Physics Opportunities for Future Circular Colliders

Jesse Thaler

Present Excitement

Afterglow of Higgs Discovery

Anticipation of LHC Run 2

Snowmass/P5

Dark matter hints in cosmic rays?
The Next Leap Forward?

50 gauss magnet technology

This talk: personal perspective (not exhaustive)
Outline

Discoveries Beyond the Standard Model

Revelations Within the Standard Model

New Opportunities for Data Analysis?
Discoveries Beyond the Standard Model

Revelations Within the Standard Model

New Opportunities for Data Analysis?
The Universe
Galaxy
Solar System
Planet
Us
Hairs
Cells
Electrons
Protons
The TeV Scale
Grand Unification
Quantum Gravity

10^{26} m
10^{11} m
10^{-4} m
10^{-19} m
10^{-34} m

--- The Standard Model ---

M33 rotation curve
Quantum Gravity

Protons
Electrons
Cells
Molecules

The Universe

Solar System
Galaxy
Planet

Grand Unification?

$10^{10} m$ $10^{11} m$ $10^{-4} m$ $10^{-19} m$ $10^{-34} m$

Matter/Anti-Matter?
Three Generations?
Neutrino Masses?
Strong CP?

The Standard Model

Dark Matter?

Dark Energy?

Inflation?

Origin of Mass?
Higgs Boson!

Grand Unification?
Quantum Gravity?

Hierarchy Problem?
Exploiting the Higgs

\[ V(h) = -m^2 h\dagger h \]

\[ \mathcal{L} \supset y_\psi \psi h \psi^c \]

c. March 2015: Barely scratched the surface

**Key FCC-ee/hh/he Targets**

- Higgs self-coupling
- Higgs compositeness
- Extended Higgs sectors
- Mass/coupling relations
- Precision electroweak
- Higgs portal to new physics

\[ x |h|^2 ? \]
\[ + |h\dagger D_\mu h|^2 ? \]
\[ + |h|^2 O_{BSM} ? \]

& electroweak phase transition, new physics in loops, neutral naturalness, …

Higgs physics alone worth investment in FCC
Exploiting the Higgs

Dimension 6 Operators

\[ O_{WW} = g_2[H]^2 W^a_{\mu\nu} W^a_{\mu\nu} \]
\[ O_{BB} = g_3[H]^2 B^a_{\mu\nu} B^a_{\mu\nu} \]
\[ O_{WB} = g g' H^1 \sigma^a H W^a_{\mu\nu} \]
\[ O_{HW} = ig (D^\mu H)^1 \sigma^a (D^\nu H) W^a_{\mu\nu} \]
\[ O_{HB} = ig' (D^\mu H)^1 (D^\nu H) B^a_{\mu\nu} \]
\[ O_H = \frac{1}{4} \partial_{\mu} |H|^2 \]
\[ O_T = \frac{1}{2} (H'^\dagger D_{\mu} H)^2 \]
\[ O_{L_{(3)}} = (i H^1 \sigma^a \tilde{D}_\mu H) (L_L^\gamma \sigma^a L_L) \]
\[ O_{L_{(3)}} = (L_L^\gamma \sigma^a L_L) (L_L^\gamma \sigma^a L_L) \]
\[ O_{L_{(1)}} = (i H^1 \tilde{D}_\mu H) (L_L^\gamma \sigma^a L_L) \]
\[ O_{L_{(1)}} = (i H^1 \tilde{D}_\mu H) (L_L^\gamma \sigma^a L_L) \]
\[ O_{\tilde{R}} = (i H^1 \tilde{D}_\mu H) (\tilde{\epsilon}_{R}^\gamma \sigma^a \tilde{L}_R) \]

FCC-ee: Bounds from Higgsstrahlung Cross Section

FCC-hh: Singlet-aided Electroweak Baryogenesis

Curtin, Meade, Yu, 2014]
**Dark Matter**

WIMP Paradigm?

- **make it**
  - SM → DM

- **fake it**
  - $Z \rightarrow \nu\bar{\nu}$

- **shake it**
  - MONO-something

- **break it**
  - $Z \rightarrow \nu\bar{\nu}$

- e.g. Pure Wino-like DM (electroweak triplet):
  - $\chi^\pm \rightarrow \Delta m \approx m_{\pi^+}$

**Disappearing Tracks**

- Thermal Relic Expectation
  - (non-thermal/partial DM equally plausible)

[Low, Wang, 2014]
Hierarchy Problem

**Chiral Symmetry Breaking** \( \rightarrow \) **Electroweak Breaking**

- \( \rho: \Gamma/m \approx 0.2 \)
- \( \sigma: \Gamma/m \approx O(1) \)
- \( \pi^0, \pi^\pm, f_{\pi} \)
- \( W^\pm, Z^0 \)
- \( h^0: \Gamma/m \leq 10^{-4} \)
- **FCC**
- **LHC Reach**
- **Indirect LEP Bounds**
- Compositeness?
- Supersymmetry?
- Extended space-time?
- ...

Jesse Thaler — Physics Opportunities for Future Circular Colliders
Hierarchy Problem

Chiral Symmetry Breaking

$10 \text{ GeV}$ .................................................$10 \text{ TeV}$

$1 \text{ GeV}$ .................................................$1 \text{ TeV}$

$0.1 \text{ GeV}$ .................................................$0.1 \text{ TeV}$

$p \, n$

$K$

$\rho$: $\Gamma/m \approx 0.2$

$\sigma$: $\Gamma/m \approx \mathcal{O}(1)$

$\Pi^0$, $\Pi^\pm$

$f_{\pi^0}$

$W^\pm$, $Z^0$

LHC Reach

compositeness?
supersymmetry?
extended space-time?
...

$[\text{Cohen, Golling, Hance, Henrichs, Howe, Loyal, Padhi, Wacker, 2013}]$

$\sigma$: $\Gamma/m < 10^{-4}$
Core Physics Goals for FCC

The Universe: $10^{26}$ m
Galaxy: $10^{11}$ m
Solar System: $10^{-4}$ m
Planet: $10^{-19}$ m
Us: $10^{-34}$ m

Exploit the Higgs
Explore the Unknown
Hierarchy Problem
Dark Matter

Frontier exploration alone worth investment in FCC
Discoveries Beyond the Standard Model

New Opportunities for Data Analysis?

Revelations Within the Standard Model

\[ 10^{-19} \text{ m} \]

\[ ? \]
A Tevatron Example

W Polarization in Top Decay $\iff$ Spontaneous Electroweak Breaking

Longitudinal: $F_0 \approx 70\% \propto m_t^2$

Transverse: $F_- \approx 30\% \propto 2m_W^2$

$F_+ \approx 0\%$

Goldstone Equivalence Theorem

$\lambda_t q h t^c \Rightarrow m_t q e^{i\pi a T^a / v} t^c$

Not just “top property”
Deserving of celebration
Towards a Deeper Understanding

Measurements $\Leftrightarrow$ Core Principles of SM

\[
\frac{d\sigma}{d\mathcal{O}} \propto \sum_i \int d\Phi_i |\mathcal{M}_i|^2 \delta\left(\mathcal{O} - \hat{\mathcal{O}}(\Phi_i)\right)
\]

Precision Calculations
Clever Observables

How can we exploit energy/luminosity/precision of FCC?
Electroweak Probes with FCC-hh

**High Mass Drell-Yan ↔ Electroweak Coupling Running**

- Model-independent test for new electroweak states

[Alves, Galloway, Ruderman, Walsh, 2014]
QCD Probes with FCC-ee

\[ e^+ e^- \rightarrow q \bar{q} \quad \text{vs.} \quad e^+ e^- \rightarrow h^0 \rightarrow g g \]

\[ C_F = 4/3 \quad \text{(quark)} \quad \text{vs.} \quad C_A = 3 \quad \text{(gluon)} \]

Higgs Event Shapes ↔ Quark/Gluon Color Scaling
Detour: Jet Substructure

Boosted Top

Boosted W/Z/H

Quark/Gluon

Neutrino (!)

Jet Grooming

Jet Grooming

Pileup

ATLAS Simulation

Z$^0 \rightarrow t\bar{t}$ (m$_t$=1.6 TeV)

anti-$k_t$ with $R=1.0$ LCW, No jet grooming applied

600 x $p_T^{\text{jet}} < 800$ GeV, $|\eta| < 0.8$

Arbitrary units

Leading jet mass, $m_{\text{jet}}$ [GeV]

[ATLAS, 2012; using Krohn, JDT; Wang, 2009]
**Textbook QCD with FCC-hh?**

\[ \text{2} \rightarrow \text{n} \approx \text{2} \rightarrow \text{n-1} \]

**Splitting Function**

\[ 1 \rightarrow 2 \]

\[ \int \frac{d\theta}{\theta} \ d\bar{z} \ P(\bar{z}) \]

Collinear singularity \(
\sim 1/\bar{z}\)

**Basis of PDF evolution, FF evolution, parton showers, NLO subtractions, …**

Measurable?
Soft Drop Grooming

Recursively drop wide-angle soft radiation

\[
\int \frac{d\theta}{\theta} \, dz \, P(z)
\]

Angular-ordered Tree

Splitting Function?

[see also Butterworth, Davison, Rubin, Salam, 2008; Dasgupta, Fregoso, Marzani, Salam, 2013]
A Standard Candle for Jets

\[
\frac{1}{\sigma} \frac{d\sigma}{dz_g} = \frac{\overline{P}_i(z_g)}{\int_{z_{cut}}^{1/2} dz \overline{P}_i(z)}
\]

\[\approx\]

independent of \(\alpha_s\) (!)

≈ independent of jet \(p_T\) and radius

≈ same for quarks and gluons

calculable deviations from universality

Soft Drop Grooming ⇔ QCD Splitting Functions

[\text{Larkoski, Marzani, JDT, 2015; see also Larkoski, JDT, 2014}]
Measurements ⇔ Core Principles of SM

W Polarization in Top Decay ⇔ Spontaneous Electroweak Breaking
Higgs Pair Production ⇔ Nature of Higgs Potential
High Mass Drell-Yan ⇔ Electroweak Coupling Running
Higgs Event Shapes ⇔ Quark/Gluon Color Scaling
Neutrino Jets ⇔ Electroweak Radiation
Soft Drop Grooming ⇔ QCD Splitting Functions

... ⇔ ...

Non-trivial, intrinsically interesting
Deviations are sure signs of new physics
Probing the Standard Model & Beyond

**Principles**

- Quantum Mechanics
- Lorentz/CPT Invariance
- Spin/Statistics
- Locality/Causality/Unitarity
- Global Symmetries
- Conservation Laws
- Spontaneous Symmetry Breaking
- Gauge Invariance
- Anomaly Cancellation
- Renormalization Group Evolution
- Effective Field Theories
- Naturalness (??)

**Paradigms**

- Chiral Mass Generation
- Quark Flavor Structure
- P/CP Violation
- Accidental B, L Conservation
- Asymptotic Freedom
- (?) Baryogenesis
- (?) Dark Matter
- (?) Unification
- (?) Supersymmetry
- (?) Extended Space-time
- (?) Neutrino Mass Generation
- (?) Strong CP

...
Discoveries Beyond the Standard Model

Revelations Within the Standard Model

New Opportunities for Data Analysis?
Better Measurements through Theory?

FCC-hh Challenge: Calorimeter Angular Resolution

Track-Corrected Measurements?

\[ m_{\text{approx}} = m_{\text{tracks}} \frac{p_T}{p_T,\text{tracks}} \]

Track-Only Measurements?

Pileup Mitigation

Theory Challenge: Track Fraction is Non-perturbative

[see e.g. Larkoski, Maltoni, Selvaggi, 2015]
Better Measurements through Theory?

Introducing Track Functions: $T_i(x, \mu)$ (Generalizes to other non-perturbative effects)

track fraction RGE, just like PDFs

Measure at FCC-ee/he, extrapolate to FCC-hh?

[Chang, Procura, JDT, Waalewijn, 2013]
[see also Waalewijn, 2012; Krohn, Lin, Schwartz, Waalewijn, 2012; Larkoski, JDT, Waalewijn, 2014]
Planning for Archival Data Access?

“Jets Without Jets”  \[ \tilde{N}_{\text{jet}}(p_{T\text{cut}}, R) = \sum_{i \in \text{event}} \frac{p_{T_i}}{p_{T_i, R}} \Theta(p_{T_i, R} - p_{T\text{cut}}) \]

In Monte Carlo…

…in QCD at \( O(\alpha_s^2) \)…

…in data?

[Bertolini, Chan, JDT, 2013; Bertolini, JDT, Walsh, 2015]
Planning for Archival Data Access?

Jets Without Jets

Extremely preliminary from Wei Xue
(limited sample size, missing MinBias, no JEC factors)

Can FCC accelerate scientific progress through judicious open data releases?

c.f. Fermi

CERN
Summary

Discoveries Beyond the Standard Model

My Big 3: Exploiting the Higgs, Dark Matter, Hierarchy Problem
Ultimate reason: Pushing the frontiers, exploring the unknown

Revelations Within the Standard Model

Novel measurements to test deep principles of nature, explore fundamental structures of quantum field theory

New Opportunities for Data Analysis?

Prospects for theory-aided measurements?
Archival data on day one (+N year offset)?
Backup Slides
Soft Drop Energy Sharing

Want: \( p(z_g) \)

Need: \( r_g \) Dynamical jet radius (safe companion)

Insight: \[ p(z_g) = \int d r_g \, p(r_g) \, p(z_g | r_g) \]

Form factor regulates collinear singularity

[\text{Larkoski, Marzani, JDT, 2015}]
Rich structures within the standard model (and QFTs)

[Reference: Larkoski, Marzani, JDT, 2015; see also Larkoski, JDT, 2013]
Joint Detector/Pileup Mitigation Development?

Prioritizes Energy Resolution?

Energy/Angle Tradeoff?

\[ \alpha_i \simeq \log \sum_j \frac{pT_j}{R_{ij}} \]

[Cacciari, Salam, Soyez, 2014]
[Bertolini, Harris, Low, Tran, 2014]