

Particle Physics

Past, Present and Future

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FROM BIG BANG TO NOW :
A THEORY-EXPERIMENT DIALOGUE

SRM University AP, Amaravati

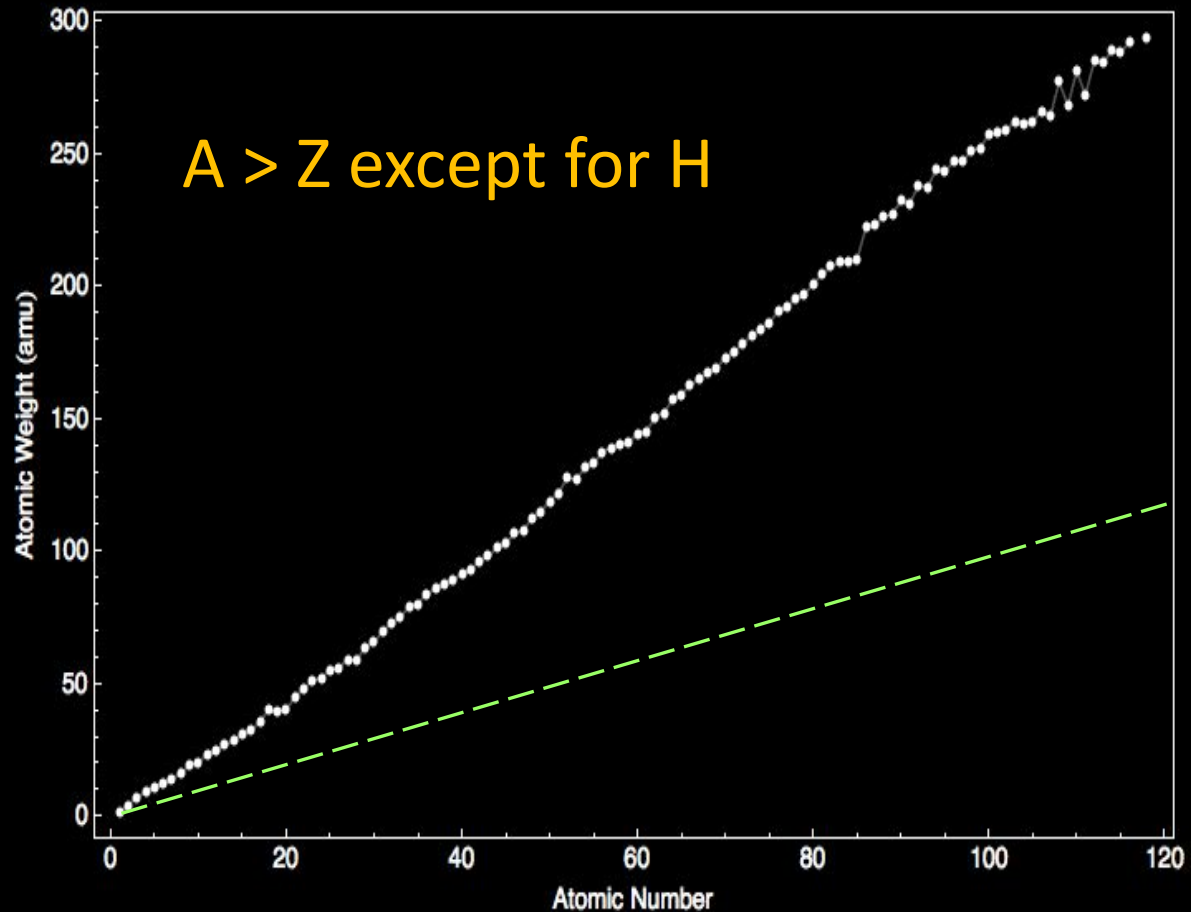
January 24, 2025

Dedicated to the memory of
Rohini M. Godbole
(1952 – 2024)





The electron and the proton were more-or-less accidental discoveries.
What we call Particle Physics today really started with the prediction and discovery of the neutron.



Marie Curie (1913):
Nucleus =
 A no of protons
 $+(A - Z)$ no of electrons



Rutherford (1920):
Nucleus =
 Z no of 'charged protons'
 $+(A - Z)$ no of 'neutral protons'

In β decay, electrons of MeV energy are emitted. Since atomic electrons have keV energies, these must come from the nucleus.



Dimitry Ivanenko (1930):

Applying Heisenberg's Uncertainty Principle (1925), electrons inside the nucleus will have energy of $1 \text{ fm}^{-1} \sim 1 \text{ GeV}$

Therefore: Nucleus = Z protons + $N = A - Z$ neutrons

β decay $\Rightarrow n \rightarrow p + e^-$ (MeV electron created by decay)

James Chadwick (1932):

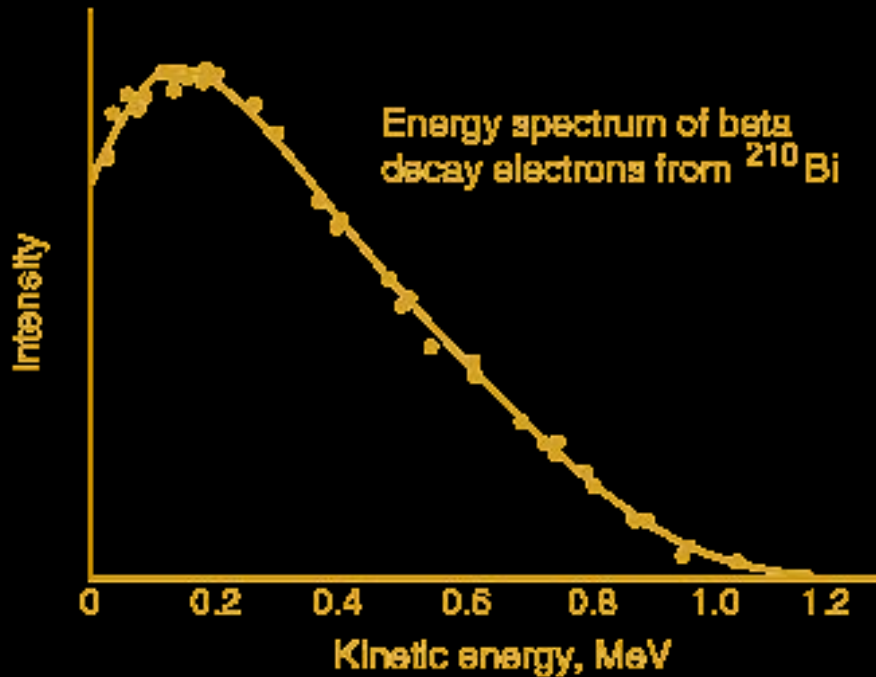
Built on (i) discovery by Bothe & Becker that $\alpha + \text{Be} \rightarrow \text{C} + X$, and (ii) discovery by Joliot Curies that $X + \text{paraffin}$ leads to emission of p . He showed that the X cannot be γ rays, but must be neutral particles of mass similar to proton $\Rightarrow$ neutron



Ivanenko's idea of $n \rightarrow p + e^-$ immediately led to the question why the emitted β particle does not have fixed energy

$$E_\beta = \frac{M_n^2 - M_p^2}{2M_n} \simeq 1.2 \text{ MeV}$$

but an energy spectrum...



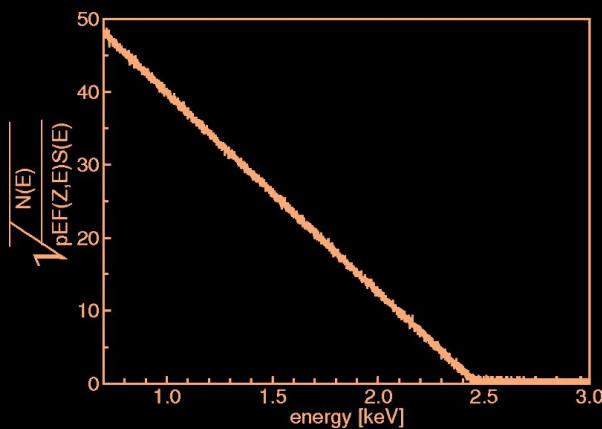
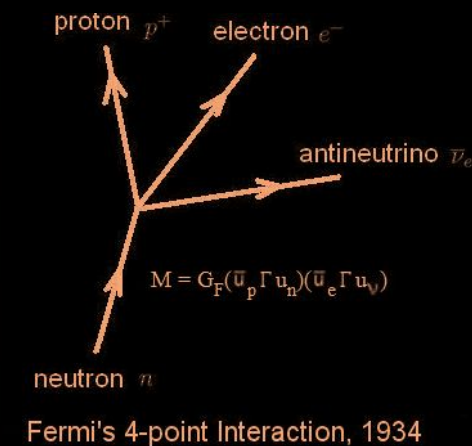
Niels Bohr (1930) thought energy conservation may be violated at the nuclear scale.



Wolfgang Pauli (1930) boldly suggested a new neutral particle carrying away the missing energy. Fermi named it the neutrino.



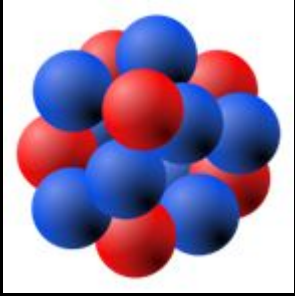
No one took the neutrino idea very seriously till Enrico Fermi (1934) integrated it into his theory of β decay... the first theory of weak interactions...



Fermi's theory of β decay was brilliantly vindicated by the careful measurements made by Franz Kurie (1936).



Eventually Frederick Reines and Clyde Cowan (1955) discovered the neutrino through the inverse β -decay process at a nuclear reactor.



The neutron discovery also created a new conundrum. If there are only positive and neutral particles in the nucleus, what prevents it from flying apart?

Werner Heisenberg (1932) guessed that there must be an attractive force between nucleons, and thus stumbled upon the strong interaction.



$$F_{pp} = \frac{e^2}{r_N^2} = \frac{e^2}{a_0^2} \frac{a_0^2}{r_N^2} = F_{At} \left(\frac{10^{-10} \text{m}}{10^{-15} \text{m}} \right)^2 = F_{At} \times 10^{10}$$

Mind-boggling strength



Heisenberg (1932) went further and noted that the mass of the proton and neutron are almost equal (differ by 0.14%), and guessed that this must be due to an underlying symmetry of the strong interaction. Drawing an analogy with spin-up and spin-down electrons, he called this isospin.

Mathematician Emmy Nöther (1918) had proved that every symmetry of a physical system corresponds to a conserved quantum number and vice versa. Combining Nöther's Theorem with Heisenberg's intuition led to a model of strong interactions where there was a symmetry under 'iso'-rotations.



Since then, particle physics has been dominated by the idea of symmetries and conserved quantum numbers.

How does the strong interaction actually work?

Hideki Yukawa (1935) imagined that it is by exchange of hitherto-unknown particles, now called pions, in the same way as electromagnetic forces are by exchange of photons. He even estimated the mass of the pion to be around $100 \text{ MeV}/c^2$.



Where to look for pions?

Carl D. Anderson (1932) had already shown the way by discovering the positron in cosmic rays.



Homi J. Bhabha and Walther Heitler (1936) soon developed the theory of cosmic ray showers. High energy extraterrestrial particles hit the nuclei in the upper atmosphere and produce showers of new particles, due to energy converted into mass.





Anderson and Seth B. Neddemeyer (1937) discovered that the 'penetrating' component of cosmic rays which reaches the ground consists mostly of particles of mass around $100 \text{ MeV}/c^2$.

Bhabha (1937) immediately pointed out that Yukawa's pions cannot penetrate 10 Km of air due to their strong interactions with nuclei in the air. So this must be a new particle – a kind of heavy electron... today it is known as the muon.



Isidore I. Rabi (1937) asked about the muon: Who ordered that?

We are still searching for the answer!

1939



1945



After WW-2 was over and his team in Cambridge
Its mass was about 260 MeV

π^+ (1947)

K^+ (1949)

π^0 (1951)

K^0 (1951)

Δ^+ (1952)

Λ^0 (1952)

Σ^+ (1953)

Ξ^+ (1953)

p (1955)

ν (1955)

n^0 (1956)

Σ^0 (1957)

Λ^0 (1958)

It was discovered by Cecil Powell
in 1947
— in the predicted ballpark

There followed a succession of new particles

discoveries in cosmic ray interactions

In this plethora of new particles there seemed to be some selection rules, permitting some decays and forbidding/suppressing others....

Ernst Stückelberg (1938) had the correct idea that these selection rules happen because the particles carry new quantum numbers which are conserved. He proposed that protons cannot decay into pions because they carry baryon number, which pions do not.



There was a class of 'strange' particles, like the $K^\pm$, K^0 , $\bar{K}^0$, Λ^0 etc. which seemed to be pair-produced in strong interactions, but decayed only through weak interactions.



Murray Gell-Mann and Abraham Pais (1956) applied Stückelberg's idea to these particles, guessing that they must carry a quantum number 'strangeness' which is conserved in strong interactions but not in weak interactions.



Gell-Mann (1957) and Yuval Ne'eman (1957) combined Heisenberg's isospin with this new quantum number to develop a theory of strong interactions based on a symmetry under the group SU(3).

This was brilliantly vindicated by the discovery of the Ω^- (1964).

Gell-Mann, and independently George Zweig (1964), realised that this symmetry simply reflects a substructure of the 'elementary' particles like mesons (pion, kaon, &c) and baryons (proton, neutron, &c). They suggested that these are made up of fundamental particles called 'quarks'. Gell-Mann named them up (u), down (d) and strange (s).



Robert Hofstadter (1962), had conducted a series of experiments in the 1960s, suggesting that the proton is not an elementary particle, but has substructure. Richard Feynman (1967) even named these particles partons.



It was the definitive experiments carried out by Jerome Friedman, Richard Taylor and Henry Kendall (1969) with the new SLAC 1 GeV collider that fully established the existence of 3 partons (=quarks!) inside the proton.





Even before quarks had been proposed, Nicola Cabibbo (1963) had realised that the quantum numbers conserved in strong interactions (flavours), 'mix' in weak interactions.

Sheldon Glashow, John Ilioupoulos and Luciano Maiani (GIM, 1969) brilliantly extended Cabibbo's idea to show that there must be a fourth quark, which they named 'charm' (c).



Burton Richter and Sam Ting (1974) independently discovered the J/ψ particle, which is a $c\bar{c}$ bound state.

Two quark doublets: $\begin{pmatrix} u \\ d \end{pmatrix}$ $\begin{pmatrix} c \\ s \end{pmatrix}$



Building on the work of Cabibbo, and of GIM, Makoto Kobayashi and Toshihide Maskawa (1973) had predicted that there should be a third generation of quarks.



Three quark doublets: $\begin{pmatrix} u \\ d \end{pmatrix}$ $\begin{pmatrix} c \\ s \end{pmatrix}$ $\begin{pmatrix} t \\ b \end{pmatrix}$



Leon Lederman (1977) led a team which discovered the b quark, again through the Υ particle, a $b\bar{b}$ bound state. Its mass is $4.3 \text{ GeV}/c^2$.

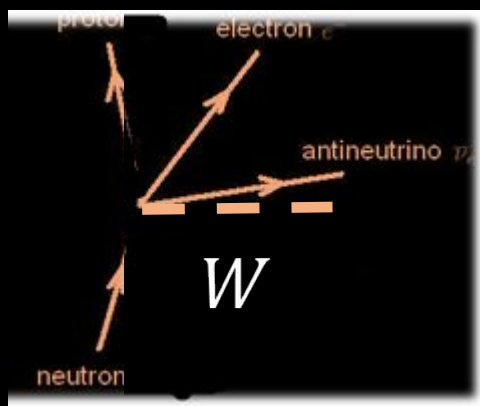
The CDF and D0 Collaborations at Fermilab (1994) eventually discovered the t quark too with a huge mass of $172 \text{ GeV}/c^2$. This decays so rapidly that it cannot form bound states.





The theory of weak interactions given by Enrico Fermi (1934) remained the gold standard for weak interactions till the 1950s.

But with the development of quantum field theory, it turned out to be inconsistent at higher energies, violating a requirement called unitarity. To save this, Julian Schwinger (1955) proposed the intermediate vector boson (IVB) theory, where unitarity is maintained.



1. To keep weak interactions short-range, the W bosons would have to be massive.
2. The IVB theory would also be non-unitary unless the currents on both sides are conserved
 $\Rightarrow$ (gauge?) symmetry.



With an amazing leap of imagination, Schwinger guessed that if both e.m. and weak interactions are gauge theories, then they may be different aspects of the same 'electroweak' theory. He gave the job of working out this unified theory to his student Sheldon Glashow, who found the right symmetries in 1961.



But with a major caveat!



As early as 1953, Wolfgang Pauli had proved that in a gauge theory, the IVBs must be massless... he mainly used this knowledge to harass Cheng Ning Yang, who had written down a non-Abelian gauge theory...

But even earlier, in 1938, Ernst Stückelberg had not only discovered this fact, but also found a solution. However, this required a massive new scalar, which no one then was willing to accept.





James
Anderson



Robert
Brout



Francois
Englert



Gerald
Guralnik



Carl
Hagen



Peter
Higgs



Giovanni
Jona-Lasinio



Tom
Kibble



Yoichiro
Nambu

The solution was found by the contributions of a bunch of people during 1960-64. The gauge symmetry governs the interactions and keeps the gauge bosons massless at high energies. But the ground state (vacuum) breaks the symmetry and hence at low energies the weak bosons appear massive. This is called spontaneous symmetry-breaking.

Peter Higgs (1964) went on to predict that a sign of this phenomenon would be the existence of a weakly-interacting neutral scalar, today called the Higgs boson.



Abdus Salam & John Ward (1966-67), and independently, Steven Weinberg (1967) then married the $SU(2) \times U(1)$ gauge theory of Glashow (1961) with the idea of Higgs *et al* to create the unified electroweak model, or the Glashow-Salam-Weinberg model.



Crucial predictions of this model: a neutral IVB (Z^0), a neutral scalar (H^0)



The great CERN bubble chamber Gargamelle discovered cosmic ray events consistent with 'neutral currents' i.e. events with exchange of Z bosons (1973).

Carlo Rubbia clinched matters by leading the teams which discovered the W and the Z bosons at CERN in (1982-83).



Gell-Mann, Harald Fritzsch and Heinrich Leutwyler (1972) wrote down a gauge theory of strong interactions at the quark level involving the group $SU(3)$. It was called quantum chromodynamics (QCD).

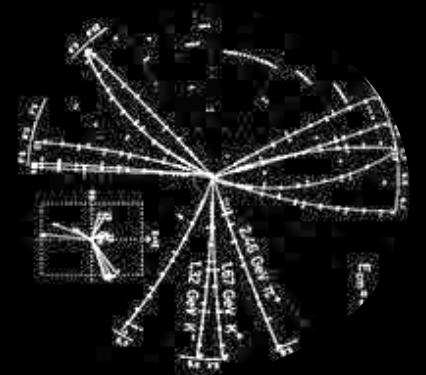


The inter-quark strong force is mediated by IVBs called gluons.



David Politzer, and independently, David Gross and Frank Wilczek (1976) discovered that strong interactions grow weaker at higher energies, permitting the use of perturbation theory. This property is called asymptotic freedom.

The existence of gluons was proved by the discovery of the so-called three-jet events at the DESY facility, Hamburg (1979).



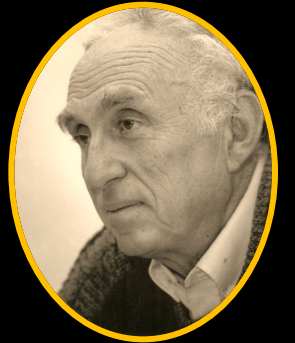
The electron (1896), the muon (1937) and the electron neutrino (1955) had already been discovered.



Lederman, Melvin Schwartz and Jack Steinberger (1962) discovered the muon neutrino.

Two lepton doublets: $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$ $\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$

Martin Perl (1975) discovered the tau lepton.

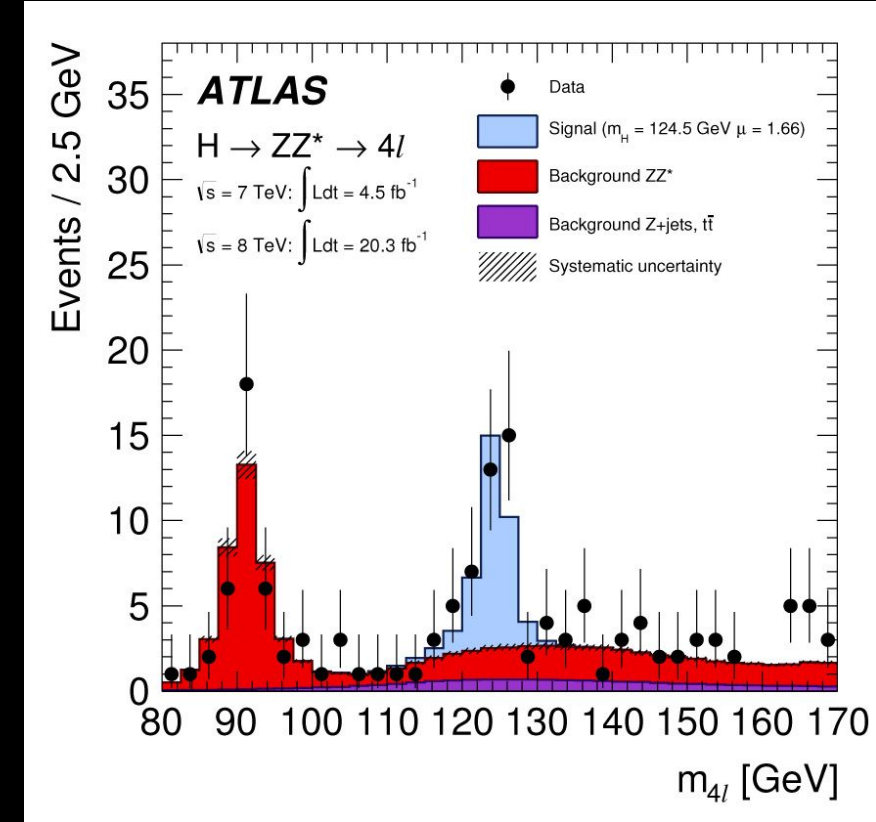


A tau neutrino was discovered at the Sudbury Neutrino Observatory (SNO) in Canada (2001).



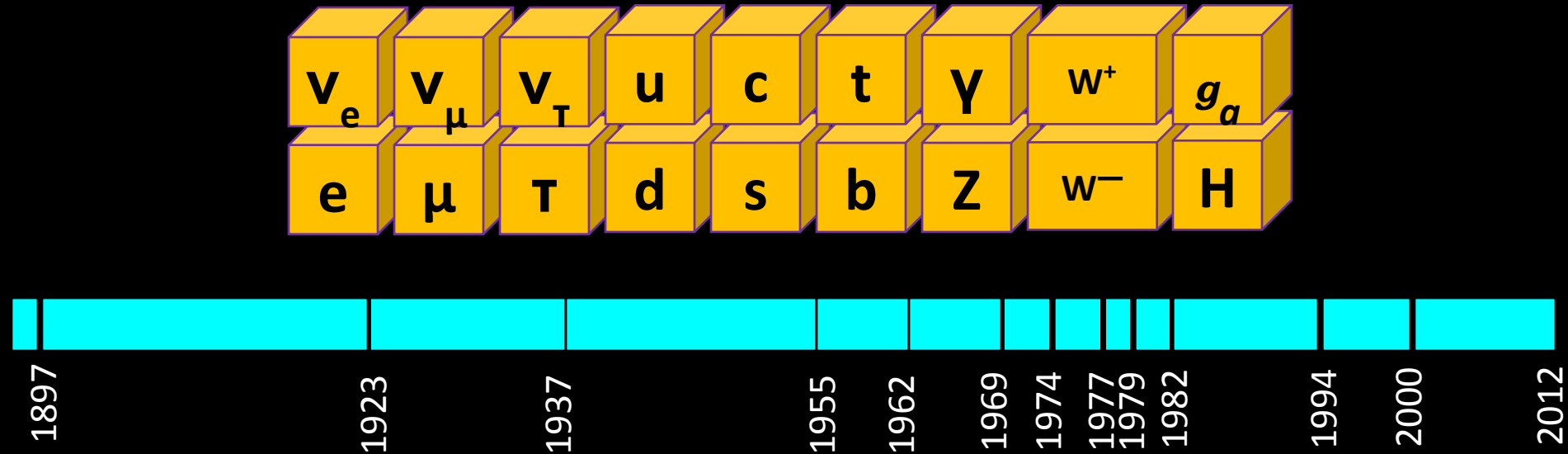
Three lepton doublets: $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$ $\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$ $\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$

Last, but not least, was the Higgs boson discovery at the CERN LHC in 2012.



The mass of the Higgs boson is $125 \text{ GeV}/c^2$. It has all the expected properties.

The Standard Model of particle physics is now complete...



... not just in particle content, but also all the forces between them are measured/inferred...

The success story of the Standard Model...

1. Gauge theories of strong, weak and electromagnetic forces.
2. Unification of weak and electromagnetic forces into electroweak theory.
3. Explanation of short-range nature of weak forces through Higgs mechanism.
4. Incorporation of parity violation.
5. Incorporation of CP violation.
6. Anomaly cancellation.
7. Renormalisability.
8. Matching all terrestrial experimental data within errors.
9. Matching precision tests of electroweak theory.
10. Matching prediction of asymptotic freedom in QCD experiments.

But...

Gauge

nism

Pari

tion



Drawbacks of the Standard Model...

1. Four unrelated ingredients...
2. 19 undetermined parameters (fitted from experiments)
3. Why (maximal) parity violation?
4. Why three generations? (Who ordered that?)
5. No understanding of hierarchy of quark masses (3 to $172,300 \text{ MeV}/c^2$)
6. No understanding of hierarchy of lepton masses (1 to $4,300,000,000 \text{ eV}/c^2$)
7. No understanding of quark (lepton?) mixings
8. 'Accidental' symmetries – baryon number, lepton number, custodial $SU(2)$
9. Instability of Higgs mass against quantum corrections (hierarchy problem)
10. Metastability of the electroweak vacuum

Drawbacks of the Standard Model... in the cosmos...

1. No candidate for particulate dark matter
2. No candidate for particulate (?) dark energy
3. Insufficient CP violation to generate matter-antimatter asymmetry

Only possible conclusion...

The Standard Model is incomplete!

New Physics

Beyond Standard Model Physics





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The experimental status of direct searches for exotic physics beyond the standard model at the Large Hadron Collider

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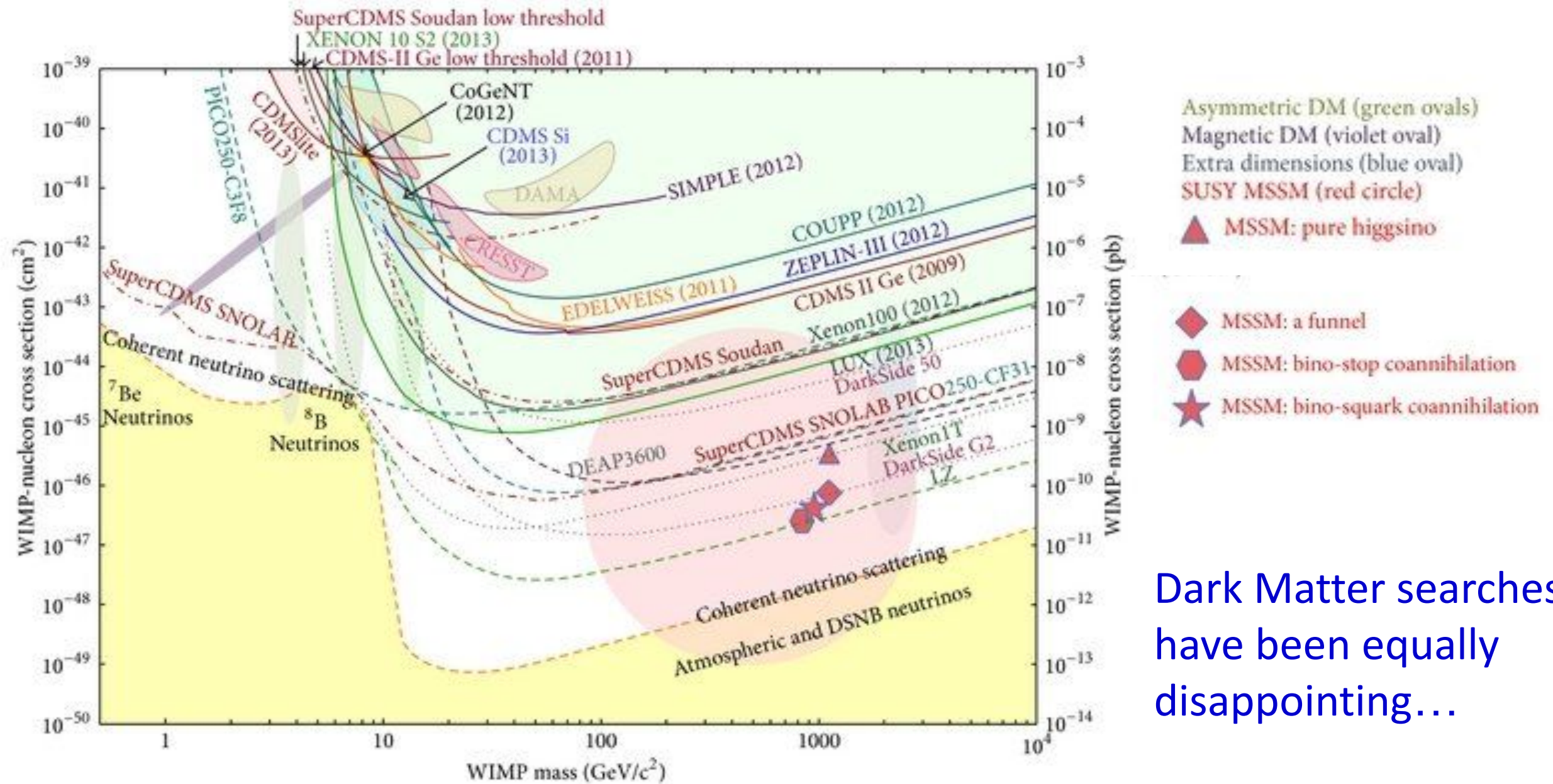
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ABSTRACT

The standard model of particle physics is an extremely successful theory of fundamental interactions, but it has many known limitations. It is therefore widely believed to be an effective field theory that describes interactions near the TeV scale. A plethora of strategies exist to extend the standard model, many of which contain predictions of new particles or dynamics that could manifest in proton-proton collisions at the Large Hadron Collider (LHC). As of now, none have been observed, and much of the available phase space for natural solutions to outstanding problems is excluded. If new physics exists, it is therefore either heavy (i.e. above the reach of current searches) or hidden (i.e. currently indistinguishable from standard model backgrounds). We summarize the existing searches, and discuss future directions at the LHC.



Dark Matter searches
have been equally
disappointing...

The Five Possible Explanations

Why have we – so far – failed to find any evidence for physics beyond the Standard Model?

1. The Philosopher's Stone explanation :

Alchemists spent centuries upon centuries seeking to make the Philosopher's Stone or Touchstone, which, by a touch would convert base metals into gold. They failed because there is no such thing, and there never was.



There is no evidence for BSM physics.

If this is just a seeming coincidence,

THEN I WOULD HAVE FELT SORRY FOR THE
DEAR LORD. THE THEORY IS INCORRECT

~~ALBERT EINSTEIN~~

chances

Or is there really an anthropic principle?

The Five Possible Explanations

Why have we – so far – failed to find any evidence for physics beyond the Standard Model?

2. The Galileo's lantern explanation :

Galileo tried to find out how fast light travels by standing on one hill and stationing an assistant with a lantern on another hill some miles away. Galileo would uncover his own lantern, and as soon as the assistant saw its glimmer, he would uncover his... This method failed because light travels much too fast... (10 km in 33 μ s)



There is BSM physics, but it exists at a much higher energy scale than we can achieve, or are planning to achieve.

Can we devise a wholly new kind of experiment just as Fizeau and Foucault did for the speed of light ? Do we have a probe of much higher energy scales?

The Five Possible Explanations

Why have we – so far – failed to find any evidence for physics beyond the Standard Model?

3. The Malaria explanation :

For many centuries, people thought that malaria was due to foul smells... The very name 'malaria' comes from 'mal' (bad) and 'air'. People would go around smelling perfumes and covering their noses. Not till Ronald Ross in 1897 was the mosquito found to be the culprit.



There is new BSM physics, but it is not of the kind we have been looking for and we have simply ignored the signals which are very much there.

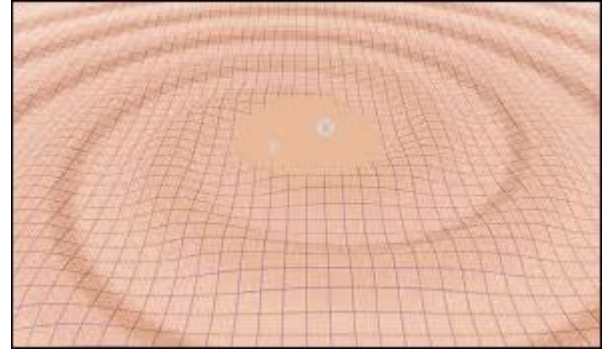
Can we search in an unbiased way which will catch BSM signals whatever they are?

The Five Possible Explanations

Why have we – so far – failed to find any evidence for physics beyond the Standard Model?

4. The Gravitational Waves explanation :

For almost a century people kept looking for gravitational waves from some sources. These all failed because gravity is so weak. Success only came in 2015 with vastly improved technology detecting a truly catastrophic cosmic event.



There is new BSM physics, and its signals have been there all along, but these are very feeble and are getting lost in the stronger SM backgrounds.

Can we enhance the S/B ratio in any way?

The Five Possible Explanations

Why have we – so far – failed to find any evidence for physics beyond the Standard Model?

5. The Uranus explanation :

The planet Uranus was discovered in 1781 by William Herschel saw its disc through his big telescope. It was then discovered that Uranus had been plotted as a star on star charts six times before – but no one had checked those charts to see if anything had moved or not.



There is BSM physics in the existing data, but in our haste to look for familiar things, we have overlooked it, or misinterpreted it.

It is worth taking a hard look again at the existing data, with some kind of unbiased analysis method.

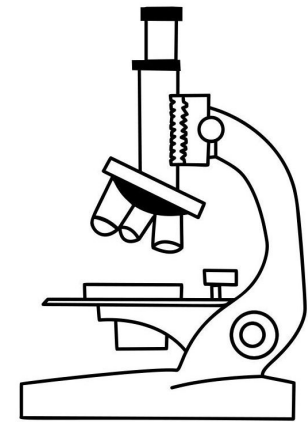
What is to be done?

1. The Philosopher's Stone explanation :

There is no BSM particle physics. Dark matter/energy are just variations of Newton's law of gravitation on large scales (MOND).

We must still answer why the Standard Model has the most unnatural structure it has.

We must then make precision measurements of the Standard Model parameters, seeking patterns which may give us insights into the reasons why this structure exists.



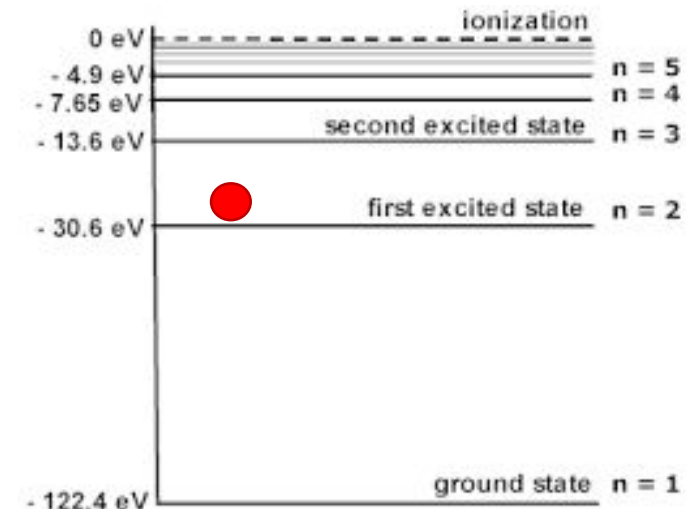
What is to be done?

2. The Galileo's Lantern explanation :

There is BSM physics at very high energy scales, far above the range of present-day machines. In this BSM physics lies the answer to all the tricky questions about the Standard Model.

In a classical theory, this argument can neither be proved or refuted. It is like claims of the existence of El Dorado – the land of gold.

Fortunately, quantum theory gives us an insight into virtual states which are inaccessible to current experiments. So study quantum corrections, i.e. rare processes, precision effects, etc.



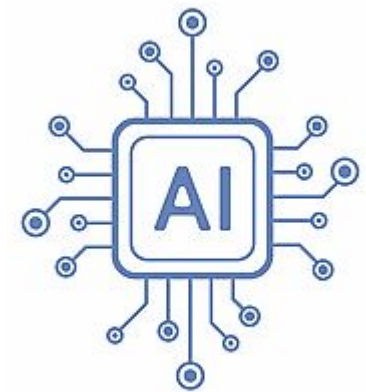
What is to be done?

3. The Malaria explanation :

There is plenty of BSM physics in the current data, but we have missed it because we have only been looking for a particular kind(s) of new physics.

Strictly speaking, there is nothing to be done except to rack our brains to find a new kind of new physics. But for that we need to be unbiased...

This is where AIML can come in and we can scan the existing data looking for very small/unusual deviations from the Standard Model predictions. Of course, we need to be imaginative in how we train the machine...



This is a major programme in particle physics today.

What is to be done?

4. The Gravitational Waves explanation :

There is a little bit of BSM physics in the current data, but we have not looked at the right processes, with the right precision.

The only way out of this is to scan all the possibilities with great precision and complete lack of bias, hoping to stumble upon the right signal.

For this, we require the framework of Standard Model Effective Theories (SMEFT), where all possible low-energy operators are written down and their coefficients fitted from data.

This is also being done but is very computation-intensive.

$$\mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{SM}}$$

$$- \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}$$

$$+ \sum_j \frac{c_j^{(8)}}{\Lambda^4} \mathcal{O}_j^{(8)} + \dots$$

What is to be done?

5. The Uranus explanation :

The BSM data is there in plain sight, but we have mistaken it for Standard Model signals.

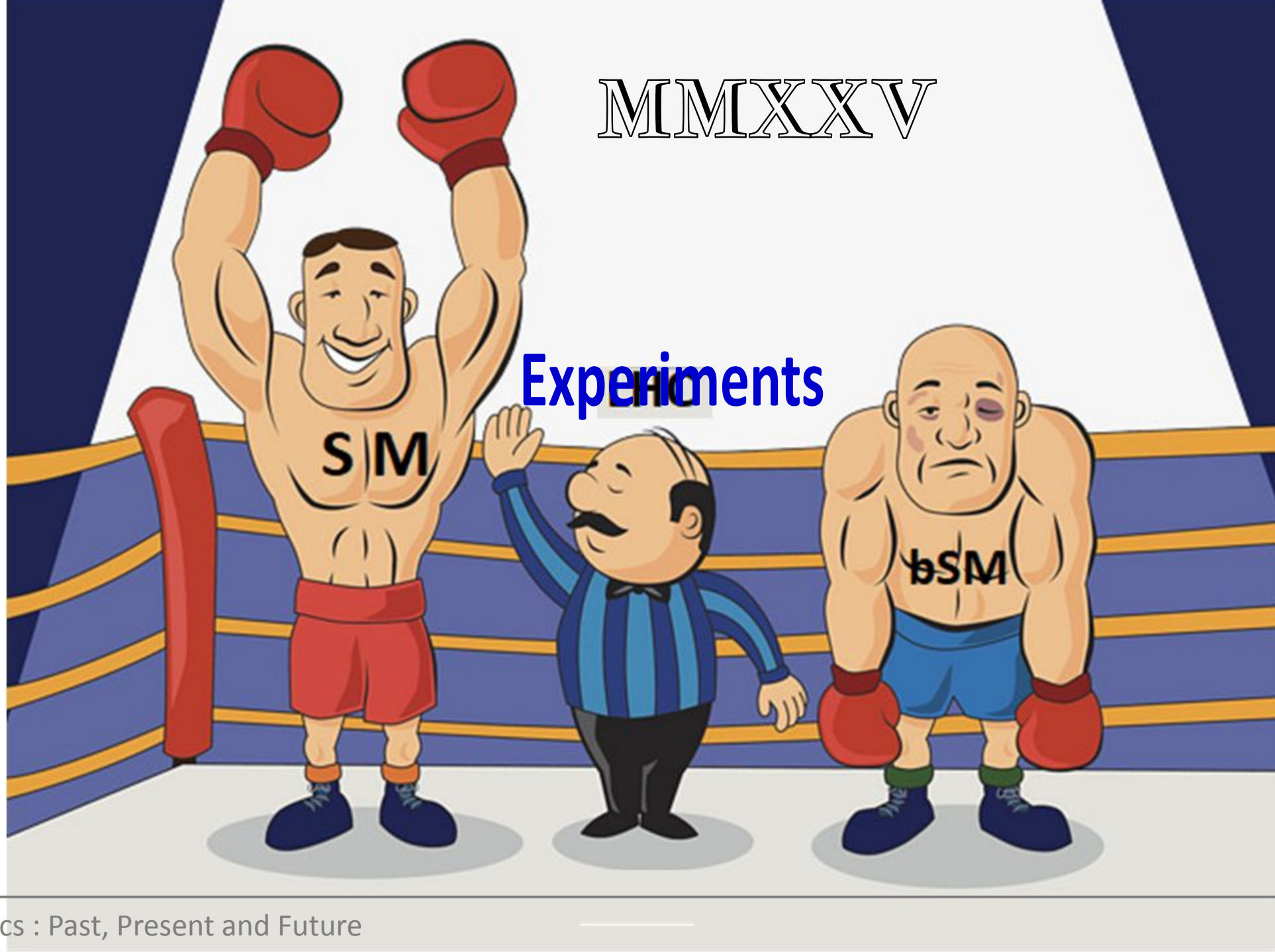
We need to revisit the existing data and see if we missed something. However, there is no guide to what to look for. Herschel succeeded because he had a more powerful instrument.

We can build more powerful machines with more energy and more flux (luminosity), so that hazy results become pinpointed. This is a brute force method, but it has been the most successful in the past.



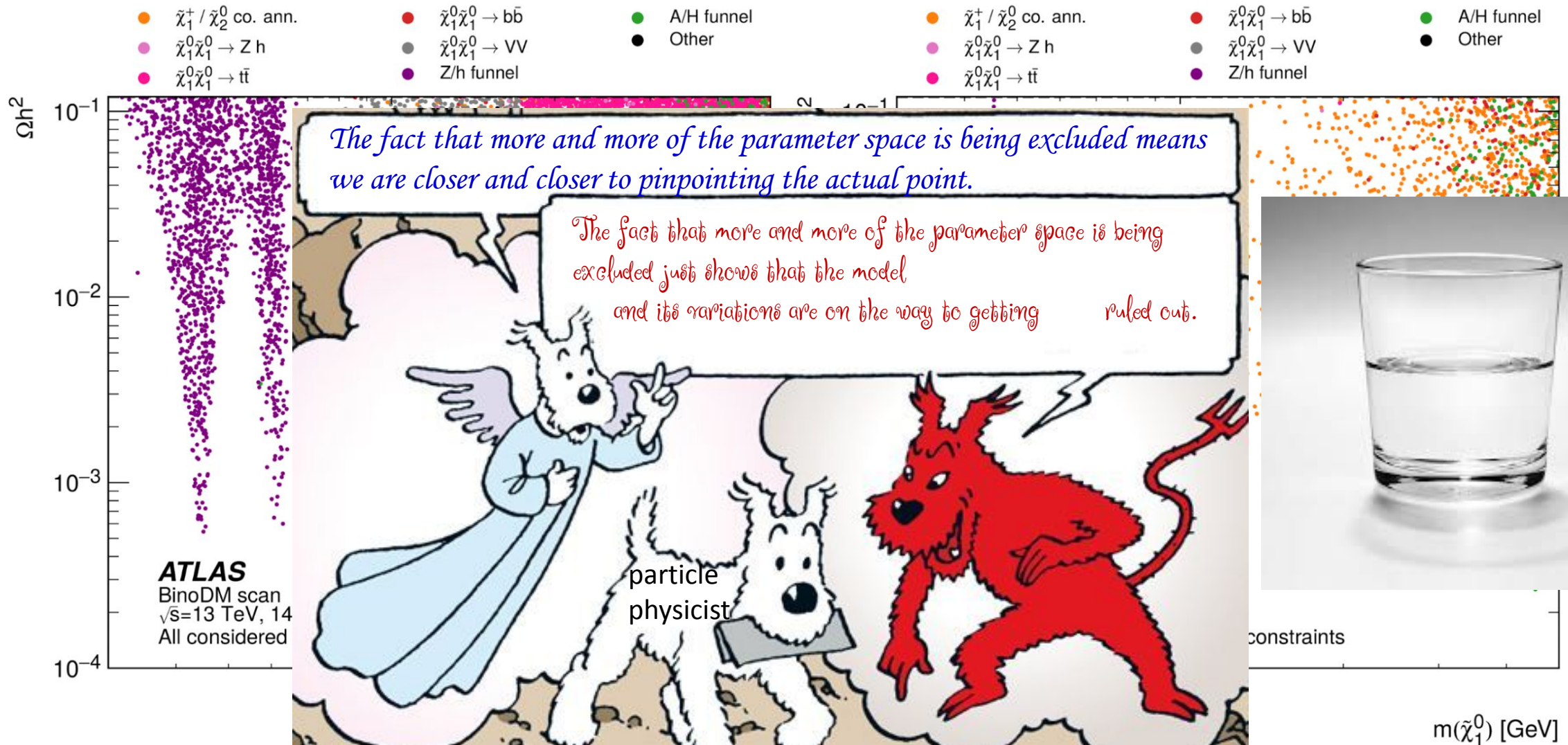
MMXXV

Experiments





It is so clear that the existing BSM ideas are dead?



The lesson of history is that sooner-or-later someone comes up with a brainwave which solves what had seemed mysterious/baffling in the past.

But there is no time scale for such a brainwave....



Till then, what we must do is to keep on acquiring and analysing as much data as possible. Hence, build colliders which have more energy, more luminosity and more precision.



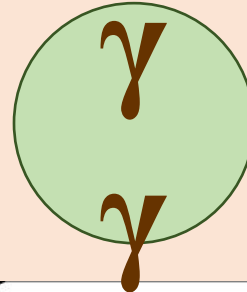
“I have no data yet. It is a capital mistake to theorise before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts.” – Sherlock Holmes

What Kind of New Colliders are Being Contemplated?

LEPTON
COLLIDERS



$e^- e^+ p \bar{p}$
 $\mu^- \mu^+$



PLASMA
WAKEFIELD
COLLIDERS

HADRON
COLLIDERS



LEPTON COLLIDERS



HADRON COLLIDERS

- Leptons in circular storage rings have enormous energy loss from synchrotron radiation; must use linacs
- Ramping up energy requires very long machine
- Each bunch crosses just once : high luminosity is a challenge
- Large e/m allows focussing into very intense bunches

- Protons/antiprotons are easy to hold in circular storage rings because of the low energy loss from radiation ($\propto \frac{1}{m^4}$)
- Ramping up energy through multiple RF cavities is possible
- Bunches cross hundreds of times leading to high luminosity
- Focussing protons is difficult because of the low e/m ratio

LEPTON COLLIDERS



HADRON COLLIDERS

- Only electroweak cross-sections are available
- Charge conservation restricts final states
- Fixed CoM
- Relatively clean environment

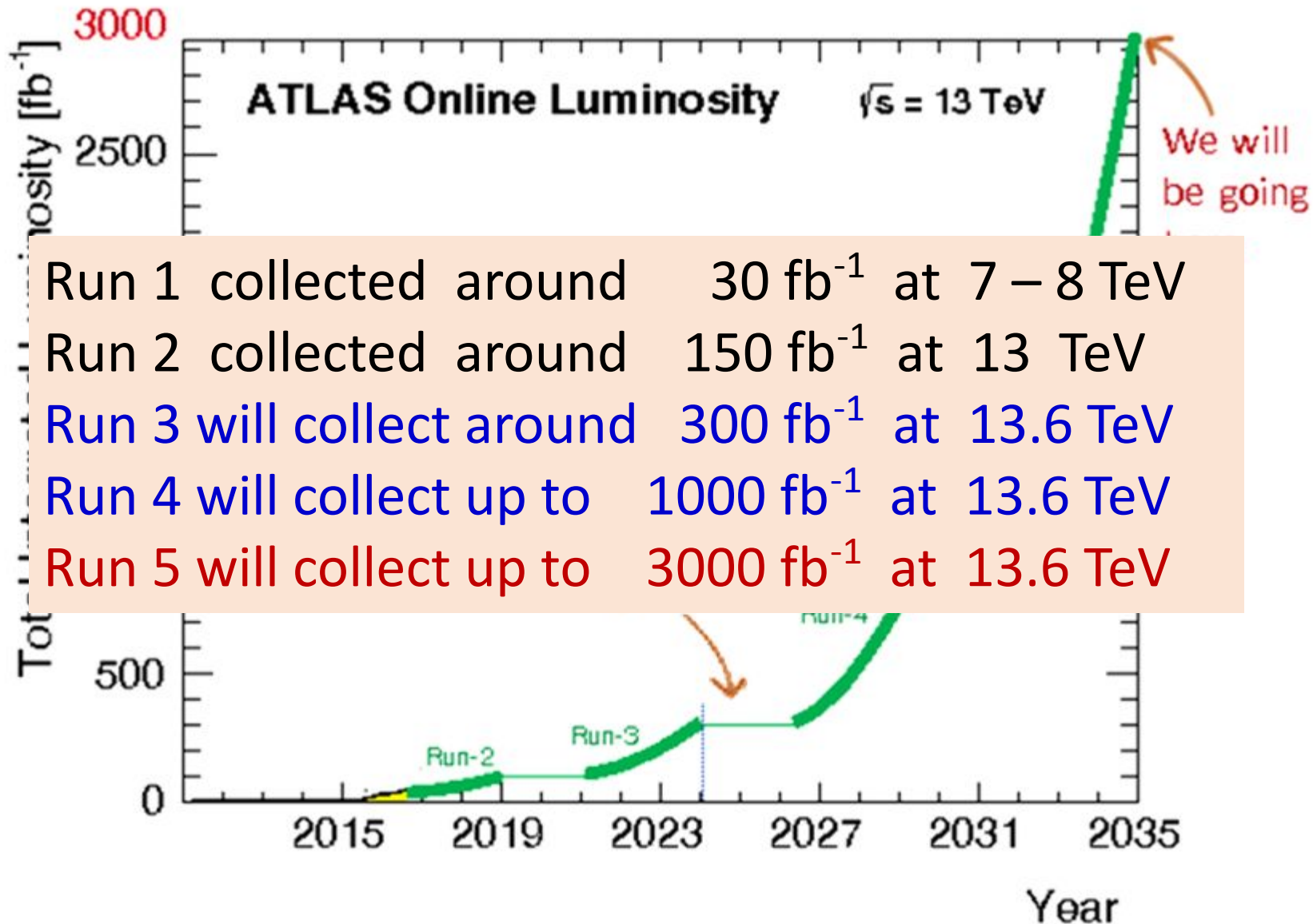


- Can produce particles through strong interactions – huge cross-section
- Wide variety of processes occur, both C and NC
- Indeterminate energy
- Lots of junk

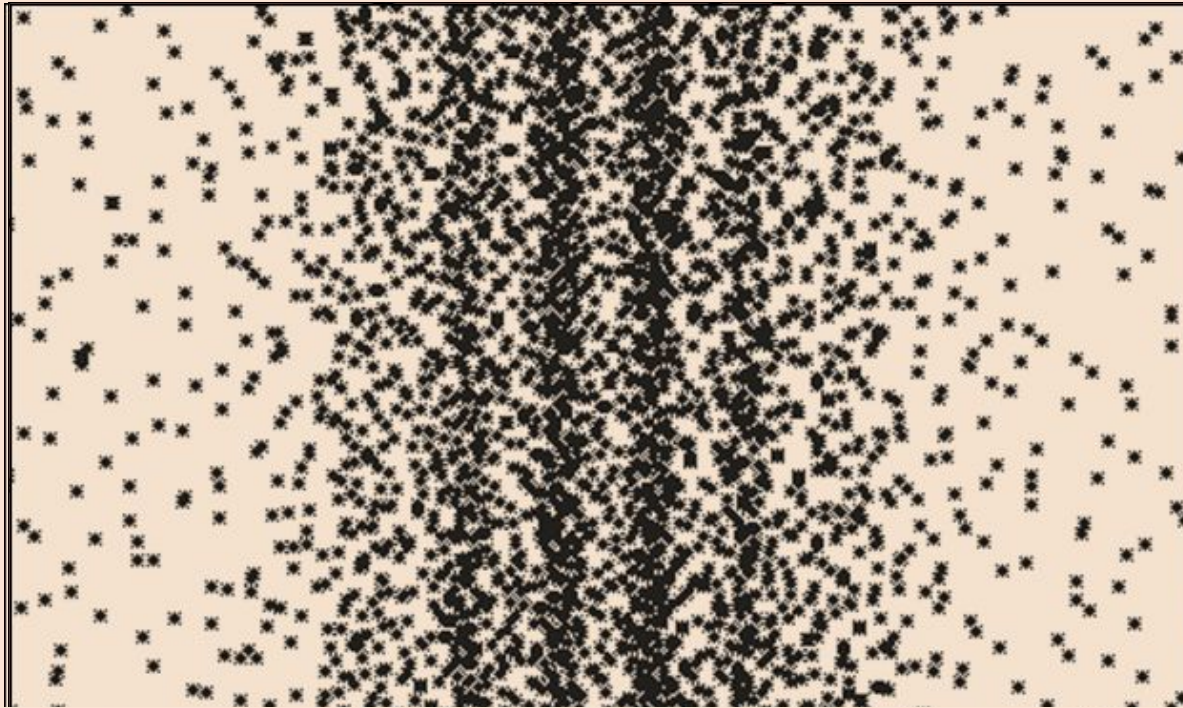


Both types need to be built...

The High Luminosity-LHC



5000



There is still plenty of scope for unknown physics
or unknown phenomena to appear at the
HL-LHC...



The High Energy-LHC or very LHC or FCC-hh



Analysis is made under the assumption:

1. Signal and background cross sections remain the same
2. Reconstruction efficiencies, etc. remain the same
3. Cross sections remain the same

Major caveats:

1. We do not know if there are new particles at some intermediate energy
2. All SM particles will appear as jets
3. We do not know how the energy scales (cosmic rays)





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NEWS • 15 JANUARY 2019

Next-generation LHC: CERN lays out plans for €21-billion super-collider

The proposed facility would become the most powerful collider ever built.

Davide Castelvecchi

CERN has unveiled its bold dream to build a new accelerator nearly four times as long as its 27-kilometer Large Hadron Collider — currently the world's largest — and up to six times more powerful.

The European particle physics laboratory, outside Geneva, Switzerland, outlined the plan in a technical report on 15 January.

The document offers several preliminary designs for a Future Circular Collider (FCC) — which would be the most powerful particle-smasher ever built — with different types of colliders ranging in cost from around €9 billion (US\$10.2 billion) to €21 billion. It is the lab's opening bid in a priority-setting process over the next two years, called the European Strategy Update for Particle Physics, and it will affect the field's future well into the second half of the century.

LHC and her hopes for international particle physics

CERN's next big thing

SUBJECTS

Funding

Particle physics

Physics

Expected to cost around
US \$ 17 billion

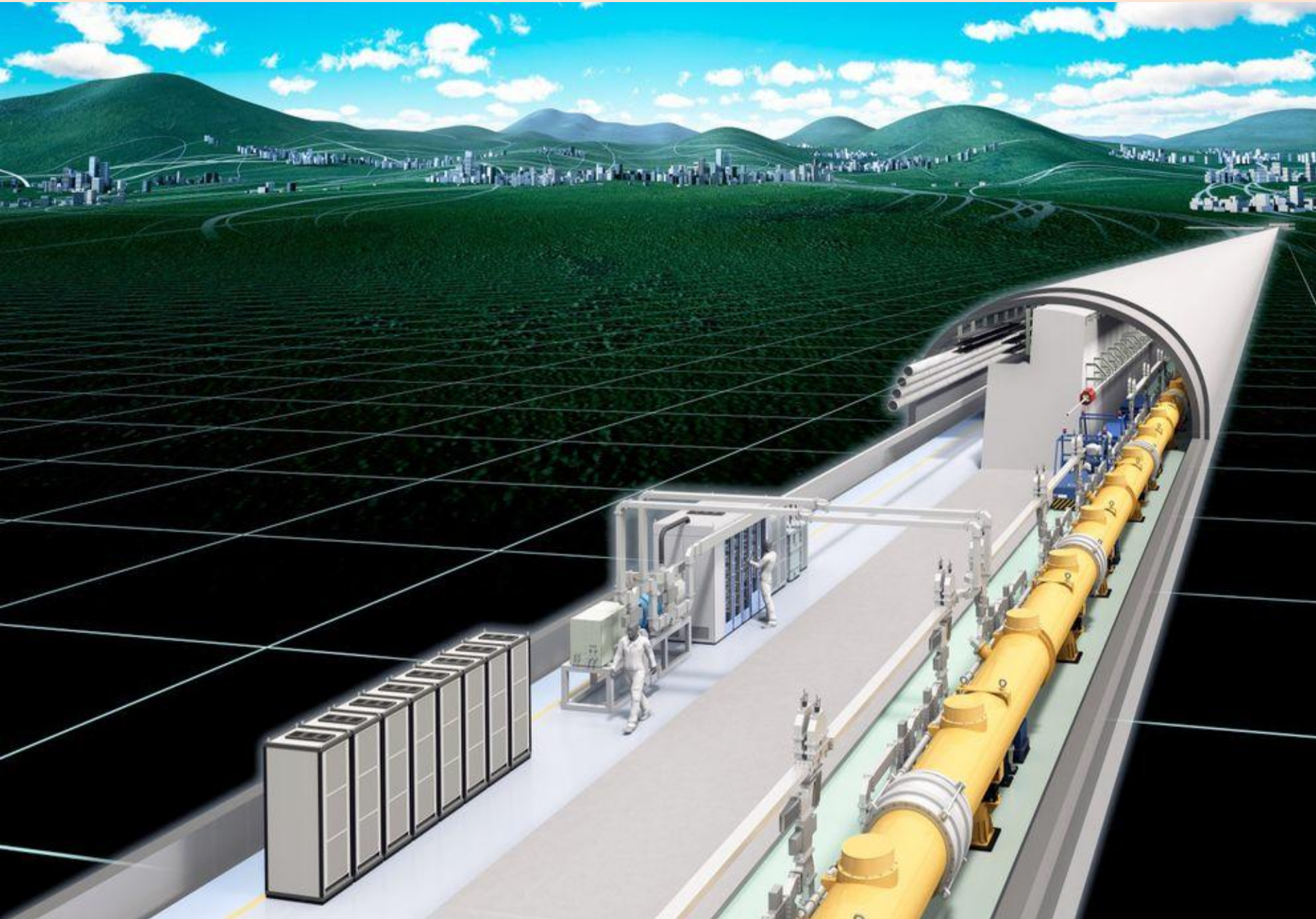
The USA's new aircraft
carriers each cost
US \$ 13 billion
There will be 10 such
vessels.

Losses in Gaza war
US \$ 19 billion
till now...

Losses in Ukraine
US \$ 488 billion
till now...

The International Linear Collider (ILC)

- The idea of a linear collider was to follow up on discoveries made at the LHC.
- This would be in the same way as the W, Z were discovered by hadron machines and then their properties were measured at LEP-1 and LEP-2.
- With the Higgs as the only discovery made at the LHC, the entire LC programme is now in jeopardy.
- Proposal to go ahead and build it anyway, irrespective of LHC results or to measure Higgs properties.
- Physics case must be strong enough.



Expected to cost
around

US \$ 7 billion

Japan willing to
contribute

US \$ 3.5 billion

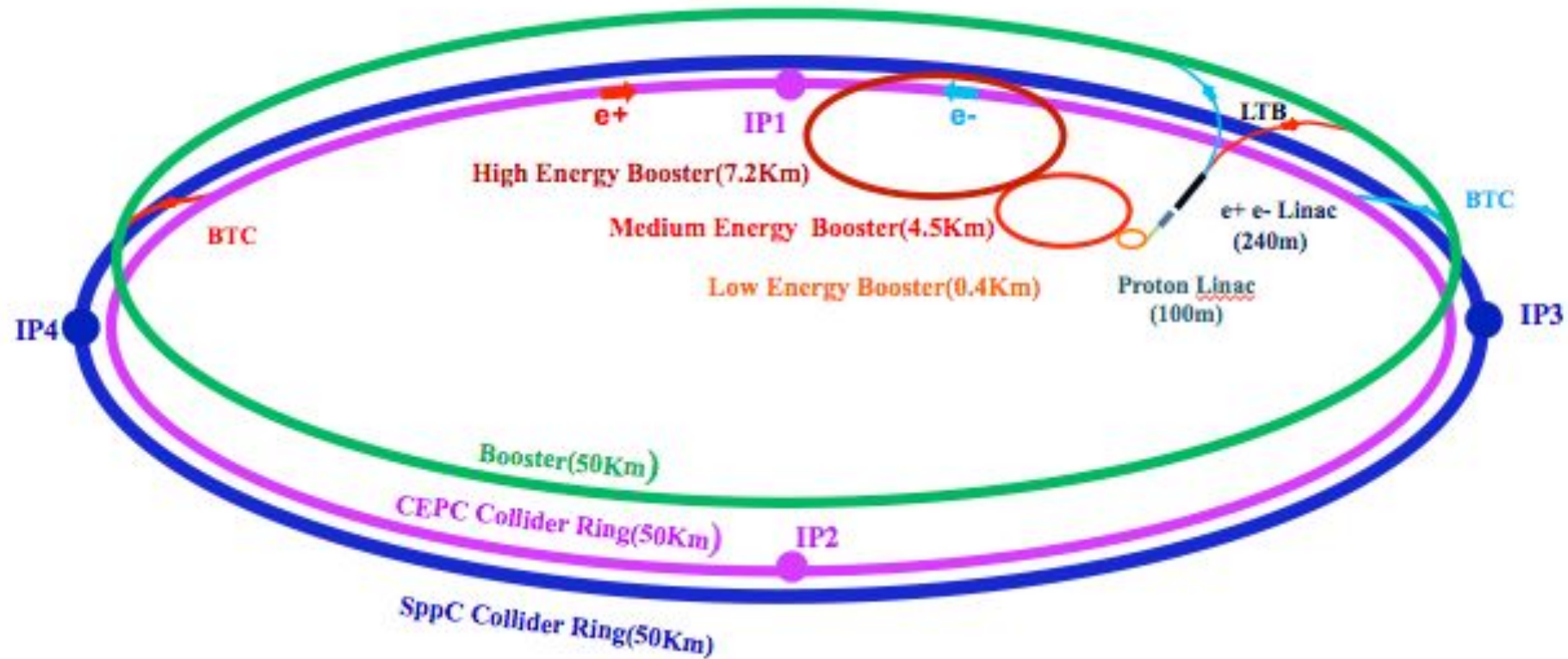
Remaining

US \$ 3.5 billion
to be contributed
by other nations

No volunteers yet!



CEPC-SppC Layout



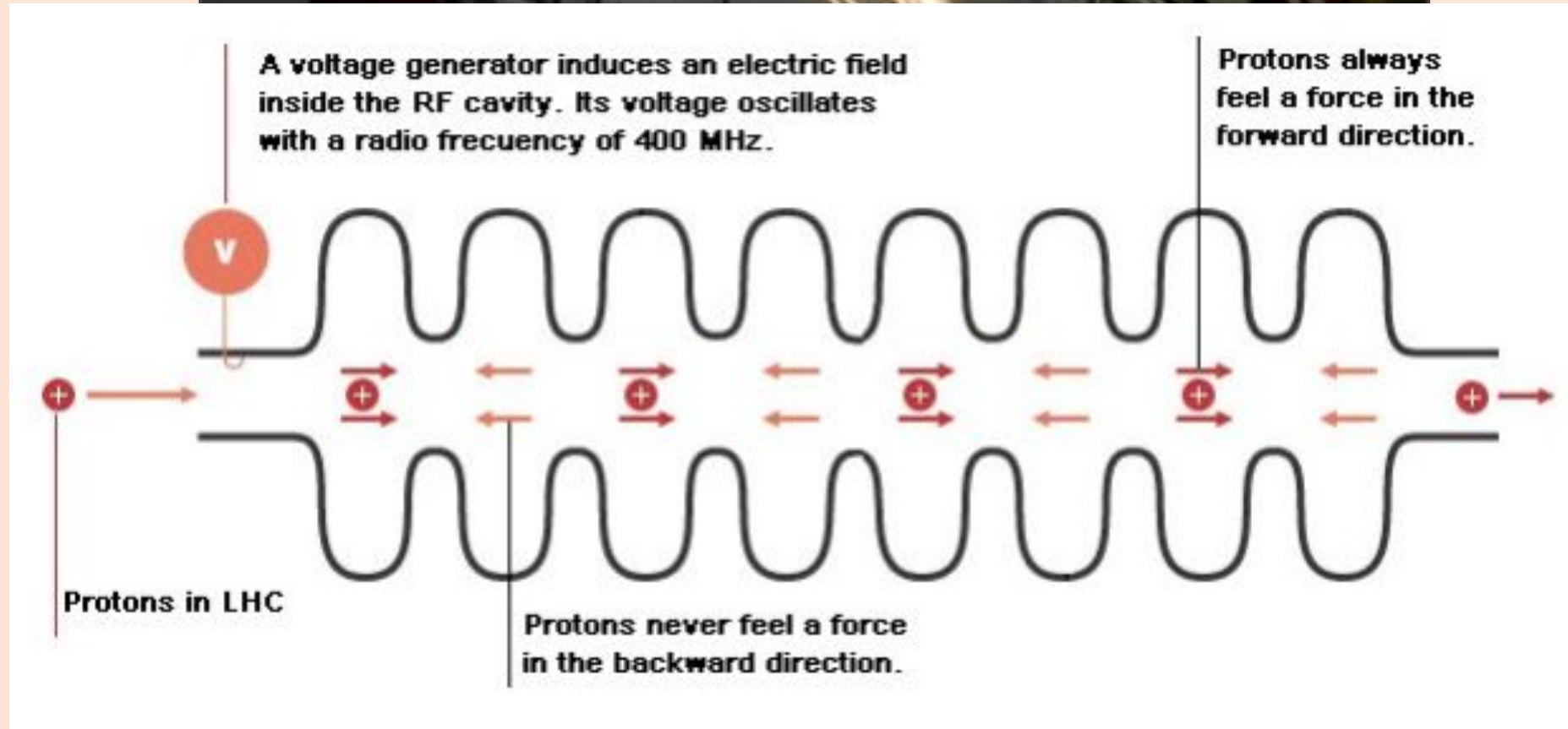
In the first phase CEPC will run at 350 GeV – 1 TeV

In the next phase SppC will run at 60 – 100 TeV

Muon Colliders (μC)

- Muon coupling to Higgs boson is around 0.00043
- Can still make a Higgs factory by tuning to Higgs mass resonance
- Smaller circular $\mu^+ \mu^-$ collider easy to make because muon mass is about 207 times electron mass
- Synchrotron radiation is negligible
- Time dilation keeps the muons quasi-stable so that many bunch-crossings can be achieved
- Beam cooling is difficult because muons decay
- We may be on the verge of finding a solution

Laser Wakefield Acceleration

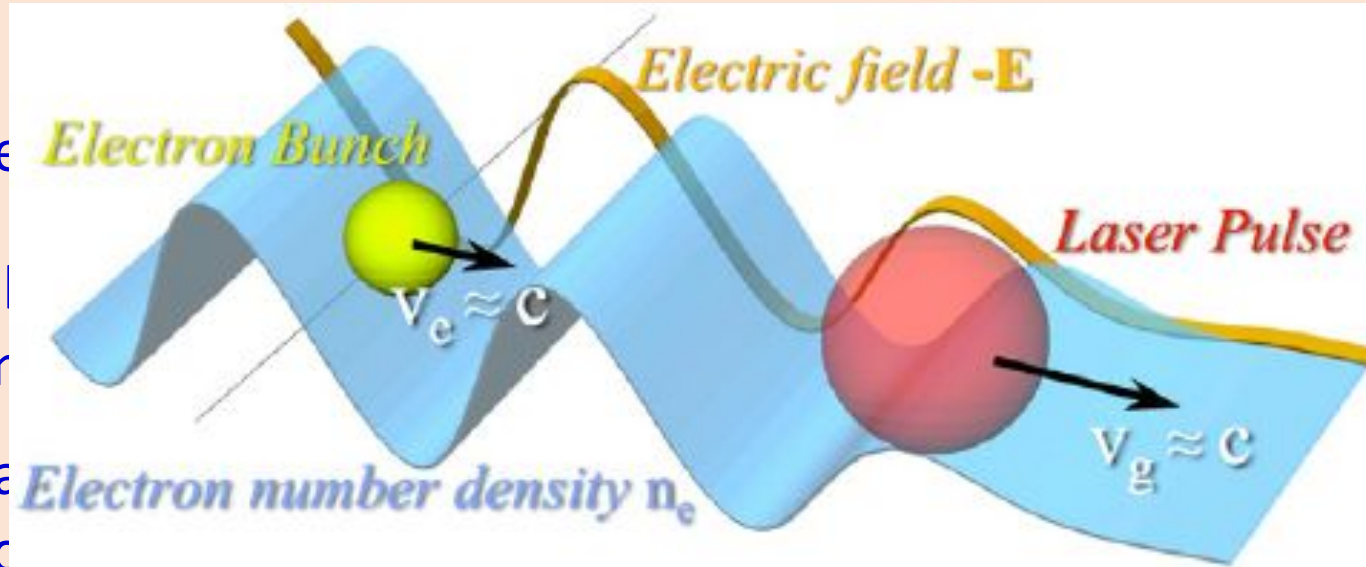


Every time a charged particle passes through one of these cavities, it gets an acceleration due to a correctly-aligned electric field (hence RF). But max field is about **100 MV/m**, before breakdown.

Laser Wakefield Acceleration

T. Tajima and J. Dawson, PRL **43**, 267 (1979)

- A plasma can support electric fields as high as about **100 GV/m – 1 TV/m**. If a cavity contains a plasma, energy imparted can be few 100 GeV per cavity, instead of 100 MeV per cavity.
- Potential to create
- A plasma in equilibrium through the plasma
- These wake oscillations are the 100 GV/m strength fields occur
- Instead of a projectile, use a short but powerful laser pulse
- Electrons are trapped in the plasma and shot out by the wakefield.



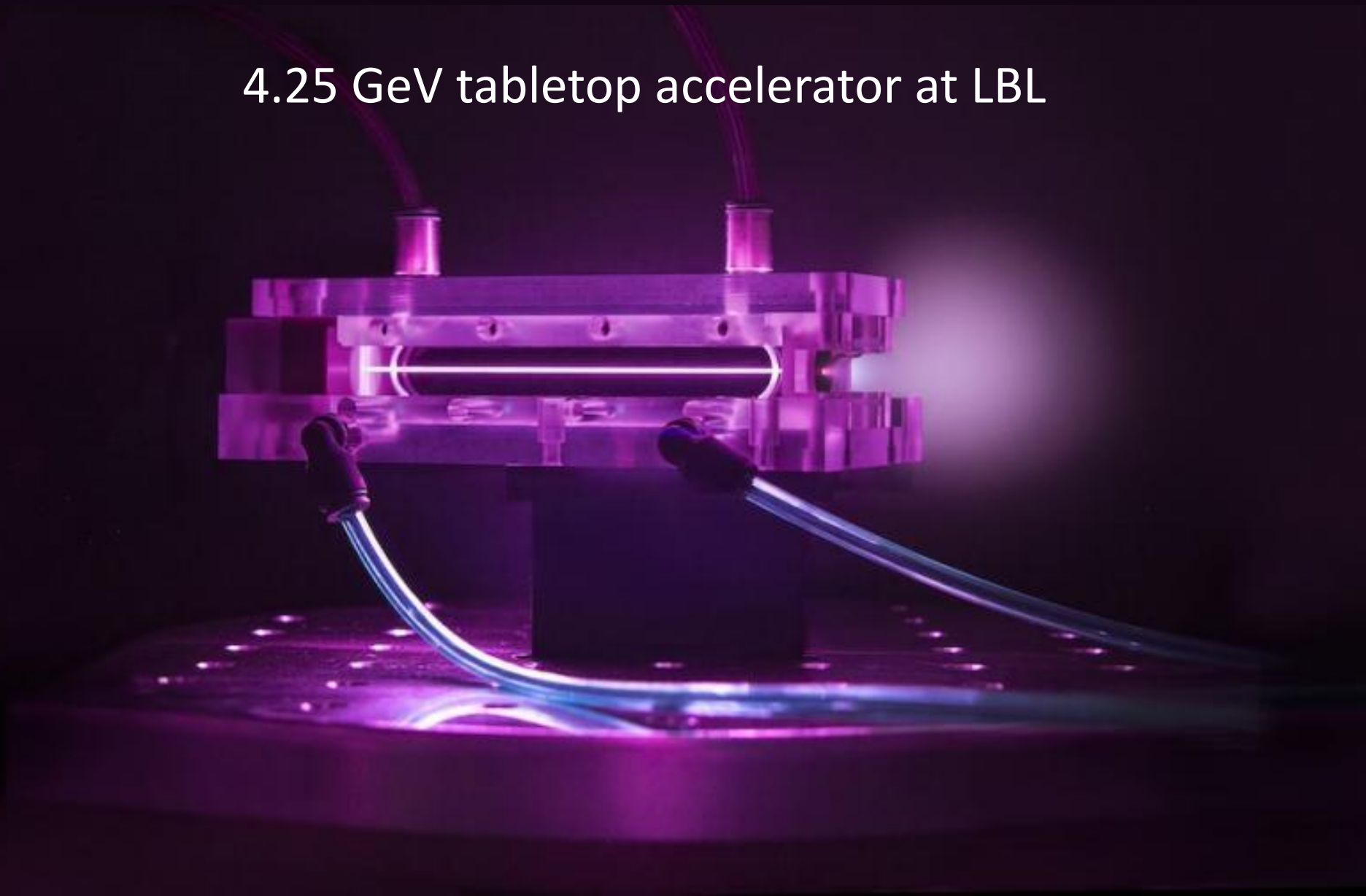
projectile passes
ile.

re the 100 GV/m

Timing

Laser Wakefield Acceleration

4.25 GeV tabletop accelerator at LBL



**THE IMPORTANT THING IS
TO NOT STOP QUESTIONING.
CURIOSITY HAS ITS OWN
REASON FOR EXISTING.**

Albert Einstein

Thank

You