Thinking about Particle Physics

A long tradition in understanding the fundamental components of the Universe
What is the world made out of?

What are we made out of?

Ogg (many years BC)
What is inside?

Aristotele (384–322 BC)
Space and all matter is continuously filled

Democritus (460–371 BC)
Matter consists of indivisible elementary particles atomos (ατομος) = indivisible

Plato (ca 428–348 BC)
Elementary symmetries

120 years of accelerating particles

1897 Accelerating electrons
Cathode ray tube
J.J. Thomson

1913 Atomic structure
Beam of alpha particles
Ernest Rutherford

1931 First circular accelerator
Ernest O. Lawrence & M. Stanley Livingston

1940 184-inch cyclotron
Lawrence in Berkeley

Today: LHC
Accelerators and discovered particles

A Brief History of Scales

$E_{\text{FT}}^{\text{FT}} = E_{\text{cm}}^2 / 2m_p$  Fix-target experiment, beam energy measured in laboratory system

$E_{\text{cm}}^{\text{CM}}$  Collision energy measured in centre of momentum system

$\lambda \approx \hbar / p$  $\tau = \sqrt{T}$  Quantum Mechanics, Atomic Physics

$10^{-10} \text{m} \leq 10 \text{ eV}$  $> 300'000 \text{ y}$  1990...  Quantum Electro Dynamics

$10^{-13} \text{m} \approx \text{MeV...GeV}$  $\approx 3 \text{ min}$  1950-65  Nuclei, Hadrons, Symmetries, Field Theory

$10^{-16} \text{m} \approx \text{GeV}$  $\approx 10^{-6} \text{ s}$  1965-75  Quarks, Gauge Theories

$10^{-18} \text{m} \approx 100 \text{ GeV} \approx 10^{-10} \text{ s}$  1975-83 SPS  Electroweak Unification, QCD

$1990 \text{ LEP}$  3 families

$1994 \text{ Tevatron}$  Top quark

Origin of mass  $10^{-35} \text{m} \approx 10^6 \text{ GeV} \approx 10^{-12} \text{ s}$  2012 LHC  Higgs

?? Proton decay ??  $10^{-35} \text{m} \approx 10^{36} \text{ GeV} \approx 10^{-32} \text{ s}$  Underground labs  Grand Unification

?? Origin of the Universe ??  $10^{-35} \text{m} \approx 10^{39} \text{ GeV} \approx 10^{-43} \text{ s}$  Planck scale  Quantum Gravity, Superstrings
A coherent picture of the Universe

→ **Particle physics** research has a long tradition of making important scientific advancement through large-scale collaborative efforts.

→ Not only at the **smallest scales**, but it allows for a coherent picture of the Universe up to the **largest scales**.

→ Many of these projects started at the **national level**, but quickly grew to become **international in scope**.

→ There is a declared goal to **educate young people and the public at large**

→ **Education** has evolved as a **strategic pillar of particle physics**, of **basic research** in general and of evidence-based decision-making around the world.

The 1st issue of Nature in 1869

**Nov 4, 1869**

A WEEKLY ILLUSTRATED JOURNAL OF SCIENCE

'http://www.nature.com/nature/about/first

'The objective which it is proposed to attain by this periodical may be broadly stated as follows. It is intended, **First, to place before the general public the grand results of scientific work and scientific discovery**; and **to urge the claims of science to move to a more general recognition in education and in daily life**.

'Secondly, to aid scientific men themselves, by giving early information of all advances made in any branch of natural knowledge throughout the world; and by affording them an opportunity of discussing the various scientific questions which arise from time to time.'
“More concerted and systematic effort toward presentation and popularization of science would be helpful in many respects; it would provide a potent antidote to overspecialization; it would bring out clearly what is significant in current research, and it would make science a more integral part of the culture of today.”

The Significance of Science
Victor F. Weisskopf, 14 April 1972, SCIENCE, VOL. 176
https://science.sciencemag.org/content/176/4031/138

Presentation and popularization of science — a critical necessity

Explaining and reaching out particle physics is a critical necessity for all involved in particle physics research to engage in. Essential for continued support from

- Decision makers
  - Politicians and funding agencies
- Young students
  - The young students of today are the potential particle physicists of tomorrow, the potential decision makers of tomorrow, will be the tax payers of tomorrow, and will be the voters of tomorrow
- Broad public
  - These are today's tax payers and deserve to be kept informed from first hand
Education & Outreach — not so easy…

- **If overdone**
  - Particle Physics (or science in general) will be seen as **over-advertized**
  - There is the highly respected reputation of science at stake

- **Getting the right level**
  - Being too close in a specific topic will easily drag you too far
  - Keep your explanations **simple but avoid being trivial**

- **When engaging in education & outreach**
  - you will find your **personal antidote against overspecialization** and learn how to **focus on the really relevant questions and topics** and **how to best explain and present these**

Critics from the street

- Not all want to know and not all care about scientific research
  - some ignore
  - some are even against

- Do we care?
  - Yes!
  - Science literacy of a society is as important as basic literacy itself
    - We live in a modern world
    - A basic understanding of the scientific method and how science achieves knowing things is indeed relevant

- If we fail, we risk an unbridgeable gap in society
  - democracies are at stake
As we entered the so-called “post-factual world” emerging from political ideologies in a growing number of modern democracies, it is more important than ever for science and society to maintain an open and transparent dialogue.

It has also become evident that the tools and methods currently used to support such a dialogue have not been as successful as we would have hoped.

Indeed, many excellent outreach activities at research centres, universities and museums often attract only those people who are already interested and appreciative of the basic and fundamental relevance of science.

Without compromising established methods, we must explore new paths to engage citizens – especially the young.

While only a fraction of young students will become scientists, and fewer still will become particle physicists, all will become ambassadors for the scientific method and evidence-based decision-making.

— HP Beck, CERN Courier (March 2017)

Reaching out further

- **How to reach out broader?**
  - This is a challenge that cannot be addressed with simply exposing scientific tools and methods more and stronger
  - Taking different routes allow for a wider audience to apprehend and esteem scientific goals, tools and merits

- **Art projects involving science topics have a big potential to widen the audience**
  - to share excitement
  - to trigger reflections inside peoples minds on the universe, on science, etc. that otherwise would never happen

- **But...**
  - Art is another elitist field and will not reach society as a whole and one needs to be careful when using the synergy between art & science
Indeed, many excellent activities at research centres, universities and museums often attract only those people who are already interested and appreciative of the basic and fundamental relevance of science. Without compromising established methods, we must explore new paths to engage citizens – especially the young.

Total attendance of the largest music festivals in the world.

Music Festivals

Faced with stiff competition from an ever growing number of festivals, festival organisers are looking to add areas and activities that are a bit different, something unexpected.

**WOMAD Music Festival**
Charlton Park, Wiltshire, UK

At the invitation of the director of the Festival (after a special visit to CERN) “Why don’t we have a World of Physics?”

Partners:
with the Lancaster University ATLAS group and the UK Institute of Physics
with support from the STFC
and involving CERN

Team camped in basic tents provided by the festival

**Physics Pavilion ran for the full 3 days offering talks ... workshops ... ATLAS virtual visit**
Physics Pavilion at WOMAD now every year since 2016

Thousands of visitors every year and few more festivals are joining in since

- WOMAD Festival [https://womad.co.uk](https://womad.co.uk)
- Colours of Ostrava [https://www.colours.cz](https://www.colours.cz)
- Pohoda Festival [https://www.pohodafestival.sk/en](https://www.pohodafestival.sk/en)
Perceptions about science that need correction

A selection of prejudices and perceptions of the broad public that persistently come up and where answers are needed

‘science of things’?

- Physics is often perceived as the ‘science of things’
  - and therefore detached (i.e. irrelevant) from life, the universe and everything.
- The contrary is true
  - As we know - but also need too state clearly
- (Particle-) physics is the basic for all understanding of life, the universe and everything
  - Chemistry is based on physics
  - Quantum mechanics, (quantum-)electrodynamics
  - Biochemistry is based on chemistry
  - Life is based on biochemistry
‘detached from life’ ?

- New findings by particle physics experiments are so detached from real life and from real problems that these are of no concern and therefore of no use
  - It’s true that knowing the Higgs existing and its mass doesn’t change everyday life.
  - Knowing that there is a Higgs mechanism responsible for mass of elementary particles, and that mass is fundamentally needed for allowing structure to build up in the Universe, puts this knowledge on a different scale.
  - We simply wouldn’t exist without the Higgs mechanism in place!

- All after all, it’s all about the Universe of being intelligible and in a combined effort, we can learn how it works

‘loss of mysteries, fascination and wonders ’ ?

- Physics, or generally ‘science’, is often perceived as dull and whatever is explained scientifically has lost its mysteries, fascination and wonders.

- The contrary is true
  - As we know - but also need too state clearly

- The archeological site analogy
  - If you don’t know about the archeological site you are visiting, all you see is a pile of old stones and perhaps some funny (maybe appealing) ornaments and scripture.
  - The more you know about the ancient culture, their habits and their lives, the more interesting the archeological site becomes

- Knowing physics allows enjoying nature more
‘loss of mysteries, fascination and wonders ’?

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‘Scientific results are always invalidated’?

- Many say that established knowledge is only valid for a short moment in time
  - and thrown over board immediately when new findings come in
  - as this happens iteratively, there will never be anything useful worth trusting
  - … and therefore, science (and scientists) can’t be trusted!

- Indeed, some (rare) bad examples do exist
  - e.g. studies based on too small or biased samples, wrong or forgotten systematics, falsified data,… — but these get corrected within the scientific process

- What needs to be stated is that empirical established knowledge will stay forever as part of human culture
  - General Relativity extends Newtonian Gravity — it does not invalidate it!
  - We know not only Newtonian Gravity, we know its limits as well, and thus understand when and where it can be applied safely!
  - The existence of the Higgs boson will stay, but its role in nature is still open for future refinements
‘Measuring electronically is not seeing’?

The act of ‘seeing’ involves all elements of a modern particle physics experiment

- Accelerating particles
  - You need a photon gun, i.e. a light bulb, a torch, or simply the sun

- Particles scattering of a target
  - photons have to scatter off an object for it being visible by eye

- Measuring scattered particles
  - On your retina, photons within an energy range of 1.6-3.3 eV are measured and converted into electrical signals

- Reconstruction and analysis
  - Energy (i.e. momentum) and rate (i.e. intensity) of photons is the information content transported to the visual cortex via the optic nerve for online pattern recognition and reconstruction
  - we perceive an image of the target object in the brain where colour coding the energy of the detected photons is used to reduce the data volume and to make it manageable

  - Colour is truly perceived pseudocolour

‘experiments are expensive and are not needed’?

- Some claim that everything can be calculated, therefore experiments are not needed - these are just ‘toys for boys’ and also for ‘girls’ — obviously!

- However, even if a theory is complete and understood, it may still be complex! As e.g. a game of chess!
  - Physics elaborates on finding the rules on how the Universe works
  - These rules are like the rules of chess
  - Knowing the rules opens up to understand chess and play the game
  - However, just knowing the rules doesn’t make you a master!
  - That explains why a particle physicist doesn’t understand solid state physics, chemistry; etc. … Unless he/she engages deeper into these topics.

- A theory is only validated within some accessible scale
  - New physics, i.e. extending the rules we know, is a big driving force in fundamental research.
More on scales – the Flat Earth analogy!

- *A flat earth is not completely wrong*
  - Imaging the world as being flat yields a reasonably good approximation of your local environment
  - No need to know the earth radius to build a house or a bridge across a river or a valley

- *An appealing nice theoretical framework*
  - An effective theory
  - Everything can be calculated easily
  - However, it is only as good as it has been verified experimentally

- *Need to measure the absolute coordinates of Vienna when I place Innsbruck at the centre of the flat plane*
  - 390 km distance (beeline)
  - Requires careful triangulation and tedious measuring

More on scales - the Flat Earth analogy!

- Flat Earth prediction is 12 km off from the measured location
  - I.e. ~3% effect!
- Discrepancy will be more important if larger distances are probed
  - Take Innsbruck to Lisbon instead!
More on scales - the Flat Earth analogy!

- Measuring the Higgs and its couplings precisely matters a lot!
- The Higgs is here a prominent and important example
- other precision data are prominently needed as well!
  - e.g. Measuring rare or SM forbidden decays

Measuring the Standard Model precisely

- **Scales matter**
  - even when a model is axiomatically well defined
  - expanding the scale at which a model is probed will either further strengthen the validity of the model or will tell when the model collapses and a new model will need to be found.

- **Old models**
  - embed in the new and better model describing the world
  - keep their validity within a limited but now well understood scope

- **Popper, Kuhn, ...?**
  - all too rigid (as we know well):
    - We still use Newtonian dynamics for most problems to solve, although we do have general relativity at hand…
International Particle Physics Outreach Group

Concerted outreach at a global scale

The International Particle Physics Outreach Group (IPPOG)

IPPOG is a network of scientists, science educators and communication specialists working across the globe in informal science education and outreach for particle physics. Our goal is to bring new dimensions to this exciting field by engaging young people and informing the public that the beauty of science is indeed becoming comprehensible from the interpretation of the most fundamental facts.

The IPPOG collaboration comprises 25 members: 8 universities, 6 experiments and 39 or as an International Laboratory and 3 association members.

Alessandro Signorini, LNF; and Steven Goff from the University of Melbourne, IPPOG Chairs

Hands-on particle physics

http://ippog.org
IPPOG Goals

Sustainable Development of Particle Physics Outreach
- Discussion forums for scientists active in Particle Physics Outreach and Informal Education
- Information exchange between individuals, institutions and laboratories
- Active working groups addressing specific challenges of global Outreach

Improving Outreach Standards Worldwide
- Development of Strategies based on current best practices and experience
- Long-Term links between scientists and education specialists
- Continual development & improvement of explanatory material

Increasing Global Reach
- Expansion to Countries and Peoples underrepresented in Particle Physics
- Usage of new methods, activities and topics to reach broader audiences
- Active online communication platforms

IPPOG – a formal scientific collaboration

Global Network
- Scientists
- Science Educators
- Communication Specialists

International Collaboration
- Countries
- Experiments
- International Labs

Bridge Builders
- Teaching Skills
- Promoting the Scientific Process
- Propagating it around the World
IPPOG Members 2021

IPPOG Membership
30 Countries, 6 Collaborations,
1 International Lab, 2 National Labs

IPPOG Brief History

1997 CERN DG Chris Llewellyn-Smith
- Invoked the European Particle Physics Outreach Group - EPPOG
- First chair: Frank Close, University of Oxford, UK
- Report to ECFA
- LEP based Masterclass program as a small-scale uni-national initiative that then evolved involving more and more countries

2011 Transition of EPPOG → IPPOG
- To recognize the global role of education and outreach

2011 First time LHC based Masterclass program

2013 European Particle Physics Strategy Update (EPPSU): IPPOG recognized as a wider impact
- shall receive adequate funding & report to Council

2016 International Collaboration with MoU
- Countries pay a membership fee – depending on GDP and PP community size
- Intl. Laboratories provide Stronger support: Monetary and in-kind
- Experiments support by providing means for E&O program, e.g. providing tools, methods, documentation, and manpower for masterclass measurement

2021 30 Countries, 1 intl. Lab, 6 experiments
IPPOG – A Scientific Collaboration since 2016

IPPOG Vision & Strategy

Geographic Expansion
- Asia
- Africa
- The Americas
- International Labs and Scientific Collaborations

Expansion in Physics Topics
- Particle Physics beyond LHC
- Neutrinos
- Astro-Particle Physics

Goals
- Bring Excitement of particle physics to students and audiences around the globe
- Instill deeper understanding of the importance of evidence-based reasoning
  - Essential for all aspects of fundamental research
  - Necessary to establish support for next generation of large-scale research infrastructure

Form a next generation of General Public, of Stakeholders, and of Physicists & Engineers
IPPOG Global Initiatives

Concerted outreach at a global scale

International Particle Physics Masterclasses

The Flagship of IPPOG!

- Students become “Researchers for a Day!”
- Invited to research institute or university
- Given introductory lectures on particle physics research
- Taught to use analysis tools to examine real data
- Spend 2 hours on research
- Discuss results via videoconference with other students around the world
International Particle Physics Masterclasses

The Measurements
- ATLAS W-Path (Study Ratio W⁺ / W⁻, extra credit for H→WW)
- ATLAS Z-Path (Measure Z Mass, extra credit for Z’ bosons, H→γγ)
- CMS (Identify W, Z, H Decays)
- ALICE Strange Particles
- ALICE R_AA Measurement
- LHCb D⁰→Kπ

New Masterclasses being explored
- IceCube
- Auger
- BELLE II
- MINERvA
- MicroBooNE

Tools & Data Continually Renewed

High-school students analyze LHC data

- **ATLAS**
  - W path (Higgs → WW)
  - Z path (discover Extra Z’ Bosons)
- **CMS**
  - WZH measurements
- **ALICE**
  - Looking for Strange Particles
  - R_AA
- **LHCb**
  - D⁰→Kπ measurement

Measurements are kept up to date and continuously improve

- Exploit known Standard Model Processes, e.g.
  - W⁺/W⁻ ratio corresponding to (uud) quarks in proton
  - Understand mass peaks of J/Psi and Z

- On the way to discover new particles
  - Higgs → WW
  - Extra Z Bosons
For example:
The CMS WZH measurement

- Students visually characterize, $W$, $Z$, and $H$ candidates in event display and extracting kinematics from objects ‘they see’ and fill spread sheets.
- Create mass plots of SM particles that decay in 2 leptons ($W, Z$), 2 photons ($H$), or 4 leptons ($H$)
- Measure $W^+W^-$ ratio in $e$ and $\mu$ leptonic channels
- 3000 events can be analyzed – with misfits, surprises, interpretation
- Website in 13 languages

For example:
The LHCb $D^0 \rightarrow K\pi$ measurement

- Students search for $D^0 \rightarrow K\pi$ decays using the Event Display looking for displaced vertices.
- Then, the lifetime of the $D0$ is measured at $\sim 1\%$ accuracy
### Masterclass Language Coverage

<table>
<thead>
<tr>
<th>Masterclass</th>
<th>Languages Supported</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALICE (Strange Particles)</td>
<td>🇪🇸 🇫🇷 🇬🇧 🇪🇺 🇨🇿 🇷🇺 🇳🇱 🇩🇪 🇨🇦 🇬🇧 🇪🇺 🇨🇿 🇷🇺 🇳🇱 🇩🇪 🇨🇦</td>
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<tr>
<td>ALICE (R_AA)</td>
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<tr>
<td>ATLAS</td>
<td>🇪🇸 🇫🇷 🇬🇧 🇪🇺 🇨🇿 🇷🇺 🇳🇱 🇩🇪 🇨🇦 🇵🇹 🇬🇧 🇪🇺 🇨🇿 🇷🇺 🇳🇱 🇩🇪 🇨🇦</td>
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<tr>
<td>CMB</td>
<td>🇪🇸 🇫🇷 🇬🇧 🇪🇺 🇨🇿 🇷🇺 🇳🇱 🇩🇪 🇨🇦 🇰🇷 🇬🇧 🇪🇺 🇨🇿 🇷🇺 🇳🇱 🇩🇪 🇨🇦</td>
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<tr>
<td>LHCb</td>
<td>🇪🇸 🇫🇷 🇬🇧 🇪🇺 🇨🇿 🇷🇺 🇳🇱 🇩🇪 🇨🇦 🇰🇷 🇬🇧 🇪🇺 🇨🇿 🇷🇺 🇳🇱 🇩🇪 🇨🇦</td>
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<tr>
<td>Hands On Cern</td>
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</tr>
</tbody>
</table>

These are the languages that are supported on [http://physicsmasterclasses.org](http://physicsmasterclasses.org).

A participating institute that doesn’t find its local language here, will prepare its own set of slides. And even if you find your local language here, you will still adapt your slides according to your local needs.

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### International Particle Physics Masterclasses

2019 Programme (before COVID !)
- 54 Countries, 239 institutes
- >14k Students
- 1k teachers

2021 Programme
- Pandemic forced to go completely virtual
- Nearly all Masterclasses given online
- Participation: 50-70 % compared to 2019
Getting major labs on board

- When organized internationally and truly globally, as IPPOG is, getting major labs on board becomes feasible.
- High-school students get a direct connection, view and impression to a lab that otherwise would not be possible.

“I did this masterclass in 2012 when in high school and that’s why I decided to study physics so I would love to encourage people to join our community.”

Masterclasses for Girls on Feb 11th 2019

United Nations Int. Day of Women and Girls in Science
Global Cosmics — Projects for High School Students

There are several projects around the world that address young people and teachers, to give them the opportunity to explore cosmic particles. e.g. International Cosmic Day, International Muon Week, etc.

IPPOG brings these initiatives together for global reach.

http://globalcosmics.org

IPPOG In Conferences

- APS April Meeting, 14 Apr, Denver, Colorado, USA
  - International Masterclasses: Particle Physics for High School Students and Teachers, Ken Cecire, IPPOG Masterclass Coordination

- LHC 2019, 20-25 May, Puebla, Mexico
  - Particle Physics Outreach as a Strategic Pillar for Society: A report from IPPOG, Sascha Mehlhase, ATLAS IPPOG Representative

- EPS HEPP 2019, 10-17 July, Ghent, Belgium
  - Future Challenges in Particle Physics Education and Outreach, Hans Peter Beck, IPPOG Chair
  - Developments in International Masterclasses, Uta Bilow, IPPOG Masterclass Coordination

- ICNFP 2019, 21-29 Aug, Kolymbari, Crete, Greece
  - The International Particle Physics Outreach Group, Despina Hatzifotiadiou, ALICE IPPOG Representative

- CHEP 2019, 4-8 Nov, Adelaide, Australia
  - International Particle Physics Masterclasses
  - The IPPOG Resource Database
  - The International Particle Physics Outreach Group
The next big infrastructure project in particle physics

IPPOG as a Strategic Pillar

Landscape of proposed large-scale infrastructures

CLIC  FCC_{ee/eh/hh}  CEPC / SppC

LHeC  ILC
Ultra-long time scales, whatever comes next

Education and Outreach a Strategic Pillar

The realization of new large scale infrastructure(s) with their research programs requires

- **deep and long R&D**
  - accelerators incl. magnets, detector incl. electronics, trigger, readout, computing

- **long-term funding scheme**
  - sustainable, reliable

- **good vision**
  - scientific leadership and flat hierarchies for allowing good ideas to be followed up, bottom-up

- **people**
  - physicists, engineers, technicians, …
  - politicians, stake holders, …
The next big-scale project

Any new big-scale project to be proposed in particle physics will need
- concerted, global education, outreach, and communication efforts,
- with a strong and engaging dialogue with
- the public and stakeholders, and adequately educating pupils and students at all ages.

To achieve this, physicists are needed who
- can engage in a scientific collaborative way
- together with educators, writers, coders, communicators...

In addition, there is a much wanted side effect when engaging with the public
- as it is your antidote against overspecialization

A prize worth paying?

Science, from the immutable logic of its mathematical underpinnings to the more fluid realms of the social sciences, is one of the most important drivers of economic progress.

In its purest form, science generates knowledge. The applied disciplines translate that knowledge into tangible benefits for society, generating new tools for basic research along the way in a constantly evolving virtuous circle.

The social sciences help us to make sense of the whole process and to understand how science is conducted, deployed, and perceived.

Rolf Heuer

Download as Open Access for free from Springer:
It is crucially important that the general public has the opportunity to inform itself knowledgeably and intelligibly on the endeavors and results of scientific research. Restricting scientific findings to a small group of people weakens the philosophical spirit of a nation and leads to its intellectual impoverishment.

Albert Einstein, Princeton 1948