BSM Physics in Run 2 of the LHC

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Sanjay Padhi

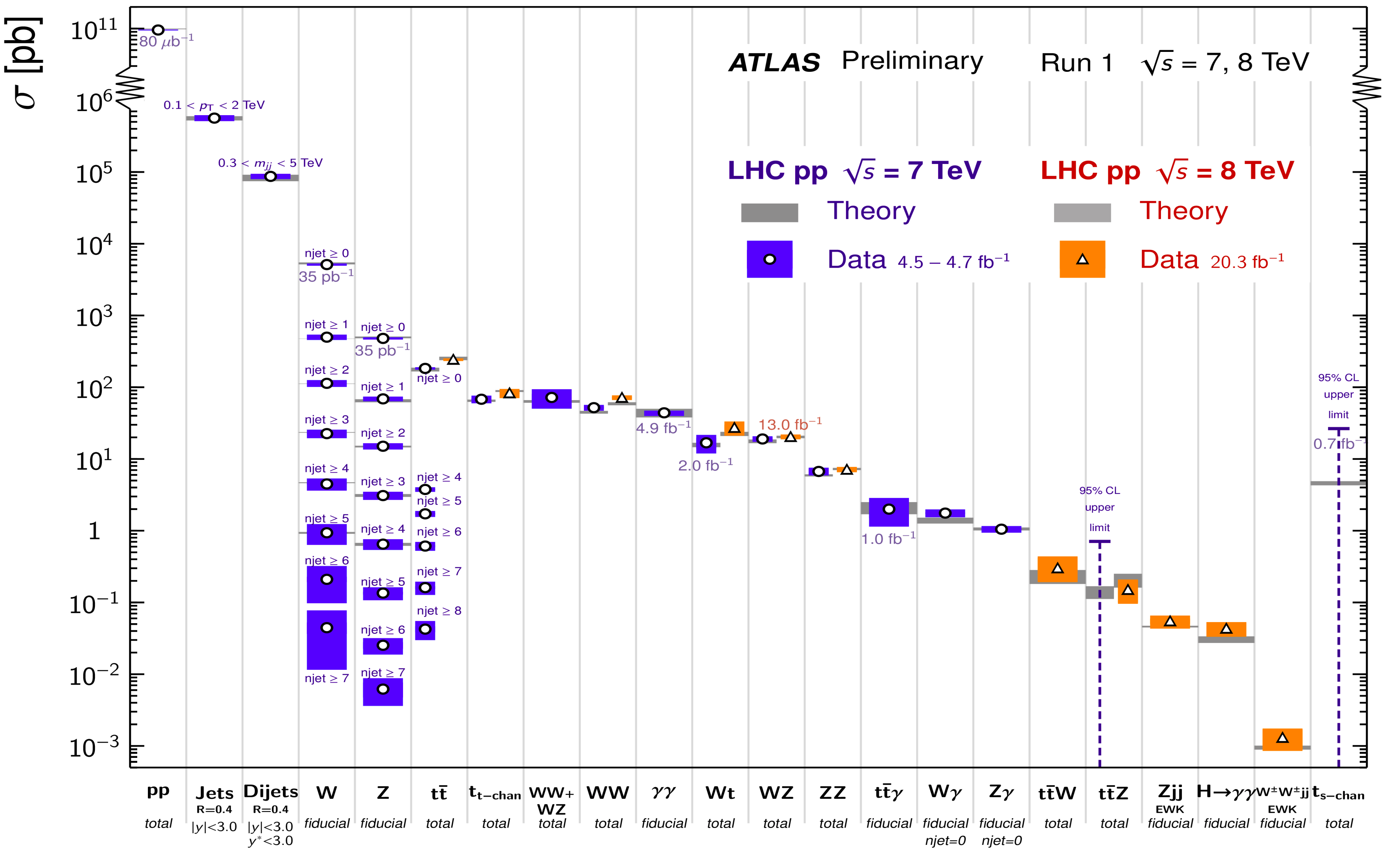
FNAL LPC/University of California, San Diego

Outline

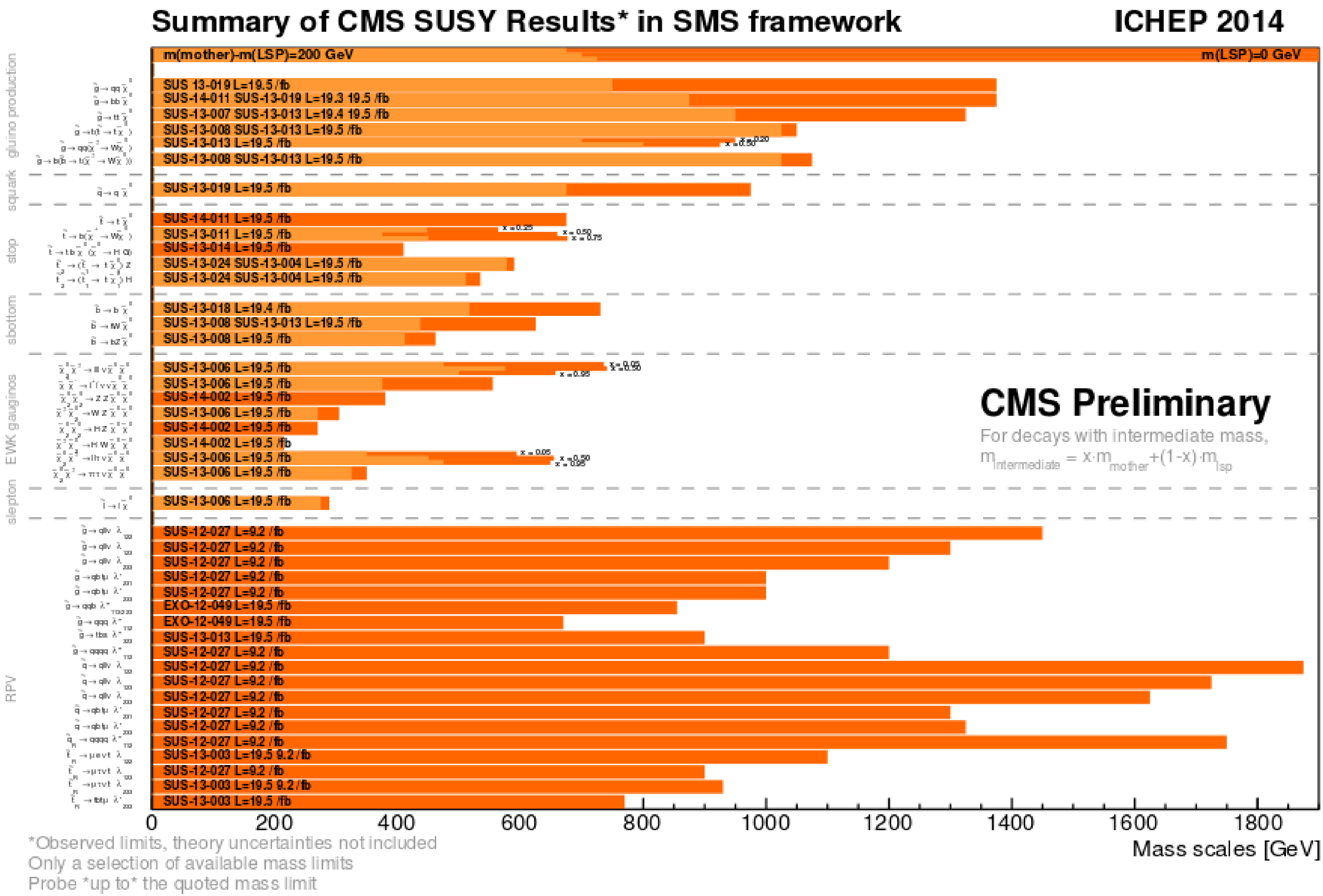
- Re-discovery of the Standard Physics at the LHC
- Review of Run-1 BSM studies
  - Colored Sector
  - Electroweak Sector
- SUSY/BSM Physics in Run-2 of the LHC
  - Naturalness as it stands
  - SUSY Colored and weak sectors
  - Other BSM Physics searches
- Summary and conclusion

Rediscovery of the SM at the energy frontier

Standard Model Production Cross Section Measurements *Status: July 2014*

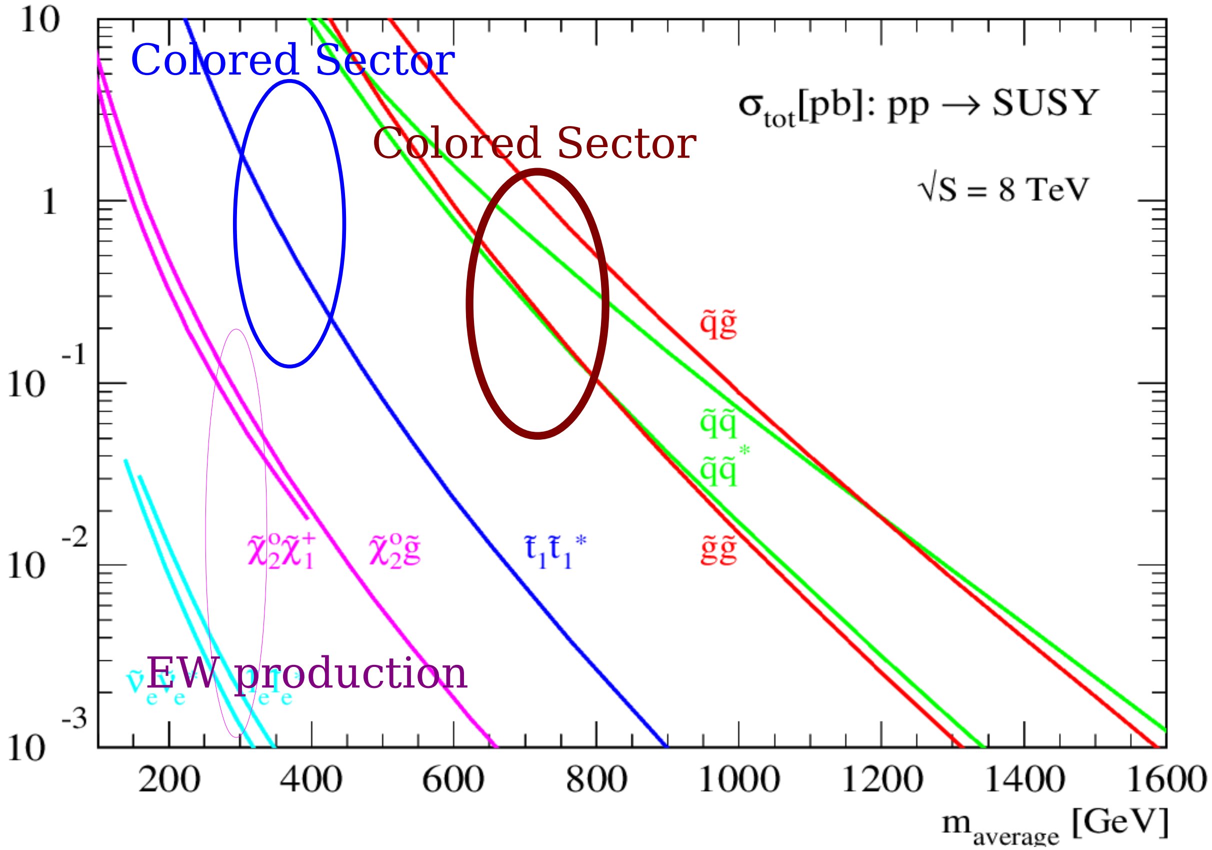


SUSY/BSM searches at the energy frontier



Search for BSM (Supersymmetry)

SUSY search strategy was driven by cross section and thus luminosity



Early analyses were dominated by broad inclusive searches

- mainly gluino and squark production

Increase in luminosity gave access to rarer channels

- Also with added motivation from *Natural* SUSY paradigm

It was quickly realized to develop exclusive search modes to cover full spectrum

SUSY Status

- Various constrained SUSY models like mSUGRA. CMSSM were severely put under pressure by the the LHC limits!
- Experiments were bound to define new benchmarks and use simplified SUSY models in order to present the results and its interpretation
- Aided by the discovery of a Higgs boson, the focus of the experimental search strategy and corresponding interpretation moves towards "*Natural SUSY*" scenarios:
  - Expect to see dedicated 3rd generation searches
  - Electroweak studies (also with Higgs in the final state)

In this talk, I plan to walk you through few key studies:

- Areas of interest, Academic Exercises & Expectations from Run-2

Let us ignore experimental challenges such as:

PileUp, Higher trigger rates (soft and displaced phys.), Boosted Jets, etc.

BSM/SUSY Search strategy

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

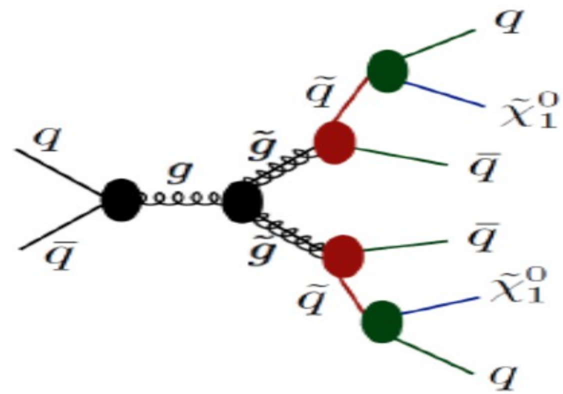
Searches are defined (explore MET +X signatures):

- Categorized by the number of leptons in final state
- Missing energy signatures
- Many include jet requirements to be sensitive to strong production
- Direct stop/sbottom production using b-tag jets
- Electroweak production – Sensitive to leptonic final state

SUSY/BSM Colored Sector Studies

Inclusive search using hadronic jets and MET

Inclusive search for multijets with large MET signature.

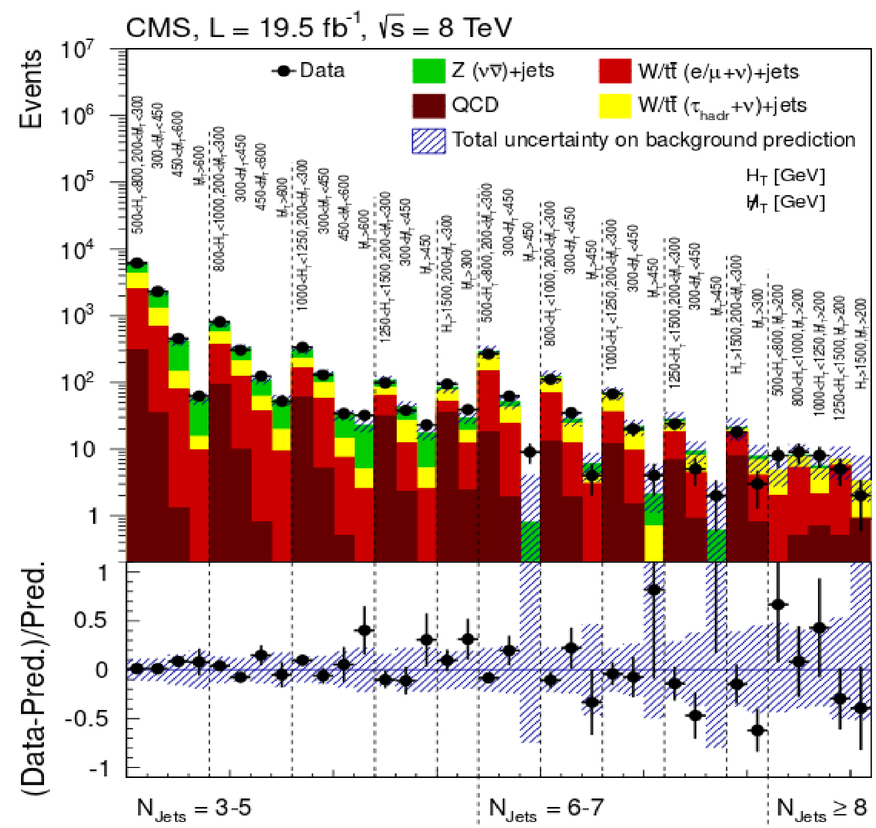


Baseline Selection:

- At least 3 jets with p_T > 50 GeV, $|\eta|$ < 2.4
- $|\Delta\phi(J_n, MET)|$ > 4.0 , n=1,2, 3

[Veto events in which H_T^{miss} is aligned with jets in the transverse plane]

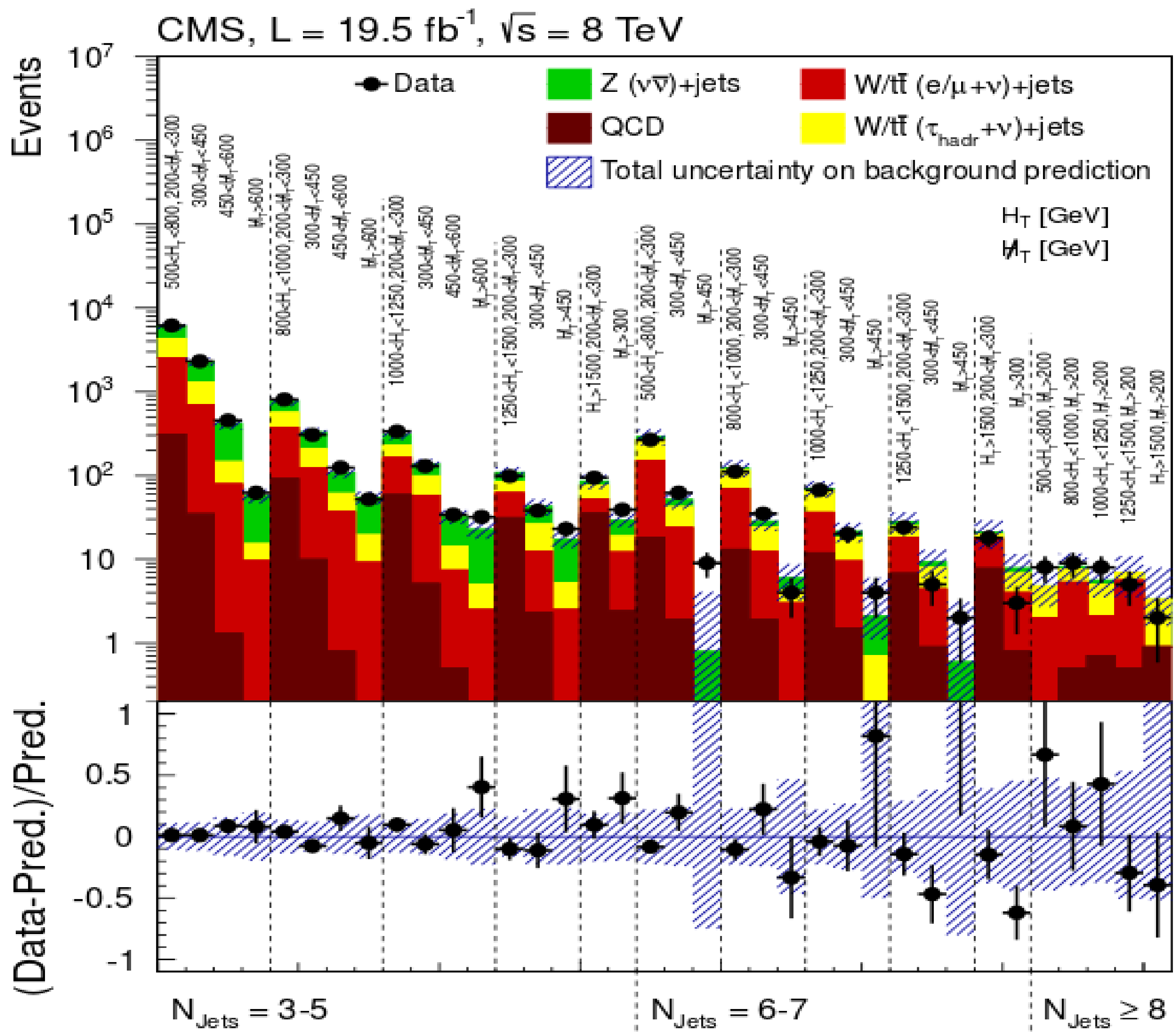
- H_T > 500 GeV, MET > 200 GeV
- Veto isolated leptons with p_T > 10 GeV
- Isolated Track Veto with pT > 15 GeV



Major backgrounds

- Z → νν + Jets
- W + Jets (where either e/μ is lost or W → τν)
- ttbar + Jets (same as above)
- QCD

Inclusive search using hadronic jets and MET



What about low MET:

High H_T or

Large Njets?

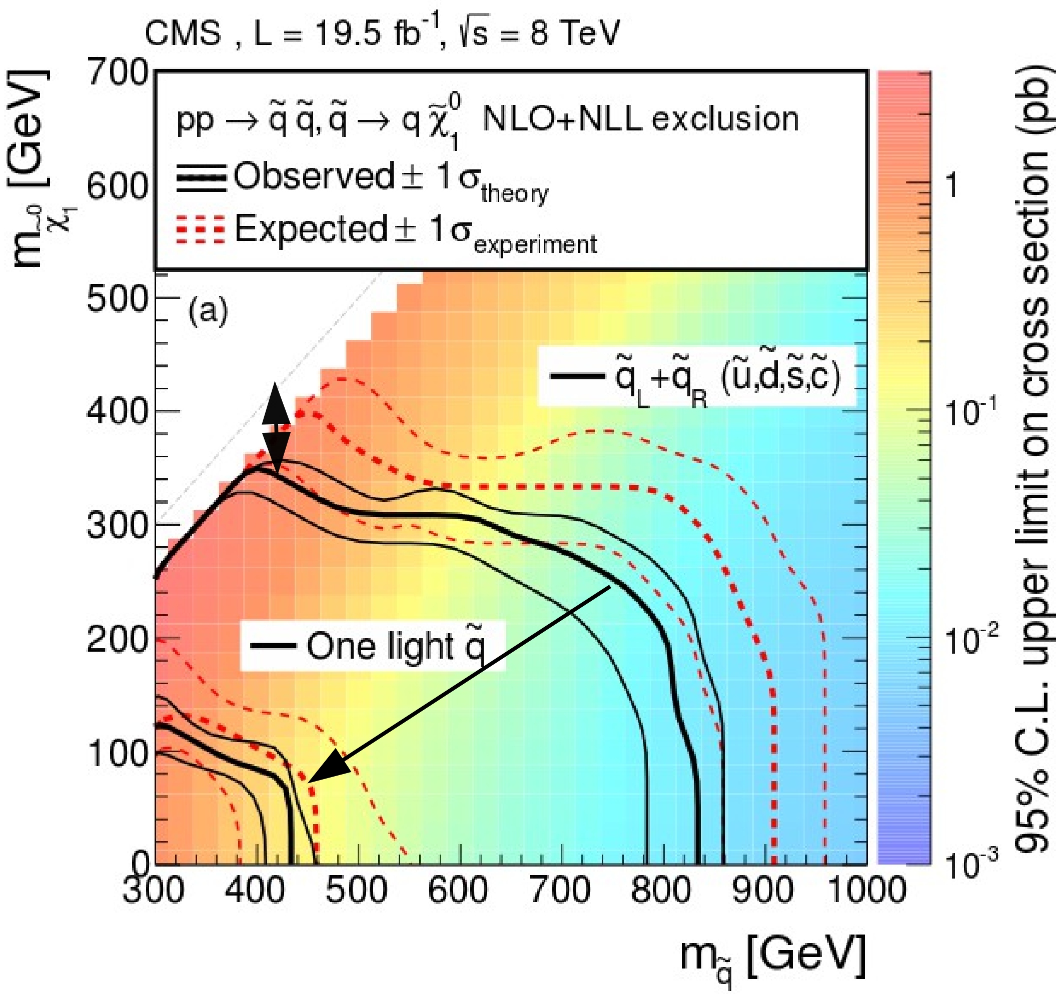
Inclusive search using hadronic jets and MET

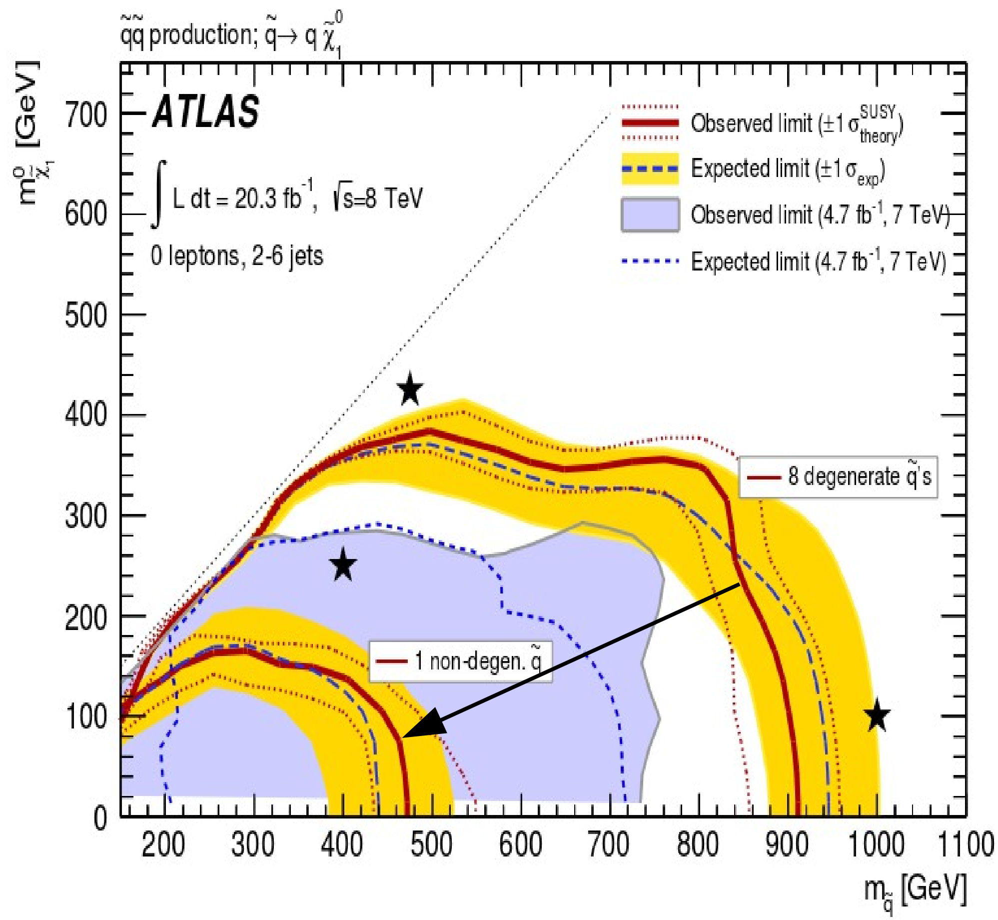
ATLAS study

Requirement	Signal Region					
	2jl	**2jm**	**2jt**	**2jW**	**3j**	**4jW**
E_T^{miss}[GeV] >	160					
$p_T(j_1)$ [GeV] >	130					
$p_T(j_2)$ [GeV] >	60					
$p_T(j_3)$ [GeV] >	–				60	40
$p_T(j_4)$ [GeV] >	–					40
$\Delta\phi(\text{jet}_{1,2,(3)}, \mathbf{E}_T^{miss})_{min}$ >	0.4					
$\Delta\phi(\text{jet}_{i>3}, \mathbf{E}_T^{miss})_{min}$ >	–					0.2
W candidates	–			$2(W \to j)$	–	$(W \to j) + (W \to jj)$
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$] >	8	15		–		
$E_T^{miss}/m_{eff}(N_j)$ >	–			0.25	0.3	0.35
m_{eff}(incl.) [GeV] >	800	1200	1600	1800	2200	1100

Inclusive search using hadronic jets and MET

Limits on SUSY squark sector



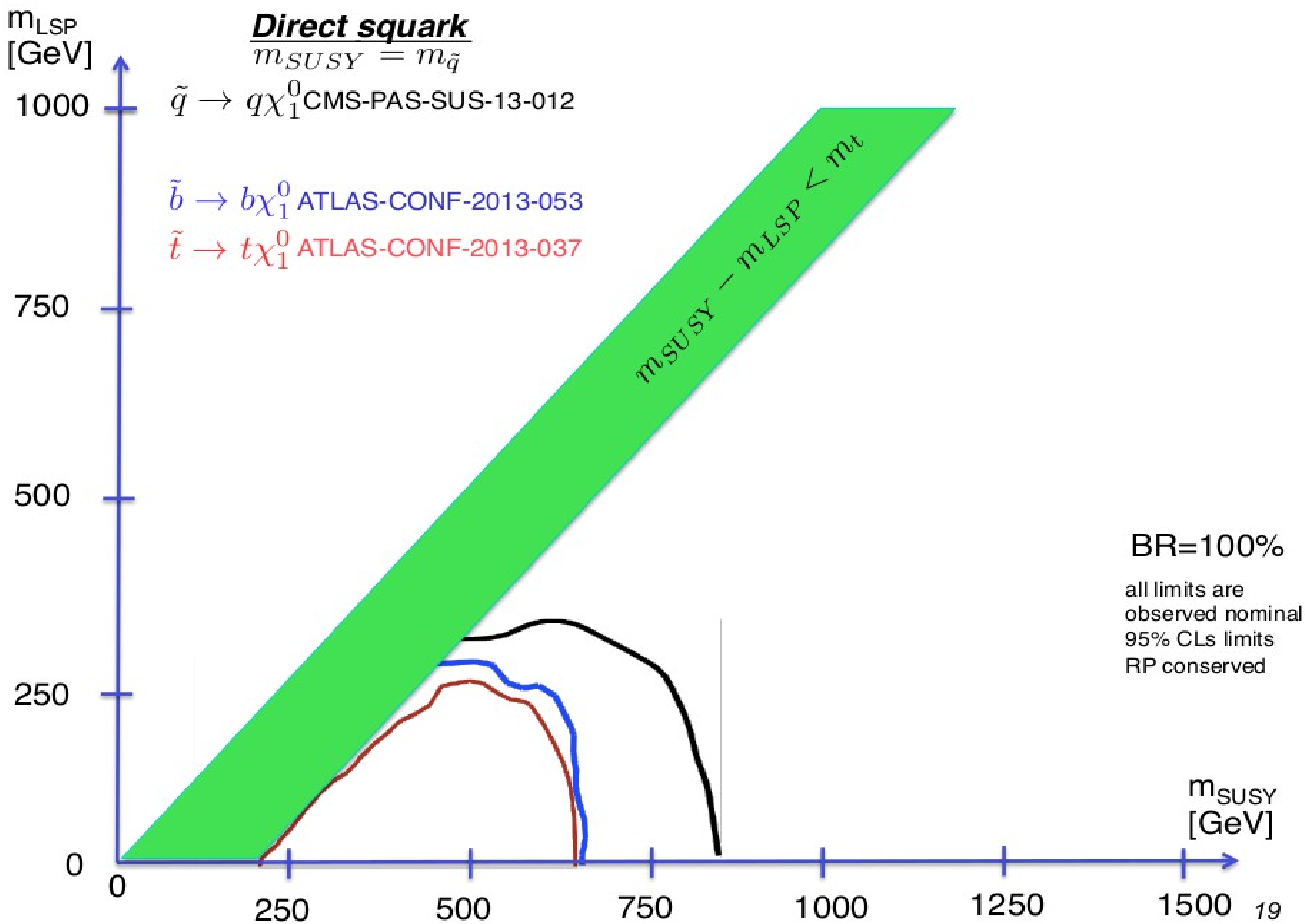


Assuming 8-fold degeneracy (100% BR) - Squarks are excluded ~900 GeV in mass

With single light squark → limits are ~450 GeV

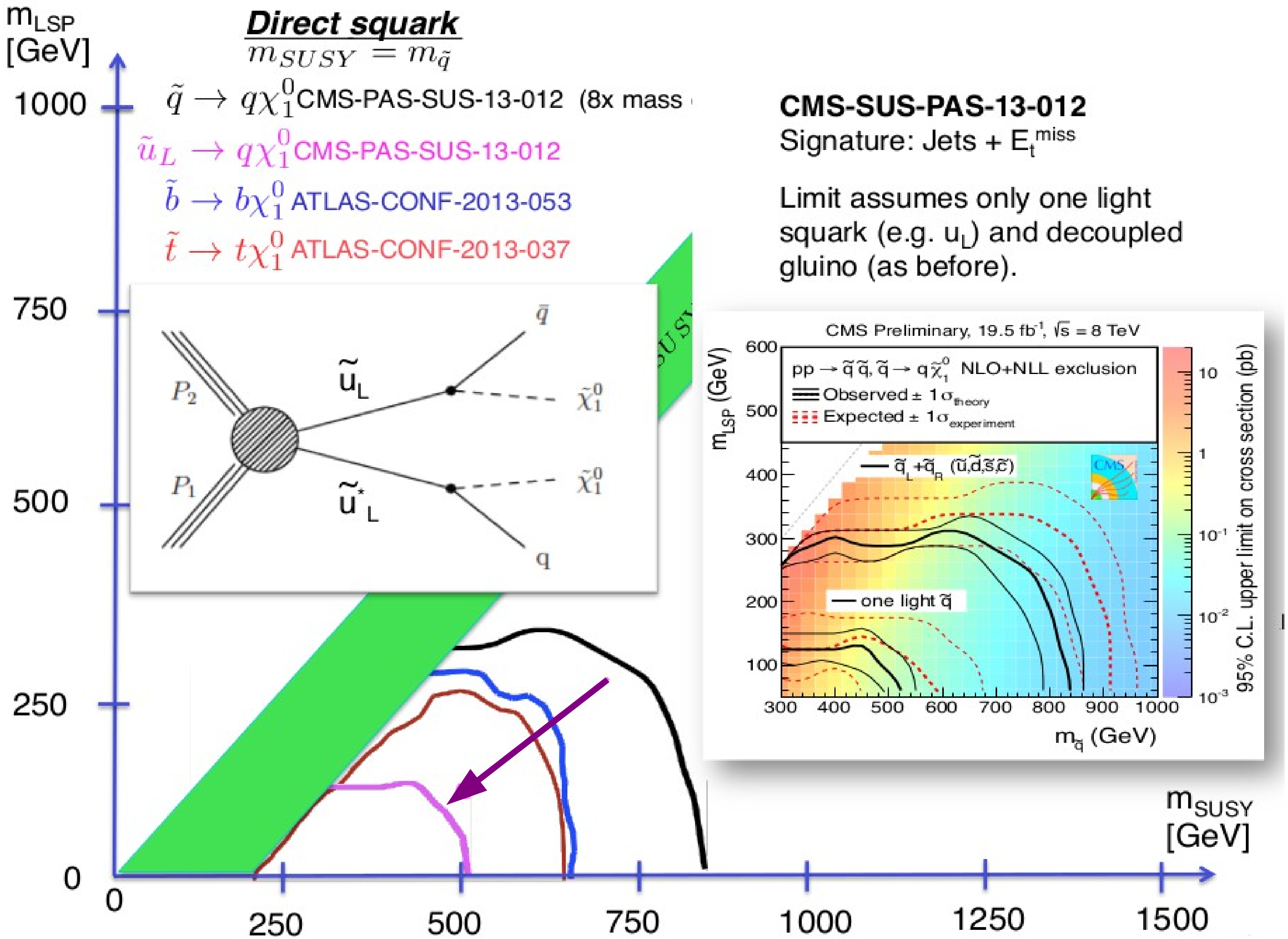
Compressed regions with low $\Delta m = m(\tilde{q}) - m(\tilde{\chi}^0)$ are also important

Inclusive search using hadronic jets and MET

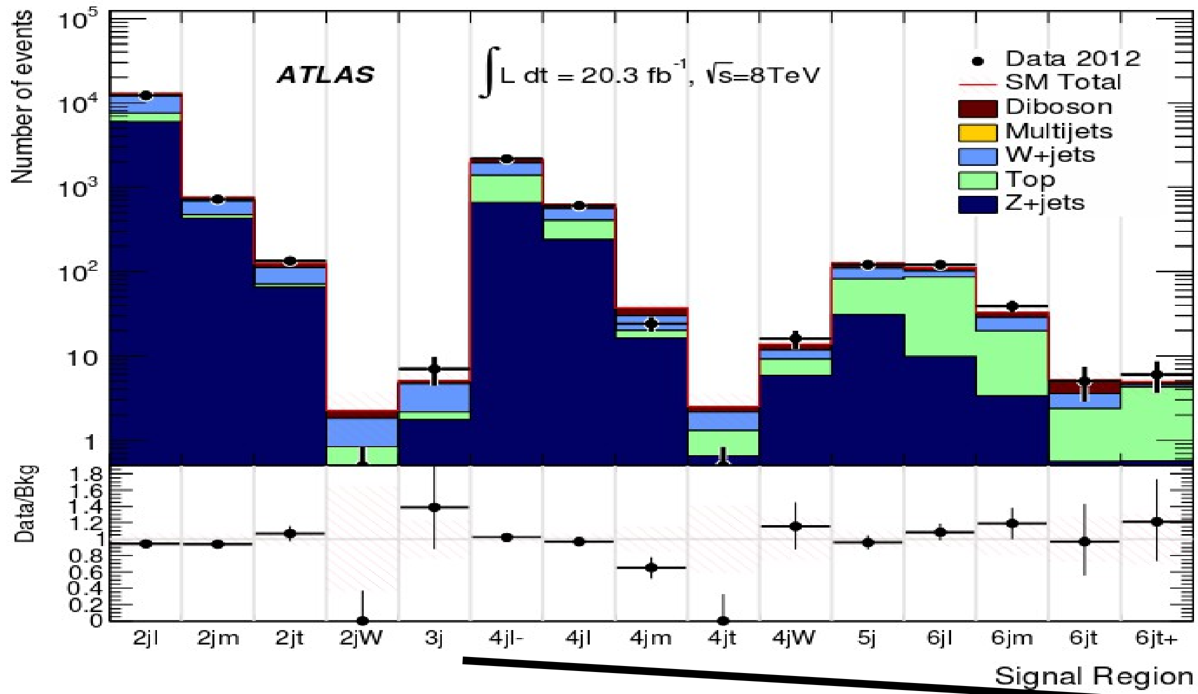


Inclusive search using hadronic jets and MET

CMS (ATLAS)1st & 2nd generation squark limits are only better than the 3rd generation when assuming BR=100%! Eight-fold mass degeneracy



Inclusive search using hadronic jets and MET (ATLAS Study)



Signal Region	2jl	2jm	2jt	2jW	3j
MC expected events					
Diboson	879	72	13	0.41	0.36
Z/γ^*+jets	6709	552	103	1.2	5.5
W+jets	5472	303	59	0.82	3.1
$t\bar{t}$(+EW) + single top	1807	54	9	0.14	0.85
Fitted background events					
Diboson	900 ± 400	70 ± 40	13 ± 6	0.41 ± 0.21	0.36 ± 0.18
Z/γ^*+jets	5900 ± 900	430 ± 40	65 ± 8	$0.39^{+0.41}_{-0.39}$	1.7 ± 1.0
W+jets	4500 ± 600	216 ± 26	40 ± 6	0.98 ± 1.0	2.5 ± 0.9
$t\bar{t}$(+EW) + single top	1620 ± 320	47 ± 8	6.5 ± 2.2	$0.44^{+0.84}_{-0.44}$	$0.42^{+0.51}_{-0.42}$
Multi-jets	115^{+140}_{-115}	$0.41^{+1.37}_{-0.41}$	$0.14^{+0.44}_{-0.14}$	$0.03^{+0.03}_{-0.03}$	$0.03^{+0.06}_{-0.03}$
Total bkg	13000 ± 1000	760 ± 50	125 ± 10	2.3 ± 1.4	5.0 ± 1.2
Observed	12315	715	133	0	7
$\langle\epsilon\sigma\rangle^{95}_{obs}$ [fb]	60	4.3	1.9	0.09	0.40

Inclusive search using hadronic jets and MET (CMS Study)

Selection N_{Jets}	H_T [GeV]	$\not{H}_T$ [GeV]	$Z \to \nu\bar{\nu}$	$t\bar{t}/W \to e,\mu+X$	$t\bar{t}/W \to \tau_h+X$	QCD	Total background	Data
6–7	500–800	200–300	22.7 ± 6.4	133 ± 59	117 ± 25	18.2 ± 9.2	290 ± 65	266
6–7	500–800	300–450	9.9 ± 3.2	22 ± 11	18.0 ± 5.1	1.9 ± 1.7	52 ± 12	62
6–7	500–800	>450	0.7 ± 0.6	$0.0^{+3.2}_{-0.0}$	$0.1^{+0.5}_{-0.1}$	$0.0^{+0.1}_{-0.0}$	$0.8^{+3.3}_{-0.6}$	9
6–7	800–1000	200–300	9.1 ± 3.0	56 ± 25	46 ± 11	13.1 ± 6.6	124 ± 29	111
6–7	800–1000	300–450	4.2 ± 1.7	10.4 ± 5.5	12.0 ± 3.6	1.9 ± 1.4	28.6 ± 6.9	35
6–7	800–1000	>450	1.8 ± 1.0	2.9 ± 2.5	1.2 ± 0.8	$0.1^{+0.4}_{-0.1}$	6.0 ± 2.8	4
6–7	1000–1250	200–300	4.4 ± 1.7	24 ± 12	29.5 ± 7.8	11.9 ± 6.0	70 ± 16	67
6–7	1000–1250	300–450	3.5 ± 1.5	8.0 ± 4.7	8.6 ± 2.7	1.5 ± 1.5	21.6 ± 5.8	20
6–7	1000–1250	>450	1.4 ± 0.8	$0.0^{+3.6}_{-0.0}$	$0.6^{+0.8}_{-0.6}$	$0.1^{+0.4}_{-0.1}$	$2.2^{+3.8}_{-1.1}$	4
6–7	1250–1500	200–300	3.3 ± 1.4	11.5 ± 6.5	6.4 ± 2.7	6.8 ± 3.9	28.0 ± 8.2	24
6–7	1250–1500	300–450	1.4 ± 0.8	3.5 ± 2.6	3.5 ± 1.9	$0.9^{+1.3}_{-0.9}$	9.4 ± 3.6	5
6–7	1250–1500	>450	0.4 ± 0.4	$0.0^{+2.5}_{-0.0}$	$0.1^{+0.5}_{-0.1}$	$0.1^{+0.3}_{-0.1}$	$0.5^{+2.6}_{-0.4}$	2
6–7	>1500	200–300	1.3 ± 0.8	10.0 ± 6.9	2.0 ± 1.2	7.8 ± 4.0	21.1 ± 8.1	18
6–7	>1500	>300	1.1 ± 0.7	3.2 ± 2.8	2.8 ± 1.9	$0.8^{+1.1}_{-0.8}$	7.9 ± 3.6	3
≥8	500–800	>200	$0.0^{+0.8}_{-0.0}$	1.9 ± 1.5	2.8 ± 1.4	$0.1^{+0.4}_{-0.1}$	$4.8^{+2.3}_{-2.1}$	8
≥8	800–1000	>200	0.6 ± 0.6	4.8 ± 2.9	2.3 ± 1.2	$0.5^{+0.9}_{-0.5}$	$8.3^{+3.4}_{-3.3}$	9
≥8	1000–1250	>200	0.6 ± 0.5	$1.4^{+1.5}_{-1.4}$	2.9 ± 1.3	$0.7^{+1.0}_{-0.7}$	$5.6^{+2.3}_{-2.1}$	8
≥8	1250–1500	>200	$0.0^{+0.9}_{-0.0}$	5.1 ± 3.5	1.4 ± 0.9	$0.5^{+0.9}_{-0.5}$	$7.1^{+3.8}_{-3.6}$	5
≥8	>1500	>200	$0.0^{+0.7}_{-0.0}$	$0.0^{+4.2}_{-0.0}$	2.4 ± 1.4	$0.9^{+1.3}_{-0.9}$	$3.3^{+4.7}_{-1.7}$	2

Inclusive search using hadronic jets and MET

Low MET and large Njet/H_T

RPV-like (Stealthy) studies : No MET

Model 1 (See: M. Strassler talk)

- Gluino : 600 GeV

- Higgsino ($\tilde{\chi}$) : 200 GeV

Signatures:

$$\tilde{g} \rightarrow tb\chi^{+}; \chi^{+} \rightarrow soft + \chi^{0}$$

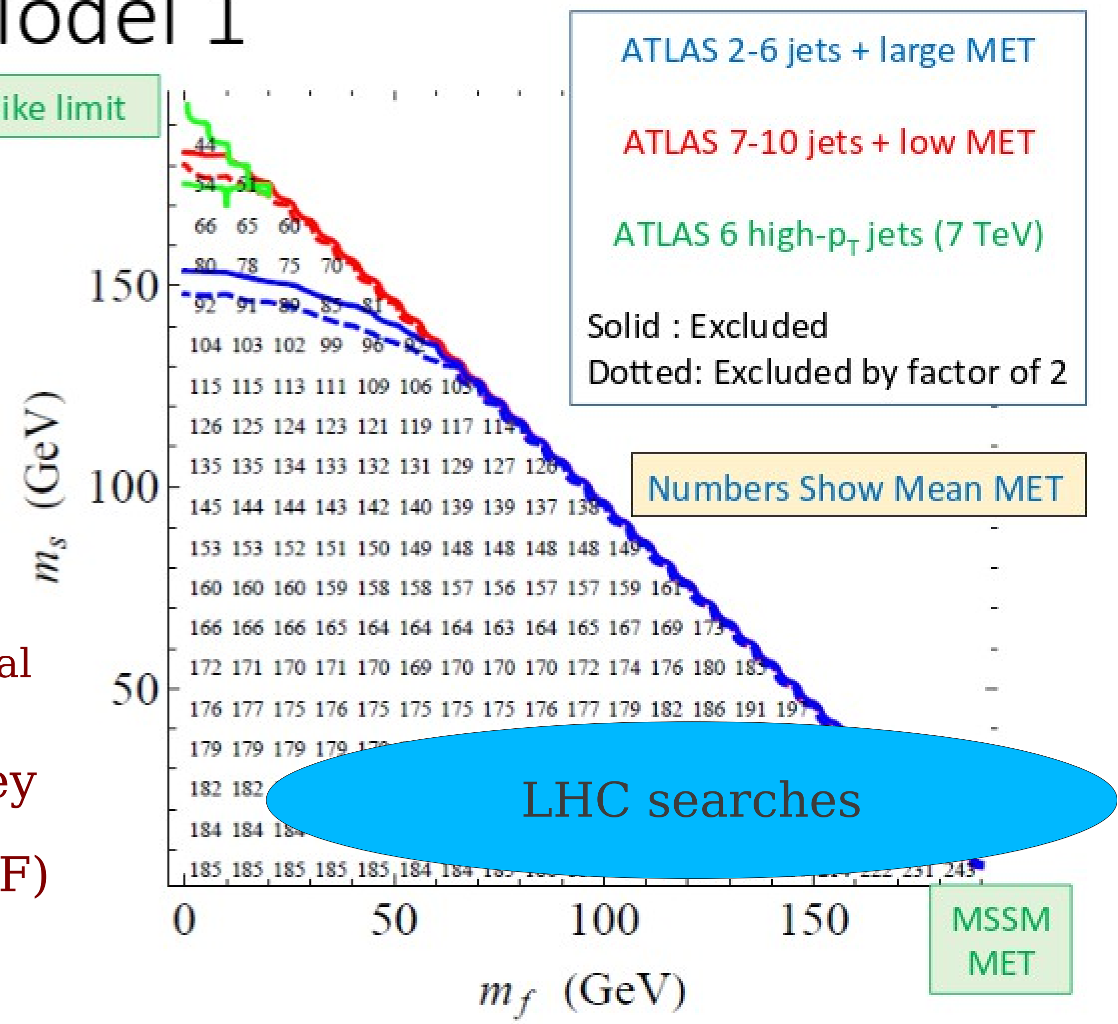
$$\tilde{g} \rightarrow \tilde{c}\bar{c}; \tilde{c} \rightarrow c\tilde{\chi}^{0}$$ c-tagging can be vital

Replace MET by effects of Hidden Valley

- Singlet Scalar (S), Singlet fermions (F)

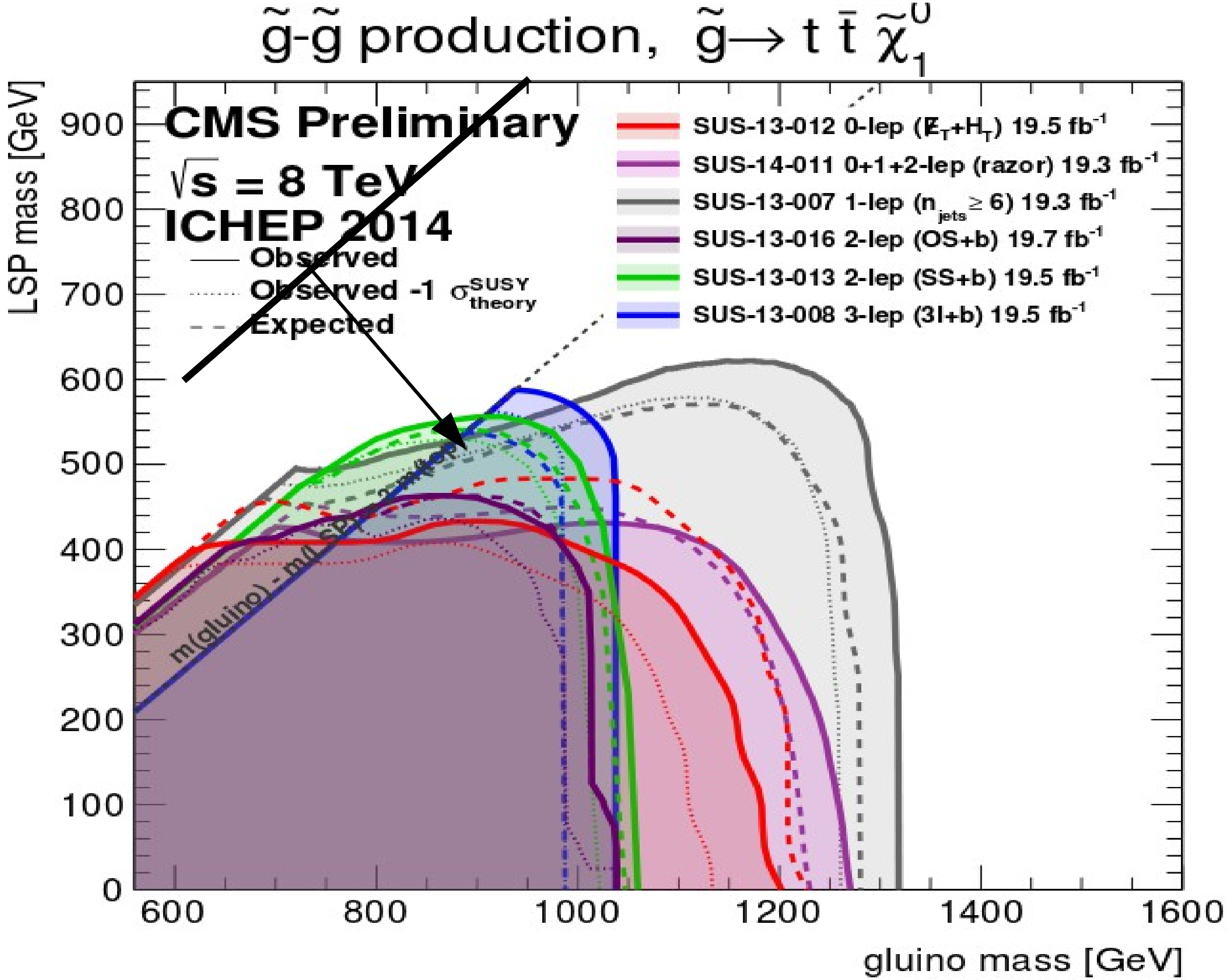
$$\tilde{\chi}^{0} \rightarrow F + S; S \rightarrow gg$$

Model 1



Low MET and multi-jet signatures → largely unexplored

Gluino pair productions



Gluinos with mass ~ 1.3 TeV are excluded (assuming large “virtual” stop masses)

For LSP mass = 50 GeV:

Gluino mass ~ 1.3 (1.1) TeV excluded with stop mass ~ 700(300) GeV

Gluino pair productions

CMS-SUS-13-007; 1lep, Large H_T/Njet (Low MET regions are also important)

$H_T > 400$ GeV						$N_b \geq 3$ Obs.		Pred.	± stat.	± syst.
$150 < \not\!\!E_T < 250$ GeV						94	MT	92	± 5	± 14
$250 < \not\!\!E_T < 350$ GeV						16	MT	14.5	± 1.3	± 2.5
$350 < \not\!\!E_T < 450$ GeV						2	MT	2.6	± 0.4	± 0.7
$\not\!\!E_T > 450$ GeV						0	MT	0.8	± 0.2	± 0.4

$H_T > 500$ GeV	$N_b = 2$ Obs.		Pred.	± stat.	± syst.	$N_b \geq 3$ Obs.		Pred.	± stat.	± syst.
$150 < \not\!\!E_T < 250$ GeV	350	LS	320	± 16	± 14	84	LS	71.1	± 3.5	± 8.3
$250 < \not\!\!E_T < 350$ GeV	55	LS	58.1	± 7.2	± 5.3	16	LS	12.4	± 1.6	± 1.8
$350 < \not\!\!E_T < 450$ GeV	10	LS	15.4	± 4.3	± 3.1	2	LS	3.1	± 0.9	± 0.7
$\not\!\!E_T > 450$ GeV	1	LS	0.7	$^{+2.3}_{-0.3}$	$^{+2.0}_{-0.2}$	0	LS	0.1	$^{+0.5}_{-0.0}$	$^{+0.4}_{-0.0}$

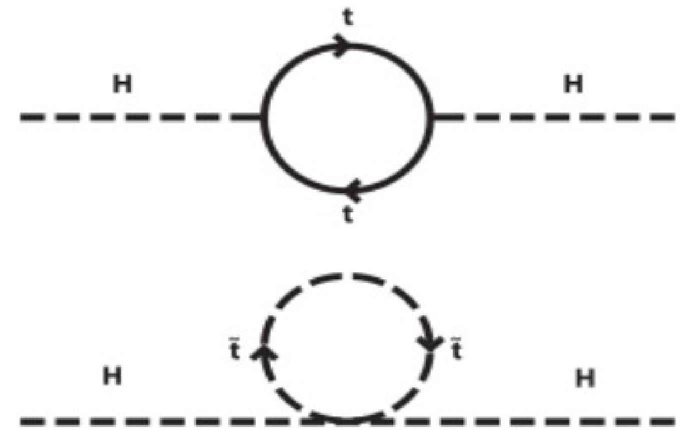
$H_T > 750$ GeV	$N_b = 2$ Obs.		Pred.	± stat.	± syst.	$N_b \geq 3$ Obs.		Pred.	± stat.	± syst.
$150 < \not\!\!E_T < 250$ GeV	141	LS	114.8	± 9.4	± 6.9	37	LS	25.9	± 2.1	± 3.1
							MT	31.8	± 2.7	± 4.8
$250 < \not\!\!E_T < 350$ GeV	26	LS	26.3	± 4.9	± 2.9	12	LS	5.9	± 1.1	± 1.0
		MT	37.9	± 4.0	± 3.5		MT	8.5	± 0.9	± 1.6
$350 < \not\!\!E_T < 450$ GeV	9	LS	10.6	$^{+3.8}_{-3.7}$	± 2.4	2	LS	2.1	± 0.7	± 0.5
		MT	9.4	± 1.4	± 2.7		MT	1.9	± 0.3	± 0.6
$\not\!\!E_T > 450$ GeV	1	LS	0.6	$^{+3.0}_{-0.2}$	$^{+1.9}_{-0.2}$	0	LS	0.1	$^{+0.7}_{-0.0}$	$^{+0.4}_{-0.0}$
		MT	3.1	± 0.7	± 1.5		MT	0.7	± 0.2	± 0.4

$H_T > 1000$ GeV	$N_b = 2$ Obs.		Pred.	± stat.	± syst.	$N_b \geq 3$ Obs.		Pred.	± stat.	± syst.
$150 < \not\!\!E_T < 250$ GeV	46	LS	43.2	± 6.1	± 3.7	14	LS	10.4	± 1.5	± 1.5
							MT	11.1	± 1.6	± 1.8
$250 < \not\!\!E_T < 350$ GeV	11	LS	9.9	± 3.1	± 1.7	4	LS	2.4	± 0.7	± 0.5
		MT	15.1	± 2.5	± 1.9		MT	3.6	± 0.6	± 0.8
$350 < \not\!\!E_T < 450$ GeV	4	LS	2.2	$^{+2.3}_{-1.6}$	$^{+2.2}_{-0.7}$	1	LS	0.4	$^{+0.5}_{-0.3}$	$^{+0.4}_{-0.2}$
		MT	4.7	± 0.9	± 1.5		MT	0.9	± 0.2	± 0.4
$\not\!\!E_T > 450$ GeV	1	LS	0.1	$^{+2.2}_{-0.1}$	$^{+3.5}_{-0.1}$	0	LS	0.0	$^{+0.4}_{-0.0}$	$^{+0.7}_{-0.0}$
		MT	2.0	± 0.5	± 1.1		MT	0.5	± 0.1	± 0.3

Top partners or SUSY stops

In order to stabilize/cancel the Higgs mass from emission and absorption of top pairs:

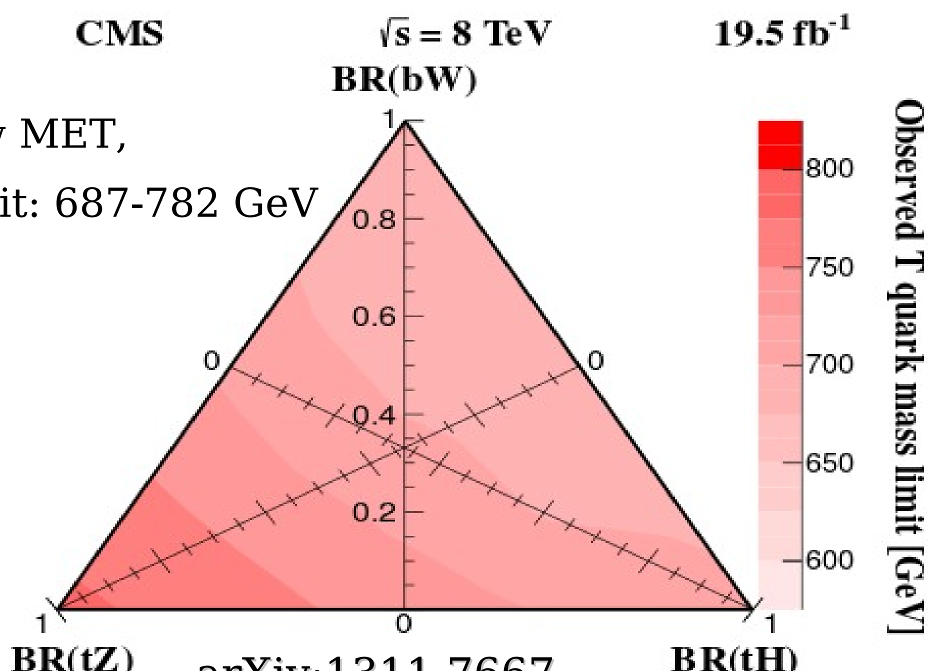
- We expect new physics will emit something with color
- Will have "top like" properties (else cannot cancel)



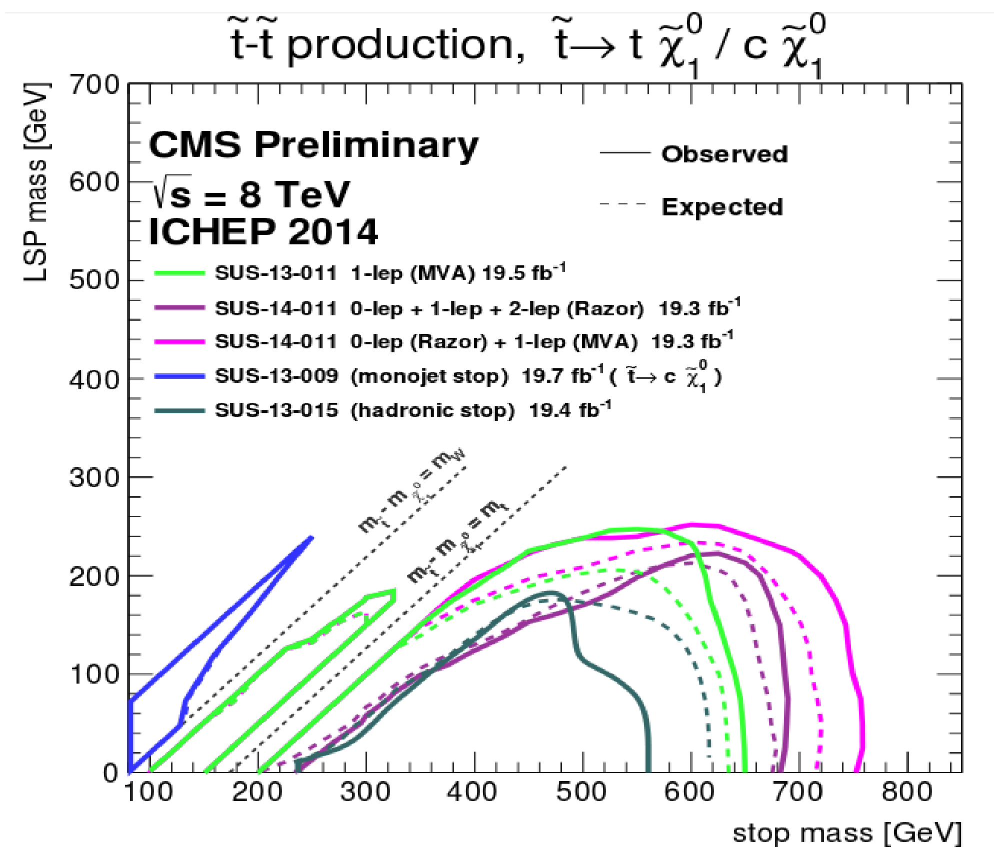
In BSM this is the "top partner studies"
In SUSY we use stop pair production

Low MET,

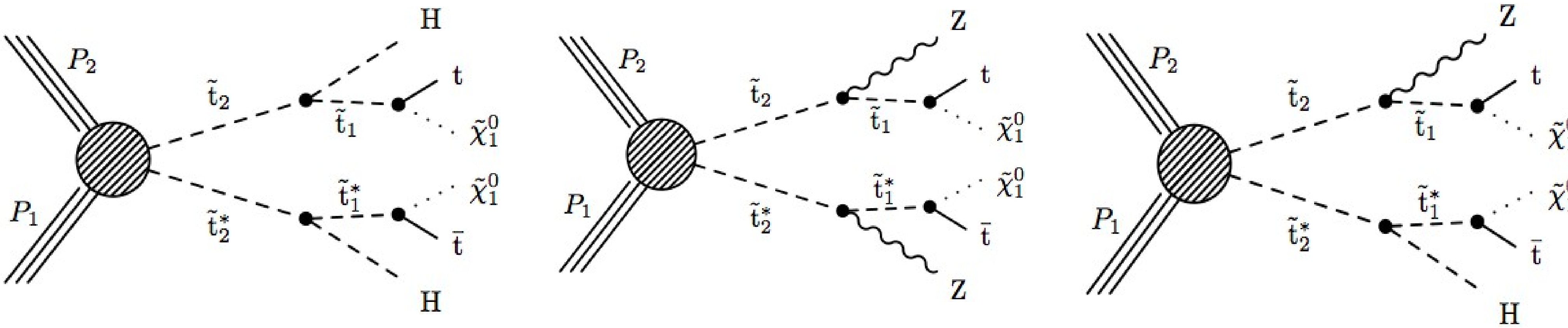
Limit: 687-782 GeV

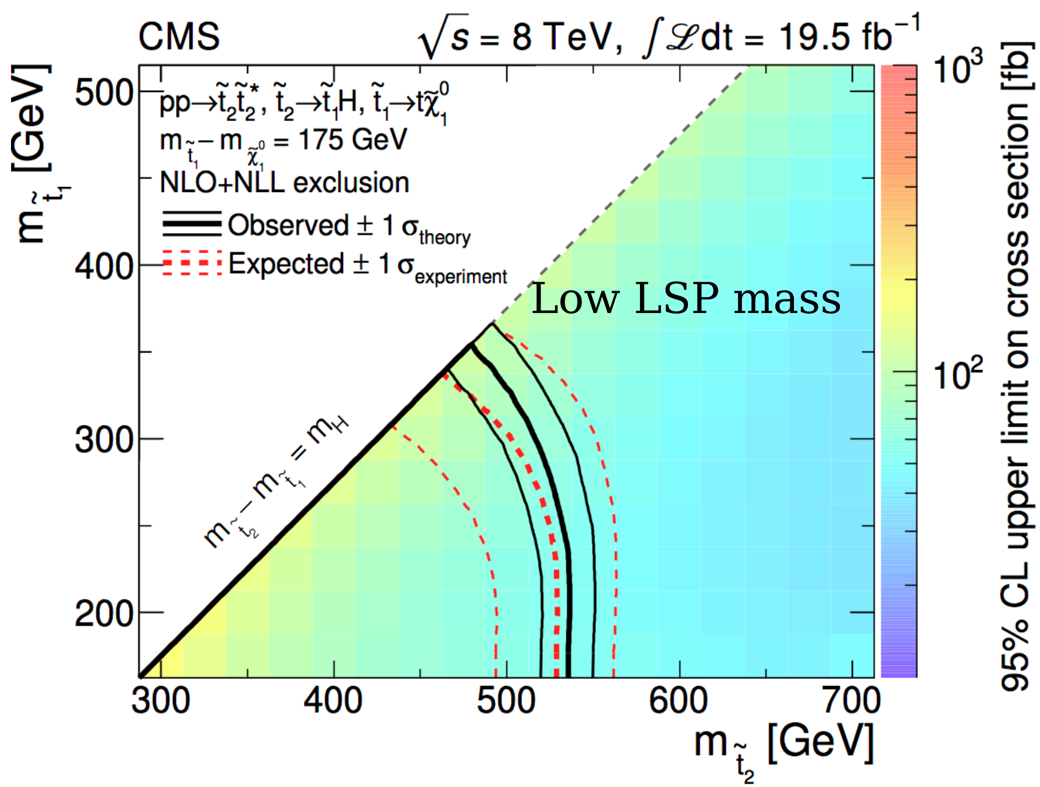


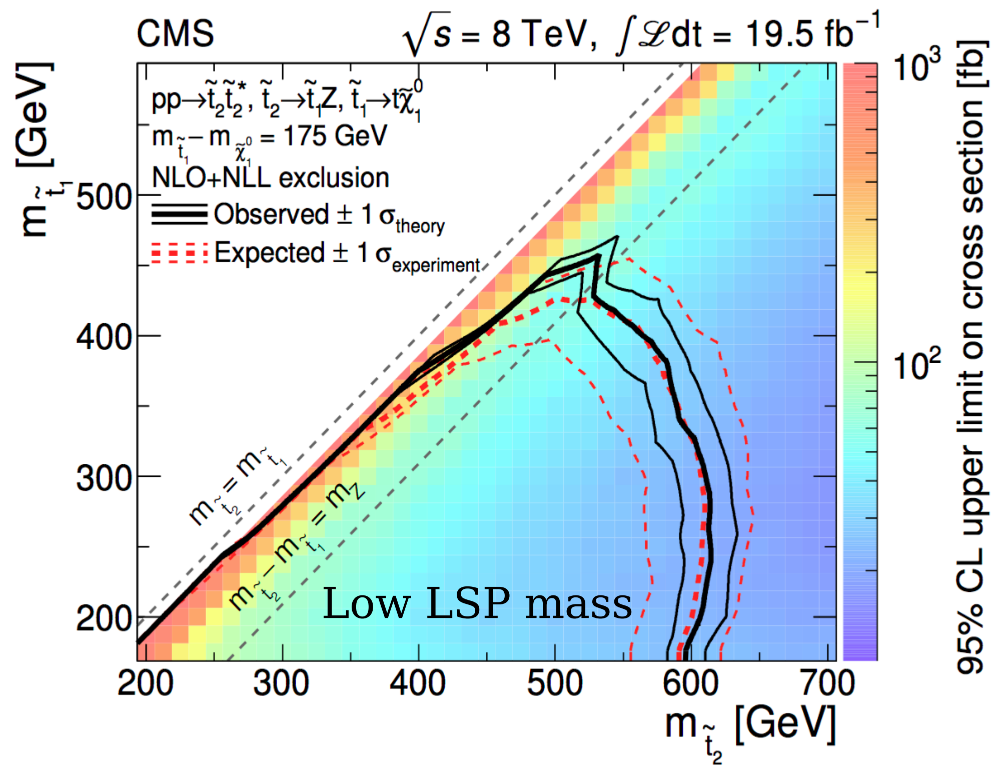
arXiv:1311.7667



Other third generation SUSY studies





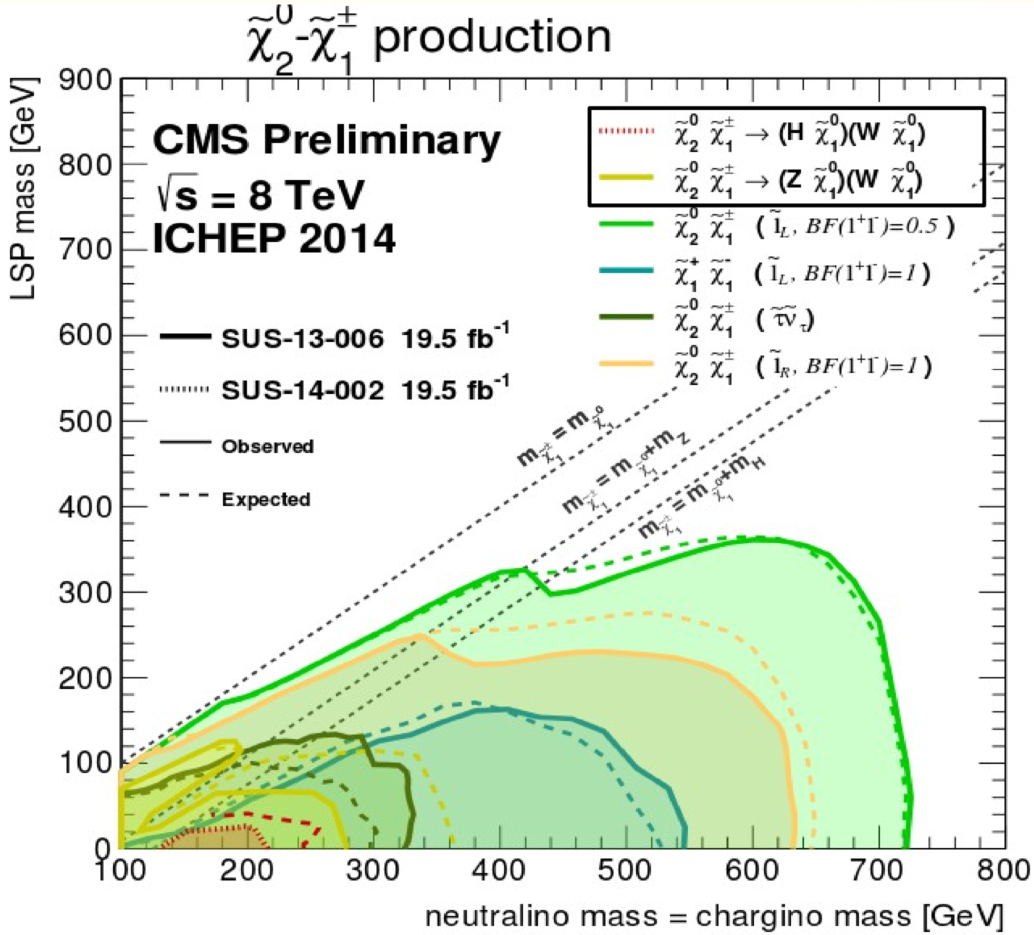


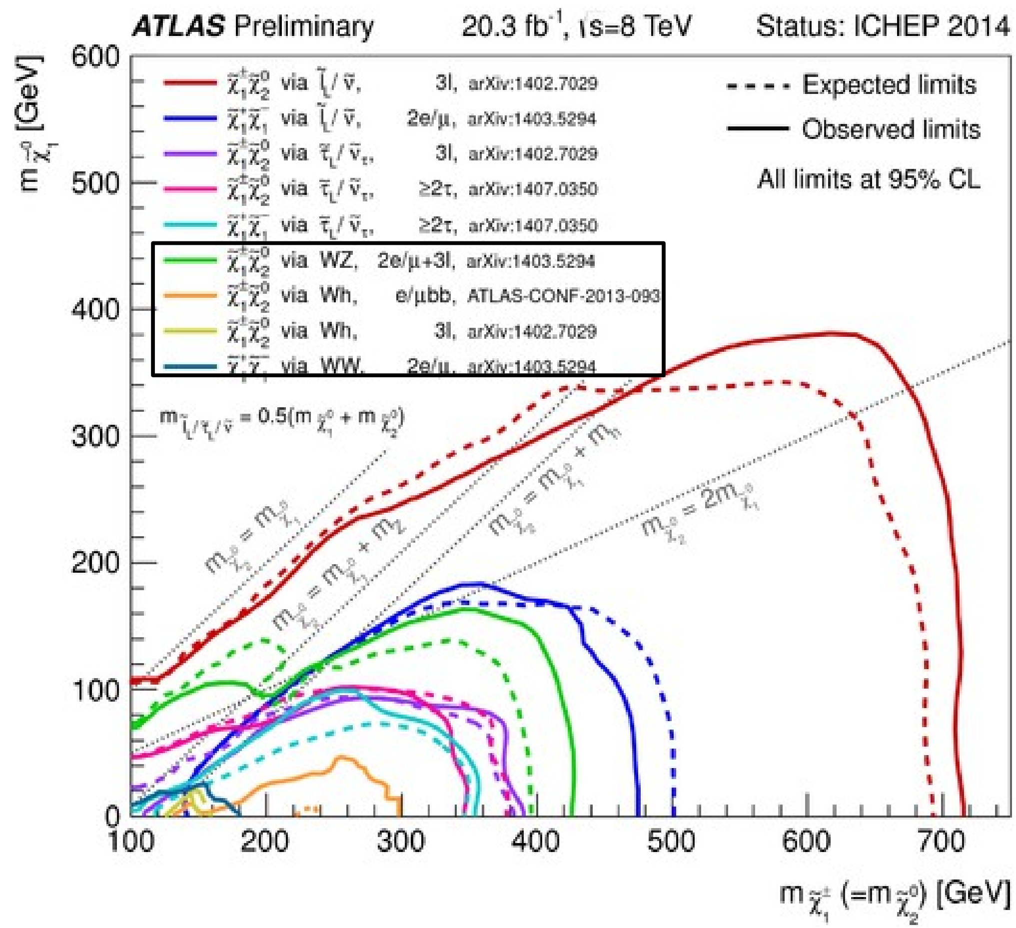
Missed opportunity: Triangular plot could provide generic BR based exclusion

Incorporating constraints from lighter states (previous slide) could be useful

SUSY Electroweak Productions

SUSY Electroweak Productions





Impressive search results!

Sleptons in the cascade provide lepton rich final states → enhance the reach

→ From naturalness point of view, not sure if there is a need?

Limits on direct production of EWinos are still weak (Opportunity for Phase-II)

Assuming LEP limits + “realistic BR” for neutralinos → current limits are negligible

Standard Model WW issues

The W^+W^- cross section measured by the ATLAS collaboration at 7 TeV & 4.7 fb^{-1}

- 53.4 ± 2.1 (stat) ± 4.5 (syst) ± 2.1 (lumi) pb [ATLAS-CONF-2012-025]

- SM NLO prediction is: 45.1 ± 2.8 pb

The W^+W^- cross section measured by the CMS collaboration at 7 TeV & 4.92 fb^{-1}

- 52.4 ± 2.0 (stat) ± 4.5 (syst) ± 1.2 (lumi) pb [CMS-PAS-SMP-12-005]

- SM NLO prediction is: 47.0 ± 2.0 pb

The W^+W^- cross section measured by the CMS collaboration at 8 TeV & 3.54 fb^{-1}

- 69.9 ± 2.8 (stat) ± 5.6 (syst) ± 3.1 (lumi) pb [CMS-PAS-SMP-12-013]

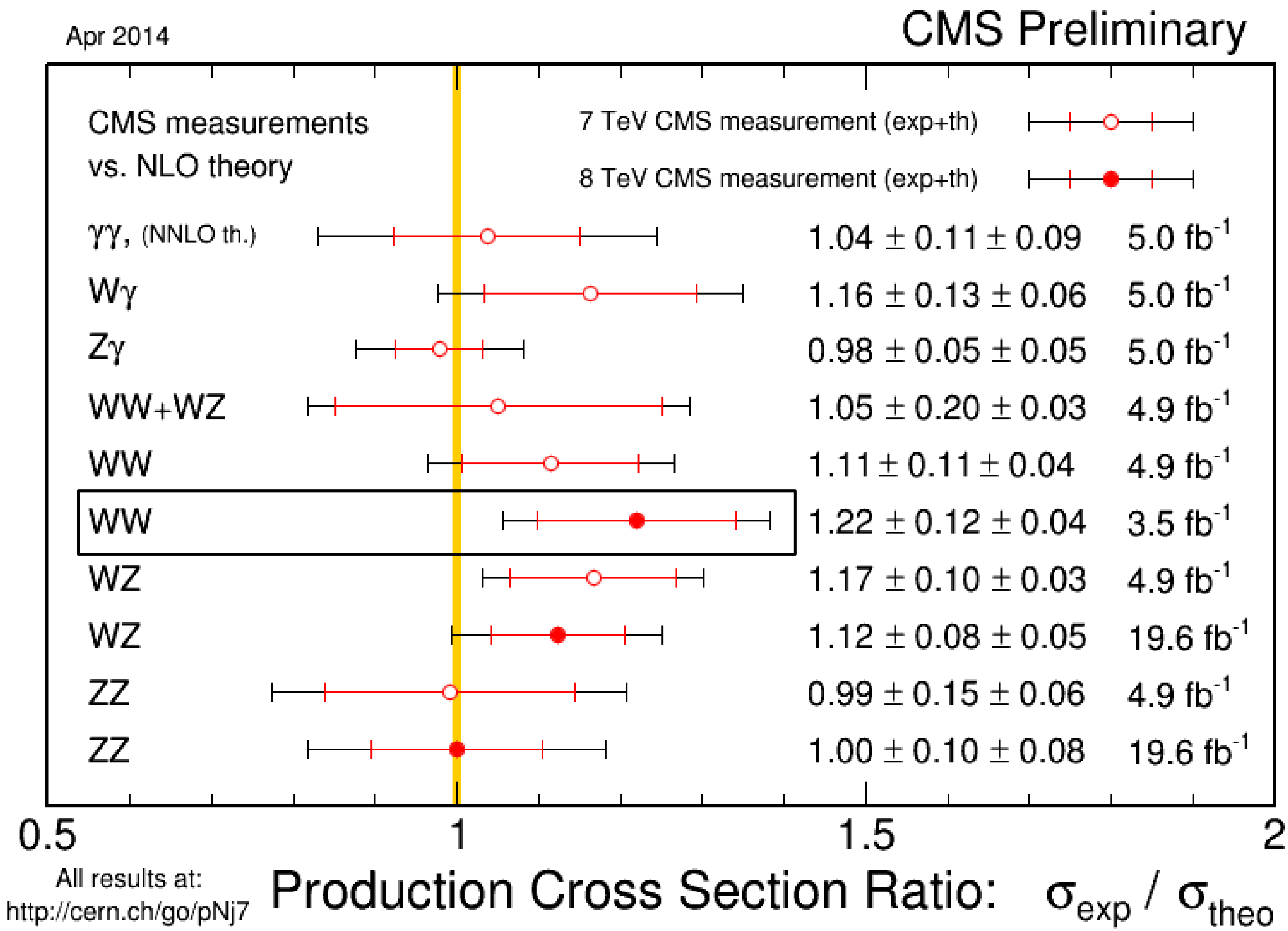
- SM NLO prediction is: 57.3 (+2.4 –1.6) pb

Both ATLAS and CMS 7 TeV results are consistent with each other

- They disagree with the SM prediction and is bit “high”

CMS 8 TeV result is even more discrepant with the SM prediction

Standard Model - WW issues



Standard Model - WW issues

Both experiments observed a total cross section ~ 15 – 20% above the SM

- Individual diagreement is at ~1-2σ level, combined at 3σ

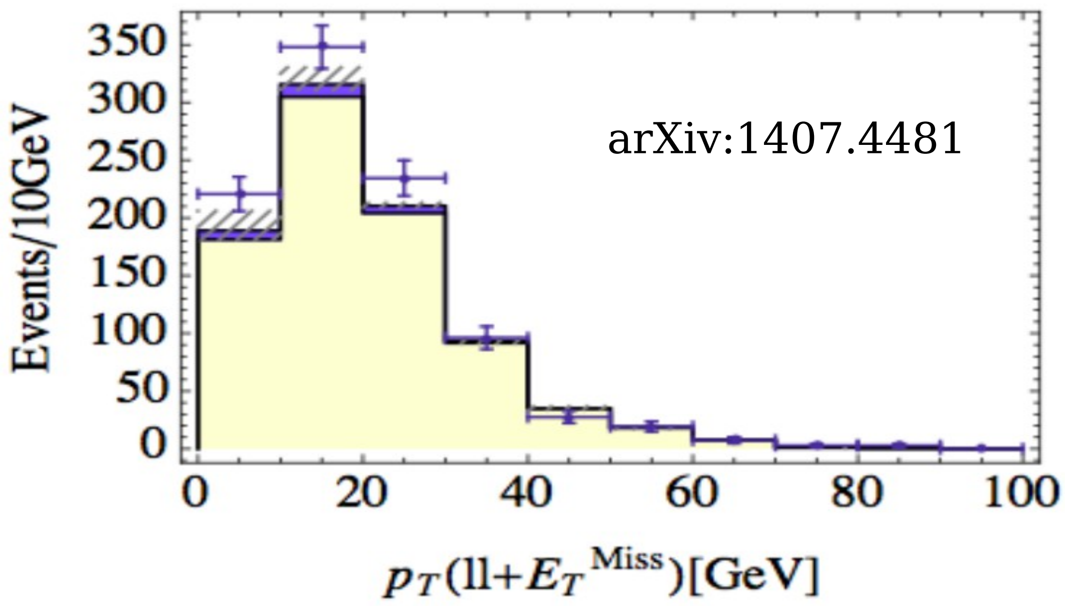
Excess seems to be at moderate p_T and invariant mass, tails are very well modeled

- Such diagreement is absent for SM WZ and ZZ final states from both exp.

The issue is also related to Jet Veto used by the experiments at a given order:

$$\epsilon^{MC}_{W^+W^-} \times \epsilon^{data}_{Z} / \epsilon^{MC}_{Z}$$

Resummation increases the differences at low pt



This can be of various reasons:

- a statistical fluctuation
- "unexplained effects"
- a new physics signature

Moreover, ratios between 13/14 TeV measurement to 7/8 TeV can further cancel various systematics.

Implications of WW anomaly

Assuming this can be from new physics such as SUSY

The dominant contribution (with moderately low cross section) can fit well with

this anomaly can be from SUSY electroweak productions.

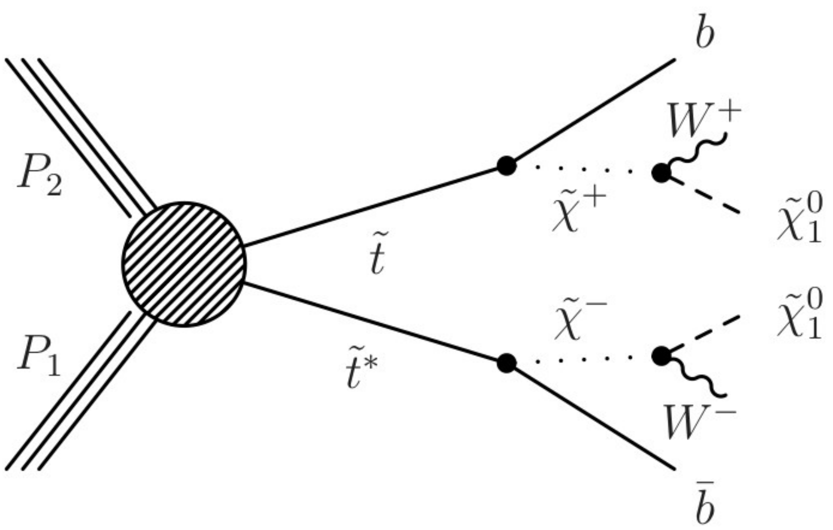
$$\chi_1^+\chi_1^- \rightarrow W^+W^-\chi_1^0\chi_1^0$$

Similarly, low mass stops compressed with charginos can also give such anomalies

There is lot happening in the literature.

Most significant contributions are from:

P. Meade et. al:



a) e-Print: arXiv:1407.4481

b) Natural SUSY in Plain Sight

- arXiv:1406.0848

c) Casting Light on BSM Physics with SM Standard Candles

- arXiv:1304.7011

SUSY/BSM Physics in Run-2 of the LHC

Naturalness in Supersymmetry

$$\frac{1}{2}M_Z^2 = \frac{(m_{H_d}^2 + \Sigma_d) - (m_{H_u}^2 + \Sigma_u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2 .$$

"Tuned" due to the Higgs mass - Colored sector

SUSY weak sector

- Individual terms on right side should be comparable in magnitude
  - **"Large" cancellations are "unnatural"**
- |μ| can be a measure of naturalness

Stop mass

Σ - arises from radiative correction → $\Sigma_u \sim \frac{3 f_t^2}{16\pi^2} \times m_{\tilde{t}_i}^2 \left(\ln(m_{\tilde{t}_i^2}/Q^2) - 1 \right)$

For, $\Sigma \approx 1/2 M_Z^2 \rightarrow m_{\tilde{t}_i} \approx 500$ GeV

Assuming μ ~ 150 (200) GeV → Mass(stop) ~ 1 (1.5) TeV

Other heavier Higgs can easily be in the TeV mass range and is perfectly natural:

$$m_A^2 \simeq 2\mu^2 + m_{H_u}^2 + m_{H_d}^2 + \Sigma_u + \Sigma_d$$

R. Barbieri

The key equations:

$$\frac{m_h^2}{2} \approx -|\mu|^2 + m_u^2 + \ldots$$

$$\delta m_u^2 \approx -\frac{3y_t^2}{8\pi^2}(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + A_t^2) \log M/m_{\tilde{t}}$$

$m_{\tilde{b}_L}$

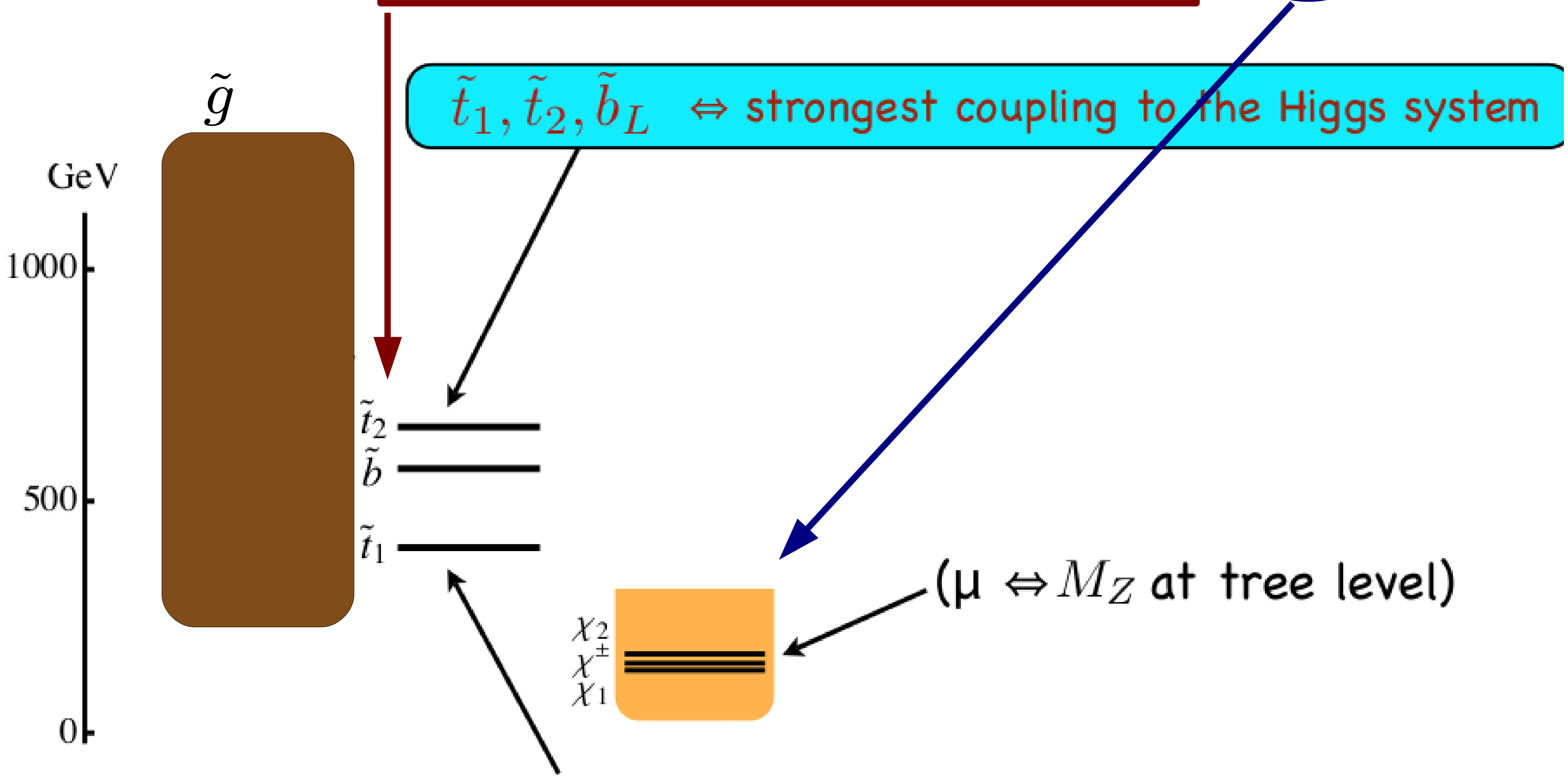
$$\delta m_{\tilde{t}}^2 \approx \frac{8\alpha_s}{3\pi} m_{\tilde{g}}^2 \log M/m_{\tilde{t}}$$

to be made more precise in any given SB-mediation scheme

see Dimopoulos, Giudice for SUGRA-mediation

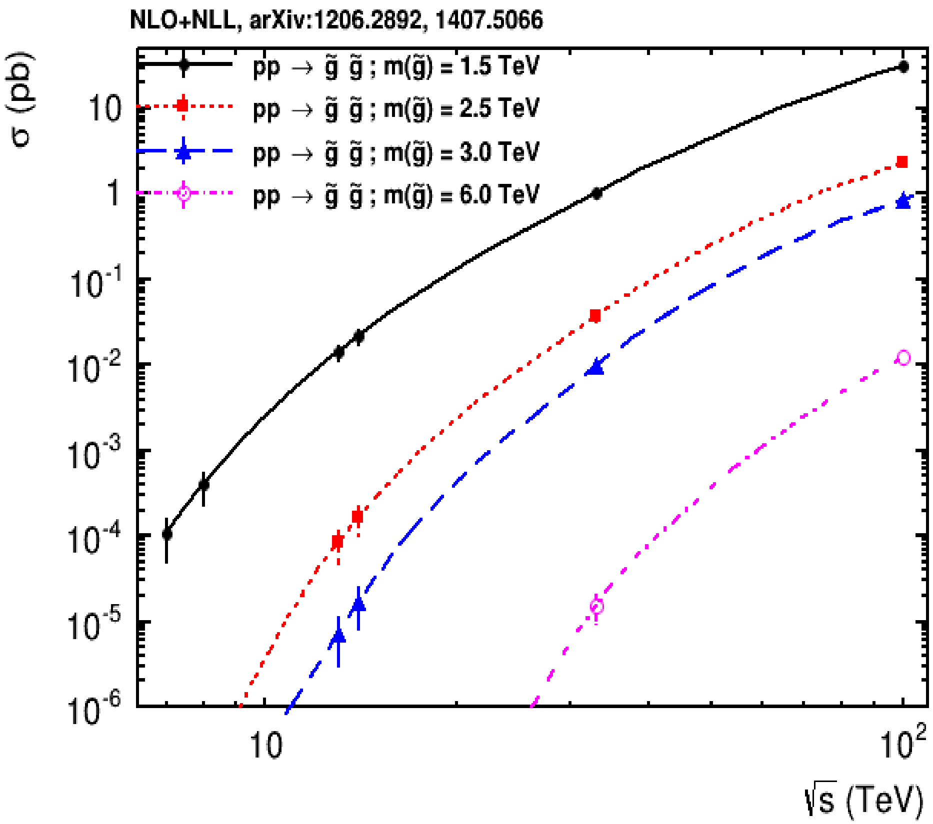
Naturalness in Supersymmetry

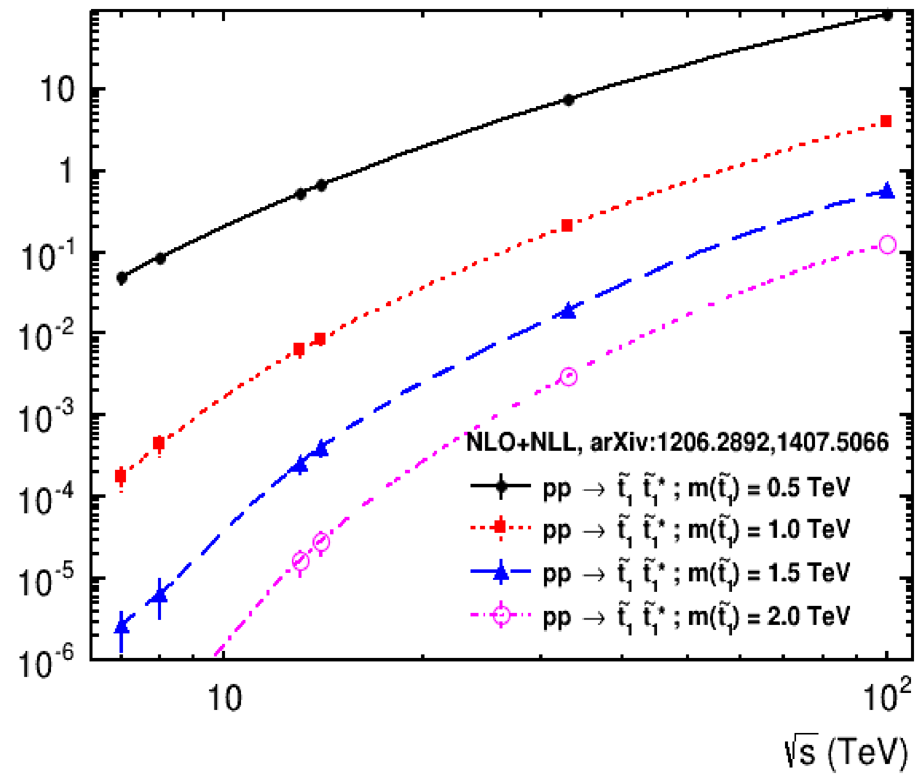
$$\frac{1}{2}M_Z^2 = \frac{(m_{H_d}^2 + \Sigma_d) - (m_{H_u}^2 + \Sigma_u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2 .$$



$\tilde{q}_1, \tilde{q}_2, \tilde{b}_R$ heavy enough (≥ $\tilde{g}$) to be ~ irrelevant

Large gain in cross section during LHC Run-2 (gluinos/stops)





Gain in order's of magnitude in cross section.

With high luminosity upgrades:

→ One should be able to access large mass ranges

Inclusive SUSY studies - $\tilde{g}\tilde{g}$

Hadronic decay modes

Cohen, Golling, Hance, Henrichs, Howe, Loyal, Padhi, Wacker

SNOW13-00193, arXiv:1310.0077, arXiv:1311.6480

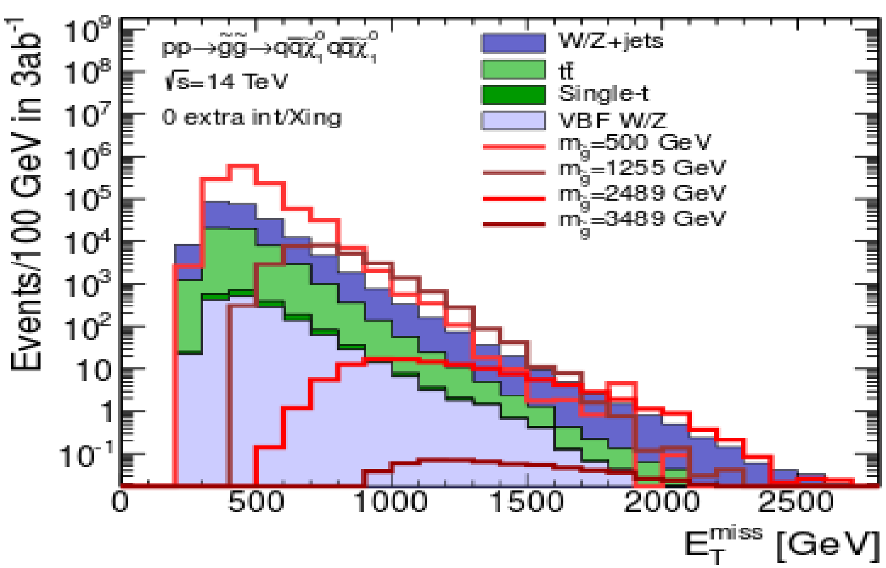
Preselection:

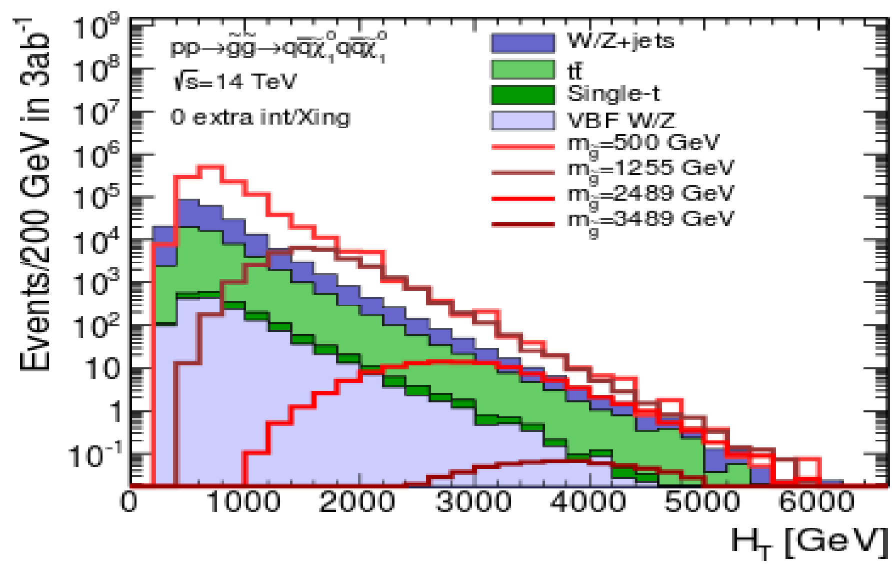
- Veto leptons with p_T > 10 GeV
- MET > 100 GeV
- At least 4 jets with p_T > 60 GeV
- Reduce QCD: MET/$\sqrt{H_T}$ > 15 GeV$^{1/2}$

Optimization over MET and H_T

$$Z \to \nu\nu, W(\to l\nu), t\bar{t}$$

Cut	V+jets	$t\bar{t}$	Total BG	$m_{\tilde{g}}$ [GeV] 500	1255	2489
Preselection	2.07×10^7	2.47×10^7	4.54×10^7	3.08×10^7	1.03×10^5	173
$E_T^{\rm miss}/\sqrt{H_T} > 15\,\text{GeV}^{1/2}$	4.45×10^5	1.20×10^5	5.65×10^5	1.34×10^6	3.14×10^4	95
$p_T^{\rm leading} < 0.4 \times H_T$	1.69×10^5	5.16×10^4	2.21×10^5	7.62×10^5	1.68×10^4	52.9
$E_T^{\rm miss} > 450$ GeV, $H_T > 800$ GeV	4.73×10^4	1.84×10^4	6.57×10^4	5.57×10^5	2.98×10^4	115
$E_T^{\rm miss} > 800$ GeV, $H_T > 1650$ GeV	1.22×10^3	554	1.78×10^3	1.14×10^4	9.36×10^3	110
$E_T^{\rm miss} > 1050$ GeV, $H_T > 2600$ GeV	55.5	30.1	85.6	297	288	57.2





Inclusive SUSY studies - $\tilde{g}\tilde{g}$

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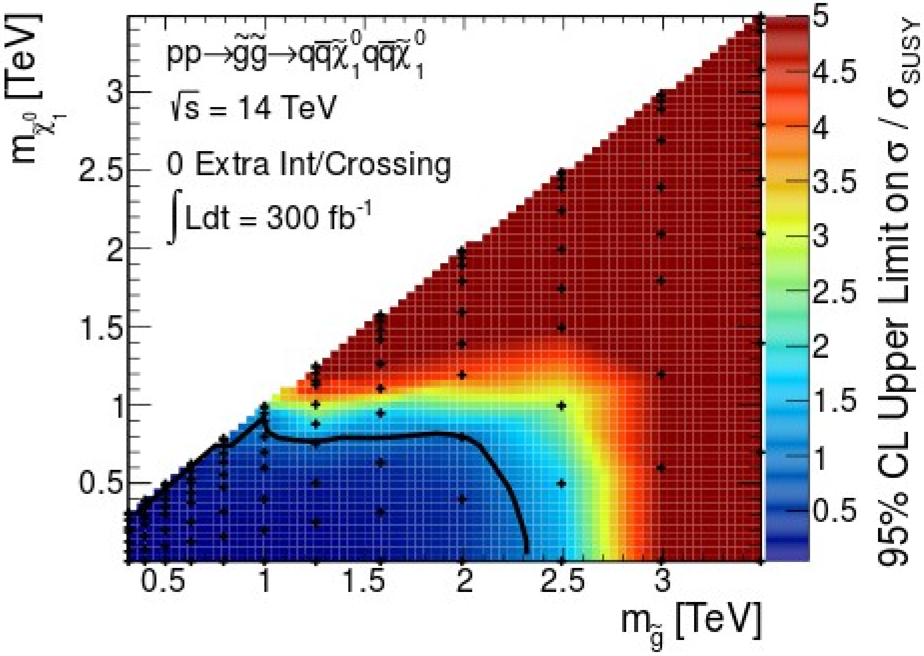
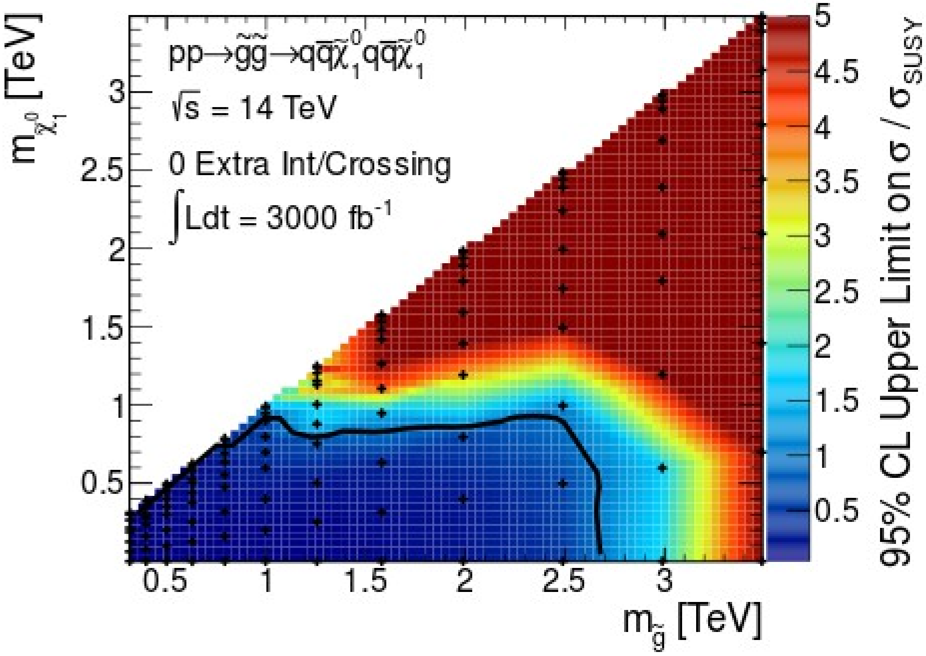




Using NLO for 3000 fb^{-1} one gets 10 events for a mass of 3.3 TeV

Current study excludes gluino mass ~ 2.7 TeV using HL-LHC

→ 175 events in fully hadronic mode

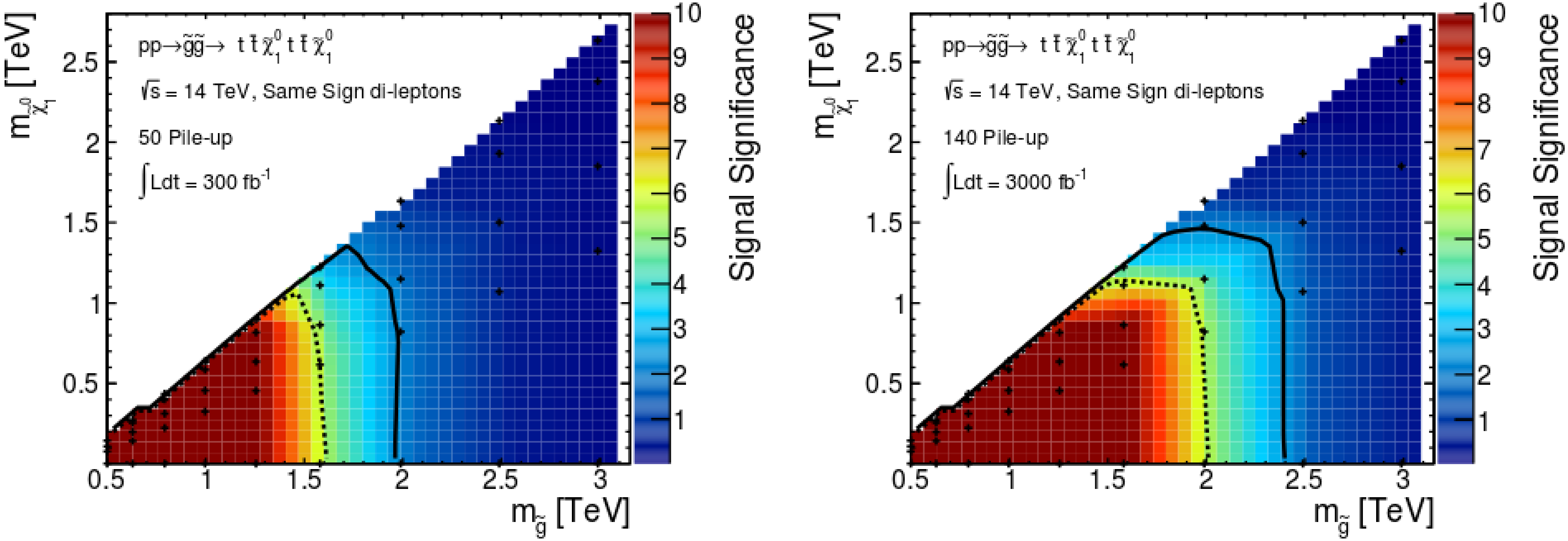
Significant regions of phase space can still be studied in the “compressed” regions

SUSY using 3rd generation squarks

$$\tilde{g}\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0 t\bar{t}\tilde{\chi}_1^0$$

Cohen, Golling, Hance, Henrichs, Howe, Loyal, Padhi, Wacker

SNOW13-00193, arXiv:1310.0077, arXiv:1311.6480



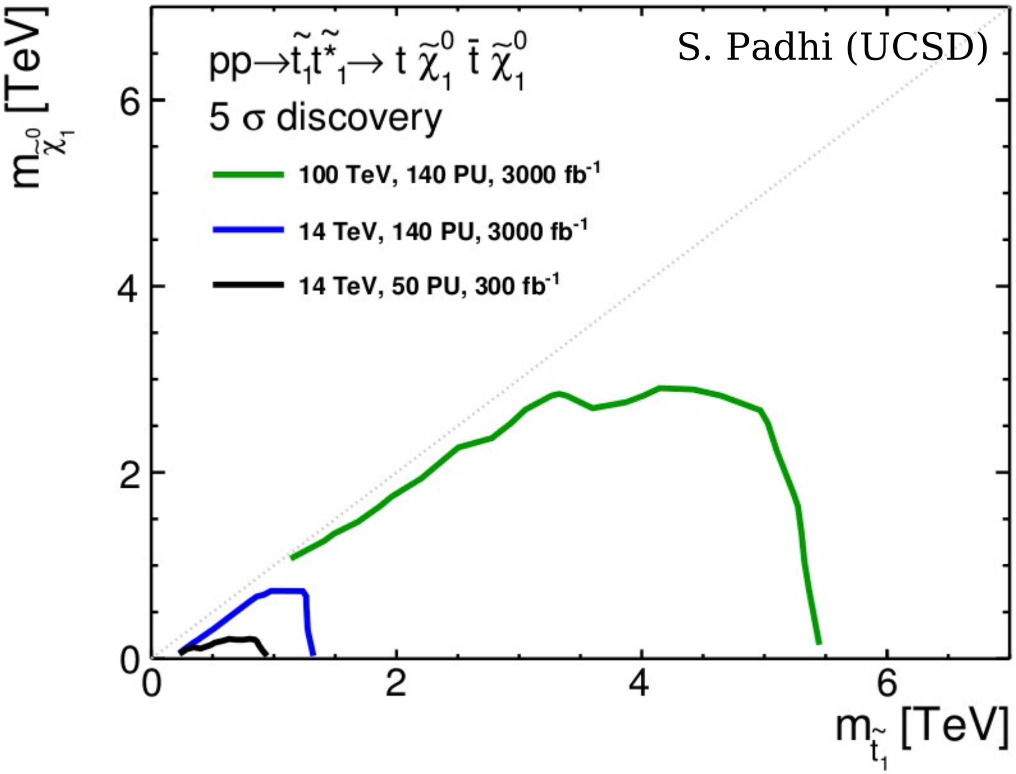
Using cross section arguments (+BR) one expects:

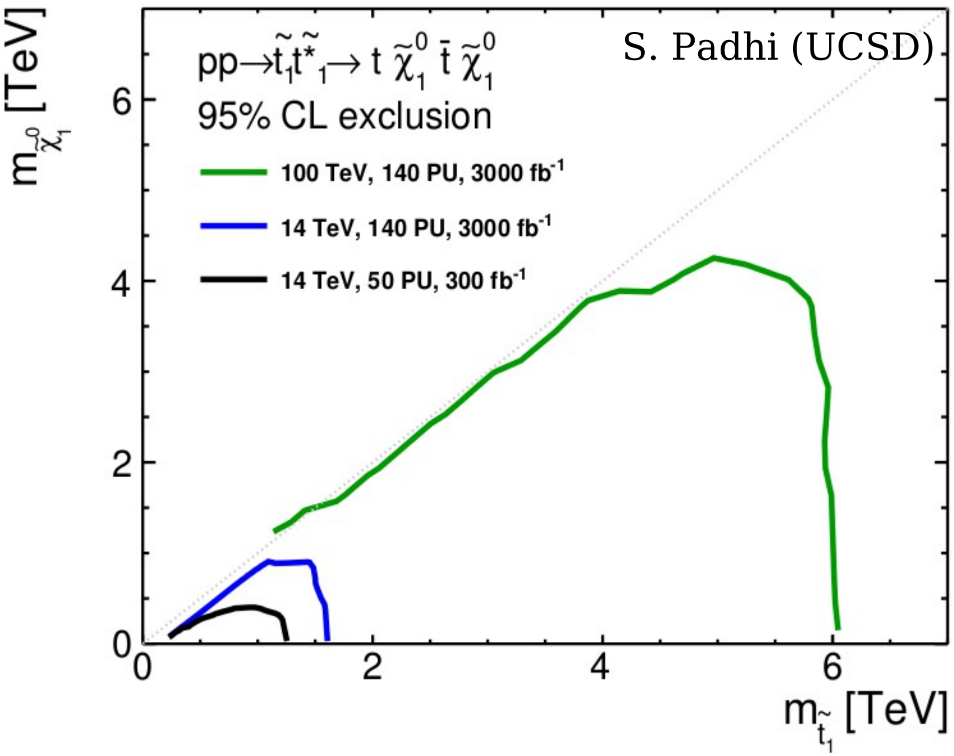
→ 10 events using 3000 fb^{-1} for a gluino mass of 2.8 TeV

With Snowmass detector and with 140 PU

→ Sensitive to gluino mass of 2.4 TeV

Direct stop production $\tilde{t} \rightarrow t\tilde{\chi}_1^0$





Preliminary results using 1-lepton mode.

→ With 140 PU & 14 TeV, stop mass up to ~1.5 TeV can be probed

arXiv:1309.1514

Collider	Energy	Luminosity	Cross Section	Mass
LHC8	8 TeV	20.5 fb^{-1}	10 fb	650 GeV
LHC	14 TeV	300 fb^{-1}	3.5 fb	1.0 GeV
HL LHC	14 TeV	3 ab^{-1}	1.1 fb	1.2 TeV
HE LHC	33 TeV	3 ab^{-1}	91 ab	3.0 TeV
VLHC	100 TeV	1 ab^{-1}	200 ab	5.7 TeV

Assume LSP based on SUSY breaking mass parameters M1, M2 and μ

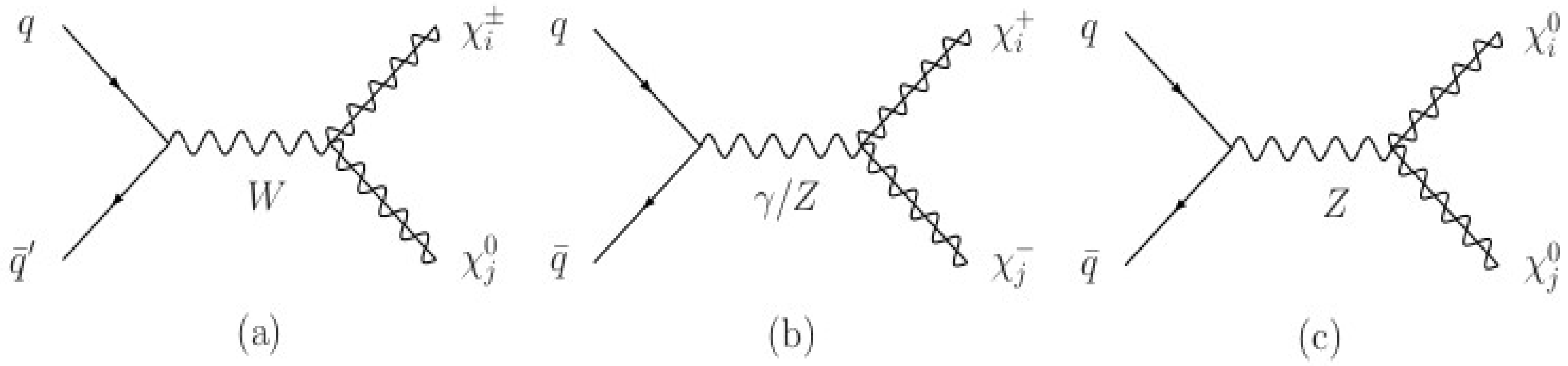
- Decouple the SUSY colored sector

There can be three cases:

a) Bino LSP (M1 < M2, μ)

b) Wino LSP (M2 < M1, μ)

c) Higgsino LSP (μ < M1, M2)



SUSY EWinos – Bino LSP

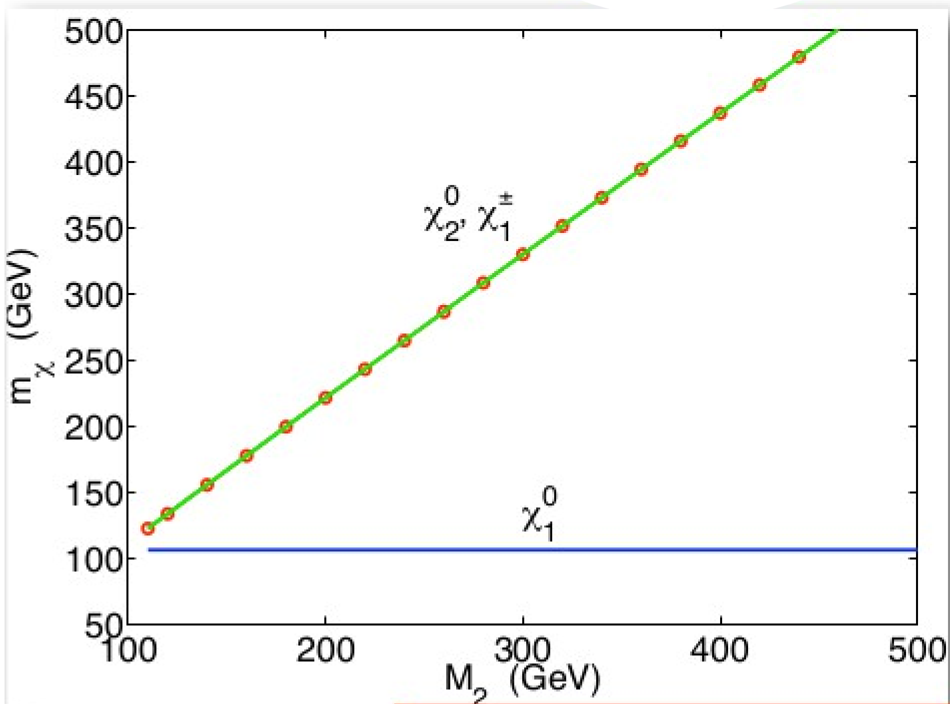
Case AI:
$M_1 < M_2 < \mu$

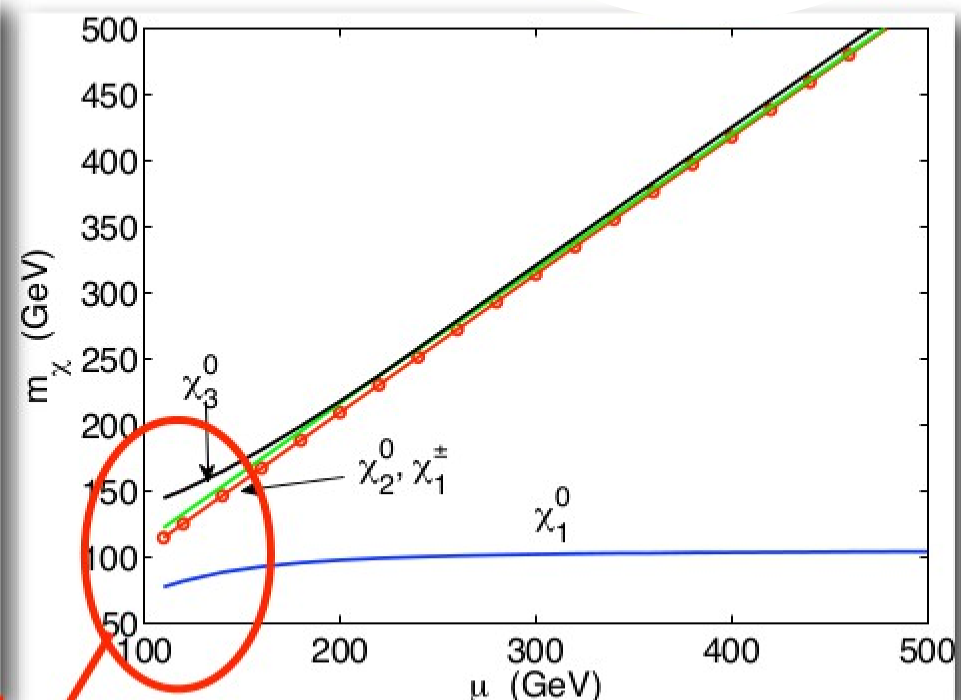
Case AII:
$M_1 < \mu < M_2$

arXiv:1309.5966

μ = 1 TeV

M2 -





large mixing, natural compressed spectrum

$$\text{Case AI}: \quad M_2 < \mu, \quad \chi_1^\pm, \chi_2^0 \text{ are Wino} - \text{like}; \chi_2^\pm, \chi_{3,4}^0 \text{ are Higgino} - \text{like};$$

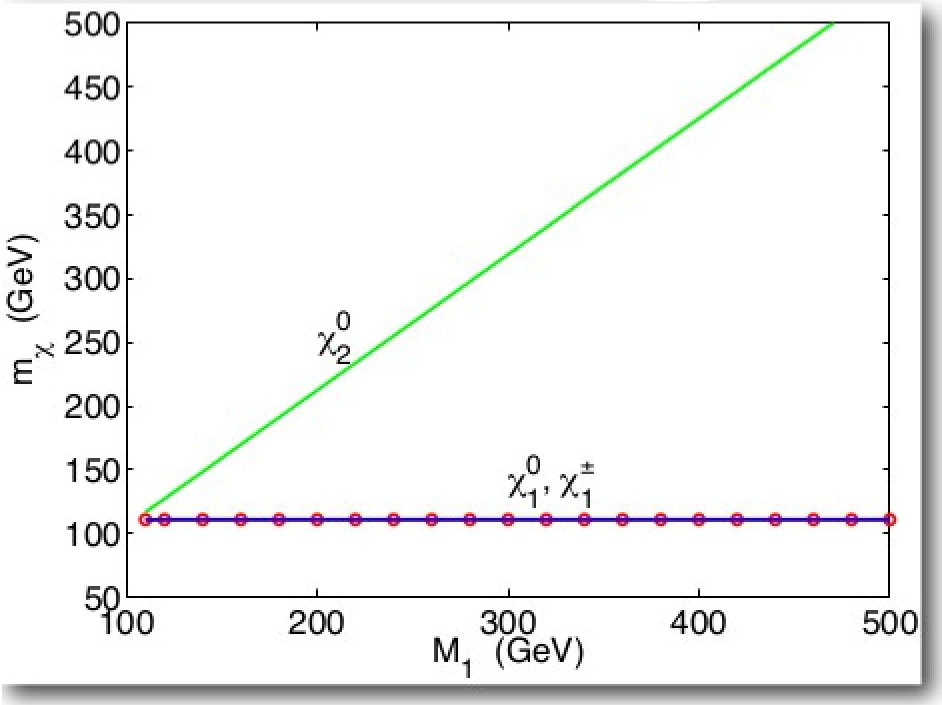
$$\text{Case AII}: \quad \mu < M_2, \quad \chi_1^\pm, \chi_{2,3}^0 \text{ are Higgino} - \text{like}, \chi_2^\pm, \chi_4^0 \text{ are Wino} - \text{like}.$$

SUSY EWinos – Wino LSP

arXiv:1309.5966

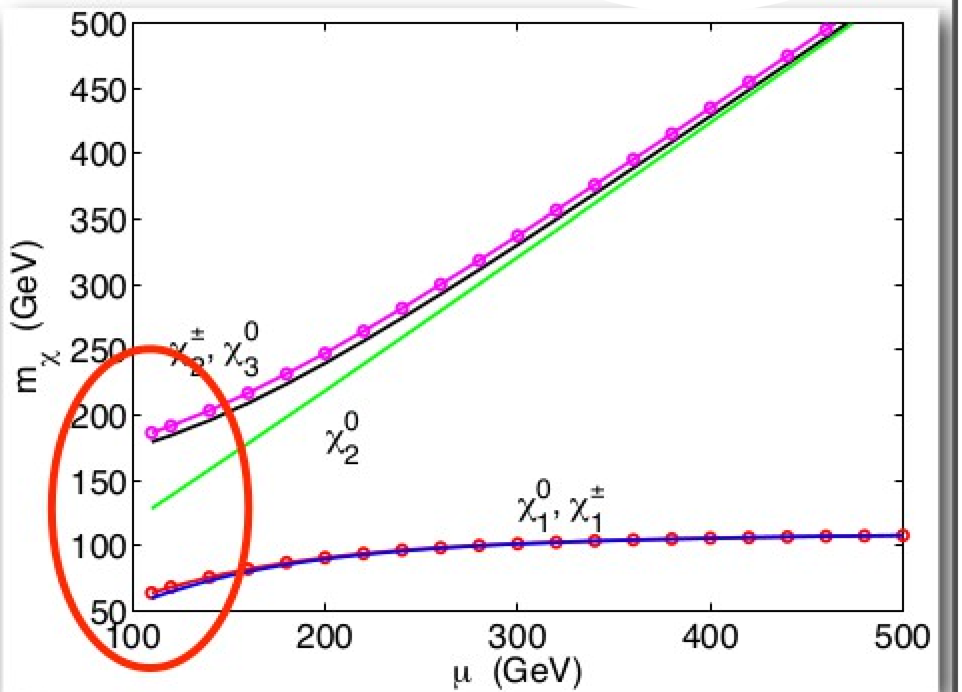
Case BI:
$M_2 < M_1 < \mu$

μ = 1 TeV



Case BII:
$M_2 < \mu < M_1$

M1 = 1 TeV



With wino LSP:

$$\text{Case BI}: \quad M_1 < \mu, \quad \chi_2^0 \text{ Bino} - \text{like}; \ \chi_2^\pm, \ \chi_{3,4}^0 \text{ Higgsino} - \text{like};$$

$$\text{Case BII}: \quad \mu < M_1, \quad \chi_2^\pm, \ \chi_{2,3}^0 \text{ Higgsino} - \text{like}; \ \chi_4^0 \text{ Bino} - \text{like}.$$

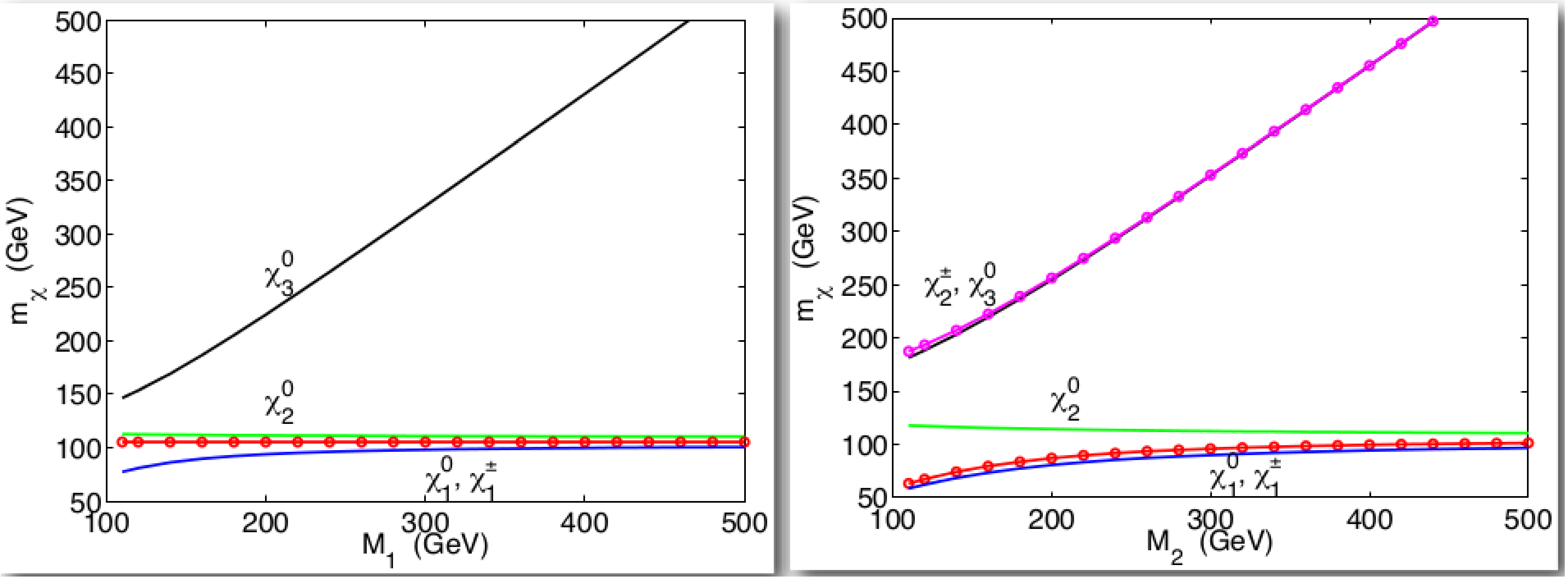
SUSY EWinos – Higgsino LSP

Case CI:
μ < M_1 < M_2

Case CII:
μ < M_2 < M_1

arXiv:1309.5966

M2 = 1 TeV M1 = 1 TeV

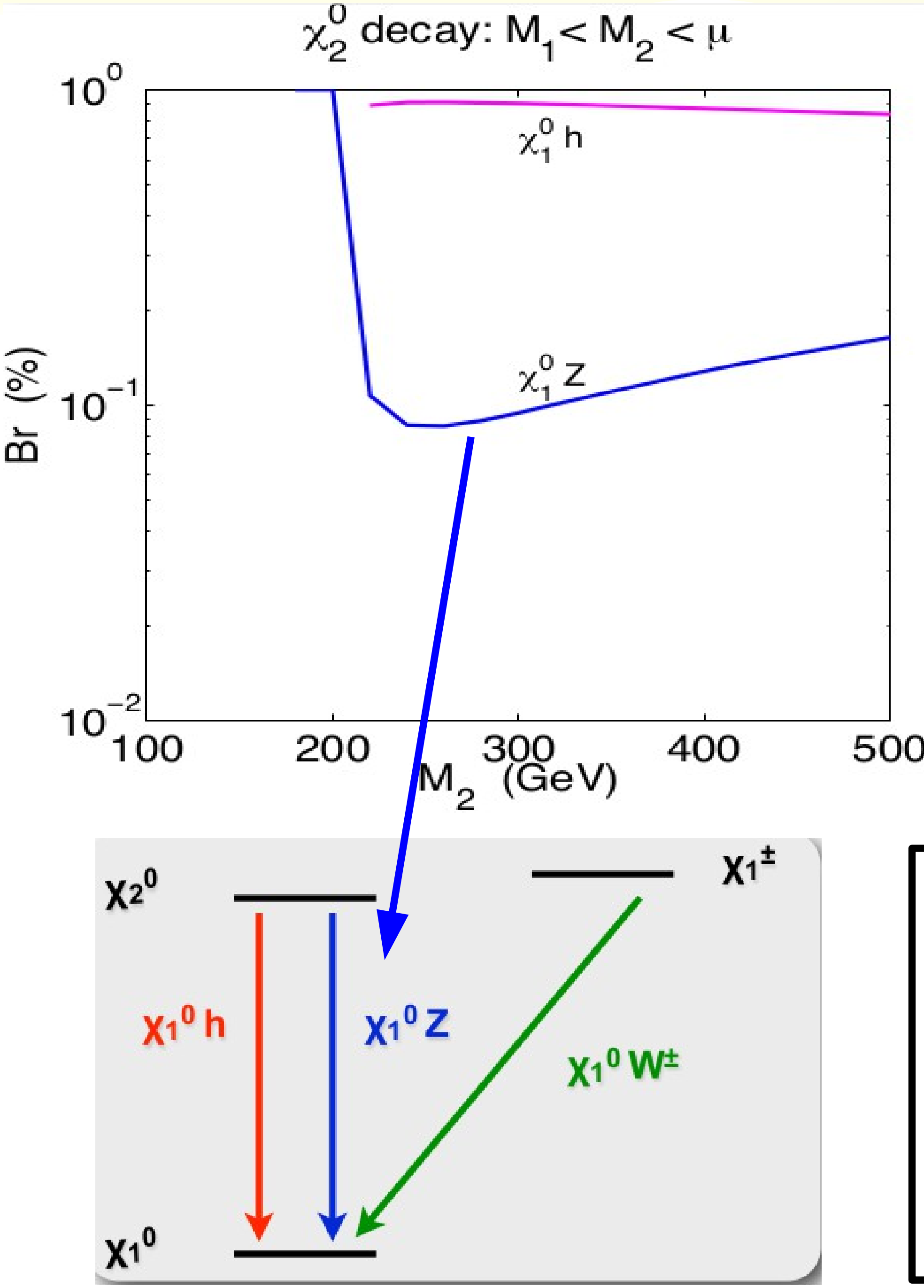


With higgsino LSP:

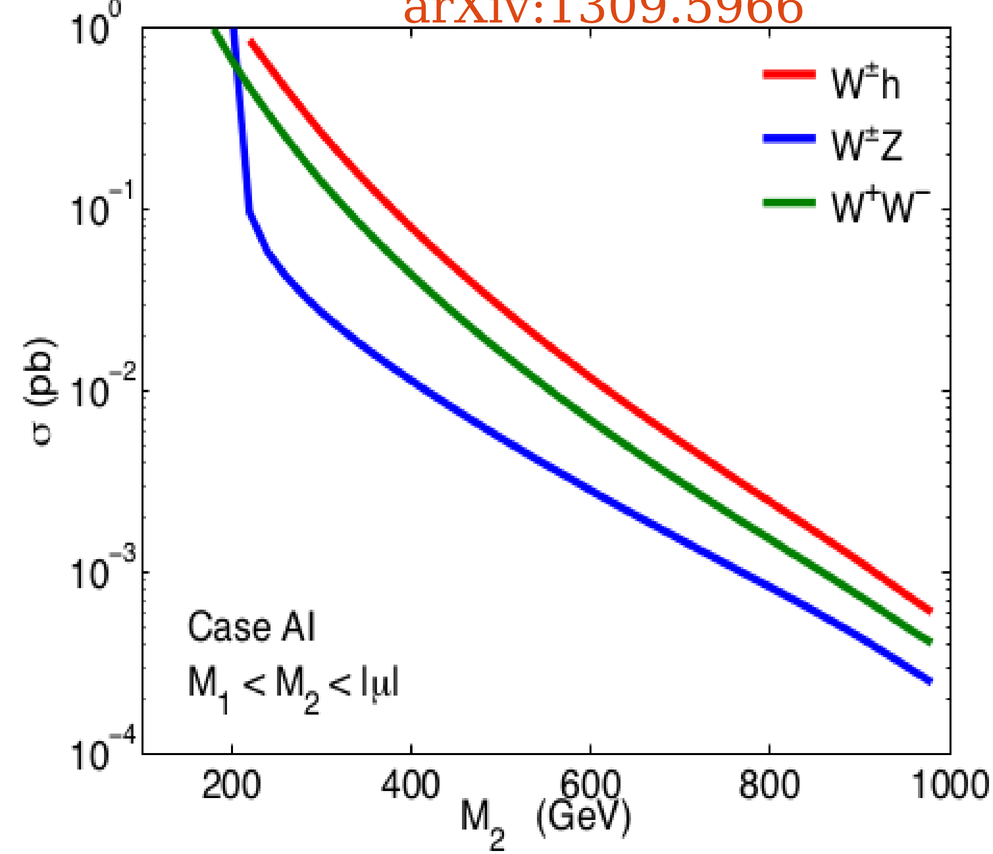
Case CI : $M_1 < M_2$, χ_3^0 Bino − like; $\chi_2^\pm$, χ_4^0 Wino − like;

Case CII : $M_2 < M_1$, $\chi_2^\pm$, χ_3^0 Wino − like; χ_4^0 Bino − like.

Production Rates for Bino LSP, Wino NLSP



arXiv:1309.5966



Decay to Higgs dominates over Z

Rich mixture of (W/Z/h)(W/Z/h) + MET

BR(WZ) < 100%

- sometimes highly suppressed

Wh complementary to WZ channel

- new discovery potential

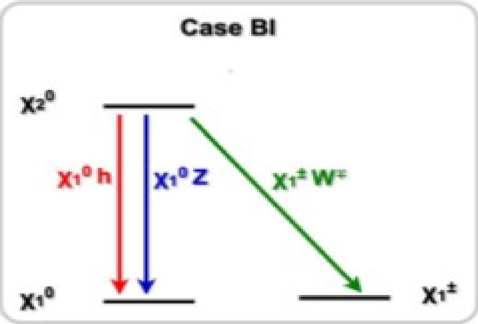
SUSY Electroweak productions

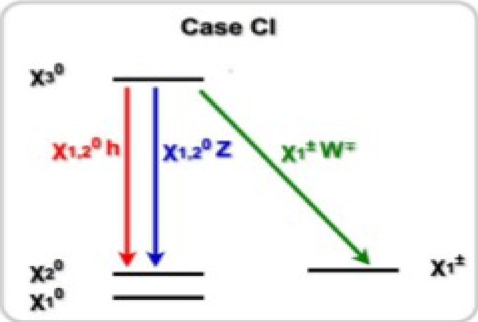
	NLSP decay Br's		Production	Total Branching Fractions (%)						
				W^+W^-	$W^\pm W^\pm$	WZ	Wh	Zh	ZZ	hh
Case AI	$\chi_1^\pm \to \chi_1^0 W^\pm$	100%	$\chi_1^\pm \chi_2^0$			18	82			
$M_1 < M_2 < \mu$	$\chi_2^0 \to \chi_1^0 h$	82%(96–70%)	$\chi_1^+ \chi_1^-$	100						
Case AII	$\chi_1^\pm \to \chi_1^0 W^\pm$	100%	$\chi_1^\pm \chi_2^0$			26	74			
$M_1 < \mu < M_2$	$\chi_2^0 \to \chi_1^0 h$	74%(90–70%)	$\chi_1^\pm \chi_3^0$			78	23			
	$\chi_3^0 \to \chi_1^0 Z$	78%(90–70%)	$\chi_1^+ \chi_1^-$	100						
			$\chi_2^0 \chi_3^0$					63	20	17
Case BI										
$M_2 < M_1 < \mu$	$\chi_2^0 \to \chi_1^\pm W^\mp, \chi_1^0 h, \chi_1^0 Z$,	68%, 27%(31 − 24%), 5%(1 − 9%),	production suppressed.							
Case BII	$\chi_2^\pm \to \chi_1^0 W^\pm$	35%	$\chi_2^\pm \chi_2^0$	12	12	32	23	10	9	2
$M_2 < \mu < M_1$	$\chi_2^\pm \to \chi_1^\pm Z$	35%	$\chi_2^\pm \chi_3^0$	12	12	26	29	11	3	7
	$\chi_2^\pm \to \chi_1^\pm h$	30%	$\chi_2^+ \chi_2^-$	12		25	21	21	12	9
	$\chi_2^0 \to \chi_1^\pm W^\mp$	67%	$\chi_2^0 \chi_3^0$	23	23	23	21	7	2	2
	$\chi_2^0 \to \chi_1^0 Z$	26%(30–24%)								
	$\chi_3^0 \to \chi_1^\pm W^\mp$	68%								
	$\chi_3^0 \to \chi_1^0 h$	24%(30–23%)								
Case CI										
$\mu < M_1 < M_2$	$\chi_3^0 \to \chi_1^\pm W^\mp, \chi_{1,2}^0 Z, \chi_{1,2}^0 h$,	52%, 26%, 22%,	production suppressed.							
Case CII	$\chi_2^\pm \to \chi_{1,2}^0 W^\pm$	51 %	$\chi_2^\pm \chi_3^0$	14	14	27	23	11	6	5
$\mu < M_2 < M_1$	$\chi_2^\pm \to \chi_1^\pm Z$	26 %	$\chi_2^+ \chi_2^-$	26		26	24	12	7	5
	$\chi_2^\pm \to \chi_1^\pm h$	23 %								
	$\chi_3^0 \to \chi_1^\pm W^\mp$	54 %								
	$\chi_3^0 \to \chi_{1,2}^0 Z$	24 %								
	$\chi_3^0 \to \chi_{1,2}^0 h$	22 %								

arXiv:1309.5966

4 out of 6 cases result in compressed spectra

Nearly degenerate LSP pair production



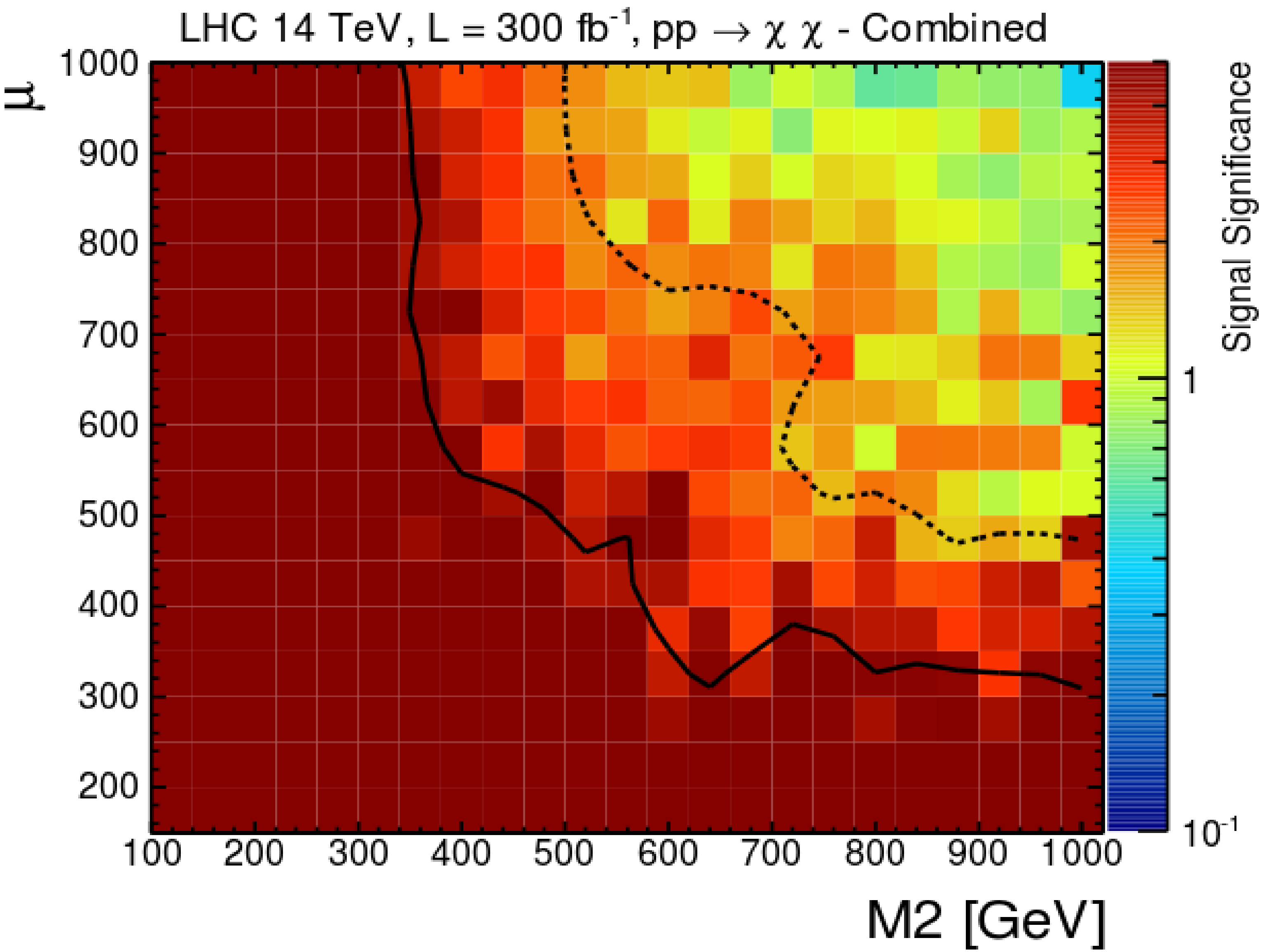


MET + ISR (Mono Jet studies)

Or VBF production

SUSY Electroweak productions

arXiv:1309.5966



Large set of final states

Unique set of signals! **Opportunity to explore using HL-LHC**

SUSY Electroweak productions

In terms of searches:

1. If both parents are un-compressed:

- Standard analysis, trigger on any or both of the visible decay products

2. If one of the parents is compressed e.g: $\chi_2^0\chi_1^\pm; M(\chi_1^\pm) \approx M(\chi_1^0)$

- Use trigger based on one visible decay product

3. If both parents are compressed

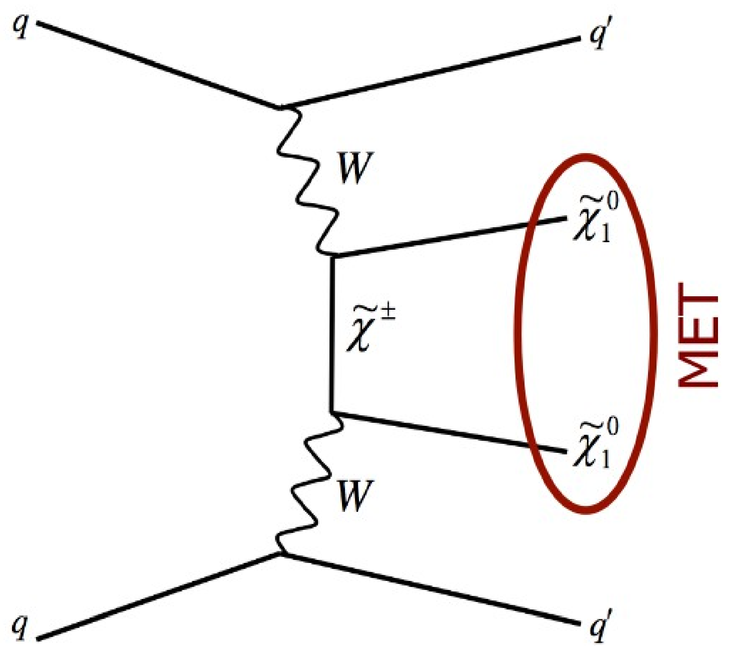
- e.g: $\chi_1^+(\to W\chi_1^0)\chi_1^-(\to W\chi_1^0); M(\chi_1^\pm) \approx M(\chi_1^0)$

- Use mono-jet kind of analysis with trigger on ISR jets or VBF studies

Compressed spectra using VBF

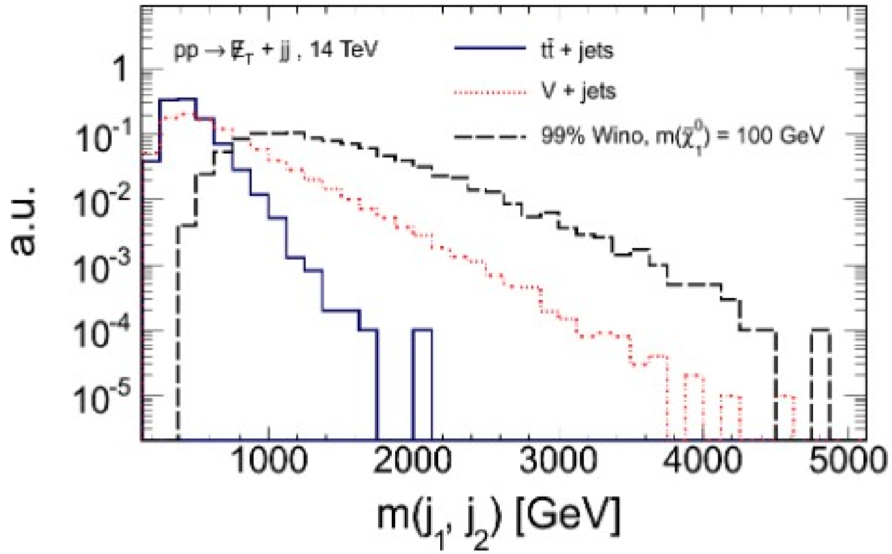
Vector Boson fusion process at the LHC

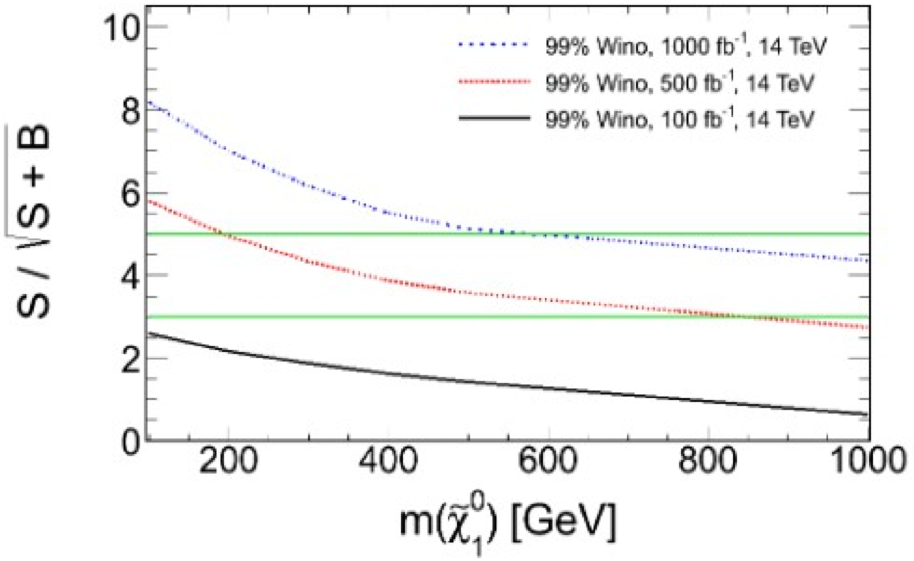
- Unique opportunity to search for new physics
- Extremely useful for compression regions
- With simplistic assumptions on simulation
  - Sensitive to New Physics at HL-LHC



Delannoy et. al.

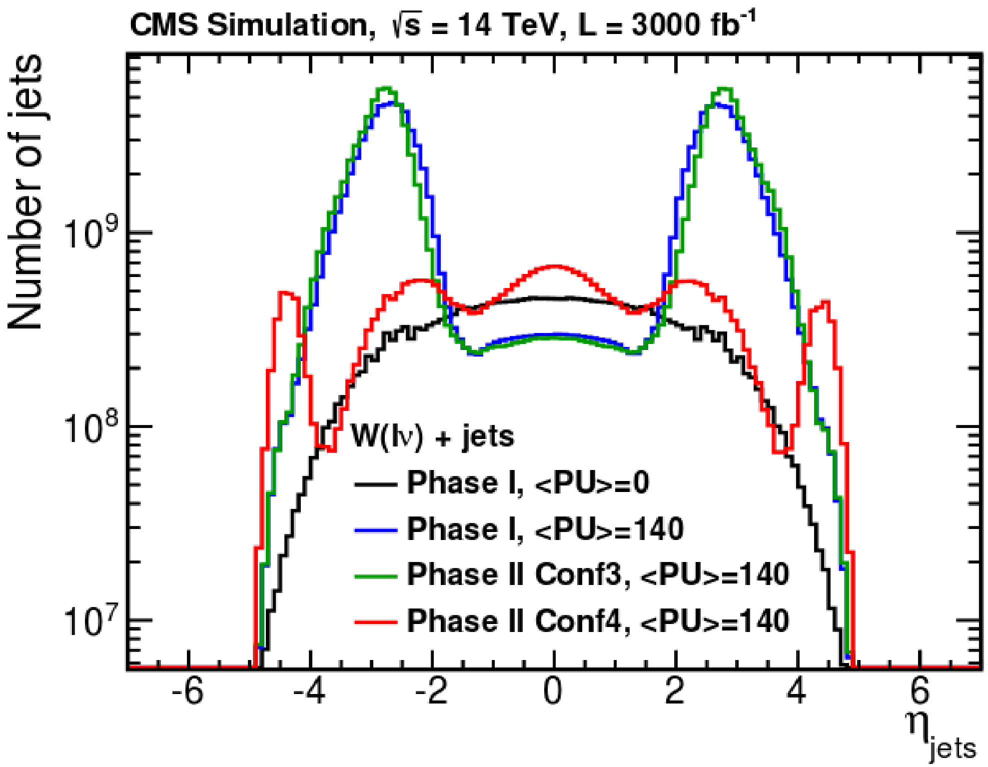
Phys. Rev. Lett. 111 (2013) 061801





Challenges with VBF SUSY EWK searches

Number of jets rises dramatically in forward region without tracking



Particle Flow with veto on charged tracks not from PV helps

→ Important to make PF work with large PU

Calorimeter segmentation can also help reduce neutral deposits

Pico-sec timing calorimeter will be very useful (Study in progress)

Other Beyond Standard Model studies

Search for ttbar Resonances

Extra Dimensions can lead to wide ttbar resonances:

e.g: Kaluza-Klein gluon (g_{KK}) via the process pp → g_{KK} → ttbar

Topcolor Z’ cases in models of strong electroweak symmetry breaking

through top quark condensation can lead to narrow resonances

from heavy Z' → ttbar

Final states:

a) dileptons + MET

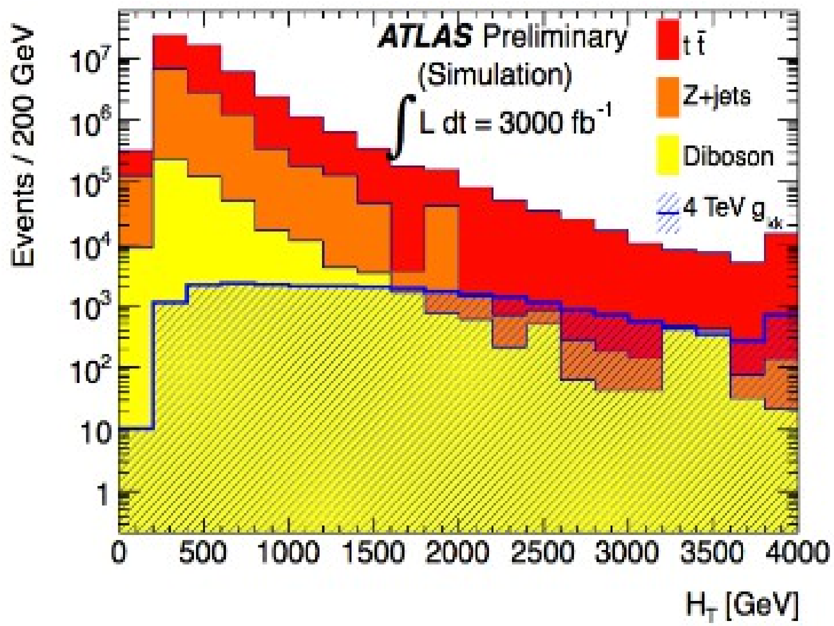
- Very clean state, difficult to reconstruct ttbar inv. mass

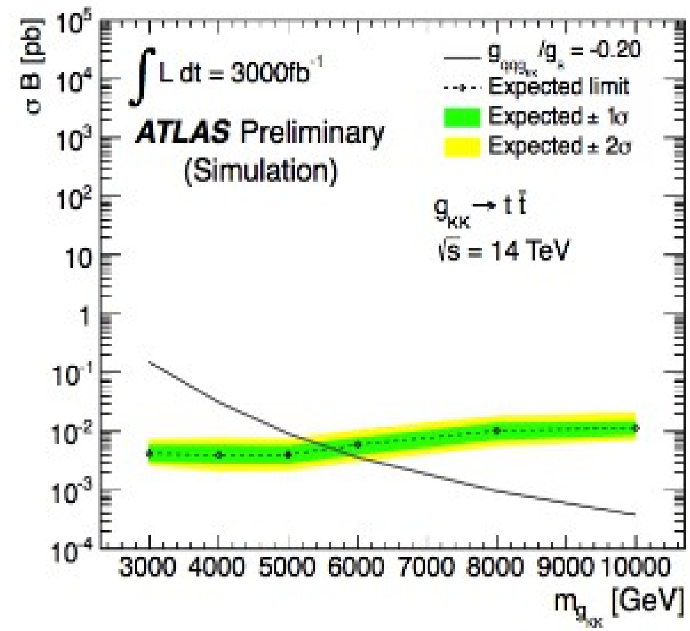
b) Semi-leptonic decays (Single lepton + MET)

- More complete reconstruction with large background

Search for ttbar Resonances

di-leptonic selection (similar results for single-lepton selection)





model	$300\,\mathrm{fb}^{-1}$	$1000\,\mathrm{fb}^{-1}$	$3000\,\mathrm{fb}^{-1}$
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
Z'_{topcolor}	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)

(in TeV)

Mass reach for Kaluza-Klein gluons or Z′ can be enhanced by 50% with 3000 fb^{-1}

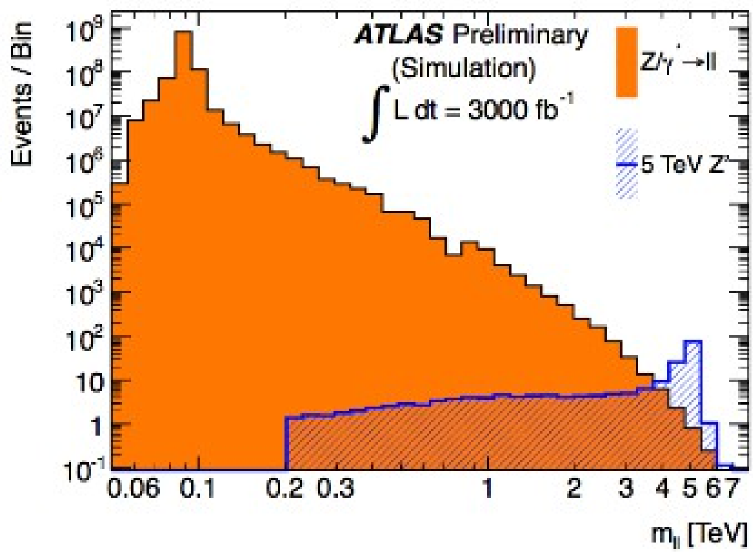
Search for ttbar Resonances

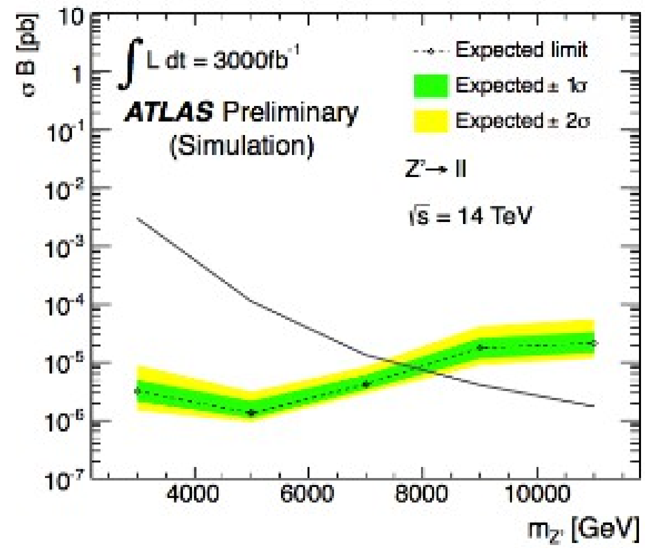
Z' decays to di-leptons

→ Main background: SM DY, ttbar, dibosons (small)

→ Upgraded detector should be able to suppress electron from γ conversion

ee final state (similar results for μμ)





model	$300\,\mathrm{fb}^{-1}$	$1000\,\mathrm{fb}^{-1}$	$3000\,\mathrm{fb}^{-1}$
$Z'_{SSM} \to ee$	6.5	7.2	7.8
$Z'_{SSM} \to \mu\mu$	6.4	7.1	7.6

(in TeV)

Mass reach for Z' → dileptons can be enhanced by 20% with 3000 fb^{-1}

Summary and Conclusions

BSM results from ATLAS and CMS show the breath of physics analyses

Low MET and High H_T studies are crucial for the next phase of the LHC

Anomalies associated with dibosons should be clarified

→ using ratios, better re-summed calculations, etc.

Missed opportunities: First Evidence of Same sign WW Vector Boson (ATLAS)

should have been discovered in 2013 using inclusive SS searches.

Huge array of measurements are possible with HL-LHC

- New Physics in colored sector as well as EW sector with Higgs in the final states
- Compressed Spectra/DM: Monojet + Vector boson scattering will essential
- Measurements of rare decays (not discussed here)

The results from ATLAS and CMS WILL set the agenda across the energy frontier for the foreseeable future!

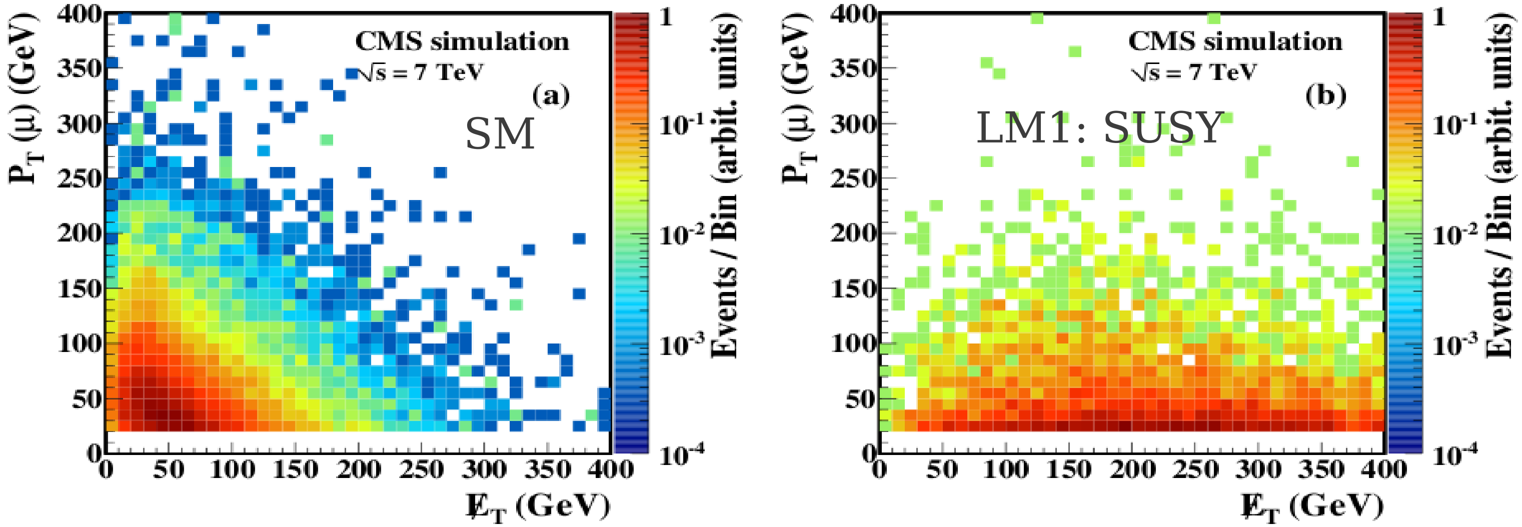
Backup slides

Lepton Spectrum method

In SM events, the neutrino and lepton p_T are anti-correlated in an event

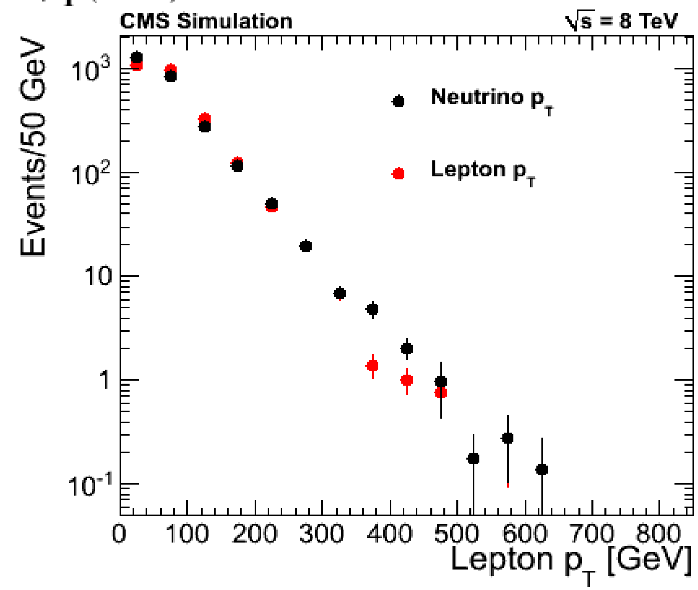
- Overall spectra are similar

In SUSY event, the correlation between MET and lepton p_T is very different



- For ttbar & Wjets: use muon p_T spectrum

- Correct for acceptance efficiency and polarization effects
- Smear lepton p_T for instru. MET using QCD templates



- Residual bkg are from ttbar dileptons and tau decays

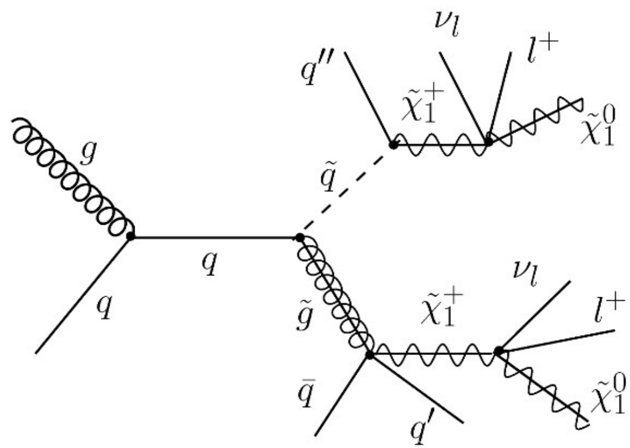
- Use control samples with dileptons and emulate the mechanism to loose a lepton
- Bkg from tau-to-lepton are modeled based on 1lep. Events
- QCD is small (~1%), use ABCD between Rel Iso & MET

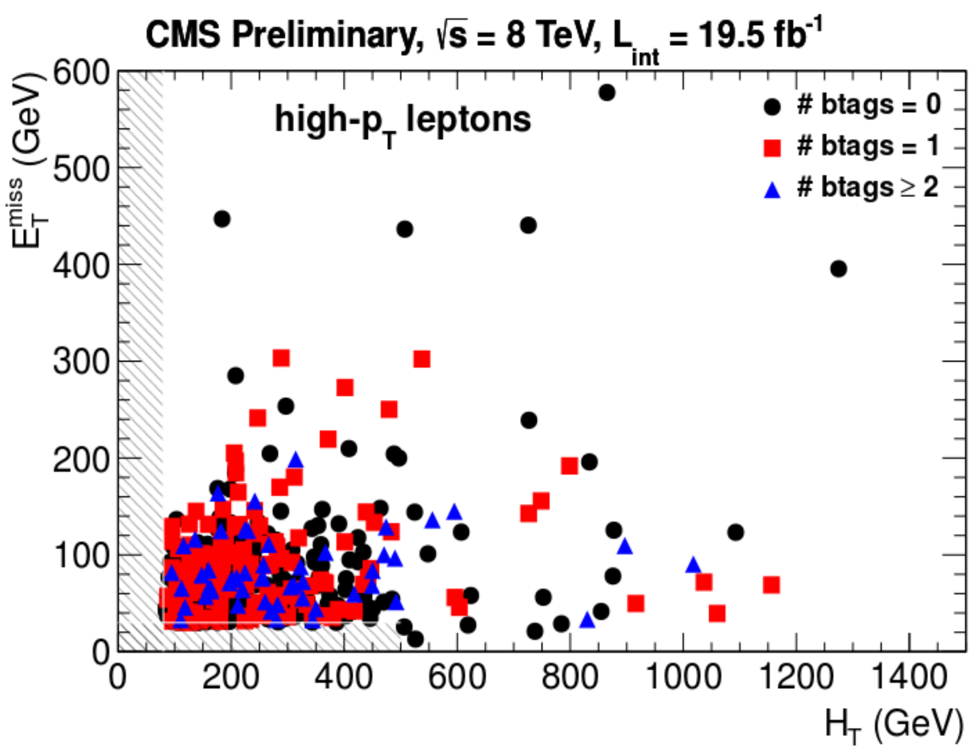
Same Sign dileptons

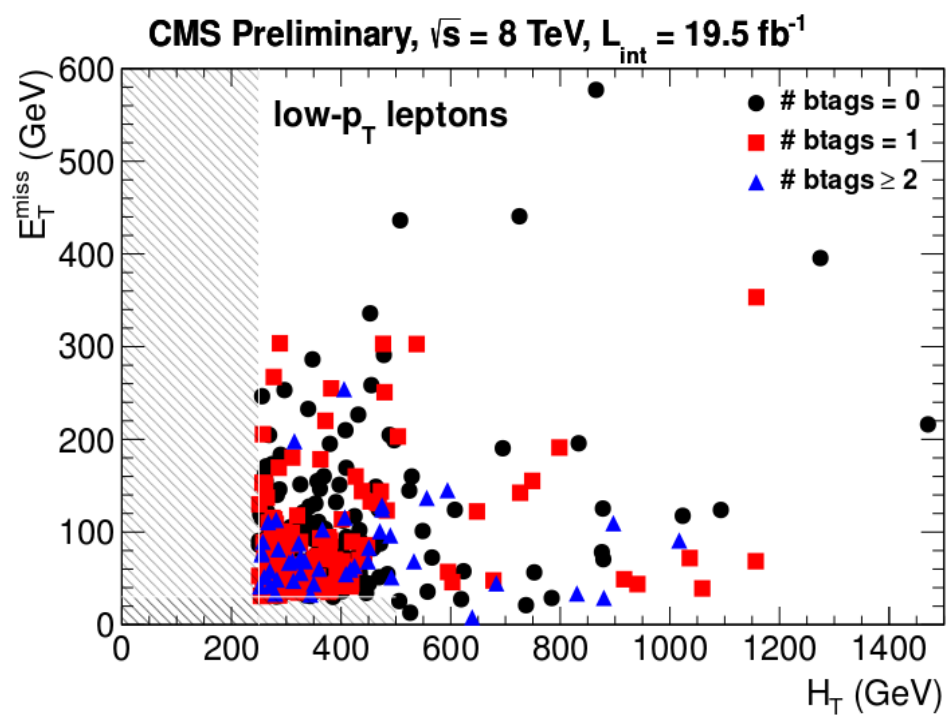
- Isolated same sign dileptons (SS) are very rare in the SM
- Several search regions with lepton flavors (e, μ) are studied
- A natural SUSY signature
  - we select two same-sign light leptons
    - -> veto events with a third lepton forming an OSSF within 15 GeV of the Z
    - -> veto events with a third lepton forming an OSSF pair with m_{ll} < 12 GeV
    - -> veto events with m_{ll} < 8 GeV (trigger)

  high-p_T analysis: 20/20 GeV

  low-p_T analysis: 10/10 GeV







Same sign dileptons – Signal regions

- 24 exclusive signal regions for high-, and low-p_T analyses
  - -> 2*N_{jets} x 2*H_T x 2*ME_T x 3*N_{btags} = 24 exclusive SRs
  - -> minimum H_T at 250 GeV for the low-p_T analysis (trigger)

Signal regions

To cover wide range of SUSY/NP scenarios

$N_{\text{b-jets}}$	E_T^{miss} (GeV)	N_{jets}	$H_T \in [200, 400]$ (GeV)	$H_T > 400$ (GeV)
$= 0$	50-120	2-3	SR01	SR02
		≥ 4	SR03	SR04
	> 120	2-3	SR05	SR06
		≥ 4	SR07	SR08
$= 1$	50-120	2-3	SR11	SR12
		≥ 4	SR13	SR14
	> 120	2-3	SR15	SR16
		≥ 4	SR17	SR18
≥ 2	50-120	2-3	SR21	SR22
		≥ 4	SR23	SR24
	> 120	2-3	SR25	SR26
		≥ 4	SR27	SR28

Special Signal regions

- For RPV SUSY
- SS top prod.

N_{jets}	$N_{\text{b-jets}}$	E_T^{miss} (GeV)	H_T (GeV)	charge	SR
≥ 2	≥ 0	> 0	> 500	$++/--$	RPV0
≥ 2	≥ 2	> 0	> 500	$++/--$	RPV2
≥ 2	$= 1$	> 30	> 80	$++/--$	SStop1
≥ 2	$= 1$	> 30	> 80	$++$ only	SStop1++
≥ 2	≥ 2	> 30	> 80	$++/--$	SStop2
≥ 2	≥ 2	> 30	> 80	$++$ only	SStop2++

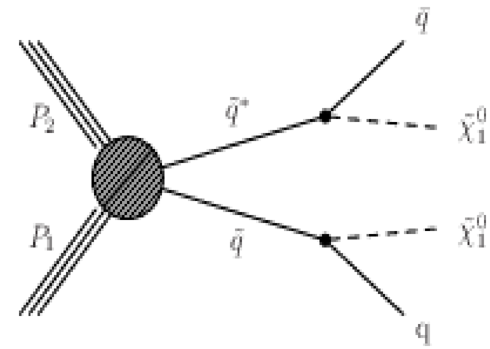
Inclusive search for 1st and 2nd generation squarks

Simplified models captures bulk of characteristics of real models

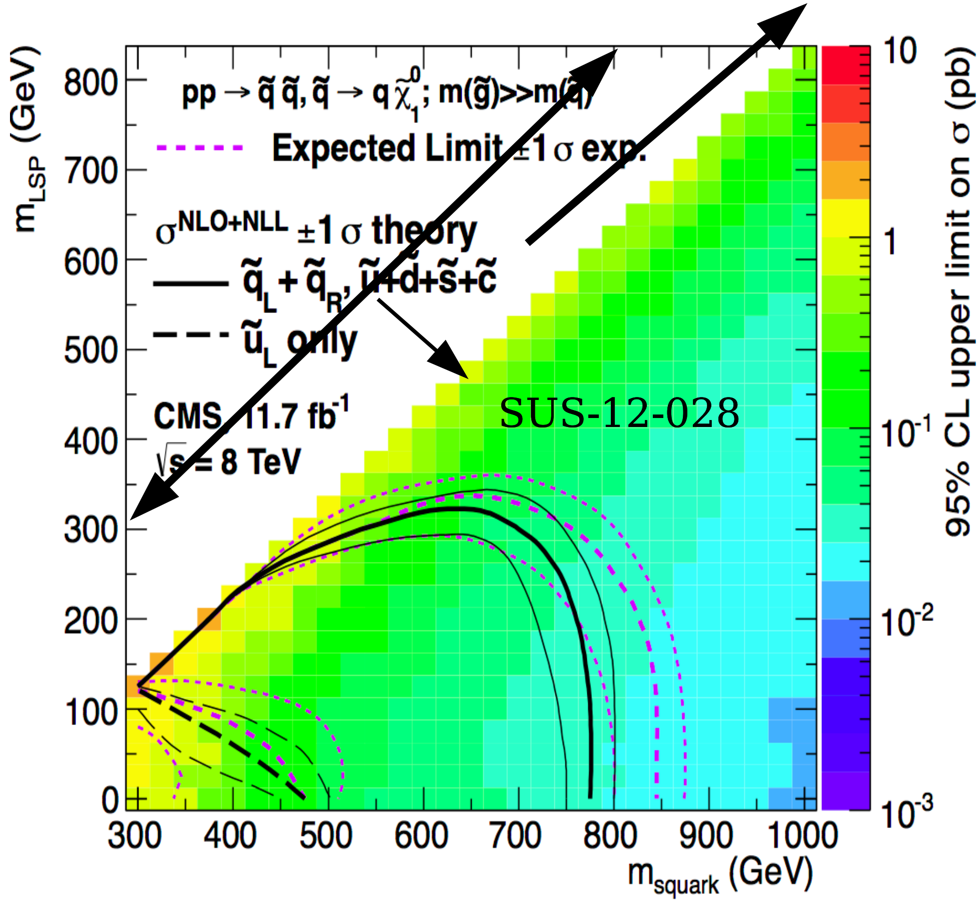
Assume 100% BR in both legs.

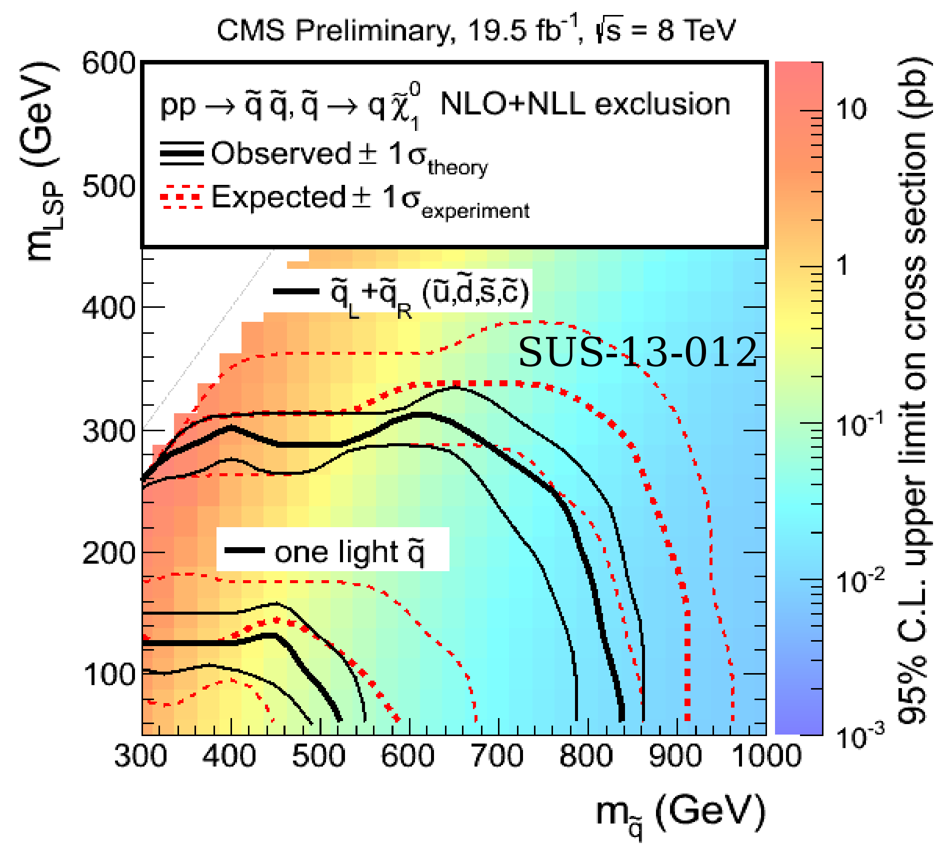
Normalize using SUSY NLO+NLL cross sections

Clean representation of potential (Not sure about the theory)



"Remember the gaps"

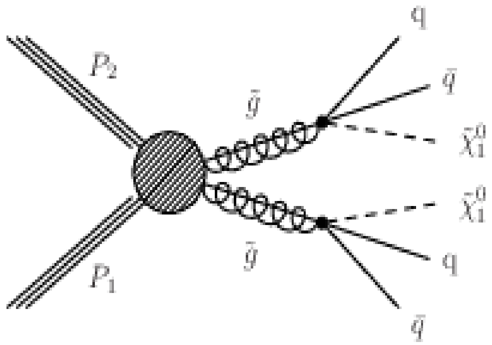


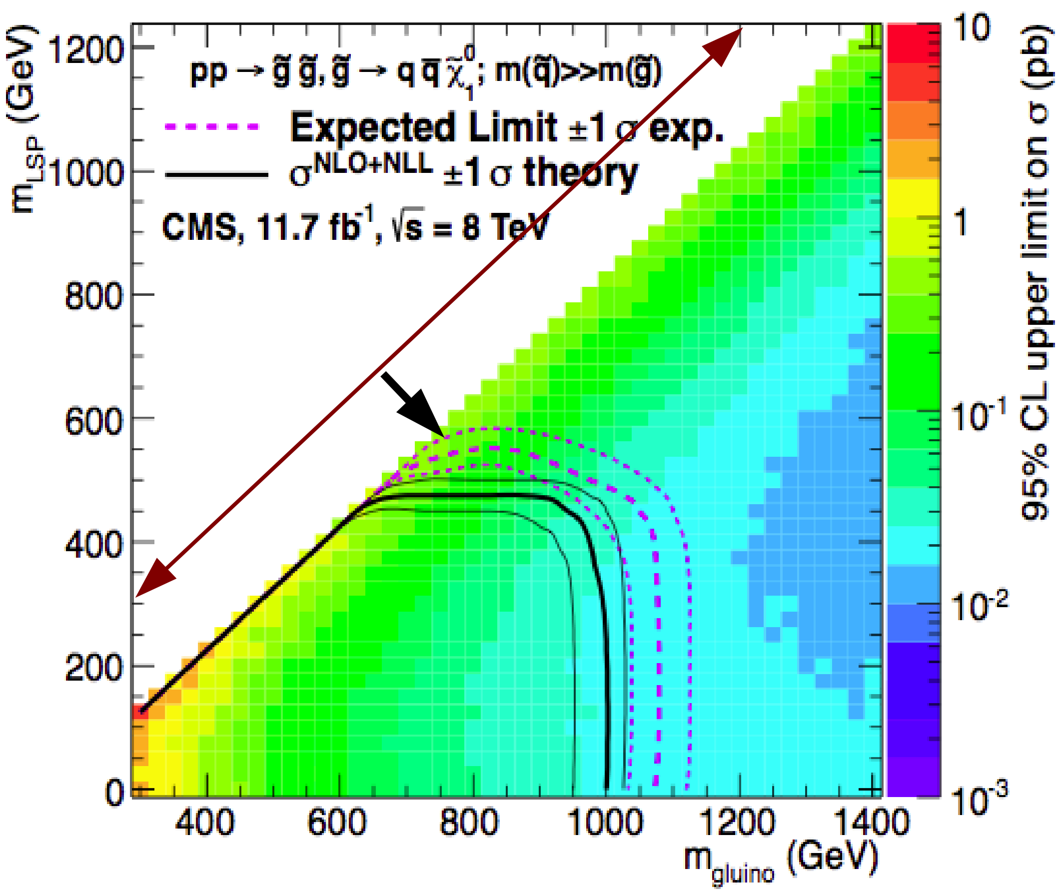


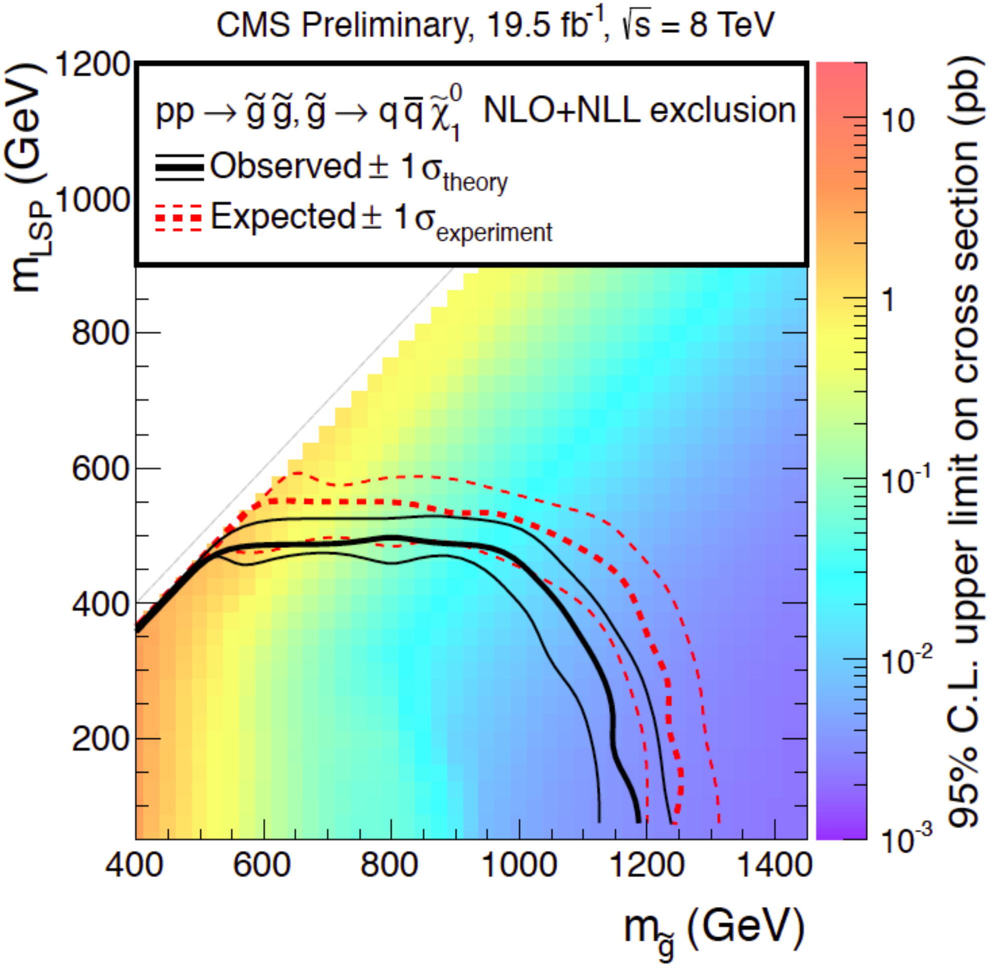
Inclusive search for gluinos cascade decays (via squarks)

Hadronic searches probes:

- Gluino masses up to 1.2 TeV
- "Compressed regions" better covered
  - in inclusive Jet/MET study





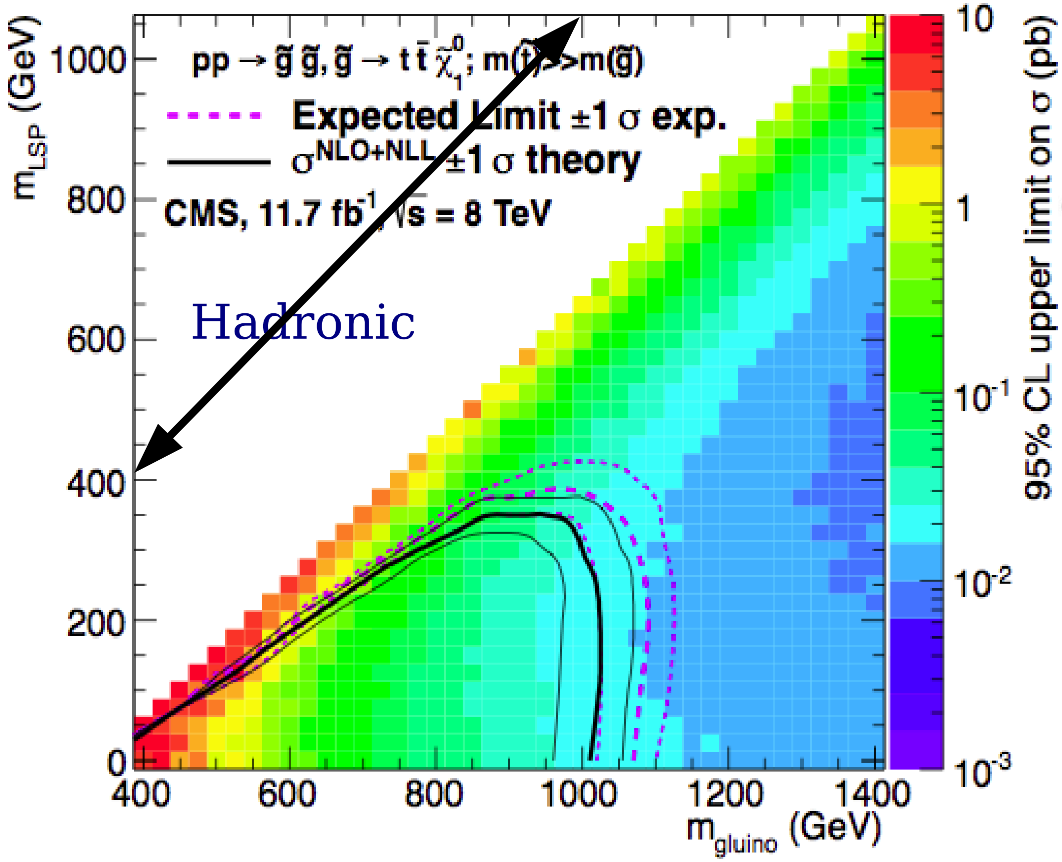


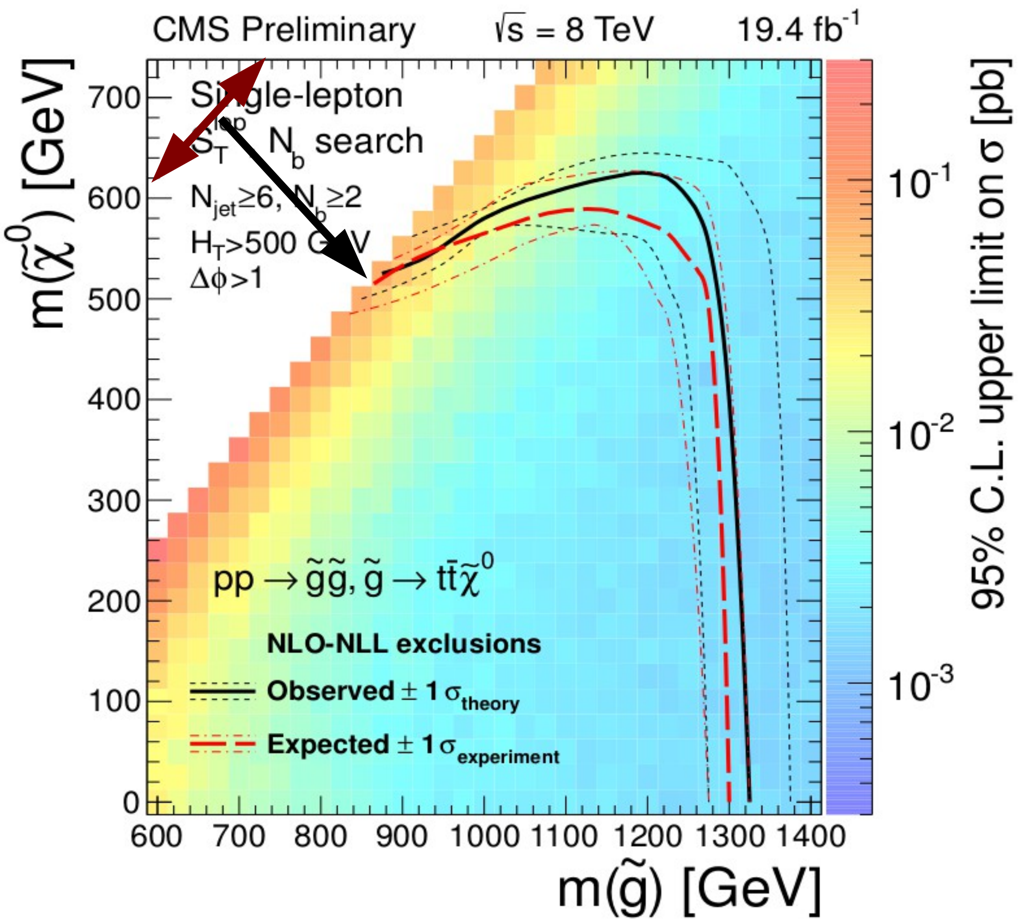
Inclusive search for gluinos cascade decays (via stops)

Gluino via stops:

- Gluino masses up to 1.3 TeV using One lepton analysis

- A large “compressed” region available for future studies



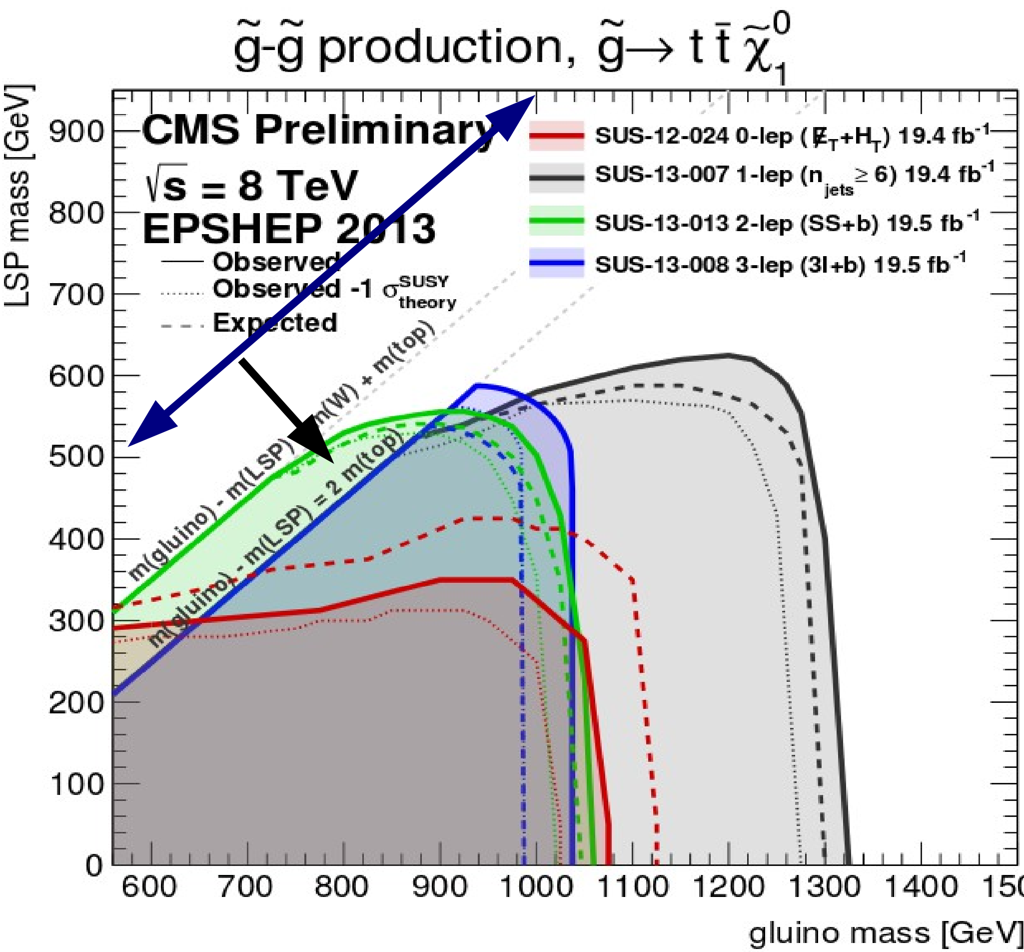


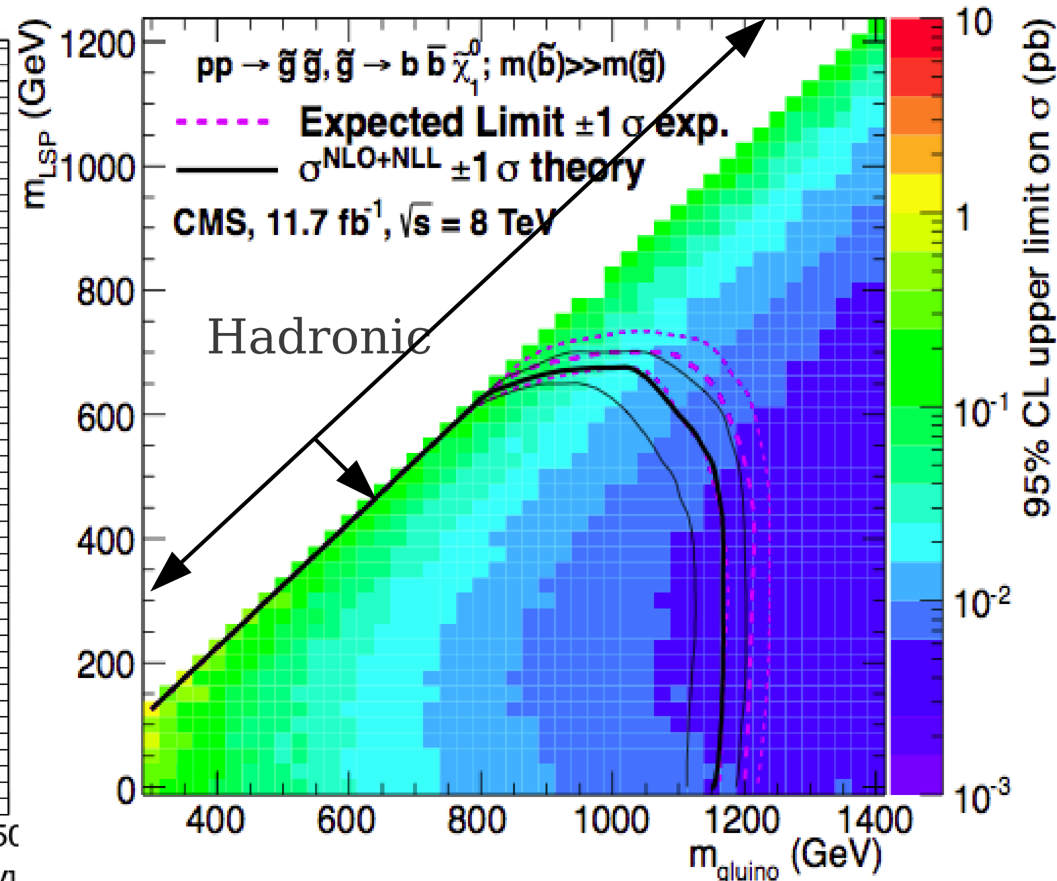
Inclusive search for gluinos cascade decays (via stops and sbottoms)

Gluino via stops or sbottoms:

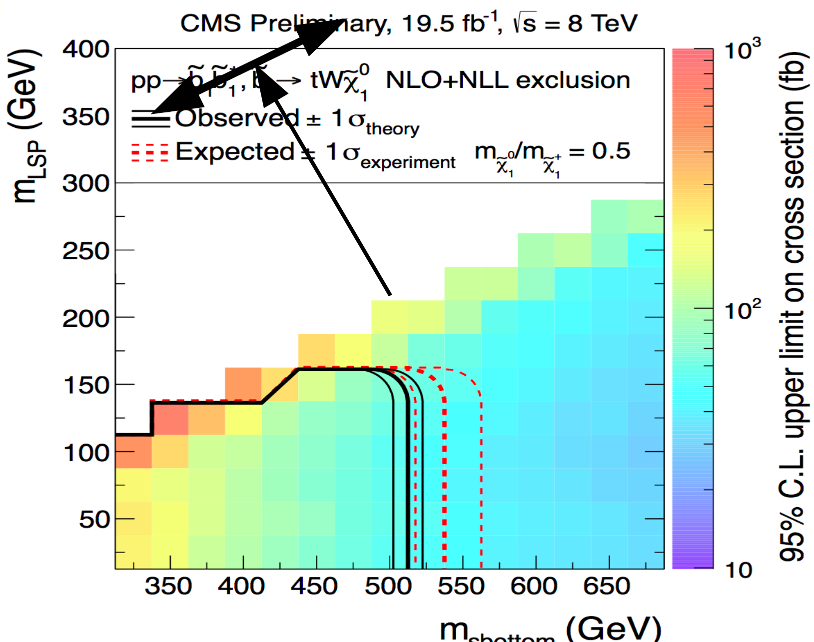
- Gluino masses up to 1.32 TeV using One lepton analysis

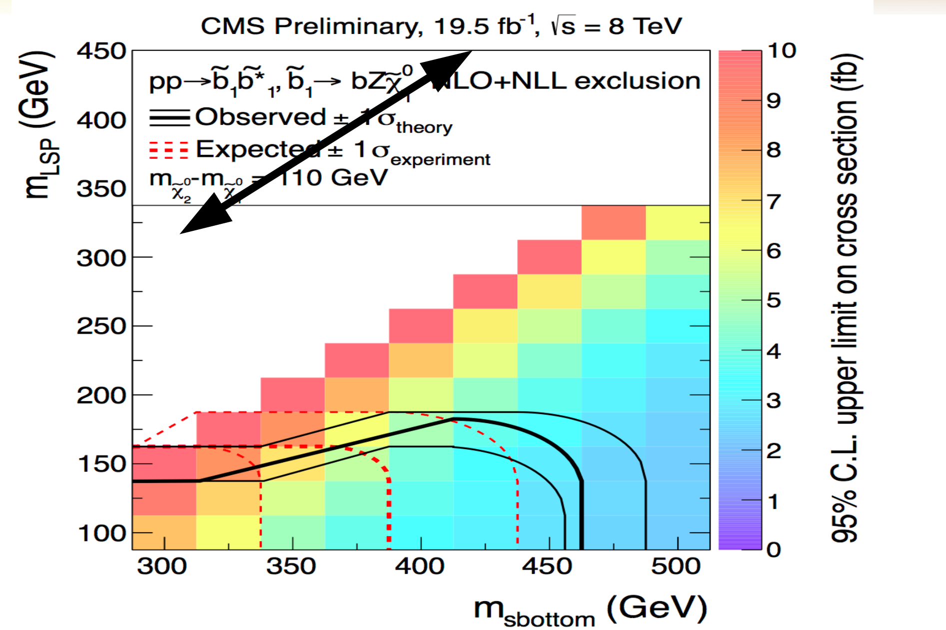
- A large “compressed” region available for future studies



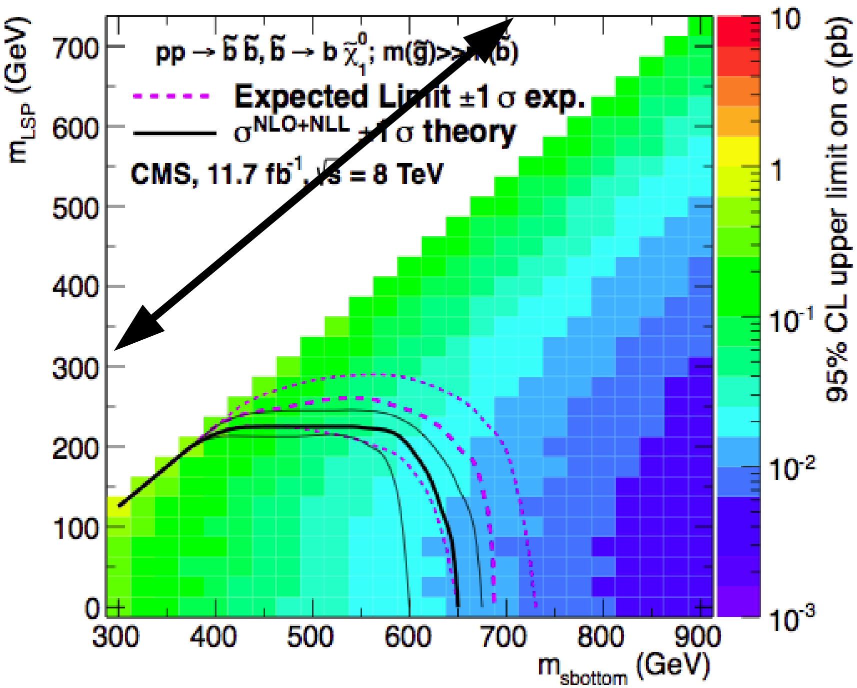


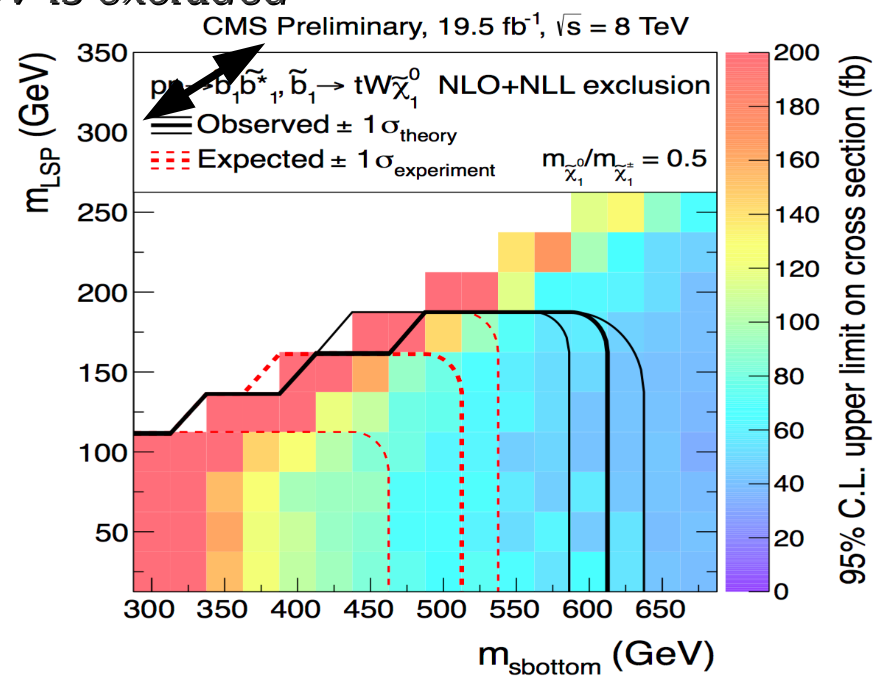
Direct sbottom pair production





Sbottom mass up to 650 GeV is excluded

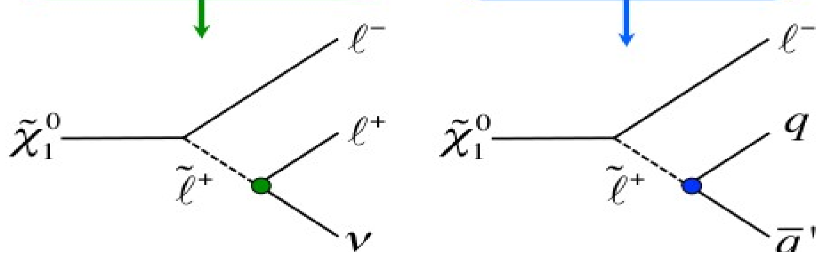




RPV Studies and Interpretations

"leptonic RPV" "semi-leptonic RPV"

$$\Delta L_{RPV} = \frac{1}{2}\lambda^{ijk} L_i L_j \bar{e}_k + \lambda'^{ijk} L_i Q_j \bar{d}_k + \ldots$$



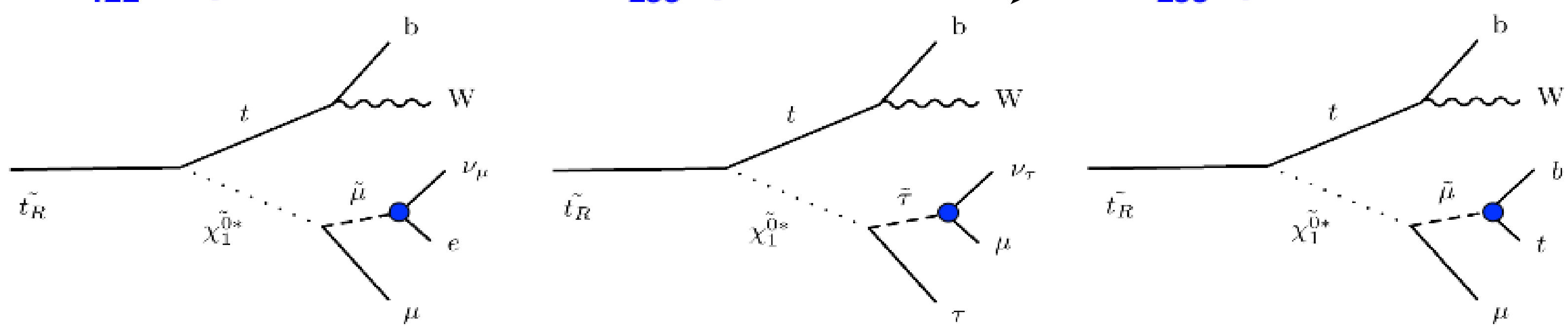
Lepton enriched final states

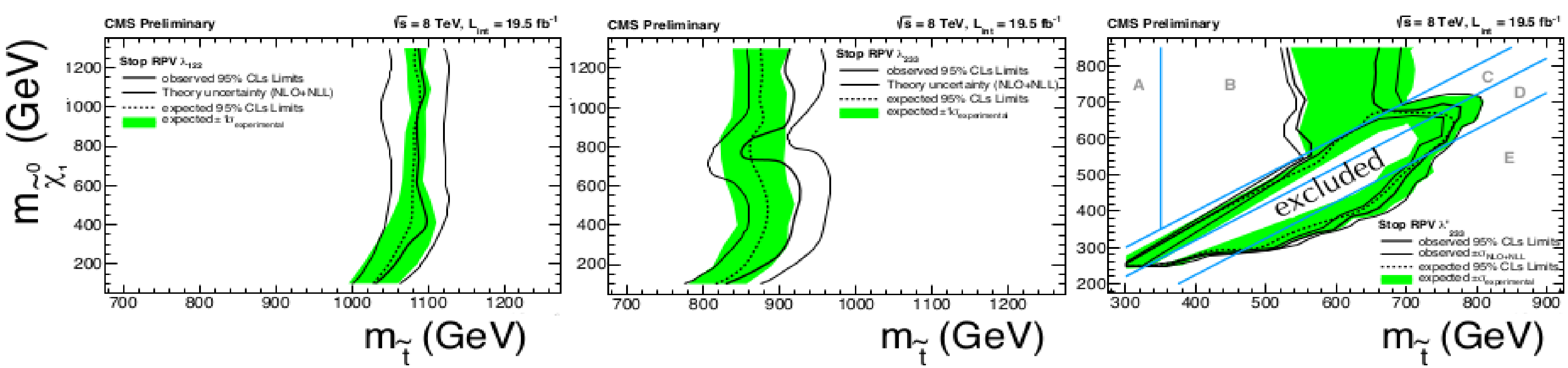
(With no MET)

leptonic RPV
λ_{122}: e,μ-enriched

leptonic RPV
λ_{233}: μ,τ-enriched

semi-leptonic RPV
λ'_{233}: μ,b,t-enriched

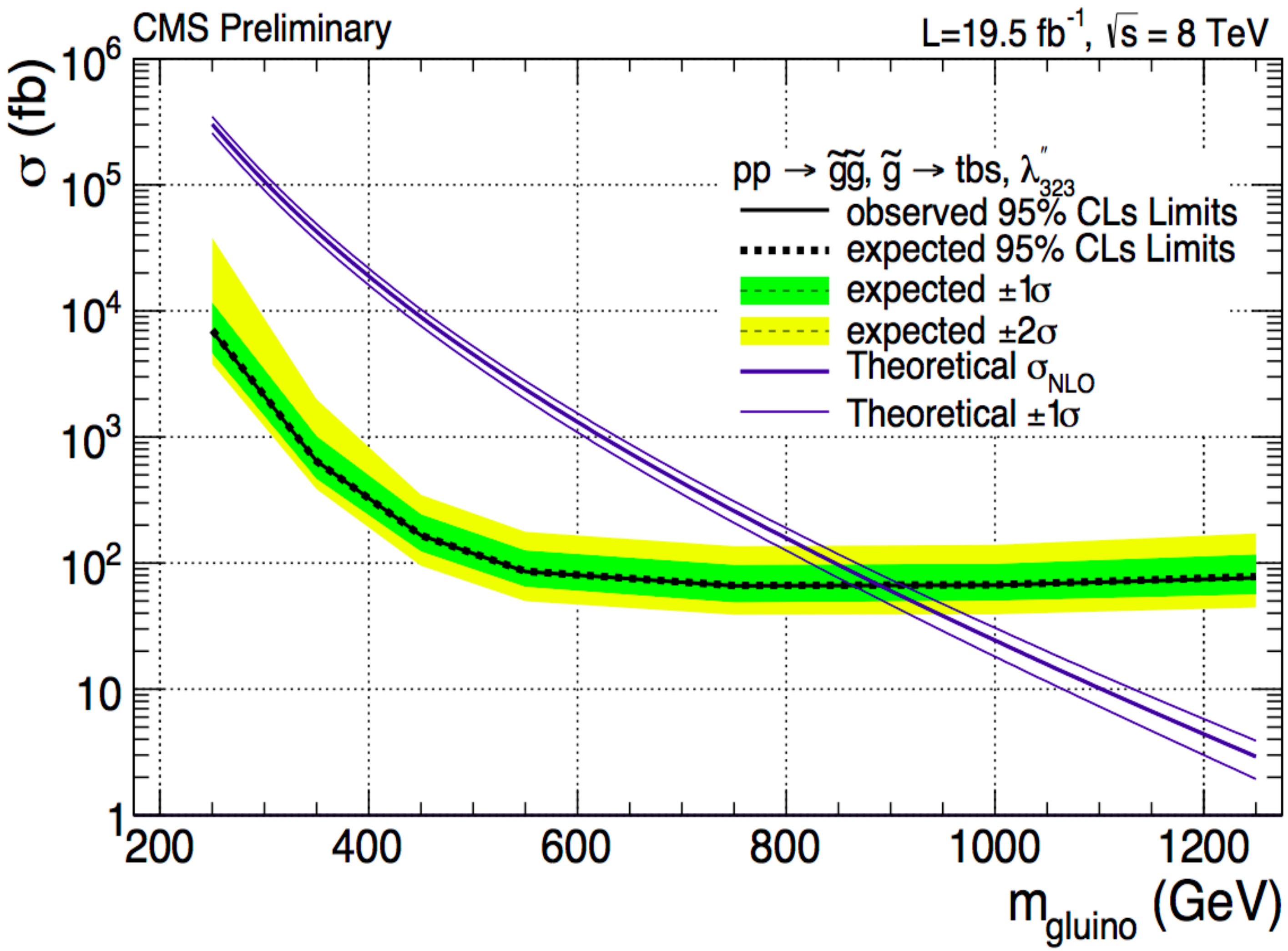




Probes stops in RPV mode up to 1.1 TeV

RPV Studies and Interpretations

Same sign dilepton study can also constrain RPV gluino decays



Gluino mass up to 950 GeV can be excluded

RPV Studies and Interpretations