Experiments at Future $pp$ Colliders

Ashutosh Kotwal
Fermilab & Duke University

Workshop on Probing the EWPT
Amherst Center for Fundamental Interactions
September 17, 2015
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**
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
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.

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

Muon chambers: detect penetrating particles behind shielding.

Hadronic calorimeter: metal sheets cause hadronic showers, sense scintillator light or charge.
Collider Detector at Fermilab (CDF)

- Muon detector
- Central hadronic calorimeter
- Central drift chamber
- Silicon detector
Particle Detection

Run Number: 158548, Event Number: 2486978
Date: 2010–07–04 06:46:45 CEST
Multijet Event in 7 TeV Collisions
Collider Luminosity and Sensor Timing

Luminosity is a measure of how often protons/antiprotons 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
- \( L \) \( \sim \) \( 10^{34} \) crossings/cm\(^2\)/sec

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

Reducing \( s \) is not easy for the accelerator; 5 ns option to be considered.

Beam power increases in inverse proportion to crossing time.

Thanks to H. Schellman.
Magnetic Tracking
ATLAS Silicon Tracker

Detect $\sim 2000\ e$ in a 350 $\mu m$ thick detector
Can measure $x,y,z$ to 10-20 $\mu m$
Fit the helical trajectory in the longitudinal magnetic field

$\Rightarrow$ Extract position, direction and momentum of charged particles
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: $p_T[\text{GeV}] = 0.3B[\text{T}]\rho[\text{m}]$

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

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

Thanks to Carsten Niubuh
Relative Momentum Error

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

- 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 \( p_T = 1\)GeV, \( L = 1m \), \( B = 1T \), \( \sigma_x = 200\mu m \) and \( N = 10 \) one obtains:

\[
\frac{\sigma(p_T)}{p_T} \approx 0.5\% \quad \text{for a sagitta } s \approx 3.8cm
\]

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

CDF achieved 0.015% with ~90 drift chamber hits, consistent with this example

Thanks to Carsten Niubuhr
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 $7 \times$ muon bending power $B_2 L^2$.
- 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$^3$).
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 $\Rightarrow$ more power
- Potential solutions (3D electronics etc) under discussion
Calorimetry
Photon and Electron Detection

Cascade of electrons and photons due to repeated pair-production and bremsstrahlung

Total absorption calorimeter
e.g. lead glass, BGO, lead tungstate (CMS)

Collect light or electric charge deposited by the shower electrons and photons
Accordian Sampling Calorimeter

ATLAS L-Ar accordion calorimeter allows fast pulse-shaping

Benefits of noble-liquid calorimeter: stable gain, uniform response, ease of segmentation, radiation-hard

Complications: cryogenic requirements, liquid purity, long drift time, out-of-time pileup effects

Vice-versa for crystal calorimeters
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 → 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 → at least comparable to CMS/ATLAS in EM resolution and PID

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

• Boosted jets from Z, W, top and H
  o Jet substructures
  o → More granular calorimeters
Calorimeter Geometry Issues

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

- Issues:
  - Dynamic range of electronics readout required scales linearly with collider energy
  - 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 $\sim 1$ mm
      - $\tau$ from Higgs separated by $\sim 5$ mm
    - 30 TeV resonance $\rightarrow$ $tt$, top decay products separated by $\sim 1$ cm
      - Tracking particles inside jets can be crucial
      - exploit particle flow algorithms to the fullest, push experience from CMS and ILC detector design effort
Proposal – 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

Baseplate for mechanical support during handling – made from W or W/Cu matching CTE of silicon.

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

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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 $X_0$ & 1 $\lambda$
- **Cold Volume Sensors at** – 30 °C

Thanks to R. Rusack, ECFA 2014
$b$-tagging
CMS Barrel Pixel detector

½ of BPIX
Multiple $pp$ Interactions (pileup)

CMS event with 78 pileup
Design Performance for HL-LHC

**ATLAS Simulation**

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

**Light jet rejection**

- $\tilde{t}t$, IP3D+SV1

**b-jet efficiency**

IBL = current, ITk = HL-LHC design (3 → 4 pixel layers, smaller pixels)
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 $\text{SO}(5) \rightarrow \text{SO}(4)$
  - Examples: Holographic Higgs, Little Higgs models...
  - Electroweak vev “$v$” is small compared to $\text{SO}(5)$ 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
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

(a) The pseudo-rapidity distributions of the forward jets.
### TABLE I. 5σ discovery mass reach for the \( \eta \to HH \to 4\tau \) resonance, at a \( pp \) collider with \( \sqrt{s} = 100 \) TeV, as a function of integrated luminosity \( \mathcal{L} \).

<table>
<thead>
<tr>
<th>( \mathcal{L} ) (ab(^{-1}))</th>
<th>( \Gamma/M = 5% )</th>
<th>( m_\eta ) (TeV)</th>
<th>( \Gamma/M = 20% )</th>
<th>( \Gamma/M = 70% )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.85(^a)</td>
<td>1.75</td>
<td>2.81</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.33</td>
<td>2.25</td>
<td>3.42</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.78</td>
<td>2.90</td>
<td>4.18</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>2.30</td>
<td>3.56</td>
<td>4.94</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>2.90</td>
<td>4.33</td>
<td>5.83</td>
<td></td>
</tr>
</tbody>
</table>
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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 $\mathcal{L} = 10 \text{ ab}^{-1}$, 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
TABLE V. 5σ discovery mass reach for the $\eta \to HH \to 4\tau$ resonance, as a function of the $\sqrt{s}$ of a pp collider. The fractional resonance width $\Gamma_\eta/m_\eta$ is fixed at 70%. These results are illustrated in Fig. 14.

<table>
<thead>
<tr>
<th>$\mathcal{L}$ (ab$^{-1}$)</th>
<th>$\sqrt{s} = 50$ TeV</th>
<th>$\sqrt{s} = 100$ TeV</th>
<th>$\sqrt{s} = 200$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.89</td>
<td>2.81</td>
<td>3.85</td>
</tr>
<tr>
<td>3</td>
<td>2.31</td>
<td>3.42</td>
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</tr>
<tr>
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<td>2.83</td>
<td>4.18</td>
<td>5.63</td>
</tr>
<tr>
<td>30</td>
<td>3.36</td>
<td>4.94</td>
<td>6.60</td>
</tr>
<tr>
<td>100</td>
<td>3.97</td>
<td>5.83</td>
<td>7.74</td>
</tr>
</tbody>
</table>
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

Scaling behavior of sensitivity with integrated luminosity and collider energy

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

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
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
ECAL Clean-up Using Timing

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

- $O(30 \text{ ps})$ 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

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CMS Simulation Preliminary

EE

- Jets from PU
- Jets from Primary Vertex

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Paolo Meridiani  
Timing Performance of CMS ECAL and Prospects
**ECAL Clean-up using Timing**

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Summary
Whole Picture – The Drivers

Radiation damage:

\[ 0.01 \text{ ab}^{-1} \text{ (Tevatron)} \rightarrow 0.3 \text{ ab}^{-1} \text{ (LHC)} \rightarrow 3 \text{ ab}^{-1} \text{ (HL-LHC)} \rightarrow 10+ \text{ ab}^{-1} ? \]
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/SSC were designed
  – We must prepare for a broader range of possible new physics

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

• Substantial knowledge & experience on detector design will be gained from HL-LHC upgrade
Summary

- **Experimental guidelines:**
  - Be ambitious (we have >25 years to do R&D)
  - What experimental capabilities does the physics require?

- **Accelerator capabilities:**
  - 100 TeV $pp$ center-of-mass energy is a baseline “round number”
  - Is 50 TeV enough? Will the physics reach be substantially higher with 200 TeV?
  - CERN FCC proposal is 100 TeV, initial Chinese proposal is 55 TeV with 16 Tesla magnets
  - LHC uses 8.4 Tesla magnets, Fermilab has demonstrated an 11 Tesla magnet

- **Integrated luminosity**
  - 10 ab$^{-1}$ is a good starting point
  - CERN-FCC has proposed 17 ab$^{-1}$ target
  - Useful to compare 3 ab$^{-1}$, 10 ab$^{-1}$ and 30 ab$^{-1}$ sensitivities
  - Motivate higher luminosity if needed to produce definitive answer
Forming an international collaboration to study:

- **$pp$-collider ($FCC-hh$)** → defining infrastructure requirements
  - $\sim 16 \text{~T} \Rightarrow 100 \text{~TeV}$ $pp$ in 100 km
  - $\sim 20 \text{~T} \Rightarrow 100 \text{~TeV}$ $pp$ in 80 km

- **$e^+e^-$ collider ($FCC-ee$)** as potential intermediate step

- **$p-e$ ($FCC-he$)** option

- 80-100 km infrastructure in Geneva area
Chinese Site 300 km East of Beijing

Minimum 55 km tunnel
The Future: CEPC+SppC

- For about 8 years, we have been talking about “What can be done after BEPCII in China”
- Thanks to the discovery of the low mass Higgs boson, and stimulated by ideas of Circular Higgs Factories in the world, CEPC+SppC configuration was proposed in Sep. 2012
The VLHC proposal was well developed with all major technical solutions documented, including many details on the tunneling.

Very important outcome was that there are no technical "show stoppers" in building 175 TeV pp collider.

Denisov, FCC Wroshhop, March 2015
100 TeV hadron collider: 4.5 dipoles in a 270 km tunnel

Peter McIntyre, Saeed Assadi, James Gerity, Joshua Kellams, Tom Mann, Chris Mathewson, Al McInturff, Nate Pogue, Akhdiyor Sattarov, Klaus Smit

Texas A&M University
Summary of Fermilab/USA Study Group Activities
Physics Case and Detector Goals

**Strategy:**
- Physics case studies should be published in refereed journals
- Arguments should be “interesting” not just for particle physicists but also other fields of physics, other fields of science
- We will need broad support from all scientists for (at least) the science case
- Planning a series of “theme” workshops focusing on Dark Matter (December 4-6 @ Fermilab), Electroweak Baryogenesis, 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
  - “how to convert ATLAS / CMS analysis into VHEPP study over the weekend”
  - Additional paper and visibility with only 10% more work!
Physics Case and Detector Goals

• Generate interest in the US HEP Community for physics case studies for a VHEPP (very high energy \(pp\)) collider

• Form collaborations between theorists and experimentalists to publish fairly detailed truth-level studies of “key” channels
  
  − Electroweakino dark matter (Ismail Ahmed, AVK)
  
  − \(1^{\text{st}}\) order phase transition via additional scalar (P. Winslow, J. M. No, M. Ramsey-Musolf, AVK) – PRD in progress
  
  − \(tt\bar{t}\) resonances and highly boosted tops with substructure (S. Chekanov, J. Love, J. Proudfoot, AVK) – PRD published
  
  − Vector boson scattering (AVK, S. Chekanov, M. Low) – PRD published

• Biweekly Seminar + Brainstorming Session Thursday 1 PM CST via ReadyTalk/Indico on some “hot topic” relevant for VHEPP
  
  − Announcement on Fermilab Today / Labwide Calendar & VHEPP Mailing list
  
  − VLHCPHYSICS@fnal.gov (or email me at kotwal@fnal.gov)
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
Forward Jet Coverage for Longitudinal VBS

$V_L V_L \rightarrow \eta \rightarrow HH$

$5\sigma$ discovery mass reach
Detector Concept Focus

- **Strategy:**
  - Focus on high-granularity calorimeters
  - Resolve highly-boosted vector bosons and Higgs bosons, top quarks
  - Tau-lepton requirements (say boosted to 1 TeV) present an interesting challenge
    - Can tau-decay products (photons from pi0) be resolved at ~1mm separation?

- **Resources:**
  - work with GEANT simulations using ILC-SOFT on OSG
    - tungsten-silicon high-granularity calorimeter
    - HL-LHC plug upgrade

- **Planning a series of “theme workshops” on this topic and others**
- **GOAL:** White Paper on key physics case topics and detector requirements in a few years