Compressed Mass Scenarios via VBF Dijet and ISR Jet Tagging at Future Circular Hadron Colliders

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VHEPP Physics Seminar
Fermilab, July 23, 2015
A 100-TeV collider is powerful in producing heavy objects.

<table>
<thead>
<tr>
<th>Hadron Collider (*(\sqrt{s}))</th>
<th>Gluino/Squark Mass Reach (M)</th>
<th>(M/\sqrt{s})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron (2 (\text{TeV}))</td>
<td>(\sim 400 \text{ GeV})</td>
<td>0.20</td>
</tr>
<tr>
<td>LHC (8 (\text{TeV}))</td>
<td>(\sim 1.7 \text{ TeV})</td>
<td>0.21</td>
</tr>
<tr>
<td>LHC (14 (\text{TeV}))</td>
<td>(\sim 2.8 \text{ TeV}^*)</td>
<td>0.20*</td>
</tr>
<tr>
<td>FCC (100 (\text{TeV}))</td>
<td>(\sim 20 \text{ TeV}^*)</td>
<td>0.20*</td>
</tr>
</tbody>
</table>

(*) just use a naïve scaling

- Understanding the limitations at the LHC14 will be an important step for FCC100pp
- Today’s talk – selected topics on SUSY Searches via VBF dijet and ISR jet tagging from present results and/or prospects
- Summary
100-300 TeV pp Collider

http://arxiv.org/abs/1402.5973

270 km x $3000/m = $810M

CMS via VBF/ISR at FCC
Table 3. Main parameters of hadron colliders of 100 and 270 km circumference.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Higgs factory</th>
<th>hadron collider</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Collision energy</td>
<td>0.24</td>
<td>100</td>
</tr>
<tr>
<td>Dipole field</td>
<td>0.046</td>
<td>15</td>
</tr>
<tr>
<td>Luminosity/L.P.</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$\beta^*$</td>
<td>50x0.1</td>
<td>110</td>
</tr>
<tr>
<td>Total synch. power</td>
<td>100</td>
<td>4.2</td>
</tr>
<tr>
<td>Critical energy</td>
<td>430</td>
<td>4.0</td>
</tr>
<tr>
<td>Synch power/meter/bore</td>
<td>580</td>
<td>26</td>
</tr>
<tr>
<td>Emittance damping time</td>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>Luminosity lifetime</td>
<td>0.3</td>
<td>18</td>
</tr>
<tr>
<td>Energy loss/turn</td>
<td>2100</td>
<td>4.3</td>
</tr>
<tr>
<td>RF accel. voltage:</td>
<td>6000</td>
<td>100</td>
</tr>
<tr>
<td>Acceleration time</td>
<td>.01</td>
<td></td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>250</td>
<td>50</td>
</tr>
<tr>
<td>Beam-beam tune shift</td>
<td>0.09</td>
<td>.01</td>
</tr>
<tr>
<td># IPs</td>
<td>4</td>
<td>2+2</td>
</tr>
<tr>
<td># particles per beam</td>
<td>4.1</td>
<td>100</td>
</tr>
<tr>
<td>Injection energy</td>
<td>0.12</td>
<td>$&gt;3$</td>
</tr>
<tr>
<td>Superconducting temp.</td>
<td>1.8 K in SRF</td>
<td>4.5</td>
</tr>
</tbody>
</table>
Questions

- What do we do with (i) really heavy 1st/2nd generation squarks and/or gluino, and (ii) small $\Delta M$ (mass difference between NLSP and LSP)?
- How can we probe Compressed SUSY Scenarios at hadron collides?
  1) Tagging energetic jets (+ MET) from cascade decays
  2) Tagging leptons
  3) Tagging photons
  4) Tagging with timing, vetexing
  5) ISR jet, VBF dijet
- Let me focus on ISR and VBF

![ISR jet tagging and VBF-like dijet tagging](image)
Many papers to discuss the cases for e+e- colliders. See, for example, below:


Selected Papers on ISR and VBF


Chengcheng Han, Archil Kobakhidze, Ning Liu, Aldo Saavedra, Lei Wu and Jin Min Yang, “Probing light higgsinos in natural SUSY from monojet signals at the LHC,” JHEP 02 (2014) 049 [1310.4274]

Pedro Schwaller and Jose Zurita, “Compressed electroweakino spectra at the LHC”. JHEP 03 (2014) 060 [1312.7350]

Howard Baer, Azar Mustafayev, Xerxes Tata, “Monojets and mono-photons from light higgsino pair production at LHC14”, PRD 89 (2014) 055007 [1401.1162]


Howard Baer, Azar Mustafayev and Xerxes Tata, “Monojet plus soft dilepton signal from light higgsino pair production at LHC14”, PRD 90 (2014) 115007 [1409.7058]

Zhenyu Han and Yandong Liu, “MT2 to the rescue -- searching for sleptons in compressed spectra at the LHC”, PRD 92 (2015) 015010 [1412.0618]
Selected Papers on ISR and VBF


Selected Papers on ISR and VBF


CMS via VBF/ISR at FCC
FIG. 1: Production cross section as a function of $m_{\tilde{\chi}_1^0}$ after requiring $|\Delta \eta(j_1,j_2)| > 4.2$, at LHC8 and LHC14. For the pure Wino and Higgsino cases, inclusive $\tilde{\chi}_1^0\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^0\tilde{\chi}_1^\mp$, and $\tilde{\chi}_1^\pm\tilde{\chi}_1^0$ production cross sections are displayed.
ISR Invisible vs. VBF Invisible

- One energetic jet, $p_T > 110$ GeV, $|\eta| < 2.4$, and allow an additional jet ($p_T > 30$ GeV)
- $\text{MET} > 250$ GeV $\rightarrow 500$ GeV
- Veto event if $j_3 \ p_T > 30$ GeV Veto event if $\Delta \phi(j_1, j_2) > 2.5$
- Veto event if they contain isolated electrons or muons with $p_T > 10$ GeV; or hadronic tau with $> 20$ GeV

- VBF tag jet pair, $p_{T,j1}, p_{T,j2} > 50$ GeV, $|\eta| < 4.7$, $\eta_{j1} \times \eta_{j2} < 0$, $\Delta \eta_{jj} > 4.2$, and $M_{jj} > 1100$ GeV; $\Delta \phi(j_1, j_2) < 1.0$
- $\text{MET} > 130$ GeV
- Central jet veto (event that has an additional jet with $p_T > 30$ GeV and pseudorapidity between those of the two tag jets); Lepton veto with $p_T > 10$ GeV.
ISR Invisible vs. VBF Invisible

**Z/W ratio ~ 3**

<table>
<thead>
<tr>
<th>$E_T^{\text{miss}}$ (GeV)</th>
<th>&gt; 400</th>
<th>&gt; 450</th>
<th>&gt; 500</th>
<th>&gt; 550</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z(\nu\bar{\nu})+jets$</td>
<td>2740 ± 220</td>
<td>1460 ± 140</td>
<td>747 ± 96</td>
<td>362 ± 64</td>
</tr>
<tr>
<td>$W+jets$</td>
<td>1030 ± 65</td>
<td>501 ± 36</td>
<td>249 ± 22</td>
<td>123 ± 13</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>31 ± 16</td>
<td>15 ± 7.7</td>
<td>6.6 ± 3.3</td>
<td>2.8 ± 1.4</td>
</tr>
<tr>
<td>$Z(\ell\ell)+jets$</td>
<td>8.9 ± 4.4</td>
<td>5.2 ± 2.6</td>
<td>2.3 ± 1.2</td>
<td>1.0 ± 0.5</td>
</tr>
<tr>
<td>Single $t$</td>
<td>6.1 ± 3.1</td>
<td>0.9 ± 0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QCD Multijets</td>
<td>4.9 ± 3.0</td>
<td>2.0 ± 1.2</td>
<td>1.0 ± 0.6</td>
<td>0.5 ± 0.3</td>
</tr>
<tr>
<td>Diboson</td>
<td>118 ± 59</td>
<td>65 ± 33</td>
<td>36 ± 18</td>
<td>20 ± 10</td>
</tr>
</tbody>
</table>

**Total SM**

3930 ± 230 2050 ± 150 1040 ± 100 500 ± 66

**Data**

3830 1830 934 519

**Exp. upper limit +1σ**

639 410 221 187

**Exp. upper limit -1σ**

357 168 123 104

**Exp. upper limit**

452 266 173 137

**Obs. upper limit**

397 154 120 142

**Z/W ratio ~ 1/2**

<table>
<thead>
<tr>
<th>Process</th>
<th>Event yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z(\nu\bar{\nu})+jets$</td>
<td>99 ± 29 (stat) ± 25 (syst)</td>
</tr>
<tr>
<td>$W(\mu\nu)+jets$</td>
<td>67 ± 5 (stat) ± 16 (syst)</td>
</tr>
<tr>
<td>$W(e\nu)+jets$</td>
<td>63 ± 9 (stat) ± 18 (syst)</td>
</tr>
<tr>
<td>$W(\tau\nu)+jets$</td>
<td>53 ± 18 (stat) ± 18 (syst)</td>
</tr>
<tr>
<td>QCD multijet</td>
<td>31 ± 5 (stat) ± 23 (syst)</td>
</tr>
<tr>
<td>Sum (t\bar{t}, single top quark, VV, DY)</td>
<td>20.0 ± 8.2 (syst)</td>
</tr>
</tbody>
</table>

**Total background**

332 ± 36 (stat) ± 45 (syst)

**VBF H(inv.)**

210 ± 29 (syst)

**ggH (inv.)**

14 ± 10 (syst)

**Observed data**

390

**S/B**

70%

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**Lepton ID Better with low $p_T$, large $\eta$**

**CMS via VBF/ISR at FCC**

$$\sqrt{s} = 8\text{ TeV}, L = 19.5\text{ fb}^{-1}$$

**VBF H(inv.)**

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**Teruki Kamon**
DM particles have the direct couplings to the SM Higgs boson sector, $H \rightarrow \chi \chi$: (a) Limits on branching fraction of Higgs to “invisible” particles used for limits on DM, (b) Scalar, vector or fermionic couplings, (c) Limits only up to DM mass $M_\chi < M_H/2$
ISR Invisible vs. VBF Invisible


[Beyond EFT approach] See, for example, S. Baek, P. Ko, and W. Park, PRD 90 (2014) 055014 [1405.3530] for explicit expressions within UV completions

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CMS via VBF/ISR at FCC
VBF Invisible $\Delta\phi(jj)$

PLB 495 (2000) 147
arXiv:0009158

Auxiliary plot using PGS4 using the cuts in PRL 111 (2013) 061801

FIG. 3. Distributions of the azimuthal angle separation between the two tagging jets for the various background processes and the Higgs signal at $M_H = 120$ and 300 GeV. Results are shown after applying the cuts (1-3) and including the effect of a central jet veto with the survival probabilities of Table I. The lines follow the same convention as in Fig. 1.

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CMS via VBF/ISR at FCC
“Lost-lepton” is a dominant BG source in many SUSY searches. It depends on performance of the forward detector system (tracker, muon, and calorimeter).

The VBF SUSY was one of representative CMS SUSY projections for the ECFA (European Committee for Future Accelerator) workshop in 2013 [CMS PAS FTR-13-014 “Study of the Discovery Reach in Searches for Supersymmetry at CMS with 3000 fb⁻¹”].

One of key conclusions was “… the possible gain from extending the tracker up to a pseudo-rapidity of four is studied for vector boson fusion processes.”

Pile-ups: Ultra-fast timing on forward calorimeter to reject out-of-time jets?
Next Gen. Searches via VBF

- The final state is same as invisible Higgs signal, but larger $p_T$ jets
- Cross section?
  - Wino-like DM
  - Bino-Higgsino DM
- Example, disappearing tracks?

$jj + MET + X$

CMS-EXO-12-034, JHEP 01 (2015) 096 [1411.6006]
Search for disappearing tracks in events with jet $p_T > 100$ GeV, MET > 100 GeV for direct production of C1N2 and C1C1.

$\Delta M = M(\tilde{\chi}_1^\pm) - M(\tilde{\chi}_1^0) \sim 100$ MeV
$\Rightarrow Br(\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm) \sim 100\%$
$P_T(\pi^\pm) \sim \Delta M \sim 100$ MeV
**“Long-Lived” (LL) Interpretations**

[EXO-13-006] “Constraints on the pMSSM, AMSB model and on other models from the search for LL charged particles in proton-proton collisions at $\sqrt{s} = 8$ TeV”, accepted for publication in EPJC

[EXO-12-034, JHEP 01 (2015) 096] Search for disappearing tracks in proton-proton collisions at $\sqrt{s} = 8$ TeV” … Disappearing tracks (as a signature of LL particle decaying inside the CMS detector) are identified as those with little or no associated calorimeter energy deposits and with missing hits in the outer layers of the tracker. Limits are set on the cross section of direct electroweak chargino production in terms of the chargino mass and mean proper lifetime.
Wino DM with ISR, VBF and DT

Wino DM with ISR, VBF and DT

Light Higgsinos in MonoJet

Detecting light Higgsinos in ISR jet tagging (Monojet events). See arXiv:1310.4274(*) for example. See also the next page. We see a reach at \( \sim 200 \text{ GeV} \) at 14 TeV \( \rightarrow 100 \text{ TeV} \)?

(*) Chengcheng Han, Archil Kobakhidze, Ning Liu, Aldo Saavedra, Lei Wu and Jin Min Yang, “Probing light higgsinos in natural SUSY from monojet signals at the LHC,” JHEP 02 (2014) 049 [arXiv:1310.4274]
# More on Higgsinos with ISR Jet

<table>
<thead>
<tr>
<th>arXiv:</th>
<th>Authors:</th>
<th>Channel:</th>
<th>$\Delta m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1409.7058</td>
<td>Baer, Tata, Mustafayev</td>
<td>1 jet + OSSF 2 leptons + MET</td>
<td>10 GeV</td>
</tr>
<tr>
<td>1401.1235</td>
<td>Han, Kribs, Martin, Menon</td>
<td>1 jet + 2 leptons + MET</td>
<td>5-50 GeV</td>
</tr>
<tr>
<td>1312.735</td>
<td>Schwaller, Zurita</td>
<td>1 jet + (0,1,2) leptons + MET</td>
<td>&lt; 5 GeV</td>
</tr>
</tbody>
</table>

**Mass Reach:**
- 1409.7058: 250 GeV
- 1401.1235: $\mu = 165$ GeV
- 1312.735: 170 GeV

- [3 $\sigma$, 1000 fb$^{-1}$]
- [3 $\sigma$, 100 fb$^{-1}$]
- [3 $\sigma$, 3000 fb$^{-1}$]

- No systematic error
- Systematics not clear
- 1% systematic error

**Backgrounds:**
- 1409.7058: $t\bar{t}$
- $Z/\gamma^*(\rightarrow \tau^+ \tau^-) + j \rightarrow l + l - j + MET$
- $WW + j$
- $Z(\rightarrow \nu \bar{\nu}) + j$ & $Z/\gamma^*(\rightarrow l + l - j)$
- $tW, tq$
- $Z(\rightarrow \nu \bar{\nu}) + b\bar{b} +$ jets
- $W(\rightarrow l \nu) + Z(\rightarrow l\ell / \tau \tau) + j$
- ...

**Cuts:**
- MET $> 100$ GeV
- $p_T(j1) > 100$ GeV
- $|\eta(j1)| < 2.5$
- N(jet) = 1
- b-veto
- N(lep) $\geq$ 2
- $m(\tau \tau)^2 < 0$
- OS/SF
- $m(ll) < 10$ GeV
- ...

- MET $> 100$ GeV
- $p_T(j1) > 100$ GeV
- $|\eta(j1)| < 2.5$
- N(jet) = 1
- b-veto
- N(lep) $\geq$ 2
- 2 isolated leptons
- $m(\tau \tau) > 150$
- ...

- MET $> 300$ GeV
- $p_T(j1) > 300$ GeV
- N(jet) $\leq$ 2
- $\Delta \phi(j1,j2) > 2.5$
- e, $\mu$, $\tau$ veto
- Additional
- MET, $p_T(j1) > 500$-700 GeV
- $p_T(j2) < 100$, $|\eta(j2)| < 2$
Wino and Higgsinos via VBF


Given a systematic uncertainty of 5% with 3000 fb⁻¹

[LHC14] 125 GeV Winos and 55 GeV Higgsinos

[100 TeV] 750 GeV Winos and 180 GeV Higgsinos

[Comments]

🔍 The forward detector system (tracking, calorimeter, muon) must be good for lepton veto and vertexing for forward jets.

🔍 Ultra-fast timing on forward calorimeter for trigger?

🔍 Central tracking, calorimeter, muon - lepton ID from 5 GeV??

<table>
<thead>
<tr>
<th>Cut</th>
<th>14 TeV Wino</th>
<th>14 TeV Higgsino</th>
<th>100 TeV Wino</th>
<th>100 TeV Higgsino</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{\text{jet}}$</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$</td>
<td>\eta(j)</td>
<td>$</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$p_T(j_{\text{tag}})$ (GeV)</td>
<td>45</td>
<td>45</td>
<td>75</td>
<td>50</td>
</tr>
<tr>
<td>$\Delta\eta(j_1,j_2)$</td>
<td>3.75</td>
<td>3.75</td>
<td>4.25</td>
<td>4.25</td>
</tr>
<tr>
<td>$\Delta\phi(j_1,j_2)$</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>$M(j_1,j_2)$ (TeV)</td>
<td>2</td>
<td>1</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>$E_T$ (GeV)</td>
<td>400 - 700</td>
<td></td>
<td>1100 - 2500</td>
<td></td>
</tr>
<tr>
<td>$p_T(j_{\text{veto}})$ (GeV)</td>
<td>45</td>
<td>45</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>$p_T(e, \mu)$ (GeV)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>$p_T(\tau)$ (GeV)</td>
<td>30</td>
<td>30</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>$\eta(e)$</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>$\eta(\mu)$</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>$\eta(\tau)$</td>
<td>2.3</td>
<td>2.3</td>
<td>2.3</td>
<td>2.3</td>
</tr>
</tbody>
</table>

We want to lower lepton $p_T$ threshold and cover larger $\eta$ coverage for future detector.
[Abstract] Discovering dark matter at high energy colliders continues to be a compelling and well-motivated possibility. Weakly interacting massive particles are a particularly interesting class in which the dark matter particles interact with the standard model weak gauge bosons. Neutralinos are a prototypical example that arise in supersymmetric models. In the limit where all other superpartners are decoupled, it is known that for relic density motivated masses, the rates for neutralinos are too small to be discovered at the Large Hadron Collider (LHC), but that they may be large enough for a 100 TeV collider to observe. In this work we perform a careful study in the vector boson fusion channel for pure winos and pure higgsinos. We find that given a systematic uncertainty of 1% (5%), with 3000 fb$^{-1}$, the LHC is sensitive to winos of 240 GeV (125 GeV) and higgsinos of 125 GeV (55 GeV). A future 100 TeV collider would be sensitive to winos of 1.1 TeV (750 GeV) and higgsinos of 530 GeV (180 GeV) with a 1% (5%) uncertainty, also with 3000 fb$^{-1}$. 
Top Squark Decay Modes

$\Delta m = m_{\tilde{t}} - m_{\tilde{h}}^0 \quad \Delta m < 0$

$\tilde{t} \rightarrow c + \tilde{\chi}_1^0$

$\tilde{t} \rightarrow b + W + \tilde{\chi}_1^0$

$\tilde{t} \rightarrow t + \tilde{\chi}_1^0$

(1) (off-shell W) (2) (off-shell top) (3) (on-shell top)

$P_1$ $P_2$

Teruki Kamon

CMS via VBF/ISR at FCC
Top Squark Results at 8 TeV

ICHEP 2014

CMS Preliminary
\( s = 8 \) TeV

\[ \tilde{t}\tilde{t} \text{ production, } \tilde{t} \rightarrow t \tilde{\chi}_1^0 / c \tilde{\chi}_1^0 \]

\[ m_{\tilde{t}1} [\text{GeV}] \]

\[ m_{W} \text{ vs } m_{\text{top}} \]

Teruki Kamon

CMS via VBF/ISR at FCC
MET in Compressed Top Squark 8 TeV

ICHEP 2014

CMS-SUS-14-001

$\tilde{t}\tilde{t}$ production, $\tilde{t} \rightarrow t \tilde{\chi}_1^0 / c \tilde{\chi}_1^0$

CMS Preliminary

$$s = 8 \text{ TeV}$$

ICHEP 2014

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CMS via VBF/ISR at FCC
3rd Generation Squark

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS14001

Accepted in JHEP [1503.08037]

[VBF] We expect a comparable result on compressed stop/sbottom.

CMS Preliminary 18.5 fb⁻¹ (8 TeV)
VBF as Tool for Compressed SUSY

VBF tagged jets (2 energetic jets with large $\Delta\eta$ separation: large $M(jj)$) in forward region, opposite hemispheres

VBF production topology in transverse plane
Challenging Compressed Stop

CMS Preliminary

pp→tt*, t→tχ^0, 1-lepton channel
SUS-13-011 BDT analysis

Expected 5σ discovery reach

m_{χ^0} [GeV]

m_{t'} - m_{χ^0} = m_W
m_{t'} - m_{χ^0} = m_t

5σ

8 TeV, 20 fb^{-1}
14 TeV, 300 fb^{-1} (conservative)
14 TeV, 300 fb^{-1} (optimistic)

(250, 240)
(300, 134)
ΔM = -7

(300, 120)
ΔM = +7

(400, 220)
ΔM = +7

(1312.1348)

(1403.2726) Δφ_{jj}

(700, 520)

Teruki Kamon
CMS via VBF/ISR at FCC
VBF+stops: 200-250 GeV at 2σ at 14 TeV

**VBF jj + stops**

**ISR jet + stops?**

**ISR γ + stops?**

**FIG. 1** (color online). Distributions of $\not{E}_T$ normalized to unity for signal (green horizontally dashed histogram) and $t\bar{t}$ + jets background (red diagonally dashed histogram) after VBF selections and lepton and $b$-jet requirements for the benchmark point with $m_t = 400$ GeV, $m_{\tilde{\chi}_1^0} = 220$ GeV.
Next Gen. Search for Compressed “X”


VBF $jj + sbottom$

ISR jet + sbottom?

ISR $\gamma + sbottom$?

VBF+sbottom: 541 (462) GeV at 95%CL (3\sigma) at 14 TeV & 50PU

$\tilde{b}_1, \tilde{\chi}_1^0$:

$m(\tilde{b}_1) - m(\tilde{\chi}_1^0) = 5$ GeV, $L_{int} = 300$ fb$^{-1}$

- $pp \rightarrow \tilde{b}_1\tilde{b}_1 jj$, 0b + 1b, NoPU
- $pp \rightarrow \tilde{b}_1\tilde{b}_1 jj$, 0b + 1b, 50PU
- $pp \rightarrow \tilde{b}_1\tilde{b}_1 jj$, 0b + 1b, 140PU

Significance

$m(\tilde{b}_1)$ [GeV]
Electroweak (EWK) Sector

- $\tilde{\chi}_2^0 - \tilde{\chi}_1^\pm$ production

CMS Preliminary
\(\sqrt{s} = 8\) TeV
ICHEP 2014

CMS via VBF/ISR at FCC

- Wino-Chargino and Bino-LSP
  - Up to ~700 and ~300 GeV for light slepton case
  - Up to 320 and 100 GeV for W and Z cases

- Lower limits for
  - heavy slepton
  - being Higgsinos
  - small mass difference (compressed spectra)
The first SUSY search of its kind ... in public (March 2015)
Inclusive muon trigger and diTau trigger
mu-mu, mu-e, mu-tau, tau-tau ; OS & LS

Run 2: VBF + soft lepton triggers

Terminate Kamon

CMS via VBF/ISR at FCC
SUSY VBF

MG5, |Δη| > 4.2

QCD2QED2 + QCD0QED4

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MG5, |Δη| > 4.2

QCD2QED2 + QCD0QED4

SUS-14-005

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CMS via VBF/ISR at FCC
SUSY VBF vs. Direct

**MG5, |Δη| > 4.2**

**QCD2QED2 + QCD0QED4**

**CMS Preliminary** 19.7 fb\(^{-1}\) (8 TeV)

$\chi^0_1 \rightarrow \tau \nu_\tau$, $\chi^0_2 \rightarrow \tau \tau$, $m_{\chi_1} - m_{\chi_0} = 5$ GeV

$\pm 1\sigma$, $m(\chi^0_2) - m(\chi^0_0) = 50$ GeV

$\pm 1\sigma$, $m(\chi^0_1) = 0$ GeV

$\sigma(pp \rightarrow \chi \chi)$ (LO)

$\sigma_{\text{theory}}$

$\sigma_{\text{experiment}}$

**SUS-14-005**

$x \sim 0.95$ (maximum sensitivity)

**CMS via VBF/ISR at FCC**

**EPJC 74 (2014) 3036 [1405.7570]**

$x = 0.5$ (maximum sensitivity)
SUSY + Another Higgs Wanted

- MSSM Higgs (e.g., $A^\pm$ and $H^+H^-$), Non-MSSM Higgs
- Colored Sectors
  - Gluinos
  - Heavier(?) 1st/2nd generation scalar quarks (squarks)
  - Lighter(?) 3rd generation squarks (stop, sbottom)
- Charginos ($C1, C2$), Neutralinos ($N1, N2, N3, N4$), decaying into:
  - Leptons, Higgs, $W, Z$
- LSP?
  - Lightest Neutralino ($N1$): Bino-like, Wino-like, Higgsino-like...

[Example] Higgsino LSP $\rightarrow$ chargino and neutralinos below 200 GeV, with mass splittings of order 10 GeV. It is very difficult for LHC to observe these particles.
  - Gravitino
- Sleptons
  - Selectrons and smuons - mass degenerate?
  - Special case: Stau is lighter.
- Displaced Tracks
- Long-Lived (LL)
- RPV + ???

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CMS via VBF/ISR at FCC
Run2 and Beyond

FCC will be powerful in producing heavy objects.

<table>
<thead>
<tr>
<th>Hadron Collider ( (\sqrt{s}) )</th>
<th>Gluino/Squark Mass Reach (M)</th>
<th>( M/\sqrt{s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron (2 TeV)</td>
<td>( \sim 400 \text{ GeV} )</td>
<td>0.20</td>
</tr>
<tr>
<td>LHC (8 TeV)</td>
<td>( \sim 1.7 \text{ TeV} )</td>
<td>0.21</td>
</tr>
<tr>
<td>LHC (14 TeV)</td>
<td>( \sim 2.8 \text{ TeV}^* )</td>
<td>0.20*</td>
</tr>
<tr>
<td>FCC (100 TeV)</td>
<td>( \sim 20 \text{ TeV}^* )</td>
<td>0.20*</td>
</tr>
</tbody>
</table>

(*) just use a naïve scaling

[Run1 at 8 TeV] the LHC8 has started probing a TeV physics: discovery of a Higgs boson with null results on BSM (or we may be seeing hints?).

[Run2 at 13 TeV] Exciting! Understanding the limitations of the LHC13 will be an important step toward the next energy frontier.

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CMS via VBF/ISR at FCC
100 TeV collider, powerful; “VBF” luminosity, stronger.

Physics menu with VBF dijet and ISR jet tagging: Invisible, Higgsino, Wino, Stop, Sbottom, Slepton

But, the forward detector system (tracking, calorimeter, muon) must be good for lepton veto and vertexing for forward jets.

Ultra-fast timing on VF calorimeter for trigger?

Central tracking, calorimeter, muon - lepton ID from 3-5 GeV??
Backups
90% CL observed upper (expected) limit on $B(H\to\text{inv}) = 0.51(0.38)$

95% CL observed upper (expected) limit on $B(H\to\text{inv}) = 0.58(0.44)$

Upper limits on the spin-independent DM-nucleon cross section in Higgs-portal models, derived for $m_H = 125\text{GeV}$, and $B(H\to\text{inv}) < 0.51$ at 90% CL, as a function of the DM mass.

Stop decay $\leftrightarrow$ Stop mixing & neutralino/chargino composition & $\Delta m = m_t - m_{\tilde{\chi}_1^0}$

<table>
<thead>
<tr>
<th>LSP</th>
<th>Allowed stop decays</th>
<th>Why</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\chi}_1^0 = \tilde{B}_3$</td>
<td>$\tilde{t}_L \rightarrow t_L \tilde{\chi}_1^0$ $\tilde{t}_R \rightarrow t_R \tilde{\chi}_1^0$</td>
<td>U(1) couples L to L and R to R SU(2) only acts on L Only couples to down-type</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0 = \tilde{W}_3$</td>
<td>$\tilde{t}_L \rightarrow t_L \tilde{\chi}_1^0$ none</td>
<td>Higgs couple L to R (mass term)</td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0 = \tilde{H}_d$</td>
<td>$\tilde{t}_L \rightarrow t_R \tilde{\chi}_1^0$ $\tilde{t}_R \rightarrow t_L \tilde{\chi}_1^0$</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\chi}_1^0 = \tilde{H}_u$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Top Squark Decay Modes

(m - on-shell top)

(0 - off-shell W)

$\tilde{t} \rightarrow t + \tilde{\chi}_1^0$

$\Delta m = m_t - m_{\tilde{\chi}_1^0}$
Monojet: Remarks

Limitation of EFT $\rightarrow$ Simplified Model with $M_*$

- EFT is valid when mediator mass ($M_*$) > a few TeV
- The couplings required are large comparing this with known couplings:
  - strong interaction $\sim 1.2$
  - weak interaction $\sim 0.6$
- Theory is non-perturbative if $\sqrt{g_q g_{DM}} > 4\pi$
- Width larger than mass, so unlikely mediator will be identified as a particle

- Region I: EFT limit is good!
- Region II: EFT limit is too weak!
- Region III: EFT limit is too strong!

See, for example, arXiv:1308.6799 for further reading.
- MET $> 140$ GeV
- One energetic photon, $p_T > 145$ GeV, $|\eta| < 1.4442$
- Veto on jets, leptons, and pixel seeds (hit pattern in the pixel detector) $\Delta\phi(\text{photon},\text{MET}) > 2$
- MinMET $> 120$ GeV, Prob($\chi^2$) (Reduce fake MET events)
Monophoton: Results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO12047

Vector operator
spin independent (SI)

\[ \mathcal{O}_V = \frac{(\bar{\chi} \gamma_\mu \chi)(\bar{q} \gamma^\mu q)}{\Lambda^2} \]

Axial-vector operator
spin-dependent (SD)

\[ \mathcal{O}_{AV} = \frac{(\bar{\chi} \gamma_\mu \gamma_5 \chi)(\bar{q} \gamma^\mu \gamma_5 q)}{\Lambda^2} \]
DM particles have the direct couplings to the SM Higgs sector, $H \rightarrow \chi \chi$

- Limits on branching fraction of Higgs to "invisible" particles used for limits on DM
- Can be scalar, vector or fermionic couplings
- Limits only up to DM mass $M_X < M_H/2$

- Veto events with an identified electron, or muon with $p_T > 10$ GeV.
- VBF tag jet pair, $p_{T,j1}, p_{T,j2} > 50$ GeV, $|\eta| < 4.7$, $\eta_{j1}, \eta_{j2} < 0$, $\Delta \eta_{jj} > 4.2$, and $M_{jj} > 1100$ GeV
- $MET > 130$ GeV
- $\Delta \phi(j1,j2) < 1.0$
- Central jet veto (event that has an additional jet with $p_T > 30$ GeV and pseudorapidity between those of the two tag jets)
Remark on Compressed “X”

- Displaced vertex
- Disappearing track
- Stable massive particle

"non-pointing" γ
"delayed" γ

CMS Dark Matter
Top/Bottom Squark Results at 8 TeV

**SUS-14-001**

**Fig. 9**

- **CMS**
  - Combined multijet t-tagged & dijet b-tagged searches
  - Monojet search
  - Observed only

- $m_{\tilde{\chi}_1^0}$ vs. $m_t$ (GeV)
- $m_{\tilde{b}}$ vs. $m_b$ (GeV)
- $m_t^2 = m_{\tilde{t}}^2 = m_{\tilde{\chi}_1^0}^2$
- $m_{\tilde{b}}^2 = m_{\tilde{\chi}_1^0}^2$
- $m_{\tilde{b}}^2 + m_{\tilde{\chi}_1^0}^2 = m_t^2$

- $Br(\tilde{t} \rightarrow t \tilde{\chi}_1^0) = \text{variable}$
- $Br(\tilde{t} \rightarrow c \tilde{\chi}_1^0) = 100\%$
- Observed only

**SUS-14-001**

**Fig. 10**

- **CMS**
  - Combined monojet & dijet b-tagged searches
  - $Br(\tilde{b} \rightarrow b \tilde{\chi}_1^0) = 100\%$

- $m_{\tilde{\chi}_1^0}$ vs. $m_b$ (GeV)
- Observed $\pm 1 \sigma_{\text{th}}$
- Expected $\pm 1 \sigma_{\text{Exp}}$

- NLO-NLL exclusion
3rd Generation Squark

CMS Preliminary

- **Observed**
  - SUS-13-011 1-lep (MVA) 19.5 fb^{-1}
  - SUS-14-011 0-lep + 1-lep + 2-lep (Razor) 19.3 fb^{-1}
  - SUS-14-011 0-lep (Razor) + 1-lep (MVA) 19.3 fb^{-1}
  - SUS-13-009 (monojet stop) 19.7 fb^{-1} (\bar{t} \rightarrow c \tilde{\chi}_1^0)
  - SUS-13-015 (hadronic stop) 19.4 fb^{-1}

- **Expected**

**ICHEP 2004**

**CMS Dark Matter**

SUS-14-001 [1503.08037]

- SUS-13-009 (monojet stop)
- SUS-13-015 (stop)
- SUS-13-018 (sbottom)

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Monojet/Monophoton

- One energetic jet, $p_T > 110$ GeV, $|\eta| < 2.4$, and allow an additional jet ($p_T > 30$ GeV); MET > 250 GeV
- Veto event if $j_3 p_T > 30$ GeV
- Veto event if they contain isolated electrons or muons with $p_T > 10$ GeV; or hadronic tau with $> 20$ GeV

One energetic photon, $p_T > 145$ GeV, $|\eta| < 1.4442$; MET > 140 GeV
- Veto on jets, leptons, and pixel seeds (hit pattern in the pixel detector)
- $\Delta \phi(\text{photon,MET}) > 2$
- MinMET > 120 GeV, Prob($\chi^2$) (Reduce fake MET events)
EFT ($\Lambda$) $\Rightarrow$ a minimal framework ($M^*$, couplings, DM types) for a comprehensive interpretation of collider results with other experiments (e.g., Direct Detection). See O. Buchmueller, S. Malik, M. Dolan, and C. McCabe, arXiv:1407.8257

Region I: EFT limit is good!
Region II: EFT limit is too weak!
Region III: EFT limit is too strong!

- EFT is valid for heavy mediator mass ($M_*$) $>$ a few 10 TeV; The couplings required are large comparing this with known couplings:
- Theory is non-perturbative if $\sqrt{g_q g_{DM}} > 4\pi$
- Width larger than mass, so unlikely mediator will be identified as a particle
DM with Rasor

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO14004

$\Lambda = \text{Contact interaction scale}$

Results are comparable to those in the CMS monojet analysis.
Monolepton ($W \rightarrow l \nu$) and Monotop ($jjb$)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO13004

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G12022

PRL 114 (2015) 101801 [1410.1149]

[Note] $\xi = -1$ and 0 are not gauge invariant simplified models

Vector operator
spin independent (SI)

$10^{-40}$

CMS preliminary 2012 20 fb$^{-1}$ $\sqrt{s} = 8$ TeV

$\chi$-nucleon $\sigma$ (cm$^2$)

$\chi$-nucleon $\sigma$ (cm$^2$)

DM coupling set to 0.1 for $q = u/d$ [1106.6199]

Exclude scalar (vector) DM masses below 327 (655) GeV

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CMS Dark Matter