



# SUSY: Expectations for Run 2, HL-LHC, VLHC

**Loukas Gouskos**

University of California, Santa Barbara

on behalf of the ATLAS and CMS collaborations

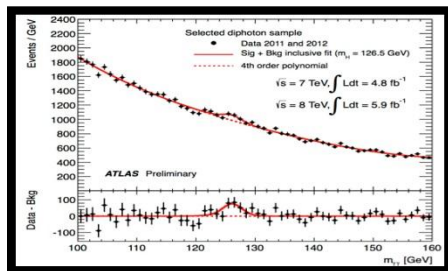
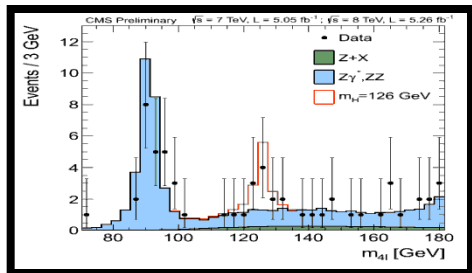
## ■ **Outline:**

- ◆ Introduction
- ◆ The search for SUSY at the LHC: Run 2 to the HL-LHC
- ◆ SUSY expectations with a 100 TeV hadron collider
- ◆ Summary



# Introduction

- Discovery of a BEH scalar @ ~125 GeV completes SM

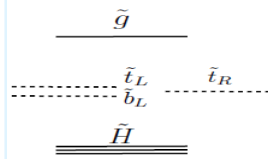


July 4, 2012

- Still many open questions
- SUPerSYmmetry; very appealing extension:

## Hierarchy problem

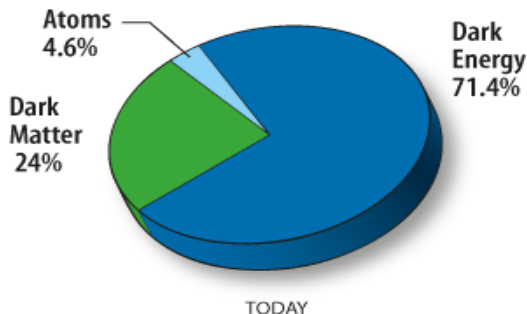
Papucci et al.  
hep-ph 1110.6926



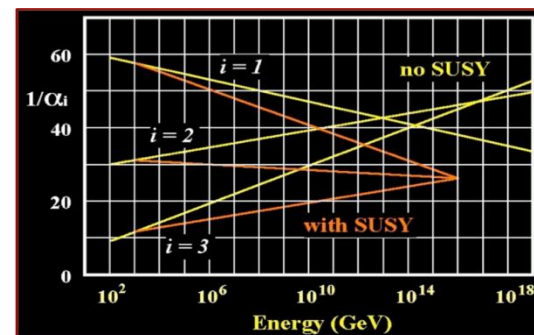
~ TeV

decoupled SUSY

## Dark Matter



## Unification



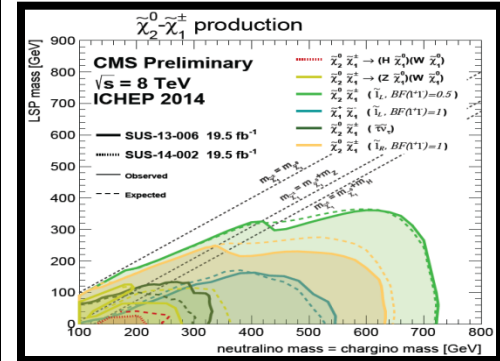
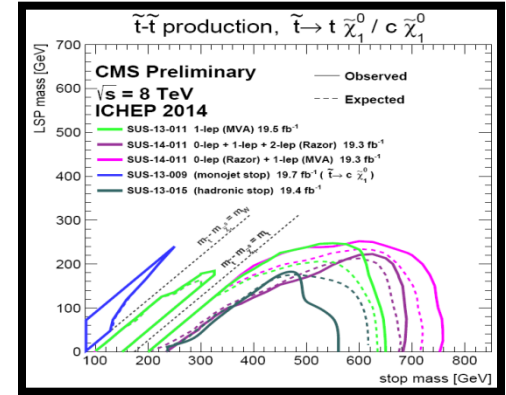


# Introduction (2)



- ... but SUSY not “just around the corner”

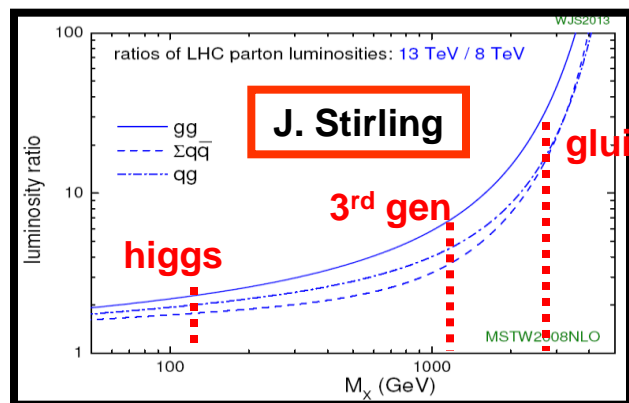
ATLAS SUSY Searches* - 95% CL Lower Limits									
Status: ICHEP 2014									
Model	$\epsilon, \mu, \tau, \gamma$	Jets	$E_{\text{miss}}^{\text{sig}}$	$[L d\Gamma(\text{fb}^{-1})]$	Mass limit				
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{g}, \tilde{u}$	1.7 TeV	$m(\tilde{g})=m(\tilde{u})$	1405.7875
	MSUGRA/CMSSM	1 $\epsilon, \mu$	3-6 jets	Yes	20.3	$\tilde{g}, \tilde{u}$	1.2 TeV	any $m(\tilde{g})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{g}, \tilde{u}$	850 GeV	$m(\tilde{g})=0 \text{ GeV}, m(\tilde{u})=m(2^{\text{nd}} \text{ gen. } \tilde{q})$	1308.1841
	$\tilde{g}\tilde{g}, \tilde{q}\tilde{q} \rightarrow \tilde{g}\tilde{g}$	0	2-6 jets	Yes	20.3	$\tilde{g}, \tilde{u}$	1.1 TeV	any $m(\tilde{g})$	1405.7875
	$\tilde{g}\tilde{g}, \tilde{q}\tilde{q} \rightarrow \tilde{g}\tilde{g}$	1 $\epsilon, \mu$	3-6 jets	Yes	20.3	$\tilde{g}, \tilde{u}$	1.33 TeV	$m(\tilde{g})=0 \text{ GeV}, m(\tilde{u})=0.5(m(\tilde{g})+m(\tilde{q}))$	1405.7875
	$\tilde{g}\tilde{g}, \tilde{q}\tilde{q} \rightarrow \tilde{g}\tilde{g}$	2 $\epsilon, \mu$	0-3 jets	-	20.3	$\tilde{g}, \tilde{u}$	1.10 TeV	$m(\tilde{g})=0 \text{ GeV}, m(\tilde{u})=0.5(m(\tilde{g})+m(\tilde{q}))$	ATLAS-CONF-2013-062
	GMSB (if NLSP)	2 $\epsilon, \mu$	2-4 jets	Yes	4.7	$\tilde{g}, \tilde{u}$	1.12 TeV	$m(\tilde{g})=0 \text{ GeV}, m(\tilde{u})=0.5(m(\tilde{g})+m(\tilde{q}))$	ATLAS-CONF-2013-089
	GMSB (if NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	20.3	$\tilde{g}, \tilde{u}$	1.24 TeV	$\tan\beta > 20$	1407.0603
	GGM (bino NLSP)	2 $\gamma$	-	Yes	20.3	$\tilde{g}, \tilde{u}$	1.28 TeV	$m(\tilde{g})=50 \text{ GeV}, m(\tilde{u})=50 \text{ GeV}$	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $\ell, \mu + \gamma$	-	Yes	4.8	$\tilde{g}, \tilde{u}$	900 GeV	$m(\tilde{g})=200 \text{ GeV}, m(\tilde{u})=200 \text{ GeV}$	ATLAS-CONF-2012-144
3 $\gamma$ gen. squarks direct production	GGM (higgsino-bino NLSP)	1 $b$	Yes	4.8	619 GeV	$\tilde{g}, \tilde{u}$	1.28 TeV	$m(\tilde{g})=200 \text{ GeV}, m(\tilde{u})=200 \text{ GeV}$	1211.1167
	GGM (higgsino NLSP)	2 $\epsilon, \mu$ (Z)	0-3 jets	Yes	5.8	$\tilde{g}, \tilde{u}$	690 GeV	$m(\tilde{g})=200 \text{ GeV}, m(\tilde{u})=200 \text{ GeV}$	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$\tilde{g}, \tilde{u}$	645 GeV	$m(\tilde{g})=10^{14} \text{ eV}$	ATLAS-CONF-2012-147
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	0	3 $b$	Yes	20.1	$\tilde{g}, \tilde{u}$	1.25 TeV	$m(\tilde{g})=400 \text{ GeV}, m(\tilde{u})=400 \text{ GeV}$	1407.0600
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	0-1 $\epsilon, \mu$	3 $b$	Yes	20.1	$\tilde{g}, \tilde{u}$	1.1 TeV	$m(\tilde{g})=350 \text{ GeV}, m(\tilde{u})=350 \text{ GeV}$	1308.1841
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	0-1 $\epsilon, \mu$	3 $b$	Yes	20.1	$\tilde{g}, \tilde{u}$	1.34 TeV	$m(\tilde{g})=400 \text{ GeV}, m(\tilde{u})=400 \text{ GeV}$	1407.0600
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	0-1 $\epsilon, \mu$	3 $b$	Yes	20.1	$\tilde{g}, \tilde{u}$	1.3 TeV	$m(\tilde{g})=300 \text{ GeV}, m(\tilde{u})=300 \text{ GeV}$	1407.0600
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	0	2 $b$	Yes	20.1	$\tilde{g}, \tilde{u}$	100-620 GeV	$m(\tilde{g})=90 \text{ GeV}, m(\tilde{u})=90 \text{ GeV}$	1308.2631
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	2 $\epsilon, \mu$ (SS)	0-3 $b$	Yes	20.3	$\tilde{g}, \tilde{u}$	275-440 GeV	$m(\tilde{g})=2 \text{ GeV}, m(\tilde{u})=2 \text{ GeV}$	1404.2500
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	1-2 $\epsilon, \mu$	1-2 $b$	Yes	4.7	$\tilde{g}, \tilde{u}$	110-167 GeV	$m(\tilde{g})=55 \text{ GeV}, m(\tilde{u})=55 \text{ GeV}$	1208.4305, 1209.2102
3 $\gamma$ gen. squarks indirect production	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	2 $\epsilon, \mu$	0-2 jets	Yes	20.3	$\tilde{g}, \tilde{u}$	130-210 GeV	$m(\tilde{g})=m(\tilde{u})=m(W)-50 \text{ GeV}, m(\tilde{g}) < m(\tilde{u})$	1403.4853
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	2 $\epsilon, \mu$	1-2 jets	Yes	20.3	$\tilde{g}, \tilde{u}$	215-530 GeV	$m(\tilde{g})=1 \text{ GeV}, m(\tilde{u})=1 \text{ GeV}$	1403.4853
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	2 $\epsilon, \mu$	2 jets	Yes	20.3	$\tilde{g}, \tilde{u}$	150-580 GeV	$m(\tilde{g})=200 \text{ GeV}, m(\tilde{u})=200 \text{ GeV}$	1308.2631
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	1 $\epsilon, \mu$	1 $b$	Yes	20.1	$\tilde{g}, \tilde{u}$	210-640 GeV	$m(\tilde{g})=0 \text{ GeV}, m(\tilde{u})=0 \text{ GeV}$	1407.0583
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	1 $\epsilon, \mu$	2 jets	Yes	20.1	$\tilde{g}, \tilde{u}$	260-640 GeV	$m(\tilde{g})=0 \text{ GeV}, m(\tilde{u})=0 \text{ GeV}$	1408.1122
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	0	mono-jet	Yes	20.3	$\tilde{g}, \tilde{u}$	90-240 GeV	$m(\tilde{g})=m(\tilde{u})=85 \text{ GeV}$	1407.0608
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	2 $\epsilon, \mu$ (Z)	1 $b$	Yes	20.3	$\tilde{g}, \tilde{u}$	150-580 GeV	$m(\tilde{g})=150 \text{ GeV}, m(\tilde{u})=150 \text{ GeV}$	1403.5222
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	3 $\epsilon, \mu$ (Z)	1 $b$	Yes	20.3	$\tilde{g}, \tilde{u}$	290-690 GeV	$m(\tilde{g})=200 \text{ GeV}, m(\tilde{u})=200 \text{ GeV}$	1403.5222
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	2 $\epsilon, \mu$	0	Yes	20.3	$\tilde{g}, \tilde{u}$	90-325 GeV	$m(\tilde{g})=0 \text{ GeV}, m(\tilde{u})=0.5(m(\tilde{g})+m(\tilde{u}))$	1403.5294
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	2 $\epsilon, \mu$	0	Yes	20.3	$\tilde{g}, \tilde{u}$	140-465 GeV	$m(\tilde{g})=0 \text{ GeV}, m(\tilde{u})=0.5(m(\tilde{g})+m(\tilde{u}))$	1403.5294
EW direct	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	2 $\tau$	-	Yes	20.3	$\tilde{g}, \tilde{u}$	100-350 GeV	$m(\tilde{g})=0 \text{ GeV}, m(\tilde{u})=0.5(m(\tilde{g})+m(\tilde{u}))$	1407.0350
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	2 $\tau$	-	Yes	20.3	$\tilde{g}, \tilde{u}$	420 GeV	$m(\tilde{g})=0 \text{ GeV}, m(\tilde{u})=0.5(m(\tilde{g})+m(\tilde{u}))$	1402.7029
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	2-3 $\epsilon, \mu$	0	Yes	20.3	$\tilde{g}, \tilde{u}$	285 GeV	$m(\tilde{g})=m(\tilde{u})=0, m(\tilde{g})=0, \text{ sleptons decoupled}$	1403.5294, 1402.7029
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	1 $\epsilon, \mu$	2 $b$	Yes	20.3	$\tilde{g}, \tilde{u}$	620 GeV	$m(\tilde{g})=m(\tilde{u})=0, m(\tilde{g})=0, \text{ sleptons decoupled}$	ATLAS-CONF-2013-093
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	0	4 $\epsilon, \mu$	Yes	20.3	$\tilde{g}, \tilde{u}$	270 GeV	$m(\tilde{g})=m(\tilde{u})=0, m(\tilde{g})=0.5(m(\tilde{g})+m(\tilde{u}))$	1405.5086
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	1 $\ell$	Yes	20.3	1.5	$\tilde{g}, \tilde{u}$	475 GeV	$m(\tilde{g})=m(\tilde{u})=180 \text{ MeV}, m(\tilde{g})=0.2 \text{ ns}$	ATLAS-CONF-2013-069
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	1-5 jets	-	Yes	27.9	$\tilde{g}, \tilde{u}$	632 GeV	$m(\tilde{g})=100 \text{ GeV}, 10 \mu\text{m} < \text{BR}(\tilde{g}) < 1000 \text{ s}$	1210.6984
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	1-2 $\mu$	-	Yes	15.9	$\tilde{g}, \tilde{u}$	230 GeV	$10 < \tan\beta < 50$	ATLAS-CONF-2013-058
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	1 $\mu$ displ. vtx	-	Yes	4.7	$\tilde{g}, \tilde{u}$	1.0 TeV	$0.4 < \tau(\tilde{g}) < 2 \text{ ns}$	1304.6310
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	1 $\mu$ displ. vtx	-	Yes	20.3	$\tilde{g}, \tilde{u}$	1.61 TeV	$1.5 < \tau < 156 \text{ ns}, \text{BR}(\tilde{g})=1, m(\tilde{g})=108 \text{ GeV}$	ATLAS-CONF-2013-092
Long-lived particles	Direct $\tilde{g}\tilde{g}$ prod. long-lived $\tilde{g}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{g}, \tilde{u}$	1.1 TeV	$J_{\text{EW}}=0.10, J_{\text{H}}=0.05$	1212.1272
	Stable, stopped $\tilde{g}$ hadron	1-2 $\mu$	-	Yes	20.3	$\tilde{g}, \tilde{u}$	750 GeV	$m(\tilde{g})=m(\tilde{u}), \tau_{\text{had}} < 1 \text{ mm}$	1212.1272
	GMSB, stable $\tilde{g}$ , $\tilde{g} \rightarrow \tilde{g} + \tilde{g}$	1-2 $\mu$	-	Yes	20.3	$\tilde{g}, \tilde{u}$	450 GeV	$m(\tilde{g})=0.2 m(\tilde{g}), J_{\text{EW}}=0, J_{\text{H}}=0$	1404.2500
	GMSB, $\tilde{g} \rightarrow \tilde{g} + \tilde{g}$ , long-lived $\tilde{g}$	2 $\gamma$	-	Yes	20.3	$\tilde{g}, \tilde{u}$	916 GeV	$m(\tilde{g})=0.2 m(\tilde{g}), J_{\text{EW}}=0, J_{\text{H}}=0$	1405.5086
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	1 $\mu$ displ. vtx	-	Yes	20.3	$\tilde{g}, \tilde{u}$	850 GeV	$\text{BR}(\tilde{g})=\text{BR}(\tilde{u})=0.5$	1405.5086
	LFV $pp \rightarrow \tilde{g}\tilde{g} + X, \tilde{g}\tilde{g} \rightarrow e\mu + \tau$	2 $\epsilon, \mu + \tau$	-	Yes	4.6	$\tilde{g}, \tilde{u}$	1.35 TeV	$\text{BR}(\tilde{g})=\text{BR}(\tilde{u})=0.5$	ATLAS-CONF-2013-091
	Bilinear RPV CMSSM	2 $\epsilon, \mu$ (SS)	0-3 $b$	Yes	20.3	$\tilde{g}, \tilde{u}$	750 GeV	$\text{BR}(\tilde{g})=\text{BR}(\tilde{u})=0.5$	1404.2500
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	2 $\epsilon, \mu$	0	Yes	20.3	$\tilde{g}, \tilde{u}$	450 GeV	$m(\tilde{g})=0.2 m(\tilde{g}), J_{\text{EW}}=0, J_{\text{H}}=0$	1405.5086
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	3 $\epsilon, \mu + \tau$	-	Yes	20.3	$\tilde{g}, \tilde{u}$	916 GeV	$\text{BR}(\tilde{g})=\text{BR}(\tilde{u})=0.5$	ATLAS-CONF-2013-091
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	0	6-7 jets	Yes	20.3	$\tilde{g}, \tilde{u}$	850 GeV	$\text{BR}(\tilde{g})=\text{BR}(\tilde{u})=0.5$	1404.2500
RPV	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	2 $\epsilon, \mu$ (SS)	0-3 $b$	Yes	20.3	$\tilde{g}, \tilde{u}$	750 GeV	$m(\tilde{g})=0.2 m(\tilde{g}), J_{\text{EW}}=0, J_{\text{H}}=0$	1405.5086
	$\tilde{g}\tilde{g} \rightarrow \tilde{g}\tilde{g}$	3 $\epsilon, \mu + \tau$	-	Yes	20.3	$\tilde{g}, \tilde{u}$	916 GeV	$\text{BR}(\tilde{g})=\text{BR}(\tilde{u})=0.5$	ATLAS-CONF-2013-091
Other	Scalar gluon pair, sgluon $\rightarrow \tilde{g}\tilde{g}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon $\rightarrow \tilde{g}\tilde{g}$	2 $\epsilon, \mu$ (SS)	2 $b$	Yes	14.3	sgluon	350-600 GeV	$m(\tilde{g})=80 \text{ GeV}, \text{limit of } 687 \text{ GeV for D8}$	ATLAS-CONF-2013-051
WIMP interaction (D5, Dirac $\chi$ )	Scalar gluon pair, sgluon $\rightarrow \tilde{g}\tilde{g}$	0	mono-jet	Yes	10.5	$\tilde{g}, \tilde{u}$	704 GeV		ATLAS-CONF-2012-147
	WIMP interaction (D5, Dirac $\chi$ )	0	mono-jet	Yes	10.5	$\tilde{g}, \tilde{u}$	704 GeV		ATLAS-CONF-2012-147



- $M[\tilde{g}] > \sim 1.4 \text{ TeV}$
- $M[\tilde{u}, \tilde{d}] > \sim 1.3 (0.6) \text{ TeV}$
- $M[\text{gauginos}] > \sim 0.3-0.7 \text{ TeV}$

NB.  
(a) Assume  $\text{BR} \sim 100\%$   
(b) Probed regions depend strongly on mass parameters [i.e.  $m(\chi^0)$ ]

- **However, many SUSY scenarios remain open**
  - ◆ SUSY at higher mass scales [i.e. not probed @ 7/8 TeV]
    - Benefit from the increase in energy
  - ◆ Low cross section SUSY processes [i.e. EWK production]
    - Benefit from the increase in  $L_{\text{int}}$
  - ◆ Compressed spectra [i.e. small mass dif. between sparticles]
    - SM-like signature: dedicated searched, benefit from E &  $L_{\text{int}}$
- **Access these scenarios [and more] with hadron colliders: LHC@14 TeV [Run2], HL-LHC, V-LHC [100 TeV]**



- ◆ Big [or Huge] gain in production of heavy particles
  - i.e. factor of 30-40 for gluinos ~1.5 TeV
- ◆ SM gains a factor of 2-4
- ◆ With  $\sim 2 \text{ fb}^{-1}$  @13 TeV reach 8 TeV sensitivity
  - New territory reached early in 2015

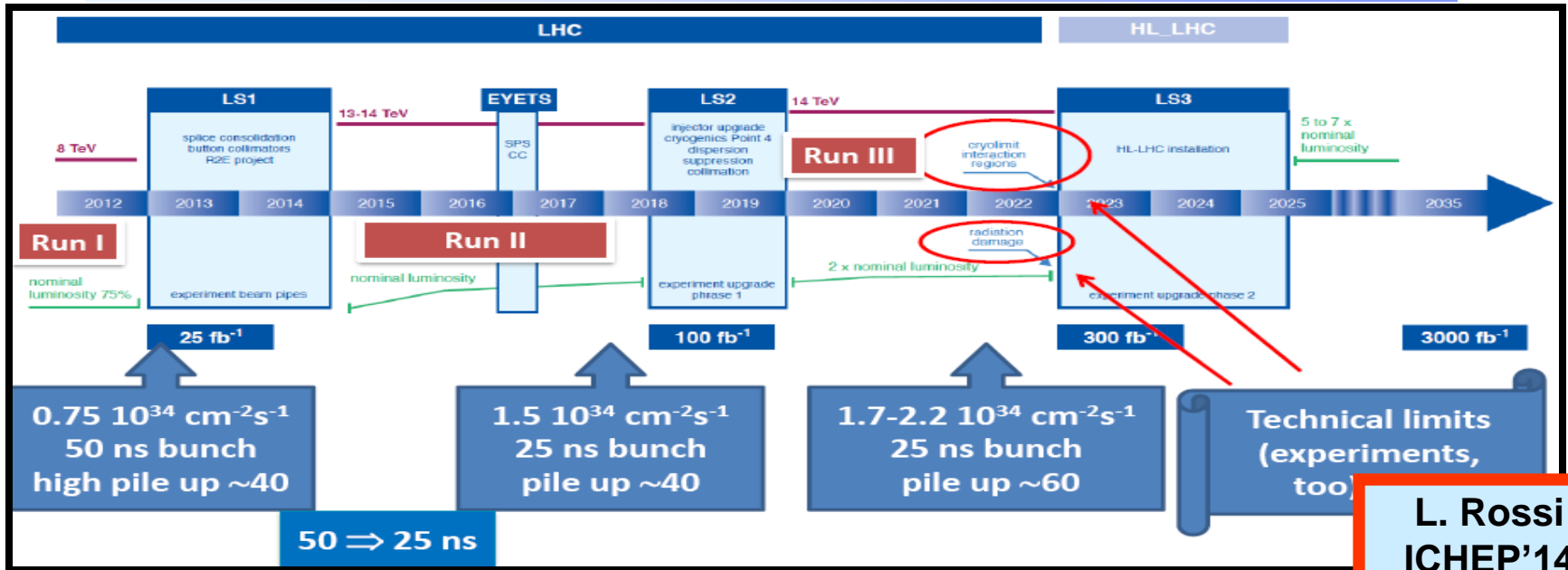


# The search for SUSY at the LHC: Run 2 to the HL-LHC





# LHC & HL-LHC roadmap



- **End of Run 2 [ $\sim 300 \text{ fb}^{-1}$ ]:** some detector subsystems and much of the front-end electronics, trigger, need to be replaced
- **Replacements with improved physics capabilities are in the pipe-line**
  - ◆ details on upgrades from M. Nagel [ATLAS] & D. Abbaneo [CMS]



# Making the case..



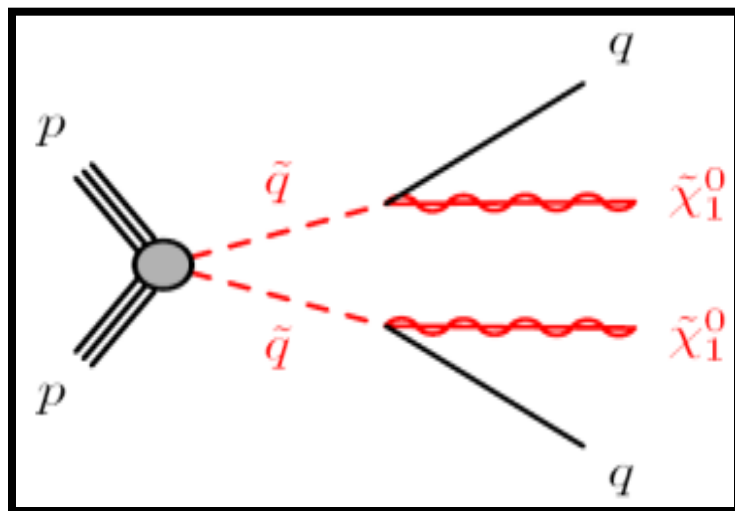
- **Projected results based on 8 TeV searches with optimized selection to account for increased  $E$  and  $L_{\text{int}}$** 
  - ◆ Conservative approach, we will very likely do better
- **Several scenarios for background (BKG) systematics**
- **Realistic [as possible] detector and response based on LHC Run 1 data-taking**
- **Interpretation of results using Simplified Model Spectra [SMS]**
  - ◆ generic description; few free parameters [i.e. sparticle mass, and production x-section]
  - ◆ study specific processes: assume 100% BR for each process
- **Results should be interpreted as indicative of the performance expected; not quite detailed predictions yet (at this early stage)**



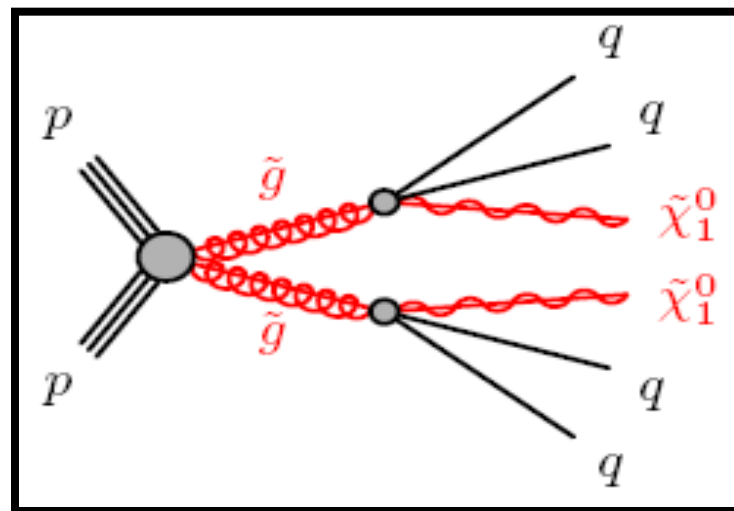
# Strongly produced SUSY [ $\tilde{g} \rightarrow \tilde{q}$ ]

- Early access of new territory in gluino-gluino (gl-gl) & squark-squark (sq-sq) production
- Signature: jets (two to many) & large  $ME_T$ 
  - ◆ 0-lepton final state dominates search for 1<sup>st</sup> and 2<sup>nd</sup> generation squarks

direct squark production



Gluino-mediated squark production

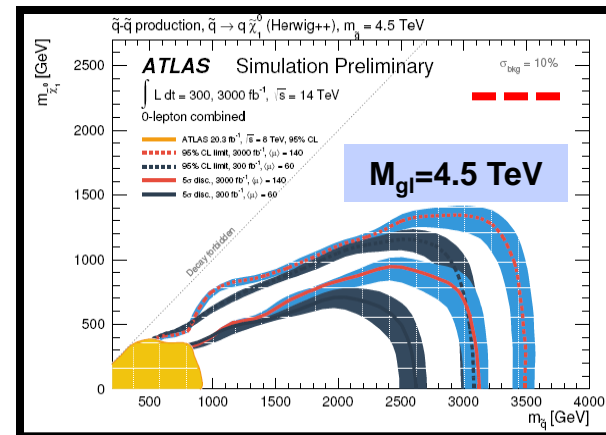
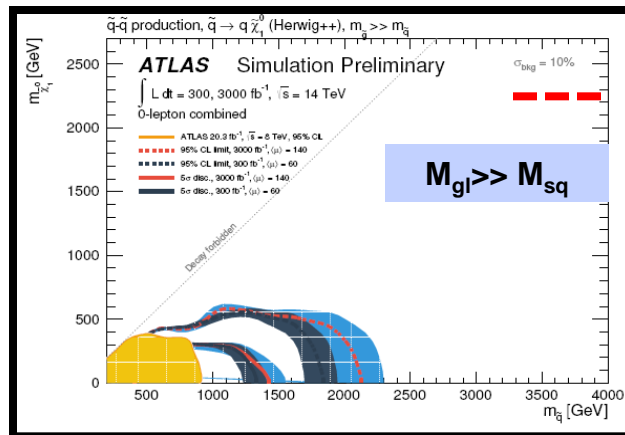
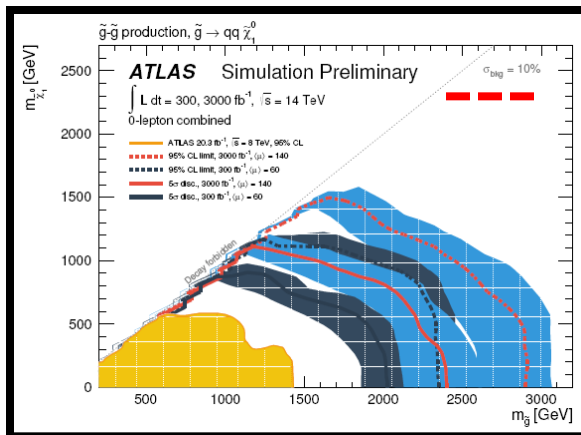




# Strongly produced SUSY [ $\tilde{g} \rightarrow \tilde{q}$ ] (2)



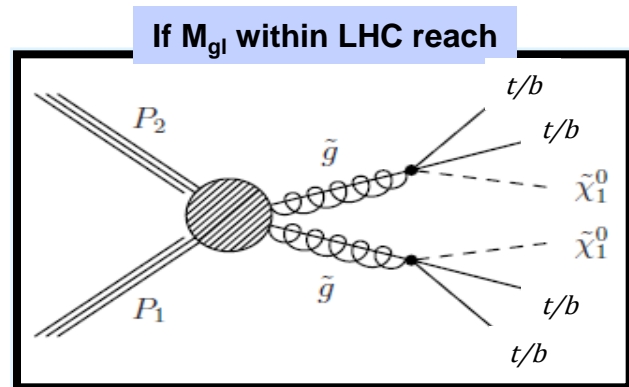
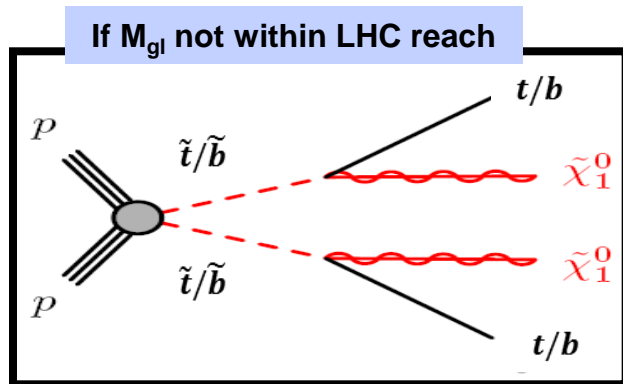
- Search carried out in multiple signal regions based on:
  - $M_{\text{eff}} [= M_{E_T} + \Sigma p_T(\text{jet})]$ ;  $M_{E_T}/M_{\text{eff}}$ ;  $M_{E_T}/(H_T)^{1/2}$



	$M[\text{gl}] (2\sigma/5\sigma) [\text{TeV}]$	$M[\text{sq}] (2\sigma/5\sigma) [\text{TeV}]$	$M[\text{sq}] (2\sigma/5\sigma) [\text{TeV}] (M[\text{gl}]=4.5 \text{ TeV})$
Run 2	2.4 / 2.0	1.4 / 1.9	3.1 / 2.7
HL-LHC	2.8 / 2.4	2.1 / 1.5	3.5 / 3.1

Any hints from new particles in Run 2 become observations at the HL-LHC

- **“Naturalness” requires light [ $\sim$ TeV] stop/sbottoms**
  - ◆ Direct production or gluino-induced production



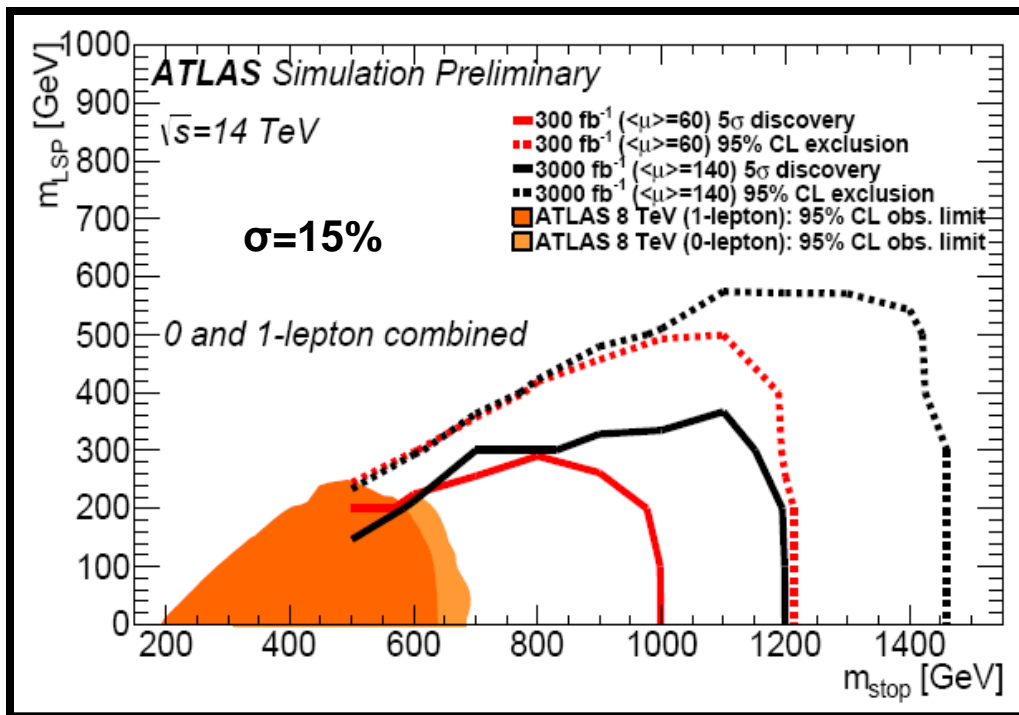
- **Most “Natural” SUSY scenarios predict light 3<sup>rd</sup> gen squarks [ $<1-1.2$  TeV] and gluinos [ $<2$  TeV]**
- **Dedicated searches exploit these scenarios**
  - ◆ 0 & 1 lepton final states in the case of stops, for instance, drive the sensitivity
- ◆ **Results provide important tests of the viability of Natural SUSY**

## 0 & 1 lepton final states for direct-stop production

◆ Search regions based on  $ME_T$ ,  $ME_T/(H_T)^{1/2}$ ,  $M_T[I, ME_T]$

● 0-lep:  $M_T[b, ME_T]$ ,  $N_{jts} \geq 6$ ,  $N_{bjets} \geq 2$

● 1-lep:  $M_T[I, ME_T]$ ,  $N_{jts} \geq 3$ ,  $N_{bjets} \geq 1$



■ Run 2 can set tight limits on direct-stop [Naturalness]

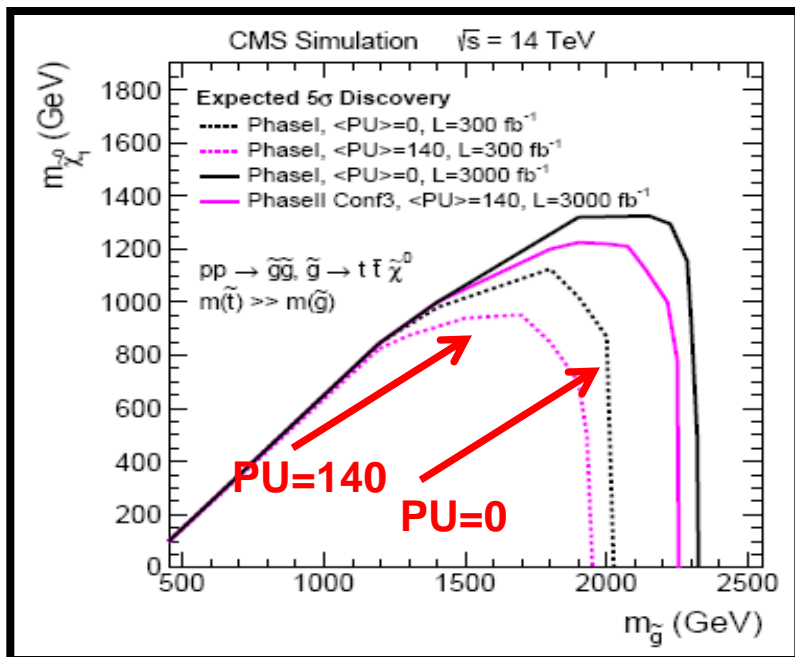
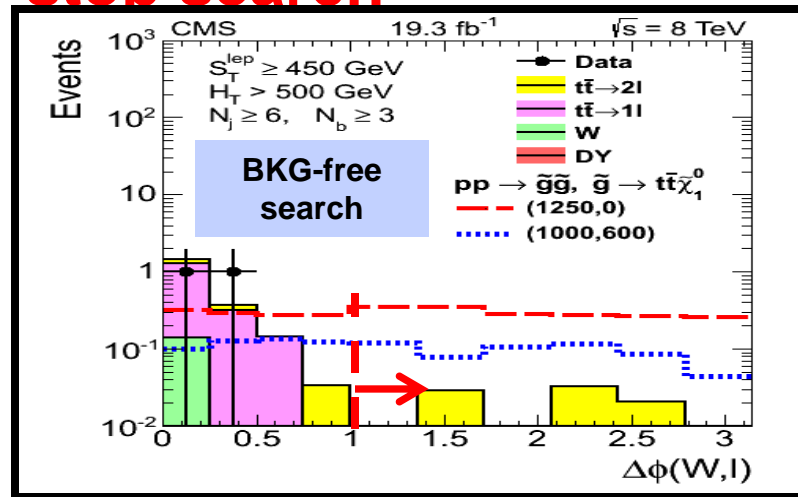
■ Following BEH particle discovery, best motivated region probed with HL-LHC

◆ ~1.2 TeV stops discoverable with HL-LHC

■ HL-LHC powerful for challenging models

## 1 lepton channel important for stop search

- ◆ Gluino-induced stops based on  $S_T^{\text{lep}} = p_T[l] + ME_T$  &  $\Delta\phi(l, W)$
- ◆  $N_{\text{jts}} \geq 6$ ,
- ◆ Multiple SR in:  $N_{\text{bjts}}$  and  $S_T^{\text{lep}}$



- Energy increase significant impact in gluino production
- Run2: probe gluinos  $\rightarrow$  2 TeV
  - ◆ Results important for Natural SUSY
- small gain with HL-LHC  $\sim 0.3$  TeV
  - ◆ But extends reach to more compressed spectra
- Robust search against PU

- Dedicated searched for direct sbottom production

- Search utilizes  $M_{CT}$ :

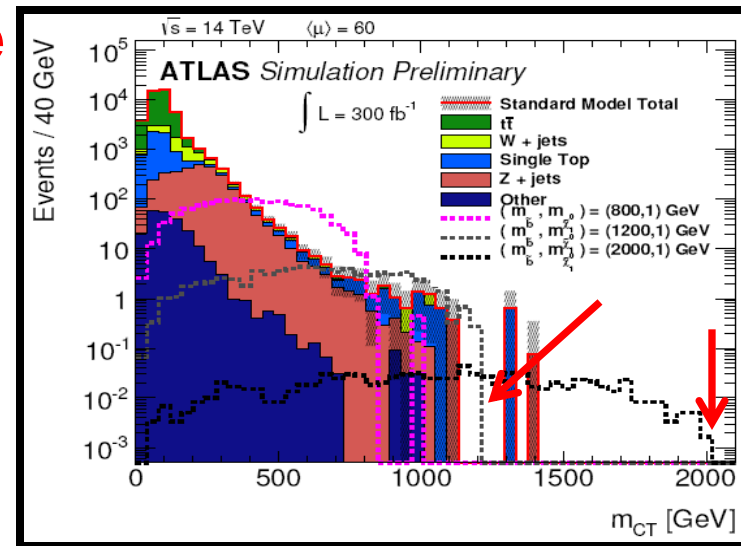
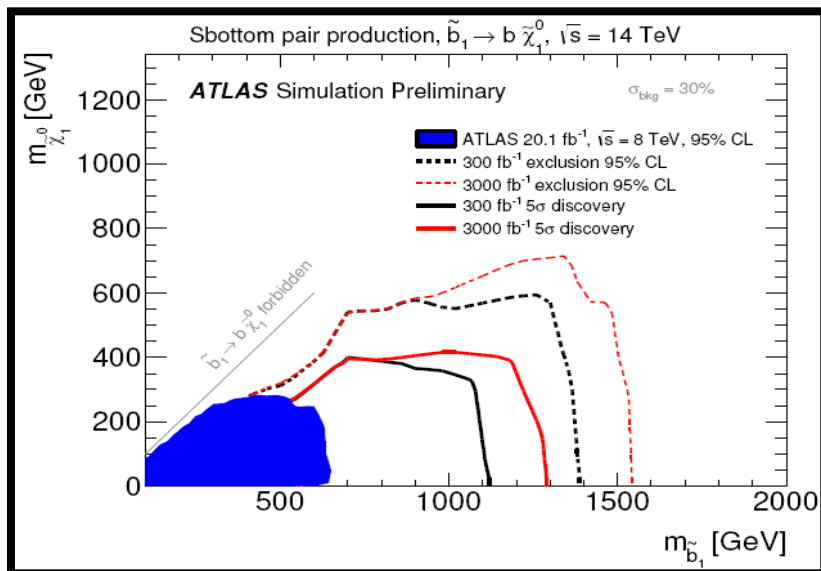
$$M_{CT}^2(J_1, J_2) = [E_T(J_1) + E_T(J_2)]^2 - [\mathbf{p}_T(J_1) - \mathbf{p}_T(J_2)]^2$$

$$= 2p_T(J_1)p_T(J_2)(1 + \cos \Delta\phi(J_1, J_2)),$$

- Important variable to characterize signal

- ◆ Endpoint at the mass of the sparticle:

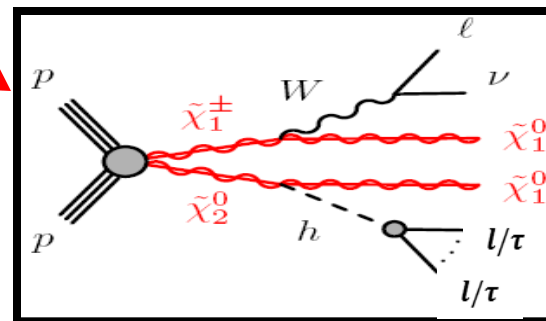
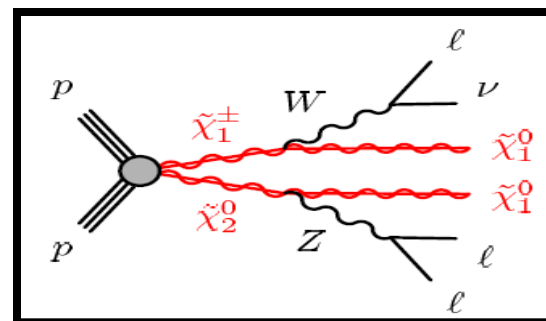
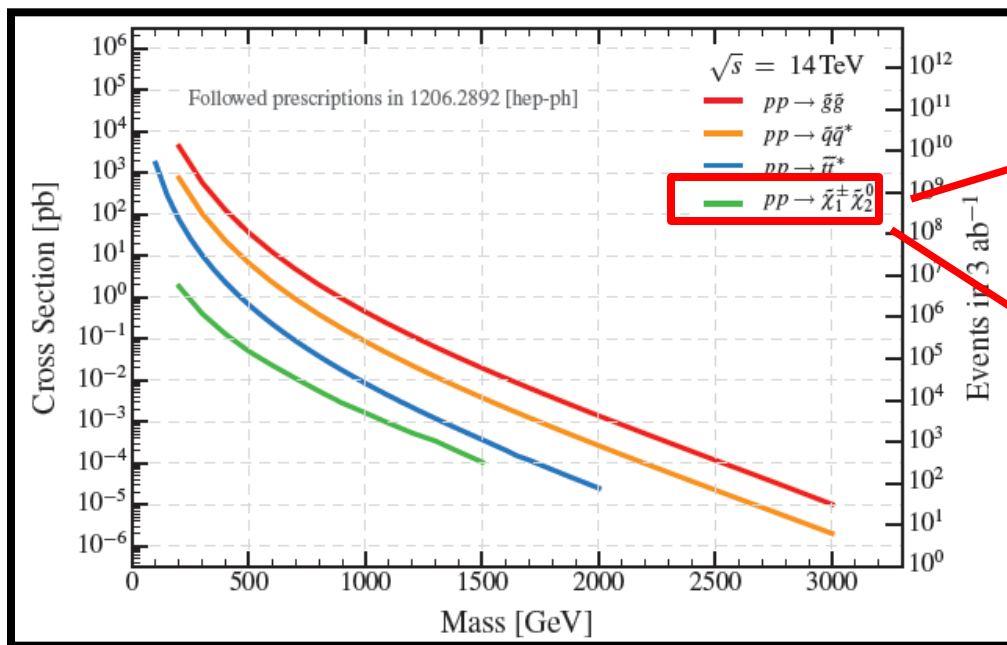
$$m_{CT}^{\max} = \frac{m^2(\tilde{b}) - m^2(\tilde{\chi}_1^0)}{m(\tilde{b})}.$$



- Sbottoms up to 1.4 TeV in Run2
  - ◆ Still [some] for Natural SUSY
- HL-LHC important to discover heavy sbottoms or significantly constraint naturalness



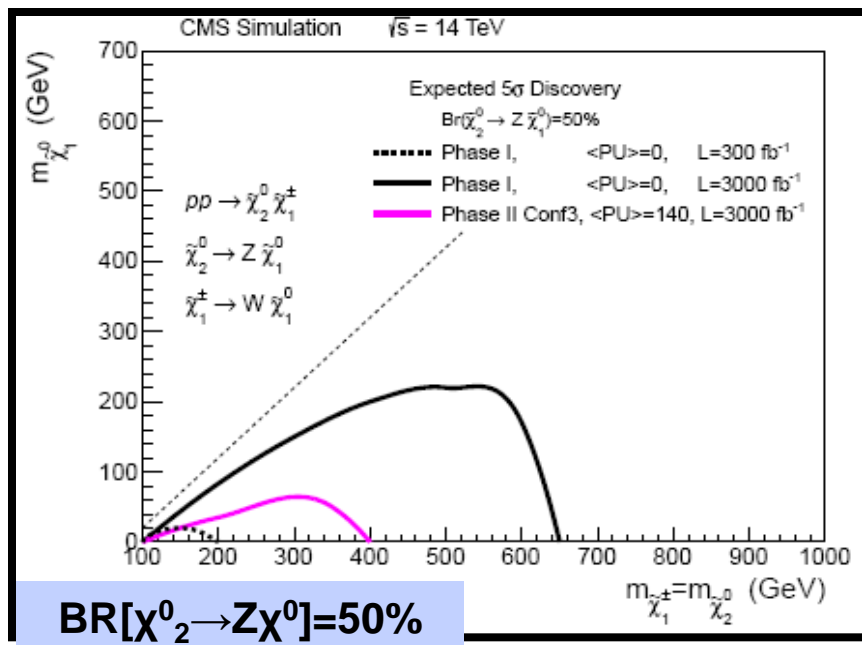
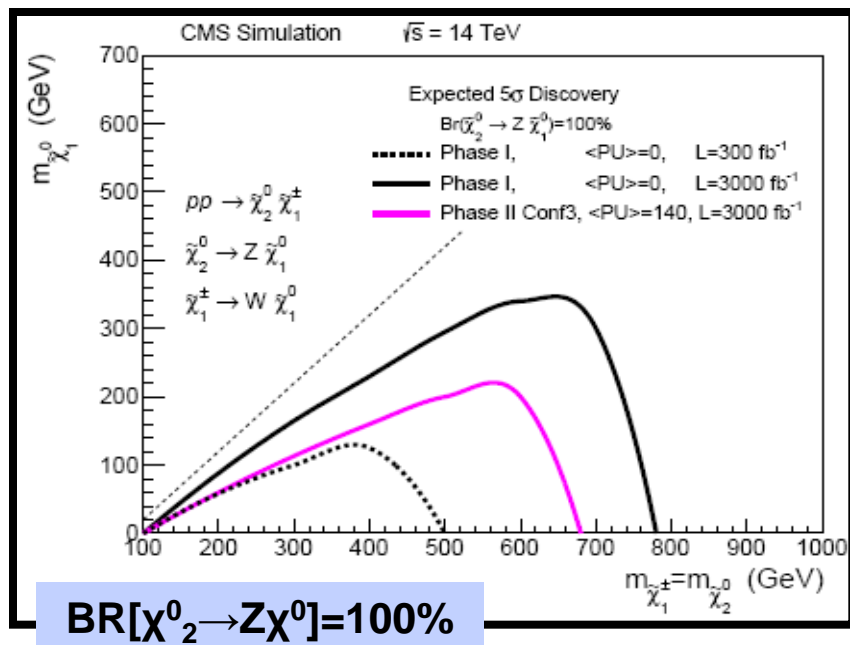
- Naturalness arguments suggest light  $\chi^0/\chi^\pm$
- If gluinos/squarks heavy [outside LHC reach], EWK-ino processes would dominate SUSY production



- Multi-lepton final states drive sensitivity

$\chi_2^0/\chi_1^\pm$ : Wino-like  
 $\chi_1^0$ : Bino-like

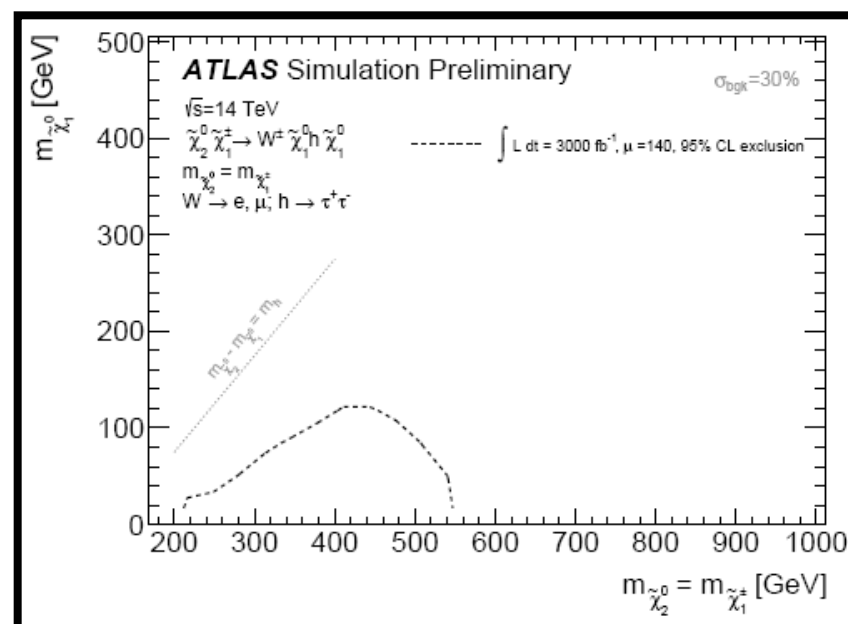
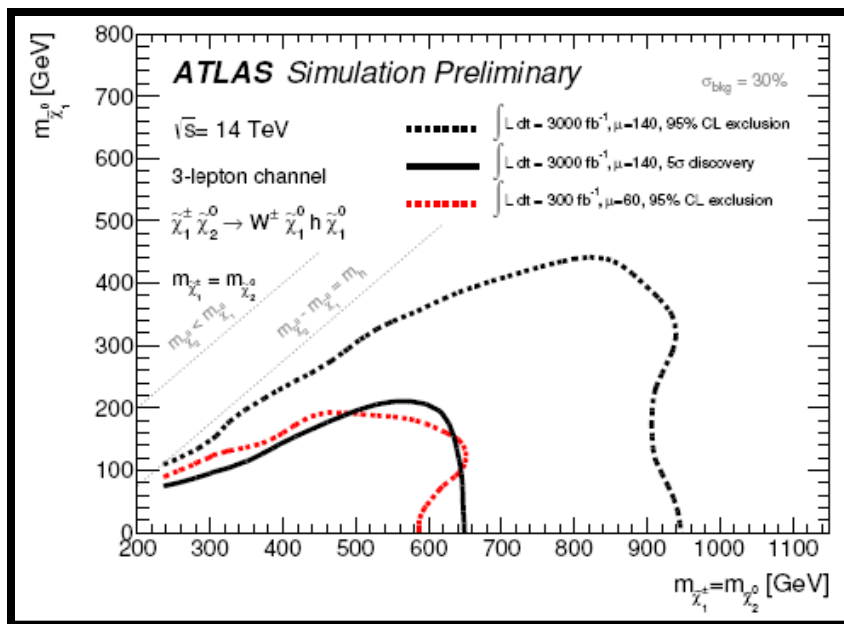
- **WZ-mediated direct production of  $\chi^0/\chi^\pm$**
- **Multiple search regions with large  $ME_T$  and  $M_T[l_W, ME_T]$ :**
  - ◆ **3 lepton final state**



- **HL-LHC: significant impact on mass reach [ $\rightarrow$ TeV scale]**
  - ◆ **Realistic scenario with BR=50% accessible only through HL-LHC**

- WHiggs (Wh)-mediated direct production of  $\chi^0/\chi^\pm$
- Multiple search regions with large MET:
  - ◆ “3 leptons” & “1 lepton + tau-pair” final states

BR 100%



- HL-LHC: significant impact on mass reach [ $\rightarrow$ TeV scale]
  - ◆ 3-lepton final state discoverable only with HL-LHC
  - ◆ 1-lepton + tau-pair accessible only through HL-LHC



# SUSY expectations with a 100-TeV hadron collider

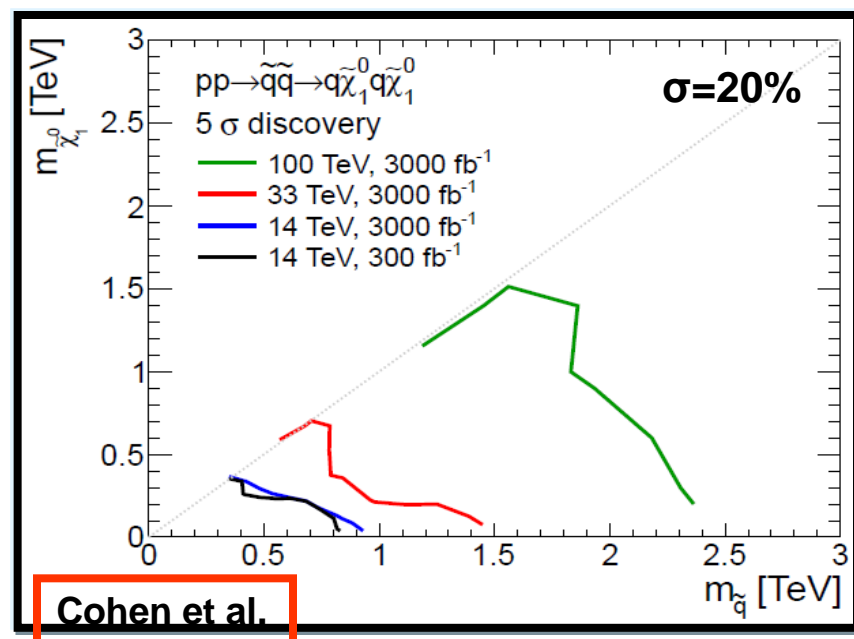
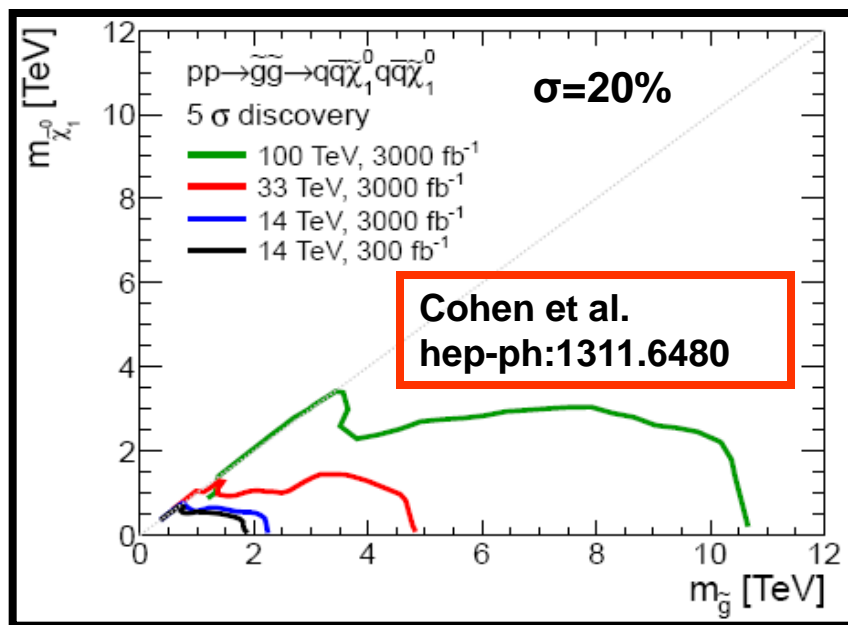


# Run2, HL-LHC; What's next?



- **Both LHC-Run2 & HL-LHC important for SUSY hunting**
- **Optimistic scenario [or scenario 1]:**
  - ◆ Discover/Observe SUSY at LHC [ $\sim$ TeV scale] and then of course get the mechanism for the “hierarchy problem” [and for dark matter if R-Parity Conserving]
  - ◆ Need a SUSY-factory to study the properties [mass spectrum, branching fractions, etc..]
    - **SUSY-factory: Very High Energy collider [i.e. 100 TeV p-p]**  
→ i.e.  $10^3$  increase in prod. x-sec of 1 TeV stop wrt 14 TeV
- **Pessimistic scenario [or scenario 2]:**
  - ◆ No hints from SUSY after HL-LHC
    - **Natural-SUSY in trouble [though not dead]**
    - **Other SUSY models alive [i.e. split-SUSY]**
    - **SUSY mass spectrum very high [ $>O(10$  TeV)]**
  - ◆ Need a powerful hadronic collider to really explore the FT issue
    - ◆ **And since SUSY is to this day the best remaining explanation, to continue SUSY-hunting**

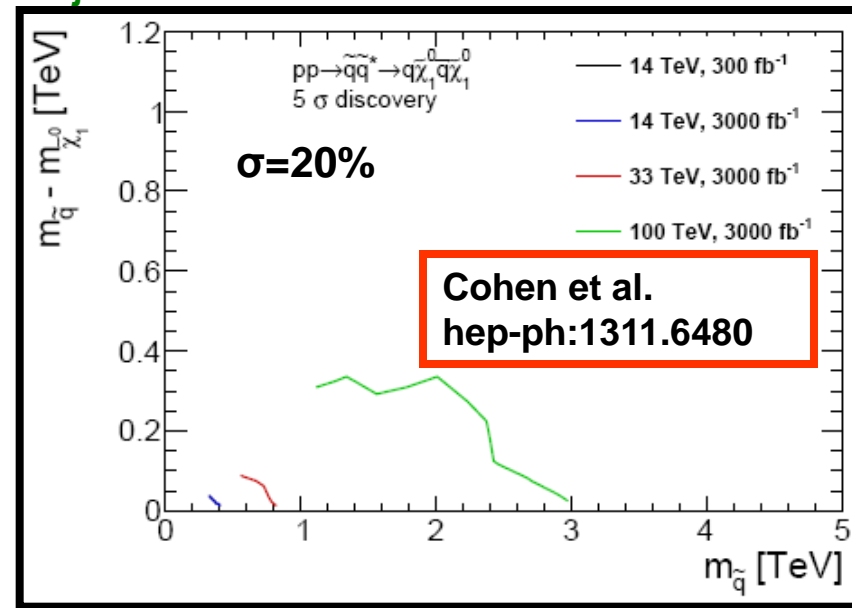
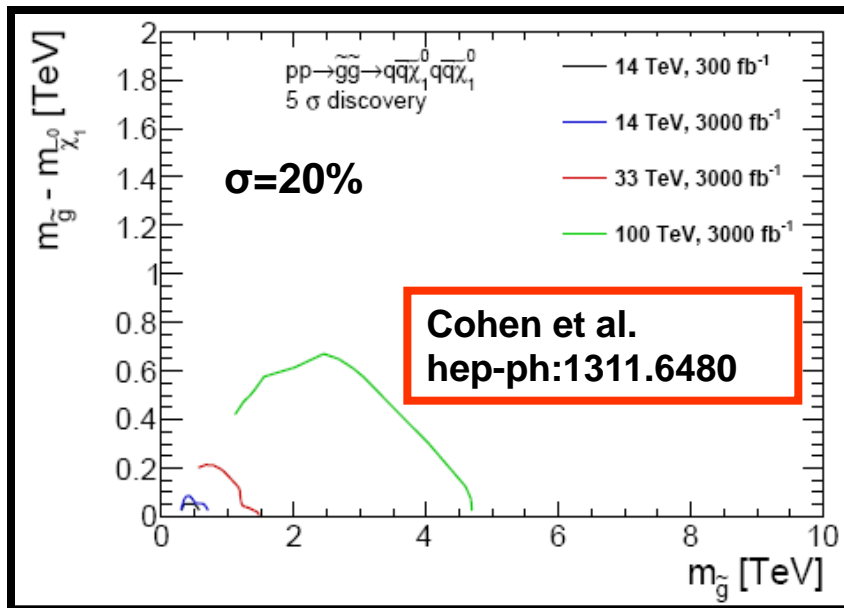
- **HL-LHC [14 TeV] : probe theories ~1% fine tuning**
- **Collider @100 TeV: probe theories ~0.01% fine tuning**  
[N. Arkani-Hamed FCC Feb'14]



- **100 TeV collider significantly boosts the reach for strongly produced SUSY**



- **Compressed spectra: challenging scenarios**
  - ◆ Need excellent understanding of uncertainties, usage of shape fits or multivariate techniques
    - Selection: 1 hard ISR jet, low  $N_{jts}$  [not aligned to  $ME_T$ ]



**A Very high energy Large Hadron Collider [V-LHC] would be the ultimate push of the frontier in HEP [independently of what we learn from LHC]**



# V(ery high energy)-LHC



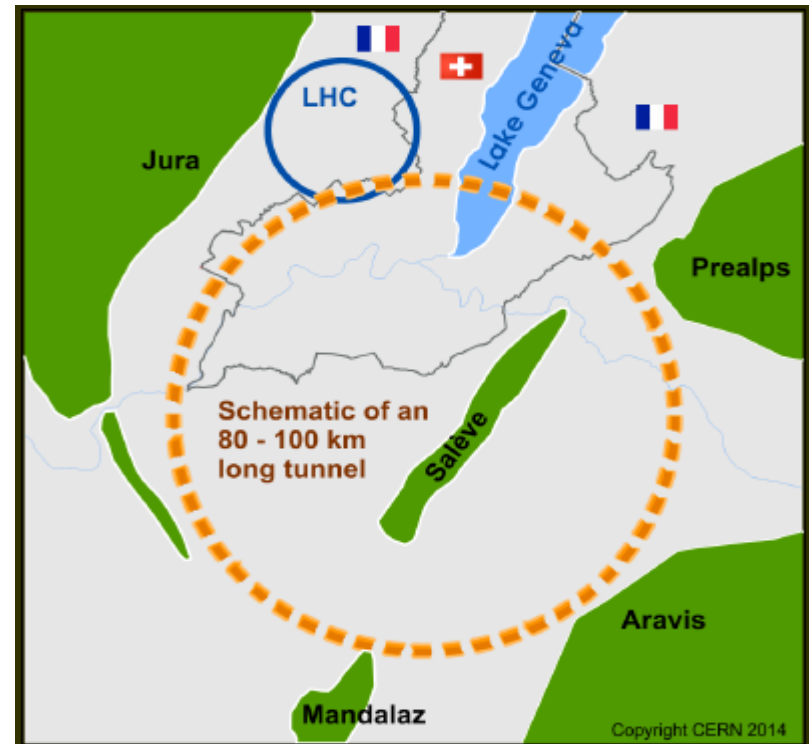
- A VLHC is important for SUSY [or any kind of New Physics] and for SM rare processes
- An 80-100 km circular tunnel is one option under consideration
  - ◆ p-p, e-p, e-e [more details in M. Klute talk]

F. Gianotti  
LHCP 2014

CERN FCC: international design study for Future Circular Colliders in 80-100 km ring:

- 100 TeV pp: ultimate goal (FCC-hh)
- 90-350 GeV  $e^+e^-$ : possible intermediate step (FCC-ee)
- $\sqrt{s} = 3.5-6$  TeV ep: option (FCC-eh)

Goal of the study: CDR in ~2018.





# Summary



# Summary



- **Discovery of BEH particle completes SM puzzle**
- **Many open questions; SUSY very appealing extension**
  - ◆ SUSY has yet to join the party
    - .. But still a highly anticipated guest ☺
- **Increase in CM Energy at 13/14 TeV enhances production x-sec, while increased L enhances small x-sec processes and challenging scenarios [e.g. compressed spectra]**
- **Full exploitation of the LHC capabilities [Run2 and HL-LHC] very important for SUSY [and much more!]**
  - ◆ At the end of HL-LHC able to probe theories down to 1% FT
- **An O(100 TeV) hadron collider should be the next step after HL-LHC [i.e. V-LHC]**
  - ◆ Able to probe theories down to 0.01% FT

**Programs in preparation and under consideration for years to come will be critical in our discovery or abandonment of SUSY**



# Additional material



# Public results



- **ATLAS:**

- ◆ <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies>

- **CMS:**

- ◆ <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP>



