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

Loukas Gouskos

University of California, Santa Barbara

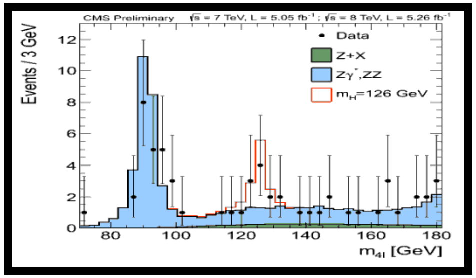
on behalf of the ATLAS and CMS collaborations

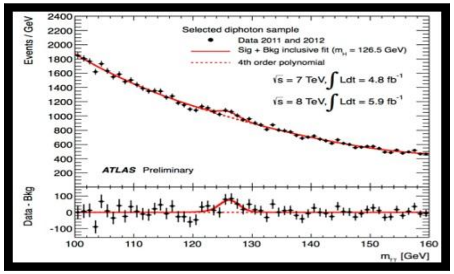
- **Outline:**
  - **Introduction**
  - **The search for SUSY at the LHC: Run 2 to the HL-LHC**
  - **SUSY expectations with a 100 TeV hadron collider**
  - **Summary**

Introduction

Introduction

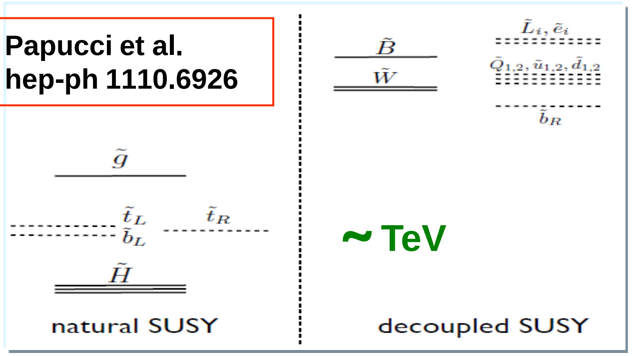
- **Discovery of a BEH scalar @ ~125 GeV completes SM**



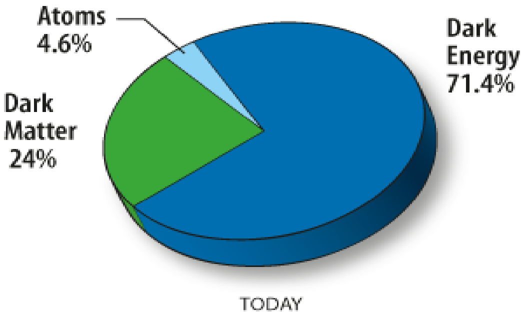


- **Still many open questions**
- **SUperSYmmetry; very appealing extension:**

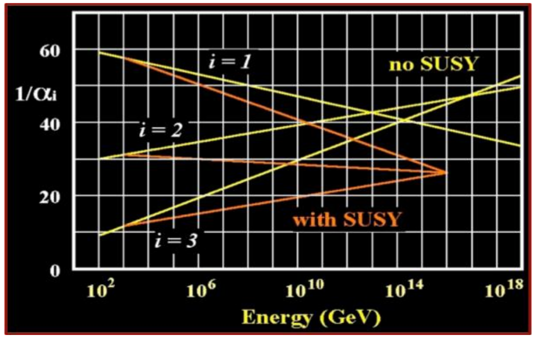
Hierarchy problem



Dark Matter

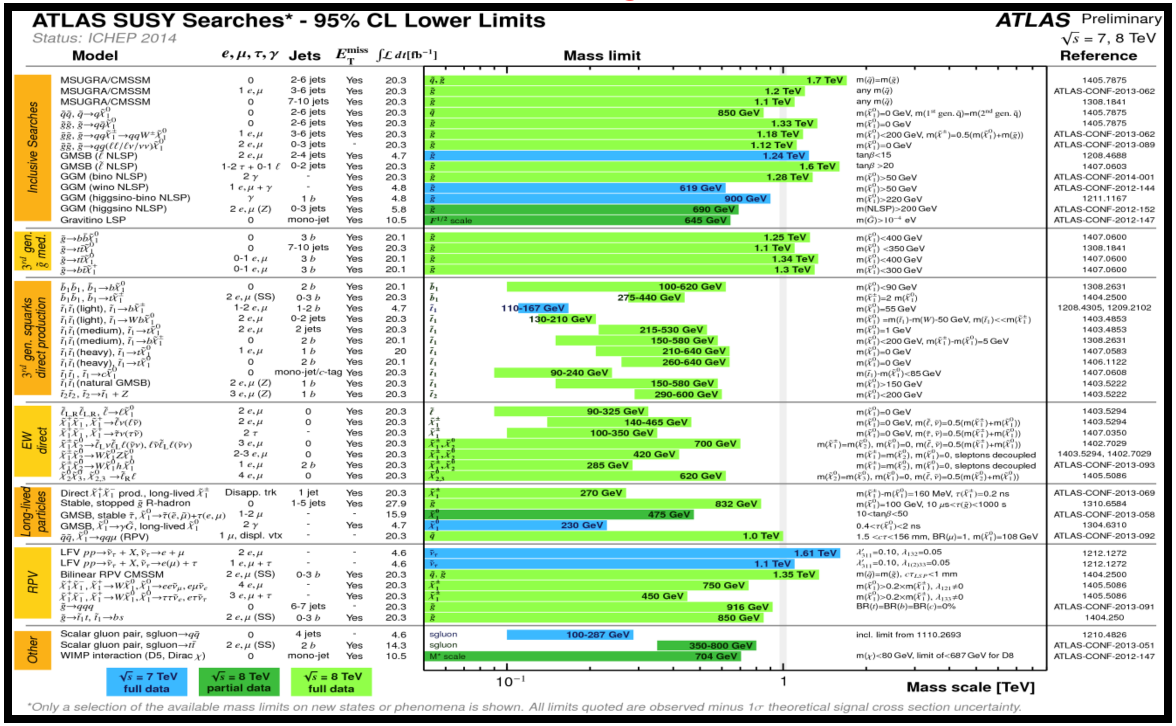


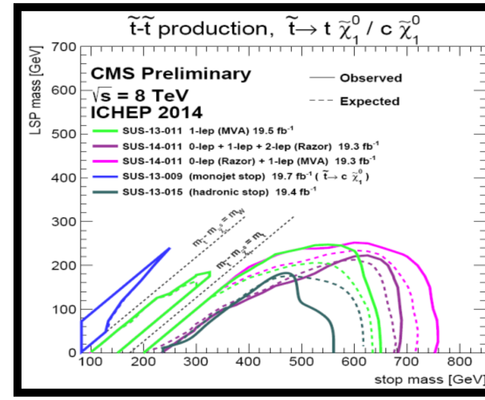
Unification

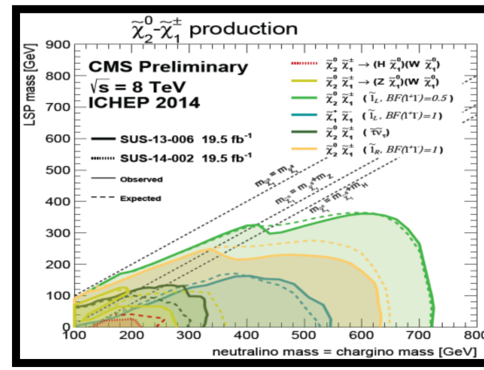


Introduction (2)

- … but SUSY not "just around the corner"





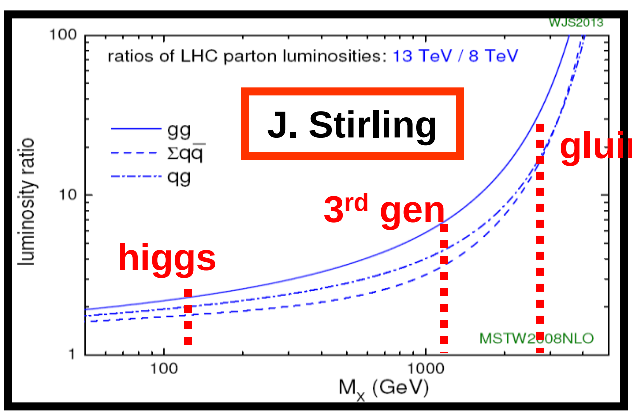


- **M[g] > ~1.4 TeV**
- **M[sq1,2 (3)]> ~1.3 (0.6)TeV**
- **M[gauginos] > ~0.3-0.7 TeV**

NB.
(a) Assume BR~100%
(b) Probed regions depend strongly on mass parameters [i.e. m(χ^0)]

Introduction (3)

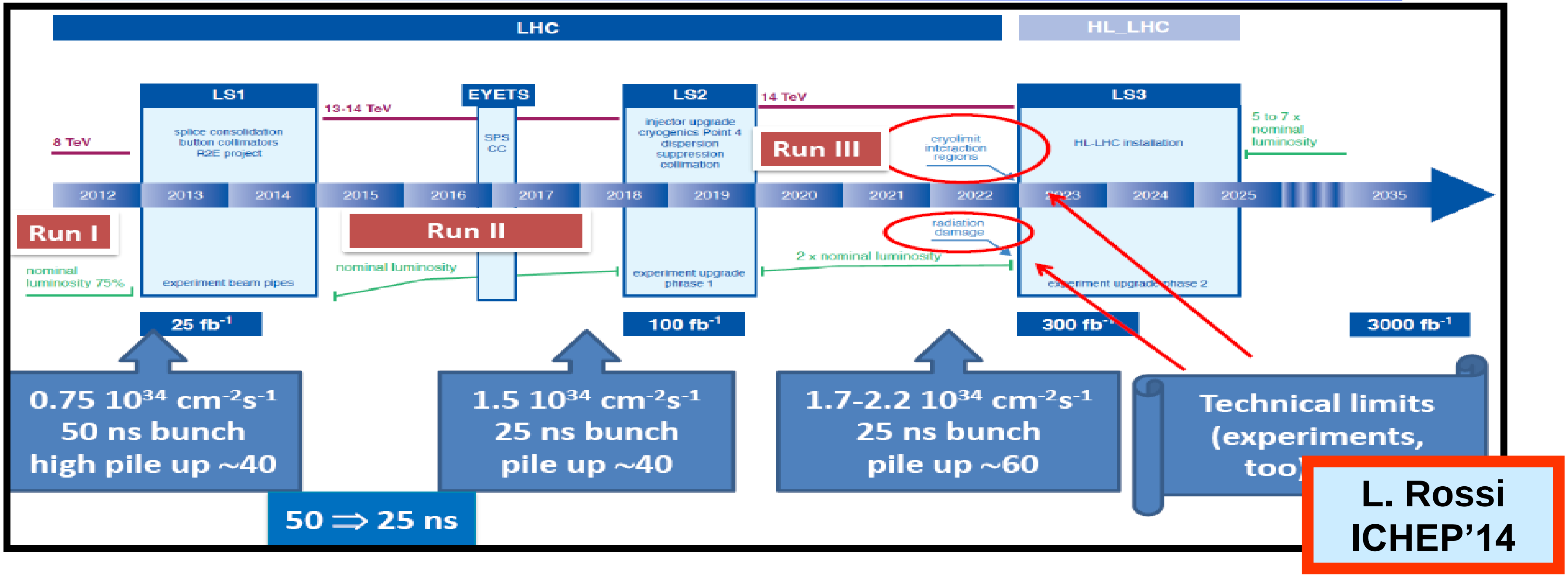
- **However, many SUSY scenarios remain open**
  - SUSY at higher mass scales [i.e. not probed @ 7/8 TeV]
    - Benefit from the increase in energy
  - Low cross section SUSY processes [i.e. EWK production]
    - Benefit from the increase in L_{int}
  - Compressed spectra [i.e. small mass dif. between sparticles]
    - SM-like signature: dedicated searched, benefit from E & L_{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 ~2 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 [~300 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]**

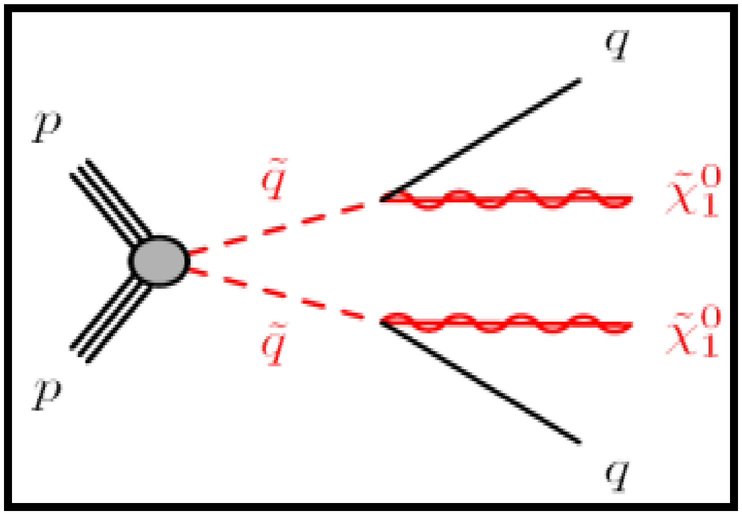
Making the case..

- **Projected results based on 8 TeV searches with optimized selection to account for increased E and L_{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)**

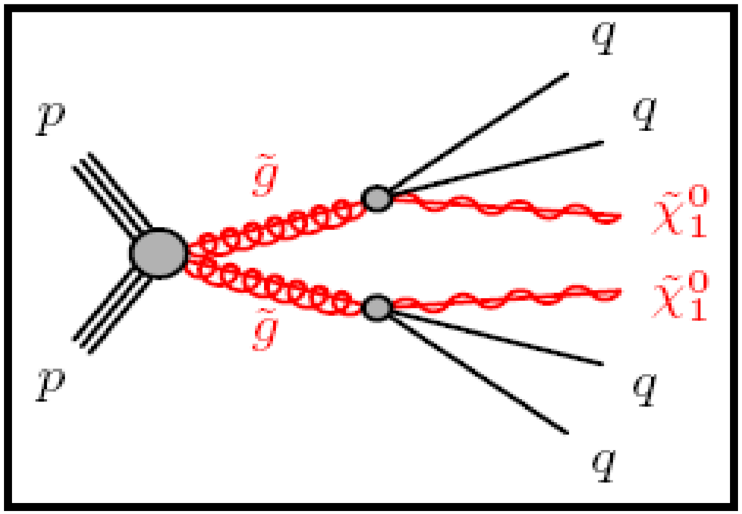
Strongly produced SUSY [$\tilde{g} \rightarrow \tilde{q}$]

- **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 1st and 2nd generation squarks**

direct squark production

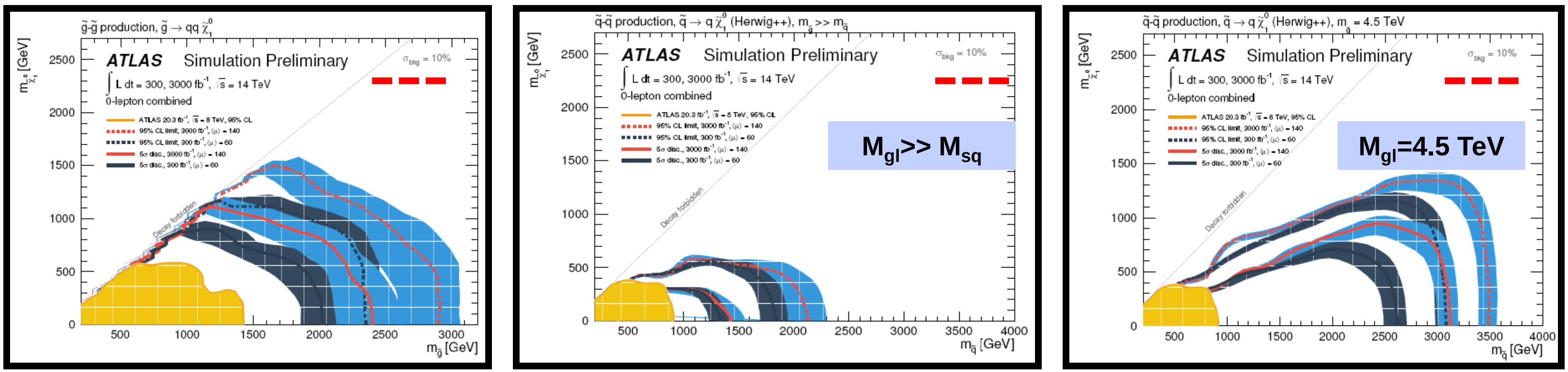


Gluino-mediated squark production



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

- **Search carried out in multiple signal regions based on:**
  - M_{eff}[= ME_T + Σp_T(jet)]; ME_T/M_{eff}; $ME_T/(H_T)^{1/2}$



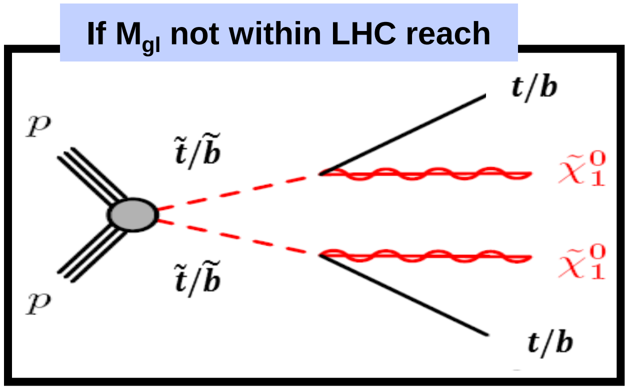
	M[gl] (2σ/5σ) [Tev]	M[sq] (2σ/5σ) [Tev]	M[sq] (2σ/5σ) [Tev] (M[gl]=4.5 TeV)
Run 2	2.4 / 2.0	1.4 / 1.9	3.1 / 2.7
HL-LHC	2.8 / 2.4	2.1 / 1.5	3.5 / 3.1

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

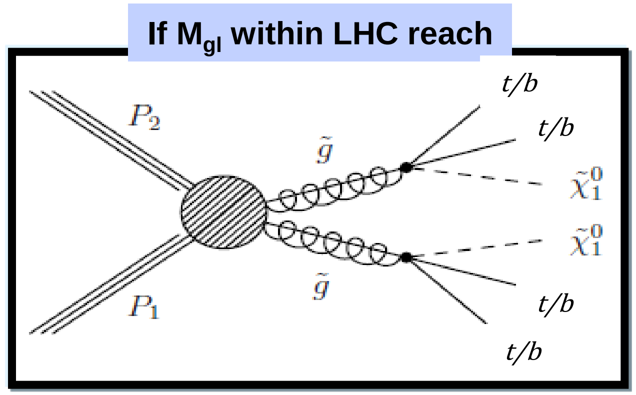
Strongly produced SUSY [$\tilde{t}/\tilde{b}$]

- **"Naturalness" requires light [~TeV] stop/sbottoms**
  - **Direct production or gluino-induced production**

If M_{gl} not within LHC reach



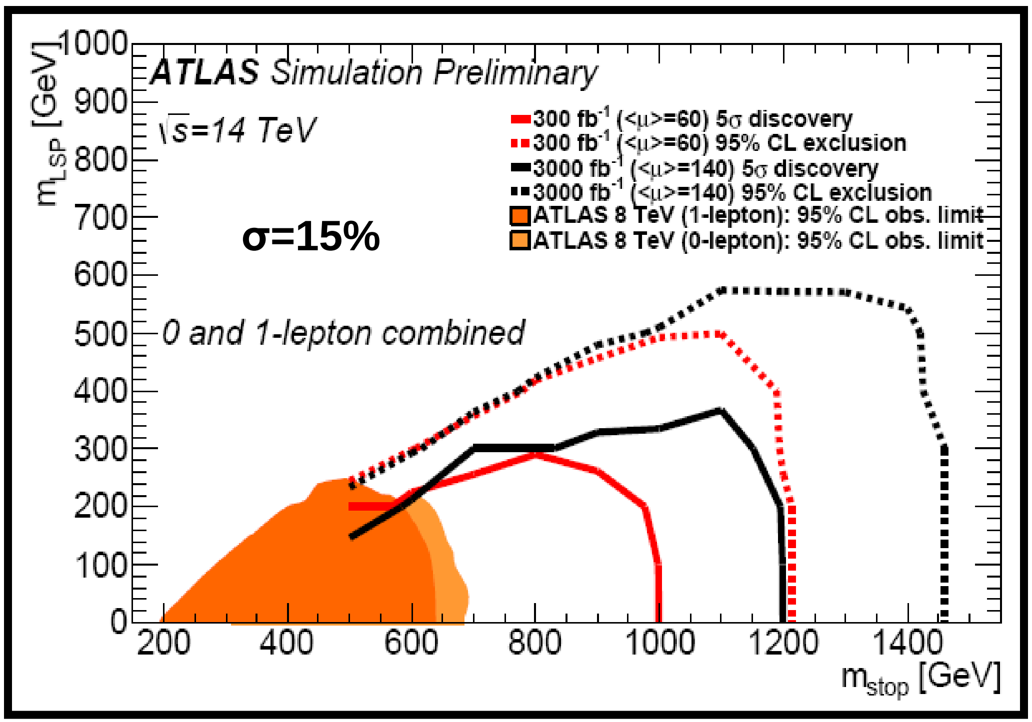
If M_{gl} within LHC reach



- **Most "Natural" SUSY scenarios predict light 3rd 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**

Strongly produced SUSY [$\tilde{t}/\tilde{b}$] (2)

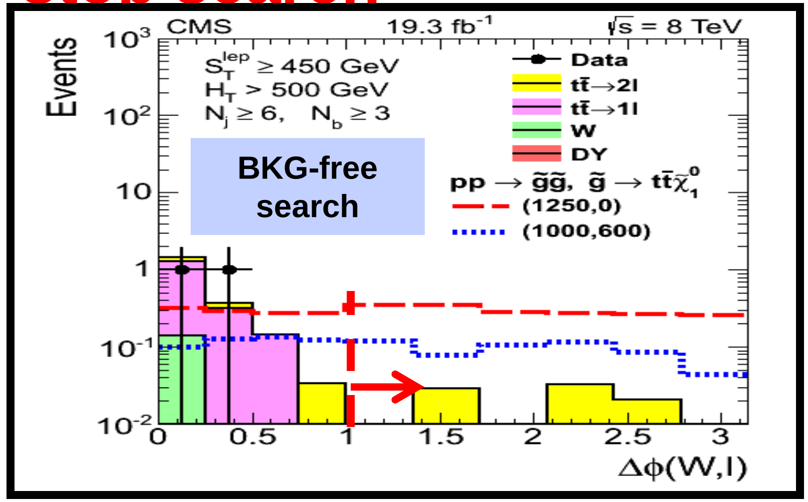
- **0 & 1 lepton final states for direct-stop production**
  - **Search regions based on ME_T, $ME_T/(H_T)^{1/2}$, $M_T[l,ME_T]$**
    - **0-lep: $M_T[b,ME_T]$, N_{jts}>=6, N_{bjets}>=2**
    - **1-lep: $M_T[l,ME_T]$, N_{jts}>=3, N_{bjets}>=1**

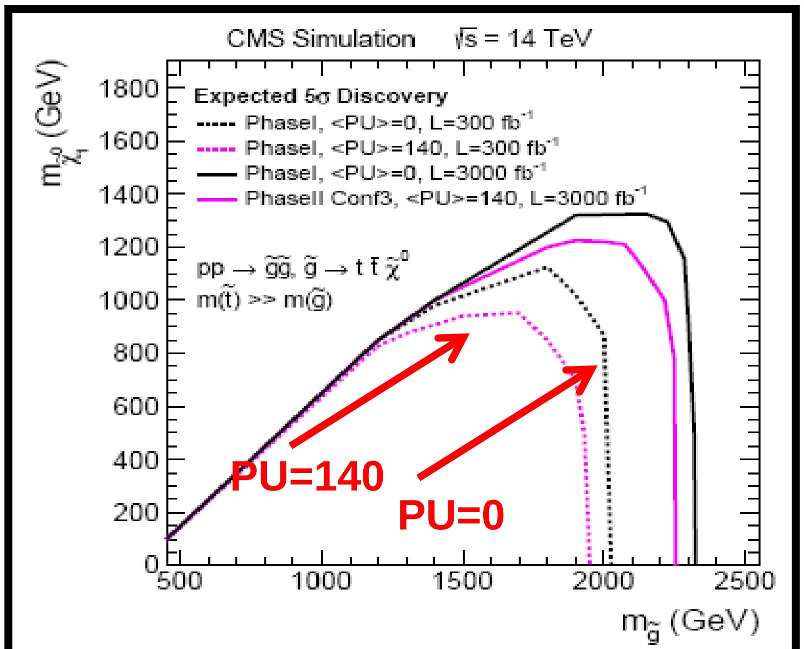


- **Run 2 can set tight limits on direct-stop [Naturalness]**
- **Following BEH particle discovery, best motivated region probed with HL-LHC**
  - **~1.2 TeV stops discoverable with HL-LHC**
- **HL-LHC powerful for challenging models**

Strongly produced SUSY [$\tilde{t}/\tilde{b}$] (3)

- **1 lepton channel important for stop search**
  - Gluino-induced stops based on $S_T^{lep} = p_T[l] + ME_T$ & $\Delta\varphi(l,W)$
  - $N_{jts} >= 6$,
  - Multiple SR in: N_{bjts} and S_T^{lep}





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

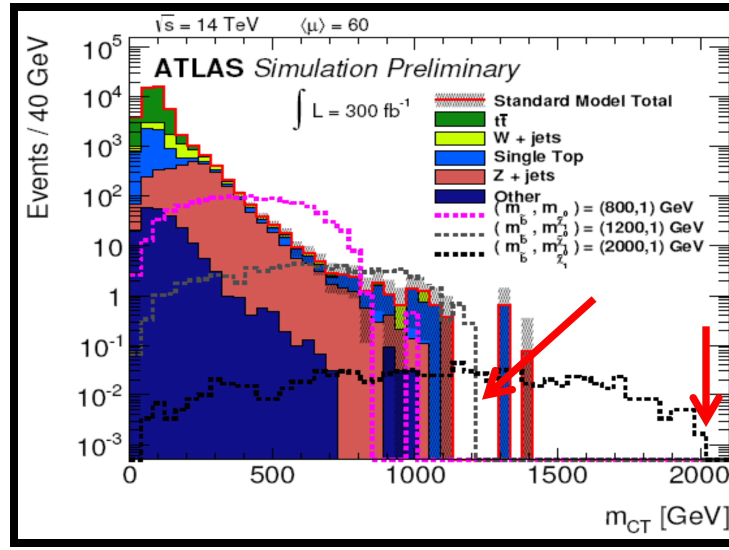
Strongly produced SUSY $[\tilde{t}/\tilde{b}]$ (4)

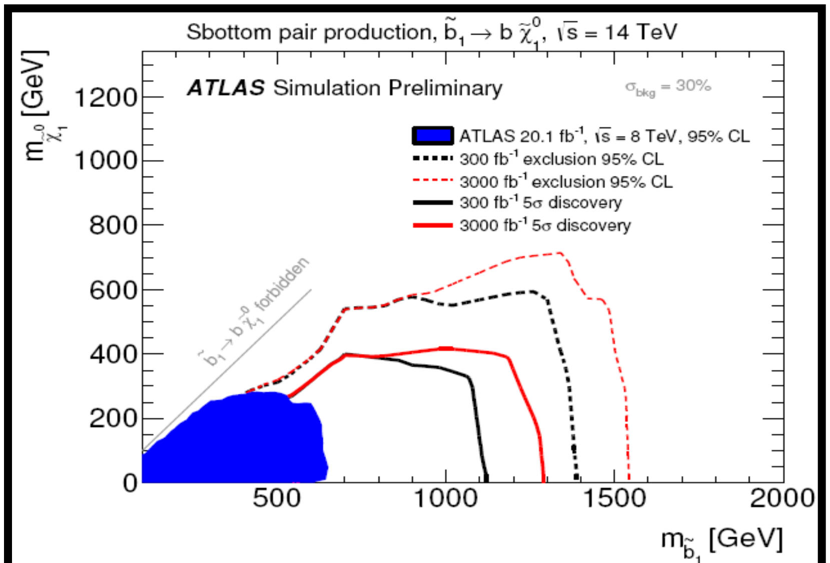
- **Dedicated searched for direct sbottom production**
- **Search utilizes M_{CT}:**

$$\begin{aligned} M^2_{CT}(J_1, J_2) &= [E_T(J_1) + E_T(J_2)]^2 - [\mathbf{p}_T(J_1) - \mathbf{p}_T(J_2)]^2 \\ &= 2p_T(J_1)p_T(J_2)(1 + \cos\Delta\phi(J_1, J_2)), \end{aligned}$$

- **Important variable to characterize signal**
  - **Endpoint at the mass of the sparticle:**

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

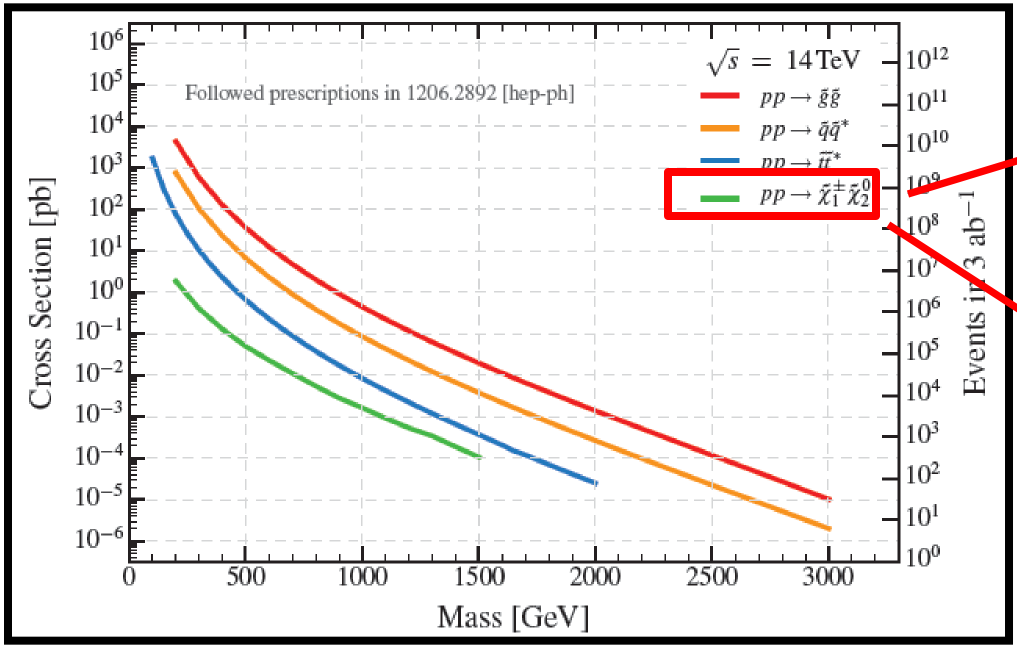


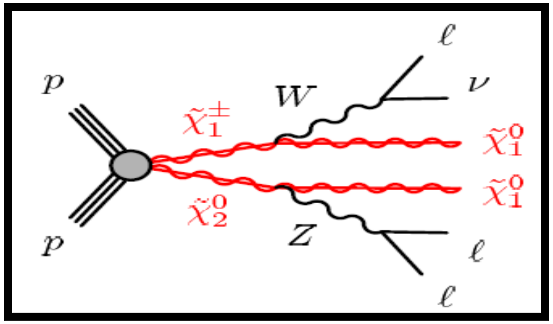


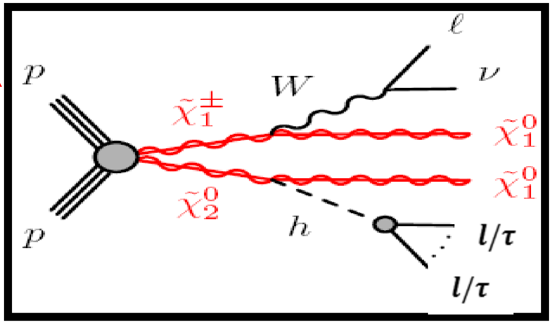
- **Sbottoms up to 1.4 TeV in Run2**
  - **Still [some] for Natural SUSY**
- **HL-LHC important to discover heavy sbottoms or significantly constraint naturalness**

EWK SUSY [$\tilde{\chi}^{\pm}/\tilde{\chi}^{0}$]

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





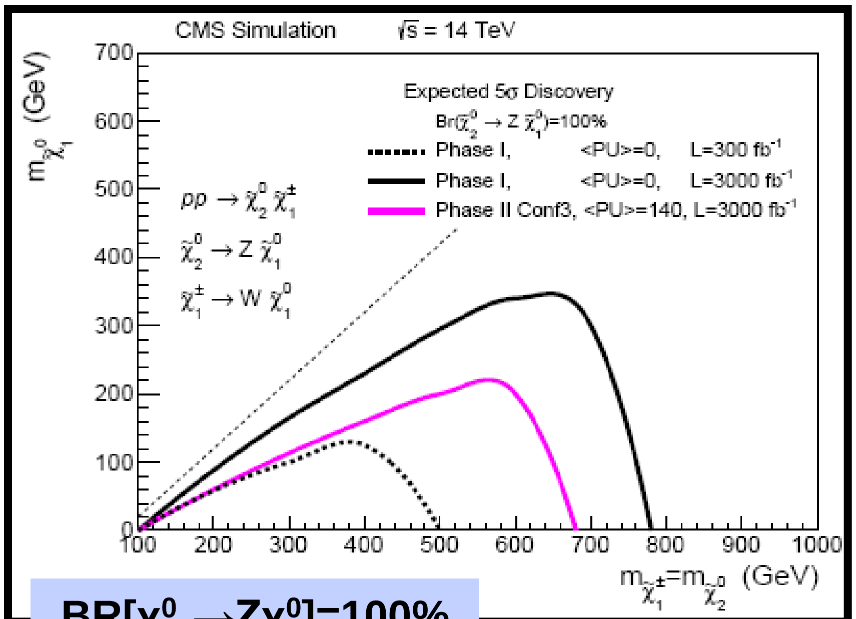


$\chi^0_2/\chi^{\pm}_1$: Wino-like
χ^0_1: Bino-like

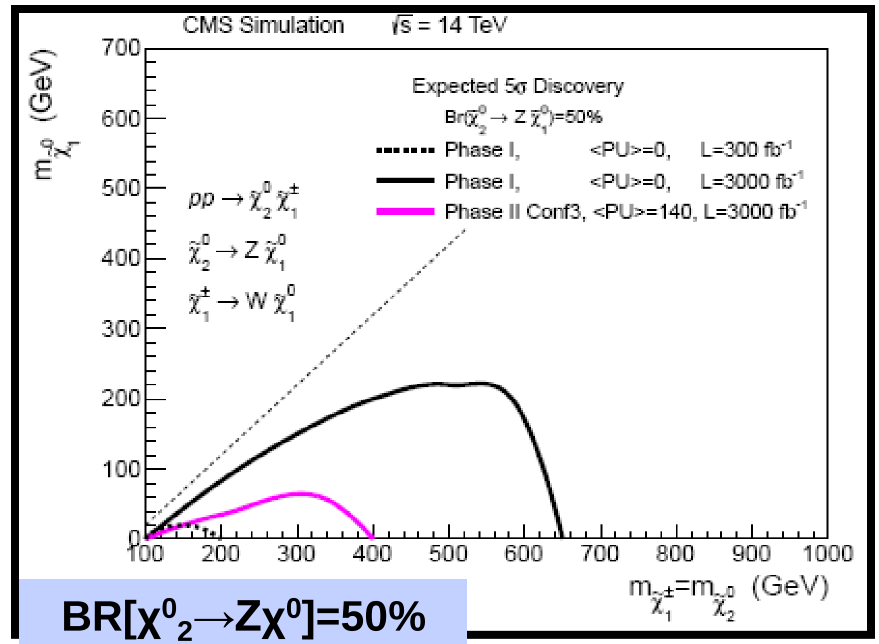
- **Multi-lepton final states drive sensitivity**

EWK SUSY $[\tilde{\chi}^{\pm}/\tilde{\chi}^{0}]$ (2)

- **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**



BR[$\chi^0_2 \to Z\chi^0$]=100%



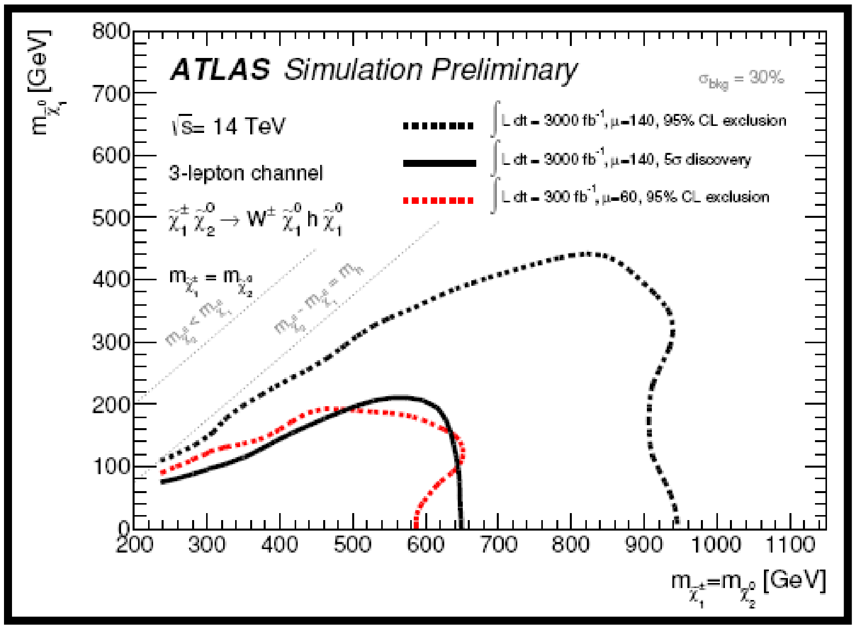
BR[$\chi^0_2 \to Z\chi^0$]=50%

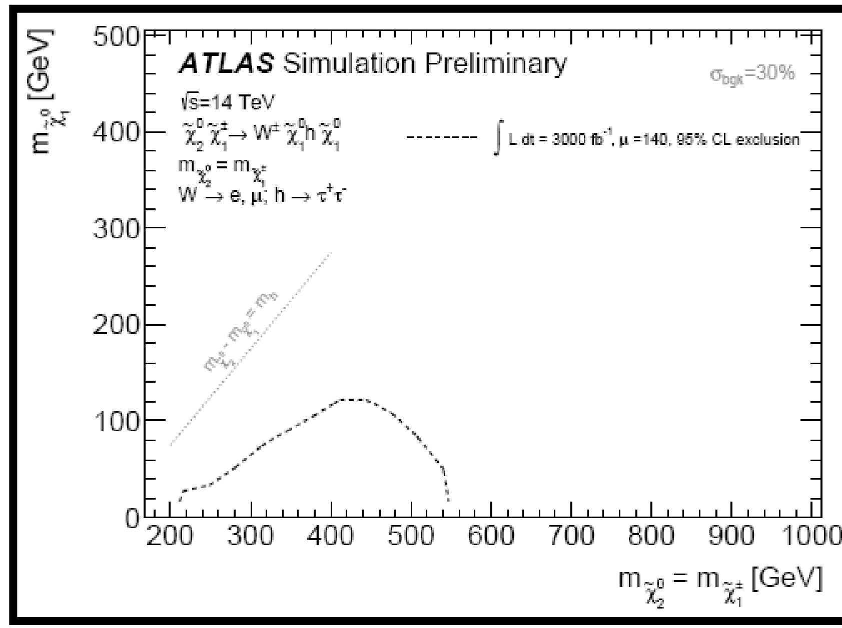
- **HL-LHC: significant impact on mass reach [→TeV scale]**
  - **Realistic scenario with BR=50% accessible only through HL-LHC**

EWK SUSY $[\tilde{\chi}^{\pm}/\tilde{\chi}^{0}]$ (3)

- **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 [→TeV scale]**
  - **3-lepton final state discoverable only with HL-LHC**
  - **1-lepton + tau-pair accessible only through HL-LHC**

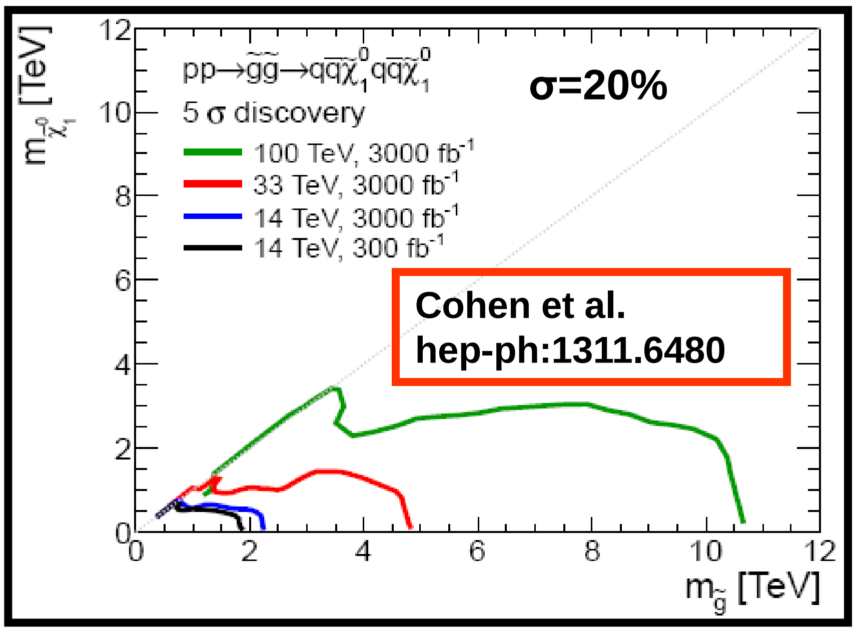
SUSY expectations with a 100-TeV hadron collider

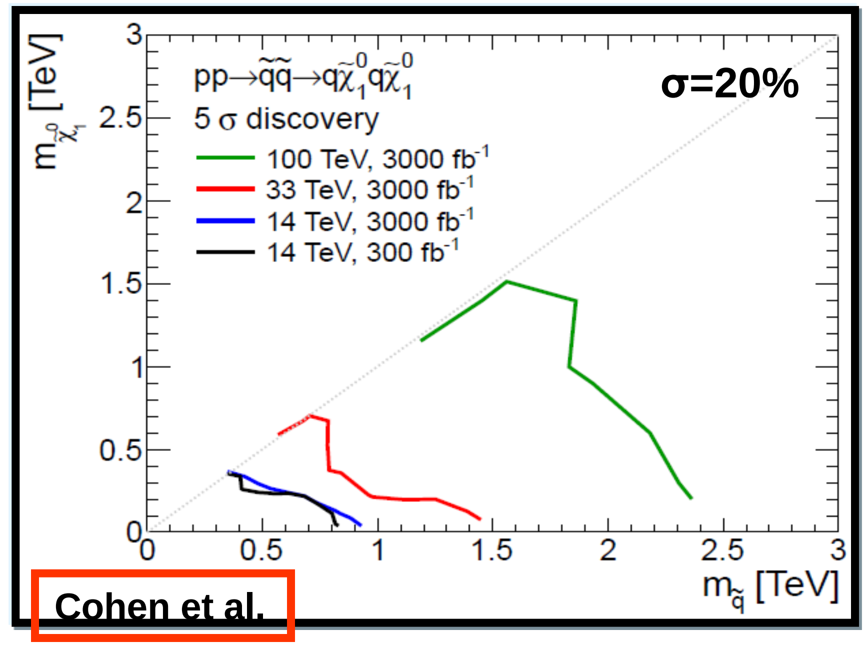
Run2, HL-LHC; What's next?

- **Both LHC-Run2 & HL-LHC important for SUSY hunting**
- **Optimistic scenario [or scenario 1]:**
  - **Discover/Observe SUSY at LHC [~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**

Run2, HL-LHC; What's next? (2)

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

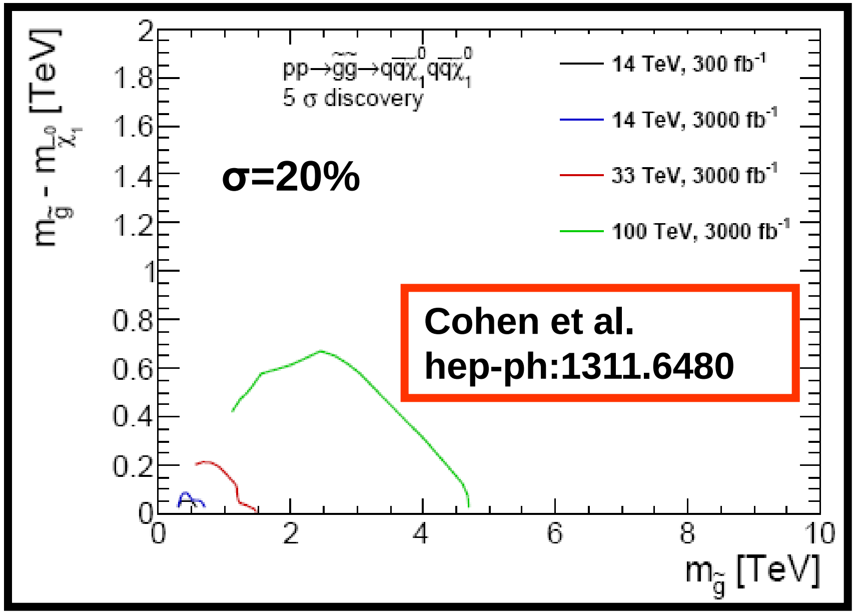


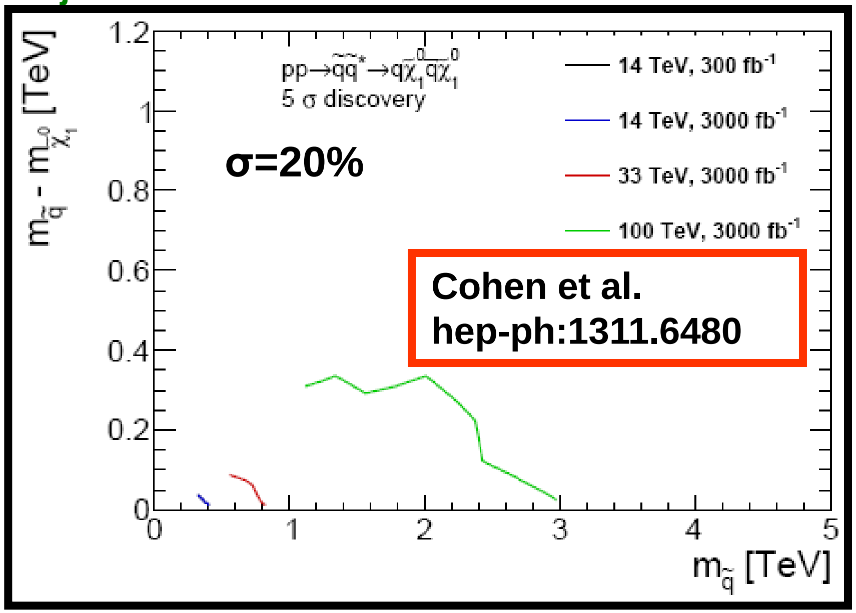


- **100 TeV collider significantly boosts the reach for strongly produced SUSY**

Run2, HL-LHC; What's next? (3)

- **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]

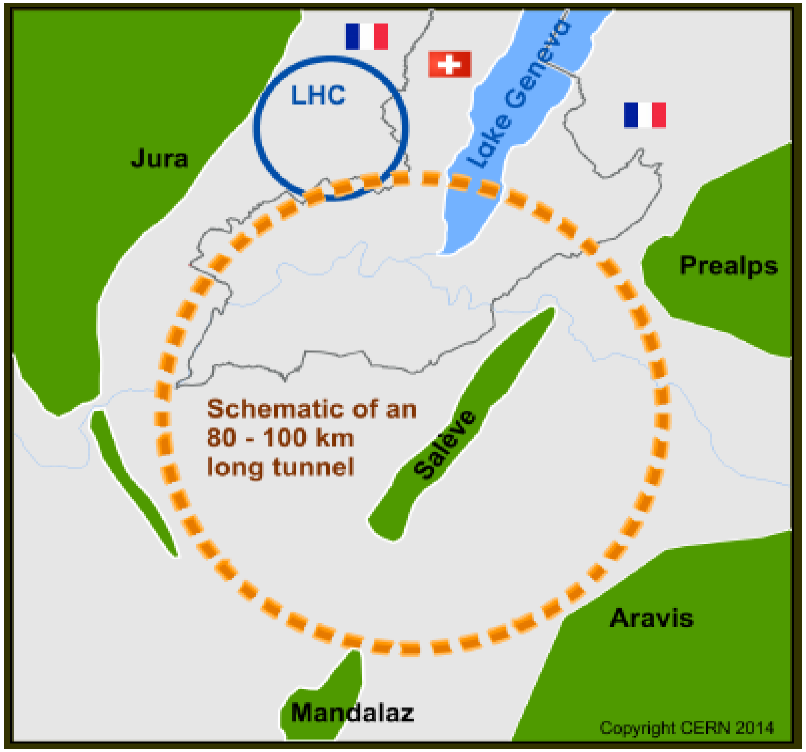
V(ery high energy)-LHC

- **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**

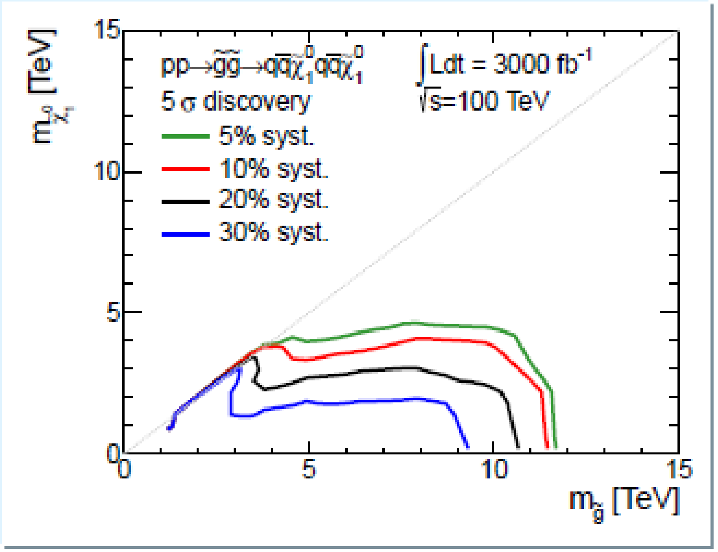
Programs in preparation and under consideration for years to come will be critical in our discovery or abandonment of SUSY

Additional material

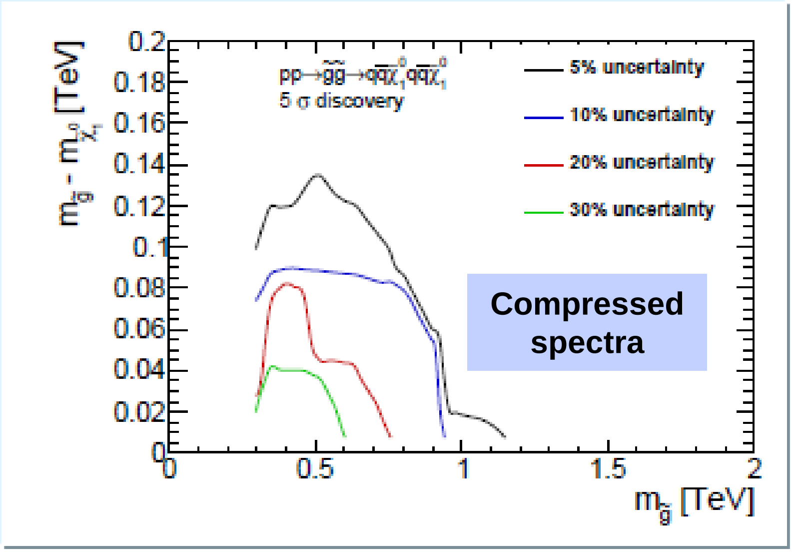
Public results

- **ATLAS:**
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies
- **CMS:**
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP

FCC 100 TeV

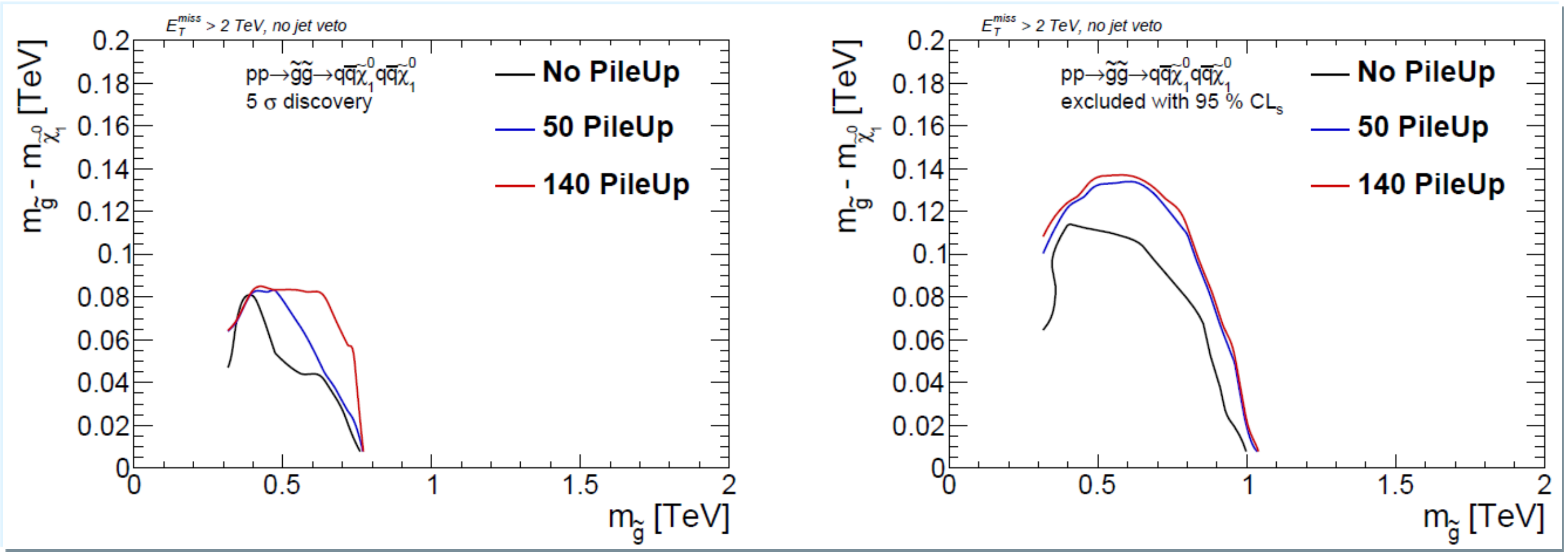


$pp \to \tilde{g}\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 q\bar{q}\tilde{\chi}_1^0$
5 σ discovery
5% syst.
10% syst.
20% syst.
30% syst.
$\int$ Ldt = 3000 fb^{-1}
$\sqrt{s}$=100 TeV
$m_{\tilde{\chi}_1^0}$ [TeV]
$m_{\tilde{g}}$ [TeV]



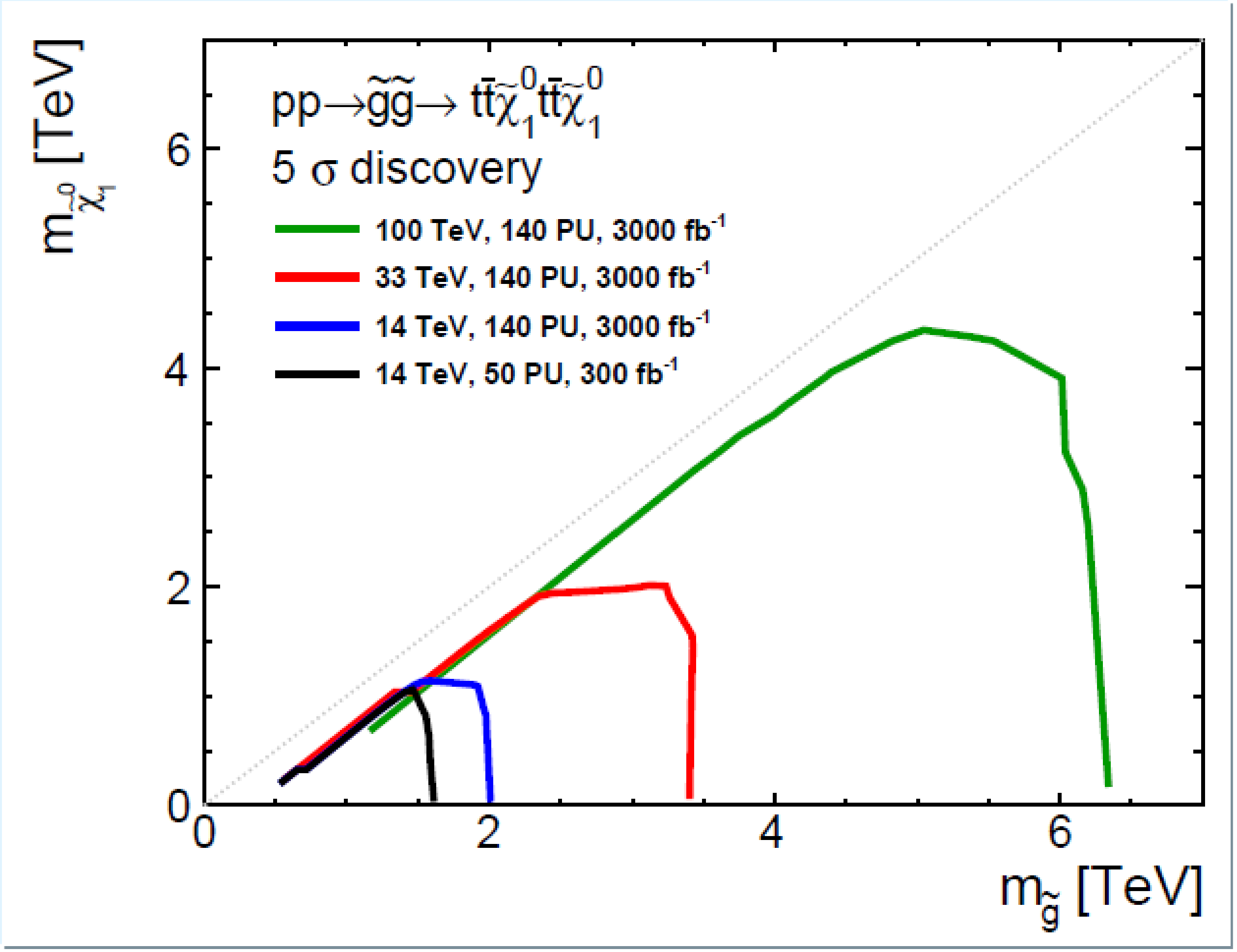
$pp \to \tilde{g}\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 q\bar{q}\tilde{\chi}_1^0$
5 σ discovery
5% uncertainty
10% uncertainty
20% uncertainty
30% uncertainty
Compressed spectra
$m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$ [TeV]
$m_{\tilde{g}}$ [TeV]

FCC 100 TeV



E_T^{miss} > 2 TeV, no jet veto
$pp \to \tilde{g}\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 q\bar{q}\tilde{\chi}_1^0$
5 σ discovery
No PileUp
50 PileUp
140 PileUp
$m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$ [TeV]
$m_{\tilde{g}}$ [TeV]
E_T^{miss} > 2 TeV, no jet veto
$pp \to \tilde{g}\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 q\bar{q}\tilde{\chi}_1^0$
excluded with 95 % CL_s
No PileUp
50 PileUp
140 PileUp
$m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$ [TeV]
$m_{\tilde{g}}$ [TeV]

FCC 100 TeV



$pp\to\tilde{g}\tilde{g}\to t\bar{t}\tilde{\chi}_1^0 t\bar{t}\tilde{\chi}_1^0$
5 σ discovery
100 TeV, 140 PU, 3000 fb^{-1}
33 TeV, 140 PU, 3000 fb^{-1}
14 TeV, 140 PU, 3000 fb^{-1}
14 TeV, 50 PU, 300 fb^{-1}
$m_{\tilde{\chi}_1^0}$ [TeV]
$m_{\tilde{g}}$ [TeV]
0
2
4
6