Physics and Experiments at Future $pp$ Colliders

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Naturalness

The Unexpected

Future Colliders

Dark Matter

BSM Workshop
T. D. Lee Institute and Shanghai Jiao Tong University
July 2018
Dawn of a New Age

- **2008 Nobel Prize in Physics**
  "for the discovery of the mechanism of spontaneously broken symmetry in subatomic physics"

- **2013 Nobel Prize in Physics**
  "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"
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?
Spontaneous Symmetry Breaking of Gauge Symmetry

- Scalar Higgs field develops a vacuum expectation value (VeV) via spontaneous symmetry breaking
  - Goldstone modes appear as the new longitudinal modes of gauge bosons

- Phase transition $\rightarrow$ vacuum state possesses non-trivial quantum numbers
  - Dynamical origin of this phase transition is not known
  - Implies vacuum is a condensed, superconductor-like state
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 \( \rightarrow \) 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>
</tr>
<tr>
<td>W, Z</td>
<td>1</td>
</tr>
<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

\[ L = \left( h_{ij} \bar{\psi}_i \psi_j H + \text{h.c.} \right) - \lambda |H|^4 + \mu^2 |H|^2 - \Lambda_{CC}^4 \]
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
Radiative Stability of Higgs potential parameters
The top quark mass, the W boson mass and the mass of the Higgs boson provides a stringent test of the standard model at loop level
Example II - Test of QCD Quantum Loops at High Energy

Running of strong coupling has been confirmed experimentally.
Why is the Higgs Boson so Light?

\[
m^2_H - m^2_{\text{bare}} = \left( \begin{array}{c} H \\ H \end{array} \right) + \left( \begin{array}{c} t \\ H \\ H \end{array} \right) + \left( \begin{array}{c} W,Z \\ H \end{array} \right)
\]

\[
\lambda \int \Lambda \, d^4k \frac{1}{(k^2 - m^2_H)^2} \sim \Lambda^2 \lambda
\]

For the first time, we have additive corrections to parameters which are quadratically divergent.

The Higgs boson ought to be a very heavy particle, naturally.

However, observed \( m_H \ll \Lambda \)
Fine-tuning Problem of Higgs Boson Mass

- The divergent integral in this quantum loop must be regulated by a high-momentum cutoff, $\Lambda$, which could be the gravitational Planck energy scale $M_{\text{planck}} \sim 10^{19}$ GeV

  - Loop calculation gives Higgs boson mass correction $\sim M_{\text{planck}}^2$

- Physical Higgs boson mass $\sim 125$ GeV

- Therefore need extreme “fine-tuning” of bare lagrangian parameters at high energy
Radiative Corrections to Higgs Self-Coupling

- \( \lambda |\phi|^4 \) receives radiative corrections from Higgs and top-quark loops (from Paul Steinhardt)
Stability of Electroweak Vacuum

The diagram shows the relationship between the top mass $M_t$ in GeV and the Higgs mass $M_h$ in GeV. The regions are divided into:
- **Instability**
- **Meta-stability**
- **Stability**
- **Non-perturbativity**

The current best-fit value is indicated with a box within the meta-stability region.
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 $\text{VeV}$) 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 $10^{-4}$
Supersymmetric Colored Top Partner Sensitivity

(Čohen et al., 2014)

Fine-tuning $\sim m_{\text{stop}}^{-2} \sim 10^{-4}$

A big jump beyond LHC
Discovering or eliminating “natural” low-energy SUSY
Exploring New Territory – Squarks and Gluinos

Summary from FCC Report:

Squark & gluino discovery potential up to 10-20 TeV

Full exploration of “low-scale” SUSY
Expect $O(1)$ deviations from SM in self-coupling coefficient
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 self-coupling

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC@100TeV 3/ab</td>
<td>30\textsuperscript{\textdegree}40%</td>
<td>30%</td>
<td>15%</td>
</tr>
<tr>
<td>FCC@100TeV 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>
</tbody>
</table>

Details:
- $\lambda_{HHH}$ modification only
- $c\rightarrow b$ & $j\rightarrow \gamma$ included
- Background systematics
  - $b\bar{b}\gamma\gamma$ not matched
  - $m_{\gamma\gamma} = 125 \pm 1$ GeV
- Full EFT approach
  - No $c\rightarrow b$ & $j\rightarrow \gamma$
  - Marginalized
  - $b\bar{b}\gamma\gamma$ matched
  - $m_{\gamma\gamma} = 125 \pm 5$ GeV
  - Jet / $W_{had}$ veto
- $\lambda_{HHH}$ modification only
  - No marginalization
  - $b\bar{b}\gamma\gamma$ matched
  - $m_{\gamma\gamma} = 125 \pm 3$ GeV

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...

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

\[ \Rightarrow \text{ Baryogenesis at EW Scale} \]

\[ \Rightarrow \ldots \]

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

$\langle \phi \rangle = 0 \rightarrow \langle \phi \rangle = \phi(T)$ Discontinuous

Nucleation of True Vacuum Bubbles (in False Vacuum Sea)


Sudden Change in Higgs VEV
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

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

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

Discovery potential across entire parameter space

(P. Winslow, J.M. No, M.J. Ramsey-Musolf, AVK)
Guidance for Detector Design

- As long as Standard Model continues to work, “higher energy is better”
- Covering the “Naturalness-motivated” models push towards higher masses
- Dark Matter, Electroweak Baryogenesis may relate to physics at lower masses and smaller couplings
- Other reasons that new physics may hide at low mass with weak couplings
  - “Neutral Naturalness” (partners without QCD color charge)
  - e.g. twin Higgs, Hidden Sector
  - Higgs portal to new sector (SM interactions via Higgs only)

- Implications for detector design: larger dynamic range of $p_T$ of objects
  - Starting at ~20 GeV leptons, photons and $b$-quarks (same as LHC, e.g. $gg \rightarrow HH$)
  - Going up to ~7 times the highest $p_T$ probed at LHC
- Also large rapidity range for all objects due to higher longitudinal boost
Collider Luminosity and Energy

- Collider luminosity evolution for high-mass reach

(from L-T. Wang)
## 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
Magnetic Tracking
10-fold increase in luminosity → ~7 TeV increase in mass reach

Exploring New Territory - New Weak Gauge Interactions

![Graph showing the discovery reach for various models with different colors and markers. The x-axis represents the mass of the Z' and W' (TeV), and the y-axis represents the cross section (fb). The graph includes data for models like SSM, LRM, ψ, χ, η, and I, with discovery reach values at 1 ab⁻¹, 10 ab⁻¹, and 100 ab⁻¹.]

**Discovery reach**

T. Rizzo, arXiv:1403.5465

<table>
<thead>
<tr>
<th>Model</th>
<th>1 ab⁻¹</th>
<th>10 ab⁻¹</th>
<th>100 ab⁻¹</th>
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</thead>
<tbody>
<tr>
<td>SSM</td>
<td>23.8</td>
<td>33.3</td>
<td>41.3</td>
</tr>
<tr>
<td>LRM</td>
<td>22.6</td>
<td>31.5</td>
<td>39.5</td>
</tr>
<tr>
<td>ψ</td>
<td>20.1</td>
<td>29.1</td>
<td>37.2</td>
</tr>
<tr>
<td>χ</td>
<td>22.7</td>
<td>30.6</td>
<td>38.2</td>
</tr>
<tr>
<td>η</td>
<td>20.3</td>
<td>29.8</td>
<td>38.0</td>
</tr>
<tr>
<td>I</td>
<td>22.4</td>
<td>29.2</td>
<td>36.2</td>
</tr>
</tbody>
</table>
Maintaining Fractional $p_T$ Resolution

- Resolution gain with number of hits on track is slow (improves as $\sqrt{N}$)
- Resolution improves linearly with $BL^2 \sim$ stored magnetic field energy in tracker
- Resolution improves linearly with hit resolution

Four tracker/magnet geometries being considered:
- see Dr. Marcello Mannelli's talk at Fermilab's “Next Steps in the Energy Frontier – Hadron Collider” Workshop

https://indico.fnal.gov/conferenceOtherViews.py?view=standard&confId=7864

Stored energy in the tracker magnetic field in the 50-100 GJ range (similar to ITER)
2. Option 1: Solenoid-Yoke + Dipoles (CMS inspired)

- **Solenoid:** 10-12 m diameter, 5-6 T, 23 m long
  + massive Iron yoke for flux shielding and muon tagging.

- **Dipoles:** 10 Tm with return yoke placed at z≈18 m.
  Practically no coupling between dipoles and solenoid.
  They can be designed independently at first.
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.
2. Option 3: Toroids + Solenoid + Dipoles (ATLAS +)

- 1 Air core Barrel Toroid with 7 x muon bending power $B_x L^2$.
- 2 End Cap Toroids to cover medium angle forward direction.
- 2 Dipoles to cover low-angle forward direction.
- Overall dimensions: 30 m diameter x 51 m length (36,000 m³).
Twin Solenoid & Dipole system – bare coils

Properties:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>TS cold mass</td>
<td>3.2 kt</td>
</tr>
<tr>
<td>TS vacuum vessel mass</td>
<td>2.4 kt</td>
</tr>
<tr>
<td>TS stored energy</td>
<td>53 GJ</td>
</tr>
<tr>
<td>Dipoles cold mass</td>
<td>2x 380 t</td>
</tr>
<tr>
<td>Dipoles vac. vessel mass</td>
<td>To be det.</td>
</tr>
<tr>
<td>Dipoles stored energy</td>
<td>2x 1.5 GJ</td>
</tr>
<tr>
<td>Free bore</td>
<td>12 m</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>27 m</td>
</tr>
<tr>
<td>System length</td>
<td>42 m</td>
</tr>
<tr>
<td>Total stored energy</td>
<td>56 GJ</td>
</tr>
</tbody>
</table>

(from Herman ten Kate)
This is a reference detector that ‘can do the job’ and that is used to define the challenges. The question about the specific strategy for detectors at the two IPs is a different one.

Skip outer coil for baseline cost estimates...

(from Werner Riegler)
Improving Hit Resolution

- Smaller pixels with silicon sensors have multiple advantages
  - Improved hit resolution linearly improves momentum resolution at high $p_T$
  - Higher granularity improves two-track resolving power
    - Helps resolve close-by tracks and maintain track reconstruction efficiency in
      - high-density environment (inside boosted jets)
      - High-occupancy environment (pileup at high L)
- Issues:
  - Higher readout rate required
  - Power may be dominated by inter-pixel capacitance, which does not reduce with pixel size
    - More pixels => more power
- Potential solutions (3D electronics etc) under discussion
Dark Matter
Direct Searches for Dark Matter

WIMP-nucleon cross section \([\text{cm}^2]\)

WIMP Mass \([\text{GeV}/c^2]\)

[Billard et al.]

Z-exchange

Higgs exchange

1 Neutrino Event
3 Neutrino Events
10 Neutrino Events
30 Neutrino Events
100 Neutrino Events
SUSY Neutralino WIMP Relic Surface

- Supersymmetric partners of photon, Z boson or Higgs boson provide generic model of weakly interacting Dark Matter

- Combinations of Neutralino mass parameters that produce the correct relic abundance, along with Dark Matter particle (LSP) mass

Bramante et al, ArXiv:1510.03460
Phys. Rev. D91 (2015) 054015

(in the limit that other SUSY is heavy and decoupled)
Disappearing Track from Wino WIMP Decay

- \( M_{\text{Dark Matter}} < 1.8 \text{ TeV} (g_{\text{DM}}^2/0.3) \) based on WIMP thermal relic hypothesis

100 TeV \( pp \) collider covers most of the parameter space – 30 \( \text{ab}^{-1} \) will double the mass reach

Disappearing track: almost degenerate, long-lived \( \text{Wino}^+ \rightarrow \text{Wino}^0 \) requires robust tracking for reconstructing partial-length tracks

M. Low, L-T Wang, ArXiv:1404.0682 (mono-jet channel)
Compressed Spectrum WIMPs

\[ pp \rightarrow (\tilde{\chi}_2^0 \rightarrow \gamma \tilde{\chi}_1^0) \ (\tilde{\chi}_1^{\pm} \rightarrow \ell^{\pm} \nu_\ell \tilde{\chi}_1^0) j \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^{\pm} \nu_\ell \gamma j \]

Bramante et al., Phys. Rev. D93 (2016) no.6, 063525

\[ p_{T,\ell} = [10 - 60] \text{ GeV} \quad |\eta_\ell| < 2.5 \]
\[ p_{T,\gamma} = [10 - 60] \text{ GeV} \quad |\eta_\gamma| < 2.5 \quad \Delta R_{\ell\gamma} > 0.5 \]
\[ p_{T,j} > 0.8 \text{ TeV} \quad |\eta_j| < 2.5 \quad M_{T_2}^{(\gamma,\ell)} < 10 \text{ GeV} \]

Soft leptons and photons are crucial for this signature
Collider vs Direct Detection Complementarity

Common ground (almost)
- Axial-Vector mediator
  DD and collider are equal in overall sensitivity but probe different regions of parameter space!
- Scalar mediator
  DD and collider are equal in overall sensitivity but probe different regions of parameter space!

Exclusive domains (almost)
- Vector mediator
  Besides very low DM masses DD wins clearly over collider
- Pseudo-Scalar mediator
  No competitive limits from DD (only from indirect detection). Collider provides limits similar in sensitivity to scalar limits

(from O. Buchmuller)
Collider Searches – Large Mediator Mass

- **FCC 100 TeV 1ab⁻¹** taken from arXiv:1509.02904
- **ILC 1 TeV 500 fb⁻¹** taken from arXiv:1211.2254
- **Neutrino background**
  - LHC 8 TeV 19.5 fb⁻¹
  - LHC 14 TeV 300 fb⁻¹
  - LHC 14 TeV 3000 fb⁻¹
- **LUX2013**
- **LZ 10 ton yr**
- **DARWIN 200 ton yr** taken from arXiv:1409.4075

**Axial-Vector Mediator**

\[ g_{SM} = g_{DM} = 1 \]
Calorimetry
Calorimeter Geometry Issues

- Conveniences for going to higher energy:
  - Shower depth for full containment grows as $\log(E)$
  - Energy resolution improves as $\sqrt{E}$

- Dynamic range of electronics readout required scales linearly with collider energy


11-12 interaction lengths needed – space constraints (coil radius is expensive)
Effect of HCAL Energy Resolution on Dijet Resonances

Jet resolution ∼2-3% needed for multi TeV dijet resonances

- Extend $Z' \rightarrow jj$ discovery potential by 10 TeV between $\sigma_m = 10\%$ to 1%
- Constant term will dominate at TeV energies ($\sigma/E = a/\sqrt{E} \oplus c$)
- Good shower containment is mandatory!

(from Ana Henriques)
Calorimeter Granularity

- Granularity is a KEY issue: all decay products will be boosted closer together
  - 5 TeV resonance $\rightarrow$ HH $\rightarrow$ 4 $\tau$ produces 1 TeV $\tau$-lepton
  - Photons within $\tau$-jet are separated by $\sim$2 mm
  - $\tau$-leptons from Higgs separated by $\sim$10 cm
  - 20 TeV resonance $\rightarrow$ $tt$, top decay products separated by $\sim$3 cm
  - 10 TeV Zprime $\rightarrow$ WW, boosted W $\rightarrow$ jets separated by $\sim$3 cm

- Tracking particles inside jets can be crucial

- Exploit particle flow algorithms to the fullest, push experience from CMS and ILC detector design effort
Geant4 simulation of a high-granular calorimeter for TeV-scale boosted particle

S. Chekanov
HEP/ANL

FCC Week. April 11-15, 2016
Rome, Italy

With contributions from:
A. Kotwal (Fermilab/Duke), L. Gray (Fermilab), J. Strube (PNNL), N. Tran (Fermilab), S. Yu (NCU), S. Sen (Duke), J. Repond (ANL), J. McCormick (SLAC), J. Proudfoot (ANL), A.M. Henriques Correia (CERN), C. Solans (CERN), C. Helsens (CERN)

See Sergei Chekanov's talk in BOOST2017
GEANT Simulation of Scintillator / Iron HCAL and Silicon Tracker

5 TeV hadronic $W \rightarrow \text{dijet}$ decay with 4 cm x 4 cm scintillator readout
Background simulation in progress, will investigate different pad sizes and higher $p_T$

Generated on OSG by S. Chekanov
GEANT Simulation of Silicon/Tungsten EM Calorimeter

500 GeV hadronic $\tau$-lepton decays with 4mm x 4mm silicon pads
Background simulation in progress, will investigate larger pad sizes and higher $p_T$

$$f_{\text{track}} \quad (\text{leading track momentum fraction})$$
$$= \left( \frac{p_T \text{ of highest } p_T \text{ track in core region } (\Delta R < \text{core})}{\text{Total } E_T \text{ deposited in } \Delta R < \text{core}} \right)$$

core = 0.1

Analysis by Sourav Sen (Duke graduate student)

Higgs $\rightarrow \tau\tau$ is an important channel to complement $\gamma\gamma$ and $bb$
GEANT Simulation: Si/W ECAL & Scintillator/Iron HCAL

Single pion response and resolution

- Analysis by S. Yu, N. Tran and S. Chekanov
- First look at boosted object discriminating variables
- Published in *JINST 12 (2017) no.06, P06009*
GEANT Simulation: Silicon/Tungsten EMCAL & Iron/Scintillator HCAL

Dual $K^0_L$ spatial separation (generated $\Delta\phi = 10$ mrad)

- Analysis by Nhan Tran
- Published in JINST 12 (2017) no.06, P06009

Figure 14: Azimuthal distribution of energy deposition for pair of incident $K^0_L$ particles at 100 GeV (left) and 1000 GeV (right), with the angular separation of $\Delta\phi^{K} = 0.009$ rad. Electromagnetic calorimeter cells are indicated in black while hadronic calorimeter cells are indicated in gray.
b-tagging
$b$-tagging Design Performance for HL-LHC

**ATLAS Simulation**

- pileup=0, ITk
- pileup=50, ITk
- pileup=140, ITk
- pileup=0, IBL
- pileup=50, IBL

$\bar{t}t$, IP3D+SV1

**IBL** = current, \hspace{1cm} **ITk** = HL-LHC design (3 → 4 pixel layers, smaller pixels)
**b-tagging**

- FCC stage 1 plans to deliver \(~3\) ab\(^{-1}\)
  - Similar conditions as HL-LHC, pileup \(~200\) at 25 ns bunch crossing
- FCC stage 2 plans to deliver \(~15\) ab\(^{-1}\)
  - Pileup \(~1000\)
    - or 5 ns bunch crossing? If very fast detectors have no out-of-time pileup

- Need to achieve same \(b\)-tagging performance in higher-density environments
  - Highly boosted top quarks and Higgs bosons from heavy resonance decays
  - Width of \(b\)-jet \(~300\) microns at 2 cm radius
  - Need to resolve tracks with factor \(x5\) higher local density than LHC
Forward rapidity coverage
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

![Diagram showing the process of double Higgs boson production](image)

(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

\textbf{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 (\textit{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

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

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
Summary
Physics Conclusions

- Circular proton-proton colliders at very high energy provide unprecedented discovery potential

- New territory explored with precision measurements and direct searches is strongly motivated for
  - Solving the mysteries associated with the Higgs boson
  - Discovering WIMP Dark Matter
  - Understanding the electroweak phase transition and discovering the conditions for electroweak bryogenisis

- Potential for big surprises and discovery of unexpected new principles of nature
Detector Summary

- Entering new regime on detector design and technology

- Completion of the Standard Model and its consistency with all data implies
  - Energy scale of new physics is less well-defined now than when LHC was designed
  - We must prepare for a broader range of possible new physics
  - Specialized, targeted detectors risky as target signatures are unconstrained
  - Prudent to continue CDF & D0 (Run 2), ATLAS & CMS general-purpose detector philosophy

- Need improved capabilities
  - Better track momentum resolution
  - Maintain/improve $b$-tagging at high jet $p_T$ and high track density
  - Improve hadronic $\tau$-lepton identification efficiency → high-granularity EMCAL
  - Boosted H/W/Z/top substructure → high-granularity HCAL
  - Extend forward jet coverage to rapidity $\sim 6$ for vector boson scattering
  - Extend forward tracking for rejecting top quark background and suppressing forward pileup jets
More Challenges

- Readout bandwidth driven by high granularity
  - Wireless transmission ???
- Pileup of ~1000 additional interactions: handle with precision timing?
- Triggering
  - challenging to trigger on disappearing tracks and long-lived particles

Signatures of displaced decays

- Inner Tracker green
- EM Calorimeter Blue/green
- Hadronic calorimeter Blue
- Muon system Grey

Displaced decay signatures
1. Decay in muon system - jet
2. Two body decay (lepton jet)
3. Decay in HCAL of - jet
4. Emerging jets
5. Inner Tracker decay to jets
6. Decay to jets in the IT
7. Disappearing (Invisible) LLP
8. Non-pointing γ -> e⁺e⁻...