Di-Higgs Physics at Future Circular Colliders

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Naturalness

The Unexpected

Future Colliders

Dark Matter

DiHiggs 2020 – Opportunities and Challenges
T. D. Lee Institute, Shanghai Jiao Tong University
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Old and New Questions

- How to think of the vacuum as an “electroweak condensed state”?

- How are the mysteries associated with a single, fundamental scalar field solved?

- What is the origin and nature of Dark Matter?

- What is the origin of the Baryon Asymmetry in the Universe?

- Why is Dark Energy so small but non-zero?
Fundamental vs Parametric Physics

- **Fundamental principles lead to**
  - Chiral fermions from irreducible representations of Lorentz group
    - fermions as spin \( \frac{1}{2} \) representations of Lorentz group
    - Fermi-Dirac statistics → Pauli Exclusion Principle
    - why matter occupies volume
  - Massless force mediators (gauge bosons) from gauge invariance
  - Massive gauge bosons and fermions from spontaneous breaking of gauge symmetry

- **In comparison, the breaking of gauge symmetry by the Higgs VeV is parametrically induced**
  - No dynamic or underlying principle behind it in the Standard Model
Why is Higgs Puzzling

Gauge sector

\[ L = i \bar{\psi} \gamma^\mu D_\mu \psi - \frac{1}{2} F_{\mu \nu} F^{\mu \nu} \]

<table>
<thead>
<tr>
<th>particle</th>
<th>spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>quark: u, d,...</td>
<td>1/2</td>
</tr>
<tr>
<td>lepton: e...</td>
<td>1/2</td>
</tr>
<tr>
<td>photon</td>
<td>1</td>
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<tr>
<td>W, Z</td>
<td>1</td>
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<tr>
<td>gluon</td>
<td>1</td>
</tr>
<tr>
<td>Higgs</td>
<td>0</td>
</tr>
</tbody>
</table>

h: a new kind of elementary particle

Higgs sector

\[ L = \left( h_{ij} \bar{\psi}_i \psi_j H + \text{h.c.} \right) - \lambda |H|^4 + \mu^2 |H|^2 - \Lambda^4_{CC} \]
Why is Higgs Puzzling

Ad-hoc potential, similar to and motivated by Landau-Ginzburg theory of superconductivity

Higgs potential in SM can be extrapolated to Planck scale without additional parameters; but no a-priori reason for a parameterization to respect this condition
Higgs boson puzzles

- First fundamental (?) scalar field to be discovered
- Spontaneous symmetry breaking by development of a VeV
  - But VeV is induced parametrically by ad-hoc Higgs potential, no dynamics
- Parameters of Higgs potential are not stable under radiative corrections
  - First time that the radiative correction to a particle mass is additive and quadratically divergent
  - Gauge boson masses are protected by gauge invariance
  - Fermion masses are protected by chiral symmetry of massless fermions
- Single scalar Higgs field is a strange beast, compared to fermions and gauge bosons
- Additional symmetries and/or dynamics strongly motivated by Higgs discovery
Circular $pp$ Collider
Circular $pp$ Collider Physics Goals

• Testable reasons why the Standard Model must be incomplete
  - Dark Matter could be
    • Weakly-interacting particles
    • Particles interacting through Higgs portal
    • Interacting with SM particles through gravity
  - Electroweak Baryogenesis
    • Can the electroweak phase transition (formation of Higgs VeV) provide the out-of-equilibrium condition needed for matter-antimatter asymmetry observed?
  - Can the parameter space of new physics be a bounded parameter space?
    • Can it be fully covered with a 100-TeV scale $pp$ collider?

• Naturalness – the need to explain the lightness of the Higgs mass – testing Naturalness at $10^{-4}$
Higgs Self-Coupling

Expect $O(1)$ deviations from SM in self-coupling coefficient
## Rate comparisons at 8, 14, 100 TeV

<table>
<thead>
<tr>
<th>Process</th>
<th>$N_{100}$</th>
<th>$N_{100}/N_8$</th>
<th>$N_{100}/N_{14}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg\rightarrow H$</td>
<td>16 G</td>
<td>$4.2 \times 10^4$</td>
<td>110</td>
</tr>
<tr>
<td>VBF</td>
<td>1.6 G</td>
<td>$5.1 \times 10^4$</td>
<td>120</td>
</tr>
<tr>
<td>WH</td>
<td>320 M</td>
<td>$2.3 \times 10^4$</td>
<td>66</td>
</tr>
<tr>
<td>ZH</td>
<td>220 M</td>
<td>$2.8 \times 10^4$</td>
<td>84</td>
</tr>
<tr>
<td>$ttH$</td>
<td>760 M</td>
<td>$29 \times 10^4$</td>
<td>420</td>
</tr>
<tr>
<td>$gg\rightarrow HH$</td>
<td>28 M</td>
<td></td>
<td>280</td>
</tr>
</tbody>
</table>

$N_{100} = \sigma_{100\text{TeV}} \times 20\text{ ab}^{-1}$

$N_8 = \sigma_{8\text{TeV}} \times 20\text{ fb}^{-1}$

$N_{14} = \sigma_{14\text{TeV}} \times 3\text{ ab}^{-1}$

**Statistical precision:**
- $O(100 - 500)$ better w.r.t Run I
- $O(10 - 20)$ better w.r.t HL-LHC
Measuring the Higgs Self-Coupling

- $gg \rightarrow HH$ (most promising?), $qq \rightarrow HHqq$ (via VBF)
- Reference benchmark process: $HH \rightarrow bb \gamma\gamma$
- Goal: 5% (or better) precision for SM selfcoupling

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC$_{@100\text{TeV}}$ 3/ab</td>
<td>30~40%</td>
<td>30%</td>
<td>15%</td>
</tr>
<tr>
<td>FCC$_{@100\text{TeV}}$ 30/ab</td>
<td>10%</td>
<td>10%</td>
<td>5%</td>
</tr>
<tr>
<td>$S/\sqrt{B}$</td>
<td>8.4</td>
<td>15.2</td>
<td>16.5</td>
</tr>
<tr>
<td>Details</td>
<td>✓ $\lambda_{HHH}$ modification only</td>
<td>✓ Full EFT approach</td>
<td>✓ $\lambda_{HHH}$ modification only</td>
</tr>
<tr>
<td></td>
<td>✓ $c \rightarrow b$ &amp; $j \rightarrow \gamma$ included</td>
<td>✓ No $c \rightarrow b$ &amp; $j \rightarrow \gamma$</td>
<td>✓ $c \rightarrow b$ &amp; $j \rightarrow \gamma$ included</td>
</tr>
<tr>
<td></td>
<td>✓ Background systematics</td>
<td>✓ Marginalized</td>
<td>✓ Marginalized</td>
</tr>
<tr>
<td></td>
<td>✓ $b\bar{b}\gamma\gamma$ not matched</td>
<td>✓ $b\bar{b}\gamma\gamma$ matched</td>
<td>✓ $b\bar{b}\gamma\gamma$ matched</td>
</tr>
<tr>
<td></td>
<td>✓ $m_{\gamma\gamma} = 125 \pm 1$ GeV</td>
<td>✓ $m_{\gamma\gamma} = 125 \pm 5$ GeV</td>
<td>✓ $m_{\gamma\gamma} = 125 \pm 3$ GeV</td>
</tr>
<tr>
<td></td>
<td>✓ Jet $/W_{had}$ veto</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Work in progress to compare studies, harmonize performance assumptions, optimize, etc ⇒ ideal benchmarking framework
Origin of Matter-Antimatter Asymmetry
Origin of Baryon Asymmetry

**POSSIBLE EXPLANATIONS...**

\[
\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9} \text{ (from BBN)}
\]

⇒ **Baryogenesis at EW Scale**

⇒ ...

**SAKHAROV CONDITIONS** (for dynamical generation of baryon asymmetry)

- **B Violation** ✓ Sphalerons
  

- **C/CP Violation** ✗ not enough

- Departure from Thermal Equilibrium ✗ not enough
Baryon Asymmetry and Electroweak Phase Transition

1st Order:
\[ \langle \phi \rangle = 0 \rightarrow \langle \phi \rangle = \phi(T) \text{ Discontinuous} \]

2nd Order:
\[ \langle \phi \rangle = 0 \rightarrow \langle \phi \rangle = \phi(T) \text{ Continuous} \]

In the SM \((m_h = 125 \text{ GeV})\) EW Phase Transition Smooth CrossOver
Baryon Asymmetry and Electroweak Phase Transition

1st Order:

\[ \langle \phi \rangle = 0 \rightarrow \langle \phi \rangle = \phi(T) \text{ Discontinuous} \]

Nucleation of True Vacuum Bubbles
(in False Vacuum Sea)


Sudden change in Higgs VEV

\[ \langle \varphi \rangle \neq 0 \]
\[ \langle \varphi \rangle = 0 \]
\[ \langle \varphi \rangle \neq 0 \]
Inducing First-Order Electroweak Phase Transition

\[ V(H, S) = -\mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2 + \frac{a_1}{2} (H^\dagger H) S + \frac{a_2}{2} (H^\dagger H) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4 \]

\[ m_h^2 \equiv \frac{d^2V}{dh^2} = 2\lambda v_0^2 \]
\[ m_s^2 \equiv \frac{d^2V}{ds^2} = b_3 x_0 + 2b_4 x_0^2 - \frac{a_1 v_0^2}{4x_0} \]
\[ m_{hs}^2 \equiv \frac{d^2V}{dhds} = (a_1 + 2a_2 x_0) \frac{v_0}{2}. \quad (5) \]

with \( m_{hs}^2 \) being responsible for the singlet-doublet mixing. The corresponding mass eigenstates are given by

\[ h_1 = h \cos \theta + s \sin \theta \]
\[ h_2 = -h \sin \theta + s \cos \theta \quad (6) \]

Inducing First-Order Electroweak Phase Transition

\[
V(H, S) = -\mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2 + \frac{a_1}{2} (H^\dagger H) S
+ \frac{a_2}{2} (H^\dagger H) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4
\]

\[
\lambda_{211} = \frac{1}{4} \left[ (a_1 + 2a_2 x_0) \cos^3 \theta + 4v_0(a_2 - 3\lambda) \cos^2 \theta \sin \theta \\
+ (a_1 + 2a_2 x_0 - 2b_3 - 6b_4 x_0) \cos \theta \sin^2 \theta - 2a_2 v_0 \sin^3 \theta \right]
\]

(12)

and, along with the \( \sin^2 \theta \) rescaling, modifies the rate associated with the heavy Higgs production and decay. The partial width \( \Gamma_{h_2 \rightarrow h_1 h_1} \) is given by

\[
\Gamma_{h_2 \rightarrow h_1 h_1} = \frac{\lambda_{211}^2 \sqrt{1 - 4m_1^2/m_2^2}}{8\pi m_2}.
\]

(13)

Inducing First-Order Electroweak Phase Transition

\[ V(H, S) = -\mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2 + \frac{a_1}{2} (H^\dagger H) S + \frac{a_2}{2} (H^\dagger H) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4 \]

Defining \( \Gamma^{\text{SM}}(m_2) \) as the SM Higgs width evaluated at \( m_2 \), which we take from [34], the total width for the \( h_2 \) boson is given by

\[ \Gamma_{h_2} = \sin^2 \theta \ \Gamma^{\text{SM}}(m_2) + \Gamma_{h_2 \to h_1 h_1}. \]  

(14)

The resulting signal rate (normalized to the SM value) for \( pp \to h_2 \to XX \) (with \( XX \) representing all SM final states except \( h_1 h_1 \)) is

\[ \mu_{h_2 \to XX} = \sin^2 \theta \left( \frac{\sin^2 \theta \ \Gamma^{\text{SM}}(m_2)}{\Gamma_{h_2}} \right). \]  

(15)

Can TeV-scale new physics associated with 1\textsuperscript{st} order phase transition be completely covered by a $pp$ collider?
Inducing First-Order Electroweak Phase Transition

\[ V(H, S) = -\mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2 + \frac{a_1}{2} (H^\dagger H) S \]
\[ + \frac{a_2}{2} (H^\dagger H) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4 \]

FIG. 1: Left pane: Distribution of SFOEWPT points in \( m_2 \) vs \( \cos \theta \) space. Maximum (minimum) benchmark points are shown in green (magenta). Right pane: Maximum (minimum) cross section times branching ratio as a function of \( m_2 \) at a 100 TeV pp collider, taken from Table I (Table II), is displayed as a solid green (dashed magenta) line.

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Branching ratio</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}b\bar{b}$</td>
<td>$3.33 \cdot 10^{-1}$</td>
<td>$\pm 2.20 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$\tau\tau b\bar{b}$</td>
<td>$7.29 \cdot 10^{-2}$</td>
<td>$\pm 4.80 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$W^+(\to l\nu)W^-(\to l\nu)b\bar{b}$</td>
<td>$1.09 \cdot 10^{-2}$</td>
<td>$\pm 5.93 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$\tau\tau\tau\tau$</td>
<td>$3.99 \cdot 10^{-3}$</td>
<td>$\pm 4.55 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$\gamma\gamma b\bar{b}$</td>
<td>$2.63 \cdot 10^{-3}$</td>
<td>$\pm 1.58 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$W^+(\to l\nu)W^-(\to l\nu)\tau\tau$</td>
<td>$1.20 \cdot 10^{-3}$</td>
<td>$\pm 8.56 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$\gamma\gamma\tau\tau$</td>
<td>$2.88 \cdot 10^{-4}$</td>
<td>$\pm 2.19 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$b\bar{b}\mu^+\mu^-$</td>
<td>$2.53 \cdot 10^{-4}$</td>
<td>$\pm 1.73 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$Z(\to l^+l^-)Z(\to l^+l^-)b\bar{b}$</td>
<td>$1.41 \cdot 10^{-4}$</td>
<td>$\pm 7.64 \cdot 10^{-6}$</td>
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<tr>
<td>$b\bar{b}Z(\to l^+l^-)\gamma$</td>
<td>$1.21 \cdot 10^{-4}$</td>
<td>$\pm 1.16 \cdot 10^{-5}$</td>
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<tr>
<td>$W^+(\to l\nu)W^-(\to l\nu)W^+(\to l\nu)W^-(\to l\nu)$</td>
<td>$8.99 \cdot 10^{-5}$</td>
<td>$\pm 7.73 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$\gamma\gamma W^+(\to l\nu)W^-(\to l\nu)$</td>
<td>$4.32 \cdot 10^{-5}$</td>
<td>$\pm 2.85 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$\tau\tau\mu^+\mu^-$</td>
<td>$2.77 \cdot 10^{-5}$</td>
<td>$\pm 2.29 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$Z(\to l^+l^-)Z(\to l^+l^-)\tau\tau$</td>
<td>$1.54 \cdot 10^{-5}$</td>
<td>$\pm 1.10 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$\tau\tau Z(\to l^+l^-)\gamma$</td>
<td>$1.32 \cdot 10^{-5}$</td>
<td>$\pm 1.41 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$\gamma\gamma\gamma\gamma$</td>
<td>$5.20 \cdot 10^{-6}$</td>
<td>$\pm 5.20 \cdot 10^{-7}$</td>
</tr>
<tr>
<td>$W^+(\to l\nu)W^-(\to l\nu)\mu^+\mu^-$</td>
<td>$4.15 \cdot 10^{-6}$</td>
<td>$\pm 3.07 \cdot 10^{-7}$</td>
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<tr>
<td>$Z(\to l^+l^-)Z(\to l^+l^-)W^+(\to l\nu)W^-(\to l\nu)$</td>
<td>$2.31 \cdot 10^{-6}$</td>
<td>$\pm 1.41 \cdot 10^{-7}$</td>
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<tr>
<td>$W^+(\to l\nu)W^-(\to l\nu)Z(\to l^+l^-)\gamma$</td>
<td>$1.99 \cdot 10^{-6}$</td>
<td>$\pm 1.98 \cdot 10^{-7}$</td>
</tr>
<tr>
<td>$\gamma\mu^+\mu^-$</td>
<td>$9.99 \cdot 10^{-7}$</td>
<td>$\pm 7.80 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>$\gamma\gamma Z(\to l^+l^-)Z(\to l^+l^-)$</td>
<td>$5.57 \cdot 10^{-7}$</td>
<td>$\pm 3.67 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>$\gamma\gamma Z(\to l^+l^-)\gamma$</td>
<td>$4.78 \cdot 10^{-7}$</td>
<td>$\pm 4.92 \cdot 10^{-8}$</td>
</tr>
<tr>
<td>$Z(\to l^+l^-)Z(\to l^+l^-)\mu^+\mu^-$</td>
<td>$5.35 \cdot 10^{-8}$</td>
<td>$\pm 3.95 \cdot 10^{-9}$</td>
</tr>
<tr>
<td>$Z(\to l^+l^-)\gamma\mu^+\mu^-$</td>
<td>$4.59 \cdot 10^{-8}$</td>
<td>$\pm 4.96 \cdot 10^{-9}$</td>
</tr>
<tr>
<td>$Z(\to l^+l^-)Z(\to l^+l^-)Z(\to l^+l^-)\gamma$</td>
<td>$2.56 \cdot 10^{-8}$</td>
<td>$\pm 2.55 \cdot 10^{-9}$</td>
</tr>
<tr>
<td>$Z(\to l^+l^-)Z(\to l^+l^-)Z(\to l^+l^-)Z(\to l^+l^-)$</td>
<td>$1.49 \cdot 10^{-8}$</td>
<td>$\pm 1.28 \cdot 10^{-9}$</td>
</tr>
<tr>
<td>$Z(\to l^+l^-)\gamma Z(\to l^+l^-)\gamma$</td>
<td>$1.10 \cdot 10^{-8}$</td>
<td>$\pm 1.97 \cdot 10^{-9}$</td>
</tr>
</tbody>
</table>
FIG. 2: Signal and background distributions for the $bb\gamma\gamma$ final state. The signal distributions correspond to BM10$^{\text{max}}$. The kinematic quantities shown are (top left) the invariant mass of the $bb\gamma\gamma$ system, and (top right) the $p_T$ of the leading particle from among the photons and the $b$-quarks. Also shown are the distributions of the BDT output with uniform binning (bottom left) and optimized binning (bottom right).
FIG. 7: Additional kinematics distributions for $b\bar{b}\gamma\gamma$ final state, used as inputs to the BDT. The signal distributions correspond to BM10$^{\text{max}}$.

\[ V(H, S) = -\mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2 + \frac{a_1}{2} (H^\dagger H) S + \frac{a_2}{2} (H^\dagger H) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4 \]

**FIG. 3:** The \( N_\sigma \) gaussian significance for rejecting the background-only hypothesis, obtained using the \( b\bar{b}\gamma\gamma \) final state, for each benchmark point. Different collider scenarios of energy and integrated luminosity are compared. The vertical range corresponds to the maximum and minimum signal cross sections in the \( h_2 \) mass window.

FIG. 4: Signal and background distributions for the $4\tau$ final state, where the signal corresponds to BM10$^{\text{max}}$. The kinematic quantities shown are (top left) the invariant mass of the $4\tau$ system, and (top right) the average di-$\tau$ pair mass in the event. Also shown are the distributions of the BDT output with uniform binning (bottom left) and optimized binning (bottom right).
FIG. 8: Additional kinematics distributions for $4\tau$ final state, used as inputs to the BDT. The signal distributions correspond to BM10$^{\text{max}}$. 
H → 4 τ

\[ V(H, S) = -\mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2 + \frac{a_1}{2} (H^\dagger H) S + \frac{a_2}{2} (H^\dagger H) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4 \]

**FIG. 5:** The \( N_\sigma \) gaussian significance for rejecting the background-only hypothesis, obtained using the 4τ final state, for each benchmark point. Different collider scenarios of energy and integrated luminosities are compared. The vertical range corresponds to the maximum and minimum signal cross sections in the \( h_2 \) mass window.
Inducing First-Order Electroweak Phase Transition

\[ V(H, S) = -\mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2 + \frac{a_1}{2} (H^\dagger H) S \]
\[ + \frac{a_2}{2} (H^\dagger H) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4 \]

FIG. 6: The $N_\sigma$ gaussian significance for rejecting the background-only hypothesis, obtained using the combination of the $b\bar{b}\gamma\gamma$ and $4\tau$ final states, for each benchmark point. Different collider scenarios of energy and integrated luminosities are compared. The vertical range corresponds to the maximum and minimum signal cross sections in the $h_2$ mass window.

Inducing First-Order Electroweak Phase Transition

\[ V(H, S) = -\mu^2 (H^\dagger H) + \lambda (H^\dagger H)^2 + \frac{a_1}{2} (H^\dagger H) S + \frac{a_2}{2} (H^\dagger H) S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4 \]

\[ S \rightarrow HH \rightarrow \gamma\gamma bb \text{ and } 4\tau \]

Discovery potential across entire parameter space
Why is the Higgs Boson So Light?
Why is the Higgs Boson So Light?

- Old idea: Higgs doublet (4 fields) is a Goldstone mode generated from the spontaneous breaking of a larger global symmetry
  - Higgs boson and $W_L, Z_L$ are all Goldstone bosons from, eg.
    Spontaneously breaking global $SO(5) \rightarrow SO(4)$
  - Examples: Holographic Higgs, Little Higgs models...
  - Electroweak vev “$v$” is small compared to $SO(5)$ breaking scale “$f$”

- Vector boson scattering topology
  - Quarks emit longitudinal vector bosons which interact with new (presumably strong) dynamics
  - Quarks scatter by small angle in the forward direction
Longitudinal Vector Boson Scattering

Double Higgs Boson Production in the 4τ Channel from Resonances in Longitudinal Vector Boson Scattering at a 100 TeV Collider

AVK, S. Chekanov, M. Low
Phys. Rev. D91 (2015) 114018

(a) The pseudo-rapidity distributions of the forward jets.
Forward Jet Coverage for Longitudinal VBS

\[ V_L V_L \rightarrow \eta \rightarrow HH \]

AVK, S. Chekanov, M. Low

**TABLE II.** 5\(\sigma\) discovery mass reach for the \(\eta \rightarrow HH \rightarrow 4\tau\) resonance, at a \(pp\) collider with \(\sqrt{s} = 100\) TeV and \(\mathcal{L} = 10\) ab\(^{-1}\), for various cuts values on minimum \(p_T\) of the forward jets. The fractional width of the \(\eta\) resonance is set to \(\Gamma/M = 20\%\).

<table>
<thead>
<tr>
<th>(p_T^{\text{min}} ) (GeV)</th>
<th>30</th>
<th>50</th>
<th>70</th>
<th>90</th>
<th>110</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_\eta) (TeV)</td>
<td>3.53</td>
<td>2.90</td>
<td>2.35</td>
<td>1.92</td>
<td>1.56</td>
</tr>
</tbody>
</table>

- Lower \(p_T\) threshold on forward tagging jets is preferred

- Reject pileup jets with good tracking in forward direction

- Resolve overlapping pileup jets with higher granularity / spatial resolution (*a la* CMS high-granularity endcap calorimeter for HL-LHC)
Vector Boson Scattering
Double Higgs Boson Production in the 4\tau Channel from Resonances in Longitudinal Vector Boson Scattering at a 100 TeV Collider

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TABLE III. 5\sigma discovery mass reach for the \eta \rightarrow HH \rightarrow 4\tau resonance, at a pp collider with \sqrt{s} = 100 TeV and \mathcal{L} = 10 ab^{-1}, for various cuts values on the maximum rapidity (y) of the forward jets. The fractional width of the \eta resonance is set to \Gamma/M = 20%.

<table>
<thead>
<tr>
<th>y_{\text{max}}</th>
<th>8</th>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>m_\eta (TeV)</td>
<td>2.9</td>
<td>2.9</td>
<td>2.81</td>
<td>2.42</td>
<td>1.75</td>
</tr>
</tbody>
</table>

Want jet rapidity coverage up to 6
Conclusions

- proton-proton colliders (at very high energy) provide unprecedented discovery potential in the diHiggs channel

- New territory explored with precision measurements and direct searches is strongly motivated for
  - Solving the mysteries associated with the Higgs boson and the Higgs self-coupling
  - Understanding the electroweak phase transition and discovering the conditions for electroweak baryogenesis
  - DiHiggs resonances accessible only via longitudinal vector boson scattering

- In the singlet scalar extension of the standard model, the parameter phase space enabling a strongly $1^{st}$ order electroweak phase transition is completely discoverable at a 100 TeV $pp$ collider
Backup Slides
2. Option 2: Twin Solenoid + Dipoles

Twin Solenoid: a 6 T, 12 m dia x 23 m long main solenoid + an active shielding coil

Important advantages:

✓ Nice Muon tracking space: area with 2 to 3 T for muon tracking in 4 layers.
✓ Very light: 2 coils + structures, ≈ 5 kt, only ≈ 4% of the option with iron yoke!
✓ Much smaller: system outer diameter is significantly less than with iron.