The BSM Physics Case for Future Hadron Colliders

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@ LHCP, June 9, 2021
Why Future Hadron Colliders?

There are plenty of good Standard Model answers, but this talk focuses on possibilities beyond the Standard Model.

What are the new qualitative insights about nature we would obtain from a higher-energy hadron collider?
1. Dark Matter

2. Higgs Potential / Phase Transition

3. Deciphering New Physics
SU(2) Multiplet Dark Matter

WIMPs in pure SU(2) multiplets have
\[ \tilde{\chi}^0 \tilde{\chi}^0 \rightarrow W^+ W^- \]
annihilation. Indirect detection severely constrains winos*; constrains *higgsinos* mildly.

The xenon-based experiments have strongly constrained WIMPs coupling to the Higgs boson.

* Cohen, Lisanti, Pierce, Slatyer 1307.4082
* Fan, MR 1307.4400

Krall, MR 1705.04843, using work of Cuoco, Krämer, Korsmeier 1610.03071
SU(2) multiplets dominantly scattering through loops are a real challenge, beyond the next generation of experiments.
Future Indirect Detection: CTA

Forecast Higgsino limits split. 2 - Core size

\[ \delta m_N = 2 \text{ GeV} \]
\[ \delta m_+ = 480 \text{ MeV} \]

Sensitive to mass splittings, DM profile in galactic center.

Macias, Moulin, Rinchiuso, Rodd, Slatyer 2008.00692
SU(2) Multiplet DM at 100 TeV

M Low and L-T Wang: 1404.0682

Notice **wide bands**: varying background systematics 1-2%. Big exp. challenge is well-characterized background!

Monojet searches cover much of the higgsino range.

some other 100 TeV SUSY DM studies: Cirelli, Sala, Taoso 1407.7058 (disappearing tracks for winos); Acharya, Bozek, Pongkitivanichkul, Sakurai 1410.1532 (wino->higgsino); Gori, Jung, Wang Wells 1410.6287 (multilepton, dilepton)
The mildly long lifetime of a chargino can provide an additional handle on the very pure higgsino corner of parameter space:

Fukuda, Nagata, Otono, Shirai 1703.09675

Mahbubani, Schwaller, Zurita 1703.05327
1. Dark Matter

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Electron/positron colliders: \[ \sigma(e^+e^- \rightarrow hZ) \approx 200 \text{ fb} \]

(at the peak of the cross section, c.m. energy \( \sim 250 \text{ GeV} \))

So 5/ab of data (CEPC or FCC-ee) leads to \(10^6\) Higgses. Very clean, so \(\sim0.1\%\) measurement of Higgs coupling to \(Z\).

Proton/proton collider: gluon fusion rate \(\sim 50 \text{ pb} \) @ 14 TeV and \(\sim 800 \text{ pb} \) @ 100 TeV.

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsEuropeanStrategy

1503.06056 Anastasiou, Duhr, Dulat, Herzog, Mistlberger N^3LO; CERN 100 TeV report

The true Higgs factories are hadron machines! Messier environment, but: LHC will measure \(\text{Br}(h \rightarrow \gamma\gamma)/\text{Br}(h \rightarrow ZZ^*)\) better than any planned future e+e- collider. Also great for rare decays. (Curtin et al. 1312.4992 Exotic Decays survey)
# Precision Higgs Measurements

Table 1.2: Target precision for the parameters relative to the measurement of various Higgs decays, ratios thereof, and of the Higgs self-coupling $\lambda$. Notice that Lagrangian couplings have a precision that is typically half that of what is shown here, since all rates and branching ratios depend quadratically on the couplings.

<table>
<thead>
<tr>
<th>Observable</th>
<th>Parameter</th>
<th>Precision (stat)</th>
<th>Precision (stat+syst+lumi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu = \sigma(H) \times B(H \rightarrow \gamma\gamma)$</td>
<td>$\delta \mu/\mu$</td>
<td>0.1%</td>
<td>1.45%</td>
</tr>
<tr>
<td>$\mu = \sigma(H) \times B(H \rightarrow \mu\mu)$</td>
<td>$\delta \mu/\mu$</td>
<td>0.28%</td>
<td>1.22%</td>
</tr>
<tr>
<td>$\mu = \sigma(H) \times B(H \rightarrow 4\mu)$</td>
<td>$\delta \mu/\mu$</td>
<td>0.18%</td>
<td>1.85%</td>
</tr>
<tr>
<td>$\mu = \sigma(H) \times B(H \rightarrow \gamma\mu\mu)$</td>
<td>$\delta \mu/\mu$</td>
<td>0.55%</td>
<td>1.61%</td>
</tr>
<tr>
<td>$\mu = \sigma(HH) \times B(H \rightarrow \gamma\gamma)B(H \rightarrow b\bar{b})$</td>
<td>$\delta \lambda/\lambda$</td>
<td>5%</td>
<td>7.0%</td>
</tr>
<tr>
<td>$R = B(H \rightarrow \mu\mu)/B(H \rightarrow 4\mu)$</td>
<td>$\delta R/R$</td>
<td>0.33%</td>
<td>1.3%</td>
</tr>
<tr>
<td>$R = B(H \rightarrow \gamma\gamma)/B(H \rightarrow 2e2\mu)$</td>
<td>$\delta R/R$</td>
<td>0.17%</td>
<td>0.8%</td>
</tr>
<tr>
<td>$R = B(H \rightarrow \gamma\gamma)/B(H \rightarrow 2\mu)$</td>
<td>$\delta R/R$</td>
<td>0.29%</td>
<td>1.38%</td>
</tr>
<tr>
<td>$R = B(H \rightarrow \mu\mu\gamma)/B(H \rightarrow \mu\mu)$</td>
<td>$\delta R/R$</td>
<td>0.58%</td>
<td>1.82%</td>
</tr>
<tr>
<td>$R = \sigma(t\bar{t}H) \times B(H \rightarrow b\bar{b})/\sigma(t\bar{t}Z) \times B(Z \rightarrow b\bar{b})$</td>
<td>$\delta R/R$</td>
<td>1.05%</td>
<td>1.9%</td>
</tr>
<tr>
<td>$B(H \rightarrow \text{invisible})$</td>
<td>$B@95%CL$</td>
<td>$1 \times 10^{-4}$</td>
<td>$2.5 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

from: Future Circular Collider Study, Vol. 3 (FCC-hh CDR)
Singlet Scalar with Higgs Mixing

Resonant di-Higgs production: $h_2 \rightarrow 2h_1 \rightarrow 4\tau, b\bar{b}\gamma\gamma$

Parameter space with strongly first-order phase transition can be probed

Kotwal, No, Ramsey-Musolf, Winslow 1605.06123

(Also see 4b studies for HL-LHC by Li, Ramsey-Musolf, Willocq, 1906.05289)
Electroweak Phase Transition
“Nightmare” Scenario

Singlet scalar with a $\mathbb{Z}_2$ symmetry $\phi \mapsto -\phi$

$$V(h, \phi) = V_{SM}(h) + \frac{1}{2}M^2\phi^2 + c_\phi |H|^2\phi^2$$

No mixing with the Higgs boson. Stable, invisible.

After EWSB: $h\phi^2$ vertex. Light $\phi$: invisible width of Higgs. $m_\phi > \frac{1}{2}m_h$: difficult!

Curtin, Meade, Yu 1409.0005
The Higgs Portal Above Threshold

VBF $\phi\phi jj$ (forward jets) and gluon fusion

$\sqrt{s} = 100 \text{ TeV}$, $\int L dt = 3 \text{ ab}^{-1}$

$\sqrt{s} = 100 \text{ TeV}$, $\int L dt = 30 \text{ ab}^{-1}$

(Craig, Lou, McCullough, Thalapillil arXiv:1412.0258)
1. Dark Matter

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Why is the Higgs Mass 125 GeV?

In the MSSM, largely depends on the stop mass and $\tan \beta$.

In the simplest models, this points to $m_{\tilde{t}} \gtrsim 10\text{ TeV}$

Can we test this?
Partial discovery scenario

We may get only part of the spectrum. **Example: split SUSY.**
Scalars out of reach.
But the 100 TeV collider would be a **gluino factory:** \( \sim 10^5 \) to \( 10^7 \) gluinos

Can we learn where the scalars are?

**Agrawal, Fan, MR, Xue ’17** (also see Sato, Shirai, Tobioka ’12)
Scalar mass: collider benchmark

\[ M_2 > |\mu| > M_1 \]

\[ M_3 = 2 \text{ TeV}, \quad M_2 = 800 \text{ GeV}, \quad M_1 = 200 \text{ GeV}, \quad \text{and} \quad \mu = 400 \text{ GeV}. \]

Diagnostic of scalar mass:
rate of 1-loop

\[ \tilde{g} \rightarrow \tilde{H} + g \]

so find a hard jet and Z on one side of event

\[ H_T > 2 \text{ TeV}, \quad p_T^{\text{missing}} > 1 \text{ TeV}, \quad p_T(j_1) > 1 \text{ TeV}, \quad N_{\text{jet}} < 5, \quad \text{one leptonic Z} \ (80 \text{ GeV} < m_{\ell\ell} < 100 \text{ GeV}), \quad m_{j_1Z} > m_{\text{all other jets}}, \quad M_{T2}^{\ell\ell} > 80 \text{ GeV}. \]
Scalar mass: collider benchmark

\[ M_2 > |\mu| > M_1 \]

\[ M_3 = 2 \text{ TeV}, \quad M_2 = 800 \text{ GeV}, \quad M_1 = 200 \text{ GeV}, \quad \text{and} \quad \mu = 400 \text{ GeV}. \]

SM backgrounds:

\[ Z(\rightarrow \ell^+\ell^-) + Z(\rightarrow \nu\bar{\nu}) + \text{jets} \]

\[ t\bar{t} + Z(\rightarrow \ell^+\ell^-) \]
Tan beta: collider benchmark

\[ M_2 > |\mu| > M_1 \]

\[ M_3 = 2 \text{ TeV}, \quad M_2 = 800 \text{ GeV}, \quad M_1 = 200 \text{ GeV}, \quad \text{and} \quad \mu = 400 \text{ GeV}. \]

Off-diagonal Z boson coupling!

At \( \tan \beta = 1 \), get \( h + Z + \text{MET} \) but no \( Z + Z + \text{MET} \), so measure the \( Z + Z + \text{MET} \) rate in 4 leptons.

- 2 pairs, \( |m_{\ell\ell} - m_Z| < 10 \text{ GeV} \)
- \( p_T^{\text{missing}} > 150 \text{ GeV} \)
- \( \sum_{\text{visible}} |p_T| < 600 \text{ GeV} \)
Tan beta: collider benchmark

$$M_2 > |\mu| > M_1$$

$$M_3 = 2 \text{ TeV}, \quad M_2 = 800 \text{ GeV}, \quad M_1 = 200 \text{ GeV}, \quad \text{and} \quad \mu = 400 \text{ GeV}.$$ 

SM background:

$$Z(\rightarrow \ell^+ \ell^-) + Z(\rightarrow \ell^+ \ell^-) + Z(\rightarrow \nu \bar{\nu})$$
Testing the MSSM Higgs mass hypothesis

Precision physics at future hadron collider could answer **big question**: where does the Higgs mass come from?

Would open up **new big question**: where does the SUSY breaking scale come from?

Agrawal, Fan, MR, Xue ’17
Conclusions

Powerful physics motivations for a high-energy hadron collider at ~100 TeV:

- Decisive study of SU(2) multiplet dark matter
- Measure Higgs self-coupling
- Explore parameter space for strong first-order electroweak phase transition
- Very high mass reach for new particles

But also: factory for new particles at ~few TeV. Explore their properties in detail: not just hints, but really decipher the structure of new physics!
Could CP and Flavor Lead the Way?

EDM, 1-loop
electron-flavored

$10^{-32} \text{ e cm} \implies \sim 1 \text{ PeV (!)}$

EDM, 2-loop Barr-Zee

Anything Higgs+EWK

$10^{-32} \text{ e cm} \implies \sim 50 \text{ TeV (!)}$

$\mu \rightarrow e$, 1-loop, flavor violating

$10^{-19} \text{ on Al} \implies \sim 50+ \text{ TeV (!)}$

fig. from 1308.3653: Altmannshofer, Harnik, Zupan

(w/ electron Yukawa spurions on all diagrams)
EDM Precision on the Horizon

One of several parallel approaches:

Polyatomic Molecules (e.g., YbOH)

Electron EDM: $10^{-29} e \text{ cm} \rightarrow 10^{-32} e \text{ cm}$
Charged Lepton Flavor Violation

Source: Baldini et al., 1812.06540, submission to 2020 European Strategy from COMET, MEG, Mu2e and Mu3e collaborations