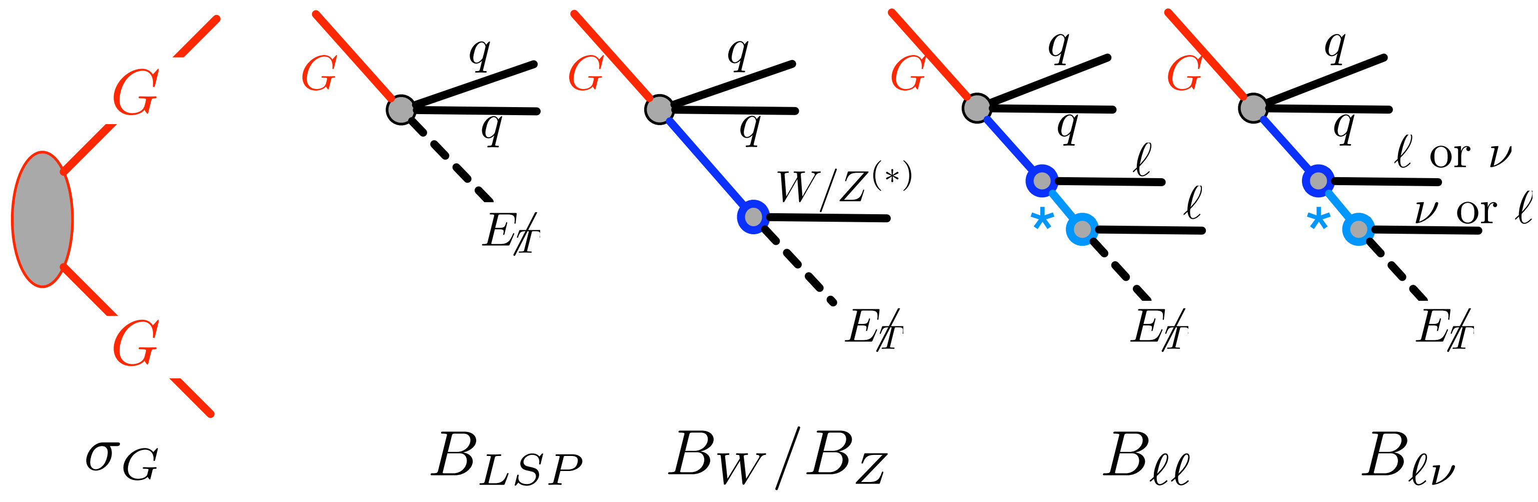
2-Lepton region (different cuts)



# of jets (p_T> 75 GeV) # of jets (p_T> 75 GeV)

(in some cases, lepton kinematics also constrains these fractions)

Constraining Masses



Masses

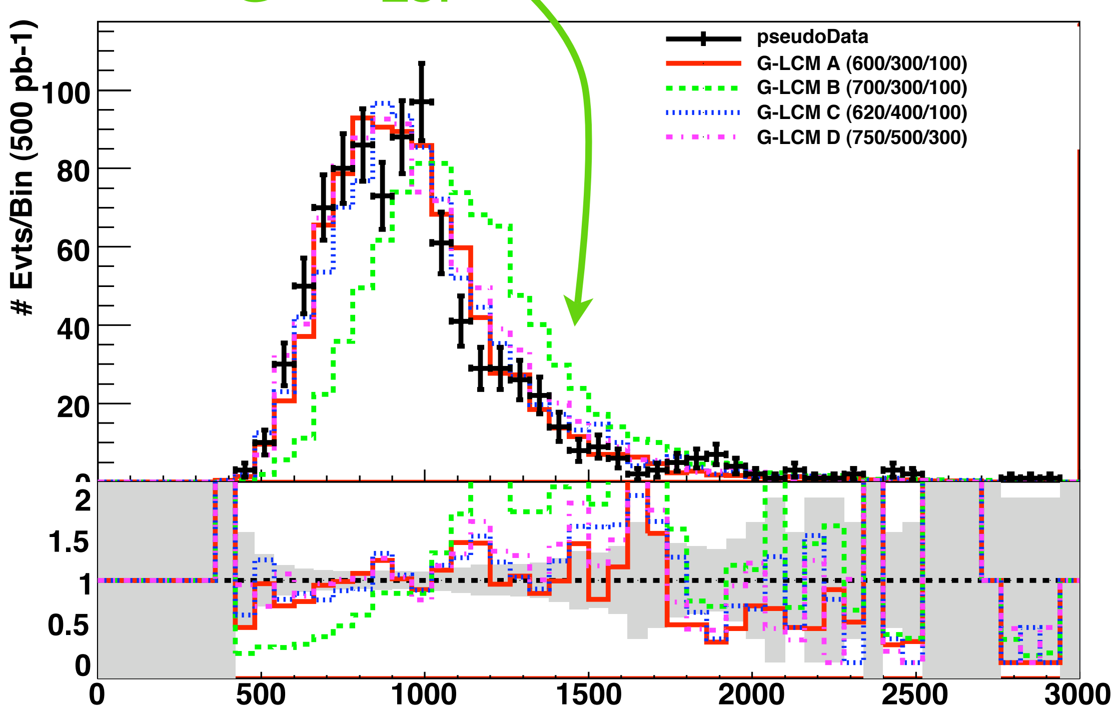
M_G

M_I

(M_L)

M_{LSP}

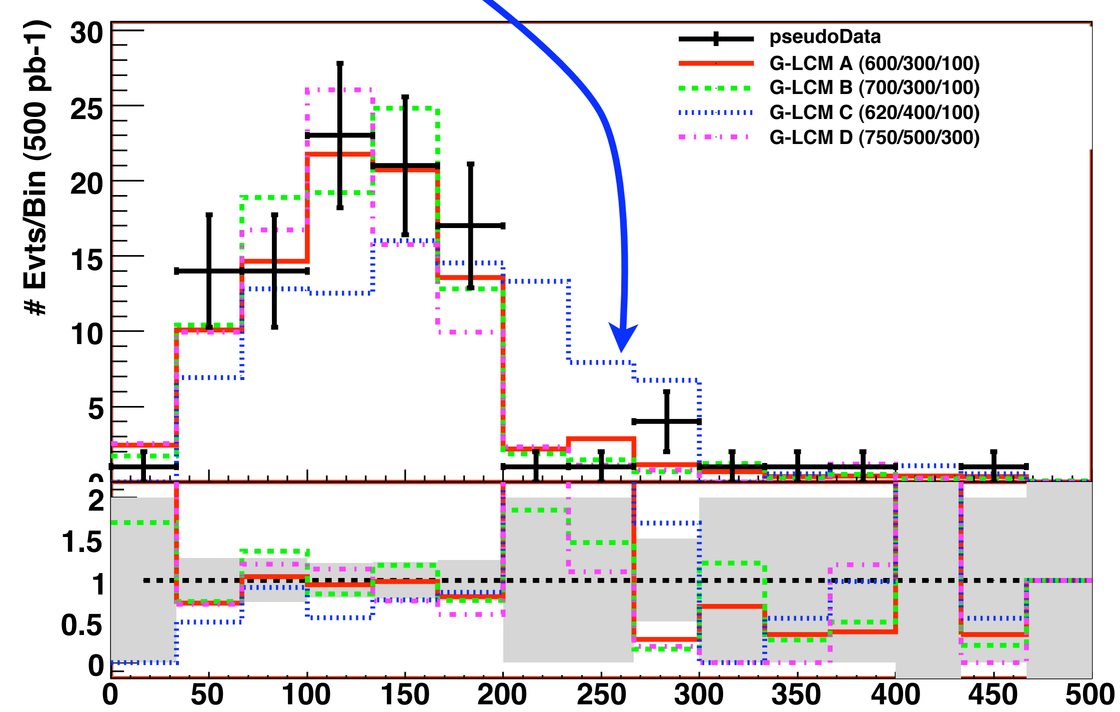
M_G-M_{LSP}:



$H_T=\sum p_T$ (GeV)

(sum over up to 4 jets + leptons
+ missing ET)

M_I-M_{LSP}:



OSSF (e+e- and μ+μ-) events:
di-lepton invariant mass

[note: this "data" is different from the other slides]

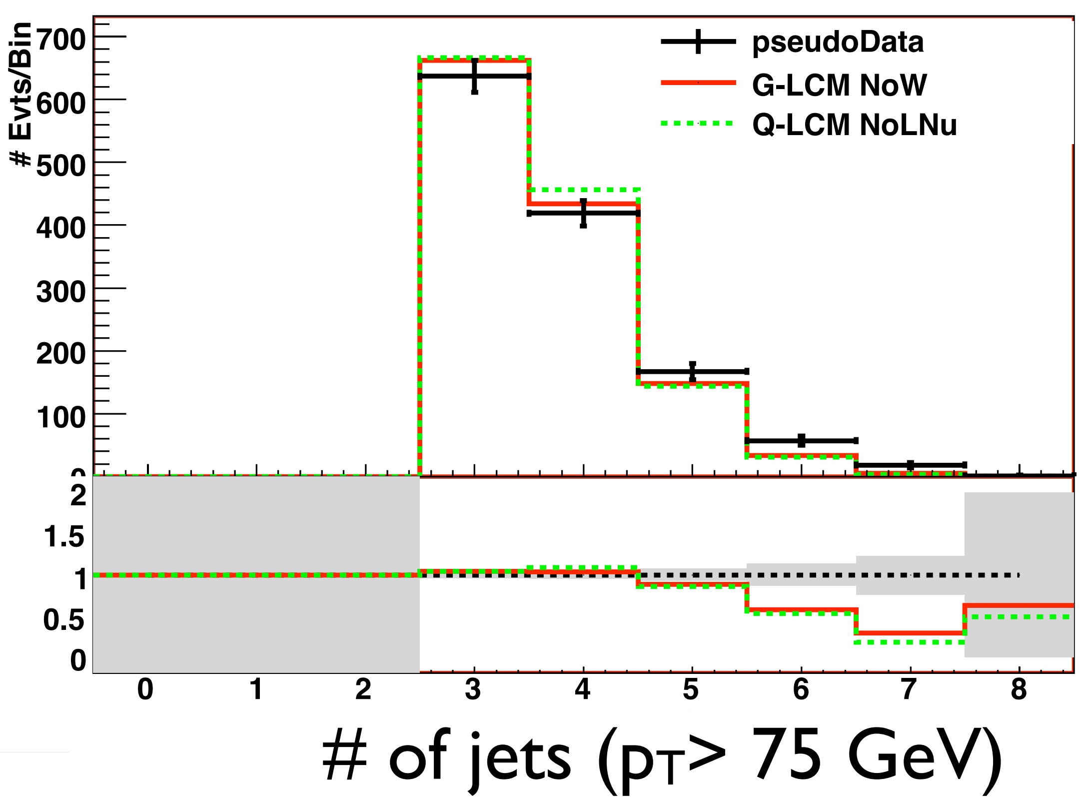
Comparing Gluon and Squark Partners

Two ways to get jet & lepton counts in simplified models:

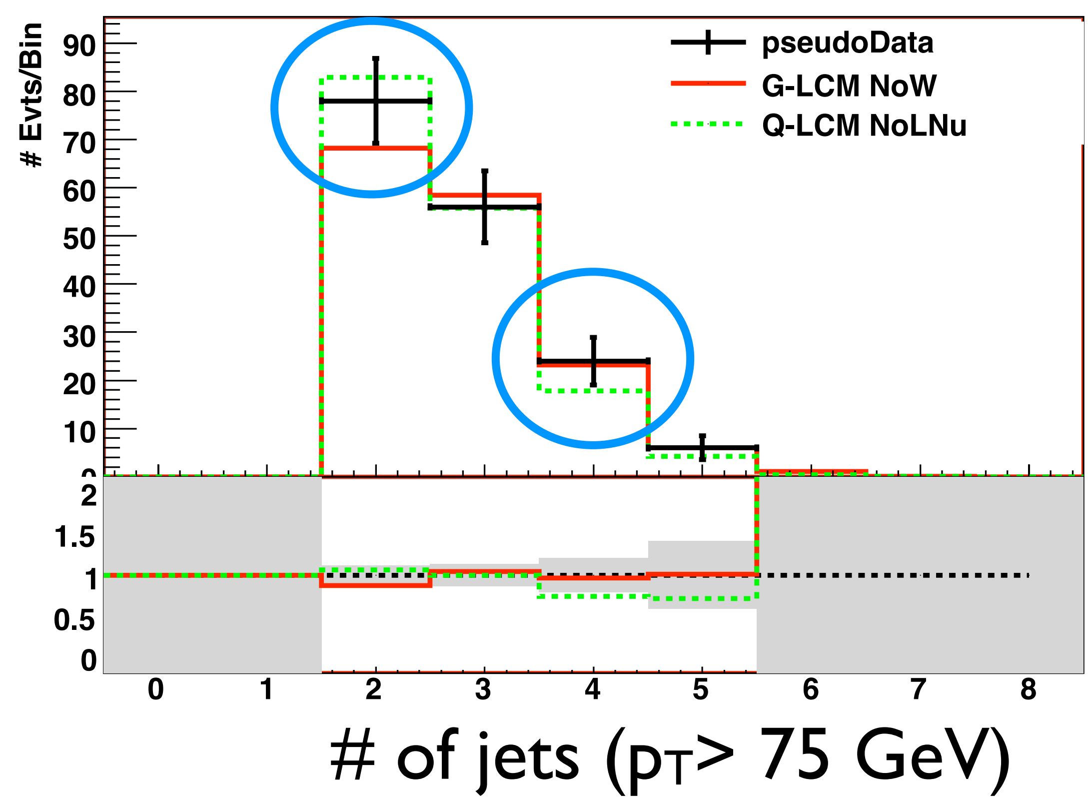
- quark partner decays to 1 jet with W's in cascades
- gluon partner decas to 2 jets with no hadronic W/Z in cascades

Real physics can interpolate between the two!

Lepton-veto region



2-Lepton region (different cuts)



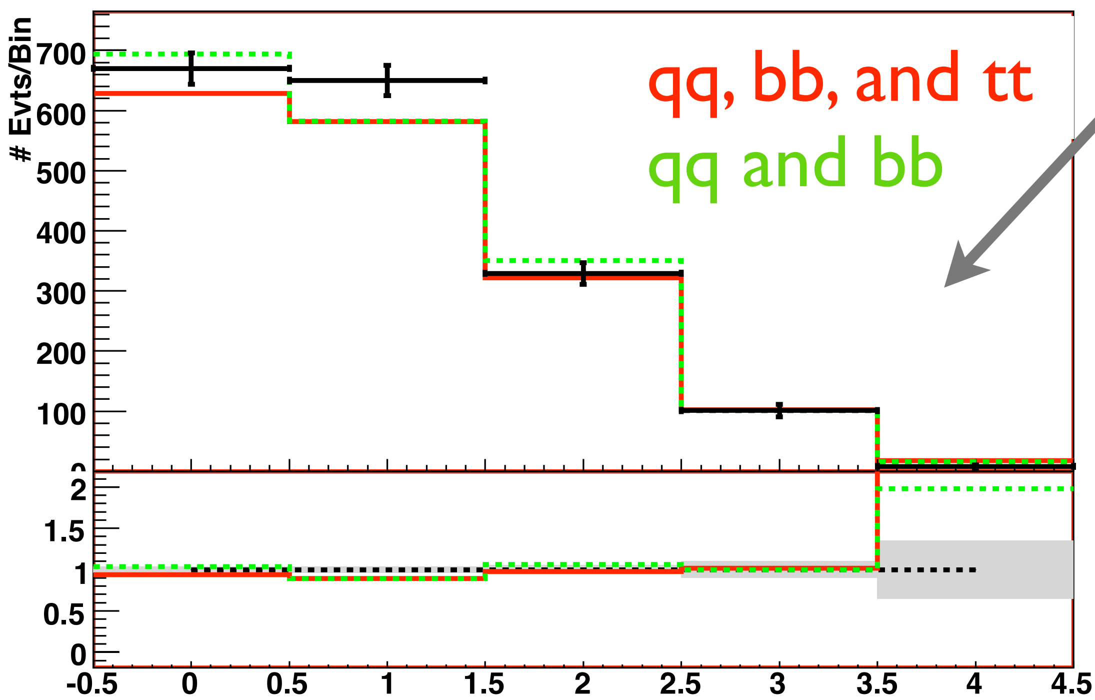
Models look different, but not distinguishable without more statistics!
Better observables also help.

Constraining σ and BR's

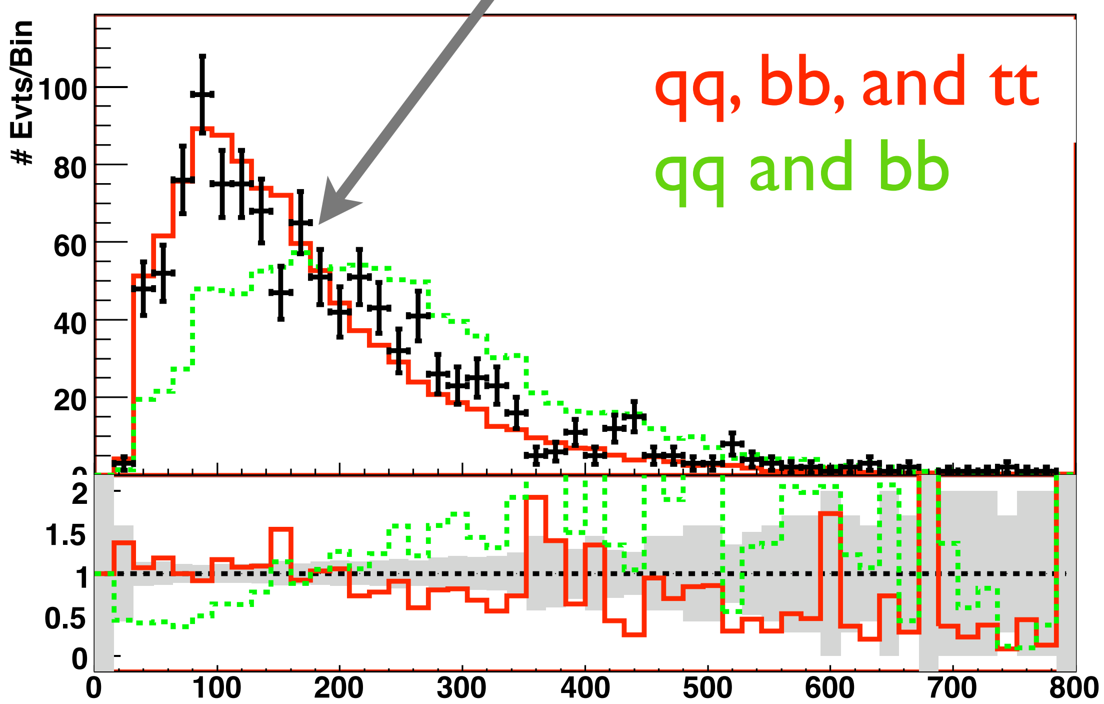
	σ (pb)	B_{qq}	B_{bb}	B_{tt}
Green	11.4	0.44	0.56	—
Red	11.4	0.33	0.03	0.64

Counts appear consistent with one pair-produced particle decaying to bb or q's (high heavy-flavor fraction)

b kinematics most consistent with top pairs



# of b-tagged jets (p_T > 30 GeV)



p_T of leading b-tagged jet

Constraining σ and BR's

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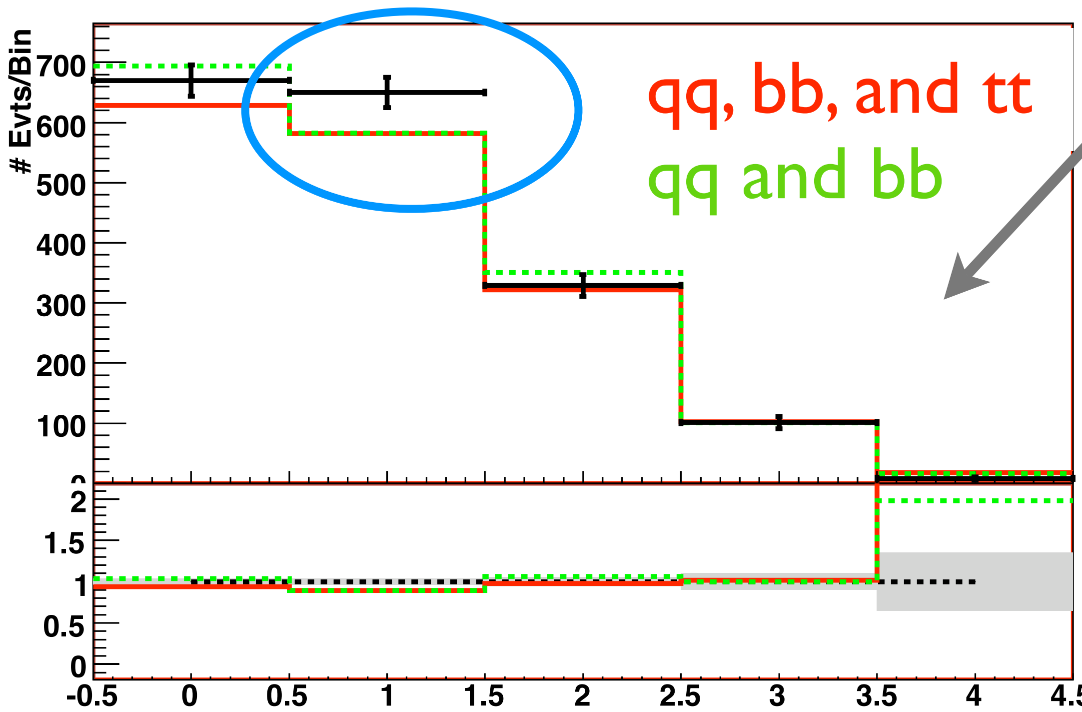

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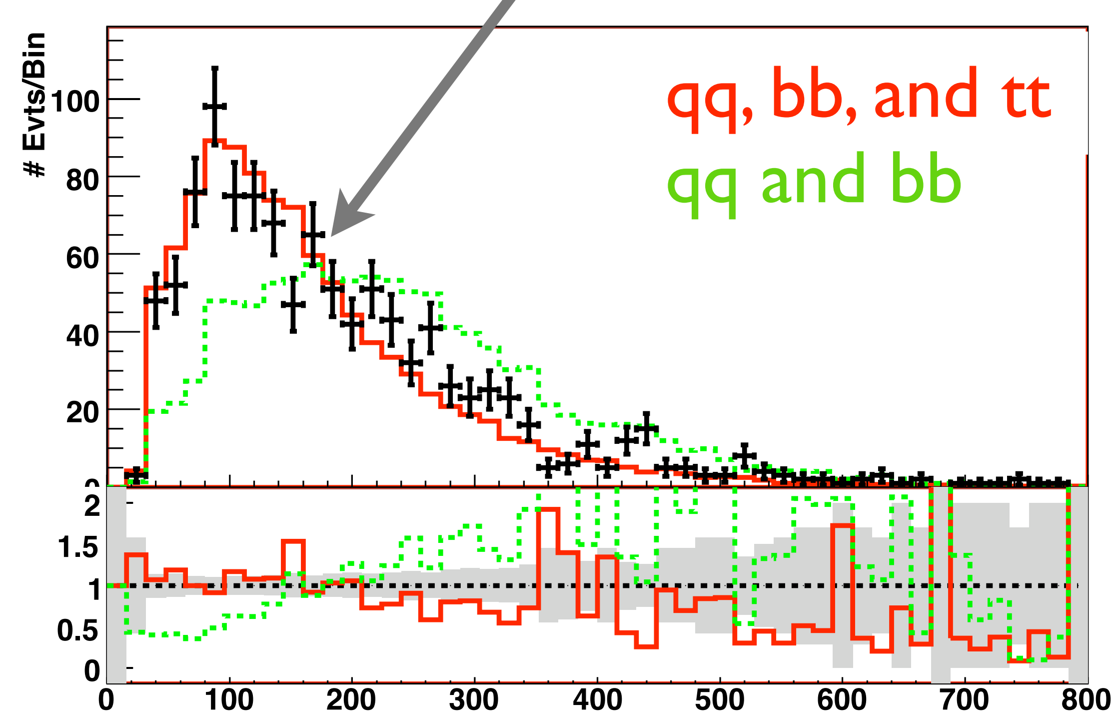

p_T of leading b-tagged jet

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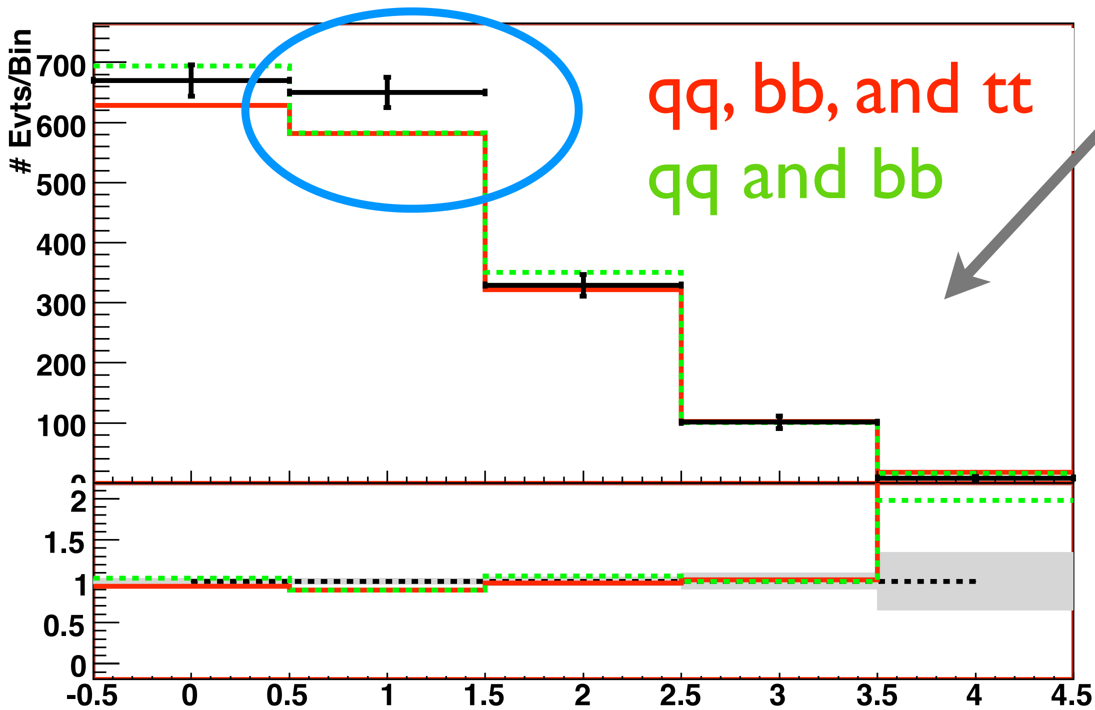
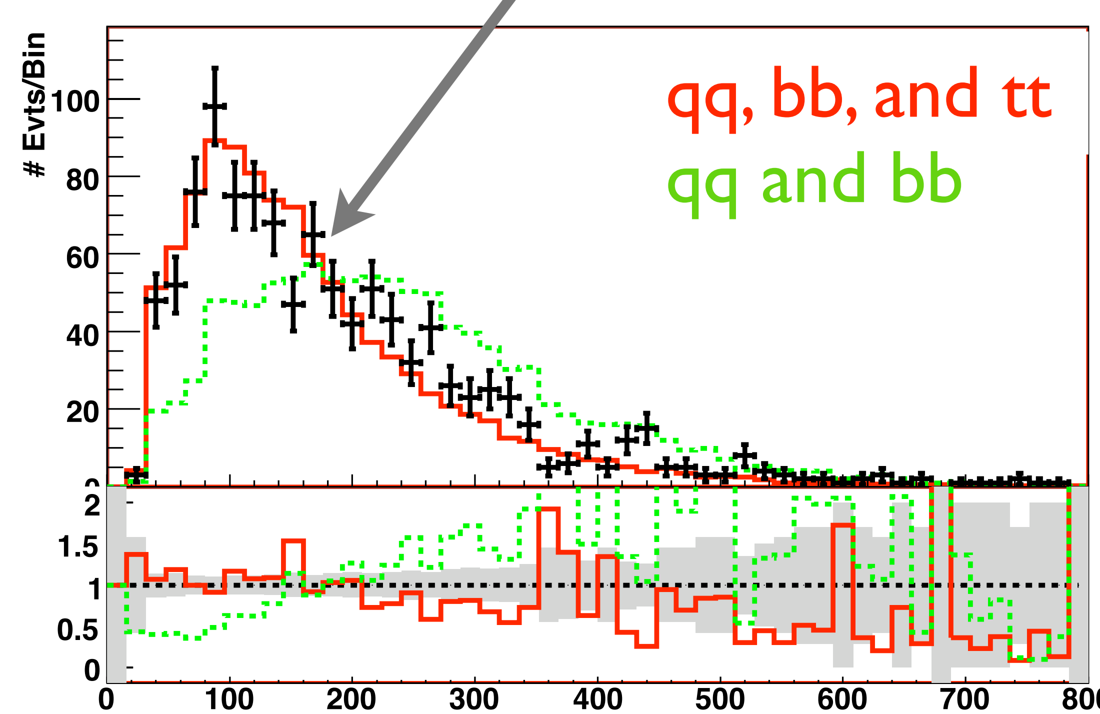


# of b-tagged jets (p_T > 30 GeV)



p_T of leading b-tagged jet

Weak deviation suggestive of additional 2b source that does not also imply 4b (e.g. in SUSY – top squark direct production, gluino-squark assoc. production)