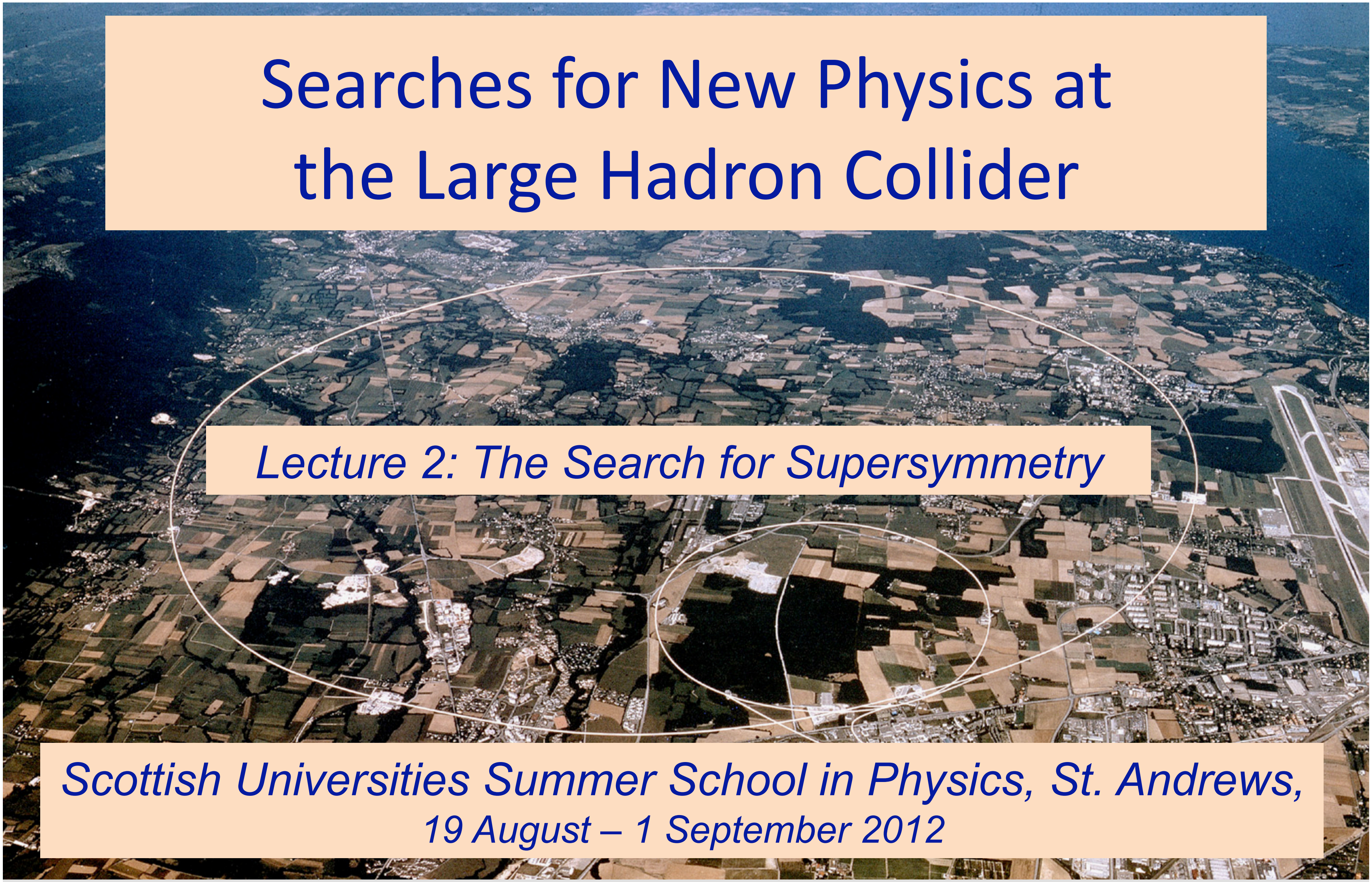

Searches for New Physics at the Large Hadron Collider

Lecture 2: The Search for Supersymmetry

Scottish Universities Summer School in Physics, St. Andrews,
19 August – 1 September 2012

Jeffrey D. Richman
Department of Physics
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Searching for SUSY

- SUSY is not one thing: it is a very broad collection of models. Many different signatures and an extensive range of analysis approaches.
- Most signatures are not "strong". For the most part, no sharp peaks.
- Nearly all analyses can be criticized. If you look carefully, you will find weak points.
- *Redundancy and multiple, cross-checking analyses using different methods are valuable (essential) if we are going to believe that an excess of events corresponds to new physics.*

SUSY Outline

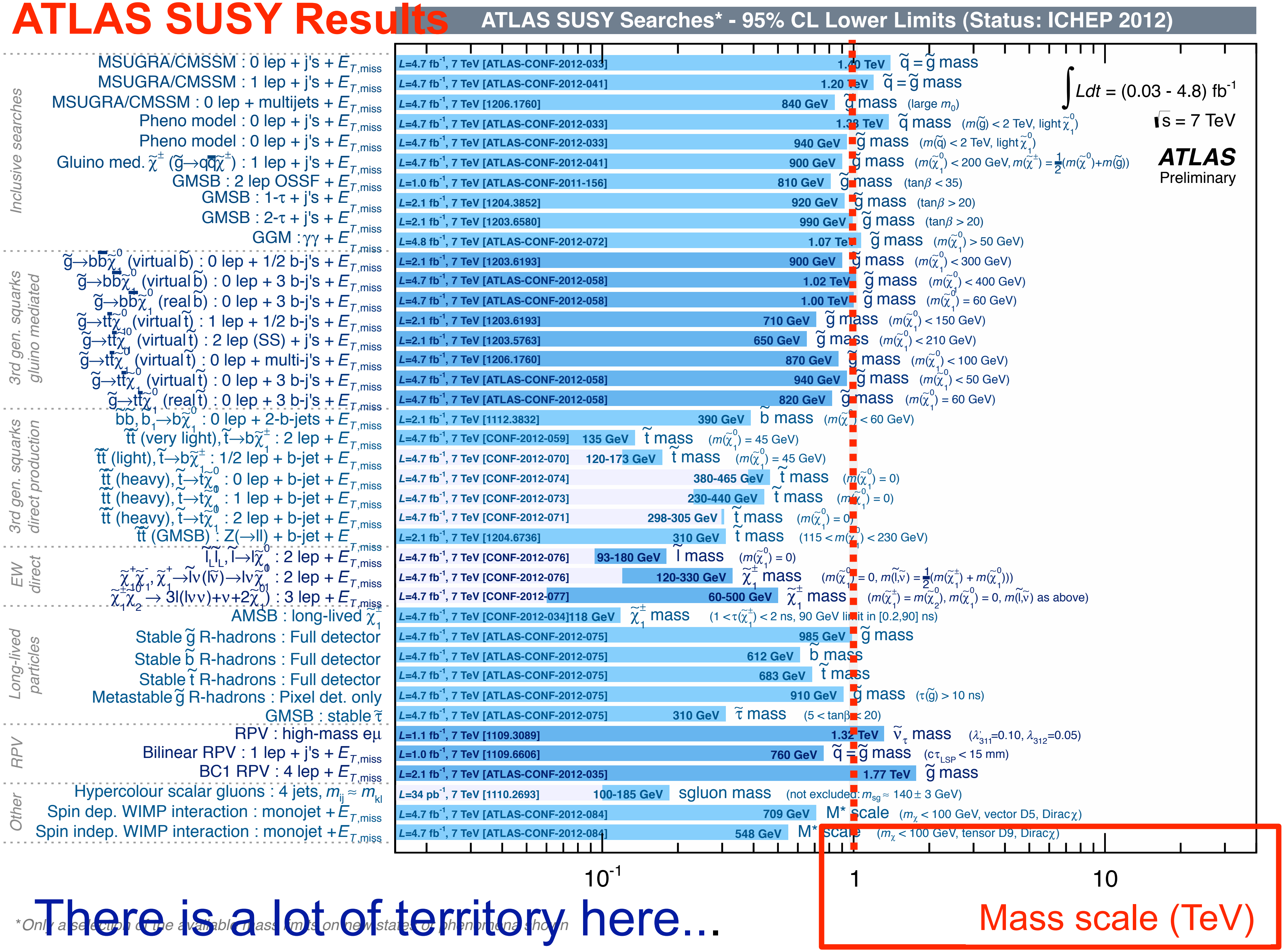
- Inclusive SUSY searches based on topologies
  - Methods for SUSY interpretation
- Searches motivated by “naturalness” (3rd generation squarks and not too heavy gluinos)

In Lecture 3

- Direct production of neutralinos & charginos
- Hiding SUSY (“exotic models”)
  - Long lived particles (e.g., long-lived gluinos in split SUSY)
  - R-parity-violating SUSY

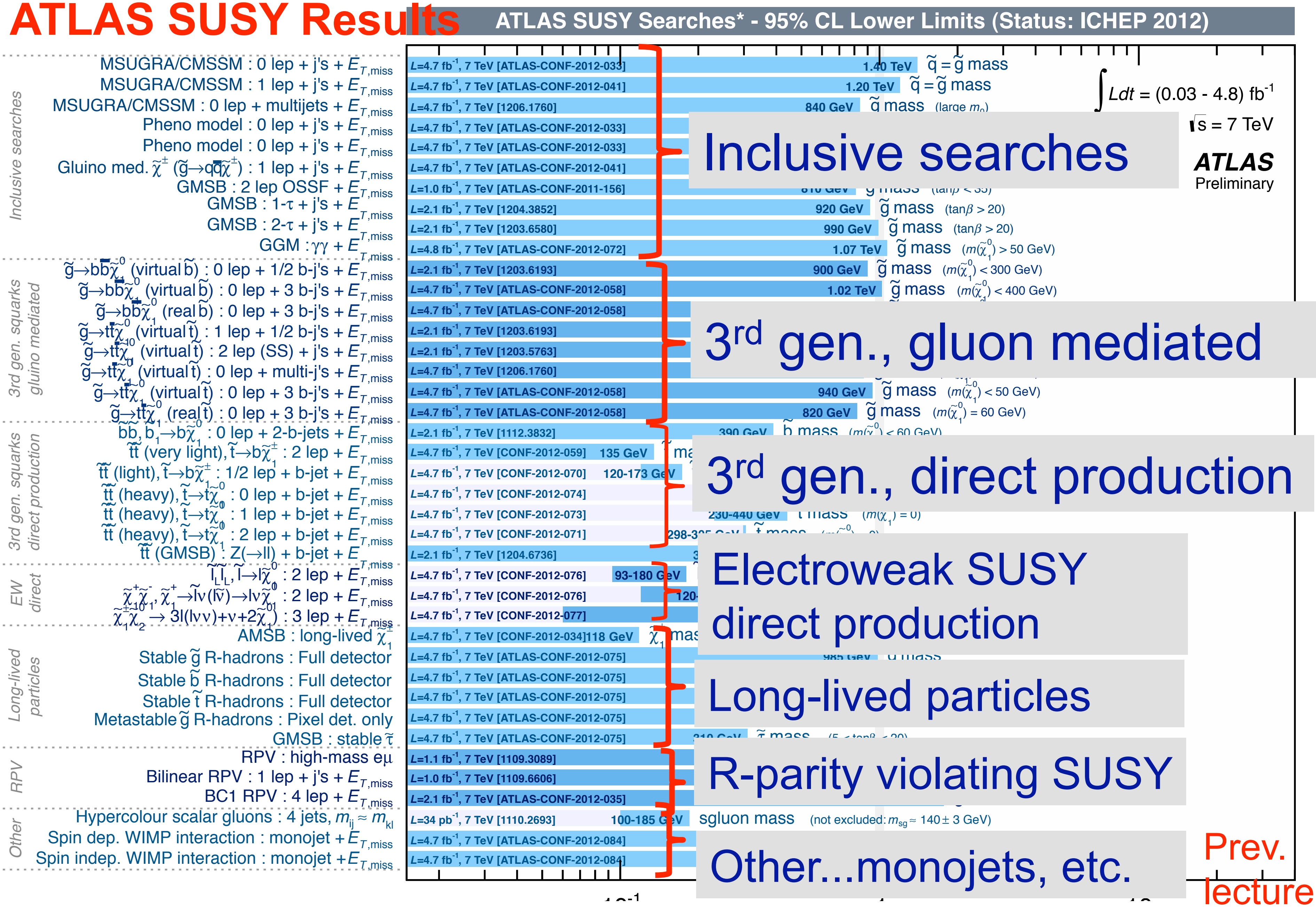
(See Lec 1 for monojet, monophoton discussion.)

ATLAS SUSY Results



There is a lot of territory here...

ATLAS SUSY Results



Inclusive searches

3rd gen., gluon mediated

3rd gen., direct production

Electroweak SUSY
direct production

Long-lived particles

R-parity violating SUSY

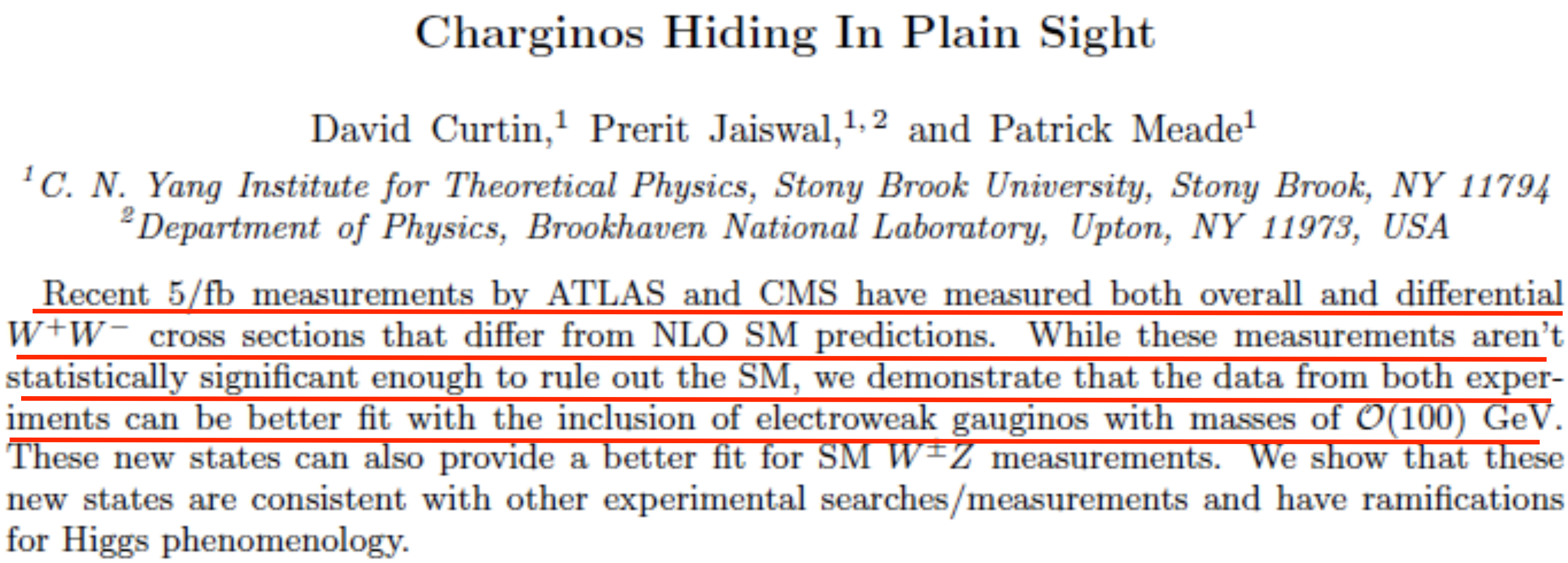
Other...monojets, etc.

Prev. lecture

But it’s not as scary as it looks: a few basic ideas, many channels

This year could be very interesting…or not!

http://arxiv.org/abs/1206.6888v1



Charginos Hiding In Plain Sight

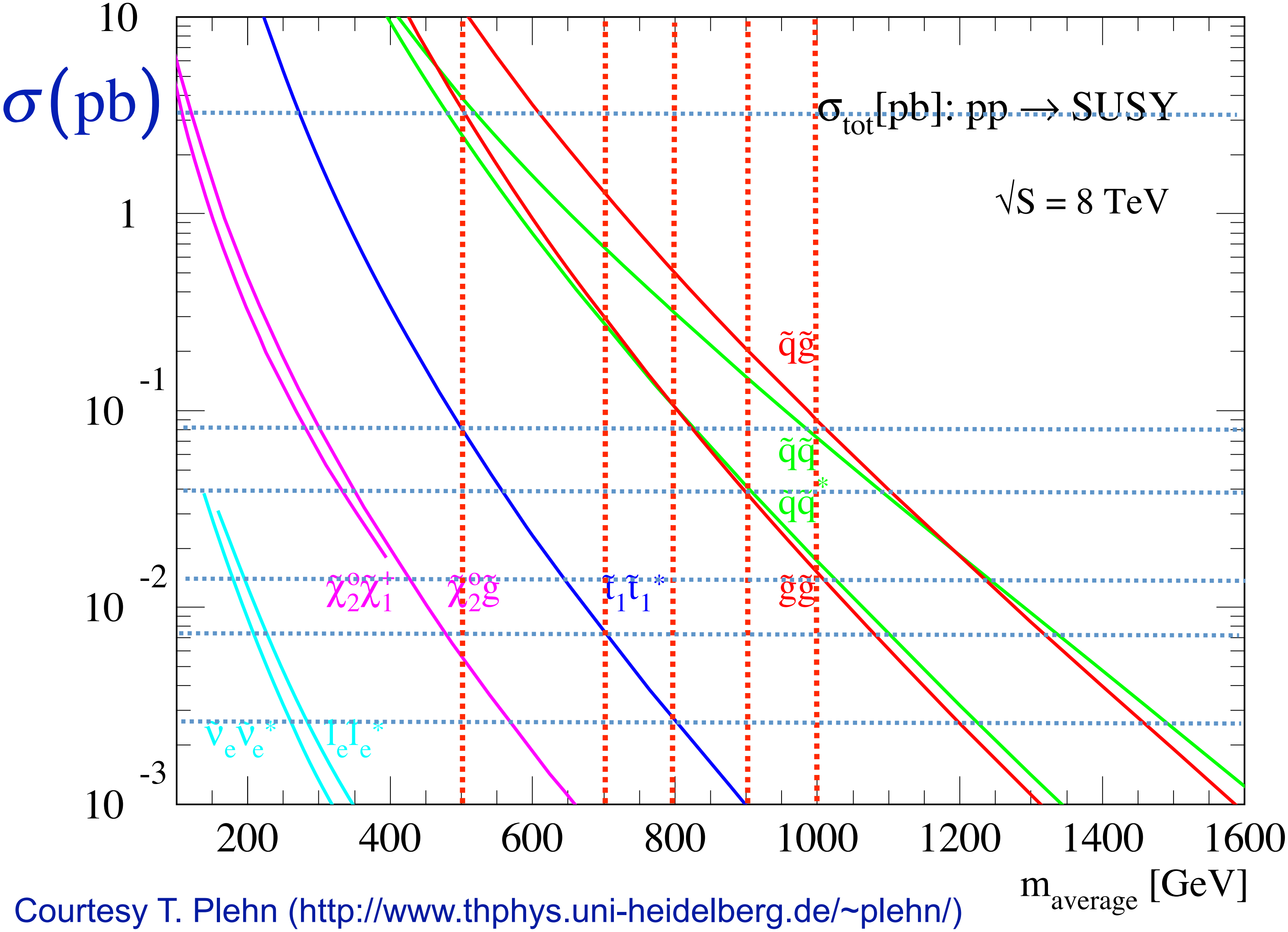
David Curtin,[1] Prerit Jaiswal,[1,2] and Patrick Meade[1]

[1] *C. N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, NY 11794*
[2] *Department of Physics, Brookhaven National Laboratory, Upton, NY 11973, USA*

Recent 5/fb measurements by ATLAS and CMS have measured both overall and differential W^+W^- cross sections that differ from NLO SM predictions. While these measurements aren't statistically significant enough to rule out the SM, we demonstrate that the data from both experiments can be better fit with the inclusion of electroweak gauginos with masses of $\mathcal{O}(100)$ GeV. These new states can also provide a better fit for SM $W^\pm Z$ measurements. We show that these new states are consistent with other experimental searches/measurements and have ramifications for Higgs phenomenology.

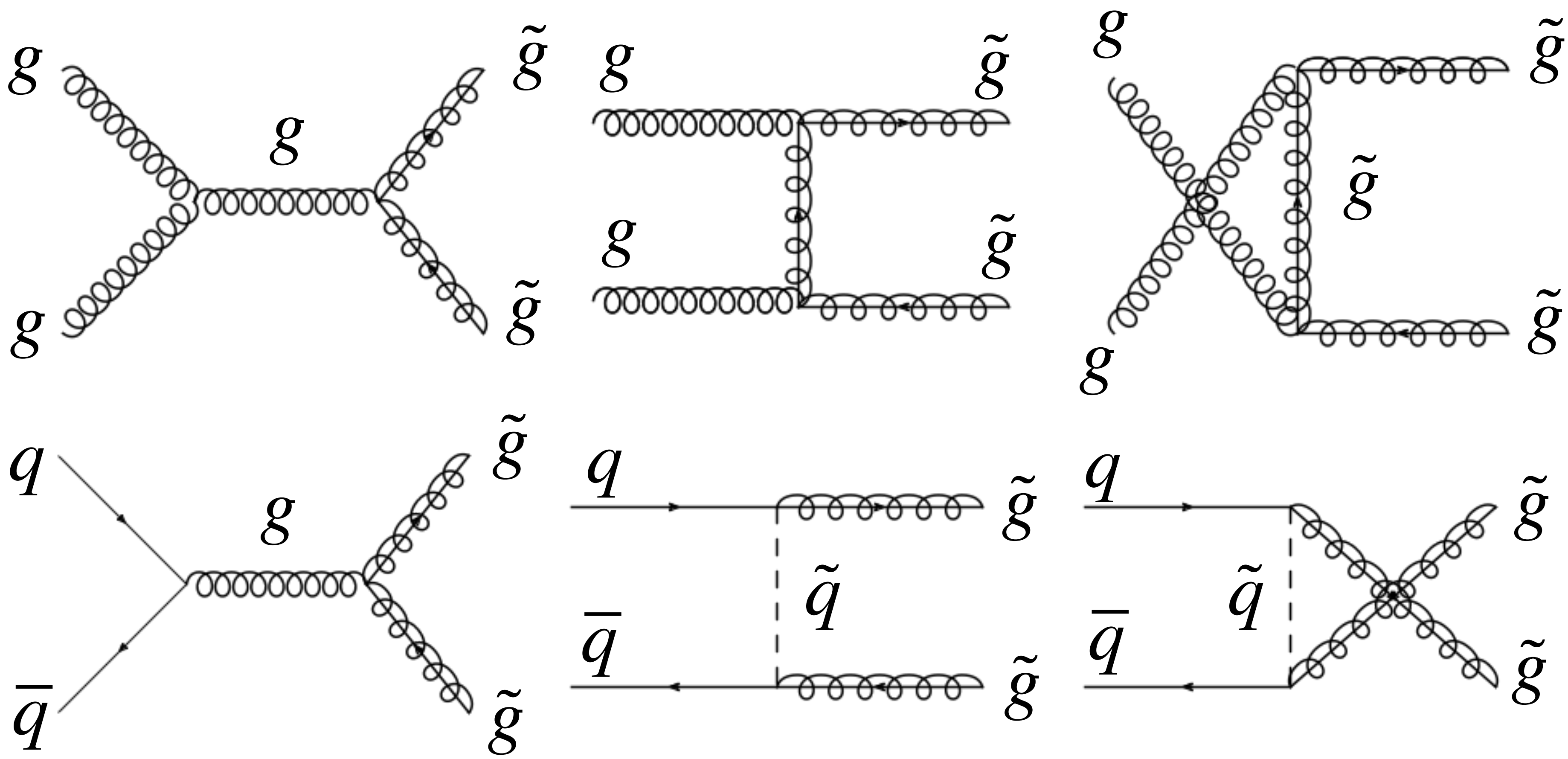
Come back to this in next lecture.

SUSY particle production at √s=8 TeV



Courtesy T. Plehn (http://www.thphys.uni-heidelberg.de/~plehn/)

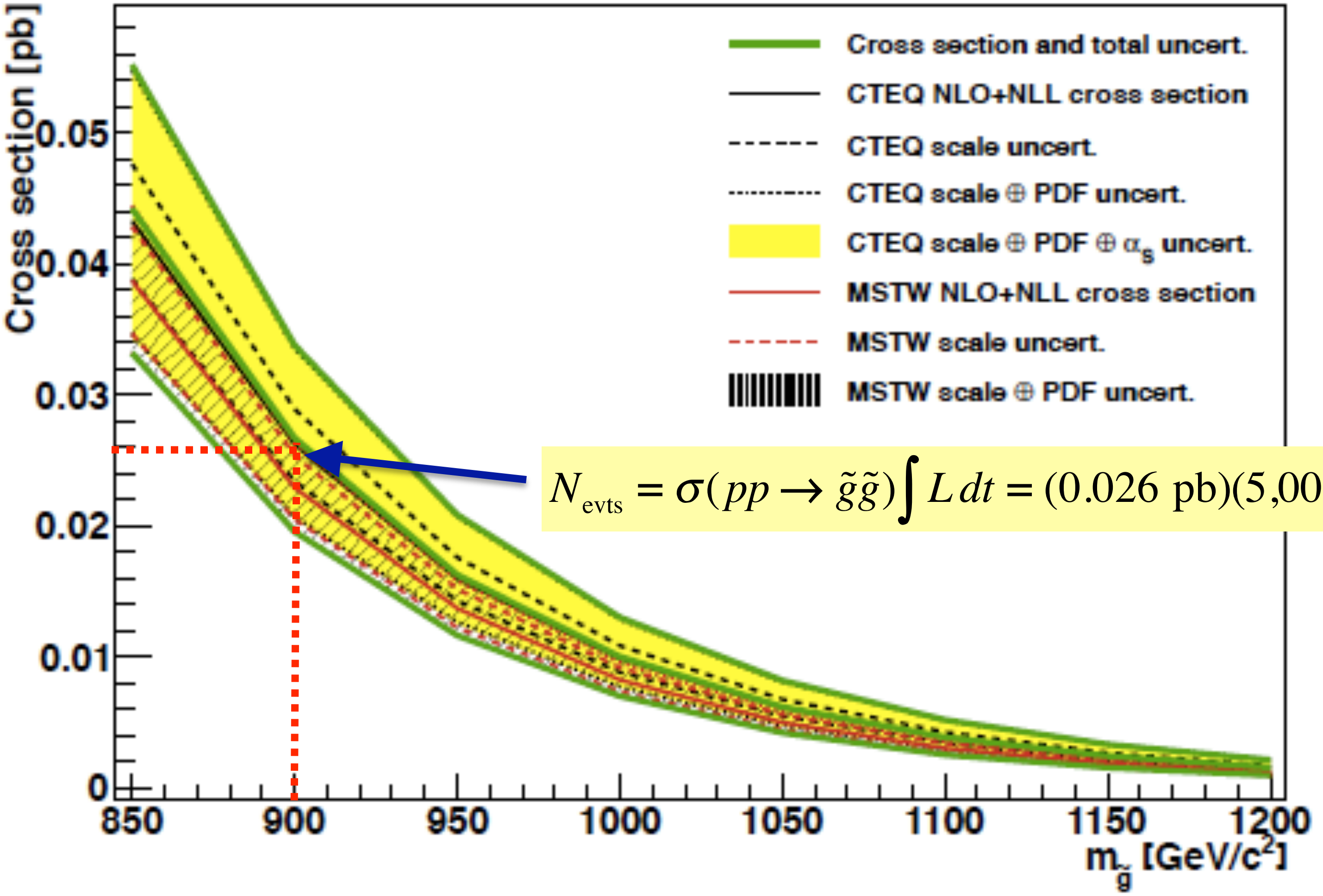
Gluino production in pp collisions



For production cross section calculations, the squark masses are often taken to be arbitrarily large – the "decoupling limit".

Gluino pair production (√s=7 TeV)

M. Kramer et al., http://arXiv/abs/1206.2892

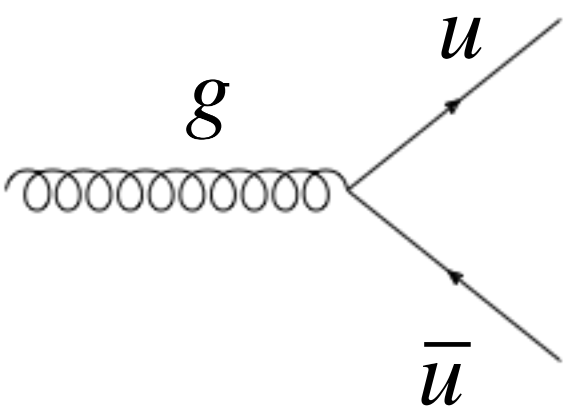


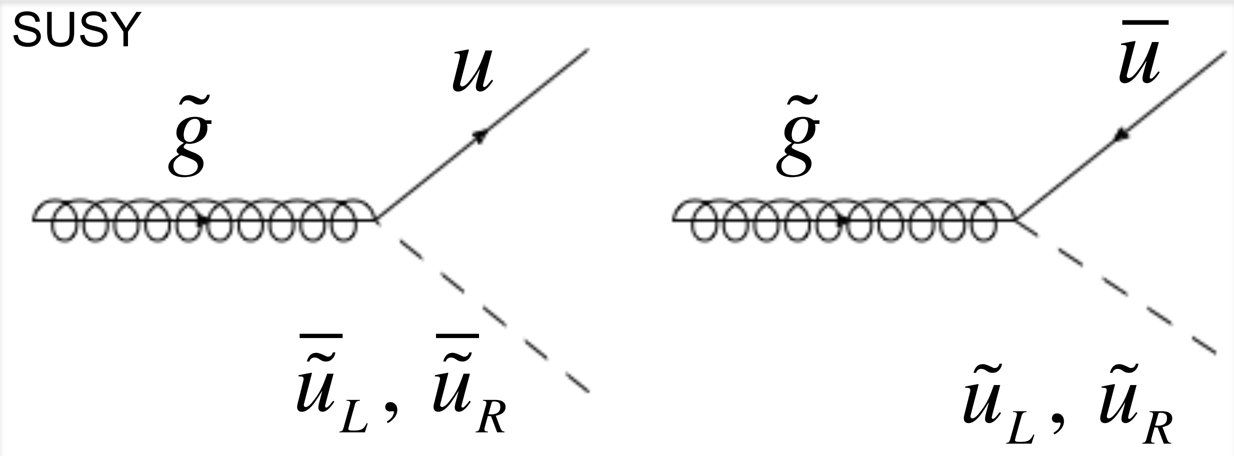
$$N_{\text{evts}} = \sigma(pp \to \tilde{g}\tilde{g})\int L\,dt = (0.026 \text{ pb})(5{,}000 \text{ pb}^{-1}) = 130$$

Calculated assuming all squarks have high mass & decouple.

Gluinos: fundamental vertices with squarks

- SUSY preserves the gauge symmetries, so the SUSY partners of the gluons must also transform according to the 8-dimensional representation of SU(3)$_C$.
- Fundamental vertex for $g \rightarrow \tilde{q}_{L,R} + \bar{q}$ has same coupling strength as that for $g \rightarrow q + \bar{q}$.





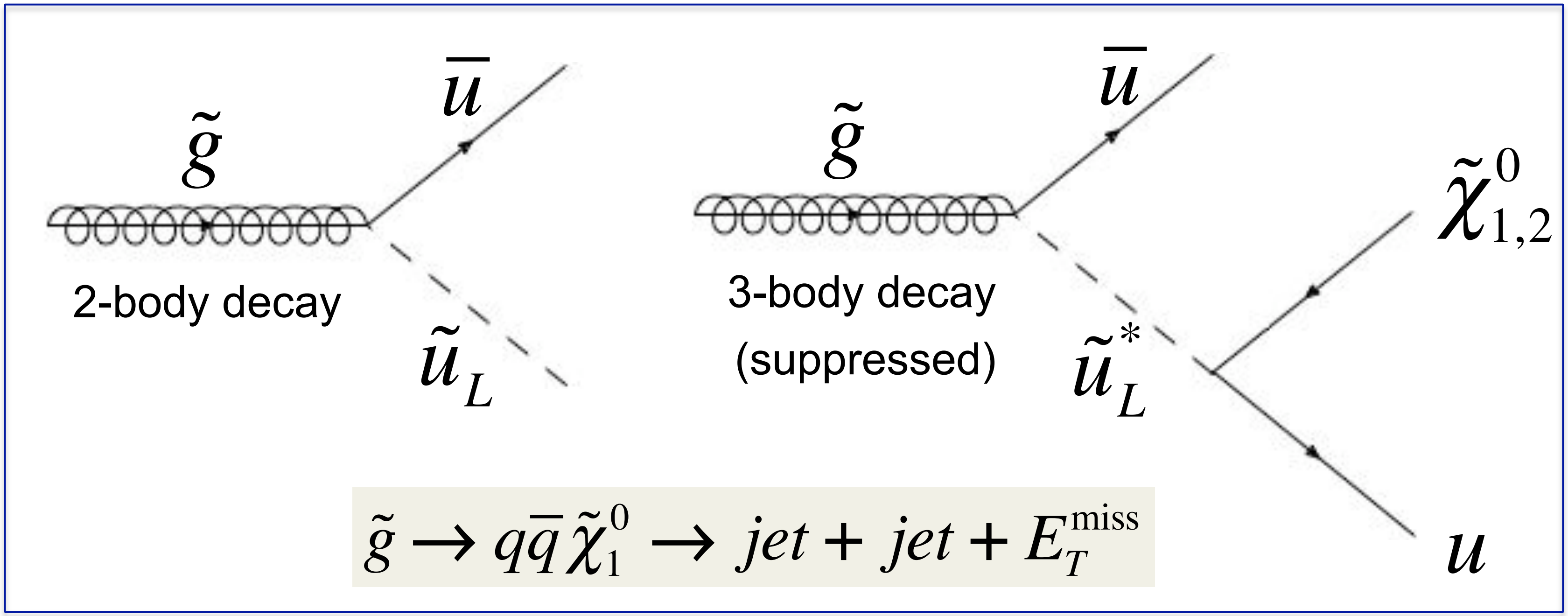
$$\tilde{g} \rightarrow u + \bar{\tilde{u}}_L\,,\ \bar{u} + \tilde{u}_L\,,\ u + \bar{\tilde{u}}_R\,,\ \bar{u} + \tilde{u}_R$$

Gluino decays to lighter and heavier squarks

- Two cases

$$m(\tilde{g}) > m(u) + m(\tilde{u}_L): \quad \text{true 2-body decay}$$

$$m(\tilde{g}) < m(u) + m(\tilde{u}_L): \quad \text{squark is virtual (3-body decay)}$$



$$\tilde{g} \to q\bar{q}\tilde{\chi}^0_1 \to jet + jet + E_T^{\text{miss}}$$

3-body decay is analogous to weak decay of low mass fermions, e.g., b → c l ν via a virtual W.

Decay table for gluinos in LM6

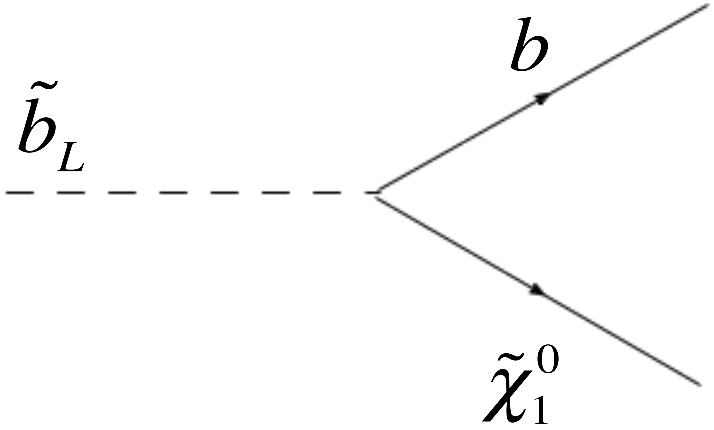
Number decay modes = 4x(5 flavors) + 2 = 22   That's a lot!

```
#          PDG            Width
DECAY    1000021     9.94317276E+00   # gluino decays
#          BR         NDA       ID1        ID2
     2.26184314E-02    2     1000001       -1   # BR(~g -> ~d_L  db)
     2.26184314E-02    2    -1000001        1   # BR(~g -> ~d_L* d )
     4.79704725E-02    2     2000001       -1   # BR(~g -> ~d_R  db)
     4.79704725E-02    2    -2000001        1   # BR(~g -> ~d_R* d )
     2.66424179E-02    2     1000002       -2   # BR(~g -> ~u_L  ub)
     2.66424179E-02    2    -1000002        2   # BR(~g -> ~u_L* u )
     4.17938806E-02    2     2000002       -2   # BR(~g -> ~u_R  ub)
     4.17938806E-02    2    -2000002        2   # BR(~g -> ~u_R* u )
     2.26184314E-02    2     1000003       -3   # BR(~g -> ~s_L  sb)
     2.26184314E-02    2    -1000003        3   # BR(~g -> ~s_L* s )
     4.79704725E-02    2     2000003       -3   # BR(~g -> ~s_R  sb)
     4.79704725E-02    2    -2000003        3   # BR(~g -> ~s_R* s )
     2.66424179E-02    2     1000004       -4   # BR(~g -> ~c_L  cb)
     2.66424179E-02    2    -1000004        4   # BR(~g -> ~c_L* c )
     4.17938806E-02    2     2000004       -4   # BR(~g -> ~c_R  cb)
     4.17938806E-02    2    -2000004        4   # BR(~g -> ~c_R* c )
     7.70945370E-02    2     1000005       -5   # BR(~g -> ~b_1  bb)
     7.70945370E-02    2    -1000005        5   # BR(~g -> ~b_1* b )
     5.17632899E-02    2     2000005       -5   # BR(~g -> ~b_2  bb)
     5.17632899E-02    2    -2000005        5   # BR(~g -> ~b_2* b )
     9.30917683E-02    2     1000006       -6   # BR(~g -> ~t_1  tb)
     9.30917683E-02    2                    6   # BR(~g -> ~t_1* t )
#
```

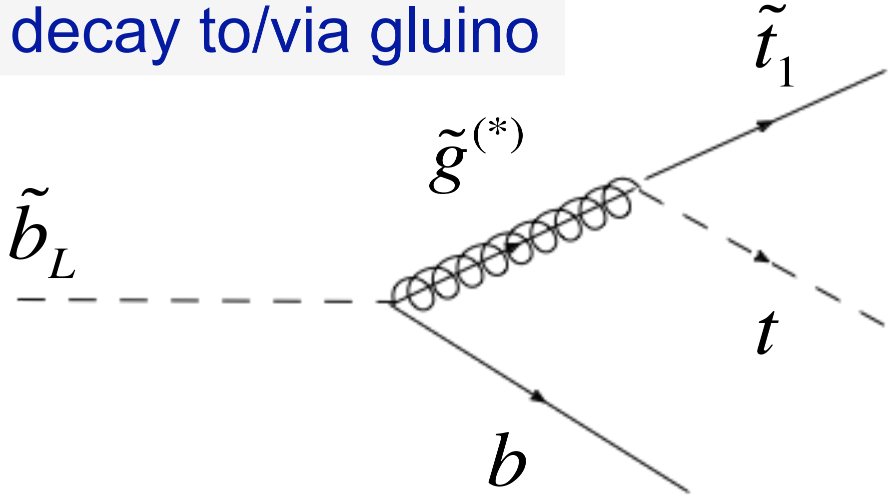
$\tilde{g} \not\rightarrow t + \bar{\tilde{t}}_2$ in LM6

Squark decay

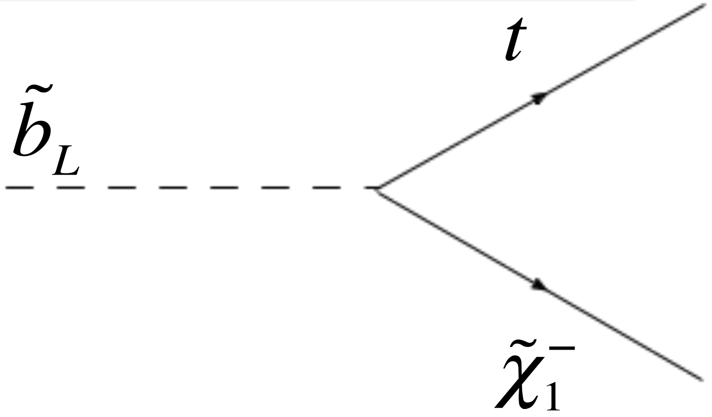
decay to/via neutralino



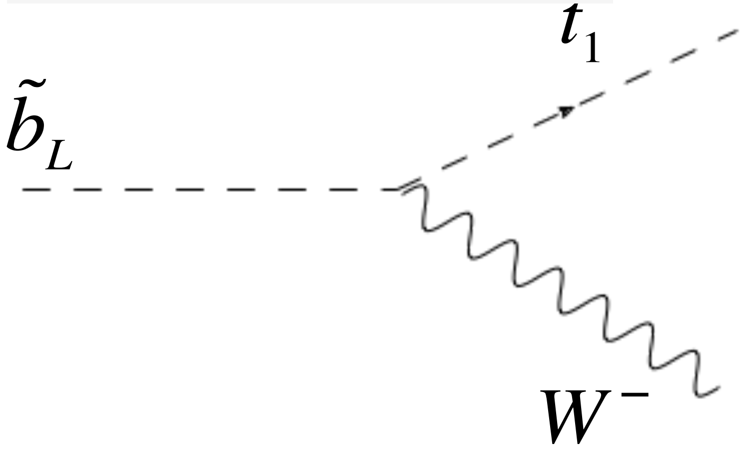
decay to/via gluino



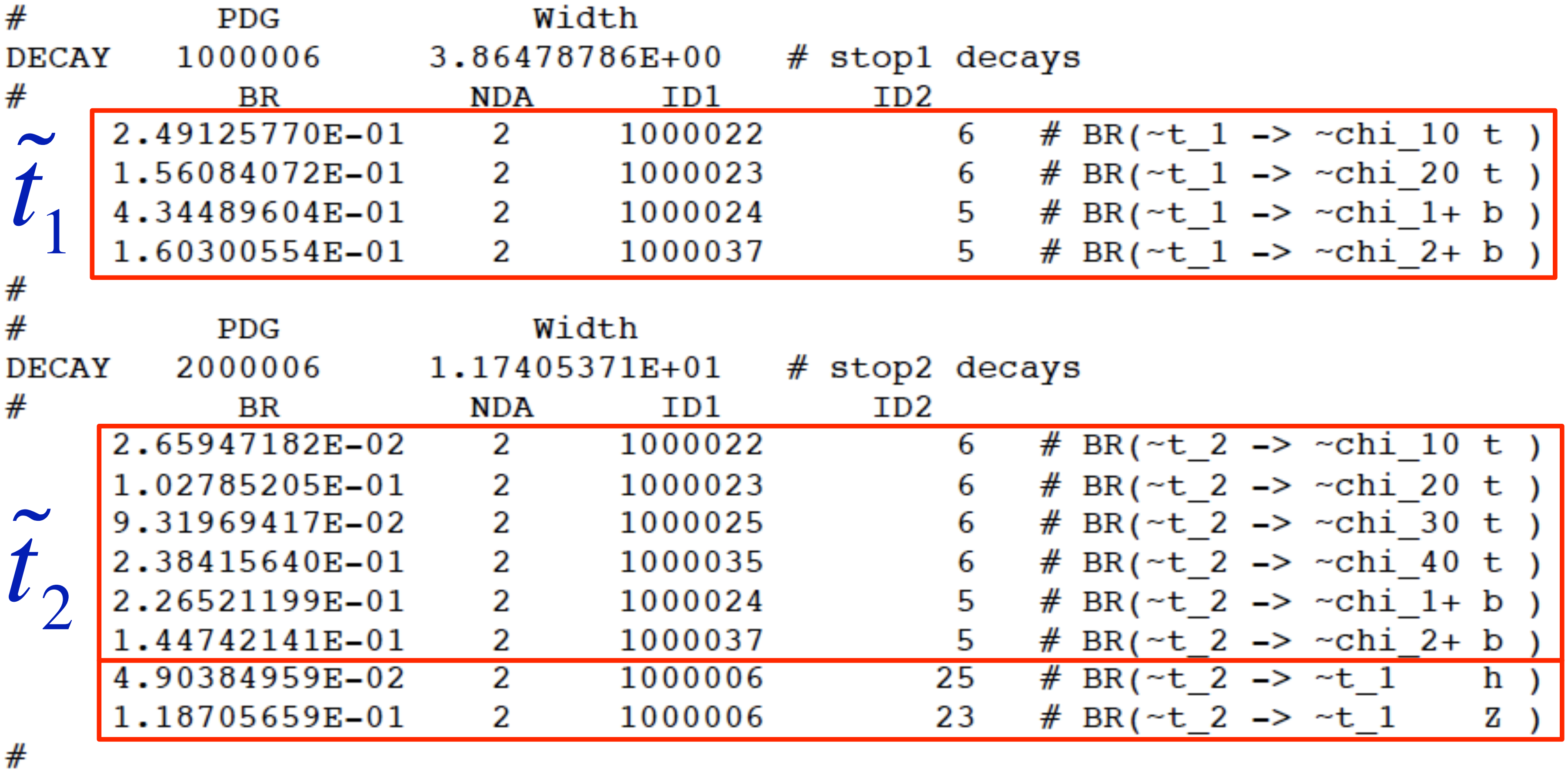
decay to/via chargino



decay to/via W, Z, h



Decay tables for stop 1,2 in LM6

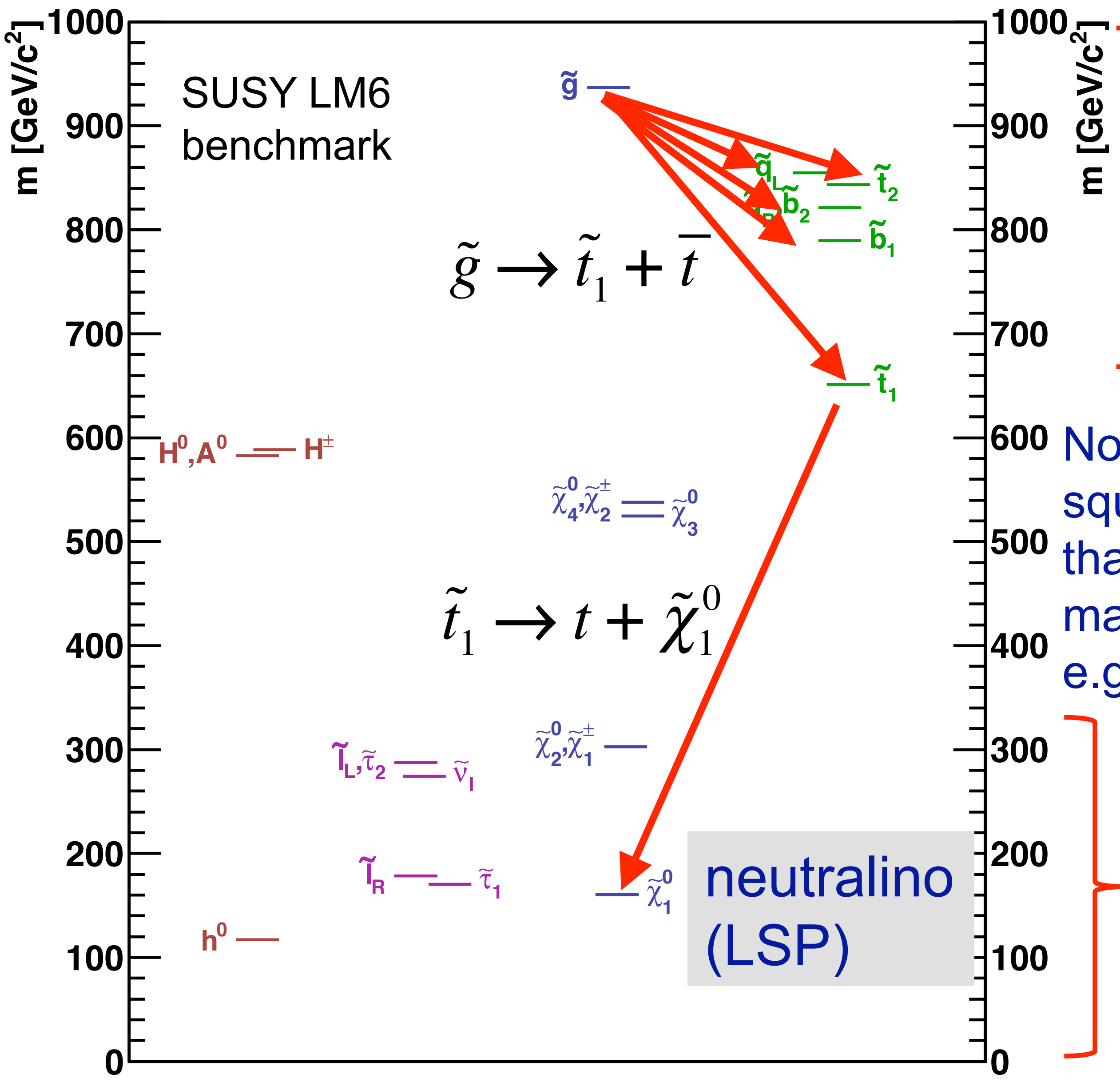


$\tilde{t}_1$

$\tilde{t}_2$

```
#         PDG             Width
DECAY    1000006      3.86478786E+00   # stop1 decays
#          BR          NDA      ID1        ID2
     2.49125770E-01     2     1000022         6   # BR(~t_1 -> ~chi_10 t )
     1.56084072E-01     2     1000023         6   # BR(~t_1 -> ~chi_20 t )
     4.34489604E-01     2     1000024         5   # BR(~t_1 -> ~chi_1+ b )
     1.60300554E-01     2     1000037         5   # BR(~t_1 -> ~chi_2+ b )
#
#         PDG             Width
DECAY    2000006      1.17405371E+01   # stop2 decays
#          BR          NDA      ID1        ID2
     2.65947182E-02     2     1000022         6   # BR(~t_2 -> ~chi_10 t )
     1.02785205E-01     2     1000023         6   # BR(~t_2 -> ~chi_20 t )
     9.31969417E-02     2     1000025         6   # BR(~t_2 -> ~chi_30 t )
     2.38415640E-01     2     1000035         6   # BR(~t_2 -> ~chi_40 t )
     2.26521199E-01     2     1000024         5   # BR(~t_2 -> ~chi_1+ b )
     1.44742141E-01     2     1000037         5   # BR(~t_2 -> ~chi_2+ b )
     4.90384959E-02     2     1000006        25   # BR(~t_2 -> ~t_1     h )
     1.18705659E-01     2     1000006        23   # BR(~t_2 -> ~t_1     Z )
#
```

Thinking about gluinos

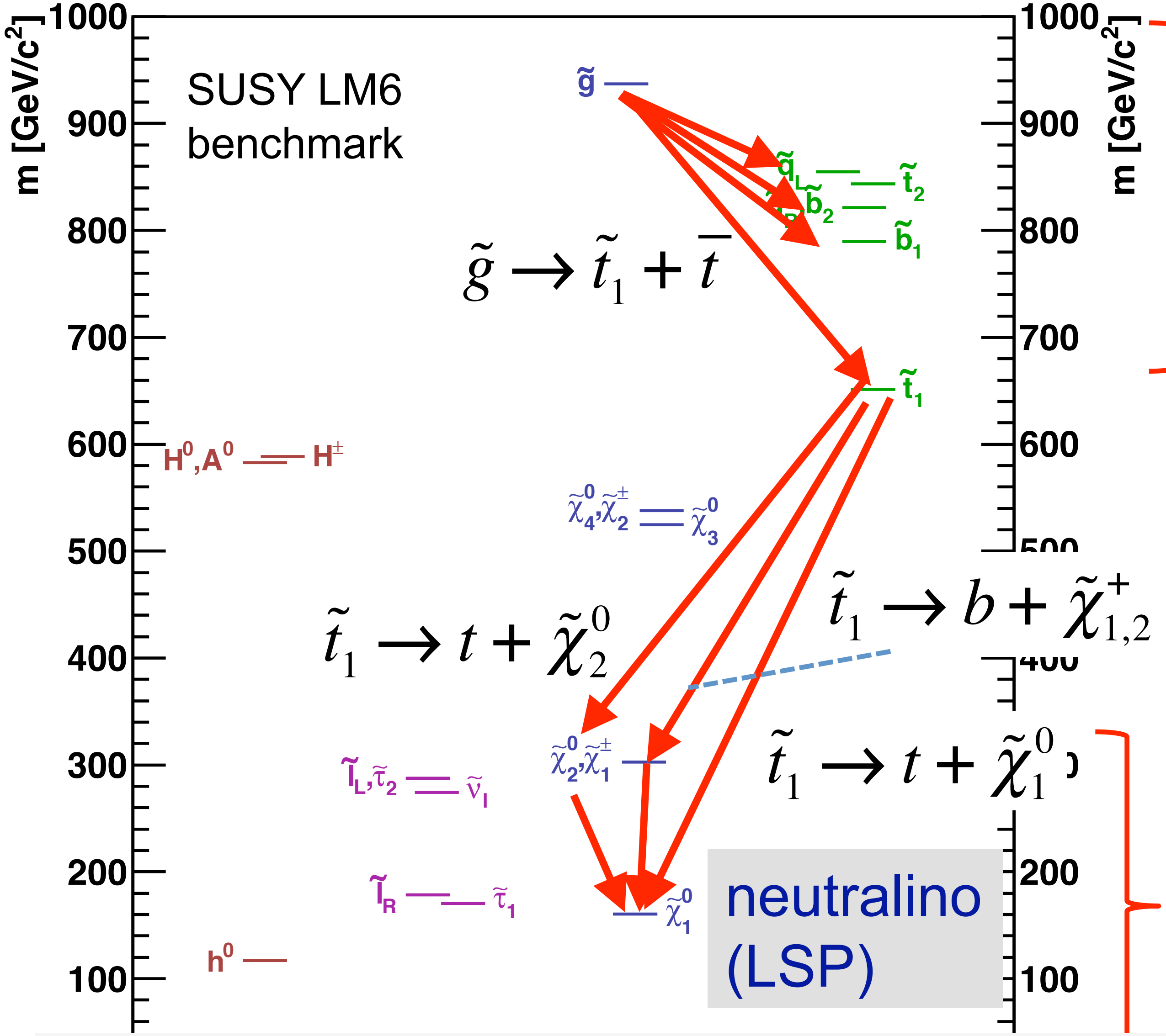


Direct production via strong processes

Nobody knows how many squarks would be lighter than the gluino: maybe 0, 1, 2, 3,??? e.g., split supersymmetry!

Direct production via electroweak processes

Things can start to get complicated



$\tilde{g} \to \tilde{t}_1 + \bar{t}$

$\tilde{t}_1 \to t + \tilde{\chi}_2^0$

$\tilde{t}_1 \to b + \tilde{\chi}_{1,2}^+$

$\tilde{t}_1 \to t + \tilde{\chi}_1^0$

neutralino (LSP)

Direct production via strong processes

Direct production via electroweak processes

Things can get pretty complicated...and there are many scenarios!

Strategy for SUSY with complex decay patterns

- Complex decay patterns, not dominated by any one (or even few) modes, can emerge in many models.
- Inclusive search strategies, based on simple topological signatures are well suited to such cases.
- Inclusive searches (can require b jets in all cases)
  - Jets + MET (or similar variable)
  - 1 lepton + Jets + MET
  - Dileptons + Jets + MET (same- or opp-sign dileptons)
  - Single photon + jets + MET
  - Two photons + jets + MET

Also on the menu: can add b-jets, tau leptons to most items! Opp. sign dileptons: can add Z bosons.

CMS: Multijets + MHT search (7 TeV)

CMS, http://arxiv.org/pdf/1207.1898.pdf

- Search variables:

$$\vec{p}_T^{\,\text{miss, jets}} = -\left[\sum_{i=\text{ jets above pT threshold}} \vec{p}_T^{\,i}\right] \rightarrow \not{H}_T \equiv \left|\vec{p}_T^{\,\text{miss, jets}}\right|$$

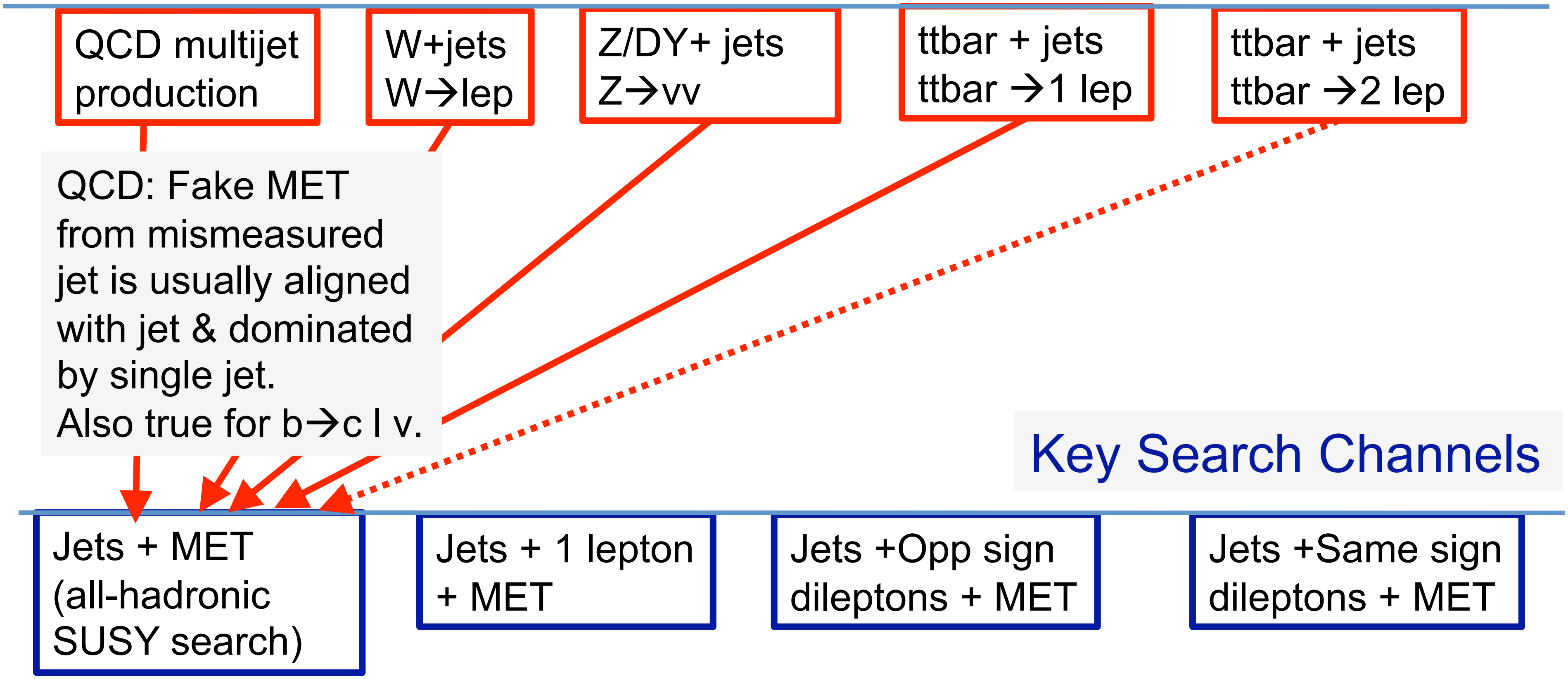
$$H_T = \sum_{i=\text{ jets above pT threshold}} \left|\vec{p}_T^{\,i}\right|$$

Why not use MET?
Data-driven method
for QCD background
uses jet-smearing
method!

- Require ≥3 jets, pT>50 GeV, |η|<2.5
- <u>ttbar, W+jets suppression</u>: veto events with isolated leptons with pT>10 GeV.
- <u>QCD suppression</u>: veto events with Δϕ(MET, Jet1)<0.5. Similar cuts for Jet2, Jet3.

Background schematic for searches with MET

Key Background Processes



QCD multijet production

W+jets
W→lep

Z/DY+ jets
Z→vv

ttbar + jets
ttbar →1 lep

ttbar + jets
ttbar →2 lep

QCD: Fake MET from mismeasured jet is usually aligned with jet & dominated by single jet.
Also true for b→c l v.

Key Search Channels

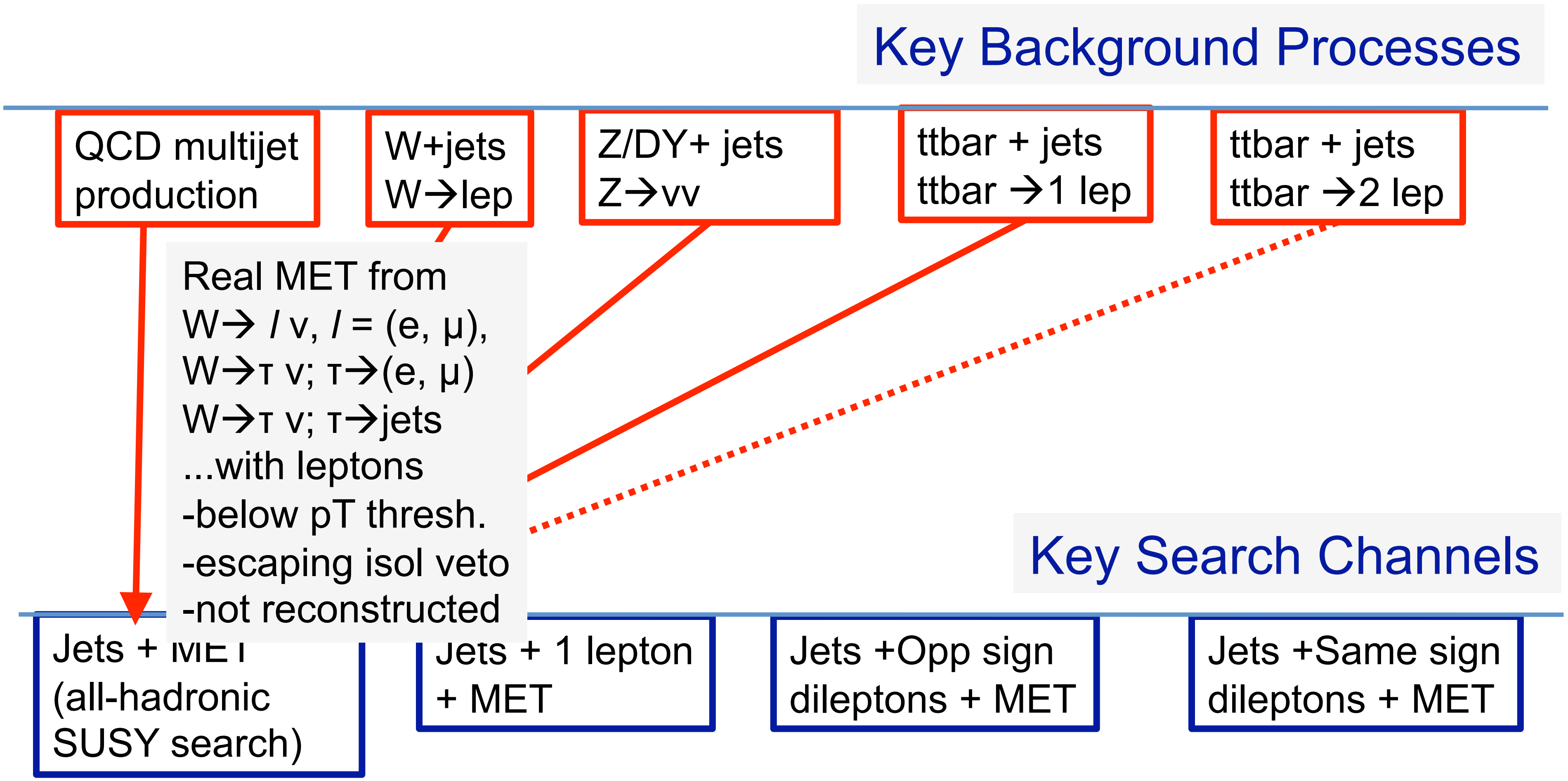
Jets + MET
(all-hadronic SUSY search)

Jets + 1 lepton
+ MET

Jets +Opp sign
dileptons + MET

Jets +Same sign
dileptons + MET

Background schematic for searches with MET



Key Background Processes

QCD multijet production

W+jets
W→lep

Z/DY+ jets
Z→νν

ttbar + jets
ttbar →1 lep

ttbar + jets
ttbar →2 lep

Real MET from
W→ *l* ν, *l* = (e, μ),
W→τ ν; τ→(e, μ)
W→τ ν; τ→jets
...with leptons
-below pT thresh.
-escaping isol veto
-not reconstructed

Key Search Channels

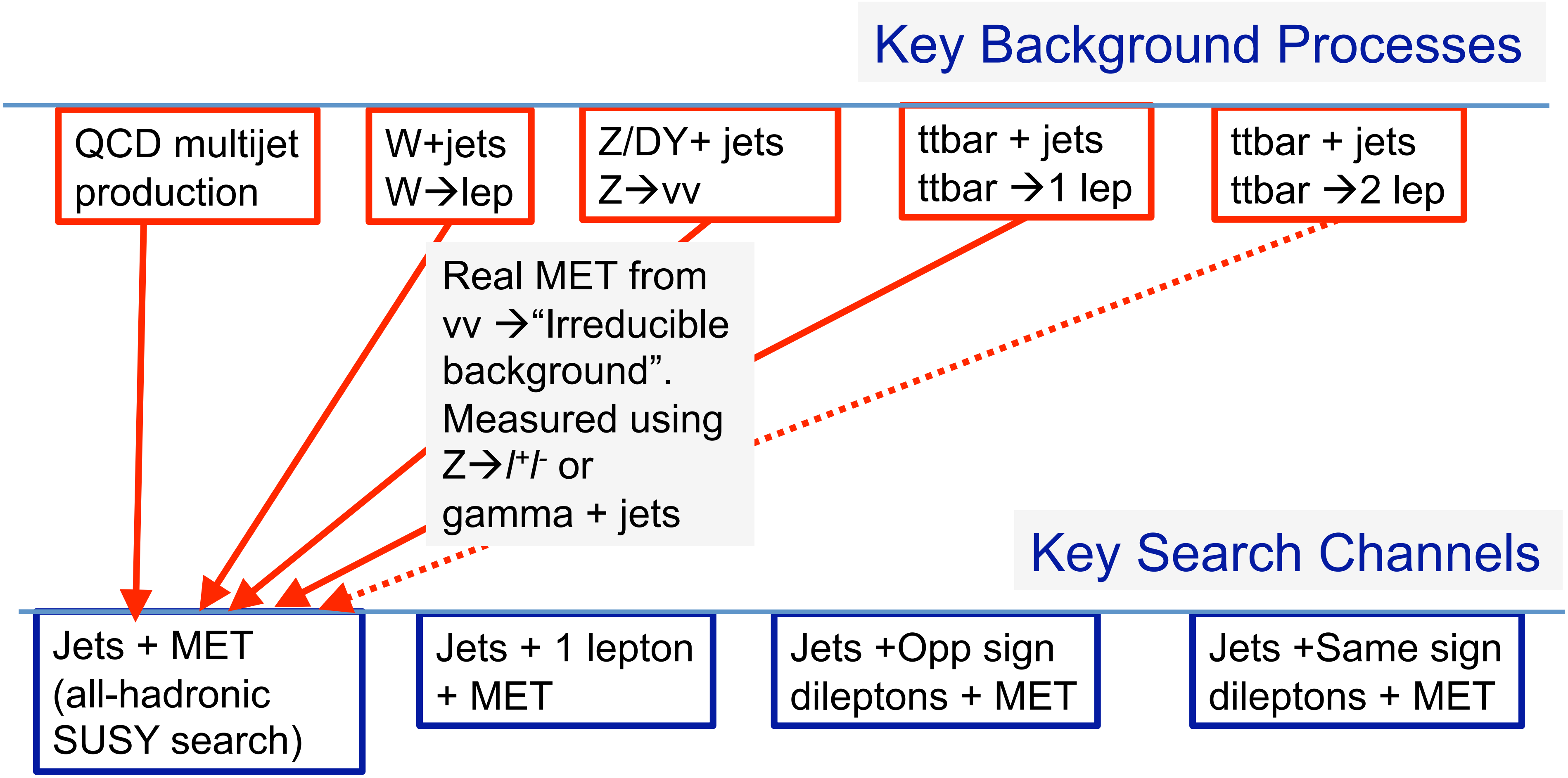
Jets + MET
(all-hadronic
SUSY search)

Jets + 1 lepton
+ MET

Jets +Opp sign
dileptons + MET

Jets +Same sign
dileptons + MET

Background schematic for searches with MET



Key Background Processes

QCD multijet production

W+jets
W→lep

Z/DY+ jets
Z→νν

ttbar + jets
ttbar →1 lep

ttbar + jets
ttbar →2 lep

Real MET from νν →"Irreducible background". Measured using Z→l^+l^- or gamma + jets

Key Search Channels

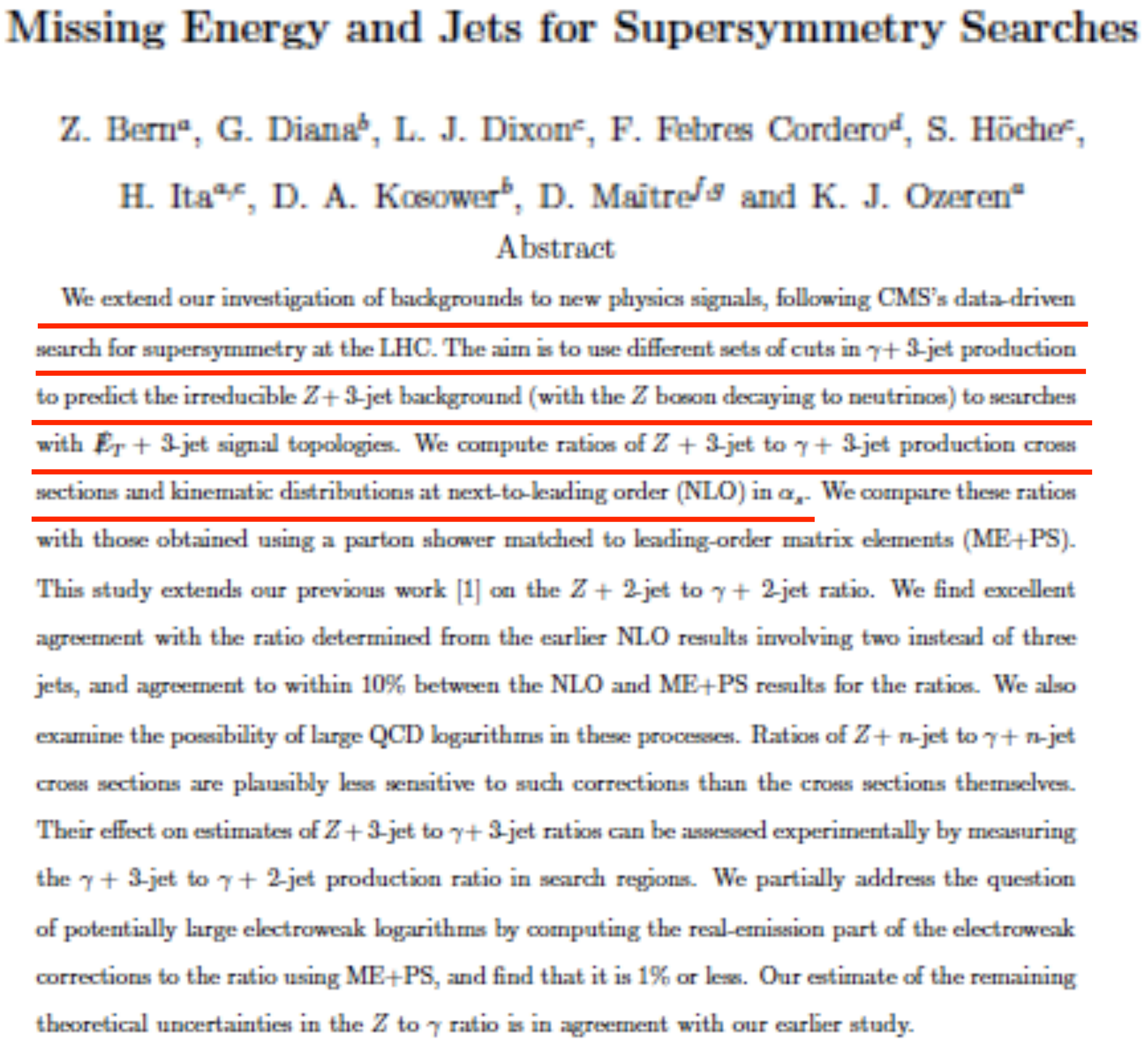
Jets + MET (all-hadronic SUSY search)

Jets + 1 lepton + MET

Jets +Opp sign dileptons + MET

Jets +Same sign dileptons + MET

http://arxiv.org/pdf/1206.6064.pdf



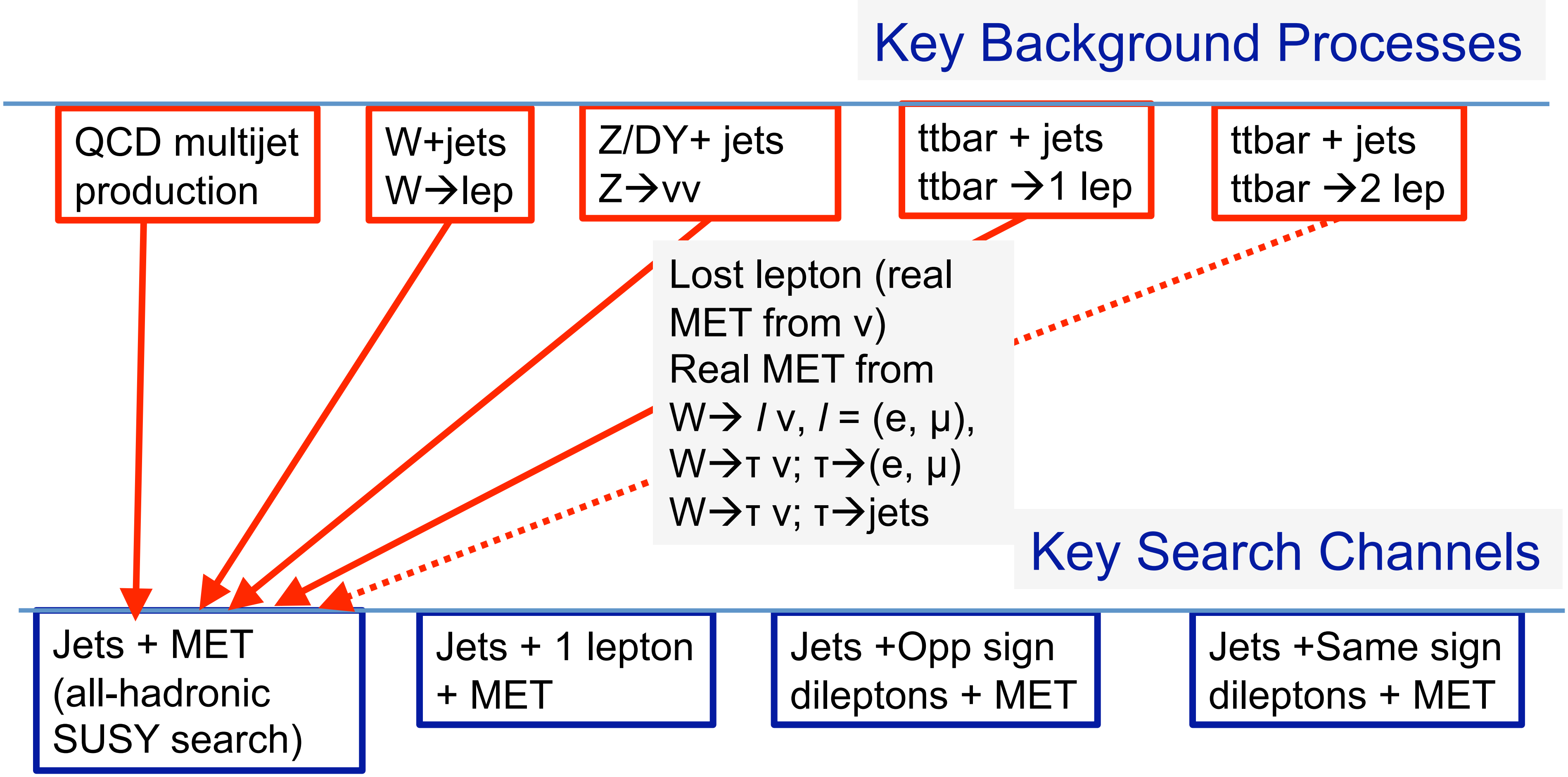
Missing Energy and Jets for Supersymmetry Searches

Z. Bern[a], G. Diana[b], L. J. Dixon[c], F. Febres Cordero[d], S. Höche[c],
H. Ita[a,e], D. A. Kosower[b], D. Maître[f,g] and K. J. Ozeren[a]

Abstract

We extend our investigation of backgrounds to new physics signals, following CMS's data-driven search for supersymmetry at the LHC. The aim is to use different sets of cuts in $\gamma+$ 3-jet production to predict the irreducible $Z+$ 3-jet background (with the Z boson decaying to neutrinos) to searches with $\not{E}_T$ + 3-jet signal topologies. We compute ratios of Z + 3-jet to γ + 3-jet production cross sections and kinematic distributions at next-to-leading order (NLO) in α_s. We compare these ratios with those obtained using a parton shower matched to leading-order matrix elements (ME+PS). This study extends our previous work [1] on the Z + 2-jet to γ + 2-jet ratio. We find excellent agreement with the ratio determined from the earlier NLO results involving two instead of three jets, and agreement to within 10% between the NLO and ME+PS results for the ratios. We also examine the possibility of large QCD logarithms in these processes. Ratios of $Z+$ n-jet to $\gamma+$ n-jet cross sections are plausibly less sensitive to such corrections than the cross sections themselves. Their effect on estimates of $Z+$ 3-jet to $\gamma+$ 3-jet ratios can be assessed experimentally by measuring the γ + 3-jet to γ + 2-jet production ratio in search regions. We partially address the question of potentially large electroweak logarithms by computing the real-emission part of the electroweak corrections to the ratio using ME+PS, and find that it is 1% or less. Our estimate of the remaining theoretical uncertainties in the Z to γ ratio is in agreement with our earlier study.

Background schematic for searches with MET



Key Background Processes

QCD multijet production

W+jets
W→lep

Z/DY+ jets
Z→νν

ttbar + jets
ttbar →1 lep

ttbar + jets
ttbar →2 lep

Lost lepton (real MET from ν)
Real MET from
W→ *l* ν, *l* = (e, μ),
W→τ ν; τ→(e, μ)
W→τ ν; τ→jets

Key Search Channels

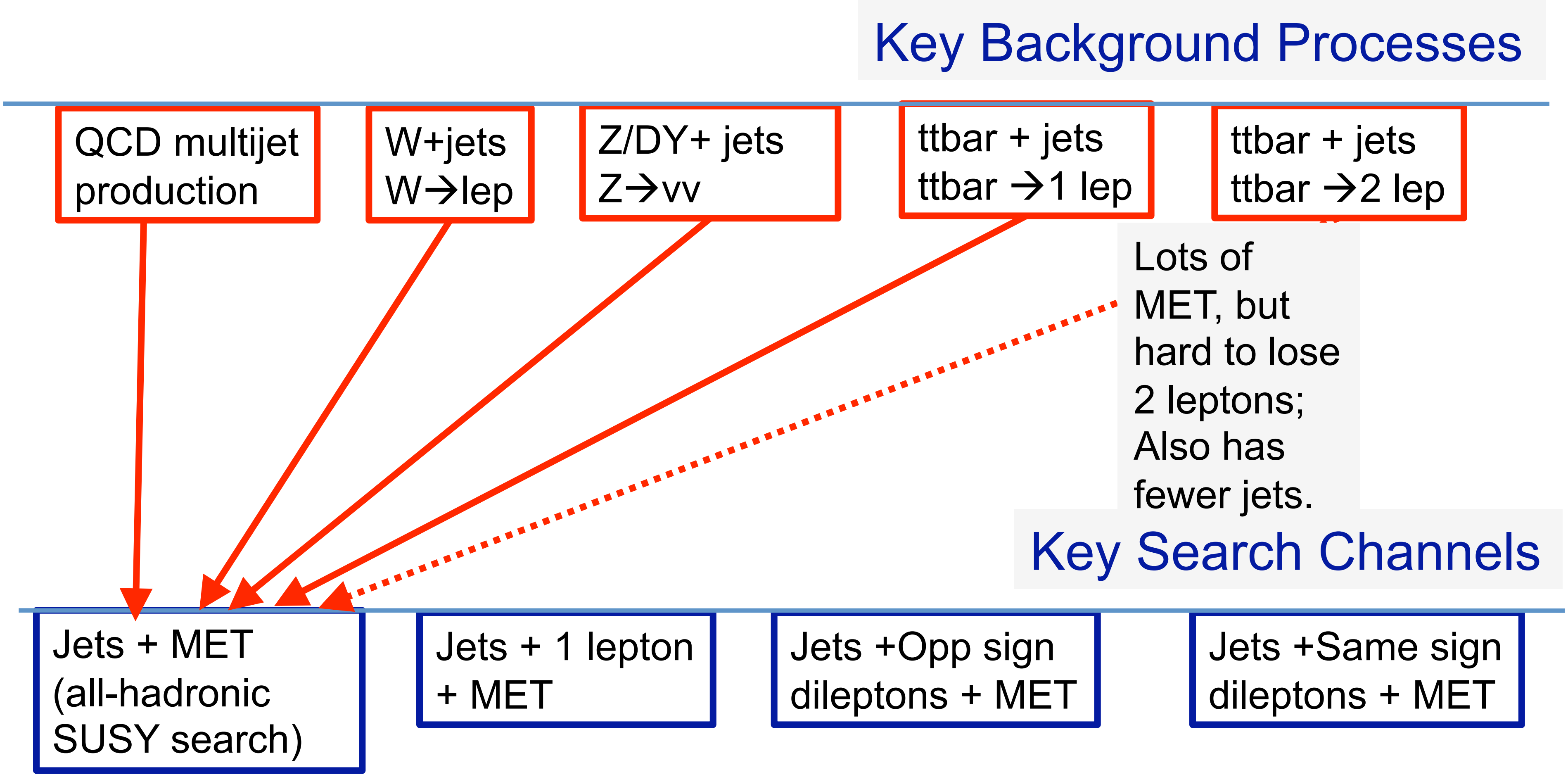
Jets + MET (all-hadronic SUSY search)

Jets + 1 lepton + MET

Jets +Opp sign dileptons + MET

Jets +Same sign dileptons + MET

Background schematic for searches with MET



Key Background Processes

QCD multijet production

W+jets
W→lep

Z/DY+ jets
Z→vv

ttbar + jets
ttbar →1 lep

ttbar + jets
ttbar →2 lep

Lots of MET, but hard to lose 2 leptons; Also has fewer jets.

Key Search Channels

Jets + MET (all-hadronic SUSY search)

Jets + 1 lepton + MET

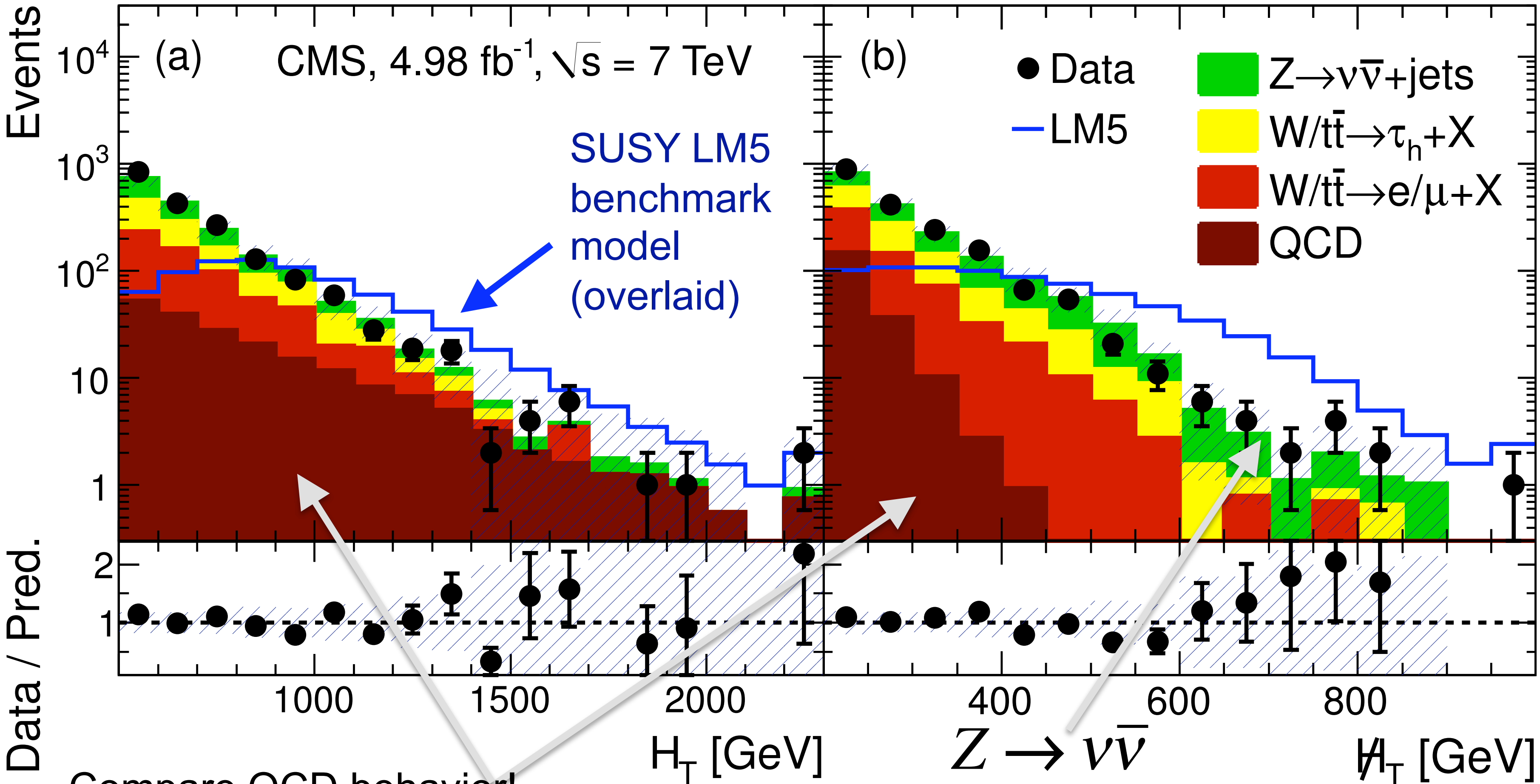
Jets +Opp sign dileptons + MET

Jets +Same sign dileptons + MET

CMS inclusive jets + MHT search

http://arxiv.org/pdf/1207.1898.pdf

Distributions of HT and HTmiss for events passing the baseline selection
Backgrounds are from data-driven estimates, not MC.



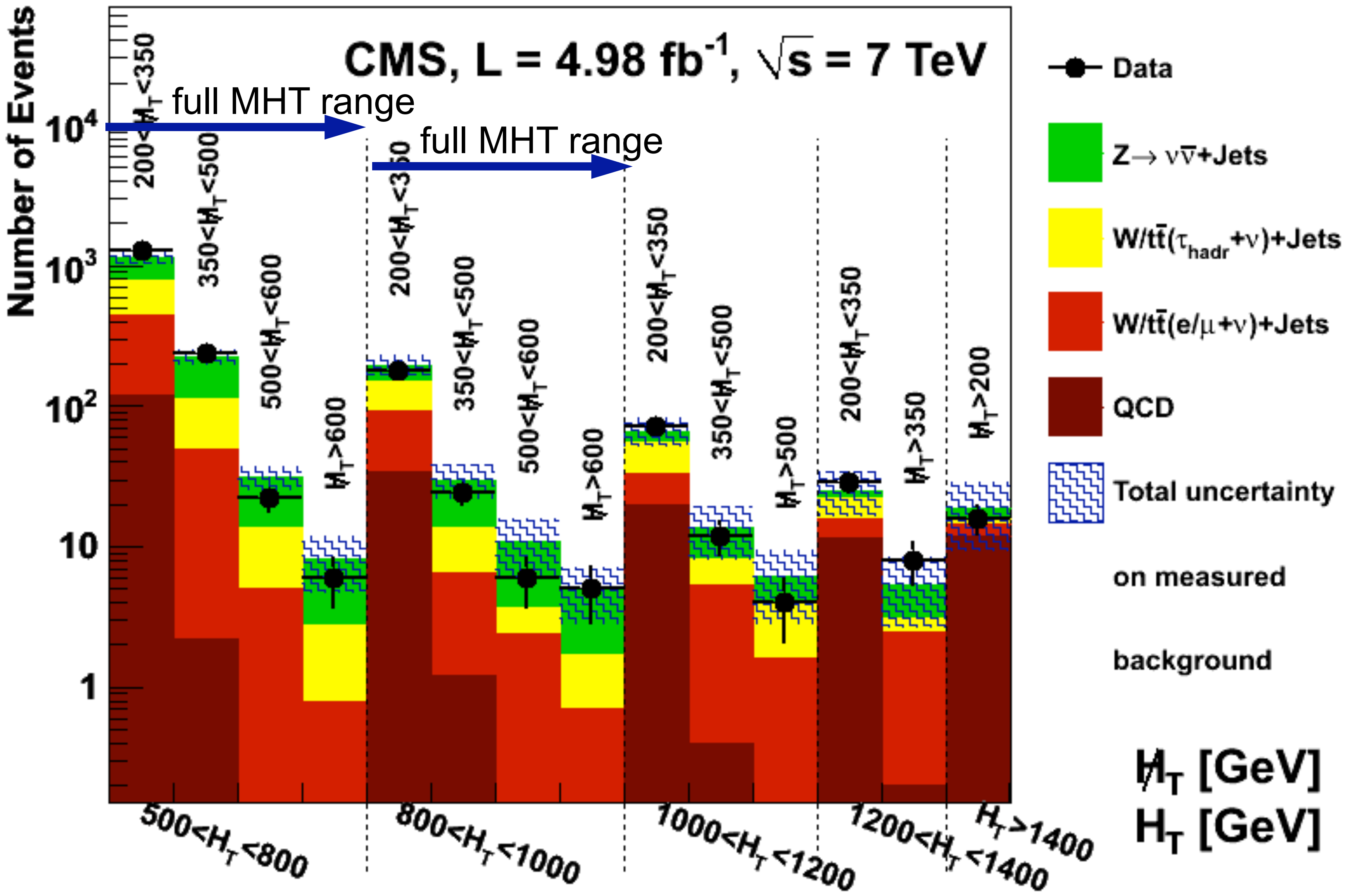
SUSY LM5 benchmark model (overlaid)

$Z \to \nu\bar{\nu}$

Compare QCD behavior!

LM5: m0 = 230 GeV, m1/2 = 360 GeV, A0 = 0, tan *b = 10, and sgn(m) > 0*

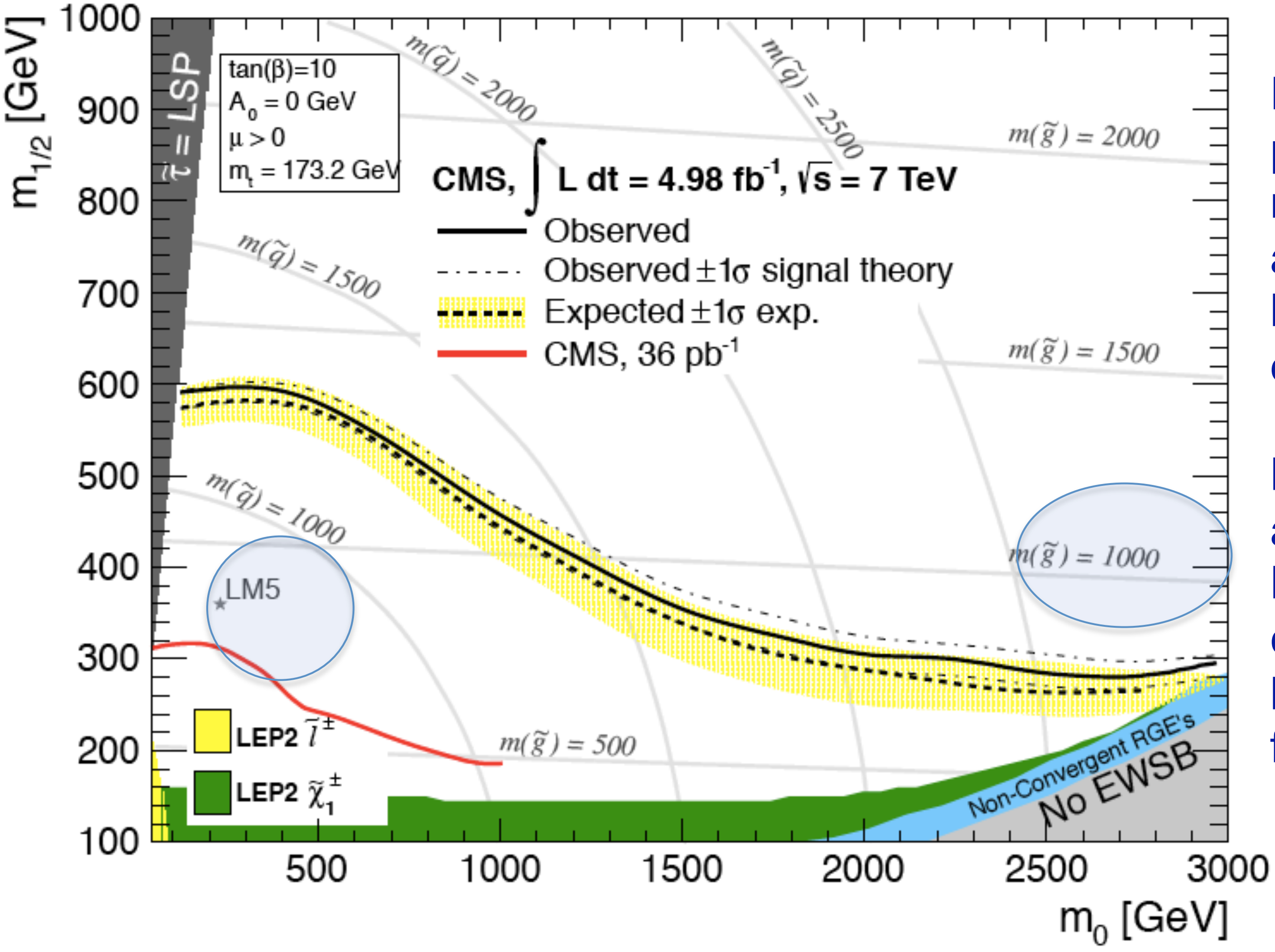
Yields vs. predictions by signal region



full MHT range

full MHT range

cMSSM exclusion region for jets + MHT search

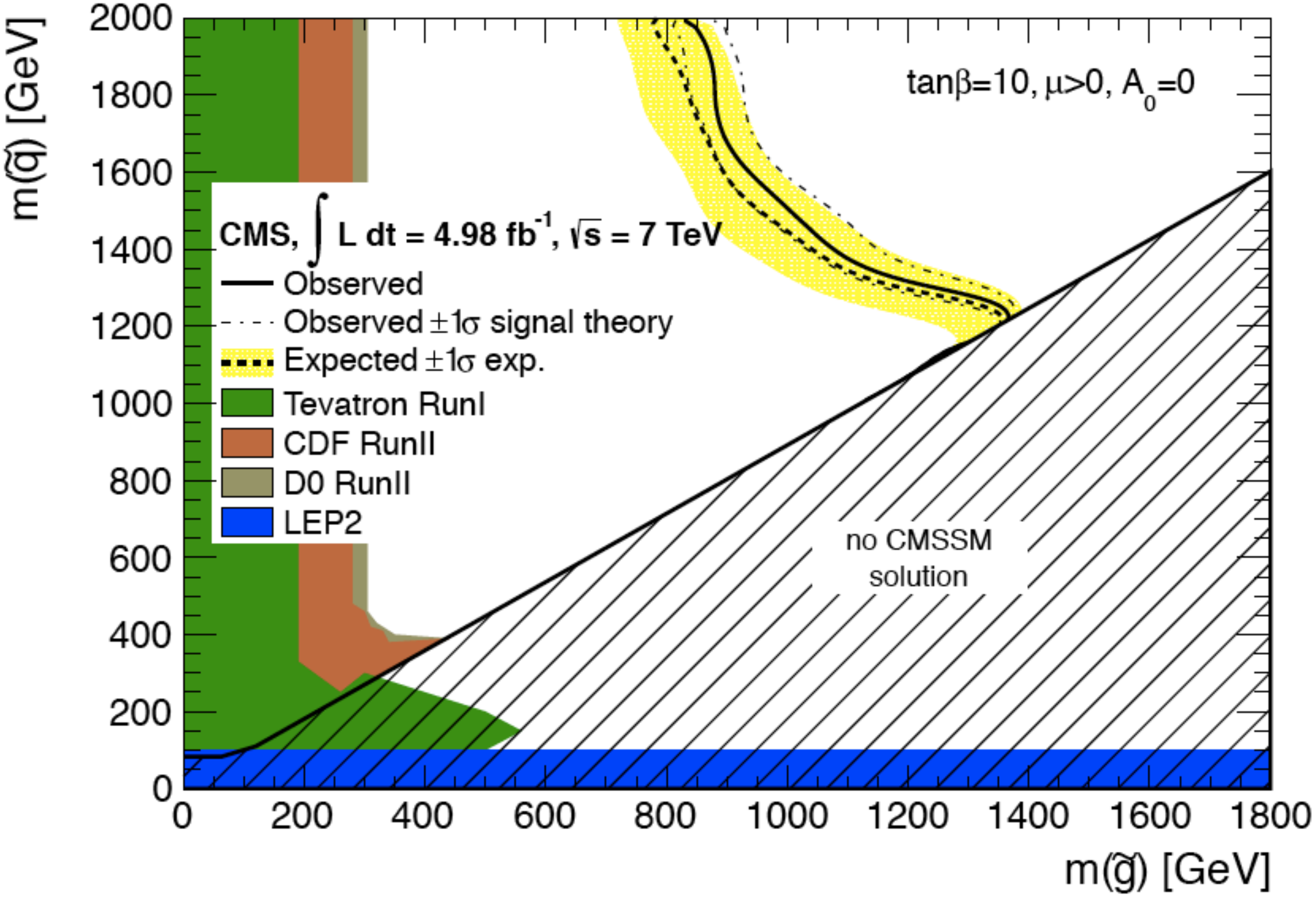


For this cMSSM param set, squark masses below 1.2 TeV and gluino masses below 720 GeV are excluded.

But these conclusions are not generic... Must be extremely careful about drawing broad conclusions from cMSSM!

In the cMSSM/mSUGRA, the gluino mass can't be too far above the squark masses.

Constraints in the m($\tilde{q}$) vs. m($\tilde{g}$) plane



Limitations of cMSSM interpretation

- People liked cMSSM because it reduced 105 parameters to just 5, defined at the GUT scale:
  - common sfermion mass: m_0
  - common gaugino mass: $m_{1/2}$
  - common trinlinear coupling A_0
  - ratio of vac. expectation values for up-type & down-type fermions: tanβ
  - sign of Higgsino mass parameter: μ

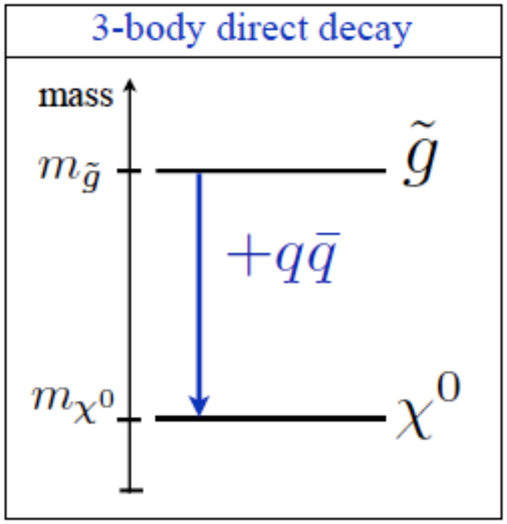
great for making pretty plots!

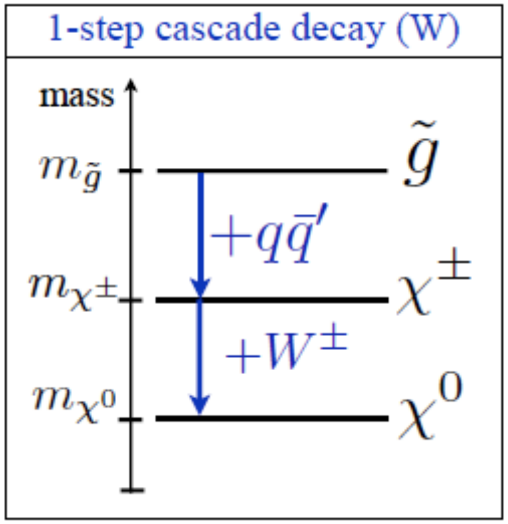
- The interpretation of SUSY results in terms of cMSSM/mSUGRA parameter space is considered ~obsolete.
- The cMSSM incorporates contraints at the GUT scale that are not well motivated. These can lead to spectra that are not sufficiently generic for searches.

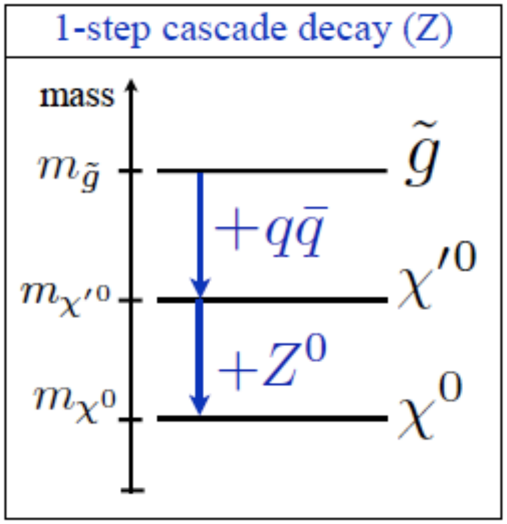
Simplified models: a new paradigm

http://arxiv.org/abs/1105.2838

- To reduce the number of NP parameters, use very simple particle spectra. *Masses specified at EW scale.*
- Each model based on an effective Lagrangian relevant for a particular process of interest.
- Experimenters establish upper limits on the cross section for the simplified model, for given masses.

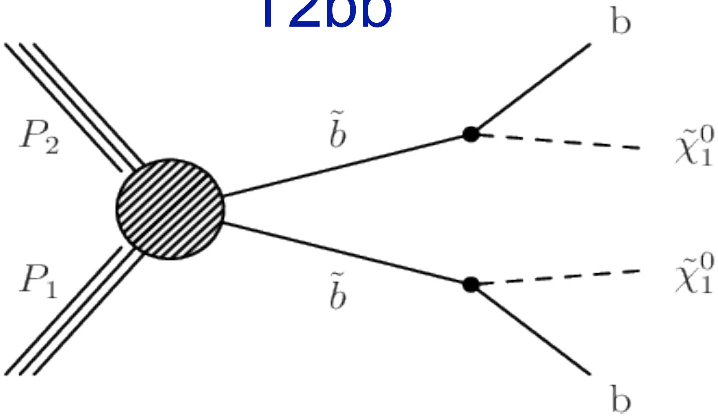




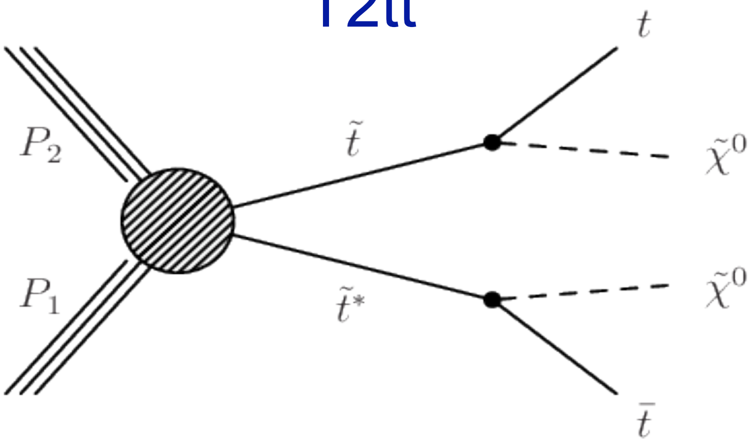


Simplified models: examples

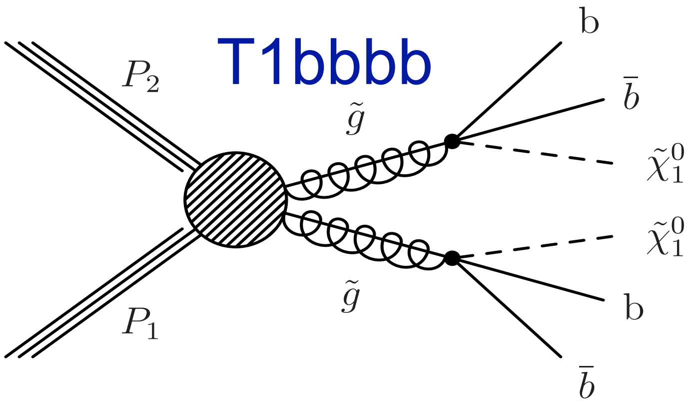
T2bb



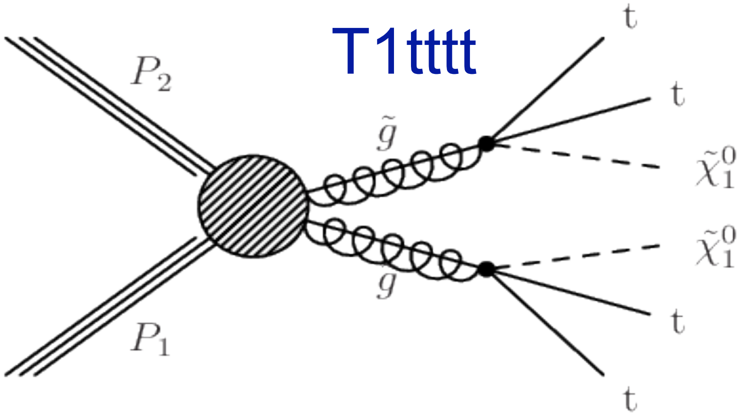
T2tt



T1bbbb



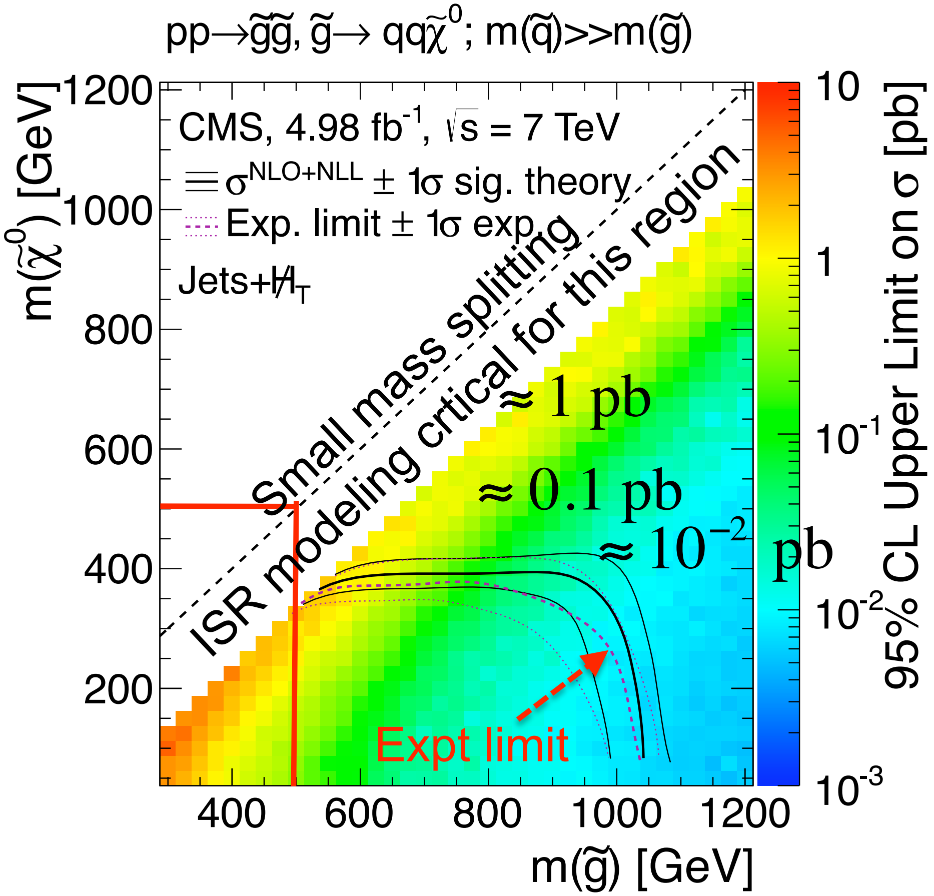
T1tttt



Tn=Topology n; n= even → squark production (gluino decoupled);
n=odd → gluino production (squark decoupled); see CMS PAS SUS-11-016.
http://cdsweb.cern.ch/record/1445580.

Simplified model interpretation: CMS jets + MHT (7 TeV)

Gluino production with 3-body decay



Small mass splitting

ISR modeling critical for this region

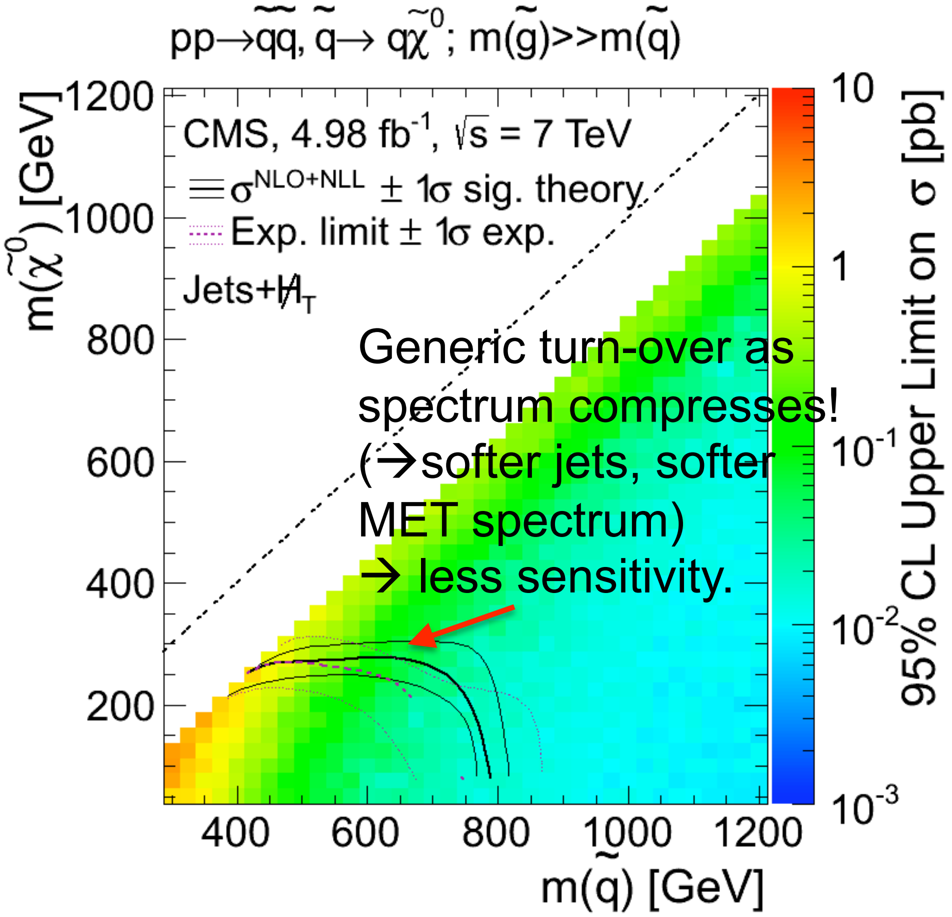
≈ 1 pb

≈ 0.1 pb

≈ 10^{-2} pb

Expt limit

Direct squark production with 2-body decay to LSP



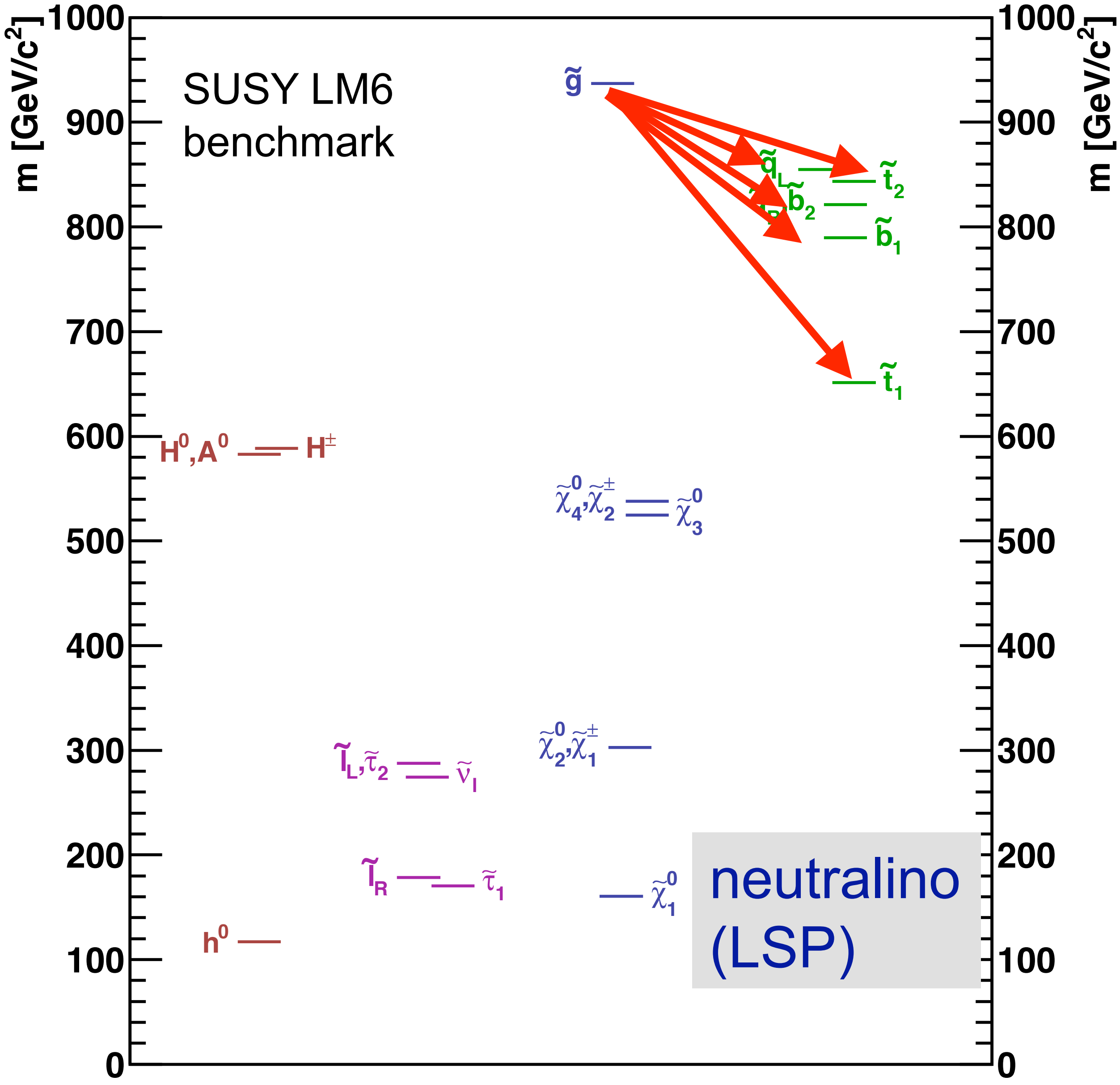
Generic turn-over as spectrum compresses! (→softer jets, softer MET spectrum) → less sensitivity.

Paradigm shift: now quote the upper limit on the cross section for the given topology.

Inclusive SUSY searches with leptons

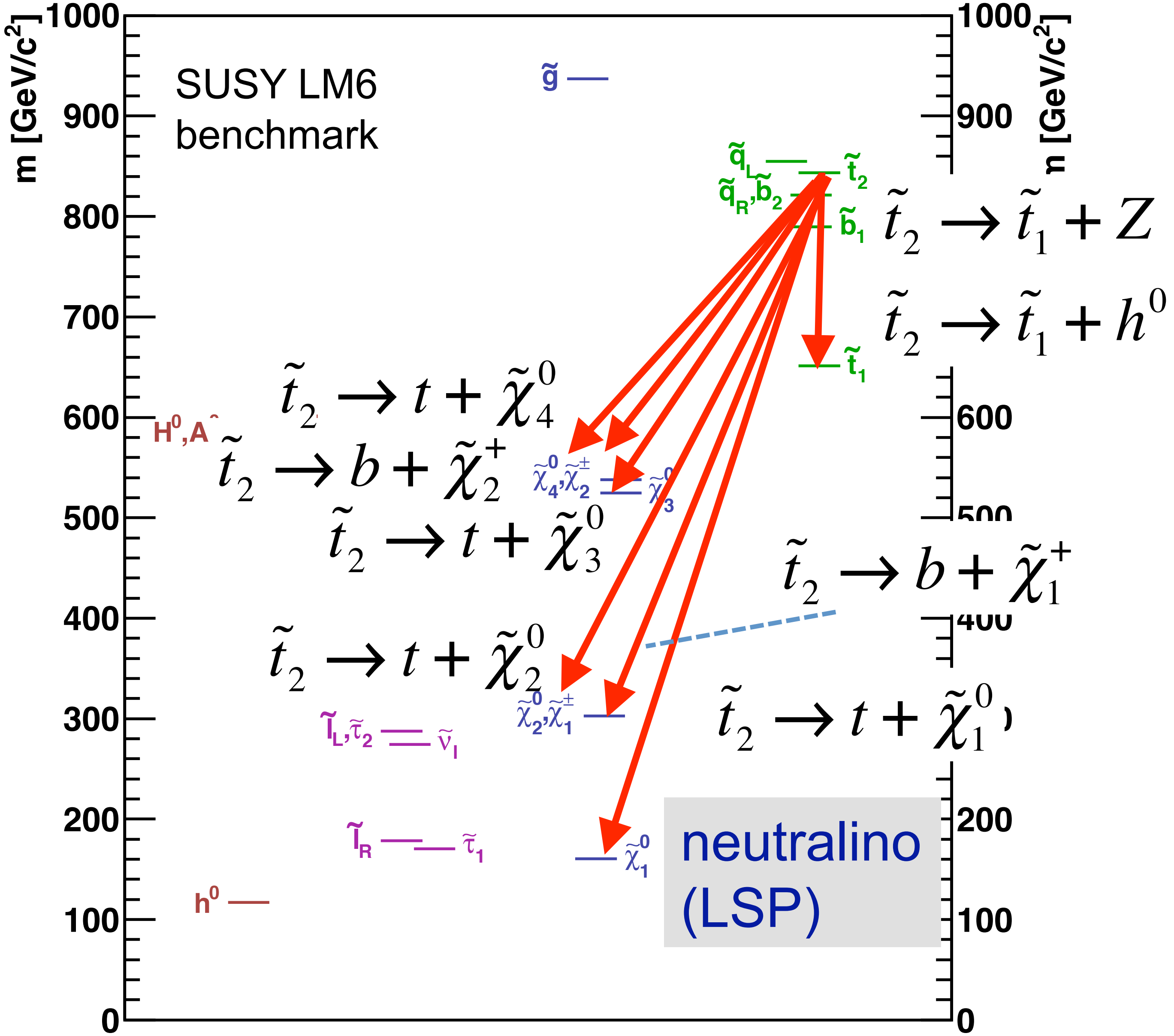
- The decay of squarks can produce neutralinos, charginos, W and Z bosons. All of these can produce leptons.
- Leptons are your friends.
- Lepton isolation is a powerful tool for suppressing QCD background and for measuring how much remains.
- ttbar is almost always a key background.
- W, Z are more important for low numbers of jets.
- b tagging suppresses W, Z.

Starting from gluinos...



neutralino (LSP)

Decays of ~t$_2$ → neutralinos, charginos, Z...



$\tilde{t}_2 \rightarrow \tilde{t}_1 + Z$

$\tilde{t}_2 \rightarrow \tilde{t}_1 + h^0$

$\tilde{t}_2 \rightarrow t + \tilde{\chi}_4^0$

$\tilde{t}_2 \rightarrow b + \tilde{\chi}_2^+$

$\tilde{t}_2 \rightarrow t + \tilde{\chi}_3^0$

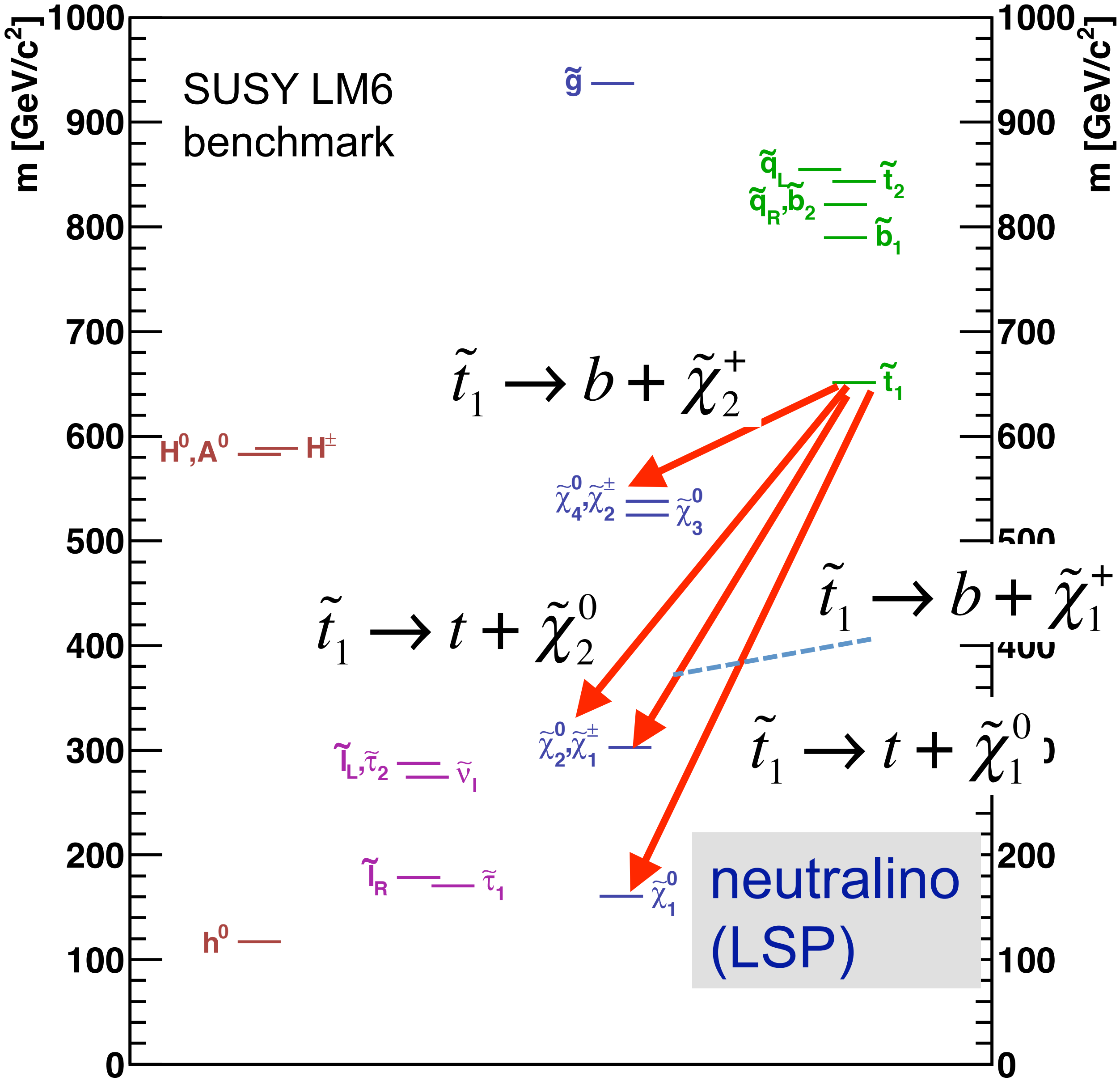
$\tilde{t}_2 \rightarrow b + \tilde{\chi}_1^+$

$\tilde{t}_2 \rightarrow t + \tilde{\chi}_2^0$

$\tilde{t}_2 \rightarrow t + \tilde{\chi}_1^0$

neutralino (LSP)

Decays of ~t$_1$ → neutralinos, charginos



$$\tilde{t}_1 \to b + \tilde{\chi}_2^+$$

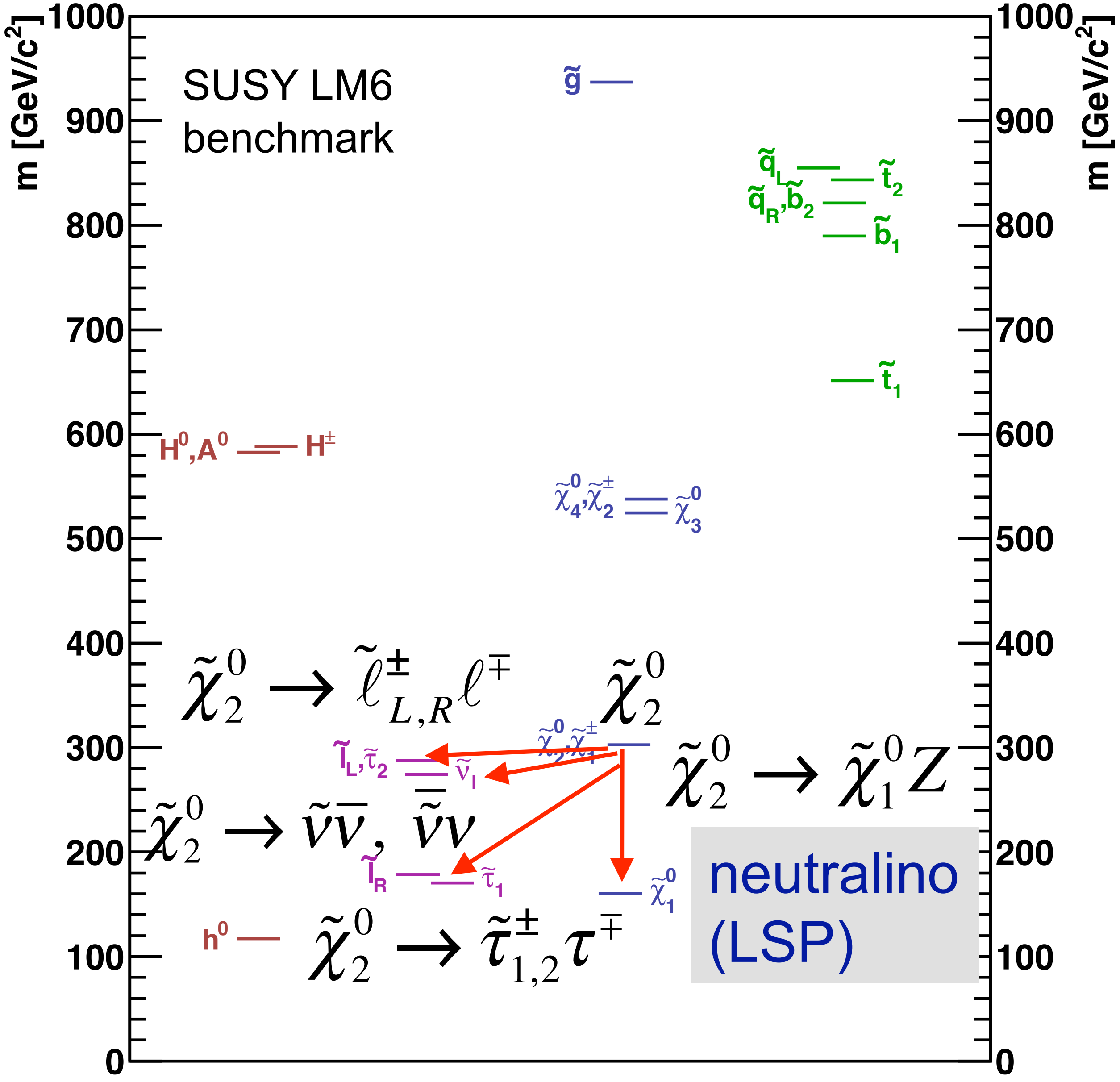
$$\tilde{t}_1 \to t + \tilde{\chi}_2^0$$

$$\tilde{t}_1 \to b + \tilde{\chi}_1^+$$

$$\tilde{t}_1 \to t + \tilde{\chi}_1^0$$

neutralino (LSP)

Decays of $\tilde{\chi}_2^0$: here come the leptons!



$$\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^\pm_{L,R} \ell^\mp$$

$$\tilde{\chi}_2^0$$

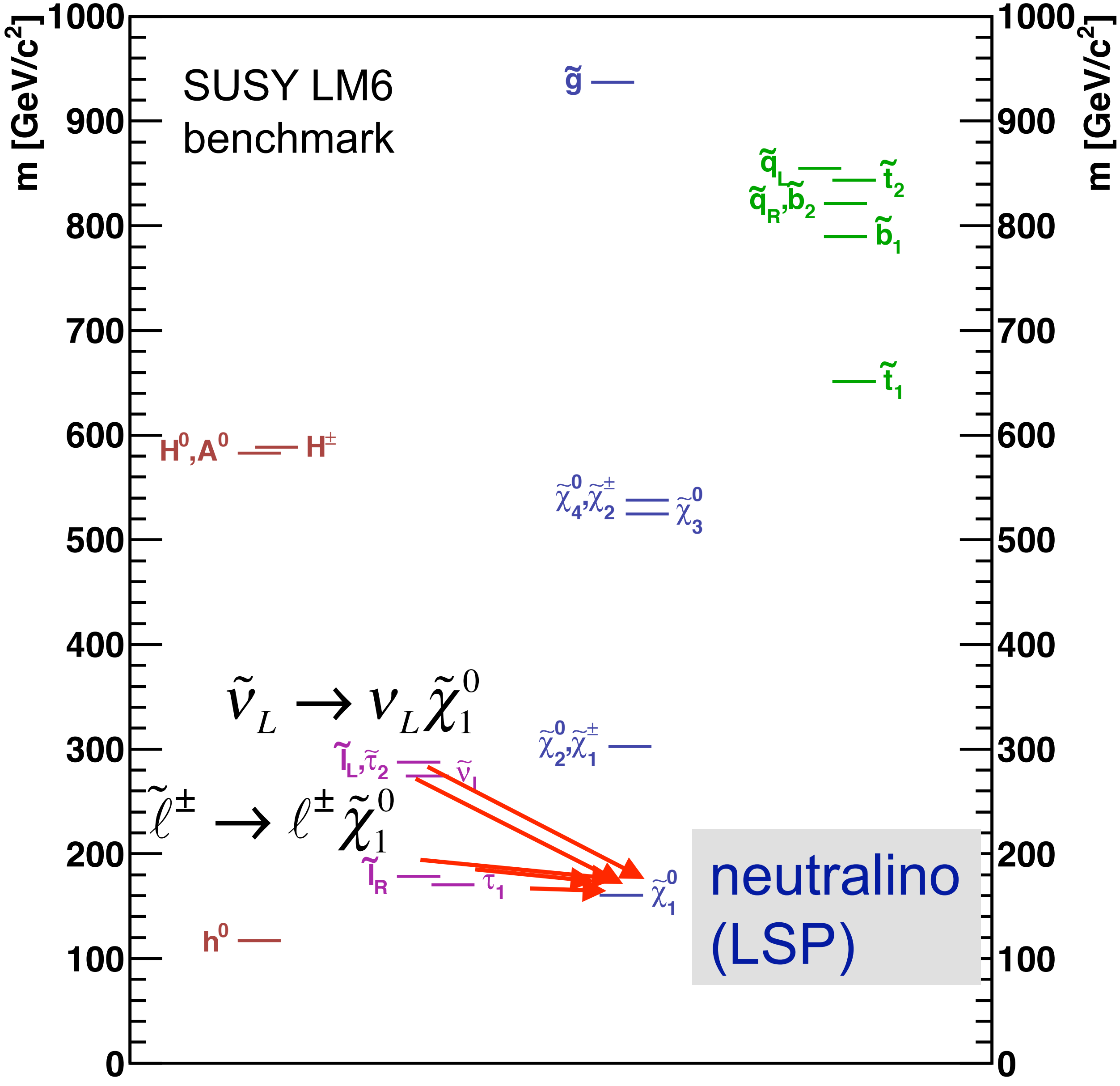
$$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z$$

$$\tilde{\chi}_2^0 \rightarrow \tilde{\nu}\bar{\nu}, \; \bar{\tilde{\nu}}\nu$$

$$\tilde{\chi}_2^0 \rightarrow \tilde{\tau}^\pm_{1,2} \tau^\mp$$

neutralino
(LSP)

Decays of $\tilde{\ell}^{\pm}_{L,R}$, $\tilde{\tau}^{\pm}_{1,2}$, $\tilde{\nu}_L$: more leptons!



$\tilde{\nu}_L \rightarrow \nu_L \tilde{\chi}^0_1$

$\tilde{\ell}^{\pm} \rightarrow \ell^{\pm} \tilde{\chi}^0_1$

neutralino
(LSP)

Decay table for $\tilde{\chi}_2^0$ in LM6

$\tilde{\chi}_2^0 \to \tilde{\ell}^{\pm}\ell^{\mp}$ $\tilde{\chi}_2^0 \to \tilde{\nu}\bar{\nu},\ \bar{\tilde{\nu}}\nu$ $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z,\ \tilde{\chi}_1^0 h$

```
#          PDG             Width
DECAY    1000023     1.84303604E-01   # neutralino2 decays
#          BR           NDA      ID1        ID2
         7.31040853E-03    2     1000022         23   # BR(~chi_20 -> ~chi_10    Z )
         7.12848974E-02    2     1000022         25   # BR(~chi_20 -> ~chi_10    h )
         3.19394658E-02    2     1000011        -11   # BR(~chi_20 -> ~e_L-      e+)
         3.19394658E-02    2    -1000011         11   # BR(~chi_20 -> ~e_L+      e-)
         5.72664801E-03    2     2000011        -11   # BR(~chi_20 -> ~e_R-      e+)
         5.72664801E-03    2    -2000011         11   # BR(~chi_20 -> ~e_R+      e-)
         3.19394658E-02    2     1000013        -13   # BR(~chi_20 -> ~mu_L-     mu+)
         3.19394658E-02    2    -1000013         13   # BR(~chi_20 -> ~mu_L+     mu-)
         5.72664801E-03    2     2000013        -13   # BR(~chi_20 -> ~mu_R-     mu+)
         5.72664801E-03    2    -2000013         13   # BR(~chi_20 -> ~mu_R+     mu-)
         8.18451584E-02    2     1000015        -15   # BR(~chi_20 -> ~tau_1-    tau+)
         8.18451584E-02    2    -1000015         15   # BR(~chi_20 -> ~tau_1+    tau-)
         2.34220380E-02    2     2000015        -15   # BR(~chi_20 -> ~tau_2-    tau+)
         2.34220380E-02    2    -2000015         15   # BR(~chi_20 -> ~tau_2+    tau-)
         9.16210759E-02    2     1000012        -12   # BR(~chi_20 -> ~nu_eL
nu_eb)
         9.16210759E-02    2    -1000012         12   # BR(~chi_20 -> ~nu_eL*    nu_e
)
         9.16210759E-02    2     1000014        -14   # BR(~chi_20 -> ~nu_muL
nu_mub)
```

continued

Decay table for $\tilde{\chi}_2^0$ in LM6

(continued)

```
      9.16210759E-02     2     -1000014          14    # BR(~chi_20 -> ~nu_muL*   nu_mu
)
      9.68607711E-02     2      1000016         -16    # BR(~chi_20 -> ~nu_tau1
nu_taub)
      9.68607711E-02     2     -1000016          16    # BR(~chi_20 -> ~nu_tau1*
nu_tau )
#
```

Decay table for $\tilde{\chi}_1^\pm$ in LM6

```
#          BR          NDA      ID1         ID2
      2.02698208E-01    2      1000012       -11    # BR(~chi_1+ -> ~nu_eL    e+  )
      2.02698208E-01    2      1000014       -13    # BR(~chi_1+ -> ~nu_muL   mu+ )
      2.14845220E-01    2      1000016       -15    # BR(~chi_1+ -> ~nu_tau1  tau+)
      6.67615515E-02    2     -1000011        12    # BR(~chi_1+ -> ~e_L+     nu_e)
      6.67615515E-02    2     -1000013        14    # BR(~chi_1+ -> ~mu_L+    nu_mu)
      1.26733953E-01    2     -1000015        16    # BR(~chi_1+ -> ~tau_1+
nu_tau)
      5.04814973E-02    2     -2000015        16    # BR(~chi_1+ -> ~tau_2+
nu_tau)
      6.90198118E-02    2      1000022        24    # BR(~chi_1+ -> ~chi_10   W+)
#
```

ATLAS: Multijets + 1 lepton + MET (8 TeV)

ATLAS, http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-104/

- Search variables:

(many thanks to Jeannette Lorenz!)

$$\vec{\boldsymbol{p}}_T^{\,\text{miss, calo clusters}} = -\left[\sum_{i=\text{ calo clusters}} \vec{\boldsymbol{p}}_T^{\,i} \right] \quad \rightarrow \quad E_T^{\text{miss}} \equiv \left| \vec{\boldsymbol{p}}_T^{\,\text{miss, calo clusters}} \right|$$

$$m_{\text{eff}}^{\text{inc}} = p_T^{\ell} + \sum_{i=1}^{N_{\text{jet}}} p_T^i + E_T^{\text{miss}} \qquad \text{jets: } p_T^i > 40\text{ GeV}$$

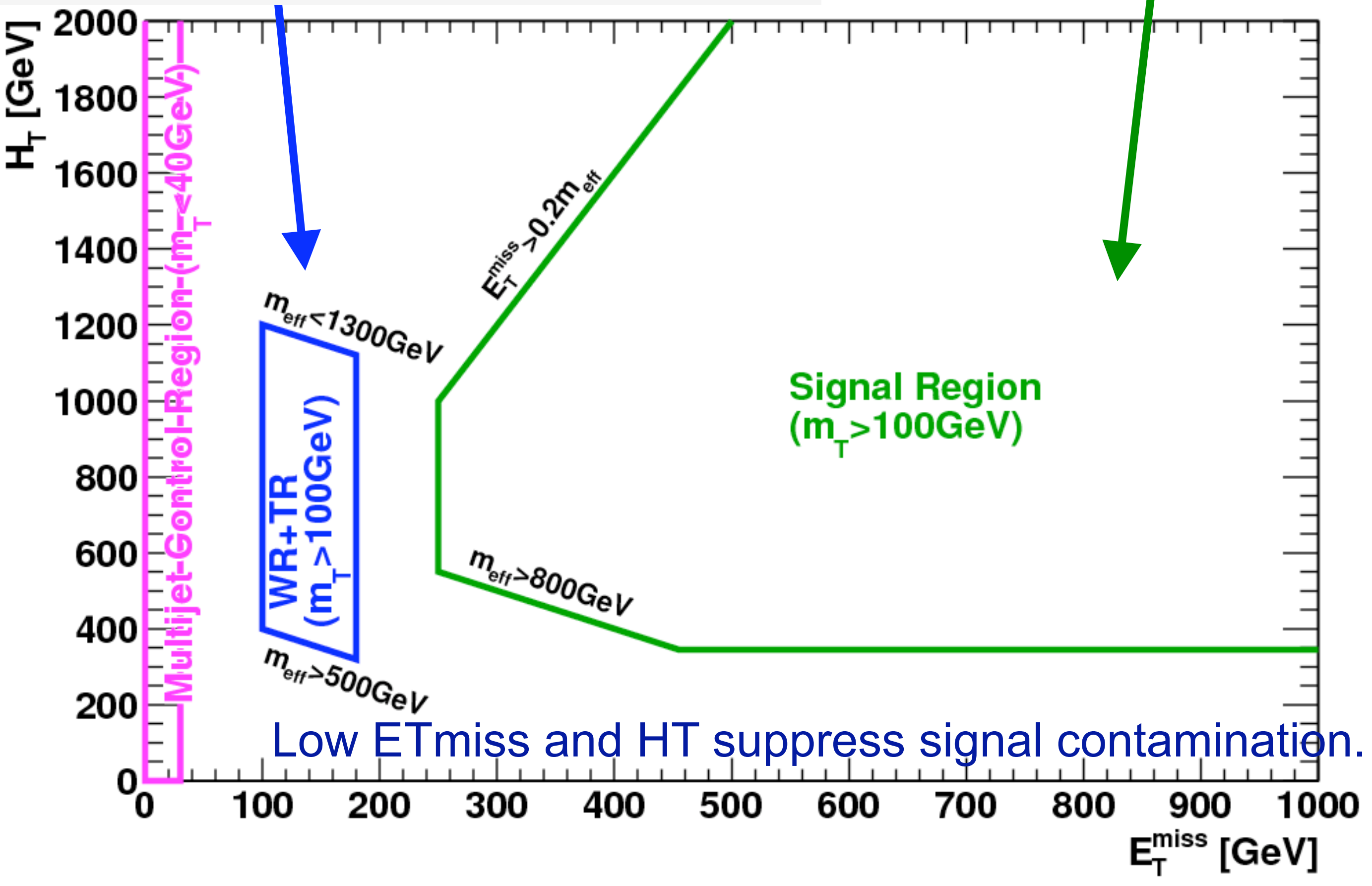
- Require ≥4 jets, pT>80 GeV, 1 isolated lepton pT>25 GeV
- M_T(*l*, MET)>100 GeV: suppresses single-lepton SM
- Veto event if has 2nd lepton pT>10 GeV
- Suppresses ttbar dileptons. Separate 1 lep & 2 lep meas.
- Perform fit to data in signal and control regions.

Signal and control regions for ATLAS analysis

Control region divided into 4 subsamples:

- ttbar → e ν: electron + b-tag
- ttbar → μ ν: muon + b-tag
- (W→e ν) + jets: electron + anti-b-tag
- (W→μ ν) + jets: muon + anti-b-tag

Signal region divided into e and mu subsamples

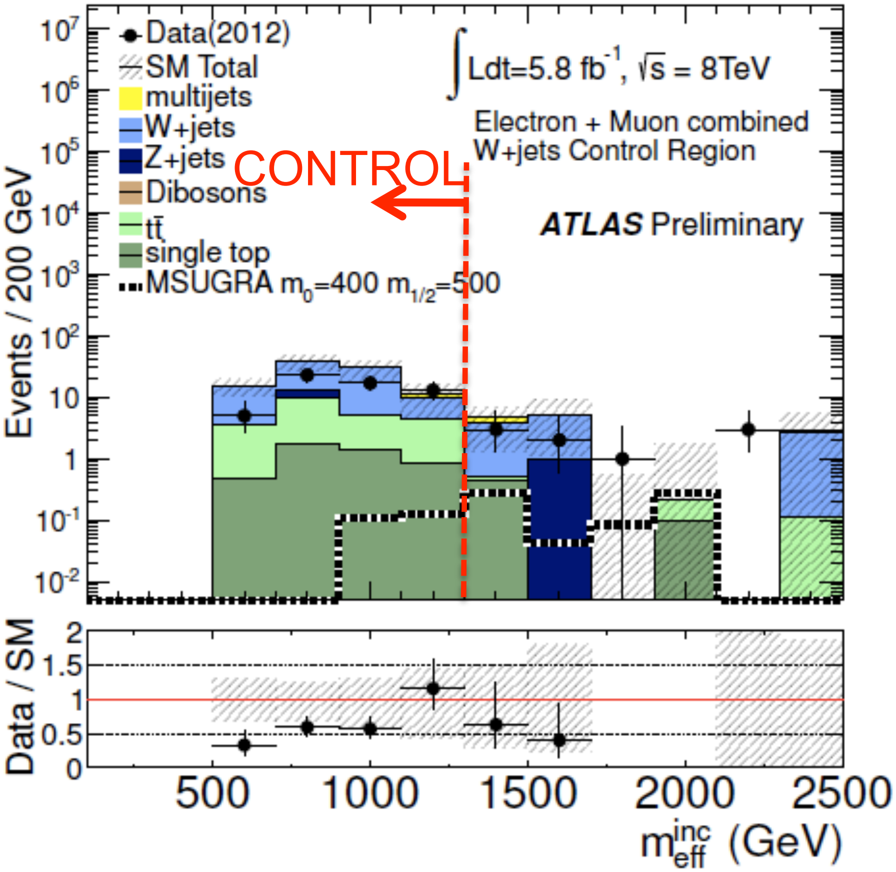


Low ETmiss and HT suppress signal contamination.

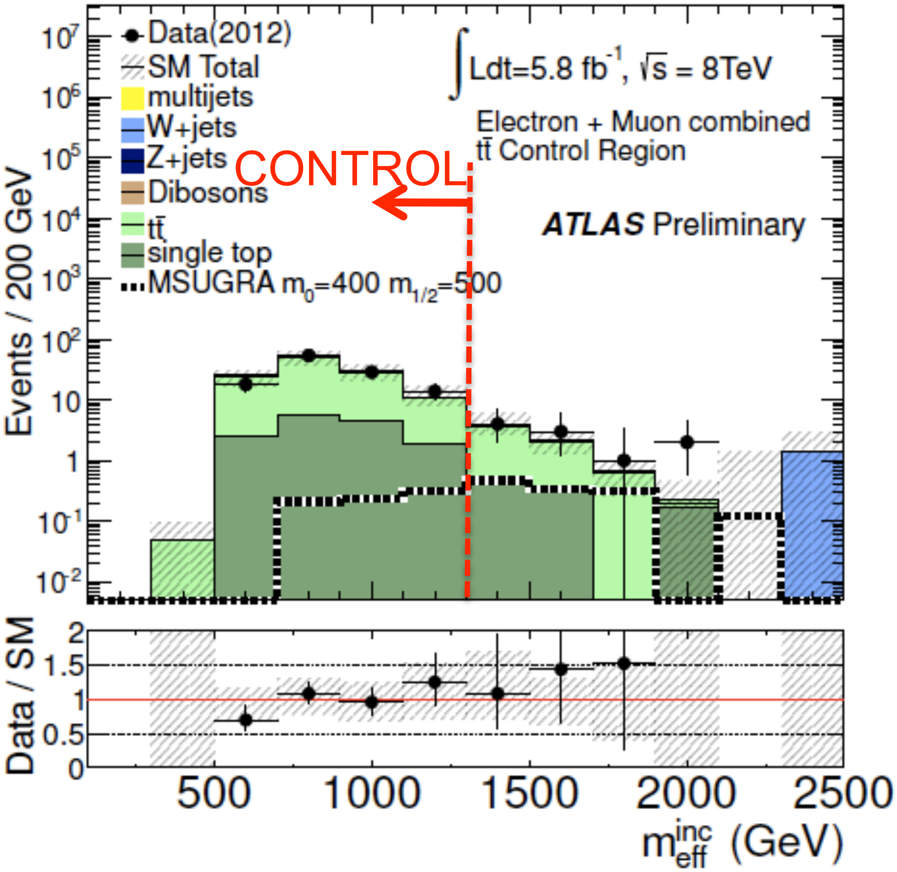
Data vs. MC comparison: e and mu

MC out-of-the-box predictions for backgrounds (not used for final result)

W + jets control region (anti-b tagged)

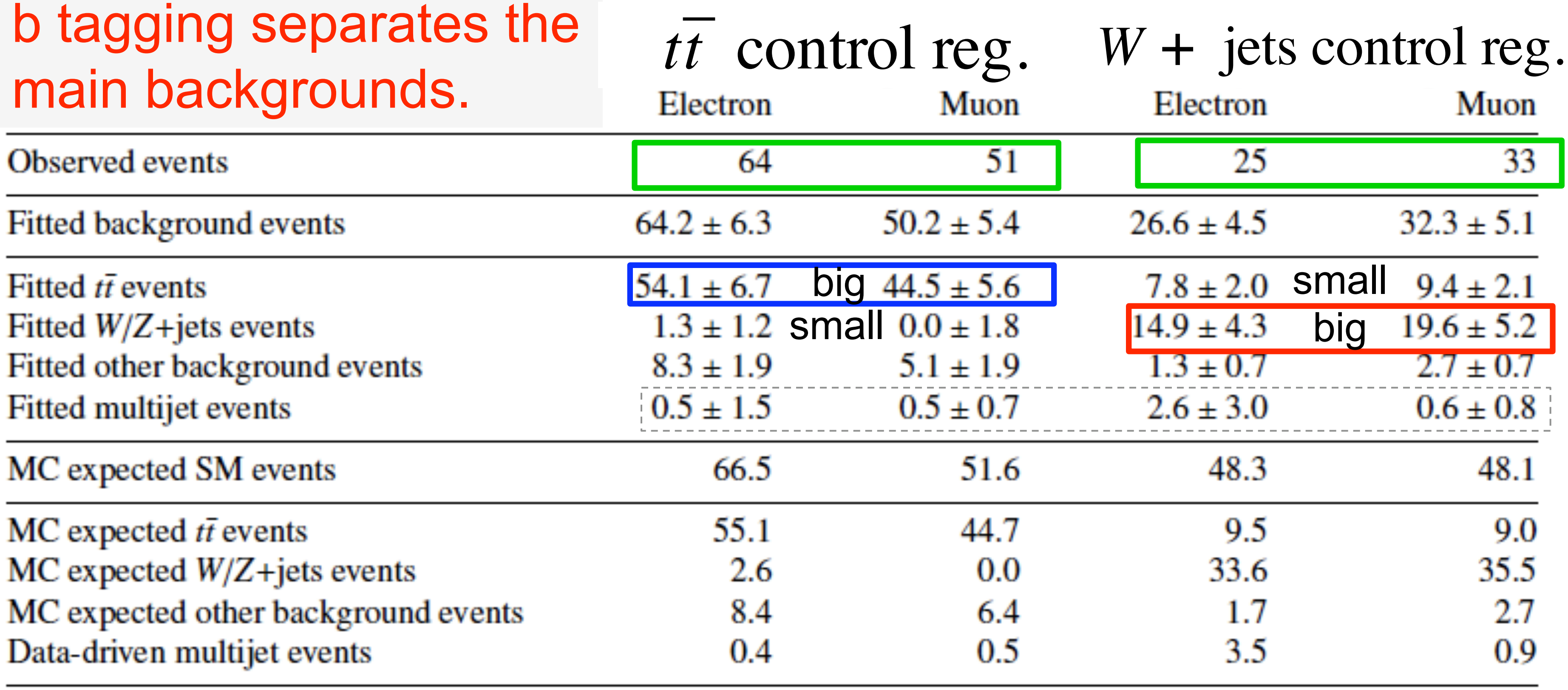


ttbar control region (anti-b tagged)



Yields and fits in the control regions

b tagging separates the main backgrounds.



	$t\bar{t}$ control reg.		$W +$ jets control reg.	
	Electron	Muon	Electron	Muon
Observed events	64	51	25	33
Fitted background events	64.2 ± 6.3	50.2 ± 5.4	26.6 ± 4.5	32.3 ± 5.1
Fitted $t\bar{t}$ events	54.1 ± 6.7	44.5 ± 5.6	7.8 ± 2.0	9.4 ± 2.1
Fitted W/Z+jets events	1.3 ± 1.2	0.0 ± 1.8	14.9 ± 4.3	19.6 ± 5.2
Fitted other background events	8.3 ± 1.9	5.1 ± 1.9	1.3 ± 0.7	2.7 ± 0.7
Fitted multijet events	0.5 ± 1.5	0.5 ± 0.7	2.6 ± 3.0	0.6 ± 0.8
MC expected SM events	66.5	51.6	48.3	48.1
MC expected $t\bar{t}$ events	55.1	44.7	9.5	9.0
MC expected W/Z+jets events	2.6	0.0	33.6	35.5
MC expected other background events	8.4	6.4	1.7	2.7
Data-driven multijet events	0.4	0.5	3.5	0.9

big small

small big

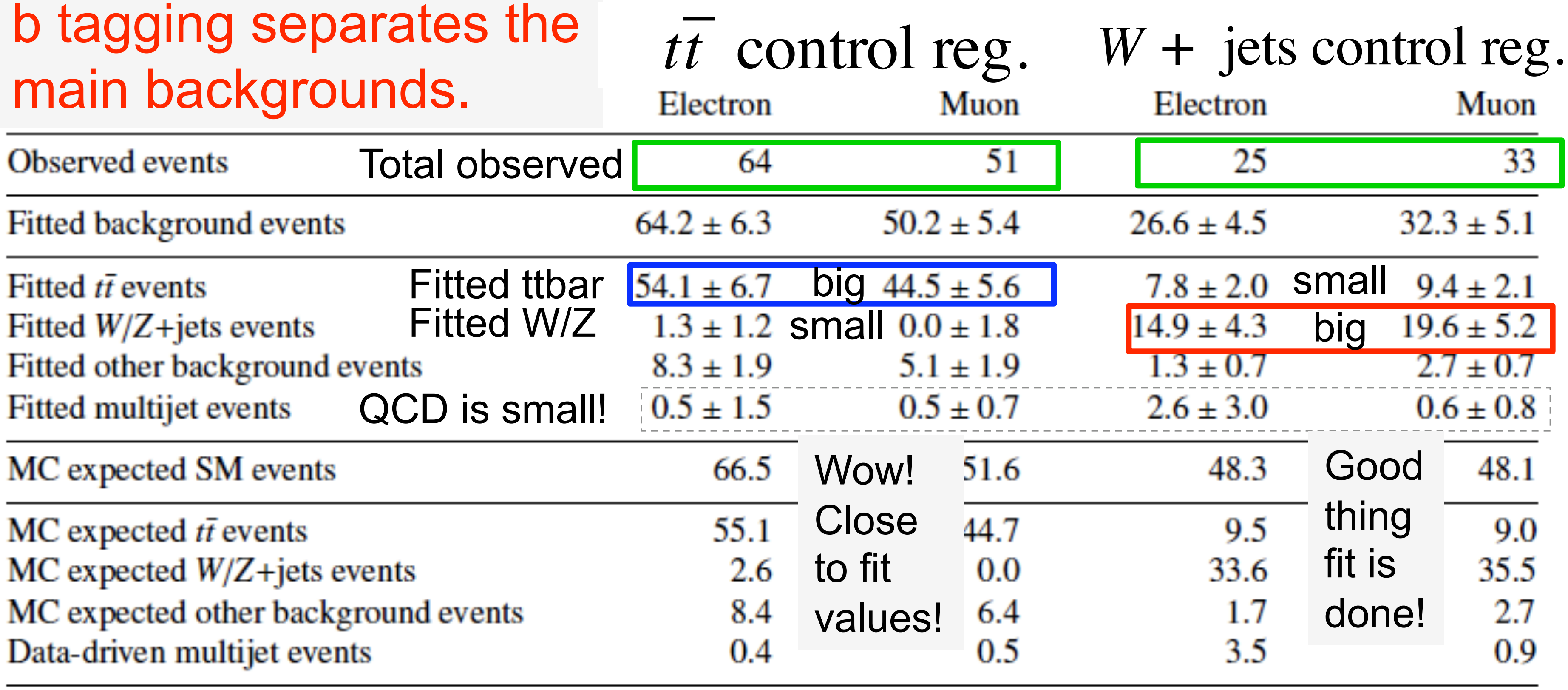
Perspective: how many ttbar and W+jets were produced?

Background	Cross section (pb)	Cross sec * BR	Events produced	Rejection
W→l nu + jets	12,190	12,190	70.78×10^6	2.8×10^{-7}
ttbar	238	238*(12/81)=35.3	0.20×10^6	2×10^{-4}

Huge suppression of W+jets → not surprising you can't use MC value!

Yields and fits in the control regions

b tagging separates the main backgrounds.



	$t\bar{t}$ control reg. Electron	$t\bar{t}$ control reg. Muon	$W+$ jets control reg. Electron	$W+$ jets control reg. Muon
Observed events	64	51	25	33
Fitted background events	64.2 ± 6.3	50.2 ± 5.4	26.6 ± 4.5	32.3 ± 5.1
Fitted $t\bar{t}$ events	54.1 ± 6.7	44.5 ± 5.6	7.8 ± 2.0	9.4 ± 2.1
Fitted W/Z+jets events	1.3 ± 1.2	0.0 ± 1.8	14.9 ± 4.3	19.6 ± 5.2
Fitted other background events	8.3 ± 1.9	5.1 ± 1.9	1.3 ± 0.7	2.7 ± 0.7
Fitted multijet events	0.5 ± 1.5	0.5 ± 0.7	2.6 ± 3.0	0.6 ± 0.8
MC expected SM events	66.5	51.6	48.3	48.1
MC expected $t\bar{t}$ events	55.1	44.7	9.5	9.0
MC expected W/Z+jets events	2.6	0.0	33.6	35.5
MC expected other background events	8.4	6.4	1.7	2.7
Data-driven multijet events	0.4	0.5	3.5	0.9

Total observed

Fitted ttbar

Fitted W/Z

QCD is small!

big

small

small

big

Wow! Close to fit values!

Good thing fit is done!

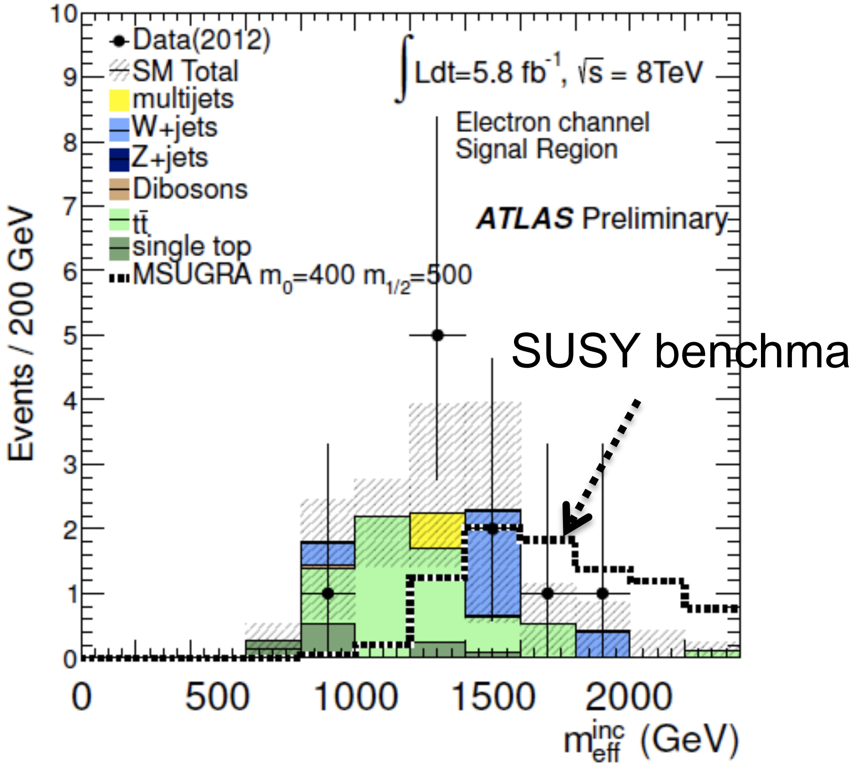
Perspective: how many ttbar and W+jets were produced?

Background	Cross section (pb)	Cross sec * BR	Events produced	Rejection
W→l nu + jets	12,190	12,190	70.78 × 10^6	2.8 ×10^{-7}
ttbar	238	238*(12/81)=35.3	0.20 × 10^6	2 × 10^{-4}

Huge suppression of W+jets → not surprising you can't use MC value!

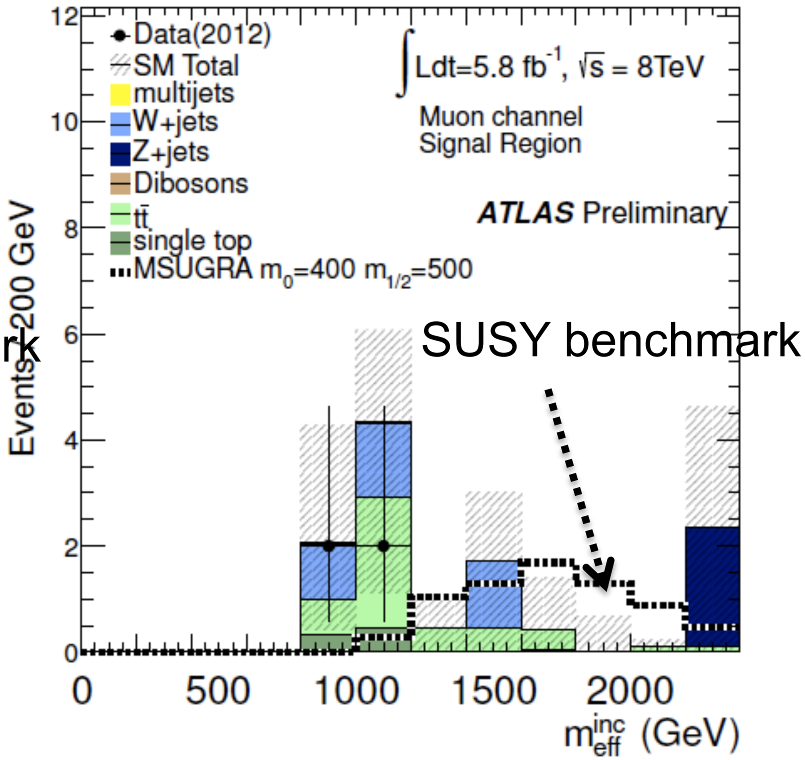
Apply fit params from control region to background MC for signal region

e signal region
(no b-tagging applied)



SUSY benchmark

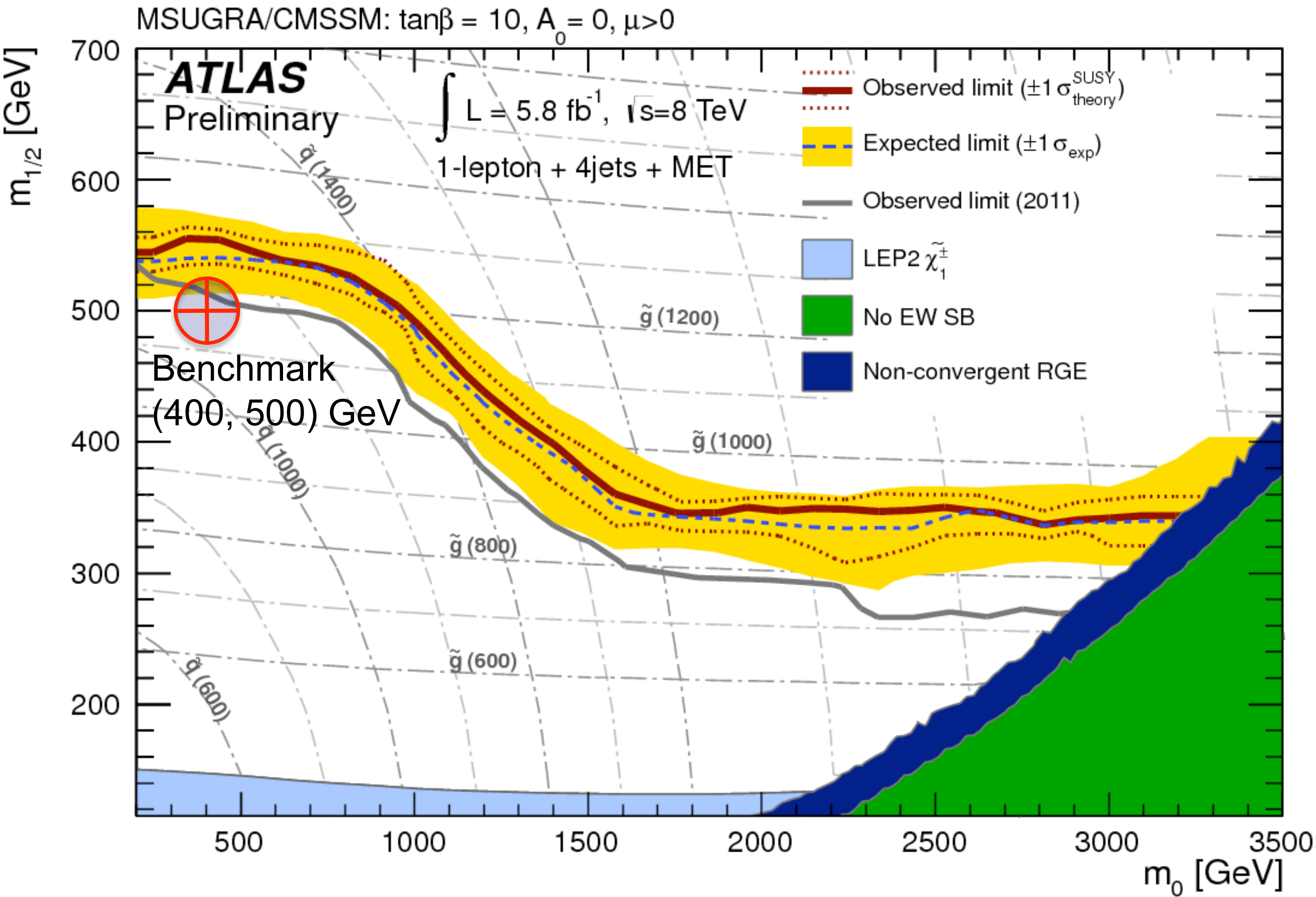
mu signal region
(no b-tagging applied)



SUSY benchmark

	electron	muon
Observed yield	10	4
Predicted background	9.0 ±2.8	7.7 ±3.2

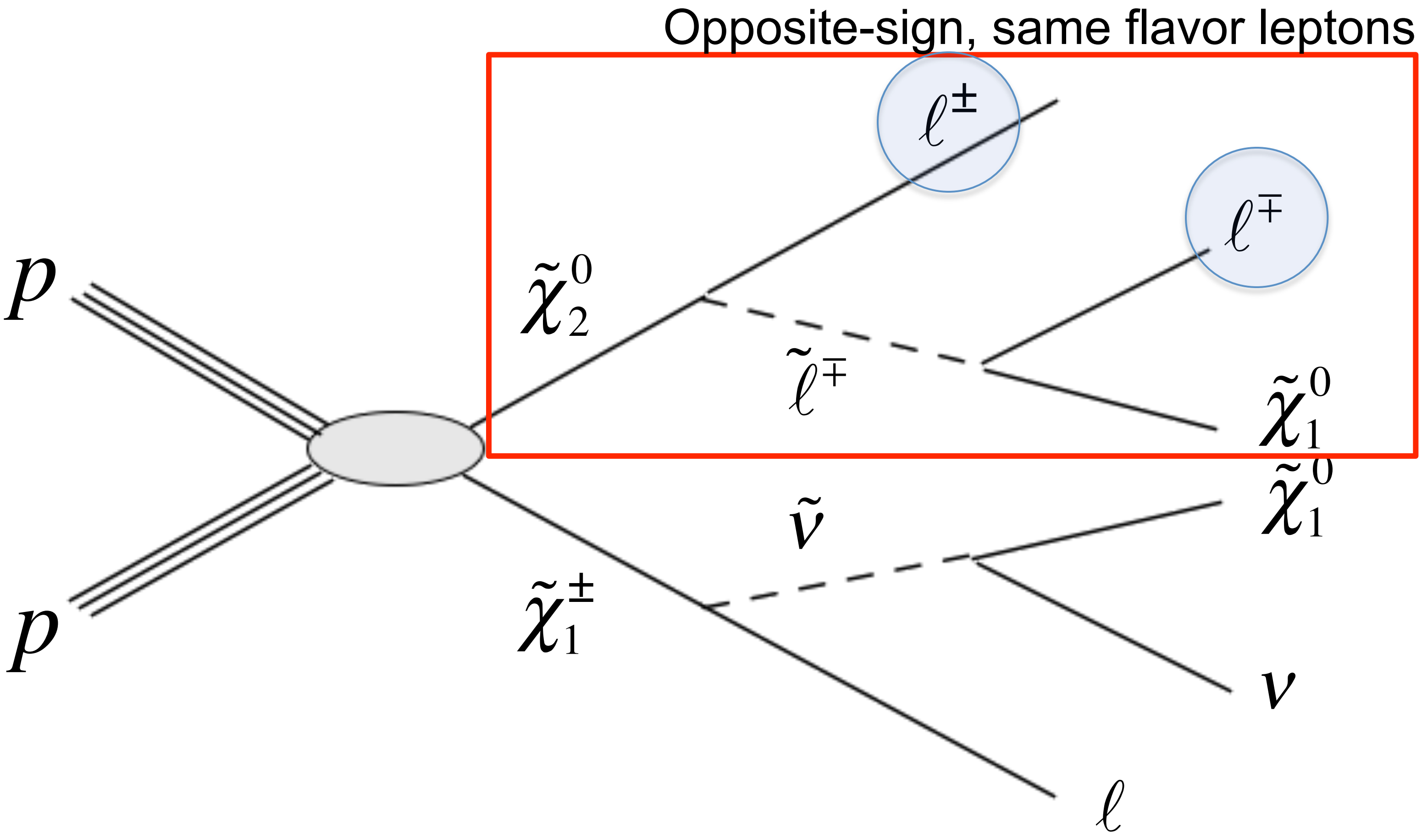
ATLAS cMSSM exclusion region (8 TeV)



Benchmark
(400, 500) GeV

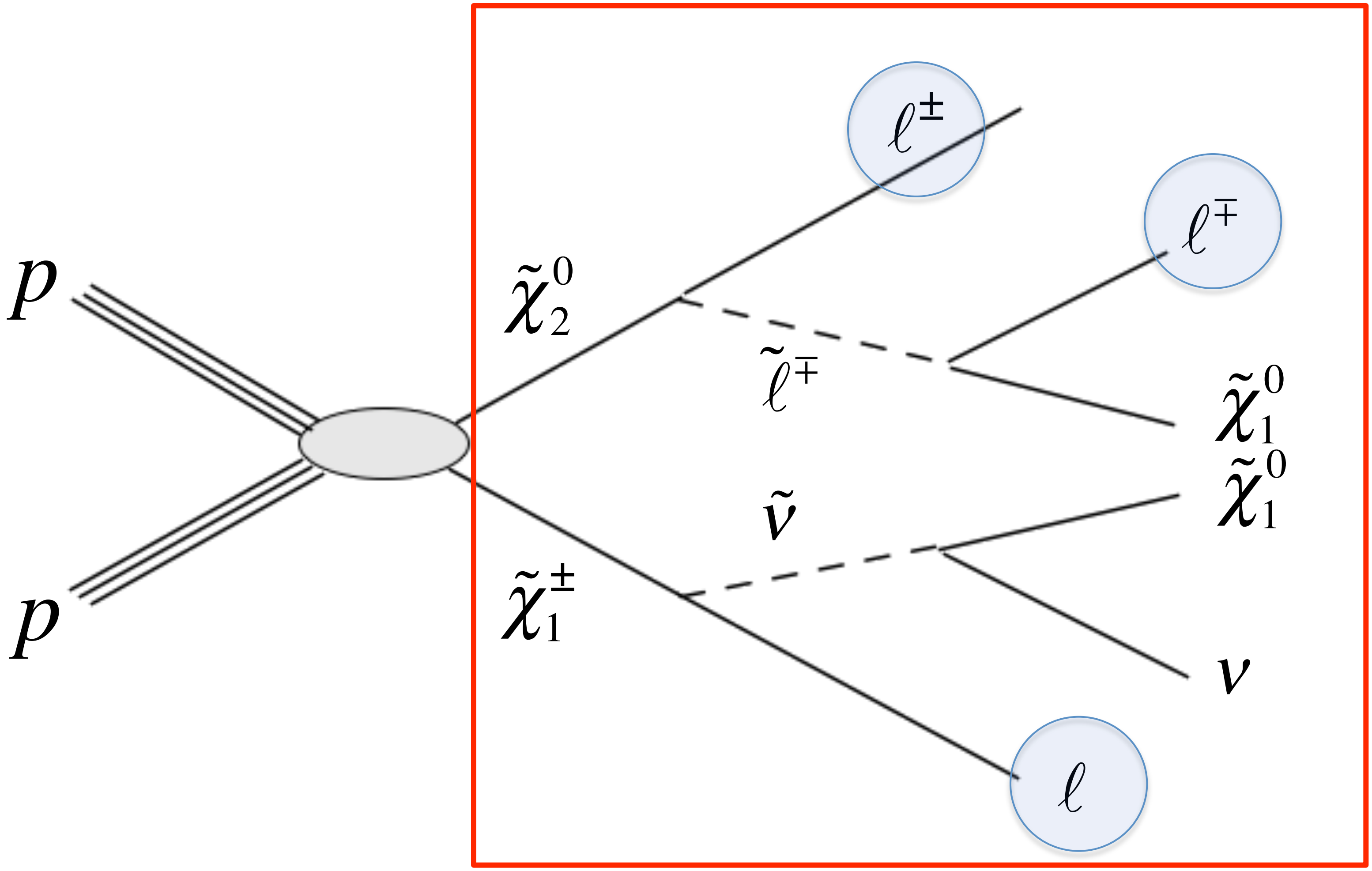
Takes into account model-by-model signal contamination of control regions.

The famous neutralino dilepton cascade



The $\tilde{\chi}_2^0$ can be produced in any process, not just direct EW production. Can produce sharp edge at upper limit of dilepton mass spectrum corresponding to kinematic cutoff.

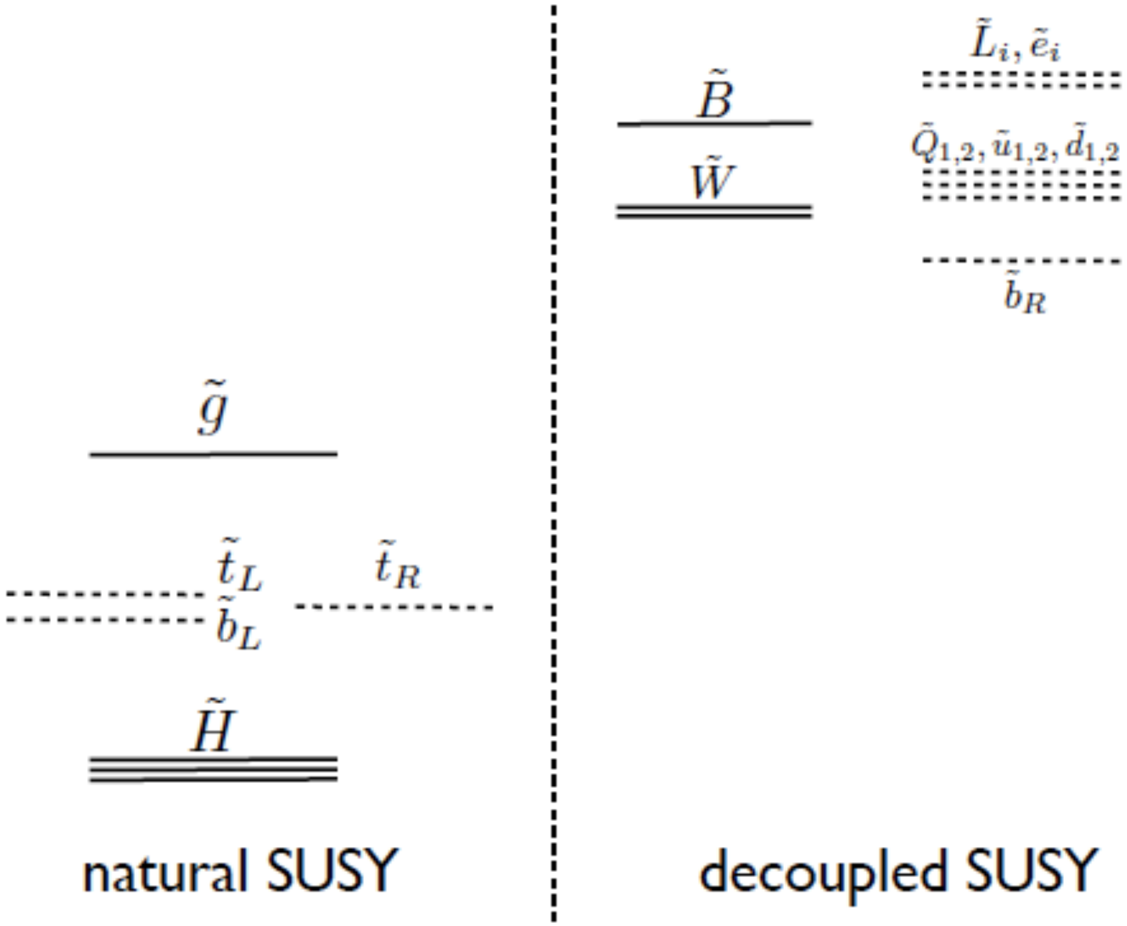
The famous SUSY trilepton signature



The $\tilde{\chi}_2^0$ can be produced in any process, not just direct EW production.

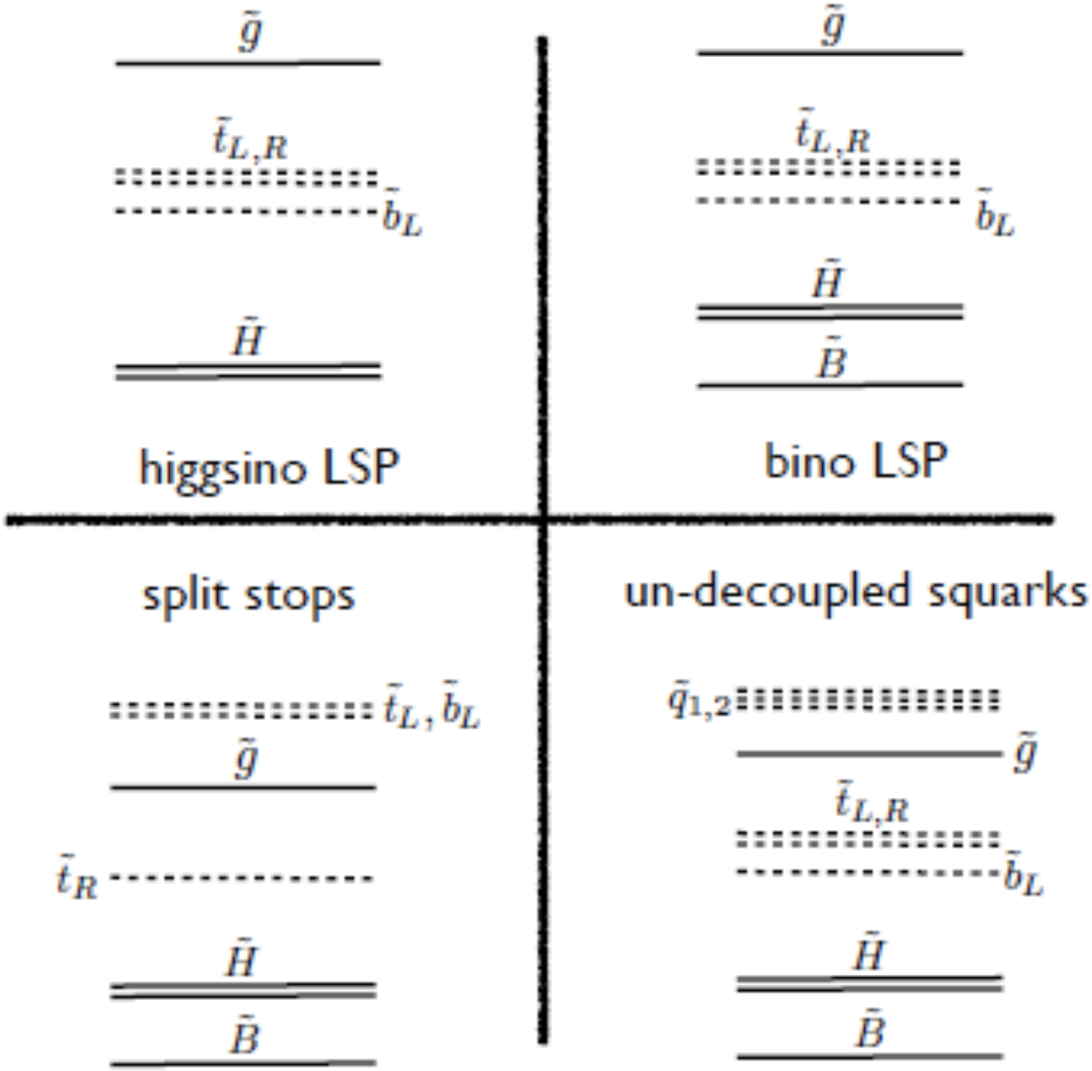
“Natural SUSY endures”: the current fashion

M. Papucci, J.T. Ruderman, and A. Weiler http://arxiv.org/abs/1110.6926



not just one scenario...

Some spectra compatible with “naturalness” considerations



M. Papucci, J.T.Ruderman, and A. Weiler, http://arxiv.org/abs/1110.6926

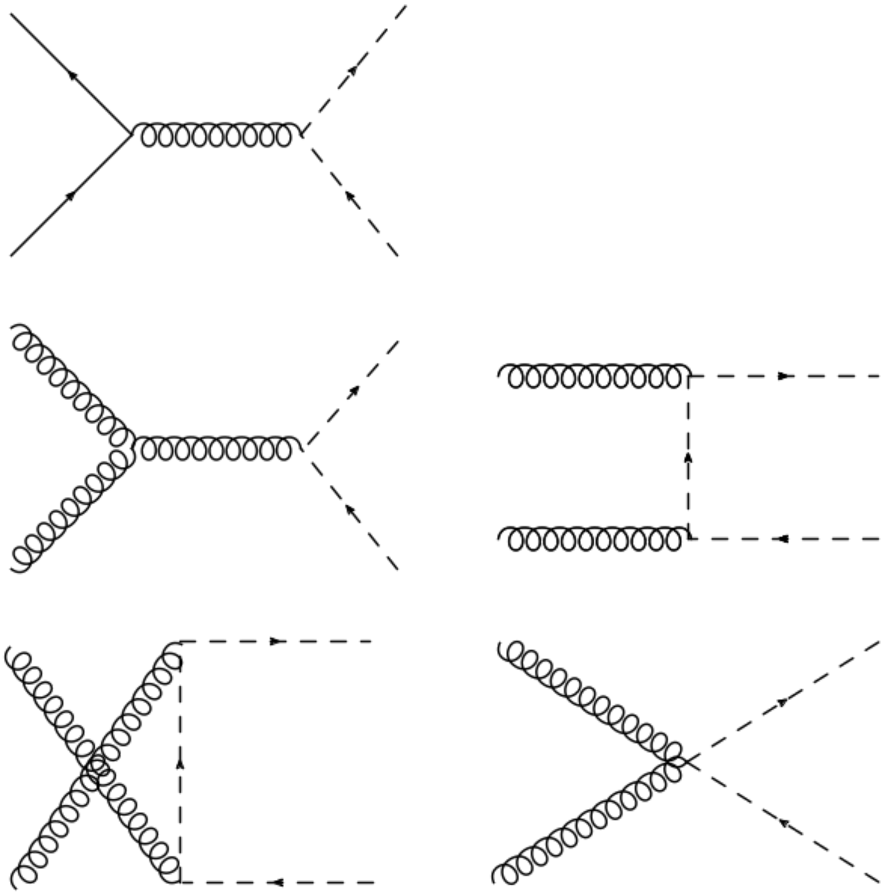
What sort of strategy should we use for this? Clearly, b-tagging will play a big role. Have to consider production & decay.

See also D. Alves, M. Buckley, P. Fox, J. Lykken, and C.-T. Yu http://arxiv.org/abs/1205.5805

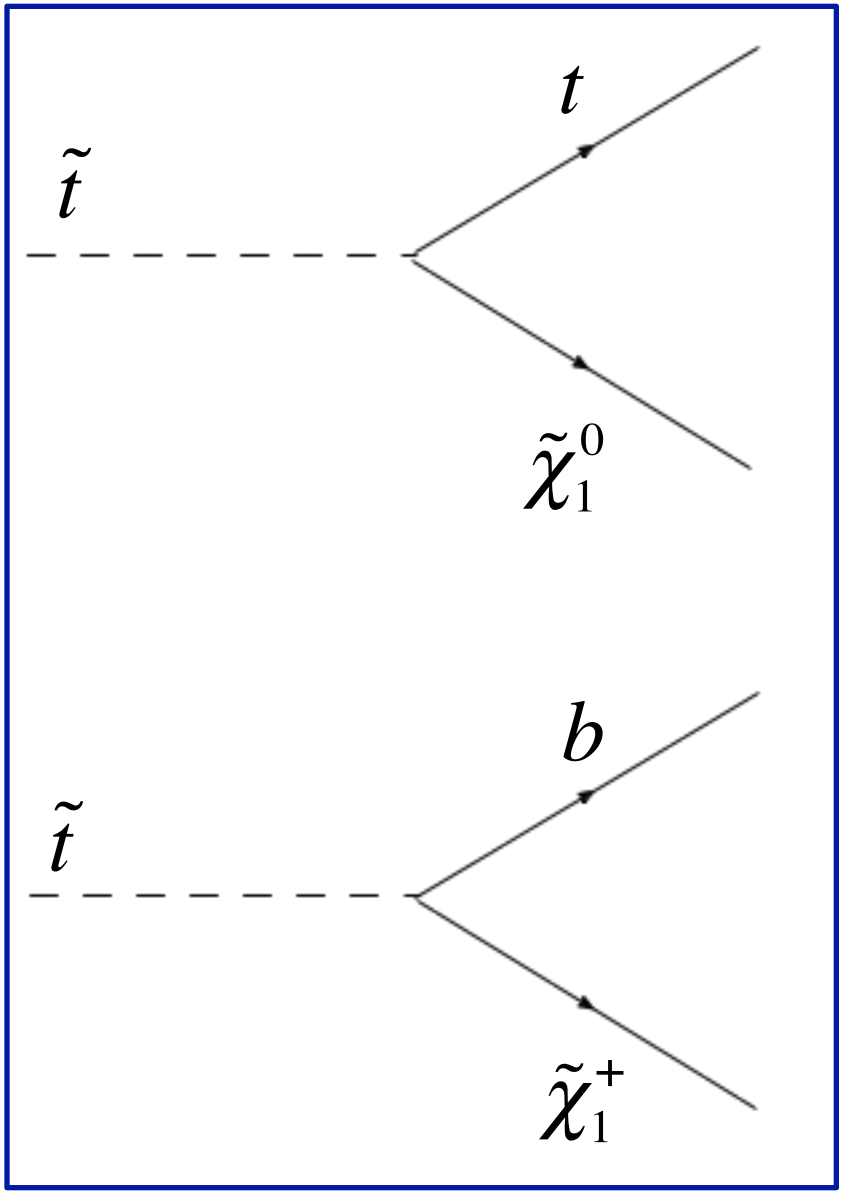
Production of scalar top ("stop")

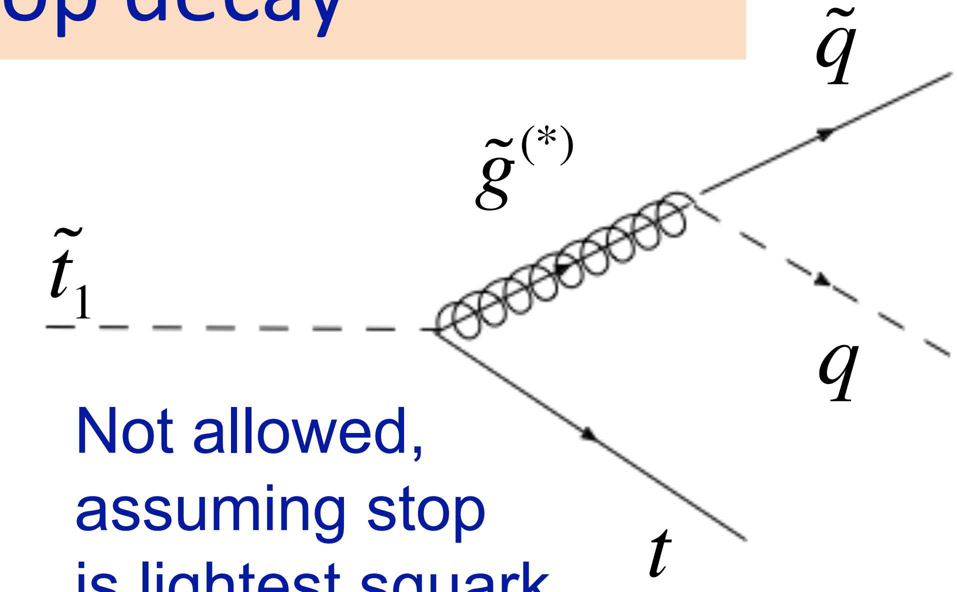
Very nice discussion in "Supersymmetric top and bottom squark production at hadron colliders", Beenakker et al. arXiv:1006.4771.

- Even for m(~t)=m(t), the cross section is much lower than that for ttbar, as a consequence of spin-related effects.
- If we find stop, and can determine its mass, then the small rate would be a probe of the spin.

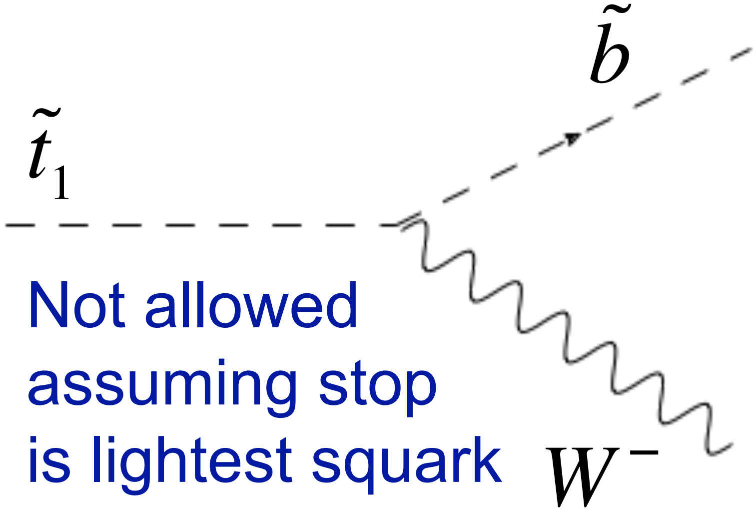


Light stop decay





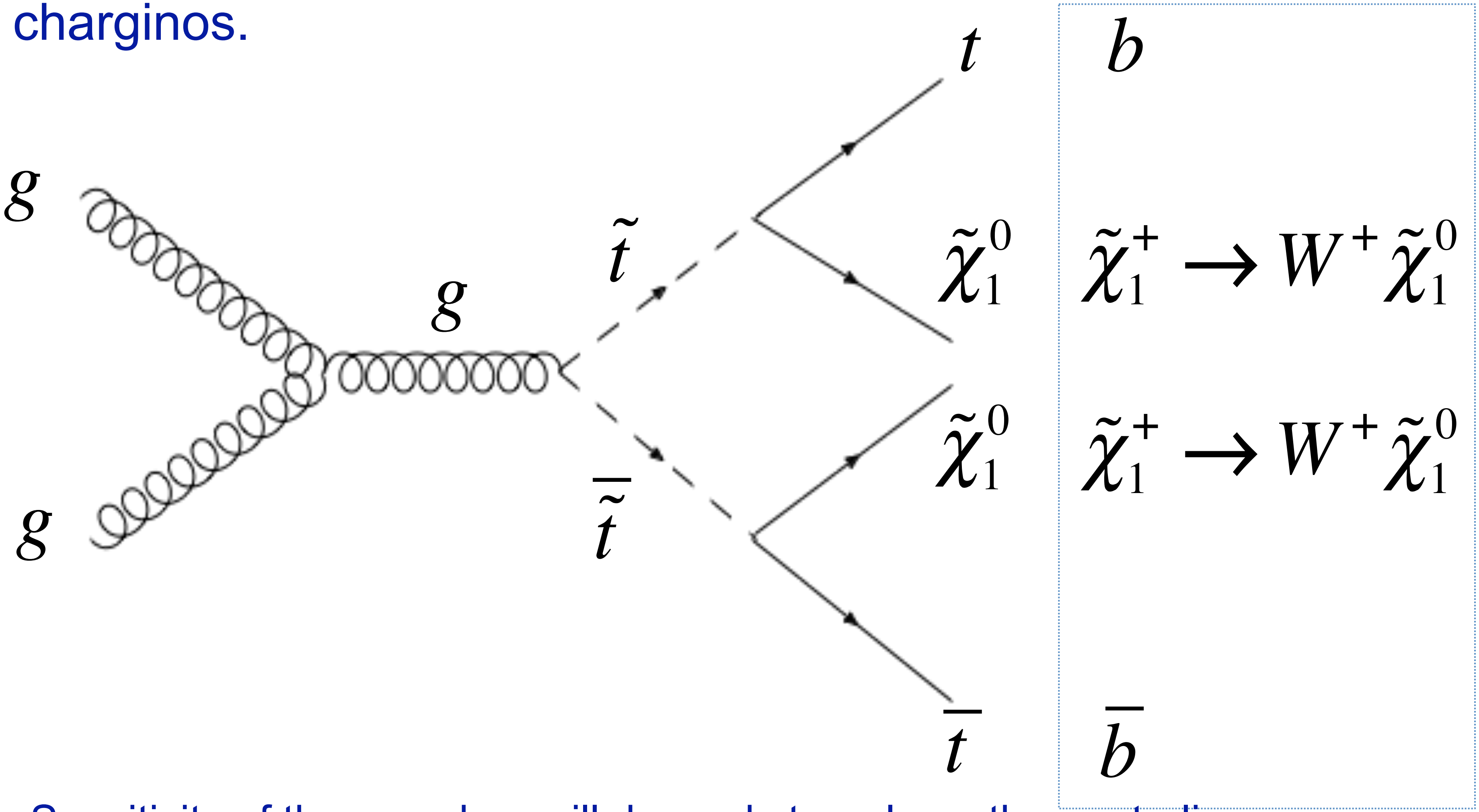
Not allowed, assuming stop is lightest squark



Not allowed assuming stop is lightest squark

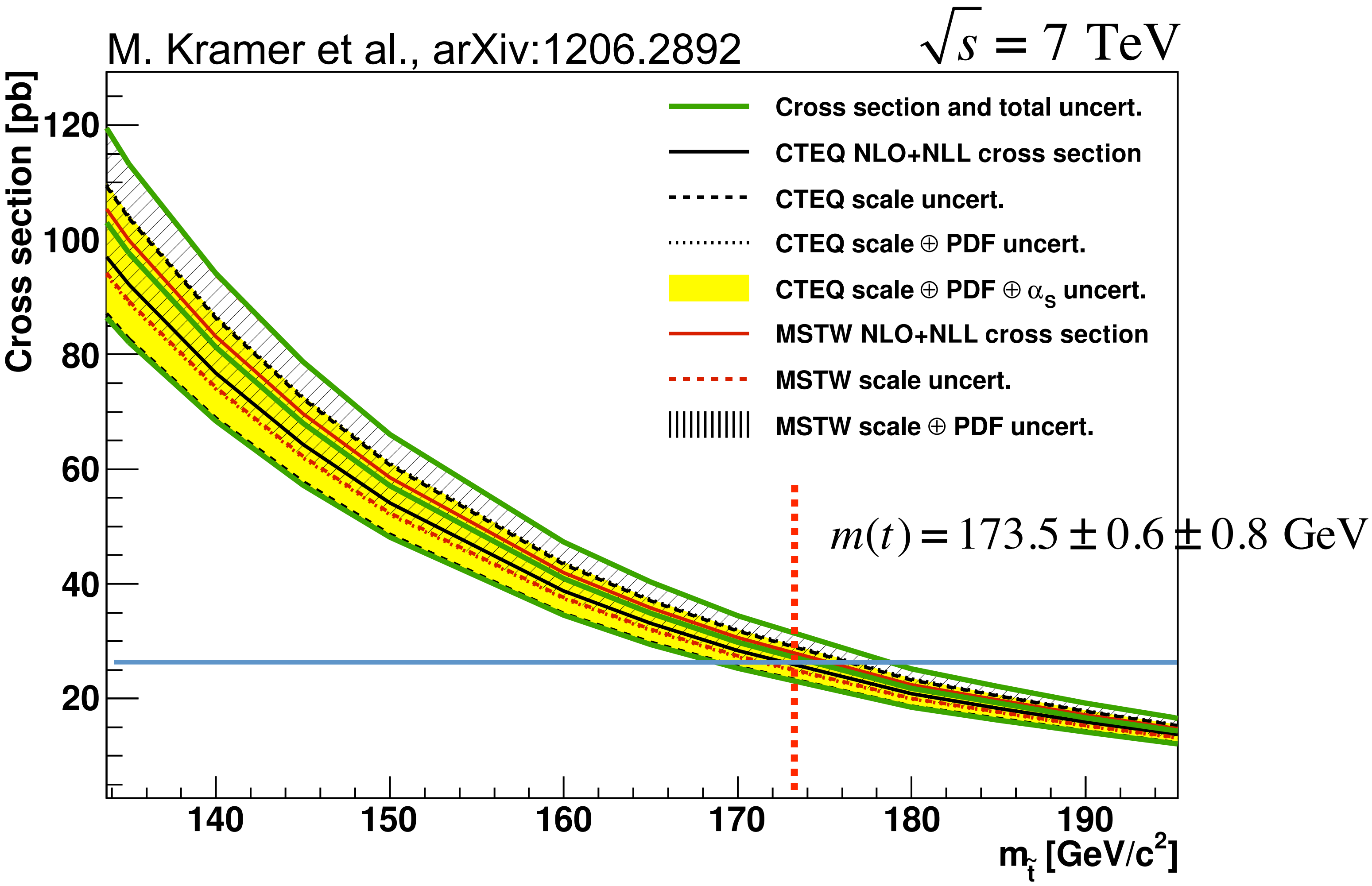
“Direct” pair production of light stops

Example: direct stop production with decay to neutralinos or charginos.



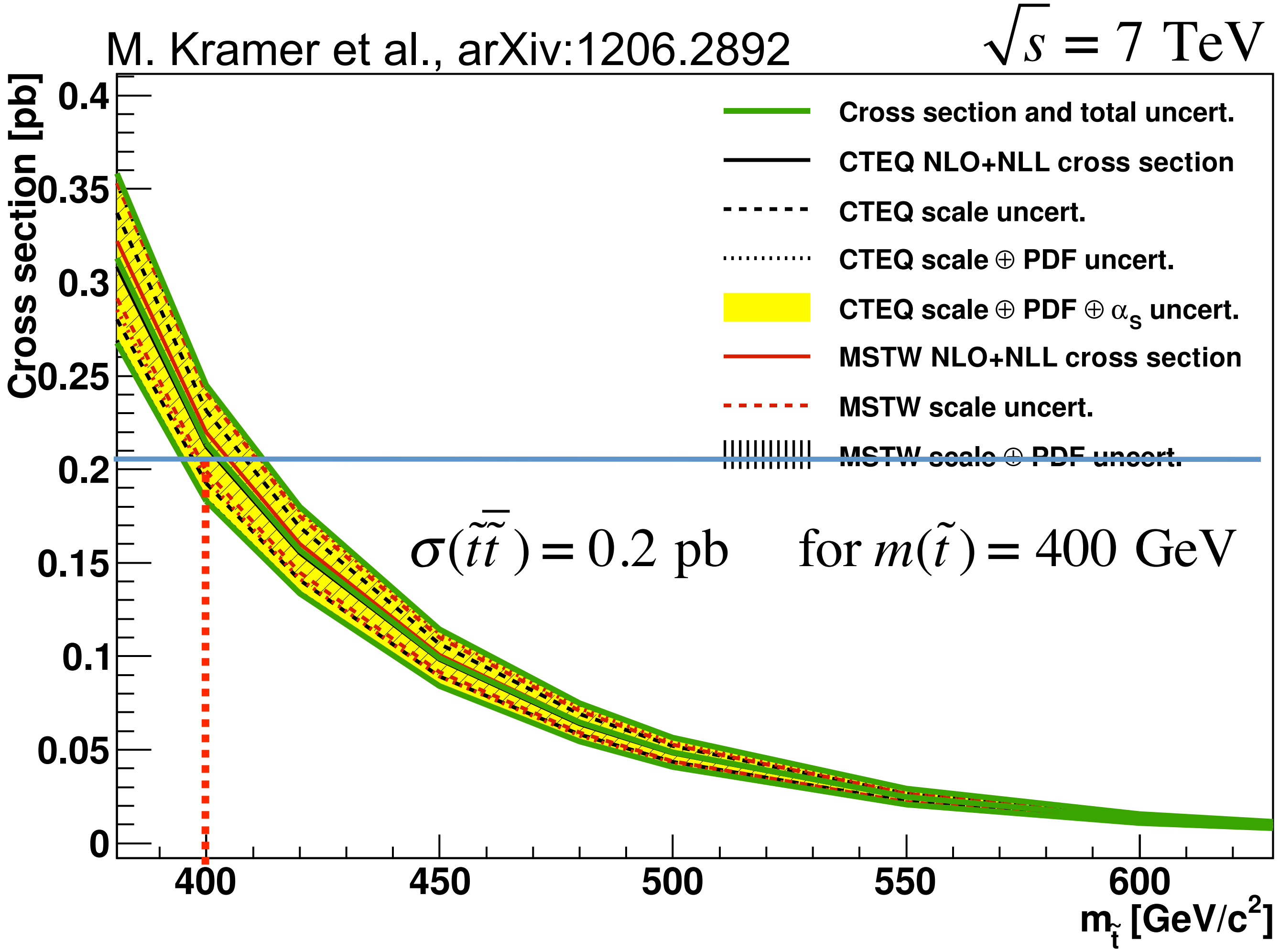
Sensitivity of the searches will depend strongly on the neutralino mass.
The channel with $\tilde{t} \to b\tilde{\chi}_1^+$ has sensitivity to lower stop mass.

Production cross section for low-mass stop



Even at the same mass, st-stbar production is suppressed relative to ttbar production.

Stop pair production: disappointingly small


M. Kramer et al., arXiv:1206.2892

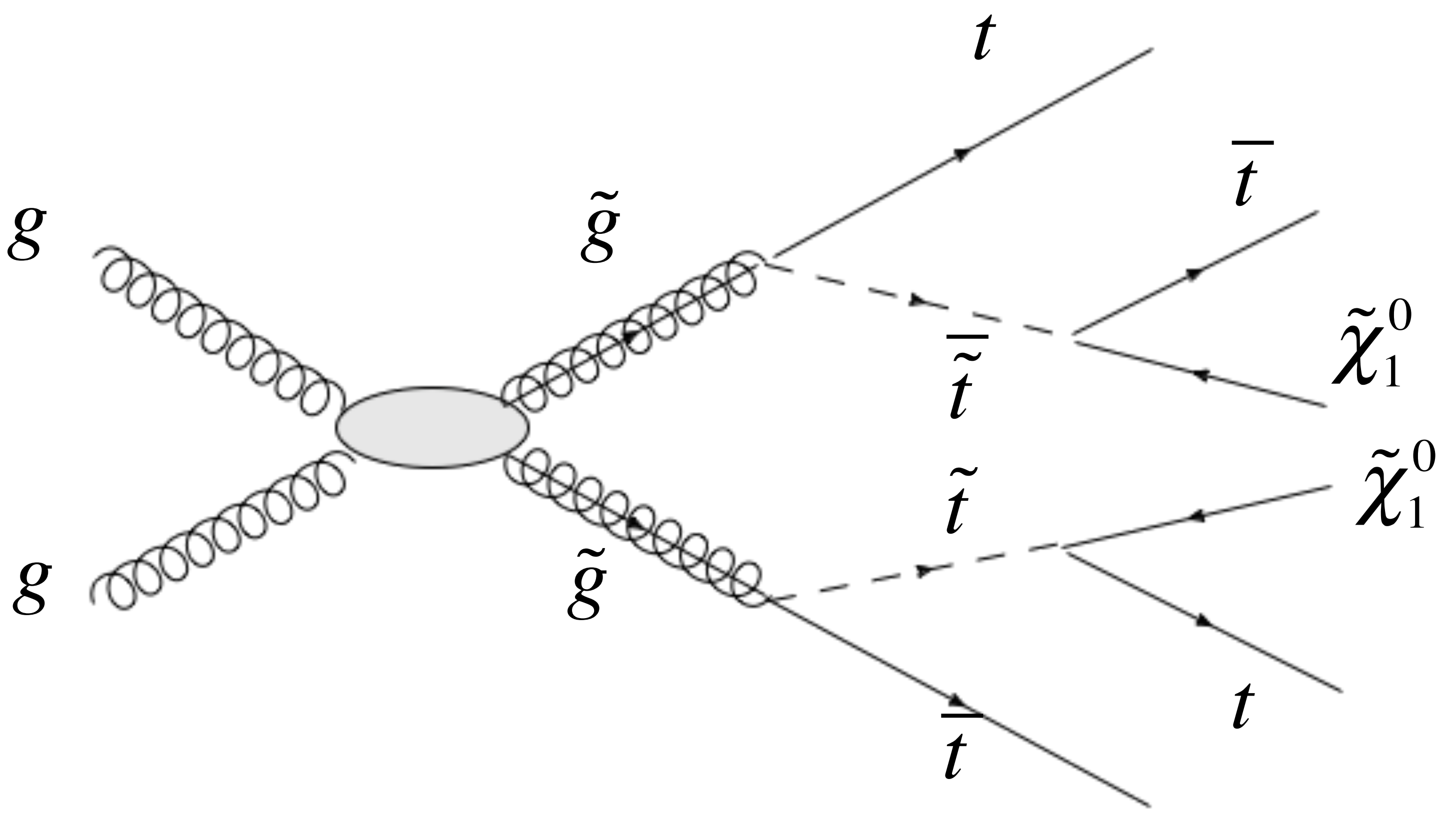
$\sqrt{s} = 7\ \text{TeV}$

$\sigma(\tilde{t}\bar{\tilde{t}}) = 0.2\ \text{pb} \quad \text{for } m(\tilde{t}) = 400\ \text{GeV}$

For 5 fb^{-1}, get 1000 events for m(stop) = 400 GeV! Sounds easy...
But σ(ttbar) = 175 pb is about 900x larger!

Gluino pair production and decay to light stop

Maybe the gluinos aren't too heavy – very large production cross section may make gluino pair production competitive.



The production of four top quarks and additional MET can lead to spectactular signatures.

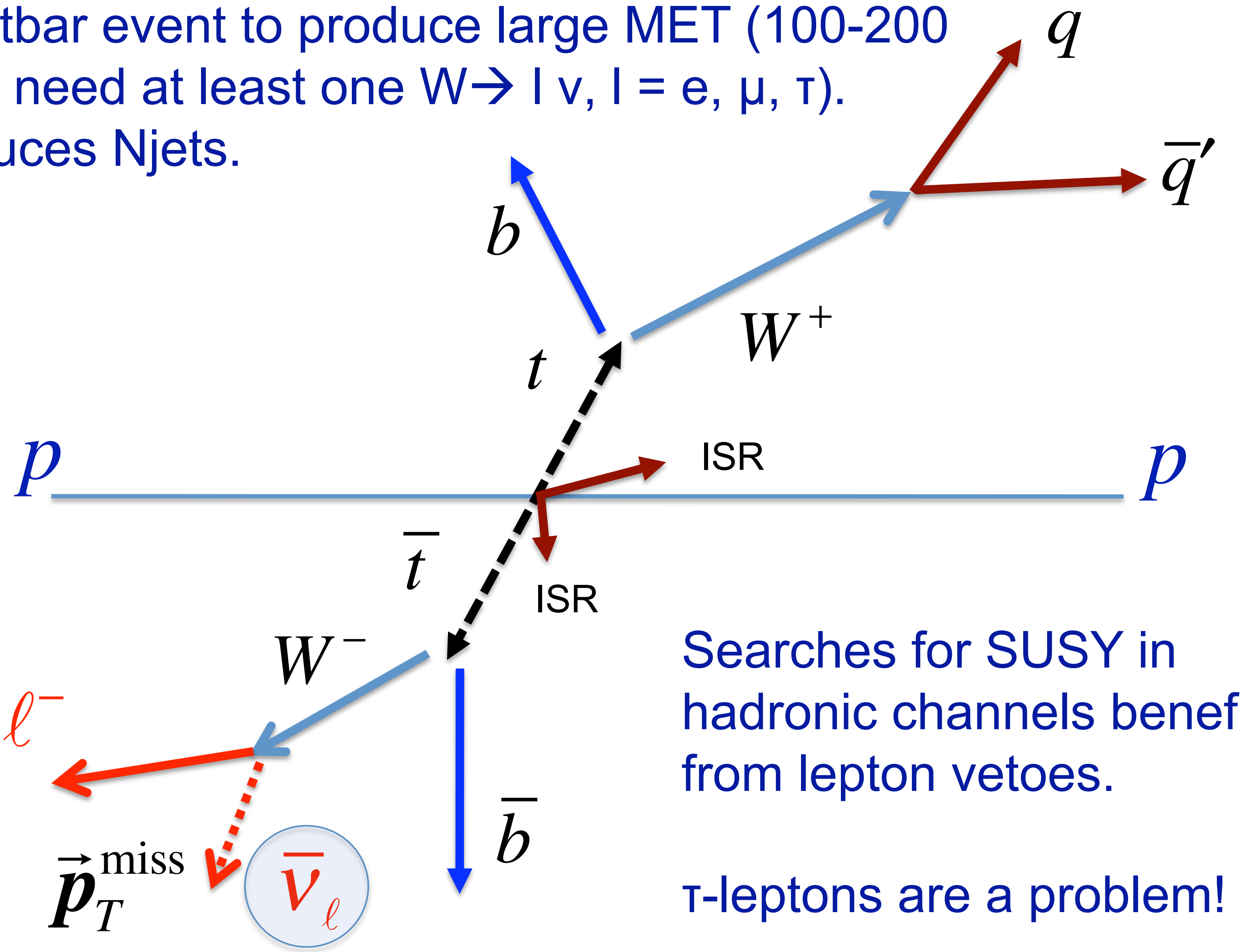
Strategies/issues for light stop

- With b-tagging, ttbar dominates the background.
- Direct production:
  - -ttbar + extra MET; correlations between t and tbar are affected (e.g., pT of top quarks can differ a lot).
  - Need to exploit kinematic differences between stop signals and ttbar. (Helpful if there are lots of signal events are around.)
- Gluino pair production: 4 top quarks + MET!
  - many jets; 4 b jets
  - can have multileptons, including <u>same-sign</u> leptons
  - many useful features as long as cross section isn't suppressed by too large gluino mass.

ttbar as a SUSY background

For a ttbar event to produce large MET (100-200 GeV) , need at least one W→ l ν, l = e, μ, τ).

→ reduces Njets.



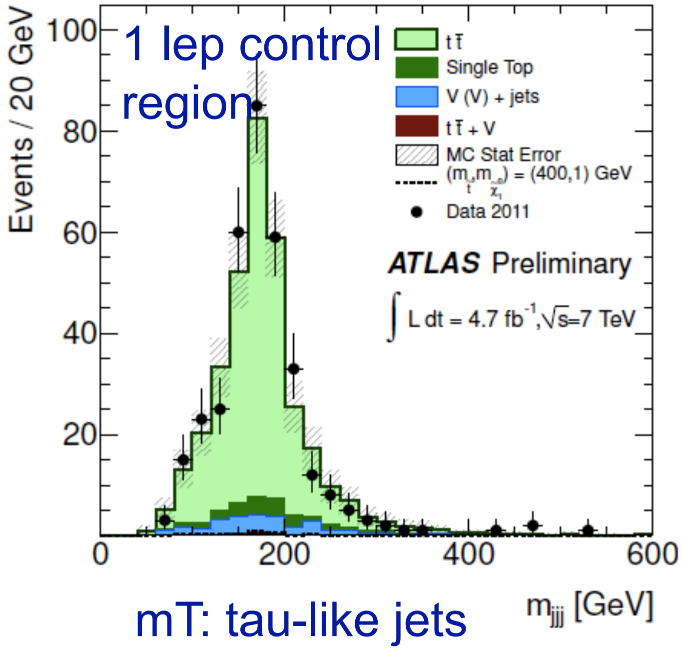
Searches for SUSY in hadronic channels benefit from lepton vetoes.

τ-leptons are a problem!

Direct stop production: 0 leptons

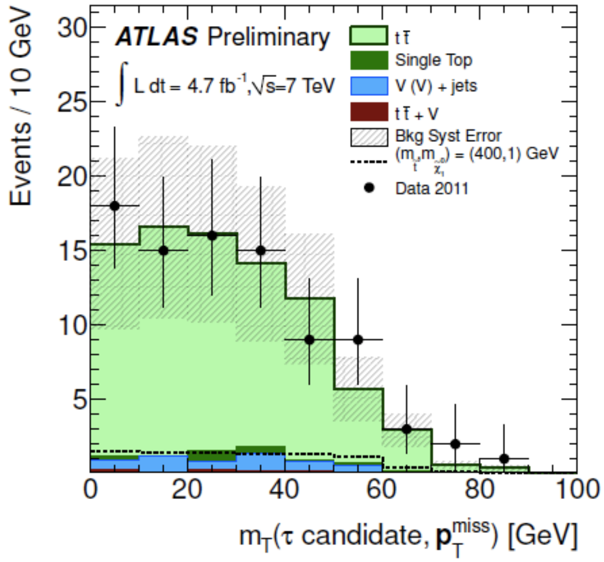
ATLAS collaboration, arXiv:1208.1447

- Require ≥6 jets, pT(leading)>130 GeV, pT>30 GeV for 5 other jets.
- 80<M(jjj)>270 GeV for consistency with top
  - both triplets
- Suppression of ttbar; W→τν
  - if tau-like jet has MT(jet, MET)<100 GeV reject event.
- Require either one tight b jet or two loose b jets
- MET must not be ~collinear with any jet



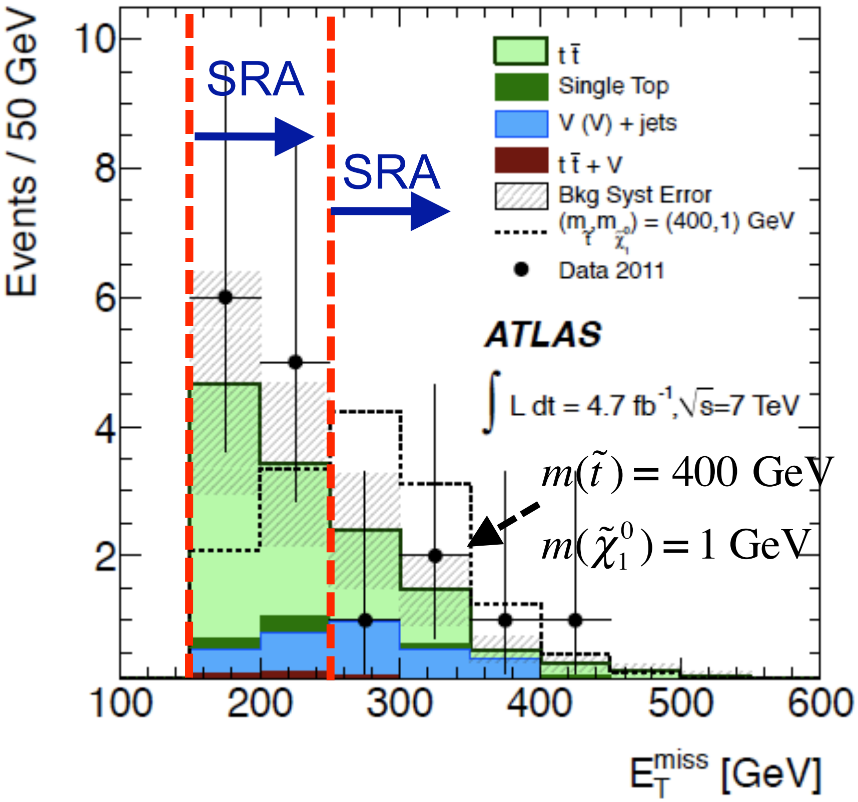
1 lep control region

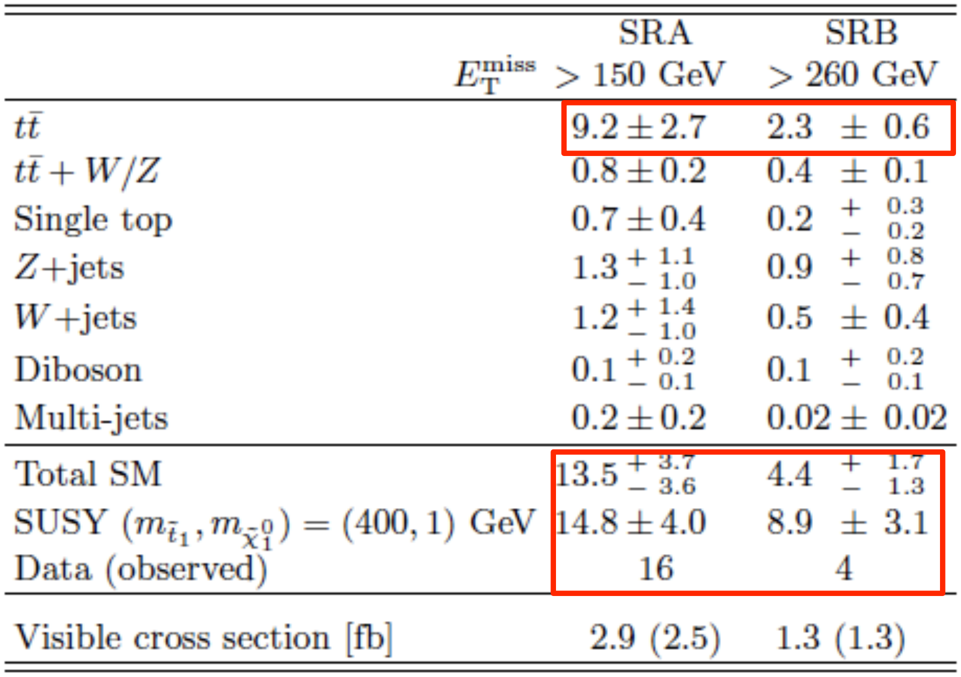
mT: tau-like jets



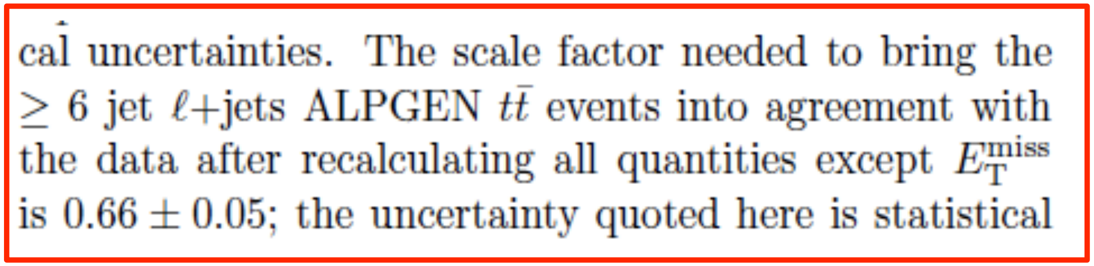
Search for direct stop production: 0 lepton

ATLAS collaboration, arXiv:1208.1447



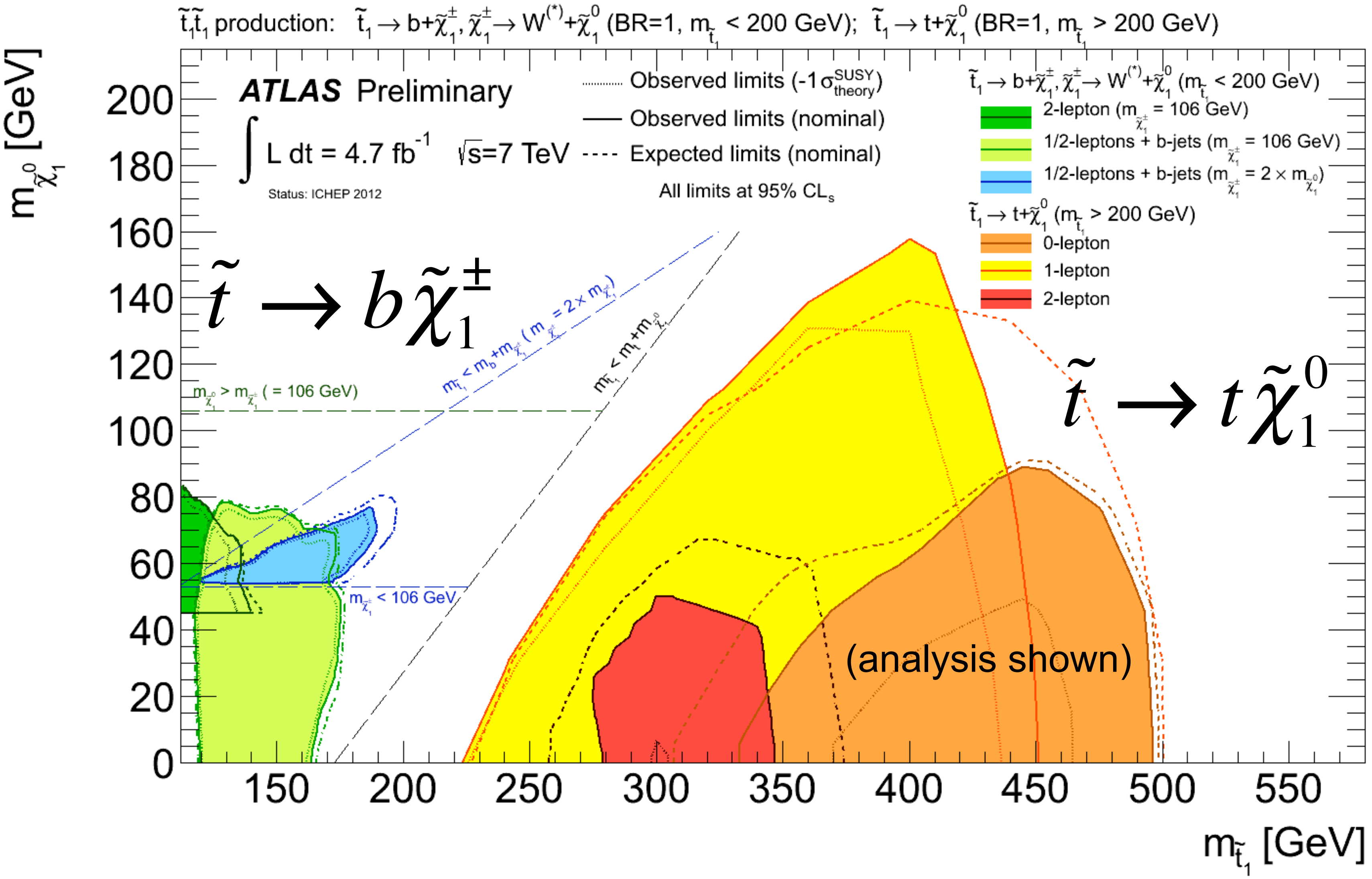


	SRA	SRB
E_T^{miss}	> 150 GeV	> 260 GeV
$t\bar{t}$	9.2 ± 2.7	2.3 ± 0.6
$t\bar{t} + W/Z$	0.8 ± 0.2	0.4 ± 0.1
Single top	0.7 ± 0.4	$0.2^{+0.3}_{-0.2}$
Z+jets	$1.3^{+1.1}_{-1.0}$	$0.9^{+0.8}_{-0.7}$
W+jets	$1.2^{+1.4}_{-1.0}$	0.5 ± 0.4
Diboson	$0.1^{+0.2}_{-0.1}$	$0.1^{+0.2}_{-0.1}$
Multi-jets	0.2 ± 0.2	0.02 ± 0.02
Total SM	$13.5^{+3.7}_{-3.6}$	$4.4^{+1.7}_{-1.3}$
SUSY $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0}) = (400, 1)$ GeV	14.8 ± 4.0	8.9 ± 3.1
Data (observed)	16	4
Visible cross section [fb]	2.9 (2.5)	1.3 (1.3)



cal uncertainties. The scale factor needed to bring the ≥ 6 jet ℓ+jets ALPGEN $t\bar{t}$ events into agreement with the data after recalculating all quantities except E_T^{miss} is 0.66 ± 0.05; the uncertainty quoted here is statistical

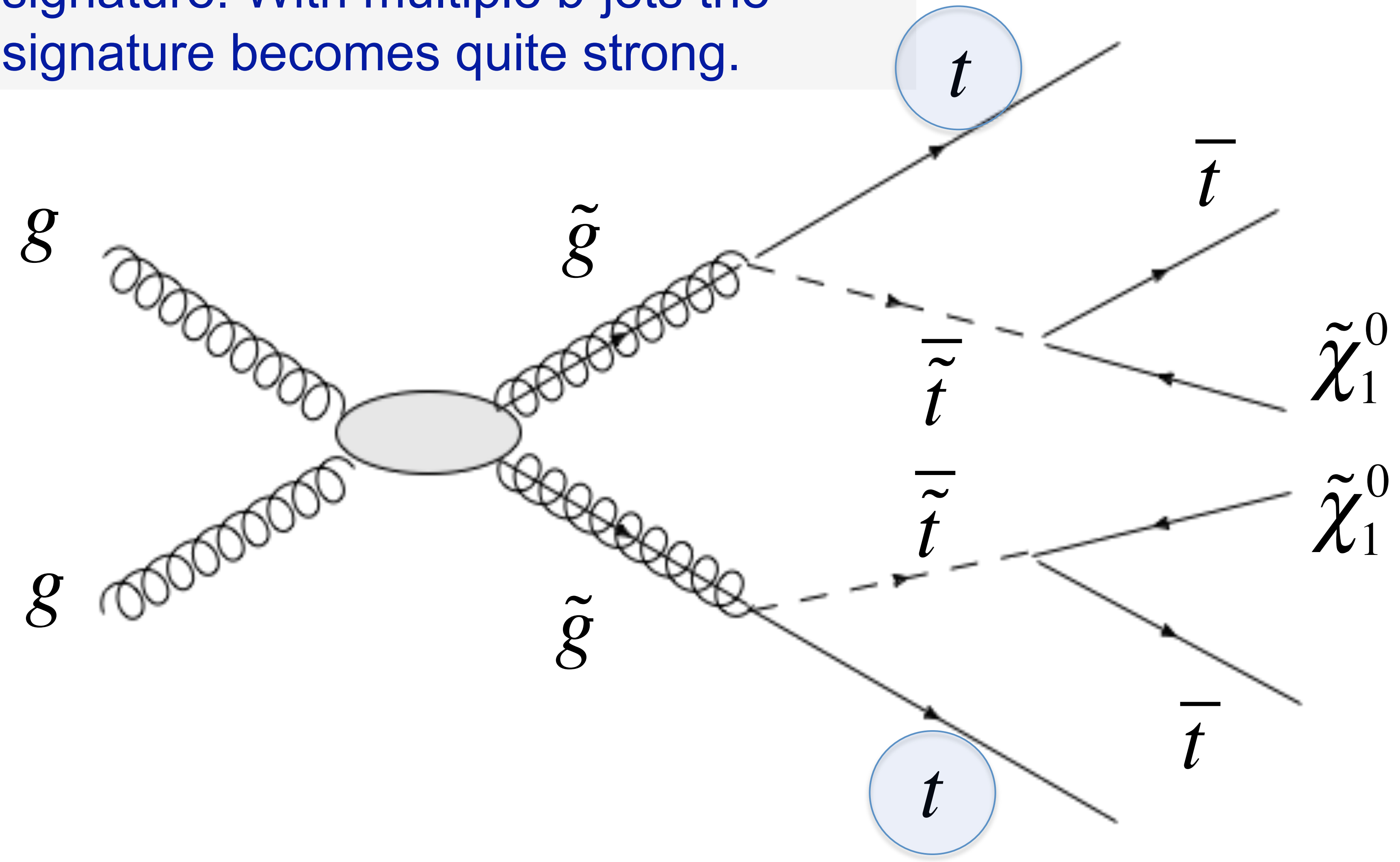
ATLAS searches for direct stop production



Stop excluded up to ~500 GeV, but strong dependence on $m(\tilde{\chi}_1^0)$

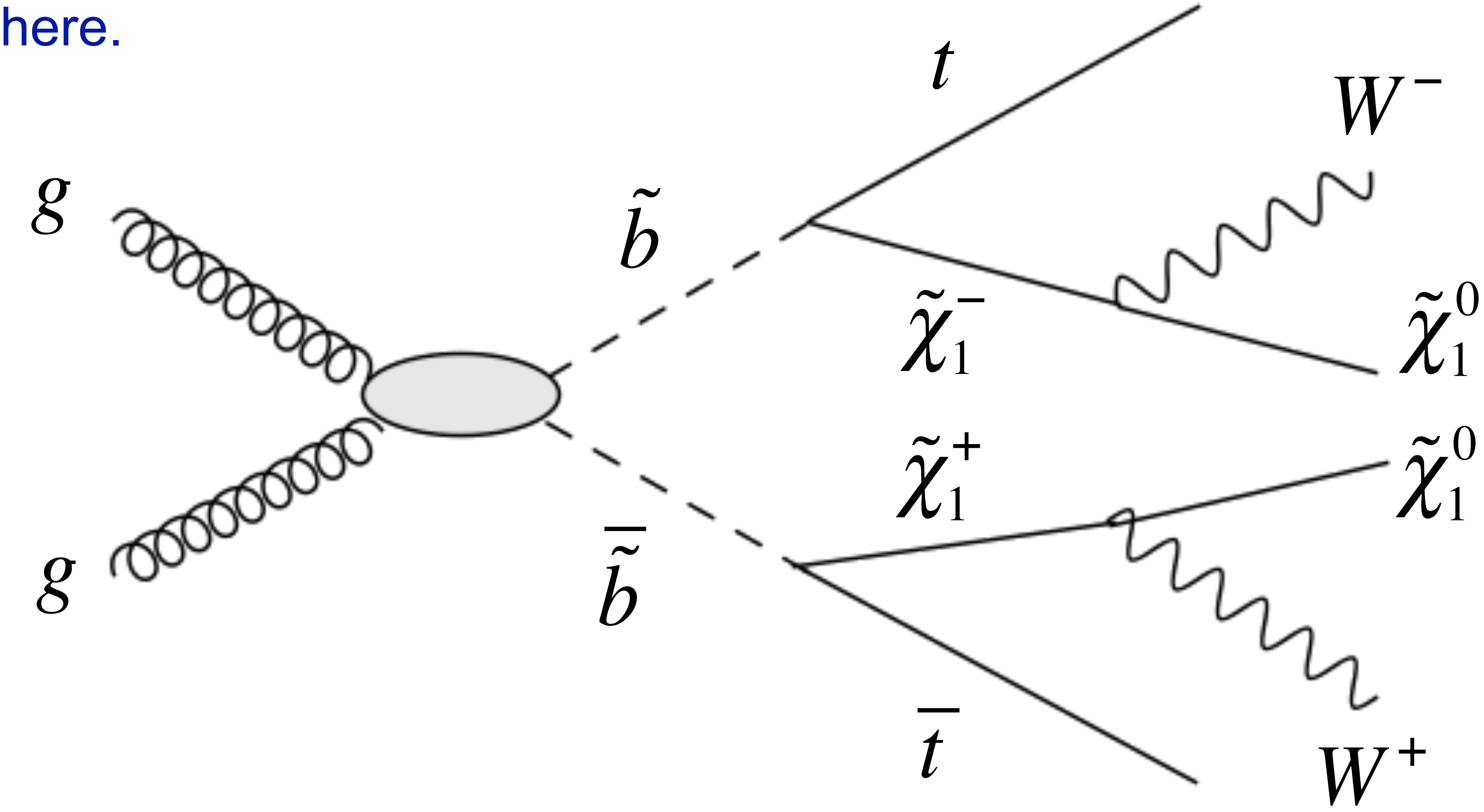
Searches with like-sign dileptons and b-jets

Like-sign dileptons are a classic SUSY signature. With multiple b-jets the signature becomes quite strong.



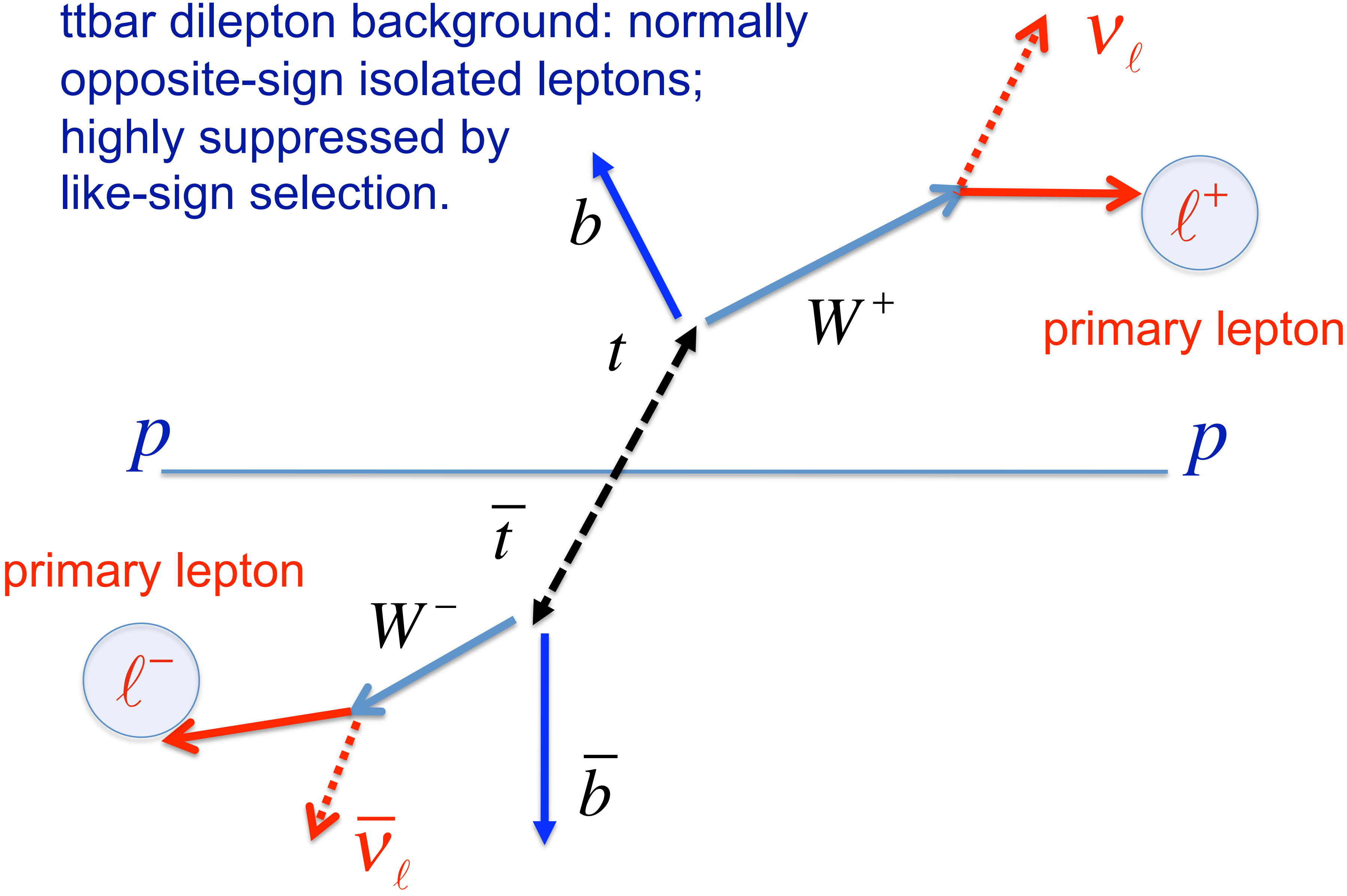
Like-sign dileptons from b-squark pairs

Can also get like-sign dileptons and multileptons from b-quark pair production. Also have b-jets here.

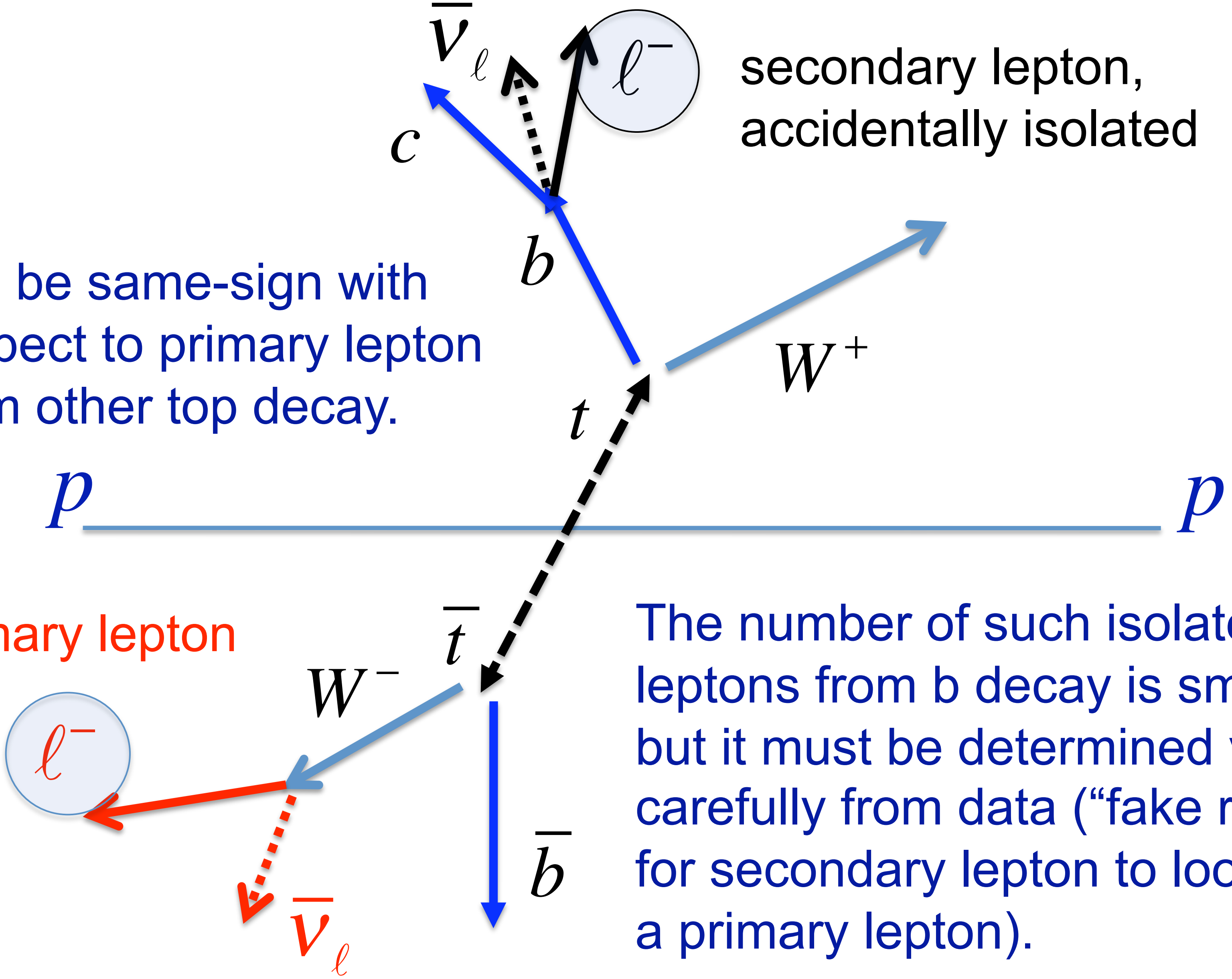


Same-sign dileptons: experimental issues

ttbar dilepton background: normally opposite-sign isolated leptons; highly suppressed by like-sign selection.



Same-sign dileptons: experimental issues



secondary lepton,
accidentally isolated

Will be same-sign with respect to primary lepton from other top decay.

primary lepton

The number of such isolated leptons from b decay is small, but it must be determined very carefully from data (“fake rate” for secondary lepton to look like a primary lepton).

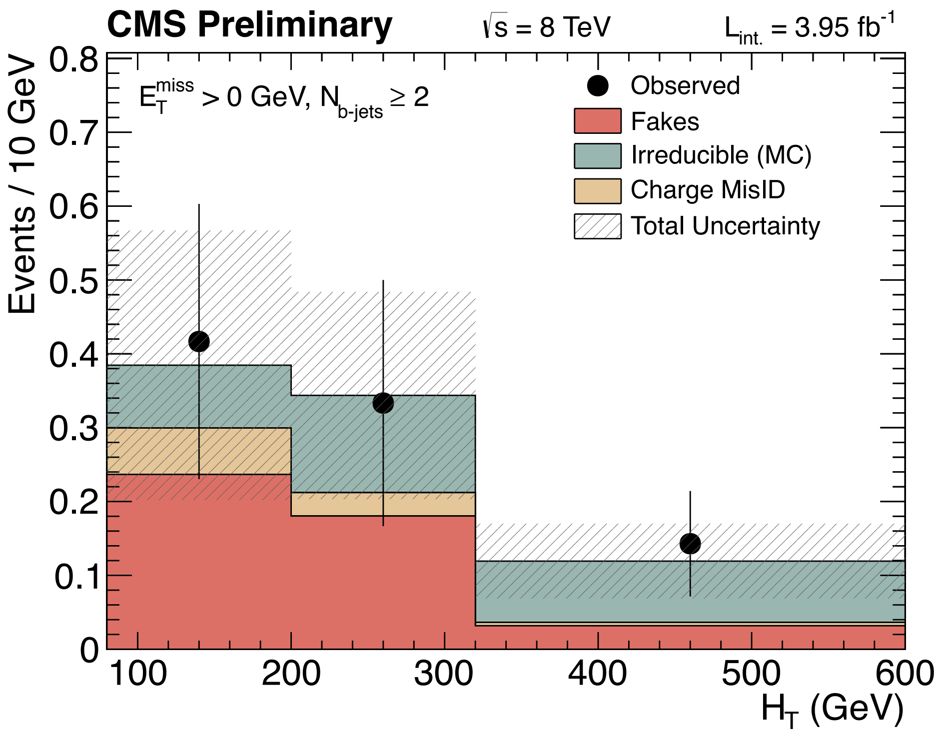
Like-sign dileptons + b jets

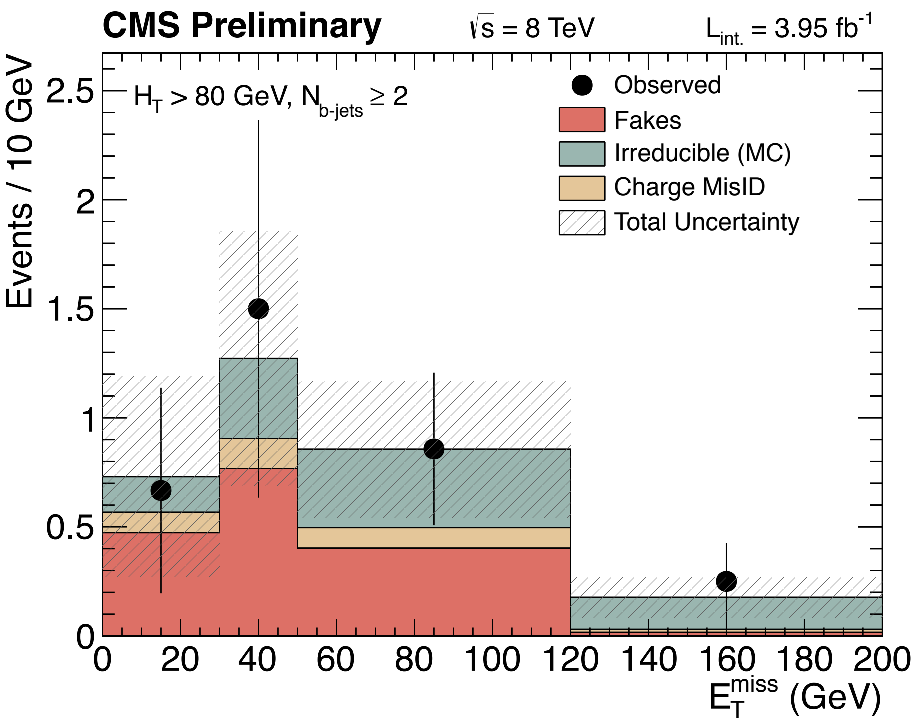
CMS–SUS-12-017 http://cdsweb.cern.ch/record/1459811

Backgrounds

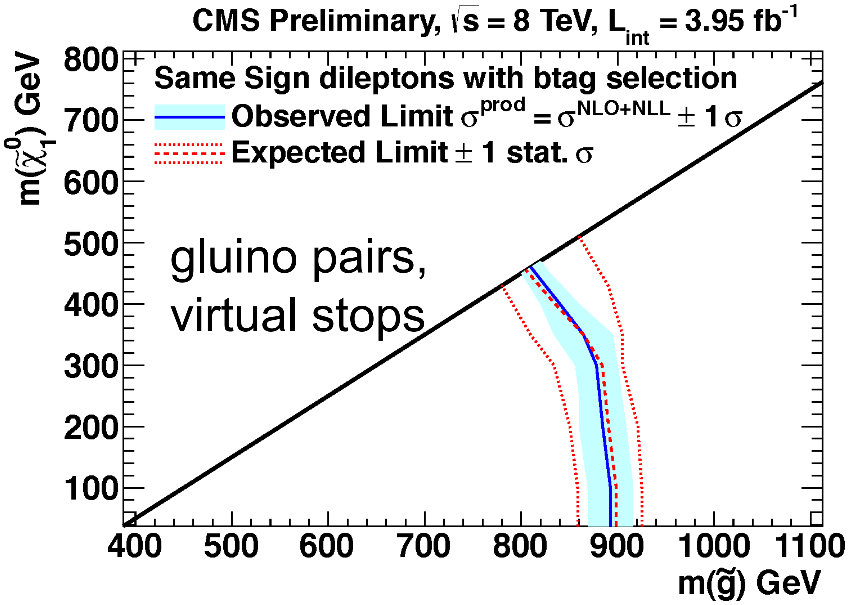
1. primary-secondary pairs
2. lepton charge mis-ID (e bremstrahlung)
3. rare SM processes: ttbar+W, ttbar+Z (~200 fb each)

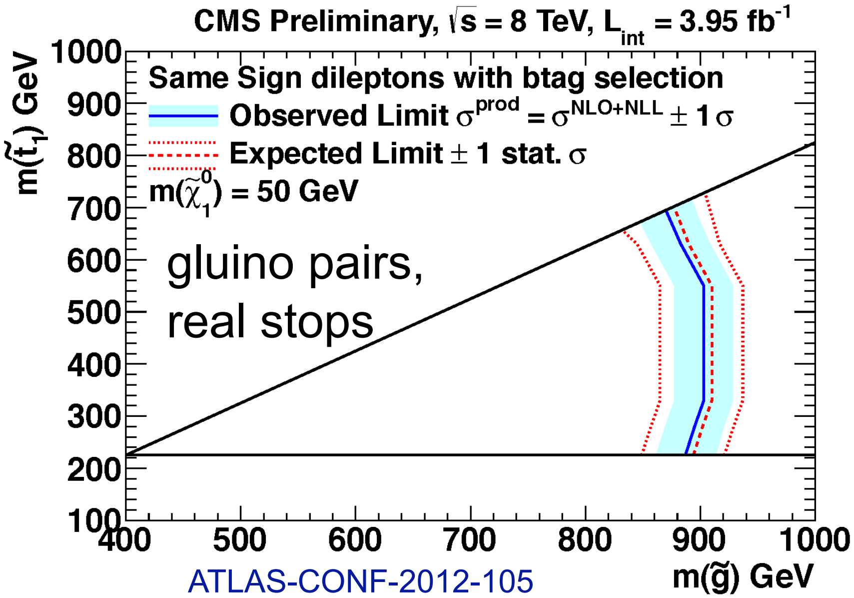
Selection 2 same-sign leptons (pT>20 GeV), ≥2 b jets (pT>40)

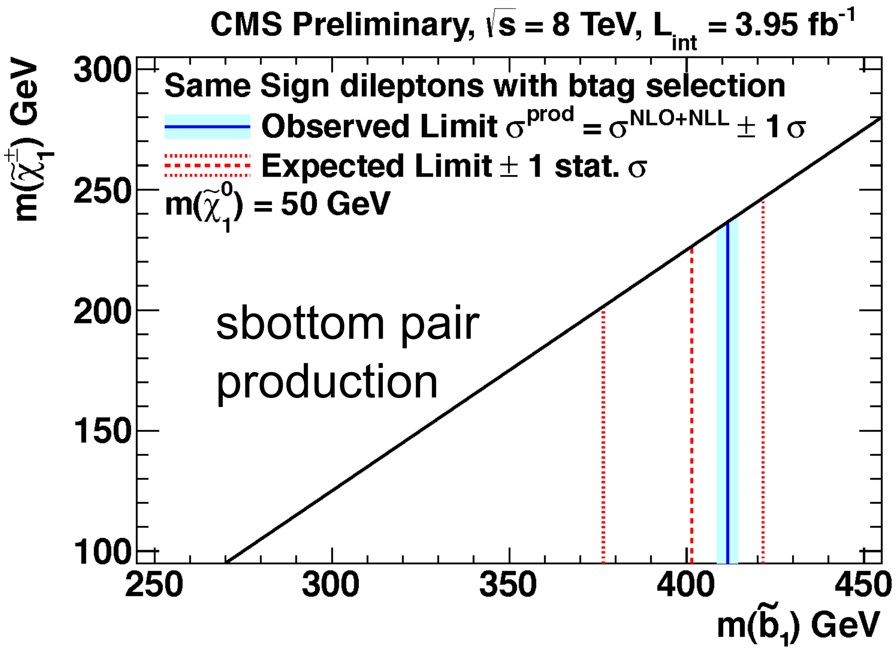




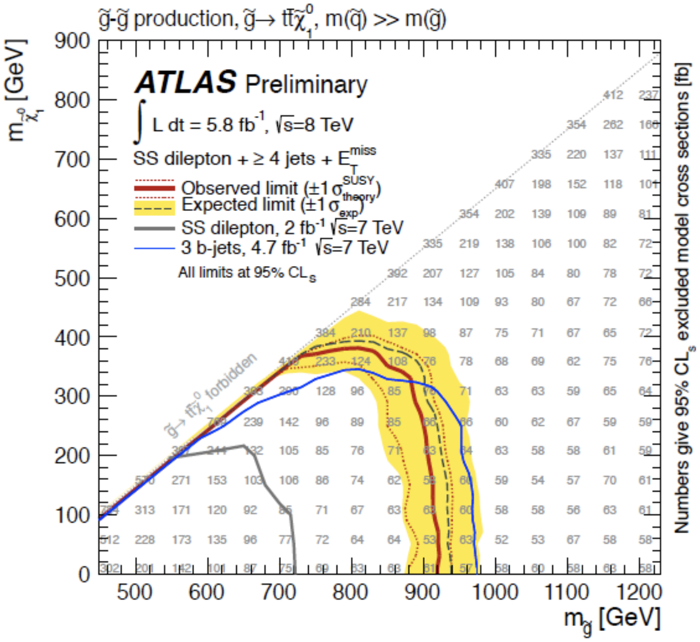
Like-sign dileptons + b-jets results



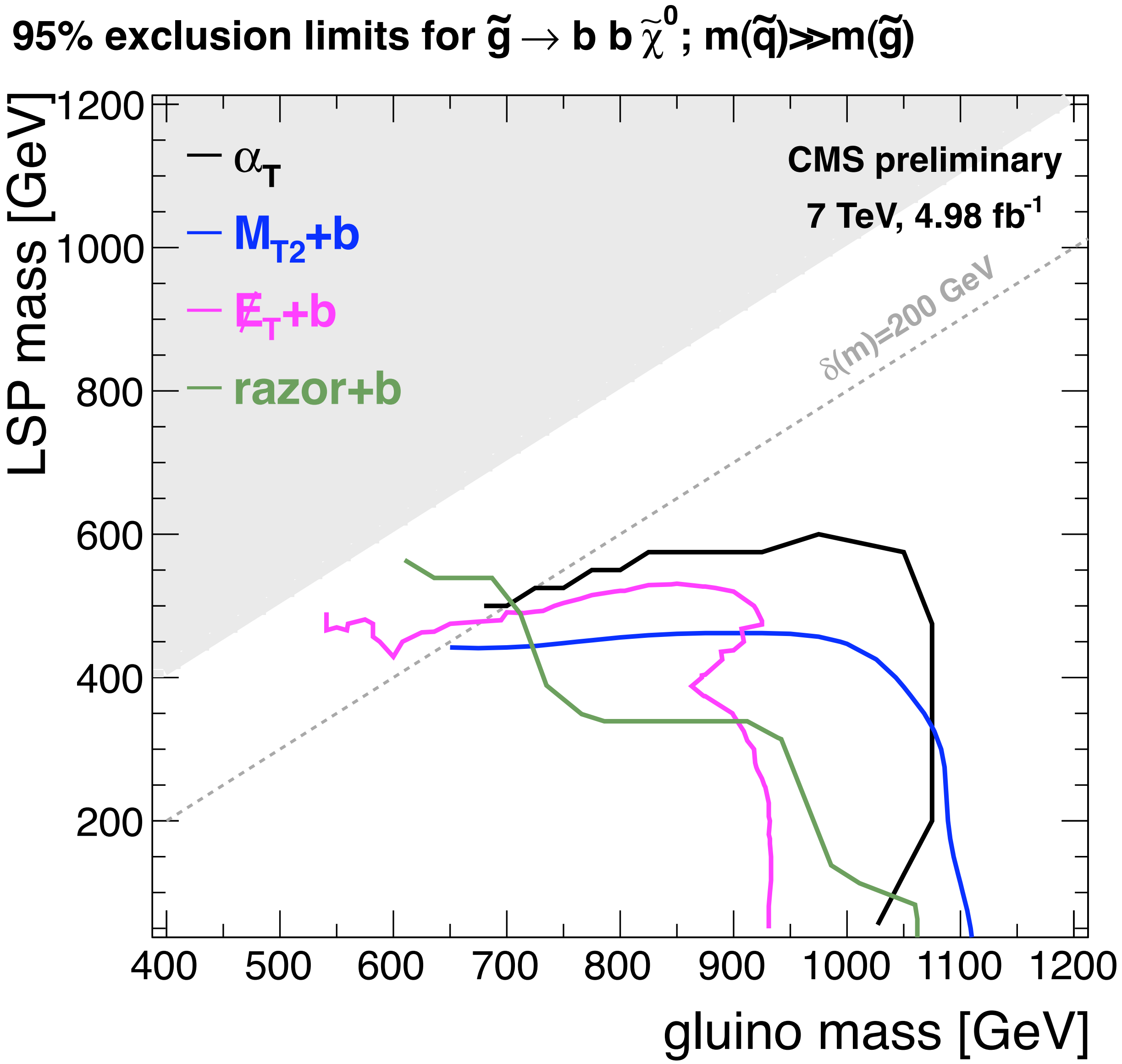




ATLAS-CONF-2012-105



Limits on gluino pair production to 4 b quarks



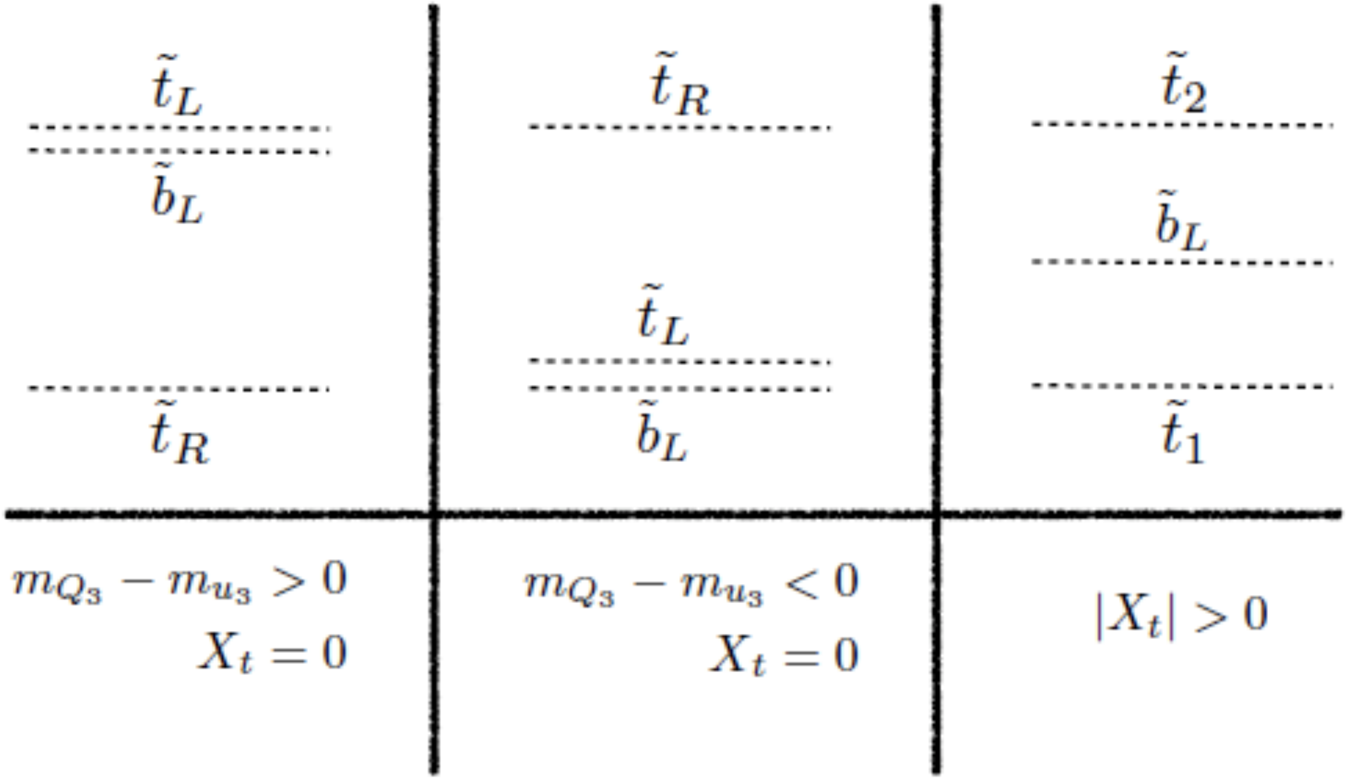
Conclusions

- SUSY searches are evolving from inclusive measurements to more focussed searches, especially for light stop/sbottom.
- The simplified-model approach is replacing CMSSM for interpretations.
- “Naturalness”-motivated searches are just beginning. The 2012 data sample will be extremely important for natural SUSY models.
- Tomorrow: Electroweak production and “exotica”.

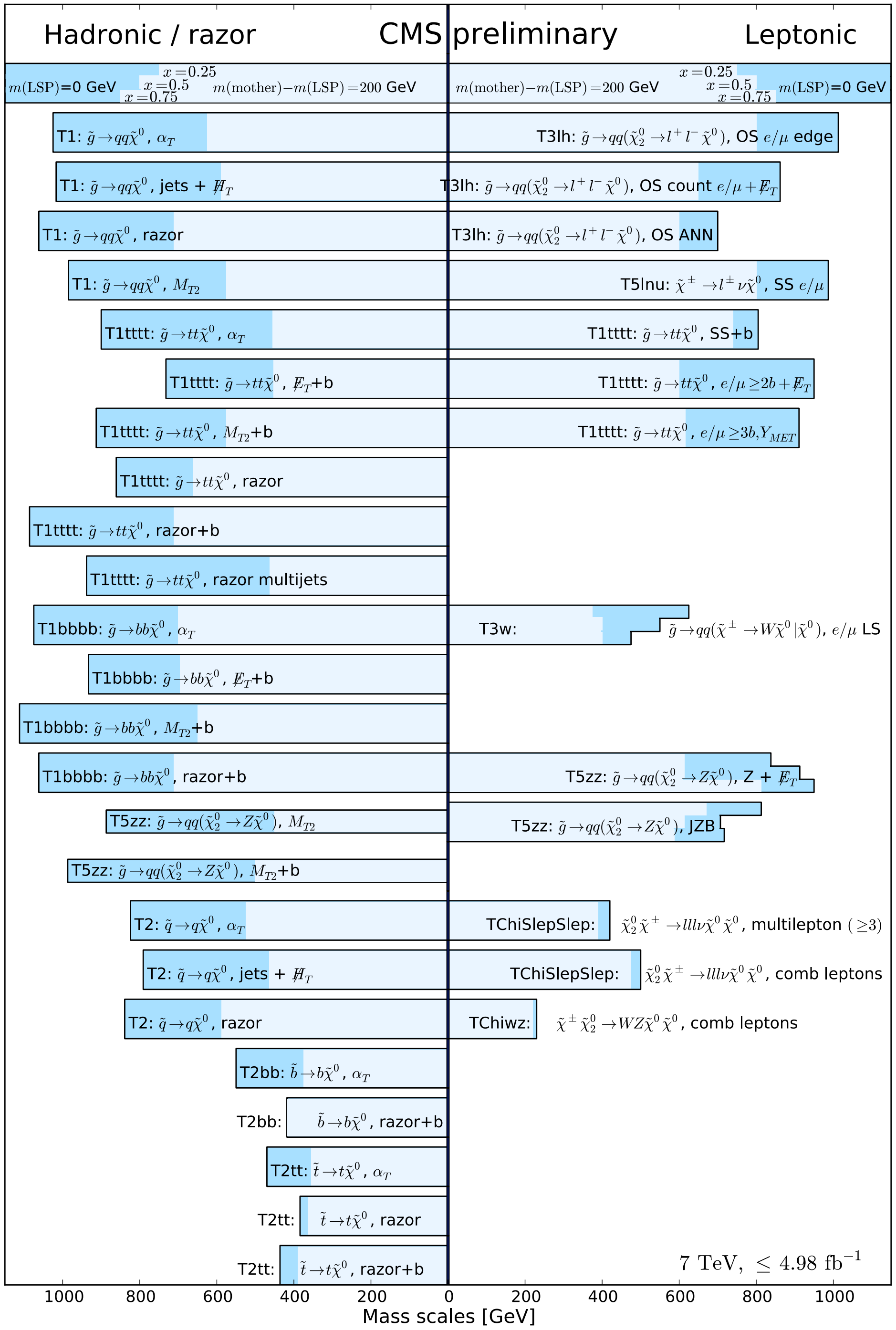
Backups

Some spectra compatible with "naturalness" considerations

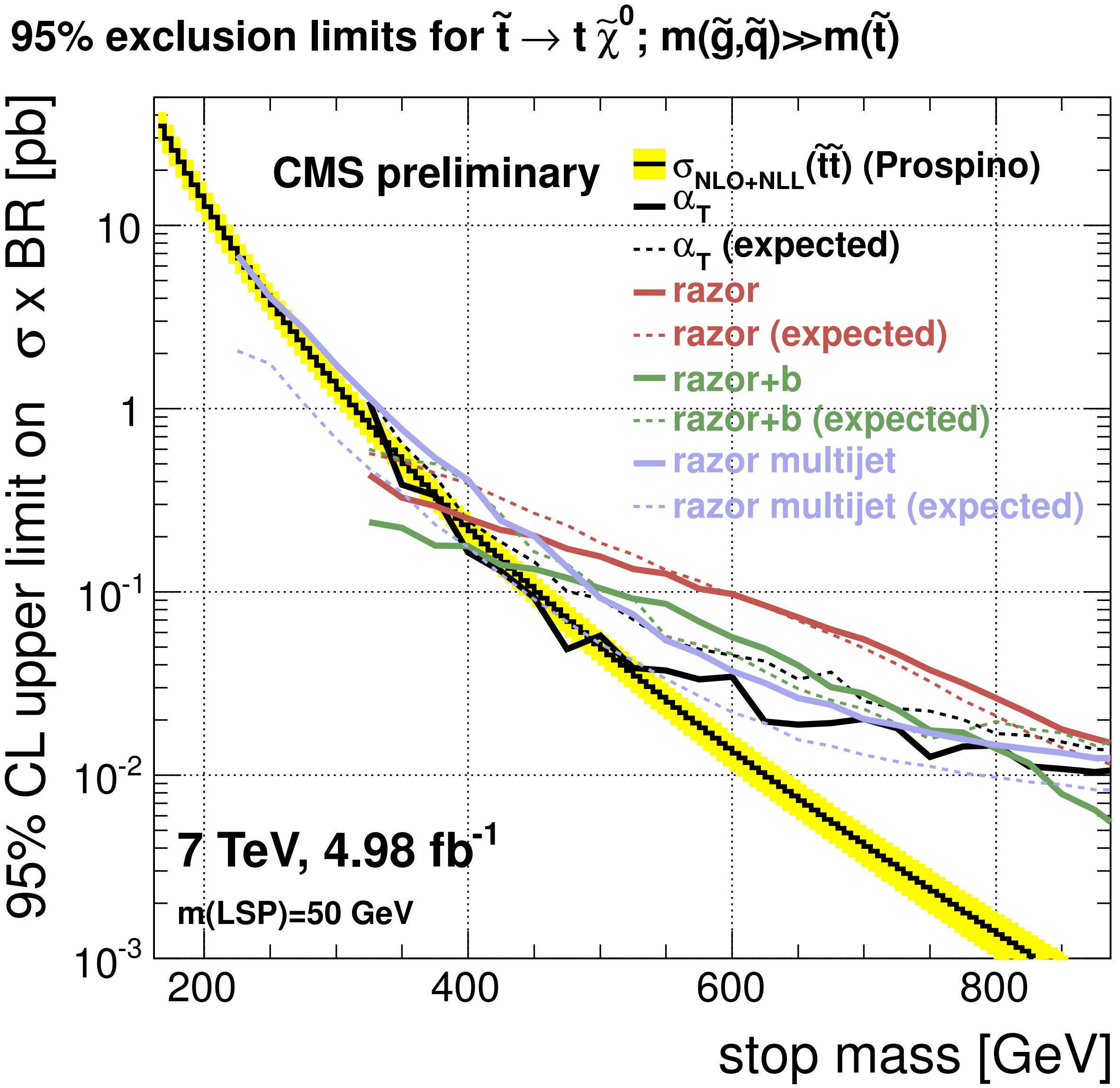
M. Papucci, J.T. Ruderman, and A. Weiler, http://arxiv.org/abs/1110.6926

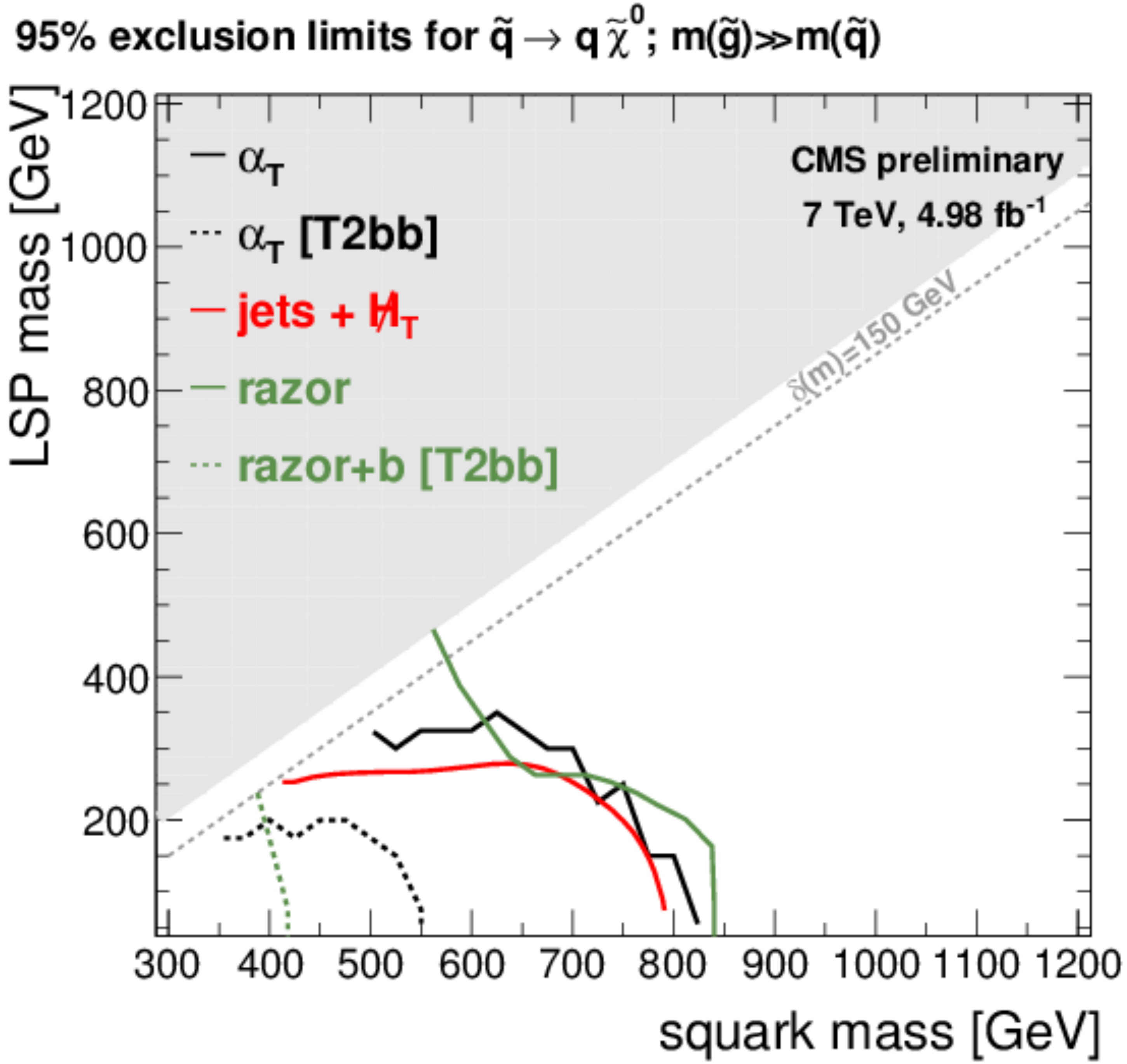


What sort of strategy should we use for this?
Clearly, b-tagging will play a big role. Have to consider production & decay.


Hadronic / razor
CMS preliminary
Leptonic
m(LSP)=0 GeV
$x=0.25$
$x=0.5$
$x=0.75$
$m(\mathrm{mother})-m(\mathrm{LSP})=200$ GeV
$m(\mathrm{mother})-m(\mathrm{LSP})=200$ GeV
$x=0.25$
$x=0.5$
$x=0.75$
m(LSP)=0 GeV
T1: $\tilde{g}\to qq\tilde{\chi}^0$, α_T
T1: $\tilde{g}\to qq\tilde{\chi}^0$, jets + $H\!\!\!/_T$
T1: $\tilde{g}\to qq\tilde{\chi}^0$, razor
T1: $\tilde{g}\to qq\tilde{\chi}^0$, M_{T2}
T1tttt: $\tilde{g}\to tt\tilde{\chi}^0$, α_T
T1tttt: $\tilde{g}\to tt\tilde{\chi}^0$, $E\!\!\!/_T$+b
T1tttt: $\tilde{g}\to tt\tilde{\chi}^0$, M_{T2}+b
T1tttt: $\tilde{g}\to tt\tilde{\chi}^0$, razor
T1tttt: $\tilde{g}\to tt\tilde{\chi}^0$, razor+b
T1tttt: $\tilde{g}\to tt\tilde{\chi}^0$, razor multijets
T1bbbb: $\tilde{g}\to bb\tilde{\chi}^0$, α_T
T1bbbb: $\tilde{g}\to bb\tilde{\chi}^0$, $E\!\!\!/_T$+b
T1bbbb: $\tilde{g}\to bb\tilde{\chi}^0$, M_{T2}+b
T1bbbb: $\tilde{g}\to bb\tilde{\chi}^0$, razor+b
T5zz: $\tilde{g}\to qq(\tilde{\chi}^0_2\to Z\tilde{\chi}^0)$, M_{T2}
T5zz: $\tilde{g}\to qq(\tilde{\chi}^0_2\to Z\tilde{\chi}^0)$, M_{T2}+b
T2: $\tilde{q}\to q\tilde{\chi}^0$, α_T
T2: $\tilde{q}\to q\tilde{\chi}^0$, jets + $H\!\!\!/_T$
T2: $\tilde{q}\to q\tilde{\chi}^0$, razor
T2bb: $\tilde{b}\to b\tilde{\chi}^0$, α_T
T2bb: $\tilde{b}\to b\tilde{\chi}^0$, razor+b
T2tt: $\tilde{t}\to t\tilde{\chi}^0$, α_T
T2tt: $\tilde{t}\to t\tilde{\chi}^0$, razor
T2tt: $\tilde{t}\to t\tilde{\chi}^0$, razor+b
T3lh: $\tilde{g}\to qq(\tilde{\chi}^0_2\to l^+l^-\tilde{\chi}^0)$, OS e/μ edge
T3lh: $\tilde{g}\to qq(\tilde{\chi}^0_2\to l^+l^-\tilde{\chi}^0)$, OS count $e/\mu+E\!\!\!/_T$
T3lh: $\tilde{g}\to qq(\tilde{\chi}^0_2\to l^+l^-\tilde{\chi}^0)$, OS ANN
T5lnu: $\tilde{\chi}^\pm\to l^\pm\nu\tilde{\chi}^0$, SS e/μ
T1tttt: $\tilde{g}\to tt\tilde{\chi}^0$, SS+b
T1tttt: $\tilde{g}\to tt\tilde{\chi}^0$, $e/\mu\geq 2b+E\!\!\!/_T$
T1tttt: $\tilde{g}\to tt\tilde{\chi}^0$, $e/\mu\geq 3b, Y_{MET}$
T3w: $\tilde{g}\to qq(\tilde{\chi}^\pm\to W\tilde{\chi}^0|\tilde{\chi}^0)$, e/μ LS
T5zz: $\tilde{g}\to qq(\tilde{\chi}^0_2\to Z\tilde{\chi}^0)$, Z + $E\!\!\!/_T$
T5zz: $\tilde{g}\to qq(\tilde{\chi}^0_2\to Z\tilde{\chi}^0)$, JZB
TChiSlepSlep: $\tilde{\chi}^0_2\tilde{\chi}^\pm\to lll\nu\tilde{\chi}^0\tilde{\chi}^0$, multilepton (≥ 3)
TChiSlepSlep: $\tilde{\chi}^0_2\tilde{\chi}^\pm\to lll\nu\tilde{\chi}^0\tilde{\chi}^0$, comb leptons
TChiwz: $\tilde{\chi}^\pm\tilde{\chi}^0_2\to WZ\tilde{\chi}^0\tilde{\chi}^0$, comb leptons
7 TeV, ≤ 4.98 fb^{-1}
1000
800
600
400
200
0
200
400
600
800
1000
Mass scales [GeV]

Limits on stop production - CMS





95% exclusion limits for $\tilde{q} \rightarrow q\,\tilde{\chi}^0$; $m(\tilde{g}) \gg m(\tilde{q})$