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

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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

- Papucci et al. hep-ph 1110.6926

\[ \tilde{b}_L, \tilde{t}_L, \tilde{b}_R, \tilde{t}_R, \tilde{H}, \tilde{\nu}_L, \tilde{\nu}_R \]

\[ \sim \text{TeV} \]

Dark Matter

- Atoms 4.6%
- Dark Matter 24%
- Dark Energy 71.4%

Unification

- July 4, 2012

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Introduction (2)

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

- \( M[g] > \sim 1.4 \text{ TeV} \)
- \( M[sq_{1,2}(3)] > \sim 1.3 \) (0.6)\( \text{TeV} \)
- \( M[\text{gauginos}] > \sim 0.3-0.7 \text{ TeV} \)

NB.
(a) Assume BR\sim 100%
(b) Probed regions depend strongly on mass parameters [i.e. \( m(\chi^0) \)]
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 $L_{\text{int}}$
  - Compressed spectra [i.e. small mass diff. 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 $\sim 1.5$ TeV
  - SM gains a factor of 2-4
  - With $\sim 2$ 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
End of Run 2 [\(~300 \text{ fb}^{-1}\)]: some detector subsystems and much of the front-end electronics, trigger, need to be replaced

Replacements with improved physics capabilities are in the pipeline

- 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 $M_E_T$
  - 0-lepton final state dominates search for 1st and 2nd generation squarks
Strongly produced SUSY $[\tilde{g} \rightarrow \tilde{q}]$ (2)

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

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

<table>
<thead>
<tr>
<th></th>
<th>$M[gl]$ (2σ/5σ) [Tev]</th>
<th>$M[sq]$ (2σ/5σ) [Tev]</th>
<th>$M[sq]$ (2σ/5σ) [Tev] (M[gl]=4.5 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 2</td>
<td>2.4 / 2.0</td>
<td>1.4 / 1.9</td>
<td>3.1 / 2.7</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>2.8 / 2.4</td>
<td>2.1 / 1.5</td>
<td>3.5 / 3.1</td>
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“Naturalness” requires light [\sim TeV] stop/sbottoms

- Direct production or gluino-induced production

Most “Natural” SUSY scenarios predict light 3rd gen squarks [\sim 1-1.2 TeV] and gluinos [\sim 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 \( M_{T}, ME_{T}/(H_{T})^{1/2}, M_{T}[l, ME_{T}] \)
  - 0-lep: \( M_{T}[b, ME_{T}], N_{jets}>=6, N_{bjets}>=2 \)
  - 1-lep: \( M_{T}[l, ME_{T}], N_{jets}>=3, N_{bjets}>=1 \)

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 $S_{T}^{lep} = p_{T}[l] + ME_{T} \& \Delta \phi(l,W)$
  - $N_{jts} \geq 6,$
  - Multiple SR in: $N_{bjts}$ and $S_{T}^{lep}$

- 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

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Rencontres du Vietnam 2014
SUSY: Expectations for Run 2, HL-LHC, VLHC
Strongly produced SUSY [$\tilde{t}/\tilde{b}$] (4)

- Dedicated searched for direct sbottom production
- Search utilizes $M_{CT}$:
  \[ M_{CT}^{2}(J_1, J_2) = \left[ E_T(J_1) + E_T(J_2) \right]^2 - \left[ p_T(J_1) - p_T(J_2) \right]^2 \]
  \[ = 2p_T(J_1)p_T(J_2)(1 + \cos \Delta \phi(J_1, J_2)). \]
- Important variable to characterize signal
  - Endpoint at the mass of the sparticle:
    \[ m_{\text{CT}}^{\text{max}} = \frac{m^2(\tilde{b}) - m^2(\tilde{\chi}_1^0)}{m(\tilde{b})}. \]
- 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

$\chi^0_2/\chi^\pm_1$: Wino-like
$\chi^0_1$: Bino-like
EWK SUSY $[\tilde{\chi}^{\pm}/\tilde{\chi}^0]$ (2)

- WZ-mediated direct production of $\chi^0/\chi^{\pm}$
- Multiple search regions with large $M_{T}$ and $M_{T}[lW, M_{T}]$:
  - 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

HL-LHC: significant impact on mass reach \([\rightarrow\text{TeV scale}]\)

- 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
Both LHC-Run2 & HL-LHC important for SUSY hunting

Optimistic scenario [or scenario 1]:

- Discover/Observe SUSY at LHC [\(~\text{TeV scale}\)] 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 [\(\geq O(10 \text{ TeV})\)]
- 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 $\sim$1% fine tuning
- Collider @100 TeV: probe theories $\sim$0.01% fine tuning
  [N. Arkani-Hamed FCC Feb’14]

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

Cohen et al.
hep-ph:1311.6480

Cohen et al.
Compressed spectra: challenging scenarios
- Need excellent understanding of uncertainties, usage of shape fits or multivariate techniques
- Selection: 1 hard ISR jet, low $N_{\text{jets}}$ [not aligned to $M_{E_T}$]

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]

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)
- √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](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies)

- **CMS:**
  - [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP)
FCC 100 TeV

Compressed spectra
FCC 100 TeV
FCC 100 TeV