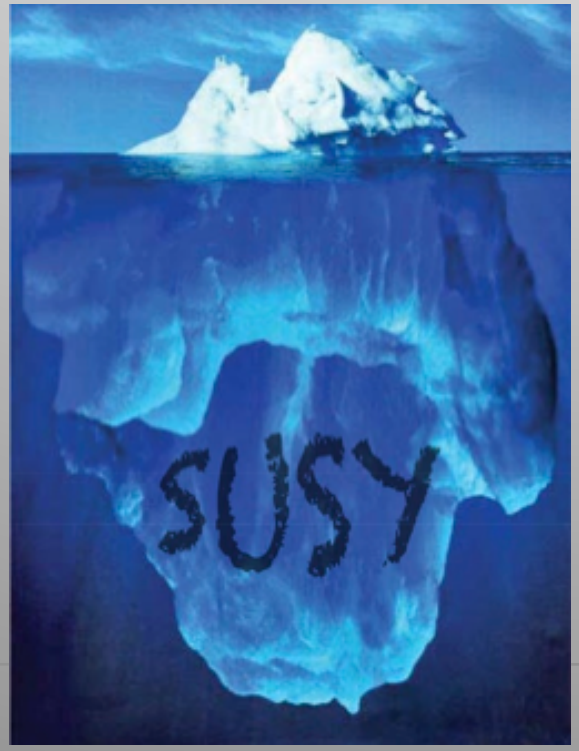
Hidden SUSY

Rethinking the experimental strategy for SUSY-(like) searches?

Some personal concluding remarks



Albert De Roeck

11/9/2011 UC-Davis

Looking for Hidden SUSY:

Last two months:

CERN "impact of LHC data on future colliders workshop"
Preparation for the European strategy meeting on particle physics

London: "Rethinking the experimental strategy for SUSY-(like) searches"

Berkeley: "Searches for Supersymmetry at the LHC"

Firenze: "Searching for new physics at the LHC"

Davis: "Hidden SUSY"

IPPP, Durham (January): "BSM 4 LHC"

Recent Discussions@ workshops

- A special role of the third generation? Look for stop, sbottom, stau…
- Split SUSY with all fermion partners very heavy, but light gauginos and gluinos
- Compressed spectra, so we see only soft particles
- FSU(5)-like models, with O(10) jets.
- Dark Matter related searches with low jet multiplicities
- Gaugino production: Multi-leptons/no jets

Recent Ideas@ workshops

- Which model regions are we missing now and should we try to 'recover'.
- More weight on optimizing 3rd generation searches?
- How well do we understand ISR (TH/EXP)?
- Optimized lepton analyses: benchmarks?
- Many jet analyses (>= 8)? Many jets + lepton (S_T), no MET, triple b-tagging
- Study boosted objects?
- Special signatures (LLPs, GMSB, stubs, kinks…)
- Running: few 100 pb^{-1} with low pile-up conditions?
- 2012 energy: higher energy or same energy:

LHC: ~ a year ago

"Data are coming! Data are coming!"

Theory Space Prior to Data

2011: LHC Impact

M. Schmaltz

Note that during 3-4 years BC (Before Collisions) we –LHC experimentalists- got more models to deal with than we needed…

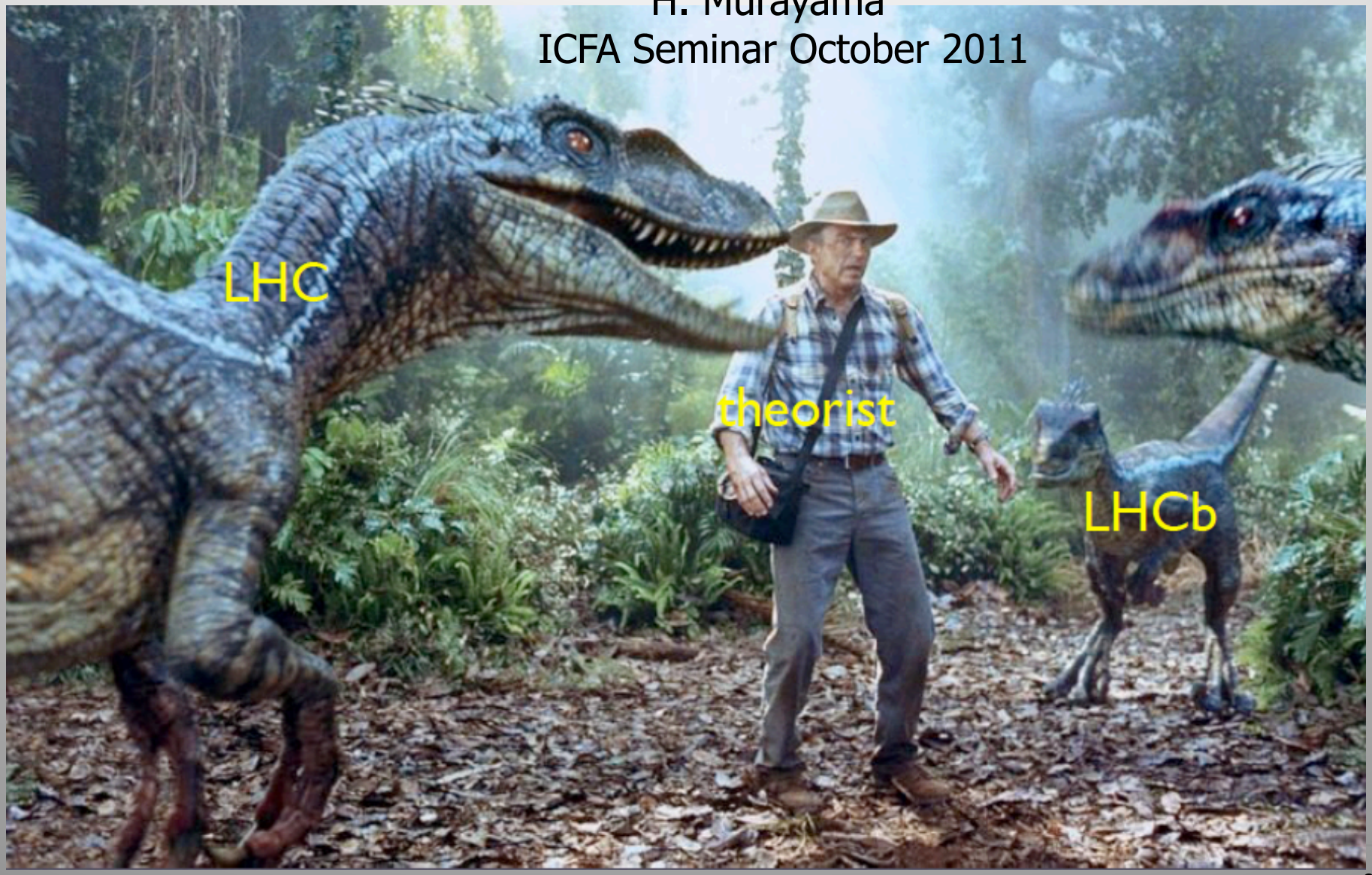
Some theorists found it a challenge to invent a model with signatures difficult for the experiments:
heavy stable charged particles, hidden valley models, Quirks…

NOW WE STRIKE BACK!!

But remember that these are still early days!!

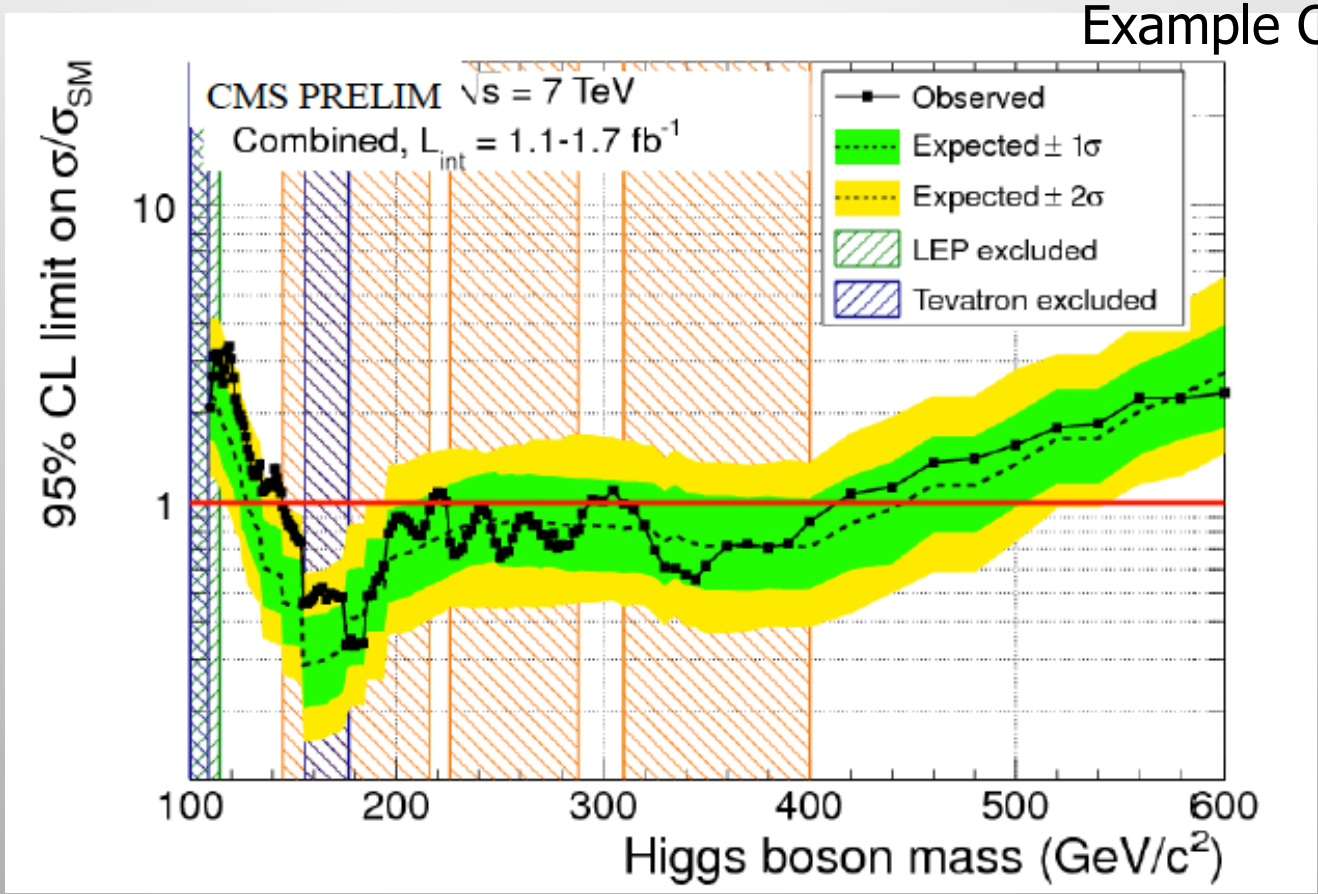
How does it feel to be a (BSM) Theorist?

H. Murayama
ICFA Seminar October 2011



Higgs Summary So Far

Example CMS

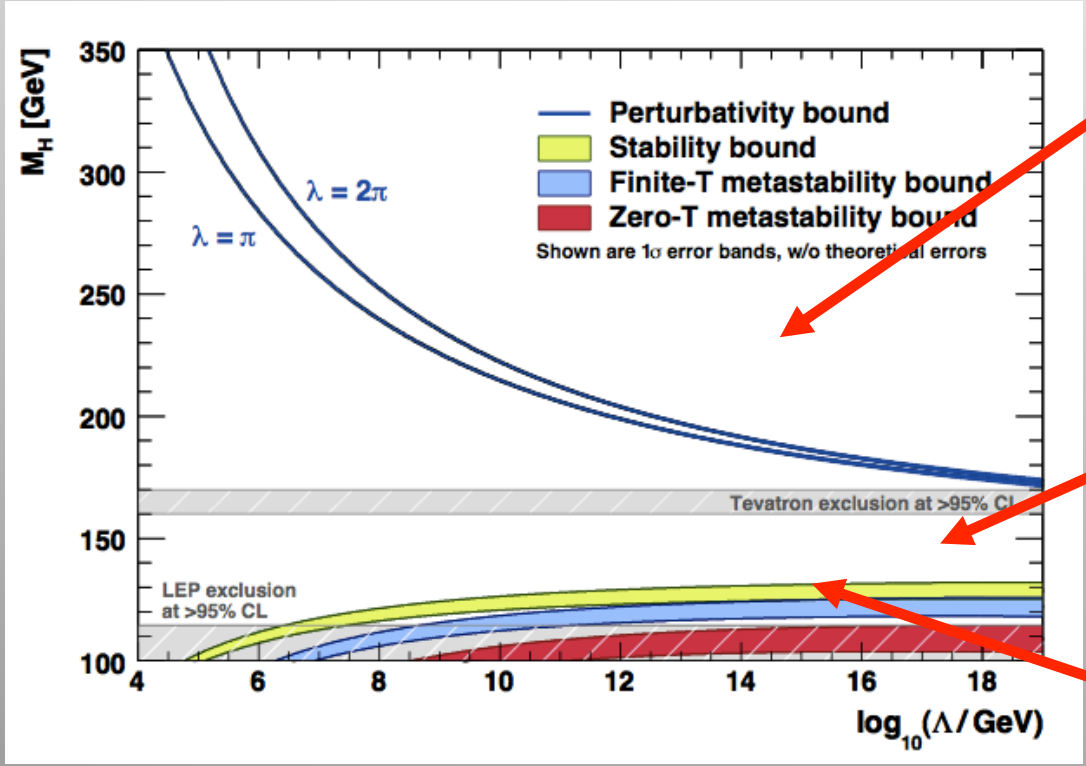


Expected 95% CL exclusion mass range: 130-440 GeV
Observed 95% CL exclusion mass range: 145-216, 226-288, 310-400 GeV

Combine ATLAS+CMS (Mid November)?
Next: full 2011 data analysis Spring 2012? LHC+Tevatron combination?

A Light Higgs: Consequences

A light Higgs implies that the Standard Model cannot be stable up to the GUT or Planck scale (10^{19} GeV)



The effective potential blows up, due to heavy top quark mass

Allowed corridor but needs strong fine-tuning…

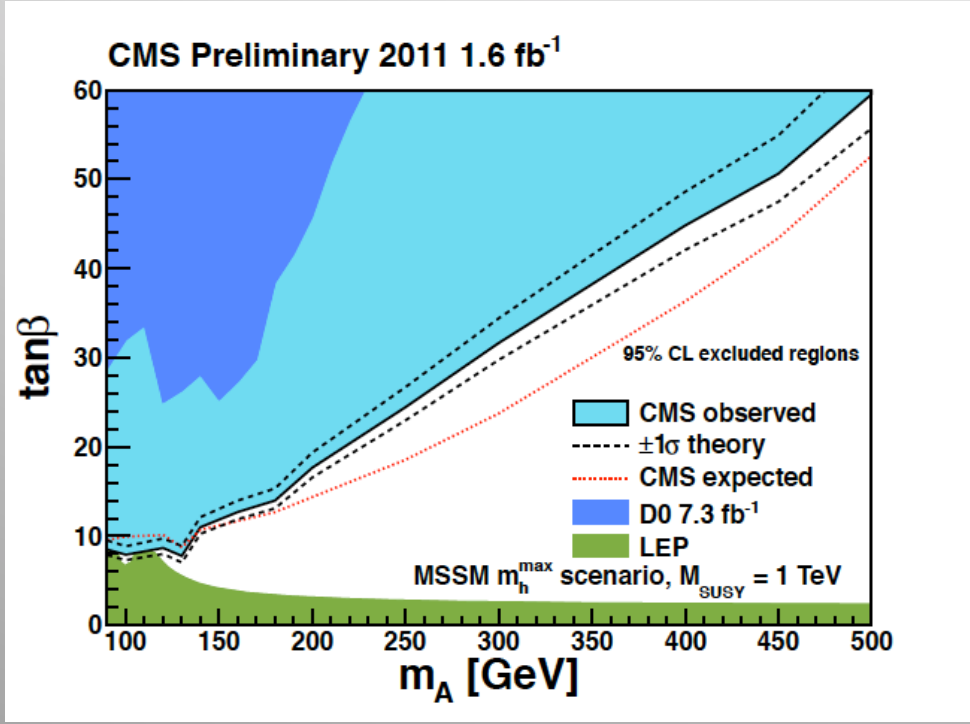
The electroweak vacuum is unstable to corrections from scales Λ >> v= 246 GeV

New physics expected in TeV range

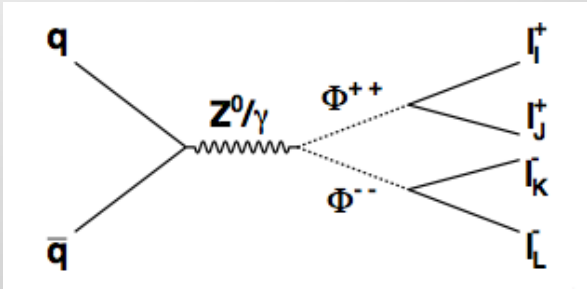
Harigaya
Matsumoto
Murayama

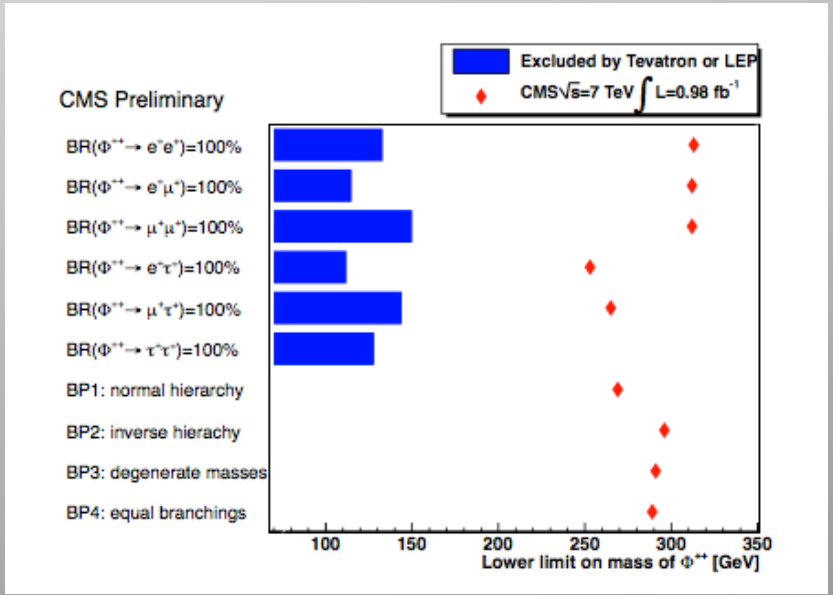
Search for BSM Higgses

MSSM Higgs → ττ



Double Charged Higgs





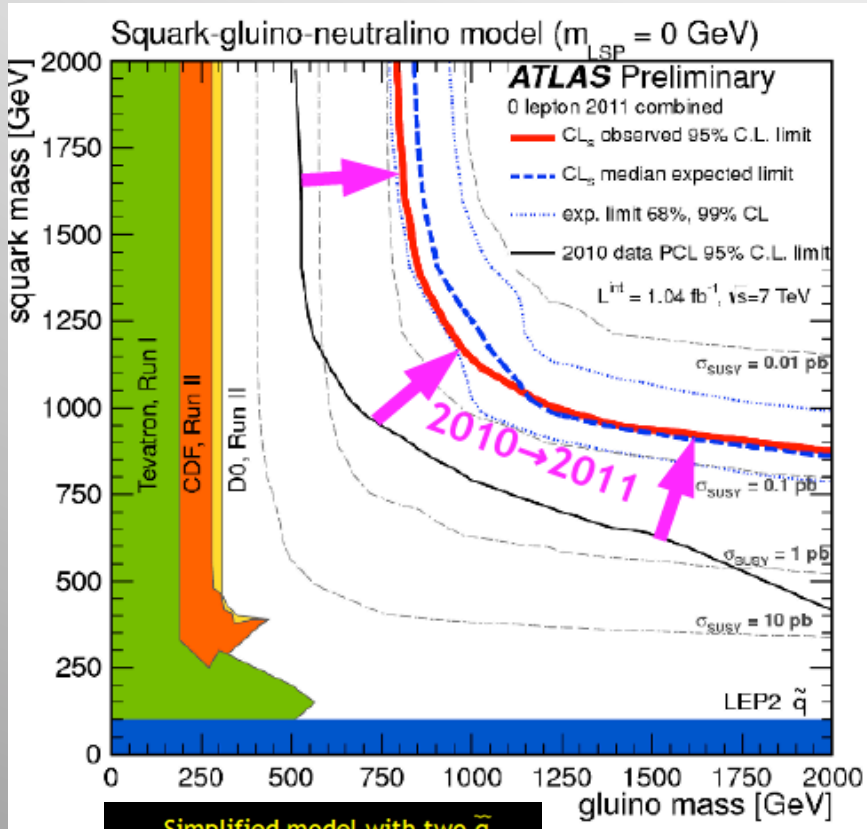
Impressive Exclusion Limits

SUSY Search: Jets + Missing E_T Channel

Limits in a simplified model

Using 1 fb^{-1}

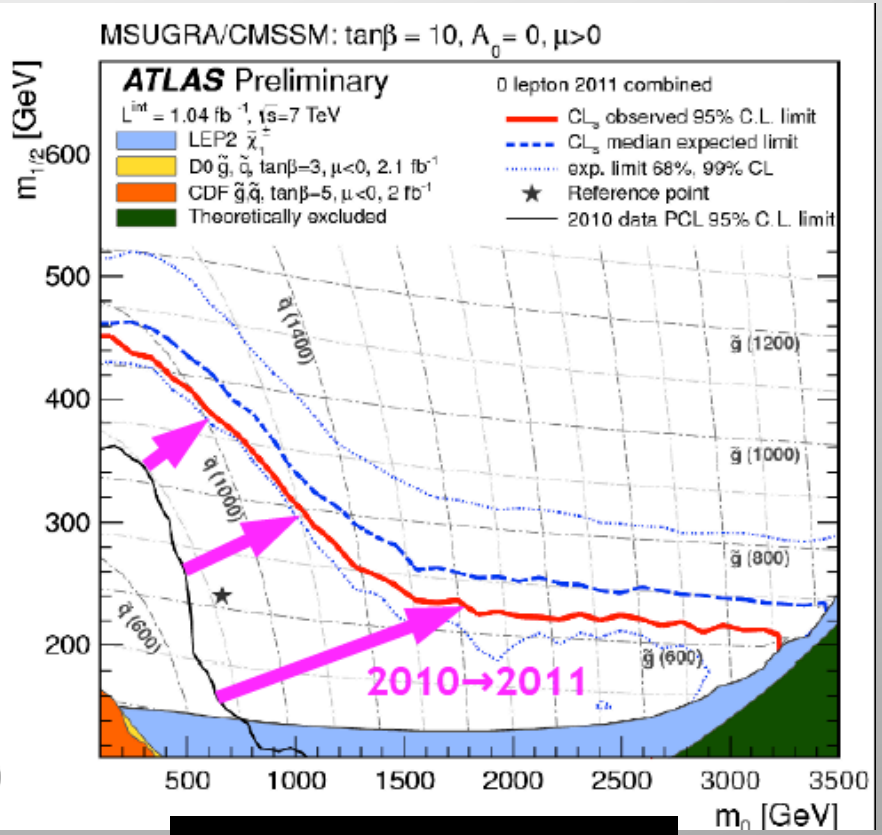
Limits in CMSSM



Simplified model with two $\tilde{q}$ generations, $m(\tilde{\chi}_1^0)$~0

$m_{\tilde{g}}$>800 GeV $m_{\tilde{q}}$>850 GeV

Equal mass case: $m_{\tilde{g}}$=$m_{\tilde{q}}$>1.075 TeV



MSUGRA/CMSSM: tanβ=10, A_0=0, μ>0

Equal mass case: $m_{\tilde{q}}$=$m_{\tilde{g}}$ > 980 GeV

Up to masses of 1 TeV excluded for equal gluino-squark masses

Extends the 2010 data limits by ~ 250 GeV

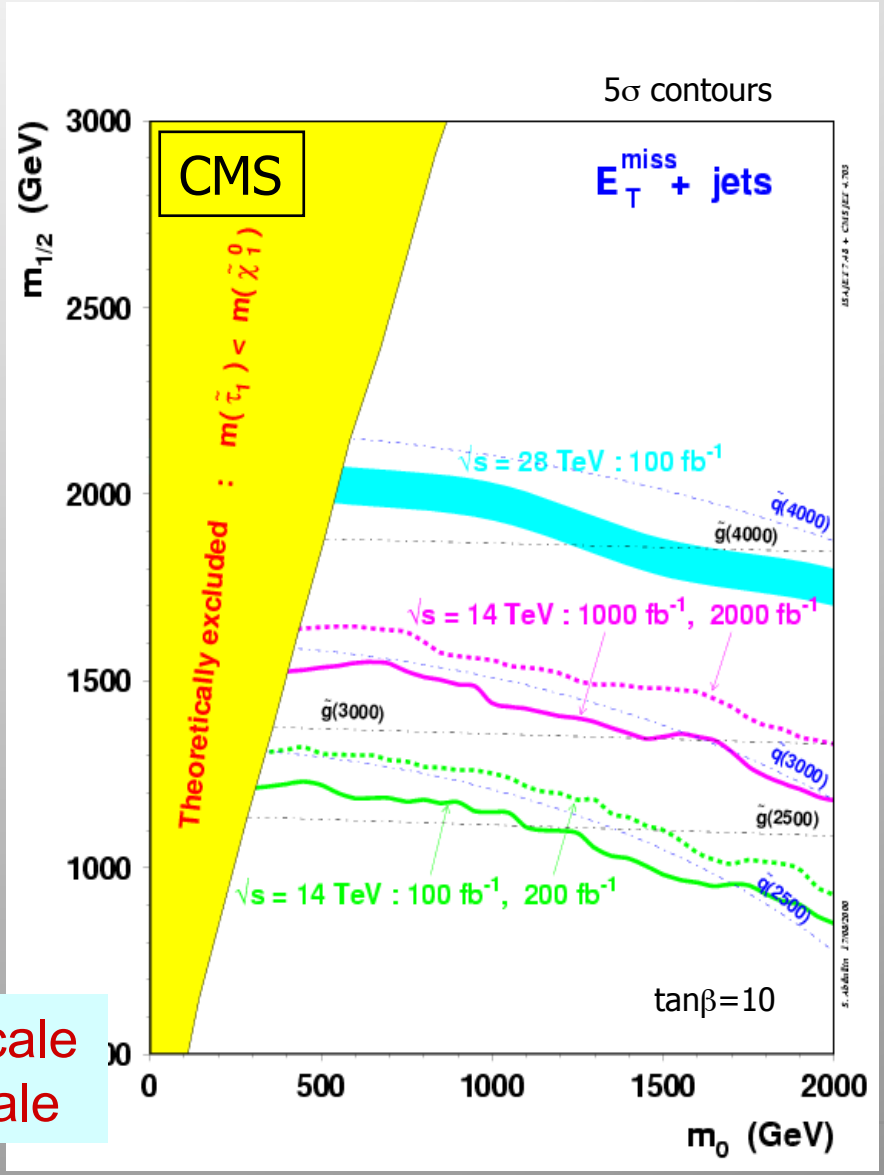
Remember: LHC, HL-LHC & HE-LHC

~2005

Impact of the HL-LHC

Extend the discovery region for squarks and gluinos by roughly 0.5 TeV, i.e. from
~2.5 TeV → 3 TeV

This extension involved high E_T jets/leptons and large missing E_T
⇒ Not much compromised by increased pile-up at SLHC

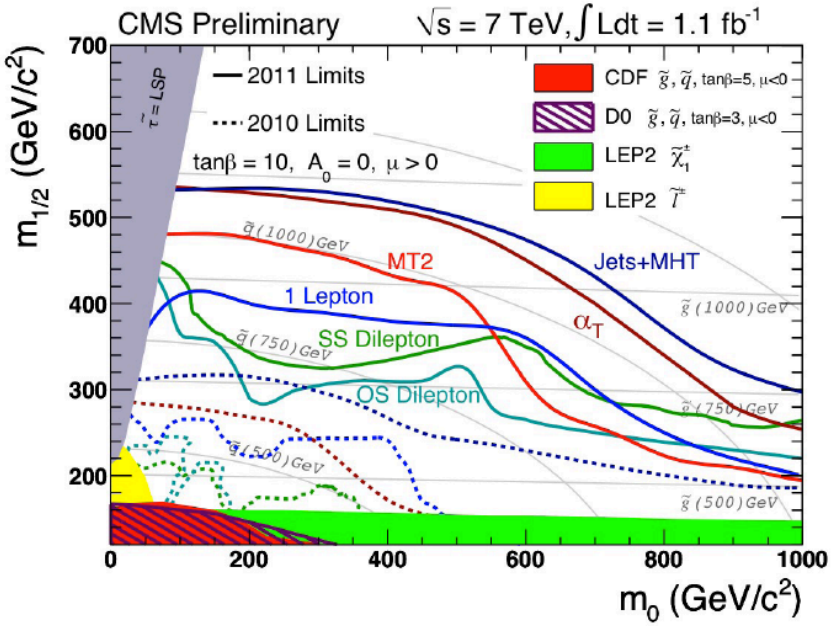


$m_{1/2}$ universal gaugino mass at GUT scale
m_0: universal scalar mass at GUT scale

SUSY Searches (Example CMS)

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

All Analyses (CMS)

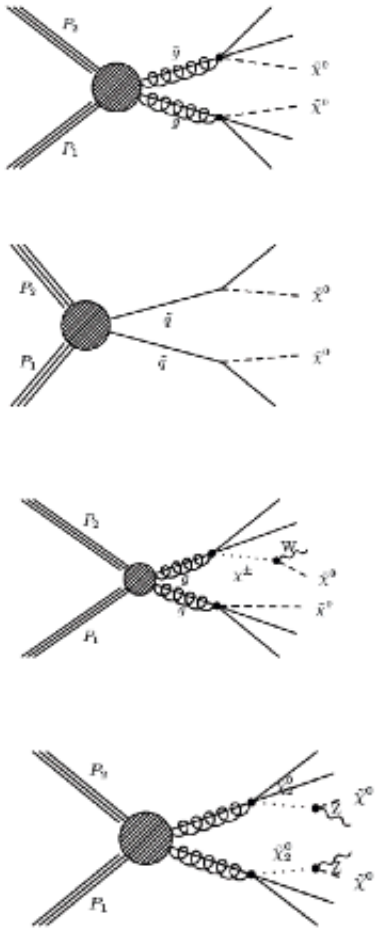


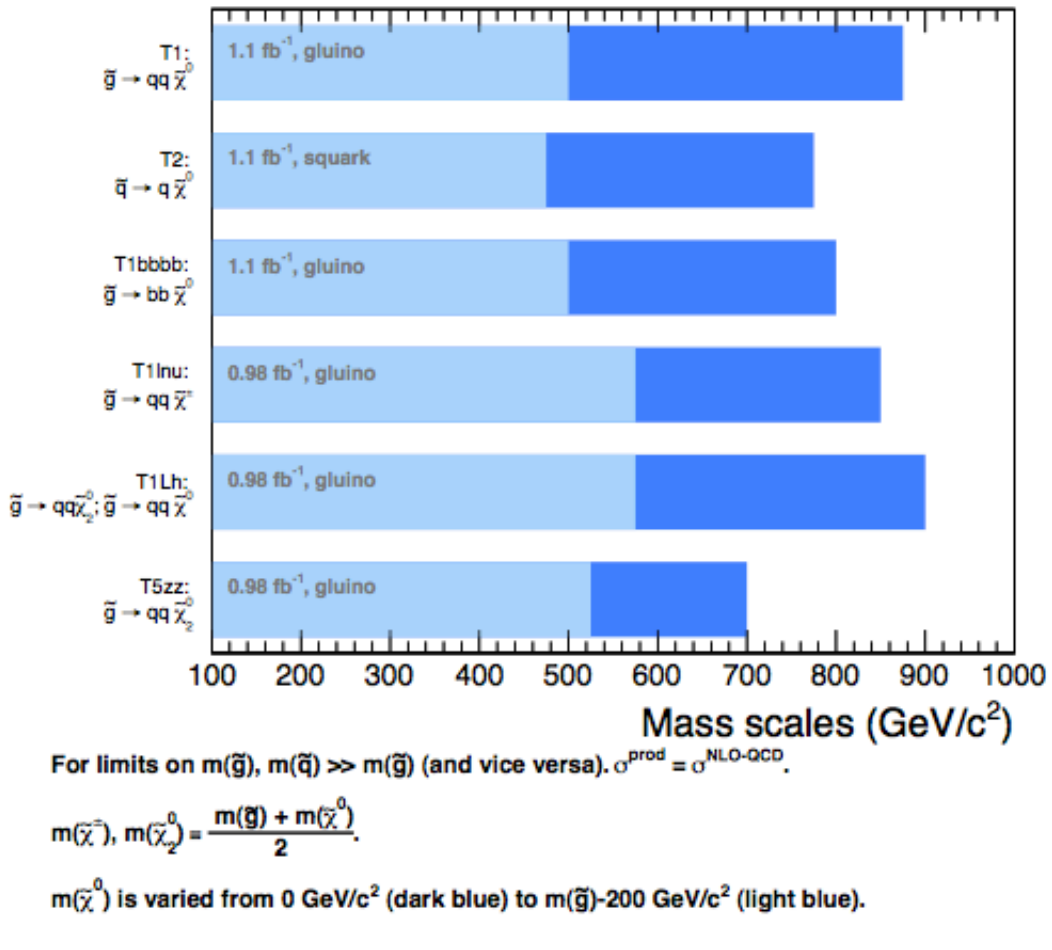
Having a large number of different analyses (a virtue!)

Different approaches for ATLAS and CMS (healthy!)

So far bit too much emphasis on "optimizing" for CMSSM (beauty contest?)

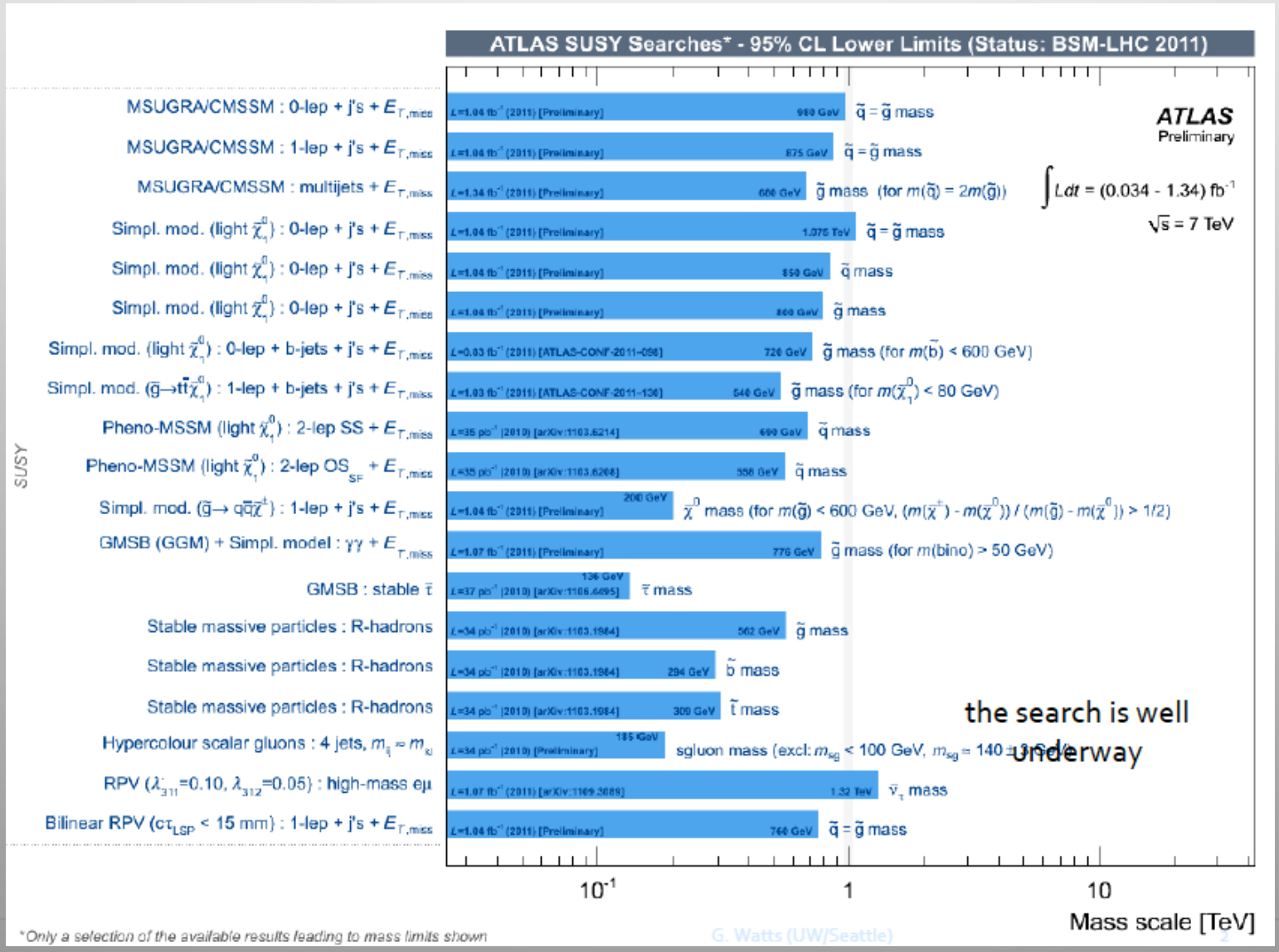
Interpretation in Simplified Models





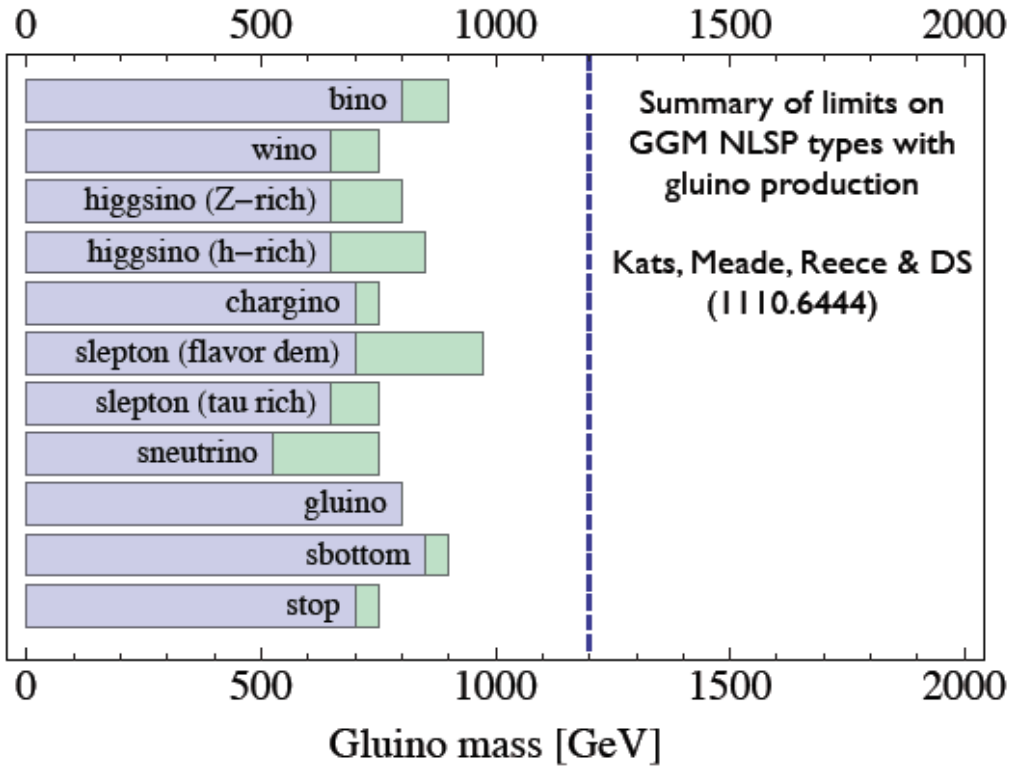
How to present best the experimental data?
Clearly an important discussion with the community; see also eg CERN workshop

Search Ranges (ATLAS)



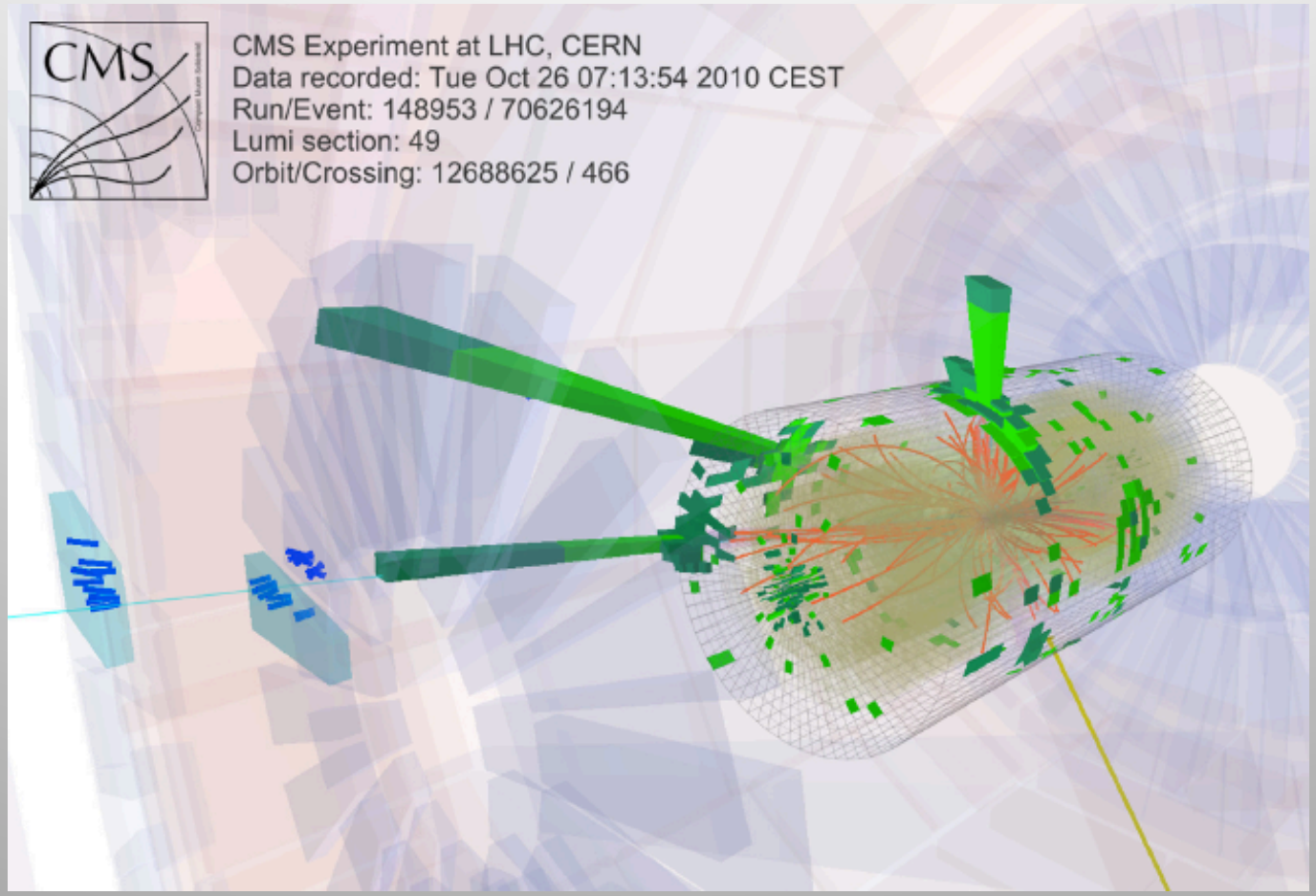
Theorists Translation

Limits, limits everywhere...



Where is SUSY hiding??

…Some Interesting Events…

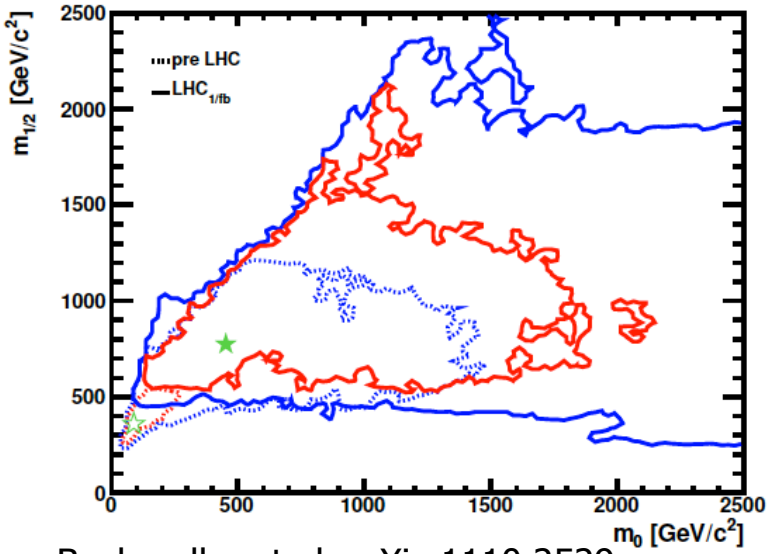


- Event with five jets and large missing transverse energy
- Total sum of transverse momentum H_T= 1132 GeV and missing transverse energy H_{TMiss} = 693 GeV

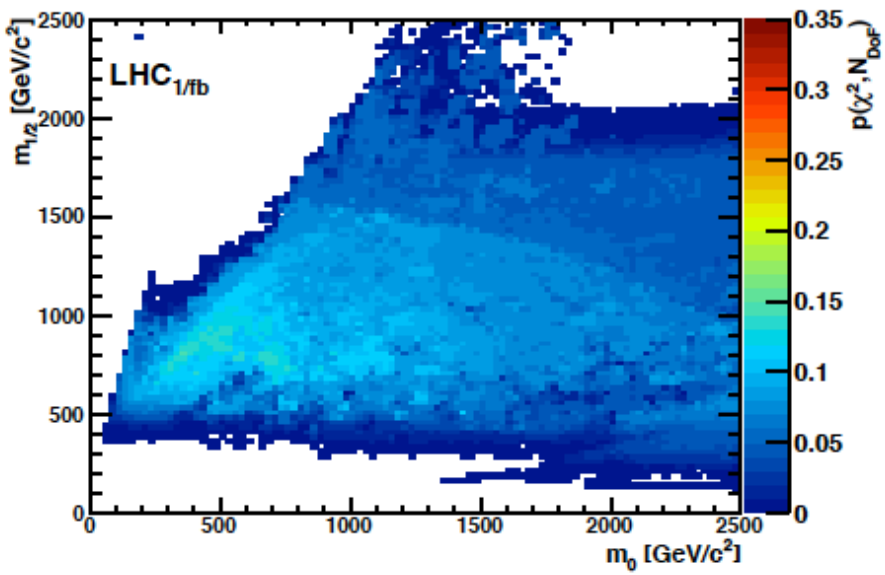
Impact of LHC Summer Results on SUSY

Simultaneous fit of CMSSM parameters m_0, $m_{1/2}$, A_0, tanβ (μ>0) to more than 30 collider and cosmology data (e.g. M_W, M_{top}, g-2, BR(B→Xγ), relic density)

"Predict" on the basis of present data what the preferred region for SUSY is (in constrained MSSM SUSY)



Buchmuller et al. arXiv 1110.2529



Include the 1 fb^{-1} SUSY searches (jet+MET), $B_s \rightarrow \mu\,\mu$ and XENON100

χ^2 probability: P(χ^2) for CMSSM

Before EPS/LP11: 43% Including EPS/LP11 results: <16%

LHC direct searches significantly constrain allowed CMSSM parameter space!

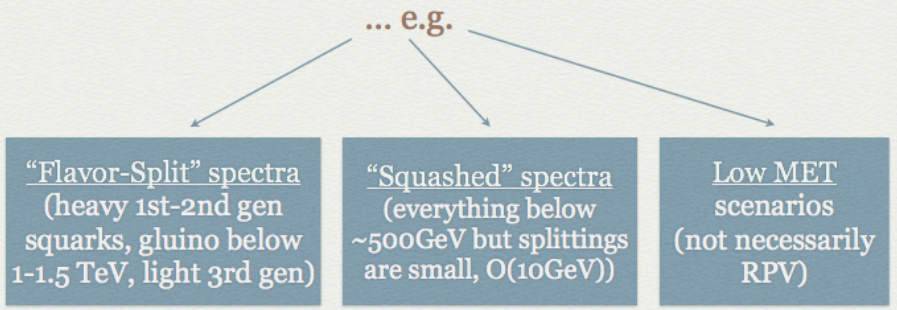
What is Next?

- Think beyond the simplest or most constrained models and optimize searches
  - pMSSM
  - NMSSM
  - Degenerate mass spectra
  - Light 3rd generation
  - Split SUSY
  - RPV SUSY
  - …
- How much of the "theory space" do we really cover? May have to revise our searches for other scenarios
- More ideas at the LPCC Workshop@CERN (Aug'11- June '12)

A lot!!

Missing something?

- Important to push limits up, but with more statistics more important to systematically close windows for light sparticles with suppressed xsec…



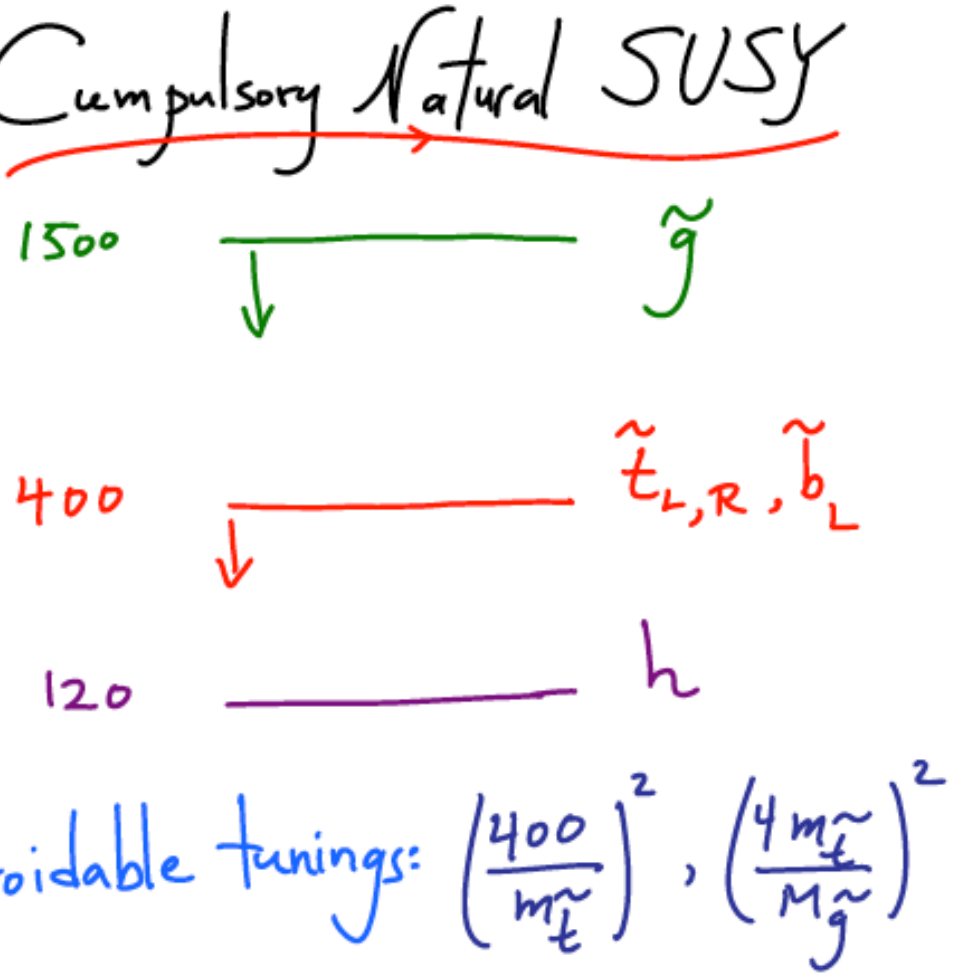
What is really needed from SUSY

N. Arkani-Ahmed
CERN 1/11/11

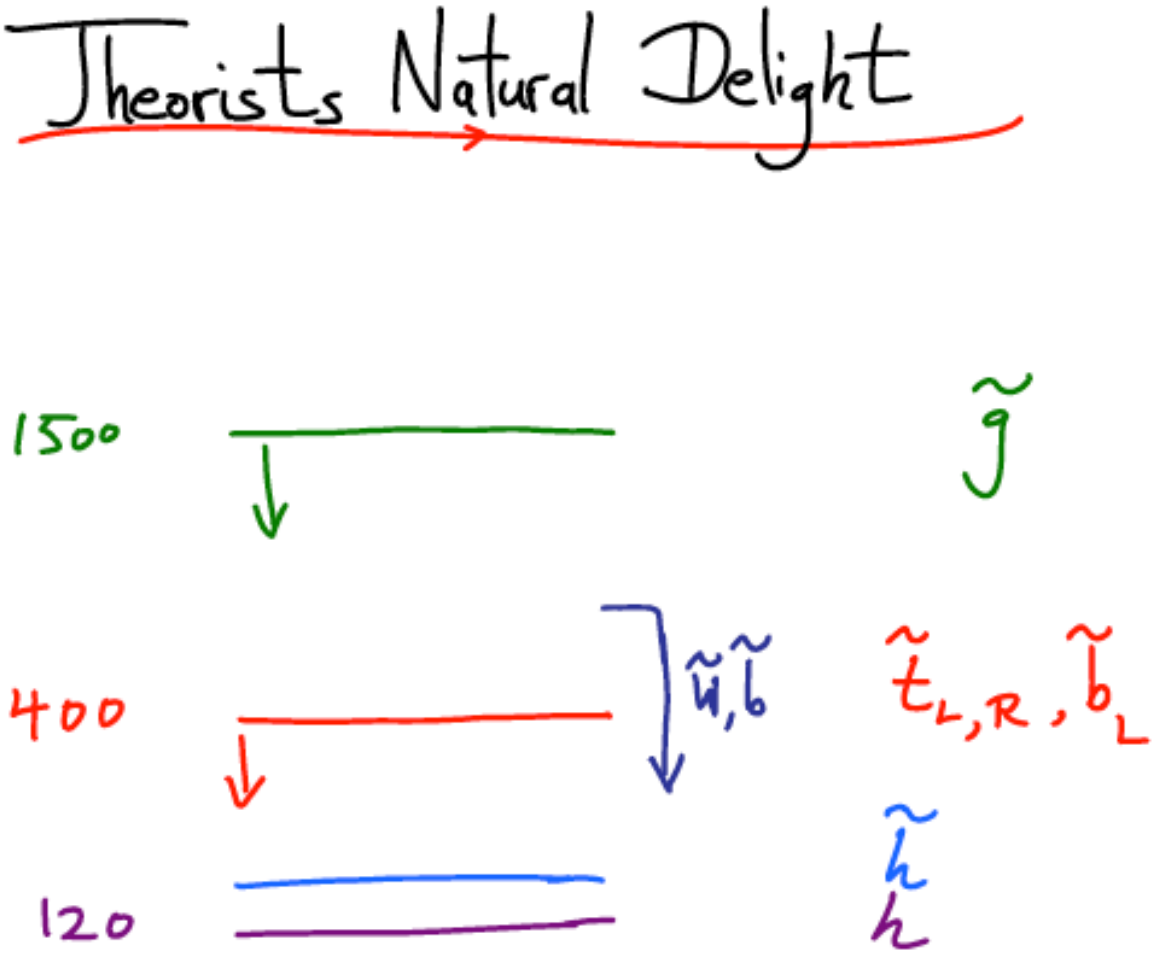
Papucci, Ruderman, Weiler arXiv:1110.6926

LHC data
Stops > 200-300 GeV
Gluino > 600-800 GeV

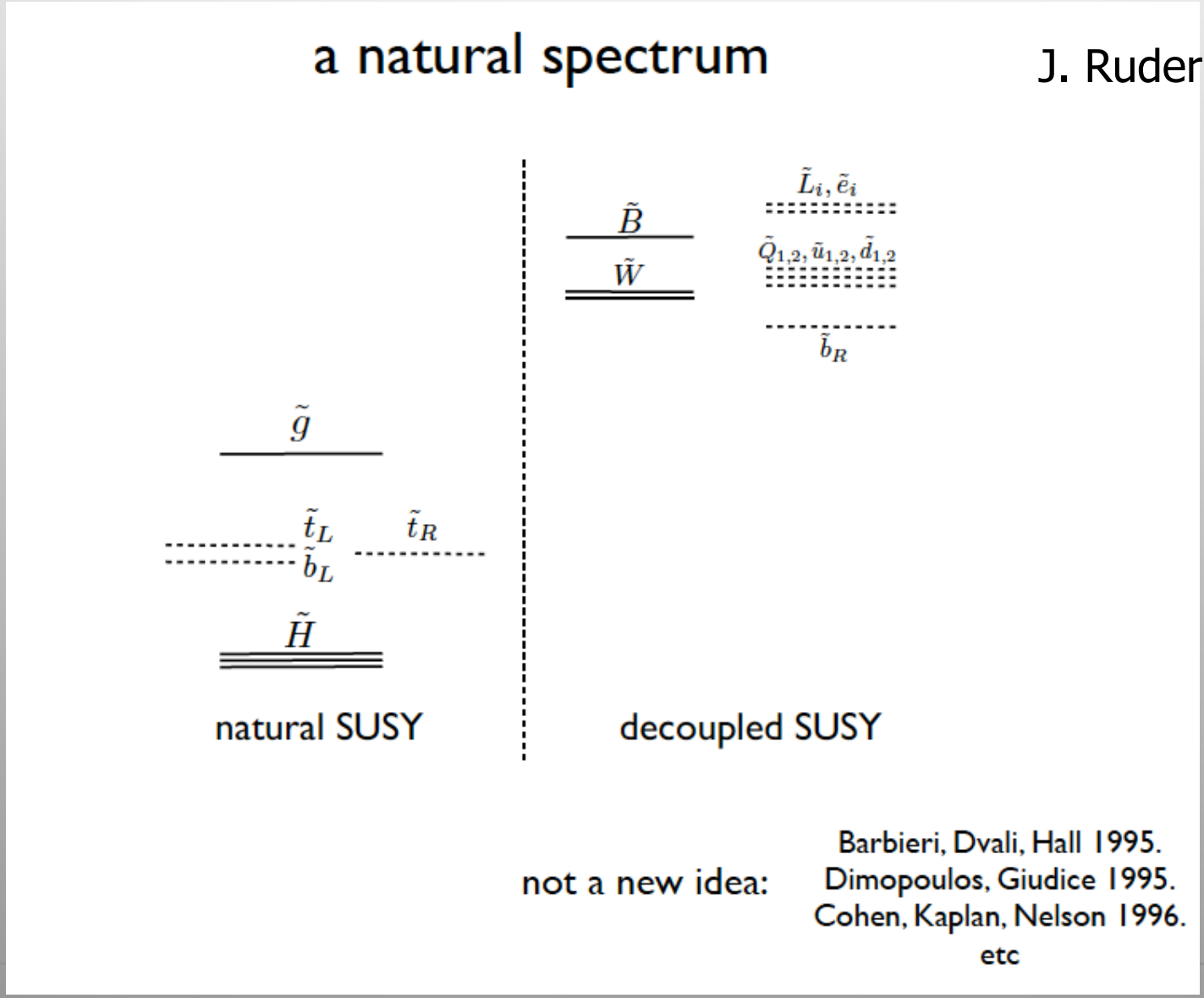
Natural SUSY survived LHC so far, but we are getting close



Beyond Minimal



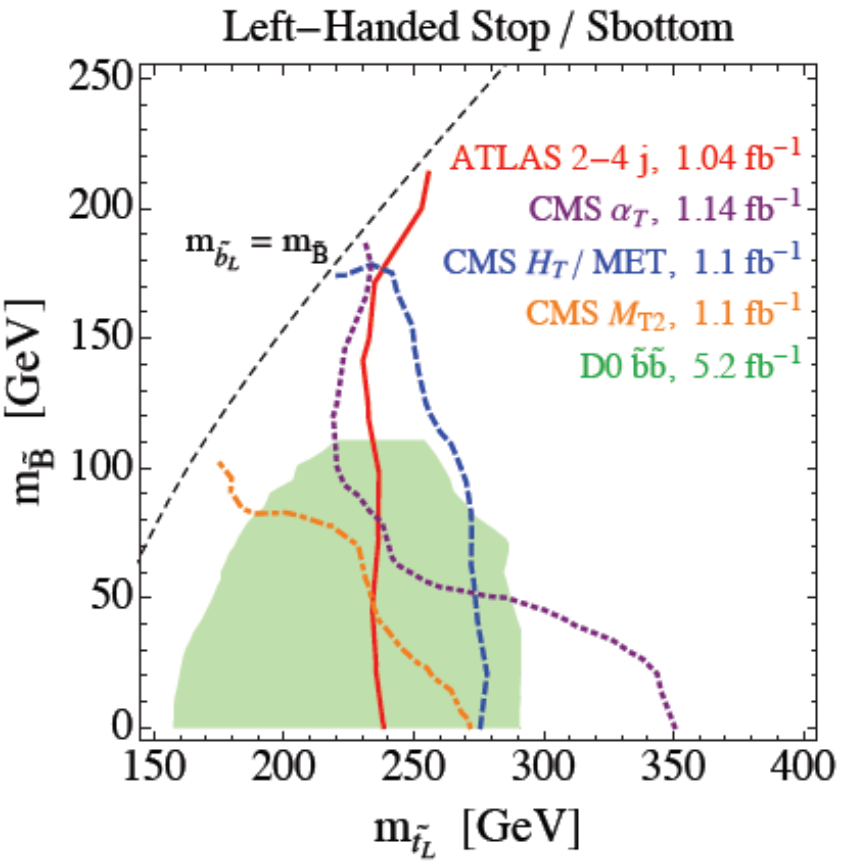
…Or as shown here…

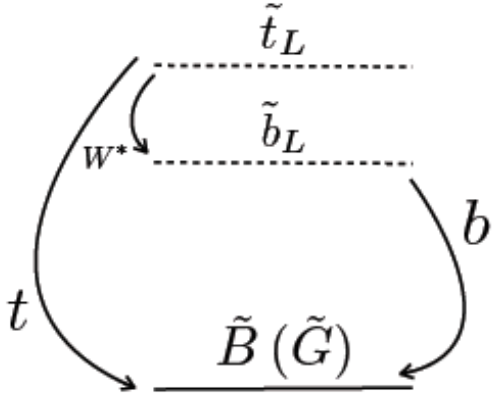


J. Ruderman

Recasting Published Analyses

(lefty) stop v bino

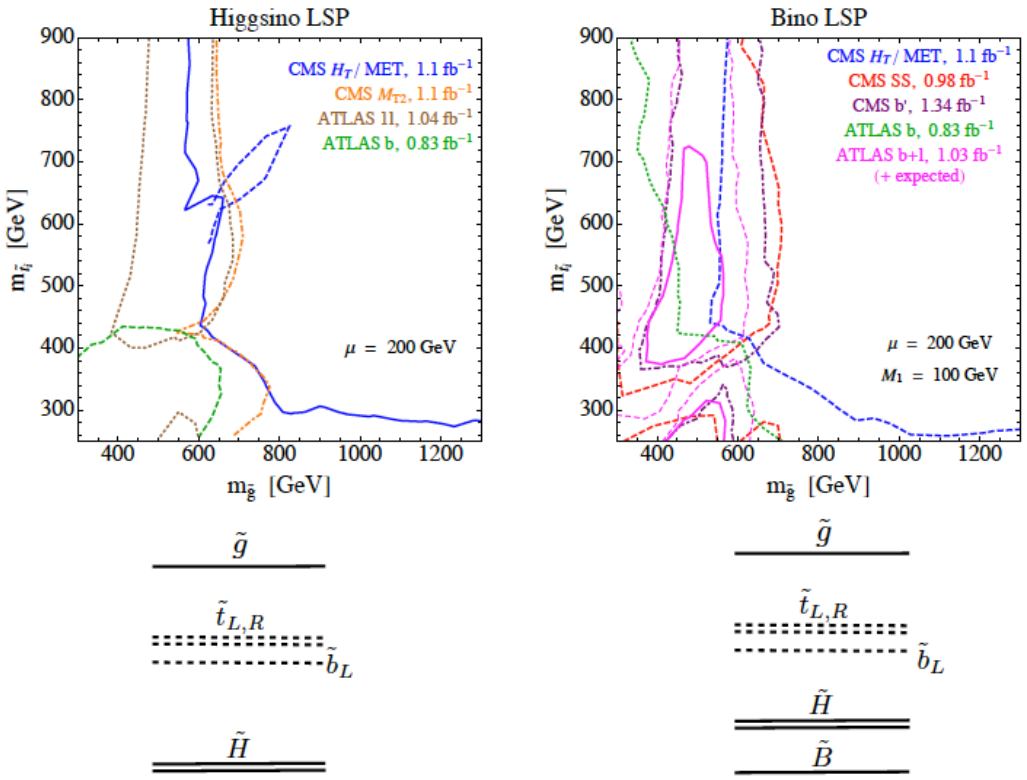




'Generic' analyses in the experiments have a say on this!

Recasting Published Analyses

gluinos decaying to stops and sbottom



- We find limits that are still consistent with ~1/3 fine tuning.

$$m_{\tilde{H}} \gtrsim 100 \text{ GeV}$$
$$m_{\tilde{t}} \gtrsim 300 \text{ GeV}$$
$$m_{\tilde{g}} \gtrsim 700 \text{ GeV}$$

So SUSY is Fine!

Somewhere between denial and anger right now…?

Model space coverage: pMSSM studies

Scan 10^7 pMSSM points with masses < 1 TeV and analyze "ATLAS" way

The Undiscovered SUSY
Why Do Models Get Missed by ATLAS?

Some of the most common contributing reasons are :

- small signal rates due to suppressed σ's which are possibly correlated with 'larger' sparticle masses
- spectrum forbids hard leptons in cascades & nj0l buried in systematics
- small mass splittings w/ the LSP (compressed spectra)
- decay chains long or ending in stable sparticles →low MET !
- inaccessibility of direct electroweak gaugino production
- will comment a bit about each of these

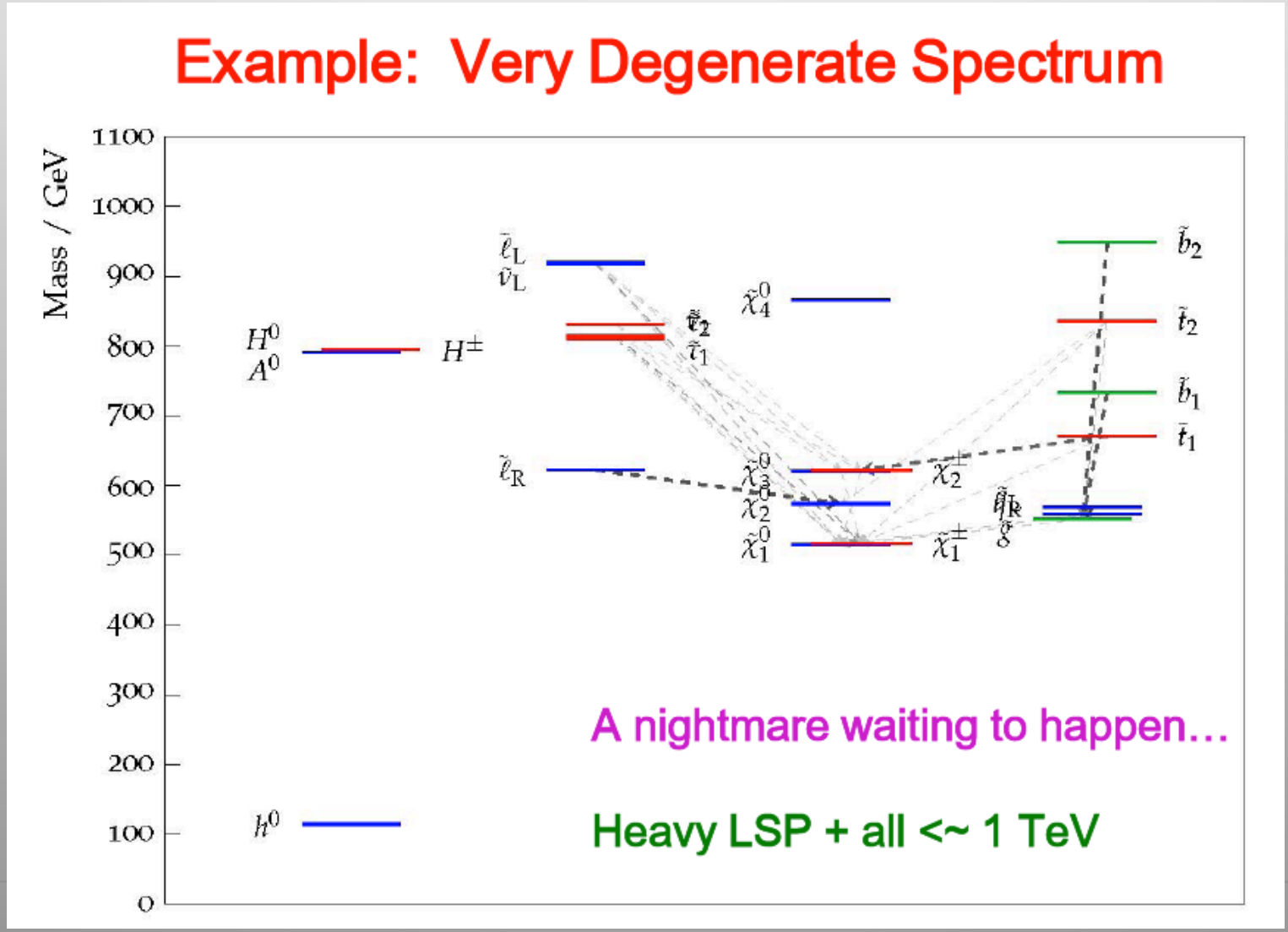
→ BUT there are many more subtle situations that have to be examined on a case-by-case basis

10

T. Rizzo et al.

Model space coverage: pMSSM studies

Example of a 'failure'

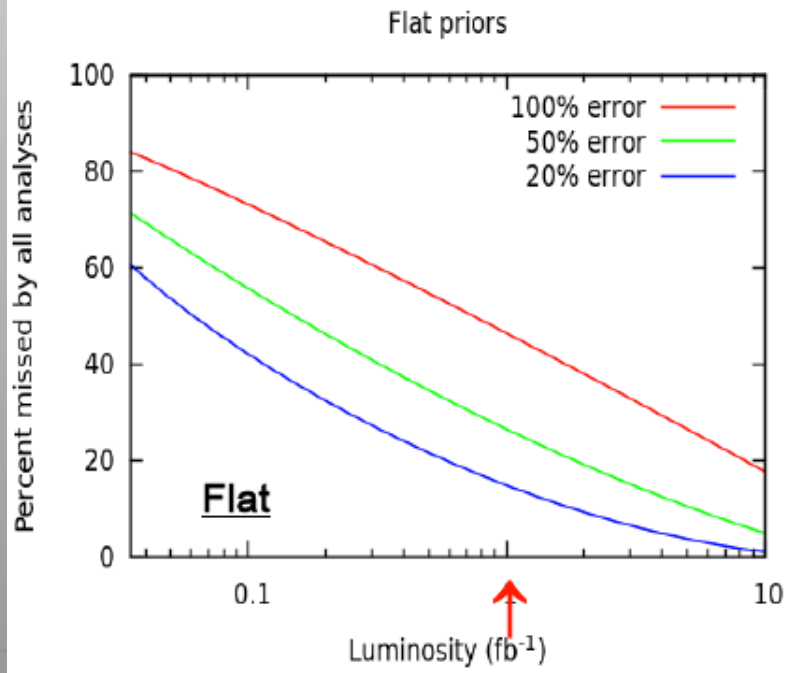


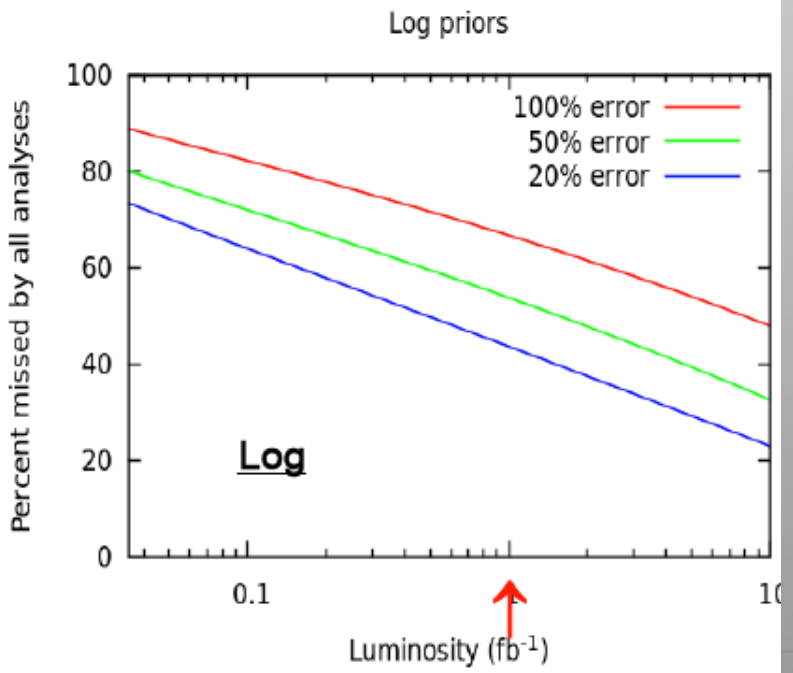
Model space coverage: pMSSM studies

Particles below 1 TeV

- What fraction of the model sets should not (yet) have been discovered ??

→ The coverage is quite good for both model sets !





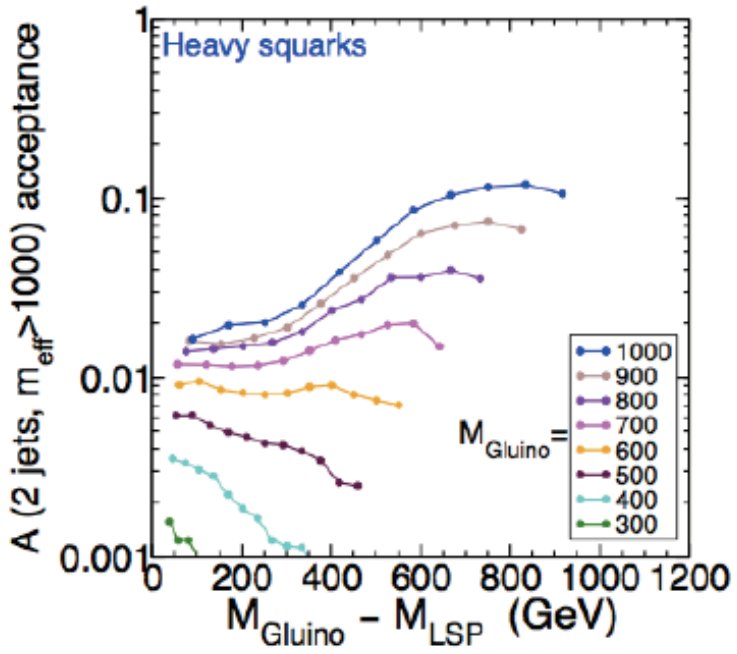
Compressed Spectra

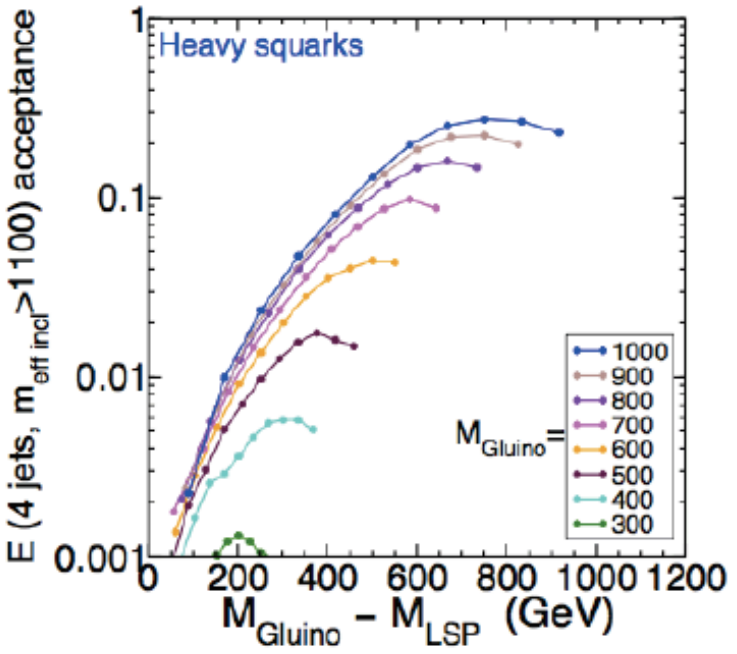
D. Stuart

Theory ideas: Compressed spectra

Steve Martin

For low compression, signal E (4 jets, inclusive m_{eff}) wins, but as the compression increases, B (3 jets) and then A (2 jets) take over.

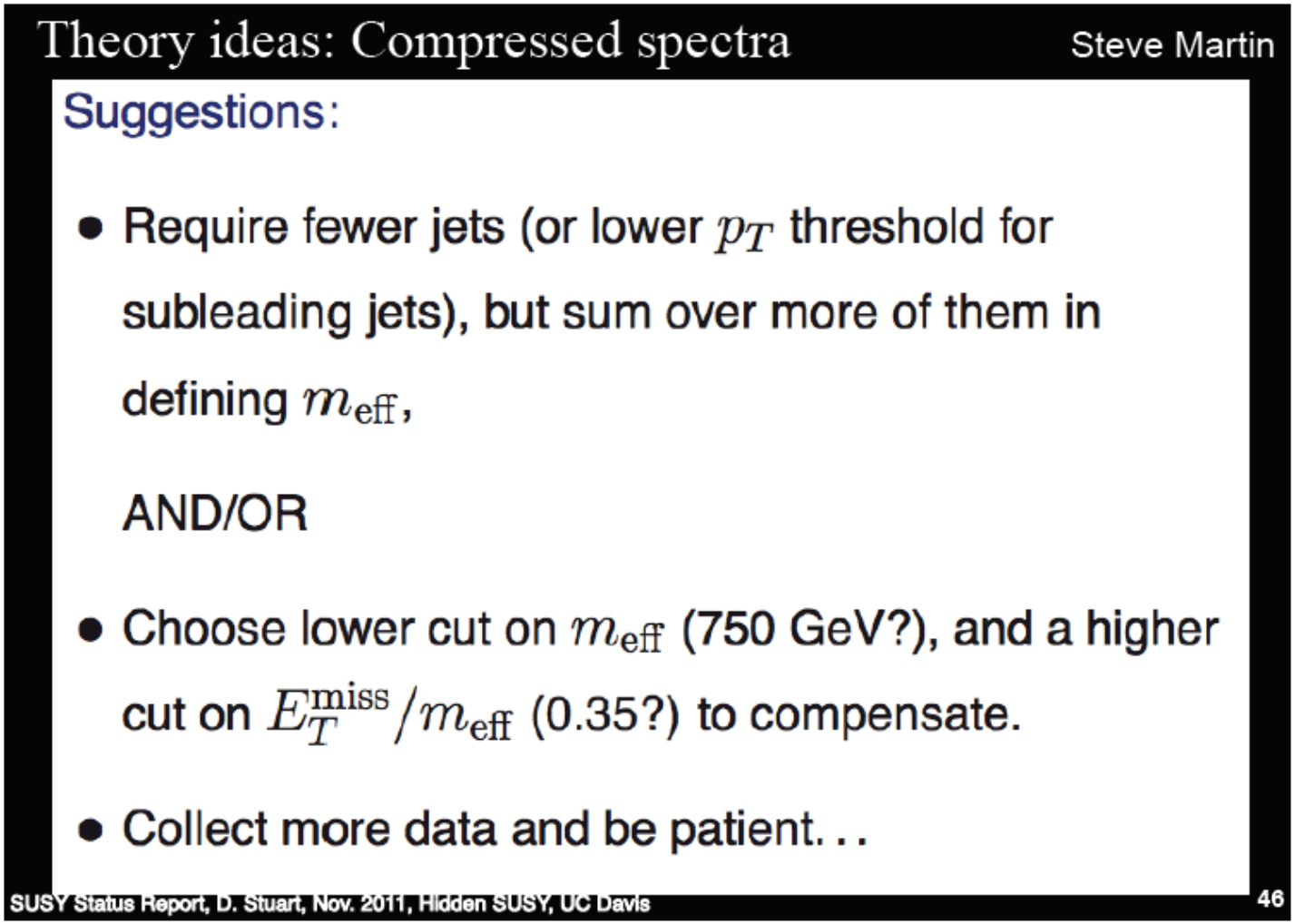




SUSY Status Report, D. Stuart, Nov. 2011, Hidden SUSY, UC Davis 44

Compressed Spectra

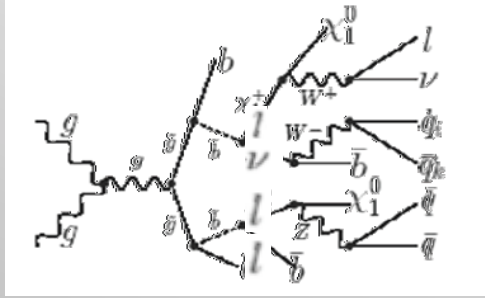
Rethink search strategies to optimize better for such scenarios

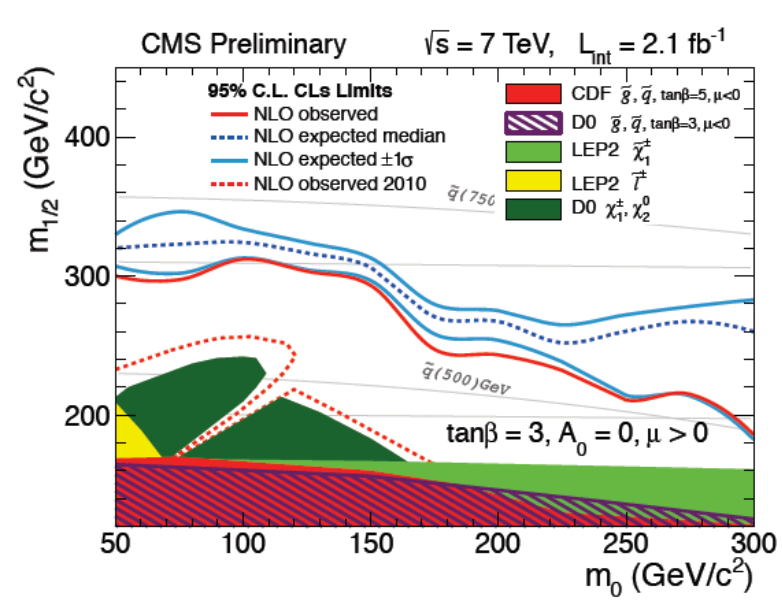


New Analyses…

Multi-leptons 3 or 4 leptons → 53 categories with low/high MET/HT, with or without Z veto

Multi-jets: 6 to 8 jets





Signal region	7j55	8j55	6j80	7j80
Multi-jets	26 ± 5.2	2.3 ± 0.7	19 ± 4	1.3 ± 0.4
$t\bar{t} \to q\ell, \ell\ell$	10.8 ± 6.7	$0^{+4.3}$	6.0 ± 4.6	$0^{+0.13}$
W + jets	0.95 ± 0.45	$0^{+0.13}$	0.34 ± 0.24	$0^{+0.13}$
Z + jets	$1.5^{+1.8}_{-1.5}$	$0^{+0.75}$	$0^{+0.75}$	$0^{+0.75}$
Total Standard Model	39 ± 9	$2.3^{+4.4}_{-0.7}$	26 ± 6	$1.3^{+0.9}_{-0.4}$
Data	45	4	26	3
$N^{95\%}_{\mathrm{BSM,max}}$	26.0	11.2	16.3	6.0
$\sigma^{95\%}_{\mathrm{BSM,max}} \times \epsilon$/fb	19.4	8.4	12.2	4.5
p_{SM}	0.30	0.36	0.49	0.16

Experiments push on…
More to come this winter!
Based on 4.7-5 fb^{-1} !!

Some small excesses in data in 3 lepton/Z veto channels but less than 2 σ significance

Searches for the Third Generation

- Extend the searches using also to leptons and jets coming from b-quarks
- Sensitive to different part of the SUSY phase space

$\tilde{g}\tilde{g}(production)$

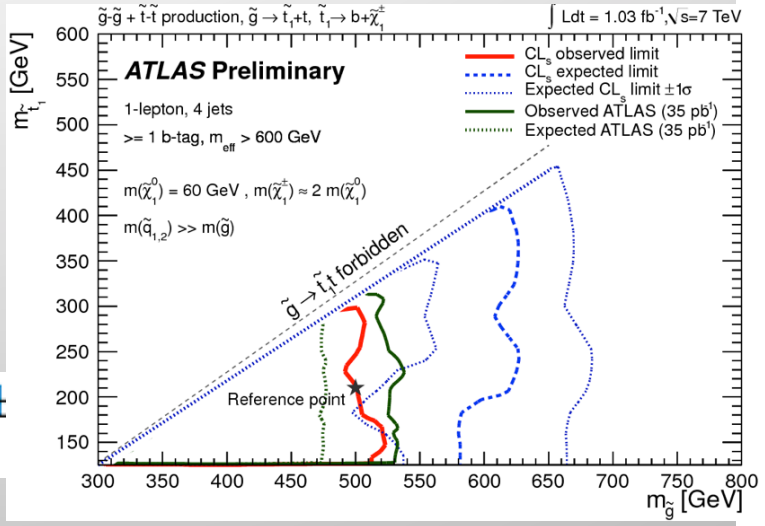
$\tilde{g} \rightarrow b\tilde{b}_1$

$\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$

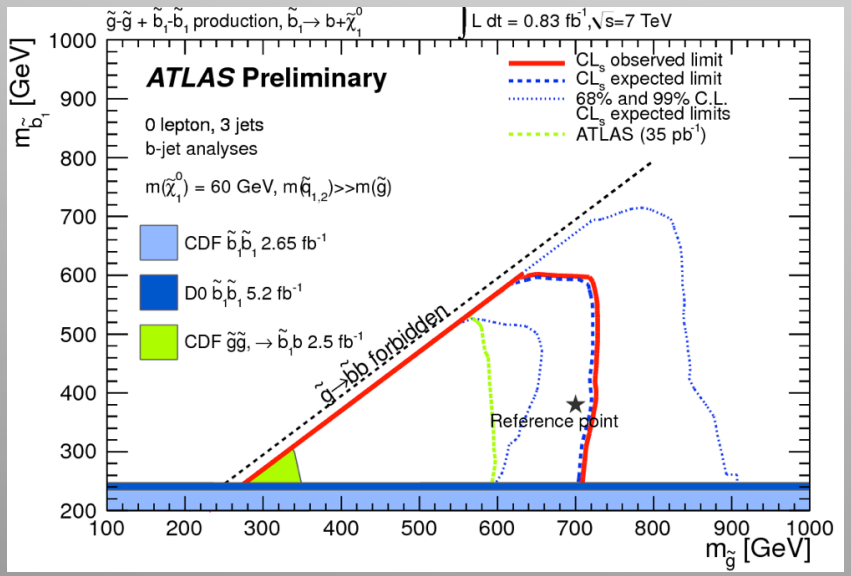
$\tilde{g} \rightarrow \tilde{t}_1 t$

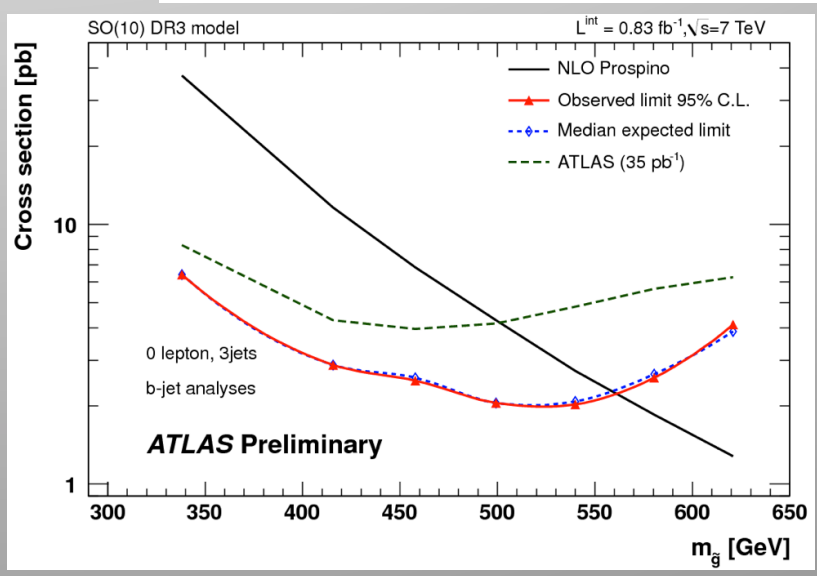
$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$

ATLAS-CONF-2011-130



ATLAS-CONF-2011-98



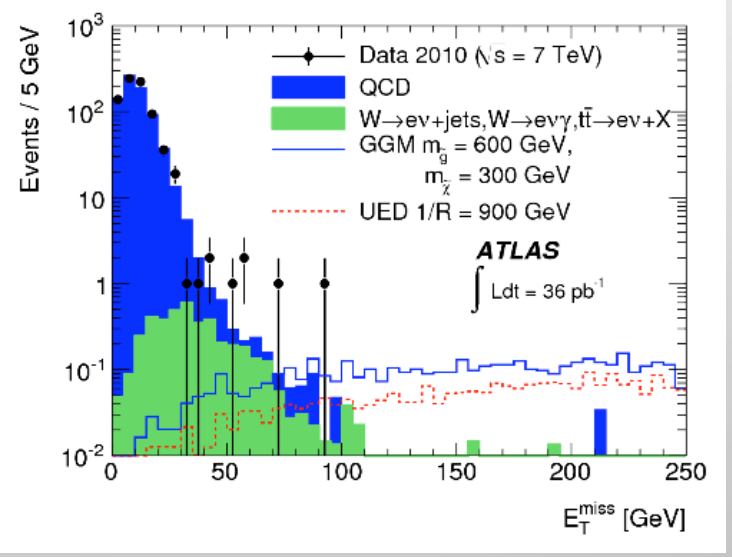


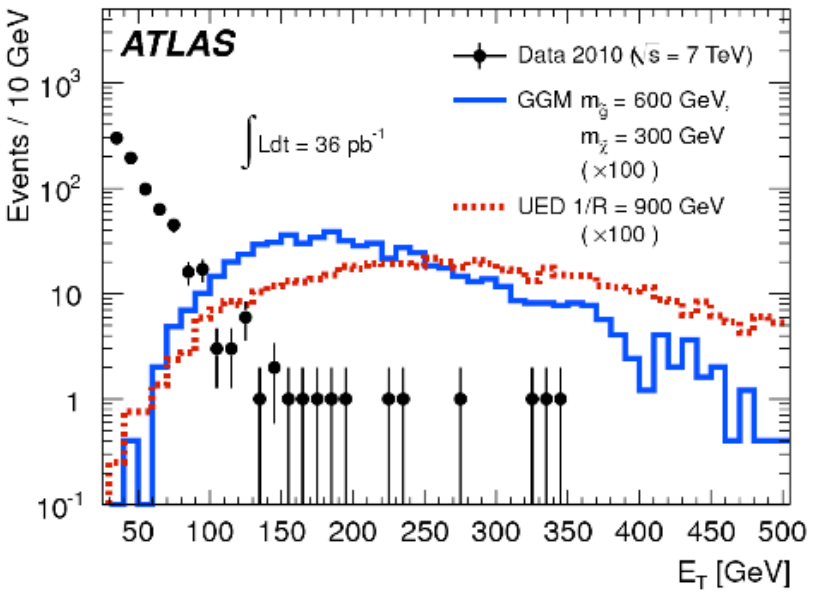
Gluinos have to be heavier than ~ 550 GeV from this search

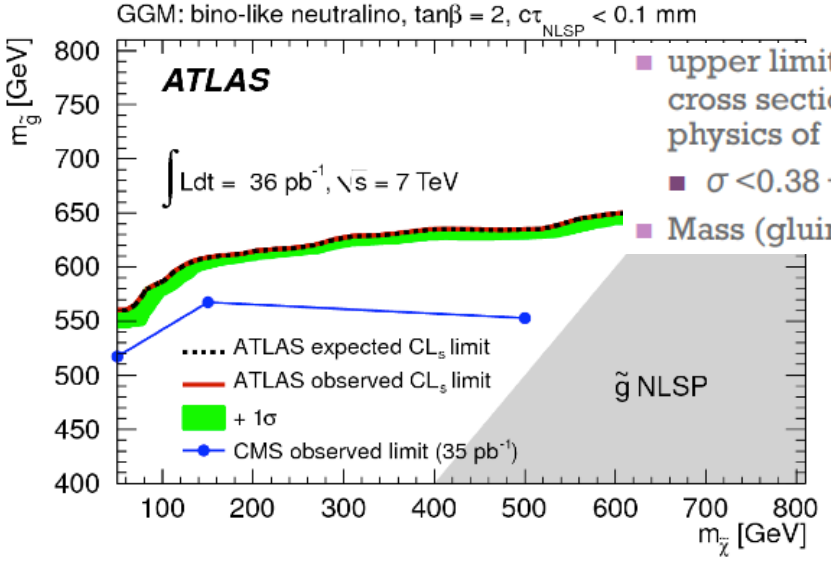
Search for Gauge Mediated SUSY

$$\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$$

- 2 photons (p_T>30,20GeV)
- E_T^{miss} > 125 GeV
- N_{signal}=0
- $N_{background}$=0.10 ±0.04(stat) ±0.05(syst)

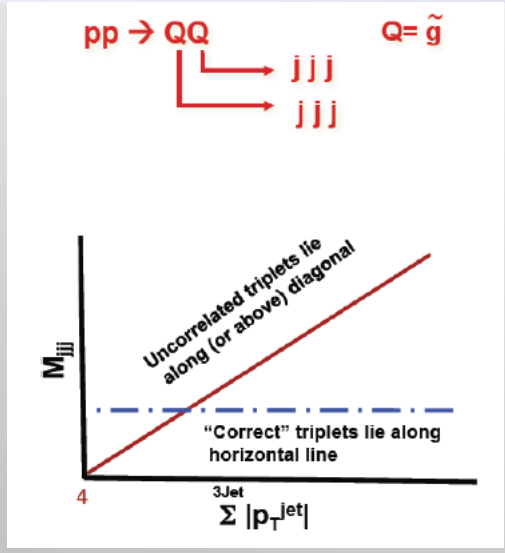






- upper limit is set on the cross section for new physics of
  - σ <0.38 –0.65pb.
- Mass (gluinos)>560 [GeV]

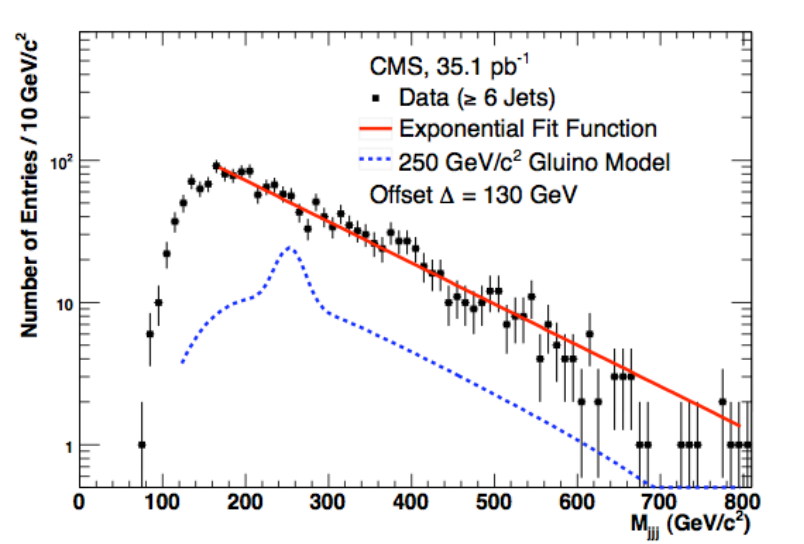
RP Violating SUSY Searches

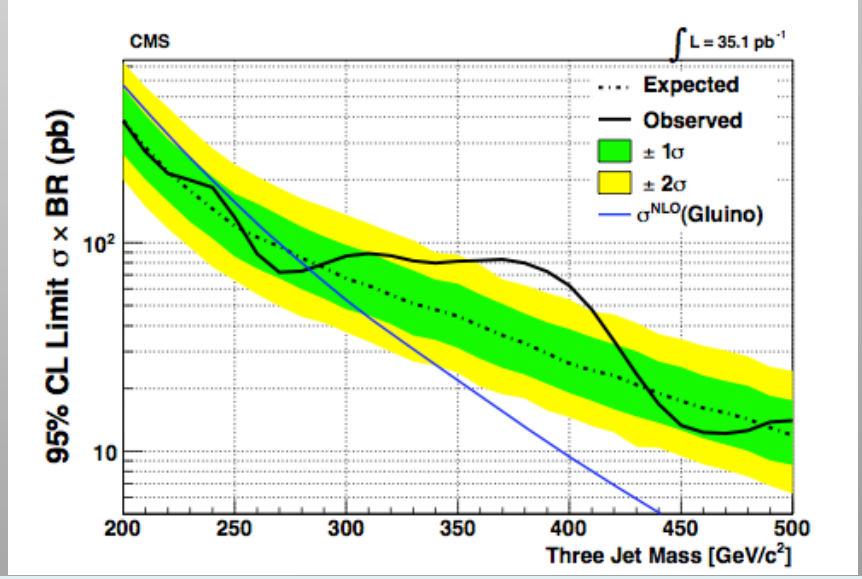


Sparticle decays into 3 jets

- Use a diagonal cut to remove combinatorial background as well as QCD background:
  - $m_{jjj} < \Sigma\ |p_T(\text{triplet})| - \alpha\ (\text{Offset})$

arXiv:1107.3084



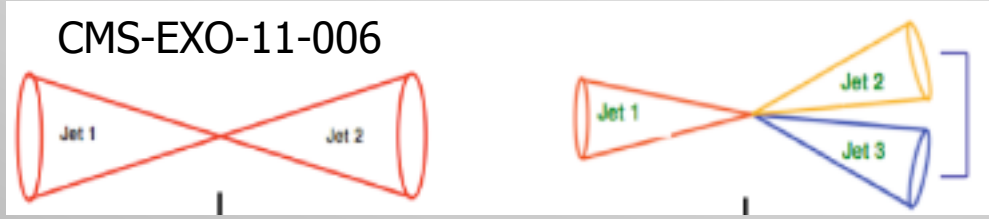


No signal for gluino masses up to 280 GeV

High mass excursion is less than 2σ taking into account look elsewhere effect

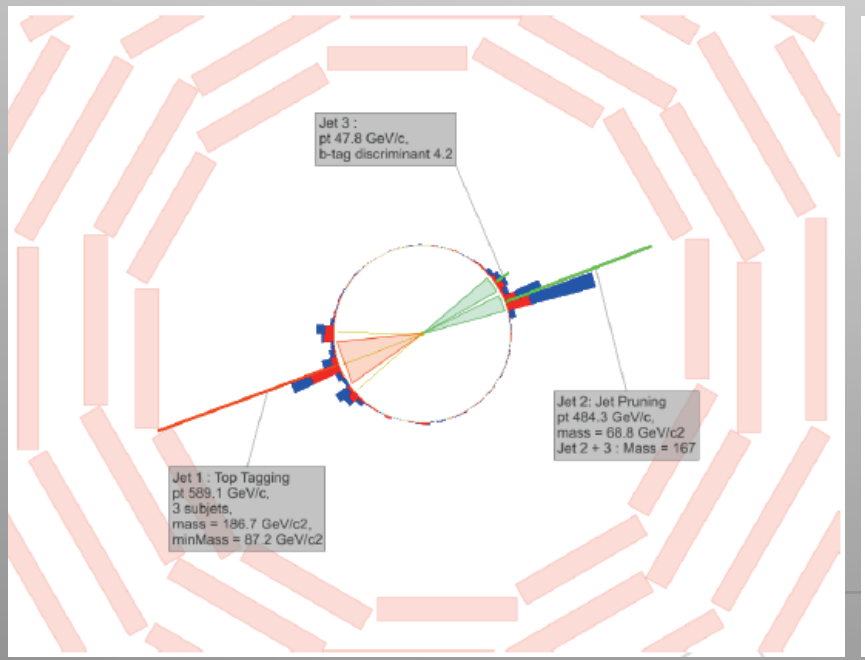
Z' → tt Search

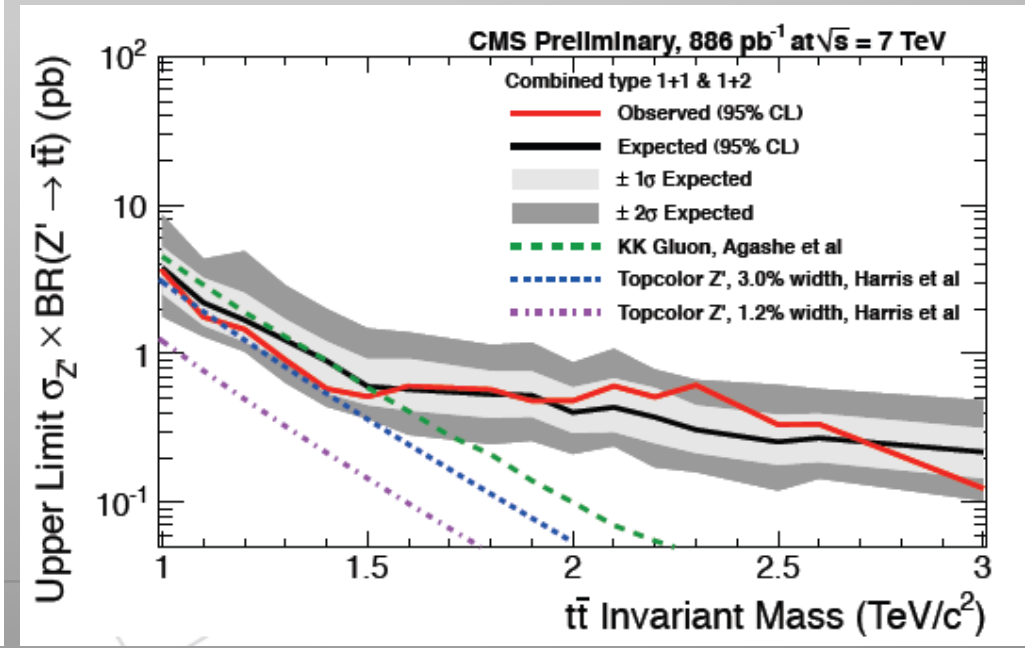
- Search in the all hadronic decay channel for the tops
- Tops are boosted for high mass Z', jets merge
- Start from Cambridge-Aachen FAT jets and apply jet pruning to find sub-jets
- QCD background estimate from data (mistag method)



Particle flow an asset for this study!

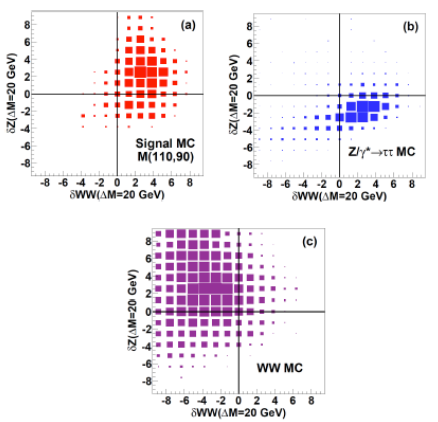
Exclude KK-Gluons 1<M<1.5 TeV

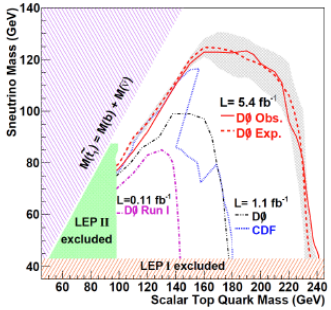




Light Top NLSP in GMSB model

D. Shih





D0 publication did not provide enough information (e.g. the definition of these discriminants) to allow us to reinterpret this search.

It would be very interesting for D0 to apply this analysis to stop NLSP, it could a strong limit!!

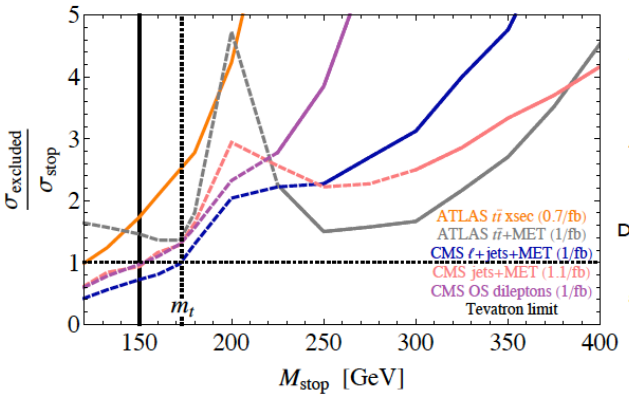
$\tilde{t} \to t + \tilde{G} \quad (m_{\tilde{t}} > m_t)$

$\tilde{t} \to W^+ + b + \tilde{G} \quad (m_{\tilde{t}} \lesssim m_t)$

"Stop NLSP"

Results: LHC

(Kats, Meade, Reece, DS 1110.6444)



ATLAS ttbar+MET will have good coverage over widest range of stop mass.

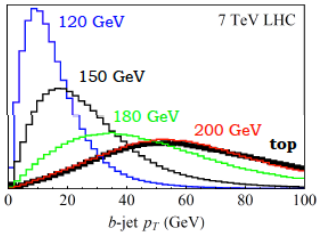
A surprise: a number of 1/fb SUSY searches could be sensitive to light stops!

Dashed lines indicate ultra-low acceptances (~10^{-4}-10^{-3}) where we don't trust our simulation of the signal tails.

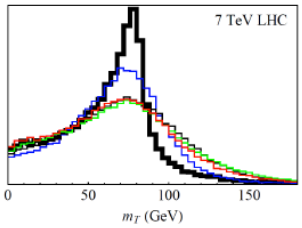
There are still no firm LHC limits on direct stop pair production. Stop could still be lighter than the top???!

Suggestions for future analyses

The *b*-jets from light stops are soft:



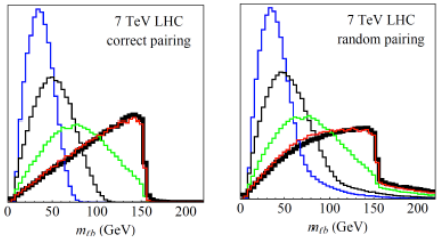
The transverse mass of the W is a good discriminator:



The lepton-*b* invariant mass has been suggested a while ago but *never used*.

Chou and Peskin
PRD 61 (2000) 055004; hep-ph/9909536

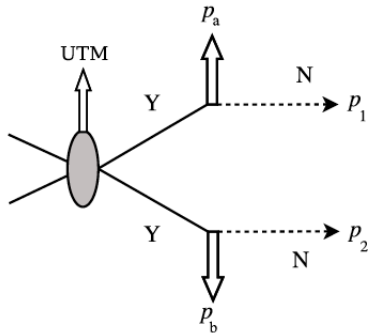
You don't even have to get the combinatorics right:



Suggestions: leptonic MT2

(for details, see 1110.6444)

- mT2: generalization of W transverse mass to events with double decay chains ending in invisible particles.
  (Barr, Lester, Stephens, Summers, ...)
- mT2 has been used for measurements of top properties, but in all cases, the full event was used (leptons+bjets+MET). Expect an endpoint at the top mass, but combinatorics is an issue.
- ttbar is the dominant background to stop NLSP, especially at the LHC. We propose computing mT2 using only the leptons and MET to reject ttbar background. Expect an endpoint at W mass and no combinatorial confusion.



(figure from Cheng & Han 0810.5178)

Collective RPV

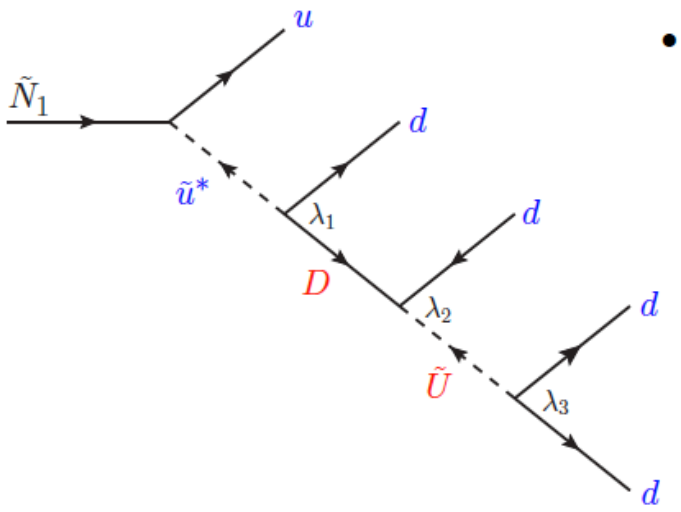
RPV through interaction with new fields

J. Ruderman

collective RPV

$$W \supset \lambda_1\, udD + \lambda_2\, UdD + \lambda_3 Udd$$

- any decay from a superpartner to SM fields must use all three couplings



- but only one couplings needs to be probed at a time, if the decays are sequential

$$m_{\tilde{N}_1} > m_D > m_{\tilde{U}}$$

Expect many objects
Soft?

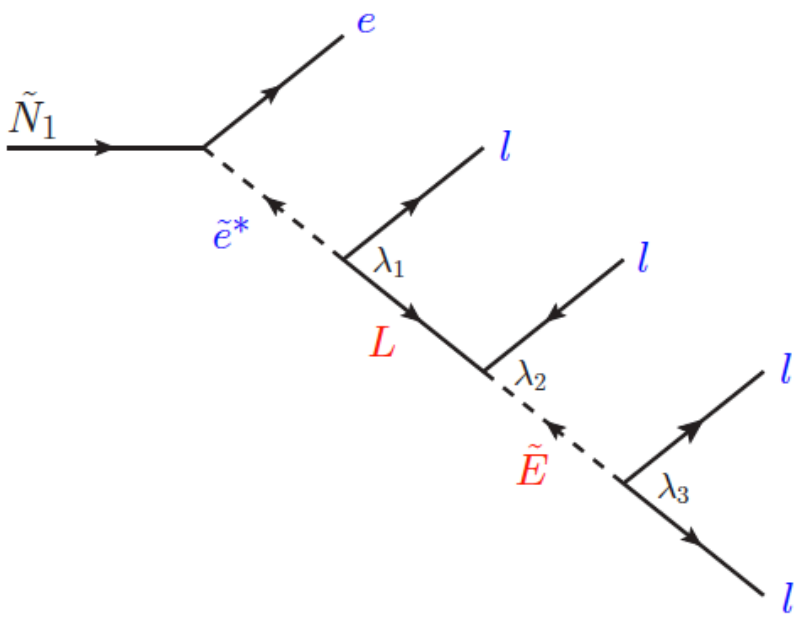
- probing more couplings means higher-multiplicity final states:

$$\tilde{N}_1 \to 5j$$

Collective RPV

there are many other ways to implement cRPV

$$W \supset \lambda_1 llE + \lambda_2 LlE + \lambda_3 Lle$$



a lepton factory!

$$\tilde{N}_1 \to 4l + 1\nu$$
$$2l + 3\nu$$

4, 6, 8 leptons per event

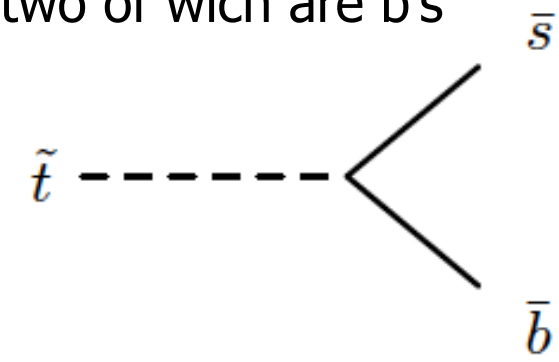
MFV SUSY

B. Heidenreich

LSP

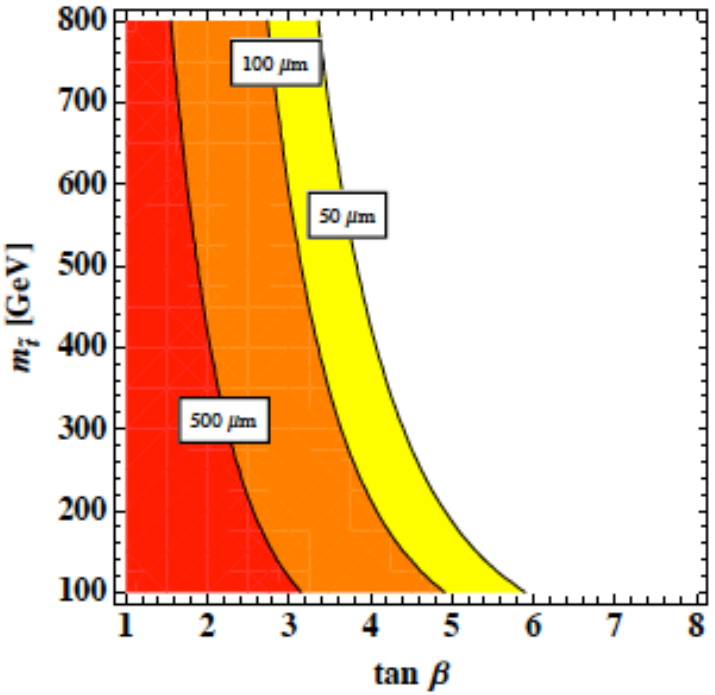
- LHC pheno will depend on LSP
- LSP not stable: can be charged, colored!
- Up-type squarks: $M^2_{\tilde{U}} = m^2_{\text{soft}} \begin{pmatrix} 1 + \alpha Y_u Y_u^\dagger + \beta Y_d Y_d^\dagger & \delta\, Y_u \\ \delta^\star\, Y_u^\dagger & 1 + \gamma Y_u^\dagger Y_u \end{pmatrix} + \dots$
- Down-type: $M^2_{\tilde{D}} = m^2_{\text{soft}} \begin{pmatrix} 1 + \alpha' Y_u Y_u^\dagger + \beta' Y_d Y_d^\dagger & \delta'\, Y_d \\ \delta'^\star\, Y_d^\dagger & 1 + \gamma' Y_d^\dagger Y_d \end{pmatrix} + \dots$
- One stop naturally light; $\tilde{b}_L$ also possible LSP
- stau LSP $\longrightarrow$ nearly degenerate spectrum
- Neutralino, chargino, gluino also possible LSPs

4 jets, two of wich are b's



$$c\tau_{\tilde{t}} \sim (2\ \mu\text{m}) \left(\frac{10}{\tan\beta}\right)^4 \left(\frac{300\ \text{GeV}}{m_{\tilde{t}}}\right) \left(\frac{1}{2\sin^2\theta_{\tilde{t}}}\right)$$

$$90\%\ b+s,\ 8\%\ b+d,\ 2\%\ d+s$$



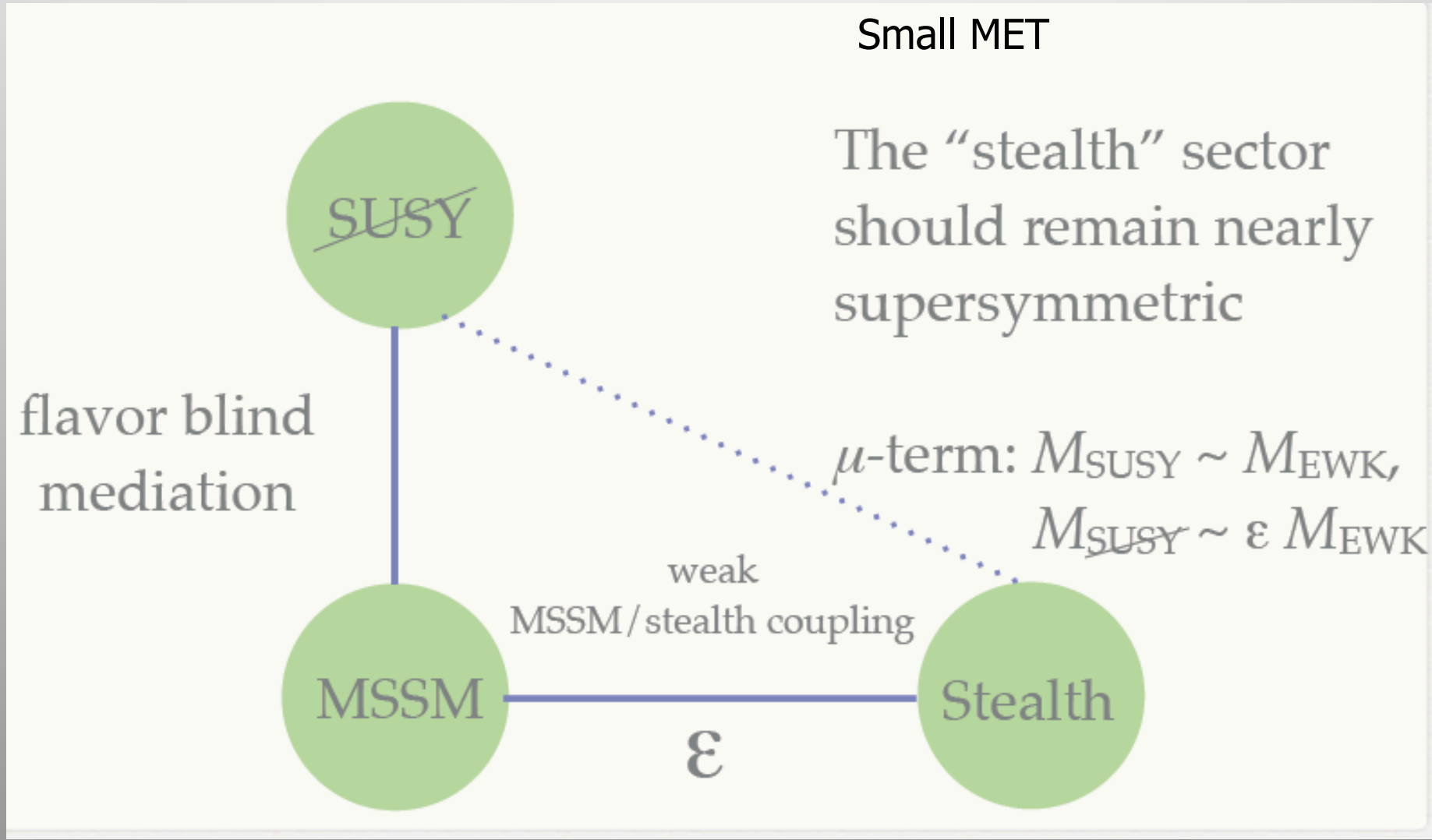
- Generically prompt (no $\not{E}_T$, no displaced vertices)
- No tops / leptons in final state. . . more b-jets, resonance?

Channels with top also possible

Stealth SUSY

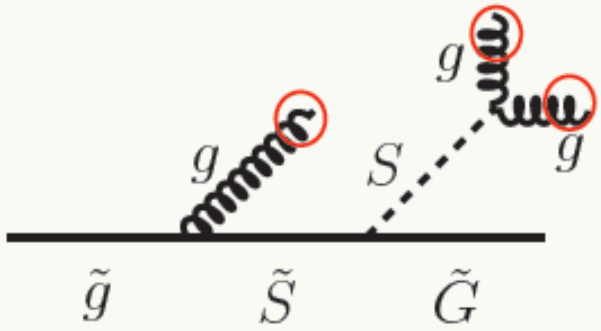
M. Reece

Small MET

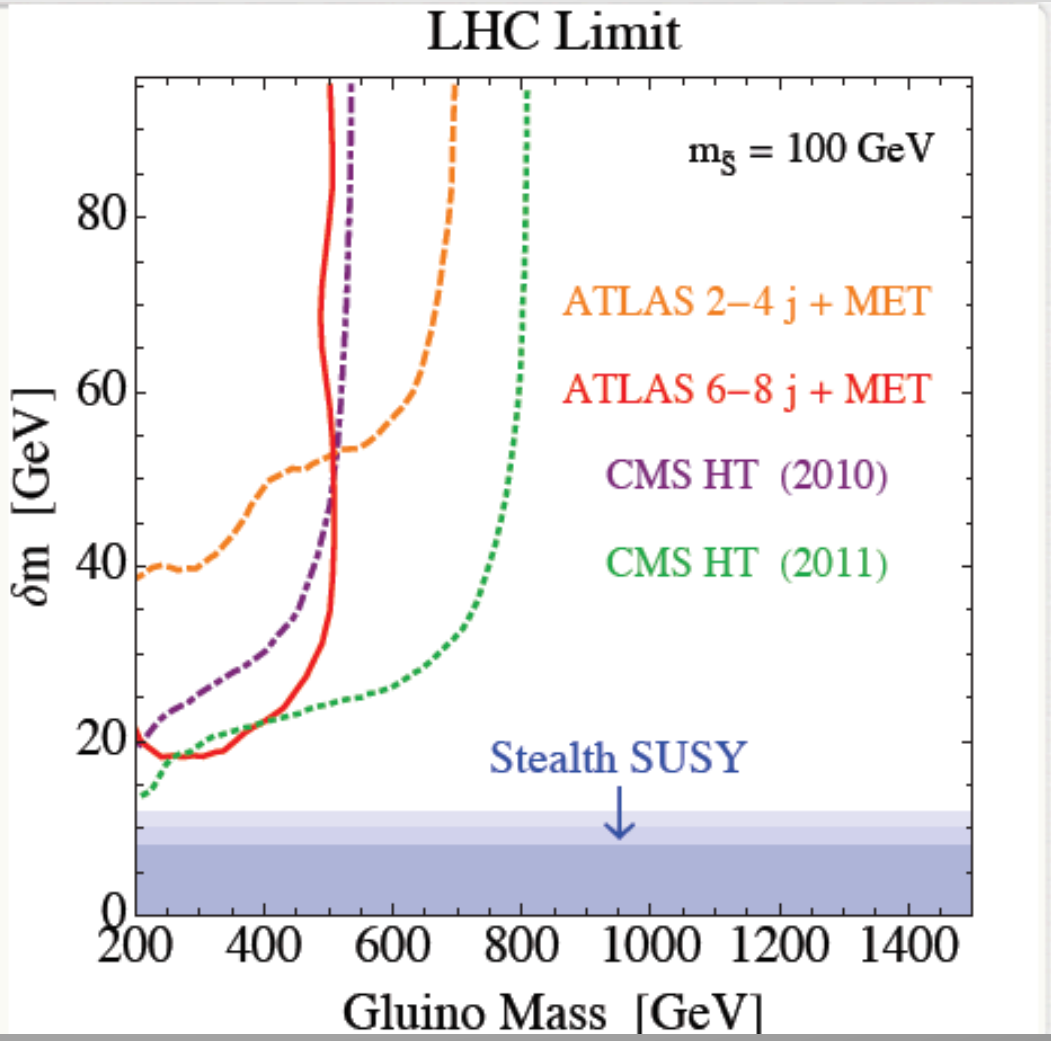


Stealth SUSY

- Gluino LVSP
- 6-jet Final States
- Low missing E_T



- *False resonances*



Long Lived Particles

Split Supersymmetry

- Assumes nature is fine tuned and SUSY is broken at some high scale
- The only light particles are the Higgs and the gauginos

- Gluino can live long: sec, min, years!

- R-hadron formation (eg: gluino+ gluon): slow, heavy particles

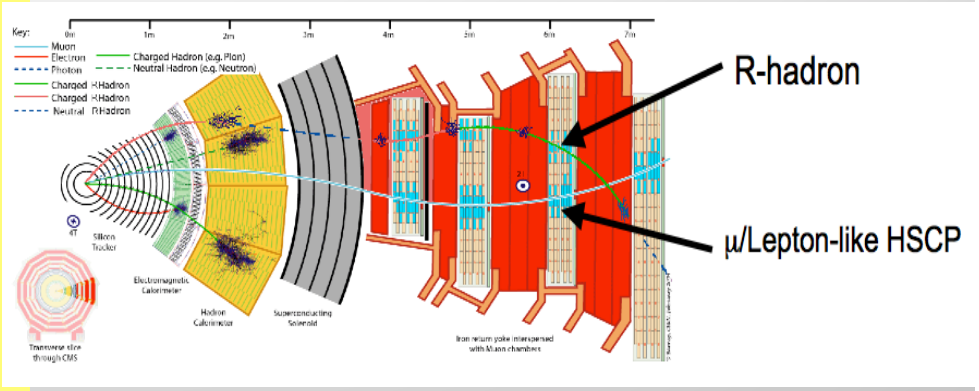
Unusual interactions with material

eg. with the calorimeters of the experiments!

Gravitino Dark Matter and GMSB

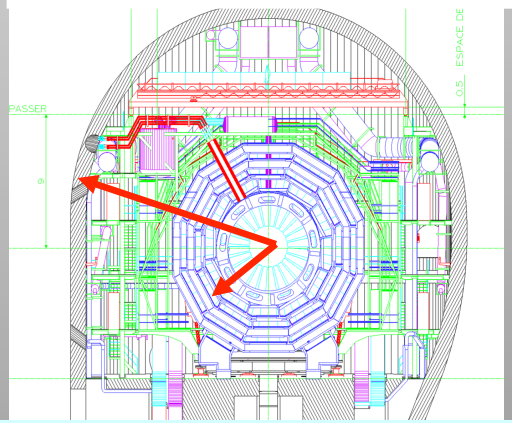
- In some models/phase space the gravitino is the LSP
- ⇒ NLSP (neutralino, stau lepton) can live 'long'.. Displaceded vertices
- ⇒ non-pointing photons

Hidden Valleys , RPV,…



⇒Challenge to the experiments!

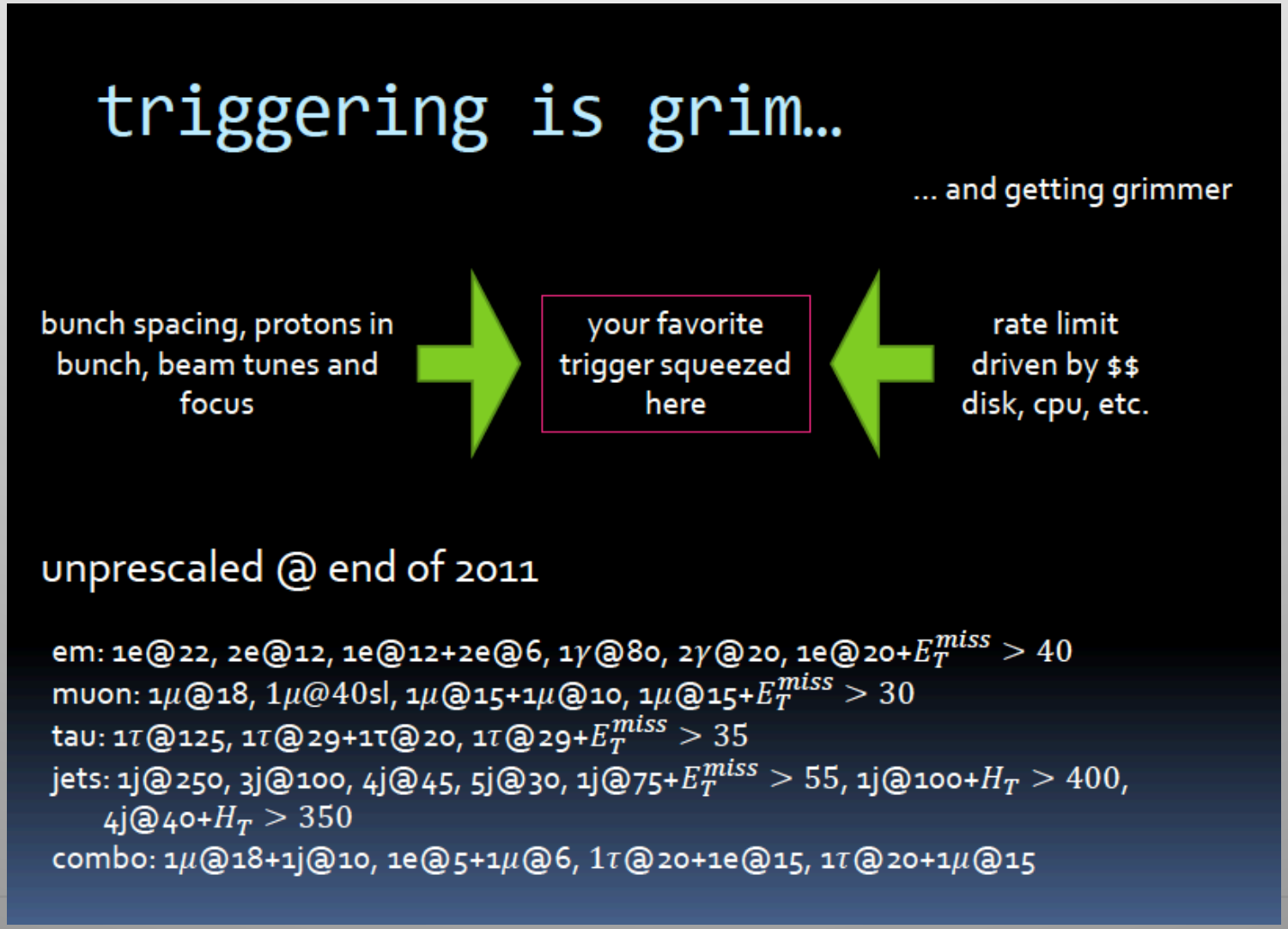
K. Hamaguchi,M Nojiri,ADR hep-ph/0612060
ADR, J. Ellis et al. hep-ph/0508198



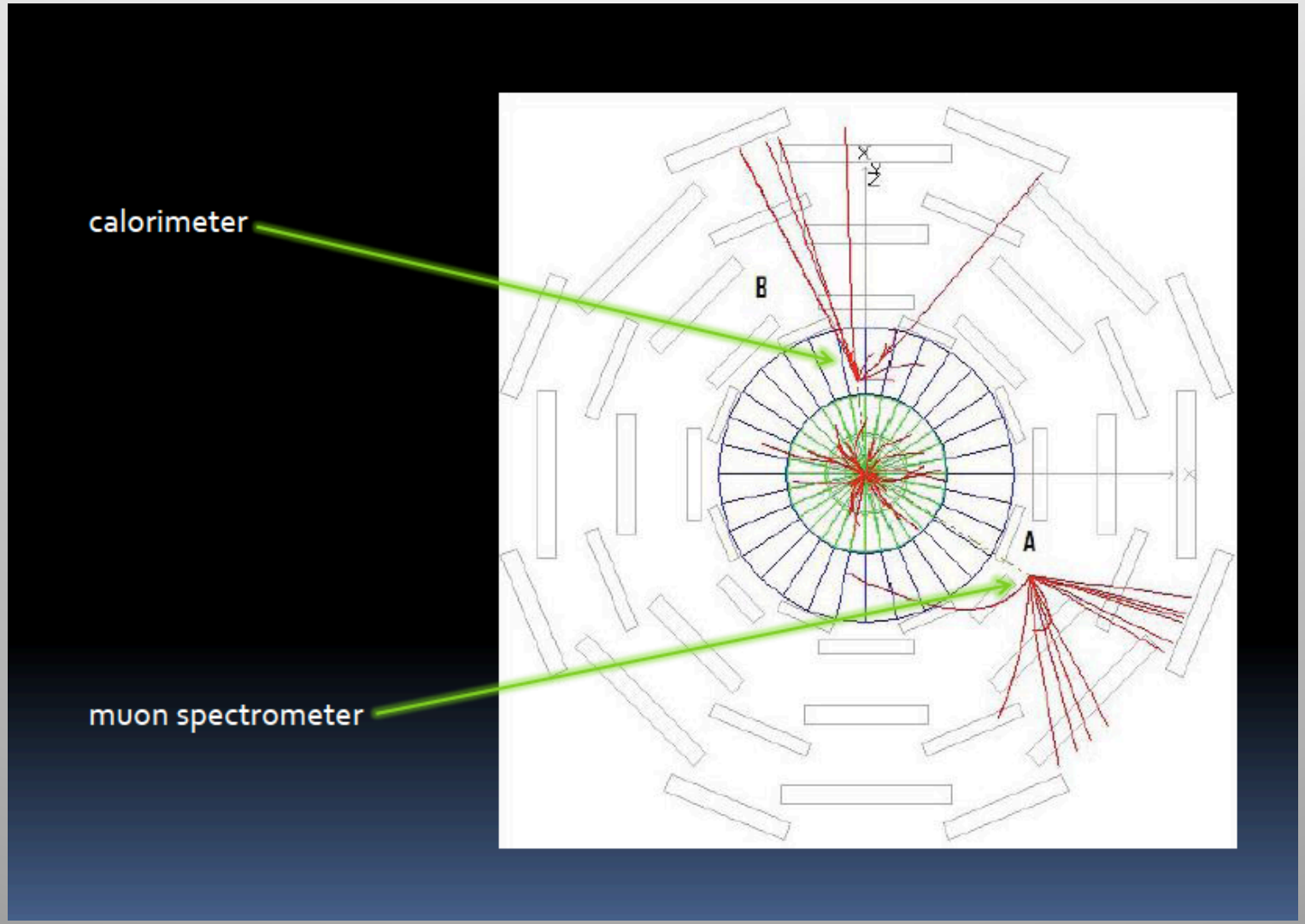
Sparticles stopped in the detector,walls of the cavern, or dense 'stopper' detector. They decay after hours---months…

Triggers….

G. Watts



“Hidden Valley”-like triggers

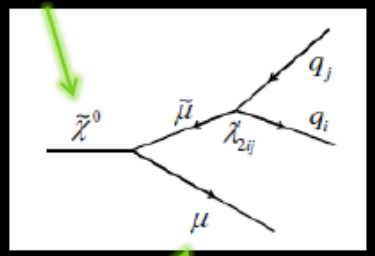


Maybe SUSY/New Physics is “hidden” in such topologies

scale [2]. Additional scenarios allowing for such a signature include split-supersymmetry [3], hidden-valley [4], dark-sector gauge bosons [5], stealth supersymmetry [6], or a meta-stable supersymmetry-breaking sector [7].

displaced vertices

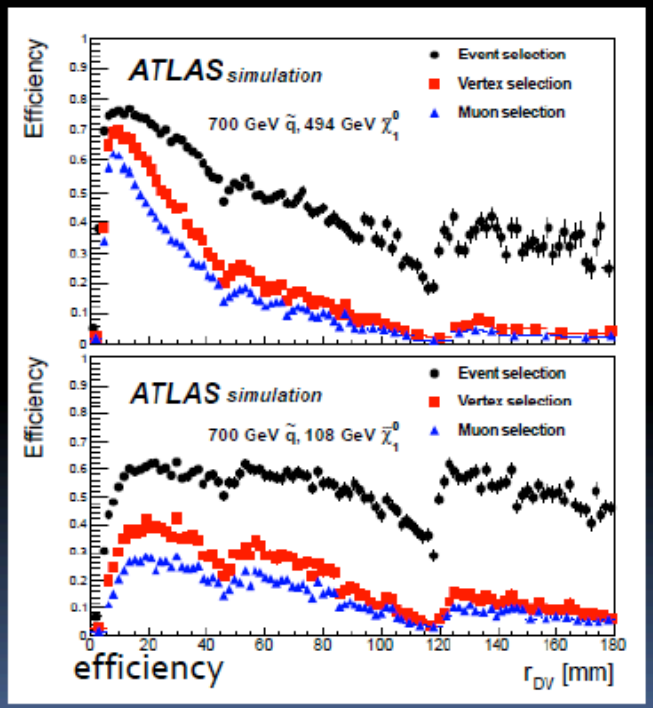
displaced vertex



trigger

SUSY++

L=33 pb^{-1}

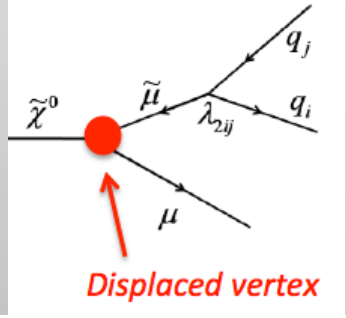


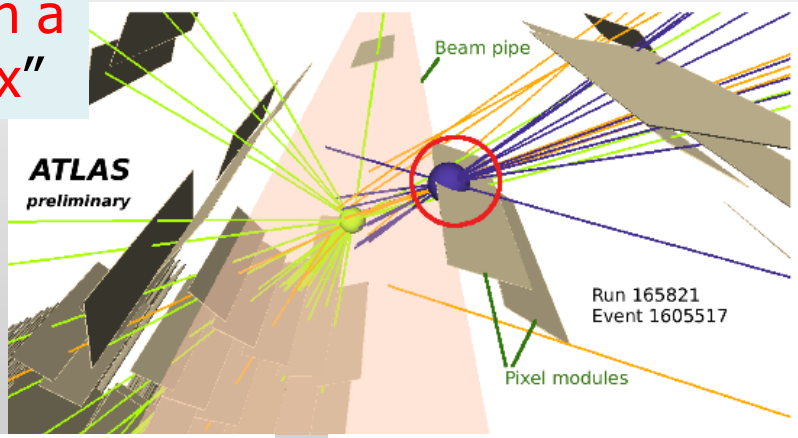
vertex reconstruction

- standard
- use tracks that have no pixel hits
- reject vertices near material

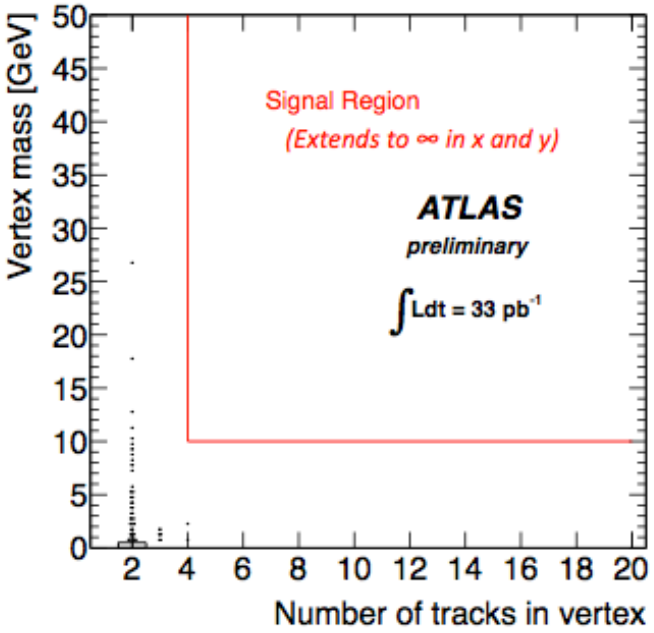
Search for RPV SUSY

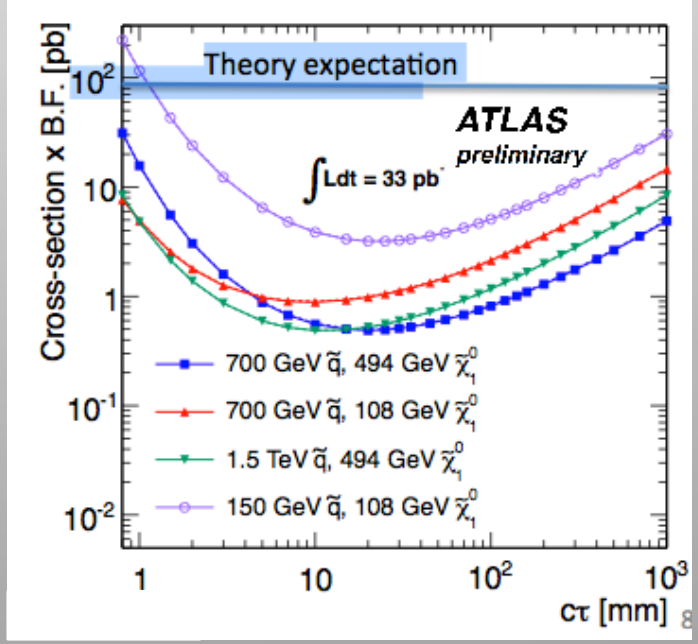
Using events with a "displaced vertex"





Event from a jet-trigger data sample, where a high-mass vertex (circled) is the result of an apparently random, large-angle intersection between a track and a low-mass hadronic-interaction vertex produced in a pixel module. The beampipe and some pixel modules are shown



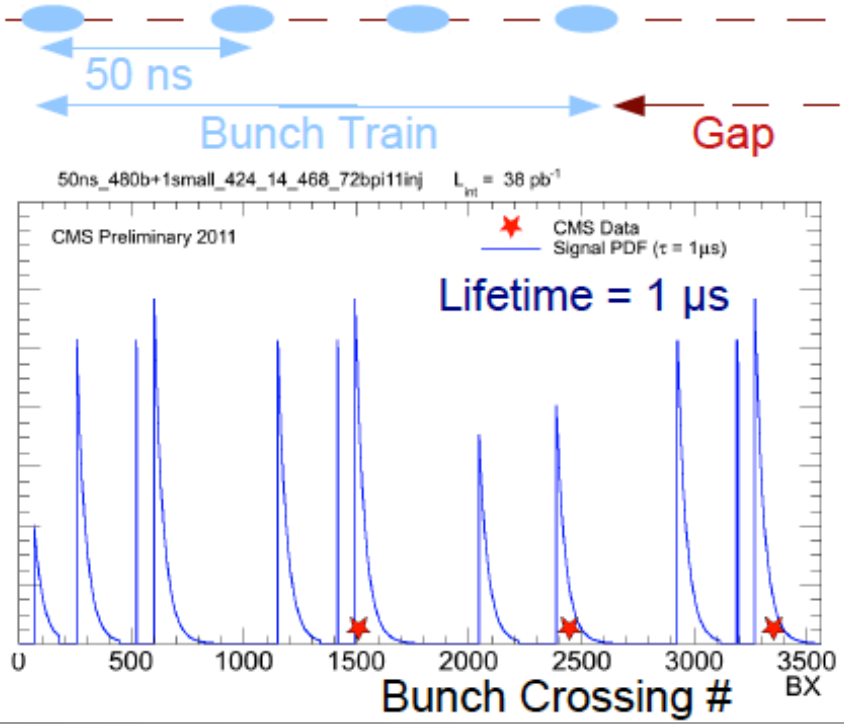


No signal found

- σ * detector acceptance * ε <0.09pb @95% Confidence level

Search for Stopped Gluinos

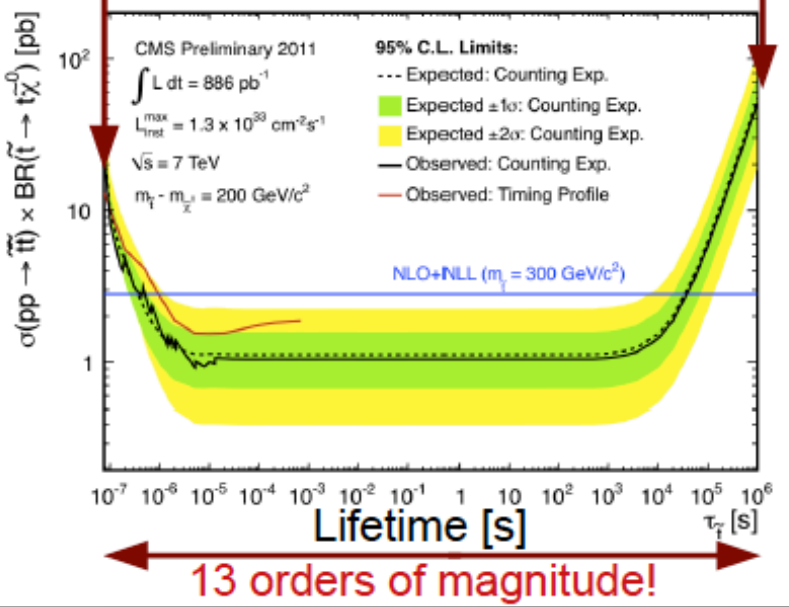
- Out-of-time decay of heavy particles stopped in the detector
- Look for signal **without** collisions:
  - → When no beam in the machine
  - → Between bunch trains



CMS-EXO-11-020

Too short-lived to be out-of-time 100 ns

Too long-lived to have decayed yet 1 month



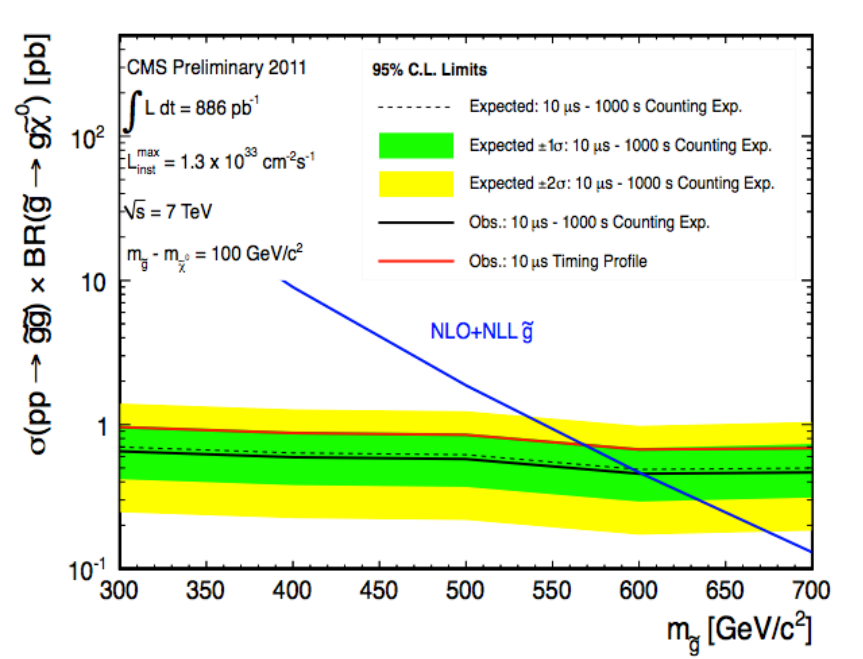
13 orders of magnitude!

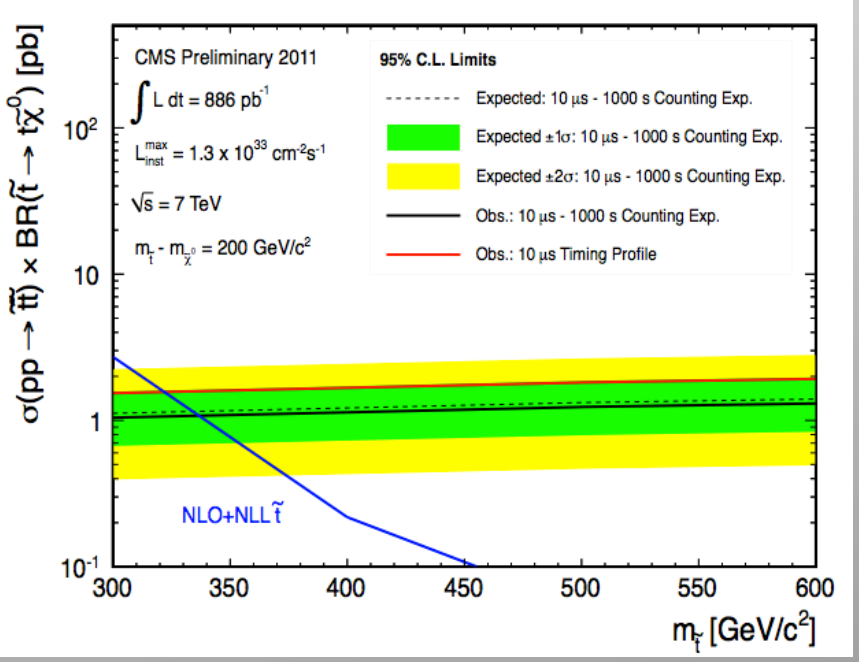
Search for Stopped Gluinos

Search for Heavy Stable Charged Particles that stop in the detectors and decay a long time afterwards (nsec, sec, hrs…)

Special data taking after the beams are dumped and during beam abort gaps

CMS-EXO-11-020





95% CL Limits: Stopped Gluinos > 600 GeV, Stopped Stop quarks> 337 GeV

Suggestions at this workshop

- Analyses with multi-b's, 3 and more, (3 b-resonances?)
- Going beyond cut and count: shape analyses…
- Monojet analyses for SUSY
- Rethink Search strategies for compressed spectra.
- Leptonic MT2
- Look out for stable charginos? Stubs? Other long lived particles?
- RPV with heavy flavor? Four jet resonances? 4 or more leptons? Boosted jets & jet substructure analysis
- Look out for stable charginos? Stubs?
- 4jet events with two b's (stop anti-stop production in MFVS)

Triggering remains an important concern

Analyses relying on ISR: how well can we rely on programs like MadGraph?

Data/Results Presentation

How can LHC data be maximally useful/usable

-Simplified models: are these really used? Suggest more SMS/analysis channel
- An experiment certified fast simulation ? Not likely
-Acceptance maps and cuts stored with each analysis? Possible (e.g Rivet)
- Recast of analyses? Not for some time I think…

Next: LPC Workshop on November 28

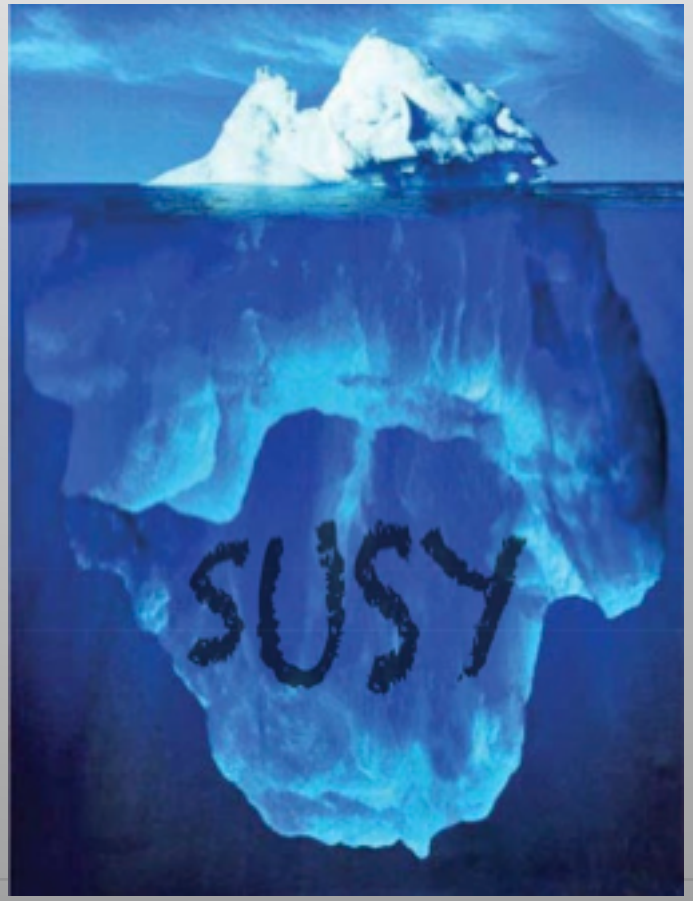
There will be an LPC workshop on 28 November (2 p.m.) to collect all information regarding requests for 2012 running from the experiments in preparation for the Chamonix LHC workshop at the beginning of Feb. 2012.

Machine parameters:
-what energy ? (3.5 TeV, 4 TeV)
-which bunch spacing ? (50ns, 25ns)
-which beta* in IP1/5 ? (0.7m, 1m ?) * crossing angle, geometric factor, operational efficiency (tight collim settings!)
-transverse emittance, bunch length?

-**Draft schedule 2012**

Thanks!

To the organizers of this meeting
The UC-Davis folks!



BACKUP