16th Topical Seminar on
Innovative Particle and Radiation Detectors

Geant4 silver anniversary

25 years enabling scientific production

Tullio Basaglia[1], Zane W. Bell[2], Daniele D'Agostino[3,4],
Paul V. Dressendorfer[2], Maria Grazia Pia[4]

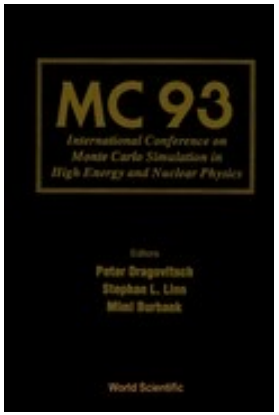
[1]*CERN (retired), Geneva, Switzerland*
[2]*IEEE, Piscataway, NJ, USA*
[3]*Univ. of Genova, Italy*
[4]*INFN Genova, Italy*

Collaboration in progress: Berkar Kaynak and Onur Potok *(Istanbul Univ., Turkey),* Elisabetta Ronchieri *(INFN CNAF, Bologna, Italy)*

Siena, 25-29 September 2023

25 years in ~~12~~ 17 minutes…

Due to limited time allocation, there is room only to highlight a few results



TOWARDS OBJECT-ORIENTED GEANT
-- ProdiG PROJECT --

Yoshinobu TAKAIWA,
Katsuya AMAKO, Jun-ichi KANZAKI, and Takashi SASAKI
KEK (National Laboratory for High Energy Physics)
1-1 Oho, Tsukuba, Ibaraki 305, Japan

MC 93, Int. Conf. on Monte Carlo Simulation in High Energy and Nuclear Physics

1993

Iwako Wasikowski
27.08.1993

S. Giani, Investigation of a class hierarchy for GEANT

MINI-WORKSHOP ON OBJECT ORIENTED GEANT

Held 24-27 August 1993 at CERN/CN/AS

1994

DRDC/94-28

Letter of intent to the DRDC

May 26, 1994

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

P58 Proposal to CERN Detector R&D Committee

CERN/DRDC/94-29
DRDC / P58
11 August 1994

GEANT 4 : an Object-Oriented toolkit for simulation in HEP

RD44 (GEANT4)

GEANT 4: an Object-Oriented toolkit for simulation in HEP

ABSTRACT & FIGURES | HOME PAGE | NOTES & PUBLICATIONS

SPOKESPERSON: Simone GIANI
Experiment secretariat e-mail: Grey.Book@cern.ch

Beam:	
Approved:	24-11-1994
	07-12-1995
	01-07-1997
	21-10-1997
Completed	14-12-1998
Finished	14-12-2008
Status:	Finished

April 1997: First alpha release

July 1998: First beta release

15 December **1998**

Geant4 0.0 is born

25th ANNIVERSARY

What has Geant4 been doing for 25 years?

1994

RD44 mandate:
creating a detector simulation toolkit necessary for the next generation of HEP experiments

"A variety of requirements also come from heavy ions physics, CP violation physics, cosmic rays physics, medical applications and space science applications. In order to meet such requirements, a large degree of functionality and flexibility has to be provided."

RD44 Status Report, 1995

1998

"Geant4 has a **multi-disciplinary** nature,
providing functionality in a set of different scientific fields.
The Geant4 Object-Oriented design allows the user to
understand, **extend**, or **customise** the toolkit in all the domains."

RD44 Status Report, 1998

Enabling scientific production

Available online at www.sciencedirect.com
SCIENCE DIRECT®
Nuclear Instruments and Methods in Physics Research A 506 (2003) 250–303
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

GEANT4—a simulation toolkit

S. Agostinelli[ae], J. Allison[as,*], K. Amako[e], J. Apostolakis[a], H. Araujo[aj], P. Arce[l,m,x,a], M. Asai[g,ai], D. Axen[i,t], S. Banerjee[bi,l], G. Barrand[an], F. Behner[l], L. Bellagamba[c], J. Boudreau[bd], L. Broglia[ar], A. Brunengo[c], H. Burkhardt[a], S. Chauvie[bj,bl], J. Chuma[h], R. Chytracek[a], G. Cooperman[az], G. Cosmo[a], P. Degtyarenko[d], A. Dell'Acqua[a,i], G. Depaola[y], D. Dietrich[af], R. Enami[ab], A. Feliciello[bj], C. Ferguson[bh], H. Fesefeldt[l,o], G. Folger[a], F. Foppiano[ac], A. Forti[as], S. Garelli[ac], S. Giani[a], R. Giannitrapani[bo], D. Gibin[m,bc], J.J. Gómez Cadenas[m,bp], I. González[q], G. Gracia Abril[n], G. Greeniaus[p,h,ag], W. Greiner[af], V. Grichine[f], A. Grossheim[m,z], S. Guatelli[ad], P. Gumplinger[h], R. Hamatsu[bk], K. Hashimoto[ab], H. Hasui[ab], A. Heikkinen[ah], A. Howard[aj], V. Ivanchenko[a,ba], A. Johnson[g], F.W. Jones[h], J. Kallenbach[aa], N. Kanaya[i,h], M. Kawabata[ab], Y. Kawabata[ab], M. Kawaguti[ab], S. Kelner[at], P. Kent[r], A. Kimura[ay,bb], T. Kodama[aw], R. Kokoulin[at], M. Kossov[d], H. Kurashige[am], E. Lamanna[w], T. Lampén[ah], V. Lara[a,l,bq], V. Lefebure[l], F. Lei[bh,be], M. Liendl[l,a,br], W. Lockman[j,bn], F. Longo[bm], S. Magni[k,au], M. Maire[ao], E. Medernach[a], K. Minamimoto[aw,al], P. Mora de Freitas[ap], Y. Morita[e], K. Murakami[e], M. Nagamatu[aw], R. Nartallo[b], P. Nieminen[b], T. Nishimura[ab], K. Ohtsubo[ab], M. Okamura[ab], S. O'Neale[s], Y. Oohata[bk], K. Paech[af], J. Perl[g], A. Pfeiffer[a], M.G. Pia[ad], F. Ranjard[n], A. Rybin[ak], S. Sadilov[a,ak], E. Di Salvo[c], G. Santin[bm], T. Sasaki[e], N. Savvas[as], Y. Sawada[ab], S. Scherer[af], S. Sei[aw], V. Sirotenko[i,al], D. Smith[g], N. Starkov[f], H. Stoecker[af], J. Sulkimo[ah], M. Takahata[ay], S. Tanaka[bg], E. Tcherniaev[a], E. Safai Tehrani[g], M. Tropeano[ae], P. Truscott[be], H. Uno[aw], L. Urban[v], P. Urban[aq], M. Verderi[ap], A. Walkden[as], W. Wander[av], H. Weber[af], J.P. Wellisch[a,l], T. Wenaus[u], D.C. Williams[j,bf], D. Wright[g,h], T. Yamada[aw], H. Yoshida[aw], D. Zschiesche[af]

[a] *European Organization for Nuclear Research (CERN) Switzerland*
[b] *European Space Agency (ESA), ESTEC, The Netherlands*
[c] *Istituto Nazionale di Fisica Nucleare (INFN), Italy*
[d] *Jefferson Lab, USA*
[e] *KEK, Japan*

*Corresponding author. Tel.: +44-161-275-4179; fax: +44-161-273-5867.
E-mail address: john.allison@man.ac.uk (J. Allison).

0168-9002/03/$ - see front matter
doi:10.1016/S0168-9002(03)01368-8

16023 citations

Most cited paper in

- **Particles & Fields Physics**
  436176 papers
- **Nuclear Physics**
  335328 papers
- **Nuclear Science & Technology**
  380632 papers
- **Instruments & Instrumentation**
  696376 papers

Most cited articles in
Astronomy & Astrophysics:
14099 citations
Radiology, Nuclear Medicine & Medical Imaging:
11906 citations

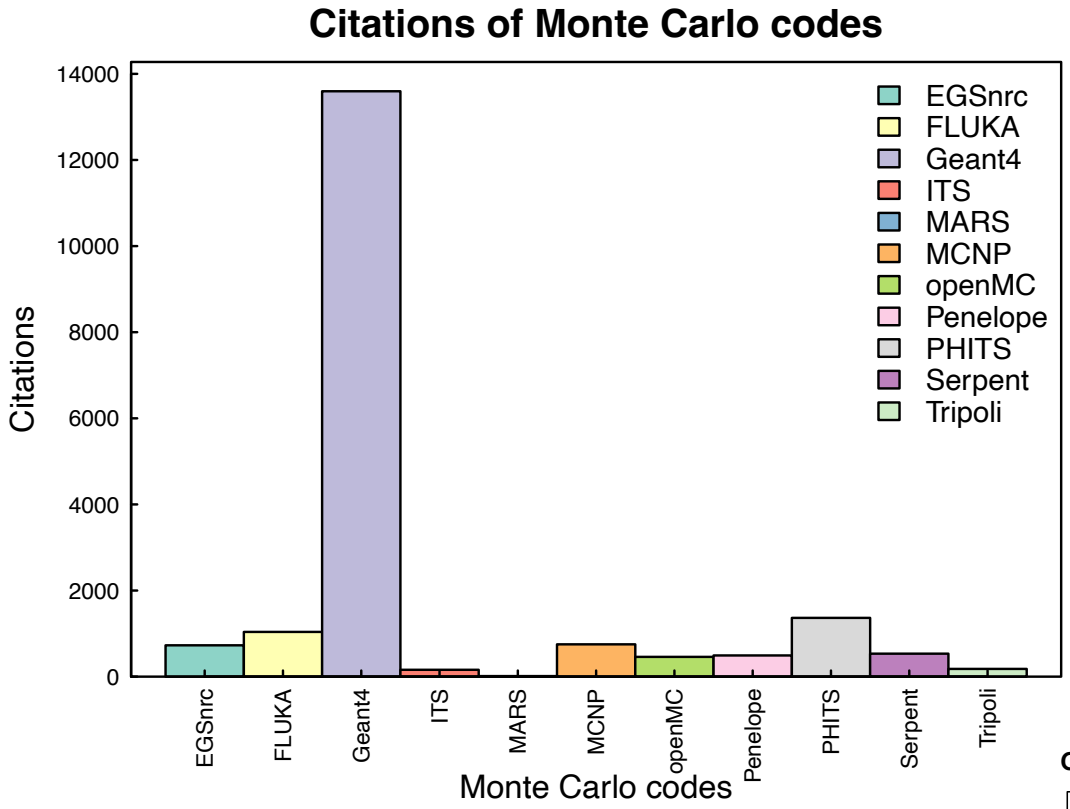
Web of Science, *Clarivate Analytics*
14 September 2023
INFN subscription coverage: 1990 ➟

Food for Thought

Maria Grazia The 5 most cited papers in **Instruments & Instrumentation** are **software** papers

Monte Carlo transport codes

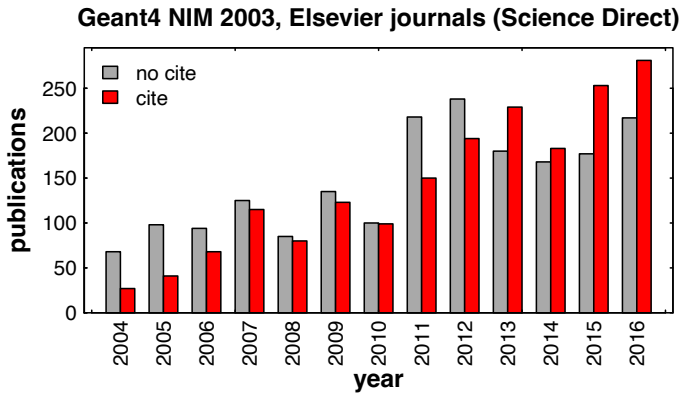
Usage characteristics



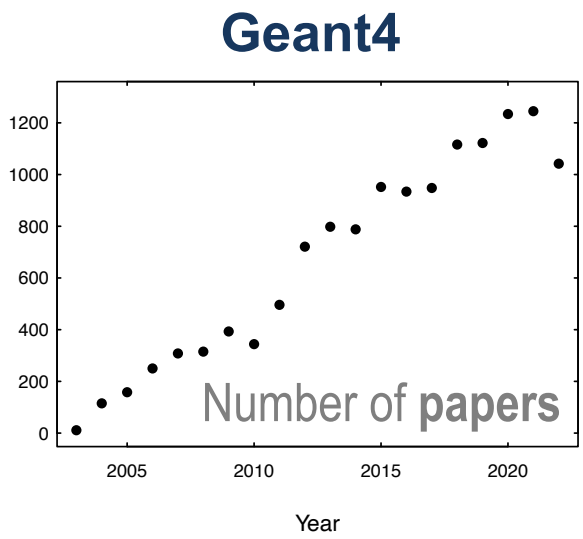
Variable publication dates of the respective reference papers
For some codes, large fraction of citations from the code's authors

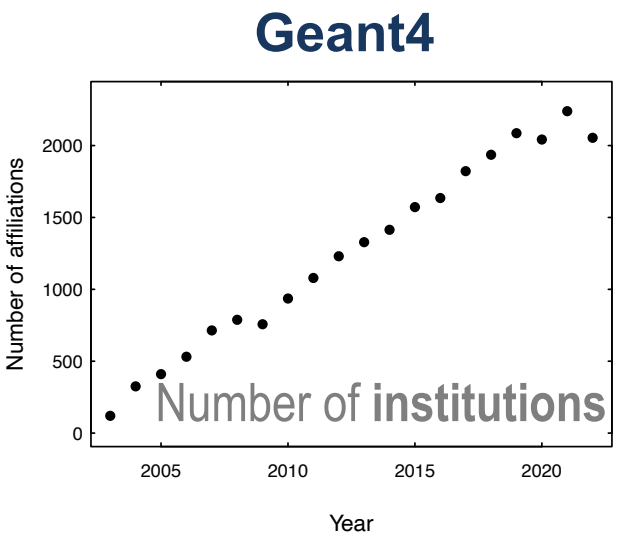
Missing citations

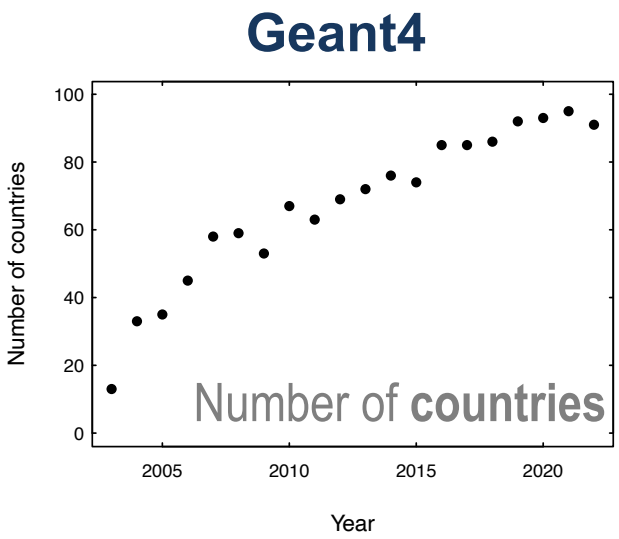
Many publications **do not cite scientific software** systems mentioned in the text and used to **produce the results**

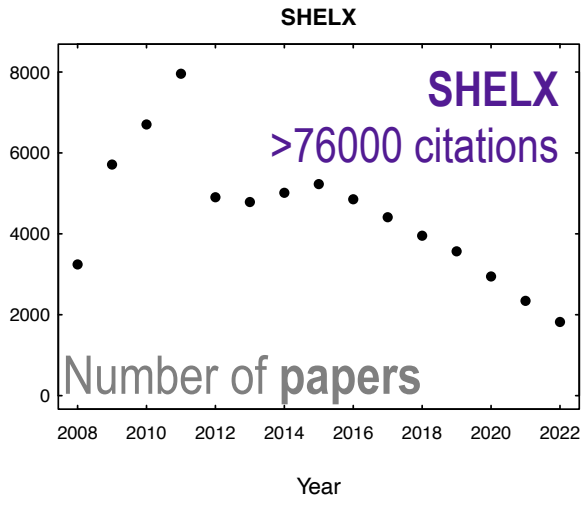


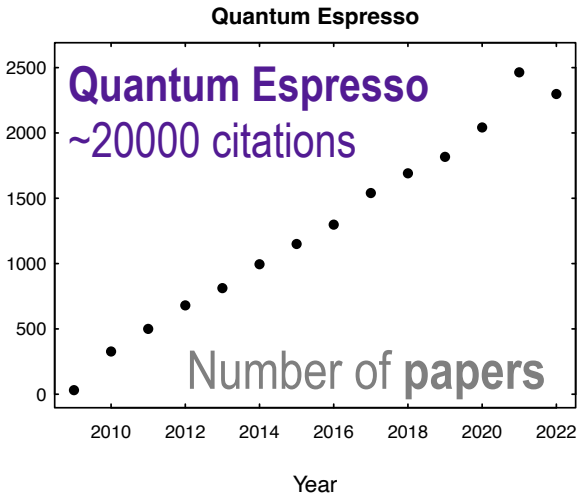
Time profile of the citations

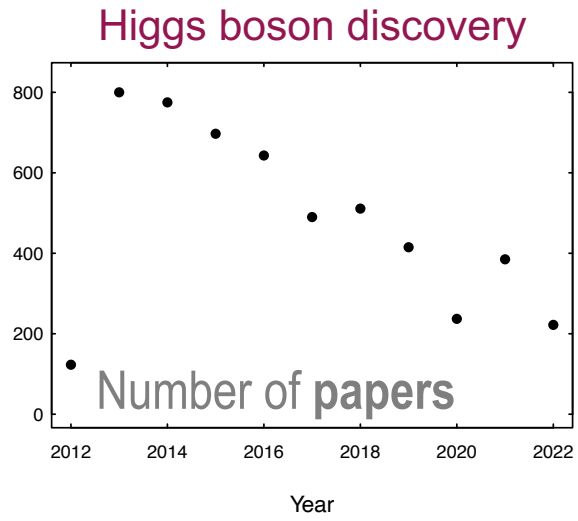








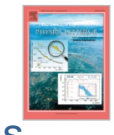




Cited by relevant papers in particle physics and more...

Physics Letters B

Volume 716, Issue 1, 17 September 2012, Pages 1-29

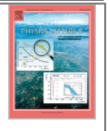


6121 citations

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

Physics Letters B

Volume 716, Issue 1, 17 September 2012, Pages 30-61



Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

Eur. Phys. J. C (2011) 71: 1534
DOI 10.1140/epjc/s10052-010-1534-9

THE EUROPEAN PHYSICAL JOURNAL C

Review

1244 citations

Heavy quarkonium: progress, puzzles, and opportunities

Search for Majorana Neutrinos Near the Inverted Mass Hierarchy Region with KamLAND-Zen

714 citations

A. Gando *et al.* (KamLAND-Zen Collaboration)
Phys. Rev. Lett. **117**, 082503 – Published 16 August 2016; Erratum Phys. Rev. Lett. **117**, 109903 (2016)

Indication of Reactor $\bar{\nu}_e$ Disappearance in the Double Chooz Experiment

967 citations

Y. Abe *et al.* (Double Chooz Collaboration)
Phys. Rev. Lett. **108**, 131801 – Published 28 March 2012

Dark Matter Results from 54-Ton-Day Exposure of PandaX-II Experiment

726 citations

Xiangyi Cui *et al.* (PandaX-II Collaboration)
Phys. Rev. Lett. **119**, 181302 – Published 30 October 2017

INSTITUTE OF PHYSICS PUBLISHING — PHYSICS IN MEDICINE AND BIOLOGY

Phys. Med. Biol. **49** (2004) 4543–4561 — PII: S0031-9155(04)80763-2

1617 citations

GATE: a simulation toolkit for PET and SPECT

First Result from the Alpha Magnetic Spectrometer on the International Space Station: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–350 GeV

797 citations

M. Aguilar *et al.* (AMS Collaboration)
Phys. Rev. Lett. **110**, 141102 – Published 3 April 2013

Measurement of the Cosmic Ray $e^+ + e^-$ Spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope

797 citations

A. A. Abdo *et al.* (Fermi LAT Collaboration)
Phys. Rev. Lett. **102**, 181101 – Published 4 May 2009

REVIEW ARTICLE | AUGUST 11 2008

Gas-assisted focused electron beam and ion beam processing and fabrication

Ivo Utke; Patrik Hoffmann; John Melngailis

Check for updates

816 citations

J. Vac. Sci. Technol. B 26, 1197–1276 (2008)
https://doi.org/10.1116/1.2955728

JHEP

PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: *November 29, 2016*
REVISED: *March 24, 2017*
ACCEPTED: *April 6, 2017*
PUBLISHED: *April 28, 2017*

594 citations

Evidence for the two-body charmless baryonic decay $B^+ \to p\bar{\Lambda}$

Dark Matter Search Results from a One Ton-Year Exposure of XENON1T

1319 citations

E. Aprile *et al.* (XENON Collaboration)
Phys. Rev. Lett. **121**, 111302 – Published 12 September 2018

IOP PUBLISHING — PHYSICS IN MEDICINE AND BIOLOGY

Phys. Med. Biol. **57** (2012) R99–R117 — doi:10.1088/0031-9155/57/11/R99

TOPICAL REVIEW

838 citations

Range uncertainties in proton therapy and the role of Monte Carlo simulations

ELSEVIER

Journal of Archaeological Science

Volume 56, April 2015, Pages 41-60

Optical dating in archaeology: thirty years in retrospect and grand challenges for the future

LETTER

doi:10.1038/nature24647

Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons

minerals

MDPI

https://www.mdpi.com/journal/minerals

Review

A Review of Sensor-Based Sorting in Mineral Processing: The Potential Benefits of Sensor Fusion

AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER

10.1029/2018GL077784

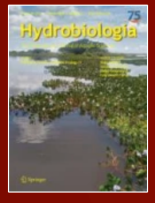
Termination of Electron Acceleration in Thundercloud by Intracloud/Intercloud Discharge

Geant4 is used in many different fields…

Home > Hydrobiologia > Article

Adineta vaga under fire: simulating the impact of radiation

ROTIFERA XVI | Open Access | Published: 16 August 2023 | (2023)



Nonlin. Processes Geophys., 27, 75–119, 2020

https://doi.org/10.5194/npg-27-75-2020

Nonlinear Processes in Geophysics

Open Access

EGU

The physics of space weather/solar-terrestrial physics (STP): what we know now and what the current and future challenges are

ELSEVIER

Journal of Food Engineering

Volume 149, March 2015, Pages 137-143

Improving phytosanitary irradiation treatment of mangoes using Monte Carlo simulation

Geosci. Instrum. Method. Data Syst., 2, 55–60, 2013

www.geosci-instrum-method-data-syst.net/2/55/2013/

doi:10.5194/gi-2-55-2013

Geoscientific Instrumentation Methods and Data Systems

Open Access

Towards a muon radiography of the Puy de Dôme

ELSEVIER

Mitochondrion

Volume 13, Issue 6, November 2013, Pages 736-742

Short communication

Predicted ionisation in mitochondria and observed acute changes in the mitochondrial transcriptome after gamma irradiation: A Monte Carlo simulation and quantitative PCR study

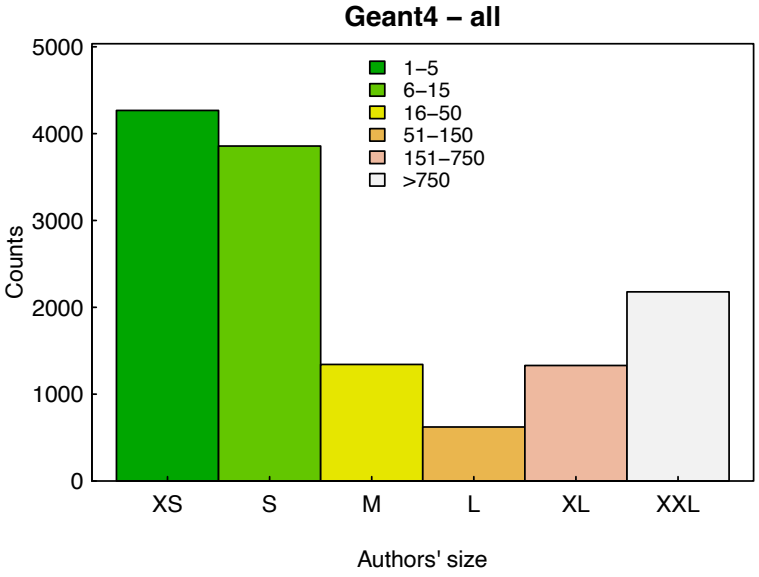
Advances in Computational Mathematics (2023) 49:62

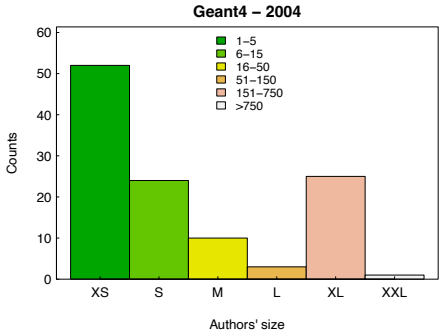
https://doi.org/10.1007/s10444-023-10065-9

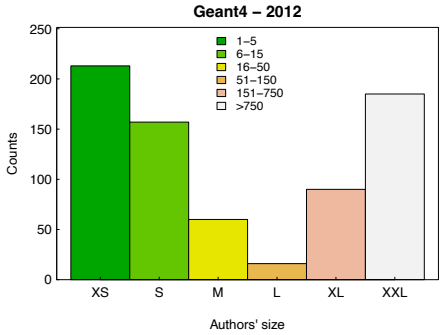
Check for updates

Finite basis physics-informed neural networks (FBPINNs): a scalable domain decomposition approach for solving differential equations

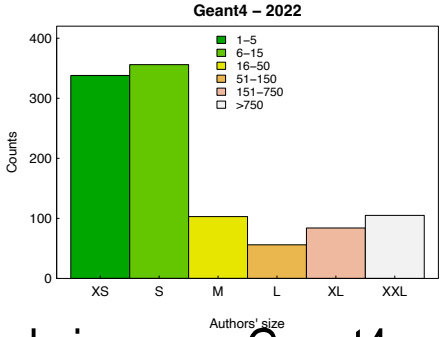
Small and big







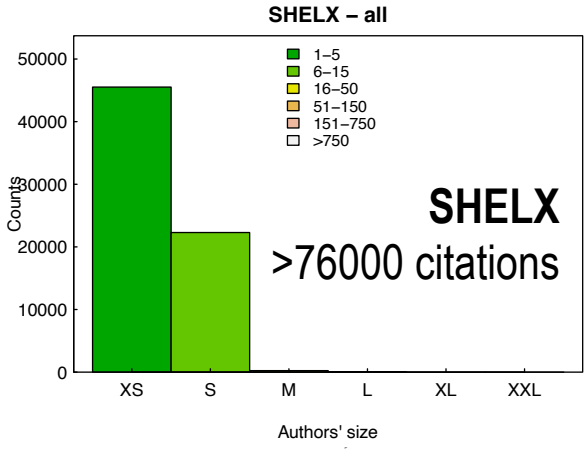
Research groups' size:
from XS to XXL

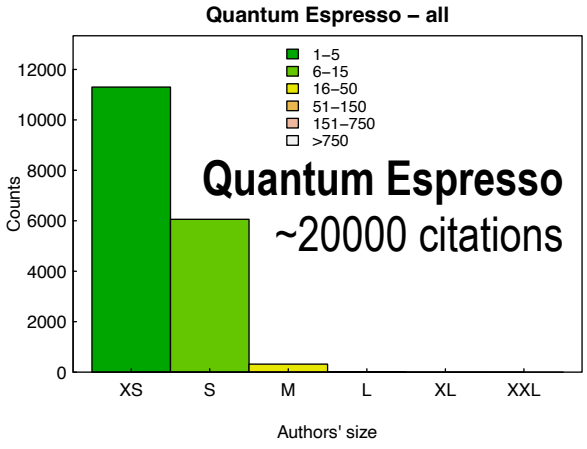


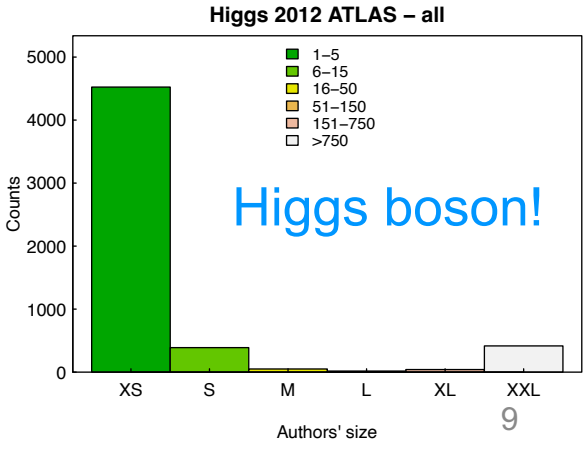
Geant4

Research groups of widely varied sizes use Geant4

Other highly cited software systems





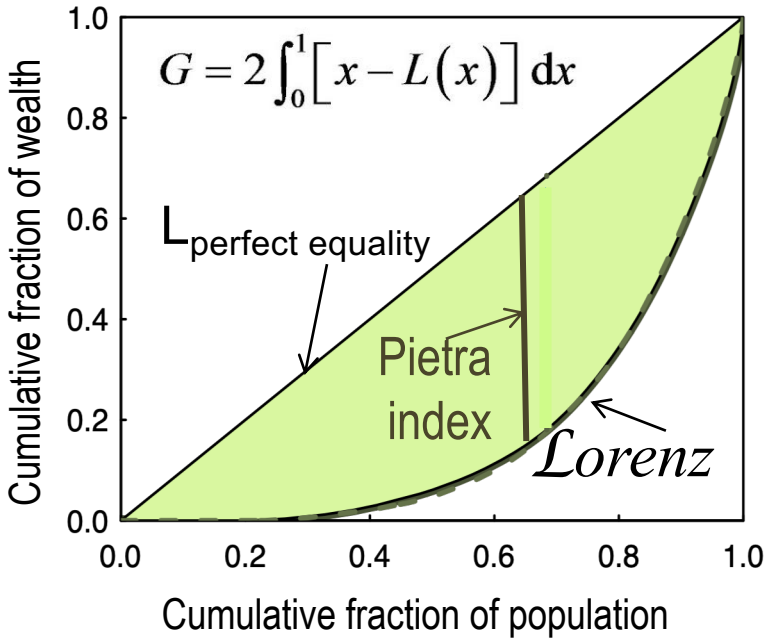


Fairness In econometrics, measured by **inequality** indices

Gini index

Most common measure of inequality

"The N richest people in the world are worth more than the poorest X%"



$0 \le \mathbf{G} \le 1$

0 → **1**

more unequal society

Pietra index

(AKA Ricci-Schutz index, Hoover index, Robin Hood index)

$$\mathbf{P} = \max(L_{pe}(x) - \mathcal{L}(x))$$

Used in derivative markets as a benchmark measure of statistical heterogeneity

Atkinson index

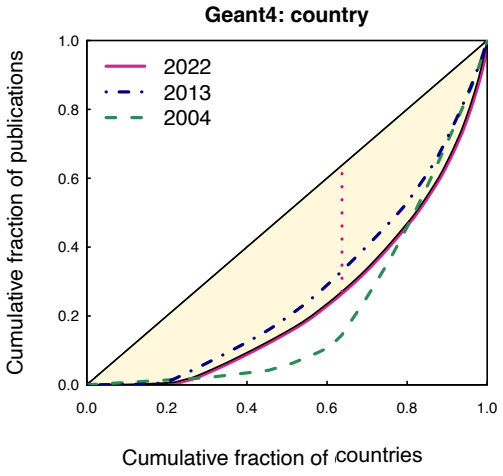
Used to calculate the proportion of total income that would be required to achieve an equal level of social welfare as at present, if incomes were perfectly distributed

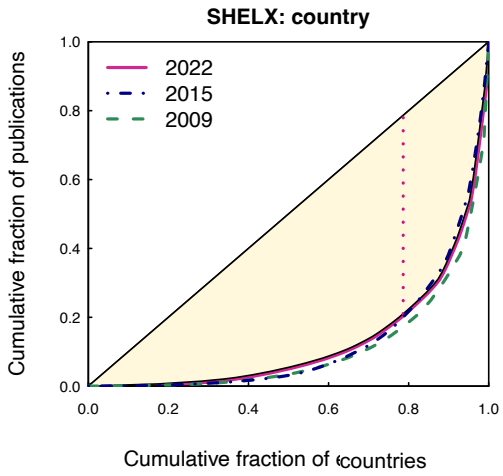
Theil index *(the same as redundancy in information theory),*
Kolm index, coefficient of variability, generalized entropy etc.

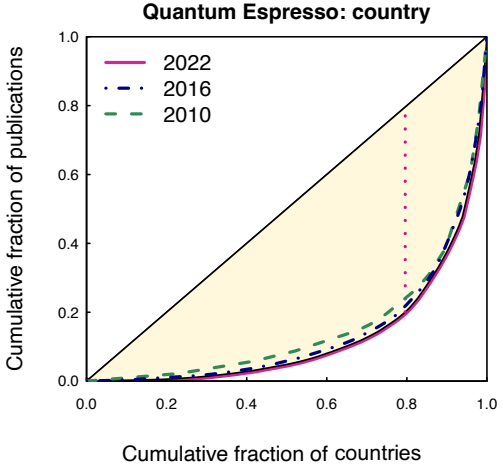
Geo-inequality

Geographical distribution evaluated by means of econometric methods

The use of Geant4 is more fairly distributed among countries



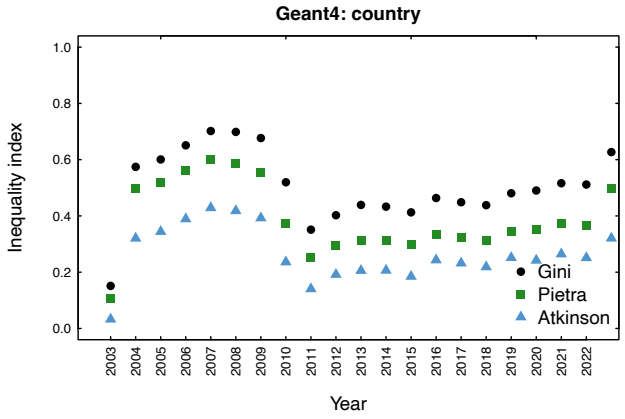


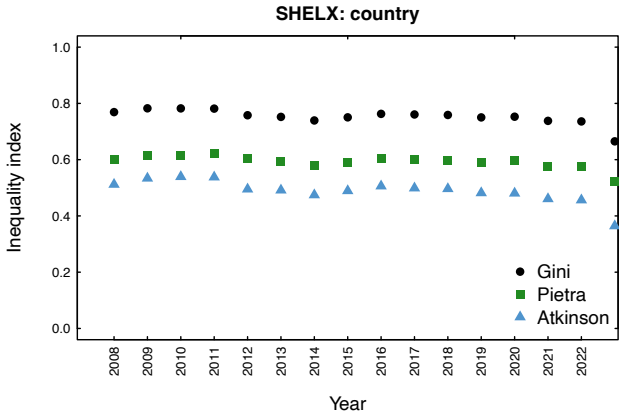


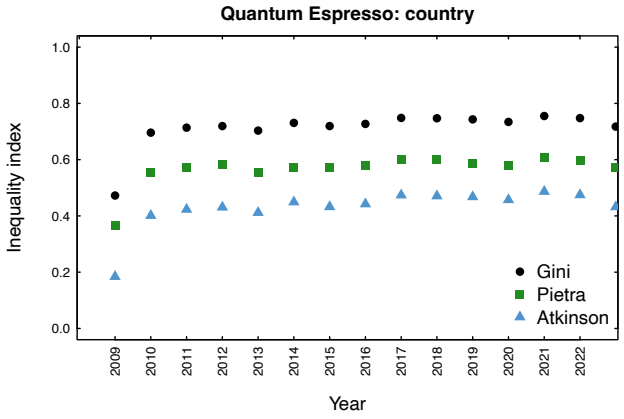
Geant4 38 countries present in > 10% of the papers

SHELX only 3 countries present in > 10% of the papers

QuantumEspresso







Similar time profile of different inequality indices

Diversity

Concept drawn from **ecology**: **number of species** and their **abundance**

- **Diversity** measures the **richness** and the **complexity** of a community
- Related to the concept of **entropy** in information theory
- Measured by several indices, with different **sensitivity to rare species**

Margalef index

$D_{Mg} = (S - 1) / \log N$

Simpson index

$$\lambda = \sum_{i=1}^{R} p_i^2$$

Shannon index

$$H = -\sum_{i=1}^{S} p_i \log p_i$$

Renyi diversity

$$^{q}H_{Renyi} = \frac{1}{1-q} \log\left(\sum_{i=1}^{S} p_i^q\right)$$

Tsallis diversity

$$^{q}H_{Tsallis} = \frac{1}{1-q}\left(\sum_{i=1}^{S} p_i^q - 1\right)$$

Recent consensus on **Hill indices** to measure diversity: mathematical functions that combine **richness** and **evenness**

Hill indices

$$^{q}D = \left(\sum_{i=1}^{S} p_i^q\right)^{1/(1-q)}$$

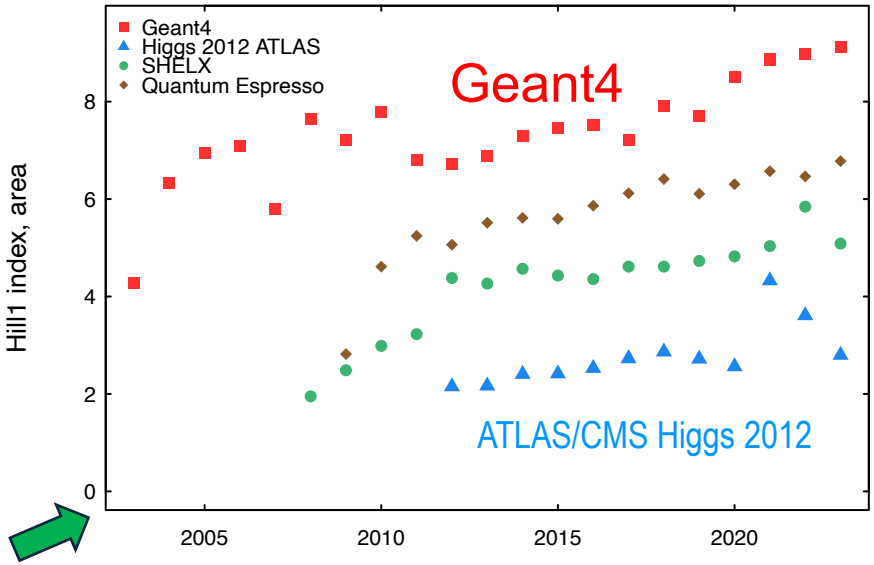
S = # of different species
p = proportion of species
q = *order of Hill index*

q	
0	number of species
1	$\lim_{q\to 1} {}^{q}D \equiv {}^{1}D = \exp\left(-\sum_{i=1}^{S} p_i \log p_i\right)$
2	$^{2}D = 1/\sum_{i=1}^{S} p_i^2$

Hill indices can be interpreted as **effective number of species**

compare the diversity of communities

Diversity of the research areas of citing papers



Mann-Kendall **trend** test

H_0: no trend

H_1: ↗ trend

Geant4: $p < 0.01$

Cox-Stuart **trend** test

H_0: no trend

H_1: ↗ trend

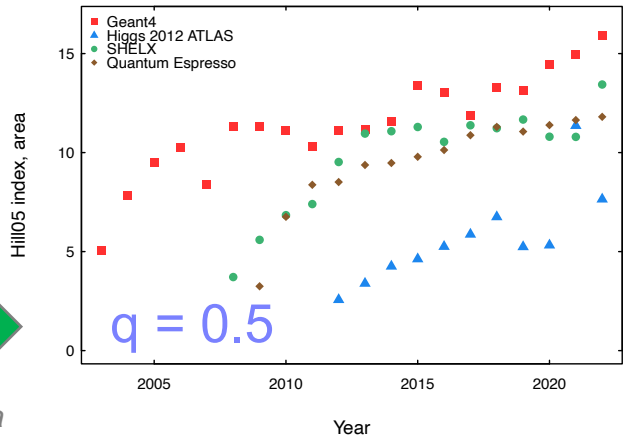
Geant4: $p < 0.01$

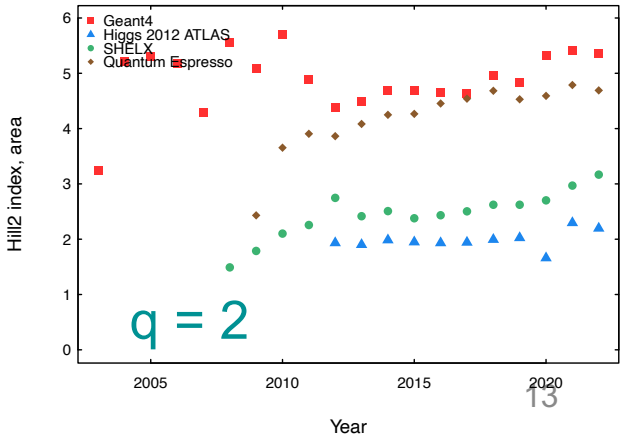
Non-univocal trends for some target papers

Geant4 citations: largest diversity, growing

Year

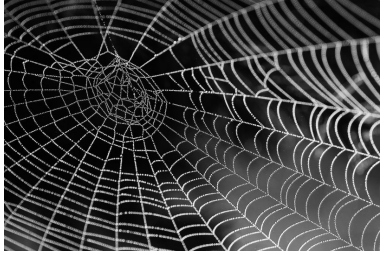
Largest diversity also when the emphasis is on **rare species** or on **more common** ones





A step forward: **the Web of Science as a web**

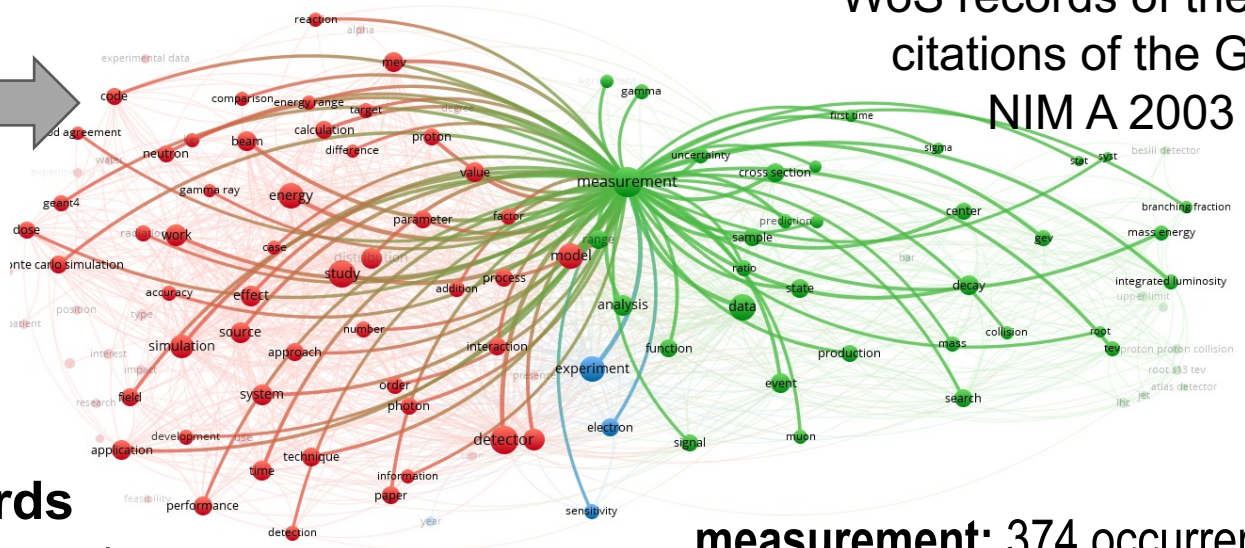
What interacts with what? Who with whom?



Network analysis over words *(in titles and abstracts)*, authors, institutes etc.

Moving from **flat** tables to **graphs**

Term	Occurrences
measurement	374
detector	324
study	307
data	
model	
experiment	273
energy	271
simulation	234
work	189
particle	187
system	180
source	177
distribution	175
analysis	169
effect	166
beam	164
decay	161
event	154
value	154
application	153



Example

WoS records of the 2022 citations of the Geant4 NIM A 2003 paper

115 relevant words

out of 21699 words occurring

in titles + abstracts of 1060 citing papers

(relevant: appearing in at least $N_{threshold}$ = 30 papers)

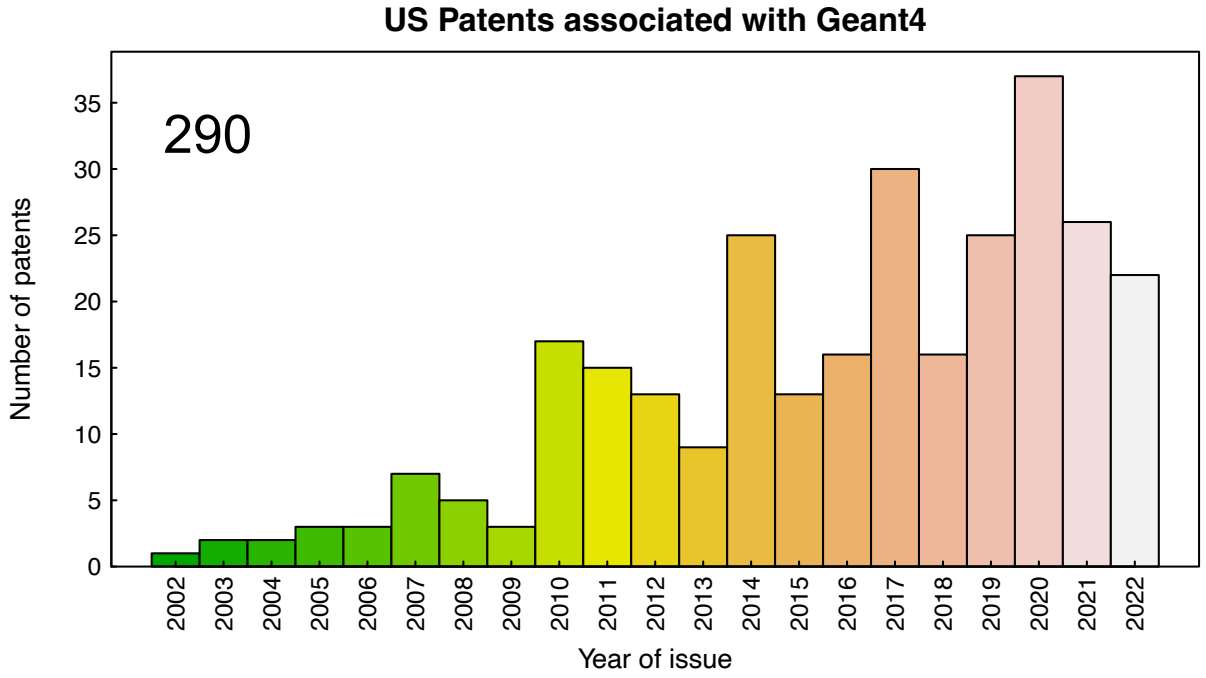
measurement: 374 occurrences

What is "measurement" related to in Geant4 citations?

The analysis **clusters the connections** in the Web of Science data

Patents

Analysis in progress



Mann-Kendall
and
Cox-Stuart
trend tests

H_0: no trend
H_1: ↗ trend

$p < 0.01$

US patents retrieved from the
United States Patent and Trademark Office (USPTO)

Conclusions

>16000 citations

Most cited paper in Particle and Fields Physics, Nuclear Physics, Nuclear Science and Technology, Instruments and Instrumentation

Most cited paper authored by **CERN**, **ESA, INFN**...

Enables small research groups and large collaborations to produce scientific results

Diverse research areas and fair geographical spread

Design

"Geant4 has a **multi-disciplinary** nature, providing functionality in a set of different scientific fields. The Geant4 Object-Oriented design allows the user to **understand**, **extend**, or **customise** the toolkit in all the domains."

Many new and original ideas

RD44

Depth of thought

Paradigm shift

Courage