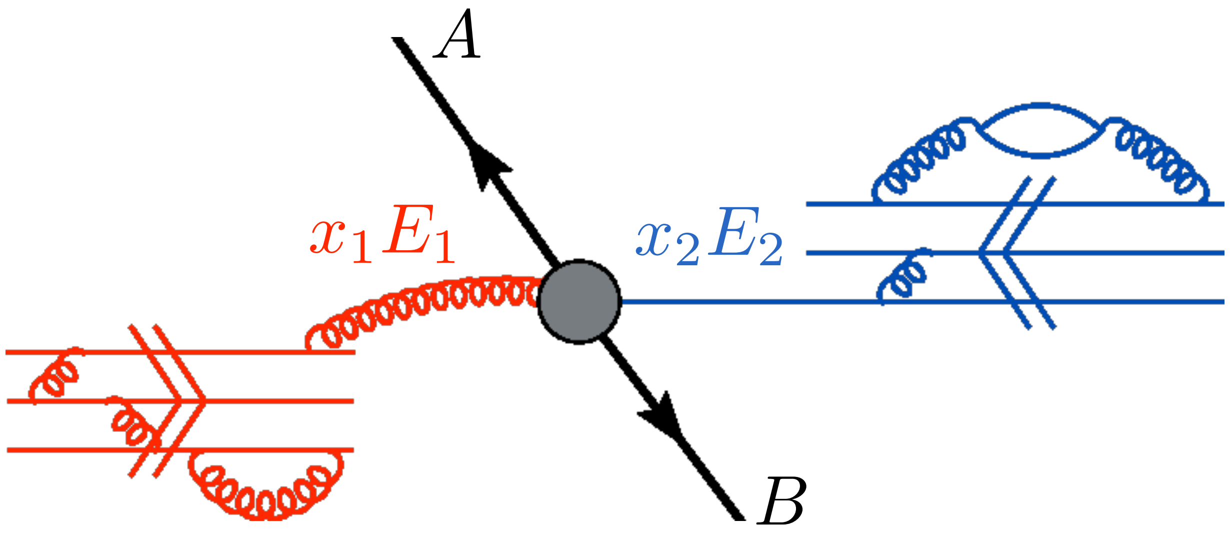
Unlocking the Structure of New Physics at the LHC

Natalia Toro

hep-ph/0703088:	Arkani-Hamed et al
0810.3921:	Alwall, Schuster, NT
work in progress:	UCSB CMS group (special thanks: S.A. Koay)

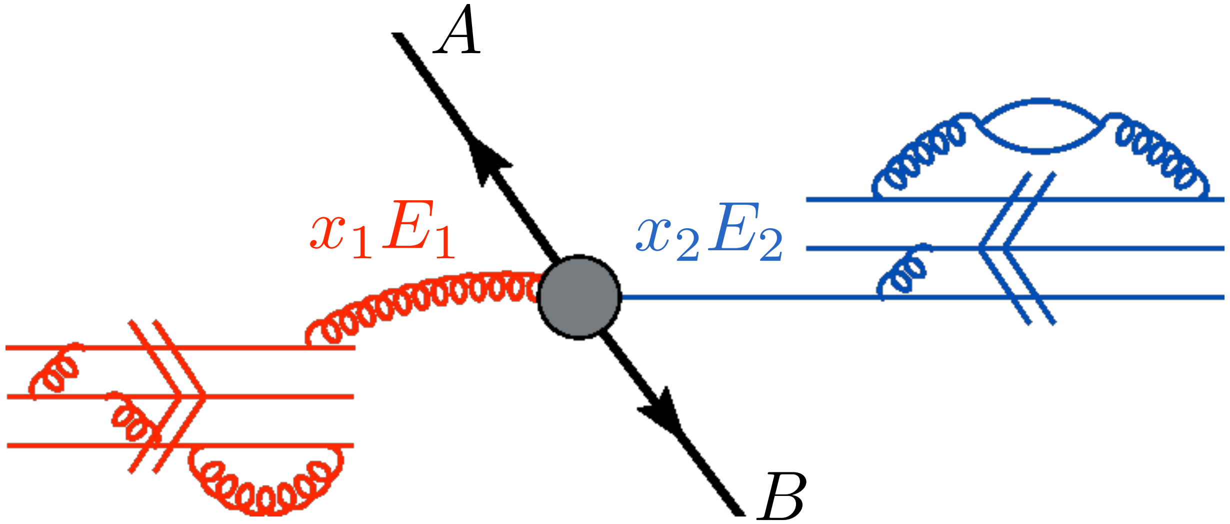
Hadron Collider 101



x_1, x_2: fraction of beam energy carried by each parton

$$\frac{d\sigma_{inc}}{d\mathrm{Vars}} = \int \frac{dx_1}{x_1}\frac{dx_2}{x_2} x_1 f_g(x_1, Q) x_2 f_q(x_2, Q) \frac{d\hat{\sigma}(qg \to AB)}{d\mathrm{Vars}}$$

Hadron Collider 101

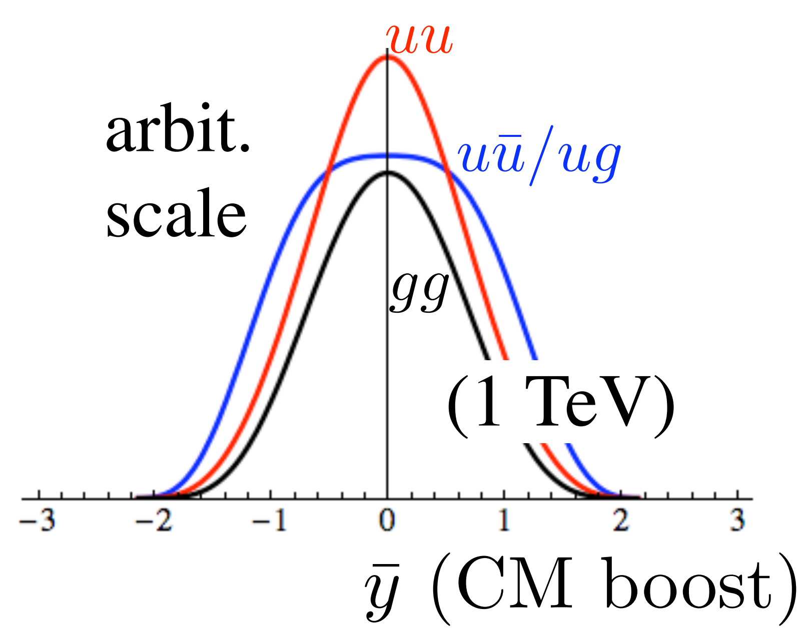


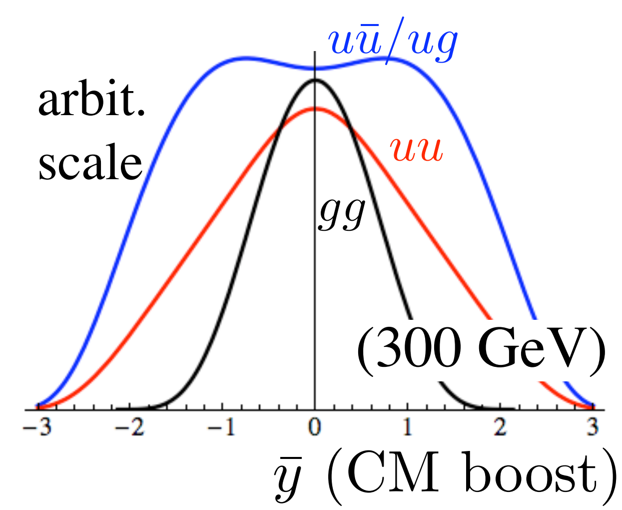
x_1, x_2: fraction of beam energy carried by each parton

$$\frac{d\sigma_{inc}}{d\text{Vars}} = \int \underbrace{\frac{dx_1}{x_1}\frac{dx_2}{x_2}}_{= \frac{d\hat{s}}{\hat{s}}\, d\bar{y}} x_1 f_g(x_1, Q)\, x_2 f_q(x_2, Q)\, \frac{d\hat{\sigma}(qg \to AB)}{d\text{Vars}}$$

parton E^2_{cm}

CM boost

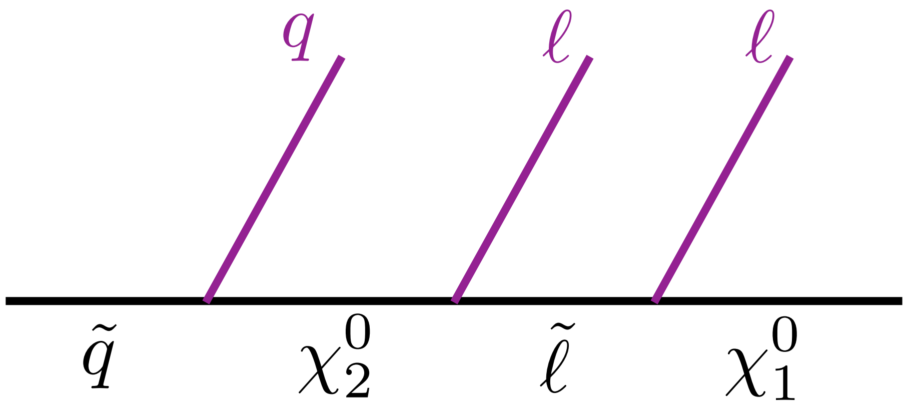




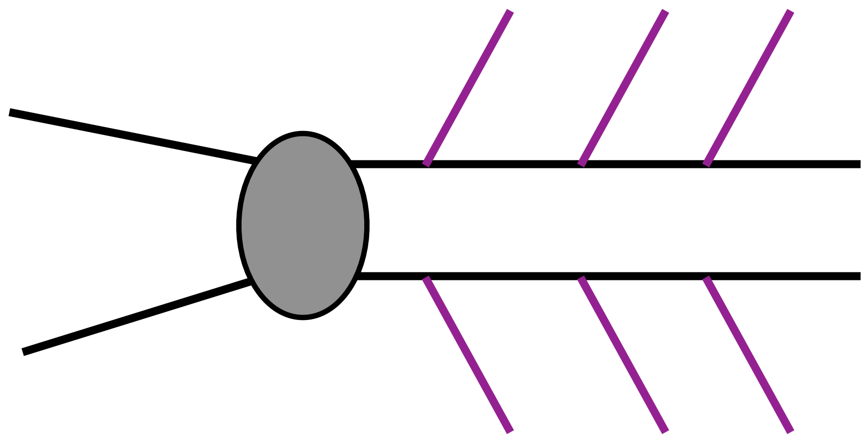
CM-frame boost ⇒multi-particle Lorentz invariants and p_T's

Multi-Particle Mass Invariants

Edge/endpoint:



Full reconstruction and m_{T2}:



Many more variables:

– precision mass measurement at hadron colliders!

To construct invariants, must pair/group particles.

To pair, must know decay topology. Not known *a priori*.

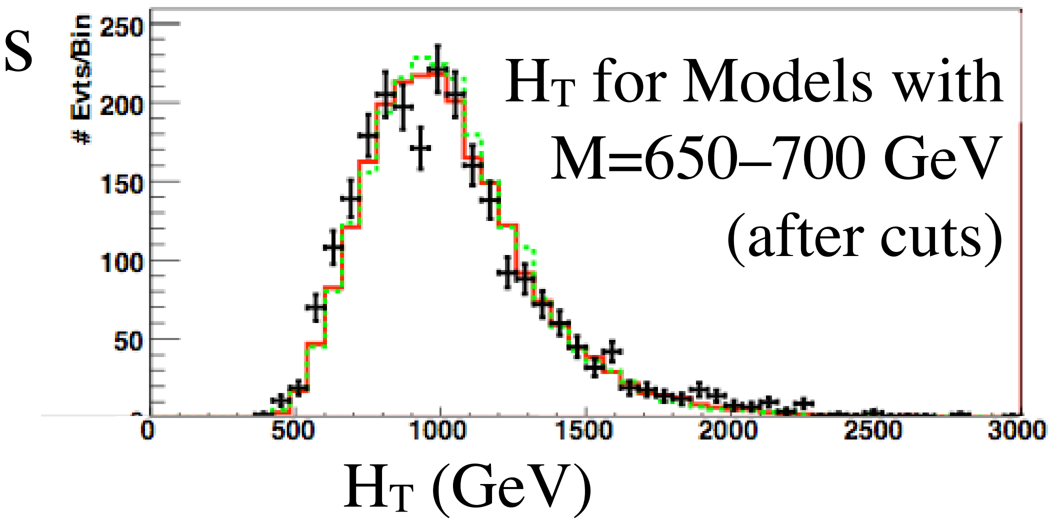
...100 fb^{-1}

What can be learned from simpler p_T's? (and lower statistics)

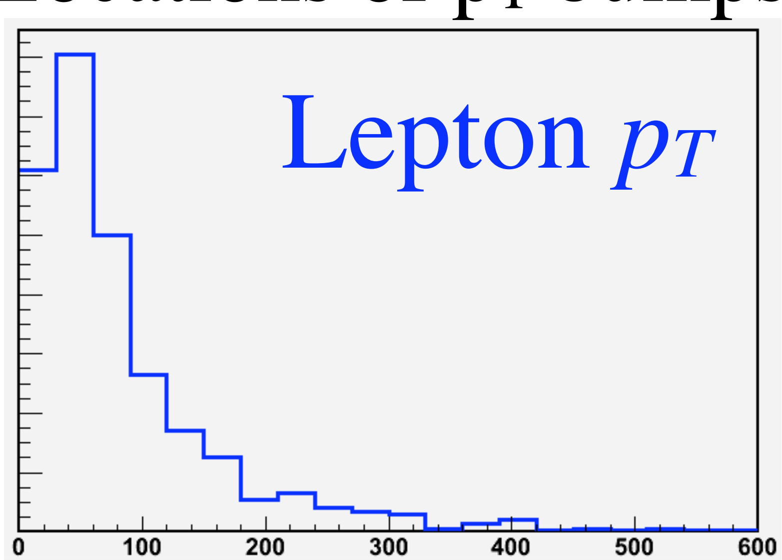
Using Transverse Momenta

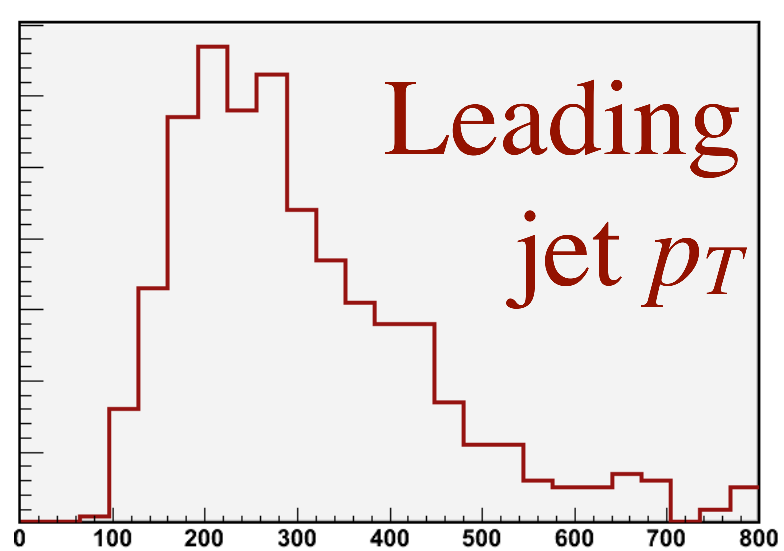
Useful combinations: $H_T = \sum |p_T|, \quad \cancel{E}_T = \sum \vec{p}_T$

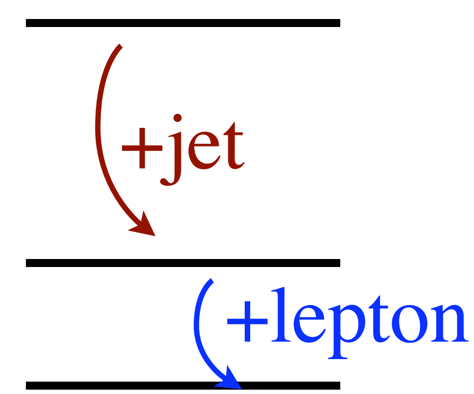
1) H_T bump ~ 1–2 x produced particle mass (depends on decay chain, LSP mass)



2) Locations of p_T bumps ~ relative mass scales







p_T, H_T, $\cancel{E}_T$ & counts are **search variables** → understood early.
They suffice to build good hypotheses for mass spectra, cascades, then isolate decay modes for precision mass measurement.

Outline

1. Hadron Collider Observables and Ambiguities
   - Goal: “Basis of Parameters” for new physics to model **most relevant** observables and address (subset of) theoretical questions.
   - p_T in Pair Production (mostly independent of M.E!)
   - p_T’s and counts insensitive to complex decay chains

2. Designing Robust and General New-Physics Searches

   (results from UCSB CMS group)

3. Building up from very simple description of new physics

p_T Distributions

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

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

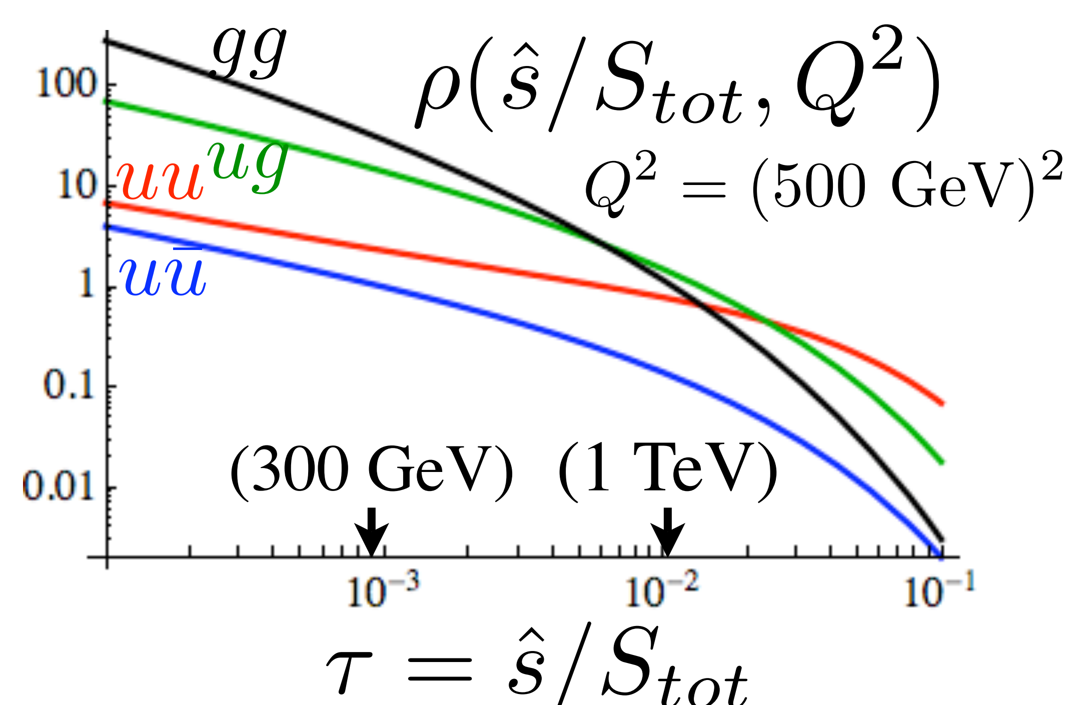
parton $E^2_{\rm cm}$ CM boost

$\int d\bar{y}$ → 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)



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

$\mathrm{p_T}$ Distributions

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

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

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

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

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

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

$\mathrm{p_T}$ Distributions

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

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

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

$$s_0^2 \frac{d\sigma}{dp_T^2} = \left(\frac{s_0}{S_{tot}}\right)^{-q} \sum_{m,n} C_{m,n} \int_{s_0+4p_T^2}^{S_{tot}} \frac{d\hat{s}}{\xi\hat{s}} (\hat{s}/s_0)^{m-q-2}\xi^n \qquad \hat{s}/s_0 = \frac{1+4p_T^2/s_0}{1-\xi^2}$$

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

p_T Distributions

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

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

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

$$s_0^2\frac{d\sigma}{dp_T^2} = \left(\frac{s_0}{S_{tot}}\right)^{-q}\sum_{m,n} C_{m,n}\int_{s_0+4p_T^2}^{S_{tot}} \frac{d\hat{s}}{\xi\hat{s}}(\hat{s}/s_0)^{m-q-2}\xi^n \qquad \hat{s}/s_0 = \frac{1+4p_T^2/s_0}{1-\xi^2}$$

$$= \left(\frac{s_0}{S_{tot}}\right)^{-q}\sum_{m,n} C_{m,n}\underbrace{\int_0^{\approx 1}\frac{2d\xi}{1-\xi^2}(1-\xi^2)^{-m+q+2}\xi^n}_{\text{Euler } B\text{-function}} \times \underbrace{(1+4p_T^2/s_0)^{m-q-2}}_{\text{shape independent of } n}$$

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....

Why bother?

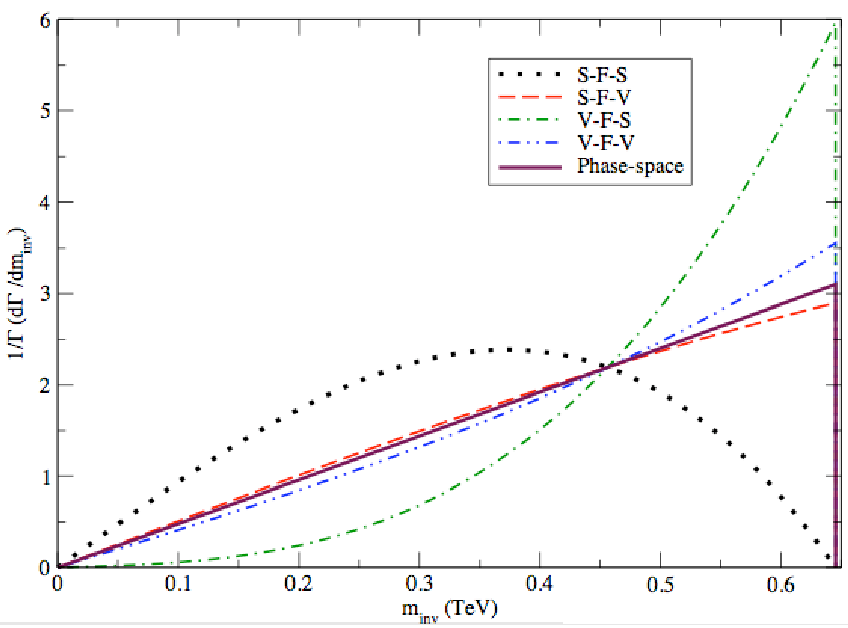
- Shape invariance: a clear guide to information that ***can be*** stripped out & still do meaningful analysis

- Why understand these?
  - Important (approximate) ambiguities to be aware of in **any** description of positive signal at LHC
  - Allows predictions, MC generation, *simulation of detector response* w/o full knowledge of model Lagrangian
  - Suggest search/interpretation strategies with **wide reach compared to no. of parameters**

How much do you need to say about model to predict LHC signals?

Specialize to models like SUSY – pair production, no fully-reconstructed decays

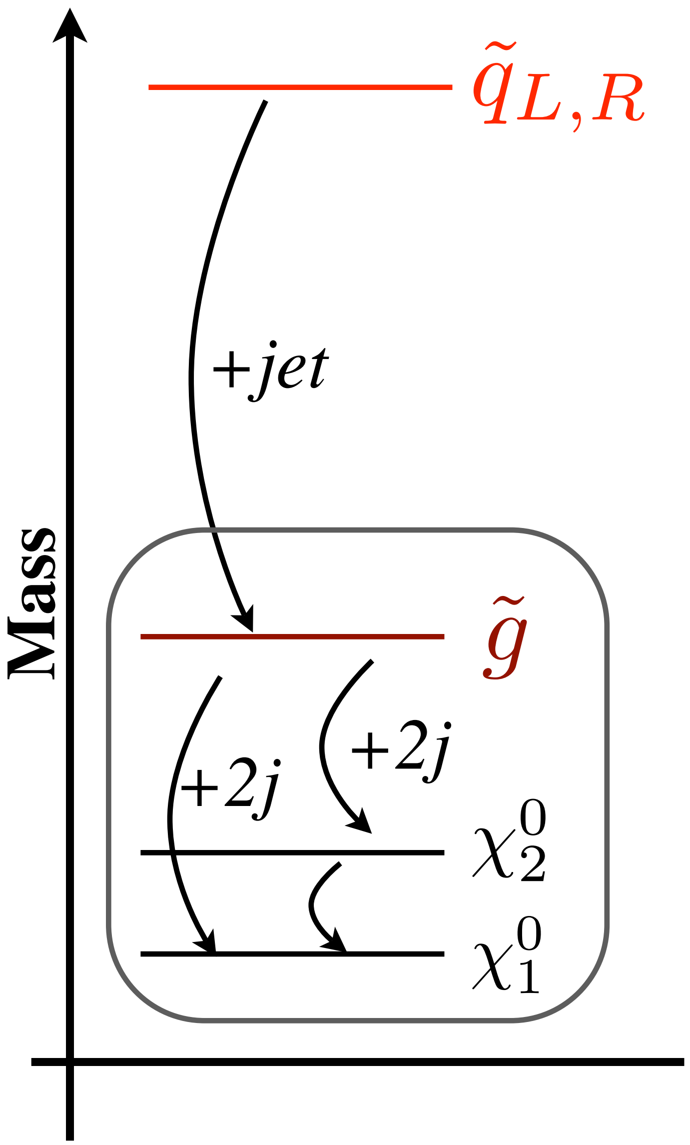
- Masses and quantum numbers of produced particles
- Production cross-sections (and near-threshold behavior)
- Branching fractions to different final states
- To predict *invariant mass distributions*, also need to know intermediate spins.



First three: **O**n-**S**hell **E**ffective **T**heory – hep-ph/0703088

Much less detail than full Lagrangian – but *even at this level* data can be ambiguous...

Squarks + Gluino Example

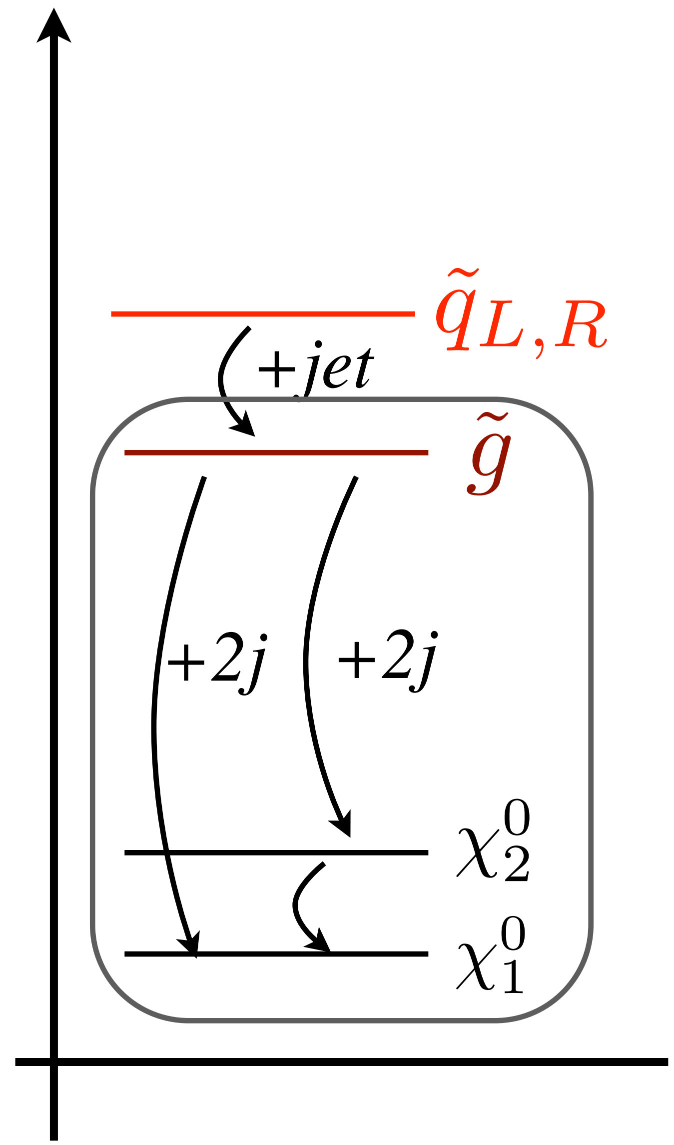


$$m_{\tilde{q}} - m_{\tilde{g}} \gg m_{\tilde{g}}$$

$$\Downarrow$$

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

can ignore squarks



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

$$\Downarrow$$

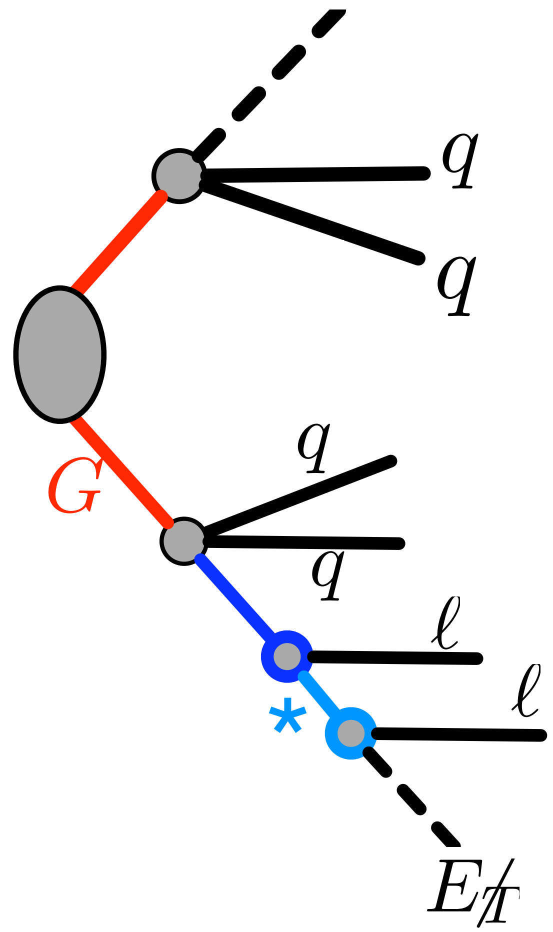
jet from squark decay **very soft**

can ignore squarks

Extreme spectra well described by fewer particles –> *can't resolve squark mass* in these cases

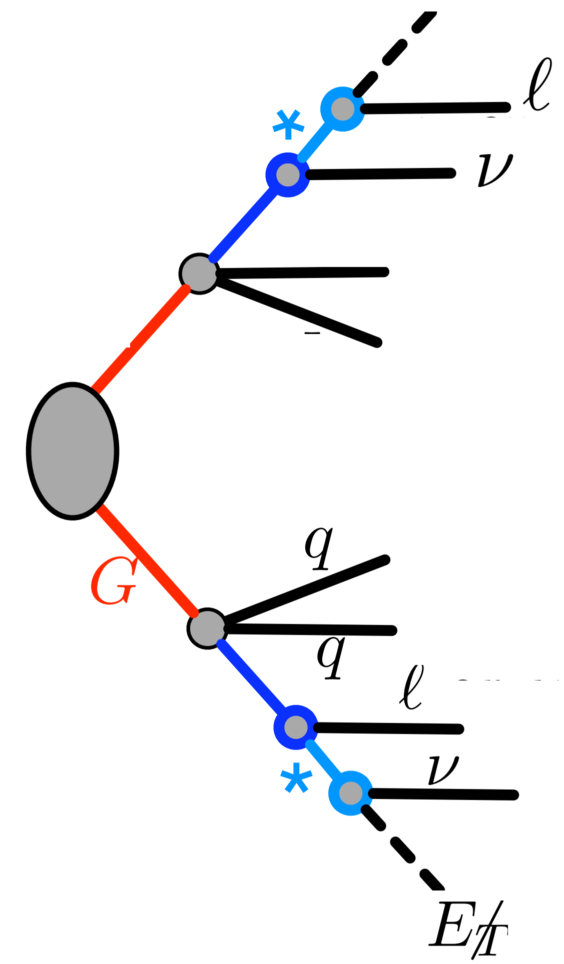
Overlapping Lepton Sources

Many handles: frequency of *n*-lepton events, flavor & sign correlations.



Two decay modes populate 0, 2, 4 leptons, flavor correlation

⟺ *distinguishable*

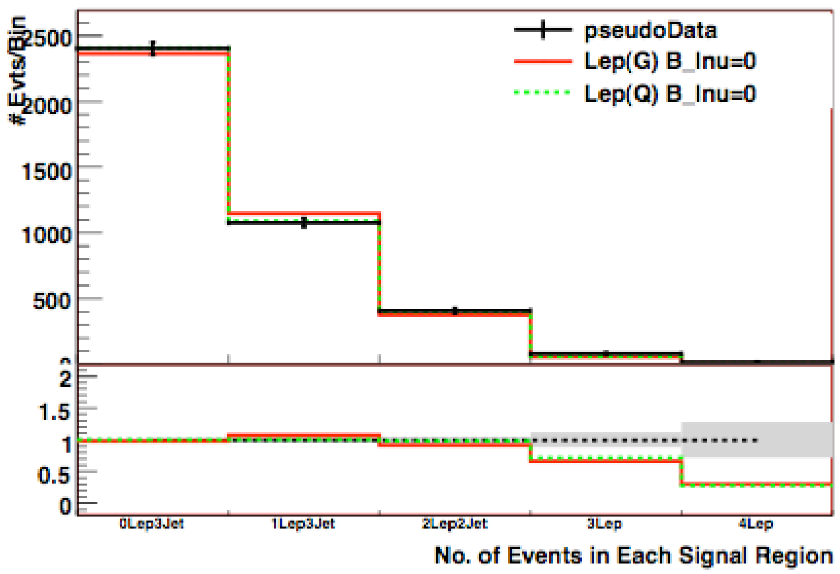


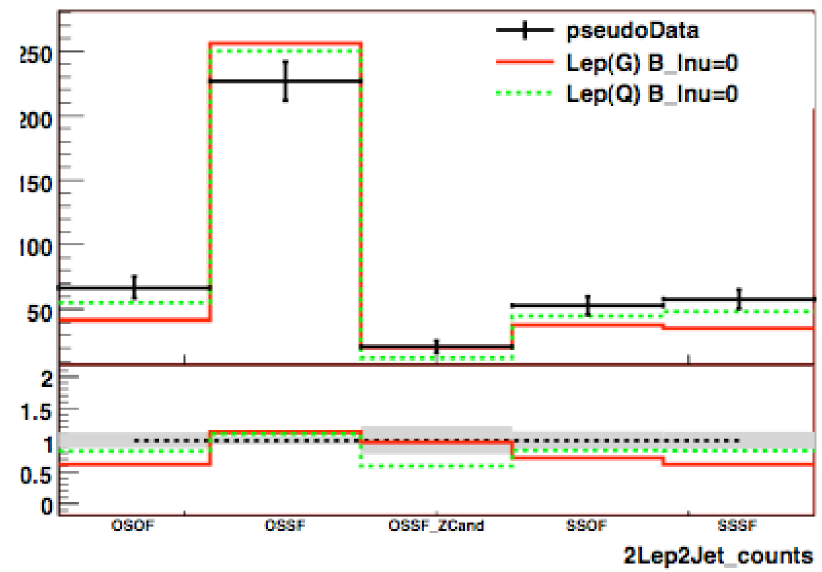
Just 2 flavor-uncorrelated leptons

but....

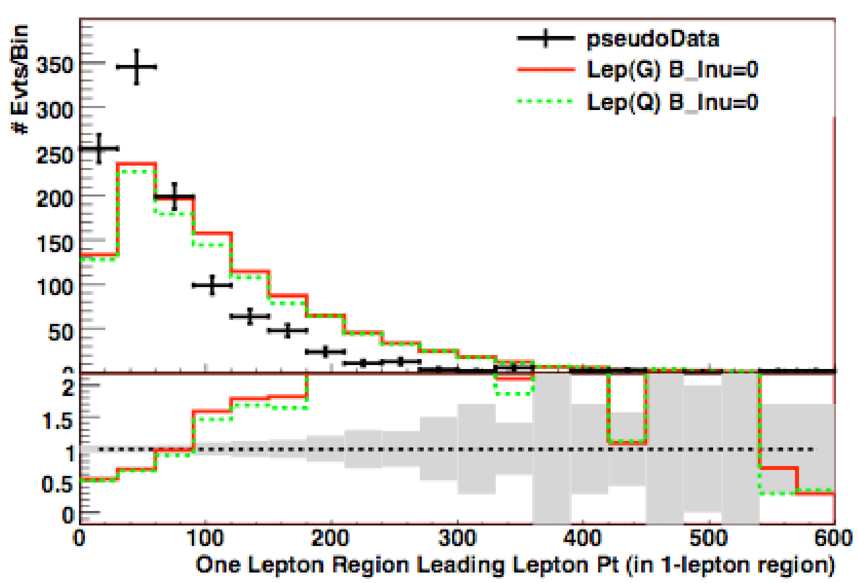
(Not) Resolving Leptonic Decays: An Example

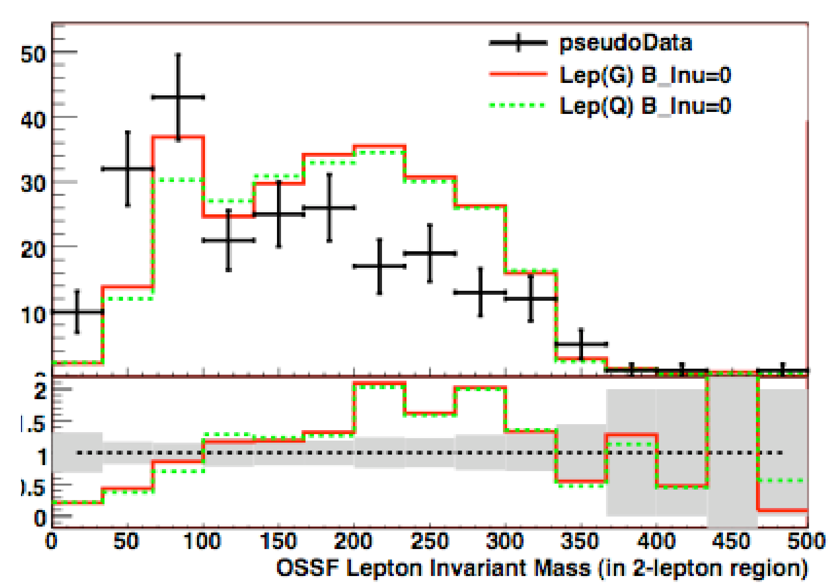
Counts:





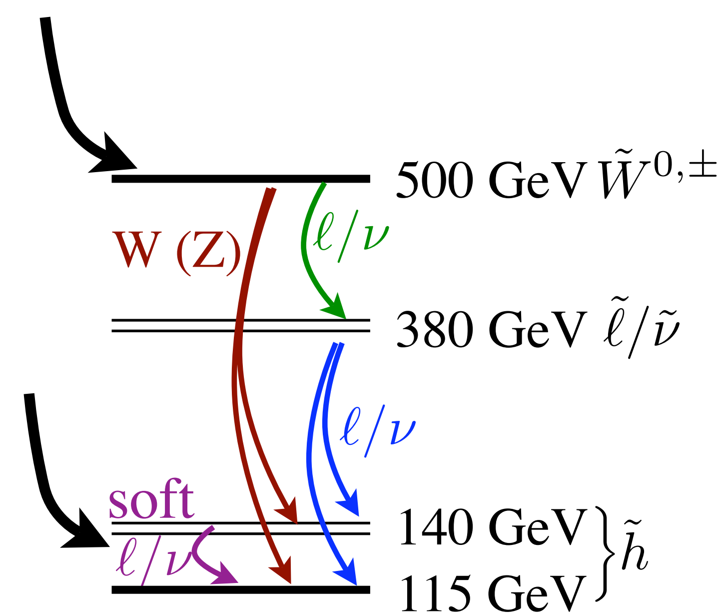
Kinematic distributions:





Points:

Model with very complicated cascades:



Red/Green:

One-stage fit
(2ℓ, W, Z, prompt)

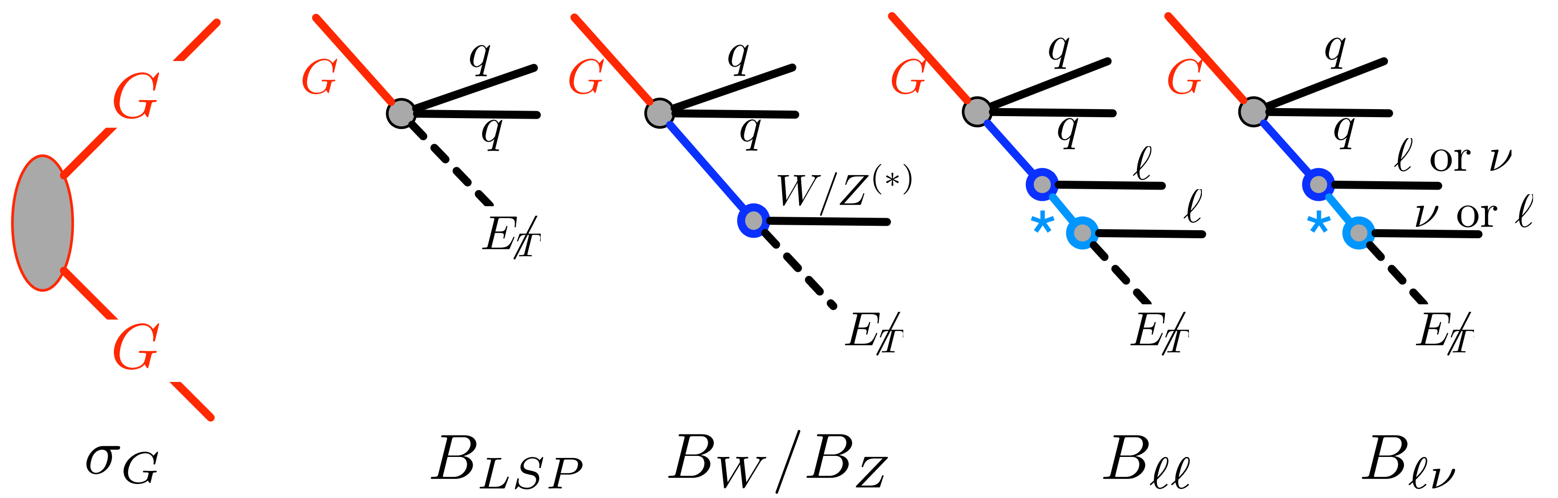
Summary

- If we're agnostic about sparticle orderings (even assume SUSY!):
  - Determining production matrix elements is hard
    (Excellent approximation: info. erased by PDF integration)
  - Determining spectrum and decay modes isn't easy
    (Overlapping processes)

- This is a **covenient misfortune!**
  - Artificially simple few-parameter models mimic wide range of SUSY (etc.) models well (in p_T's, some m's)
  - Search and first-pass characterization that is simple, broadly applicable, and transparent*
  - Precise starting point for building **evidence** of complex production/decay modes

Simplified Models of Lepton Cascades

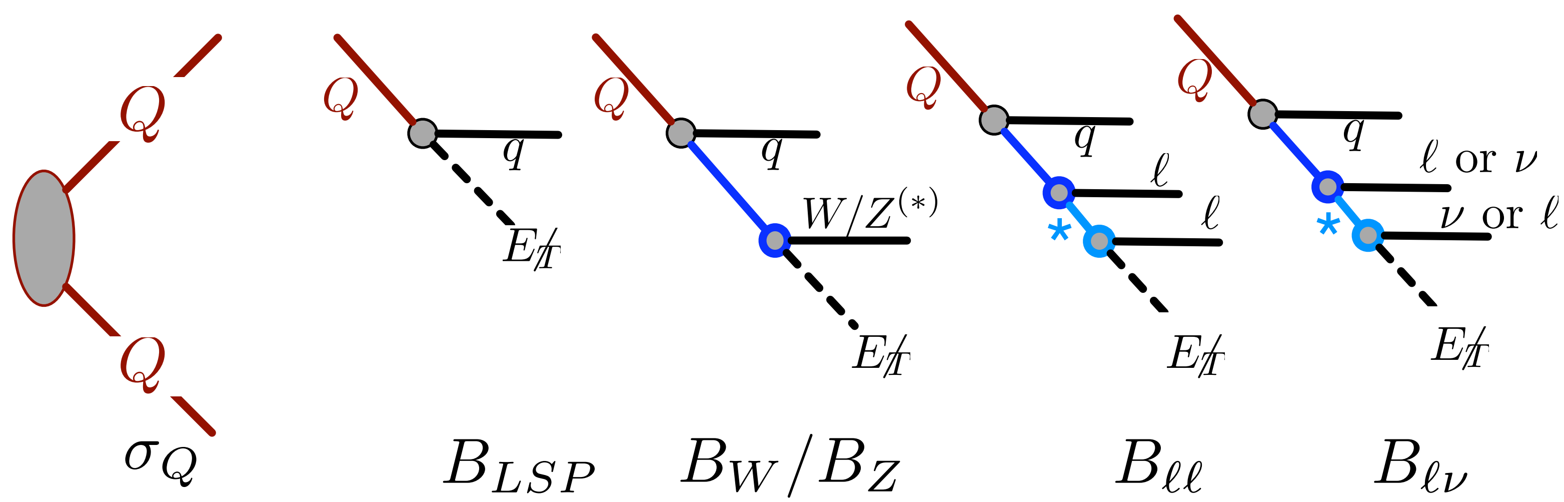
From gluon partner:



*on or off-shell

Masses
M_G
M_I
(M_L)
M_{LSP}

From quark partner:

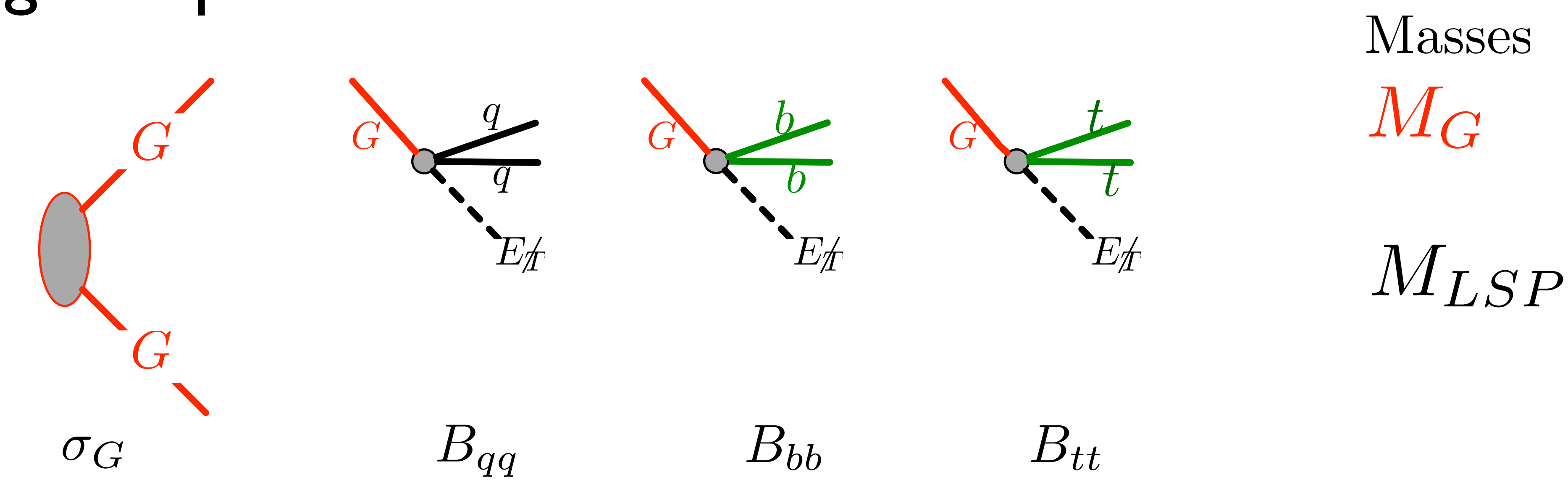


Masses
M_Q
M_I
(M_L)
M_{LSP}

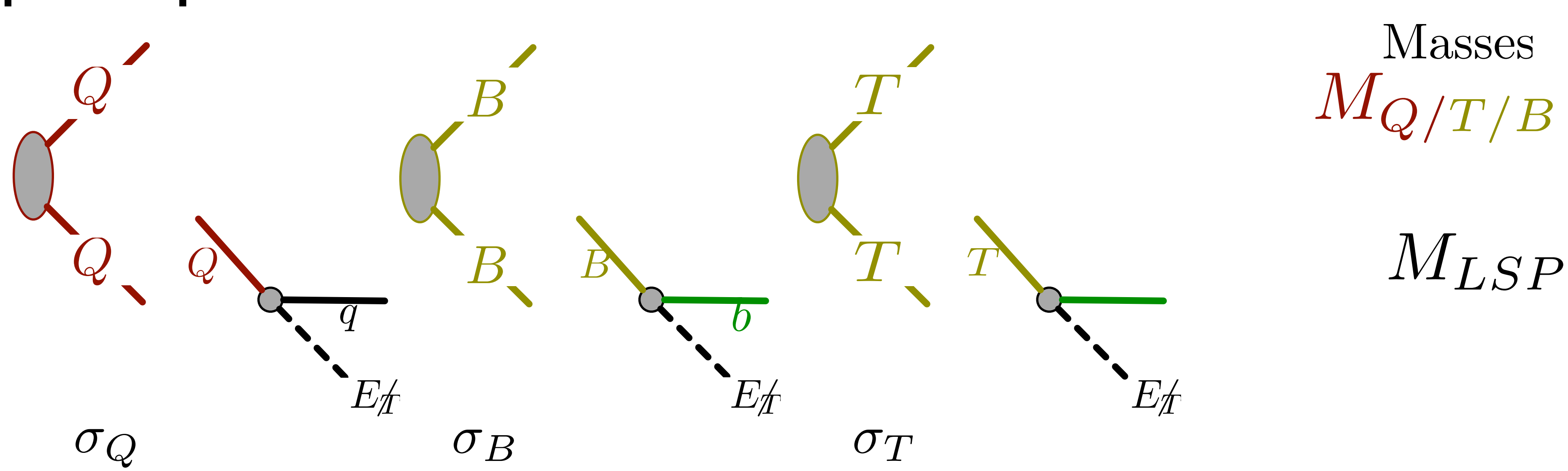
[Alwall, Schuster, Toro 0810.3921]

Heavy Flavor Models

From gluon partner:



From quark partner:



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

[Alwall, Schuster, Toro 0810.3921]

What Can We Learn Using Simplified Models?

1) Which colored particles dominate production?

Either Gluon partner G or Quark partner Q

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?

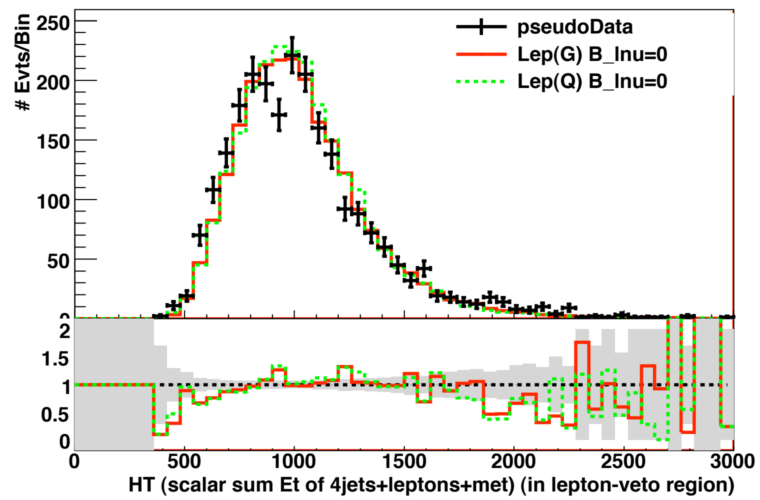
G: Produce gluon partners that decay to $q\bar{q}$, $b\bar{b}$, or $t\bar{t}$ +LSP

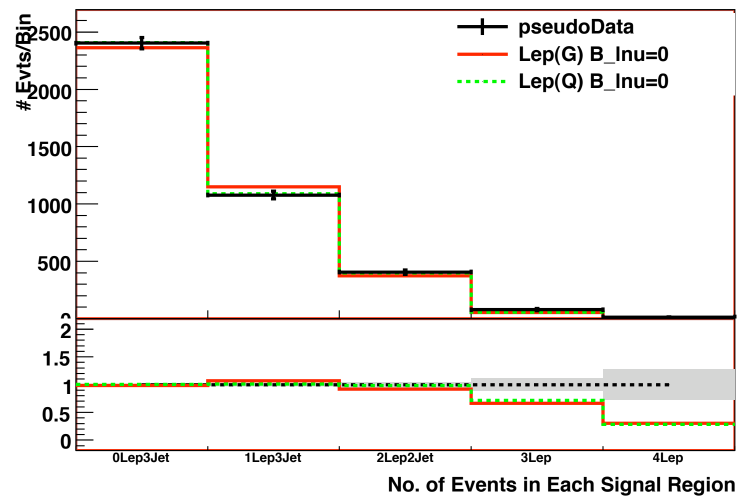
Q: Pair-produce parters of q_{12}, b, and t

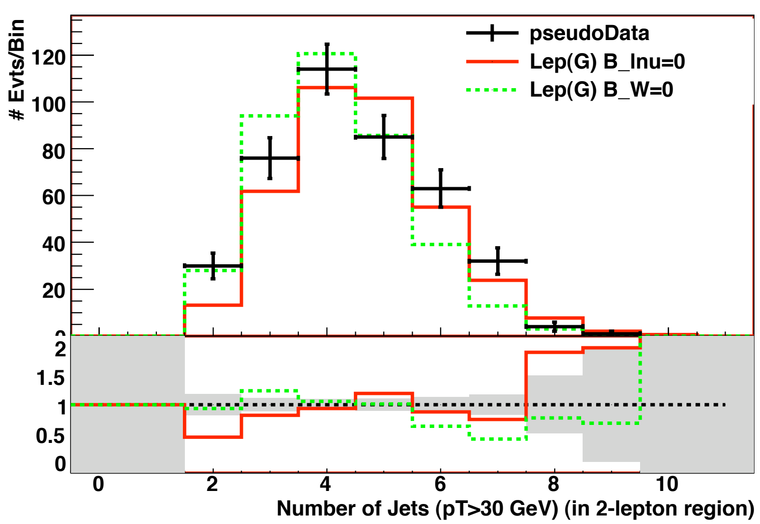
[Alwall, Schuster, Toro 0810.3921]

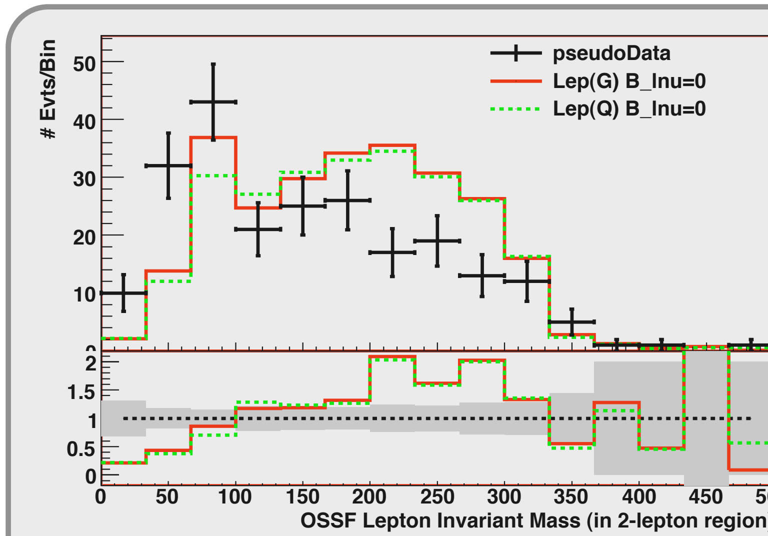
Surprising Success!

Leptonic

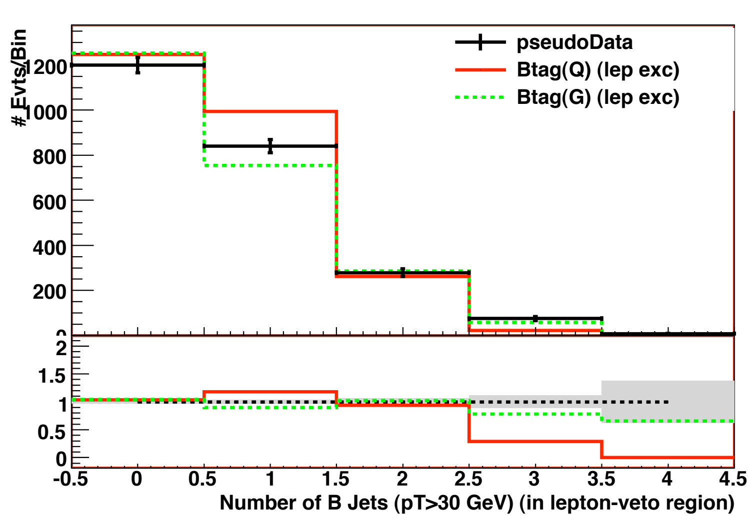


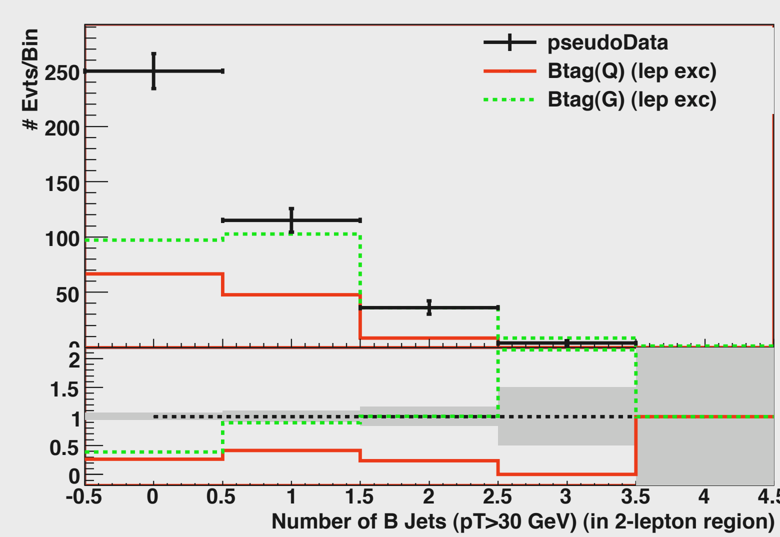




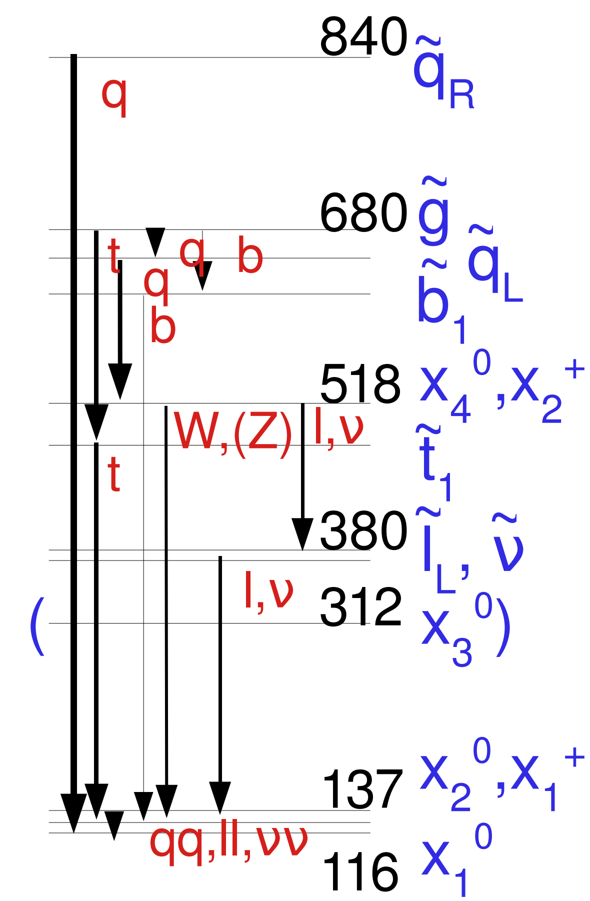


Heavy flavor





Example 2



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

Discrepancies hint at (specific!) additional structure, but extensions can't be fully constrained

Simplified Searches

- ***Optimize sensitivity*** to general models
- ***Present results*** for general models

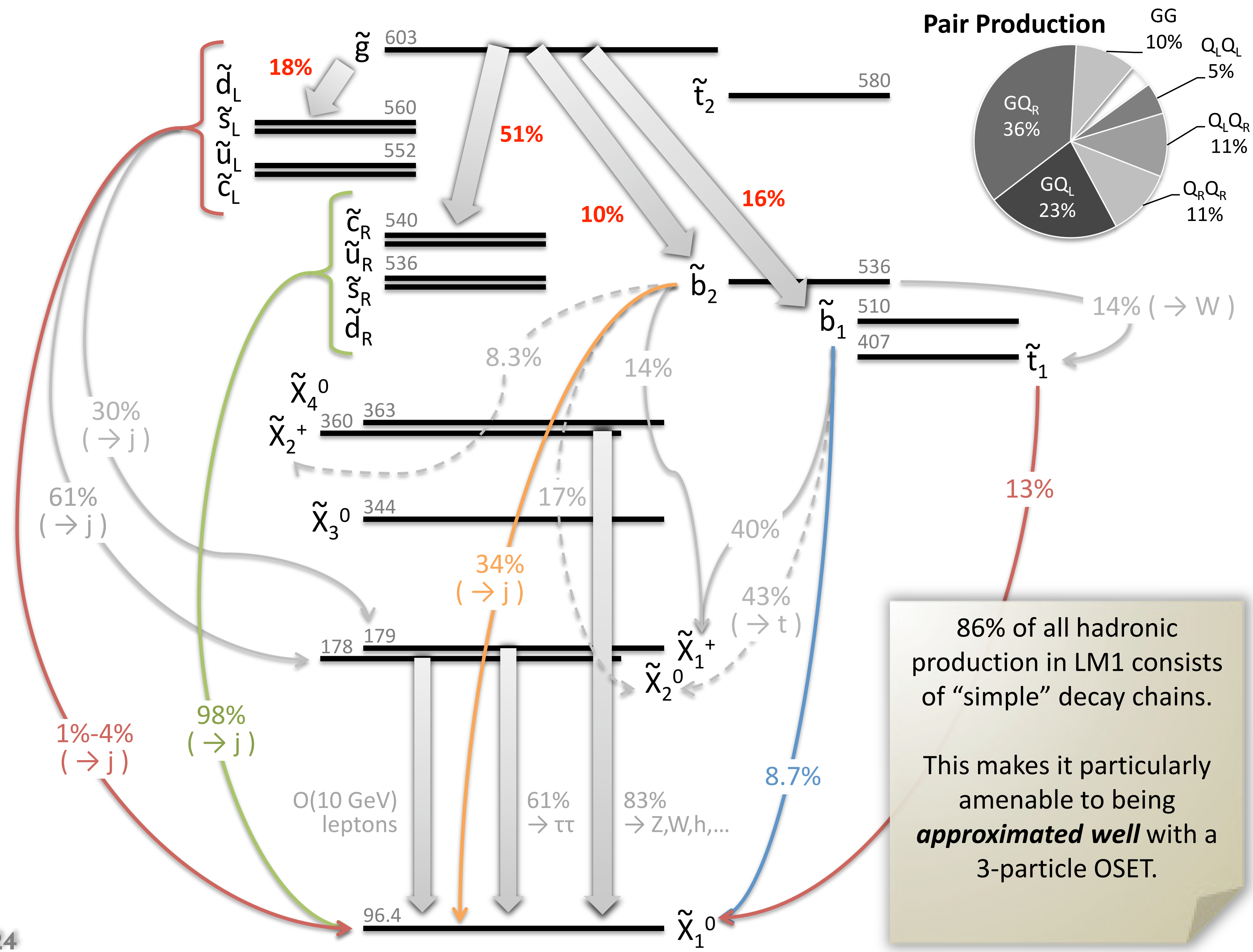
Design searches around individual topologies, with more softer or few harder jets.

(work in progress by UCSB CMS group)

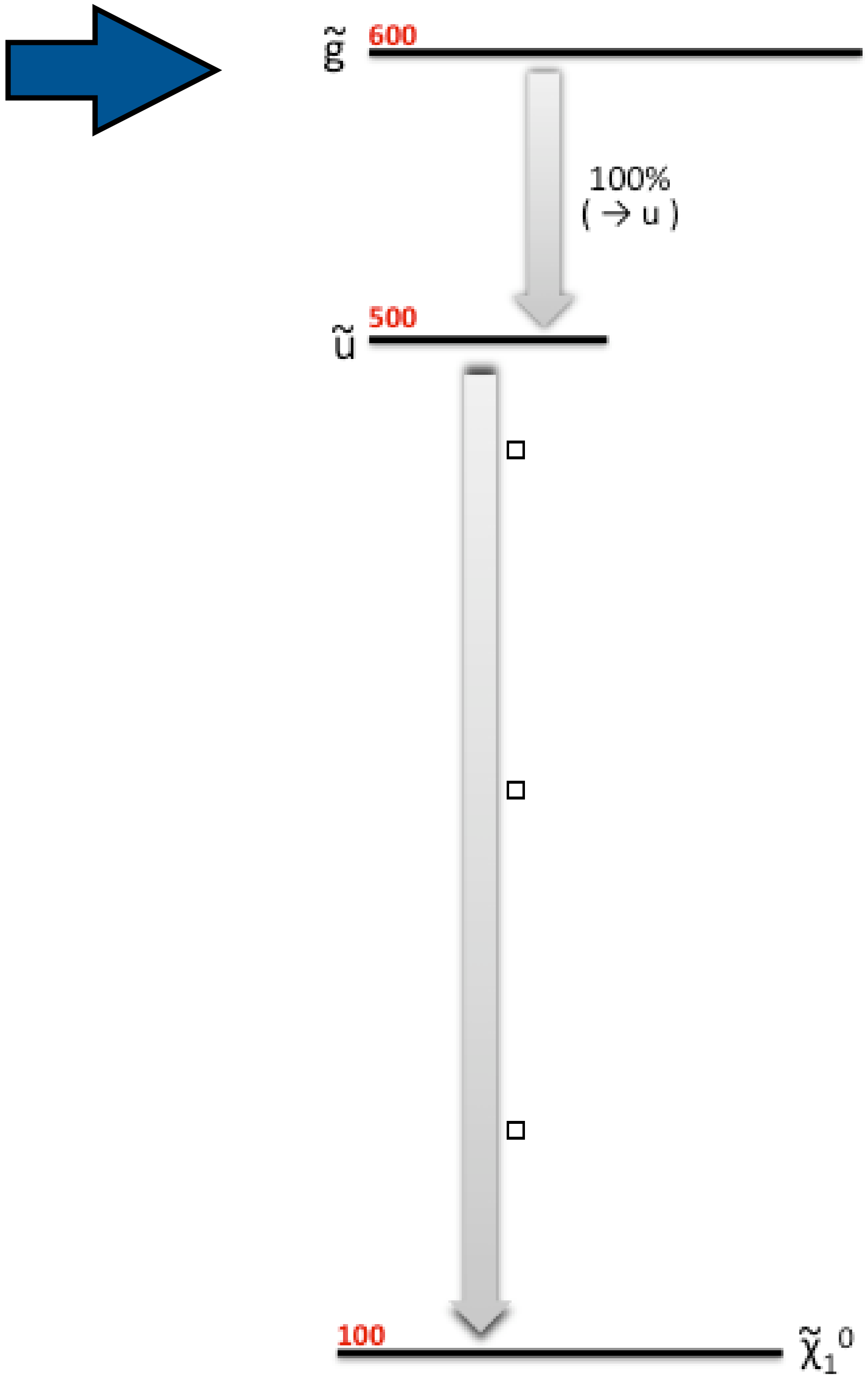
- Current study: **hadronic** searches (leptonic search study underway)
- First step: Validation of mSUGRA benchmark points LM*
  - Make sure LM* distributions are reproduced
  - Then topology-based searches guaranteed to be sensitive to LM* – ***"first, do no harm"***

e.g. Production modes in the LM1 Benchmark:

(after hadronic search cuts: lepton veto, 3 or more jets)



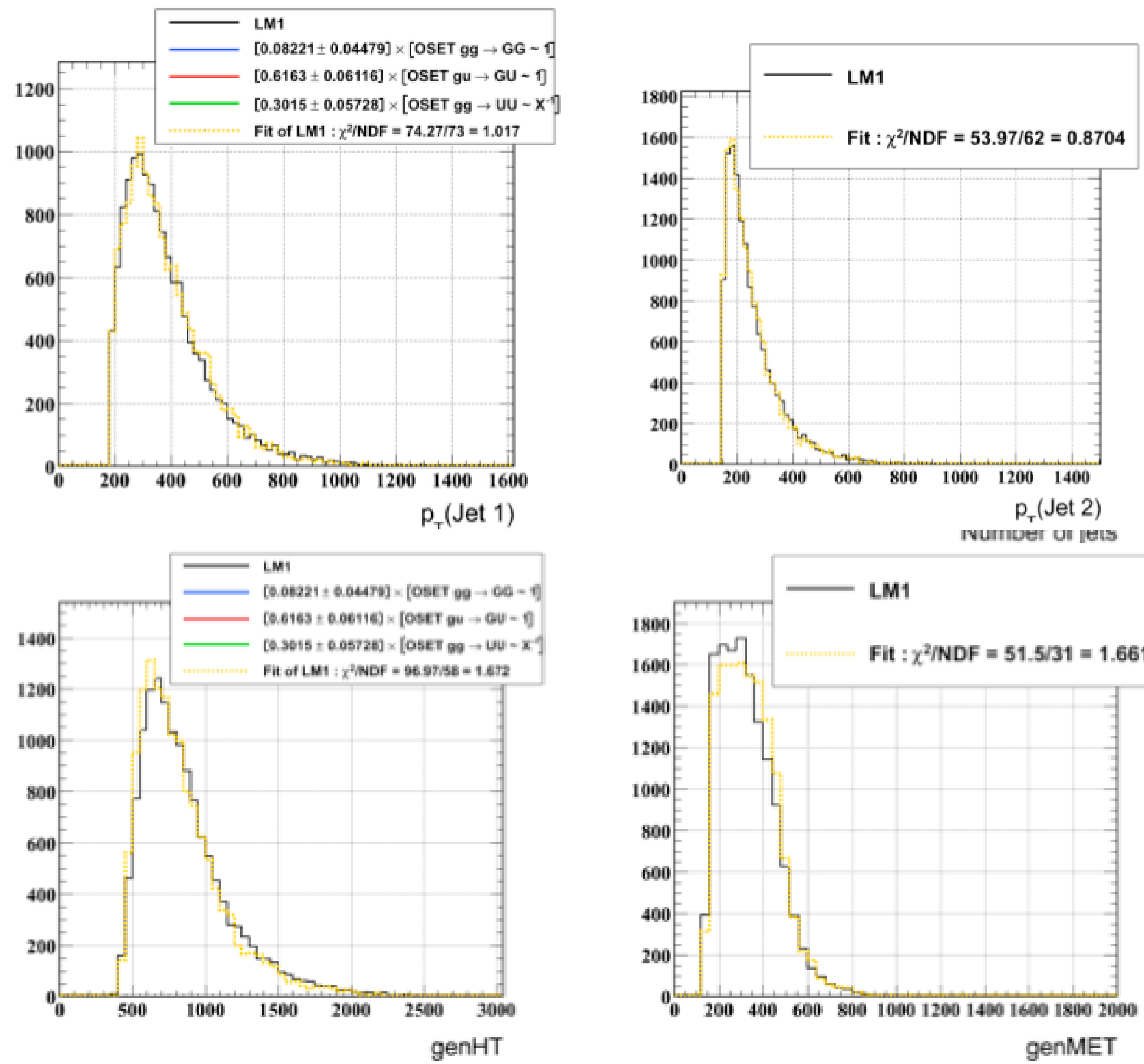
–S.A. Koay



It Works!

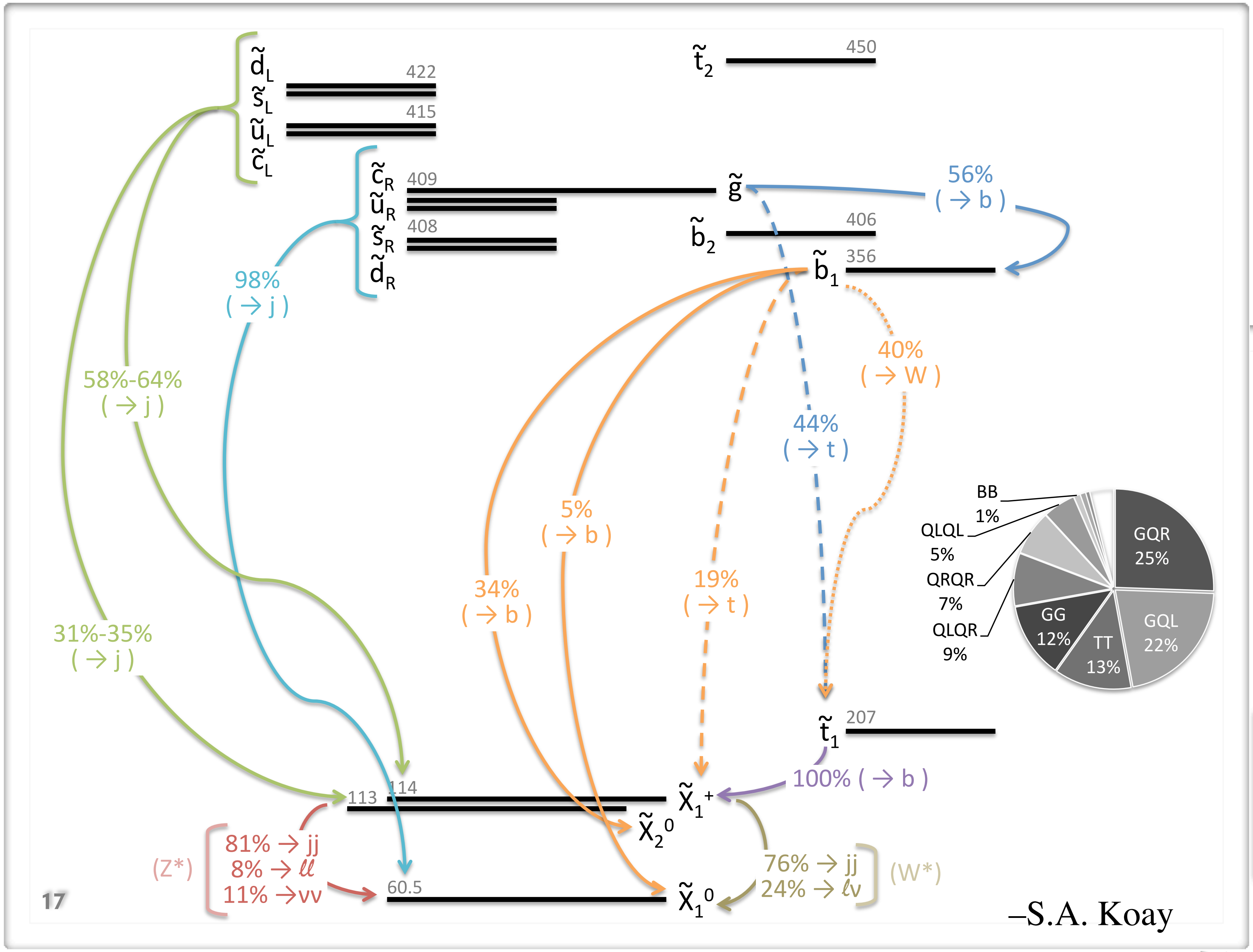
Fit $\tilde{g}\tilde{g}$, $\tilde{u}\tilde{g}$, and $\tilde{u}\tilde{u}$ production fractions (and masses, by eye) from HT, jet pT

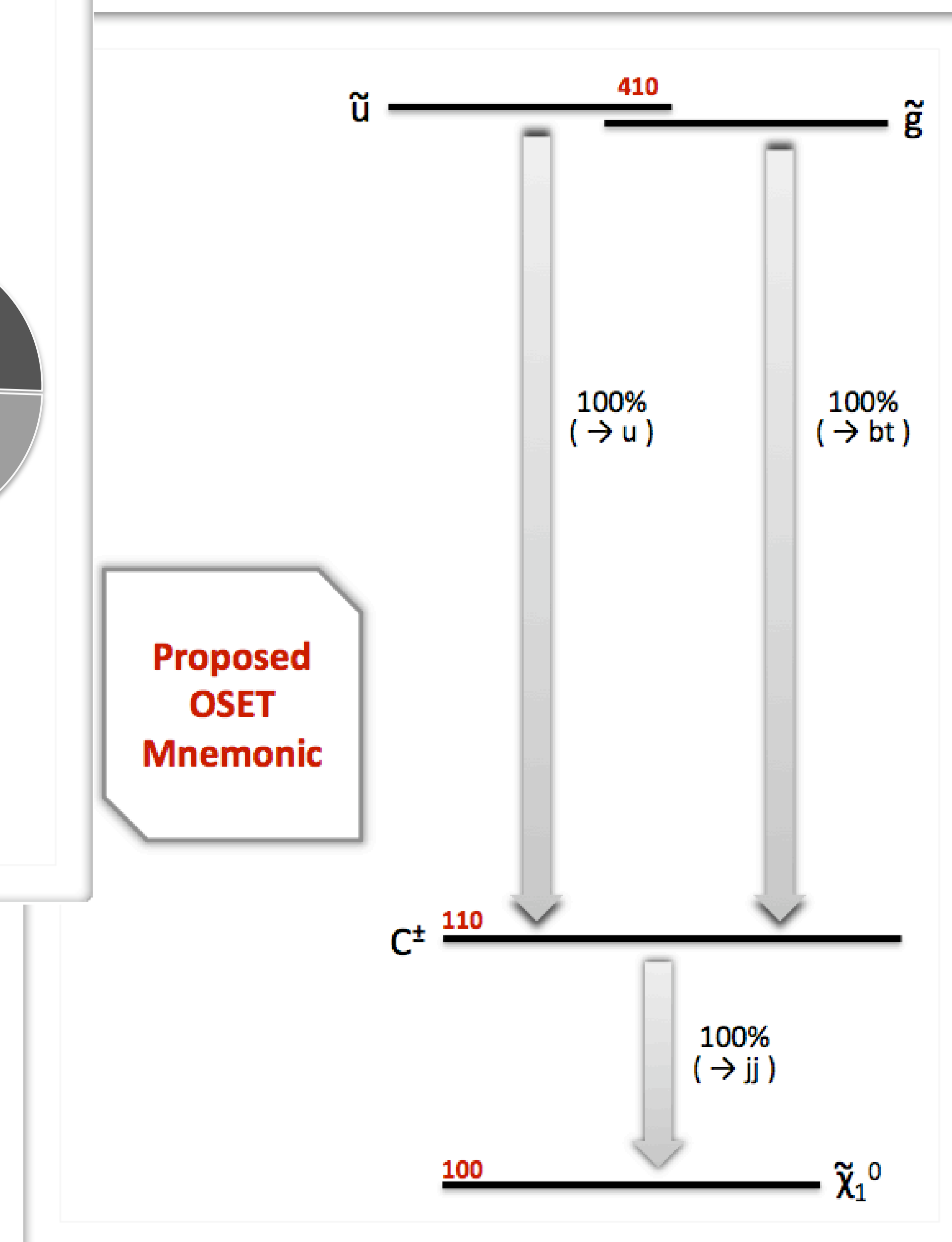
(generator-level comparison)



"Do no harm" : search optimized for this topology can discover LM1 as well as an LM1-optimized search

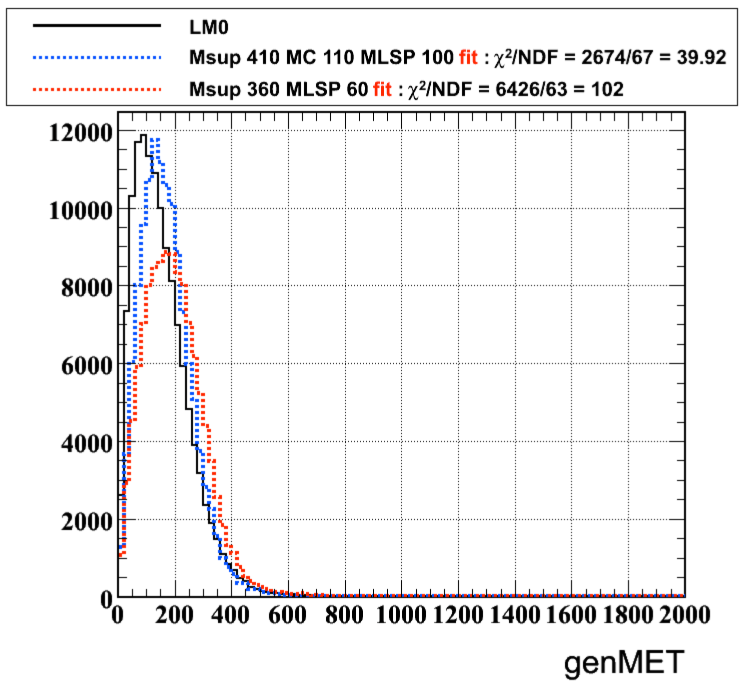
Extreme case: LM0 (significant stop production and cascade decays)

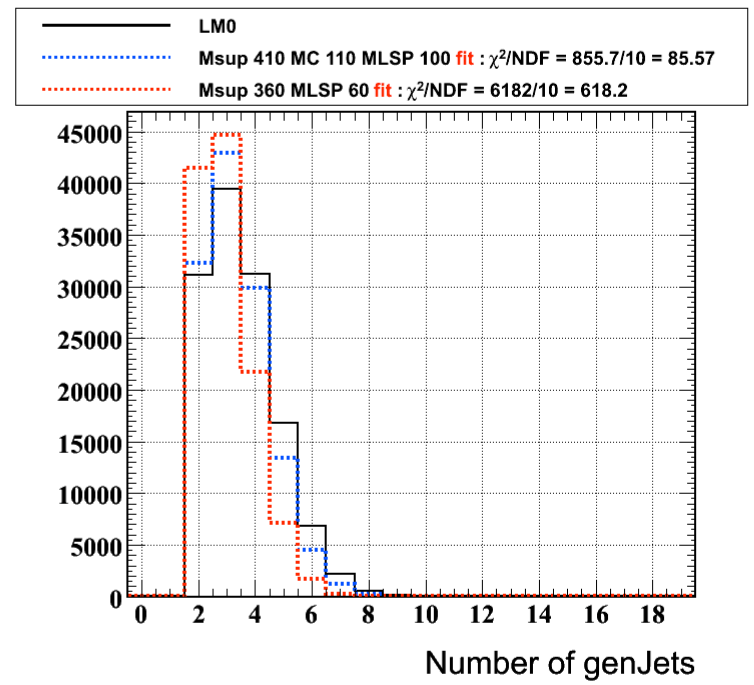


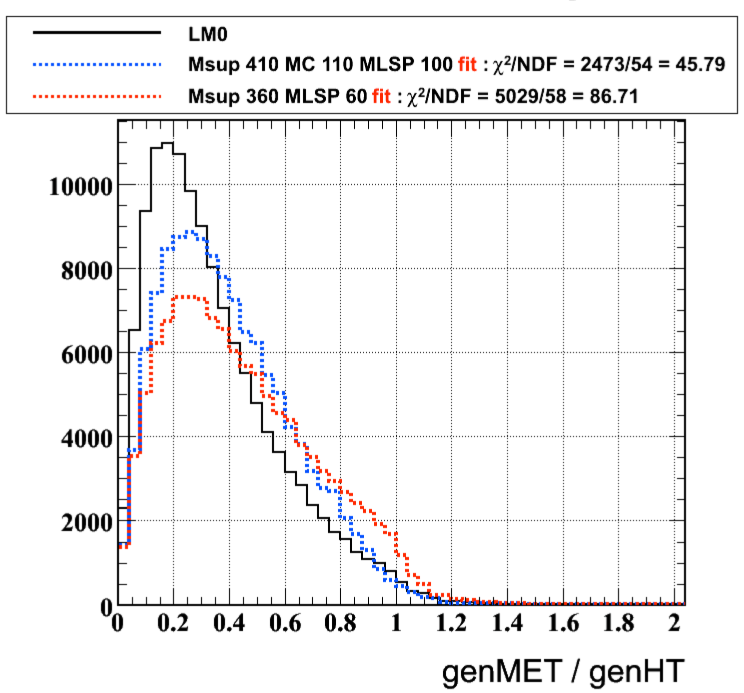


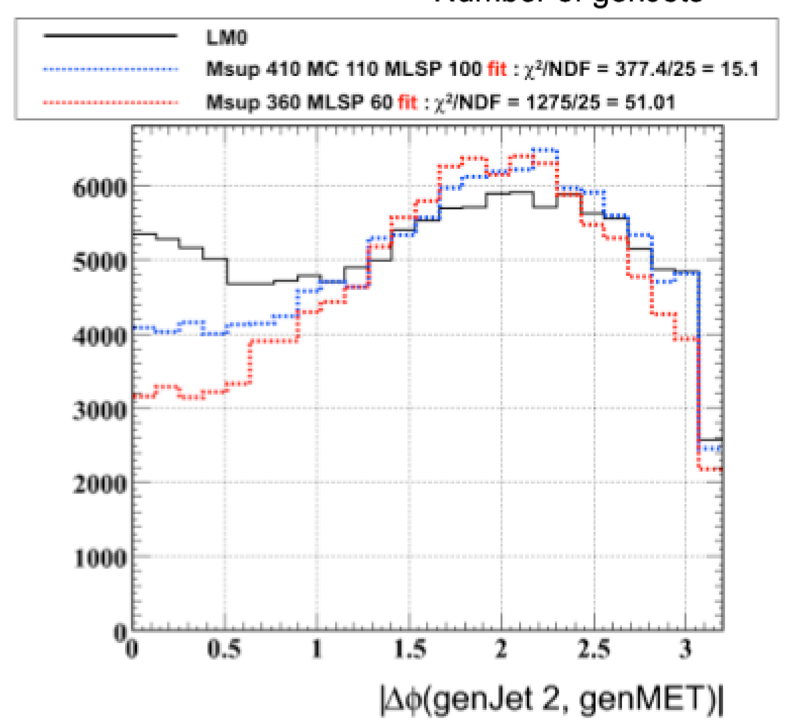
Works again! (Look at blue vs. black)

MET/HT very sensitive to cascade shape, most discrepant





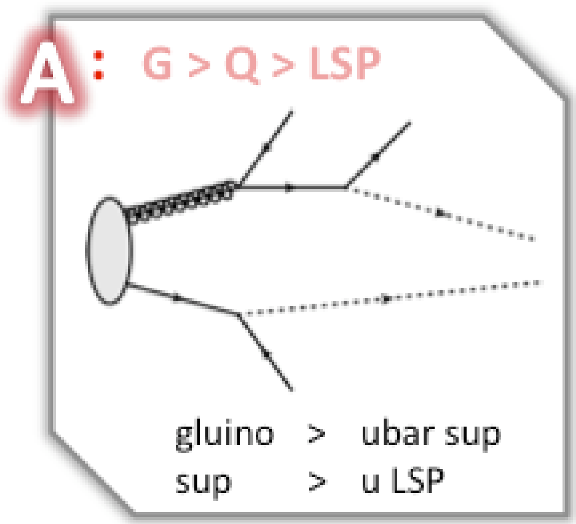




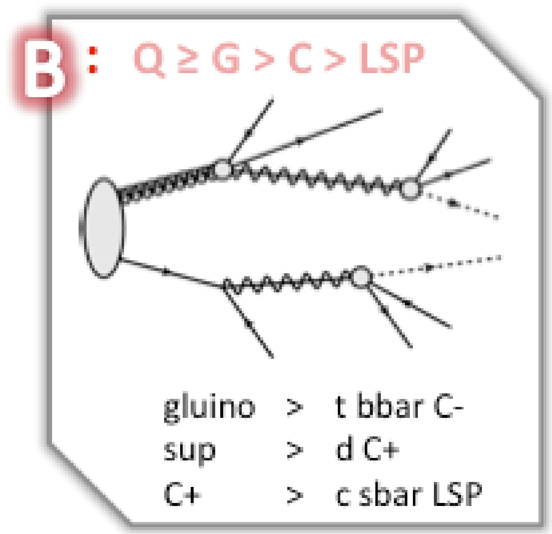
Affects efficiency of search cuts, but minor impact on distributions after cuts

Topology-Driven Searches

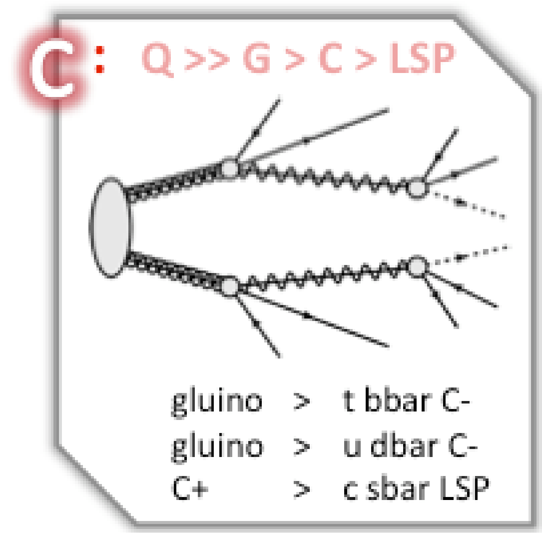
Design cuts for sensitivity to processes with more/ fewer jets, wide range of spectra.



"Three hard jets"



"~5 hadronic jets"
(Effect of cascade depends on C^+ mass)



Even more/softer jets
(not visible – ignore for now)

Fixed cuts: lepton veto, 3 jets

Optimize Jet p_T, HT, MET cuts for sensitivity to A/B topologies over wide mass range

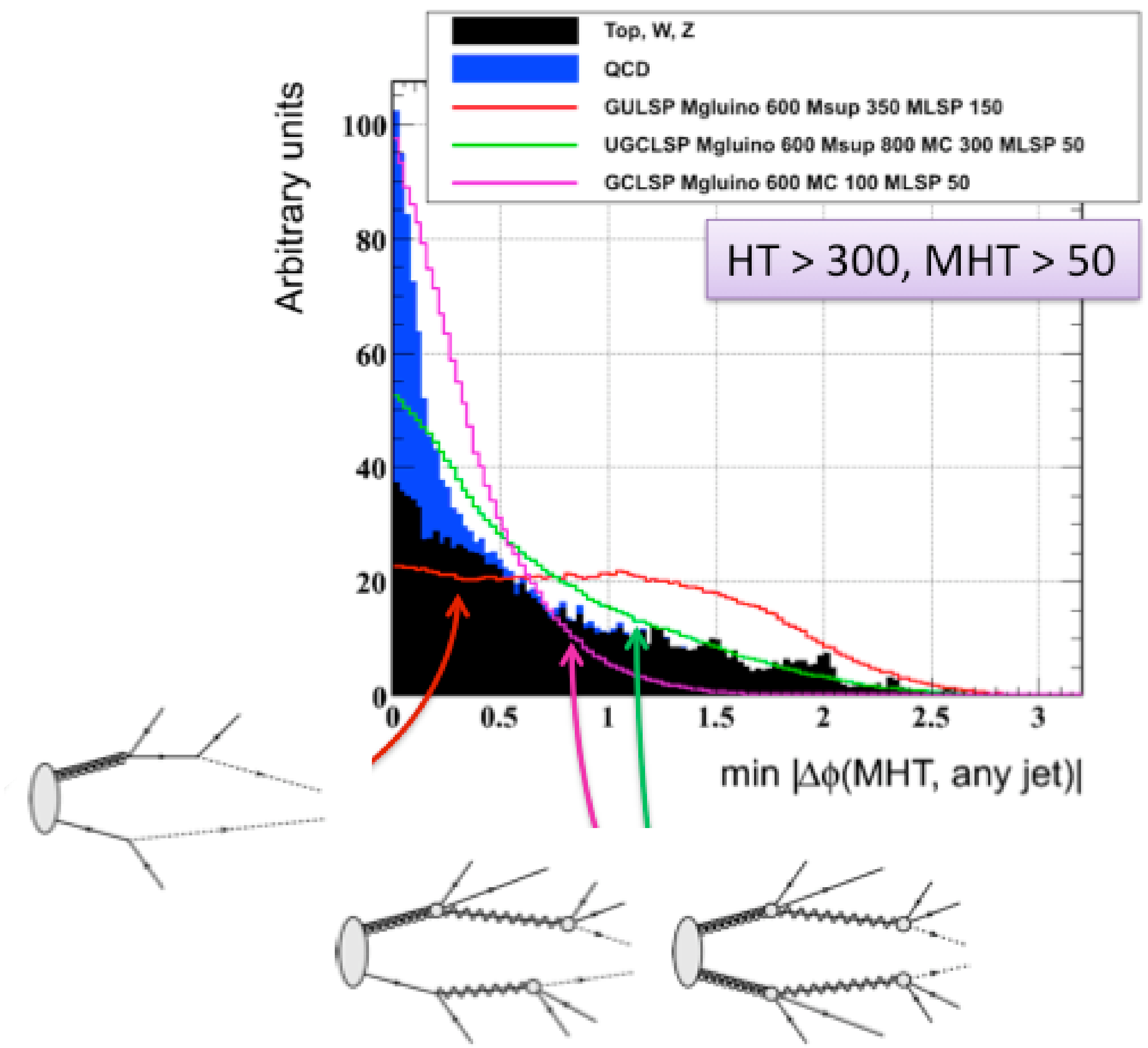
Leptonic search effort underway...

Meaningful steps beyond mSUGRA

Search Generally

Ensure sensitivity to multiple topologies

Applying deltaPhi cuts to every jet makes search insensitive to longer cascades – dangerous if they dominate!



And for wide range of mass splittings!

Present Generally

Sensitivity (and eventually exclusion) can be quoted in terms of all relevant parameters: cross-section, $m_{\tilde{g}}$, $m_{\tilde{u}}$, *and* $m_{\tilde{C}^+}$, m_{LSP}

Models with similar topologies don't require separate searches.

If ***topology*** is dissimilar, motivation to search for it is clear.

If new physics is seen in “SUSY” search, ***What Next?***

Crude “Simplified Models” from earlier are **general** starting point for analysis.

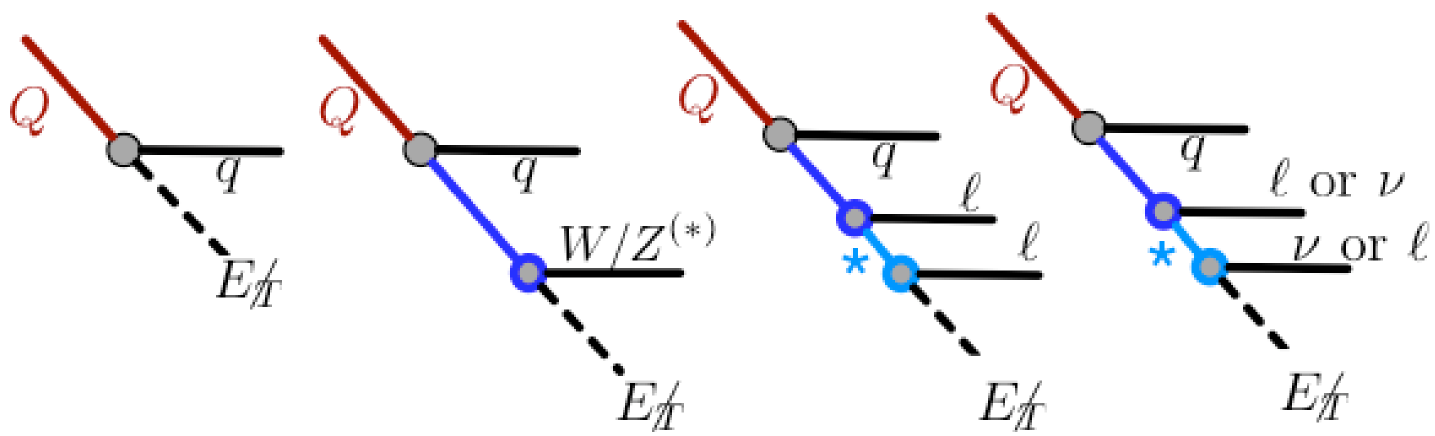
Example:

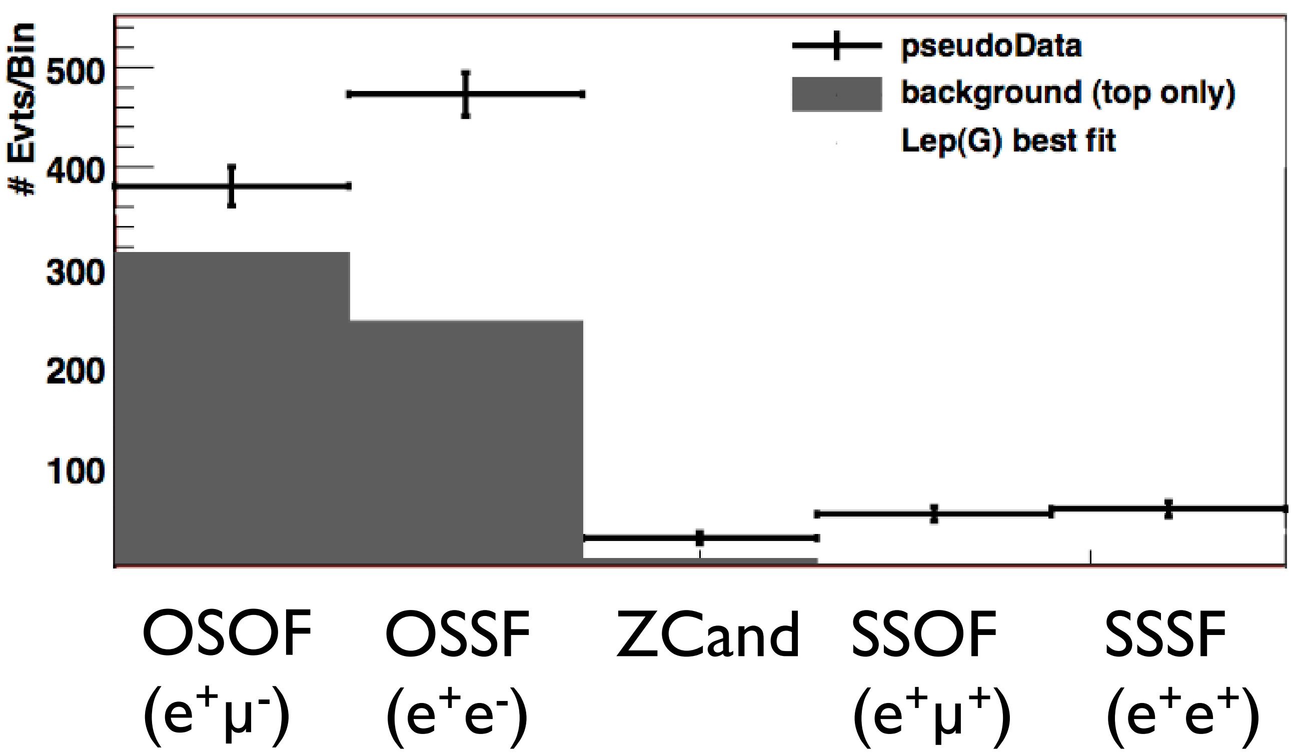
– what do they tell us?

– how do we move beyond them?

– what do we learn from simplified model fits “inside,” but not outside theorists’ analysis of published data?

Branching Ratios





5 params and 3 independent counts in 2-lepton data (under-constrained)

Additional constraint from 0-, 1- or 3-lepton data

AMBIGUITY:

W goes to 1 lepton (30%) or 0 leptons (70%).

Hard to distinguish W's from combination of direct and one-lepton cascade

Branching Ratios
(Best Fits)

Parameters that fit counts, HT, p_T(lepton):

Model / Limit	$M_{Q/G}$-M_I-M_L^*-M_{LSP}	$\sigma(pb)$	B_{ll}	$B_{\nu l+l\nu}$ $(\frac{B_{\nu l}}{B_{\nu l+l\nu}})$	B_{LSP}	B_W	B_Z
Lep(Q) / $B_W = 0$	500-440- – -100	46.1	0.0151	0.4155/–	0.5274	–	0.0420
Lep(Q) / $B_{\ell\nu} = 0$	650-440- – -100	12.8	0.0485	–	0.0	0.9244	0.0270
Lep(G) / $B_W = 0$	650-440- – -100	13.6	0.0507	0.2928/–	0.5840	–	0.0725
Lep(G) / $B_{\ell\nu} = 0$	700-440- – -100	11.5	0.0636	–	0.0	0.8710	0.0654

ambiguity –
affects conclusions!

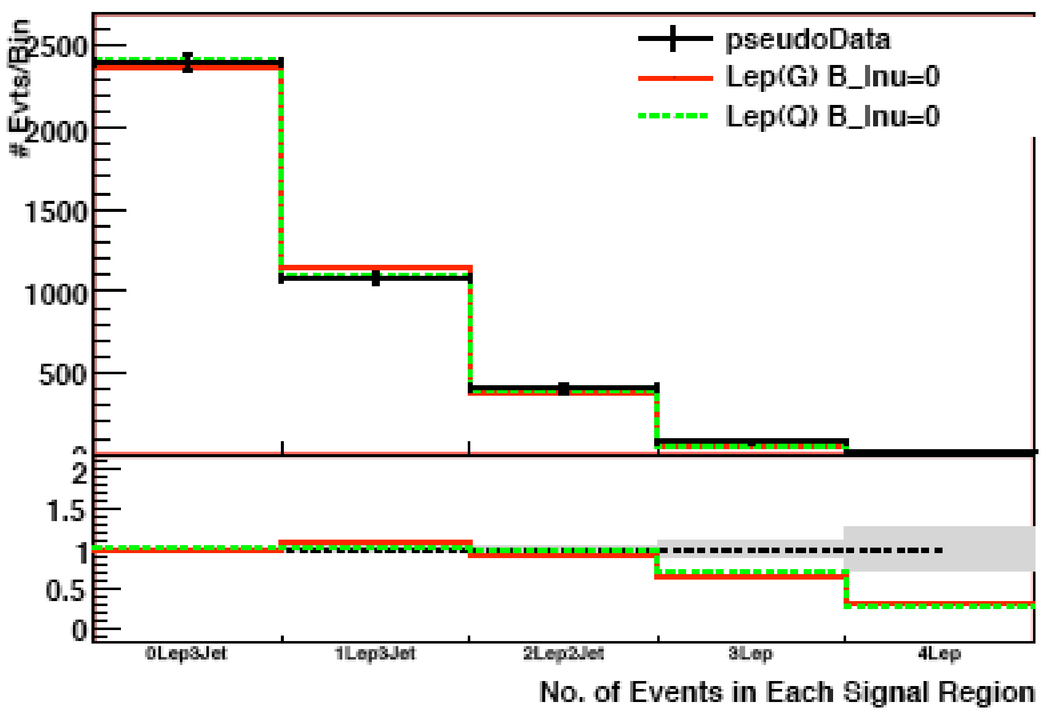
big syst. effect on
masses, xsec

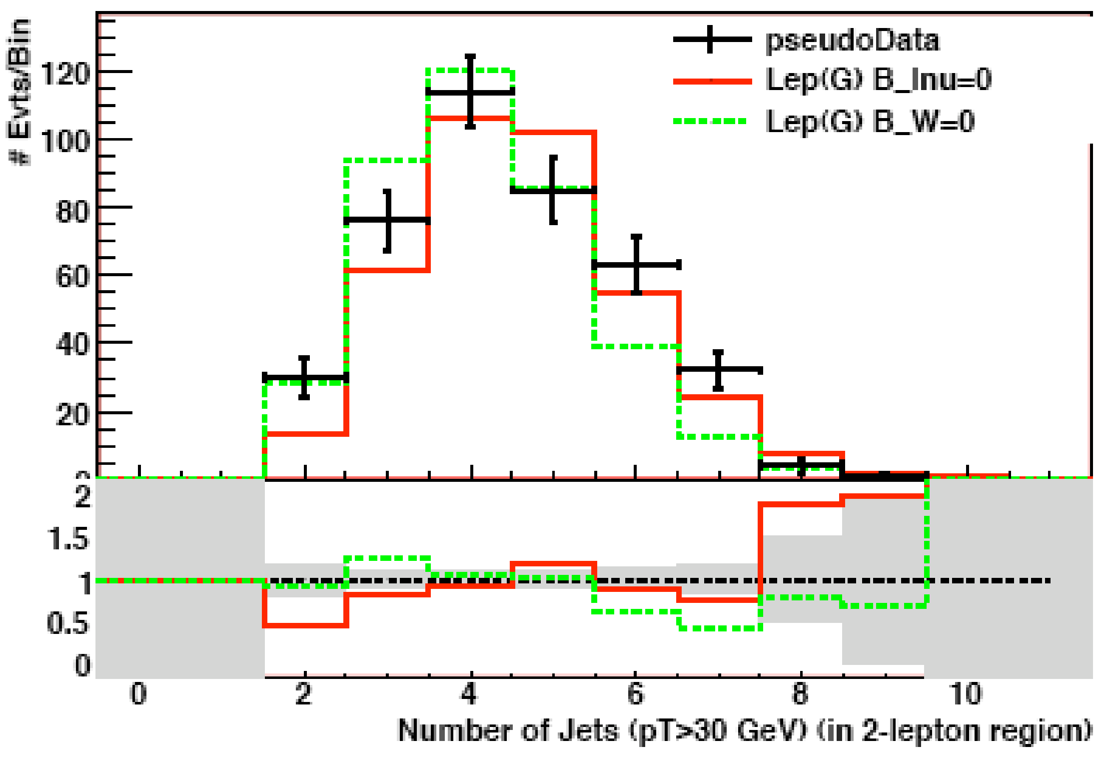
some branching
ratios more stable
than others

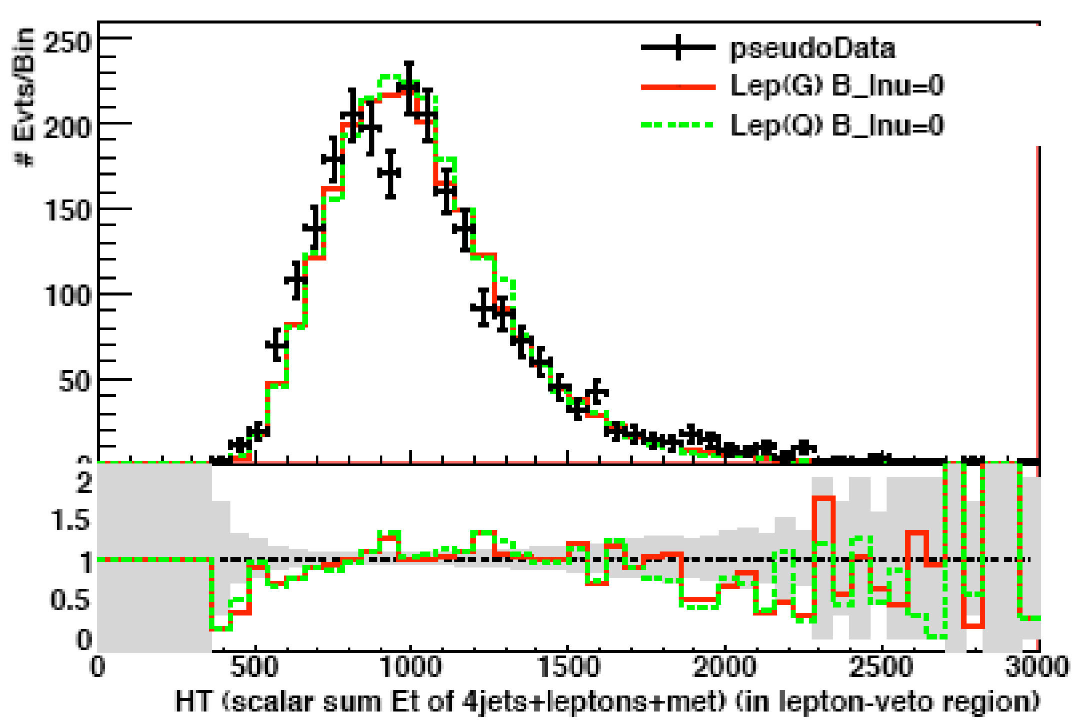
Theorist on the outside **can** estimate these from 1,2-lepton data...
but given large systematics, we're likely to make mistakes combining channels reliably

What the best fits look like

Counts, jet kinematics reproduced well!



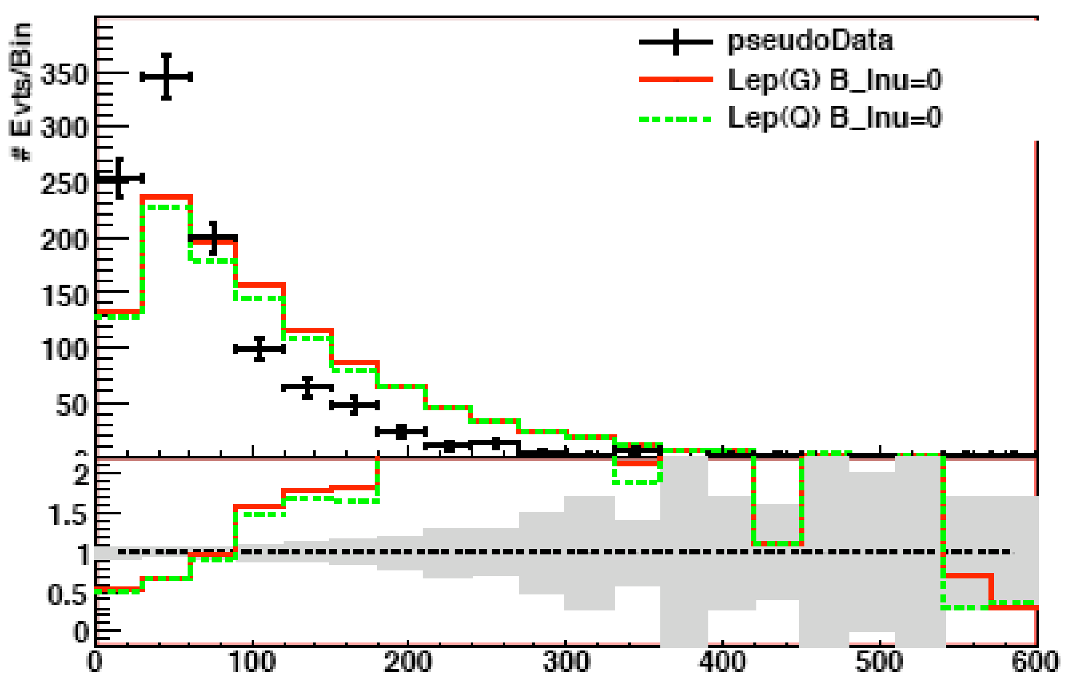




(also jet p_T plots, MET...)

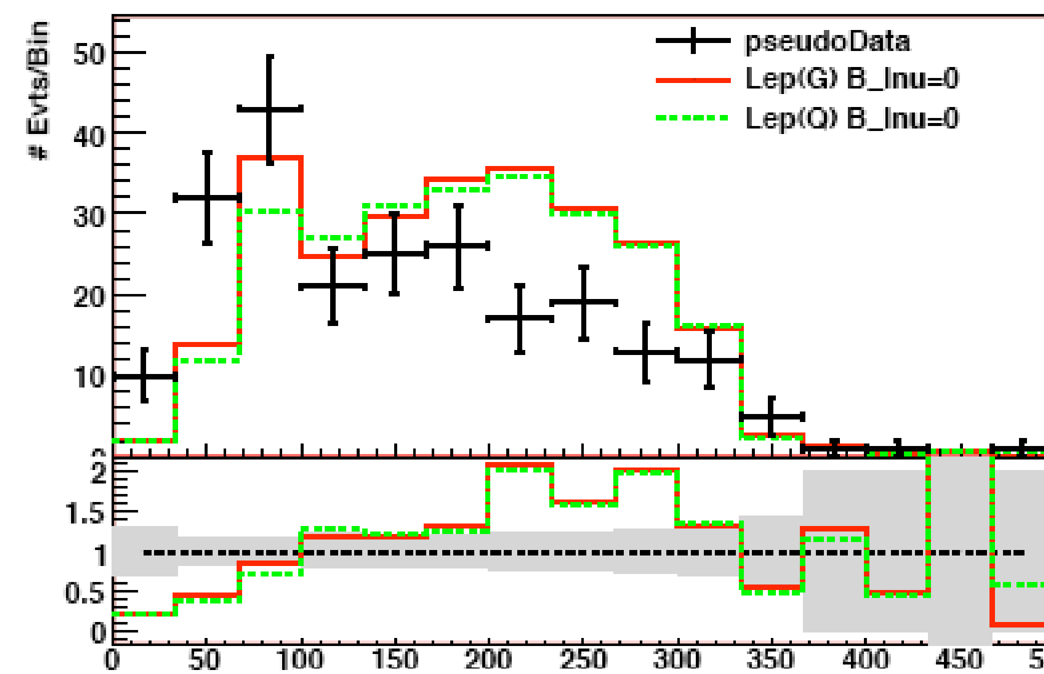
What the best fits look like

(1-lepton plots)

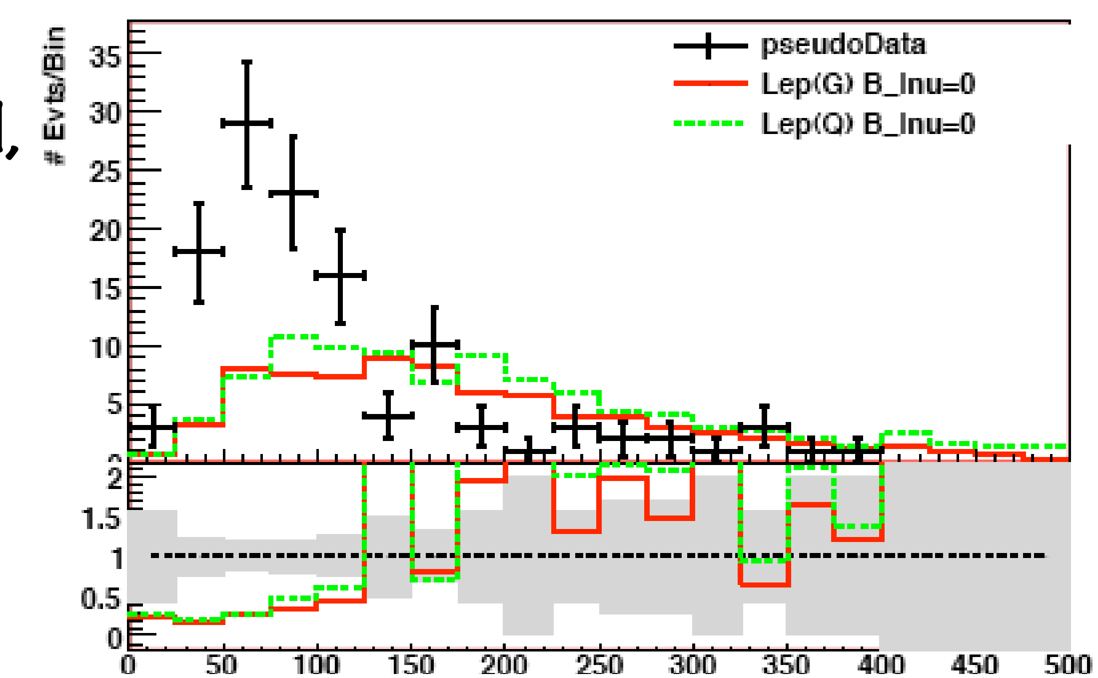


Lepton p_T

(2-lepton plots)

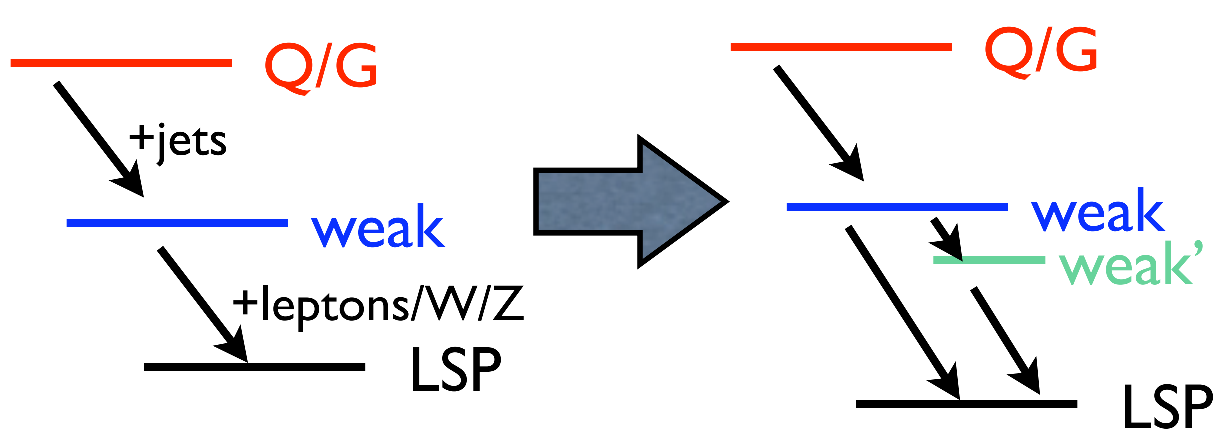


OSSF (e^+e^-) invariant mass



Opposite-flavor (eμ) invariant mass

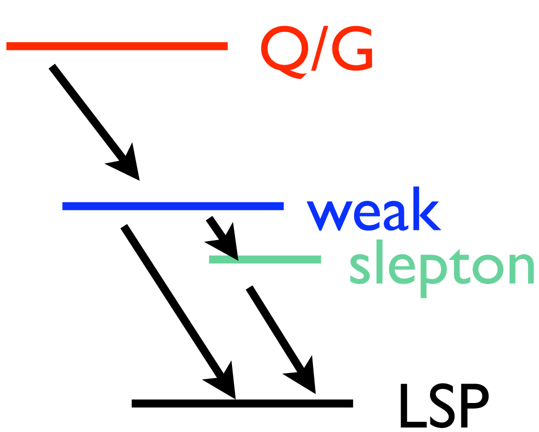
Cannot reproduce the data with these models (or with tops). Robustly demonstrating this is hard, but provides STRONG EVIDENCE for more complex source of soft, flavor-uncorrelated leptons.



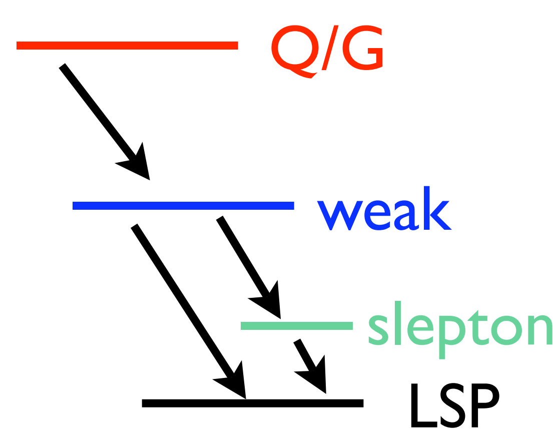
(only believable if studied by experimentalists)

Interim Conclusions and Questions

- Data consistent with squark and/or gluino production
- Need two-stage cascades to explain data
- Large rate of single-lepton cascade (+ precise numbers)
- To reproduce the 2-lepton counts (trial & error) ...on-shell slepton and **charginos**.



or



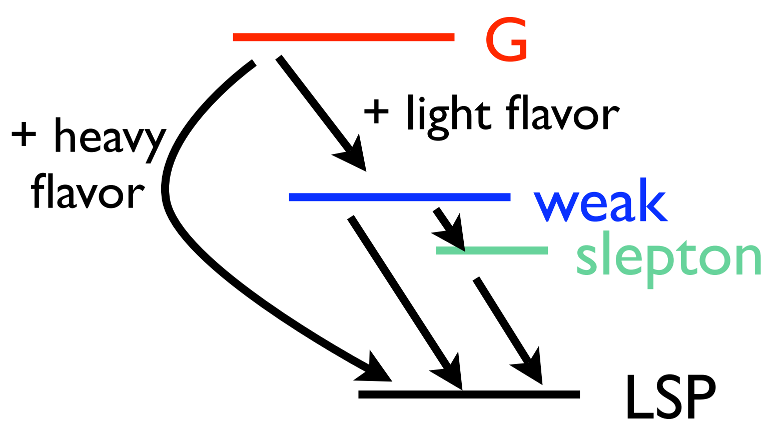
?

See if this can be confirmed from kinematics - dilepton invariant mass should have an EDGE
(this is sub-dominant source of 2-lepton events, edge didn't jump out but this motivates looking harder)

I can find SUSY models with both hierarchies, see if **any** of them are consistent with larger set of distributions in data...

More conclusions from b-jet studies

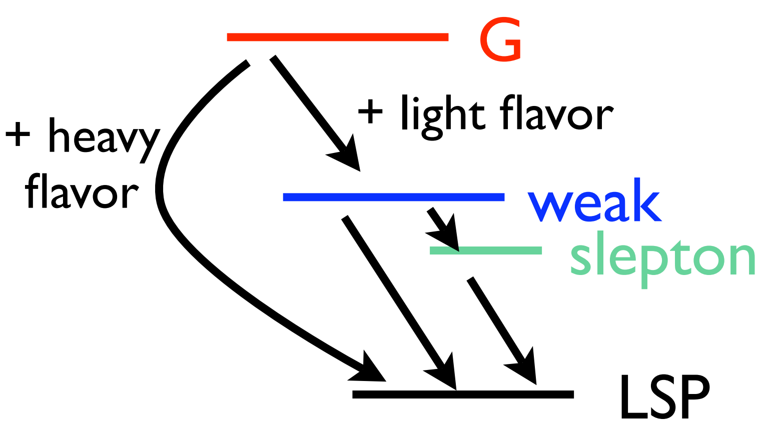
- Gluon-partner with ~60% branching fraction to heavy flavor works well. **Not** flavor-universal!
- Lepton-rich events have *fewer* b-jets



(G decay could have intermediate on-shell Q's)

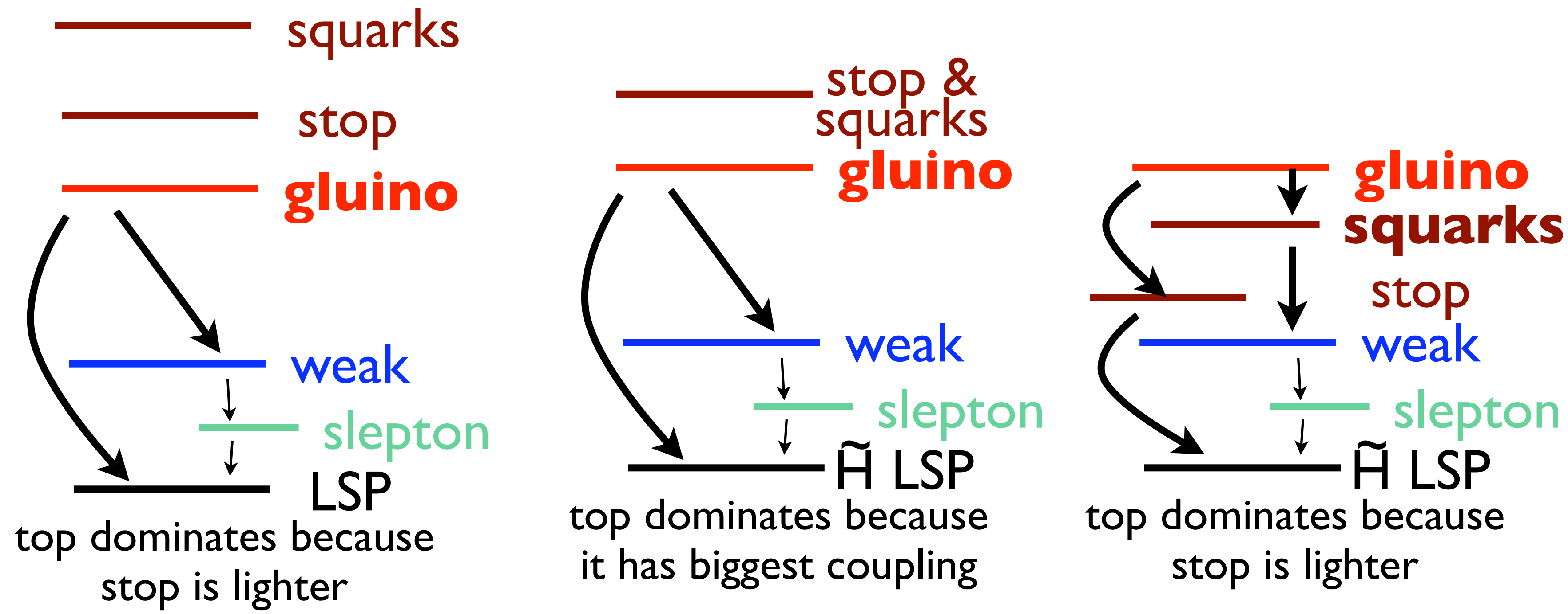
More conclusions from b-jet studies

- Gluon-partner with ~60% branching fraction to heavy flavor works well. **Not** flavor-universal!
- Lepton-rich events have *fewer* b-jets



(G decay could have intermediate on-shell Q's)

three SUSY ideas



Conclusions

Hadron colliders swallow a lot of information!
Sharpen the question: "What can be probed?"

Two natural classes of simplification:

- insensitivity to production matrix element
- smearing-together of decay chains

Used at CMS to generalize some SUSY searches

Basis for *observable* properties of new physics will assist in making sense of a discovery