Physics of Future Circular Colliders

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Naturalness

The Unexpected

Future Colliders

Dark Matter

Dark Interactions – Perspectives from Theory and Experiment
Brookhaven National Laboratory, October 2016
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?
A Century of Particle Physics

- Success #1: discovery of 6 quarks and 6 leptons
- 12 fundamental matter particles (and their antimatter counterparts) derived by combining quantum mechanics and special relativity

But the intriguing pattern of mass values is not explained

**Quarks**

\[
\begin{align*}
u &< 1 \text{ GeV} \\
c &\sim 1.5 \text{ GeV} \\
t &\sim 175 \text{ GeV} \\
d &< 1 \text{ GeV} \\
s &< 1 \text{ GeV} \\
b &\sim 4.5 \text{ GeV}
\end{align*}
\]

**Leptons**

\[
\begin{align*}
\nu_e &< 1 \text{ eV} \\
\nu_\mu &< 0.17 \text{ MeV} \\
\nu_\tau &< 24 \text{ MeV} \\
e &0.5 \text{ MeV} \\
\mu &106 \text{ MeV} \\
\tau &1.8 \text{ GeV}
\end{align*}
\]
A Century of Particle Physics

- **Success # 2: principle of gauge invariance for **predicting** the nature of fundamental forces**
  - matter particles (quarks and leptons) transform in **curved** internal spaces
  - The equations of motion predict terms that describe particle interactions with force fields

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

**Gauge sector**
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 → 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**

\[ L = \left( h_{ij} \bar{\psi}_i \psi_j H + h.c. \right) - \lambda |H|^4 + \mu^2 |H|^2 - \Lambda_{CC}^4 \]
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
Test of Quantum Loops at High Energy – Example I

- W boson mass: radiative corrections due to heavy quark and Higgs loops

Motivate the introduction of the $\rho$ parameter: $M_W^2 = \rho \left[M_W^{\text{tree}}\right]^2$

with the predictions $\Delta \rho \propto M_{\text{top}}^2$ and $\Delta \rho \propto \ln M_H$

- 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
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 - Asymptotic Freedom in QCD

QCD Lagrangian with no dimensionful parameters is scale-invariant classically BUT quantum loops induce a distance (or momentum) scale dependence!

Running of coupling constant induces an energy scale $\Lambda \sim 0.2$ GeV where coupling becomes large

$\alpha_s \rightarrow 0$ as $\mu \rightarrow \infty$ : asymptotic freedom

(2004 Nobel Prize for Gross, Wilczek, Politzer)

$\alpha_s = \frac{6\pi}{(33 - 2N_f) \ln(\mu/\Lambda)}$

$N_f =$ Number of quark flavors
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?

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 $m_H << \Lambda$
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 \( M_{\text{planck}} \sim 10^{19} \text{ GeV} \)
  - Loop calculation gives Higgs boson mass correction \( \sim M_{\text{planck}}^2 \)

- physical Higgs boson mass \( \sim 125 \text{ GeV} \)

- 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
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
A Toy Model for Strongly-Interacting Higgs Sector

- Consider a term coupling the Higgs to a singlet scalar $S$: $f \phi \phi S$
- Via $S$ exchange, can mediate scattering process: $\phi \phi \rightarrow \phi \phi$

\[
\frac{[\square - m_s^2]^{-1}}{m_s^{-2}} \sim m_s^{-2} [1 + \square / m_s^2]
\]

- For energies $<< m_s$, induces effective field theory operators:
  - Dimension-4: \((f / m_s)^2 (\phi \phi^\dagger)^2\)
  - Dimension-6: \(O_{\phi d} = (f^2 / m_s^4) \partial_\mu (\phi \phi^\dagger) \partial^\mu (\phi^\dagger \phi)\)
  - This is one of the operators predicted in strongly-interacting light Higgs models
  - alters Higgs couplings compared to SM
Next Steps for Electroweak Measurements

- Electroweak observables access all the mechanisms that can stabilize / explain the light Higgs mass
  - Is it stabilized by a symmetry such as SuperSymmetry?
  - Is the Higgs boson a pseudo Nambu-Goldstone Boson?
  - Is there new strong dynamics?
  - Do extra-dimensional models bring the Planck scale close to Electroweak scale?

- Motivation for a W/Z/Higgs factory (electron-positron collider)
Circular Electron-Positron Collider
Circular $e^+e^-$ Collider Physics Goals

- 100 billion (CEPC) to 1 trillion Z bosons (FCC-ee)
  - 10K to 100K more statistics than LEP
  - 100 times smaller statistical errors
  - Potential for probing 10 times higher mass scales in loops
  - Current electroweak precision observables already probing new physics at the few TeV scale through dim-6 operators

- 0.1-0.5 MeV W mass measurement from WW threshold scan

- 1-2 million Higgs boson events
  - 1% - 0.1% precision on many Higgs branching ratios
  - Model-independent extraction of Higgs couplings
  - Invisible Higgs branching ratio to 0.3% precision

- Using $tt$ threshold scan, top quark mass with <100 MeV precision (10 MeV statistical error) and measure top-electroweak couplings using angular distributions
Precision of Higgs Coupling Measurements

\[ \kappa_Z = \frac{g_hZ(\text{Measured})}{g_hZ(\text{SM})} \]
Effective Field Theory Analysis of Precision EWK and Higgs observables

J. Ellis, T. You, arXiv:1510.04561

Ops directly affecting EW precision observables

\[ L_{\text{dim-6}}^{\text{EWPT}} = \frac{1}{2} \frac{(\bar{c}_W + \bar{c}_B)}{m_W^2} (\mathcal{O}_W + \mathcal{O}_B) + \frac{\bar{c}_T}{v^2} \mathcal{O}_T + \frac{\bar{c}_{LL}^{(3)}}{v^2} \mathcal{O}_{LL}^{(3)} + \frac{\bar{c}_R^e}{v^2} \mathcal{O}_{R}^e, \]

\[ \bar{c}_i = c_i \frac{M^2}{\Lambda^2} \quad M \equiv v, m_W \]

Ops directly affecting Higgs properties and Triple gauge boson couplings

\[ L_{\text{dim-6}}^{\text{Higgs+TGC}} = \frac{1}{2} \frac{(\bar{c}_W - \bar{c}_B)}{m_W^2} (\mathcal{O}_W - \mathcal{O}_B) + \frac{\bar{c}_{HW}}{m_W^2} \mathcal{O}_{HW} + \frac{\bar{c}_{HB}}{m_W^2} \mathcal{O}_{HB} + \frac{\bar{c}_g}{m_W^2} \mathcal{O}_g + \frac{\bar{c}_\gamma}{m_W^2} \mathcal{O}_\gamma + \frac{\bar{c}_H}{v^2} \mathcal{O}_H + \frac{\bar{c}_f}{v^2} \mathcal{O}_f \]

<table>
<thead>
<tr>
<th>EWPTs</th>
<th>Higgs Physics</th>
<th>TGCs</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mathcal{O}<em>W = \frac{i g}{2} \left( H^\dagger D^\mu H \right) D^{\nu} W^a</em>{\mu \nu} )</td>
<td>( \mathcal{O}<em>{HW} = i g (D^\mu H)^\dagger \sigma^a (D^\nu H) W^a</em>{\mu \nu} )</td>
<td>( \mathcal{O}<em>{3W} = g \frac{e_h}{3} W^a</em>{\mu \nu} W^b_{\nu \rho} W^c_{c \rho \mu} )</td>
</tr>
<tr>
<td>( \mathcal{O}<em>B = \frac{i g'}{2} \left( H^\dagger D^\mu H \right) \partial^\nu B</em>{\mu \nu} )</td>
<td>( \mathcal{O}<em>{HB} = i g' (D^\mu H)^\dagger (D^\nu H) B</em>{\mu \nu} )</td>
<td></td>
</tr>
<tr>
<td>( \mathcal{O}_T = \frac{1}{2} \left( H^\dagger D^\mu H \right)^2 )</td>
<td>( \mathcal{O}_g = g_s^2</td>
<td>H</td>
</tr>
<tr>
<td>( \mathcal{O}_{LL}^{(3)} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma^\mu L_L) )</td>
<td>( \mathcal{O}_\gamma = g^2</td>
<td>H</td>
</tr>
<tr>
<td>( \mathcal{O}_{e} = (i H^\dagger D^\mu H)(\bar{e}_R \gamma^\mu e_R) )</td>
<td>( \mathcal{O}_H = \frac{1}{2} (\partial^\mu</td>
<td>H</td>
</tr>
<tr>
<td>( \mathcal{O}_{u} = (i H^\dagger D^\mu H)(\bar{u}_R \gamma^\mu u_R) )</td>
<td>( \mathcal{O}_f = y_f</td>
<td>H</td>
</tr>
<tr>
<td>( \mathcal{O}_{d} = (i H^\dagger D^\mu H)(\bar{d}_R \gamma^\mu d_R) )</td>
<td>( \mathcal{O}_6 = \lambda</td>
<td>H</td>
</tr>
</tbody>
</table>
Figure 9: Summary of the reaches for the dimension-6 operator coefficients with TeV scale sensitivity, when switched on individually (green) and when marginalised (red), from projected precision measurements at the ILC250 (lighter shades) and FCC-ee (darker shades). The left plot shows the operators that are most strongly constrained by EWPTs and Higgs physics, where the different shades of dark green and dark red represent the effects of EWPT theoretical uncertainties at FCC-ee. The right plot is constrained by Higgs physics and TGCs, and the different shades of light green demonstrate the improved sensitivity when TGCs are added at ILC250.
Circular $pp$ Collider
Circular \textit{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 \textit{pp} collider?
- Naturalness – the need to explain the lightness of the Higgs mass – testing Naturalness at $10^{-4}$
Supersymmetric Colored Top Partner Sensitivity

(Cohen et al, 2014)

A big jump beyond LHC
Discovering or eliminating “natural” low-energy SUSY

Fine-tuning $\sim m_{\text{stop}}^2 \sim 10^{-4}$
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>
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</tr>
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<tbody>
<tr>
<td>$FCC_{@100 TeV}$ 3/ab</td>
<td>30~40%</td>
<td>30%</td>
<td>15%</td>
</tr>
<tr>
<td>$FCC_{@100 TeV}$ 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 ✓ $c \rightarrow b$ &amp; $j \rightarrow \gamma$ included ✓ Background systematics ∙ $b\bar{b}\gamma\gamma$ not matched ✓ $m_{\gamma\gamma} = 125 \pm 1$ GeV</td>
<td>✓ Full EFT approach ∙ No $c \rightarrow b$ &amp; $j \rightarrow \gamma$ ✓ Marginalized ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 5$ GeV ✓ Jet /$W_{had}$ veto</td>
<td>✓ $\lambda_{HHH}$ modification only ✓ $c \rightarrow b$ &amp; $j \rightarrow \gamma$ included ✓ Marginalized ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 3$ GeV</td>
</tr>
</tbody>
</table>

Work in progress to compare studies, harmonize performance assumptions, optimize, etc ⇒ ideal benchmarking framework
Exploring New Territory - New Weak Gauge Interactions

10-fold increase in luminosity → ~7 TeV increase in mass reach

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>$\psi$</td>
<td>20.1</td>
<td>29.1</td>
<td>37.2</td>
</tr>
<tr>
<td>$\chi$</td>
<td>22.7</td>
<td>30.6</td>
<td>38.2</td>
</tr>
<tr>
<td>$\eta$</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>
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
Dark Matter
A consistent hypothesis is the existence of non-relativistic particles beyond the Standard Model.
WIMP Miracle

- Thermal equilibrium in the early universe.
- If $g_D \sim 0.1 \quad M_D \sim 10s \text{ GeV} - \text{TeV}$
  - We get the right relic abundance of dark matter.
- Major hint for weak scale new physics!
Searching for WIMP Dark Matter

Indirect detection:
AMS2, PAMELA, Fermi-LAT
HAWC, HESS...

Direct detection:
CDMS
CoGeNT
COUPP
CRESST
DAMA
XENON
LZ
.....

Collider searches:
LHC,
100 TeV pp ...
Direct Searches for Dark Matter

WIMP-nucleon cross section $[\text{cm}^2]$ vs. WIMP Mass $[\text{GeV}/c^2]$. The graph shows the results of various experiments and models, with lines representing different experiments such as CDMS, DAMIC, ZEPLIN-III, and EDELWEISS. The shaded regions indicate the allowed parameter space for WIMP masses and cross sections based on the experiments' sensitivities.
SUSY Neutralino Relic Surface

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

Bramante et al, ArXiv:1510.03460

(in the limit that other SUSY is heavy and decoupled)
WIMP Dark Matter

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

100 TeV pp collider covers most of the parameter space.

Can double mass reach with 30 ab\(^{-1}\)

M. Low, L-T Wang, ArXiv:1404.0682 (mono-jet channel)
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
Collider Searches – Large Mediator Mass

Axial-Vector Mediator $g_{SM}=g_{DM}=1$
Origin of Matter-Antimatter Asymmetry
Origin of Baryon Asymmetry

### Possible Explanations...

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

\[ \Rightarrow \text{Baryogenesis at EW Scale} \quad \text{TESTABLE!} \]

\[ \Rightarrow \ldots \]

### 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

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

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

In the SM ($m_h = 125$ 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

\[ \langle \phi \rangle \neq 0 \quad \langle \phi \rangle = 0 \]
\[ \langle \phi \rangle \neq 0 \]
Can TeV-scale new physics associated with 1\textsuperscript{st} order phase transition be completely covered by a \textit{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

(AVK, P. Winslow, J.M. No, M.J. Ramsey-Musolf, PRD 94, 035022 (2016))
Conclusions

- Circular electron-position colliders (at very high luminosity) and 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
Backup Slides
Target lumin and statistics for the FCC-ee programme

This is an evolving issue, the table below is the latest documented assessment, from D. d’Enterria, (EPS talk), arXiv:1601.06640

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV):</th>
<th>90 (Z)</th>
<th>125 (eeH)</th>
<th>160 (WW)</th>
<th>240 (HZ)</th>
<th>350 (tt)</th>
<th>350 (VV $\rightarrow$ H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{L}/\text{IP}$ (cm$^{-2}$ s$^{-1}$)</td>
<td>$2.2 \cdot 10^{36}$</td>
<td>$1.1 \cdot 10^{36}$</td>
<td>$3.8 \cdot 10^{35}$</td>
<td>$8.7 \cdot 10^{34}$</td>
<td>$2.1 \cdot 10^{34}$</td>
<td>$2.1 \cdot 10^{34}$</td>
</tr>
<tr>
<td>$\mathcal{L}_{\text{int}}$ (ab$^{-1}$/yr/IP)</td>
<td>22</td>
<td>11</td>
<td>3.8</td>
<td>0.87</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>Cross sections</td>
<td>43 nb</td>
<td>0.29 fb</td>
<td>4 pb</td>
<td>200 fb</td>
<td>0.5 pb</td>
<td>30 fb</td>
</tr>
<tr>
<td>Events/year (4 IPs)</td>
<td>$3.7 \cdot 10^{12}$</td>
<td>$1.3 \cdot 10^{4}$</td>
<td>$6.1 \cdot 10^{7}$</td>
<td>$7.0 \cdot 10^{5}$</td>
<td>$4.2 \cdot 10^{5}$</td>
<td>$2.5 \cdot 10^{4}$</td>
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<tr>
<td>Years needed (4 IPs)</td>
<td>2.5</td>
<td>1.5</td>
<td>1</td>
<td>3</td>
<td>0.5</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 1: Target luminosities, events/year, and years needed to complete the W, Z, H and top programs at FCC-ee. [$\mathcal{L} = 10^{35}$ cm$^{-2}$ s$^{-1}$ corresponds to $\mathcal{L}_{\text{int}} = 1$ ab$^{-1}$/yr for 1 yr = $10^7$ s].
### SM parameters from FCC-ee

M. Dam, arXiv:1601.03849

<table>
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<tr>
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<tbody>
<tr>
<td>$M_Z [\text{MeV}]$</td>
<td>Lineshape</td>
<td>$91187.5 \pm 2.1$</td>
<td>0.005</td>
<td>$&lt; 0.1$</td>
<td>QED corr.</td>
</tr>
<tr>
<td>$\Gamma_Z [\text{MeV}]$</td>
<td>Lineshape</td>
<td>$2495.2 \pm 2.3$</td>
<td>0.008</td>
<td>$&lt; 0.1$</td>
<td>QED corr.</td>
</tr>
<tr>
<td>$R_\ell$</td>
<td>Peak</td>
<td>$20.767 \pm 0.025$</td>
<td>0.0001</td>
<td>$&lt; 0.001$</td>
<td>Statistics</td>
</tr>
<tr>
<td>$R_b$</td>
<td>Peak</td>
<td>$0.21629 \pm 0.00066$</td>
<td>0.0000003</td>
<td>$&lt; 0.00006$</td>
<td>$g \to b\bar{b}$</td>
</tr>
<tr>
<td>$N_\nu$</td>
<td>Peak</td>
<td>$2.984 \pm 0.008$</td>
<td>0.00004</td>
<td>0.004</td>
<td>Lumi meast.</td>
</tr>
<tr>
<td>$A_{FB}^{\mu\mu}$</td>
<td>Peak</td>
<td>$0.0171 \pm 0.0010$</td>
<td>0.000004</td>
<td>$&lt; 0.00001$</td>
<td>$E_{\text{beam}}$ meast.</td>
</tr>
<tr>
<td>$\alpha_s(M_Z)$</td>
<td>$R_\ell$</td>
<td>$0.1190 \pm 0.0025$</td>
<td>0.000001</td>
<td>0.00015</td>
<td>New Physics</td>
</tr>
<tr>
<td>$1/\alpha_{\text{QED}}(M_Z)$</td>
<td>$A_{FB}^{\mu\mu}$ around peak</td>
<td>$128.952 \pm 0.014$</td>
<td>0.004</td>
<td>0.002</td>
<td>EW corr.</td>
</tr>
<tr>
<td>$M_W [\text{MeV}]$</td>
<td>Threshold scan</td>
<td>$80385 \pm 15$</td>
<td>0.3</td>
<td>$&lt; 1$</td>
<td>QED corr.</td>
</tr>
<tr>
<td>$N_\nu$</td>
<td>$e^+e^- \to \gamma Z(\text{inv.})$</td>
<td>$2.92 \pm 0.05$</td>
<td>0.0008</td>
<td>$&lt; 0.001$</td>
<td>?</td>
</tr>
<tr>
<td>$\alpha_s(M_W)$</td>
<td>$B_{\text{had}} = (\Gamma_{\text{had}}/\Gamma_{\text{tot}})W$</td>
<td>$B_{\text{had}} = 67.41 \pm 0.27$</td>
<td>0.00018</td>
<td>0.00015</td>
<td>CKM Matrix</td>
</tr>
<tr>
<td>$m_{\text{top}} [\text{MeV}]$</td>
<td>Threshold scan</td>
<td>$173200 \pm 900$</td>
<td>10</td>
<td>10</td>
<td>QCD</td>
</tr>
</tbody>
</table>

* $\alpha_s$ workshop, d’Enterria, Skands eds, et al, arXiv:1512.05194
** P. Janot, arXiv:1512.05544
### 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
Collider Luminosity and Energy

- Collider luminosity evolution for high-mass reach

(from L-T. Wang)
Collider Luminosity and Energy

- Collider energy wins rapidly at higher masses

\[ \frac{\sigma(W)[E_{CM}/\text{TeV}]}{\sigma(W)[100\text{TeV}]} \]

- \( E_{CM}=110 \text{ TeV} \)
- \( 120 \text{ TeV} \)
- \( 130 \text{ TeV} \)

(from M. Mangano)
Collider Luminosity and Energy

- With 100 TeV collider, 7 TeV increase in mass reach for ten-fold increase in luminosity

(from M. Mangano)
Collider Luminosity and Energy

- Collider luminosity more important for low-mass, low cross-section physics

\[ \sigma \sim L_p \cdot \hat{\sigma} \sim \frac{1}{\tau^a \hat{\sigma}}, \]

The dependence of power \( a \) on mass scale \( M = \sqrt{\hat{s}} = \sqrt{s\tau} \)
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.
• **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