THE FUTURE OF HIGH ENERGY ACCELERATORS

Future High Energy Accelerators for Particle Physics

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DESY

IPAC17, Copenhagen, May 2017
Outline

> High-energy physics and the need for accelerators/colliders
> LHC and HL-LHC
> Beyond the LHC: future hadron colliders
> Precision machines: future electron positron colliders
> Other ideas: neutrino beams, muon colliders, ...
> Some strategy considerations
> Conclusions
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Observation of a Higgs Boson: A Centennial Discovery
... but many fundamental questions remain open!

Higgs explains why particles have masses – but many parameters still unexplained!
The Standard Model is NOT the last answer.

We understand only 5% of the universe’s energy and matter content! There is dark matter and dark energy!

We don’t understand why we exist at all! Matter-antimatter asymmetry, connection to cosmology.
But ... we have a Higgs now!

> Higgs mechanism seems to be at work and explains at least partially why fundamental particles have mass.

> The Higgs is different

- it's not a quark or a lepton or a gauge boson – it's a new kind of fundamental particle;
- there is a scalar field filling up the vacuum;
- is it THE Higgs (of the SM) or just A Higgs (e.g. SUSY)?

> And why is the Higgs so light?

> We must measure the Higgs properties as precisely as possible

- mass, couplings, spin, ...

Test of Higgs potential
\[ \lambda_{hhh} = \sqrt{2} M_H \]

\[ V(H) = \frac{1}{2} M_H^2 H^2 + \sqrt{2} M_H H^3 + \]

ATLAS and CMS LHC Run 1

ATLAS+CMS

\[ \text{SM Higgs boson} \]

\[ [M, \epsilon] \text{ fit} \]

- 68% CL

- 95% CL

arXiv:1606.02266v2
Looking back in history:

- W, Z bosons discovered in the 1980s at CERN in p anti-p collisions
- Precise determination of their properties, mainly in e^+e^- (LEP, SLC) in the 1990s
- Resulted in predictions for then unknown top quark and Higgs boson

New physics accessible through precision measurements of the Higgs?
Why Man-Built Colliders?

> There are cosmic accelerators around, free of charge
  - energies up to $10^{20}$ GeV available
  - but center-of-mass energy matters! „only“ factor $\approx 30$ between LHC and highest energy cosmic rays.

> But also luminosity matters:
  - at highest energies only about 1 event per km$^2$ per year ...
  - ... compared $10^9$ pp collisions per second at the LHC!

> Example Higgs production:
  - only 1 Higgs in $10^{10}$ pp collisions
  - Identification requires laboratory conditions

> For particle physics colliders like the LHC are THE tool to use.
Hadron versus Lepton Colliders

- Proton-(anti-)proton colliders:
  - energy range high (limited by bending magnets power and ring radius)
  - composite particles, different (unknown) initial-state constituents and energies in each collision
  - complicated hadronic final states

- Discovery machines
  - only energy matters

- (Some) Precision measurement potential

- Electron-positron colliders:
  - energy range limited (by RF power)
  - point-like particles, well-defined initial-state quantum numbers and energies
  - simpler final states, well-defined missing energy

- Precision machines
  - sensitivity to new physics in quantum loop corrections!

- (Some) Discovery potential
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The Large Hadron Collider

- At least 20 years physics programme yet to come - we have only just begun:
  - very successful operation so far (2010-16) at 8-13 TeV; ~75 fb\(^{-1}\) per experiment.
  - only few percent of total luminosity:
    - \(\approx 75\ \text{fb}^{-1}\) by end of 2016
    - > 3000 fb\(^{-1}\) expected by 2035

### LHC / HL-LHC Plan

<table>
<thead>
<tr>
<th>Year</th>
<th>LHC</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>experiment beam pipes</td>
<td>HL-LHC installation</td>
</tr>
<tr>
<td>2012</td>
<td>7 TeV</td>
<td>2037</td>
</tr>
<tr>
<td>2013</td>
<td>spliced consolidation button collimators R2E project</td>
<td>5 to 7 x nominal luminosity</td>
</tr>
<tr>
<td>2014</td>
<td>8 TeV</td>
<td>2024</td>
</tr>
<tr>
<td>2015</td>
<td>13-14 TeV</td>
<td>2025</td>
</tr>
<tr>
<td>2016</td>
<td>EYETS</td>
<td>2026</td>
</tr>
<tr>
<td>2017</td>
<td>experiment upgrade phase 1</td>
<td>2 x nominal luminosity</td>
</tr>
<tr>
<td>2018</td>
<td>LS1</td>
<td>2027</td>
</tr>
<tr>
<td>2019</td>
<td>LS2</td>
<td>2028</td>
</tr>
<tr>
<td>2020</td>
<td>injector upgrade cryo Point 4 Civil Eng. P1-P5</td>
<td>cryomix interaction regions</td>
</tr>
<tr>
<td>2021</td>
<td>LS3</td>
<td>experiment upgrade phase 2</td>
</tr>
</tbody>
</table>
The High-Luminosity Large Hadron Collider

- Long shutdown from 2023-2025 with massive upgrades of LHC machine
  - HL-LHC with the goal of delivering 3000 fb$^{-1}$ until 2035
  - Development of new magnet technology for HL-LHC and beyond: Nb$_3$SN for magnets up to 12 T to replace some of the “old“ 8.33 T NbTi LHC magnets.
  - entails also major upgrade work to detectors to deal with rate and radiation.
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Hadron Collisions Beyond (HL-)LHC

- Energy matters – strong push towards higher-energy hadron colliders following the LHC.
  - note that many major HEP discoveries were made at hadron machines, i.e. bottom and top quark, W and Z bosons, tau neutrino, Higgs boson, ...

- Issue: magnet technology!
  - NbTi used for Tevatron, HERA, RHIC, LHC; need to move on to Nb3Sn, HTS, ...
> A circular tunnel @ Geneva
  - for hadrons (and leptons before)
  - „think big“ – in terms of magnet development and civil construction
  - 100 km circumference, 100 TeV cms. energy
  - CDR expected end 2018.

> Requirements:
  - >16 T dipole magnets

> Part of the FCC study
  - high-Energy LHC (HE-LHC)
    - new dipoles in LHC tunnel
  - roughly twice LHC energy
A circular e+e⁻ collider

Numerous

Alternative 2: Go circular!
HE-LHC – LHC modifications

S. Myers ECFA-EPS, Grenoble July 23, 2011

2-GeV Booster

Linac4
HE-LHC – LHC modifications

HE-LHC
>2030

SPS+, 1.3 TeV, >2030

2-GeV Booster

Linac4

ALICE

LHC 2008 (27 km)

S. Myers ECFA-EPS,
Grenoble July 23, 2011

ATLAS

CMS

TT40

TT41

TT10

TT60

TT2

PS 1959 (828 m)

LEIR 2005 (78 m)

Linac 3 Ions

n-ToF 2001

neutrons

AD 1999 (132 m)

Booster 1972 (157 m)

PS 1959 (828 m)

ISOLDE 1989

Gran Sasso

East Area

HE-LHC

CMS

ALICE

LHC 2008 (27 km)

North Area

S. Myers ECFA-EPS,
Grenoble July 23, 2011

ATLAS

Linac4

HE-LHC

>2030

SPS+, 1.3 TeV, >2030

2-GeV Booster
China CepC and SppC

> Study for a O(100 km) tunnel
  - O(100 TeV) cms energy pp collider
  - preceded by an e+e− Higgs factory (CEPC, see below)

> Baseline Design
  - 12 T dipole iron-based HTS
  - cms energy ≈ 70 TeV

> Energy Upgrade
  - 20-24 T HTS dipoles
  - cms energy ≥ 125 TeV

> Ambitious R&D for High Temperatur Superconductor

> CDR planned for end 2017
Sites under study:

1) Qinhuangdao
   (site technical exploring done)

2) Shanxi Province
   (under site technical exploring, started from Jan. 2017)

3) Near Shenzhen and Hongkong
   (site technical exploring done)
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Higgs at the LHC and at an e^+e^- collider

\[ pp \rightarrow H + X \rightarrow \gamma\gamma + X \]

Observed Higgs candidate at CMS
Higgs at the LHC and at an $e^+e^-$ collider

Observed Higgs candidate at CMS

Simulated Higgs in ILD detector @ ILC
International Linear Collider (ILC)

- Electron-Positron Collider
  - based on superconducting RF technology

- Technical design report (TDR) submitted 2013
  - $\sqrt{s} = 250 – 500$ GeV, upgrade for 1 TeV, acceleration gradient 35 MV/m
ILC Status

- Japan has expressed interest to host the ILC
  - top priority of Japanese particle physicist
  - worldwide support, e.g. ICFA
- Project under investigation by Japanese government
  - result expected in 2018
  - 90 GeV Giga-Z, 250 GeV Higgs factory, ≈ 350 GeV at t\(\bar{t}\) threshold and 500 GeV for ttH and HH
- Project is technically mature
  - demonstrated by European XFEL
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- Project is technically mature
- Demonstrated by European XFEL
CLIC: A potential multi-TeV collider

- Novel two-beam acceleration concept
- 100 MV/m gradient seems feasible
  - cms energies up to 3 TeV
- But not yet at the same level of maturity as ILC technology
- General issue for linear colliders: power consumption:

<table>
<thead>
<tr>
<th>Project</th>
<th>$\sqrt{s}$/TeV</th>
<th>Power/MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILC</td>
<td>0.5</td>
<td>163</td>
</tr>
<tr>
<td>ILC</td>
<td>1</td>
<td>240</td>
</tr>
<tr>
<td>CLIC</td>
<td>1.5</td>
<td>364</td>
</tr>
<tr>
<td>CLIC</td>
<td>3</td>
<td>589</td>
</tr>
</tbody>
</table>

- CLIC R&D ongoing at CERN
  - gradient, stability, beam handling
  - 380 GeV start version
  - input to European strategy process
Circular Electron-Positron Colliders

> FCC-ee:
  - lepton option of FCC.
  - beam energies up to the ttbar threshold, i.e. cms energy 350 GeV.
  - various staging scenarios for Z, WW, H, ttbar thresholds

> CEPC:
  - Higgs factory, i.e. cms energy 250 GeV.

> Circular: higher luminosity @250 GeV
> Linear: can reach higher energy
> Both projects are supposed to preceed the respective hadron collider
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Neutrino Beams for High-Energy Physics

- Neutrino beams offer unique potential to address fundamental questions of HEP
  - CP violation and matter-antimatter asymmetry, SM parameters, CKM matrix, mass hierarchy and mass determination
  - numerous past and ongoing experiments,
- Most recent example: TK2 with SuperKamiokande
  - neutrino beams from J-PARC facility; mainly for study of muon-to-electron oscillation studies.
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Upgrade to HyperK planned:
- J-PARC neutrino beam to 1.3 MW beam power
- 260 kton mass (water)
- Beam power 1.03 MW at 80 GeV; planned increase to 2 MW
- Compare $\nu_\mu \rightarrow \nu_e$ and anti-$\nu_\mu \rightarrow$ anti-$\nu_e$

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
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<tbody>
<tr>
<td>2017</td>
<td>begin far-site construction</td>
</tr>
<tr>
<td>2018</td>
<td>proto-DUNE at CERN</td>
</tr>
<tr>
<td>2021</td>
<td>far detector installation begins</td>
</tr>
<tr>
<td>2024</td>
<td>physics data begins (20 kt)</td>
</tr>
<tr>
<td>2026</td>
<td>neutrino beam available</td>
</tr>
</tbody>
</table>

2017: form ND consortium

The CERN Neutrino Platform
Far Future: Muon Collider

- Try to collide $\mu^+\mu^-$ rather than $e^+e^-$

- Advantages:
  - much smaller synchrotron losses: $\sim E^4/m^4r$
  - smaller facility size even for a multi-TeV machine
  - s-channel Higgs production: $\sim m^2$ factor 40000 enhancement wrt. $e^+e^-$
  - first stage could be a $\nu$-factory

- Problems:
  - muons live only for 2.2 $\mu$s
  - need very intense proton source
  - muon cooling
  - high background from muon decays (neutrinos!) at high energy
  - …

Example SUSY Higgs bosons
Far Future: Plasma Wakefield Collider

- How to achieve significantly higher gradients than 30 – 100 MV/m?
  - Plasma Wakefield Acceleration (PWA)

- Create very high electric field by pushing away electrons from atoms in a plasma
  - using very intense laser
  - or particle particle beams e.g. AWAKE at CERN

- Gradients of 10 GV/m with 1 GeV achieved in table top experiments
  - electrons accelerated from 40 to 80 GeV!

- But still many open issues
  - e.g. staging in a high energy linear collider
EuPRAXIA

- 3 M€ awarded to 16 laboratories and universities from 5 EU member states within Horizon 2020.
- Joined by 22 associated partners with additional in-kind commitments.
- Goal: produce a CDR for the worldwide first high energy plasma-based accelerator that can provide industrial beam quality and user areas.
  - Important intermediate step between proof-of-principle experiments and groundbreaking, ultra-compact accelerators for science, industry, medicine or the energy frontier.
- 14 work packages; 8 included in EU design study
  - Also application WPs: “FEL pilot application”, “HEP and other pilot applications”, …
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HEP is a Global Endeavour

> New machines are multi-billion Dollar / Euro /CHF projects
  - there can only be one of a kind?!
  - need international consensus – a slow and careful political process!

> Last round of strategy discussions has concluded in 2012/13 in various regions of the world

> Important issues in European discussion:
  - High-Luminosity LHC is decided
  - High energy physics at CERN after LHC R&D and input from LHC needed.
  - LC project: European participation in ILC project in Japan; CLIC
  - Long-baseline neutrino programme.
  - and others
Japan: Future HEP Projects
– „...Japan should take the leadership role in an early realisation of an e+e- linear collider.“

Update of European Strategy for by CERN Council (May 2013)
– LHC, incl. HL-LHC
– accelerator R&D
– strong support for ILC
– long-baseline neutrino
– importance of theory

> Different flavours in different regions of the world
> But looks like an emerging global, coherent strategy in particle physics
> Next update of European strategy 2020; US to follow 2-3 years after.

USA: Snowmass conclusions and recommendations to P5 in line with worldwide strategy statements
Conclusions

- High-energy accelerators are indispensable tools to address the most fundamental questions of nature
- The LHC is the current workhorse and immensely successful.
  - future defined until 2035 (HL-LHC programme)
- Numerous concepts and projects for both hadron and lepton collider projects around
  - also (accelerator-based) neutrino projects are important
- Next update of international strategy processes ahead of us
  - European strategy update 2020
  - important physics input from LHC
  - will guide the future
- Accelerator R&D is important for the future of particle physics!