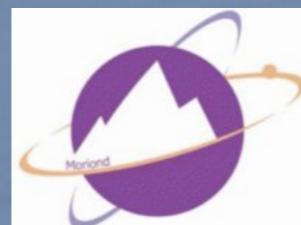


SUSY status after one year of LHC

(after 2011 LHC results)

Sabine Kraml
LPSC Grenoble

Largely based on arXiv:1109.5119 with S. Sekmen et al.



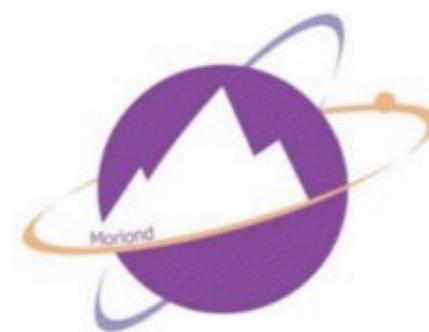
Rencontres de Moriond, Electroweak Interactions and Unified Theories
3-10 March 2012, La Thuile

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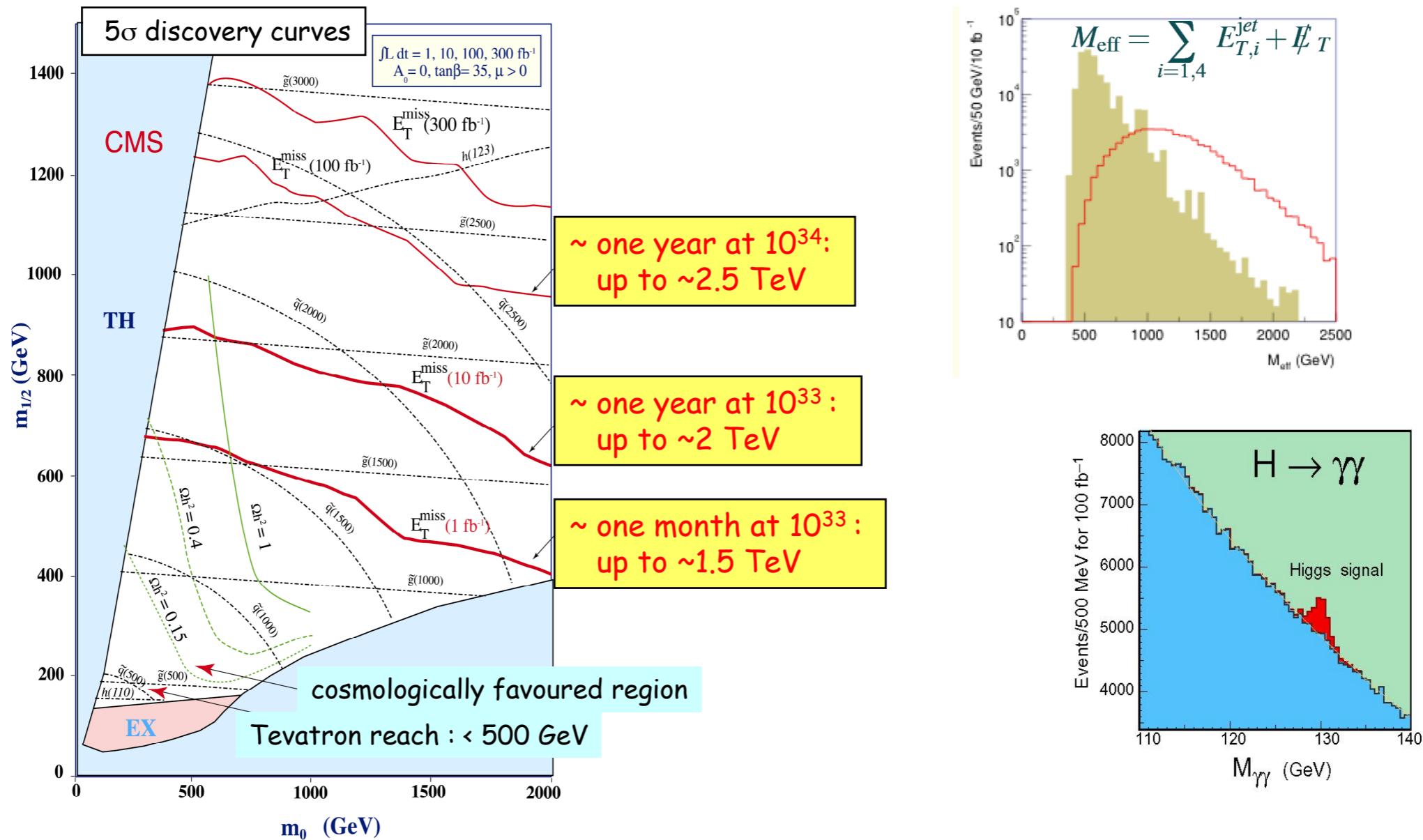
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Before LHC turn-on

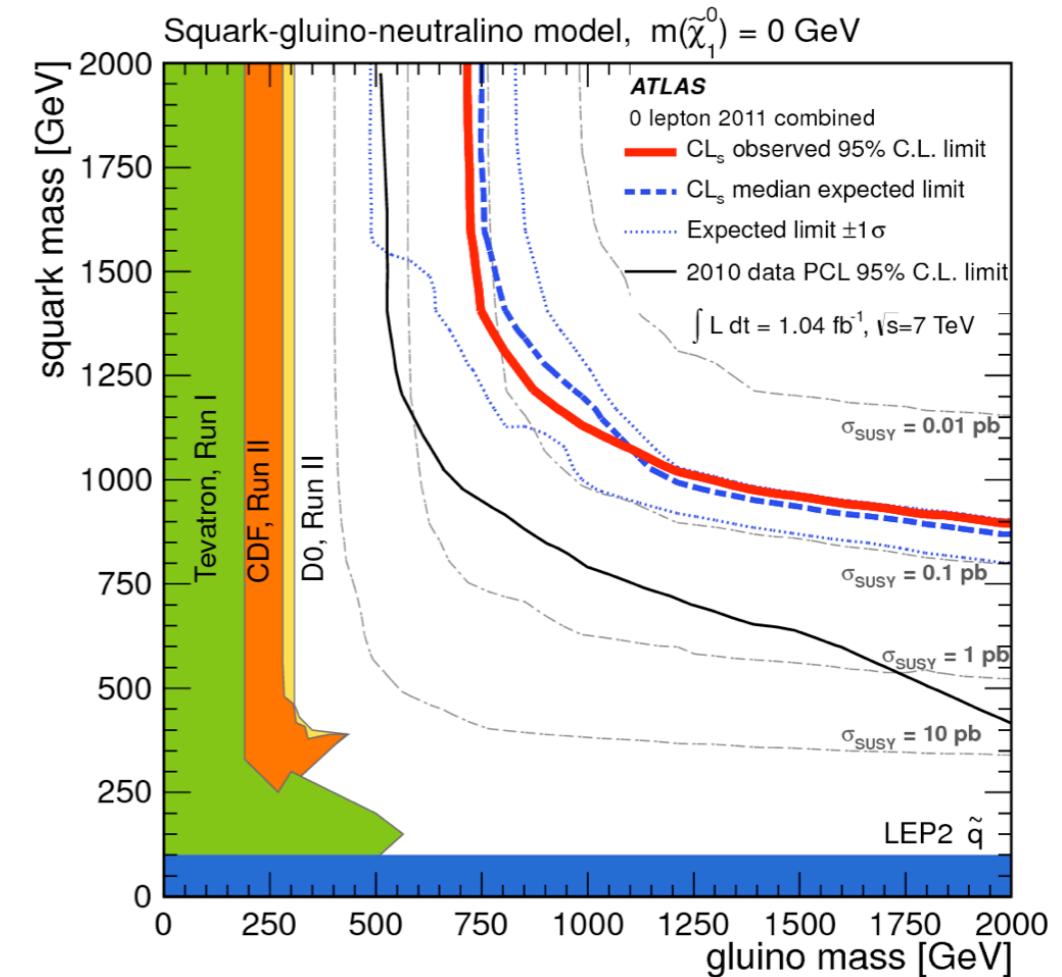
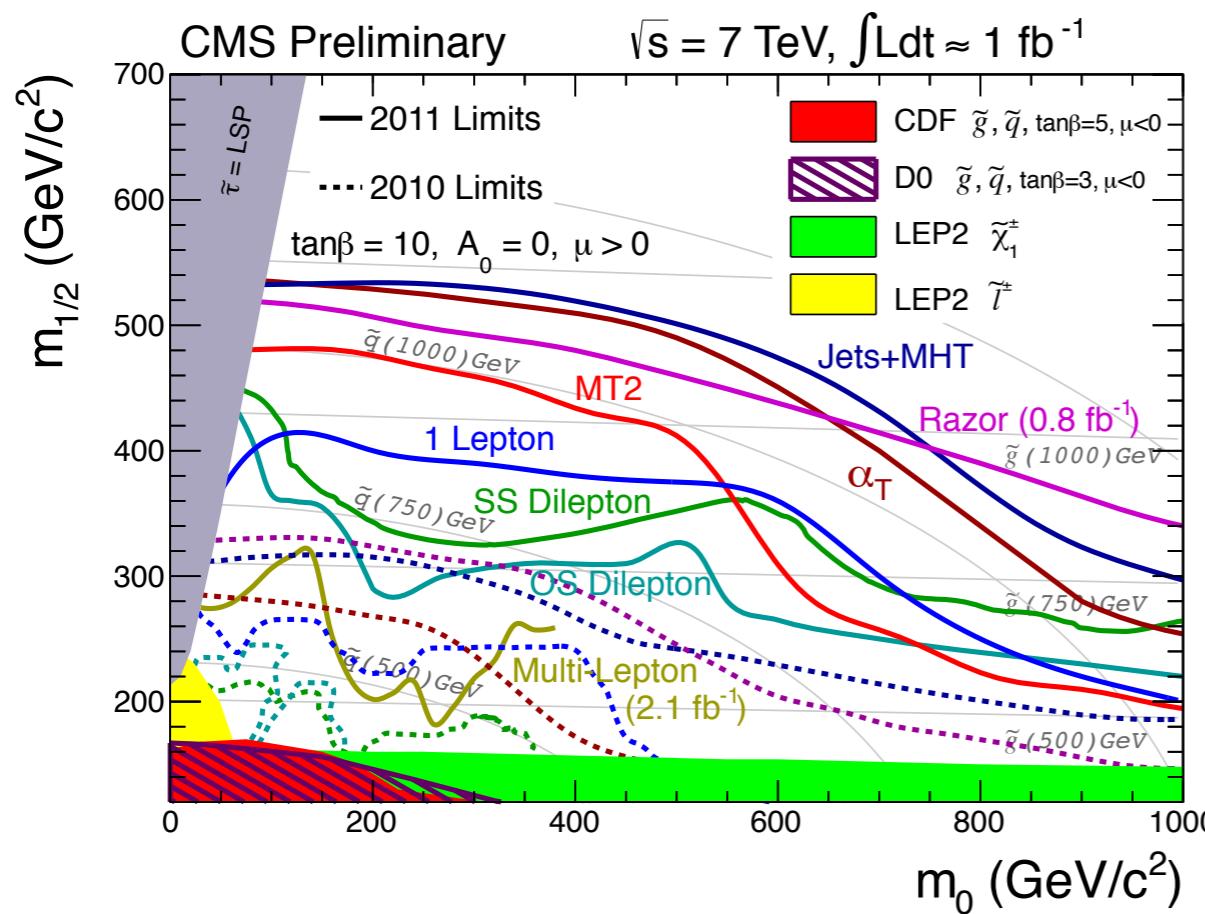
Very optimistic view: if SUSY is light (as we of course all expect...!) it will be discovered early on.



Much easier than discovering the Higgs...

Now

ATLAS, arXiv:1109:6572



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

Direct search limits are pushed higher and higher $\rightarrow M_{\text{SUSY}} > 1 \text{ TeV} ?$

In addition, precision flavor physics shows no sign of BSM $\rightarrow M_{\text{SUSY}} > O(10) \text{ TeV} ?$

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.



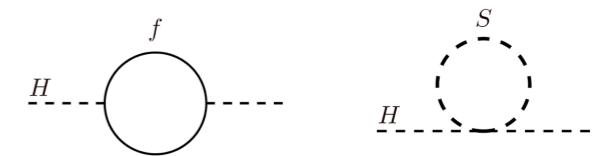
Supersymmetry predicts the existence of mysterious super particles.

Is SUSY in trouble ?



The beauties of (weak-scale) SUSY

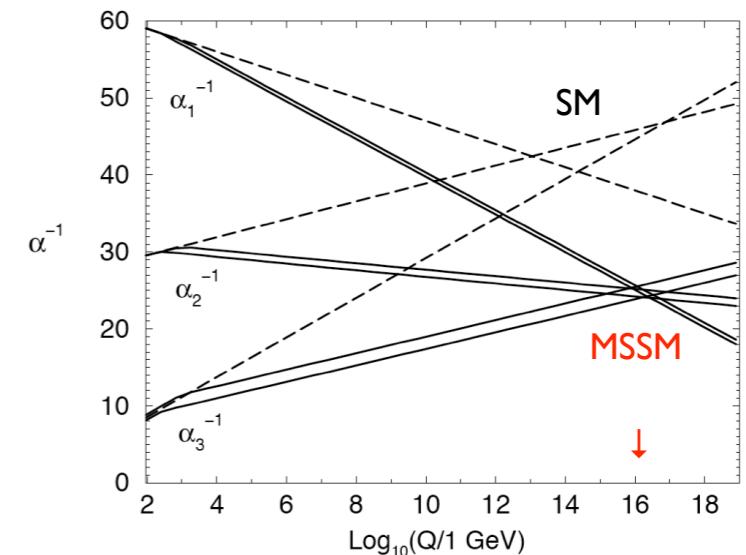
- * Solution to the gauge hierarchy problem



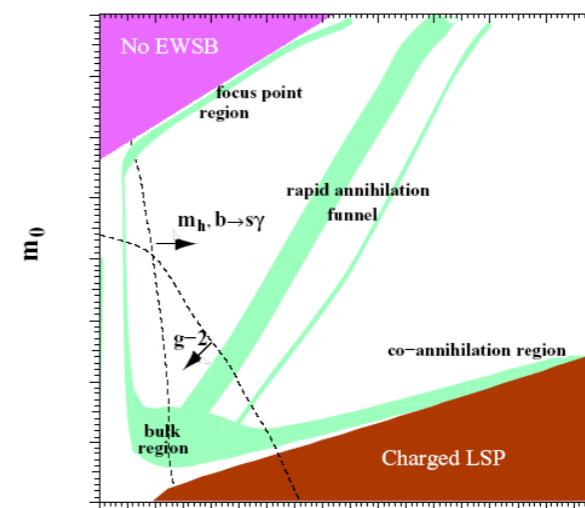
- * Gauge coupling unification

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

- * Radiative EWSB, light Higgs



- * Cold dark matter candidate



- * Very rich collider phenomenology

The beauties of (weak-scale) SUSY

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Needs light stops, light higgsinos, somewhat light gluino

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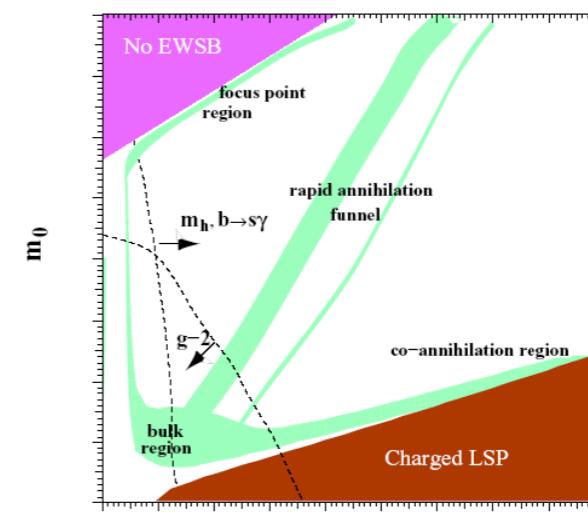
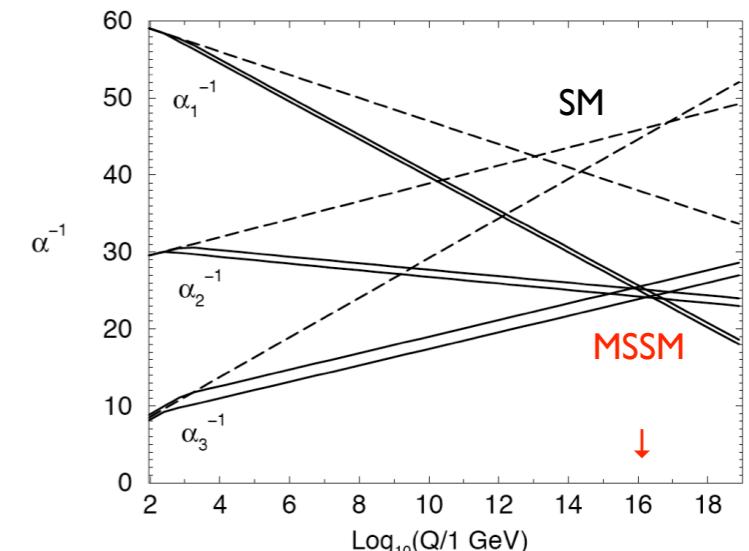
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TeV-scale fermionic states → could be split SUSY

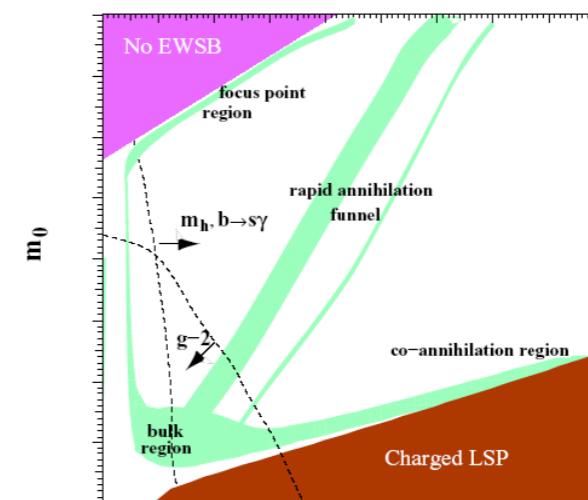
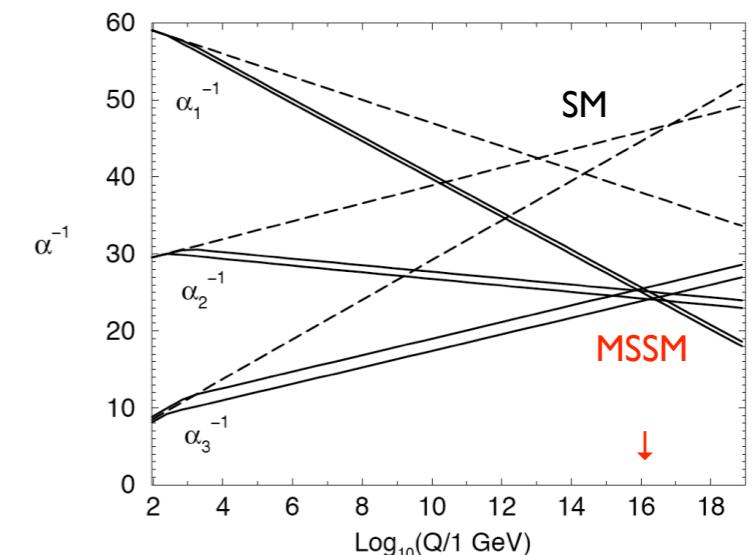
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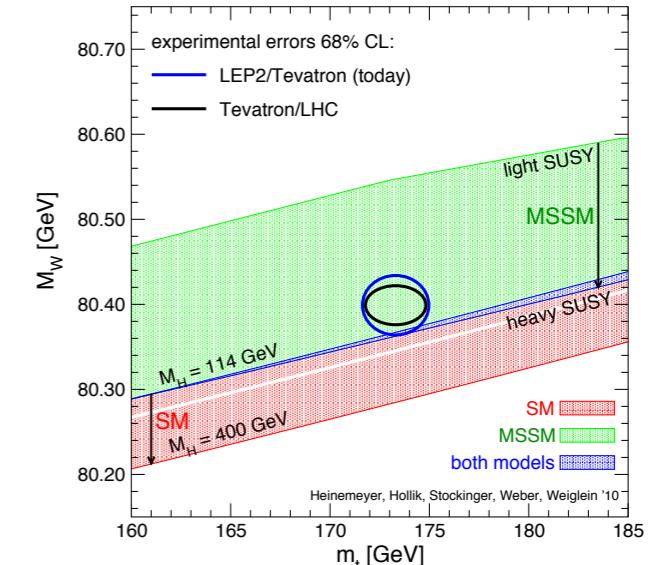
heavy top effect

$m_h > 115$ GeV prefers heavy stops (finetuning prize of LEP)
electroweak precision measurements prefer heavy SUSY

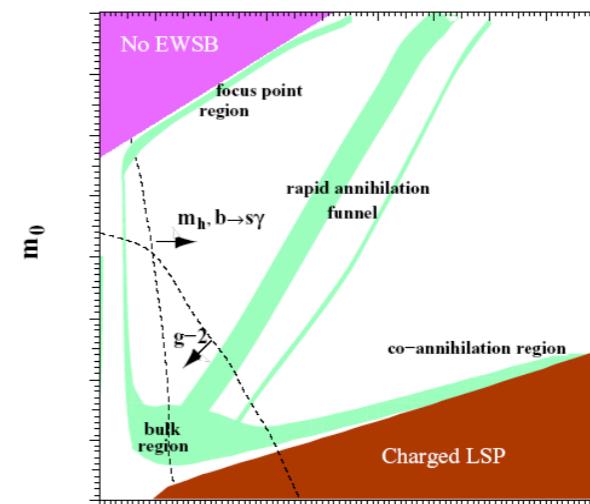
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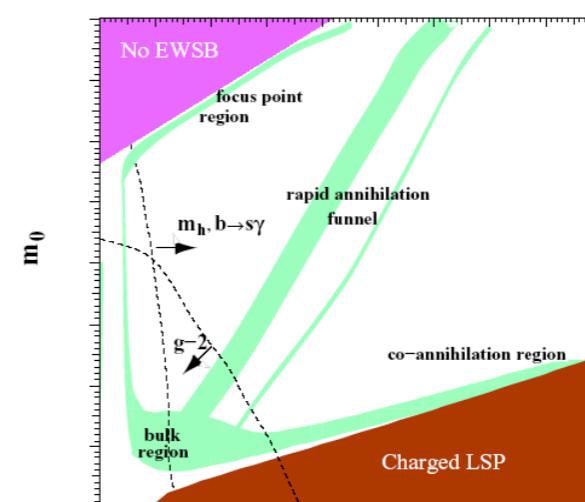
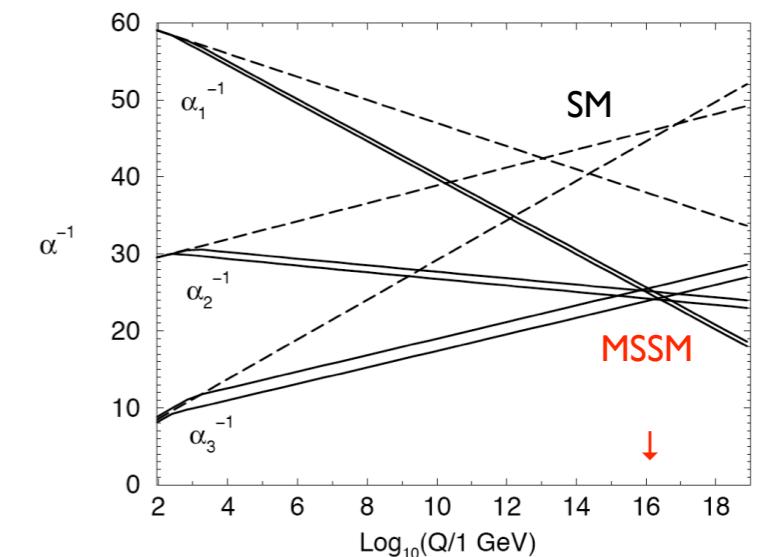
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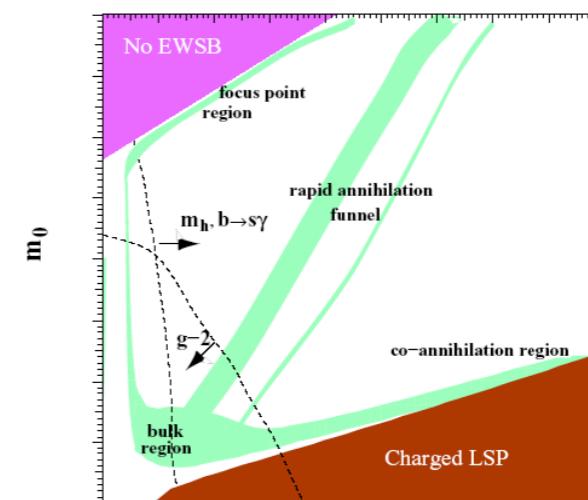
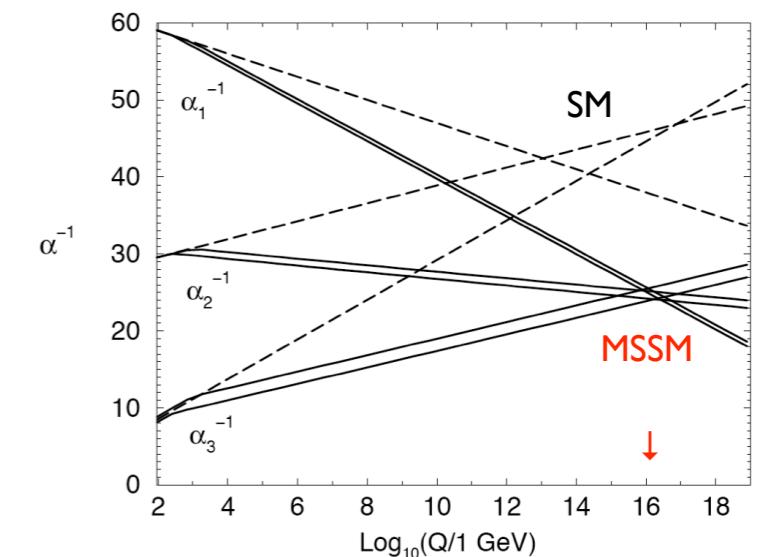
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Well, this entirely depends on phase-space ...

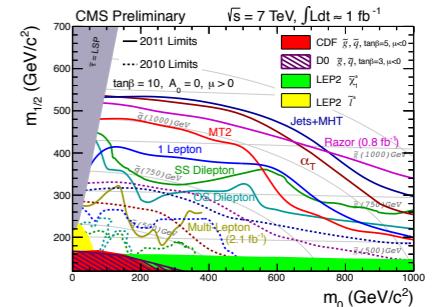
and for the time being we are just running at 1/2 force



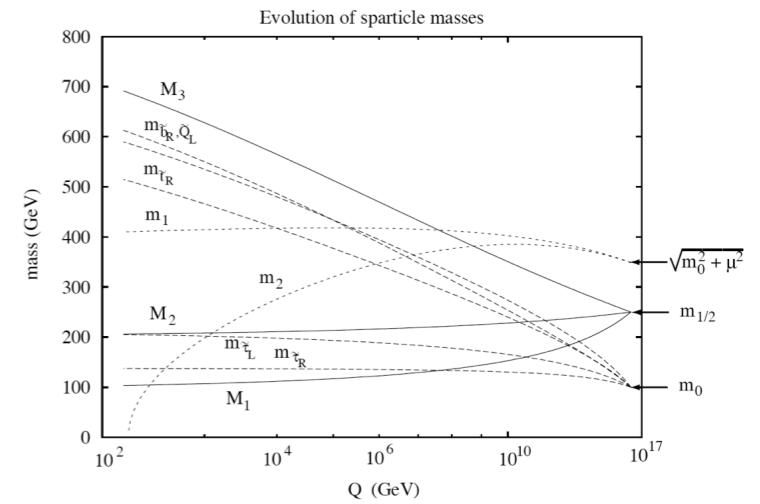
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Beware the CMSSM



- CMSSM: **Constrained** Minimal Supersymmetric Standard Model
 - Assumes rather ad-hoc boundary conditions at the GUT scale
 - universal gaugino mass $m_{1/2}$
 - universal scalar mass parameter m_0
 - universal trilinear coupling A_0
 - Consequences:



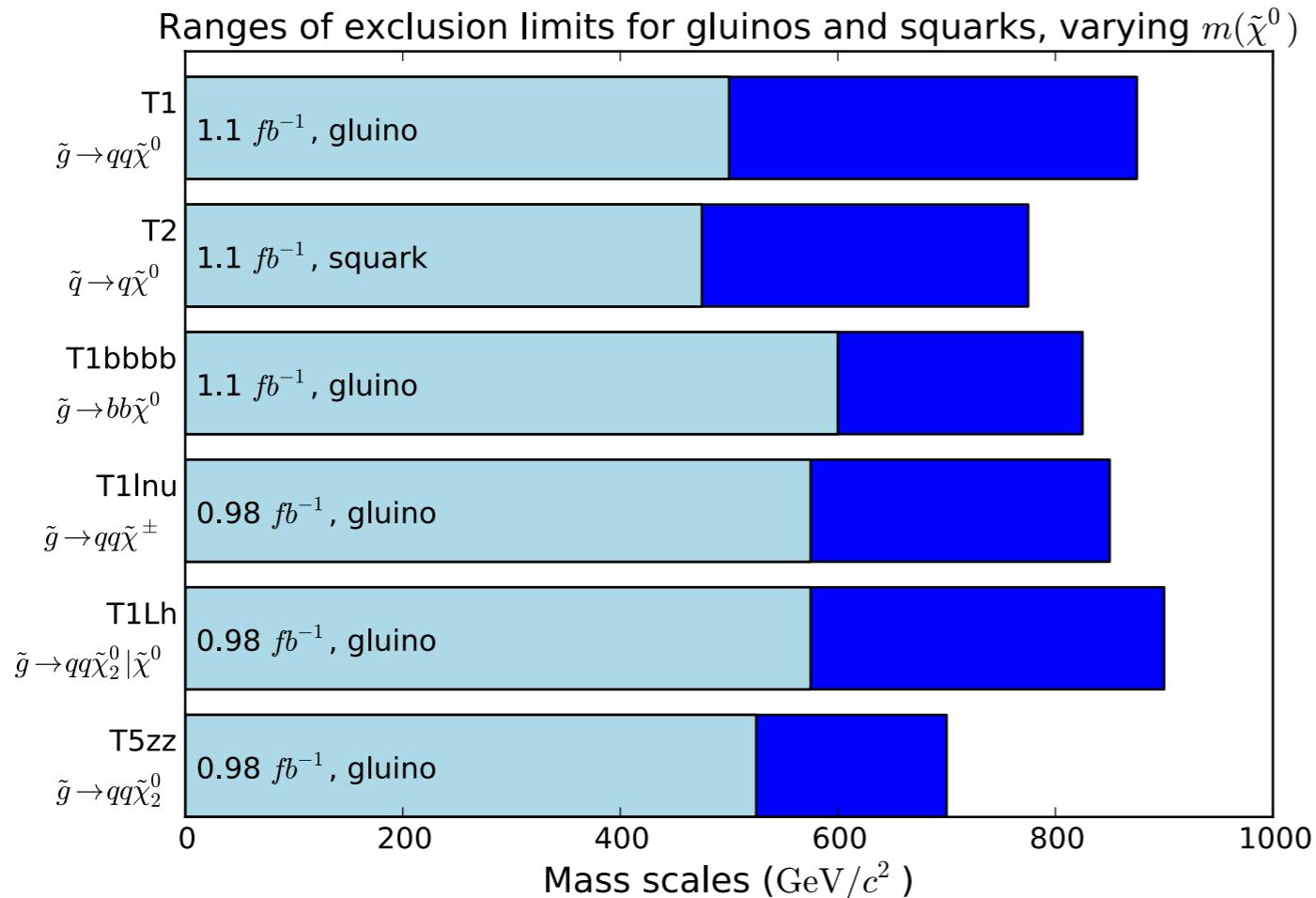
- Gluino : wino : bino (LSP) mass roughly 7 : 2 : 1 $m_{\tilde{\chi}_1^0}^2 \sim 0.4 m_{1/2}$, $m_{\tilde{g}}^2 \sim 2.8 m_{1/2}$
 - Squark masses related to gluino mass $m_{\tilde{Q}}^2 \approx m_0^2 + (5 \rightarrow 7)m_{1/2}^2$ $m_{\tilde{q}}^2 \sim m_0^2 + m_{\tilde{g}}^2$
 - Slepton masses related to gaugino and squark masses $m_{\tilde{R}}^2 \approx m_0^2 + 0.15 m_{1/2}^2$
 $m_{\tilde{L}}^2 \approx m_0^2 + 0.5 m_{1/2}^2$

● Convenient toy model for benchmark studies, but need to keep in mind that a constrained model gives a constrained phenomenology.

Beyond the CMSSM

Simplified Models

CMS preliminary



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

For limits on $m(\tilde{g}), m(\tilde{q}) > m(\tilde{\chi}^0)$ (and vice versa). $\sigma^{\text{prod}} = \sigma^{\text{NLO-QCD}}$.

$$m(\tilde{\chi}^\pm), m(\tilde{\chi}_2^0) \equiv \frac{m(\tilde{g}) + m(\tilde{\chi}^0)}{2}.$$

$m(\tilde{\chi}^0)$ is varied from 0 GeV/c² (dark blue) to $m(\tilde{g}) - 200$ GeV/c² (light blue).

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

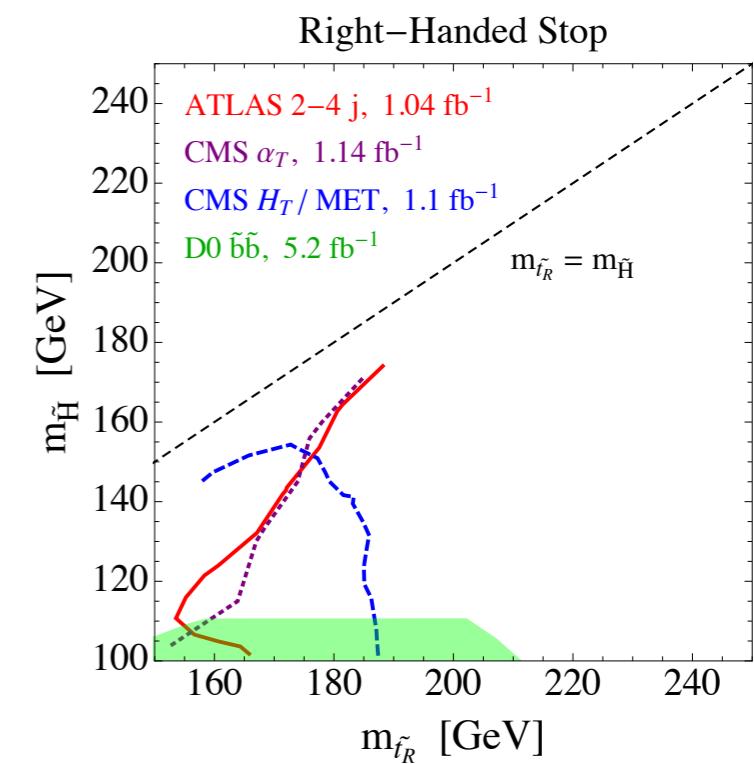
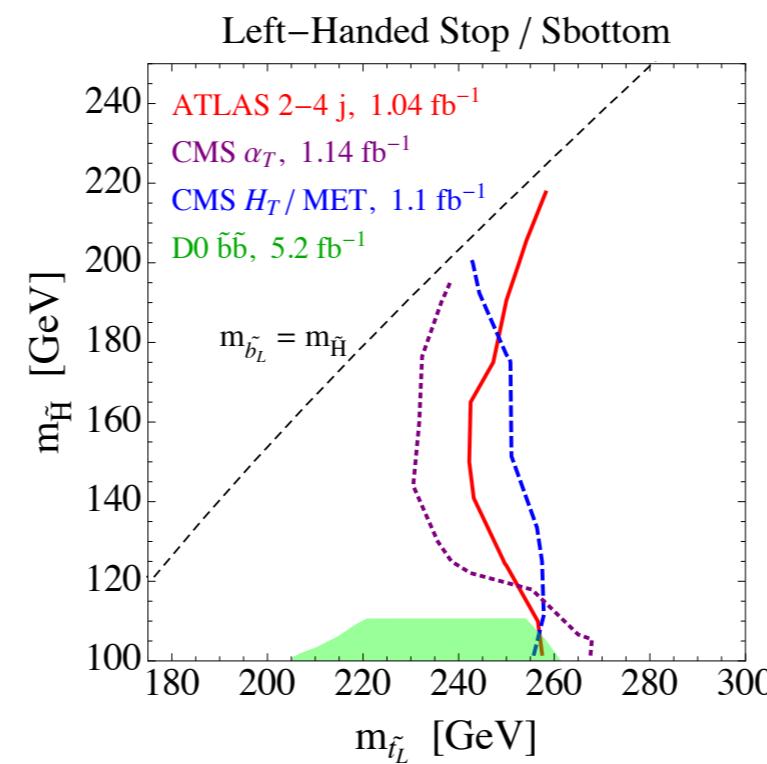
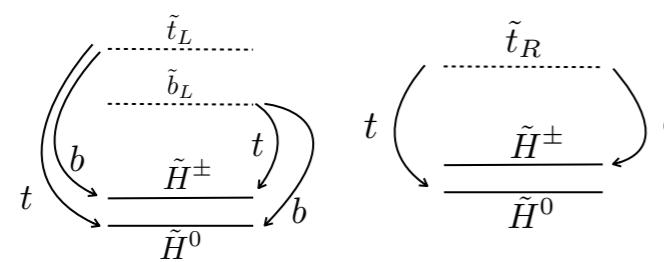
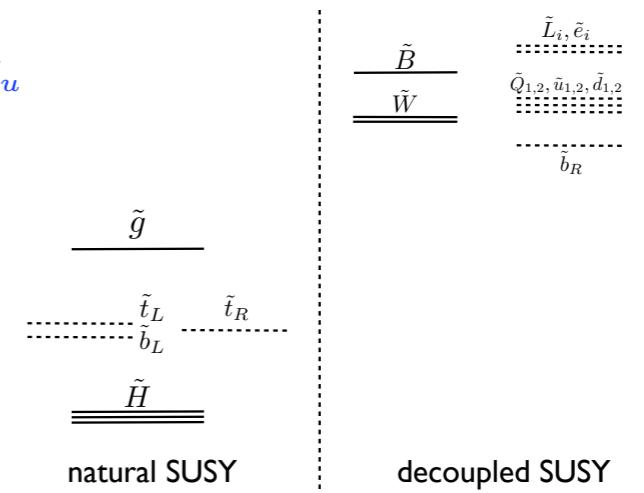
Natural SUSY endures

M. Papucci, J.T. Ruderman, A. Weiler, arXiv:1110.6926

From naturalness arguments, expect

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

- stops & left sbottom below 500–700 GeV
- higgsinos below 200–350 GeV
- a not too heavy gluino, 900–1500 GeV



So what does this imply for SUSY in general?

(without assuming a particular SUSY-breaking scheme)



Let's consider the
“phenomenological MSSM” (pMSSM)

- 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.
- **Parameters defined at the weak 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 work:
C.F.Berger et al., arXiv:0812.0980

Let's consider the
“phenomenological MSSM” (pMSSM)

“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
“SUSY without prejudice”

Interpreting LHC SUSY searches in the “phenomenological MSSM” (pMSSM)

S. Sekmen, SK, et al., arXiv:1109.5119

- Sample the pMSSM parameter space by a Markov-Chain Monte Carlo (MCMC) technique which through a likelihood function incorporates various pre-LHC measurements ($b \rightarrow s\gamma$, $B \rightarrow \mu^+\mu^-$, $g-2$, LEP mass limits, ...). neutralino LSP, no long-lived sparticles
- For a random subset of 500K points, simulate 10K events per point and calculate the signal yields for 3 disjoint CMS SUSY analyses for $\sim 1\text{fb}^{-1}$ of data (α_T hadronic, same-sign dilepton, opposite-sign dilepton)
- 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).
- 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.

Complementary study based on a flat random scan:
Arbey, Battaglia, Mahmoudi, arXiv:1110.3726

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	$BR(b \rightarrow s\gamma)$	$(3.55 \pm 0.34) \times 10^{-4}$	Gaussian
2	$BR(B_s \rightarrow \mu\mu)$	$\leq 4.7 \times 10^{-8}$ *)	$1/(1 + \exp(\frac{\mu_2 - D_2}{0.01D_2}))$
3	$R(B_u \rightarrow \tau\nu)$	1.66 ± 0.54	Gaussian
4	Δa_μ	$(28.7 \pm 8.0) \times 10^{-10} [e^+e^-]$ $(19.5 \pm 8.3) \times 10^{-10} [\text{taus}]$	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 $BR(B_s \rightarrow \mu\mu) < 1.08$ at 95% CL

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

- 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



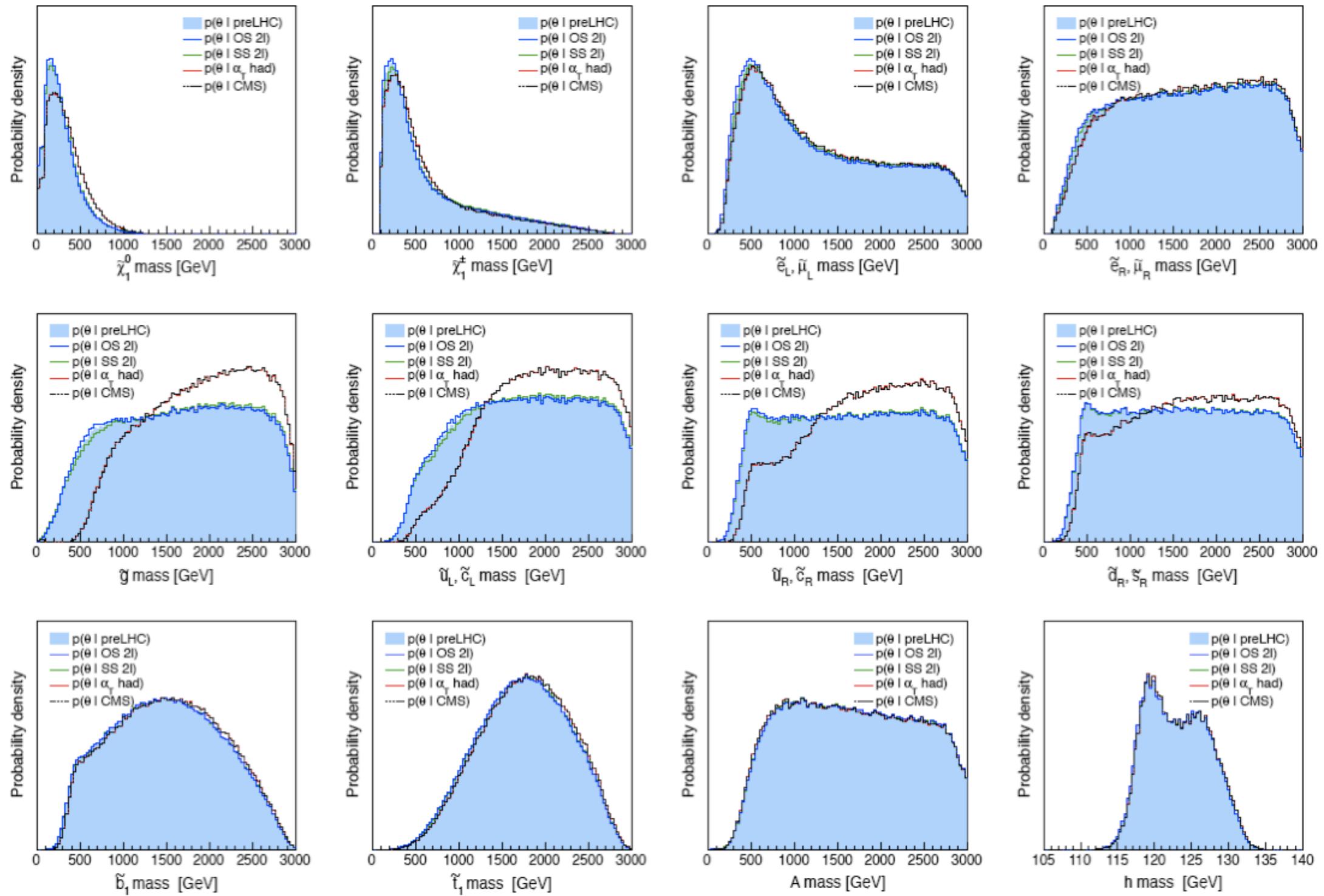
CMS analyses and likelihood - I

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

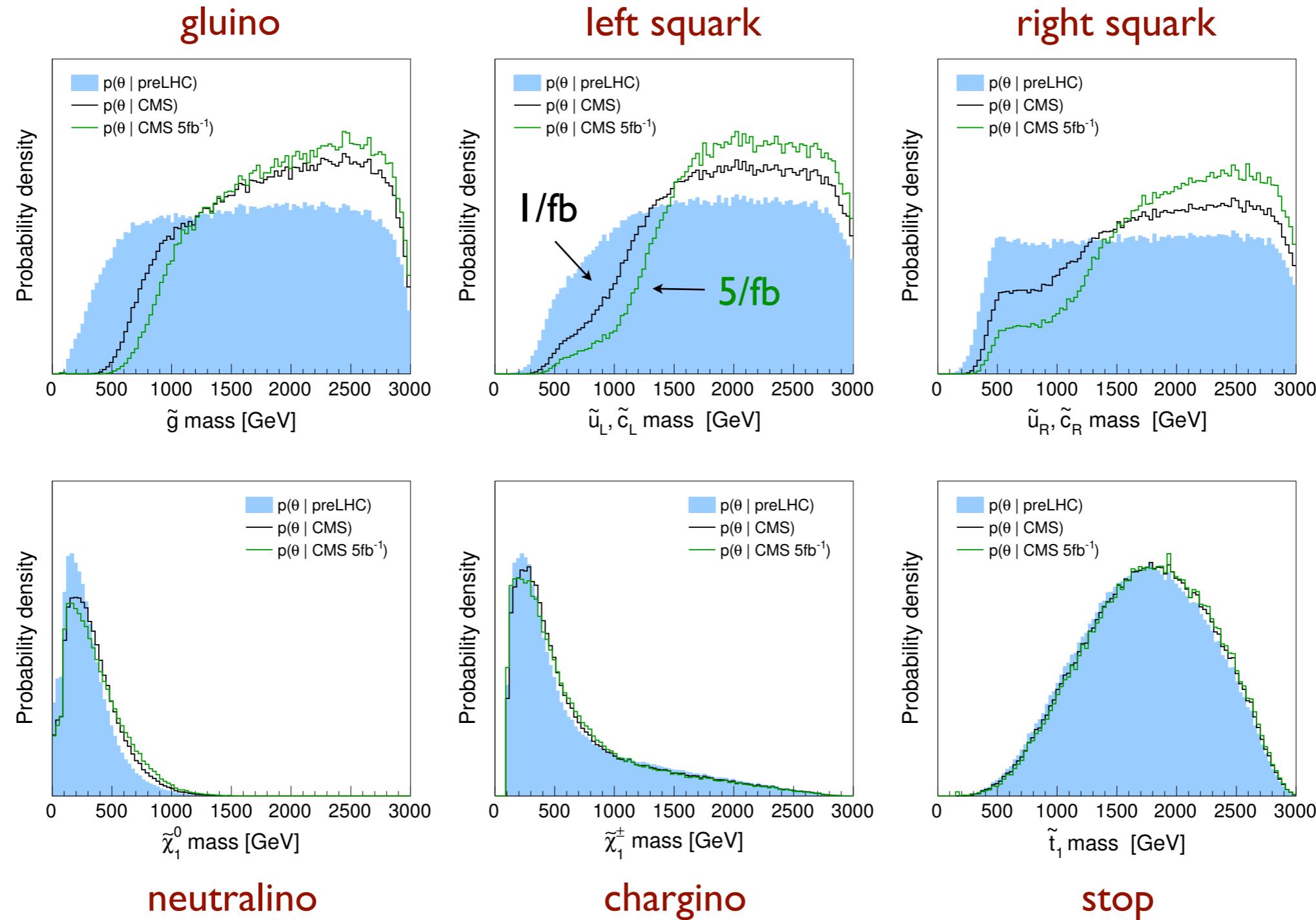
- Hadronic α_T (RA1 – CMS-SUS-11-003) 1.1 fb^{-1} : ≥ 2 jets and $\alpha_T > 0.55$, where α_T is designed to distinguish between real and fake E_T^{miss} . Shape analysis that gives results in 8 disjoint H_T bins. We use all.
- Same sign (SS) dilepton (RA5 - CMS-SUS-11-010) 0.98 fb^{-1} : Opposite sign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

Slide from S. Sekmen's talk,
30 Oct 11 at LHC2TeV workshop

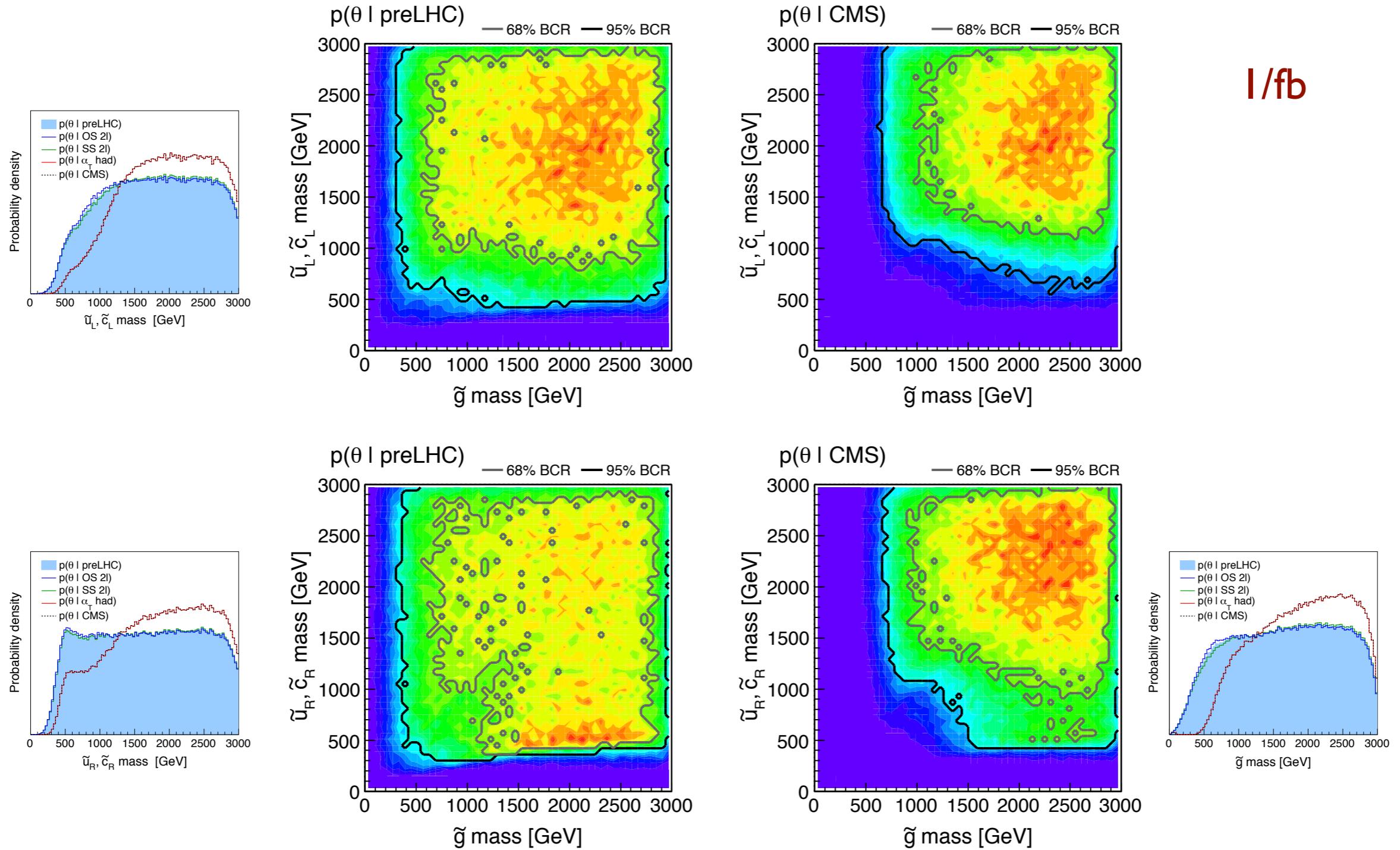
Results: posterior densities after 1/fb



Scaling to 5/fb

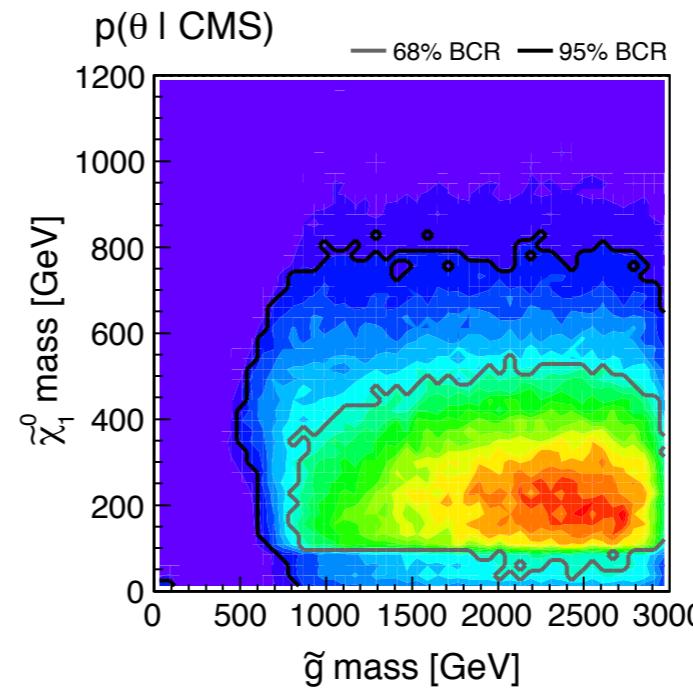
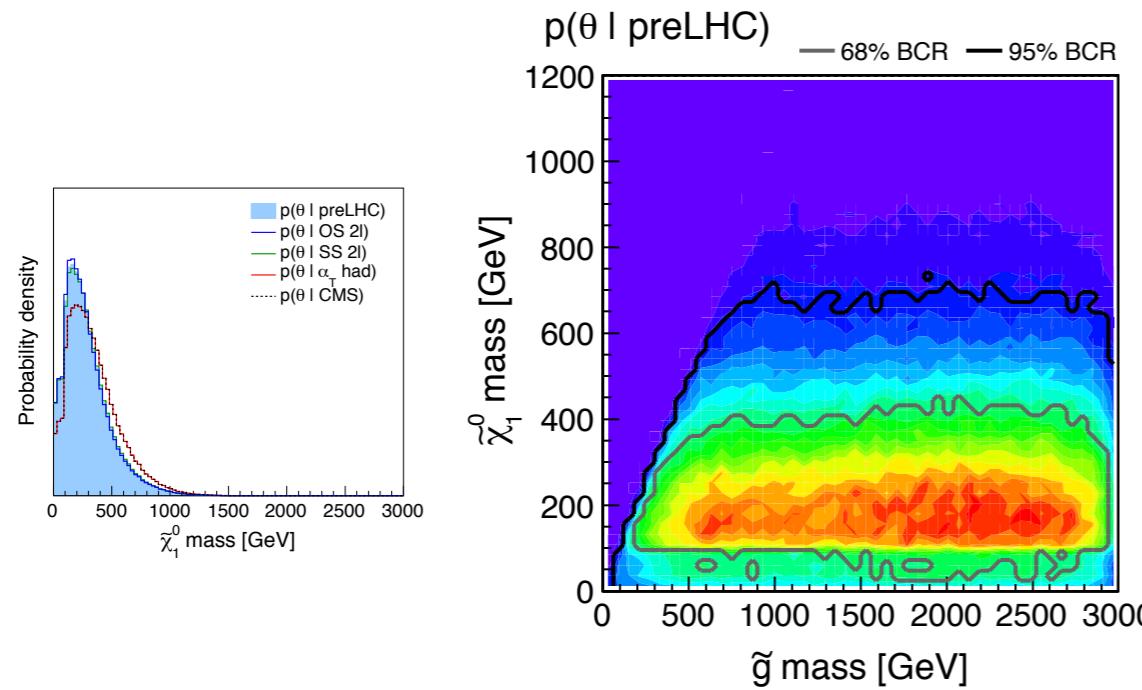


Squark versus gluino mass



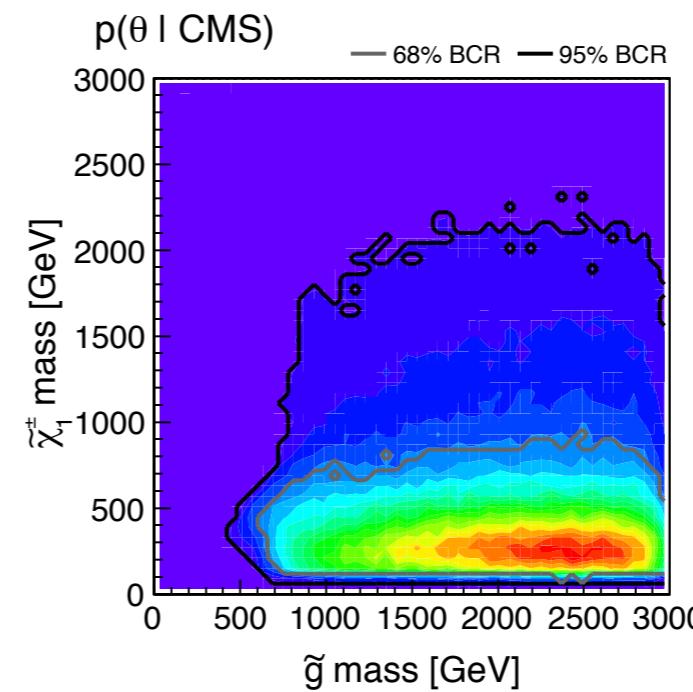
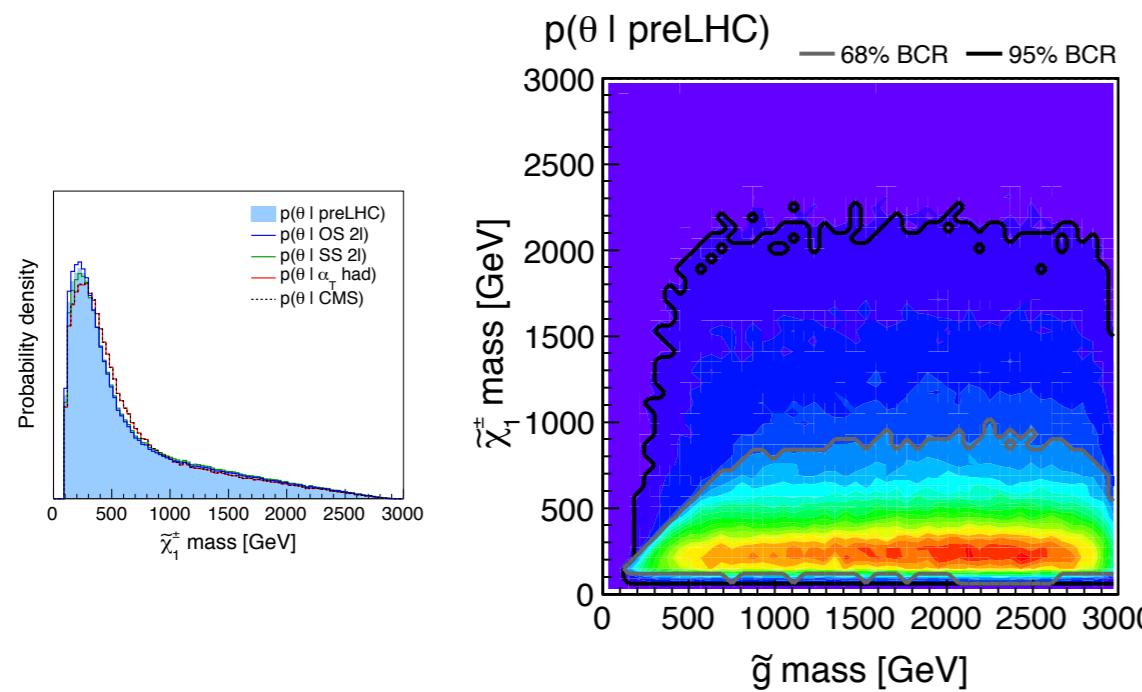
BCR: Bayesian credible region – these are not exclusion curves!

Neutralino/chargino versus gluino mass

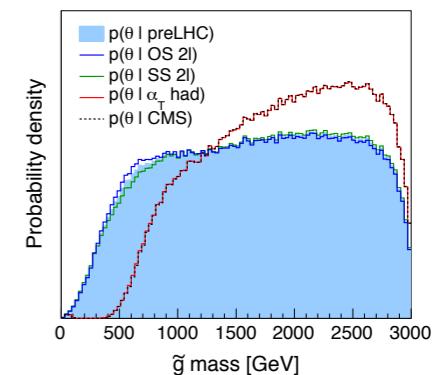


| /fb

neutralino
vs. gluino



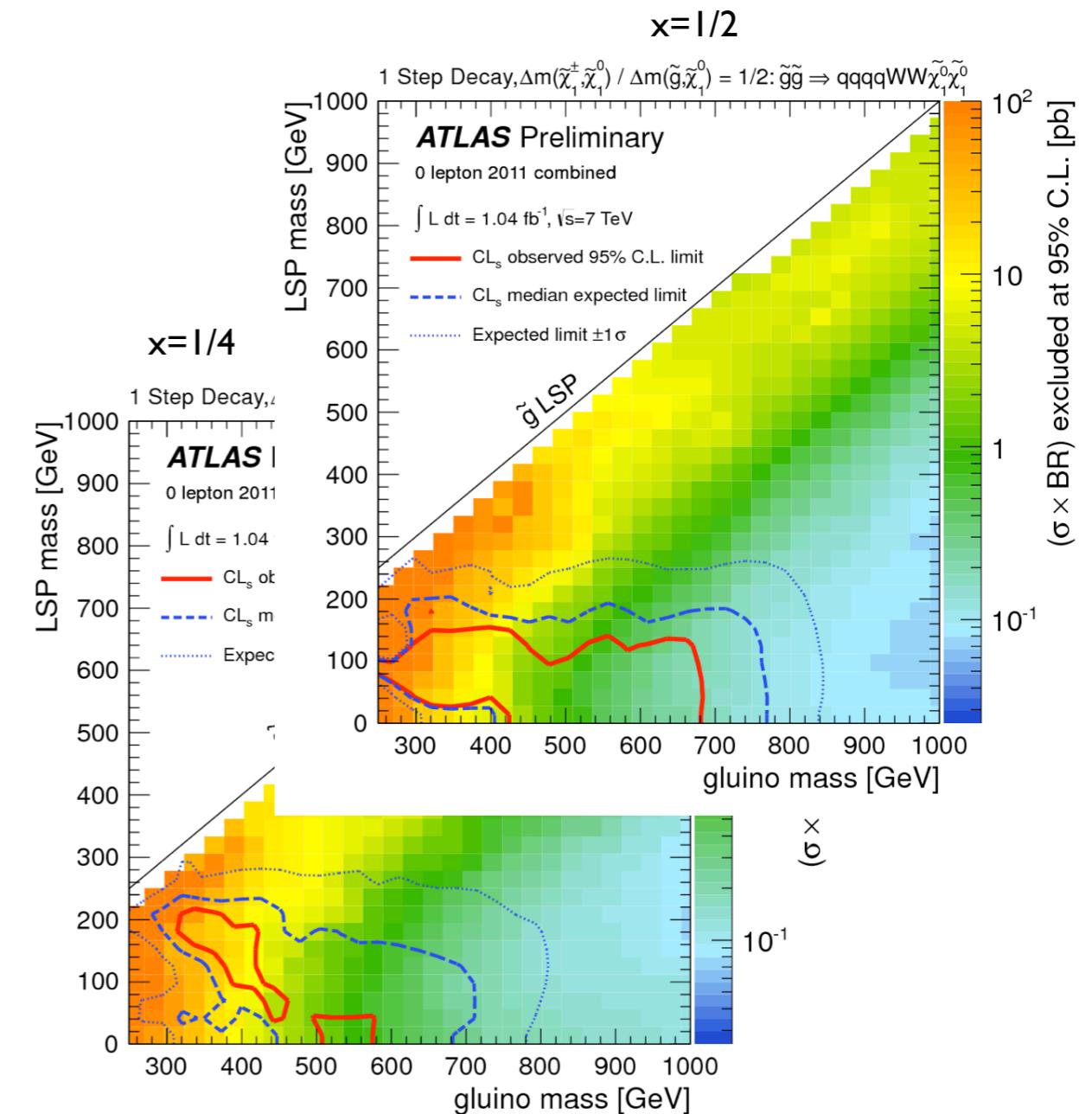
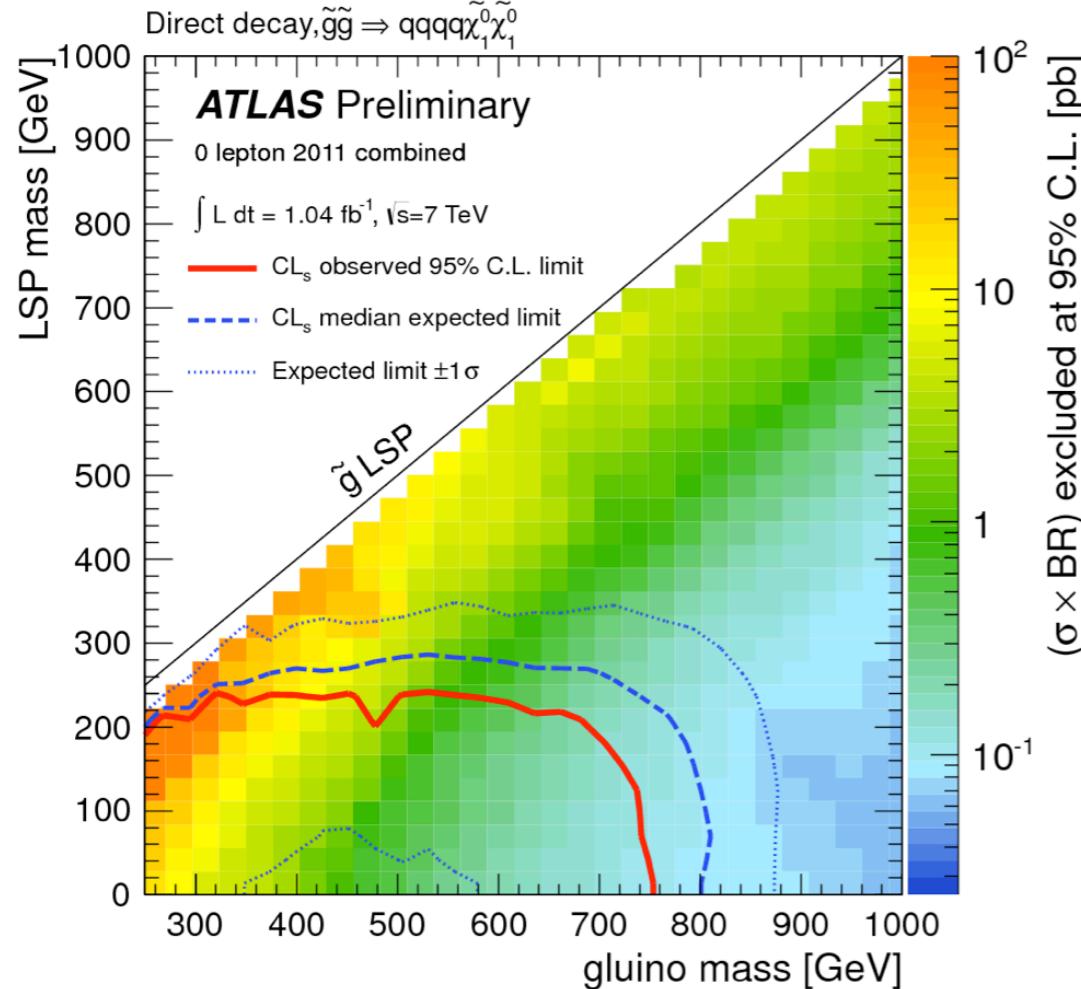
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vs. gluino



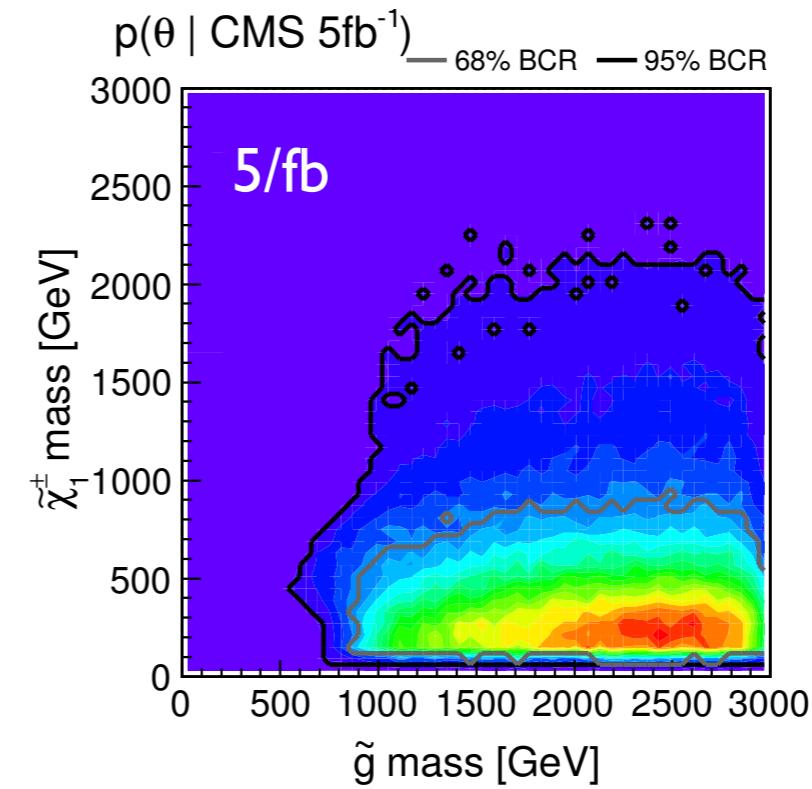
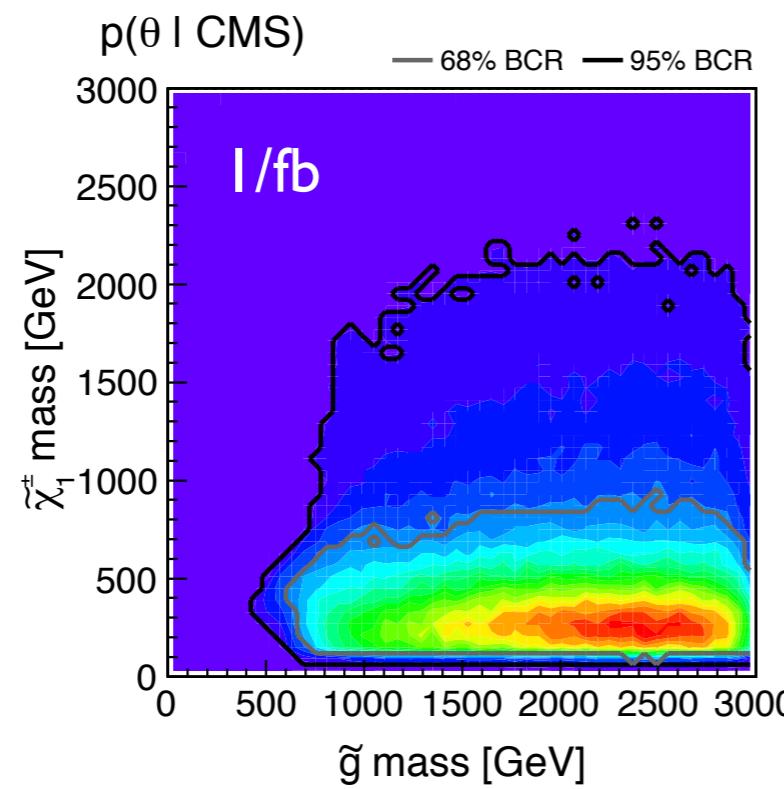
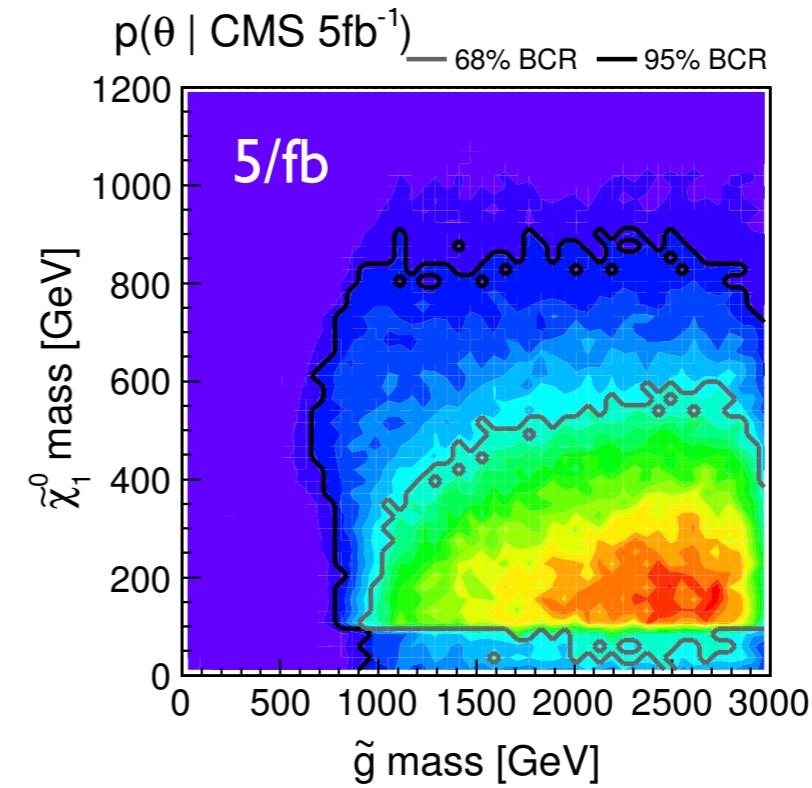
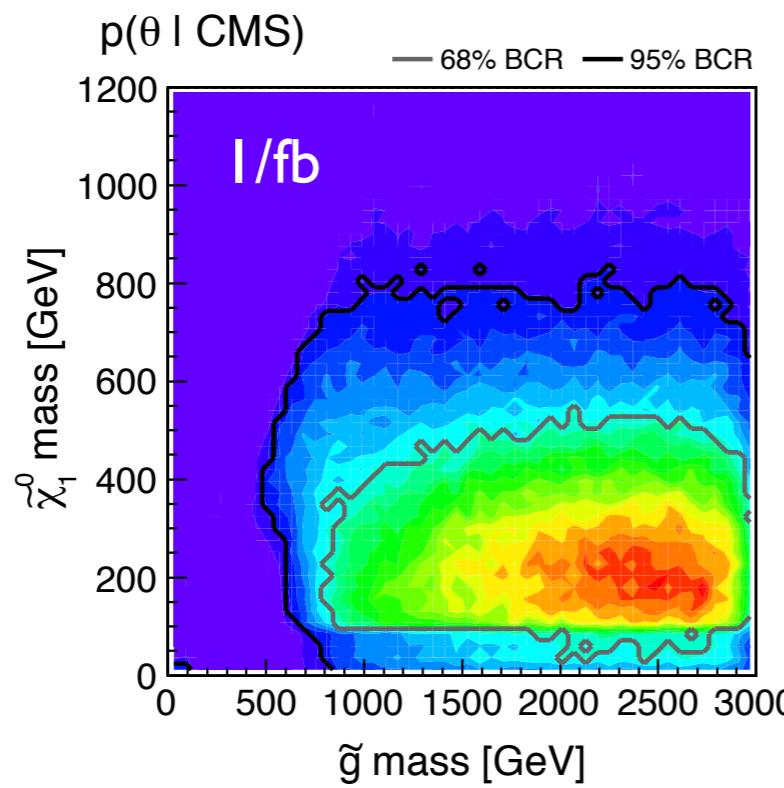
BCR: Bayesian credible region – these are not exclusion curves!

Compare with ATLAS jets+MET search

– interpretation in simplified models: **gluino** –



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

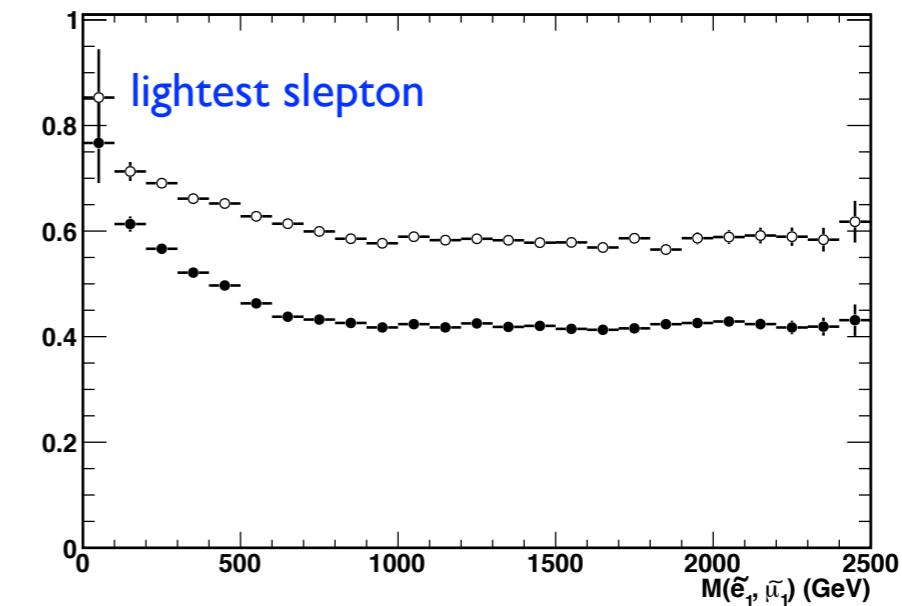
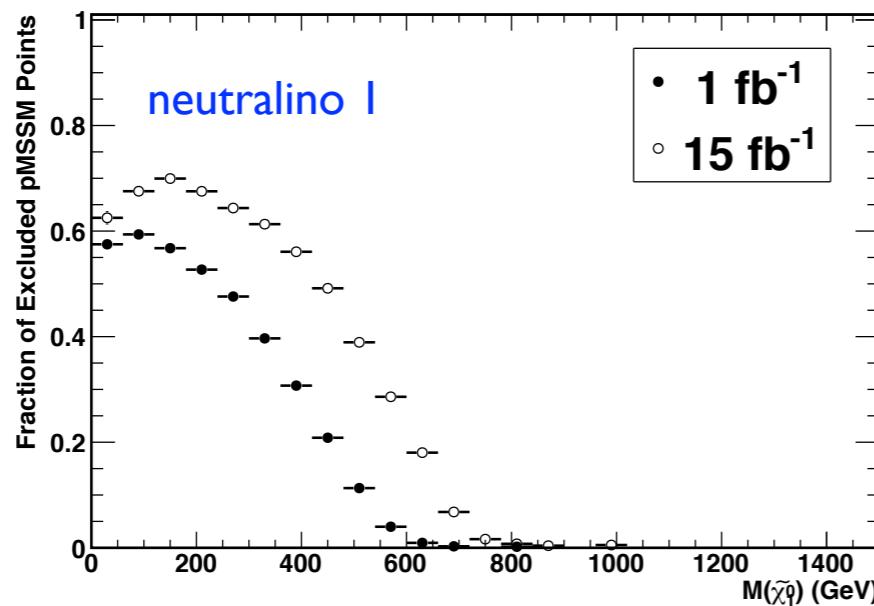
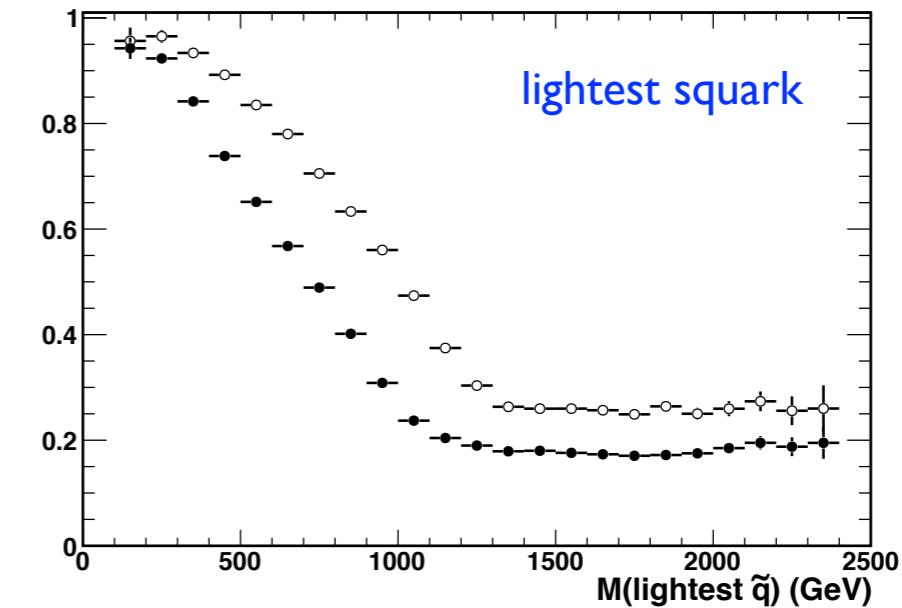
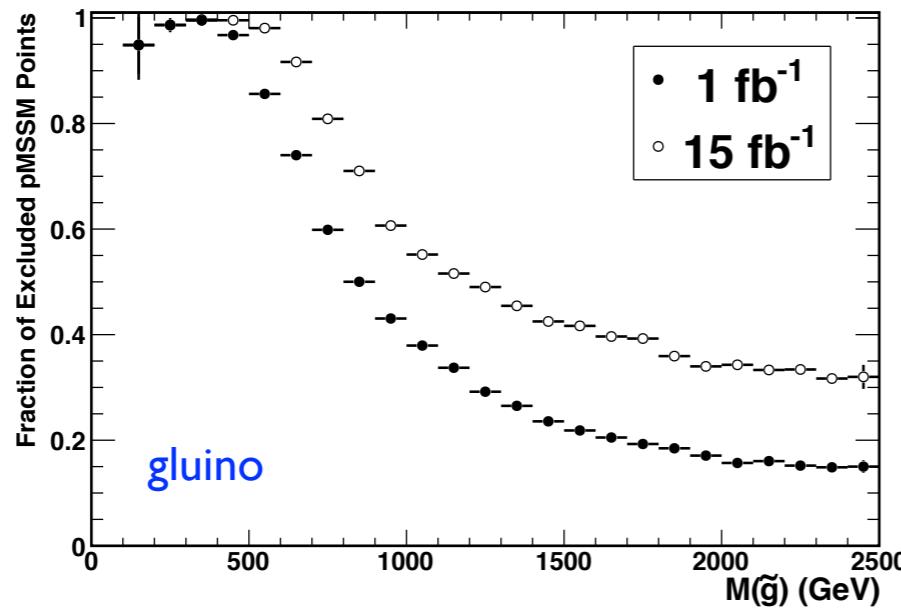


5/fb results just rescaled from 1/fb ones!

Complementary study based on a flat random scan

Arbey, Battaglia, Mahmoudi, arXiv:1110.3726

Fraction of excluded pMSSM points

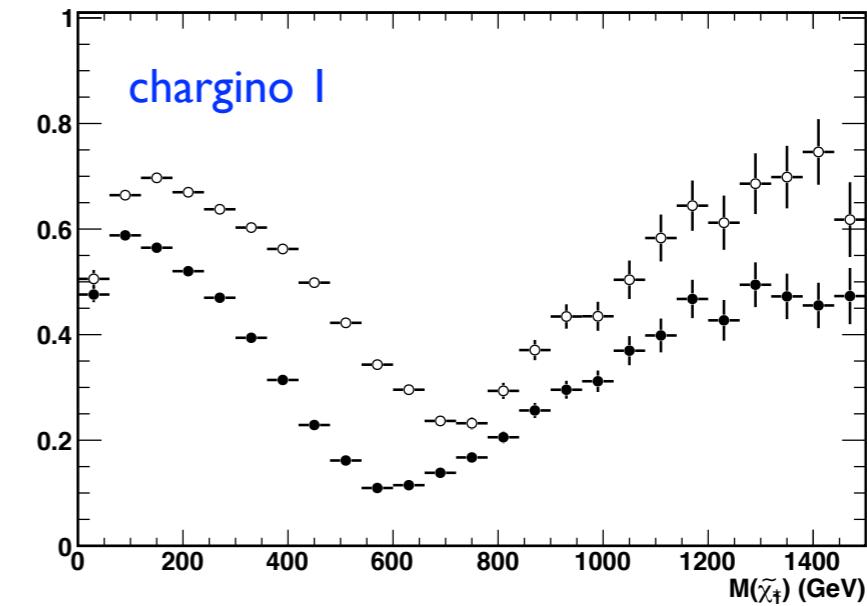
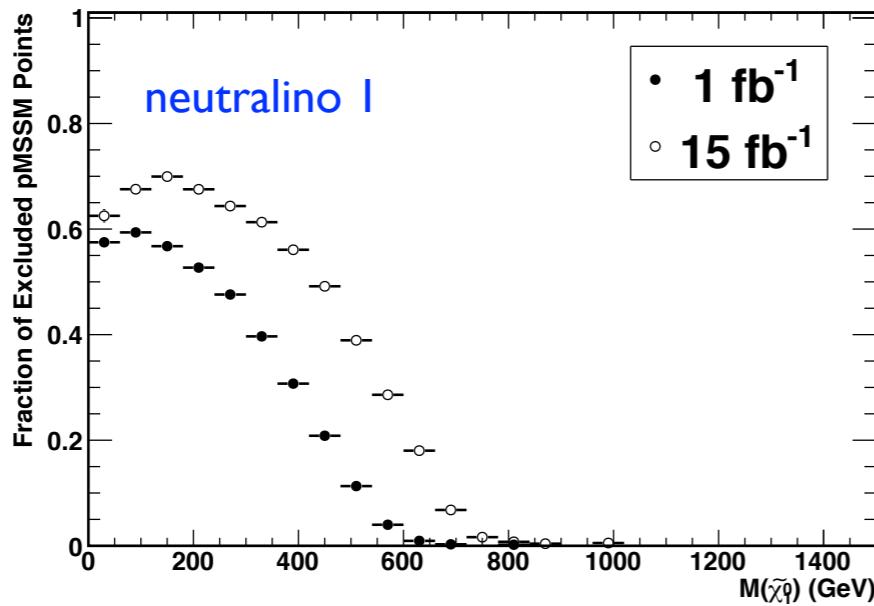
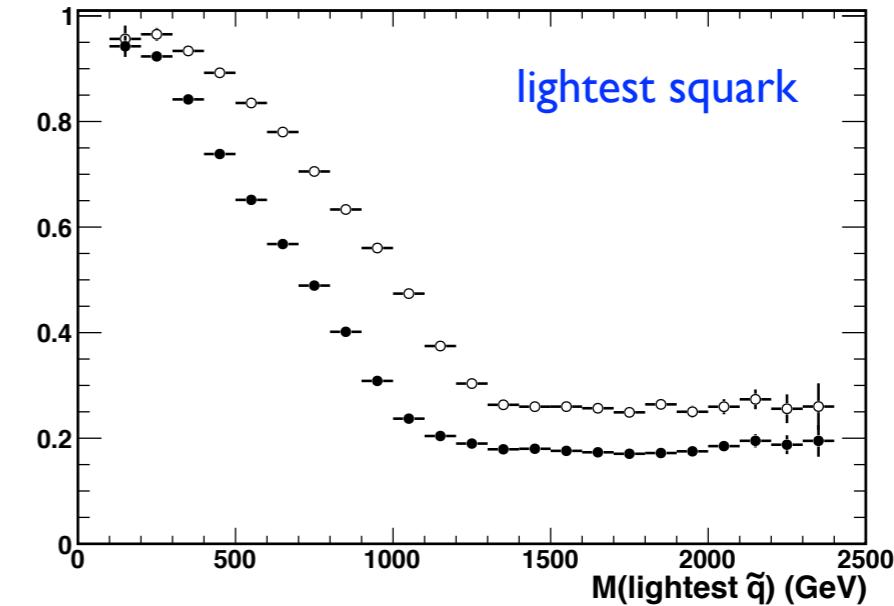
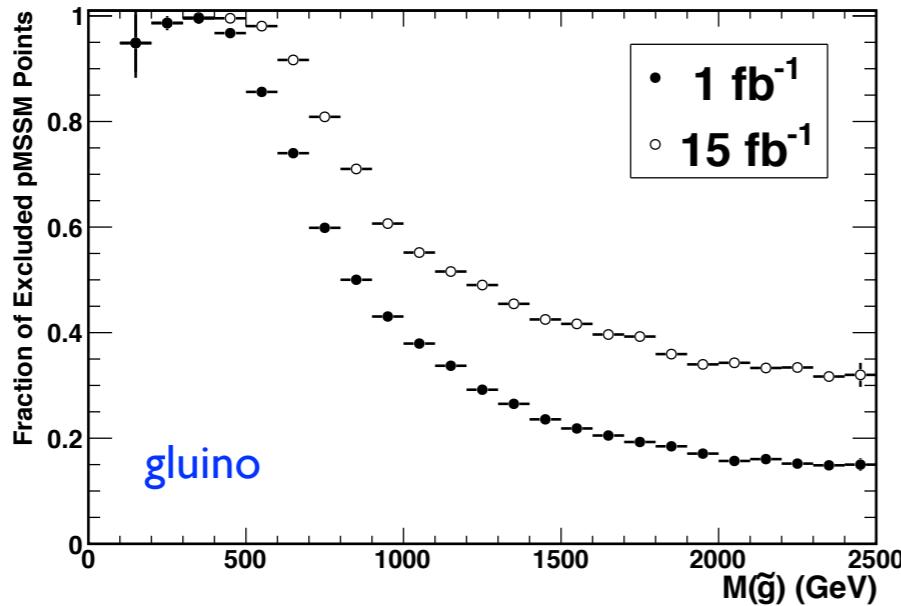


Apply 2σ constraints from flavour physics, g-2, dark matter and earlier LEP and Tevatron searches.

Complementary study based on a flat random scan

Arbey, Battaglia, Mahmoudi, arXiv:1110.3726

Fraction of excluded pMSSM points

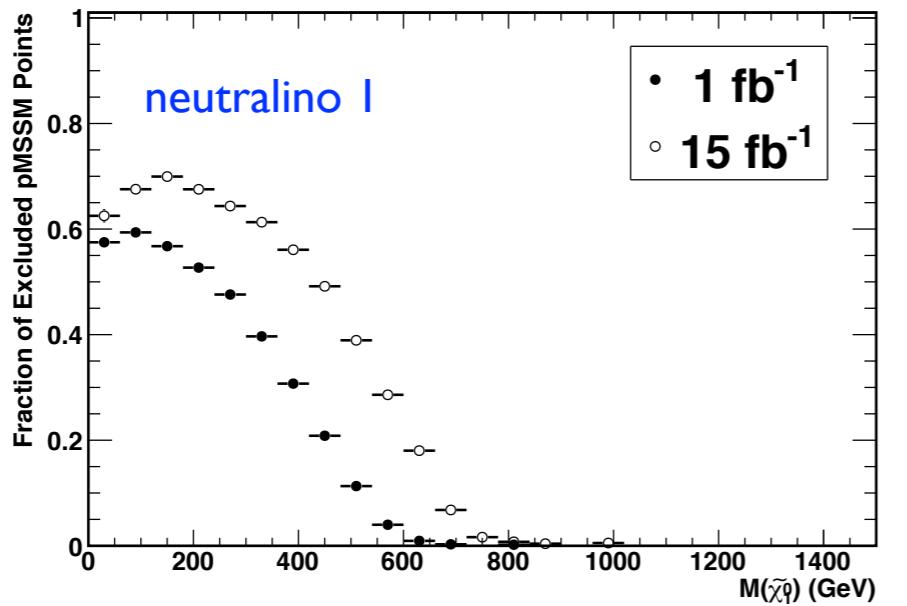
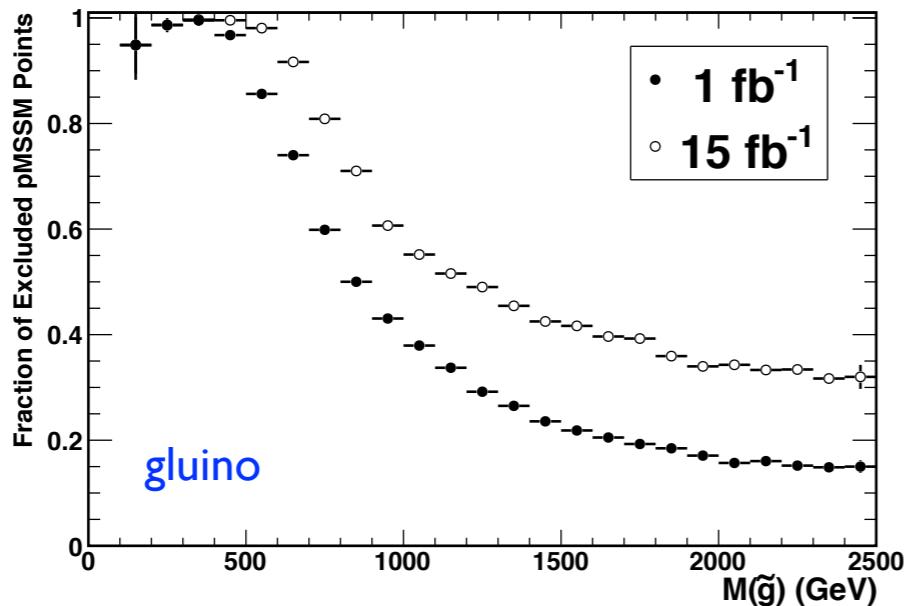


Apply 2σ constraints from flavour physics, g-2, dark matter and earlier LEP and Tevatron searches.

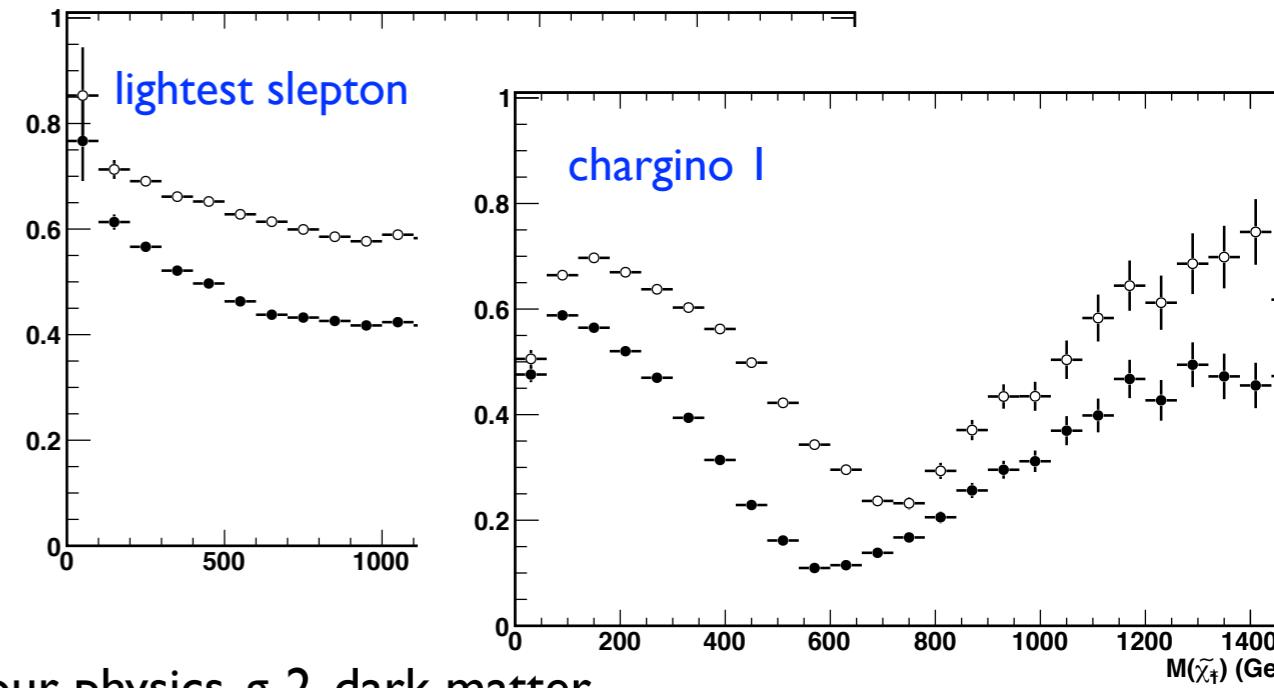
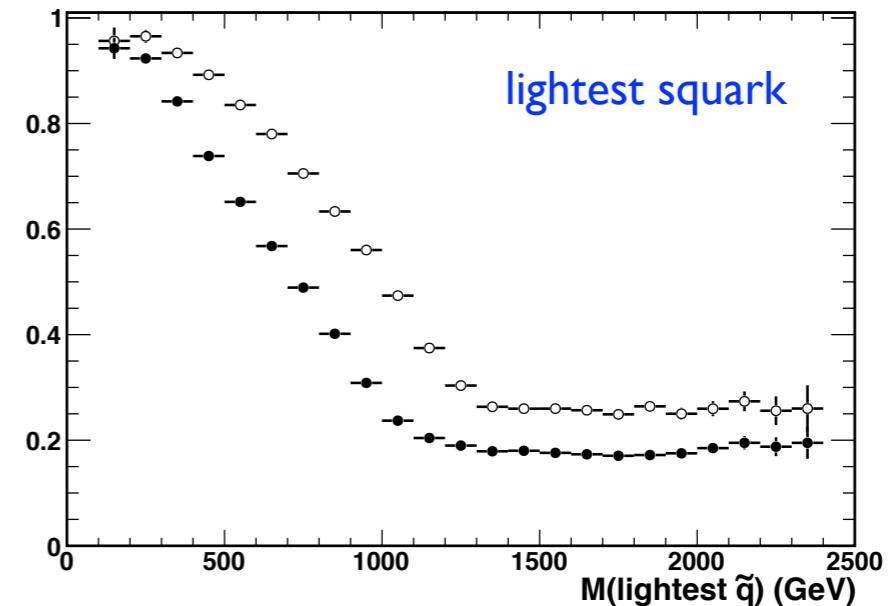
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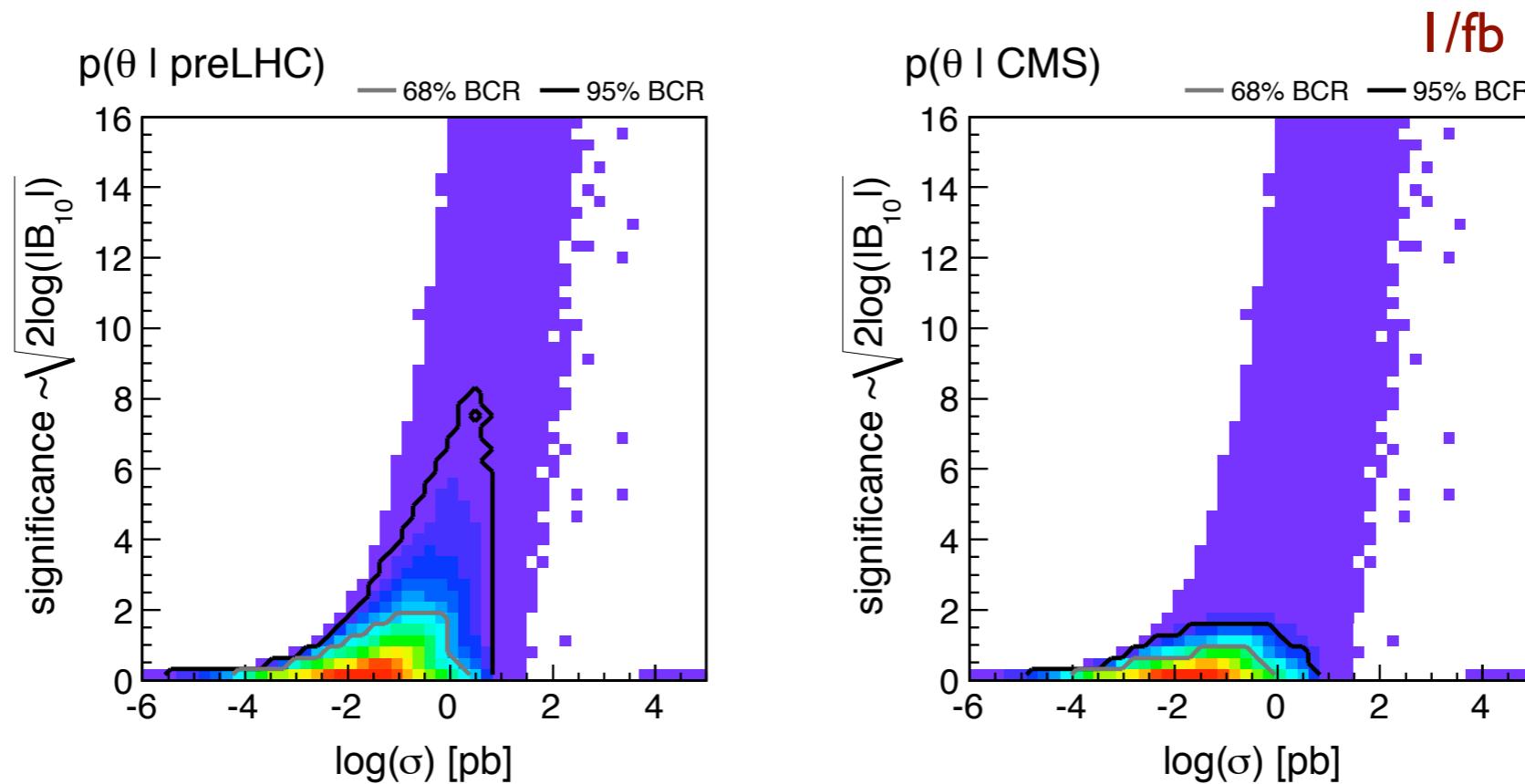


Apply 2σ constraints from flavour physics, g-2, dark matter and earlier LEP and Tevatron searches.



Signal significance versus cross section

Large cross section = high signal significance?

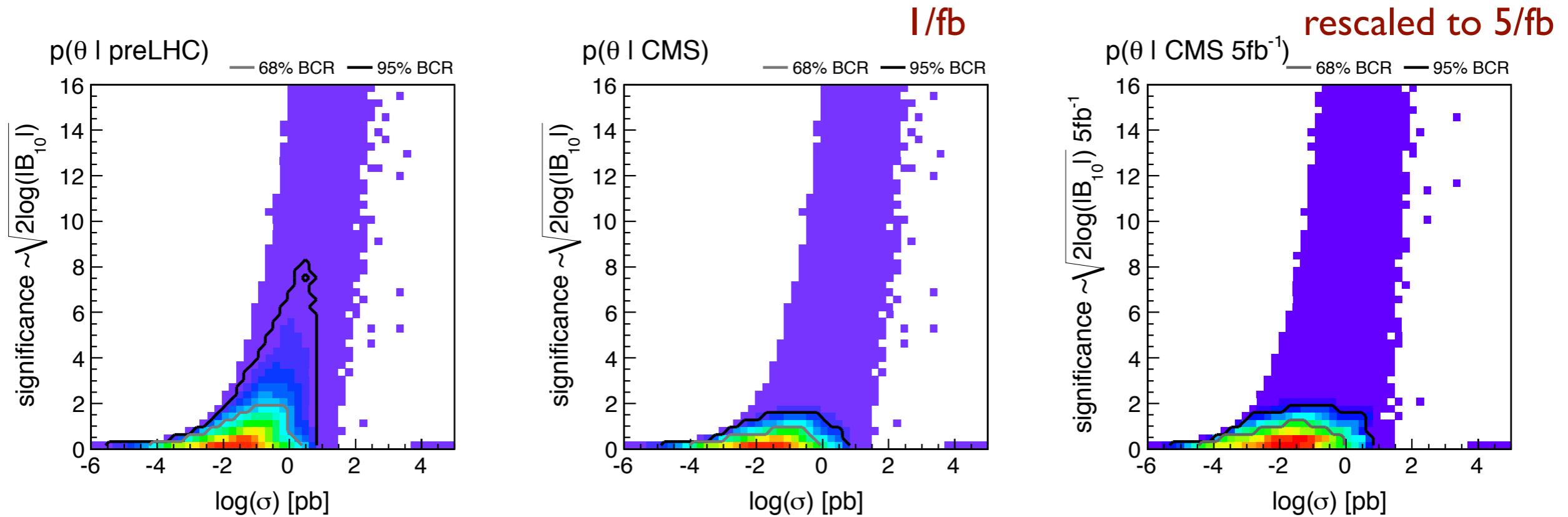


Signal of order 1 pb cross section
could have escaped detection!

Work in progress to analyze spectra with large cross section but low signal significance

Signal significance versus cross section

Large cross section = high signal significance?

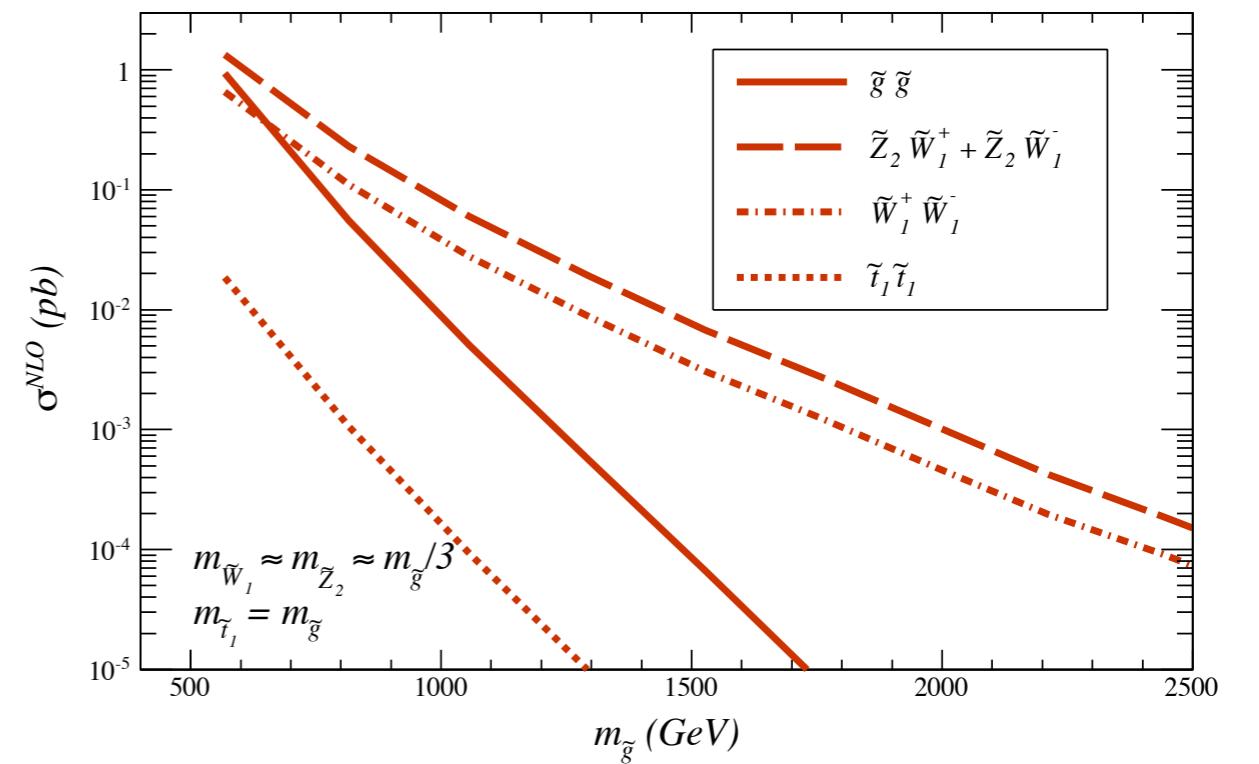


Signal of order 1 pb cross section
could still have escaped detection!

Work in progress to analyze spectra with large cross section but low signal significance

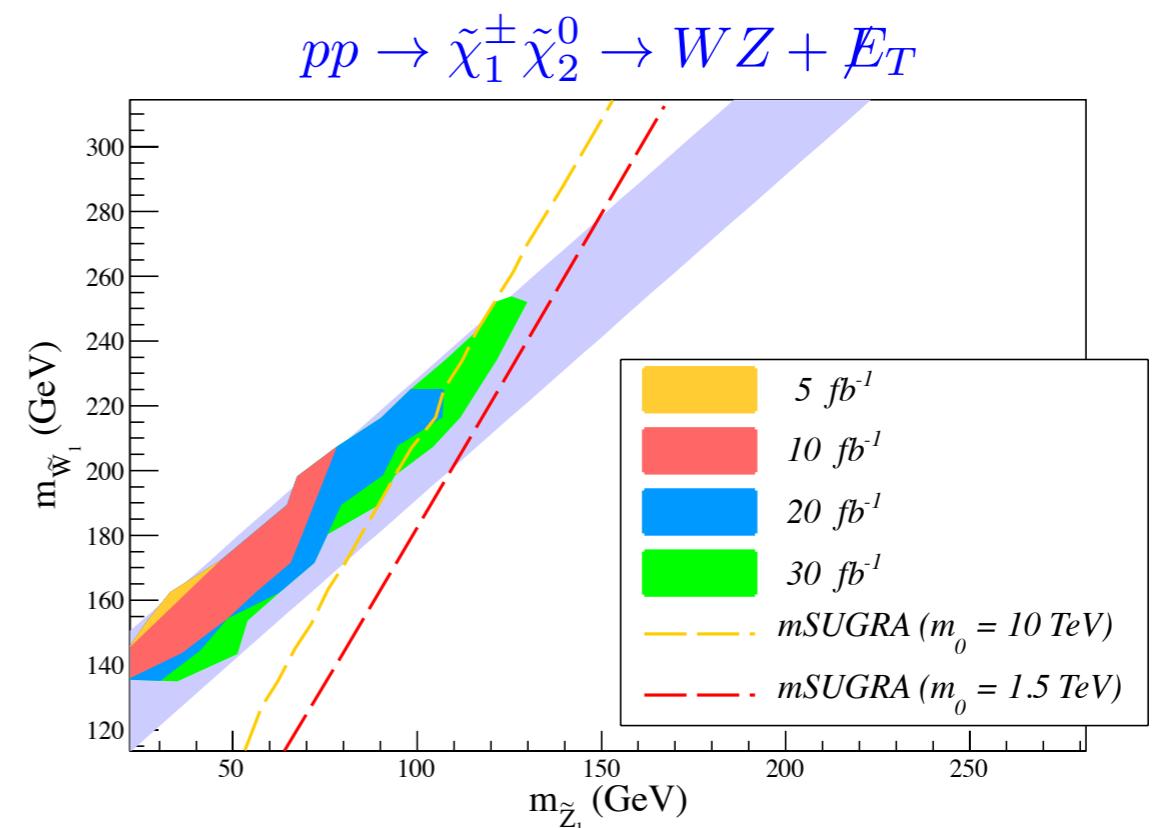
EW-inos: WZ + MET

- For gluino masses >500 GeV chargino-neutralino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production is the dominant cross section for $m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} \lesssim m_{\tilde{g}}/3$
 - 3 isolated leptons $p_T > 20$ GeV
 - $|m(\ell^+ \ell^-) - M_Z| < 10$ GeV
 - $E_T^{\text{miss}} > 50$ GeV
 - $m_T(\ell', \cancel{E}_T) > 125$ GeV
 - n(b-jets)=0
- Reach up to ~ 200 (250) GeV with 10 (30) fb^{-1}



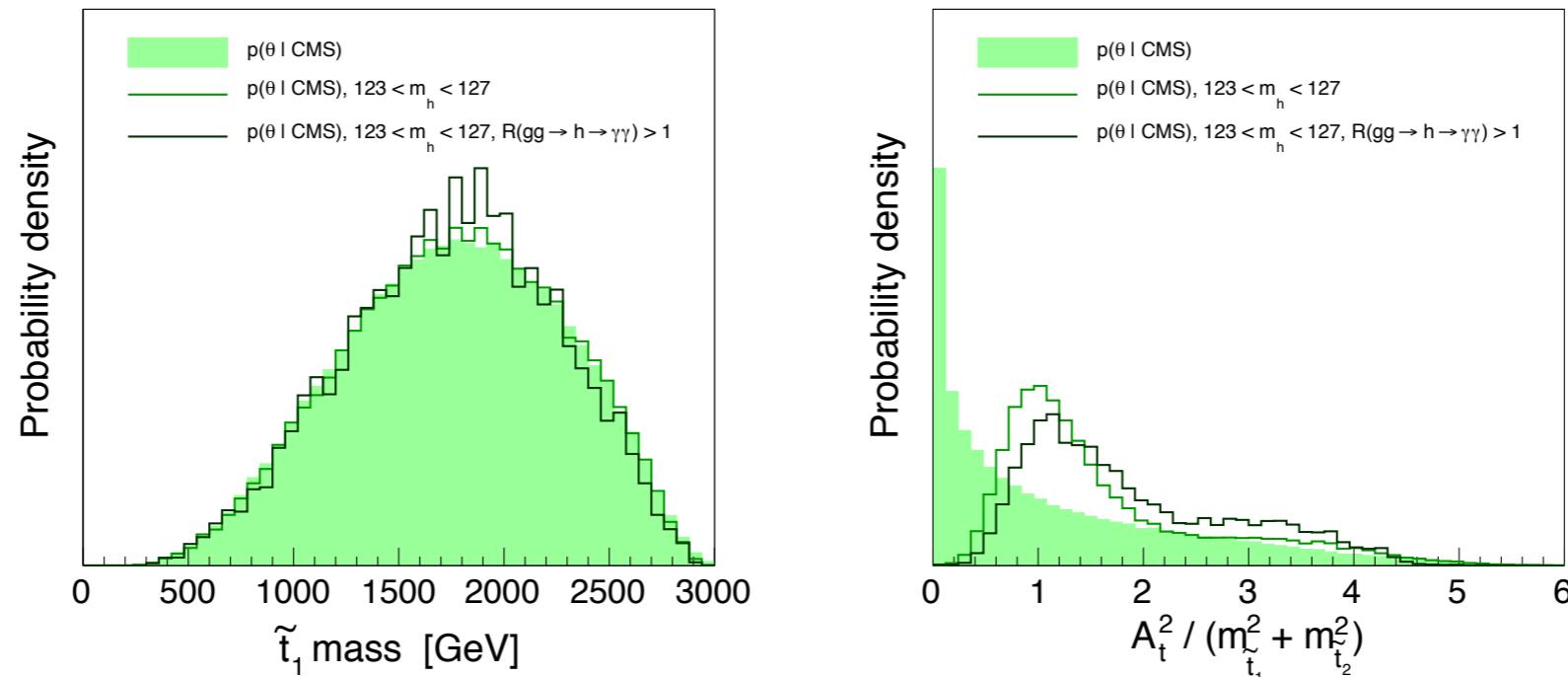
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Implications from $m_h \sim 125$ GeV

LH PhysTeV 2011 proceedings

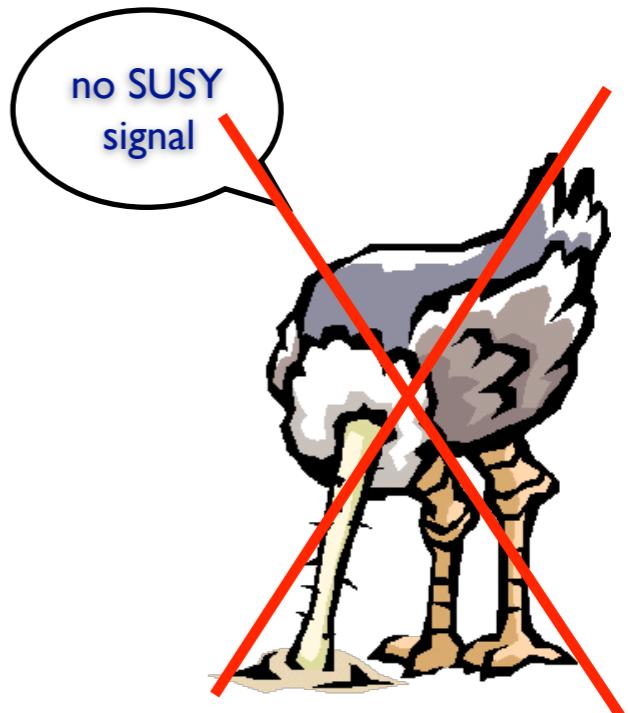


Probability distributions after 1fb^{-1} LHC SUSY searches
requiring $m_h = 123\text{-}127$ GeV

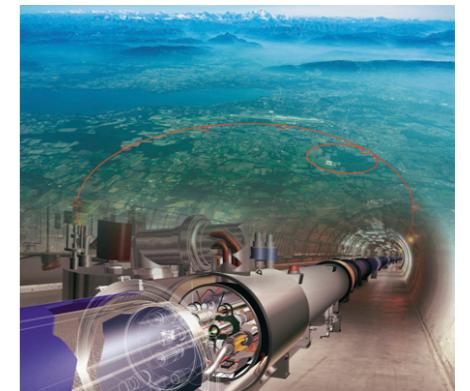
⇒ Nazila Mahmoudi's talk in the afternoon

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 \rightarrow soft jets, low E_T^{miss}
 - ★ Compressed spectra in general
 - ★ Mainly electroweak production
 - ★ Mainly stop/sbottom production
- Plenty of room where SUSY can hide
besides, EW fits and flavor physics actually prefer heavy SUSY (inverted hierarchy, heavy 1st/2nd generation squarks)
- 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.



At the dawn of a new era ...



Crossing thresholds:

- Around 1900: atomic scale

$$\frac{\hbar^2}{e^2 m_e} \approx 10^{-8} \text{ cm}$$

development of
quantum mechanics,
scientific revolution

- Around 1950: discovery of new hadron resonances, threshold of strong interaction scale

$$a_s \approx M e^{-8\pi^2/g_s^2(M)b_0} \approx 10^{-13} \text{ cm}$$

QCD

- Now: go beyond the Fermi scale

Fermi 1933



$$G_F \approx (300 \text{ GeV})^{-2} \approx 10^{-16} \text{ cm}$$

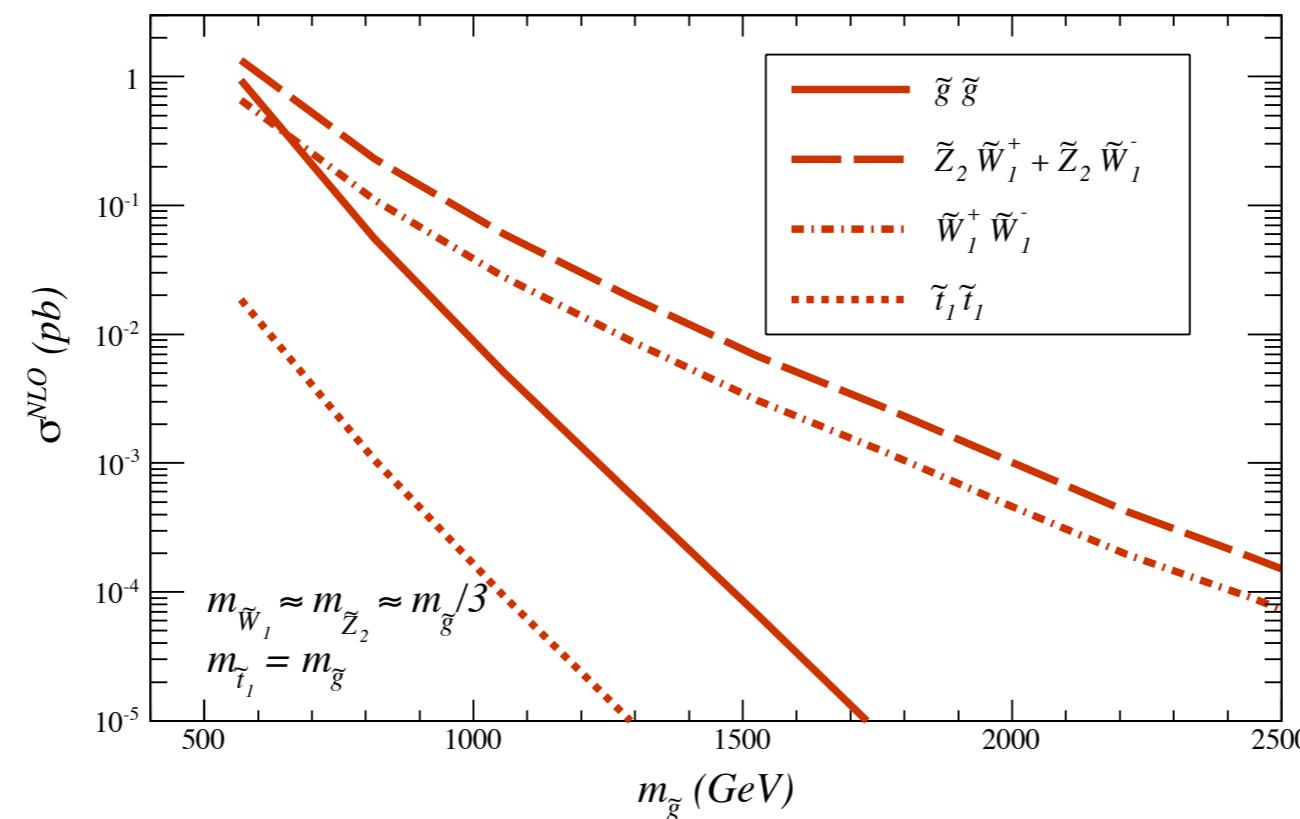
expect another
scientific revolution

NB: discovery of W and Z bosons was a milestone for establishing the Standard Model, but did not give us a complete understanding of the weak force (EW symmetry breaking)

Backup

EW-inos: WZ + MET

- For gluino masses >500 GeV chargino-neutralino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production is the dominant cross section for $m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} \lesssim m_{\tilde{g}}/3$



Tools

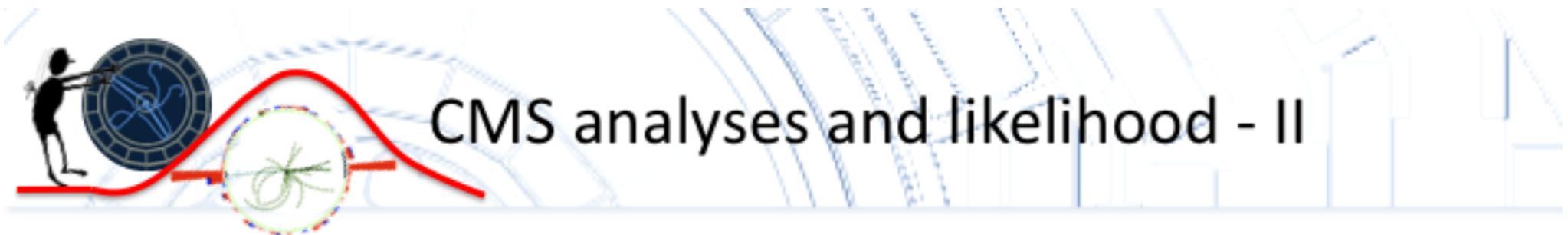
- SUSY spectrum calculation: **SOFTSUSY 3.1**
- Low energy observables: **SuperIso 3.0**
- Relic density, DD cross sections: **micrOMEGAs 2.4**
- SUSY mass limits: **micrOMEGAs 2.4**
- Higgs mass limits: **HiggsBounds 2.0.0**
- Decays: **SUSYHIT (SDECAY1.3b, HDECAY3.4)**
- SUSY event generation: **PYTHIA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

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

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 , $H_T > 400$, $\cancel{E}_T > 120$	1	2.3 ± 1.2
10	OS 2ℓ , $H_T > 300$, $\cancel{E}_T > 275$	8	4.2 ± 1.3

Assume a Poisson likelihood $\text{Poisson}(N_j|s_j + b_j)$ 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



Likelihood:

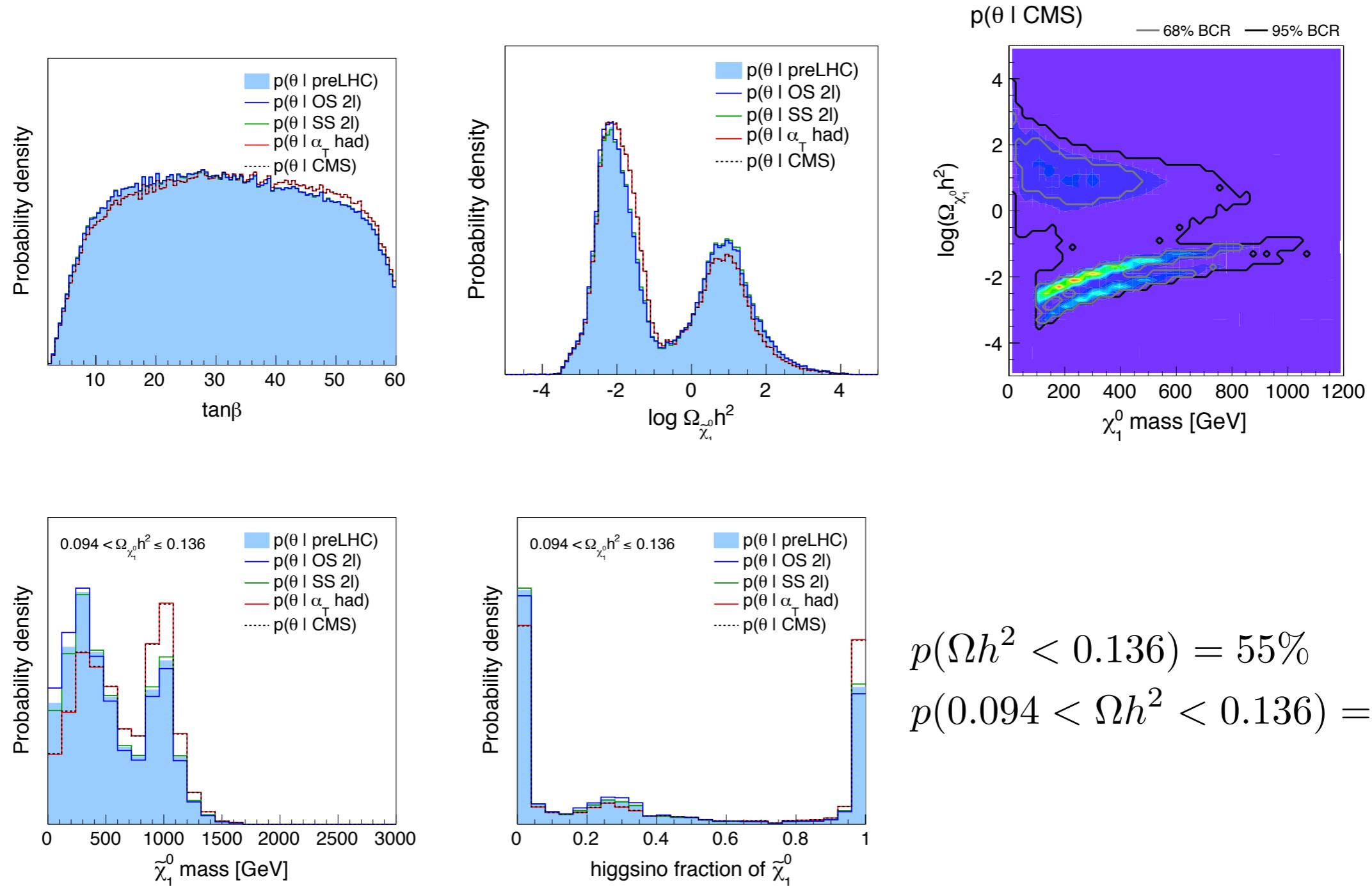
$$\begin{aligned} L_{CMS} &\equiv p(N|s, b, \delta b) \\ &= \prod_{i=1}^3 \text{Poisson}(N_i|s_i + b_i)p(b_i|\delta b_i) \quad \text{takes into account the} \\ &= \prod_{i=1}^3 \frac{e^{-(s_i+b_i)}(s_i+b_i)^{N_i}}{N_i!} \frac{e^{-k_i b_i} (k_i b_i)^{Q_i}}{\Gamma(Q_i + 1)} \quad \text{uncertainty in the BG} \\ &\quad \text{estimate} \end{aligned}$$

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

$$k_i = B_i/\delta B_i^2$$

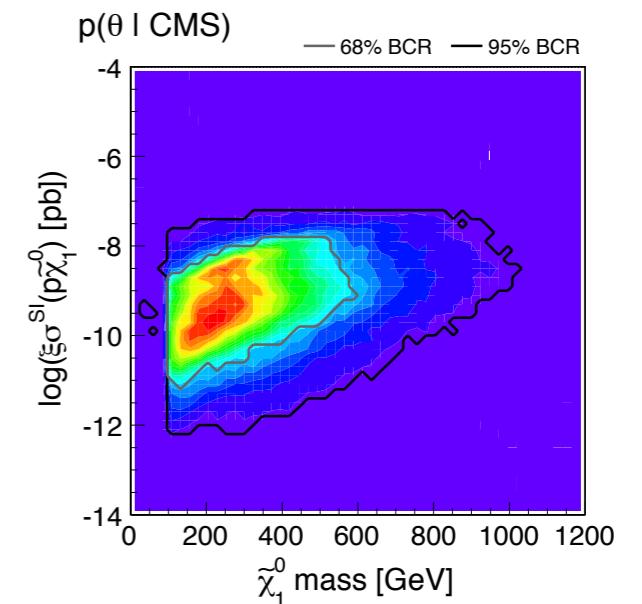
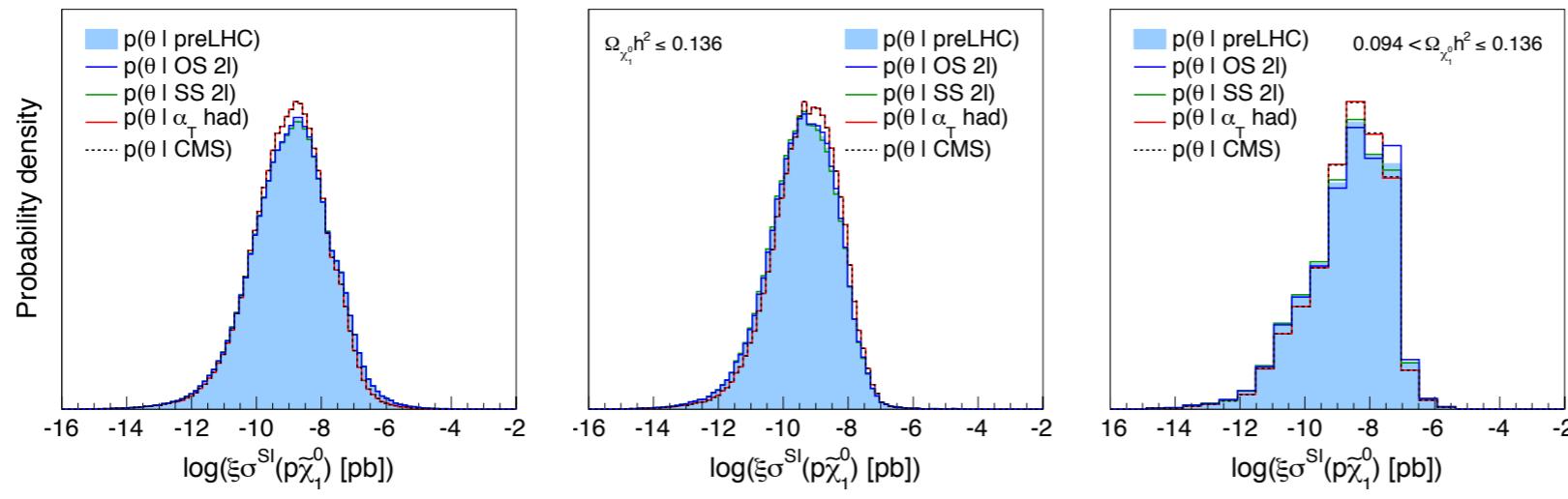
Slide from S. Sekmen's talk,
30 Oct 11 at LHC2TeV workshop

Dark matter implications

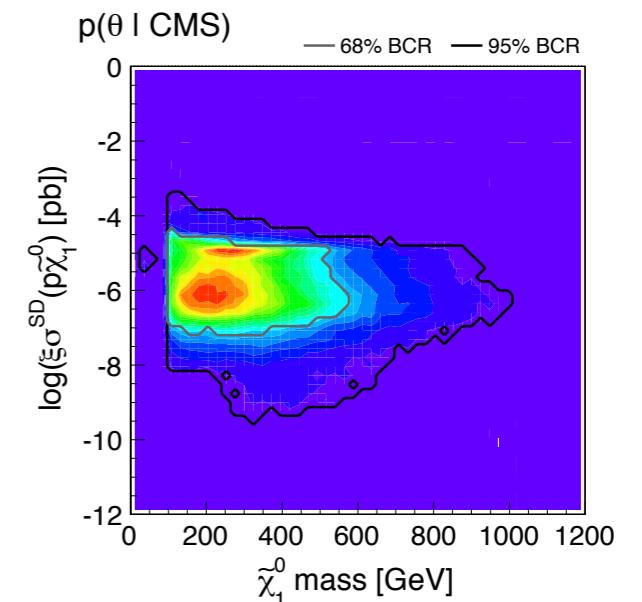
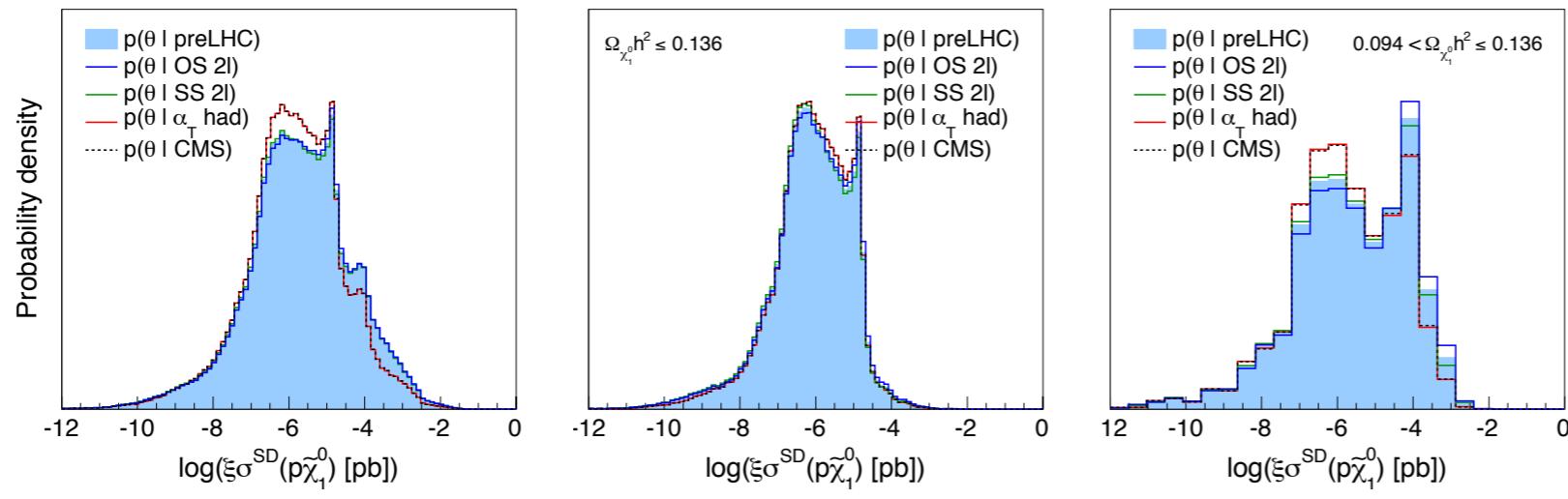


Implications for direct DM searches

spin-independent

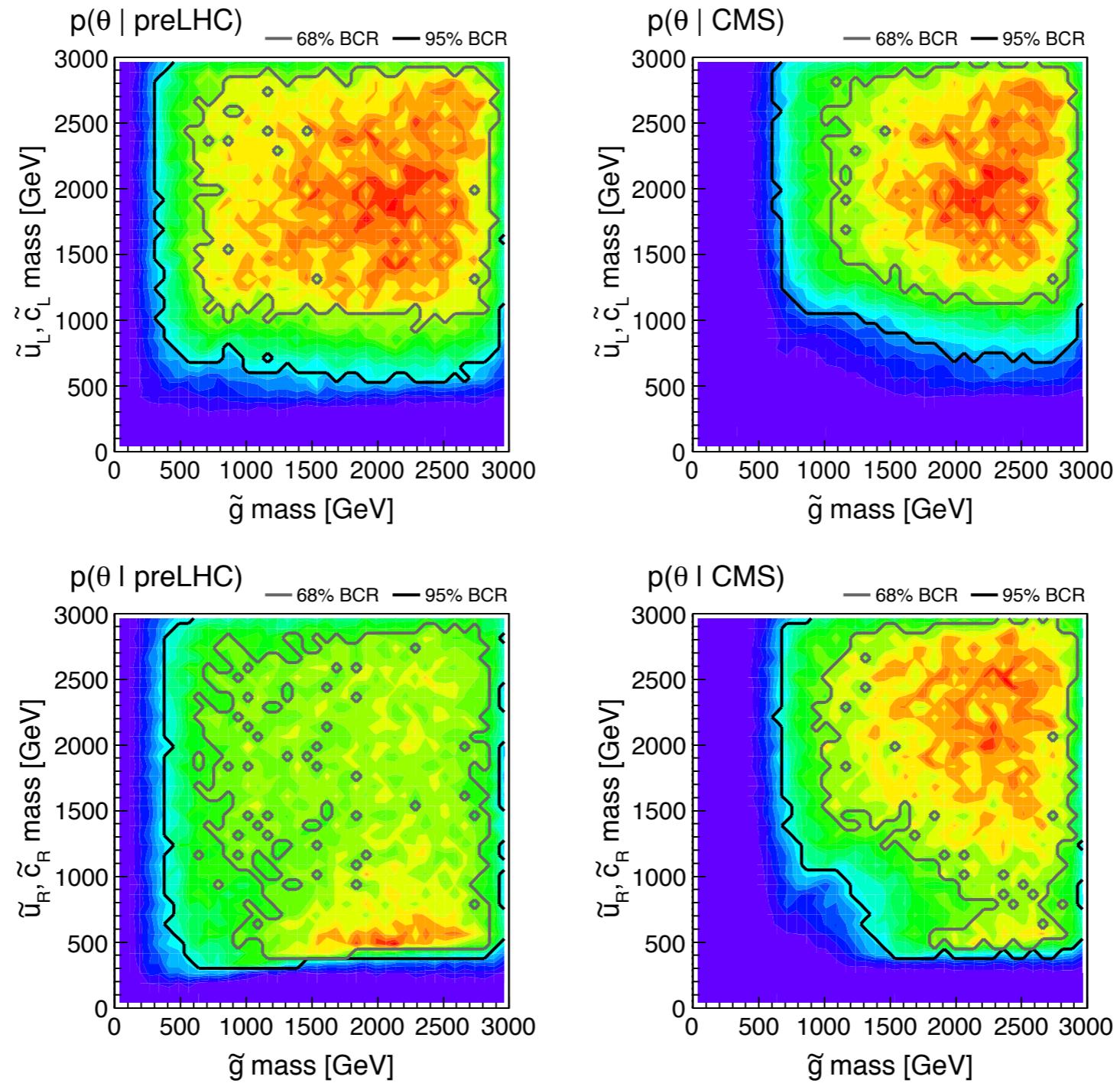


spin-dependent

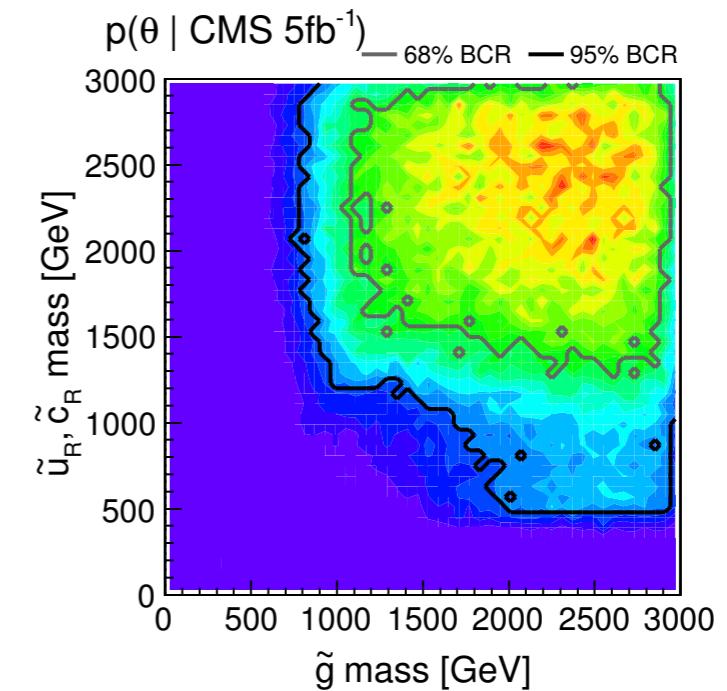
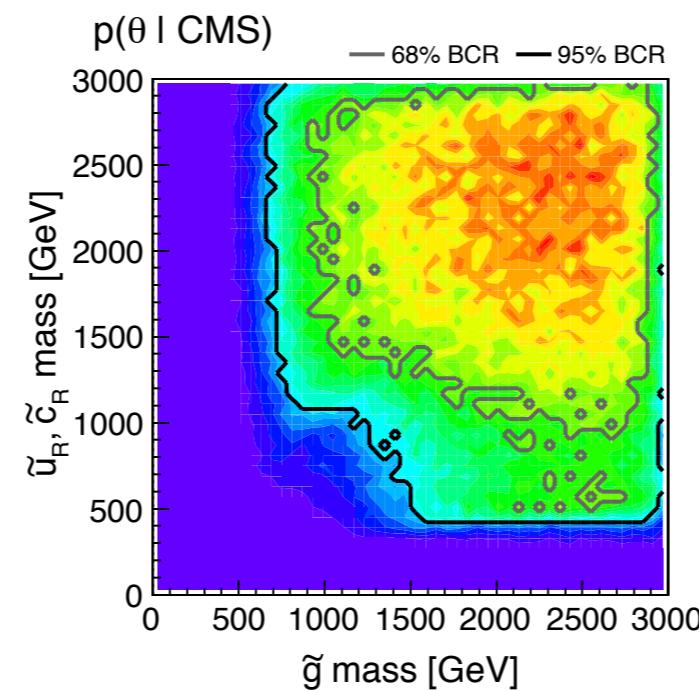
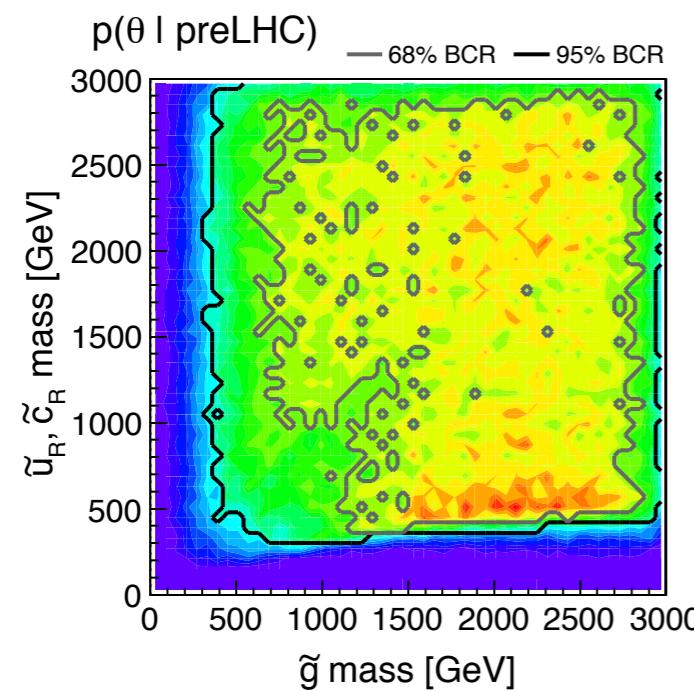
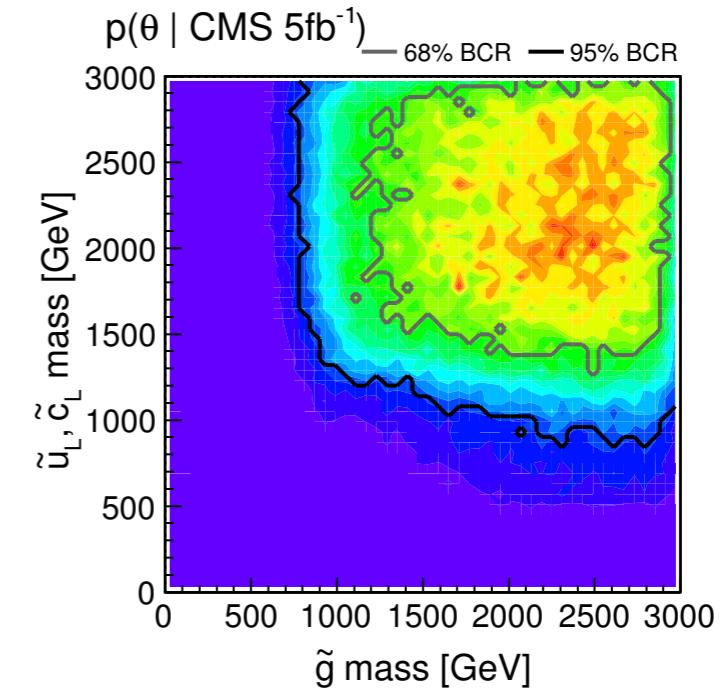
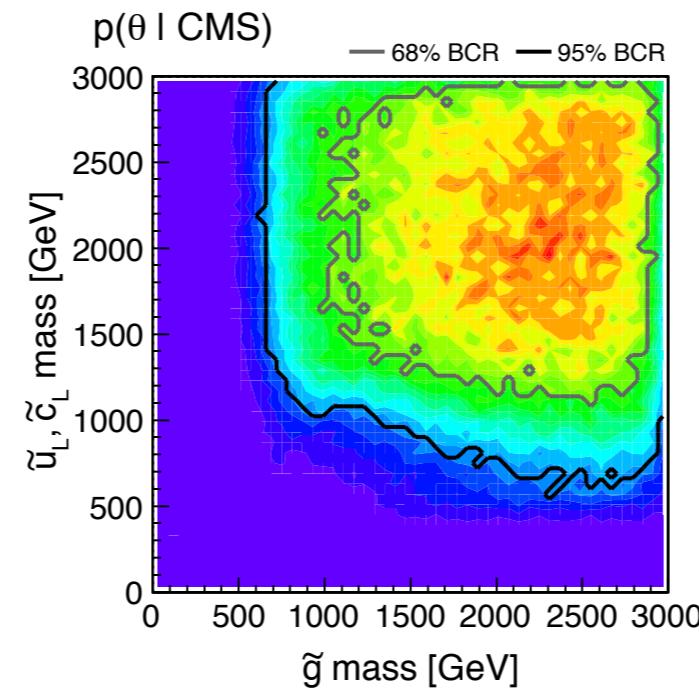
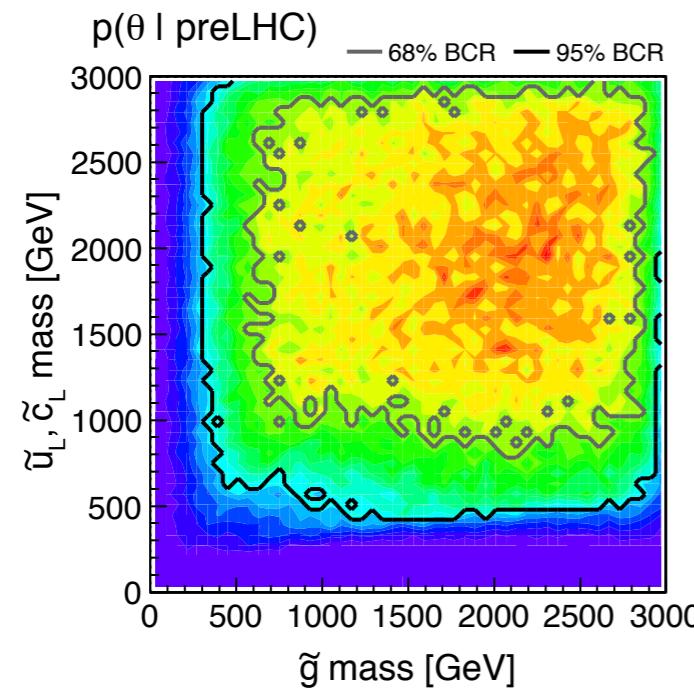


$$\xi = \Omega h^2 / 0.1123$$

Requiring $\Omega h^2 < 0.136$



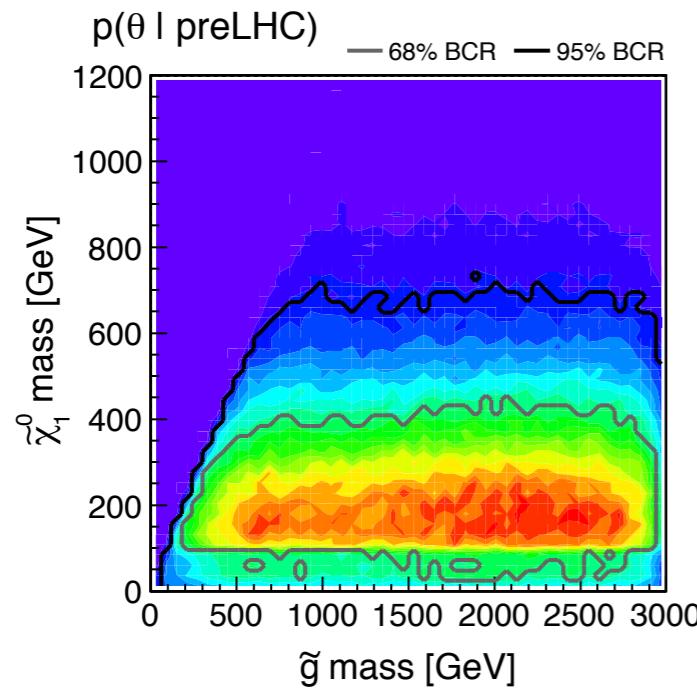
squarks



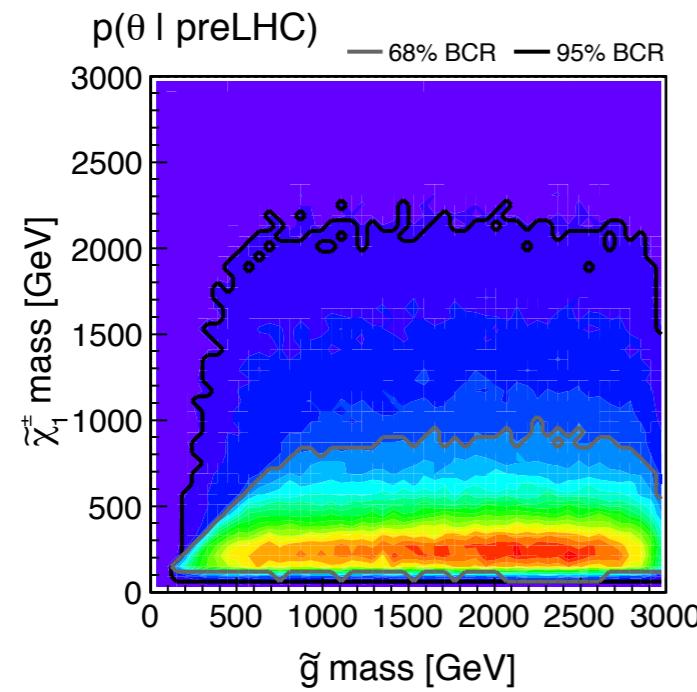
vs. gluino

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

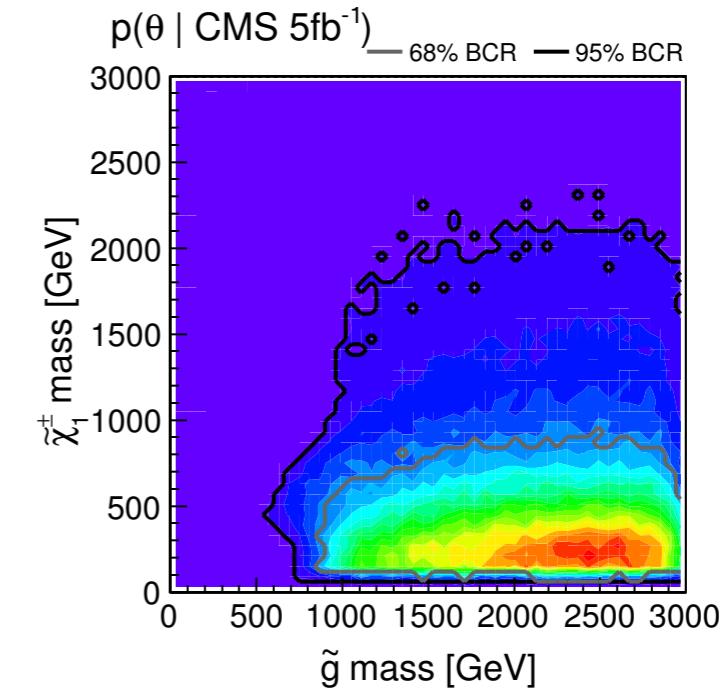
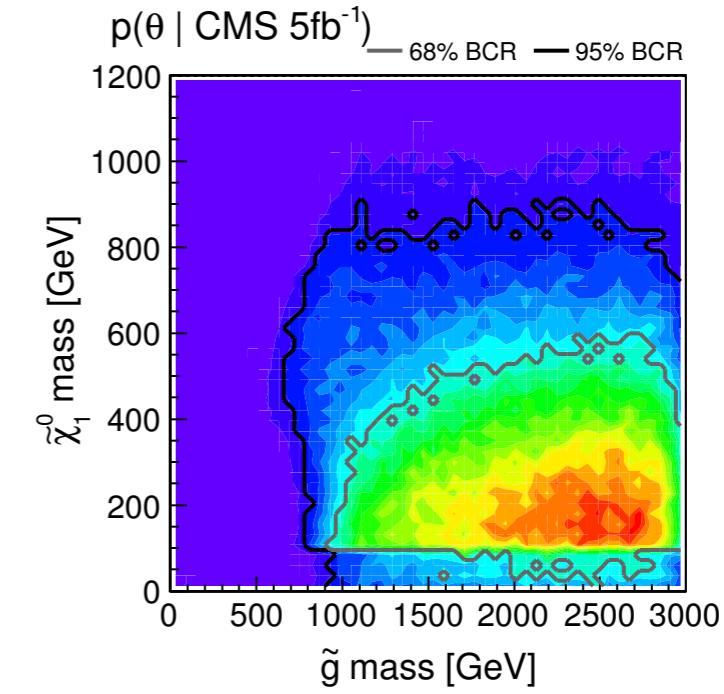
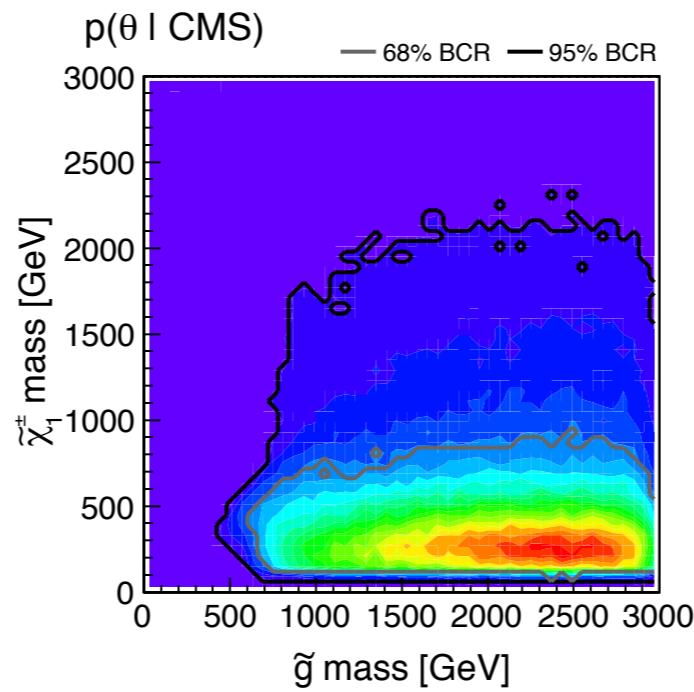
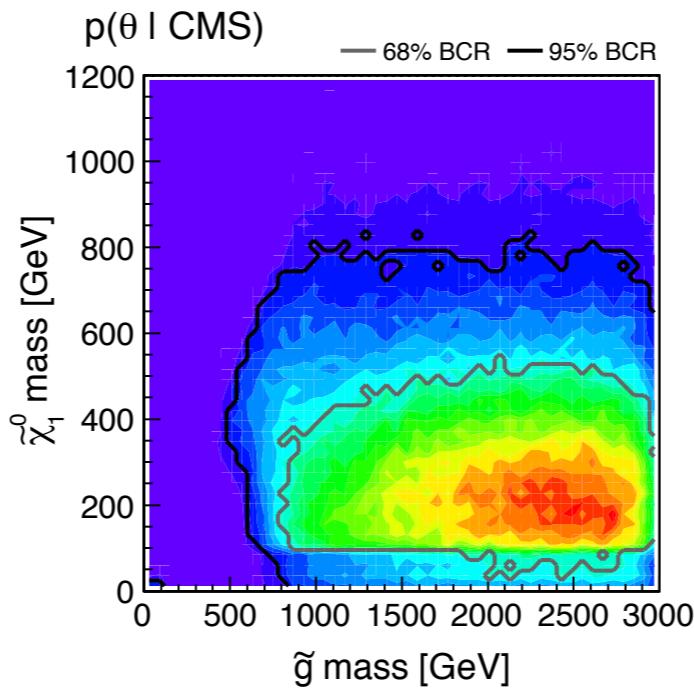
neutralino |



chargino |

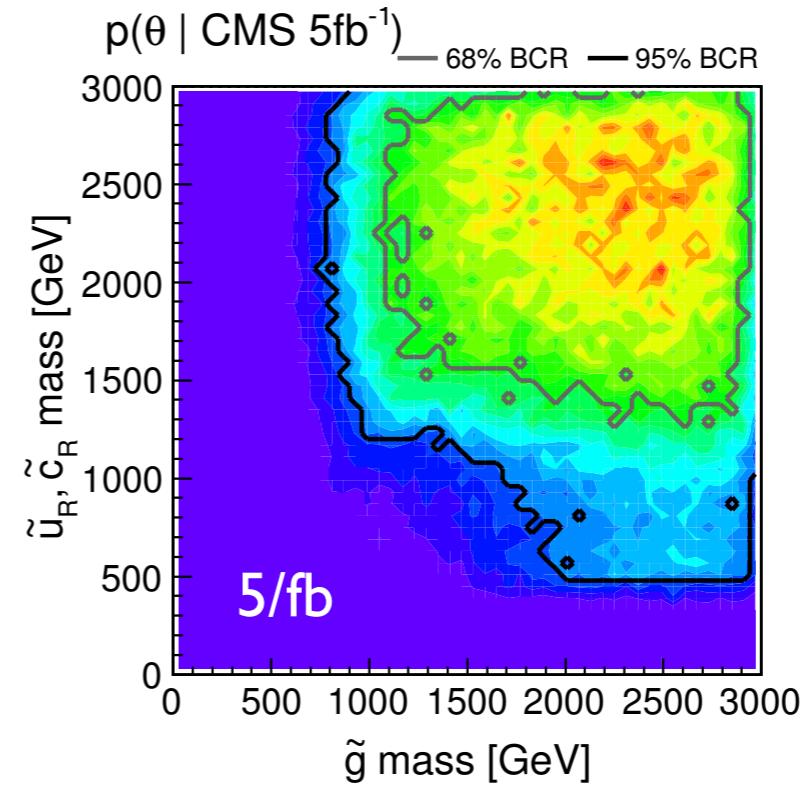
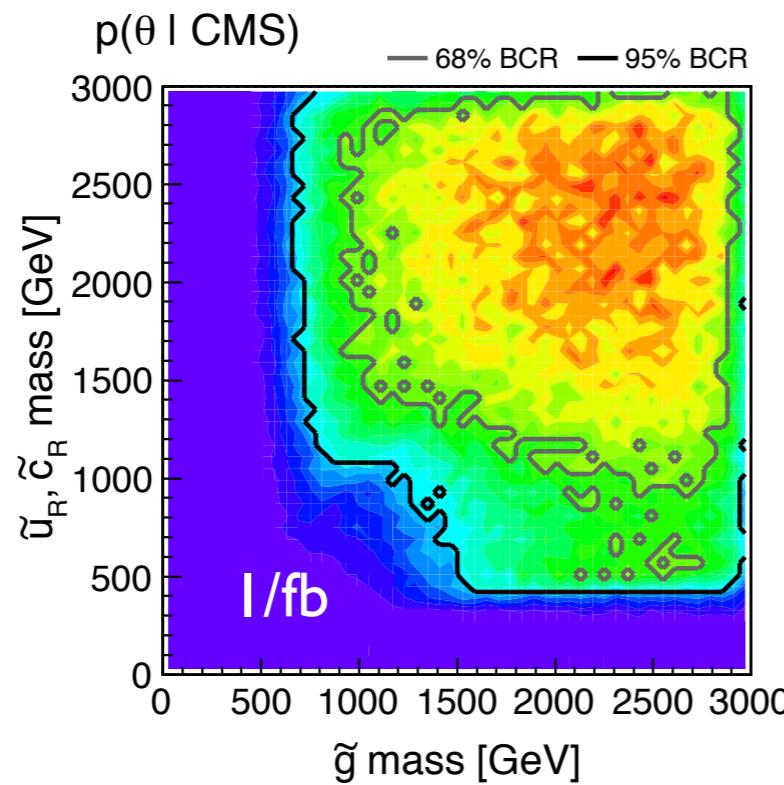
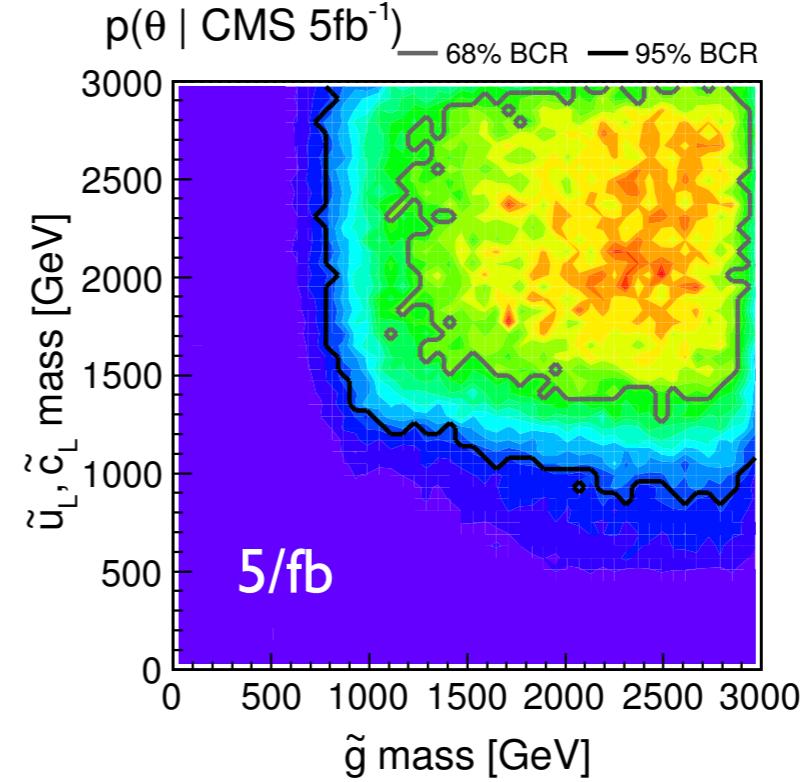
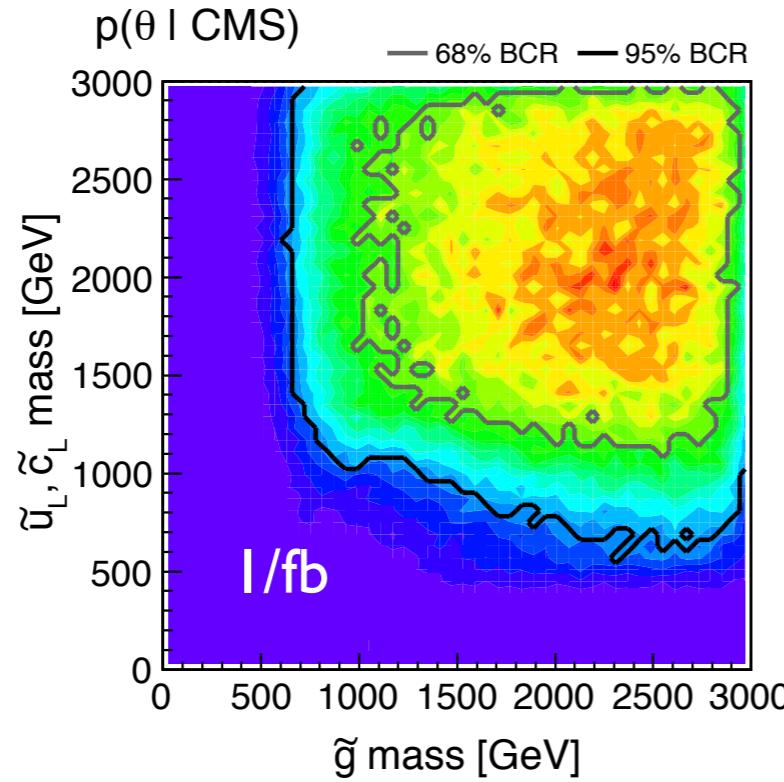


neutralino |



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

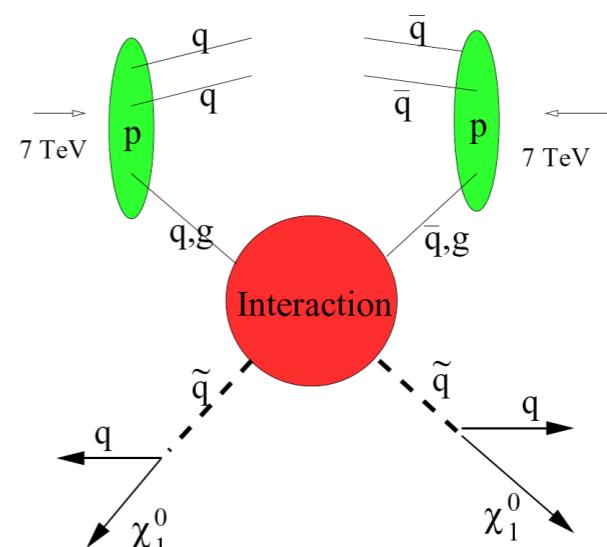
vs. gluino



5/fb results just rescaled from 1/fb ones!

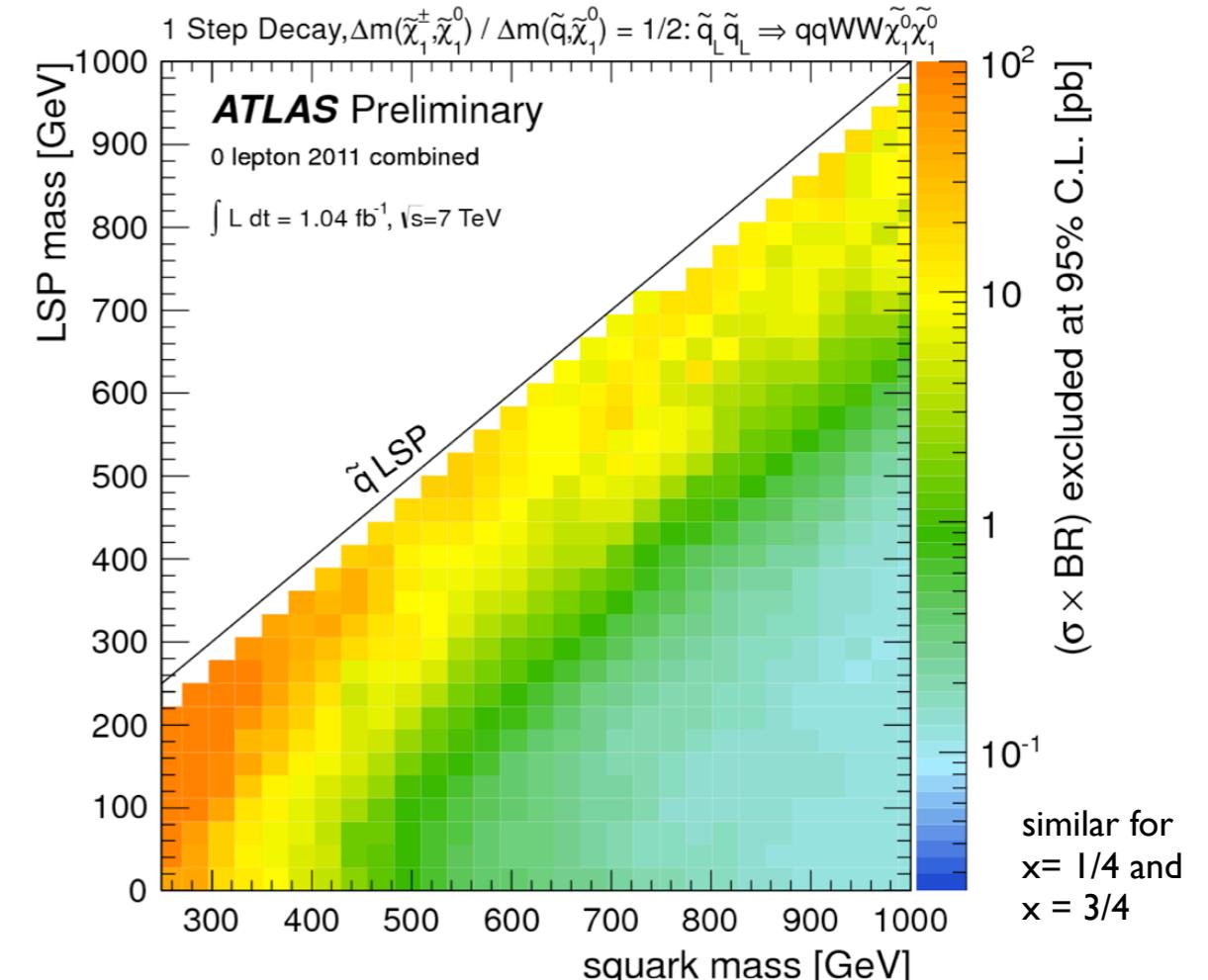
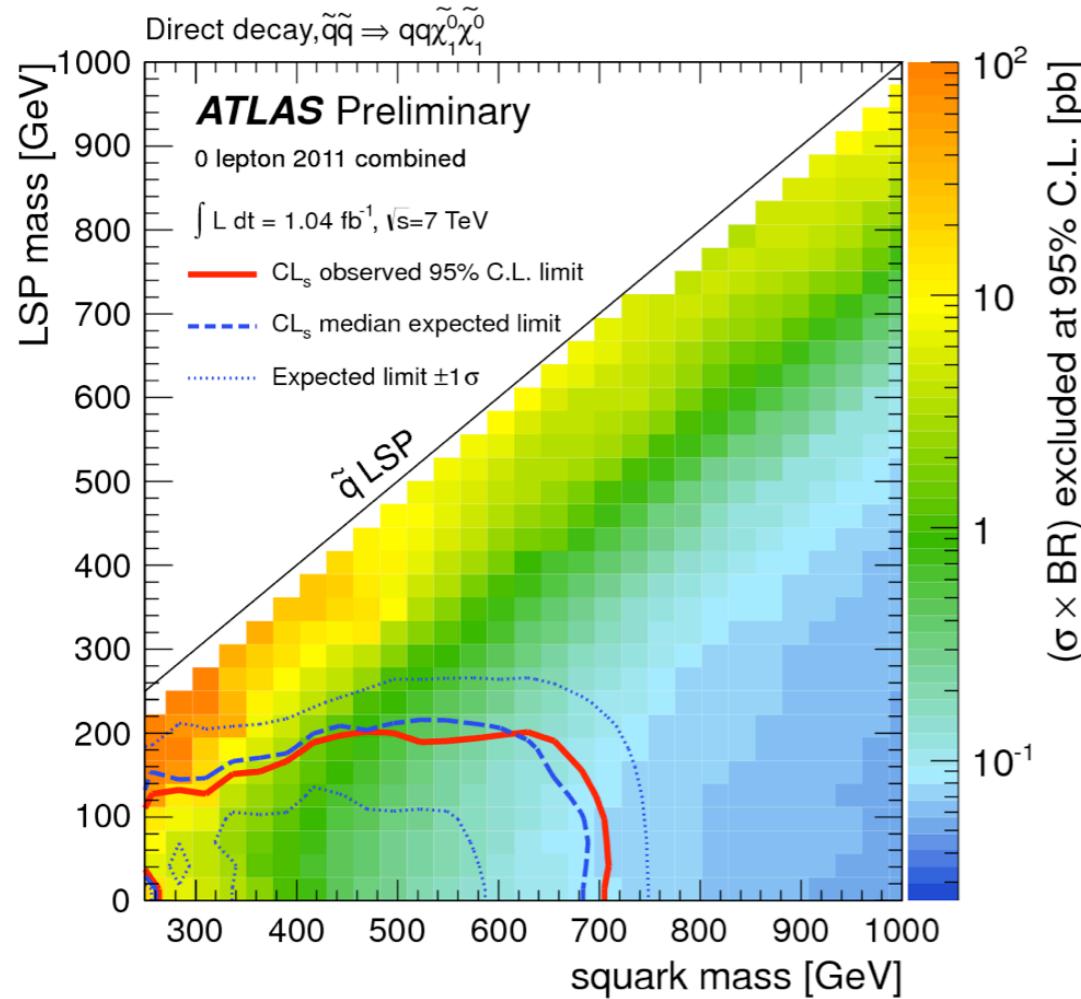
Phenomenology

- In order to avoid proton decay, one usually assumes a new conserved “**R-parity**” under which SM particles are even and SUSY ones are odd.
- In this case, SUSY particles must be produced in pairs, and every SUSY decay must lead to another SUSY particle.
- The lightest SUSY particle (**LSP**) is **stable** → **dark matter candidate**.
- At the **LHC**, we expect large production of **gluino** and/or **squark** pairs, which **cascade-decay** into the LSP.
- SUSY events are hence characterized by
 - **high-p_T multi-jets**,
 - **maybe multi-leptons**
 - **large missing energy**



ATLAS jets+MET search

– interpretation in simplified models: **squarks** –



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 leptons+MET

