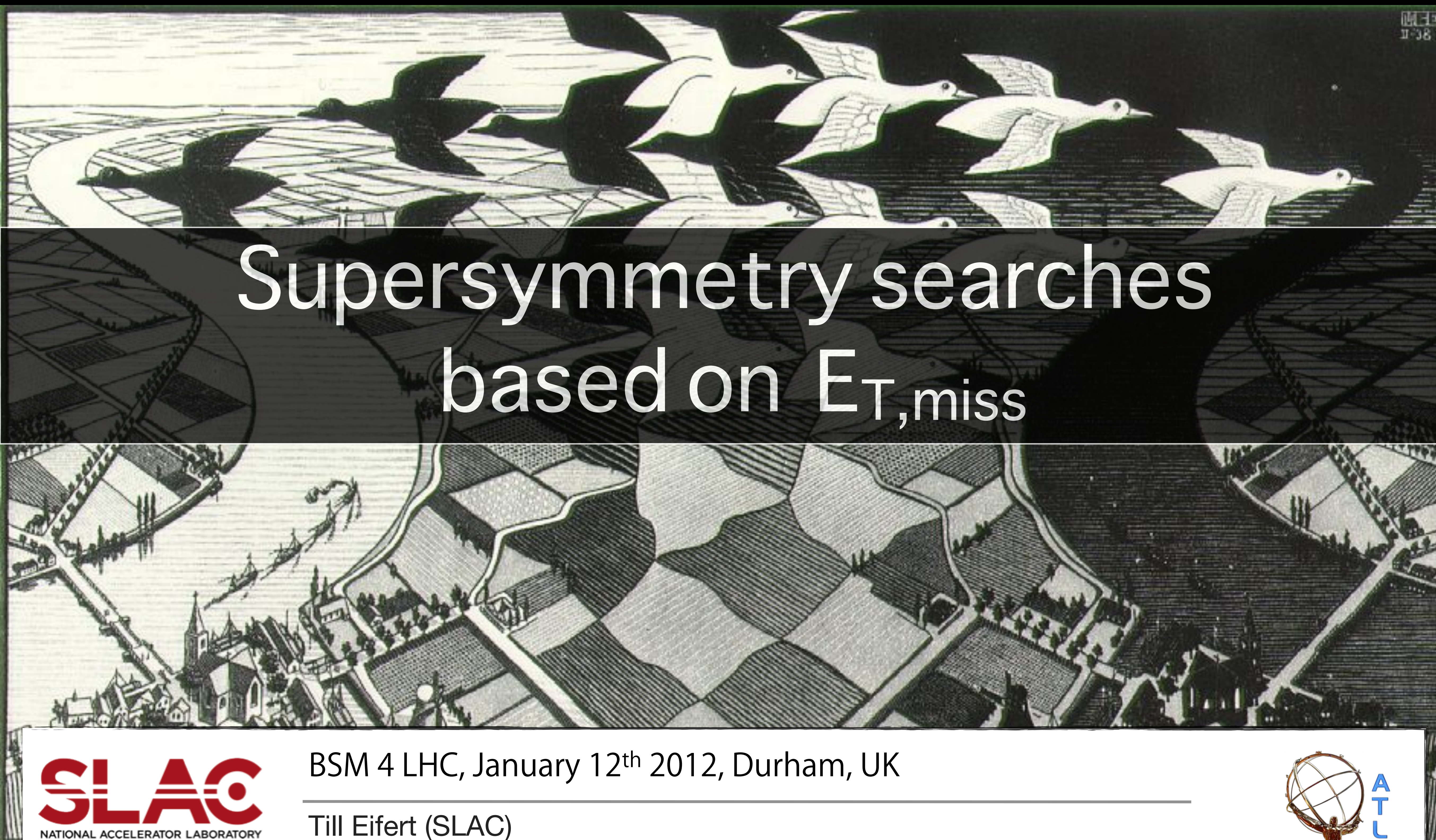


Supersymmetry searches based on $E_{T,miss}$

BSM 4 LHC, January 12th 2012, Durham, UK

Till Eifert (SLAC)

SLAC NATIONAL ACCELERATOR LABORATORY

ATLAS

Topics in this talk

- Selected Supersymmetry results
- Outlook
- Experimental challenges
- Future analyses

ATLAS RPC SUSY searches for various scenarios

lepton denotes isolated electron or muon

channel	search target	lumi	status
0 leptons + E_T^{miss} + ≥ 2-4 jets	heavy colored objects, decaying semi-invisibly w/ large mass splitting	1 fb^{-1}	Submitted to PLB (ArXiV:1109.6572) + ATLAS-CONF-2011-155
0 leptons + $E_T^{miss}/\sqrt{HT}$ + ≥6-8 jets	Long decay chains	1.3 fb^{-1}	JHEP 11 (2011) 99
1 lepton + E_T^{miss} + ≥ 3,4 jets	cascade decays with intermediate charginos/sleptons	1 fb^{-1}	Accepted by PRD (ArXiV:1109.6606)
2 leptons (SS/OS) + E_T^{miss}	intermediate charginos/sleptons; direct gaugino production	1 fb^{-1}	Submitted to PLB (ArXiV:1110.6189) + ATLAS-CONF-2011-156
multileptons	direct gaugino production	35 pb^{-1}	ATLAS-CONF-2011-039
0 (1) leptons + b-jets + E_T^{miss}	3rd gen. (sbottom, stop)	0.8(1)fb^{-1}	ATLAS-CONF-2011-098, ATLAS-CONF-2011-130,
0 leptons + ETmiss + 2 jets	direct sbottom production	2 fb^{-1}	Submitted to PRL (ArXiv:1112.3832)
2 γ + E_T^{miss}	GMSB with neutralino NLSP	1 fb^{-1}	Submitted to PLB (ArXiv:1111.4116)
+ more targeted analyses for SUSY scenarios with features not covered above			

incomplete list
(more RPV, LL, and exotics searches ready)

CMS RPC SUSY searches for various scenarios

channel	search target	lumi	status
0 leptons + E_T^{miss} + jets	heavy colored objects, decaying semi-invisibly w/ large mass splitting	1.1 fb^{-1}	α_T: PRL 107 (arxiv:1109.2352), MT2: PAS-SUS-11-005 HT/MHT: PAS-SUS-11-004 Razor: PAS-SUS-11-008
1 lepton + E_T^{miss} + ≥ 3,4 jets	cascade decays with intermediate charginos/sleptons	1 fb^{-1}	PAS-SUS-11-015
2 leptons (SS/OS) + E_T^{miss}	intermediate charginos/sleptons; direct gaugino production	1 fb^{-1}	PAS-SUS-11-010, PAS-SUS-11-011 Z+MET: PAS-SUS-11-019
multileptons	direct gaugino production	2.1 fb^{-1}	PAS-SUS-11-013
0 leptons + b-jets + E_T^{miss}	3rd gen. (sbottom, stop)	1.1 fb^{-1}	PAS-SUS-11-006
2 γ + E_T^{miss} + >=1 jet OR 1 γ + E_T^{miss} + >=3 jet	GMSB with neutralino NLSP	1.1 fb^{-1}	CMS-PAS-SUS-11-009
+ more targeted analyses for SUSY scenarios with features not covered above			

lepton denotes isolated electron, muon, and **had. tau** (some analyses)

incomplete list

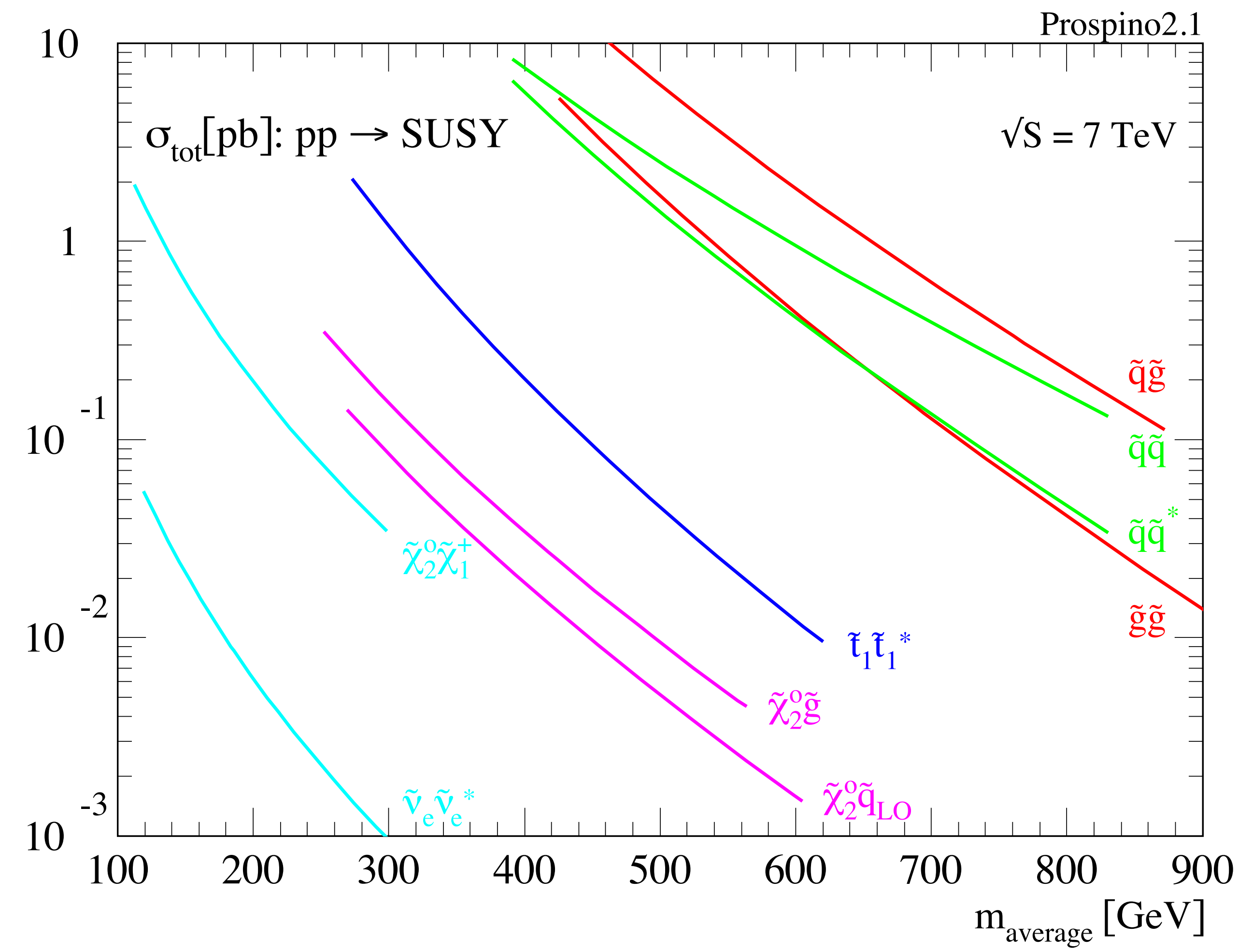
Sensitivity reach ~similar to ATLAS analyses

$H_T = \sum p_T$ $\alpha_T = E_T^{j_2} / M_T$

Search Strategy so far

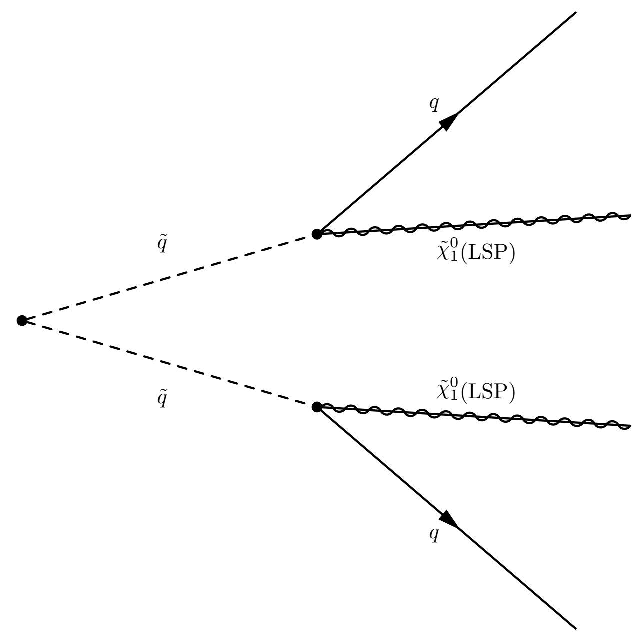
- Targeting strong production: gluinos and squarks
- Inclusive signature-based searches
- Relatively simple cut & count techniques
- Background estimates (analysis dependent):
    - fully data-driven for difficult processes, e.g. QCD fake leptons
    - semi data-driven for most major processes, e.g. W and ttbar
    - MC based for minor processes, e.g. dibosons

Cross section for pair-produced SUSY particles

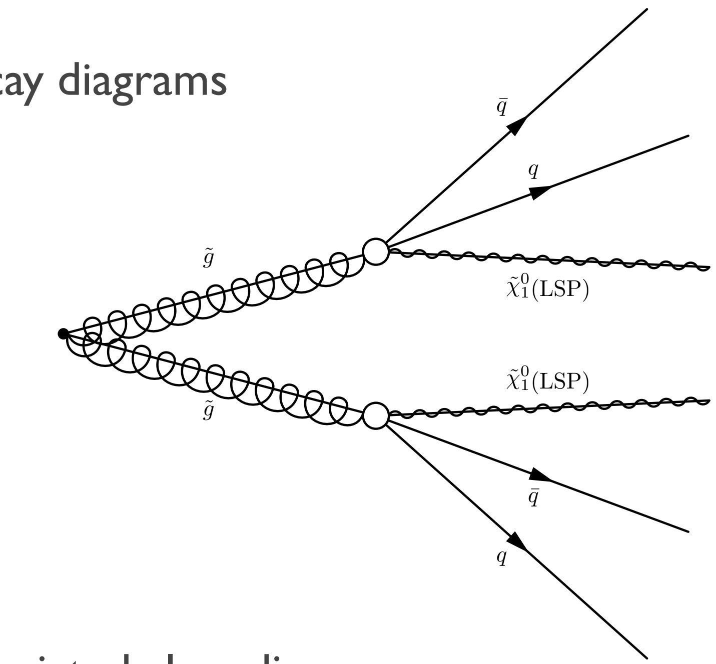


0 lepton + jets + E_t^{miss}

Targeted scenario:
Strong production of squarks & gluinos which directly decay to quark(s) and the LSP.



decay diagrams



+ associated gl-sq diagram

Pre-selection

jet + E_T^{miss} trigger, data & detector quality, good primary vertex, No lepton (el/mu)

➡ Signal-enhanced regions:

Simple classification:

➡ ≥2 jets: sq-sq production

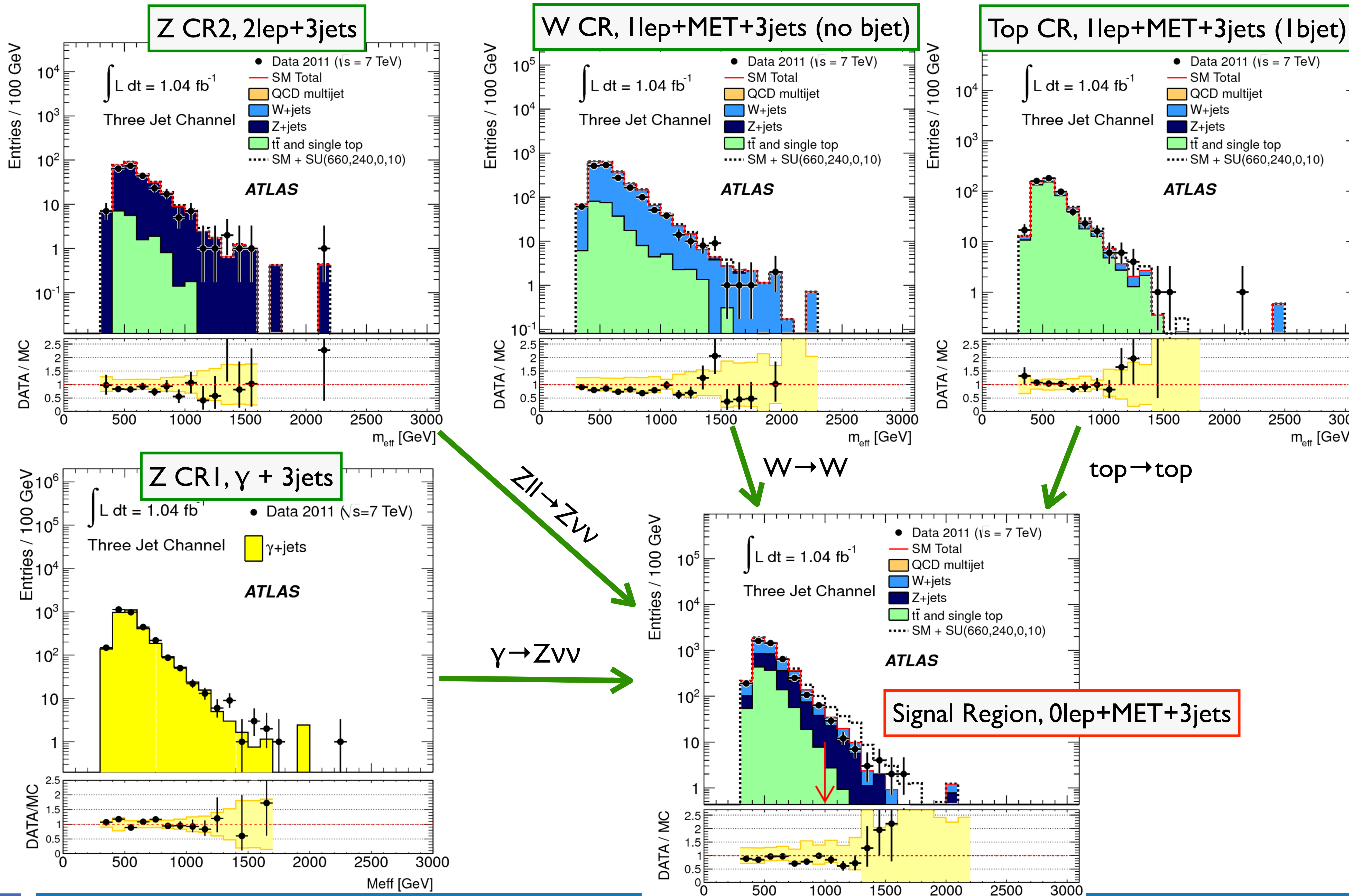
➡ ≥3 jets: associated sq-gl production

➡ ≥4 jets:gl-gl production

➡ ≥4 jets, High mass: gl-gl production with very-large mass splitting ΔM(gl, LSP)

Signal Region	≥ 2-jet	≥ 3-jet	≥ 4-jet	High mass
E_T^{miss}	> 130	> 130	> 130	> 130
Leading jet p_T	> 130	> 130	> 130	> 130
Second jet p_T	> 40	> 40	> 40	> 80
Third jet p_T	–	> 40	> 40	> 80
Fourth jet p_T	–	–	> 40	> 80
$\Delta\phi(\text{jet}, \vec{P}_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25	> 0.2
m_{eff}	> 1000	> 1000	> 500/1000	> 1100

Example background estimates

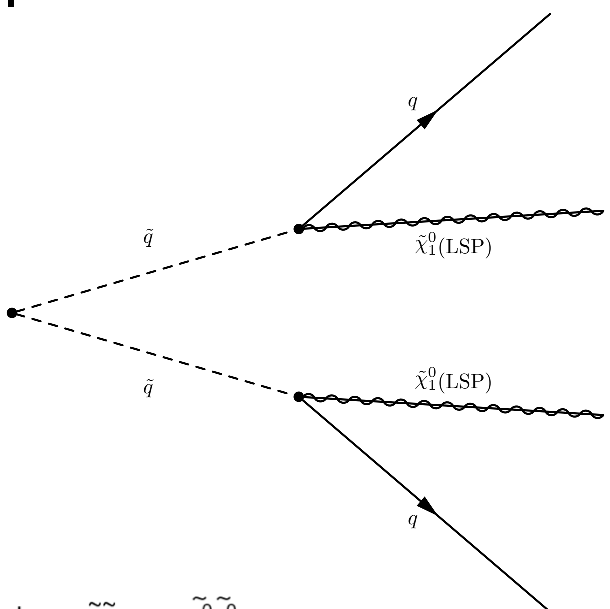


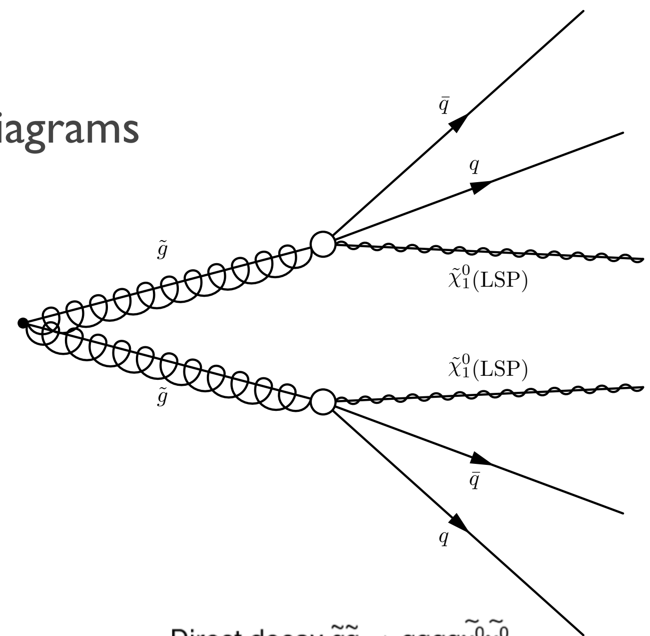
Strong prod. with direct decays

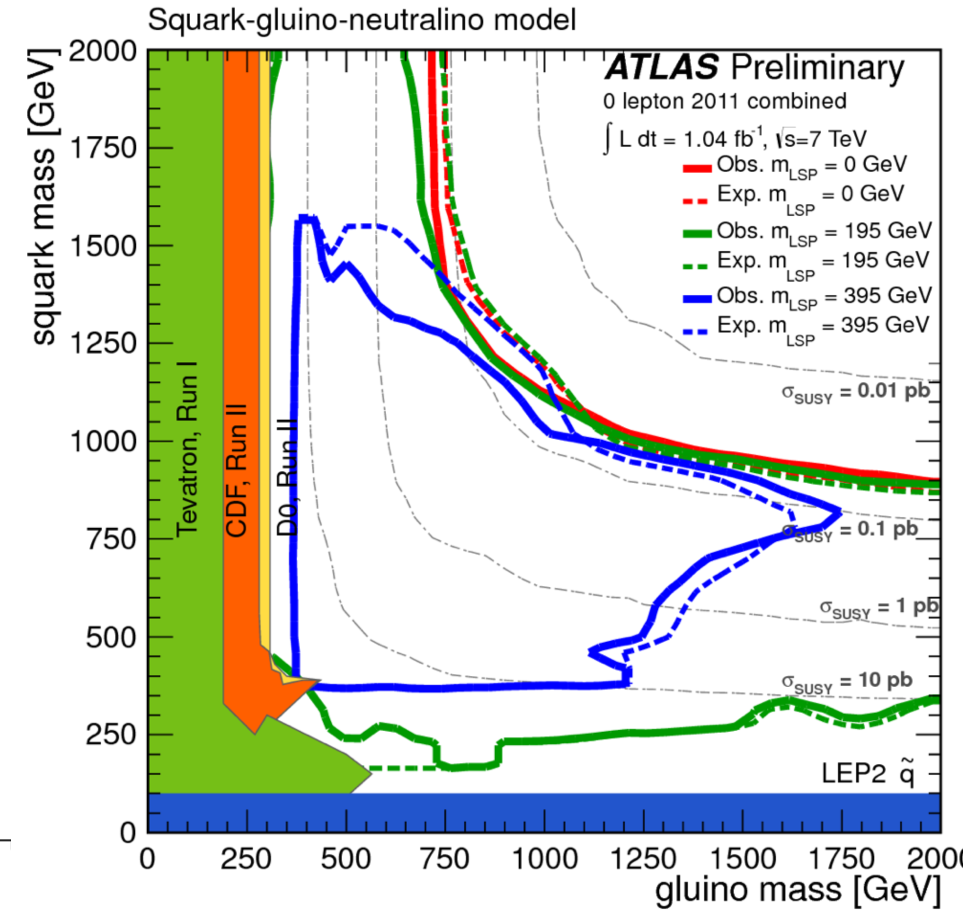
Submitted to PLB, arxiv:1109.6572 +ATLAS-CONF-2011-155

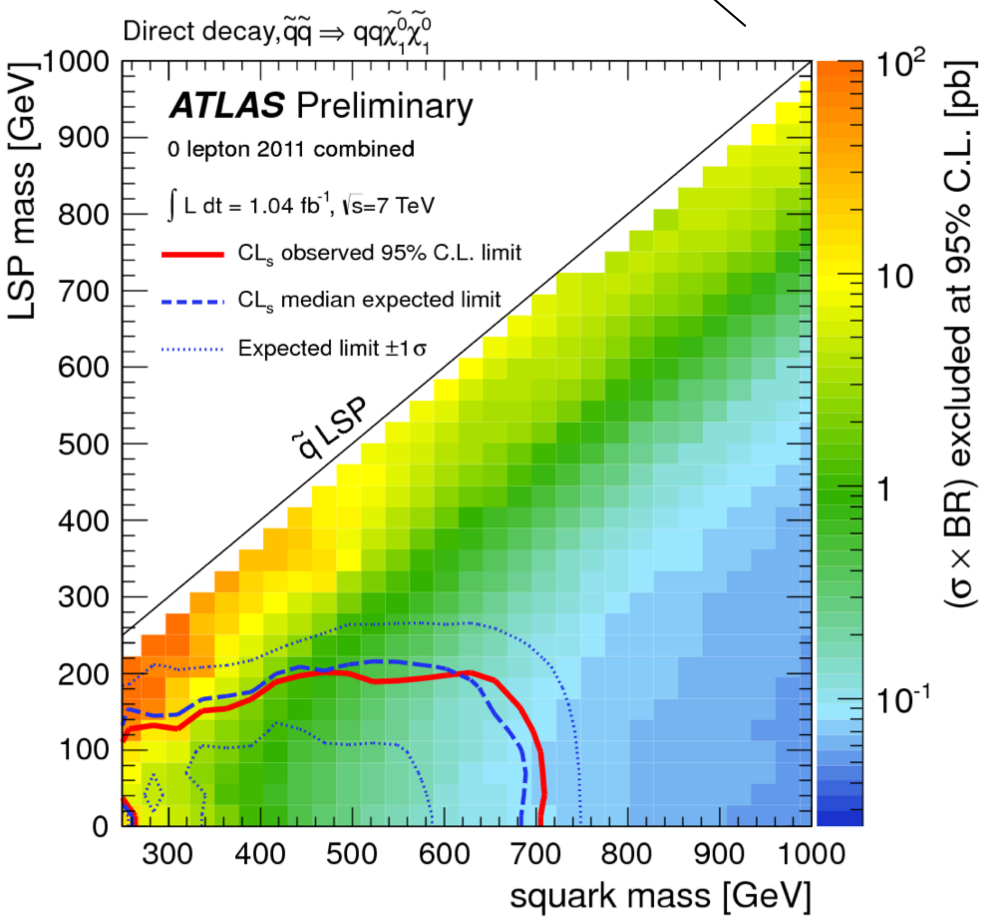
Interpretation of E_T^{miss} + ≥ 2-4 jets results in Simplified Models

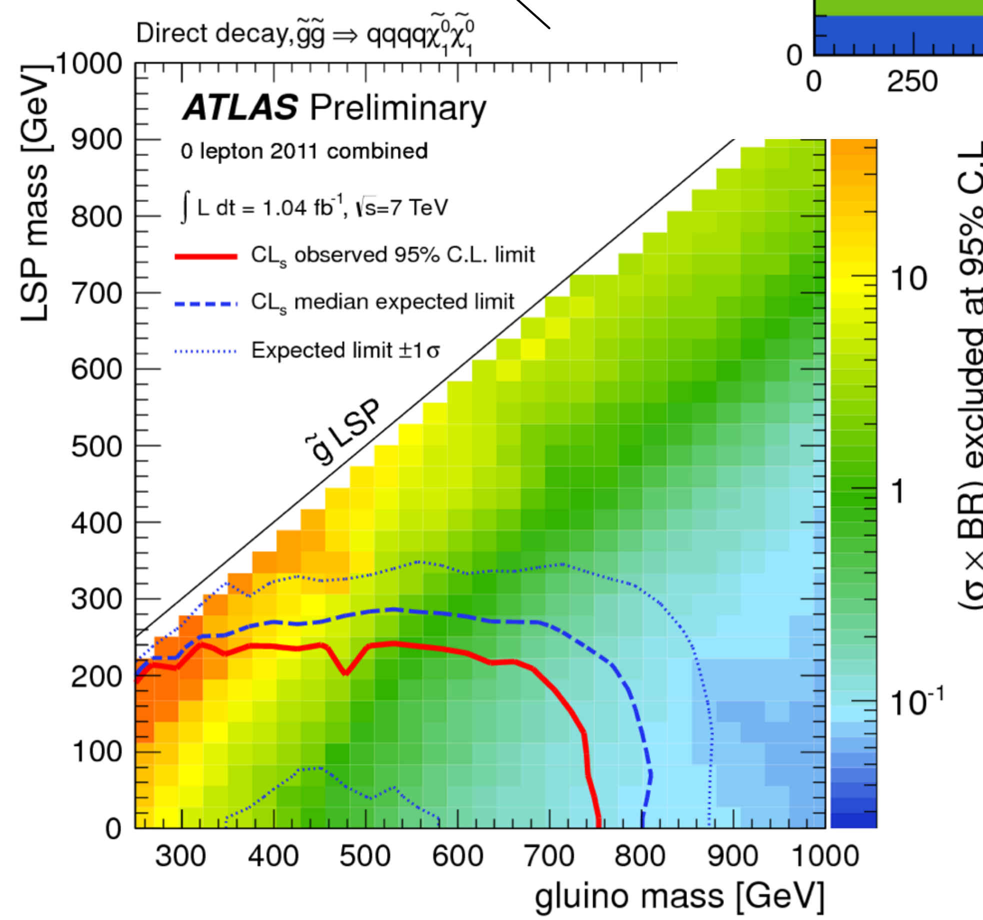
decay diagrams











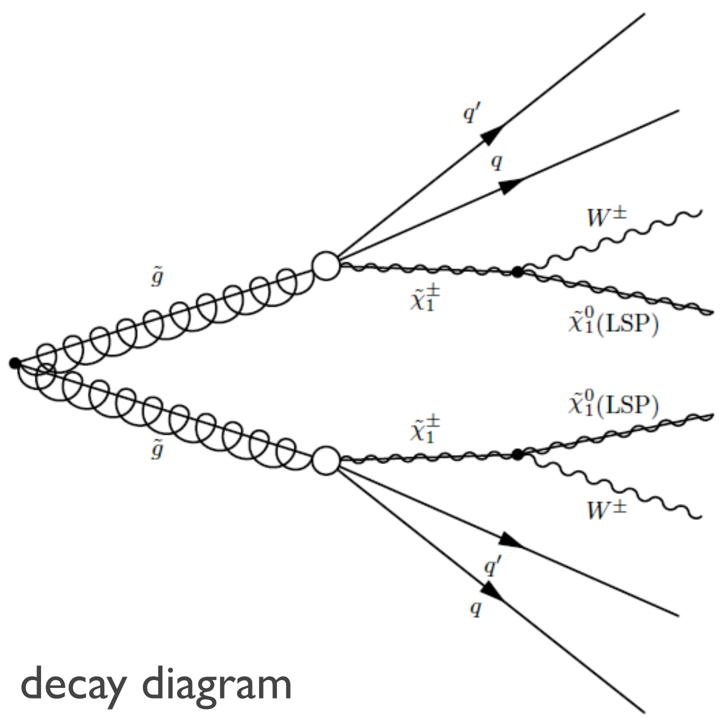
squark + gluino production, direct decays.
(incl. associated glu-sq prod.)

Similar CMS interpretations from all hadronic searches available.

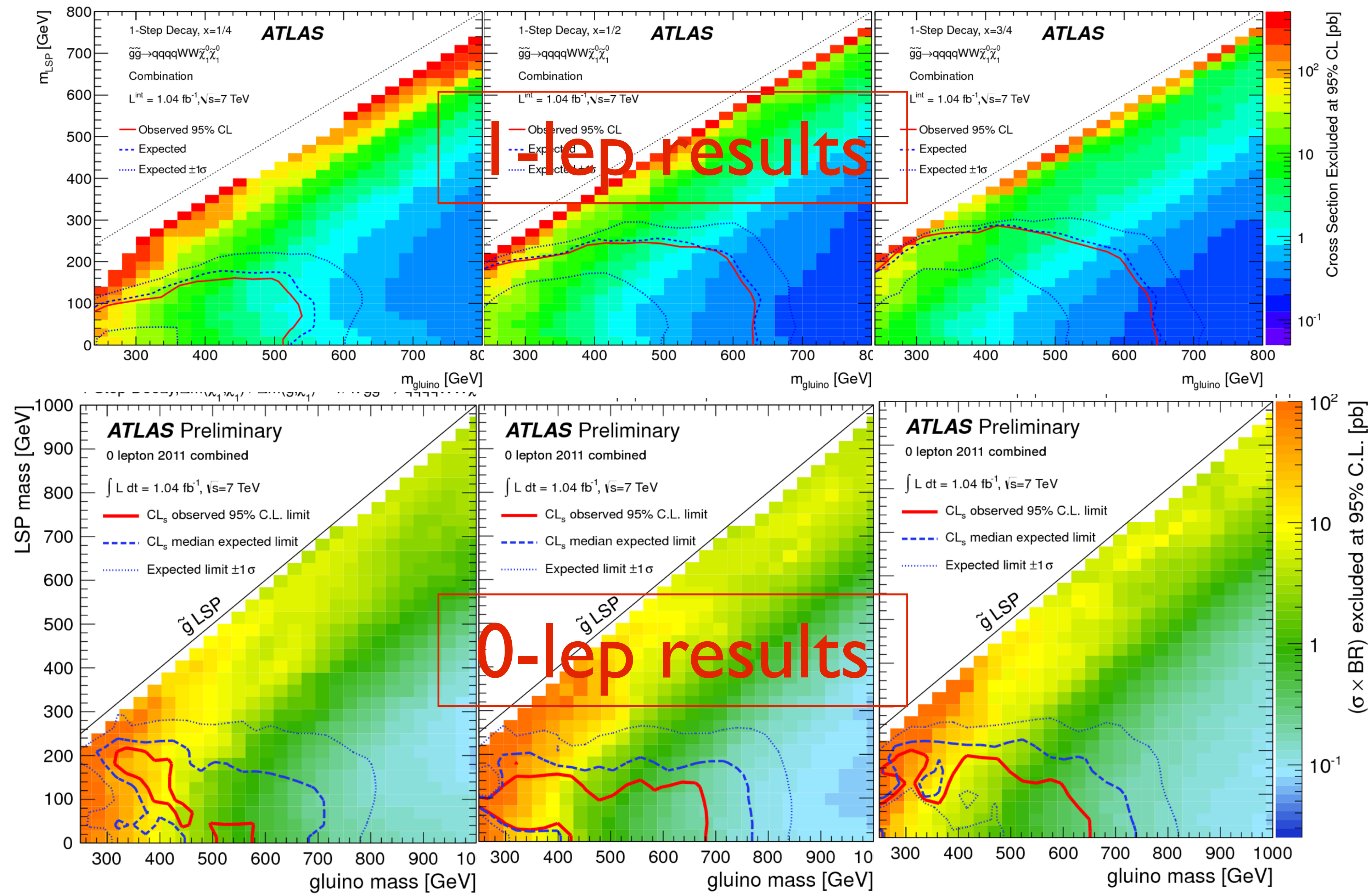
0 & 1-lep Strong prod. with 1-step decays

Interpretation of E_T^{miss} + jets & 1lep+ E_T^{miss} + jets results in Simplified Models

M_{LSP} vs M_{gluino} p-space, with intermediate $M_{chargino}$ light (left), medium (middle), heavy (right)



decay diagram

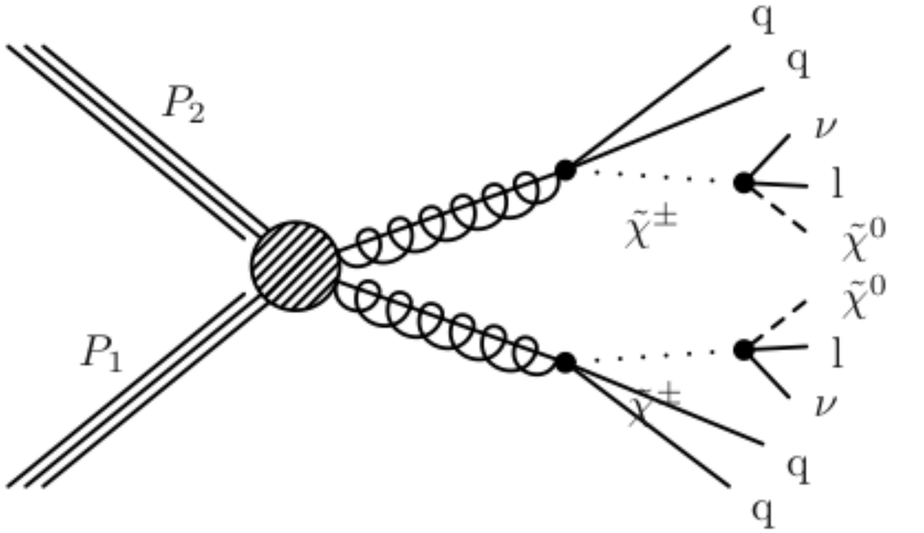


Rather similar CMS interpretations from all hadronic searches available.

Complementarity: 0-lepton pushes the limit to heavy gluinos while 1-lep stronger close to diagonal.

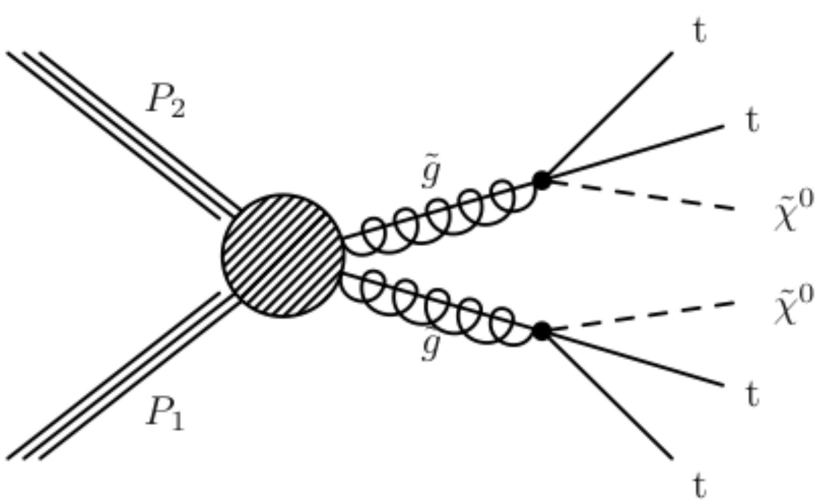
More strong production models

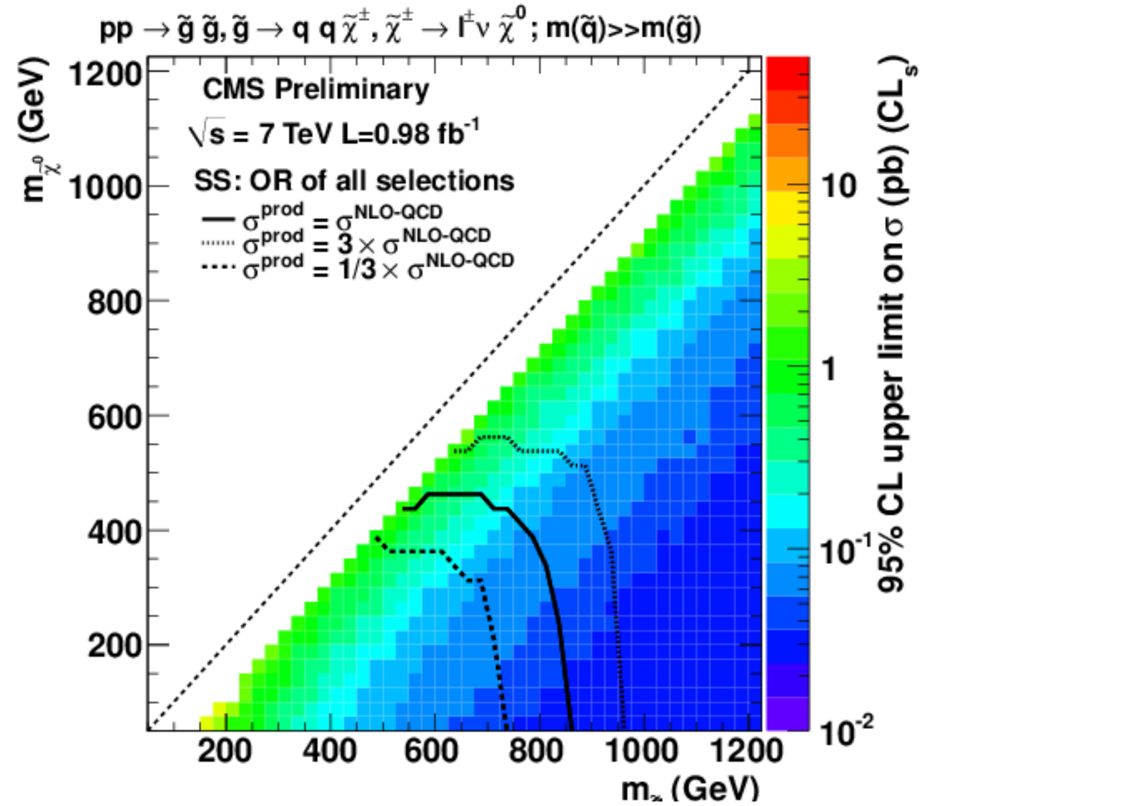
Interpretation of 2 SS-leptons + E_T^{miss} results in Simplified Models

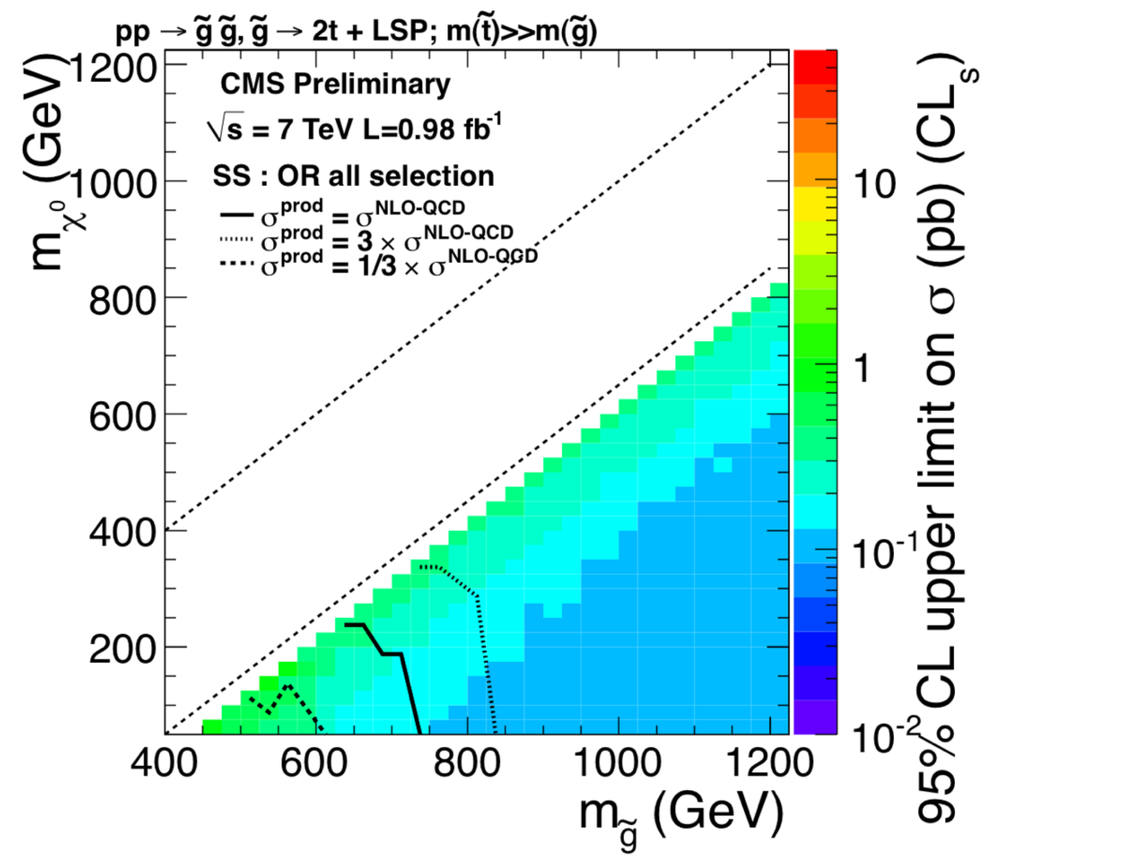


Note: $\chi^{\pm}$ forced to decay to lν χ^0 (via sleptons)

decay diagrams

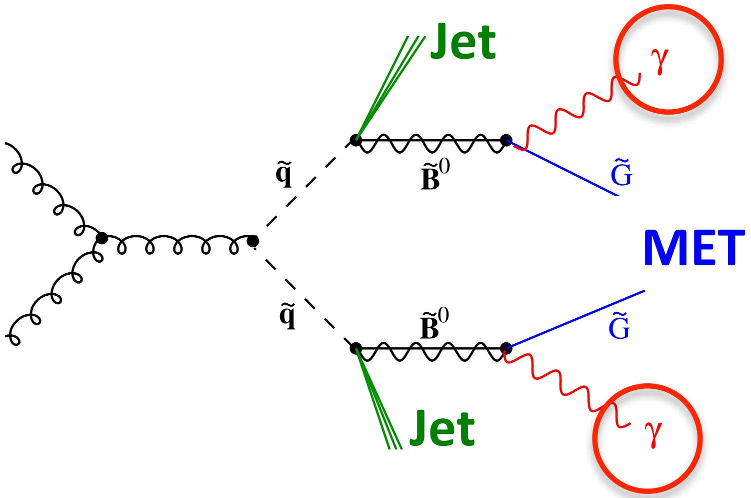






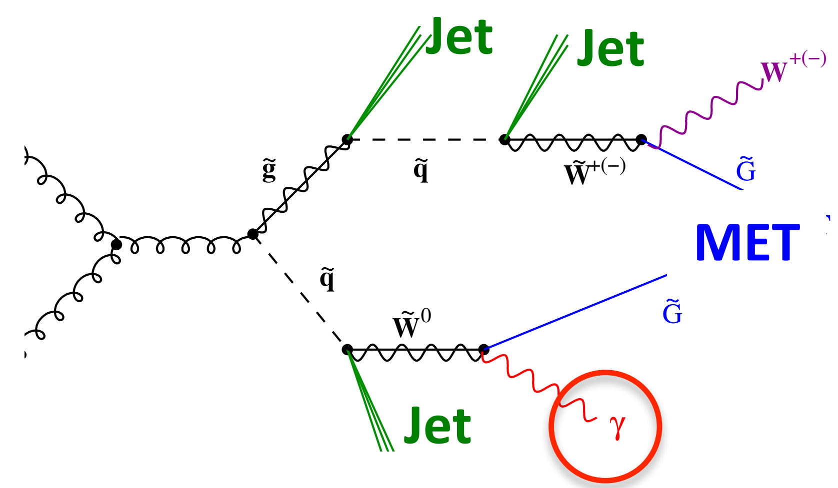
Similar ATLAS interpretations from 2 SS-leptons (coming soon), and $E_{T,miss}$+ bjets (see Monica's talk) search.

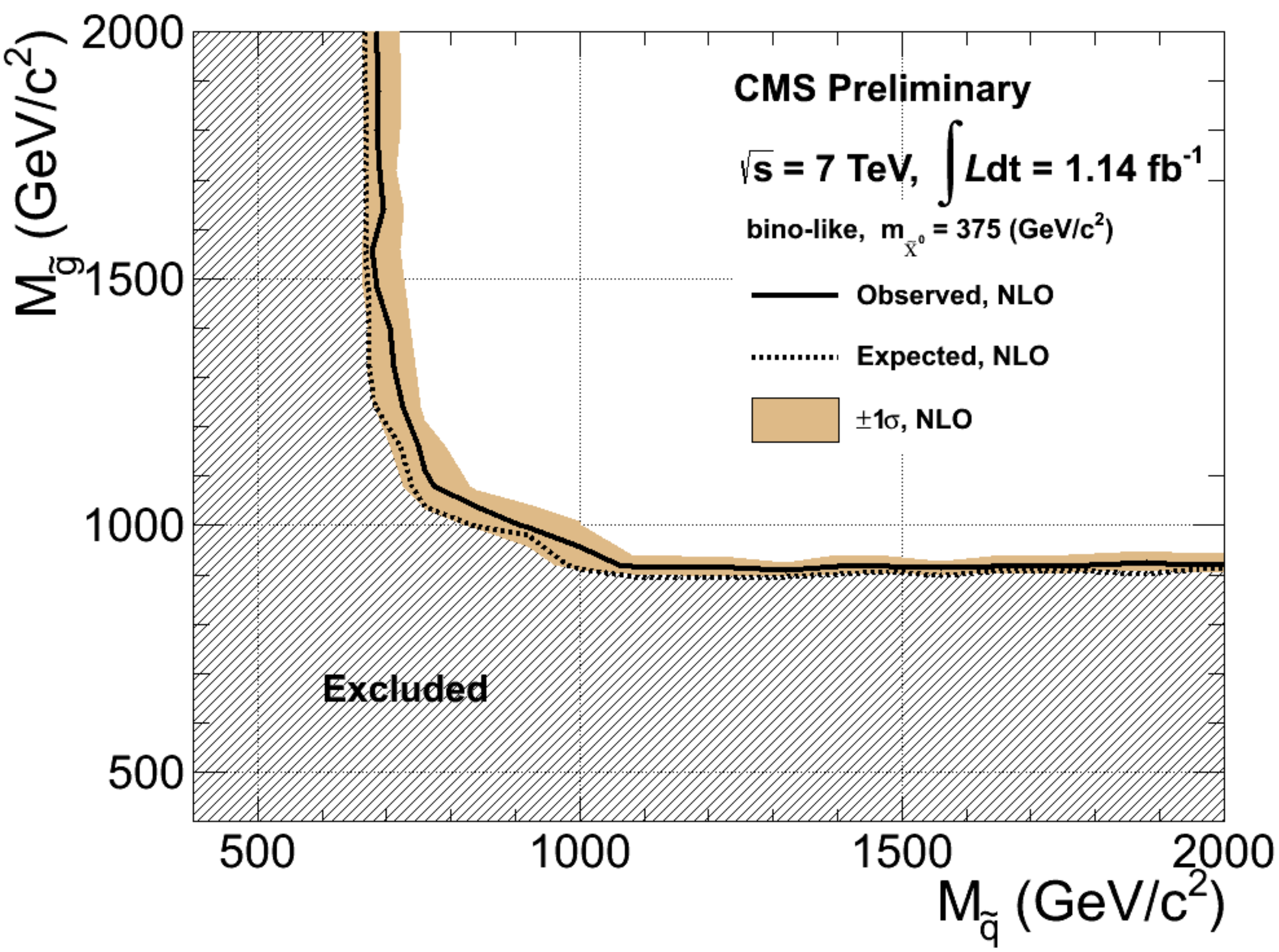
Photons, jets and MET



Gauge mediated SUSY

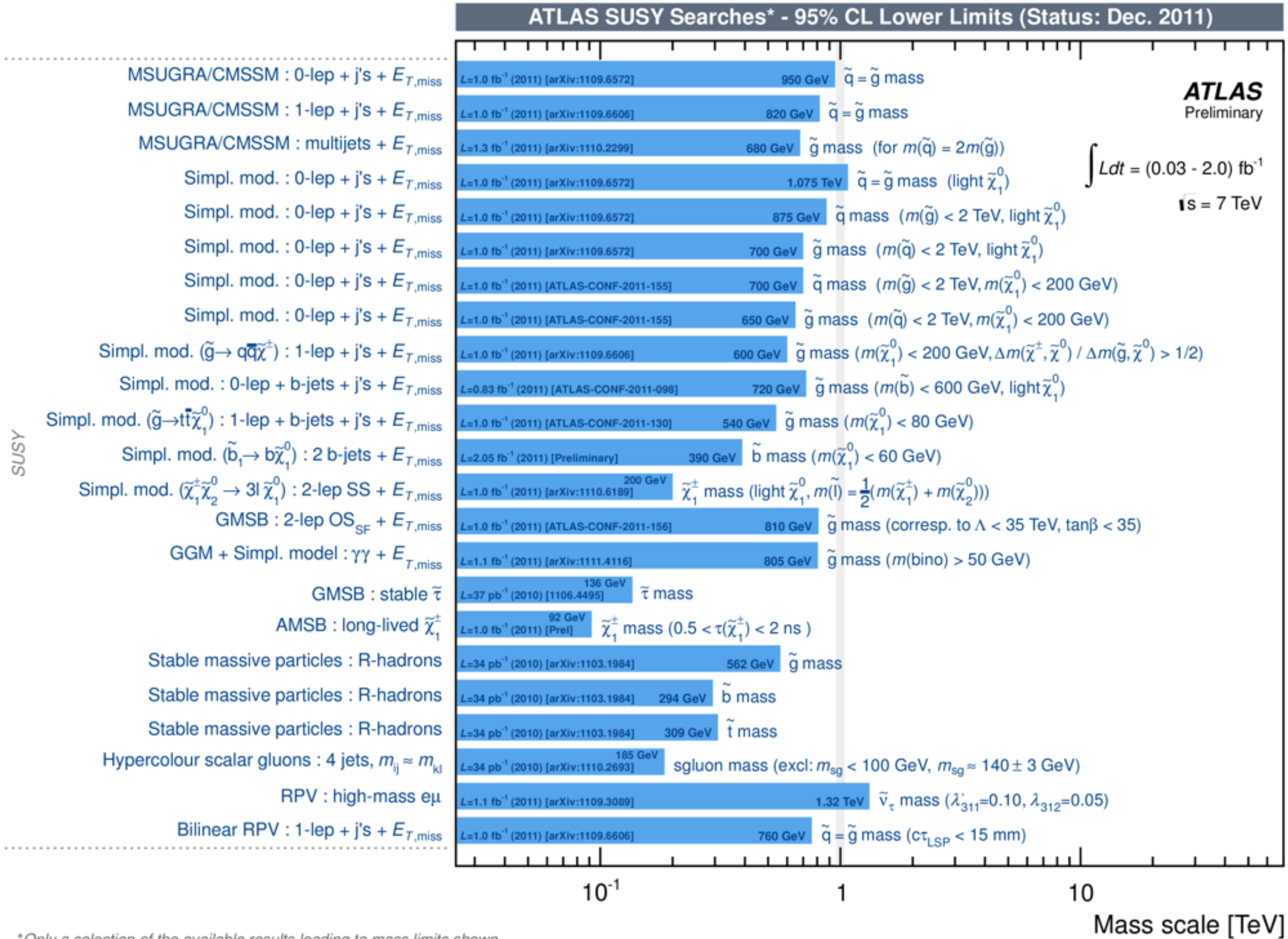
- Gravitino is LSP
- Neutralino is NLSP
- Depending on the nature of the χ^0 (bino/wino-like) and mass hierarchy; 1 or more photons





Interpretation in simplified models in GGMS where $m(\chi^0)$= 375 GeV

ATLAS SUSY search limits

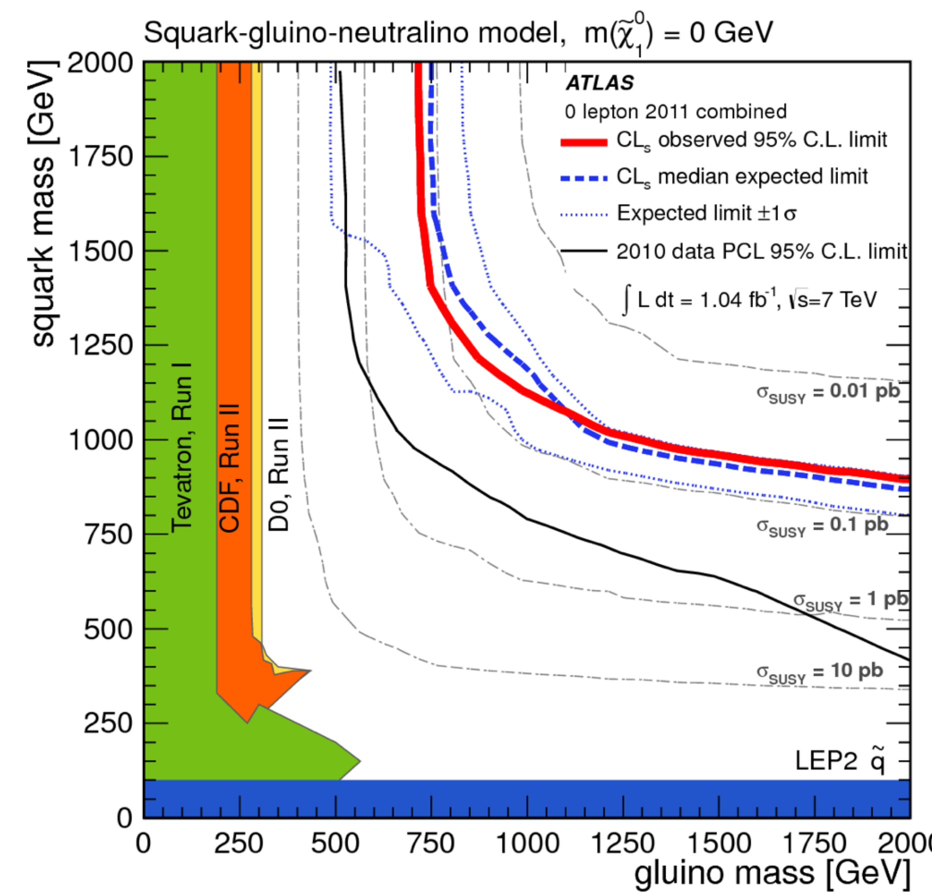


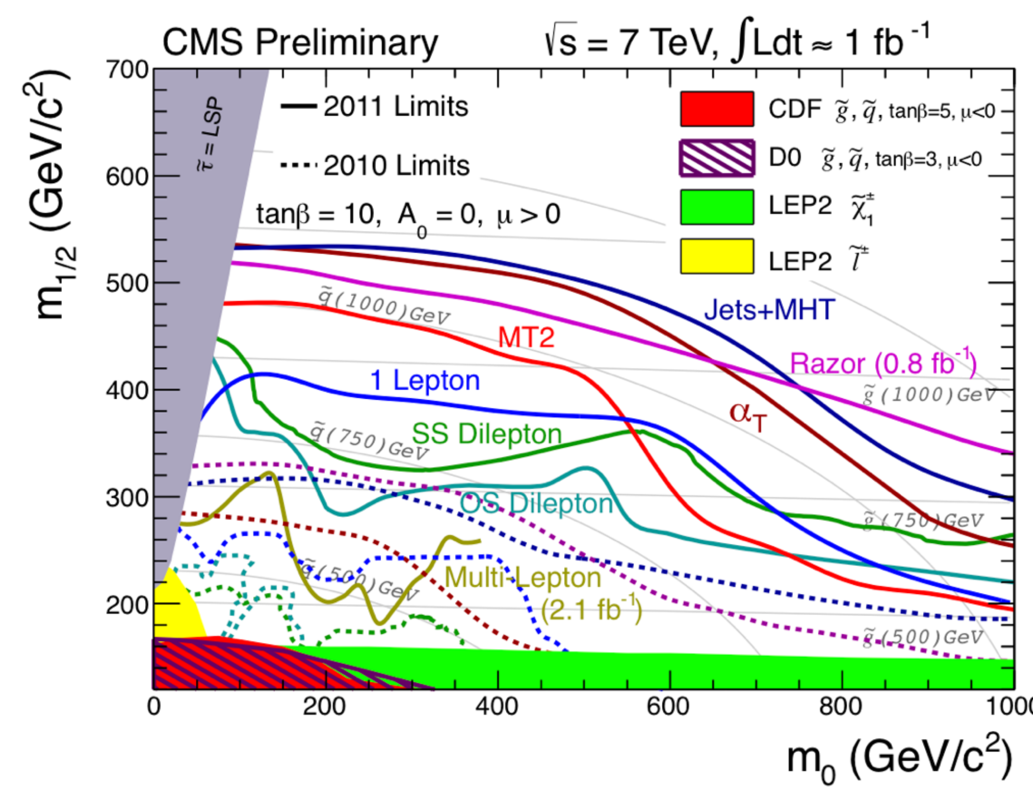
Similar plot for CMS in backup

No striking excess at the TeV scale for the "easy" signatures

SUSY landscape

- **Current LHC SUSY constraints:**
  - Squarks and gluinos >~ 1 TeV
  - This statement applies to:
    - High-scale models (e.g. MSUGRA/CMSSM)
    - or large mass hierarchies
    - for first 2 generations squarks
  - Much weaker constraints for
    - Models with some heavy squarks or gluinos
    - “Compressed” SUSY spectra
    - Third generation





What's next ?

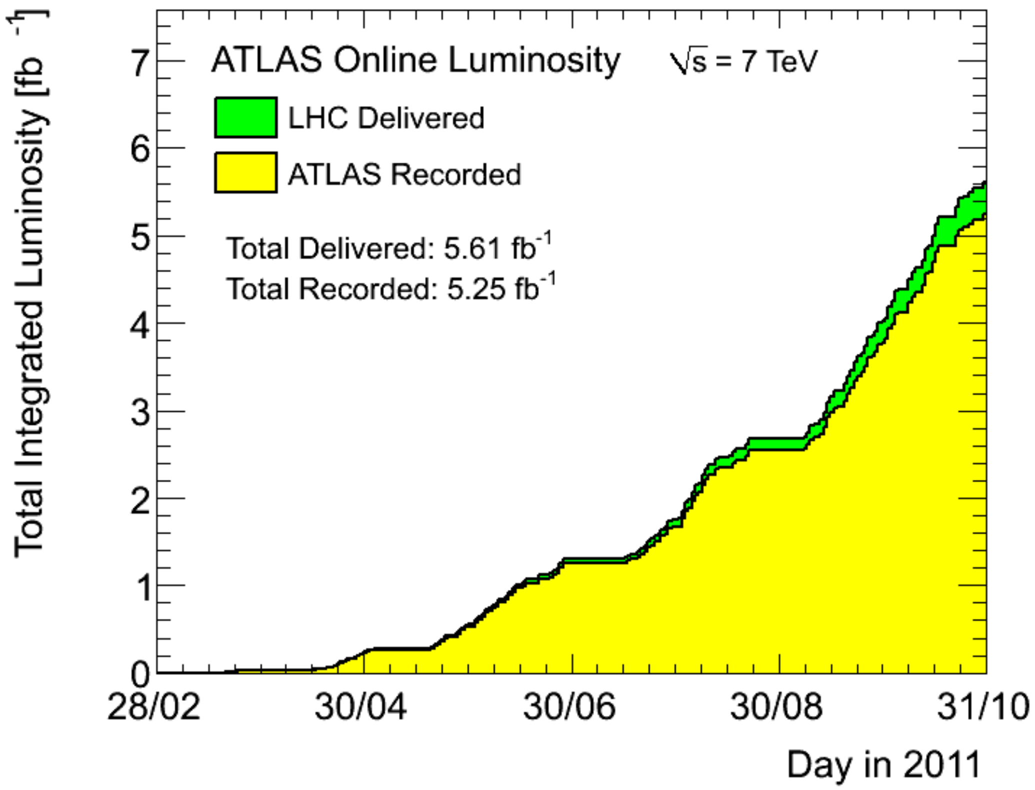
No SUSY signal found yet

(in "easy" mostly inclusive searches in first 1-2 fb^{-1} data of 2011)

- **2014+**
  - LHC increase to design collision energy $\sqrt{s}$ ~ 14 TeV
  - opens sensitivity to discover new heavy SUSY particles
    - reach up to ~2.5 TeV squarks/gluinos with 100 fb^{-1}
  - Will repeat all searches, in particular inclusive channels
- **2012**
  - Much more LHC data, maybe slight increase in collision energy (next slide)
  - Maximize SUSY coverage using:
    - dedicated analyses to target challenging signatures (thus more exclusive searches)
    - improve analysis techniques (inclusive & exclusive searches)

But the new data comes with experimental challenges ...

LHC Operation



- LHC runs amazingly well !
- Delivered >5 fb^{-1} in 2011 at 7 TeV CM energy
- ATLAS data taking efficiency ~93.5%
  - inefficiency due to turn-on at start of stable beams; and deadtime
- One good day of data taking: O(50 pb^{-1}) ≃ full 2010 dataset

From S. Myers, Dec. 7 2011, LHCC

Summary for 2012

Assumptions
E=4TeV: beta* = 0.7m: 148 days of physics: no intensity limit for 25ns

Bunch Spacing	Peak Luminosity	Integrated Luminosity (fb-1)	Pile Up	N max
50ns	5.80E+33	~16	~27	1.55E+11
25ns	3.80E+33	~10	~9	1.15E+11

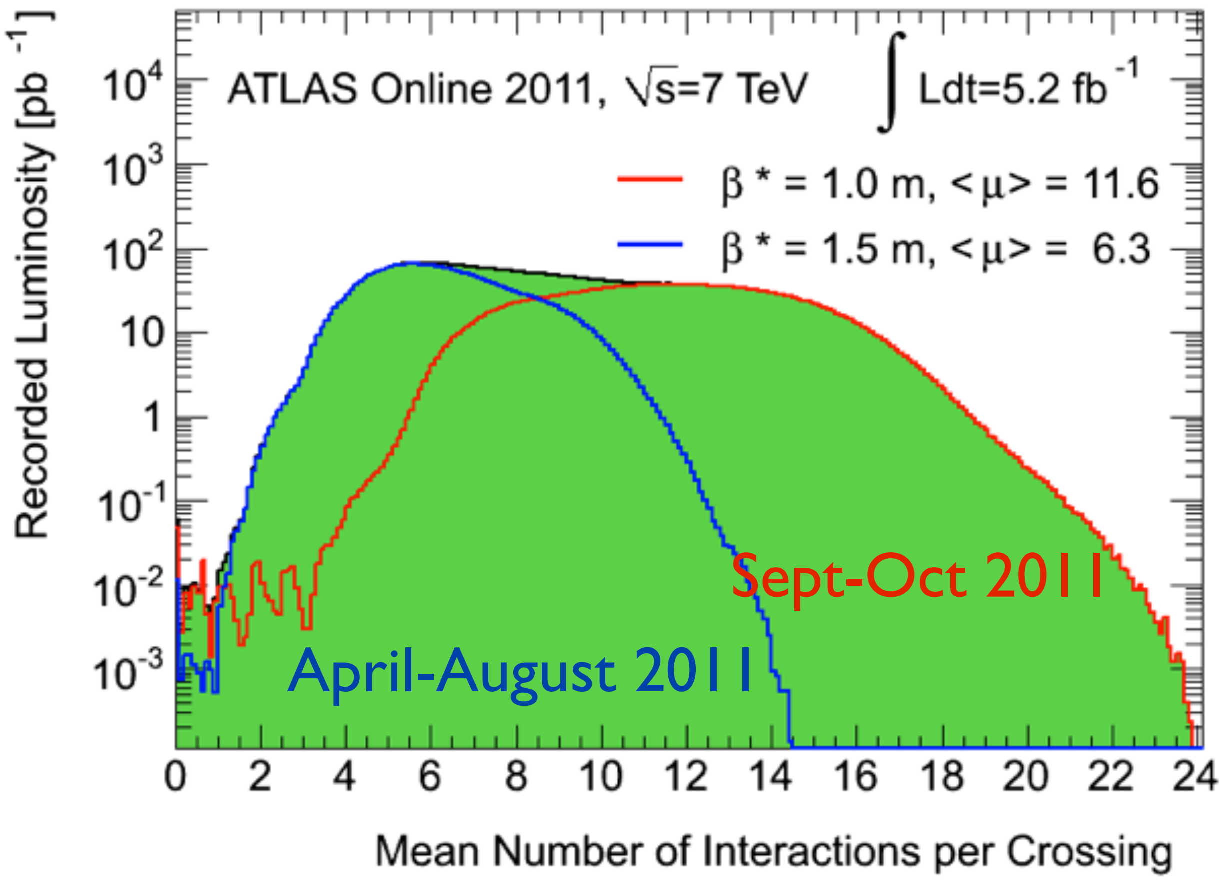
2012

- likely collision energy increase to $\sqrt{s}$ = 8 TeV
- L=10 to 16 fb^{-1}
- Pileup (see next slide) increase <mu> ~ 30 possible

Pileup Effects

... the price for high luminosity

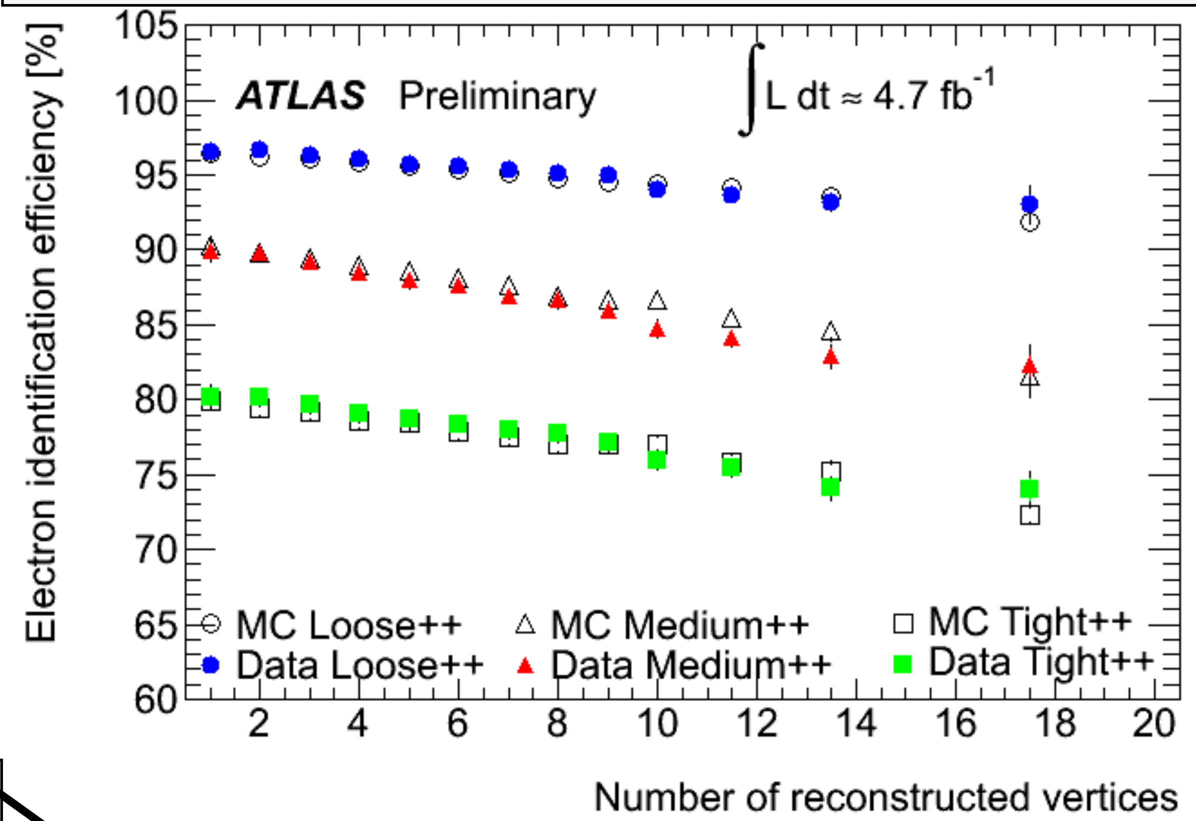
- **Pileup = number of interactions per crossing**
  - 2011 significantly higher than in 2010
  - tails up to 23
  - In-time pileup: many interactions in same bunch crossing
  - Out-of-time pileup: additional interactions in preceding bunch crossings
    - significant impact on ATLAS calorimeter reconstruction since LAr drift time is ~400 ns (bunch spacing Δt = 50 ns)
- **Challenging for physics analyses**
  - detailed simulation models <μ> and bunch train structure
  - reweight MC in analyses
  - Reconstruction s/w performance improved to accommodate Tier-0 resources
  - Detector performance reasonably unaffected
- **For SUSY analyses**
  - Affects mostly low p_T jets, low-medium E_T^{miss}, lepton isolation, triggering
  - Relatively small effect for most SUSY analyses (control-regions are more affected than signal-regions)



We might get a mean number of interactions (<μ>) ~30 in 2012.

A few examples of pileup effects in ATLAS

Simulation doing good job modeling these effects

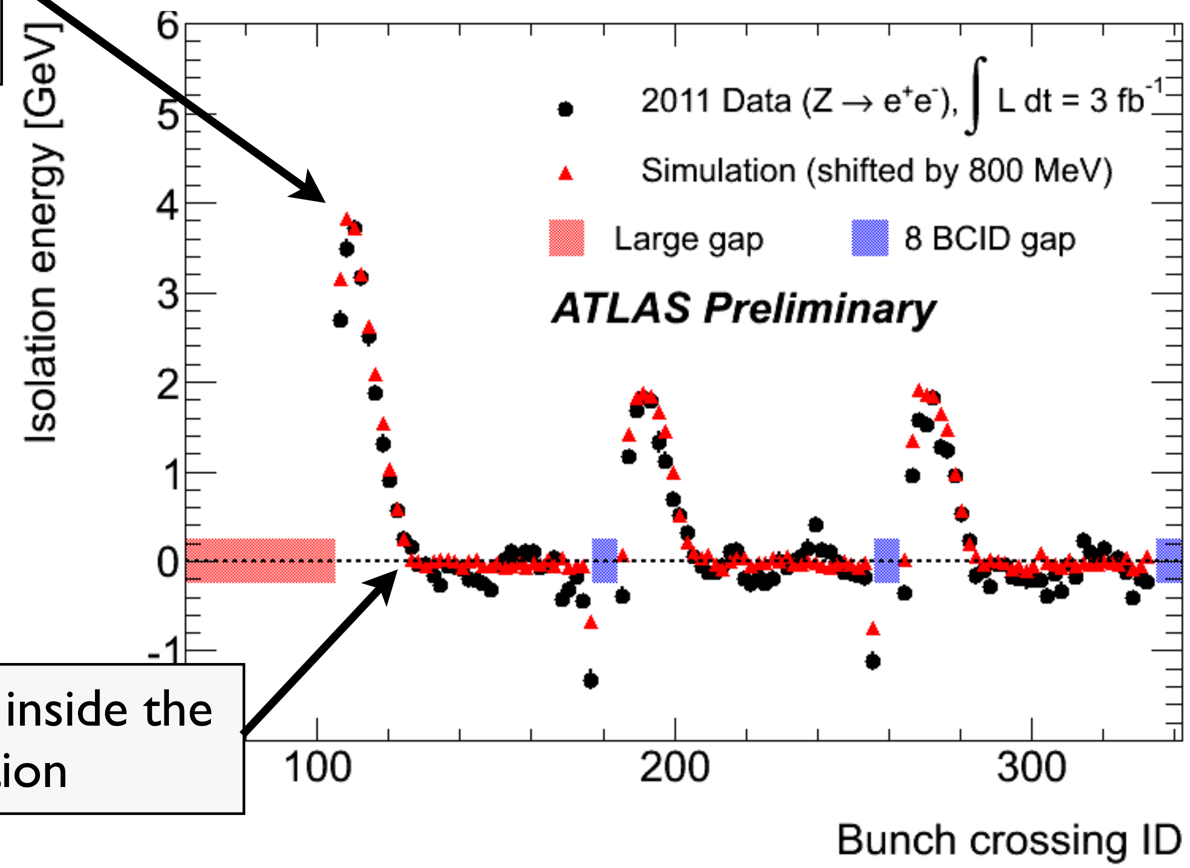


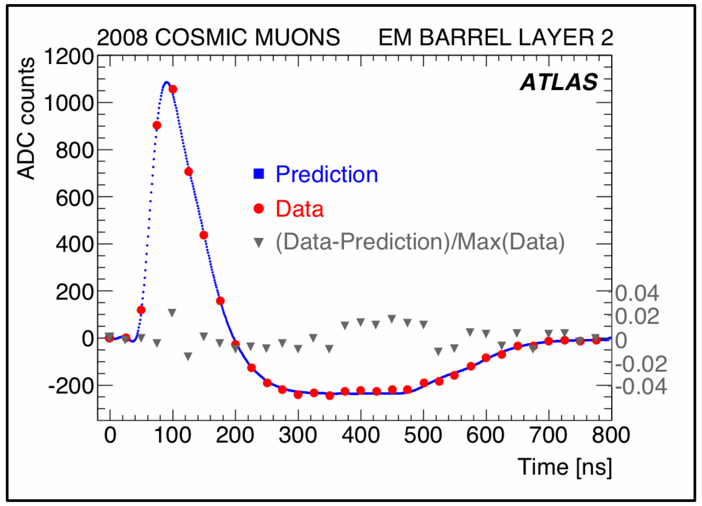
- Significant impact of pileup on electron ID
- Will re-tune cuts for 2012

Effects will increase next year due to higher mu!

- Calorimeter isolation versus out-of-time pile-up

Beginning of the train: no cancellation from previous bunches





Calorimeter bipolar pulse shape: average pile-up is zero over ~ 600 ns (12 bunches).
Well described by MC (!)

From 12 bunches inside the train: full cancellation

Trigger

➡ trigger is often driving the main analysis cuts (we can analyze only data on tape)

Challenges

- trigger rates vs thresholds
- Pile-up

2011 ATLAS Physics Proton Trigger Menu (end of run L = 3.3 10^{33} $cm^{-2}s^{-1}$)

... increasing thresholds

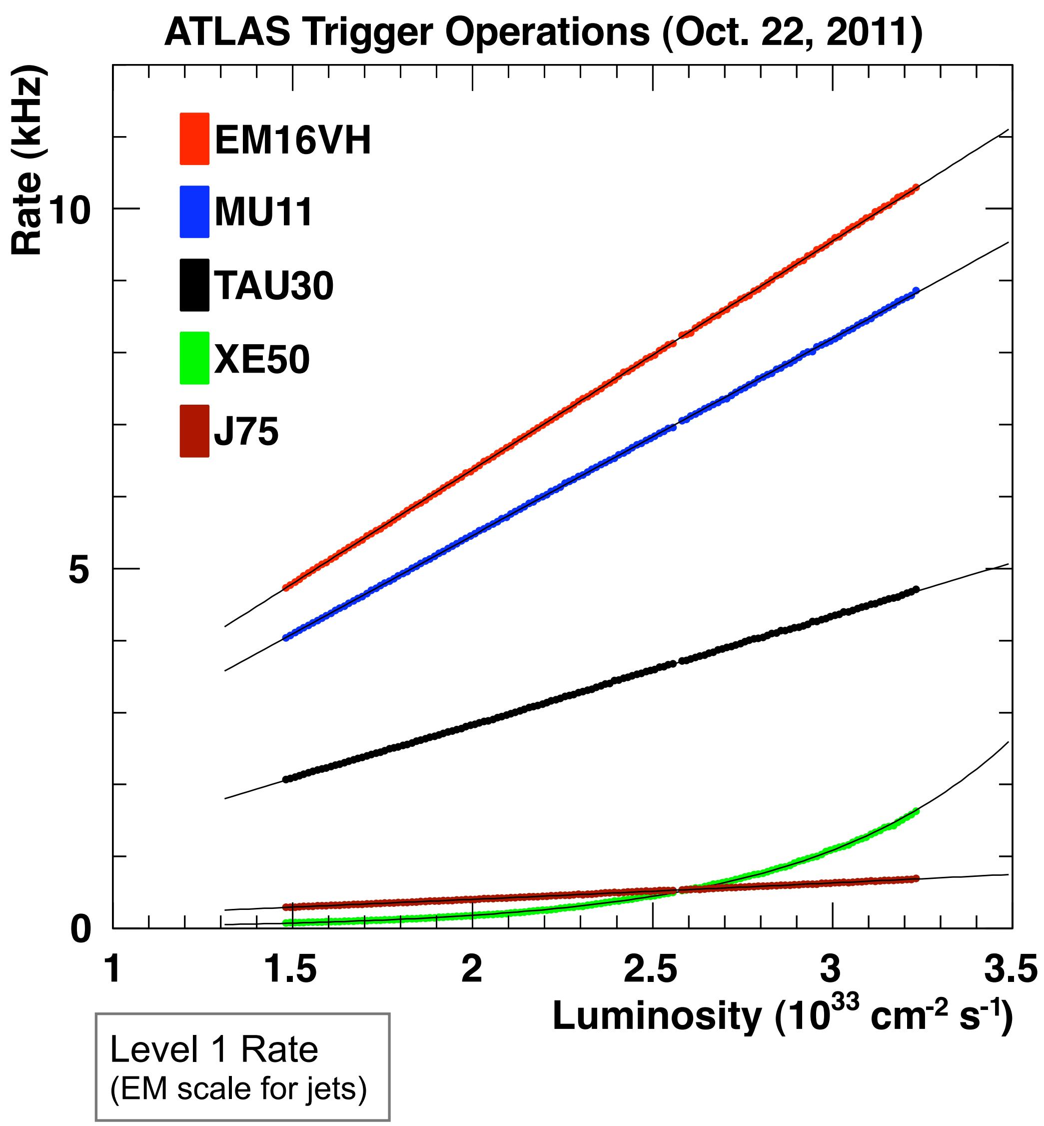
SUSY searches		Offline Selection	Trigger Selection L1	Trigger Selection EF	L1 Rate (kHz) at 3e33	EF Rate (Hz) at 3e33
SR: 1-lepton, multilept CR for W/Z samples	Single leptons	Single muon > 20GeV	11 GeV	18 GeV	8	100
		Single electron > 25GeV	16 GeV	22 GeV	9	55
SR: multilept	Two leptons	2 muons > 17, 12GeV	11GeV	15,10GeV	8	4
		2 electrons, each > 15GeV	2x10GeV	2x12GeV	2	1.3
		2 taus > 45, 30GeV	15,11GeV	29,20GeV	7.5	15
diphoton	Two photons	2 photons, each > 25GeV	2x12GeV	20GeV	3.5	5
0-lepton	Single jet plus MET	Jet pT > 130 GeV & MET > 140 GeV	50 GeV & 35 GeV	75GeV & 55GeV	0.8	18
monojet	MET	MET > 170 GeV	50 GeV	70GeV	0.6	5
multijet	Multi-jets	5 jets, each pT > 55 GeV	5x10GeV	5x30GeV	0.2	9
	TOTAL				**<75**	**~400 (mean)**

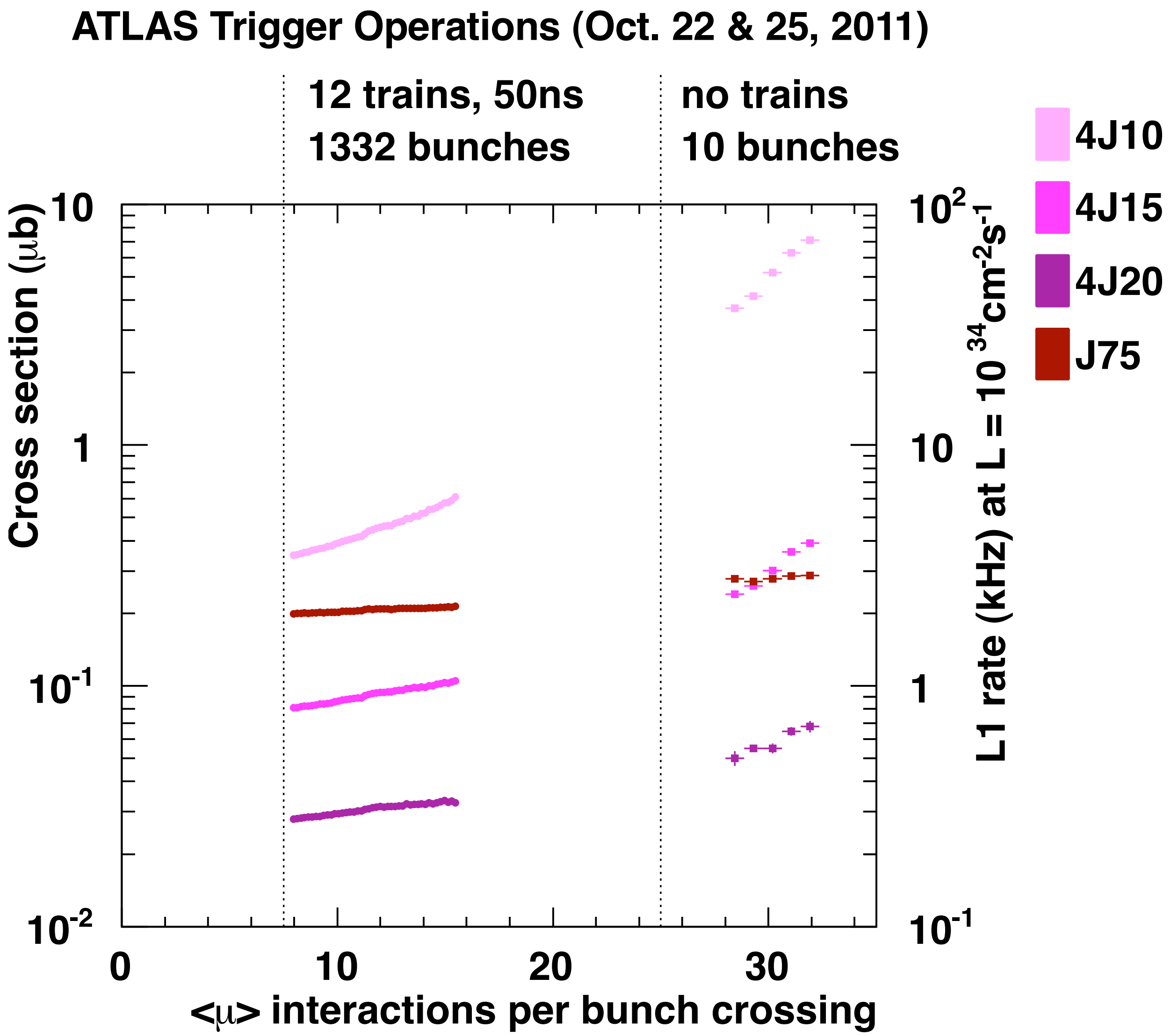
from D. Strom, Dec. 7 2011, LHCC

- Trigger menu kept ~stable in 2011
  - primary (physics) triggers never prescaled
  - supplement by supporting and monitoring triggers
- Performance of trigger well understood

- With increasing lumi for 2012 run will need to control trigger rates:
  - multi-object triggers (lower thresholds)
  - move part of offline selection to trigger-level (e.g. particle-flow in CMS)
  - dedicated triggers for signal, control region (prescaled?)

Mulit-jet Rates and $E_{T,miss}$ are especially sensitive to pileup





- Control the rate:
  - Increase noise threshold
  - Reduce angular coverage of lowest threshold
  - Raise thresholds

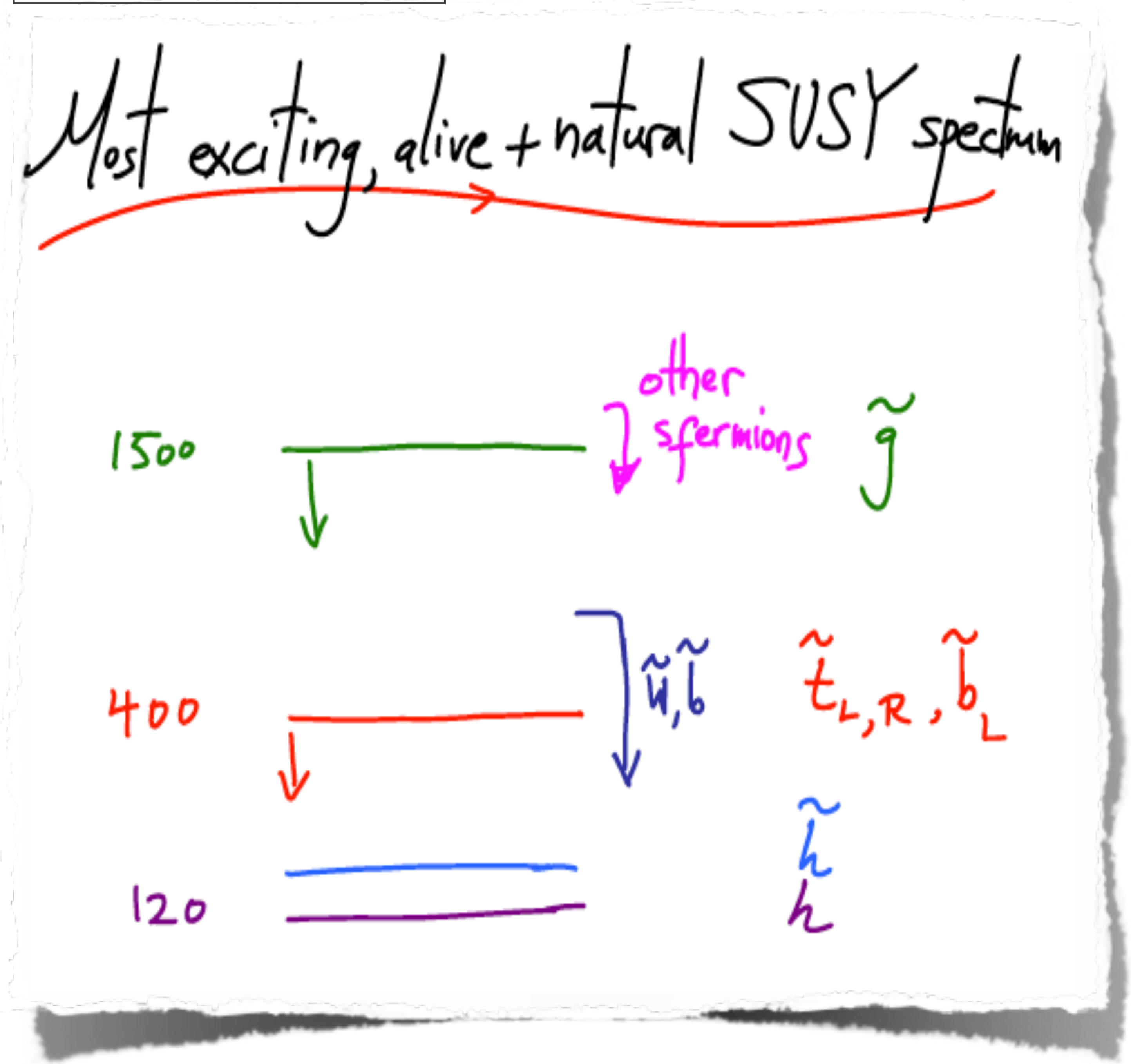
Maximize SUSY coverage

Some (obvious) remarks for 2012 Data Analyses

Light 3rd generation

Detailed discussion in Monica's talk

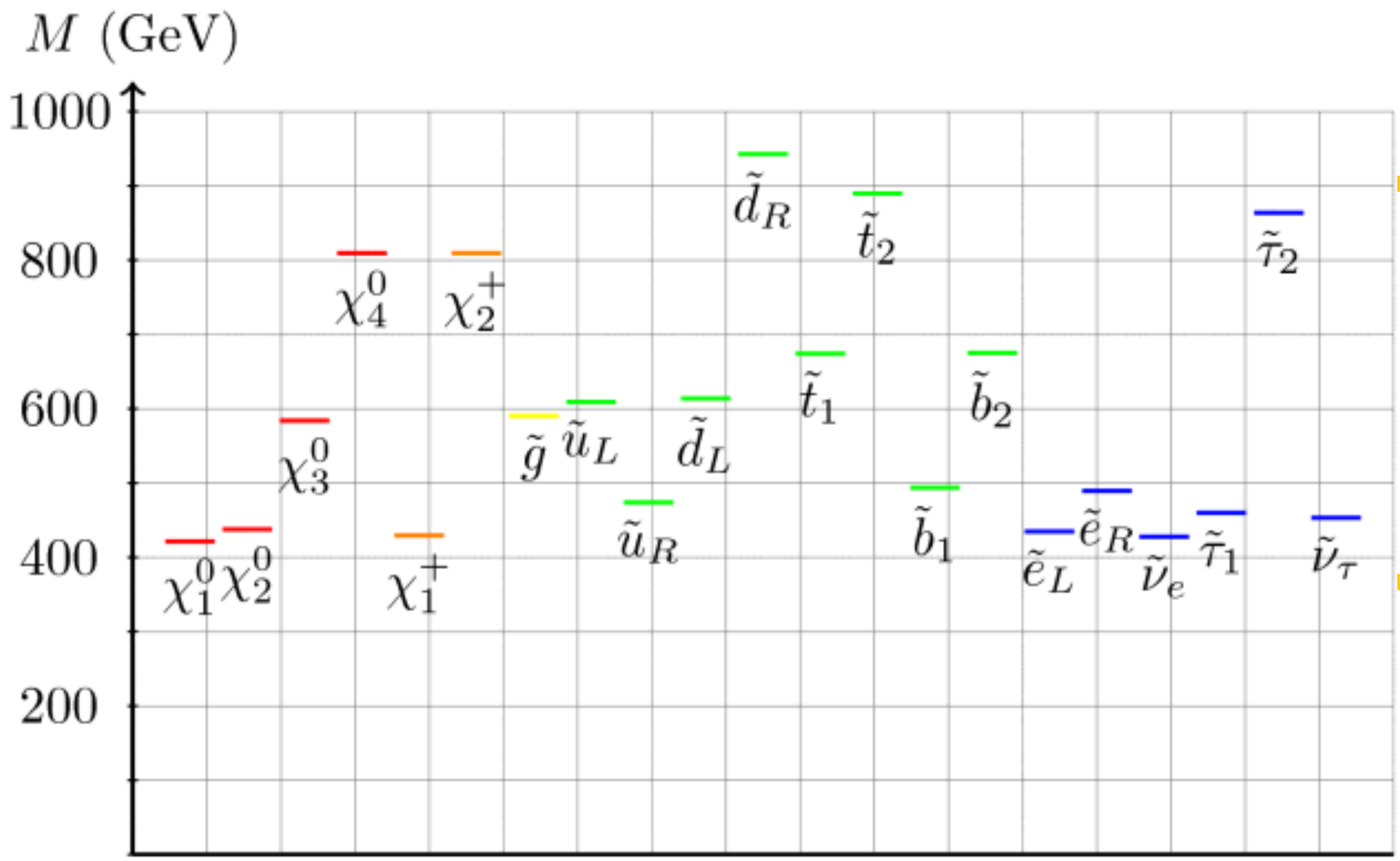
From: Nima Arkani-Hamed



- Such a spectrum preserves SUSY solution to fine-tuning ("Natural SUSY").
- Need dedicated searches for direct stop and sbottom production.
  - ATLAS direct sbottom paper out
  - Rather small number of possible decay chains
  - Optimal: dedicated exclusive analyses
  - Some decays particular challenging e.g. stop to c + LSP or small mass splitting, i.e. ΔM(stop, gaugino) small
- Need dedicated searches for gluino production with intermediate stops, sbottoms.
  - First CMS & ATLAS $E_{T,miss}$ + bjets (+lepton) results available

Main stop decays→ t+LSP; $\chi^{\pm}$+b ($\chi^{\pm}$→W+LSP, or slepton+LSP); c+LSP

Compressed spectrum



SUSY masses close together

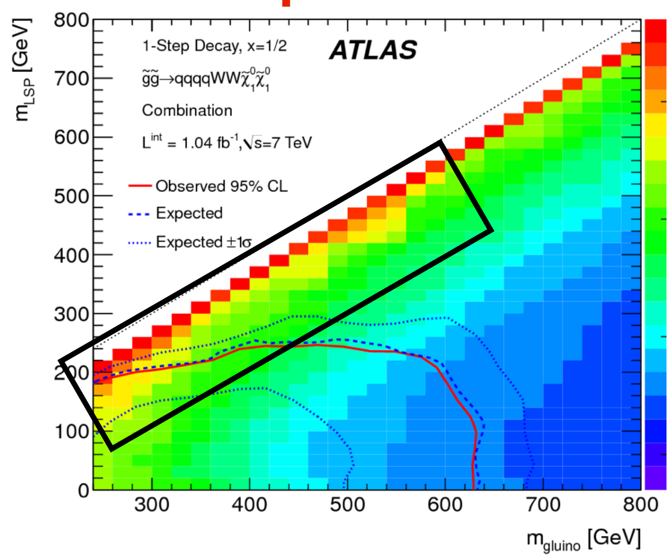
Consequences:
- Softer jets and leptons
- Softer E_T^{miss} spectrum

Challenges:
- Signal-Background discrimination
- Pileup (soft jets!)
- Trigger

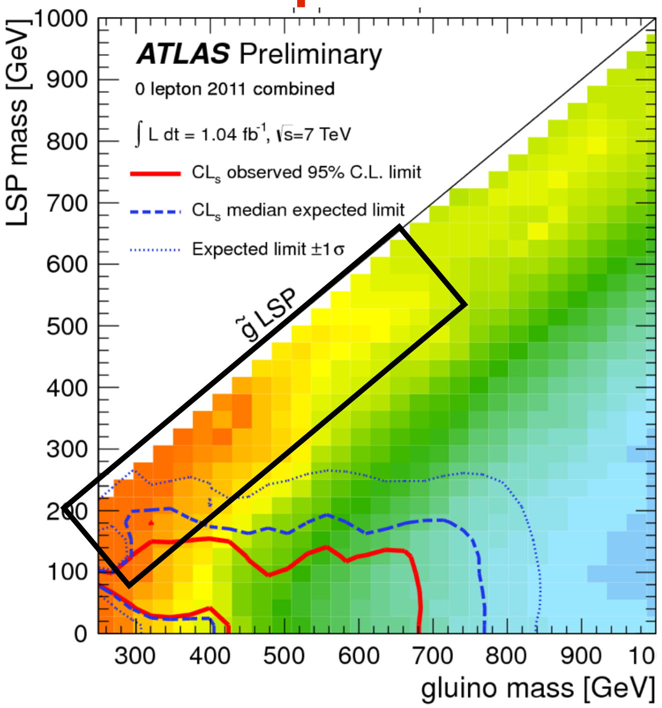
Compressed spectrum

- Lepton searches stronger (for decays with leptons)
- Need dedicated searches
  - soft-lepton(s)
  - and or soft-jets

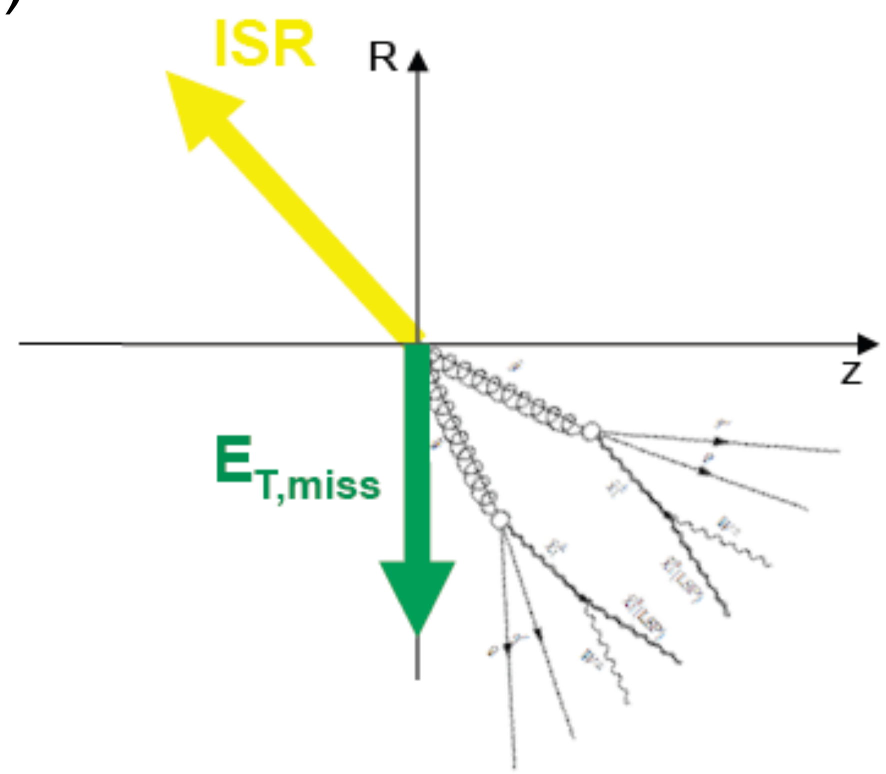
1-lep results



0-lep results



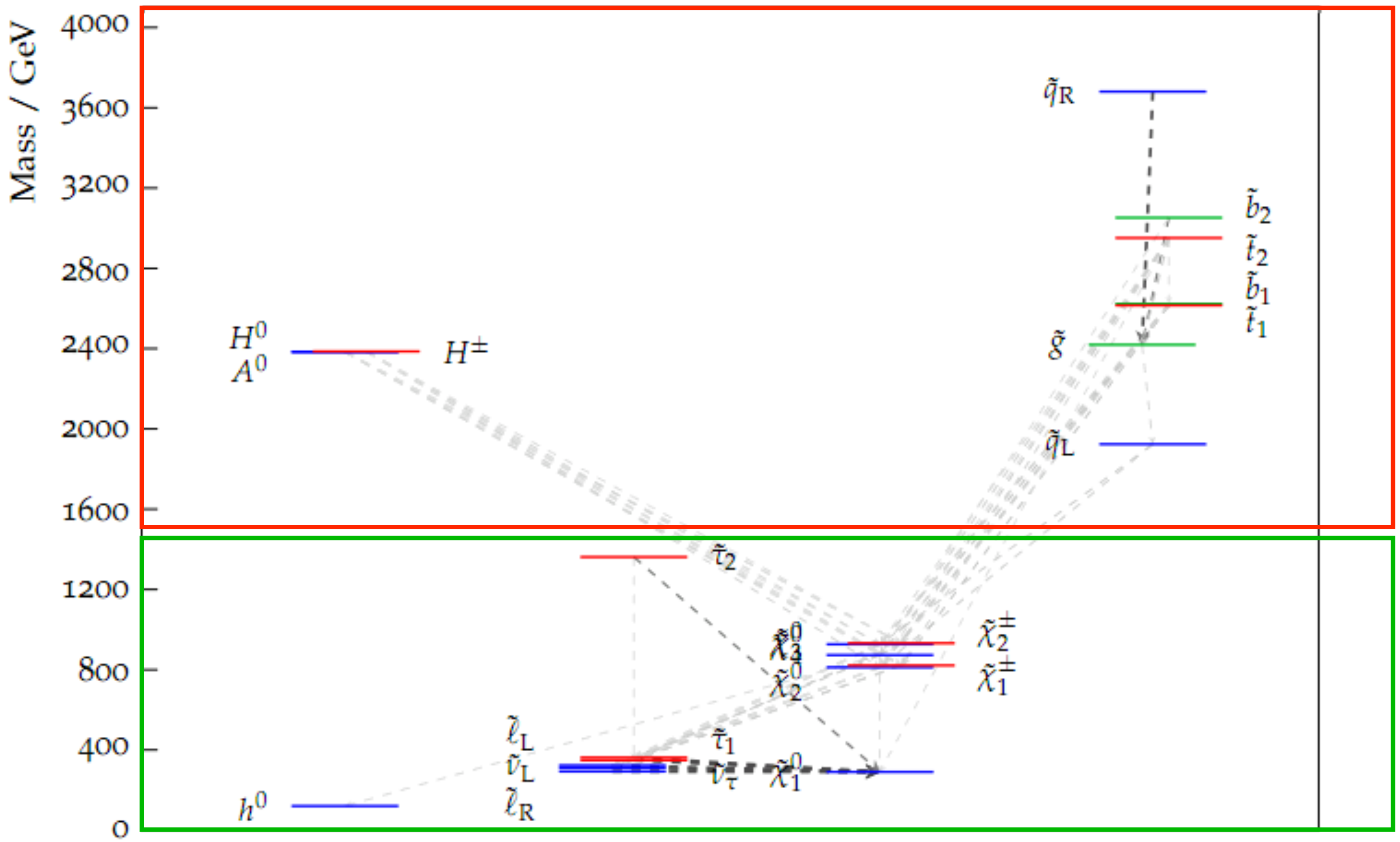
- Discriminating variables:
  - jet, lepton multiplicity
  - $E_{T,miss}$ (ISR boost)



System recoils against ISR jet:

- soft objects obtain slightly higher p_T (boost)
- $E_{T,miss}$ enhanced due to: boost & two LSPs are aligned

Weak production



strongly produced squarks & gluinos inaccessible

weakly produced SUSY particles accessible

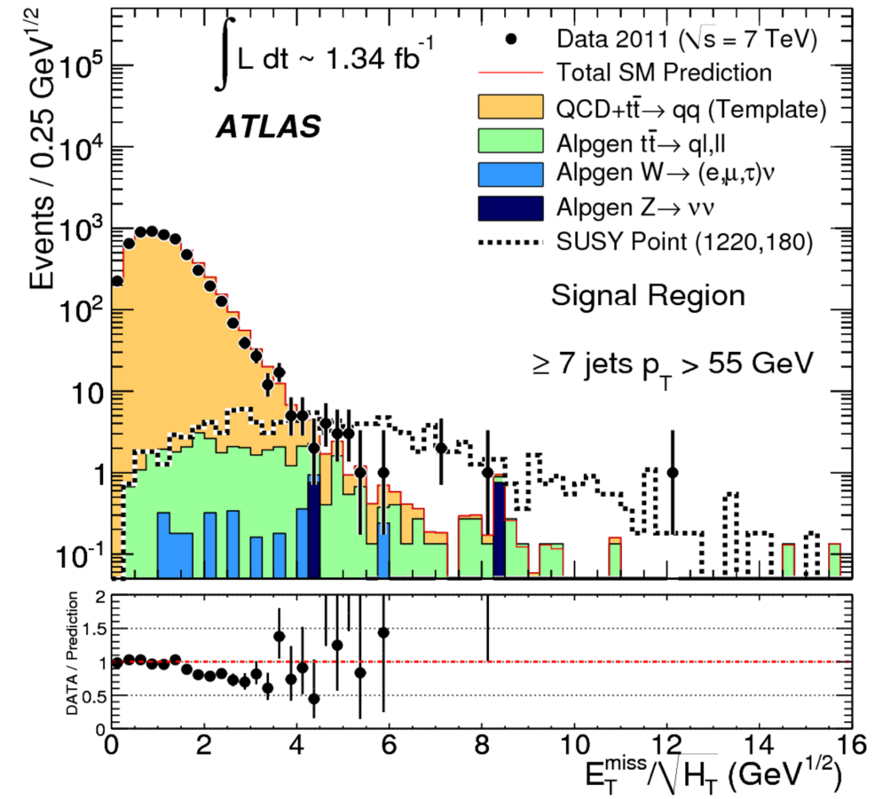
- Need searches for direct weak production modes:
  - charginos, neutrlinos, but also sleptons
- For important decay channels (emitting V bosons or via sleptons).

Small cross sections are challenging. But clear signatures allow dedicated (exclusive) searches.

Improve analyses (techniques)

1. Instead of cut & count, employ shape fits
   - OK for exclusion limits, where signal and background shapes apriori known.
   - Difficult for discovery test: would have to make assumptions about signal shape
2. Reduce systematic uncertainties
   - Experimental (e.g. JES) and theoretical (e.g. PDFs) unc.
   - In particular good for:
     i. searches with “loose” SR where systematics dominate, and
     ii. when moving to shape-exclusion-fit
3. MVAs
   - Can improve signal-background discrimination power
   - Maybe best suited for exclusive channels (search for specific signal).
4. New Discrimination variables
   - Meff, MT2, alphaT, Razor, ...
   - continue development

Example for different signal and background shapes.



Interpretation of results

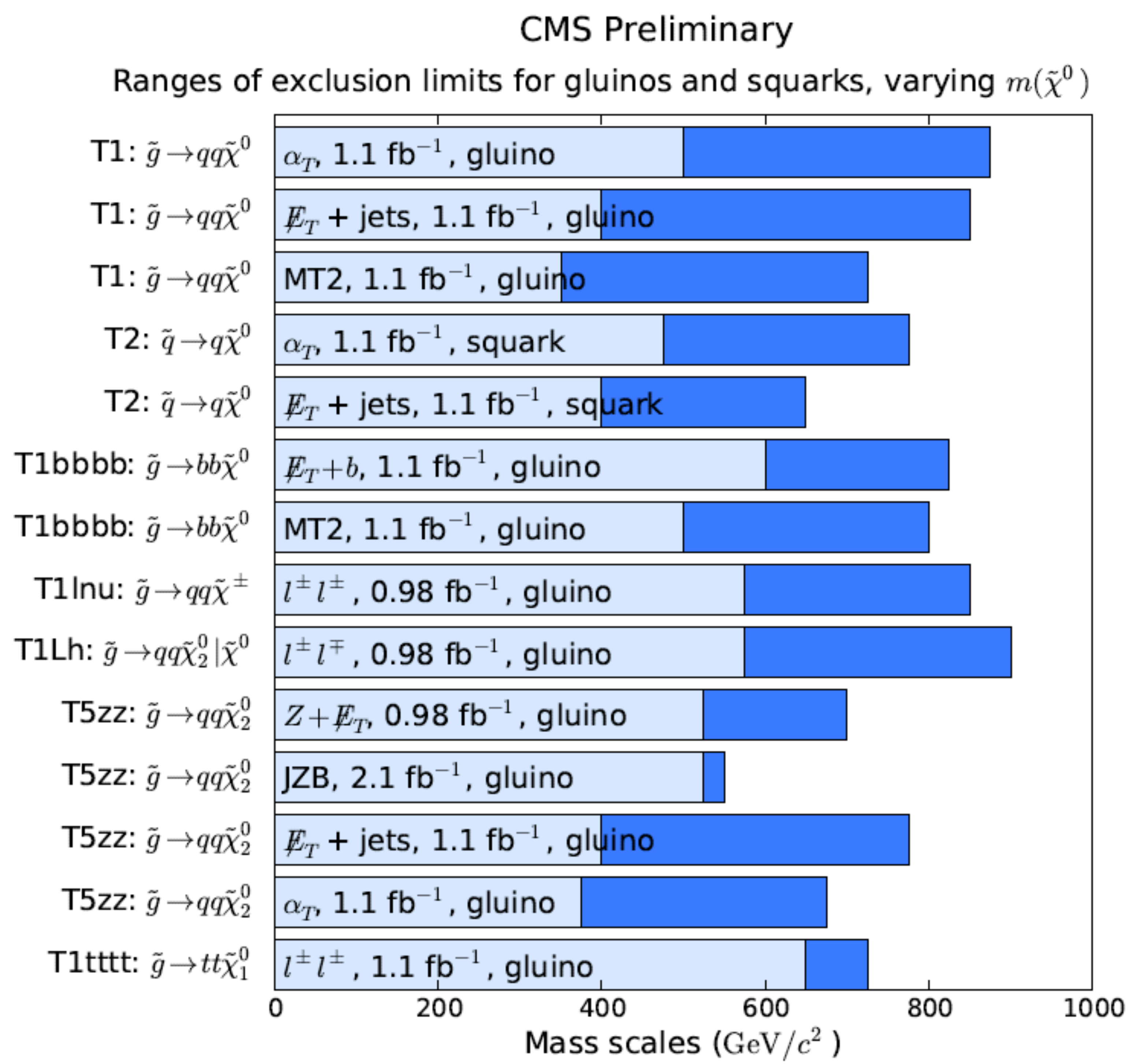
- make numerical results available (HEPdata, etc.)
- Simplified Models, unfolding, etc.

Conclusions

- **Current LHC SUSY constraints:**
  - Squarks and gluinos >~ 1 TeV
  - This statement applies to:
    - High-scale models (e.g. MSUGRA/CMSSM) or large mass hierarchies
    - for first 2 generations squarks
  - Weaker constraints elsewhere
- Until LHC moves to design collision energy in 2014
- **Maximize SUSY coverage**
  - dedicated analyses to target challenging signatures
    - light 3rd generation; compressed spectrum; weak production; and other not yet (well) covered signatures.
  - improve analyses
- Will have to adapt to increased lumi and pileup for 2012 running

Backup

CMS SUSY search limits



For limits on $m(\tilde{g}), m(\tilde{q}) >> m(\tilde{g})$ (and vice versa). $\sigma^{\mathrm{prod}} = \sigma^{\mathrm{NLO-QCD}}$.
$m(\tilde{\chi}^{\pm}), m(\tilde{\chi}_2^0) \equiv \frac{m(\tilde{g}) + m(\tilde{\chi}^0)}{2}$.
$m(\tilde{\chi}^0)$ is varied from 0 GeV/c^2 (dark blue) to $m(\tilde{g})-200$ GeV/c^2 (light blue).

How to make numerical SUSY results available

(HEPData and all that)

Nov 3rd 2011

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Results provided in Paper / CONF note

example **upper limits table**

N_{vis} σ_{vis}

Sig. Reg.	95% C.L. N events CL_s (PCL)	95% C.L. σ_{eff}(pb) CL_s (PCL)
3JA (1 btag m_{eff} >500 GeV)	240 (206)	0.288 (0.247)
3JB (1 btag m_{eff} >700 GeV)	51 (40)	0.061 (0.048)
3JC (2 btag m_{eff} >500 GeV)	65 (53)	0.078 (0.064)
3JD (2 btag m_{eff} >700 GeV)	14 (11)	0.017 (0.014)

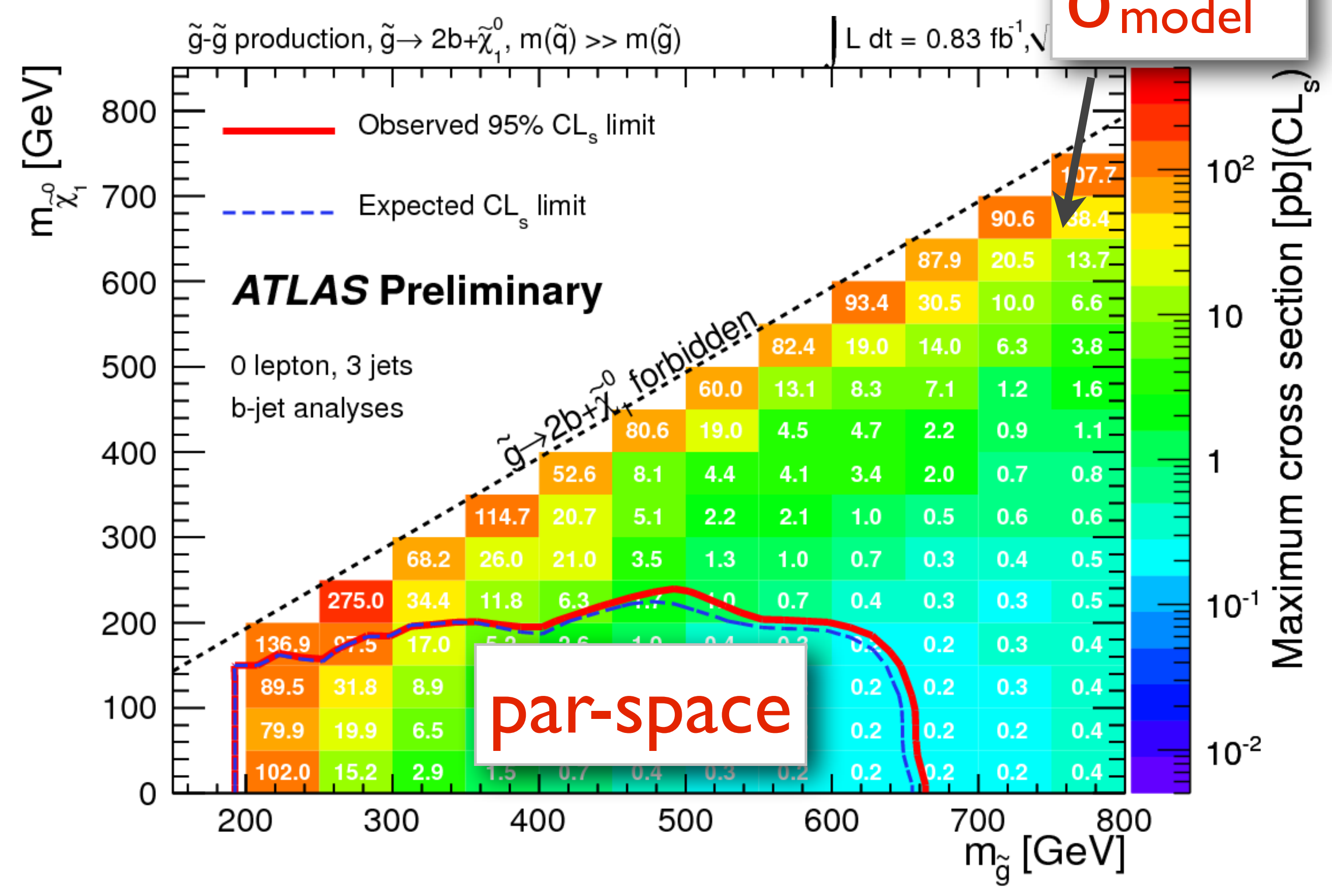
For each signal-region (SR) provide

- upper limit on the number of visible signal events in SR:
  $N_{vis} = N_{vis}(N^{obs}, N^{bkg}, \Delta^{bkg})$
- upper limit on the visible signal cross-section in SR:
  $\sigma_{vis} = A \times \varepsilon \times \sigma = N_{vis} / L$
  $\sigma_{vis}(N^{obs}, N^{bkg}, \Delta^{bkg}, L, \Delta L)$

Provide expected & observed limits

Default stats. method: CLs

example **interpretation**

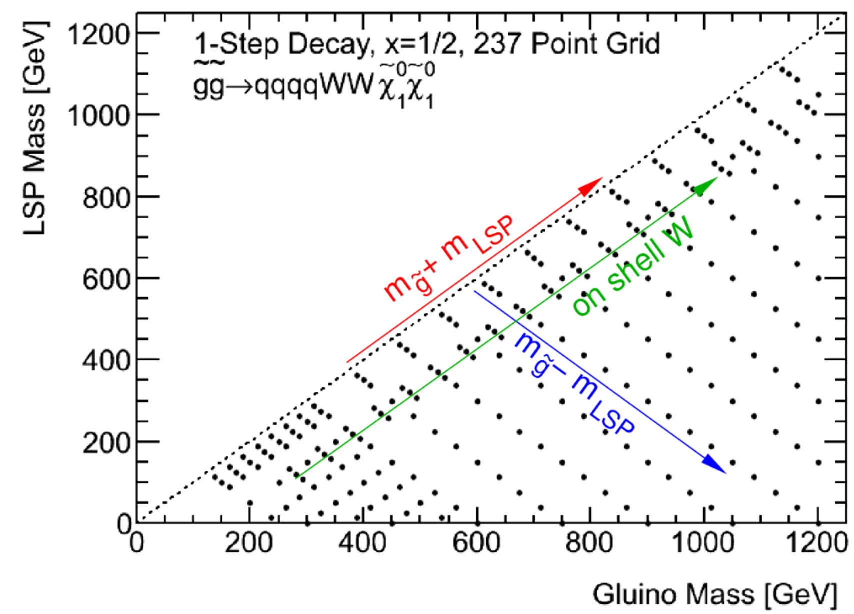


For signal model(s), using best exp. SR (per point)

- limits in the model parameter space
  CLs(N^{obs}, N^{bkg}, Δ^{bkg}, , L, ΔL, $(A \times \varepsilon)^{model}$, $\Delta(A \times \varepsilon)^{model}$, $\sigma^{sig\ prod}$, $\Delta\sigma^{sig\ prod}$)
- [optional] upper limit on the cross-section:
  $\sigma_{model} = N_{vis} / [(A \times \varepsilon)^{model} \times L]$
  $\sigma_{model}(N^{obs}, N^{bkg}, \Delta^{bkg}, L, \Delta L, (A \times \varepsilon)^{model}, \Delta(A \times \varepsilon)^{model})$

Input to HEPdata (starting with winter 2012 results)

example "plane"



- Plots, interpretation (CLs limits) from paper
- For each signal region, and for all relevant models
  - acceptance (A), defined next page [$A = N_{fiducial}/N_{total}$]
  - efficiency (ε), defined next page [$\varepsilon = N_{fiducial\text{-}reco}/N_{fiducial}$]
  - Δ^{tot} total systematic and theoretical signal uncertainty,
    not including MC stat. unc.
  - CLs value
- For all relevant models
  - Number of generated MC events (can be used to derive all signal MC stat. unc.)
  - σ^{tot} total signal production cross section
- Relevant models:
  - E.g. small number of simplified models (easy kinematics facilitate theorists debugging their cutflow)
  - no smoothing/interpolation between points

A theorists can probe his/her favorite model(s) by:

- take our background estimate (per SR): $N^{tot} \pm \Delta^{tot}$ (numbers in publication)
- implement event selection (per SR), validate against our acceptance numbers (in HEPdata)
- implement a detector simulation, validate against our efficiency numbers (in HEPdata)
- run on favorite model, and calculate sensitivity/limits

Definition of "fiducial" (or what's A and ε)

Guiding idea for fiducial cuts:

- defined using truth and hadron level quantities
- can be implemented by a theorist (w/o detector simulation)

Use a **common definition** for all ATLAS SUSY public results !

A×ε is the full event selection efficiency at detector level.

Acceptance $A = N_{fiducial} / N_{total}$

where fiducial cuts are based on following objects:

- truth electrons/muons/E_T^{miss} (non-interacting)
- hadron level jets
- heavy-flavor: b-quark matched to jet, at parton level

all above with analysis cuts on pT, eta.

Apply

- object overlap-removal (in eta-phi space)

Efficiency $\varepsilon = N_{fiducial\text{-}reco} / N_{fiducial}$

where fiducial-reco cuts are our nominal analysis cuts, applied to detector level variables.
Differences to Acceptance include:

- Reconstruction inefficiencies
- Full particle identification cuts
- Resolution effects
- trigger inefficiencies

Note that ε can be bigger or smaller than one.

From Patrick Meade

WHAT DO THEORISTS NEED?

- Efficiencies for various objects and rough parametrization as a function of pT or eta
  - →Provide A and ε separately for signal grid(s) in HEPdata
- More explicit understanding of how other objects are treated
  - →Provide accurate description in paper.
- Simulated event yields for several signal points
  - →Provide (σ, A, ε) for signal grid(s) in HEPdata
- Detailed description of CLs calculation, how systematics are treated, likelihood functions
  - →Provide details of stats. methods(*) in paper
  - →Provide tot. systematics for signal grid(s) in HEPdata
- Precise definitions of variables!
  - →Should be contained in every paper

(*) e.g. describe combination of el, mu channels