Experiments at Future $pp$ Colliders for Beyond-SM Physics

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Setting the Stage –

• Science Drivers
  - Use the Higgs boson as a new tool for discovery
  - Pursue the physics associated with neutrino mass
  - Identify the new physics of dark matter
  - Understand cosmic acceleration: dark energy and inflation
  - Explore the unknown: new particles, interactions, and physical principles
**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?

- **Naturalness** – the need to explain the lightness of the Higgs mass
Guidance for Detector Design

- As long as Standard Model continues to work, “higher energy is better”
- Naturalness arguments 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
Executive Summary

- Entering new regime on all fronts
  - Accelerator physics and design
  - Detector technology and design

- 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

- Detectors will need to be more capable on all fronts
  - Faster
  - Much higher resolution
  - Much higher granularity
  - Much more forward-detection capability
  - Much higher bandwidth, smarter triggers

- HL-LHC upgrade will provide much experience and insights
All-Purpose Detector Goals in a Nutshell

- Maximize $A \times \varepsilon$: all detectable particles
  - should be detected and over as much of the angular phase space as possible
  - And be well-measured over as much of their energy spectrum as possible (or of most importance to the interesting signals)

- Leptons of interest: electrons, muons and $\tau$-leptons

- Photons

- Quarks and gluons hadronize to jets of particles

- $b$-quarks are special and need to be distinguished from other jets

- Undetectable particles like neutrinos and Dark Matter can only have their transverse momentum sum inferred
  - Catch all visible momentum
  - Impose transverse momentum conservation
  - Hermeticity is important
All-Purpose Detector Goals in a Nutshell (2)

• Minimize B: reducible backgrounds from mis-identified particles
  - High rate of fragmentation pions, kaons, and photons misidentified as prompt electrons, photons and muons
  - Generic jets mis-identified as $b$-quark jets
  - Electrons and generic jets mis-identified as $\tau$ leptons
  - Energy resolution of detected particles, or missed visible energy due to missing instrumentation, leads to fake missing $p_T$ signature
  - Hermetic detectors have become very important

• Maximize $\Delta t \times L$: enable data-taking in high instantaneous luminosity environment
  - Large number of particles from additional (uninteresting) pp collisions
    • Can confuse/obfuscate the particles from the interesting collision
  - Total exposure of sensors to radiation flux scales with integrated luminosity and falls off with distance from collision point
    • Radiation damage causing degradation of sensor efficiency and increasing noise
Particle Detection

Drift chamber:
reconstruct particle trajectory by sensing ionization in gas on high voltage wires

Electromagnetic (EM) calorimeter:
metal sheets cause $e/\gamma$ shower, sense light or charge

Hadronic calorimeter:
metal sheets cause hadronic showers, sense scintillator light or charge

Muon chambers:
detect penetrating particles behind shielding

Silicon detector:
reconstruct particle trajectory by sensing ionization in planar silicon sensors (diodes)
Particle Detection

Multijet Event in 7 TeV Collisions
Magnetic Tracking
Momentum is determined by measurement of **track curvature** $\kappa = 1/\rho$ in B field:

Measure **sagitta** $s$ of the track. For the momentum component transverse to B field:

$$p_T = qB\rho$$

Units: $p_T[\text{GeV}] = 0.3B[\text{T}]\rho[\text{m}]$

$$\frac{L/2}{\rho} = \sin\frac{\theta}{2} \approx \frac{\theta}{2} \text{ (for small } \theta) \Rightarrow \theta \approx \frac{L}{\rho} = \frac{0.3B \cdot L}{p_T}$$

$$s = \rho\left(1 - \cos\frac{\theta}{2}\right) \approx \rho\left(1 - \left(1 - \frac{1}{2}\frac{\theta^2}{4}\right)\right) = \rho\frac{\theta^2}{8} \approx \frac{0.3L^2B}{8p_T}$$
Relative Momentum Error

For 3 points the relative momentum resolution is given by:
\[
\frac{\sigma(p_T)}{p_T} = \frac{\sigma_s}{s} = \frac{\sqrt{3}}{2} \sigma_x \cdot \frac{8p_T}{0.3BL^2}
\]

- degrades linearly with transverse momentum
- improves linearly with increasing B field
- improves quadratically with radial extension of detector

In the case of \( N \) equidistant measurements according to Gluckstern [NIM 24 (1963) 381]:
\[
\frac{\sigma(p_T)}{p_T} = \frac{\sigma(\kappa)}{\kappa} = \frac{\sigma_x \cdot p_T}{0.3BL^2 \sqrt{(N + 4)}}
\]
(for \( N \geq 10 \), curvature \( \kappa = 1/\rho \))

Example: For \( p_T = 1\text{GeV} \), \( L = 1\text{m} \), \( B = 1\text{T} \), \( \sigma_x = 200\mu\text{m} \) and \( N = 10 \) one obtains:
\[
\frac{\sigma(p_T)}{p_T} \approx 0.5\% \quad \text{for a sagitta } s \approx 3.8\text{cm}
\]

Important track detector parameter: \( \frac{\sigma(p_T)}{p_T^2} \) (%/GeV)
Highest Mass Leptonic Resonances

- HL-LHC studies showed $Z' \rightarrow ll$ reach up to 6.5 TeV
- Scaling to 100 TeV collider $\Rightarrow$ 45 TeV with 150 ab$^{-1}$ or 38 TeV with 15 ab$^{-1}$
  - 7 TeV change in mass reach for factor of 10 change in luminosity

\[ M(W') = 46.5 \text{ TeV} @ 100 \text{ ab}^{-1} \]
\[ M(W') = 39 \text{ TeV} @ 10 \text{ ab}^{-1} \]
\[ M(W') = 31.5 \text{ TeV} @ 1 \text{ ab}^{-1} \]

\[ \text{W production, SM-like couplings to quarks} \]
\[ \text{Int Lum (ab}^{-1}) \text{ for 100 Events at 100 TeV} \]

\[ (M_{\text{reach}} @ 10 \times \text{Lum})/(M_{\text{reach}} @ \text{Lum}) \]

\[ \Rightarrow \text{producing 20 TeV leptons} \]
Dielectron Mass Spectrum

Multi-TeV masses probed at LHC
Dimuon Mass Spectrum

Multi-TeV masses probed at LHC
Demands on $p_T$ Resolution

- High-mass dimuon resonances most demanding on tracker momentum resolution
- If universal coupling to leptons, dielectron channel is reliable
- Non-universal couplings plausible:
  - Higgs mechanism: additional Higgs bosons with $H \rightarrow \mu\mu$
  - Left-right seesaw model of neutrino masses

Prudent to maintain muon $p_T$ resolution (%) from LHC to 7x higher $p_T$
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

Three 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)

Need to measure muon momentum after shielding, to eliminate mis-measured decays-in-flight with very high reconstructed $p_T$
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 $z \approx 18$ 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 $B_z L^2$.
- 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 m$^3$).
Twin Solenoid & Dipole system — bare coils

(from Herman ten Kate)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</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>Dipole cold mass</td>
<td>2 x 380 t</td>
</tr>
<tr>
<td>Dipole vac. vessel mass</td>
<td>To be det.</td>
</tr>
<tr>
<td>Dipole stored energy</td>
<td>2 x 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>
- For a ~10 TeV muon, average energy loss ~ 1 GeV / cm ~ 16 GeV / interaction length ~ 200 GeV in hadronic calorimeter, with long tailed distribution
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
Direct Searches for Dark Matter

WIMP—nucleon cross section [cm²]

WIMP Mass [GeV/c²]

Z-exchange

Higgs exchange

[Billard et al.]
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

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

100 TeV $pp$ collider covers most of the parameter space

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

\[ p_{T,\ell} = [10 - 60] \text{ GeV} \quad |\eta_\ell| < 2.5 \]
\[ p_{T,\gamma} = [10 - 60] \text{ GeV} \quad |\eta_\gamma| < 2.5 \]
\[ p_{T,j} > 0.8 \text{ TeV} \quad |\eta_j| < 2.5 \]
\[ p_T > 1.2 \text{ TeV} \]
\[ \Delta R_{\ell\gamma} > 0.5 \]
\[ M_{T2}^{(\gamma,\ell)} < 10 \text{ GeV} \]

Soft leptons and photons are crucial for this signature
Compressed Spectrum WIMPs

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

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

Figure 7. **Left panel:** Points on the relic neutralino surface, which will be excluded or discovered using a disappearing track search with 15 ab\(^{-1}\) at a 100 TeV collider. At smaller values of |\(\mu\)| the higgsino still mixes enough to cause the mass splitting of the wino plateau to be too large for the disappearing track search to be effective. **Right panel:** Points which will be excluded or discovered using a compressed search for \(pp \rightarrow \ell^\pm \gamma j \not{p_T}\).
Covering the WIMP Surface

Figure 8. A combination of $2\sigma$ exclusions from future indirect (CTA and HAWC), direct (XENON1T and LZ), and collider searches (charged tracks and compressed events at 100 TeV) are shown over the surface of thermal relic neutralinos.

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

100 TeV $pp$ collider, combined with direct and indirect searches, covers the parameter space of WIMP satisfying relic density.
Calorimetry
Requirements at 100 TeV collider

The detector has to cover wide range of signatures

• Detection of high mass states
  o Dijet resonances or compositeness, $M_{q^*} \sim 50$ TeV
  o $Z'$ or $W'$ to leptons, $m_{Z'} \sim 30$ TeV
  o $\rightarrow$ Deeper calorimeters, higher dynamic range

• Precision measurements of the Higgs boson properties, and Higgs in BSM production
  o Precision lepton/photon in complex events, $b$, $c$, tau tagging
  o $\rightarrow$ at least comparable to CMS/ATLAS in EM resolution and PID

• Vector boson fusion and scattering
  o Forward jets $\rightarrow$ more forward coverage, up to $\eta=6$

• Boosted jets from $Z$, $W$, top and $H$
  o Jet substructures
  o $\rightarrow$ More granular calorimeters

Thanks to Hong Ma
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
GEANT Simulations

- **Strategy:**
  - Focus on high-granularity calorimeters
  - Resolve highly-boosted vector and Higgs bosons, top quarks, $\tau$-leptons

- GEANT4 simulations with ILCSOFT (installed by S. Chekanov at Argonne with some help from SLAC, PNNL)
- Geometry tuning and sample generation (Chekanov and AVK)
- Analysis by Nhan Tran (Fermilab CMS postdoc), Shin-Shan Yu (Asst. Prof. in Taiwan), Sourav Sen (Duke graduate student)
- Lindsey Gray (Fermilab CMS) is our Particle Flow Algorithm expert consultant
- **Samples created on OSG on 1-week timescale – need more analysts!**
Silicon High Granularity Calorimeter

- Good cluster energy resolution
- Very detailed topographical information
- Excellent two particle cluster resolving power
- Suitable for particle flow reconstruction in a high particle density environment

Thanks to R. Rusack, ECFA 2014
Silicon High Granularity Calorimeter

Good cluster energy resolution

Very detailed topographical information

Excellent two particle cluster resolving power

Suitable for particle flow reconstruction in a high particle density environment

Thanks to R. Rusack, ECFA 2014
Proposal – Si-HGC for CMS Endcap

**CMS Calorimeter Concept**

- **Back - HCAL** - 12 layers of Brass/Scintillator 5.5 $\lambda$
- **Front - HCAL** - 12 layers of Brass/Si 3.5 $\lambda$
- **ECAL** - 30 layers of W/Pb/Si $25 \times_0$ & 1$\lambda$
- **Cold Volume Sensors at - 30° C**

Thanks to R. Rusack, ECFA 2014
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)
GEANT Simulation of Scintillator / Iron HCAL and Silicon Tracker

5 TeV hadronic $W \rightarrow$ 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 $p_T$

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

core = 0.1

Analysis by Sourav Sen (Duke graduate student)
GEANT Simulation of Scintillator / Iron HCAL

Single pion response and resolution

- Analysis by Nhan Tran → now looking at two-particle separating power *versus* granularity
- First look at boosted object discriminating variables
- Targeting NIM paper
Granularity Requirements for Boosted Top Quarks

Sensitivity to new high-mass states decaying to $t\bar{t}$ at a 100 TeV collider

B. Auerbach, S. Chekanov, J. Love, J. Proudfoot, and A. V. Kotwal
Phys. Rev. D 91, 034014 – Published 17 February 2015
Effect of HCAL transversal segmentation on jet sub-structure

Delphes+HepSim  S. Chekanov

Jet mass
\( p_T > 10 \text{ TeV} \)

- Improve \( \sigma_m \) of sub-jettiness variables compared to \( \Delta \eta \times \Delta \phi = 0.1 \times 0.1 \) for high \( P_T \) jets by:
  - 80% for \( \Delta \eta \times \Delta \phi = 0.05 \times 0.05 \)
  - 120% for \( \Delta \eta \times \Delta \phi = 0.025 \times 0.025 \)

Need at least 2-4 times better granularity than ATLAS/CMS \( \Delta \eta \times \Delta \phi = 0.1 \times 0.1 \rightarrow 0.025 \times 0.025 \)
Effect of HCAL transversal segmentation on jet sub-structure

Tile Calorimeter geometry proposed: arXiv:1604.01415
Carli et al

Jet mass
pT > 10 TeV

Delphes+HepSim
S. Chekanov

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Need at least 2-4 times better granularity than ATLAS/CMS $\Delta\eta\times\Delta\phi=0.1\times0.1 \rightarrow 0.025\times0.025$
b-tagging
b-tagging Design Performance for HL-LHC

ATLAS Simulation

IBL = current,

ITk = HL-LHC design (3 → 4 pixel layers, smaller pixels)
**b-tagging**

- FCC stage 1 plans to deliver $\sim 3 \text{ ab}^{-1}$
  - Similar conditions as HL-LHC, pileup $\sim 200$ at 25 ns bunch crossing
- FCC stage 2 plans to deliver $\sim 15 \text{ ab}^{-1}$
  - Pileup $\sim 1000$
    - 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 $\sim 300$ 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

The pseudo-rapidity distributions of the forward jets.

(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

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**TABLE II.** 5σ 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)
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
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TABLE III. 5$\sigma$ discovery mass reach for the $\eta \to HH \to 4\tau$ resonance, at a $pp$ collider with $\sqrt{s} = 100$ TeV and $\mathcal{L} = 10\text{ ab}^{-1}$, 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 at least
Vector Boson Scattering
Double Higgs Boson Production in the 4τChannel from Resonances in Longitudinal Vector Boson Scattering at a 100 TeV Collider

AVK, S. Chekanov, M. Low
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Scaling behavior of sensitivity with integrated luminosity and collider energy

\[ m_\eta^{5\sigma} \propto \mathcal{L}^\alpha \quad \quad m_\eta^{5\sigma} \propto (\sqrt{s})^\beta \]

Find approximate scaling coefficients (with some dependence on resonance width)

Factor of 10 more luminosity: 50% higher mass reach

Doubling of collider energy: 40% higher mass reach
VV → WW Scattering

For $W^+W^-$ final state in VBS, $tt$ background is problematic. Forward $b$-tagging can veto $tt$ to reduce it to a manageable level.
Timing
Collider Luminosity and Sensor Timing

Luminosity is a measure of how often protons get close enough to interact.

\[ L = f \frac{n_1 n_2}{4\pi S_x S_y} \]

- \( f \) = beam crossing frequency
- \( n \) = protons/bunch
- \( s \) = transverse beam size
- \( L \approx 10^{34} \text{ crossings/cm}^2/\text{sec} \)

Reducing pileup by reducing \( n \) requires increasing \( f \Rightarrow \) faster detectors

50 ns → 25 ns at LHC

5 ns option to be considered

Beam power increases in inverse proportion to crossing time (unless \( s \) reduced)
ECAL Clean-up Using Timing

- **Effect of timing cut** on $\sum E_T^{ECAL}$ variable
  - sum of all ECAL hits with E > 1GeV.

- $O(30 \text{ ps})$ resolution detector simulated

- Require ECAL timing (time-of-flight subtracted) within a **90 ps** window

- Most of the **PU extra energy gone**
  - able to almost recover no PU conditions

- Timing-based selection looks **promising for high PU environment**

---

![CMS Simulation Preliminary](image)

- Events Normalized to Unit Area
- Time [ns]
- Blue line: Jets from PU
- Red line: Jets from Primary Vertex
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Whole Picture – The Drivers

Radiation damage:
0.01 ab\(^{-1}\) (Tevatron) → 0.3 ab\(^{-1}\) (LHC) → 3 ab\(^{-1}\) (HL-LHC) → 15 ab\(^{-1}\)
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

- Detectors will need to be more capable on all fronts
  - Faster
  - Larger dynamic range
  - Much higher resolution
  - Much higher granularity
  - Much more forward-detection capability
  - Much higher bandwidth, smarter triggers

- HL-LHC upgrade will provide experience and insights, but need to look beyond
Physics Case Studies and Seminars in US

• Biweekly Seminar + Brainstorming Session Thursday 1 PM CST via ReadyTalk/Indico on some “hot topic” relevant for FCC-\textit{hh}
  - Announcement on Fermilab Today / Labwide Calendar & Mailing list
  - VLHCPHYSICS@fnal.gov (or email me at kotwal@fnal.gov)

• Theme workshop series
  - Dark Matter (December 4-6, 2015 @ Fermilab)
  - Electroweak Baryogenesis (September 17-19, 2015 @ Univ. Mass Amherst)
  - New Symmetries
  - High-Granularity Calorimetry...

• Resources:
  - Full analysis chain available for MADGRAPH + PYTHIA showering → Ntuples → repository → C++ analysis code
  - Argonne HEP analysis cluster for CPU and Ntuple storage
  - Quick ramp-up for anyone to pursue any model and channel of interest
  - Need experimentalists with analysis experience collaborating with theorists
backup
Origin of Baryon Asymmetry

Possible Explanations...

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

$\Rightarrow$ Baryogenesis at EW Scale

$\Rightarrow$ ...

SAKHKAROV CONDITIONS (for dynamical generation of baryon asymmetry)

- $B$ Violation $\checkmark$ Sphalerons
  

- $C/CP$ Violation $\times$ not enough

- Departure from Thermal Equilibrium $\times$ 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
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 with next collider