Collider Experiments
the LHC & beyond

Roger Forty (CERN)
Lecture 4
Lecture 4: Looking beyond

1. Searches at the LHC
   *Supersymmetry, other BSM, Dark Matter*

2. Hints of new physics?
   *Flavour anomalies, W mass, g-2*

3. Widening the search
   *Long-lived/feebly-interacting particles, beyond colliders*

4. Future colliders
   *HL-LHC, Higgs factories & beyond*

This final lecture looks beyond the Standard Model, to see where new physics might be found, and also beyond the LHC towards future colliders.
Introduction

• To recap some of the unanswered questions, which lead us to think that the Standard Model cannot be the full story:
  – Why are there 3 generations of quarks & leptons?
  – Are quarks & leptons fundamental, or made up of even more fundamental particles?
  – What is the reason for the pattern of masses?
  – What gives neutrinos their mass?
  – Why do we observe matter & almost no antimatter, if there is symmetry between them?
  – What is Dark Matter that can't be seen but has gravitational effects in the cosmos?
  – How does gravity fit in?
  – Why is the Higgs boson so light?

• SM likely not to be wrong, but a low-energy limit of a more complete theory (like Newtonian mechanics being superseded by Special Relativity)
The Higgs mass is on the electroweak scale (125 GeV), but is unstable w.r.t. large predicted quantum corrections

\[ m_H^2 = m_0^2 + \delta m_H^2 \]

\[ \delta m_H^2 \approx \frac{3G_F}{4\sqrt{2}\pi^2} \left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2 + \ldots\right) \Lambda^2 \]

These should inevitably make the mass huge, comparable to scale \( \Lambda \) at which new physics appears — unknown, but could be as high as the Planck scale* — unless there is incredible fine-tuning in the cancellation between the quadratic radiative corrections and bare mass.

Acceptable fine tuning is a matter of theoretical taste — if an explanation cannot be found, may otherwise have to fall back on the anthropic principle: hypothesis that copies of universe exist (multiverse) with differing parameters, and the parameters of our universe are special because they must be suitable to sustain life, so that we can measure them — drawback = untestable idea?

*Planck scale is the energy \( \sim 10^{19} \) GeV at which quantum effects of gravity become significant.
1. Searches at the LHC

- When the LHC was built, front-runner for an explanation was **Supersymmetry** – hypothesis that a symmetry exists related to particles’ spin, between fermions and bosons: each SM boson would have a fermion “super-partner”, and each fermion have a boson super-partner.

- Super-partners would then contribute with the opposite sign to the loop corrections to the Higgs mass providing cancellation of the divergent terms.

\[ \lambda^2 + \lambda \approx 0 \]

- The Higgs sector is extended to include 4 other scalar states, plus a whole zoo of new particles.

- **Squarks**
- **Neutralino** (mixed with \( \tilde{W}, \tilde{Z} \))
- **Sleptons**

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Collider Experiments 4: Searching for new physics
Supersymmetry

• If Supersymmetry was exact, then the super-partners would have the same masses as the SM particles – and would already have been seen

• So the symmetry must be broken, and many of the super-partners have higher mass to explain why they have not been seen

However, if this breaking is too great, the cancellation of the divergent terms becomes weaker and fine-tuning would still be required

→ Supersymmetry was expected to show up at the TeV scale

• Would not be the first time that the particle content has been doubled: already happened when antiparticles were introduced, a symmetry based on electric charge – but they were found soon after their prediction

• To avoid proton decay, an extra conservation rule is introduced (R-parity), opposite for SM particles and their super-partners: in this case the lightest supersymmetric particle (LSP) will be stable and becomes a candidate to explain Dark Matter (usually the *neutralino* \( \sim_0^1 \))

\[ R = (-1)^{3B-3L+2s} \]

• For particle with baryon/lepton numbers \( B \), \( L \) & spin \( s \) \n
→ +1 for SM particles, -1 for super-partners

\[ \rho \begin{cases} d_R & \tilde{s}_R \tilde{u}_L \tilde{e}_L^+ \\ u_R & \tilde{u}_R \tilde{d}_L \tilde{\nu}_L \end{cases} \]
Unification of forces

• Another argument made in favour of Supersymmetry: coupling constants “run” with energy due to quantum corrections, and evolving the coupling constants of the Standard Model measured at LEP to higher energy, they do not coincide:

\[ \alpha_1, \alpha_2, \alpha_3 \] are the coupling constants of the \( SU(3)_C \otimes SU(2)_L \otimes U(1) \) group corresponding to electromagnetic, weak and strong interactions

• With the addition of Supersymmetry unification of the couplings becomes possible at a single Grand Unified Theory scale \( \sim 10^{16} \text{ GeV} \)
Supersymmetry signatures

- Spectacular signatures were expected, with the complicated decay chains giving multiple jets and missing transverse energy (MET) from the LSP.
Search results

- However, no significant signals have been seen
- → limits set across the parameter space of super-partners
Is Supersymmetry hiding?

• Most searches for Supersymmetry require the presence of substantial MET, assumed to originate from the neutralinos that escape detection.

• But Supersymmetry could appear without missing $E_T$:
  – *Compressed* Supersymmetric spectra, i.e. a small mass difference between the LSP and top squark, and two LSP momenta balance.
  – *Top “corridor”:* stop pair production looks identical to $t\bar{t}$.
  – *$R$-parity violating* Supersymmetry: terms violate either Lepton or Baryon number conservation; together this could lead to rapid proton decay $\rightarrow$ allow only few couplings to be non-zero [arXiv:1209.0764](https://arxiv.org/abs/1209.0764).

• Many of these options contain no invisible particles, but rather extra leptons or extra jets, that may form resonances.

• So searches continue, but perhaps the masses are too high for the LHC (or Supersymmetry is not the answer).
Supersymmetry: space is squeezed

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Beyond the SM: other ideas

- A wide variety of exotic ideas, but often repeating signatures in the final states

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Theories

- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4th generation ($t', b'$)
- LRSM, heavy neutrino
- etc...

Experimentally-driven approach: search for the signatures, keeping an open mind to the source of any non-Standard Model signals
Extra dimensions

• Why are there four dimensions of space-time $(x,y,z,t)$ in our world?

Extending to extra dimensions is an alternative approach to solving the hierarchy problem, lowering the cut-off scale $\Lambda$ to the TeV scale

• Extra dimension(s) would need to be “rolled up” (compactified) to avoid being noticed

• Randall-Sundrum models add a 5th warped dimension, so that gravity can have a similar strength to the other forces (in the bulk) but is weak in our 4-dimensional world

• Such models can have new particles that are excitations of SM particles, e.g. a Kaluza-Klein excitation of the gluon ($g_{KK}$) which can decay preferentially to top-antitop pairs that look like a resonance in the $M_{tt}$ spectrum
Example: $tt$ resonance search

- $tt$ resonances are reconstructed from daughter top quarks via $t \to bW$ decay $t \to bW \to b\ell\nu$ (26.7%) or $\to bqq$ (66.5%)
- Boosted topology, single lepton channel
- Resonances are produced from colliding valence quarks and sea anti-quarks
  At high masses, resonance is smeared
- Analysis is a generic resonance search, set limits for explicit models: $g_{KK}$ and $Z'$

- Exactly one high $p_T$ electron or muon
- No isolation requirement
- At least two high $p_T$ jets
- Large MET to reject multijet background
- 1 top-tagged jet
- Enriched $W$ sample used to measure top-tag misidentification
- $M_{tt}$ used as final observable
Results

- No signal seen → set limits
- Best limits at the time for $t\bar{t}$ resonances

Models with extra dimensions can also predict the formation microscopic **Black Holes** at LHC collisions → very high multiplicity events

e.g. model of Arkani-Hamed, Dimopoulos and Dvali (ADD)

- No evidence found for them

**Phys Rev D88 (2013) 072001**
Search strategies

- If no mass bumps are found, i.e. the object being searched for has higher mass than that accessible at the LHC, one can still search for deviations in the *tails* of distributions by making precise measurements. This is the essence of the *Effective Field Theory* approach – becoming more important as no clear mass bumps of new particles have been seen yet.

\[
\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum \frac{c_i O_i}{\Lambda^2}
\]
No BSM signals seen so far

Overview of CMS EXO results

<table>
<thead>
<tr>
<th>CMS</th>
<th>36 fb$^{-1}$ (13 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M$_{H^{0}}$</td>
<td>$1803.06543$ (2J)</td>
</tr>
<tr>
<td>M$_{H^{0}}$</td>
<td>$1806.08643$ (2J)</td>
</tr>
<tr>
<td>M$_{H^{0}}$</td>
<td>$1803.11212$ (2J)</td>
</tr>
<tr>
<td>M$_{H^{0}}$</td>
<td>$1806.08643$ (2J)</td>
</tr>
<tr>
<td>M$_{H^{0}}$</td>
<td>$1811.08806$ (2J + 2J)</td>
</tr>
<tr>
<td>M$_{H^{0}}$</td>
<td>$1806.08643$ (2J)</td>
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<tr>
<td>M$_{H^{0}}$</td>
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<td>M$_{H^{0}}$</td>
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<td>M$_{H^{0}}$</td>
<td>$1808.09082$ (2J + 2J)</td>
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<td>M$_{H^{0}}$</td>
<td>$1808.09082$ (2J + 2J $+$ 6 J $+$ 6 J)</td>
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</tr>
<tr>
<td>M$_{H^{0}}$</td>
<td>$1812.10443$ (2J)</td>
</tr>
</tbody>
</table>

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included.)

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Dark Matter searches

- The search for Dark Matter (assuming it is made of particles) is complicated by its unknown mass → extremely wide range of masses to search

- If DM interacts with SM particles, does so through a mediator

- Colliders offer unique opportunity to study mediator’s properties (mass, spin)

Simplified models: describe dark matter without being constrained to a specific theory

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Dark Matter at colliders

- DM assumed to be weakly interacting → leaves no signal in the detectors
- Identify DM production by looking for other particles recoiling against it, e.g. from initial-state radiation: understanding of MET crucial!

Spurious detector signals can cause fake MET: control regions used to derive data-driven corrections to the background expectation

As seen in the detector:
Example: monojet-W/Z search

- No signal seen, limits set
  - here on the DM mass versus mediator mass plane

- Comparison (model-dependent) to non-collider searches: *direct detection* at underground experiments – collider results powerful in the low mass region
2. Hints of new physics?

- Although no convincing BSM signal has been found in the searches, there has frequently been excitement when possible hints seen

- Good example is the peak in the diphoton mass spectrum seen in 13 TeV data (2015) – like a heavy Higgs signal at around 750 GeV

- ATLAS significance = 3.9 $\sigma$ local/2.0 $\sigma$ global (accounting for the “look-elsewhere” effect)

- Similar bump seen by CMS!

- Would clearly have been new physics if confirmed: over 200 theory papers published on its possible interpretation...

- But then the following year’s data ruled it out – most likely it was a statistical fluctuation

Are there other hints that currently survive? → will discuss three “anomalies”
1) Flavour anomalies

- Currently the largest evidence for disagreement with the Standard Model seen so far at the LHC are known as the “flavour anomalies” seen by LHCb.

- FCNC processes involving the transition $b \rightarrow s \ell^+ \ell^-$ provide a rich set of observables to probe for new physics.

- There is a systematic failure of theory to describe the differential branching fractions at low momentum transfer $q^2$, or some of the angular distributions.

- Even more striking signals seen when comparing decay modes to electrons or muons.
Lepton Universality

- In the Standard Model gauge bosons have identical couplings with each of the three families of leptons, known as **Lepton Universality**

- The decays $B^+ \rightarrow K^+\mu\mu$ and $B^+ \rightarrow K^+ee$ are both decays of the form $b \rightarrow s\ell^+\ell^-$ and in the Standard Model they should occur with the same rate (apart from lepton mass effects, which are small here)

- Experimentally this is studied by making the double ratio with the resonant (via $J/\psi$) and non-resonant decays:

\[
R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \rightarrow J/\psi(\rightarrow \mu^+\mu^-)K^+)} / \frac{\mathcal{B}(B^+ \rightarrow K^+e^+e^-)}{\mathcal{B}(B^+ \rightarrow J/\psi(\rightarrow e^+e^-)K^+)}
\]

Early results were surprisingly low: also for a similar channel with an excited kaon ($K^*$)

- $3.1\sigma$ below SM
- $\sim2.5\sigma$ below SM

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Flavour anomalies (2)

- A different hint of Lepton Universality violation has been seen in the decays $B^0 \to D^{(*)+} \ell \nu$, this time comparing the modes with muons or tau leptons.

- Mass effects are larger here, so SM prediction is around 0.3. These are tree-level decays, so it would be surprising to see new physics.

- Similar ratios constructed, known as $R(D)$ & $R(D^*)$.
  Biggest discrepancy was seen by BaBar.
  Combining all results, 3.2 $\sigma$ away from SM.

\[
R(D^*) = \frac{\mathcal{B}(B^0 \to D^{*+} \tau^+ \nu)}{\mathcal{B}(B^0 \to D^+ \mu^+ \nu)}
\]

Theorists have tried combining all anomalies, finding very significant discrepancy with SM.
Latest news

- In a recent publication LHCb has updated (and extended) its analyses of $R_K$ and $R_{K^*}$, using improved analysis techniques.
- In addition to possible statistical fluctuations, a systematic correction was found due to underestimated hadronic misidentification background in the electron sample → little green peaks (importance of systematic studies!)

Updated results are consistent with the Standard Model → this element of the flavour anomalies has therefore gone away

The other flavour tensions with SM still remain to be understood, but the situation is less dramatic now

arXiv:2212.09152
2) W mass anomaly

- **New CDF result for** $m_W$ **last year:** 0.01% precision
  - Uses entire dataset collected from the Tevatron collider at Fermilab, based on 4.2 million W boson candidates (about four times the number used in the analysis CDF previously published in 2012)

- **Discrepancy with the SM expectation from EW fits at level of** $7\sigma$

- **However, result is also in significant tension with average of previous measurements from LEP, LHCb, ATLAS, D0**
  - Misunderstanding of the proton structure or QCD could manifest differently depending on C.M. energy, $p-\bar{p}$ vs $p-p$ collisions, or different analysis choices

  → wait to see when consistency between experiments has been clarified
3) g-2 anomaly

- An elementary particle with intrinsic angular momentum (spin, $S$) and charge $q$ has magnetic moment $\mu$ given by: $\mu = g \frac{q}{2m} S$.
- Dirac predicted $g = 2$ at tree-level, but this receives corrections from virtual particles in loop diagrams → increases the value.
- “Anomalous magnetic moment” of lepton $\ell$: $a_\ell = (g_\ell - 2)/2$

Their measurement is a long-standing precision test of the Standard Model.

- $a_e = 0.001 \ 159 \ 652 \ 180 \ 7 \pm 3$ measured to 0.24 ppb!
- SM prediction: agrees, triumph for QED!
- $a_\mu = 0.001 \ 165 \ 920 \ 6 \pm 4$ measured to 0.37 ppm
- SM prediction: close but doesn’t quite agree!
- $a_\tau = -0.018 \pm 0.017$
- SM prediction difficult to measure due to its short lifetime

arXiv:1911.00367
$a_\mu$ calculation

- Many contributions to $a_\mu$, classified as QED, Weak and Hadronic:

\[ a_\mu = \text{QED} (116584719) \times 10^{-12} \]
\[ 0.001 \text{ ppm} \]

\[ a_\mu = \text{Weak} (154) \times 10^{-12} \]
\[ 0.01 \text{ ppm} \]

\[ a_\mu = \text{HVP} (6845) \times 10^{-12} \]
\[ 0.37 \text{ ppm} \]

\[ a_\mu = \text{HLbL} (92) \times 10^{-12} \]
\[ 0.15 \text{ ppm} \]

(Contributions to value in units of $10^{-12}$)

Contributions to uncertainty on prediction

HVP = Hadronic Vacuum Polarization
HLbL = Hadronic Light-by-Light

Example of a few of the many diagrams that have been calculated (here 5-loop for the QED part)

An amazing amount of work!

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g-2 experiment

At “magic” momentum 3.1 GeV/c, focusing electric field doesn’t affect spin precession

g-2 muon storage ring (at Fermilab)

Fit to the data

\[ \chi^2/\text{ndf} = 8519/4165 \]
precision: 1.35 ppm
g-2 result

- First result from the new Fermilab experiment last year is in excellent agreement with the previous experiment (at BNL). 
  
  
  
  
  arXiv:2205.06336

- Confirms discrepancy with the SM prediction, currently at $4.2 \sigma$

- However, there are new calculations of the most uncertain part of the prediction (HVP) from Lattice QCD, which would reduce the discrepancy – the theory community are working to understand this tension between predictions, to consolidate the comparison with experiment.

Affect of different theoretical groups’ calculations of HVP on the $a_\mu$ result
3. Widening the search

- No convincing hints of physics beyond the Standard Model seen so far at the LHC – consider whether we could be missing new particle decays?
- Most searches share the basic reconstruction of tracks:

  \[ \text{e.g. } pp \rightarrow t \bar{t} \rightarrow \mu \text{ b} \]

  Even the b-quarks only travel a few mm before decaying

  Wide variety of lifetimes seen for SM particles – maybe in the Dark Sector too?
Long-lived particles

- Requiring track origin near to IP could miss BSM particles with long lifetimes

Plenty of theoretical predictions
  - Split Supersymmetry
  - Gravitino Dark Matter
  - Hidden Valley

- Predict particles that travel $\sim m$ with lifetime $\sim 100$’s ns, or lose so much energy that they “stop” somewhere in the detector and decay much later

- Challenge for experiments: need to change triggering strategy and object reconstruction! Look for:
  - Energy deposit in calorimeter with no tracks pointing to it
  - Large energy loss $dE/dx$
  - time of flight $< \text{speed of light}$

$\rightarrow$ signature-driven searches

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Example: $Z + \text{single neutral LLP}$

- Popular scenario in dark-sector models with additional $U(1)_d$ dark gauge symmetry

- **Experimental signature:**
  - $Z_d$ decays within the Hadron calorimeter
  - Jets have little deposits in the ECAL & no charged tracks pointing to the PV
  - Corresponds to decay lengths for $Z_d$ between few cm and tens of meters

- $Z_d$ jet selection requires no track $p_T > 1$ GeV and uses jet timing

- **No excess observed:** set limits

<table>
<thead>
<tr>
<th>Minimum jet $E_T$</th>
<th>40 GeV</th>
<th>60 GeV</th>
<th>80 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background Data</td>
<td>175 ±22</td>
<td>33.0 ±4.4</td>
<td>13.2 ±3.5</td>
</tr>
<tr>
<td>Expected UL</td>
<td>65</td>
<td>17</td>
<td>10</td>
</tr>
<tr>
<td>Observed UL</td>
<td>50</td>
<td>18</td>
<td>13</td>
</tr>
</tbody>
</table>

(On signal yields)

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ArXiv:1811.02542
Stopping LLPs

• Heavy (~100 GeV) LLPs lose kinetic energy and will stop while traversing detector

• If these stopped LLPs have lifetimes > ~10s of ns their decays will be reconstructed as separate events from the beam crossing where they were produced
  – most easily identified when there are no proton bunches in the detector

• Search for out-of-time (w.r.t bunch crossing) deposits in the HCAL or muon pairs in the muon detector

• Backgrounds: cosmic rays, beam-halo and detector noise

<table>
<thead>
<tr>
<th>LHC period</th>
<th>Trigger livetime [hrs]</th>
<th>HCAL noise</th>
<th>Cosmic ray muons</th>
<th>Beam halo</th>
<th>Total background</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>135</td>
<td>0.4^{+2.9}_{-0.4}</td>
<td>2.6 ± 0.9</td>
<td>1.1 ± 0.1</td>
<td>4.1^{+3.0}_{-1.0} (6.2)</td>
</tr>
<tr>
<td>2016</td>
<td>586</td>
<td>0.0^{+9.8}_{-0.0}</td>
<td>8.8 ± 3.1</td>
<td>2.6 ± 0.2</td>
<td>11.4^{+10.3}_{-3.1} (17.4)</td>
</tr>
</tbody>
</table>

Muon-pair time difference

Data

Limits set on lifetime from 100 ns to 10 days

JHEP 05 (2018) 127
Highly ionizing particles

• Magnetic monopoles are a prime example of this type. They would make Maxwell’s equations more symmetric but aren’t found in normal matter – if you break a magnetic dipole (bar magnet), you get two more dipoles.

• Dirac (1931) formulated a consistent description of a magnetic monopole within the framework of quantum physics, related to the quantization of charge: if any magnetic monopole exists then the electric charge is quantized in units of \( e = \frac{2\pi \hbar}{\mu_0 g_D} \)
where \( g_D \) is magnetic charge, \( \mu_0 \) is permeability of free space. The value of \( g_D \) is \( \sim 68.5e \) – so would be very highly ionizing.

• Might be produced at colliders: would give unusual tracks, parabolic along axis of solenoid field...
MoEDAL

- MoEDAL is dedicated to this type of search
  Uses plastic foils: Nuclear Track Detector (NTD), deployed around the LHCb VELO as a passive detector
  HIPs would leave ionization trails, revealed as large holes when etched

- Aluminium blocks also deployed to trap monopoles: material samples passed through superconducting SQUID magnetometers to look for induced non-decaying current from a transported monopole

- No monopole candidates found, limits set

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arXiv:2112.05806
Feebly interacting particles

- Weakly Interacting Massive Particles (WIMPs) have been a popular candidate for Dark Matter: with mass in the 100 GeV range and interaction strength like the weak force, they would be produced thermally in the Big Bang with the right abundance – many searches made, but have not found them so far.

- However, there could be other Dark Matter candidates with lower mass (MeV – GeV) and weaker coupling, such as the Dark Photon (A’) that would have a long lifetime & decay to $e^+e^-$.

- FASER is a new small experiment at the LHC to search for such weakly interacting particles.
FASER

• Studying the intensity frontier at the LHC: most light hadrons are produced along the beam axis, perhaps other light new physics particles too?

• The FASER experiment is situated ~ 500 m from the ATLAS collision point, on the beam collision axis line-of-sight in an unused former service tunnel.
Neutrinos at the LHC

- Neutrinos produced in the pp collisions of the LHC are also mostly in the forward direction, and can be detected at FASER in an emulsion detector, allowing another test of the Standard Model.
- First candidate collider neutrino events have been seen in a prototype of the emulsion detector.

<table>
<thead>
<tr>
<th>150 fb⁻¹ @14 TeV</th>
<th>νₑ</th>
<th>νᵦ</th>
<th>νᵣ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main production source</td>
<td>kaon decay</td>
<td>pion decay</td>
<td>charm decay</td>
</tr>
<tr>
<td># traversing FASERν</td>
<td>$O(10^{11})$</td>
<td>$O(10^{12})$</td>
<td>$O(10^9)$</td>
</tr>
<tr>
<td>25 cm x 30 cm</td>
<td>~1300</td>
<td>~20000</td>
<td>~20</td>
</tr>
<tr>
<td># interacting in FASERν</td>
<td>(1.1 ton tungsten)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

First candidate collider neutrino events have been seen in a prototype of the emulsion detector.
FASERν & SND

• Small spectrometer installed to detect the close $e^+e^-$ tracks; emulsion detector added in front to detect neutrinos: FASERν (covers $\eta > 9$)

• SND is a similar detector on the opposite side of ATLAS, but slightly off axis ($7.2 < \eta < 8.4$) → enhances the neutrinos coming from heavier hadron decays such as charm

Predicted sensitivity

FASER installation in 2021
Forward Physics Facility

- FASER and SND are making good progress, but the access tunnels where they are sited are too small to exploit full physics potential in the forward region of the LHC

- A new shaft has been proposed to be dug 620 m from the ATLAS interaction point, with a 65 m-long underground cavern to host more/larger experiments

- At the moment there are 5 proposed experiments to be situated in the FPF with different capabilities and covering different rapidity regions

- Facility is not approved for now – decision will probably only be taken in a few years’ time
Physics Beyond Colliders

• LHC (including its future HL-LHC phase) is the flagship of the CERN programme, providing data at the energy frontier for the next 20 years. A future collider should follow after the LHC, but not before mid-2040s.

• *Physics Beyond Colliders* study initiated to maintain a diverse physics programme at CERN, help to fill gaps between colliders: use the injector complex at CERN for fixed-target physics at the intensity frontier – searching for rare or weakly-coupled physics with high intensity beams.

• A current example of such experiments is **NA62**, that searches for the very rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at the SPS.

• When NA62 has been completed at the end of Run 3 (2025) there is the opportunity to upgrade the intensity of the beam-line and either extend the study of kaon physics (proposal **HIKE**) or make a beam-dump to search for new physics such as Heavy Neutral Leptons (at the proposed **SHiP** experiment or a competing off-axis proposal, **SHADOWS**).

• This intensity upgrade has just been **strongly supported** by the CERN Research Board (on Monday) – approval is expected by end of this year.
NA62

- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is a very rare decay ($BR_{SM} \sim 10^{-10}$) but precisely predicted: another good place to look for new physics in loop diagrams

- Single track in the final state, use an intense beam containing $K^+$ and study the missing mass in the decay due to the neutrinos

$$m_{miss}^2 = (p_K - p_\pi)^2$$

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{NA62Run1} = \left(1.10^{+0.40}_{-0.35(stat)} \pm 0.03(syst)\right) \cdot 10^{-10}$$
SHiP

- Standard Model was originally written down without right-handed neutrinos ($\nu$ assumed to be massless)
- Neutrino oscillations imply they are massive, and introducing right-handed sterile partners could help to explain dark matter and the baryon asymmetry of the universe: *Heavy Neutral Leptons*
- SHiP is a proposed experiment to search for these & other dark-sector particles, via a beam-dump at SPS

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Roger Forty

Collider Experiments 4: Searching for new physics

PoS(ICHEP2016)490

vMSM arXiv: 1301.5516

SHiP sensitivity to HNLs (projected)
4. Future Colliders

• Having a diverse programme of experiments at lower energy is important, but much of recent progress in particle physics has been driven by colliders.

• The long term strategy for particle physics in Europe (and CERN) is decided in a process that takes place about every 6 years: the ESPP update (latest held in 2020).

• There is a similar consultation in the Americas known as the Snowmass process, followed by prioritization (P5) that is currently in progress expected to report soon.

• Clear priorities were set in the latest European strategy update:
  
  1. Full exploitation of the LHC (including its HL-LHC phase: discussed here as a future collider).

  2. The next collider after the LHC should be an $e^+e^-$ Higgs Factory.

  3. The long-term future of European particle physics should be a collider at the energy frontier with $E_{\text{CM}} \geq 100$ TeV.
**HL-LHC**

- Approved upgrade of the LHC to increase luminosity to 5 (or even 7) x $10^{34}$ cm$^{-2}$s$^{-1}$
- Energy will not be changed very much, may be pushed up to the design value of 14 TeV in centre-of-mass, or just beyond (currently 13.6 TeV)
- Significant changes to the LHC machine, making good progress, to be ready in 2029 and run until 2042, integrating a total of 3000 fb$^{-1}$/experiment > 10x current sample
- The luminosity is increased with stronger focusing at IP: 12 T inner-triplet magnets require use of new superconductor, Nb$_3$Sn
- Low $\beta^*$ requires larger beam crossing angle, would reduce luminosity by factor $R \rightarrow$ rotate bunches to collide head on (crab cavities)
Upgraded experiments

• The increased luminosity will mean increased pileup to ~200 overlapping interactions, and increased radiation so the experiments also need to be upgraded (or life would be hard...)

• For ATLAS and CMS these are known as their Phase-II upgrades, which are already designed and now moving into production: includes new silicon pixel detectors, trackers, the HGCAL, etc.

• To combat the pileup, **fast timing** is a key ingredient: as the bunches pass through each other, collisions occur at different *times* as well as *positions*
  Pileup can be reduced by cutting on the vertex $z$ and selecting on vertex time $t$: “4D vertexing” $(x,y,z,t)$

![Simulation of 200 pileup vertices](image-url)
Fast timing

- Timing layers added by both ATLAS (endcaps only) and CMS (endcaps and barrel) as part of their Phase II upgrades for HL-LHC

**MIP Timing Detector (MTD)**

**Barrel (BTL)** instrumented with scintillator bars

**Endcaps (ETL)** with silicon detectors (LGAD)

Technology selected according to requirements:

- Both detectors cost ~ 10 MCHF, but...
- BTL covers 3x area of ETL with 25x fewer channels
- However, it would not handle 10x higher radiation
Timing layer technology

- **Fast scintillator** used for barrel: LYSO crystals (Lutetium Yttrium Orthosilicate) excellent radiation tolerance, high light yield (∼40,000 photons/MeV) fast scintillation rise-time (<100 ps) relatively short decay-time (∼40 ns)

- 166k LYSO crystals readout with SiPMs at each end attached to the inner wall of tracker support tube (radius = 1.15 m, length = ±2.6 m)
  
  Time resolution: 35 ps at start, 60 ps at end of HL-LHC

  Time-of-flight particle ID as a bonus: 2σ K-π separation up to $p \sim 2$ GeV/c

- Endcaps use **LGAD** (Low-Gain Avalanche Diodes) silicon detectors with internal gain

  LGADs can achieve 30 ps resolution but degrades with radiation dose → may need to be replaced during run

S. Grinstein, IAS-HEP 2021
HL-LHC prospects

• If new physics signal seen in Run 3 → first detailed exploration with well understood machine and experiments

Otherwise extend direct discovery potential by 20-30% in mass reach

• In either case: >100 million Higgs produced → measure Higgs couplings to a few percent including 2nd generation via \( H \rightarrow \mu^+\mu^- \) + first sensitivity to HH production
LS4 upgrades

- LHCb and ALICE have just been upgraded for Run 3. They plan future upgrades to make use of the high luminosity available at HL-LHC, after ATLAS/CMS. Planned to be installed in Long Shutdown 4 (LS4) currently scheduled in ten years’ time (2033-34) so there is still time for exciting R&D.

- LHCb also plans to use fast timing, e.g. 4D tracking in the VELO and a novel Time-Of-Flight system:

- Aim to record 300 fb\(^{-1}\) of data → greatly improved precision on flavour observables.
ALICE 3

- ALICE is planning a radical all-new experiment for their upgrade in LS4
- Replace the TPC with an extremely light-weight silicon tracking system + running at higher rate
- Exciting ideas, but first need to be approved (after checking that enough funding is available)

Aiming for only 0.05% $X_0$ per layer!

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Collider Experiments 4: Searching for new physics
Higgs Factory

• Now the Higgs boson has been discovered, the highest priority future collider is an $e^+e^-$ Higgs factory, to study it in great detail

• There are 4 (at least) implementations under discussion, none of them approved yet
  All target associated production $e^+e^- \rightarrow ZH$
  “Higgstrahlung” → will measure unbiased Higgs boson properties by selecting $Z$ decay & looking at everything that recoils against it
  Sensitive to possible invisible Higgs decays

• Main choice is between linear or circular colliders: linear are better at high energy, circular at low energy, performance quite similar at the energy for ZH (240 GeV)

• Linear: ILC (Japan) or CLIC (CERN)

• Circular: FCC (CERN) or CEPC (China)
1) International Linear Collider (ILC)

- Mature technology, discussed for over 20 years, based on superconducting niobium RF cavities at 1.3 GHz frequency giving accelerating gradient ~ 35 MV/m
- Two separate linacs, for $e^+$ and $e^-$ beams, with single IP Baseline 250 GeV (30 km), upgradeable to 1 TeV
- Possible site selected in Japan, but no recent progress towards approval from the Japanese government
2) Compact Linear Collider (CLIC)

- Normal conducting cavities allow for higher frequency 12 GHz → higher gradient ~ 100 MV/m
- Different stages considered: 380 GeV (11 km) up to 3 TeV (50 km), could be sited in CERN region
- *Two-beam* acceleration system with a low energy high current drive beam powering the RF cavities of the main linac

Accelerating structure \( (d \sim 1 \text{ cm}) \)
3) Future Circular Collider (FCC)

- Feasibility of a 91-km circular tunnel studied at CERN: could be ready (technically) by ~ 2045
- Use developments made at B Factories: e.g. continuous injection → enormous luminosity possible at low energy – running on the Z would repeat whole of LEP in a few minutes, integrate $10^{12}$ Z decays, and $>10^6$ Higgs bosons
- Possibility of 4 IPs → 4 experiments

4) CEPC (China): very similar design to FCC
CLIC (or ILC technology) is kept as a backup in case FCC turns out to be too expensive (estimated ~ 11 BCHF)

Tentative running schedule
$e^+e^-$ collisions → known as FCC-ee
Higgs Factory experiments

- Experiments for an $e^+e^-$ Higgs Factory are similar to those used at LEP, but aiming for higher precision: radiation and pileup are less severe than at the LHC.
- Common developments are being discussed between the different proposed facilities.
- At FCC-ee expect to measure H couplings to better than 1%, $m_W$ and $m_Z$ to < 1 MeV, $m_t$ to < 20 MeV from threshold scan, etc.

HH only directly accessible at higher energy
RICH for a Higgs Factory

- Example of R&D towards a future Higgs factory – that I am working on now
- Adaptation of a twin-radiator RICH (similar to an original design in LHCb) to a 4π detector at a future Higgs Factory, such as FCC-ee: aiming to be as compact & light as possible: 20 cm thick, 5% of $X_0$
- Concept inspired by the compound eye of an insect: named “Array of RICH Cells”

M. Tat, ECFA workshop

CLD (one of the proposed experiments)
Event display

Example of studies made with simulation: display of a Z event containing a $B_s \rightarrow D_s K$ decay in the ARC detector – to be followed up with prototypes in the next few years

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Upgrade II optimization
**s-channel production?**

- This might appear attractive for studying the Higgs (i.e. $E_{CM} = m_H$, like $e^+e^- \rightarrow Z$ at LEP) but it is tough: low cross-section and $\Gamma_H (4 \text{ MeV}) \ll$ beam energy spread (100 MeV). FCC-ee might just be able to measure it, with dedicated running over a few years.

- Try using muons instead of electrons? Higher mass $\rightarrow$ larger cross-section.

**Muon colliders** are being studied, but statistics in the $s$-channel are lower than for $e^+e^- \rightarrow ZH$, plus design is complicated & $\mu$ decay $\rightarrow$ severe background in detector.

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Collider Experiments 4: Searching for new physics  
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Sustainability

- Accelerators need to be powered by electricity, recently cost has increased plus environmental concerns

- The LHC uses ~ 200 MW when running. Electricity provided to CERN is already climate friendly – nuclear (France) + renewable (Switzerland): 90% carbon-free

- But we must continue to strive for improvement for future colliders: e.g. more efficient RF, increased use of renewable energy, possible use of Energy Recovery Linac technology to extract energy from beams after the collision, or permanent magnets, etc.

- FCC-ee is the most energy efficient of the Higgs factory proposals (up to the energy for $t\bar{t}$ production)
Going further

• After the Higgs factory, the priority will be to push the energy frontier as far as possible, in particular if deviations from the Standard Model have been seen in the precision Higgs + Electroweak measurements

• Advanced accelerating techniques are under study to reach higher accelerating gradients → more compact colliders

• Limitation in current RF structures from discharges due to material imperfections → avoid solid structures, use a plasma instead

• Wakefields can be induced in a plasma using a laser or drive beam, then injected electrons “surf” the waves to high energy

• Aim to reach gradients > GV/m e.g. at the AWAKE facility at CERN (but more tricky to accelerate e+)
FCC-hh

- It is planned to re-use FCC tunnel for a hadron collider at the energy frontier in the same way that the LHC followed LEP
- Circumference is 3.5 x LHC, need to use high-field magnets to reach $\geq 100$ TeV p-p collisions: $\text{Nb}_3\text{Sn}$ should achieve 16 T, high-temperature superconductor (HTS) even higher; start date only $\sim 2070 \rightarrow$ time for R&D!
- At high energy can make detailed study of HH production and the Higgs potential, extend search for new physics by a big step – experiments even larger than at LHC, need to resist very high radiation dose and pileup $O(1000)$
Summary (Lecture 4)

• The Standard Model is very successful, but we know it is not the full story. Many searches have been made at the LHC, but so far no clear sign of new physics has been seen: Supersymmetry, Dark Matter or other BSM.

• Hints of new physics have been claimed in a few corners – the flavour anomalies, W mass from CDF, muon g-2 – but they remain unconvincing, further experimental and/or theoretical study needed.

• As a result, the searches are being widened: both within the LHC, e.g. looking for long-lived particles, or going beyond colliders to search for feebly-interacting particles – new experiments are being proposed now.

• There is a clear future for collider physics, first with higher luminosity at HL-LHC, where fast timing will be important to suppress pileup; and then at a new future collider, most likely to be an e+e- Higgs factory.

• The feasibility of the FCC is under study at CERN, with a decision expected around 2026; if approved it will provide physics for many decades to come: an electroweak and Higgs Factory (FCC-ee) followed by a hadron collider (FCC-hh) at 100 TeV or beyond – a very exciting prospect!
I hope you will participate in this adventure furthering the quest to understand the hidden secrets of the universe

N.C. Flammarion (1888)