Searching for surprises at the highest energies

Inaugural lecture

Alexander Tapper — 19th June 2024

Why?

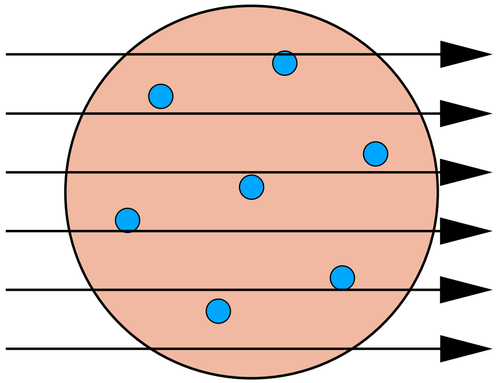
Matter

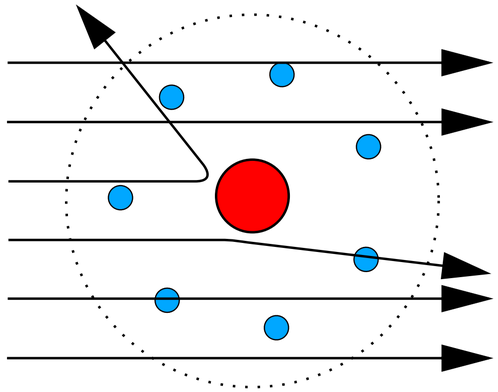
δοκεῖ δὲ αὐτῶι τάδε· ἀρχὰς εἶναι τῶν ὅλων ἀτόμους καὶ κενόν, τὰ δ'ἄλλα πάντα νενομίσθαι [δοξάζεσθαι]. (Diogenes Laërtius, Democritus, Vol. IX, 44)

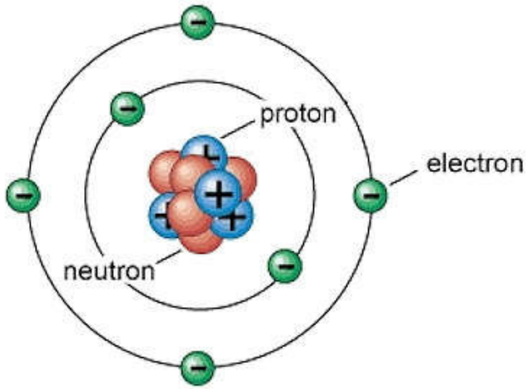
The first principles of the universe are atoms and empty space; everything else is mere opinion

Democritus 460 - 370 BC

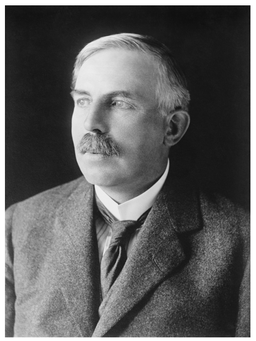
Matter







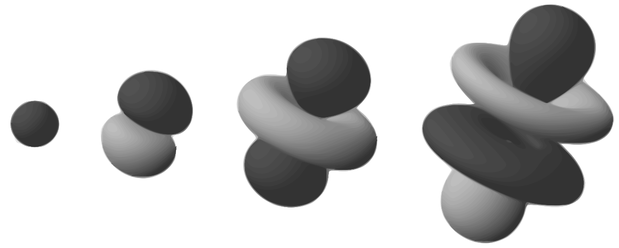
Thompson

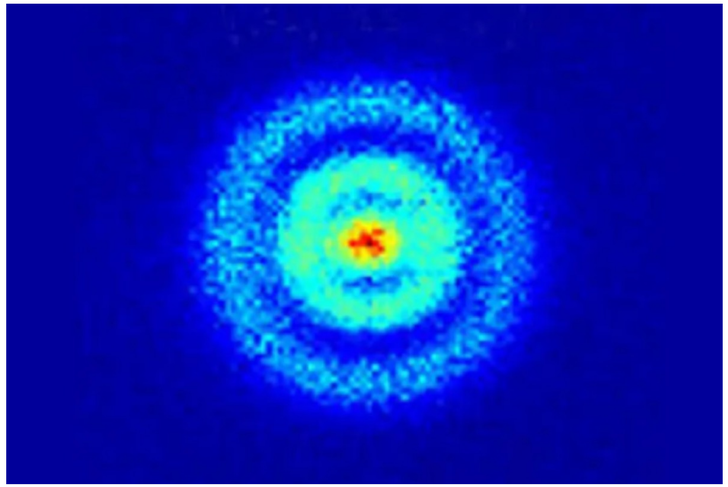


Rutherford

Bohr

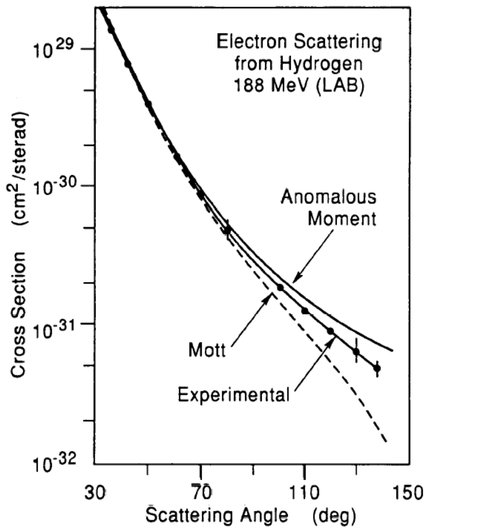
Matter

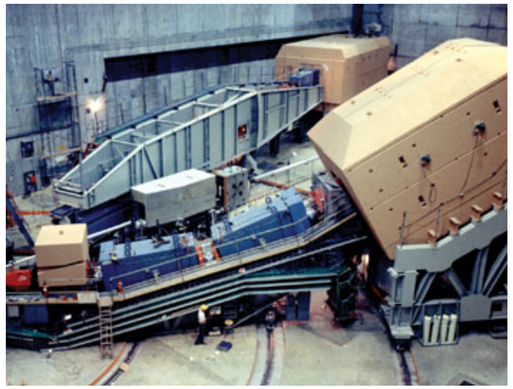




Phys. Rev. Lett. 110, 213001 (2013)

Phys. Rev. 98, 217 (1955)





Electromagnetism

Maxwell

Clarendon Press Series

A TREATISE

ON

ELECTRICITY AND MAGNETISM

BY

JAMES CLERK MAXWELL, M.A.

LL.D. EDIN., F.R.SS. LONDON AND EDINBURGH

HONORARY FELLOW OF TRINITY COLLEGE,

AND PROFESSOR OF EXPERIMENTAL PHYSICS

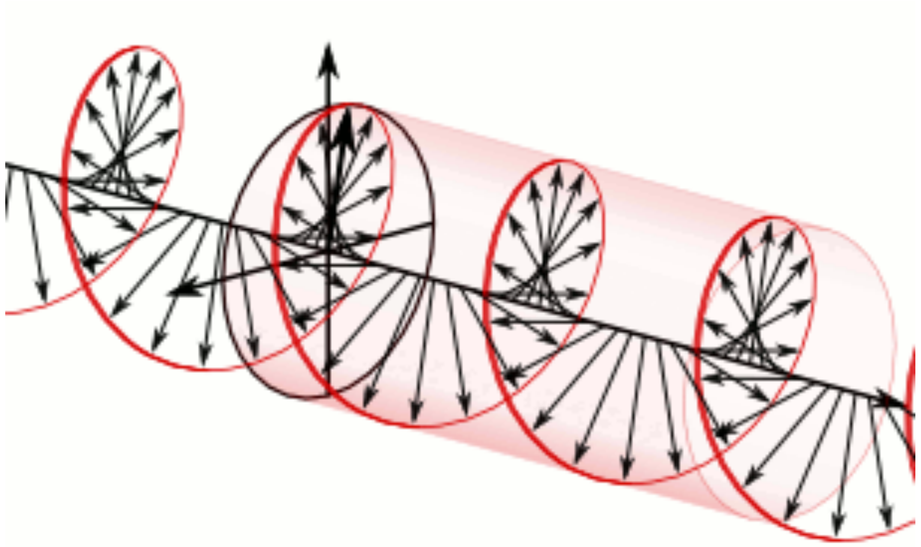
IN THE UNIVERSITY OF CAMBRIDGE

VOL. II

Oxford

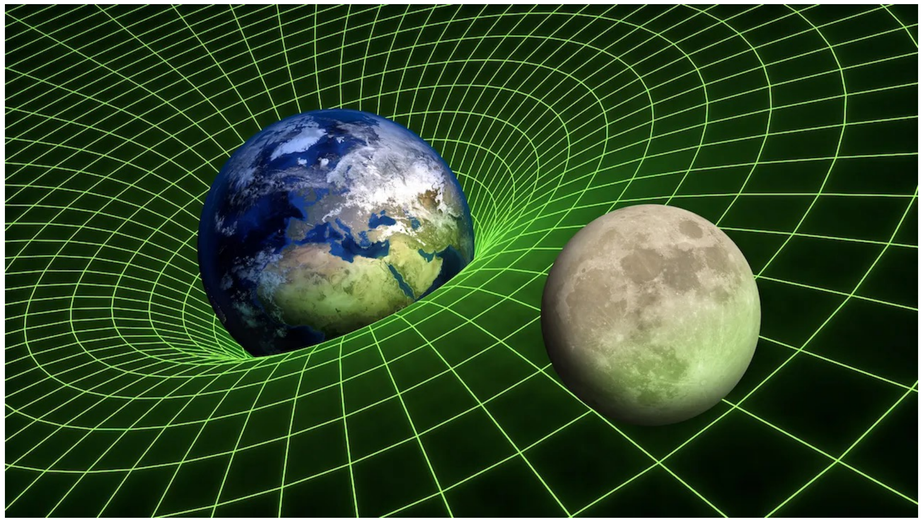
AT THE CLARENDON PRESS

1873

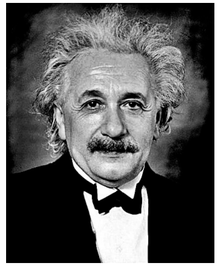


Other forces

Gravity

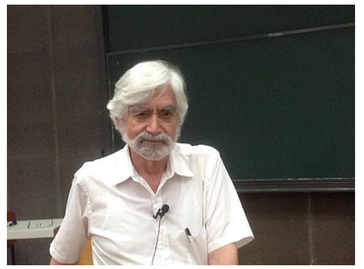


Newton



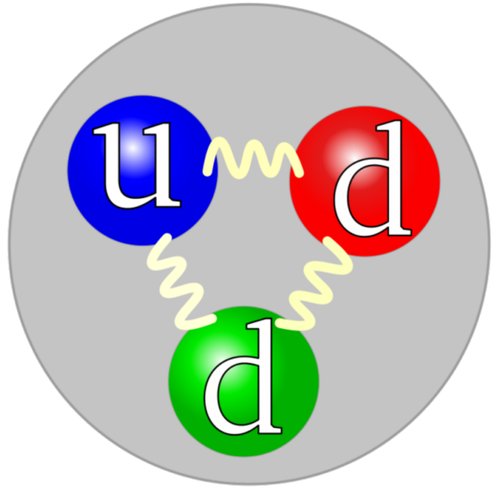
Einstein

Gell-Mann

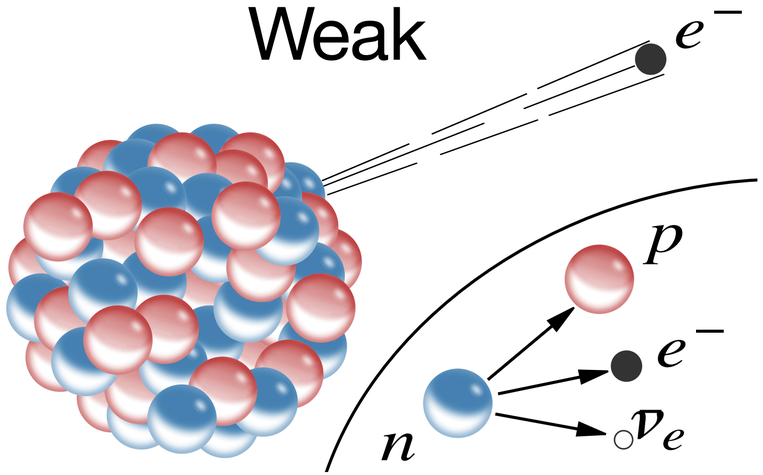


Zweig

Strong



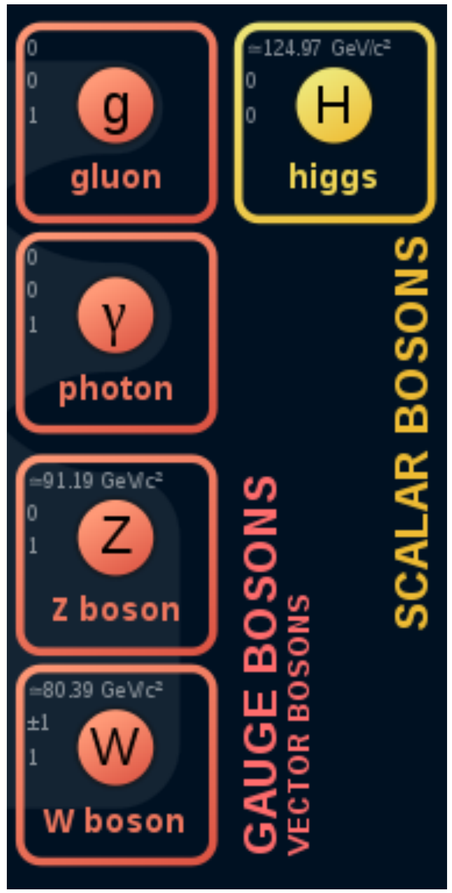
Weak



Pauli

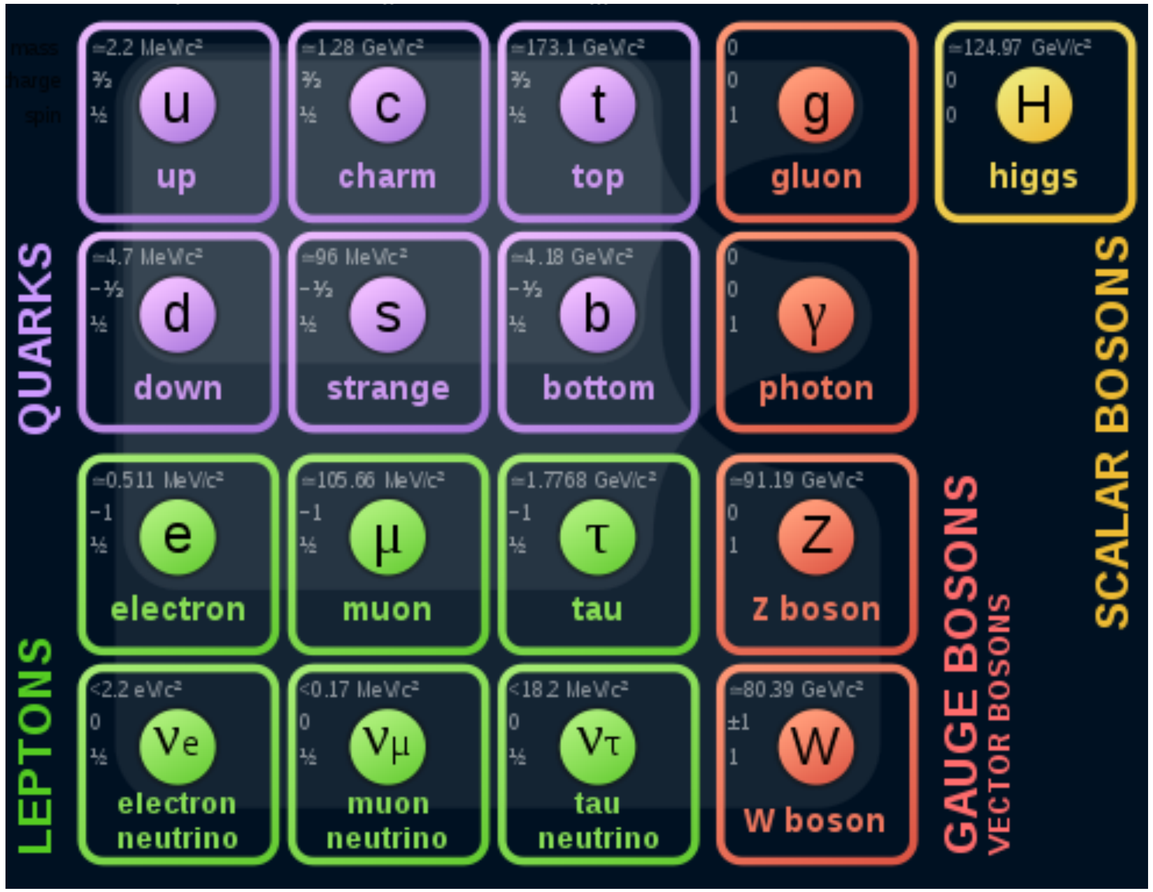
Fermi

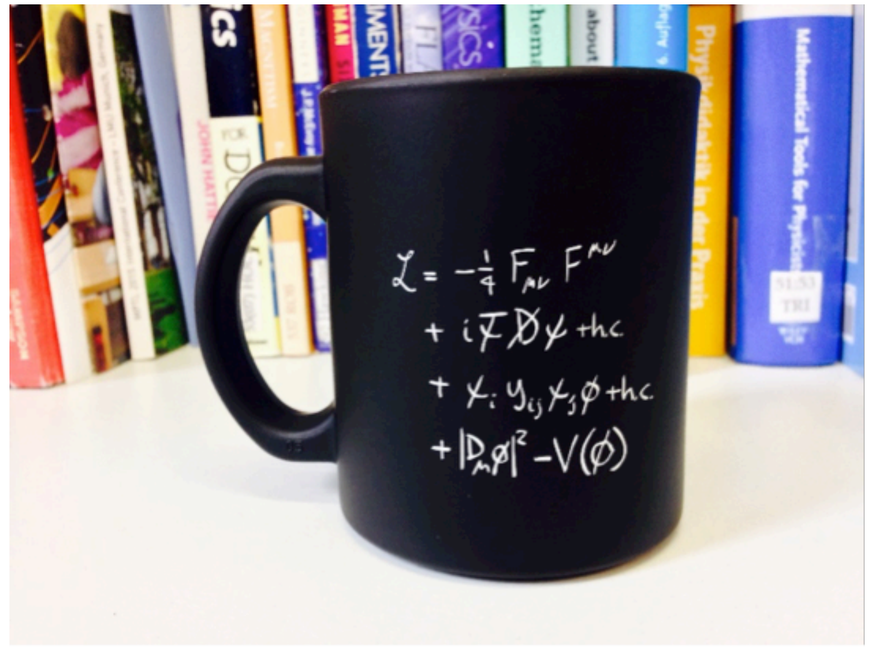
Matter & forces



Forces *carried* by particles

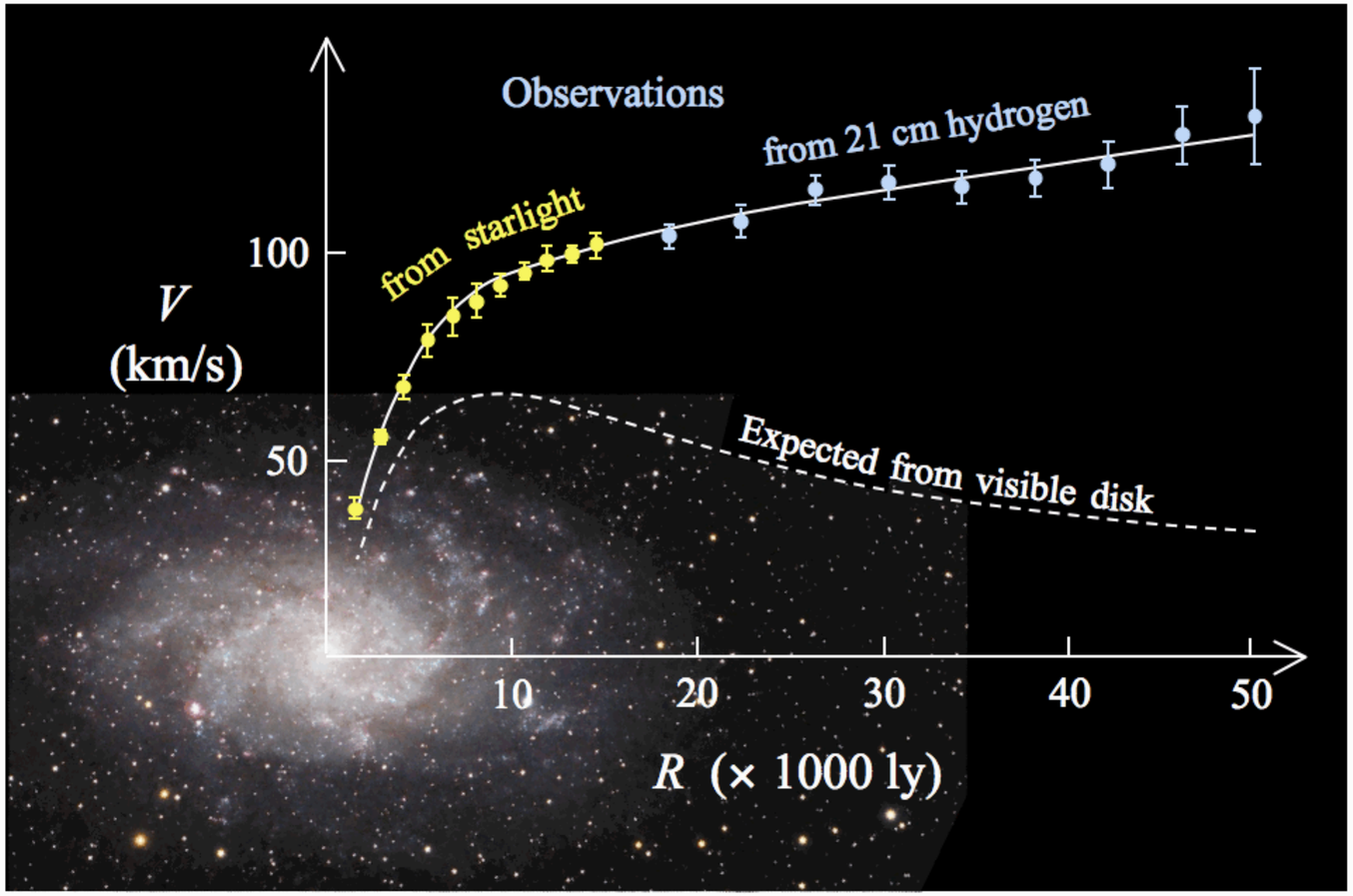
Matter & forces



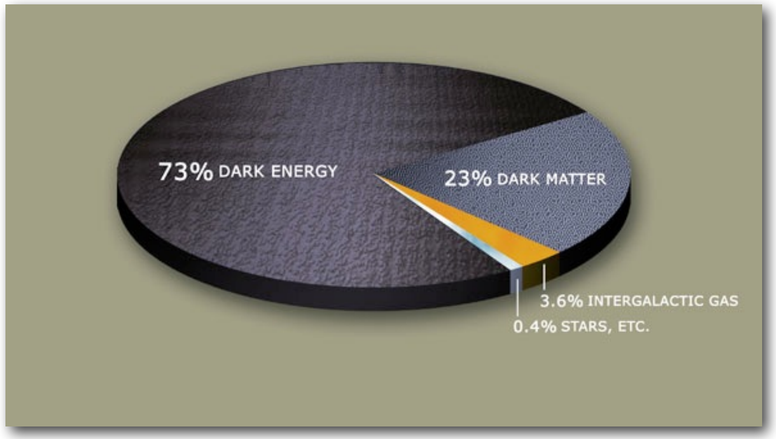


The *Standard Model*

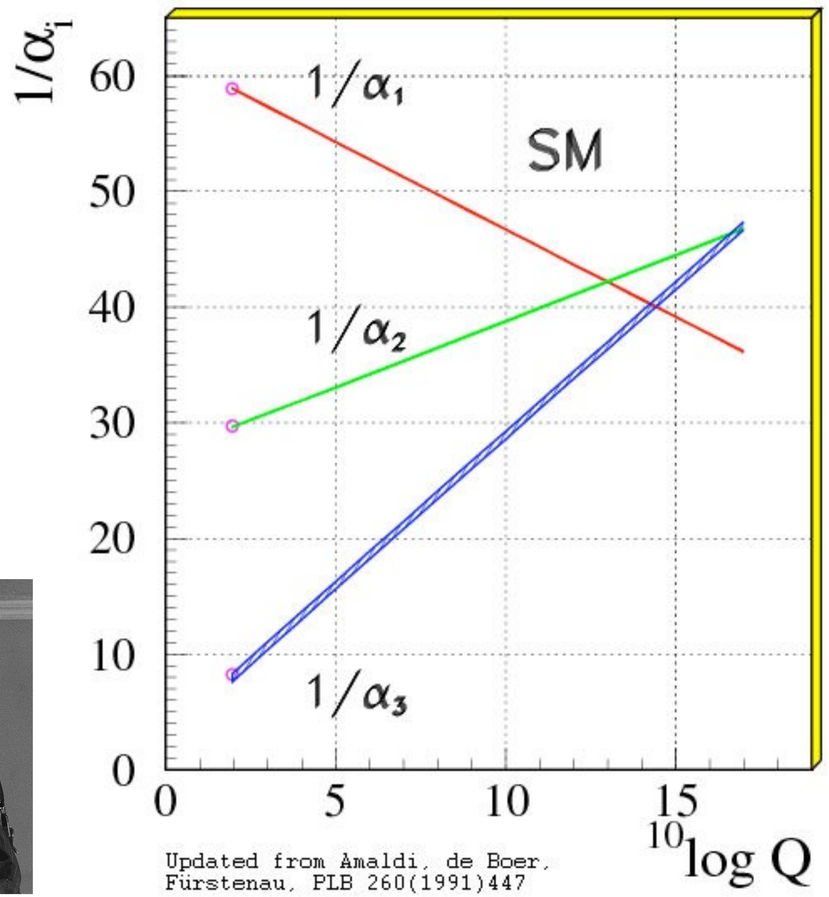
Dark Matter

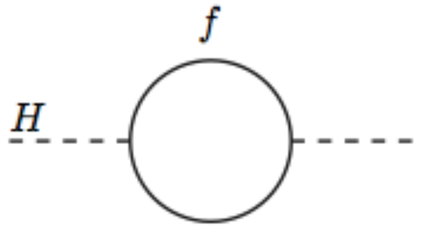


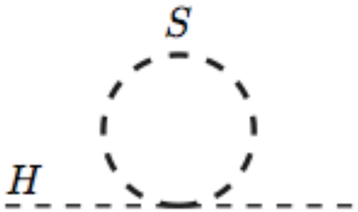
Vera Rubin



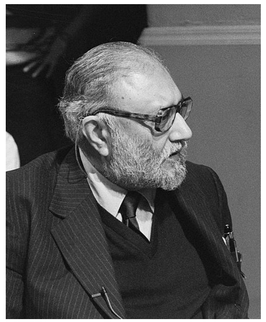
Unification of forces & hierarchy problem





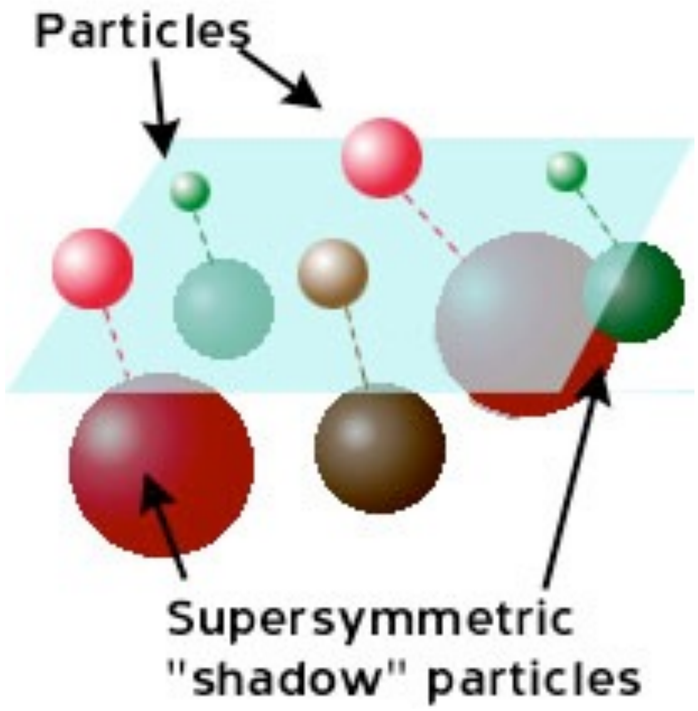


Colossal coincidence? (yuk!)

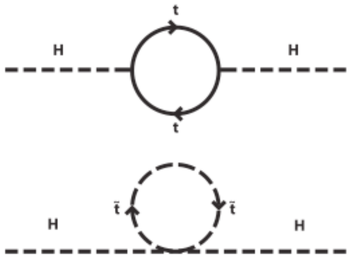


Abdus Salam

Potential solution — supersymmetry



- Provides dark matter candidate
- Solves hierarchy problem
- Coleman-Mandula



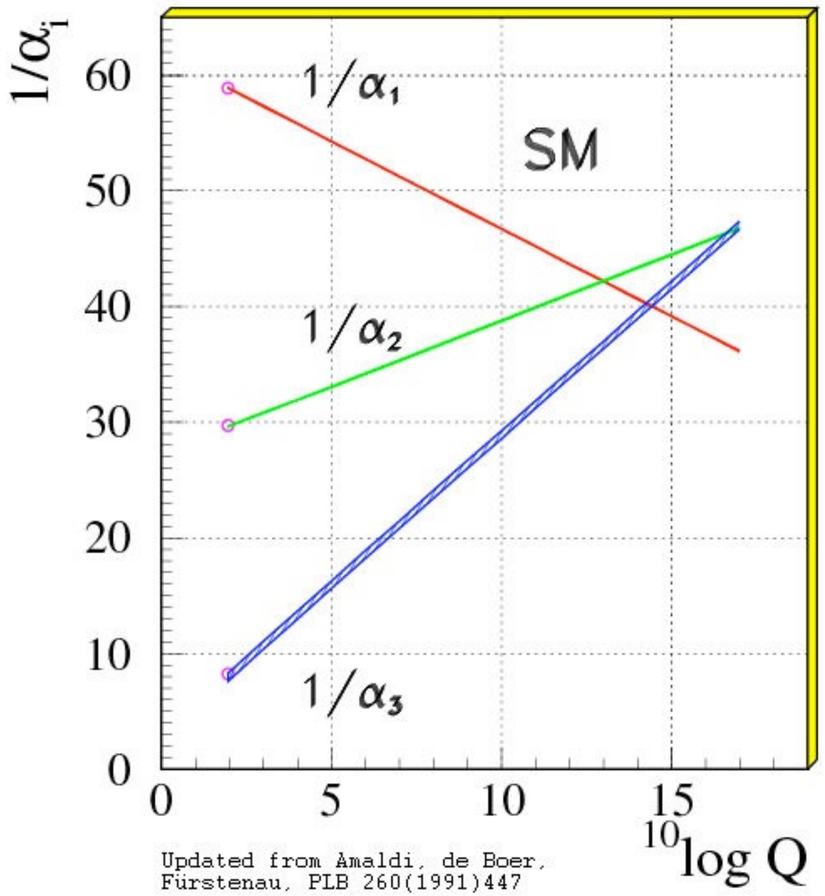
PHYSICAL REVIEW VOLUME 159, NUMBER 5 25 JULY 1967

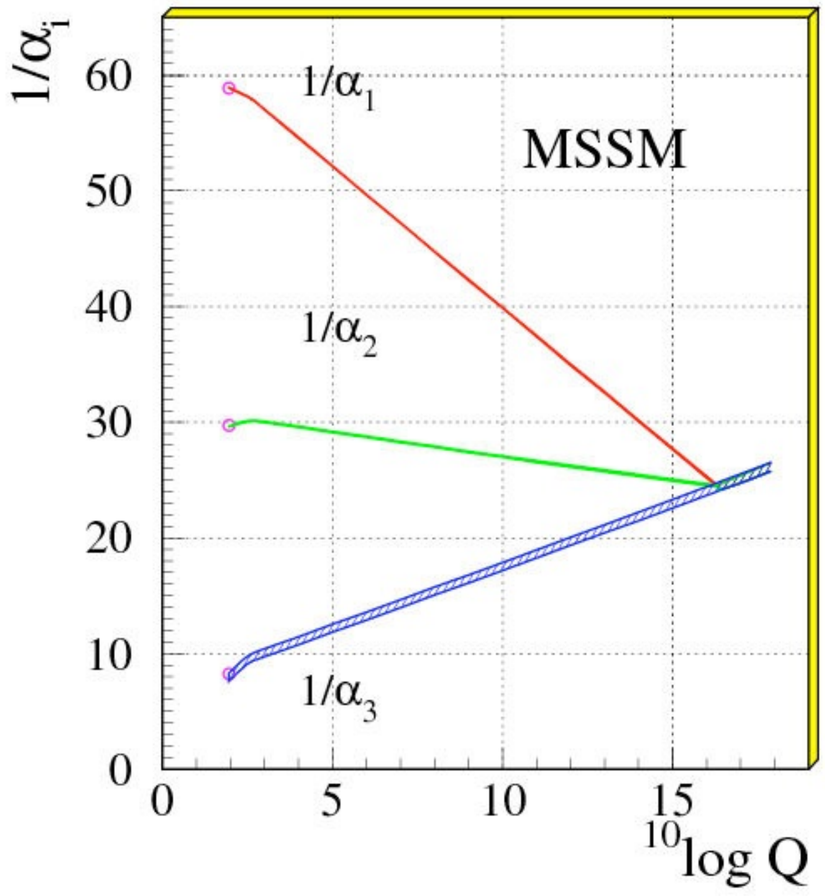
All Possible Symmetries of the *S* Matrix*

SIDNEY COLEMAN† AND JEFFREY MANDULA‡
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts
(Received 16 March 1967)

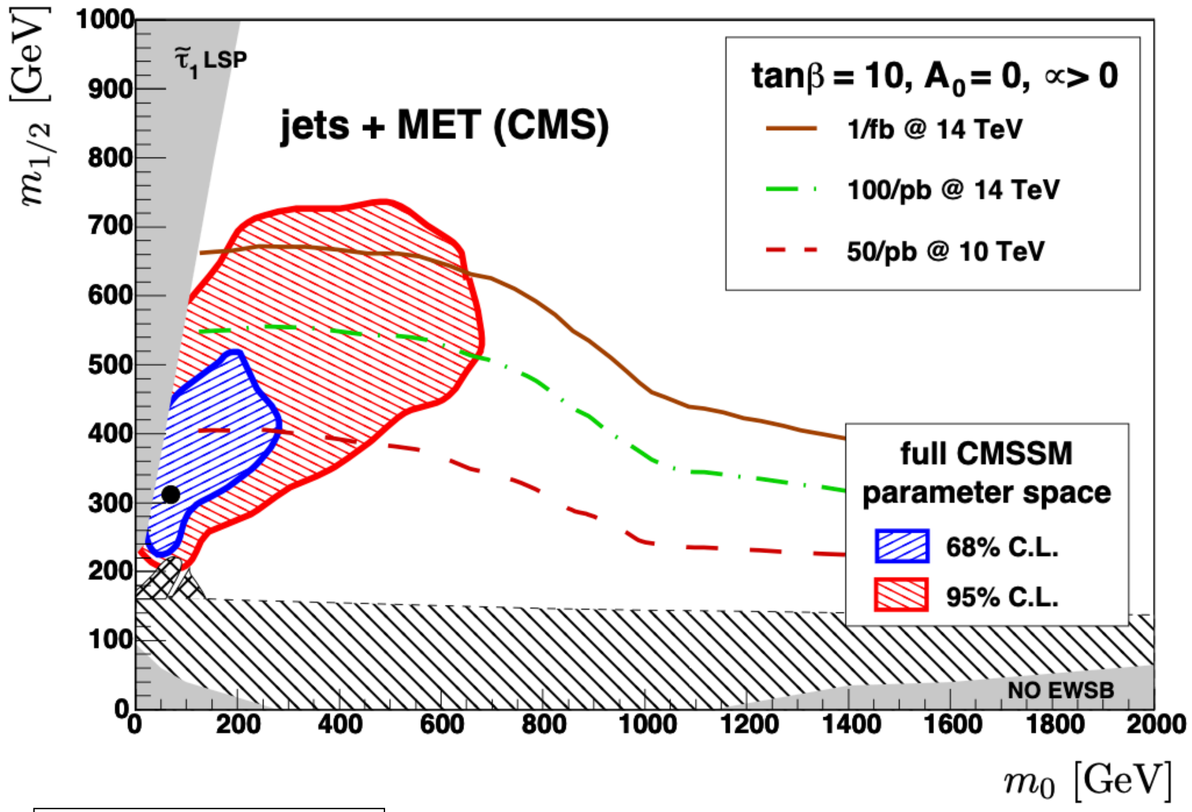
We prove a new theorem on the impossibility of combining space-time and internal symmetries in any but a trivial way. The theorem is an improvement on known results in that it is applicable to infinite-parameter groups, instead of just to Lie groups. This improvement is gained by using information about the *S* matrix; previous investigations used only information about the single-particle spectrum. We define a symmetry group of the *S* matrix as a group of unitary operators which turn one-particle states into one-particle states, transform many-particle states as if they were tensor products, and commute with the *S* matrix. Let *G* be a connected symmetry group of the *S* matrix, and let the following five conditions hold: (1) *G* contains a subgroup locally isomorphic to the Poincaré group. (2) For any $M>0$, there are only a finite number of one-particle states with mass less than M. (3) Elastic scattering amplitudes are analytic functions of s and t, in some neighborhood of the physical region. (4) The *S* matrix is nontrivial in the sense that any two one-particle momentum eigenstates scatter (into something), except perhaps at isolated values of s. (5) The generators of *G*, written as integral operators in momentum space, have distributions for their kernels. Then, we show that *G* is necessarily locally isomorphic to the direct product of an internal symmetry group and the Poincaré group.

Unification of forces

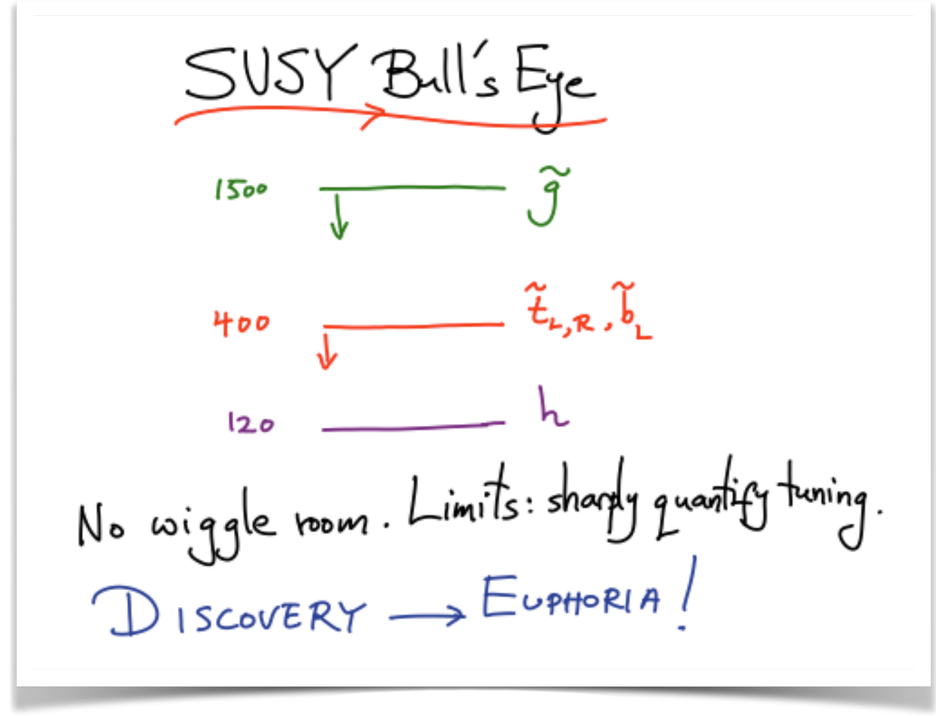




The starting point



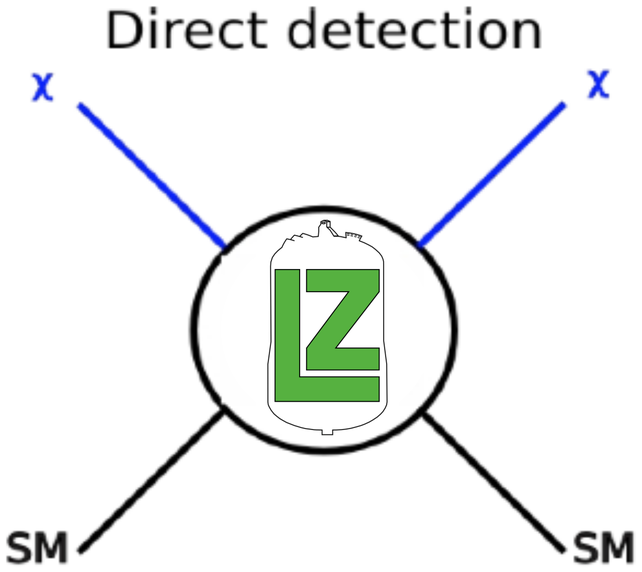
JHEP 09 (2008) 117

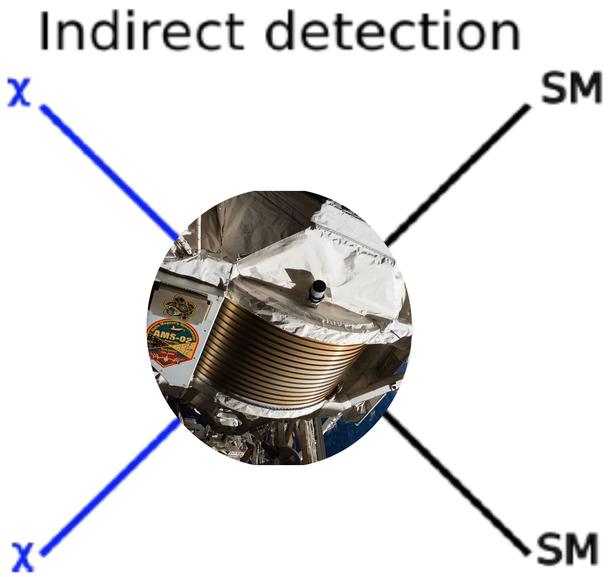


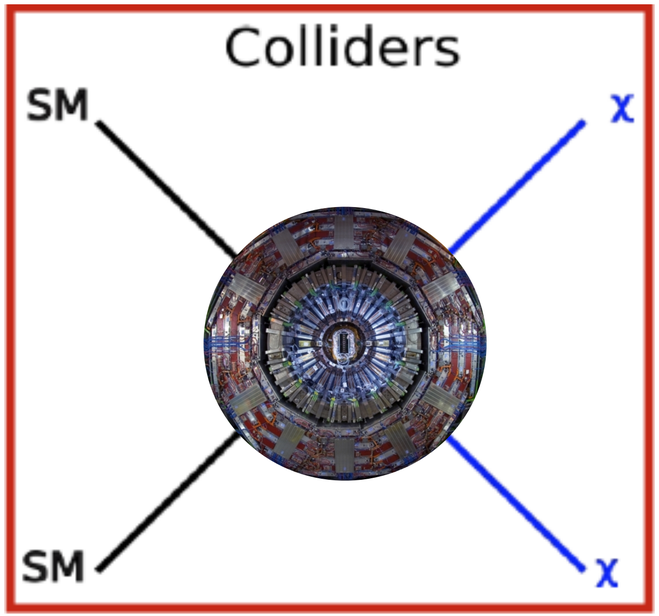
N. Arkani-Hamed (2011)

How?

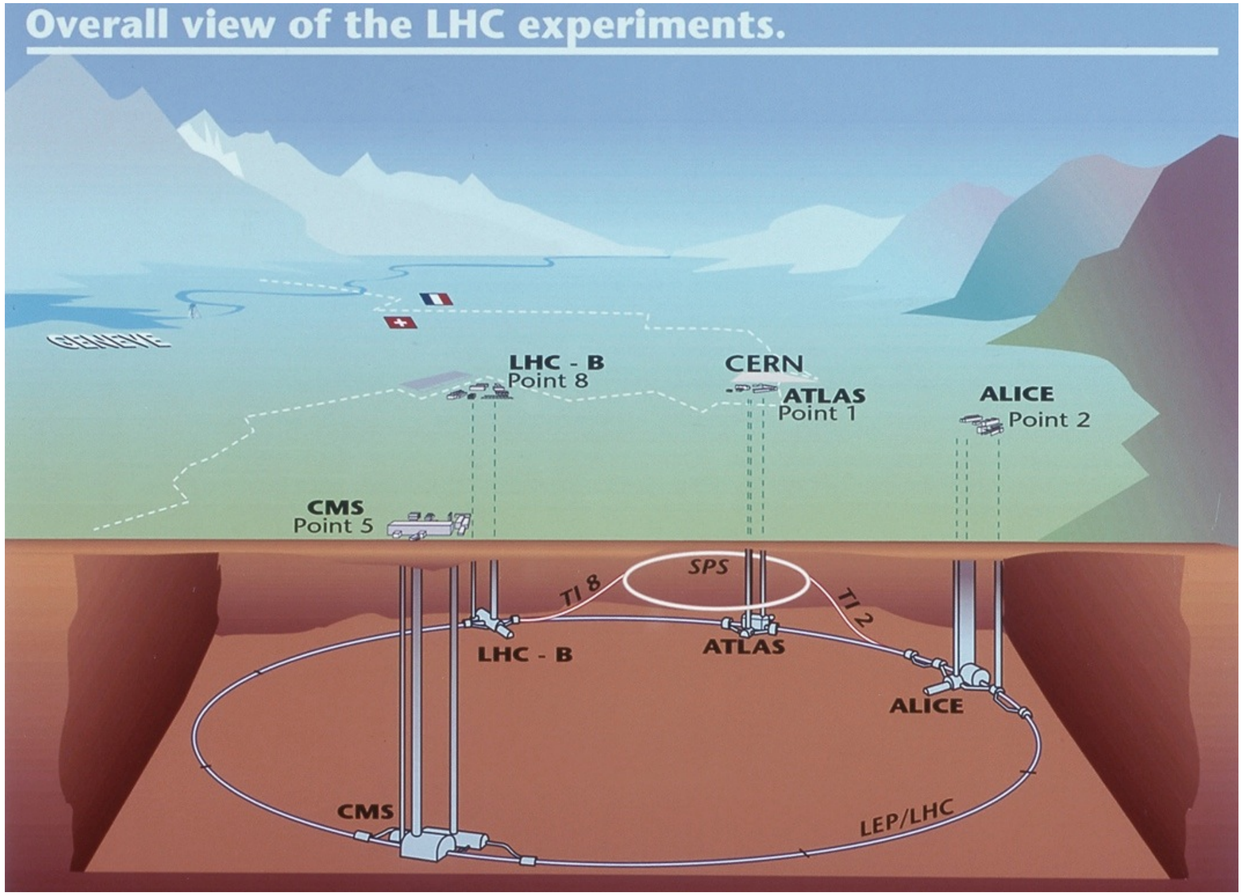
Searching for dark matter (supersymmetry)

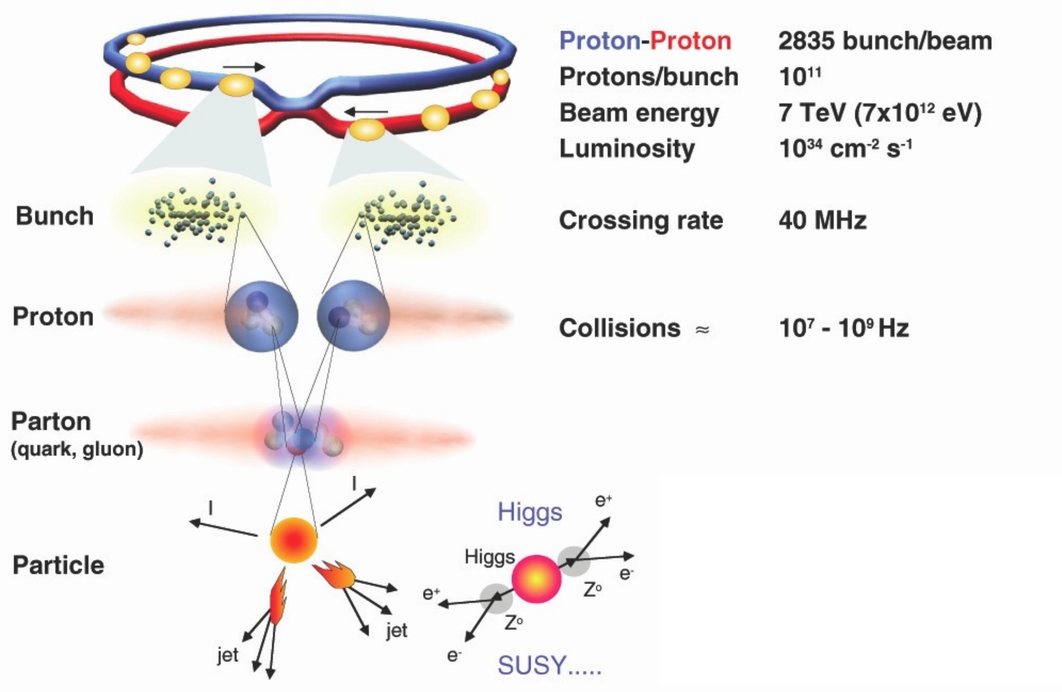




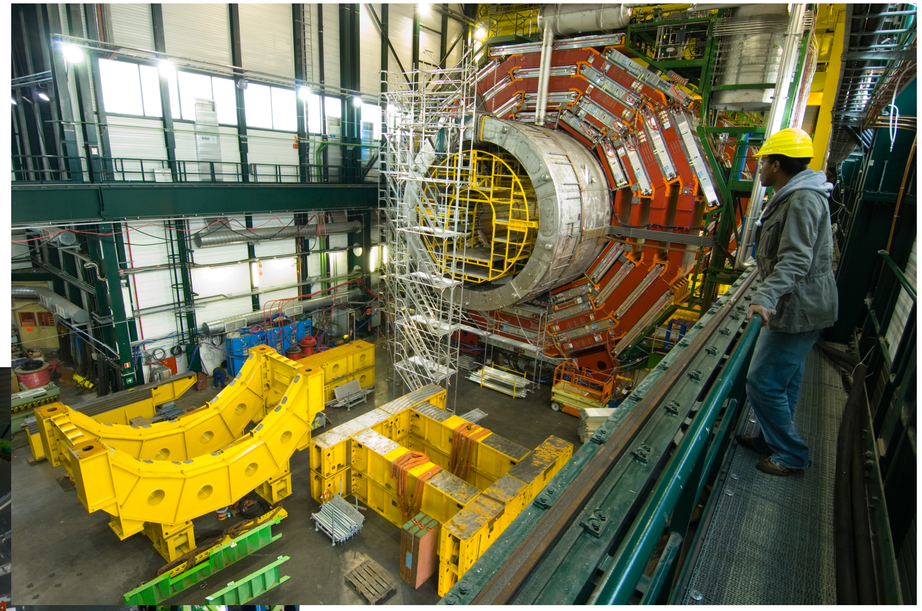


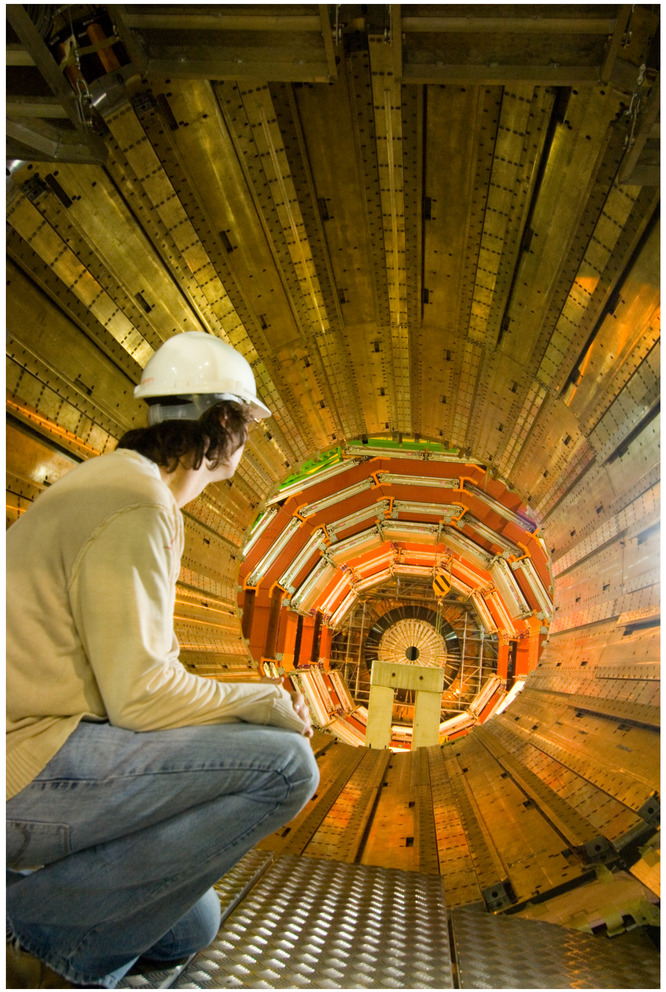
The Large Hadron Collider @ CERN



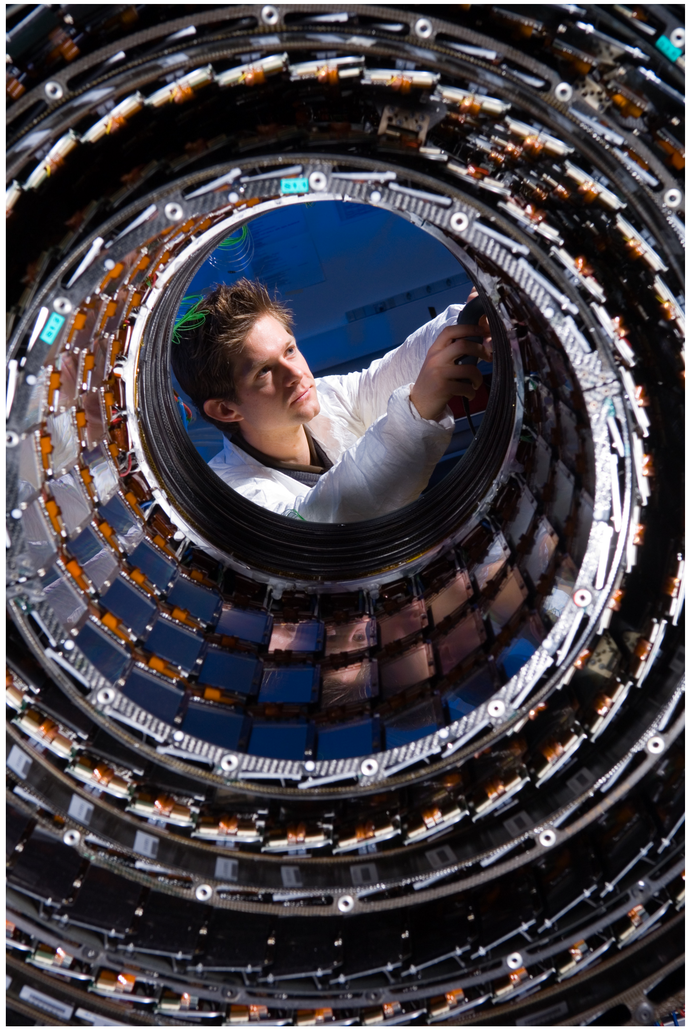


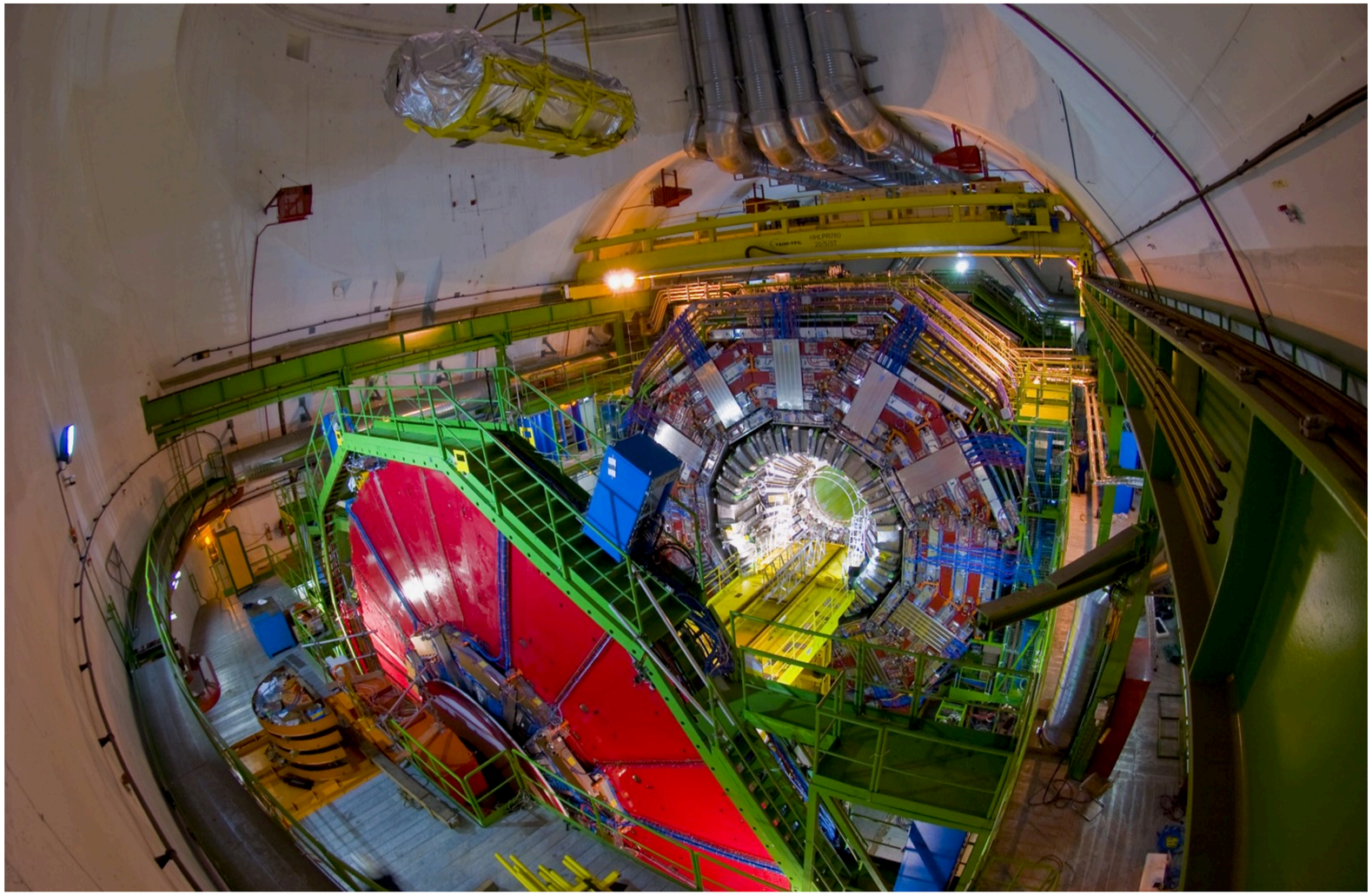
Building CMS



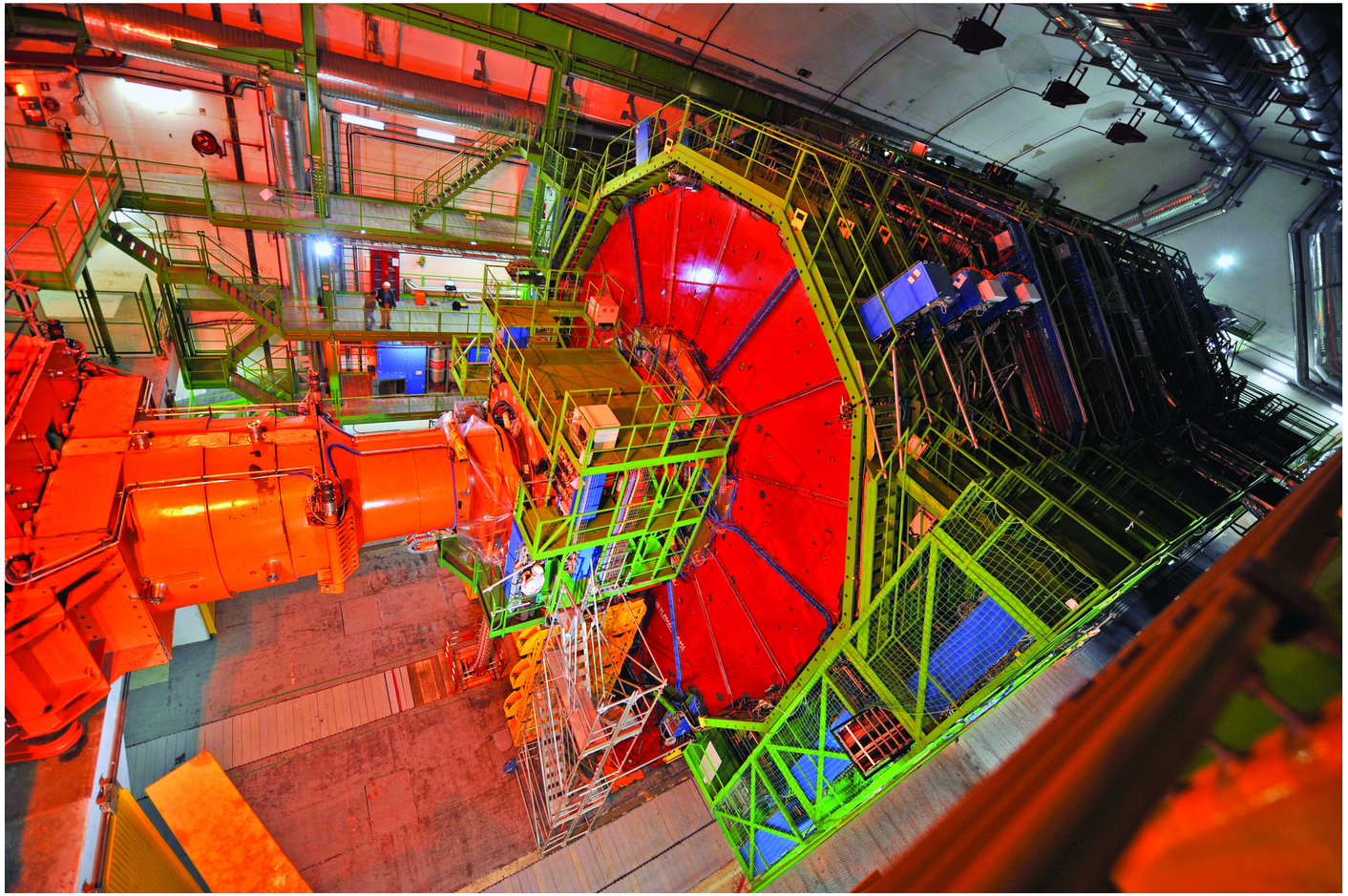


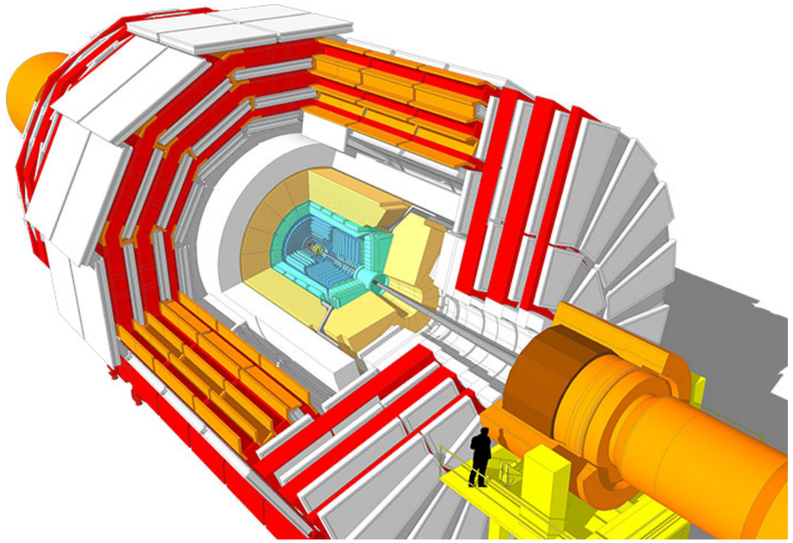
Building CMS



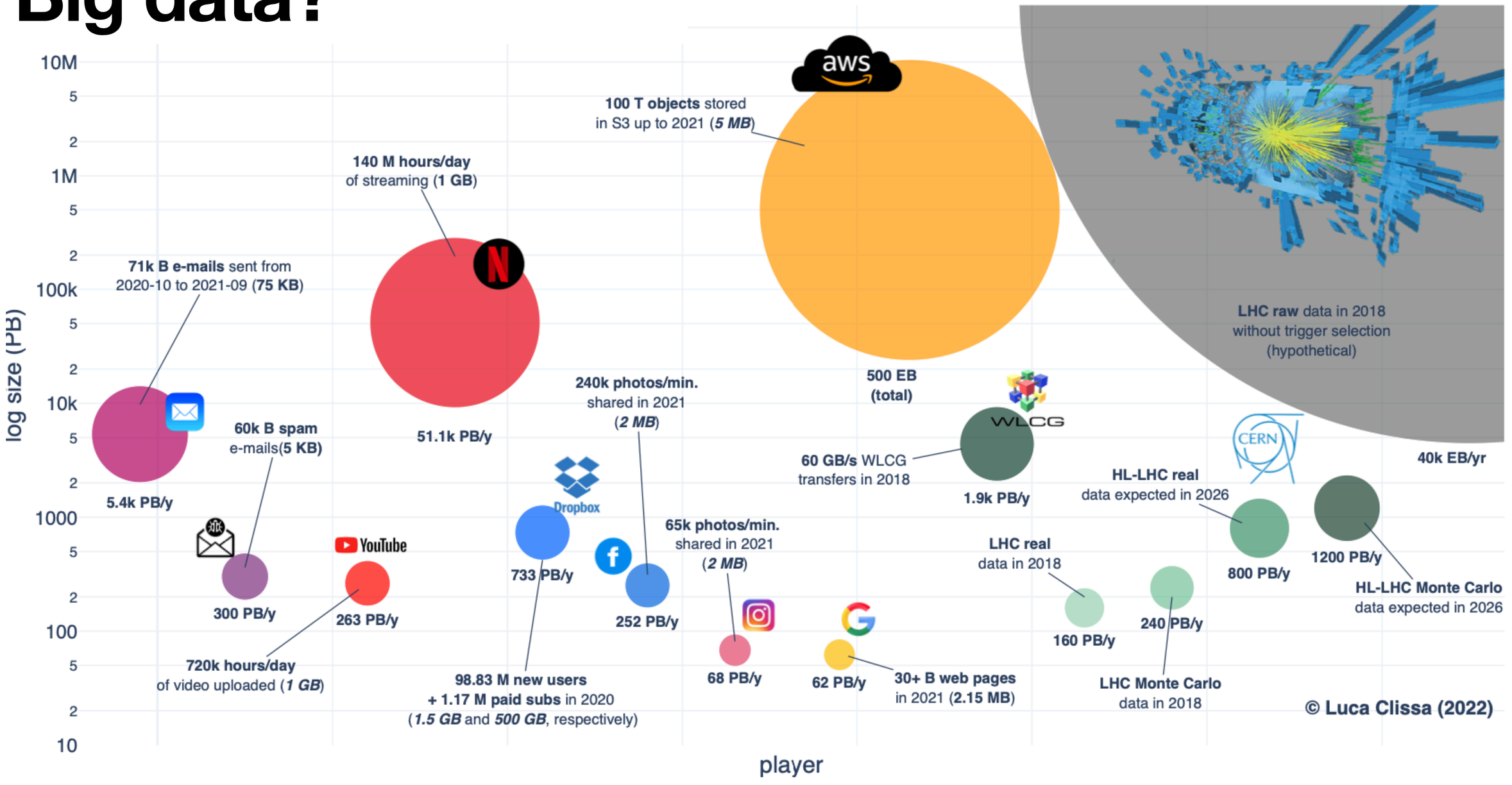


CMS (finally) finished

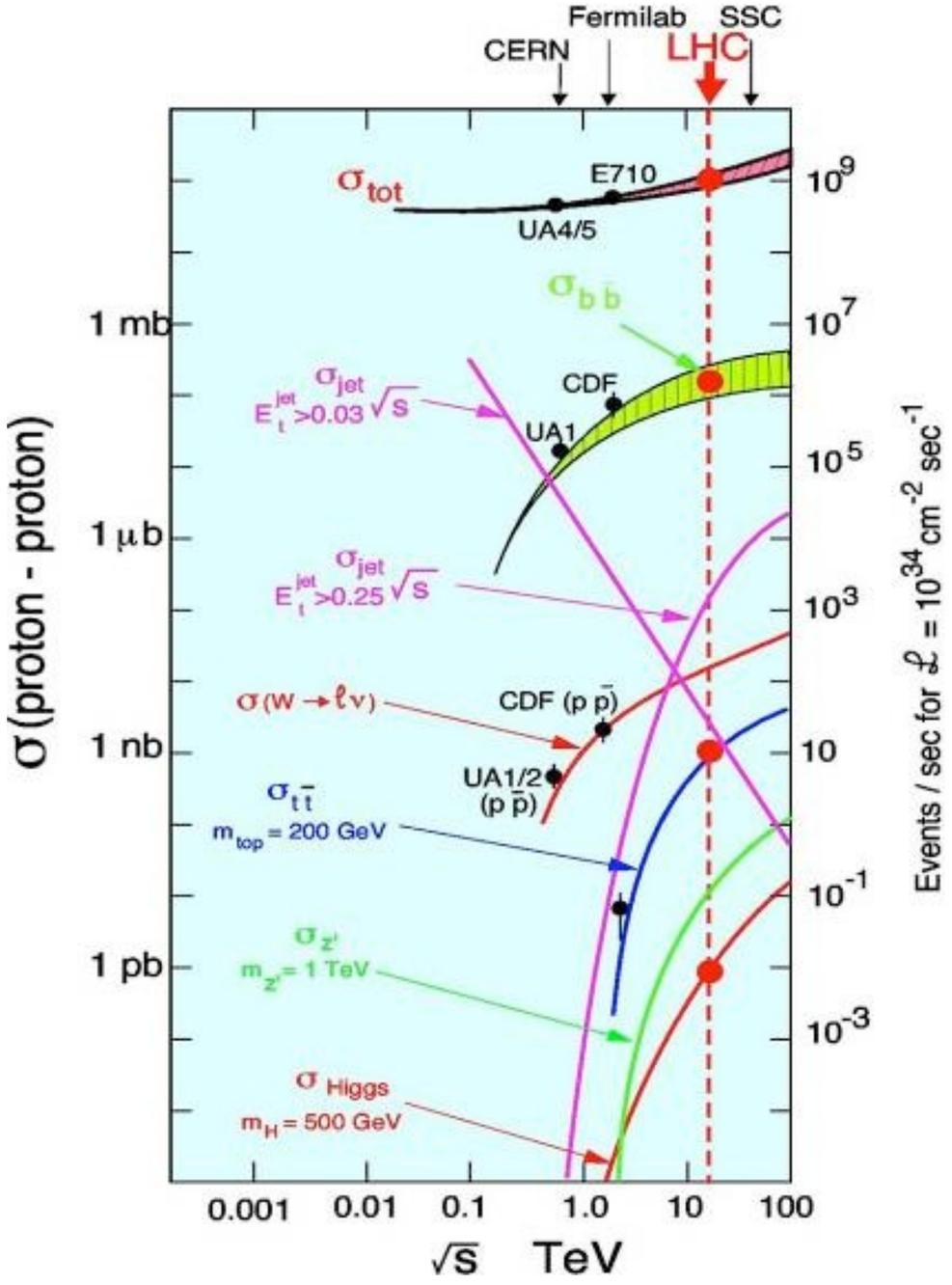




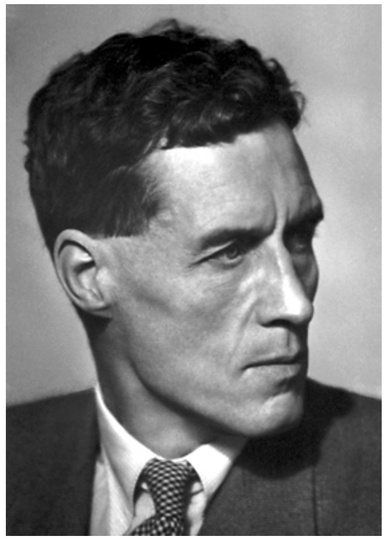
Big data?


log size (PB)
10M
5
2
1M
5
2
100k
5
2
10k
5
2
1000
5
2
100
5
2
10
player
71k B e-mails sent from 2020-10 to 2021-09 (75 KB)
5.4k PB/y
60k B spam e-mails(5 KB)
300 PB/y
720k hours/day of video uploaded (1 GB)
140 M hours/day of streaming (1 GB)
51.1k PB/y
263 PB/y
240k photos/min. shared in 2021 (2 MB)
733 PB/y
98.83 M new users + 1.17 M paid subs in 2020 (1.5 GB and 500 GB, respectively)
65k photos/min. shared in 2021 (2 MB)
252 PB/y
68 PB/y
100 T objects stored in S3 up to 2021 (5 MB)
500 EB (total)
62 PB/y
30+ B web pages in 2021 (2.15 MB)
60 GB/s WLCG transfers in 2018
1.9k PB/y
LHC raw data in 2018 without trigger selection (hypothetical)
40k EB/yr
HL-LHC real data expected in 2026
800 PB/y
1200 PB/y
HL-LHC Monte Carlo data expected in 2026
LHC real data in 2018
160 PB/y
240 PB/y
LHC Monte Carlo data in 2018
© Luca Clissa (2022)

What happens?



Triggering



Patrick Blackett

“ .. I set about, therefore, the devising of a method of making cosmic rays take their own photographs …”

Nobel Lecture, 1948

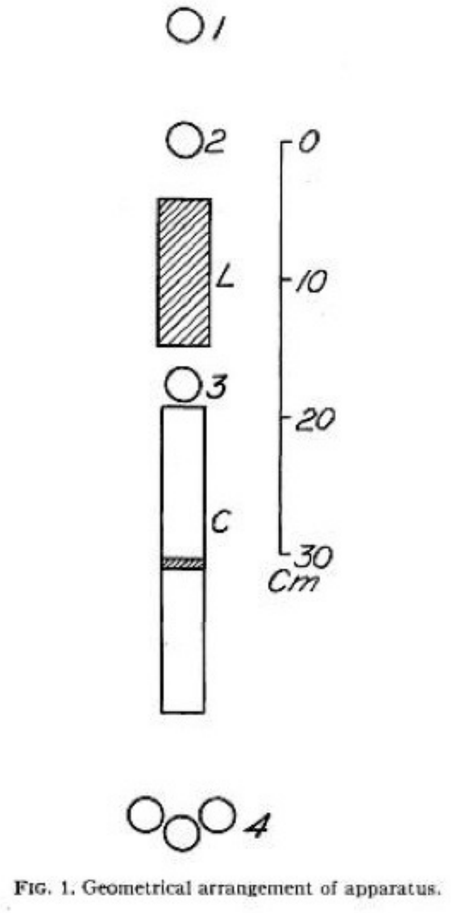
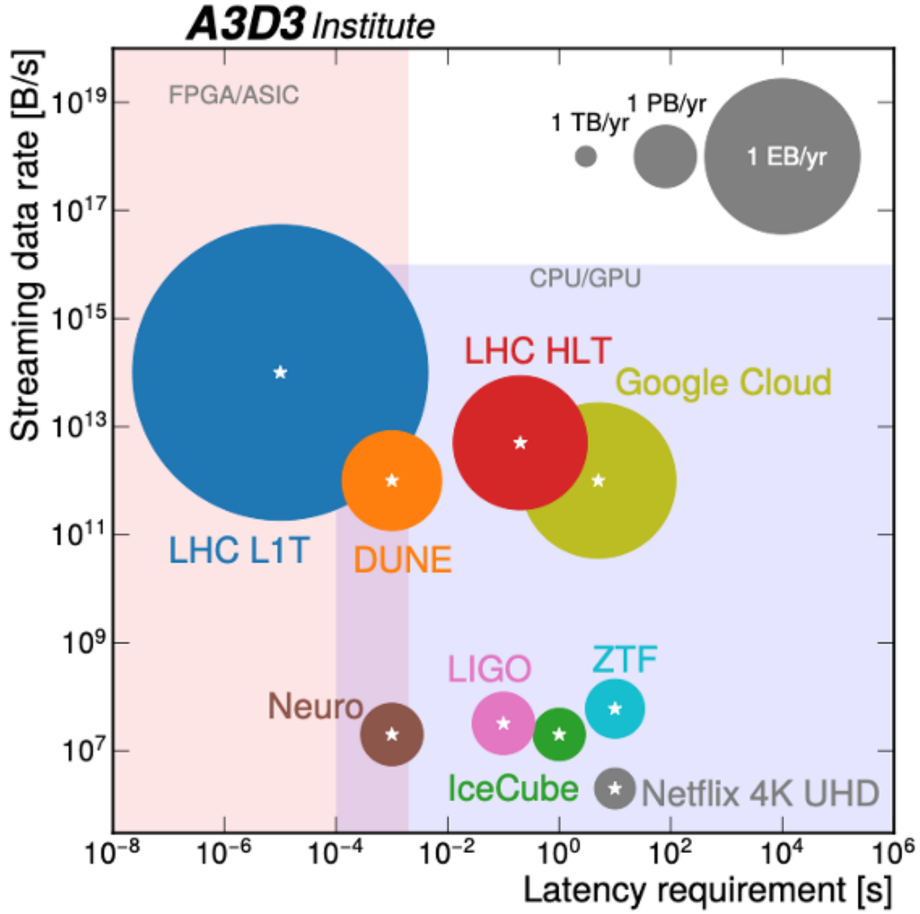
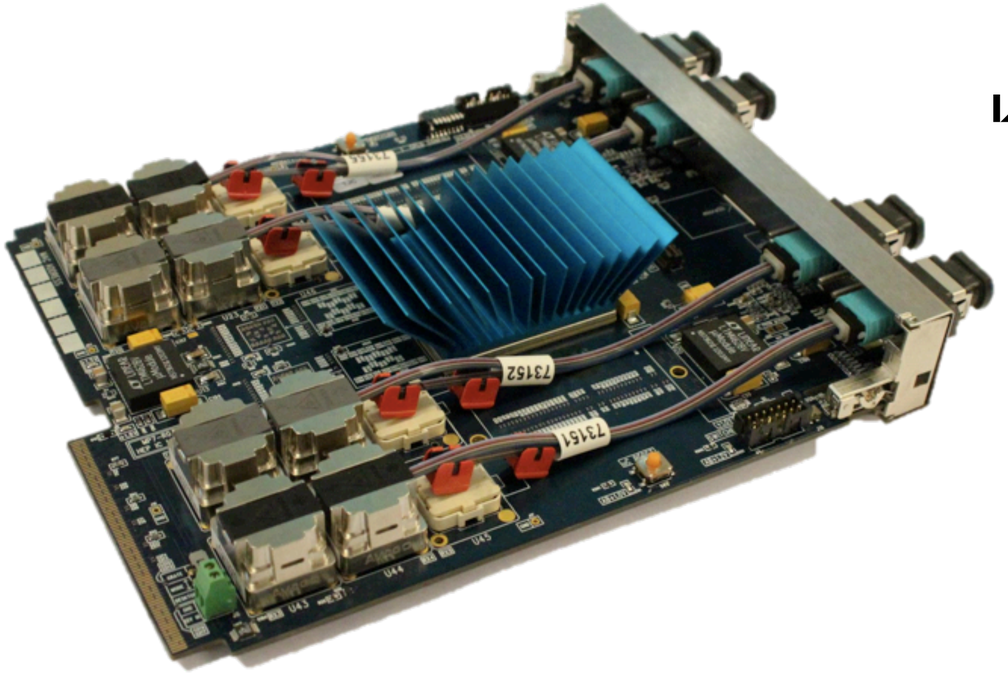


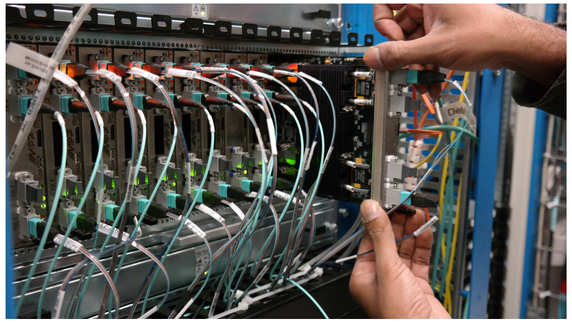
FIG. 1. Geometrical arrangement of apparatus.

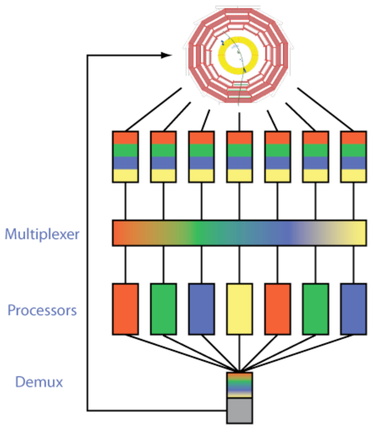
Building our own computers





IMPERIAL MPZ





Time-Multiplexed Trigger

What did we learn?

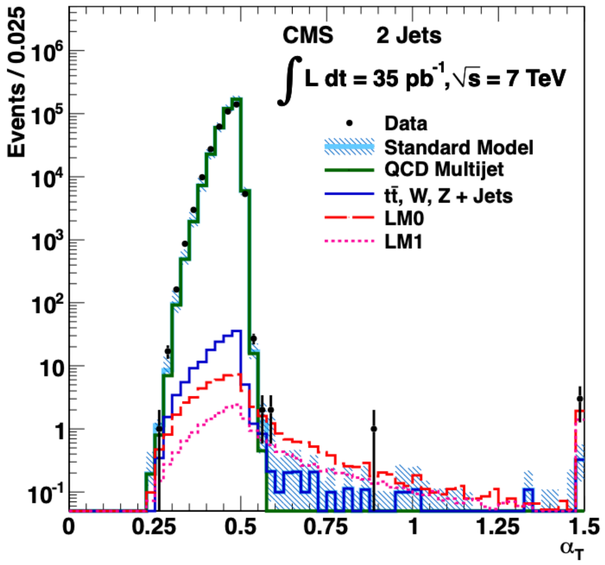
First look

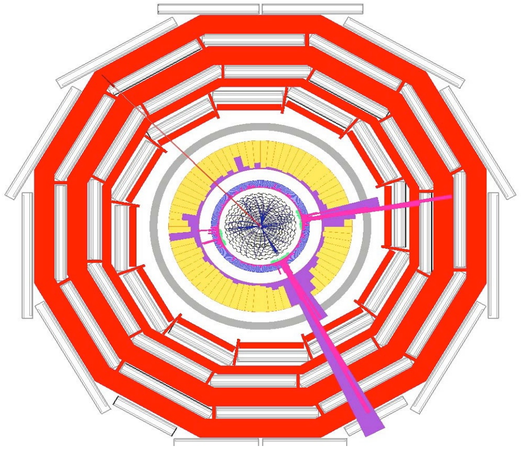
Search for Supersymmetry in pp Collisions at 7 TeV in Events with Jets and Missing Transverse Energy

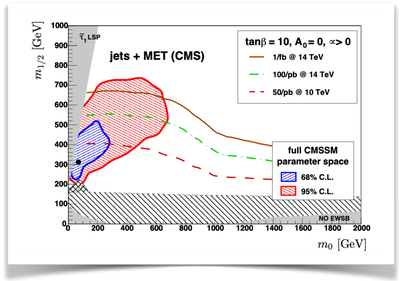
The CMS Collaboration*

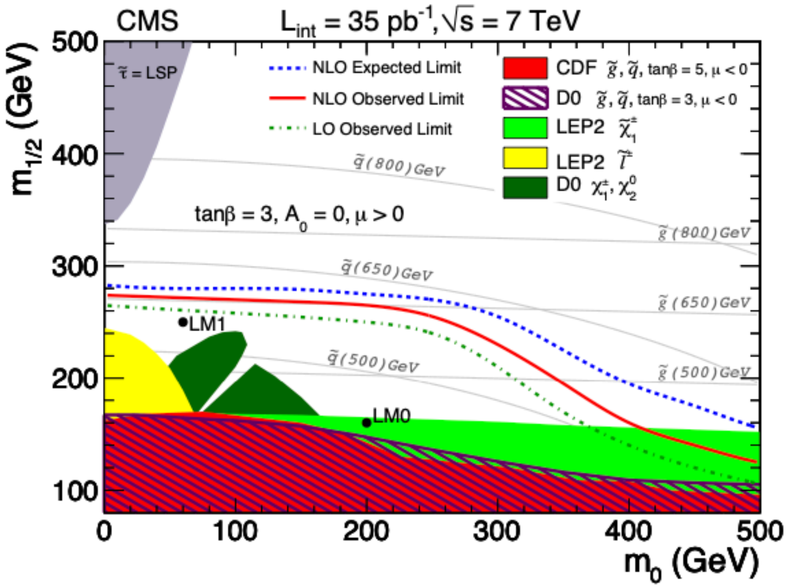
Abstract

A search for supersymmetry with R-parity conservation in proton-proton collisions at a centre-of-mass energy of 7 TeV is presented. The data correspond to an integrated luminosity of 35 pb^{-1} collected by the CMS experiment at the LHC. The search is performed in events with jets and significant missing transverse energy, characteristic of the decays of heavy, pair-produced squarks and gluinos. The primary background, from standard model multijet production, is reduced by several orders of magnitude to a negligible level by the application of a set of robust kinematic requirements. With this selection, the data are consistent with the standard model backgrounds, namely $t\bar{t}$, W + jet and Z + jet production, which are estimated from data control samples. Limits are set on the parameters of the constrained minimal supersymmetric extension of the standard model. These limits extend those set previously by experiments at the Tevatron and LEP colliders.









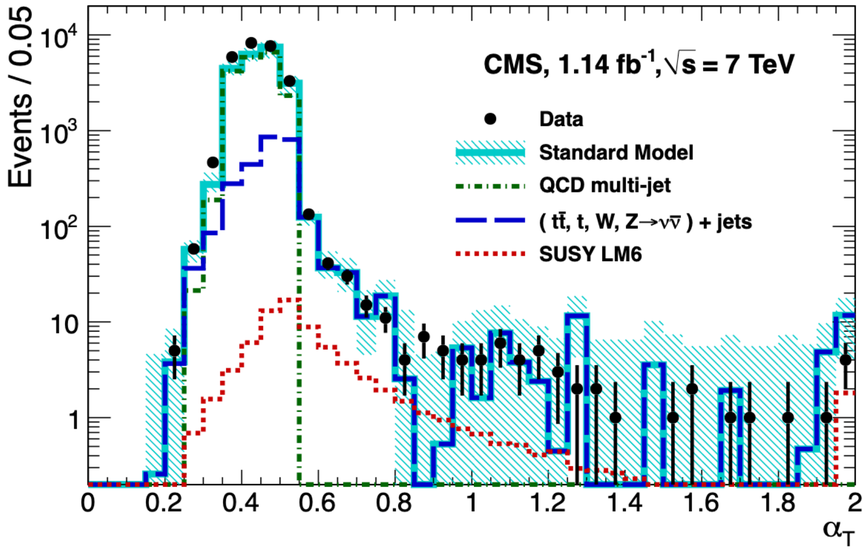
Look again

Search for Supersymmetry at the LHC in Events with Jets and Missing Transverse Energy

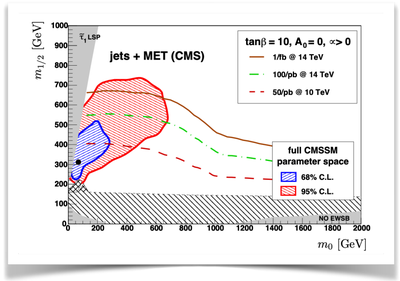
The CMS Collaboration*

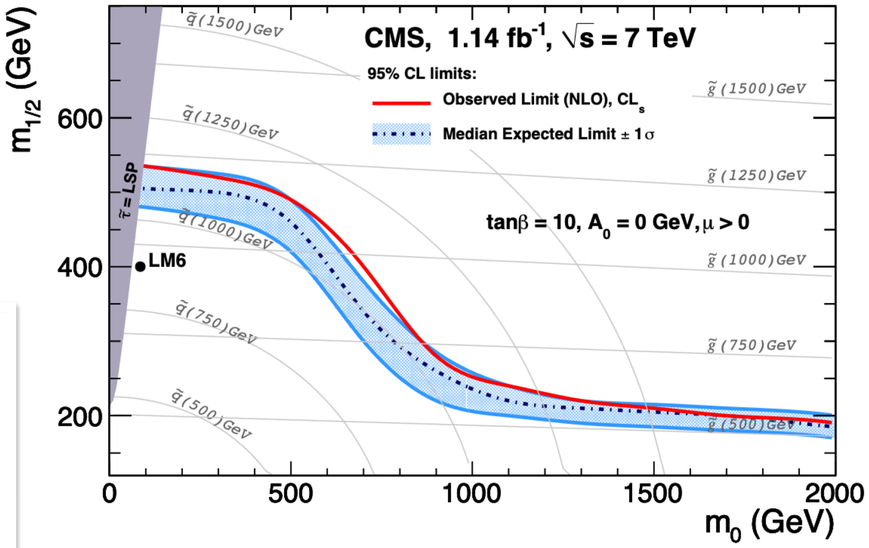
Abstract

A search for events with jets and missing transverse energy is performed in a data sample of pp collisions collected at $\sqrt{s} = 7$ TeV by the CMS experiment at the LHC. The analyzed data sample corresponds to an integrated luminosity of 1.14 fb^{-1}. In this search, a kinematic variable, α_T, is used as the main discriminator between events with genuine and misreconstructed missing transverse energy. No excess of events over the standard model expectation is found. Exclusion limits in the parameter space of the constrained minimal supersymmetric extension of the standard model are set. In this model, squark masses below 1.1 TeV are excluded at 95% CL. Gluino masses below 1.1 TeV are also ruled out at 95% CL for values of the universal scalar mass parameter below 500 GeV.



~30x larger data sample





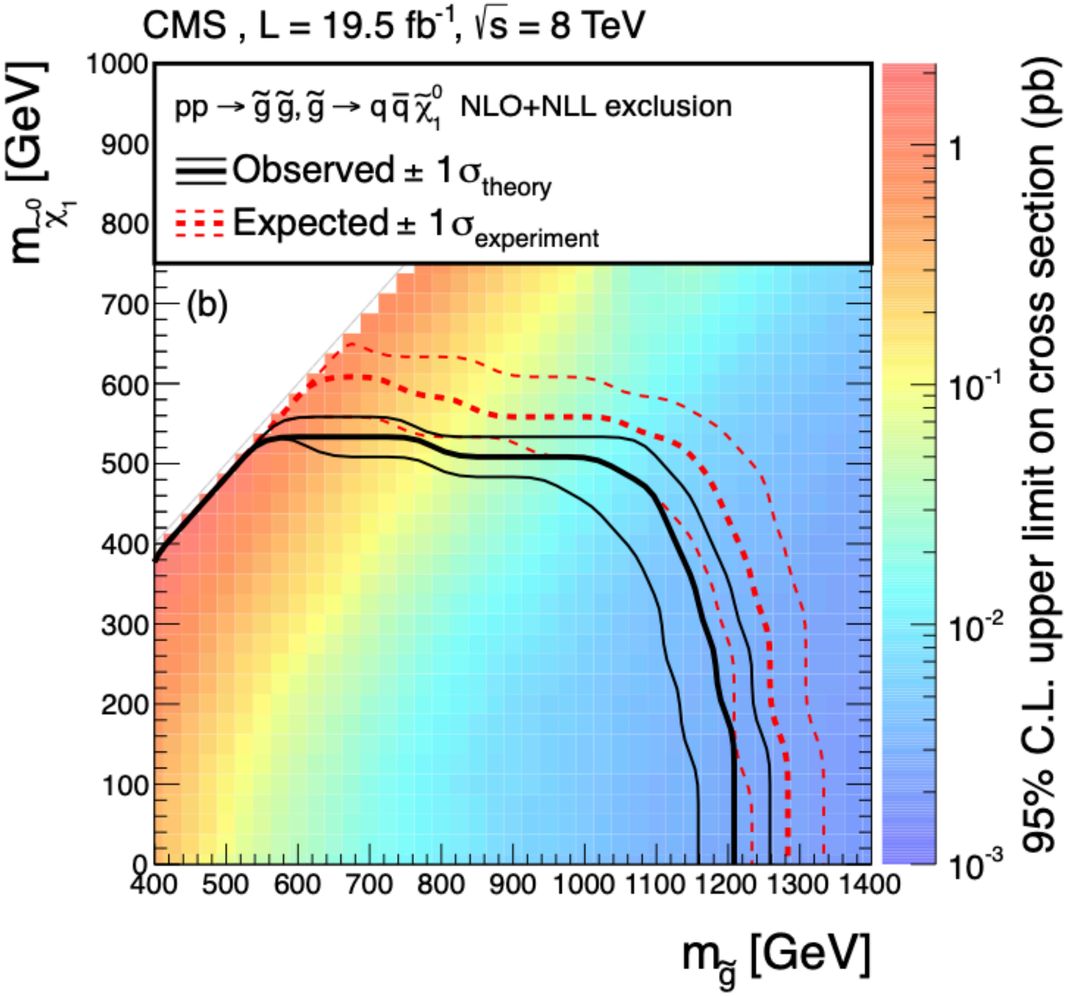
And again …

Search for new physics in the multijet and missing transverse momentum final state in proton-proton collisions at $\sqrt{s} = 8\,\text{TeV}$

The CMS Collaboration*

Abstract

A search for new physics is performed in multijet events with large missing transverse momentum produced in proton-proton collisions at $\sqrt{s} = 8\,\text{TeV}$ using a data sample corresponding to an integrated luminosity of $19.5\,\text{fb}^{-1}$ collected with the CMS detector at the LHC. The data sample is divided into three jet multiplicity categories (3–5, 6–7, and $\geq$8 jets), and studied further in bins of two variables: the scalar sum of jet transverse momenta and the missing transverse momentum. The observed numbers of events in various categories are consistent with backgrounds expected from standard model processes. Exclusion limits are presented for several simplified supersymmetric models of squark or gluino pair production.



~20x larger data sample

slightly higher energy 7 → 8 TeV

Once more …

A search for new phenomena in pp collisions at $\sqrt{s} = 13$ TeV in final states with missing transverse momentum and at least one jet using the α_T variable

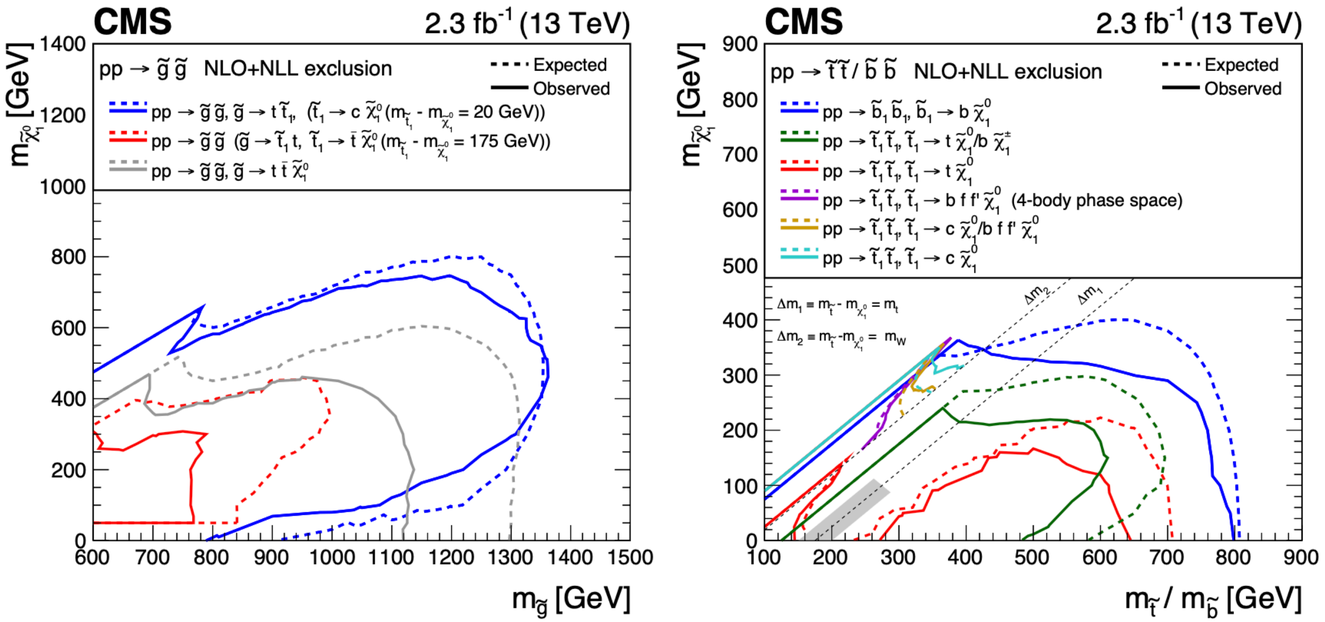
The CMS Collaboration*

Abstract

A search for new phenomena is performed in final states containing one or more jets and an imbalance in transverse momentum in pp collisions at a centre-of-mass energy of 13 TeV. The analysed data sample, recorded with the CMS detector at the CERN LHC, corresponds to an integrated luminosity of 2.3 fb^{-1}. Several kinematic variables are employed to suppress the dominant background, multijet production, as well as to discriminate between other standard model and new physics processes. The search provides sensitivity to a broad range of new-physics models that yield a stable weakly interacting massive particle. The number of observed candidate events is found to agree with the expected contributions from standard model processes, and the result is interpreted in the mass parameter space of fourteen simplified supersymmetric models that assume the pair production of gluinos or squarks and a range of decay modes. For models that assume gluino pair production, masses up to 1575 and 975 GeV are excluded for gluinos and neutralinos, respectively. For models involving the pair production of top squarks and compressed mass spectra, top squark masses up to 400 GeV are excluded.

~2x smaller data sample

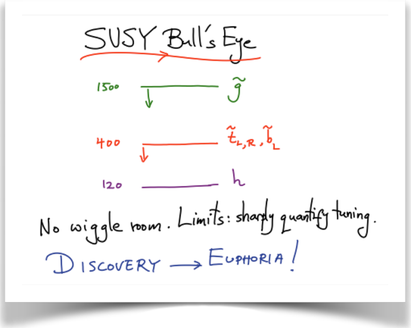
higher energy 8 → 13 TeV



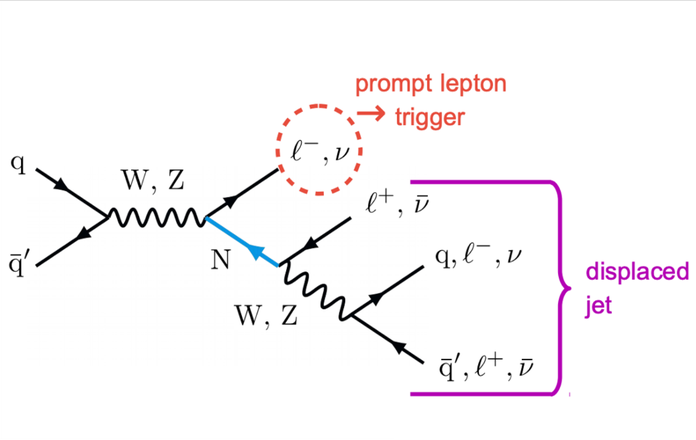
Probed up to expected masses more or less

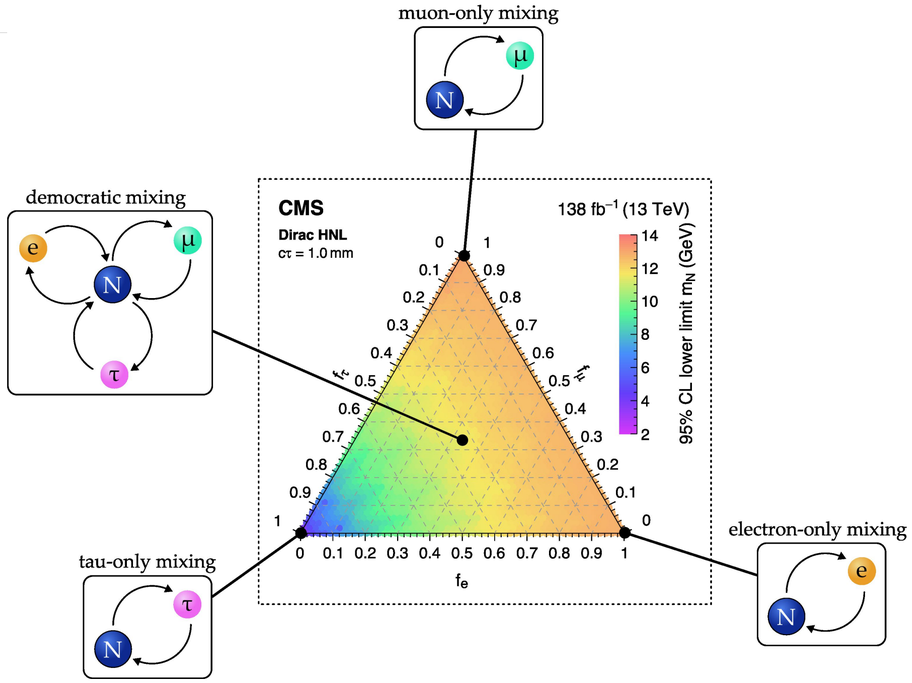
No hint of a discovery …

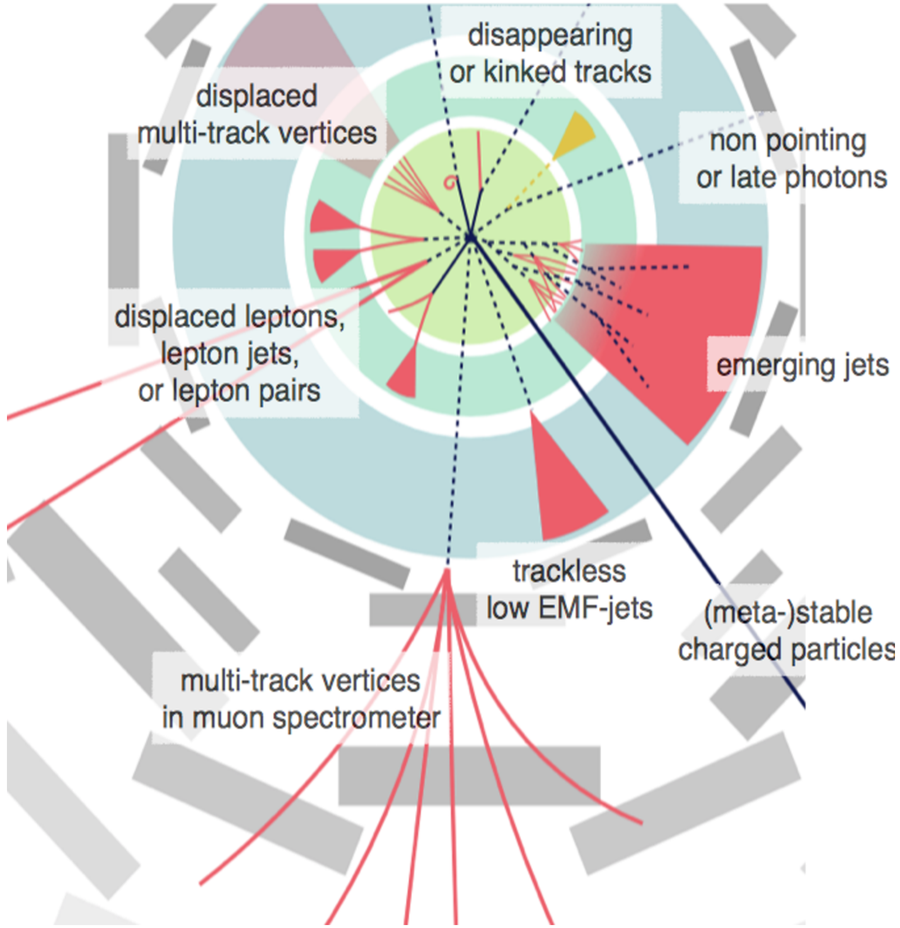
… but 1000+ citations



Looking elsewhere (with AI)







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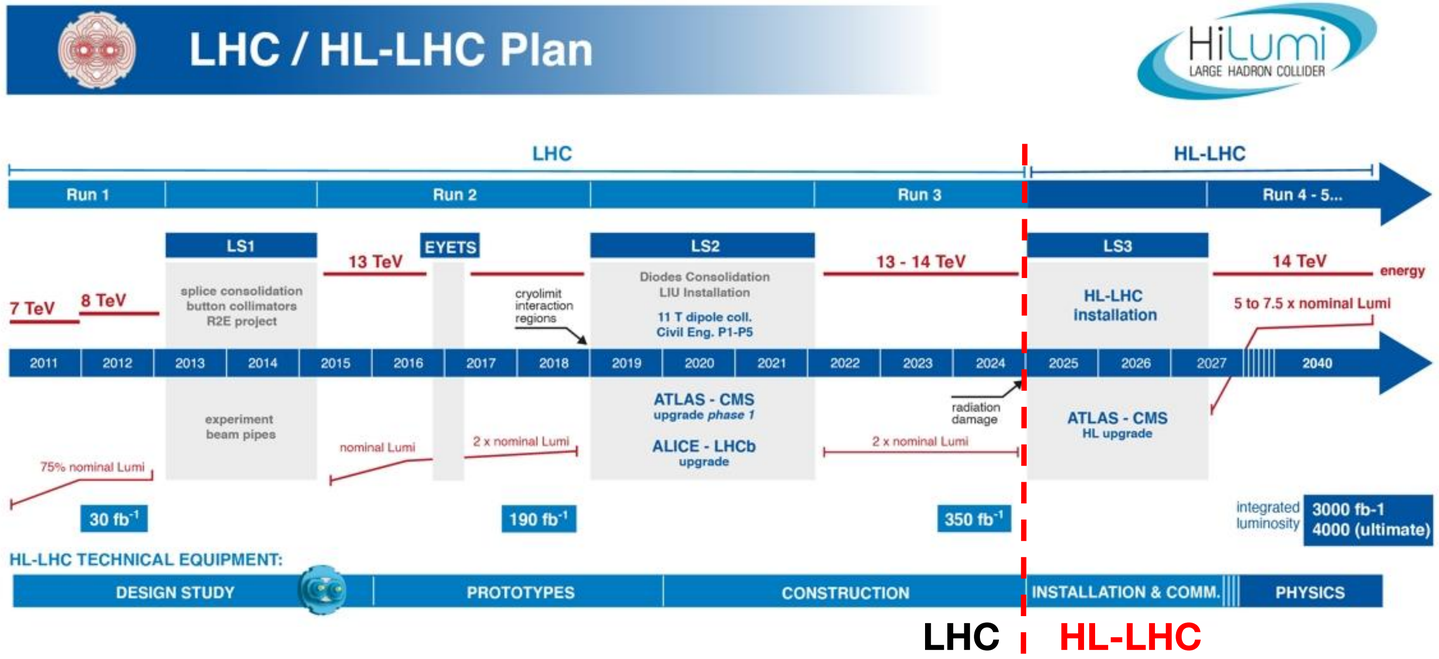
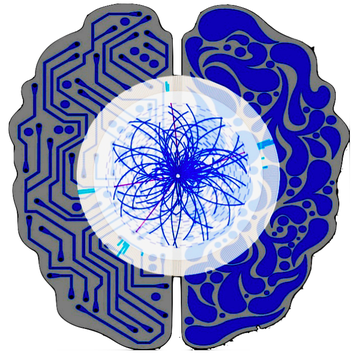
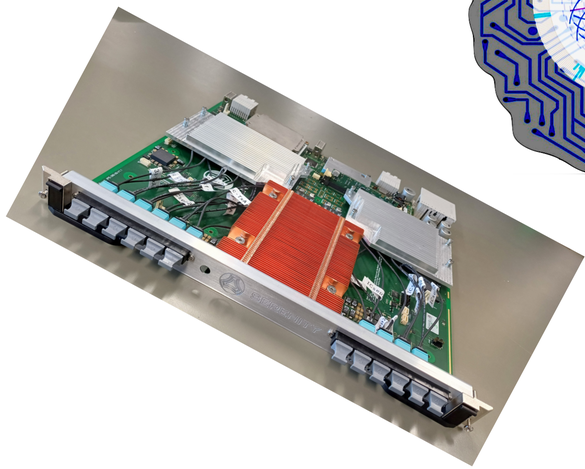
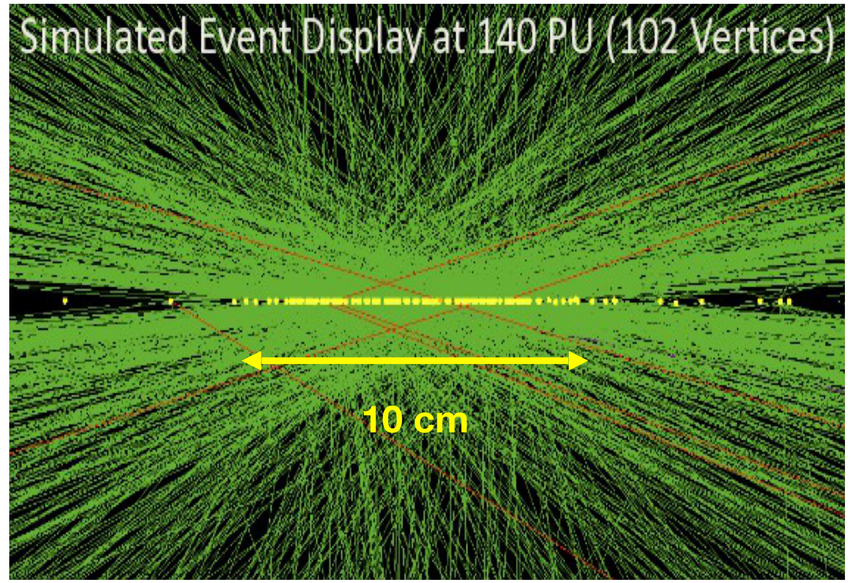
The future


LHC / HL-LHC Plan
HiLumi
LARGE HADRON COLLIDER
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13 TeV
13 - 14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
cryolimit
interaction
regions
Diodes Consolidation
LIU Installation
11 T dipole coll.
Civil Eng. P1-P5
HL-LHC
installation
5 to 7.5 x nominal Lumi
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2040
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
radiation
damage
ATLAS - CMS
HL upgrade
75% nominal Lumi
nominal Lumi
2 x nominal Lumi
2 x nominal Lumi
30 fb-1
190 fb-1
350 fb-1
integrated
luminosity
3000 fb-1
4000 (ultimate)
HL-LHC TECHNICAL EQUIPMENT:
DESIGN STUDY
PROTOTYPES
CONSTRUCTION
INSTALLATION & COMM.
PHYSICS
LHC
HL-LHC






Simulated Event Display at 140 PU (102 Vertices)
10 cm

Why was it worth it?

The science …

Physics

Supersymmetry doesn’t seem to be the solution to the hierarchy problem — though may well exist at higher than TeV scale

No evidence (yet) for dark matter particles

Challenges us to think of new ideas!

Technology

Trigger systems are challenging technology but vital to science programme

Expanding to do more realtime processing and (much) more AI on chip, even quantum computing

The students … thanks

A. Mastronikolis
T. Alves
P. Pradeep
T. Ourida
K. Law
L. Våge
C. Brown
V. Čepaitis
V. Milošević
A. Shtipliyski
S. Summers
A. Elwood
M. Baber
R. Lucas
B. Mathias
A. Sparrow
J. Marrouche

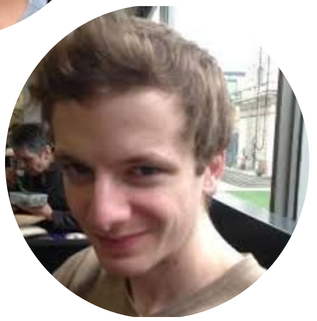













The moral of the story …

Thanks

Rob Bainbridge

Oliver Buchmüller

Costas Foudas

Andy Rose

Greg Iles

Ken Long

Geoff Hall

Paul Dauncey

Gavin Davies

And many more @Imperial and all over the world…

Thanks