Implications of current LHC results for supersymmetry

and neutralino dark matter

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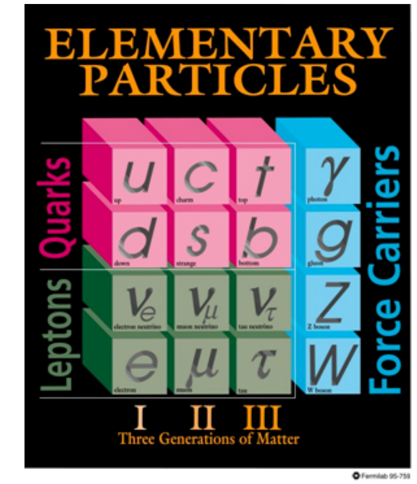
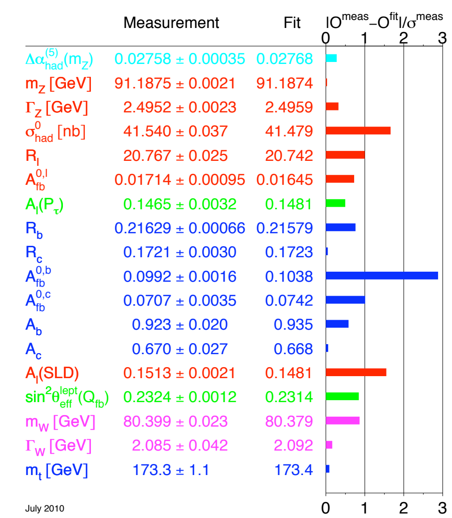
The Standard Model



<1973: theoretical foundations of the SM

- renormalizability of SU(2)xU(1) with Higgs mech. for EWSB
- asymptotic freedom, QCD as gauge theory of strong force
- KM description of CP violation

Followed by more than 30 years of consolidation



- **experimental** verification via **discovery** of
  - gauge bosons: gluon, W, Z
  - matter fermions: charm, 3rd family
- experimental **precision measurements**
  - EW radiative corrections
  - running of the strong coupling
  - CP violation in the 3rd generation
- technical **theoretical advances** (higher-order calculations...)

Only missing piece: the Higgs ?

NB: Unitarity tells us that the dynamics of EWSB should become apparent around the TeV scale.

... and beyond

The Standard Model is tremendously successful,
nevertheless it can't be the ultimate theory. Too many open questions.

- Why are there 3 generations of quarks and leptons?
- What is the origin of flavour mixing an CP violation?
- Why is the SM anomaly free?
- Can the different interactions (and matter fields) be unified?
- What stabilizes the electroweak scale?
- ....

Attempts to answer these questions, in particular regarding the naturalness and hierarchy problem, let us expect new physics at TeV energies.

(another) genuine motivation to build the LHC

Besides, the experimental evidences of neutrino masses, dark matter and the baryon asymmetry tell us that we are missing something fundamental.

Supersymmetry

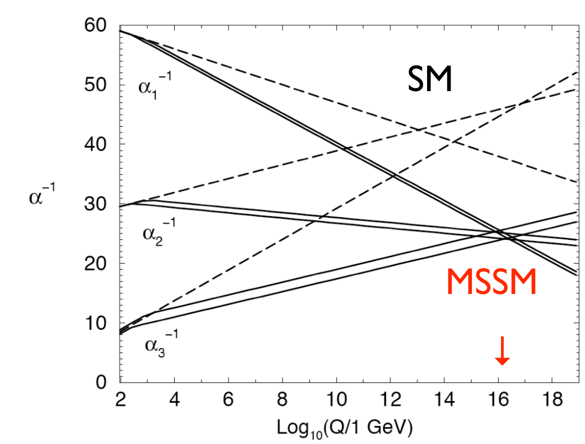
The beauties of SUSY:

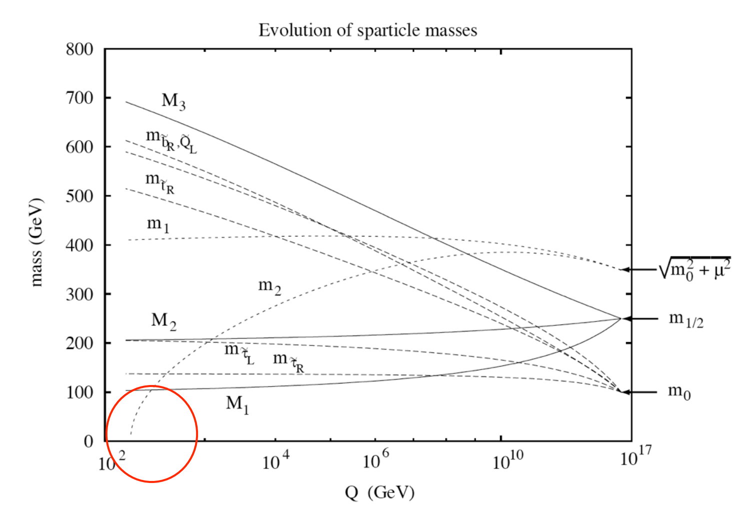
- Unique extension of space-time symmetries
- Solution to the gauge hierarchy problem
- Gauge coupling unification
- Radiative EWSB, light Higgs
- Cold dark matter candidate
- Very rich collider phenomenology

➯ Most popular and best-studied BSM theory

"Provided superpartners exist at or around the TeV scale"

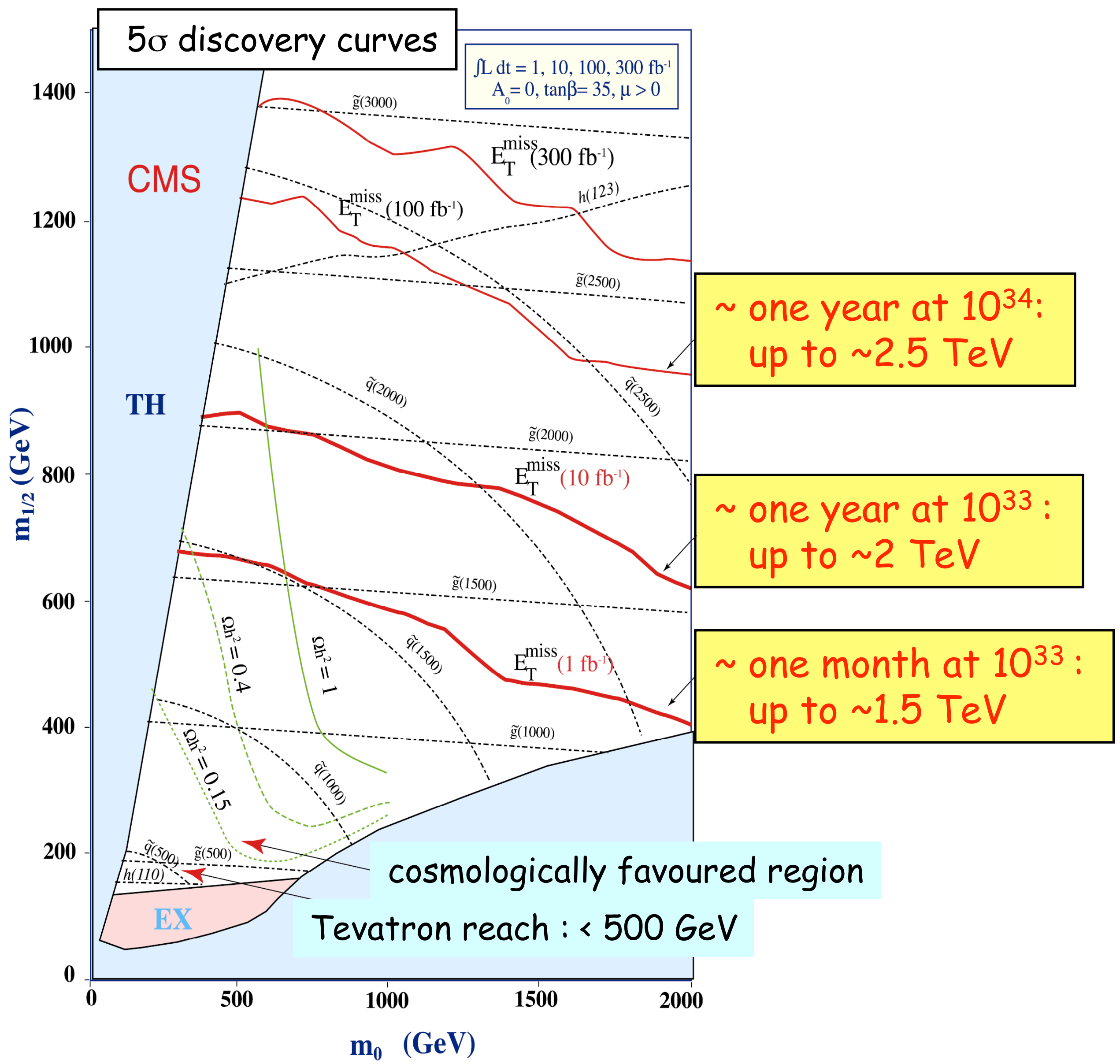
$$\delta m_H^2 = \left(\frac{g_f^2}{16\pi^2}\right)(\Lambda^2 + m_f^2) - \left(\frac{g_S^2}{16\pi^2}\right)(\Lambda^2 + m_S^2)$$
$$= \mathcal{O}\left(\frac{\alpha}{4\pi}\right)\,|m_S^2 - m_f^2|$$

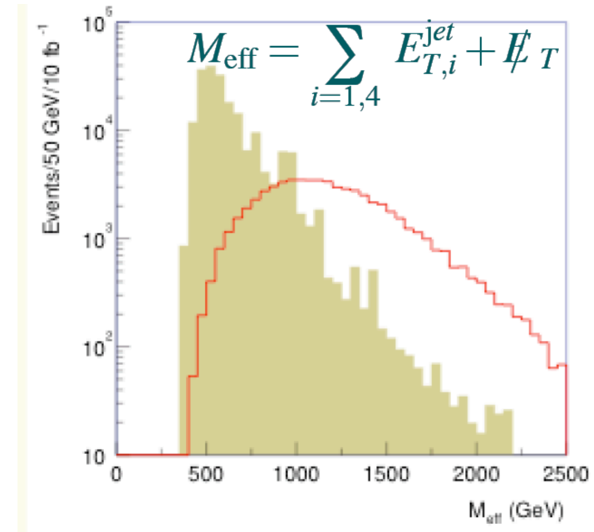


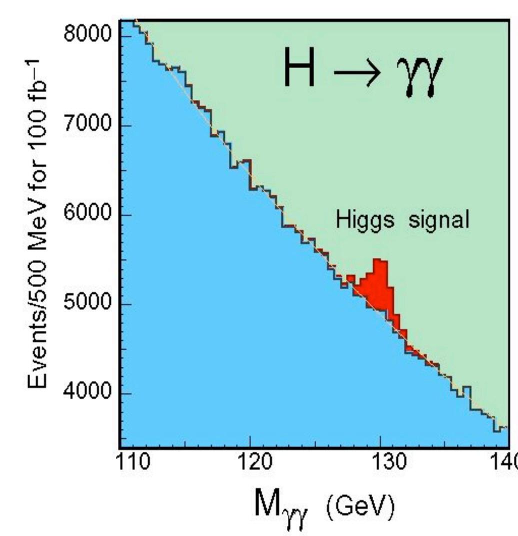


Before LHC turn-on

Very optimistic view: if SUSY is light (as we expect…!) it will be discovered early on.

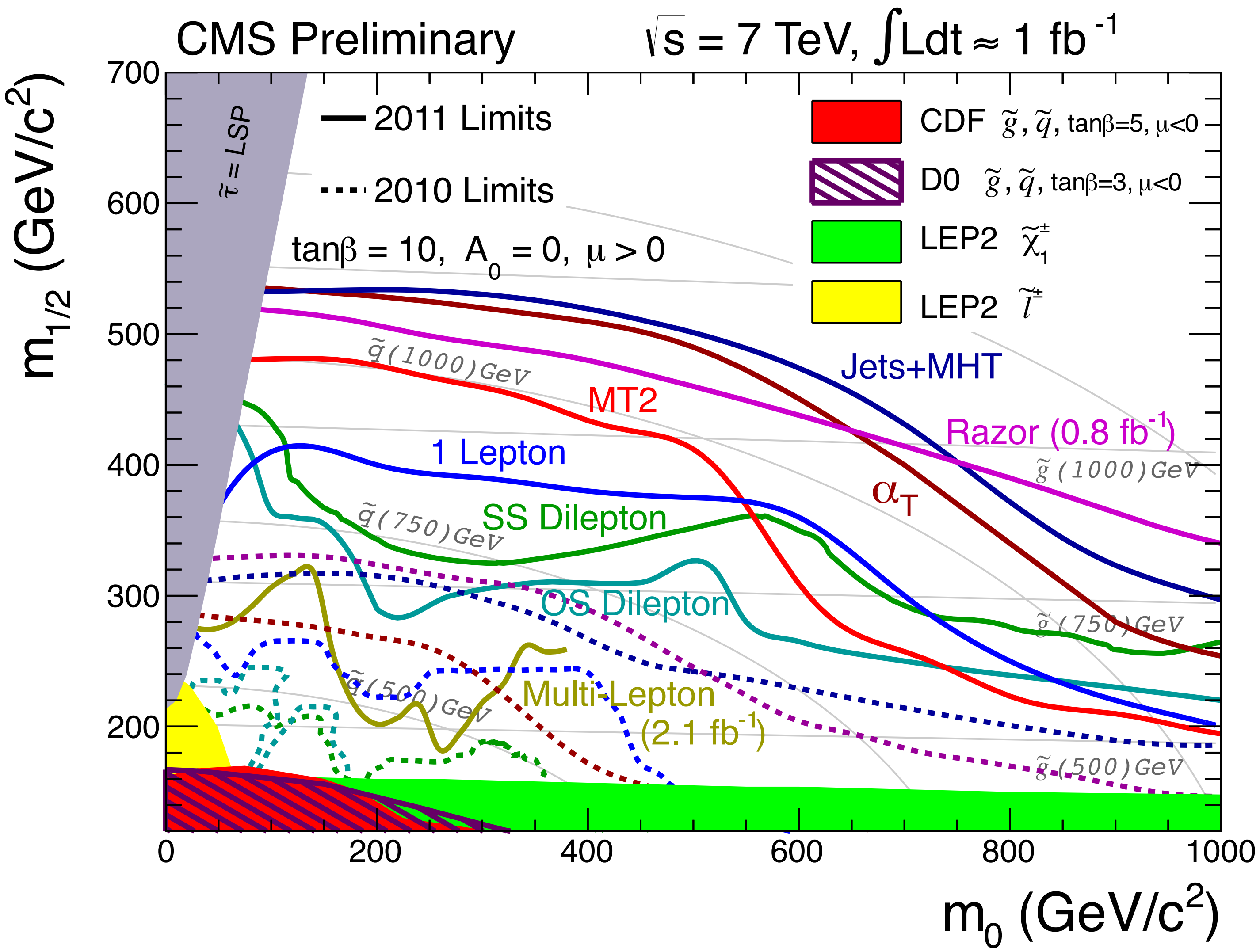






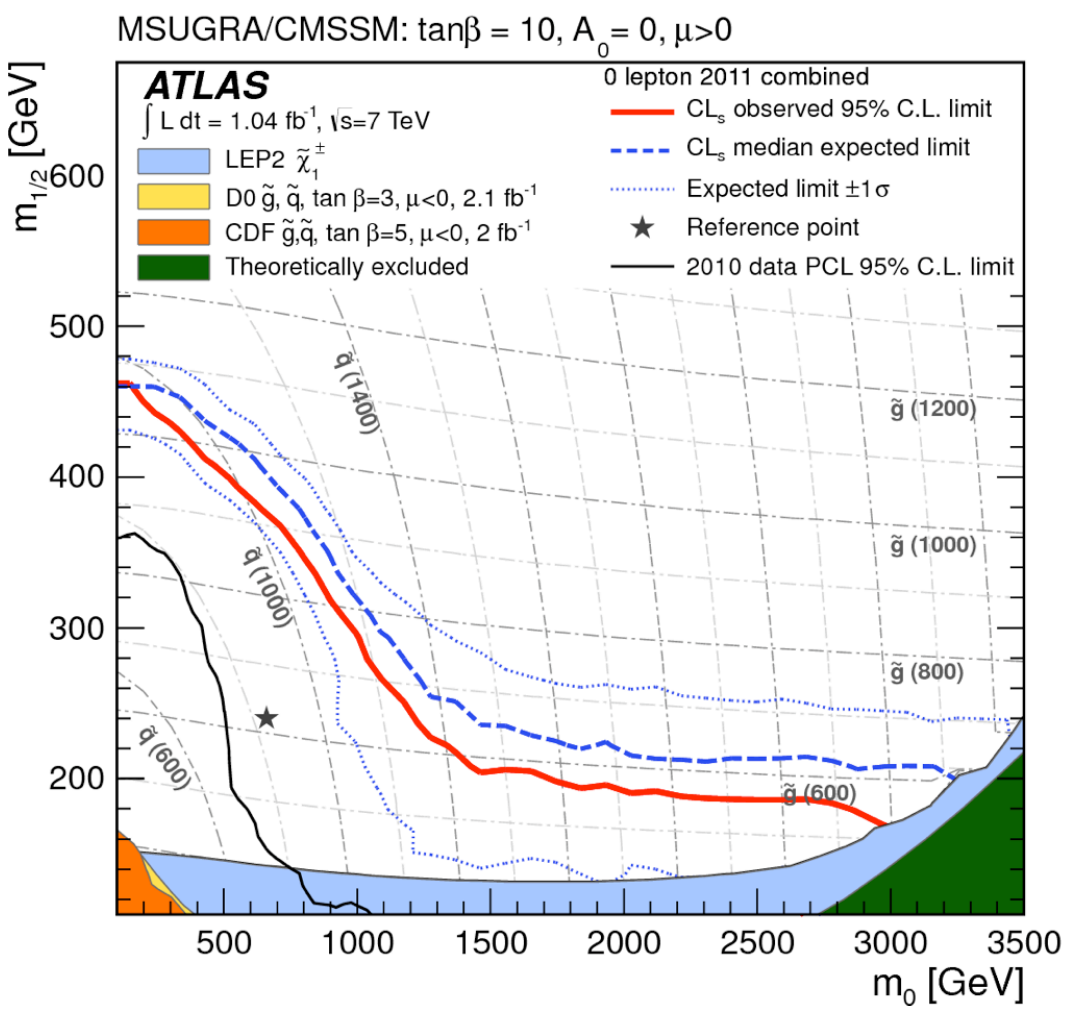
Much easier than discovering the Higgs…

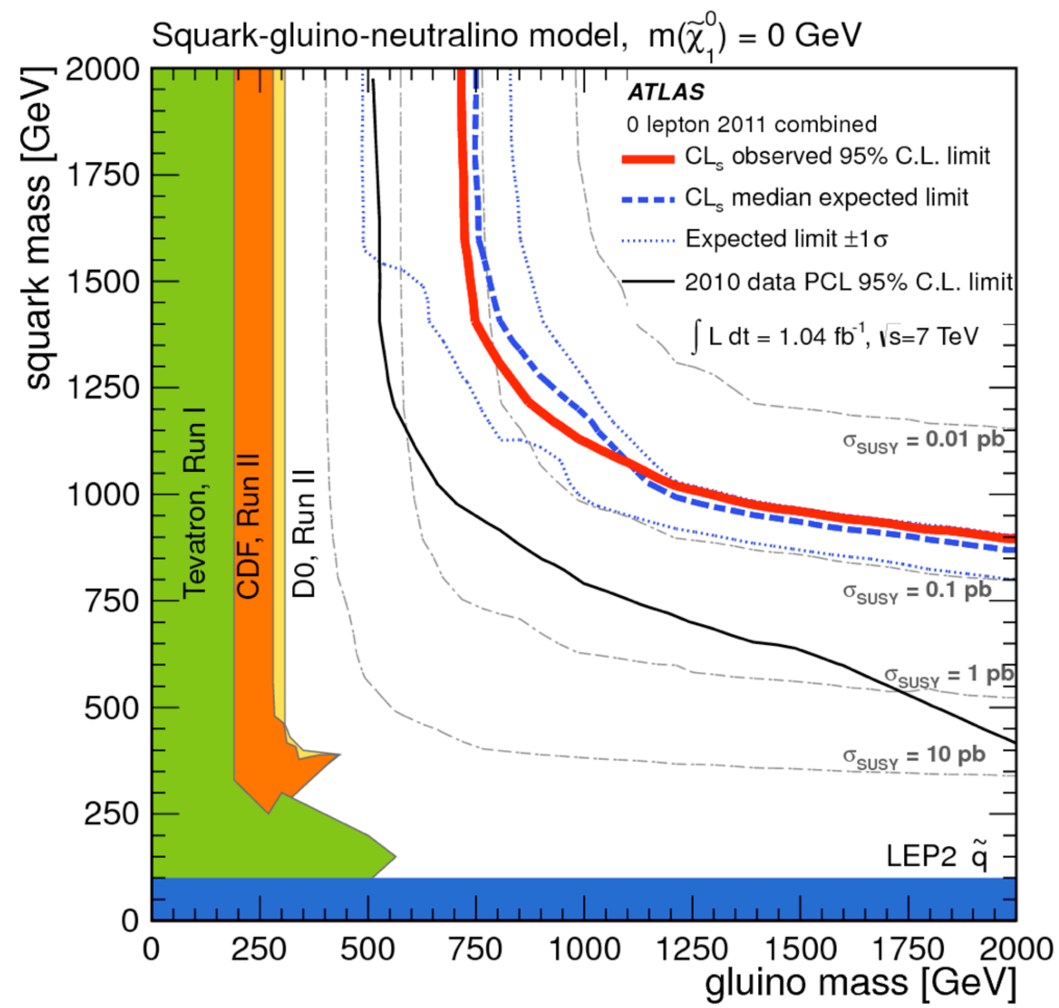
Now



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

ATLAS, arXiv:1109:6572





Looks grim :-(?

27 August 2011 Last updated at 06:41 GMT

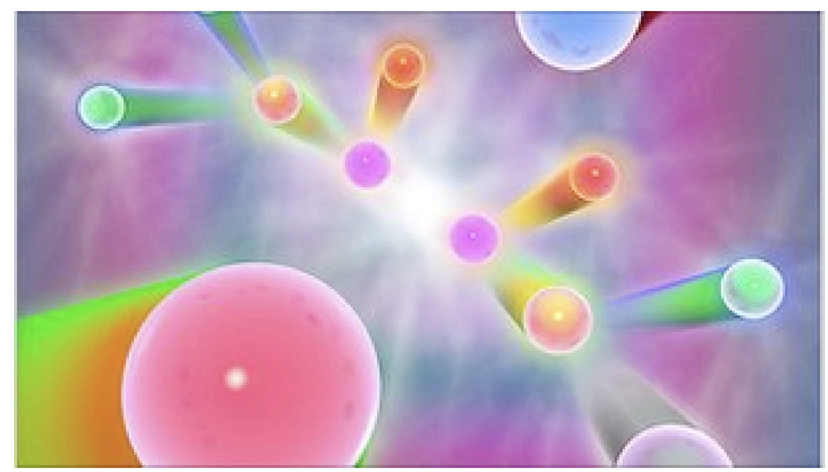
LHC results put supersymmetry theory 'on the spot'

By Pallab Ghosh
Science correspondent, BBC News

Results from the Large Hadron Collider (LHC) have all but killed the simplest version of an enticing theory of sub-atomic physics.

Researchers failed to find evidence of so-called "supersymmetric" particles, which many physicists had hoped would plug holes in the current theory.

Theorists working in the field have told BBC News that they may have to come up with a completely new idea.



Supersymmetry predicts the existence of mysterious super particles.

This looks grim!

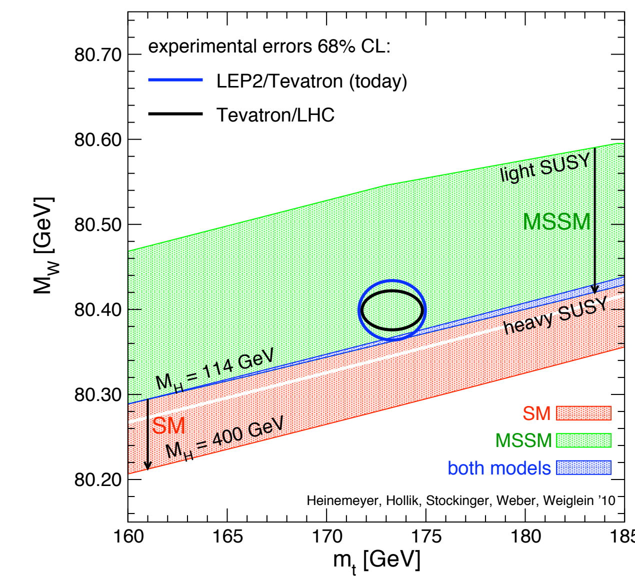
Let's reconsider

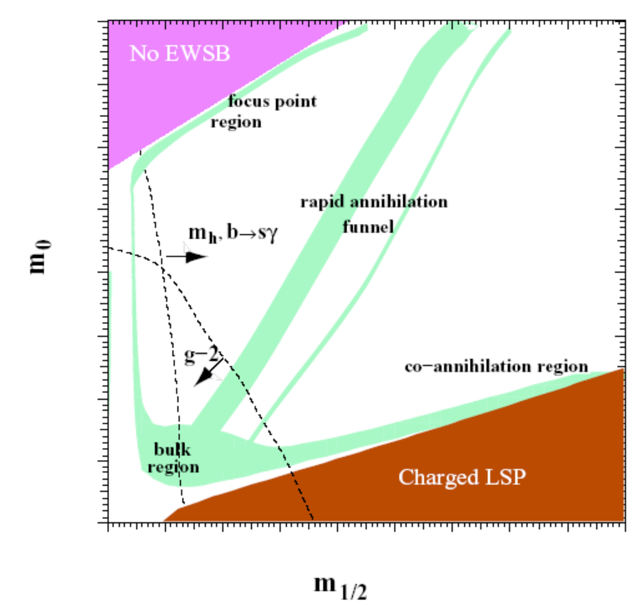
Arguments for weak-scale SUSY

- Solution to the gauge hierarchy problem
  Needs light stops, light higgsinos, somewhat light gluino
- Gauge coupling unification
  TeV-scale fermionic states → could be split SUSY
- Radiative EWSB, light Higgs
  heavy top effect
  m_h>115 GeV prefers heavy stops (finetuning prize of LEP)
  electroweak precision measurements prefer heavy SUSY
- Cold dark matter candidate
  TeV-scale LSP could do the job, just needs some
  efficient annihilation mechanism, e.g. higgsino LSP
- Very rich collider phenomenology
  Well, this entirely depends on phase-space ...
  and for the time being we are just running at 1/2 force

➪ Still great, but more "honest" prospects

$$\delta m_H^2 = \left(\frac{g_f^2}{16\pi^2}\right)(\Lambda^2 + m_f^2) - \left(\frac{g_S^2}{16\pi^2}\right)(\Lambda^2 + m_S^2) = \mathcal{O}\left(\frac{\alpha}{4\pi}\right)|m_S^2 - m_f^2|$$





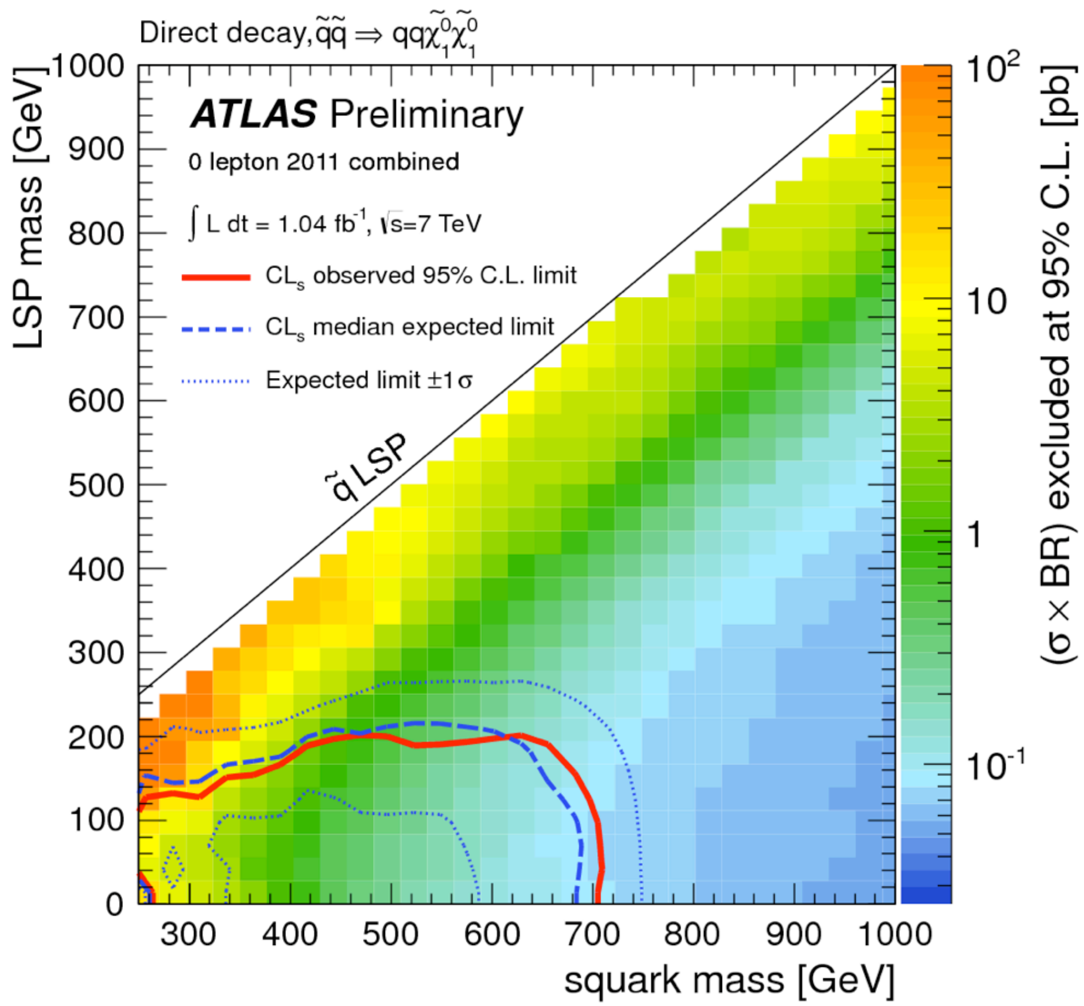
Beyond CMSSM limits: simplified model spectra

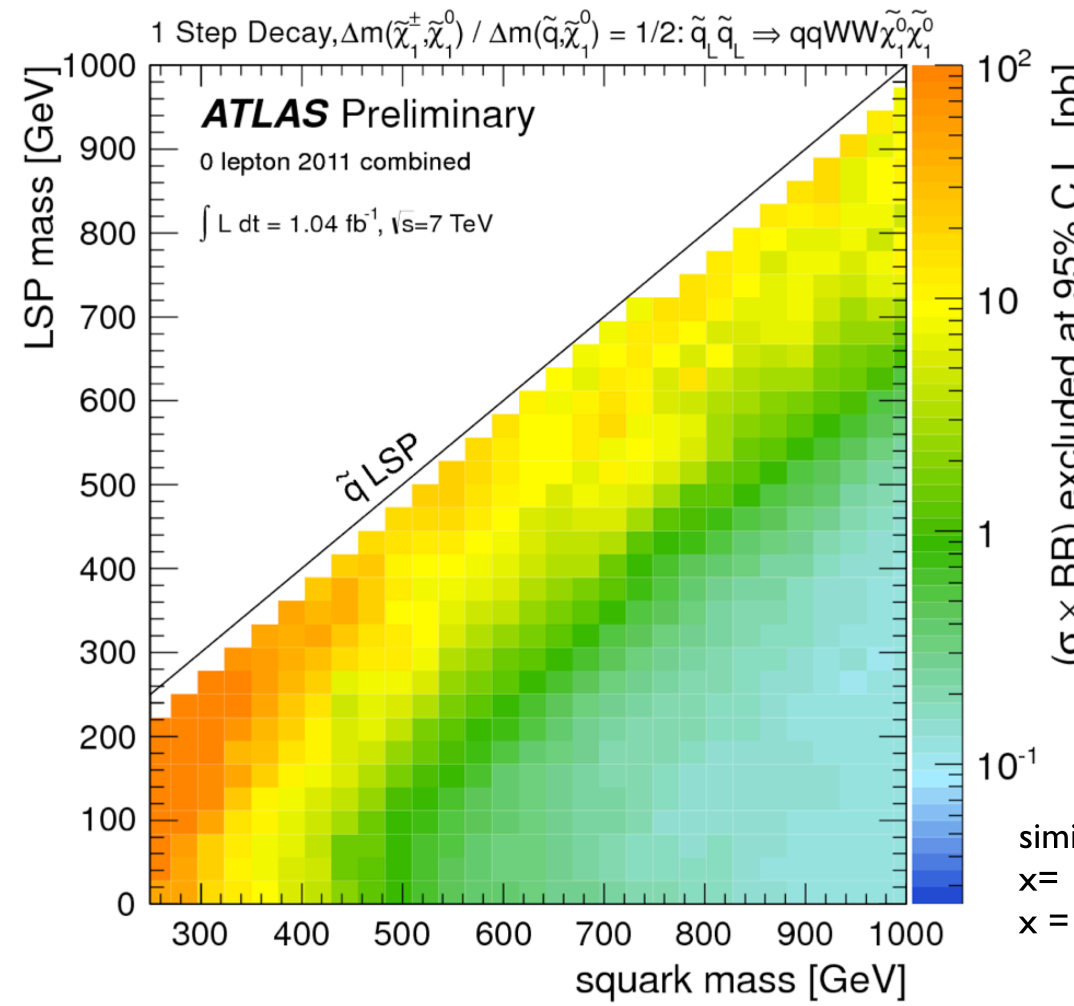
A simplified model is defined by an effective Lagrangian describing the interactions of a small number of new particles. Simplified models can equally well be described by a small number of masses and cross-sections. These parameters are directly related to collider physics observables, making simplified models a particularly effective framework for evaluating searches and a useful starting point for characterizing positive signals of new physics.

D. Alves et al., arXiv:1105.2838

ATLAS jets+MET search

– interpretation in simplified models: squarks –





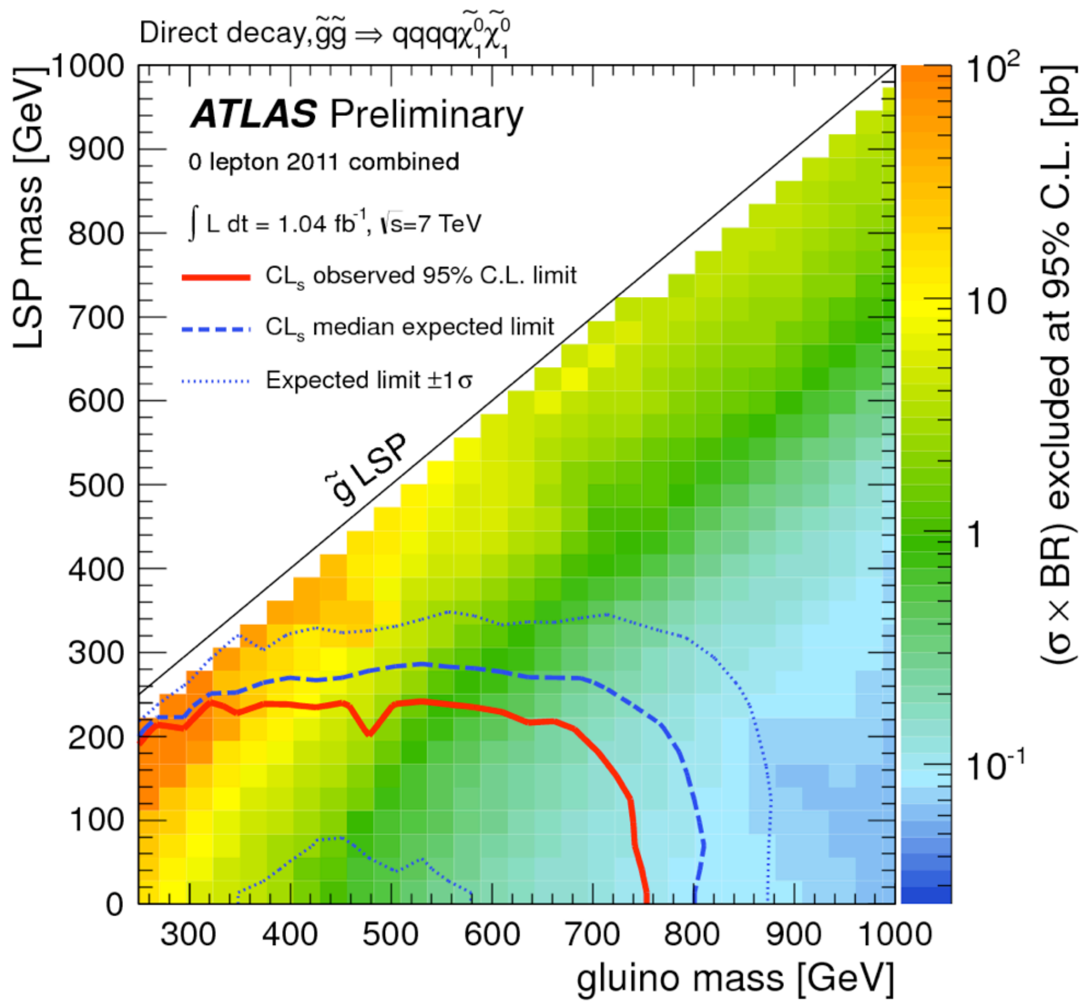
similar for x= 1/4 and x = 3/4

Exclusion limits in the squark-LSP mass plane for direct [left] and one-step [right] squark decays.

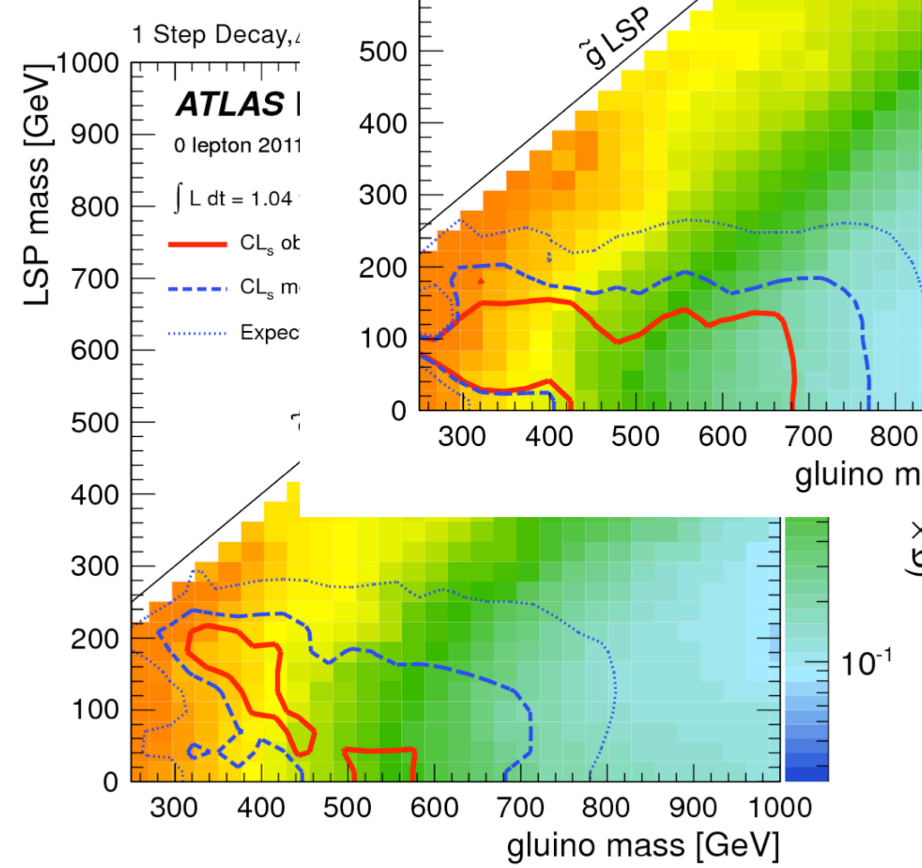
NB: In the case of direct decays, the cross-section for squark_{L,R} production is assumed, however, squark_R production is neglected for the one-step cascade grids, effectively halving the production cross-section. This only applies to the limit contours. For the one-step cascade grids, the nominal cross-sections are too low for any model points to be excluded at 95% C.L., hence no limit contours are drawn.

ATLAS jets+MET search

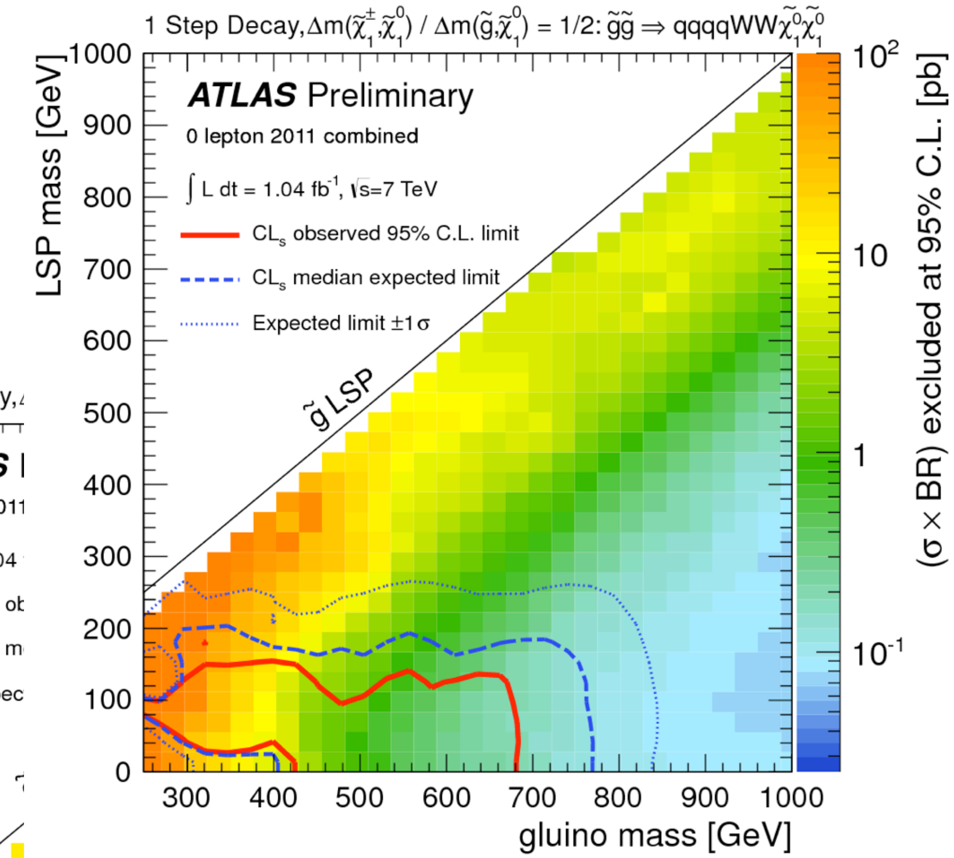
– interpretation in simplified models: gluino –



x=1/4

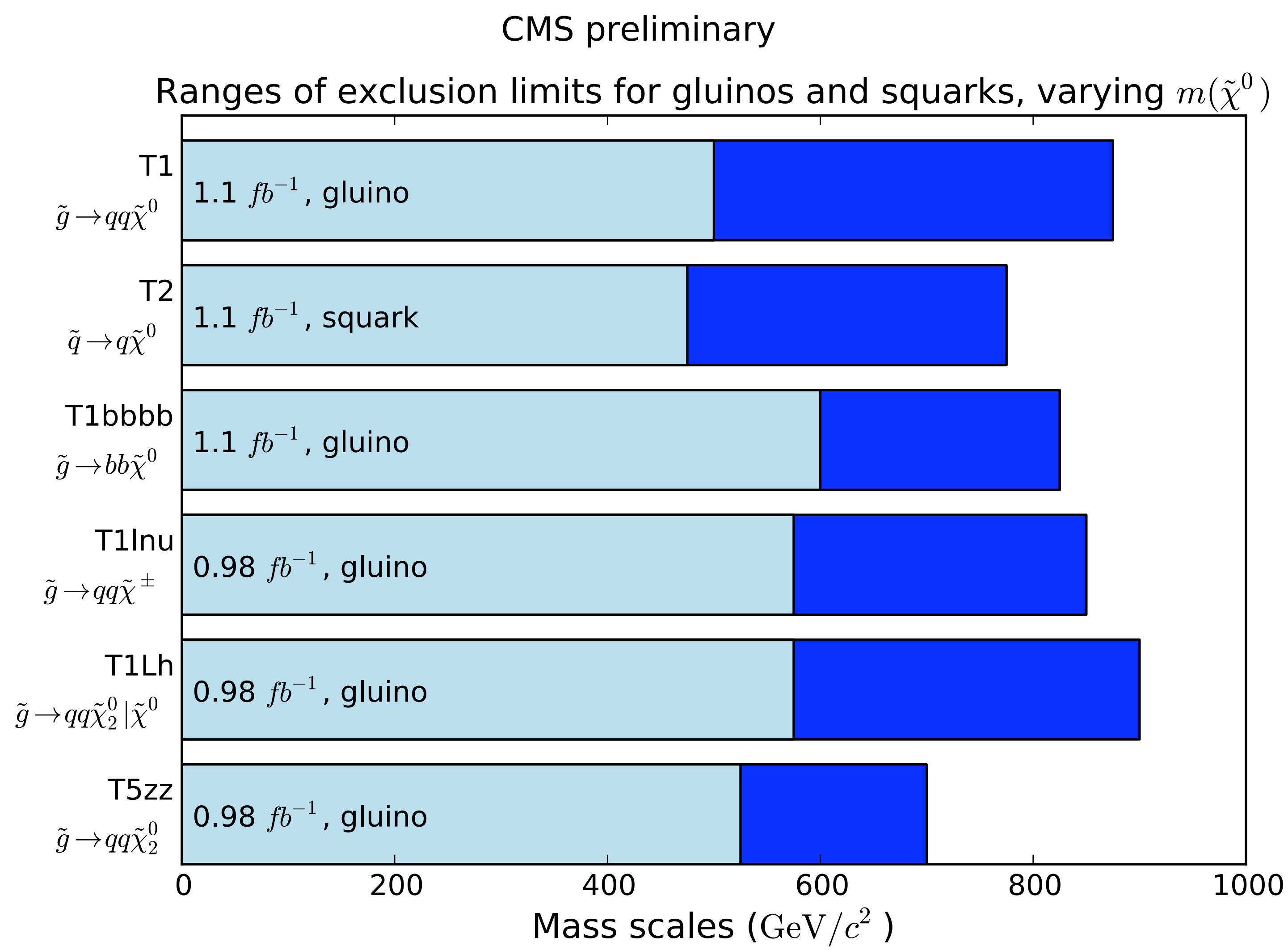


x=1/2



Exclusion limits in the gluino-LSP mass plane for direct and one-step gluino decays.

CMS results for simplified model spectra



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).

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

So what does this imply for SUSY in general?

Interpreting LHC SUSY searches in the phenomenological MSSM

S. Sekmen, SK, J. Lykken, S. Moortgat, S. Padhi, L. Pape,
M. Pierini, H.B. Prosper, M. Spiropulu

- We interpret within the phenomenological MSSM (pMSSM) the results of SUSY searches published by the CMS collaboration based on the first 1 fb-1 of data taken during the 2011 LHC run at 7 TeV.
- The pMSSM is a 19-dimensional parametrization of the MSSM that captures most of its phenomenological features. It encompasses and goes beyond, a broad range of more constrained SUSY models.
- Performing a global Bayesian analysis, we obtain posterior probability densities of parameters, masses and derived observables.
- In contrast to constraints derived for particular SUSY breaking schemes, such as the CMSSM, our results provide more generic conclusions on how the current data constrain the MSSM.

arXiv:1109.5119

pMSSM

- 19-dimensional parametrization of the R-parity conserving MSSM with parameters defined at the SUSY scale

  - the gaugino mass parameters M_1, M_2, M_3;
  - the ratio of the Higgs VEVs $\tan\beta = v_2/v_1$;
  - the higgsino mass parameter μ and the pseudo-scalar Higgs mass m_A;
  - 10 sfermion mass parameters $m_{\tilde{F}}$, where $\tilde{F} = \tilde{Q}_1, \tilde{U}_1, \tilde{D}_1, \tilde{L}_1, \tilde{E}_1, \tilde{Q}_3, \tilde{U}_3, \tilde{D}_3, \tilde{L}_3, \tilde{E}_3$ (imposing $m_{\tilde{Q}_1} \equiv m_{\tilde{Q}_2}$, $m_{\tilde{L}_1} \equiv m_{\tilde{L}_2}$, etc.),
  - 3 trilinear couplings A_t, A_b and A_τ ,

  Assumptions: no new CP phases, flavor-diagonal sfermion mass matrices and trilinear couplings, 1st/2nd generation degenerate and A-terms negligible, lightest neutralino is the LSP.

- Pioneering studies:

  "SUSY without prejudice" [C.F. Berger et al., arXiv:0812.0980]

  "Fitting the phenomeological MSSM" [S.S. AbdusSalam et al., arXiv:0904.2548]

"The pMSSM leads to a much broader set of predictions for the properties of the SUSY partners as well as for a number of experimental observables than those found in any of the conventional SUSY breaking scenarios such as mSUGRA [CMSSM]. This set of models can easily lead to atypical expectations for SUSY signals at the LHC."

from the conclusions of arXiv:0812.0980

Method

- Sample the pMSSM parameter space by a Markov-Chain Monte Carlo (MCMC) technique which through a likelihood function incorporates various pre-LHC measurements ($b \rightarrow s\gamma$, g-2, ...).
- For a random subset of 500K points, simulate 10K events per point and calculate the signal yields for 3 disjoint CMS SUSY analyses for ~1fb^{-1} of data (α_T hadronic, same-sign dilepton, opposite-sign dilepton)
- Use Bayesian statistics with flat prior to obtain posterior probability distributions for masses, parameters, etc.
- In practice: re-weight the pre-LHC likelihood of these 500K points with the "CMS likelihood" (since the analyses are disjoint, the total likelihood is the product of the individual L's).
- The main result are posterior distributions.

Tools

- SUSY spectrum calculation: SOFTSUSY 3.1
- Low energy observables: SuperIso 3.0
- Relic density, DD cross sections: micrOMEGAs 2.4
- SUSY mass limits: micrOMEGAs 2.4
- Higgs mass limits: HiggsBounds 2.0.0
- Decays: SUSYHIT (SDECAY1.3b, HDECAY3.4)
- SUSY event generation: PYTHIA 6.4
- Interfacing: SUSY Les Houches Accord
- Generic detector simulation: DELPHES 1.9

PS. needed lots of fixes to make everything work....

Analysis setup

- Markov-Chain Monte Carlo sampling of pMSSM parameter space

i	Observable μ_i	Experimental result D_i	Likelihood function $L(D_i\|\mu_i)$
1	$BR(b \to s\gamma)$	$(3.55 \pm 0.34) \times 10^{-4}$	Gaussian
2	$BR(B_s \to \mu\mu)$	$\leq 4.7 \times 10^{-8}$ *)	$1/(1+\exp(\frac{\mu_2 - D_2}{0.01 D_2}))$
3	$R(B_u \to \tau\nu)$	1.66 ± 0.54	Gaussian
4	Δa_μ	$(28.7 \pm 8.0) \times 10^{-10}$ $[e^+e^-]$ $(19.5 \pm 8.3) \times 10^{-10}$ [taus]	Weighted Gaussian average
5	m_t	173 ± 1.1 GeV	Gaussian
6	$m_b(m_b)$	$4.19^{+0.18}_{-0.06}$ GeV	Two-sided Gaussian
7	$\alpha_s(M_Z)$	0.1176 ± 0.002	Gaussian
8	m_h	LEP&Tevatron (HiggsBounds)	$L_8 = 1$ if allowed. $L_8 = 10^{-9}$ if m_h' sampled from $Gauss(m_h, 1.5)$ is excluded.
9	sparticle masses	LEP (micrOMEGAs)	$L_9 = 1$ if allowed $L_9 = 10^{-9}$ if excluded

*) we re-weight a posteriori with the new limit BR(Bs→μμ)<1.08 at 95% CL

$$|M_i| \leq 3 \text{ TeV}$$
$$|\mu| \leq 3 \text{ TeV}$$
$$m_A \leq 3 \text{ TeV}$$
$$m_{\tilde{F}} \leq 3 \text{ TeV}$$
$$|A_{t,b,\tau} \leq 7 \text{ TeV}$$
$$2 \leq \tan\beta \leq 60$$

- We use a flat prior for parameters and sample 1.5×10^7 points
- Distribution of points maps the total likelihood, $L_{\text{preLHC}} = \sum_{i=1}^{9} L_i$
- Draw a random subset of 5×10^5 points for simulation

CMS analyses and likelihood - I

We consider the following 3 public disjoint CMS SUSY analyses using ~1 fb^{-1} 7 TeV 2011 data:

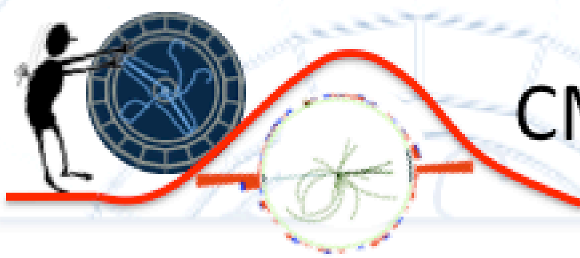
- Hadronic α_T (RA1 – CMS-SUS-11-003) 1.1 fb^{-1}: ≥2 jets and $\alpha_T > 0.55$, where α_T is designed to distinguish between real and fake E_T^{miss}. Shape analysis that gives results in 8 disjoint H_T bins. We use all.
- Same sign (SS) dilepton (RA5 - CMS-SUS-11-010) 0.98 fb^{-1}: Opposite sign dilepton analysis. 8 correlated analysis regions. We use $H_T > 400$, $E_T^{miss} > 120$.
- Opposite sign (OS) dilepton (RA6 – CMS-SUS-11-011) 0.98 fb^{-1}: Same sign dilepton analysis. 2 correlated analysis regions. We use $H_T > 300$, $E_T^{miss} > 275$.

Slide from Sezen Sekmen's talk, 30-08-11 at LHC2TeV workshop, CERN

CMS results used

j	Analysis and search region (values in GeV)	Observed event count (N_j)	Data-driven SM BG estimate ($B_j \pm \delta B_j$)
1	α_T hadronic, $275 \leq H_T < 325$	782	$787.4^{+31.5}_{-22.3}$
2	α_T hadronic, $325 \leq H_T < 375$	321	$310.4^{+8.4}_{-12.4}$
3	α_T hadronic, $375 \leq H_T < 475$	196	$202.1^{+8.6}_{-9.4}$
4	α_T hadronic, $475 \leq H_T < 575$	62	$60.4^{+4.2}_{-3.0}$
5	α_T hadronic, $575 \leq H_T < 675$	21	$20.3^{+1.8}_{-1.1}$
6	α_T hadronic, $675 \leq H_T < 775$	6	$7.7^{+0.8}_{-0.5}$
7	α_T hadronic, $775 \leq H_T < 875$	3	$3.2^{+0.4}_{-0.2}$
8	α_T hadronic, $875 \leq H_T$	1	$2.8^{+0.4}_{-0.2}$
9	SS 2ℓ, $H_T > 400$, $\not{E}_T > 120$	1	2.3 ± 1.2
10	OS 2ℓ, $H_T > 300$, $\not{E}_T > 275$	8	4.2 ± 1.3

Assume a Poisson likelihood $\mathrm{Poisson}(N_j|s_j + b_j)$ with expected count $s_j + b_j$ and compute the marginal likelihood $L_j = p(N_j|s_j)$ by integrating over the expected background b_j



CMS analyses and likelihood - II

Likelihood:

$$
\begin{aligned}
L_{CMS} &\equiv p(N|s,b,\delta b) \\
&= \prod_{i=1}^{10} Poisson(N_i|s_i+b_i)p(b_i|\delta b_i) \\
&= \prod_{i=1}^{10} \frac{e^{-(s_i+b_i)}(s_i+b_i)^{N_i}}{N_i!}\frac{e^{-k_i b_i}(k_i b_i)^{Q_i}}{\Gamma(Q_i+1)}
\end{aligned}
$$

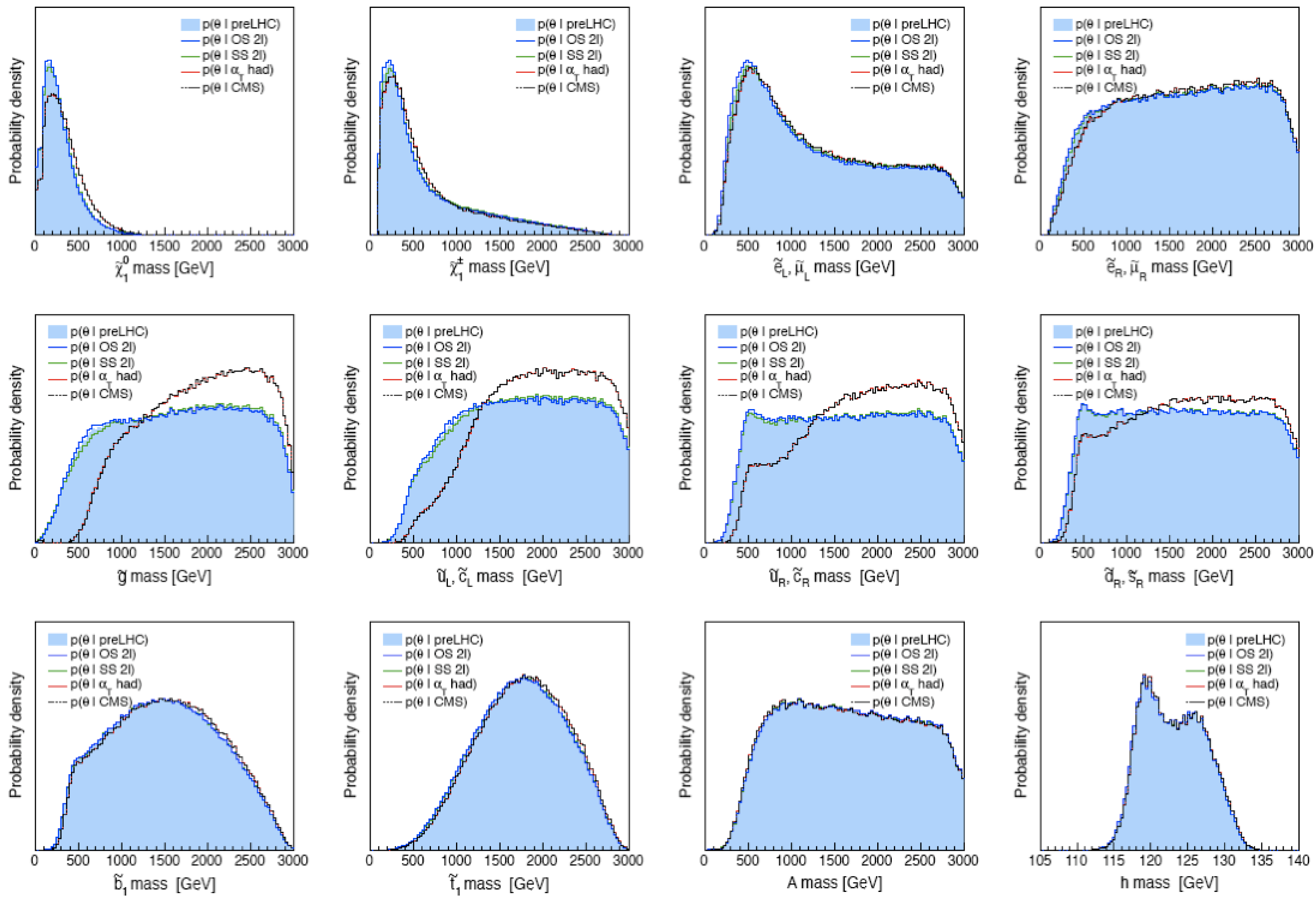
takes into account the uncertainty in the BG estimate

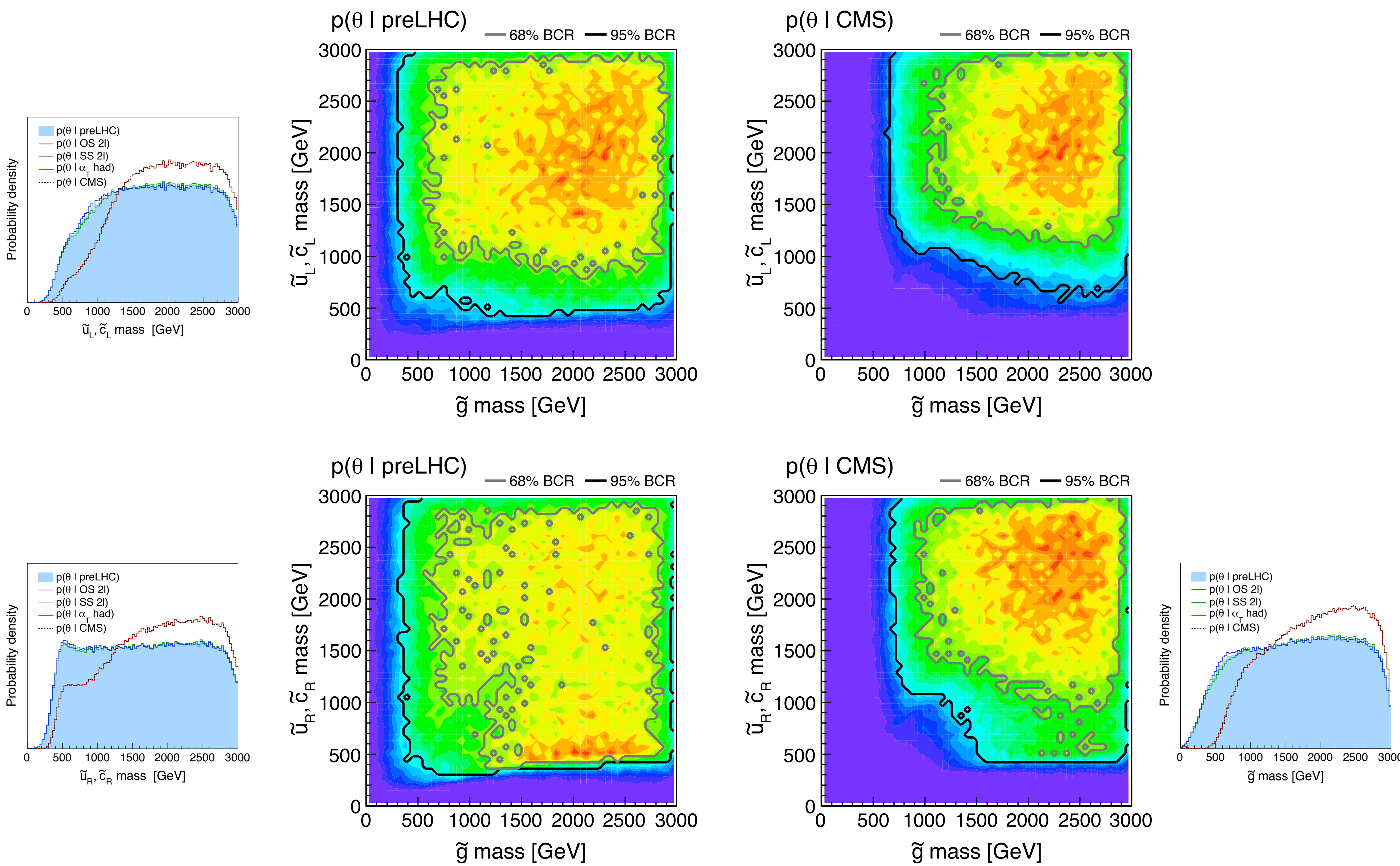
where $Q_i = (B_i/\delta B_i)^2$

$k_i = B_i/\delta B_i^2$

Slide from Sezen's talk, 30-08-11 at LHC2TeV workshop, CERN

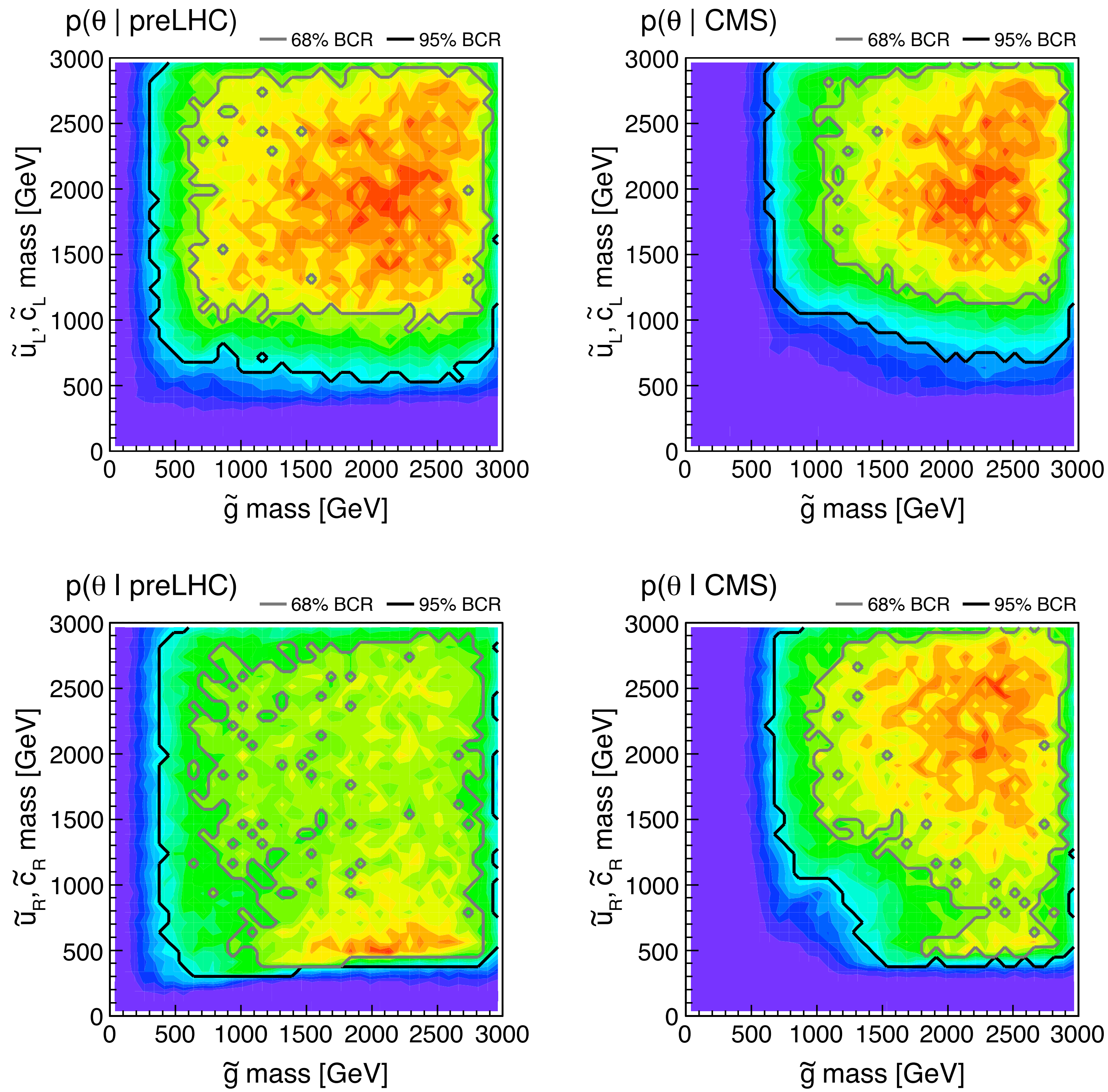
Results: posterior densities





BCR: Bayesian credible region – these are not exclusion curves!

Requiring $\Omega h^2 < 0.136$



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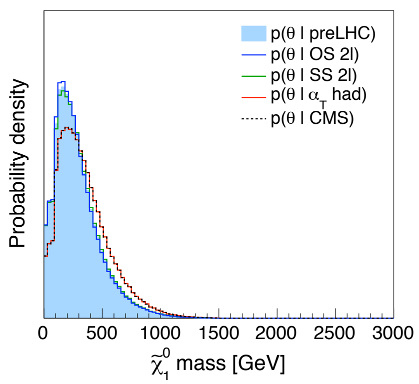
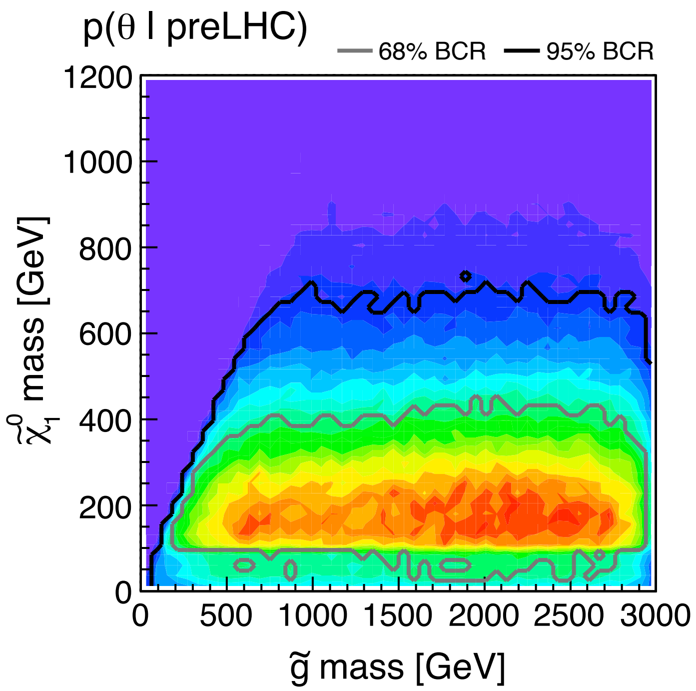
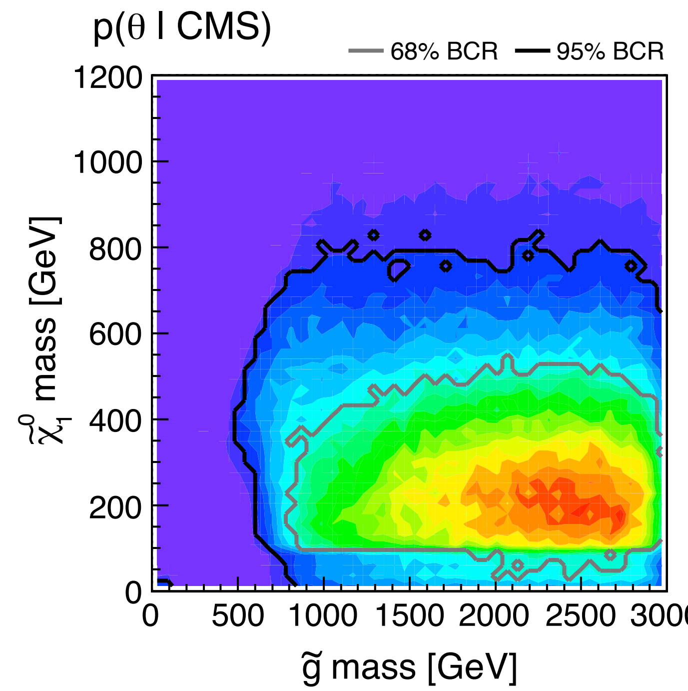
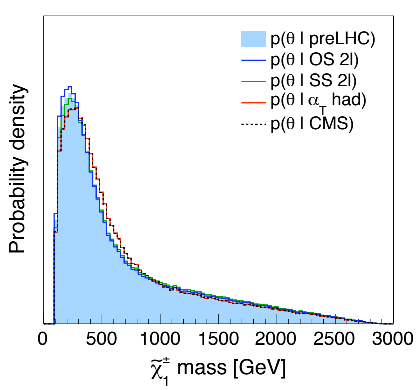
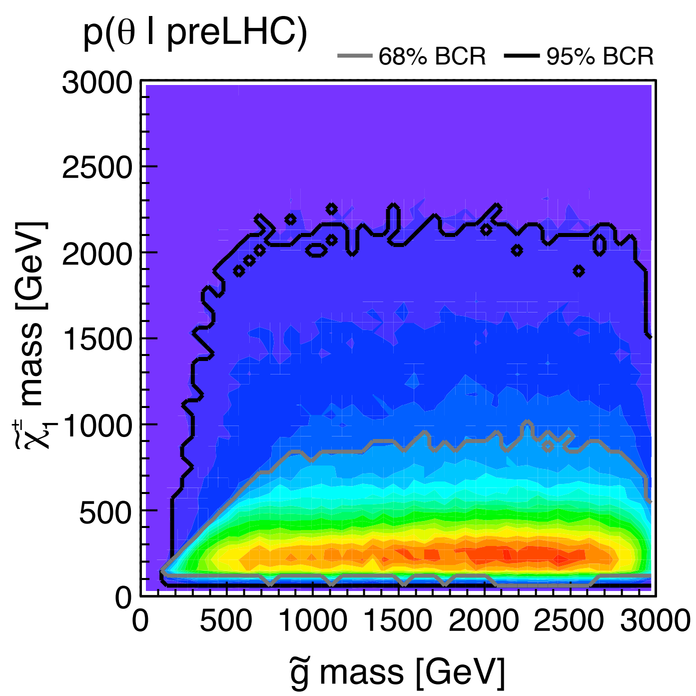


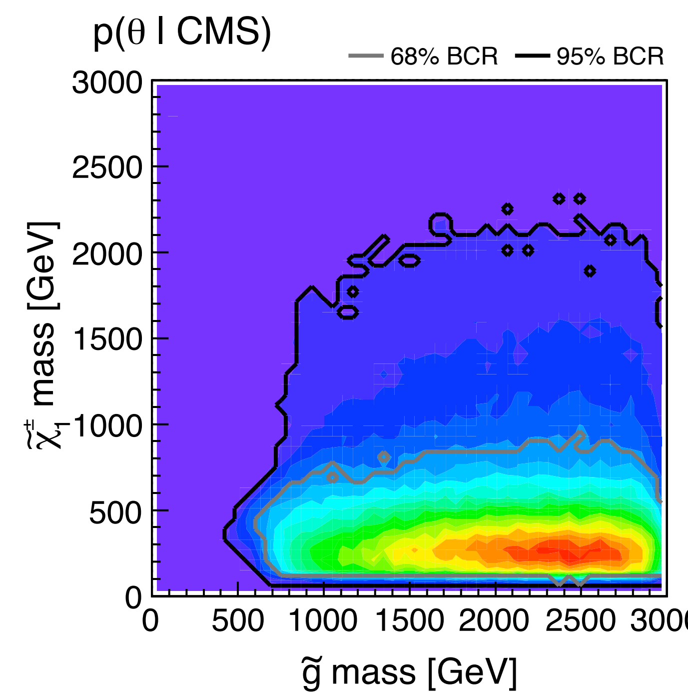




neutralino
vs. gluino

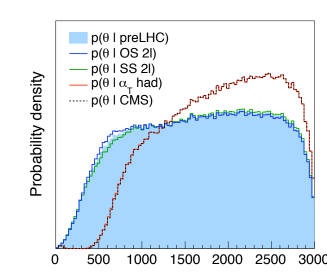






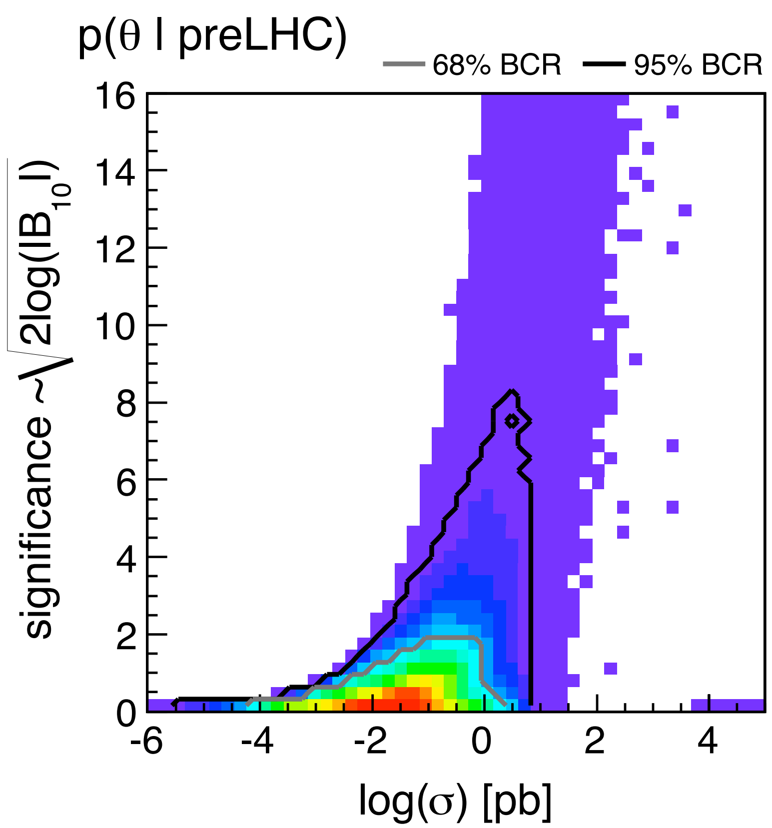
chargino
vs. gluino

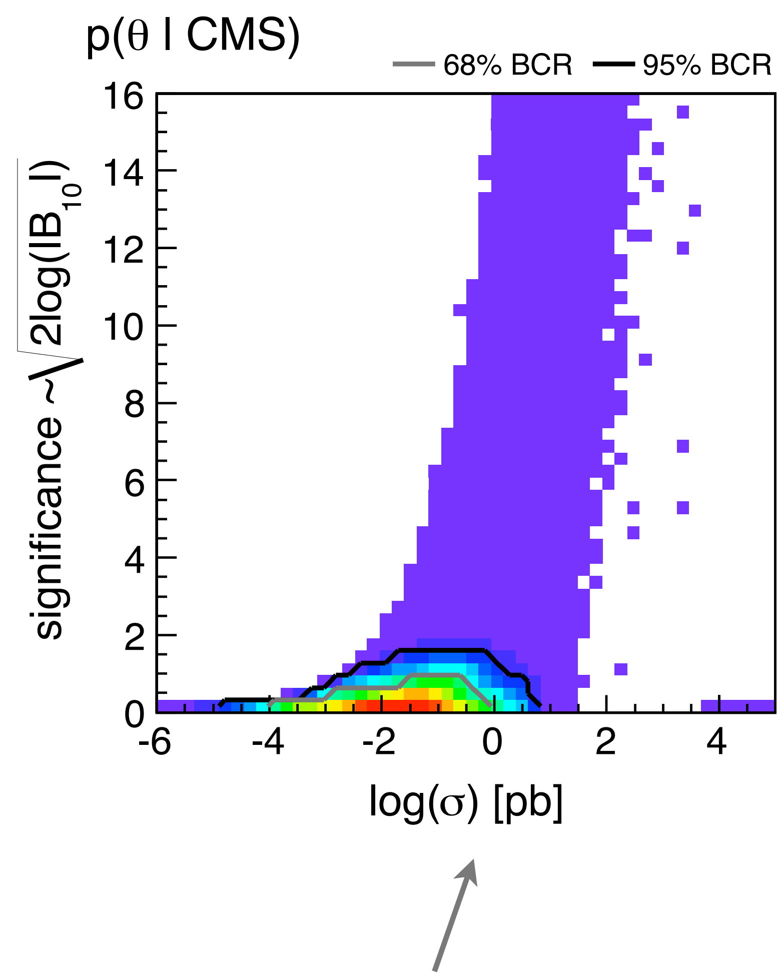
BCR: Bayesian credible region – these are not exclusion curves!



Signal significance versus cross section

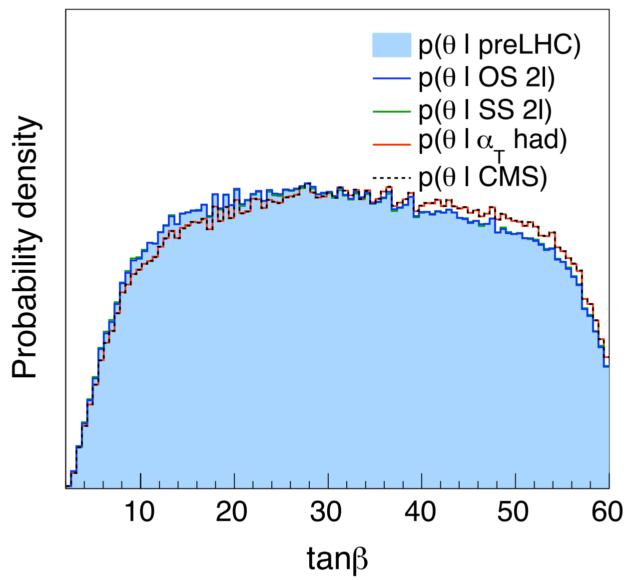
Large cross section = high signal significance?

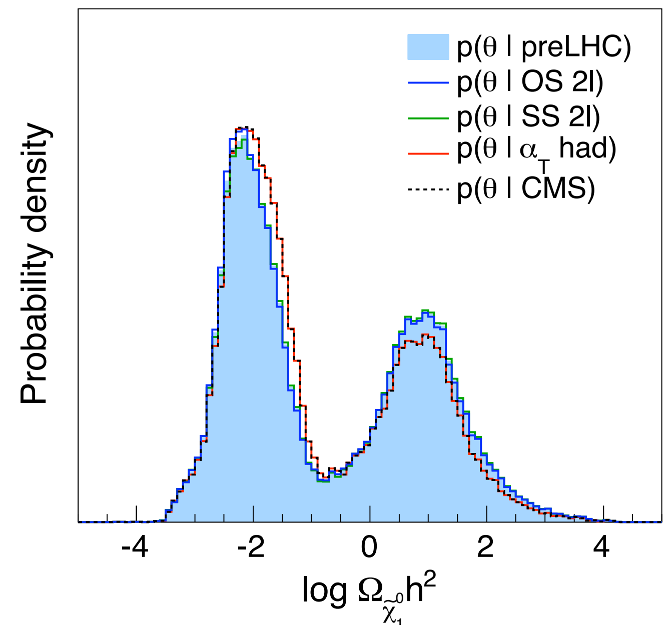


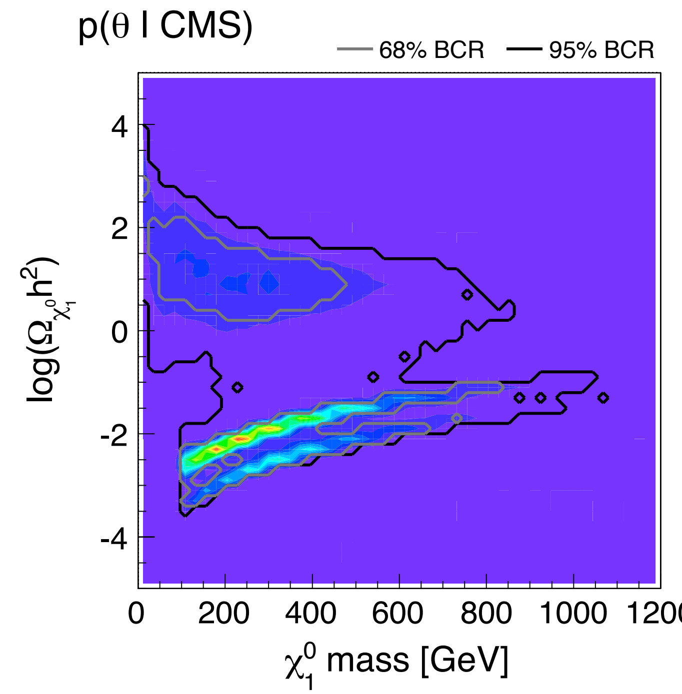


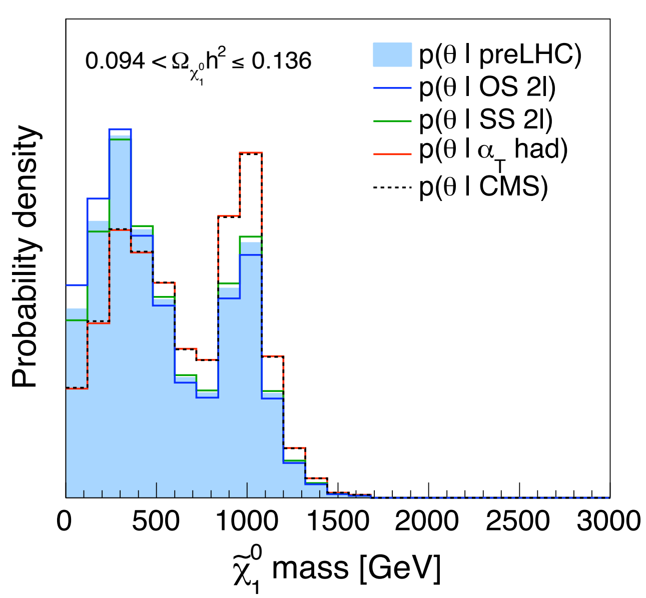
Signal of order 1 pb cross section could have escaped detection!

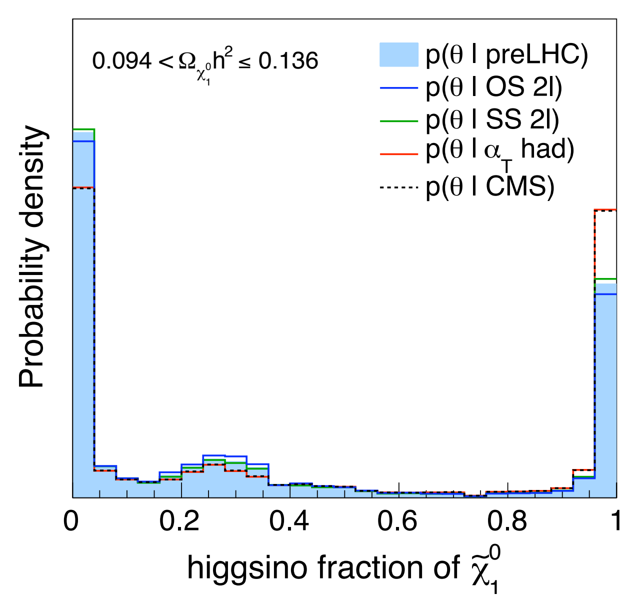
Dark matter implications









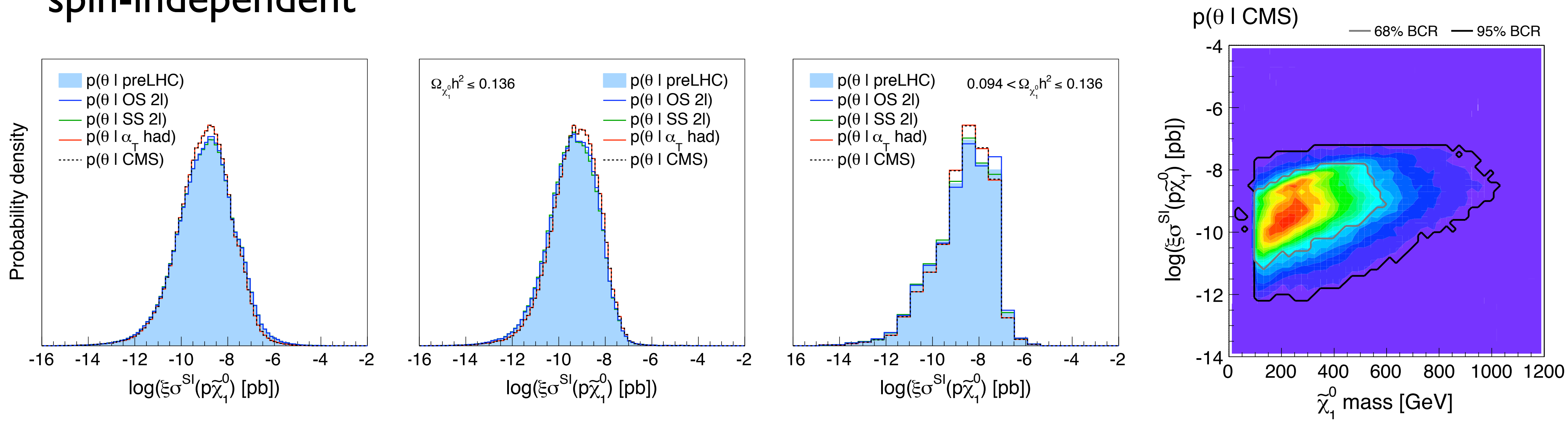


$$p(\Omega h^2 < 0.136) = 55\%$$

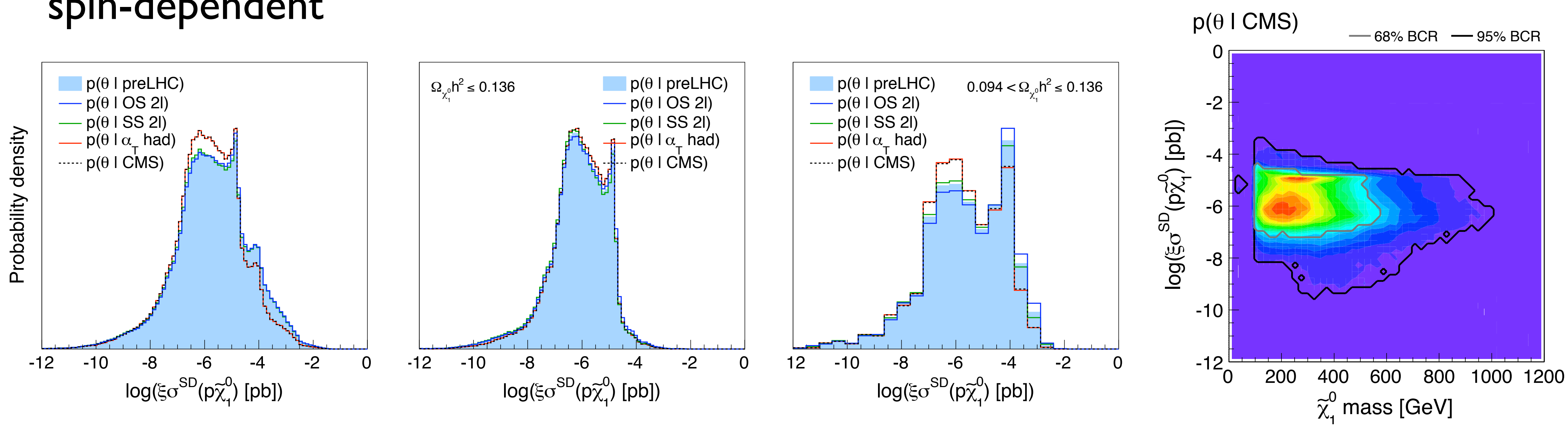
$$p(0.094 < \Omega h^2 < 0.136) = 1\%$$

Implications for direct DM searches

spin-independent

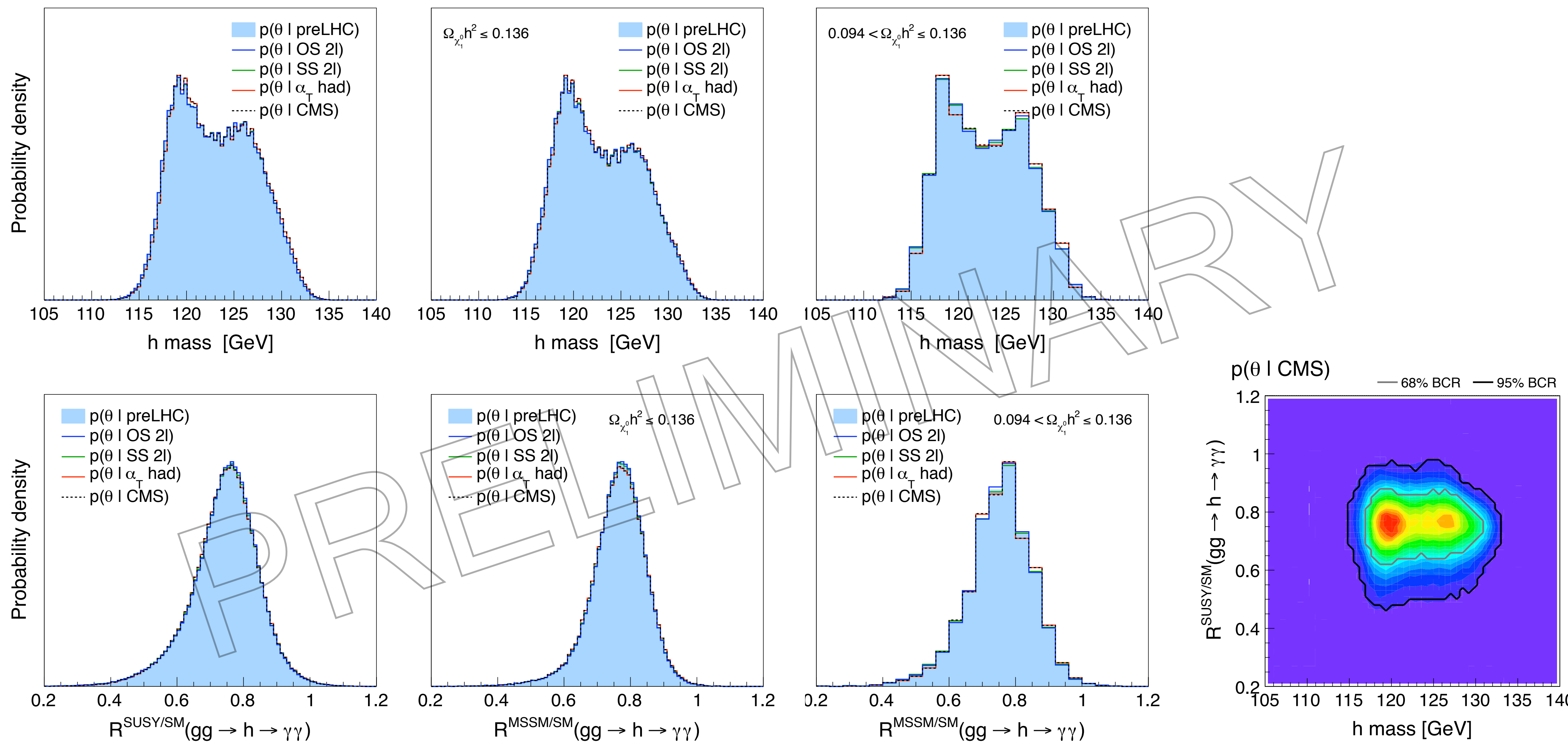


spin-dependent



$$\xi = \Omega h^2/0.1123$$

Implications for Higgs



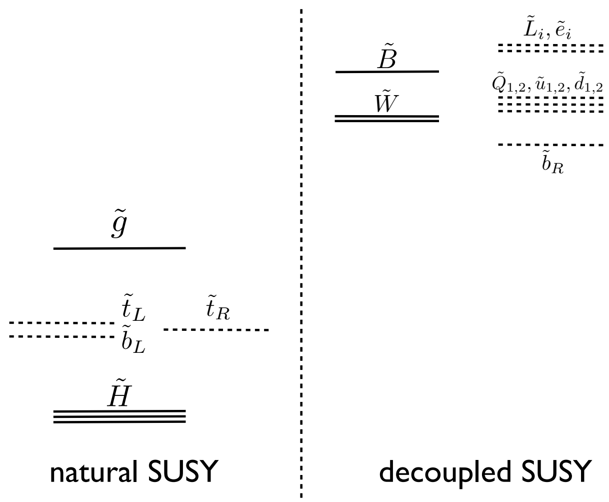
arXiv:1110.6926

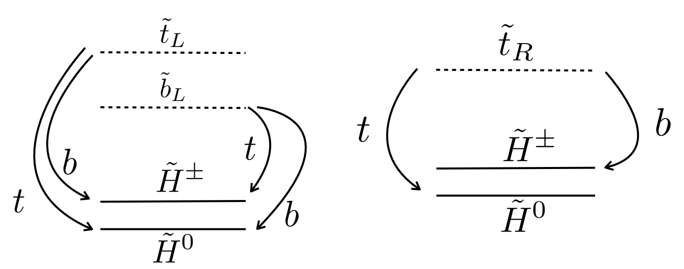
Natural SUSY endures

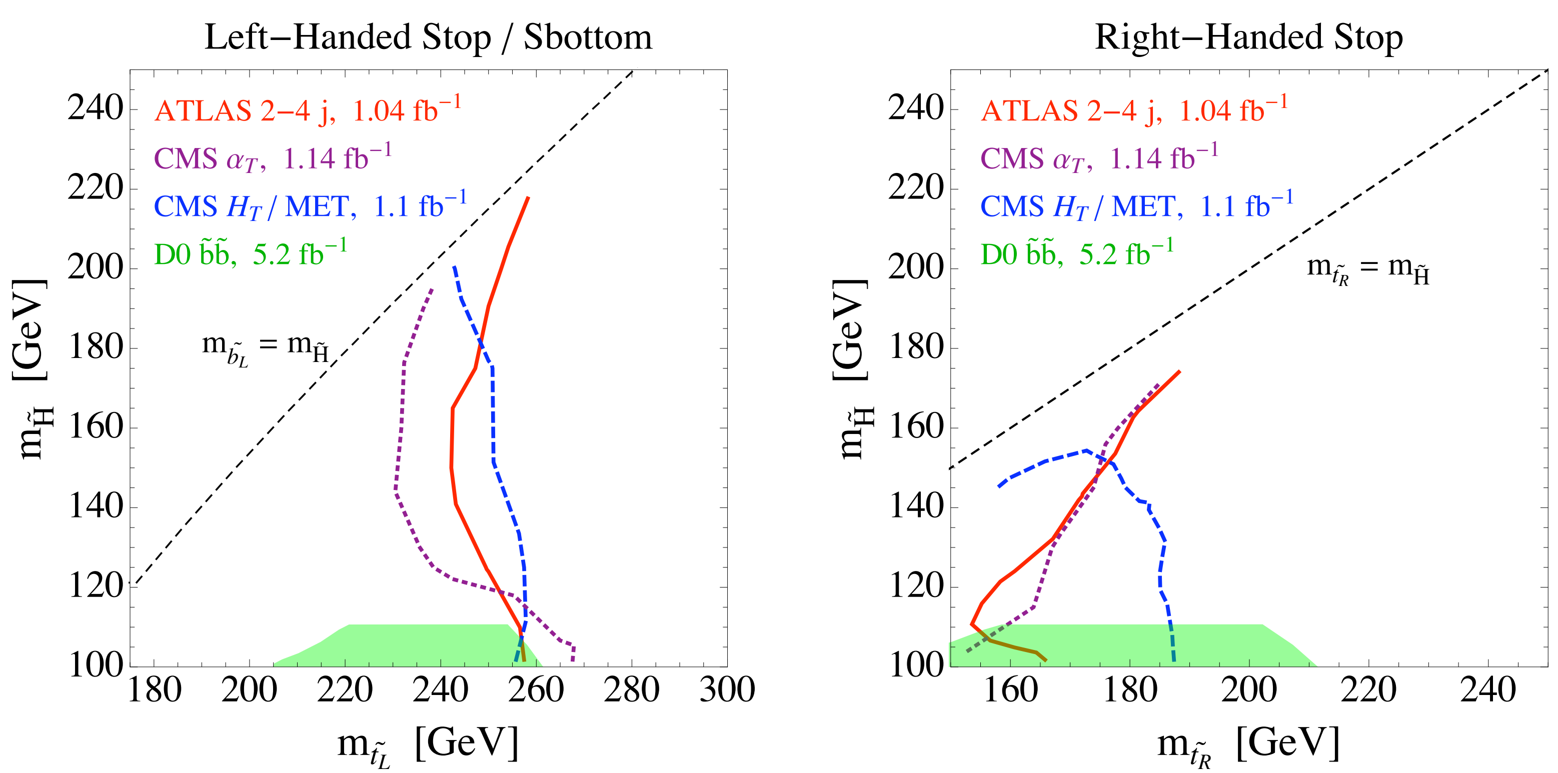
M. Papucci, J.T. Ruderman, A.Weiler

From the requirement of naturalness

- ➡ stops & left sbottom below 500−700 GeV
- ➡ higgsinos below 200−350 GeV
- ➡ a not too heavo gluino, 900−1500 GeV







Conclusions

- LHC results are pushing squark and gluino mass limits to ~1 TeV; expectations for early discoveries were too optimistic

- Current searches are not (yet) sensitive to
  - ★ Small mass differences → soft jets, low E_T^{miss}
  - ★ Compressed spectra in general
  - ★ Mainly electroweak production
  - ★ Mainly stop/sbottom production

no need for this

- Plenty of room where SUSY can hide
  besides, EW fits and flavor physics actually prefer heavy SUSY

- SUSY DM stays compelling case
  interesting complementarity between LHC and DD

- We definitely need [the means] to interpret LHC results in terms of a wide range of models, including pMSSM.

Needs communication between experimentalists (collaborations!) and theorists