Particle - Colliders
past-present-future

Hermann Schmickler (ex-CERN)

With some slides taken from:

G.Papotti (CERN): CAS 2016, Budapest
W.Herr (CERN): CAS 2018, Constanta
M.Benedikt(CERN): CAS@ESI 2018
Outline

• Why colliding beams?
• Past high energy frontier colliders
• A glimpse at physics experiments
• Collider figures of merits:
  c.m.s. energy and luminosity
  Details on luminosity
  Detector Occupancy in hadron collisions
• Possible future colliders:
  circular, linear, pp, e^+e^-, μ^+μ^-
Fixed-target vs head-on beam collisions

- Relativistic invariant
  \[(\Sigma m)^2 c^4 = (\Sigma E)^2 - (\Sigma \mathbf{p})^2 c^2\]
- In the laboratory frame
  \[4m^2 c^4 = (E_A + E_B)^2 - (p_A + p_B)^2 c^2\]
- Let \(E^*\) be the total energy available in the collision
- In the center-of-mass frame
  \[\mathbf{p}^* = \mathbf{p}_A^* + \mathbf{p}_B^* \equiv 0\]
  \[4m^2 c^4 = E^{*2}\]
  \[E^{*2} = (E_A + E_B)^2 - (p_A + p_B)^2 c^2\]

- Fixed-target
  \[p_B = 0 \ ; \ E_B = mc^2\]
  \[E^{*2} = E_A^2 - p_A^2 c^2 + m^2 c^4 + 2E_A mc^2\]
  \[E^{*2} = 2m^2 c^4 + 2E_A mc^2 \approx 2E_A mc^2\]
  \[E^* \approx \sqrt{2E_A mc^2}\]

- Head-on collision
  \[E^* = E_A + E_B\]
Past/Existing High Energy Frontier Colliders

Only referring to the highest energy

Lepton colliders:

- **LEP** (Large Electron Positron Colliders)
  - $Z_0$ factory at 90GeV electron-positron cms energy
  - $W^+W^-$ factory at 160GeV
  - Maximum 209 GeV cms energy for higgs search
    (bad luck: $e^+e^- \rightarrow Z^0H$ needs about 250 GeV)
  - Closed in the year 2000

- **SLC** (Standford Linear Collider)
  - $Z_0$ factory at 90GeV electron-positron cms energy
  - Single linac for $e^+$ and $e^-$, two return arcs for collision
  - Closed in summer 1998

Hadron colliders

- **LHC** (Large Hadron Collider):
  - Proton-proton with 13TeV
  - Ion-ion operation
Considered Future High Energy Frontier Colliders

Circular colliders:
- **FCC (CERN)** (Future Circular Collider)
  - FCC-hh: 100TeV proton-proton cms energy, ion operation possible
  - FCC-e^+e^-: Potential intermediate step 90-350 GeV lepton collider
  - FCC-he: Lepton-hadron option
- **CEPC / SppC** (China)
  - CEPC: e^+e^- 240GeV cms
  - SppC: pp 70TeV cms

Linear colliders
- **ILC** (International Linear Collider): e^+e^-, 500 GeV cms energy, Japan considers hosting project
- **CLIC** (Compact Linear Collider): e^+e^-, 380GeV-3TeV cms energy, CERN hosts collaboration

Others
- Muon collider (has gained again interest, also studied at CERN)
- Plasma wakefield acceleration (PWA) as linear collider...not yet ready
- Lepton – hadron colliders (LHeC, e-RHIC)
LEP (at CERN)

27 km circumference
e\textsuperscript{+}e\textsuperscript{-} collider
4 experiments: ALEPH, DELPHI, L3, OPAL
CMS energy: 90GeV (LEP I) - 209GeV (LEP II)
Peak Luminosity: $10^{32}$cm\textsuperscript{-2}s\textsuperscript{-1}

Precision measurements of the W and Z Bosons
Confirmation: only 3 lepton/quark families

Highest particle speed in any accelerator
SLC (at SLAC)

Electron-positron linear collider
2 experiments: first MARK II, then SLD
CMS energy: 92GeV
Peak Luminosity: $2 \times 10^{30} \text{cm}^{-2} \text{s}^{-1}$

The only linear collider so far

Confirmation of LEP results
The LHC (at CERN)

27 km circumference (the LEP tunnel!)
Nominal CMS energy: 14TeV
Peak Luminosity: $10^{34}$ cm$^{-2}$s$^{-1}$
Operation: 2009-today

Highest particle energy in any accelerator

Discovery of the Higgs particle in 2012
Exclusions on supersymmetry
Modern Particle Accelerators are Gigantic!

- RHIC, BNL, Long Island (USA)
- KEKb, KEK, Tsukuba, Japan
- HERA, DESY, Hamburg, Germany
- Tevatron, Fermilab, Chicago, USA
What do physicists with their data?  
...short outline in a nutshell

• The primary interaction is not visible.
• Physicists measure identity and energy/momentum of secondary particles, which emerge from the primary interaction.
• Physicists make model assumptions about the primary interaction and compare observables like the angular distribution of the produced secondary particles with the model. If it fits in all aspects, they declare the model the “truth”. (historic example: Rutherford scattering)
• Quantitative measurements like the mass of a new particle are possible, if all secondary particles are measured and the invariant mass is computed.
• It is very useful to know the total energy of the original collision, which is only the case for collisions of elementary particles (leptons).
• Most of the processes have “background” signals with similar signature. Very careful simulations of this background must accompany every measurement.

• Nowadays particle detectors are industrial installations with 1000’s of collaborating scientists and engineers. They have enormous dimensions.
Particle identification: a CMS slice

or “what the experiments do with the collisions”
Discovery of the 125 GeV Higgs boson (2012)
The decays of the Higgs boson, observed in the CMS and ATLAS detectors

\[ H \rightarrow \gamma \gamma \]

\[ H \rightarrow ZZ \rightarrow 4l \]
Discovery of the 125 GeV Higgs boson (2012)
The decays of the Higgs boson, observed in the CMS and ATLAS detectors

\[ H \rightarrow \gamma\gamma \]

\[ H \rightarrow ZZ \rightarrow 4l \]
Collider figures of merit:

1. **c.m.s. energy**: higher energy means particles with higher masses can be produced
2. **Luminosity**: A number characterizing a collider to produce a certain number of events of a given process in a given time

• **First: The cross section of a physics process:**

  *cross-section* $\sigma_{\text{ev}}$ expresses the likelihood of the process to be produced by particle interaction
  
  • $\sigma_{\text{ev}}$ can be understood as an “area”, which the beam has to hit.
  • Unit for cross-section: [m$^2$]
  • in nuclear- and high energy physics smaller units: 1 barn (1 b = $10^{-24}$ cm$^2$)
definition: Luminosity (L)

\[ R = \frac{dN_{ev}}{dt} = L(t)_{ev} \]

- Luminosity \( L \) relates cross-section \( \sigma \) and event rate \( R = \frac{dN_{ev}}{dt} \) at time \( t \):
  - quantifies performance of collider
  - relativistic invariant and independent of physical reaction

\[ N_{ev} = \int_{ev} L(t)dt \]

- accelerator operation aims at maximizing the total number of events \( N_{ev} \) for the experiments
  - \( \sigma_{ev} \) is fixed by Nature for every event type
  - aim at maximizing \( \int L(t)dt \)

- Luminosity unit: \([\text{m}^{-2}\text{s}^{-1}]\)

- The **integrated luminosity** \( \int Ldt \) is frequently expressed as the inverse of a cross section
  \( \text{pb}^{-1} = 10^{36} \text{ cm}^{-2} \) or \( \text{fb}^{-1} = 10^{39} \text{ cm}^{-2} \)
Example: LHC

Total integrated luminosity LHC Run 2: 150 fb\(^{-1}\)
Total cross section pp collisions: 100 mb

→ \(N_{\text{collisions}} = 150 \times 10^{12} \text{ mb}^{-1} \times 100 \text{ mb} = 15 \times 10^{15} \text{ events} \) !!!
→ On average a bit less than 100 charged tracks per event!
→ Only a small fraction gets recorded….still Pbytes of data

→ Total cross section for Higgs production: About 60 pb → About 9 \(\times 10^6\) Higgs produced
→ Higgs cross-section for Diphoton-decay: About 60 fb → 9000 events to analyse

H. Schmickler, CAS 2023
Details on luminosity

- derivation from machine parameters

- reduction factors
  - transverse offset
  - crossing angles
  - hourglass effect
  for electrons in addition
  - beam disruption
  - beam strahlung

- Need for luminosity control in high energy pp collisions
L from machine parameters -1-

• intuitively: more L if there are more protons and they more tightly packed

\[ L \propto N_{b1} N_{b2} \mu_{x,y} \]

\[ L \mu_{N_{b1}N_{b2}K} x,y, z, z_0 \]

• \( K = \) kinematic factor (CAS lecture, “Kinematics of Particle Beams I - Relativity”)
• \( N_{b1}, N_{b2}: \) bunch population
• \( \rho_{1,2}: \) density distribution of the particles (normalized to 1)
• \( x,y: \) transverse coordinates
• \( z: \) longitudinal coordinate
• \( z_0: \) “time variable”, \( z_0 = c t \)
• \( \Omega_{x,y}: \) overlap integral
L from machine parameters -2-

- for a circular machine can reuse the beams \( f \) times per second (storage ring)
- for \( n_b \) colliding bunch pairs per beam
- for uncorrelated densities in all planes:
  \[
  (x, y, z, t) = x(x) \, y(y) \, z(z) \, vt
  \]

\[
L = 2nf \, n_b \, N_{b1} \, N_{b2} \, f
\]

- for Gaussian bunches:
  \[
  u(u) = \frac{1}{\sqrt{2}} \exp \left( \frac{(u - u_0)^2}{2} \right) ; \; u=x, y
  \]

- for equal beams in \( x \) or \( y \): \( \sigma_{1x} = \sigma_{2x}, \sigma_{1y} = \sigma_{2y} \)

- can derive a closed expression:
  \[
  L = \frac{n_b \, N_{b1} \, N_{b2} \, f}{4 \, x \, y}
  \]

- \( f \): revolution frequency
- \( n_b \): number of colliding bunch pairs at that Interaction Point (IP)
- \( N_{b1}, N_{b2} \): bunch population
- \( \sigma_{x,y} \): transverse beam size at the collision point

<table>
<thead>
<tr>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n_b = 2808 )</td>
</tr>
<tr>
<td>( N_{b1}, N_{b2} = 1.15 \times 10^{11} ) ppb</td>
</tr>
<tr>
<td>( f = 11.25 ) kHz</td>
</tr>
<tr>
<td>( \sigma_x, \sigma_y = 16.6 ) ( \mu )m</td>
</tr>
<tr>
<td>( L = 1.2 \times 10^{34} ) ( \text{cm}^{-2}\text{s}^{-1} )</td>
</tr>
</tbody>
</table>
need for small $\beta^*$

- expand physical beam size $\sigma_{x,y}$:
  - * means “at the IP”

- try and conserve low $\varepsilon$ from injectors
  - In addition explicit dependence on energy ($1/\gamma_r$)
  - intensity $N_b$ pays more than $\varepsilon$ and $\beta^*$
  - design low $\beta^*$ insertions
  - limits by triplet aperture, protection by collimators
  - in LHC nominal cycle: “squeeze”

$$\begin{align*}
  x^* &= 4p_b^* e \\
  y^* &= \sqrt{r^*} \\
  L &= \frac{n_b^* N_{b1}^* N_{b2}^* f_r}{4}
\end{align*}$$

### LHC
- $\beta^* = 18 \Rightarrow 0.55 \text{ m}$
- $\varepsilon = 3.75 \ \mu\text{m}$
- $\gamma_r = 7463$
- $\sigma_{x,y} = 16.6 \ \mu\text{m}$

Relative beam sizes around IP1 (Atlas) in collision

J. Jowett

H. Schmickler, CAS 2023
Luminosity reduction factors \( (F_i) \)

\[ L = L_{\text{ideal}} \times F_1 \times F_2 \times F_3 \ldots \]

- transverse offsets
- crossing angles and crab cavities
- hourglass effect
transverse offsets -1-

• in case the beams do not overlap in the transverse plane (e.g. in x)

• more generally

\[ L = n_b N_{b1} N_{b2} f \exp \left\{ \frac{x^2}{4} \frac{y^2}{4} \right\} \]

<table>
<thead>
<tr>
<th>( \Delta x )</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1 ( \sigma )</td>
<td>0.779</td>
</tr>
<tr>
<td>2 ( \sigma )</td>
<td>0.368</td>
</tr>
<tr>
<td>3 ( \sigma )</td>
<td>0.105</td>
</tr>
<tr>
<td>4 ( \sigma )</td>
<td>0.018</td>
</tr>
<tr>
<td>5 ( \sigma )</td>
<td>0.002</td>
</tr>
</tbody>
</table>
For experts: transverse offsets -2-

- more general expression including different beam sizes:
  - $\sigma_{1x} \neq \sigma_{2x}$, $\sigma_{1y} \neq \sigma_{2y}$

\[
L = \frac{n_b N_{b1} N_{b2} f}{2} \sqrt{\frac{\frac{2}{x,1} + \frac{2}{x,2}}{\frac{2}{y,1} + \frac{2}{y,2}}} \exp\left\{ \frac{(x)^2}{2\left(\frac{2}{x,1} + \frac{2}{x,2}\right)} \right\} \left\{ \frac{(y)^2}{2\left(\frac{2}{y,1} + \frac{2}{y,2}\right)} \right\}
\]
crossing angles

- to avoid parasitic collisions when there are many bunches
  - otherwise collisions elsewhere than in interaction point only
    - e.g.: CMS experiment is 21 m long, common vacuum pipe is 120 m long

- luminosity is reduced as the particles no longer traverse the entire length of the counter-rotating bunch

\[
L = \frac{n_b N_1 N_2 f}{4} \frac{1}{\sqrt{1+\left(\frac{z \tan \frac{x}{2}}{y}\right)^2}}
\]

\[
- \frac{z \tan \frac{x}{2}}{2}
\]
is called the Piwinski angle

valid for small \( \phi \) and \( \sigma_z >> \sigma_x, \sigma_y \)

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<tr>
<th>LHC</th>
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<tbody>
<tr>
<td>( \phi )</td>
<td>285 ( \mu )rad</td>
</tr>
<tr>
<td>( \sigma_z )</td>
<td>7.5 cm</td>
</tr>
<tr>
<td>( F )</td>
<td>0.84</td>
</tr>
</tbody>
</table>
hourglass effect

- \( \beta \) depends on longitudinal position \( z \)
  - see W. Hillert, "Transverse Beam Dynamics"

- then beam size \( \sigma_{x,y} \) depends on \( z \)
  - if \( \beta^* \gg \sigma_z \), effect is negligible
  - if \( \beta^* \sim \sigma_z \), bunch samples bigger \( \beta \) than \( \beta^* \)

\[
(z) \approx \left(1 + \left(\frac{z}{\sigma_z}\right)^2\right)\\
\]

- L reduction is non-negligible for long bunches and small \( \beta \)

<table>
<thead>
<tr>
<th>LHC</th>
<th>HL-LHC</th>
</tr>
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<tbody>
<tr>
<td>( \beta^*/\sigma_z &gt; 7 )</td>
<td>( \beta^*/\sigma_z \sim 2 )</td>
</tr>
<tr>
<td>( F \sim 1 )</td>
<td>( F \sim 0.90 )</td>
</tr>
</tbody>
</table>
beam-beam force

\[ F(r) \propto \frac{N_b}{r} \left( 1 - \frac{e^2}{2r^2} \right) \]

- important for high brilliance beams
  - i.e. high luminosity …
- gives an amplitude dependent tune shift
  - for small amplitude, linear tune shift
- the slope of the force at zero amplitude is called the beam-beam parameter

\[ F \mu \quad r \quad \text{with} \quad \frac{\partial (r^*)}{\partial r} = \frac{N_b r_0}{4r^2} \]

- indicates the strength of the beam-beam force
  - but does not describe changes to the optical functions, non-linear part…

**LHC**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>( \sigma_{x,y} )</td>
<td>16.6 ( \mu \text{m} )</td>
</tr>
<tr>
<td>( \beta^* )</td>
<td>0.55 m</td>
</tr>
<tr>
<td>( N )</td>
<td>( 1.15 \times 10^{11} ) ppb</td>
</tr>
<tr>
<td>( \xi )</td>
<td>0.0037</td>
</tr>
</tbody>
</table>
linear colliders:
additional reduction/enhancement factors

disruption, pinch effect
beamstrahlung
disruption effects

- strong field by one beam bends the opposing particle trajectories
- quantified by disruption parameter
  \[ D_{x,y} = \frac{2r_e N_b z}{r_{x,y} \left( \frac{x}{x} + \frac{y}{y} \right)} \]
  \( D_{x,y} \) normally > 1
- nominal beam size is reduced by the disruptive field (*pinch effect*)
  - additional focusing for the opposing beam

- \( r_e \): electron classical radius
- \( N_b \): bunch population
- \( \sigma_{x,y,z} \): beam size at the collision point
- \( \gamma \): relativistic factor
beamstrahlung

- disruption at the interaction point is a strong bending:
- results in synchrotron radiation (*beamstrahlung*)
  - causes spread of centre-of-mass energy
  - high energy photons increase detector background

- quantified by beamstrahlung parameter $Y$

\[
Y = \frac{\langle E + B \rangle}{B_C} \frac{5}{6} \frac{r_e^2 r N_b}{r \left( x + y \right)}
\]

- with $B_C \frac{m^2 c^3}{e\hbar} \approx 4.4 \times 10^{13}$ Gauss
Not too much Luminosity please (in pp)…

- LHC pp experiments will need luminosity control
  - if too high can cause high voltage trips then impact efficiency
  - might have event size or bandwidth limitations in read-out
  - too many simultaneous event cause loss of resolution
- ...experiments also care about:
  - time structure of the interactions: pile up $\mu$
    - average number of inelastic interactions per bunch crossing

$$\langle R \rangle = \left\langle \frac{dN_{ev}}{dt} \right\rangle = f$$

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</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>21</td>
<td>4</td>
<td>17</td>
<td>37</td>
<td>17</td>
<td>41</td>
</tr>
</tbody>
</table>

- $f =$ bunch repetition frequency
- spatial distribution of the interactions: pile-up density
  - e.g. HL-LHC: accept max pile up density of 1.3 events/mm
- quality of the interactions (e.g. background)
- size of luminous region
  - e.g. need constant length (input to MonteCarlo simulations)
Luminosity levelling

• some experiments need to limit the pile-up
  • thus luminosity per bunch pair
    • e.g. $\mu < 2.1$ at LHCb in 2012

• stay as long as possible at the maximum value that experiment can manage
  • which is lower than what the machine could provide

• maintain the luminosity constant over a period of time (i.e. the fill)

• possible techniques (making use of the mentioned reduction factors)
  • by transversely offsetting the beams at the IP
  • by changing $\beta^*$
  • by decreasing the crossing angle
  • by bunch length variations
Possible future colliders: Some physics arguments

- Hadron collisions: collision of compound particles
  - Mix of quarks, anti-quarks and gluons: variety of processes
  - Parton energy spread
  - QCD processes large background sources
    total cross section increases with log s;
    “interesting cross sections” decrease with s
  - Hadron collisions ⇒ large discovery range

- $e^+e^-$ collisions: collision of elementary particles
  - Collision process known
  - Well defined energy (except TeV range)
  - Other physics background very limited
  - All cross sections decrease with c.m.s. energy

- Lepton-hadron is also possible (last HERA e-p @DESY)
  - small physics potential

- Muons same arguments as for Electrons, but
  - no synchrotron radiation
  - short lifetime of muons
  - difficult to get high luminosity (cooling of produced muon beams)
All quarks

These & other methods $\rightarrow$ whole set of quarks & antiquarks

NB: also strange and charm quarks

- valence quarks ($u_V = u - \bar{u}$) are hard
  $x \rightarrow 1 : xq_V(x) \sim (1 - x)^3$
  quark counting rules
  $x \rightarrow 0 : xq_V(x) \sim x^{0.5}$
  Regge theory

- sea quarks ($u_S = 2\bar{u}, \ldots$) fairly soft (low-momentum)
  $x \rightarrow 1 : xq_S(x) \sim (1 - x)^7$
  $x \rightarrow 0 : xq_S(x) \sim x^{-0.2}$
The LHC: signals much smaller than “bkg”

- General event properties
- Heavy flavor physics
- Standard Model physics
  - QCD jets
  - EWK physics
  - Top quark
- Higgs physics
- Searches for SUSY
- Searches for ‘exotica’
Higgs Physics in $e^+e^-$ Collisions

- Precision Higgs measurements
- Model-independent
  - Higgs couplings
  - Higgs mass
- Large energy span of linear colliders allows to collect a maximum of information:
  - ILC: 500 GeV (1 TeV)
  - CLIC: ~350 GeV – 3 TeV

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Three main present study lines:

• Big LEP/LHC-type collider rings
  – FCC-ee (or/and CepC in China)
  – Later a proton collider in the same tunnel
    have produced CDRs, working on TDR

• Linear colliders
  – CLIC and ILC
    have produced CDRs, presently using developed technologies for other projects

• Muon colliders
  (Production chain and acceleration/decay ring)
    long standing study, very difficult technologies needed, has gained new momentum in the last years
e+ e- Ring Collider Energy Limitation

Advantage: Beam is used many times for collisions

Lepton beam energy is low on a big radius
-> magnets are not a problem

But synchrotron radiation is:

\[ \Delta E \propto \left( \frac{E}{m} \right)^4 \frac{1}{R} \]

At LEP2 lost 2.75GeV/turn for E=105GeV

Pay for installed voltage (ΔE) and size (R), so scale as:

\[ R \propto E^2 \]

⇒ \[ \Delta E \propto E^4 / E^2 \]
⇒ \[ \Delta E \propto E^2 \]
⇒ \[ \Delta E \propto R \]

\[ C_R = a_R E^2 + b_R \]

-> use heavier particles, e.g. muons
-> or linear collider
(-> or try to push a bit harder on cost)
Linear Collider Energy Limitation

Hardly any synchrotron radiation

Beam can only be used only once
-> strong beam-beam effects

Acceleration gradient is an important issue

\[ C_L = a_L E + b_L \]
Simplified Cost Scaling Comparison

Linac:

\[ C_L = a_L E + b_L \]

Ring:

\[ C_R = a_R E^2 + b_R \]

There will always be an energy range where linear colliders are more cost effective

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Circular vs. Linear Colliders

Circular, adding four experiments

China prepares a project similar to FCC-ee


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International FCC collaboration (CERN as host lab) to study:

- **pp-collider (FCC-hh)**
  - main emphasis, defining infrastructure requirements
- **80-100 km tunnel infrastructure** in Geneva area, site specific
- **$e^+e^-$ collider (FCC-ee)**, as potential first step
- **p-e (FCC-he) option**, integration one IP, FCC-hh & ERL
- **HE-LHC** with FCC-hh technology

$\sim 16 \, \text{T} \Rightarrow 100 \, \text{TeV} \, pp \, \text{in} \, 100 \, \text{km}$
CepC/SppC study

Qinhuangdao (秦皇岛)

CepC, SppC

100 km

50 km

easy access
300 km east from Beijing
3 h by car
1 h by train

"Chinese Toscana"

Yifang Wang

CAS, Archamps, 29 June 2018
Tunnel implementations (laser straight)

Central MDI & Interaction Region
Muons are leptons like electrons & positrons but with a mass (105.7 MeV/c^2) 207 times larger

- Negligible synchrotron radiation emission (\( \alpha \ m^{-2} \))
  - Multi-pass collisions (1000 turns) in collider ring
    - High luminosity with reasonable beam power and wall plug power consumption
      - relaxed beam emittances & sizes, alignment & stability
    - Multi-detectors supporting broad physics communities
    - Large time (15 \( \mu \)s) between bunch crossings
  - No beam-strahlung at collision:
    - narrow luminosity spectrum
  - Multi-pass acceleration in rings or RLA:
    - Compact acceleration system and collider
    - Cost effective construction & operation
  - No cooling by synchrotron radiation in standard damping rings
    - Requires development of novel cooling method
Strong coupling to Higgs mechanism through the s channel

- Cross section enhanced by \((m_\mu/m_e)^2 = 4 \times 10^4\) with sharp peak at 126 GeV resonance

  • Muon-based Higgs factory with unique properties
    - 10^3 less luminosity required than with e^+/e^-
    - at half colliding beam energy (63 GeV/beam)
    - Enabling direct Higgs mass and width measurements by energy scan with high resolution thanks to narrow luminosity spectrum

  • Requires colliding beams with extremely small momentum spread \((4 \times 10^{-5})\) and high stability

→ The Muon based Higgs Factory concept
Muons: Issues & Challenges

- **Limited lifetime: 2.2 μs (at rest)**
  - Race against death: generation, acceleration & collision before decay
  - Muons decay in accelerator and detector
    - Shielding of detector and facility irradiation
    - Collider and Physics feasibility with large background environment?
      Not by beamstrahlung as with e+/e- but by muon decay (e, ν)
      Reduced background at high energy due to increased muon lifetime

- Decays in neutrinos:
  - Ideal source of well defined electron & muon neutrinos in equal quantities whereas Superbeams by pion decay only provide muon ν:

  The neutrino factory concept

  Generated as tertiary particles in large emittances
  - powerful MW(s) proton driver and pion decay
  - novel (fast) cooling and acceleration methods

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Muon Accelerator Program (MAP)

Muons based facilities and synergies

Key Challenges

- Fast cooling ($\approx$2µs) by $10^6$ (6D)
- Fast acceleration mitigating $\mu$ decay
- Background by $\mu$ decay
- $\approx 10^{13} - 10^{14}$ $\mu$ / sec

Key R&D

- MW proton driver
- MW class target
- NCRF in magnetic field
- Ionization cooling
- High field solenoids (30T)
- High Temp Superconductor
- Cost eff. low RF SC Fast pulsed magnet (1kHz)
- Detector/mac hine interface

Neutrino Factory (NuMAX)

<table>
<thead>
<tr>
<th>Proton Driver</th>
<th>Front End</th>
<th>Cooling</th>
<th>Acceleration</th>
<th>$\mu$ Storage Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC Linac</td>
<td>Capture</td>
<td>Initial</td>
<td>0.2–1 GeV</td>
<td>$\mu^+$ \rightarrow $\nu$</td>
</tr>
<tr>
<td>Accumulator</td>
<td>Channel</td>
<td>Cooling</td>
<td>1–5 GeV</td>
<td>$\mu^-$ \rightarrow $\nu$</td>
</tr>
<tr>
<td>Buncher</td>
<td></td>
<td></td>
<td></td>
<td>5 GeV</td>
</tr>
</tbody>
</table>

Muon Collider

<table>
<thead>
<tr>
<th>Proton Driver</th>
<th>Front End</th>
<th>Cooling</th>
<th>Acceleration</th>
<th>Collider Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC Linac</td>
<td>Capture</td>
<td>Initial</td>
<td>$\mu^+$</td>
<td>$E_{COM}$</td>
</tr>
<tr>
<td>Accumulator</td>
<td>Channel</td>
<td>Cooling</td>
<td>$\mu^-$</td>
<td>Higgs Factory</td>
</tr>
<tr>
<td>Buncher</td>
<td></td>
<td></td>
<td>$\nu$</td>
<td>to</td>
</tr>
<tr>
<td>Combiner</td>
<td></td>
<td></td>
<td>$\nu$</td>
<td>$\approx 10$ TeV</td>
</tr>
</tbody>
</table>

Factory Goal:

$10^{21} + &$ per year within the accelerator acceptance

Collider Goals:

$126$ GeV $\Rightarrow$ $\approx 14,000$ Higgs/yr
$Multi$-$TeV$ $\Rightarrow$ $Lumi > 10^{34}cm^2s^{-1}$

H.Schmickler, CAS 2023

Mark Palmer
The main technology challenges

- **FCC – hh**
  - SC dipole magnets with 16T or 20T field strength
  - machine protection and beam collimation

- **FCC-e⁺e⁻**
  - by design limited to 100 MW synchrotron radiation power
  - @350 GeV cms energy > 10GV energy loss/turn
  - huge RF plants based on SC-RF

- **CLIC**
  - 100 MV/m gradient for acceleration
  - Uses drive-beam of 100 A! (electrons) to power main linac
  - vertical beam size at IP = 1nm for high luminosity (10^{34})
  - very high demand on alignment of RF (wakefields) and on quadrupole mechanical stability (in order to maintain small emittance)

- **Muon collider**
  - 6D cooling in short time
  - fight against short lifetime of muons \(\rightarrow\) rapid cycling magnets
  - superconducting magnets for high collision rate (small circumference)
  - full beam gets “lost” permanently inside the magnets: shielding

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Summary

• Interesting time ahead of us in high energy physics
  → LHC still “usefull” until about the years 2035-2040
  → LHC will get a luminosity upgrade around the year 2027
    (5-10 times integrated luminosity/year)
• HE-LHC (LHC tunnel filled with FCC pp magnets) is also an actively discussed option
• CERN presently tries to rewrite LEP-LHC history by scheduling FCC $e^+e^-$ before FCC-pp
• Cost of new projects big issue in crisis times
• In parallel research for alternatives: PWA, linear colliders, $\mu$-collider

• All options require a lot of resources and collaboration across the whole world → maybe your future?
• Backup Slide
Drive beam time structure

Bunch charge: 8.4 nC, Current in train: 100 A

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Power extraction structure PETS

- must extract efficiently >100 MW power from high current drive beam
- passive microwave device in which bunches of the drive beam interact with the impedance of the periodically loaded waveguide and generate RF power
- periodically corrugated structure with low impedance (big \( a/\lambda \))
- ON/OFF mechanism

\[
P = \frac{I^2 L^2 F_b^2}{R/Q} \left( \frac{R}{Q} \right) \frac{1}{4v_g}
\]

P - RF power, determined by the accelerating structure needs and the module layout.
I - Drive beam current
L - Active length of the PETS
\( F_b \) - single bunch form factor (≈ 1)

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12 GHz PETS assembly

8 bars, as received from VDL

PETS octants assembly

I. Syratchev

H. Schmickler, CAS 2023
### Past/present circular colliders

<table>
<thead>
<tr>
<th>Machine</th>
<th>Years in operation</th>
<th>Beam type</th>
<th>Beam energy [GeV]</th>
<th>Luminosity [cm⁻² s⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISR</td>
<td>1971-'84</td>
<td>p p</td>
<td>31</td>
<td>&gt;2x10³¹</td>
</tr>
<tr>
<td>LEP I</td>
<td>1989-'95</td>
<td>e+ e-</td>
<td>45</td>
<td>3x10³⁰</td>
</tr>
<tr>
<td>LEP II</td>
<td>1995-2000</td>
<td>e+ e-</td>
<td>90-104</td>
<td>10³²</td>
</tr>
<tr>
<td>KEKB</td>
<td>1999-2010</td>
<td>e+ e-</td>
<td>8 x 3.5</td>
<td>2x10³⁴</td>
</tr>
<tr>
<td>SppS</td>
<td>1981-'84</td>
<td>p anti-p</td>
<td>315 (400)</td>
<td>6x10³⁰</td>
</tr>
<tr>
<td>TEVATRON</td>
<td>1983-2011</td>
<td>p anti-p</td>
<td>980</td>
<td>2x10³²</td>
</tr>
<tr>
<td>LHC</td>
<td>2008-?</td>
<td>p p (Pb)</td>
<td>7000</td>
<td>10³⁴</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>~2026-2037</td>
<td>p p (Pb)</td>
<td>7000</td>
<td>5x10³⁴</td>
</tr>
<tr>
<td>FCC-hh</td>
<td>2040+</td>
<td>p p (Pb)</td>
<td>50000</td>
<td>2-3x10³⁵</td>
</tr>
<tr>
<td>FCC-ee</td>
<td>2040+</td>
<td>e+ e-</td>
<td>45-175</td>
<td>~10³⁶</td>
</tr>
</tbody>
</table>