Small Particles, Big Science:

The LHC and the search for the Theory of Everything

Andrew W. Rose

Imperial College London

Overview

- The search for the “Theory of Everything”
- All about symmetry
- The Standard Model of Particle Physics
- The LHC and the experiments
- The Future

Socrates, Antisthenes,
Chrysippus, Epicurus

The search for the "Theory of Everything"

A thoroughly modern pursuit

"According to convention there is a sweet and a bitter, a hot and a cold, and according to convention there is colour. In truth there are atoms and a void."

//

"That atoms and the vacuum were the beginning of the universe; and that everything else exists only in opinion."

Democritus (c.460-370BC)

"You say there *is* a void; therefore the void is not nothing; therefore there is not the void."

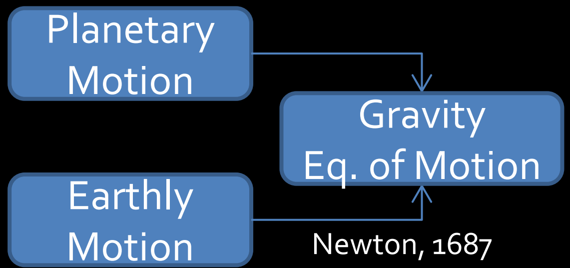
Parmenides (c.515-460BC)

//

"Moreover, it is plain that everything continuous is divisible into divisibles that are infinitely divisible: for if it were divisible into indivisibles, we should have an indivisible in contact with an indivisible, since the extremities of things that are continuous with one another are one and are in contact"

Aristotle, Physics VI, 350BC

Where are we now?



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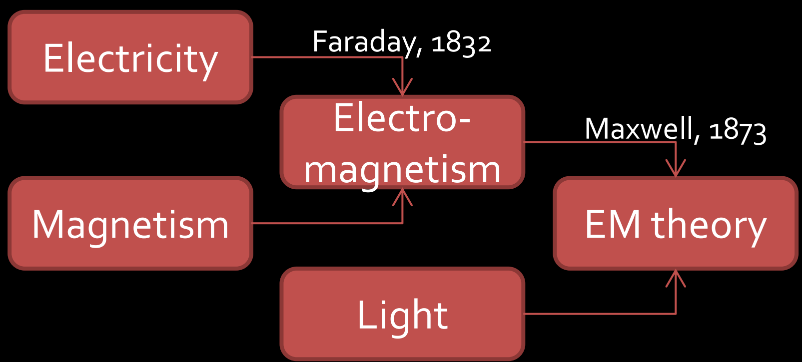

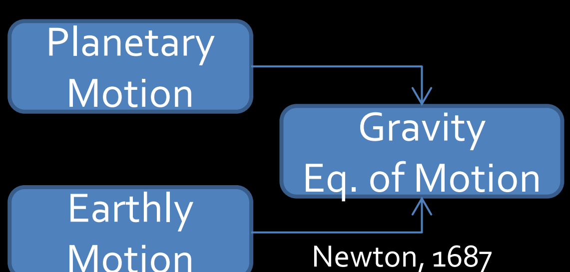

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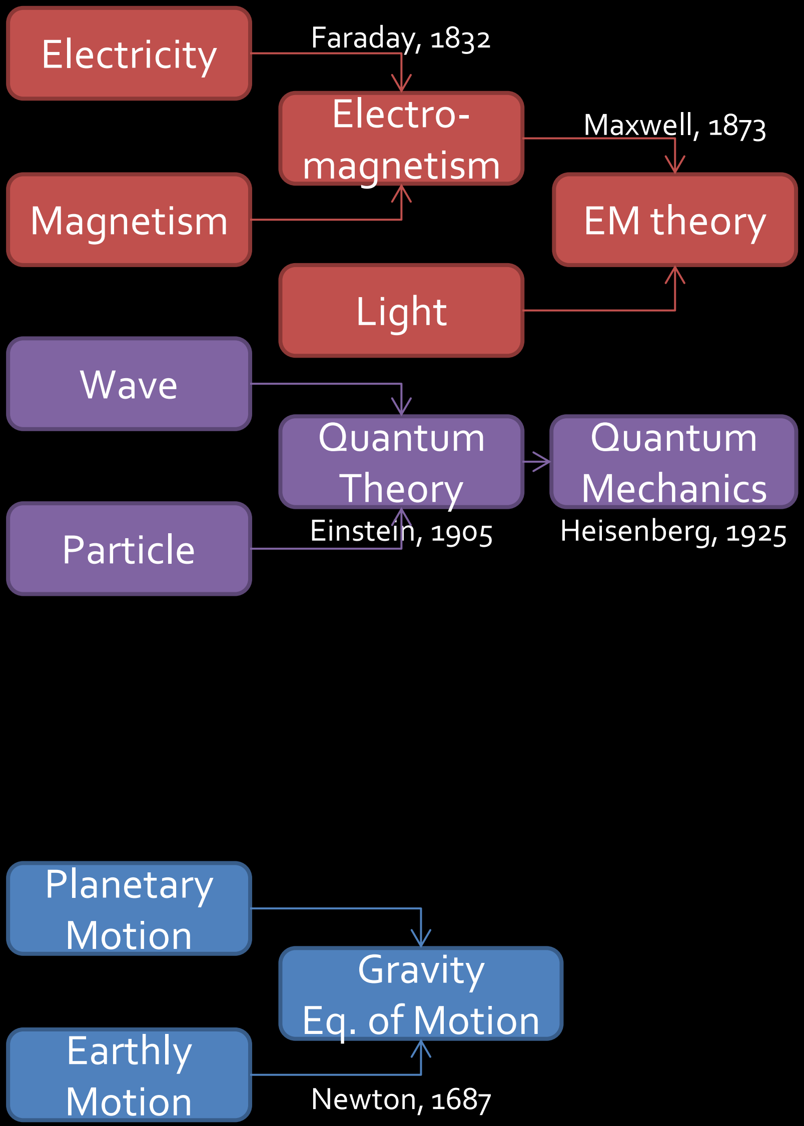

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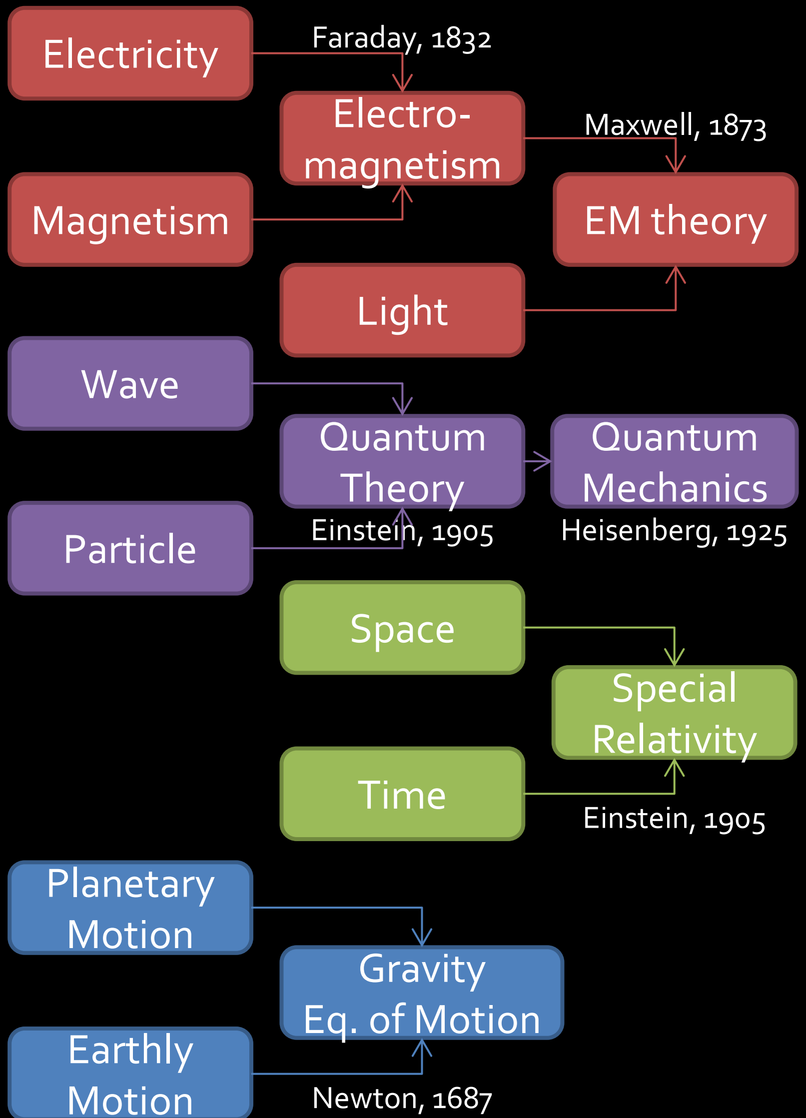

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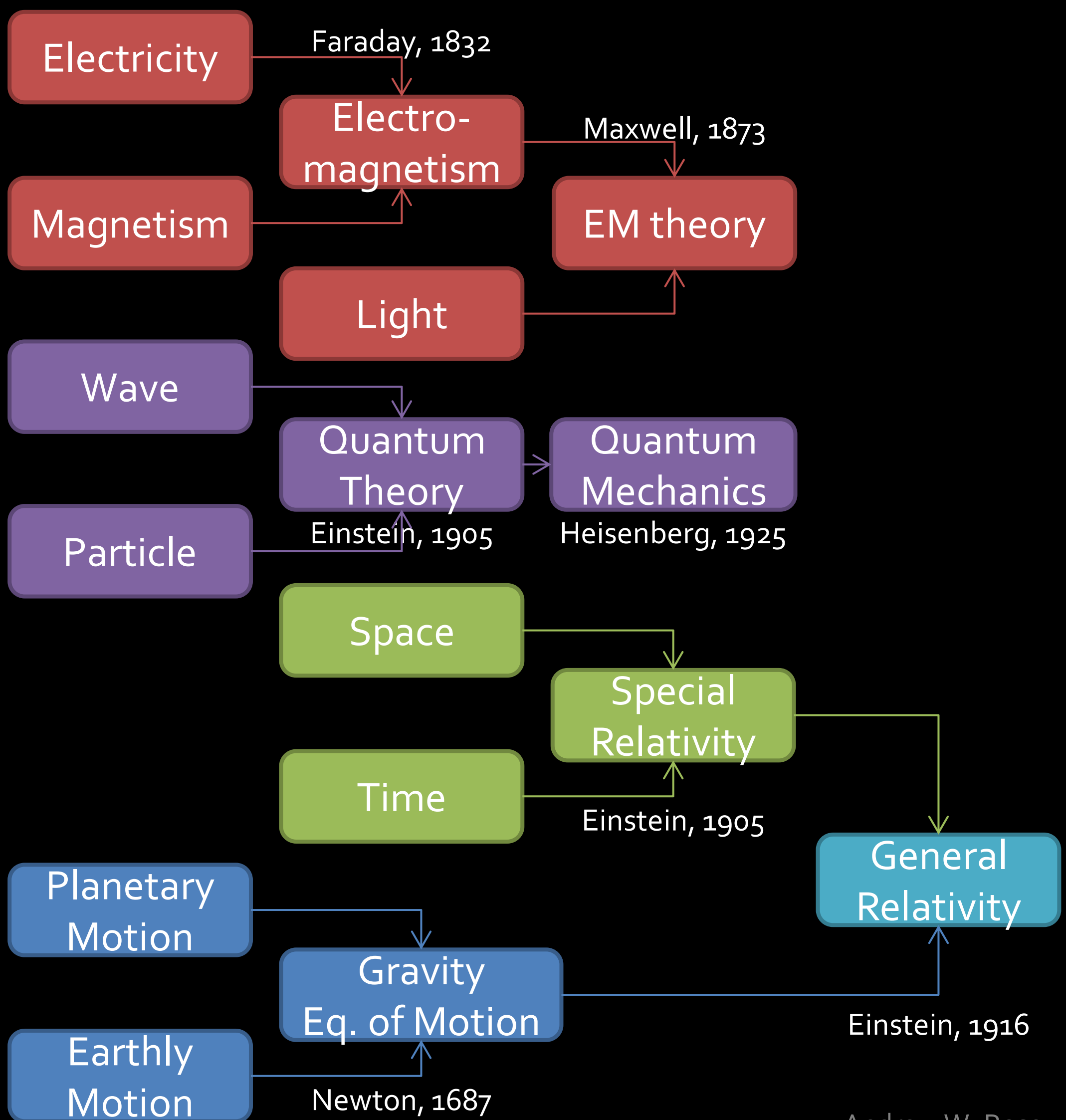

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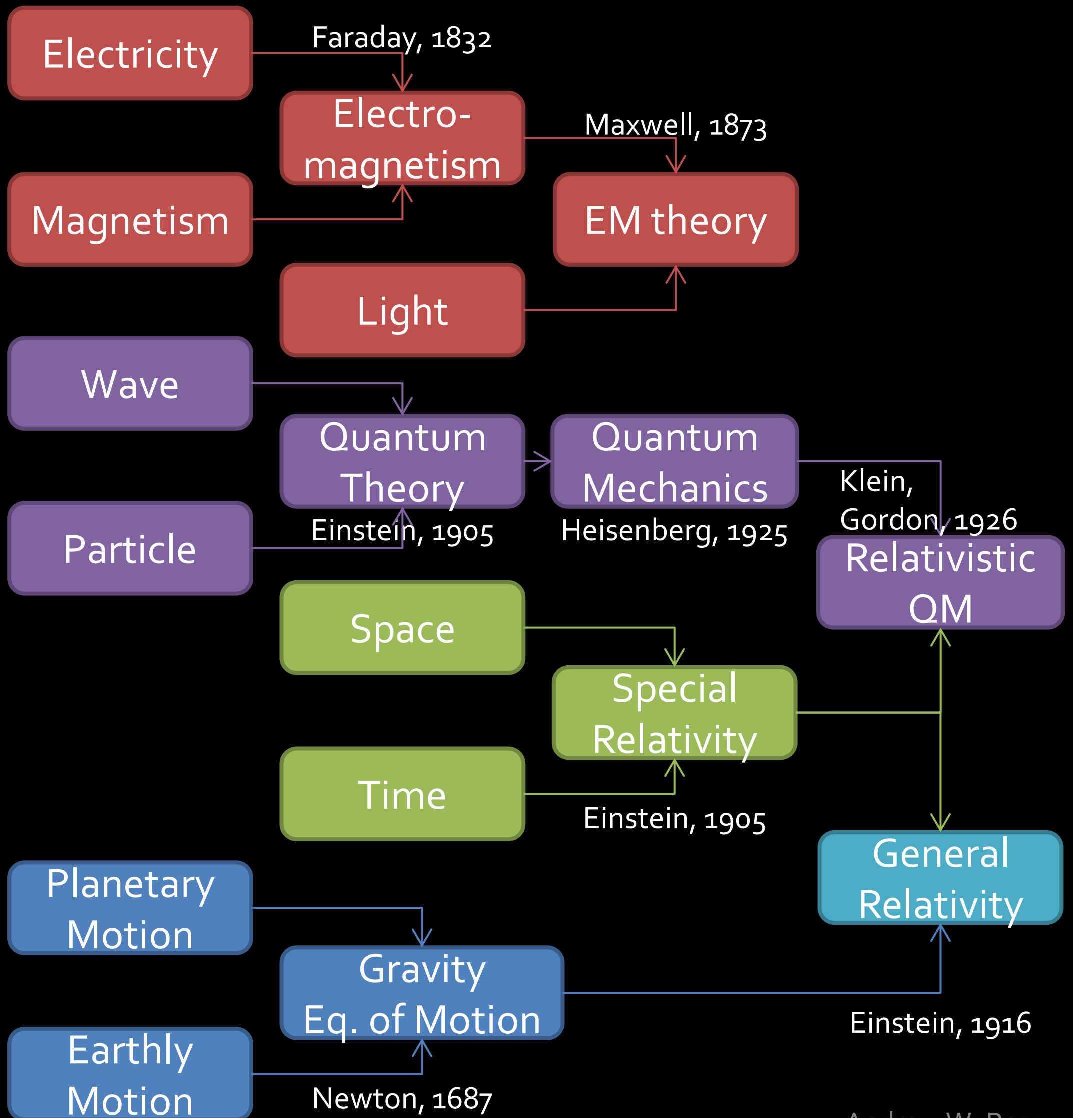
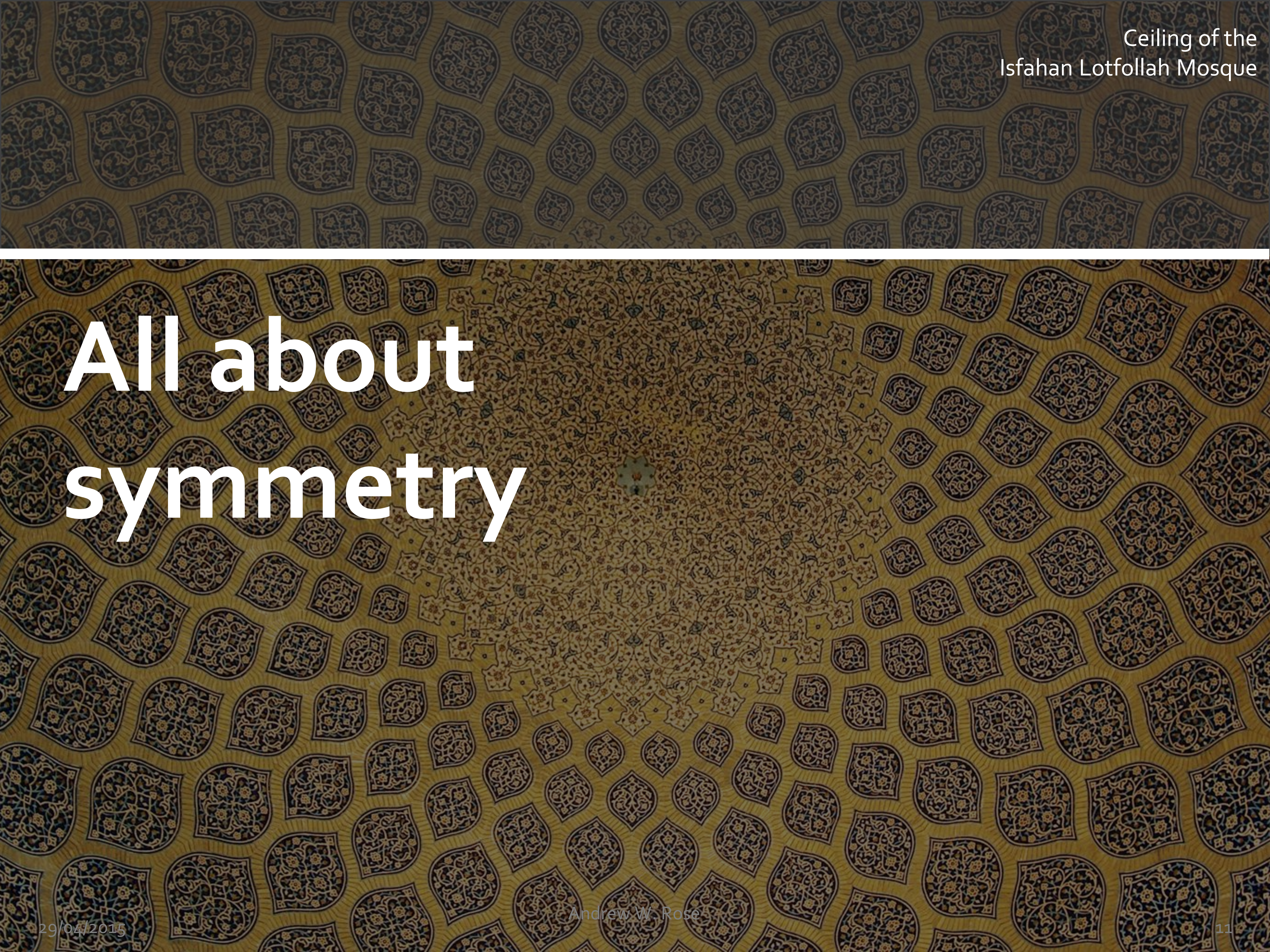


All about symmetry



Ceiling of the
Isfahan Lotfollah Mosque

THE NEW YORK TIMES, TUESDAY, MARCH 27, 2012

Amalie "Emmy" Noether

The Mighty Mathematician You've Never Heard Of

Scientists are a famously anonymous lot, but few can match in the depths of her perverse and unmerited obscurity the 20th-century mathematical genius Amalie Noether.

Albert Einstein called her the most "significant" and "creative" female mathematician of all time, and others of her contemporaries were inclined to drop the modification by sex. She invented a theorem that united with magisterial concision two conceptual pillars of physics: symmetry in nature and the universal laws of conservation. Some consider Noether's theorem, as it is now called, as important as Einstein's theory of relativity; it undergirds much of today's vanguard research in physics, including the hunt for the almighty Higgs boson. Yet Noether herself remains utterly unknown, not only to the general public, but to many members of the scientific community as well.

When Dave Goldberg, a physicist at Drexel University who has written about her work, recently took a little "Noether poll" of several dozen colleagues, students and online followers, he was taken aback by the results. "Surprisingly few could say exactly who she was or why she was important," he said. "A few others knew her name but couldn't recall what she'd done, and the majority had never heard of her."

Noether (pronounced NER-ter) was born in Erlangen, Germany, 130 years ago this month. So it's a fine time to counter the chronic neglect and celebrate the life and work of a brilliant theorist whose unshakable number love and irrationally robust sense of humor helped her overcome severe handicaps — first, being female in Germany at a time when most German universities didn't accept female students or hire female professors, and then being a Jew-

GROUNDBREAKING Emmy Noether's theorem united two pillars of physics: symmetry in nature and the universal laws of conservation.

symmetry in nature, some predictability or homogeneity of parts, you'll find lurking in the background a corresponding conservation — of momentum, electric charge, energy or the like. If a bicycle wheel is radially symmetric, if you can spin it on its axis and it still looks the same in all directions, well, then, that symmetric translation must yield a corresponding conservation. By applying the principles and calculations embodied in Noether's theorem, you'll see it's angular momentum, the Newtonian impulse that keeps bicyclists upright and on the move.

Some of the relationships to pop out of the theorem are startling, the most profound one linking time and energy. Noether's theorem shows that a symmetry of time — like the fact that whether you throw a ball in the air tomorrow or make the same toss next week will have no effect on the ball's trajectory — is directly related to the conservation of energy, our old homily that energy can be neither created nor destroyed but merely changes form.

The connections that Noether forged are "critical" to modern physics, said Lisa Randall, a professor of theoretical particle physics and cosmology at Harvard. "Energy, momentum and other quantities we take for granted gain meaning and even greater value when we understand how these quantities follow from symmetry in time and space."

Dr. Randall, the author of the newly published "Knocking on Heaven's Door," recalled the moment in college when she happened to learn that the author of Noether's theorem was a she. "It was striking and even exciting and inspirational," Dr. Randall said, admitting, "I was surprised by my reaction."

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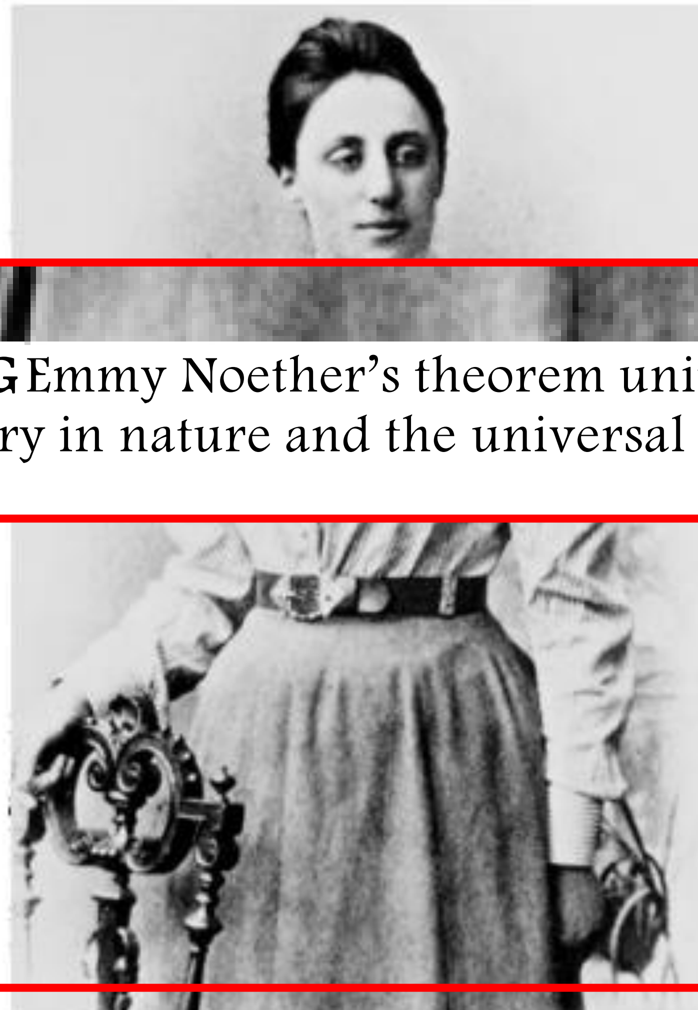

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For her part, Noether left little record of how she felt about the difficulties she

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Symmetry
Spatial Translation
Time Translation
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Conservation Law
Momentum
Energy
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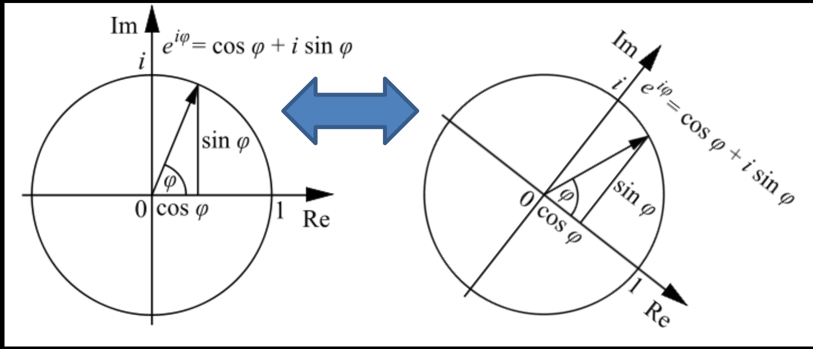
Symmetry
Spatial Translation
Time Translation
Rotational Symmetry
Complex Phase

Conservation Law
Momentum
Energy
Angular Momentum
Charge

Phase (gauge) invariance

Our theory should not depend on the precise phase of the wave-function

"Where is the start of a circle?"



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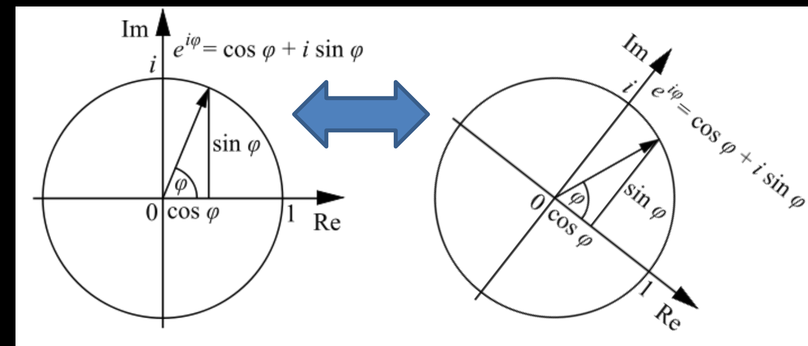

Trivially satisfied if our equation is of the form:

$$L \propto \psi^\dagger \cdots \psi$$

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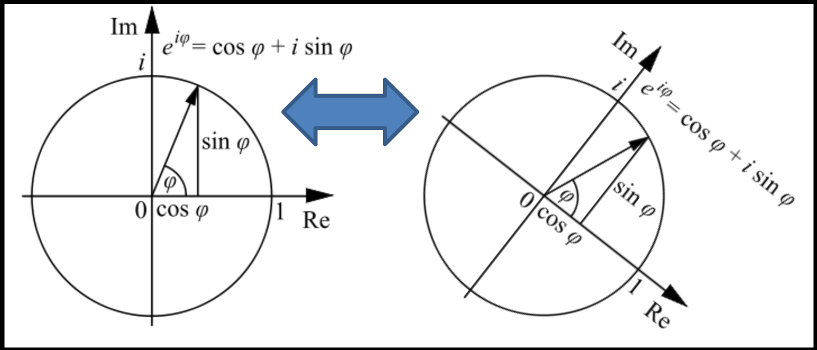

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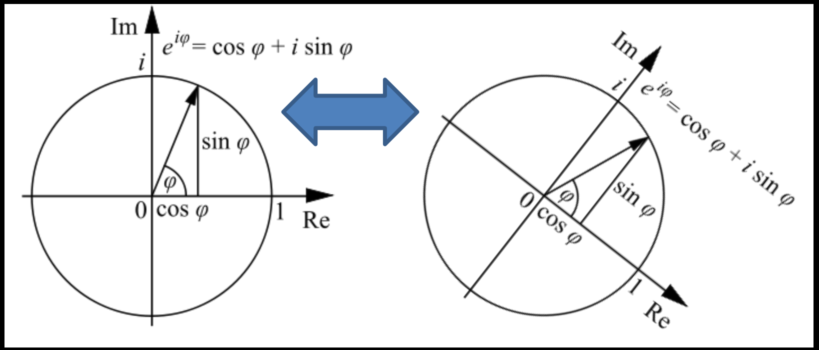

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Dirac/Spin-½/Fermion Lagrangian

$$L = i\psi^\dagger\gamma^0\gamma^\mu\partial_\mu\psi - \psi^\dagger\gamma_0 m\psi$$

$$= i\bar{\psi}\gamma^\mu\partial_\mu\psi - \bar{\psi}m\psi$$

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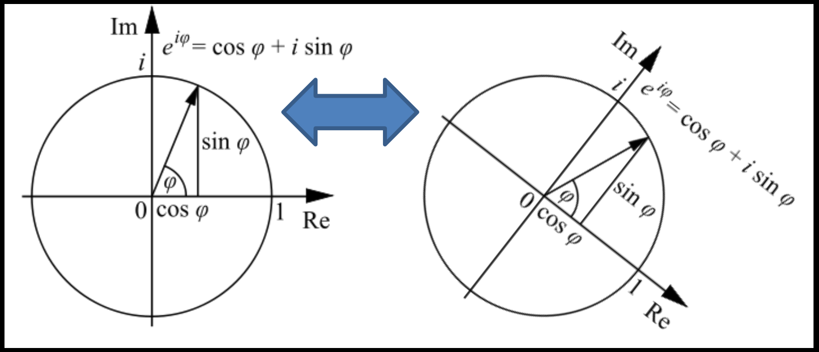

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Kinetic term

Mass term

Local phase (gauge) invariance

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<u>Can we make the phase vary in space/time</u>

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$$\psi \rightarrow \psi e^{i\phi}, \;\; A_{\mu} \rightarrow A_{\mu} - \frac{1}{q}\partial_{\mu}\phi$$

Local phase (gauge) invariance

$$L = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - \bar{\psi}m\psi$$
$$= \underbrace{\boxed{i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi}}_{\text{Kinetic term}} - \underbrace{\boxed{\bar{\psi}m\psi}}_{\text{Mass term}} + q\bar{\psi}A_{\mu}\psi$$

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Incoming fermion destroyed

Boson

Outgoing fermion created

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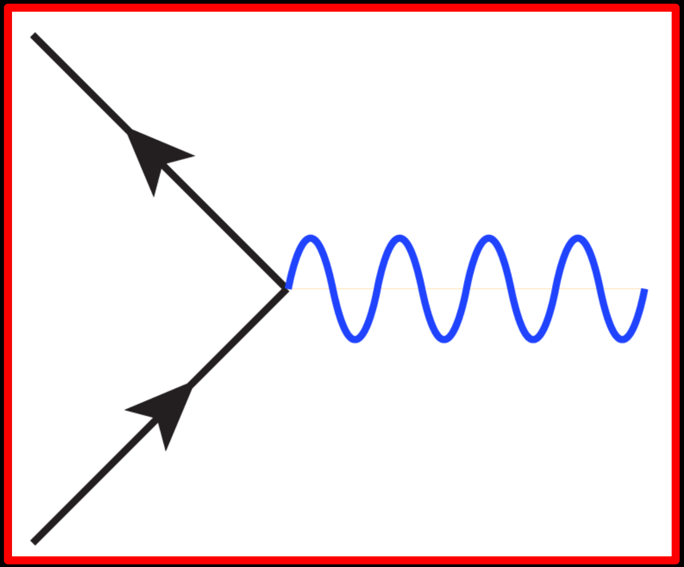

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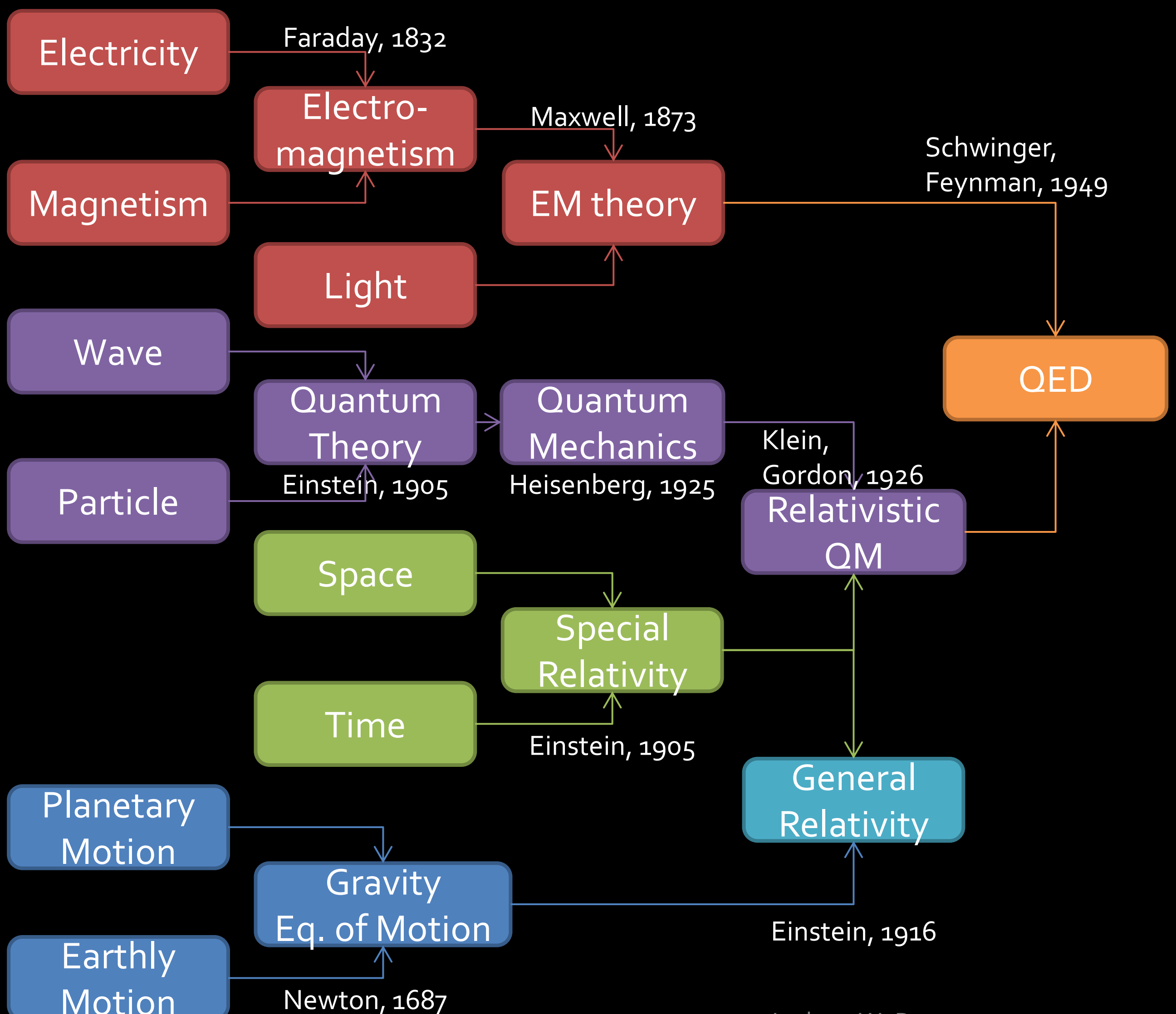


QED

The most accurate theory ever devised:

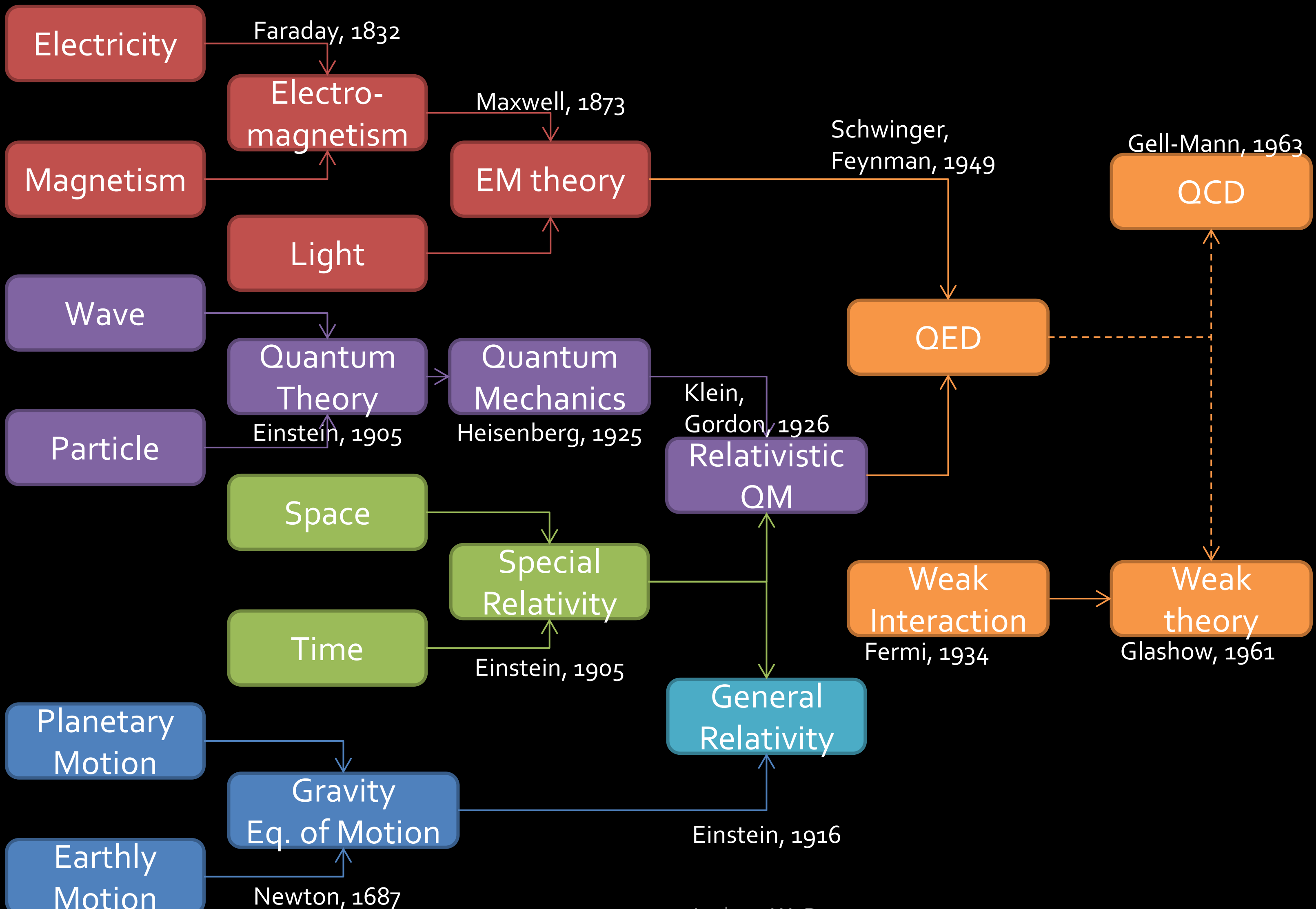
- Electron's spin g-factor: $g/2 = 1.001\ 159\ 652\ 180\ 85\ (76)$

(better than one part in a trillion)

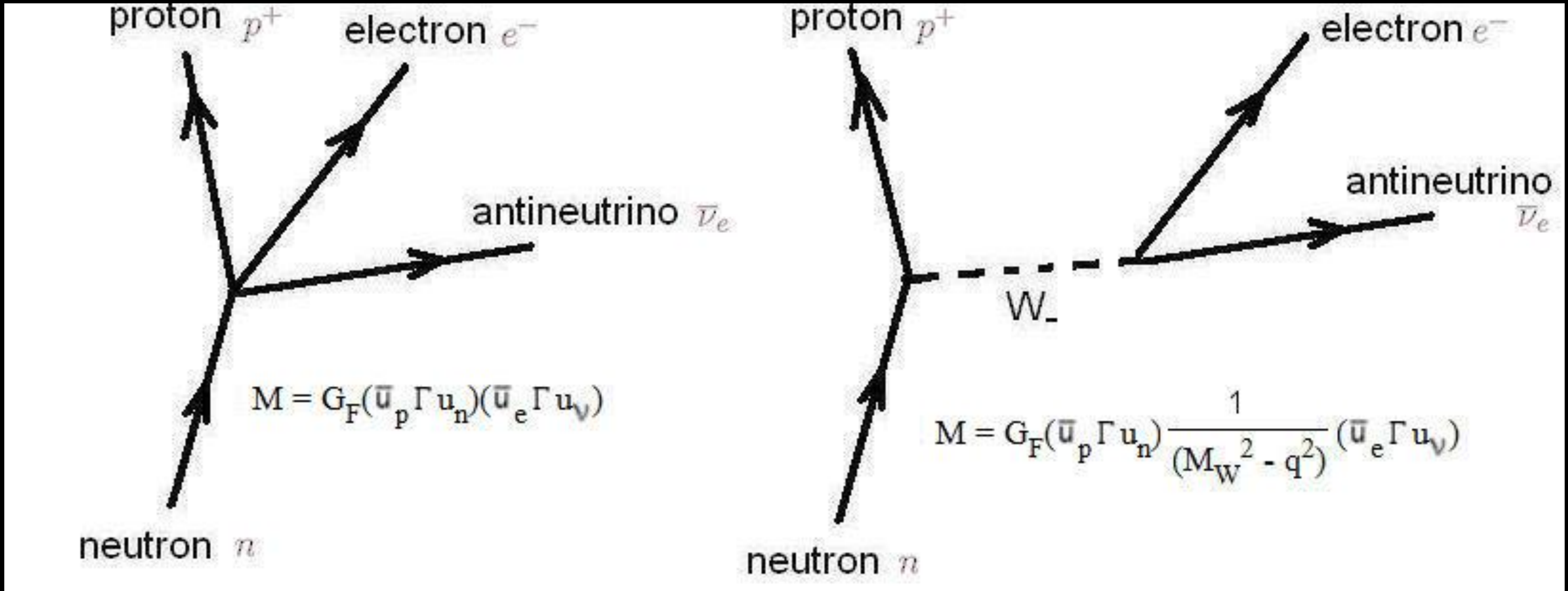
- Coupling constant: $\alpha^{-1} = 137.035\ 999\ 070\ (98)$

(better than a part in a billion)

Where are we now?



The electroweak problem

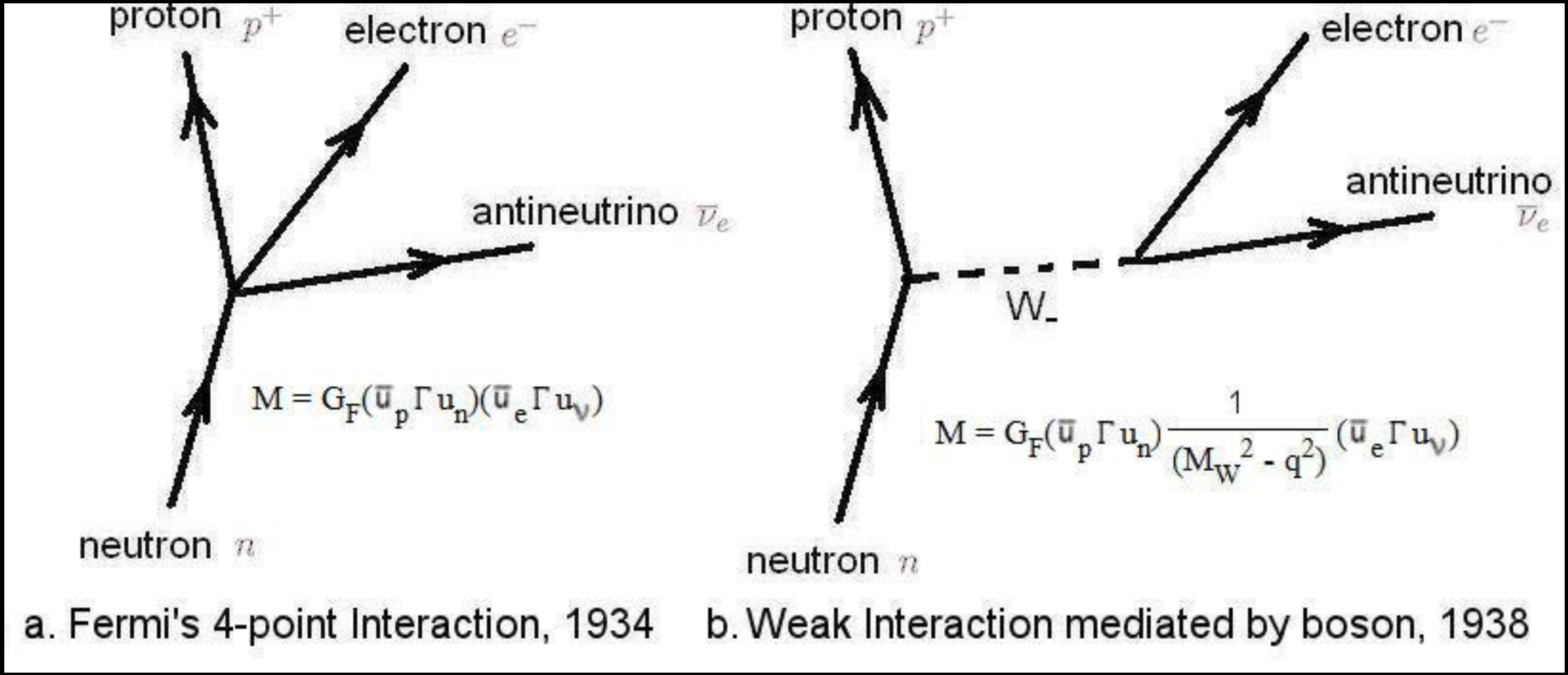


a. Fermi's 4-point Interaction, 1934 b. Weak Interaction mediated by boson, 1938

Weak force originally posited to be a point-like interaction

Quickly changed to be mediated by a heavy boson

The electroweak problem



Weak force originally posited to be a point-like interaction

Quickly changed to be mediated by a heavy boson

But the maths doesn't work – the theory is not renormalizable
– with the benefit of hindsight it becomes clear why

Massive Bosons

$$L = \boxed{\frac{1}{2}m^2 A^{\mu} A_{\mu}}$$

Mass term

Massive Bosons

$$L = \boxed{\tfrac{1}{2}m^2 A^\mu A_\mu} \longleftarrow \text{Mass term}$$

But we required: $A_\mu \rightarrow A_\mu - \frac{1}{q}\,\partial_\mu \phi$

$$A^\mu A_\mu \rightarrow \left(A^\mu - \frac{1}{q}\,\partial^\mu \phi\right)\left(A_\mu - \frac{1}{q}\,\partial_\mu \phi\right) \neq A^\mu A_\mu$$

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Photon seems OK: Observe $m_\gamma < 10^{-22} m_e$

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Not ideal for the W & Z bosons which are observed to be heavier than an entire Iron nucleus

Why do we care about phase (gauge) invariance?

- The establishment of unitarity of a renormalizable set of Feynman rules requires Ward identities, a consequence of gauge invariance
- The rules in the renormalizable gauge are equivalent to those in the unitary gauge only when the theory is gauge invariant

Veltman, ‘t Hooft, 1972

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If the theory is not gauge invariant it is worth
DIDDLY SQUAT

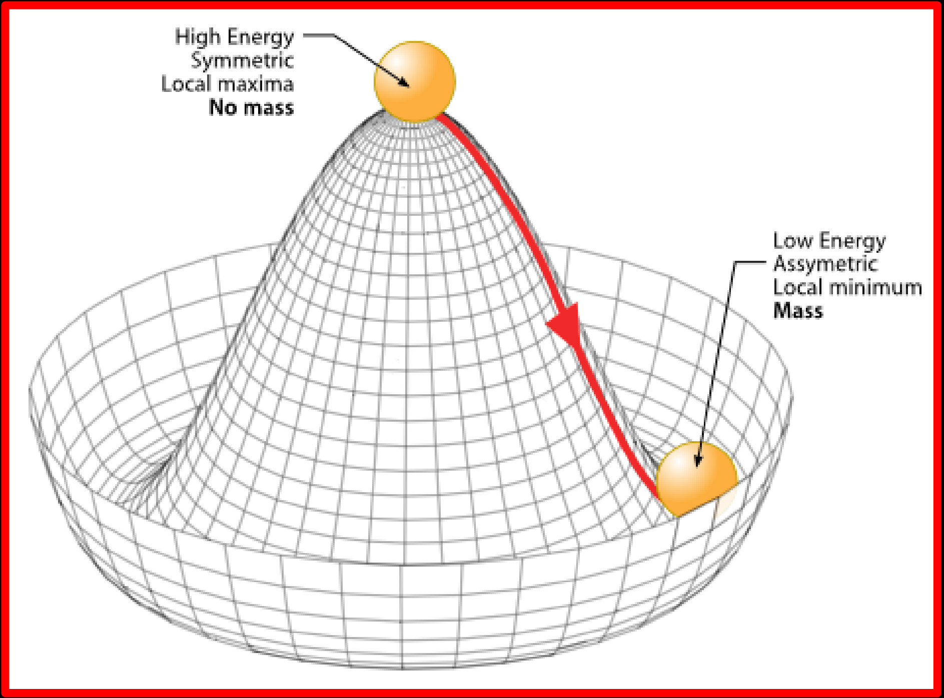
The Higgs (-Schwinger-Anderson-Kibble-Guralnik-Hagen-Englert-Brout) Mechanism

We can devise a Lagrangian which is

symmetric across the origin

but which is

asymmetric about the minimum



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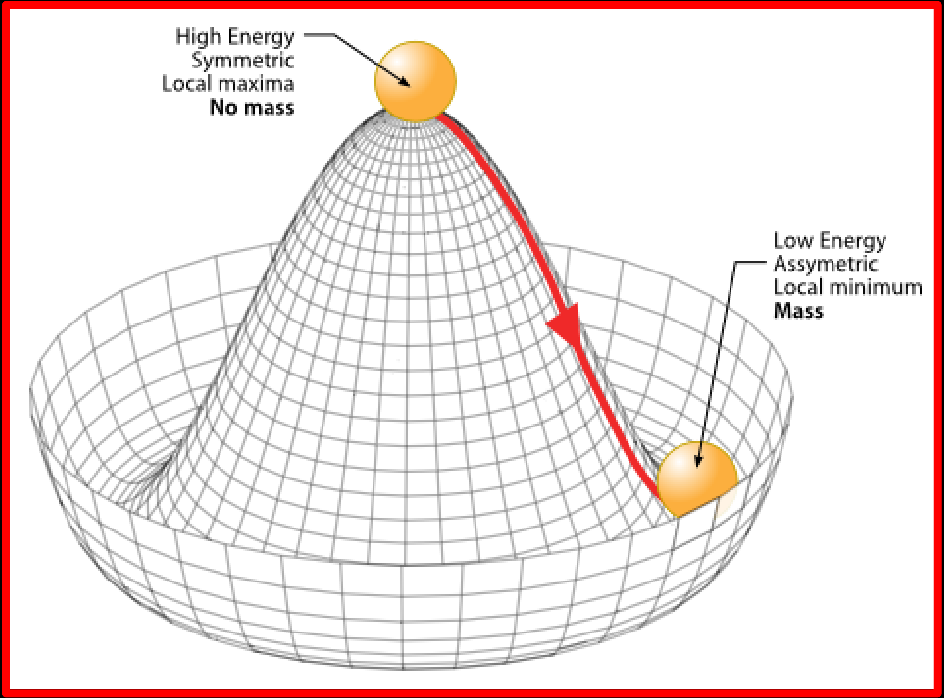

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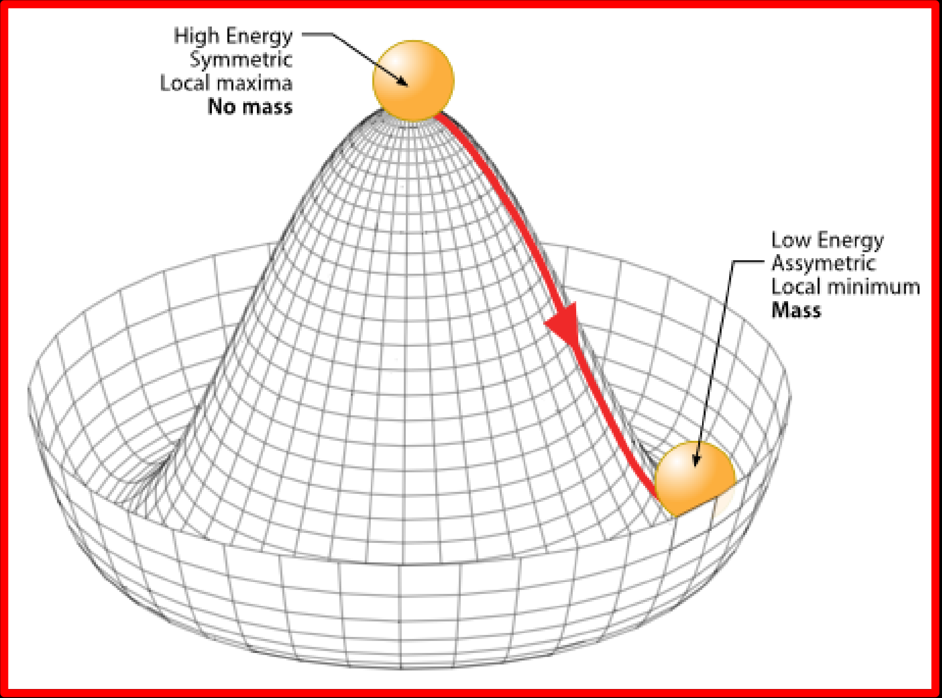
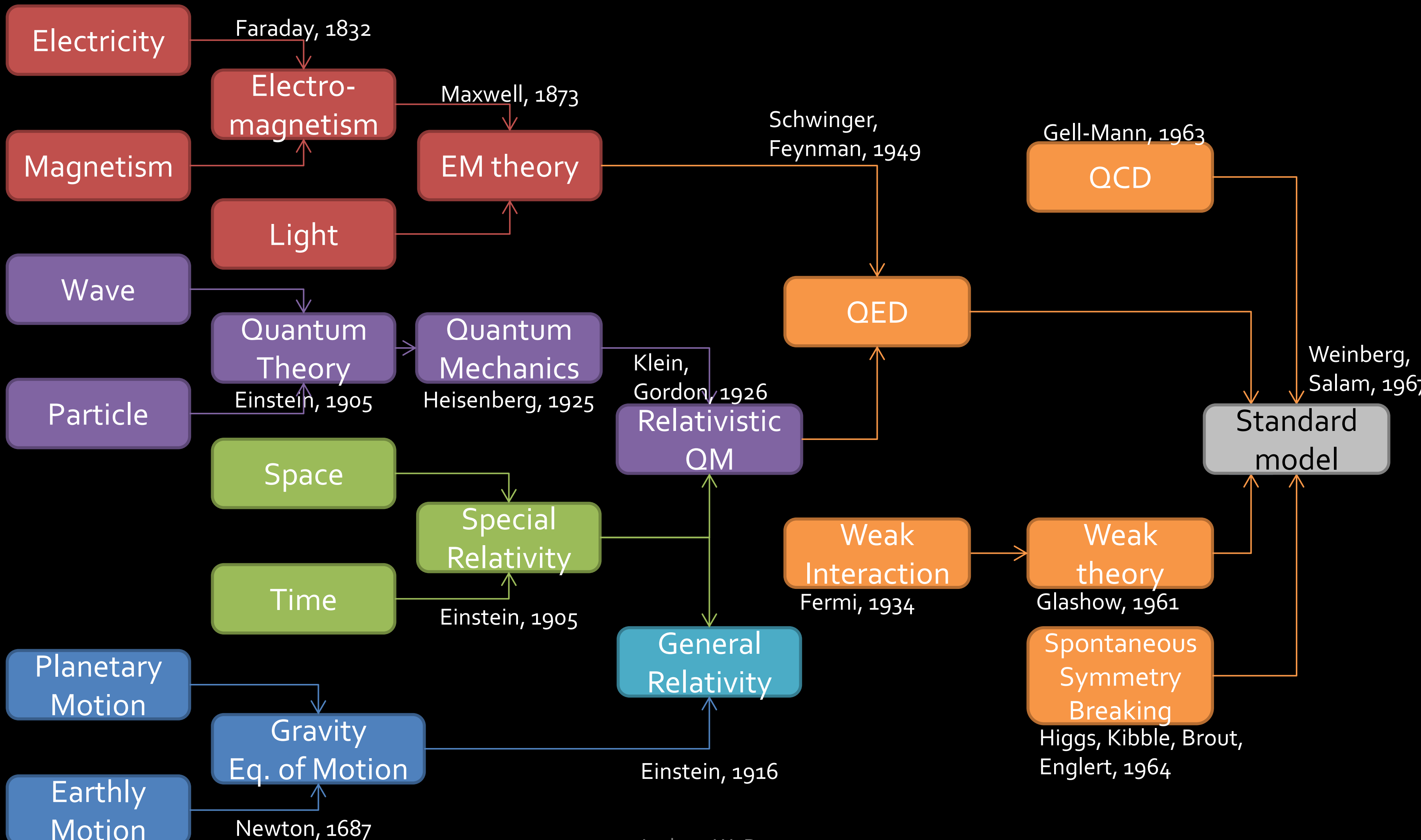
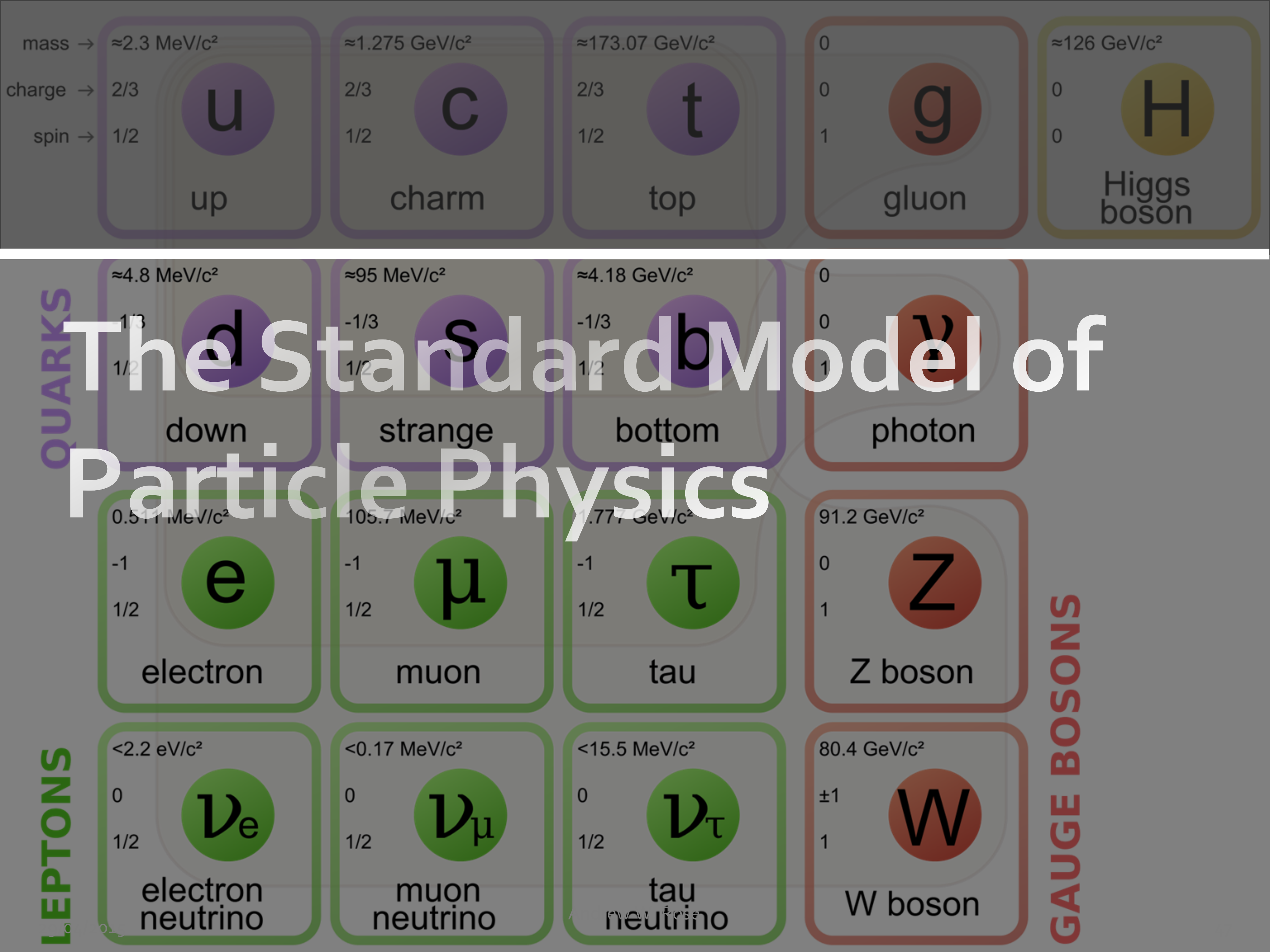


If we require this new field to be phase (gauge) invariant, these massless bosons get "absorbed" by our massless gauge bosons, turning them into massive gauge bosons

Where are we now?

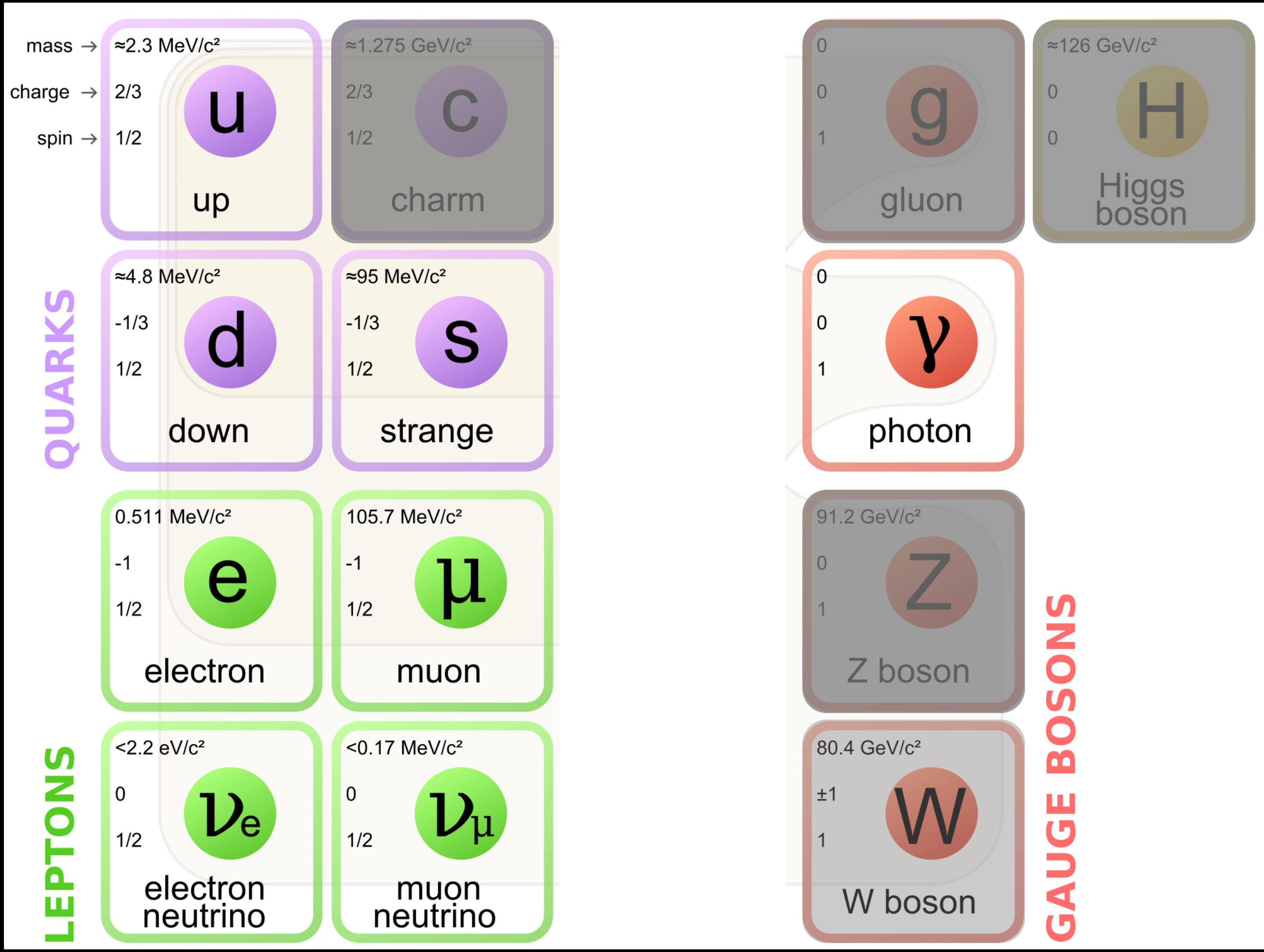


The Standard Model of Particle Physics



The Standard Model: 1967

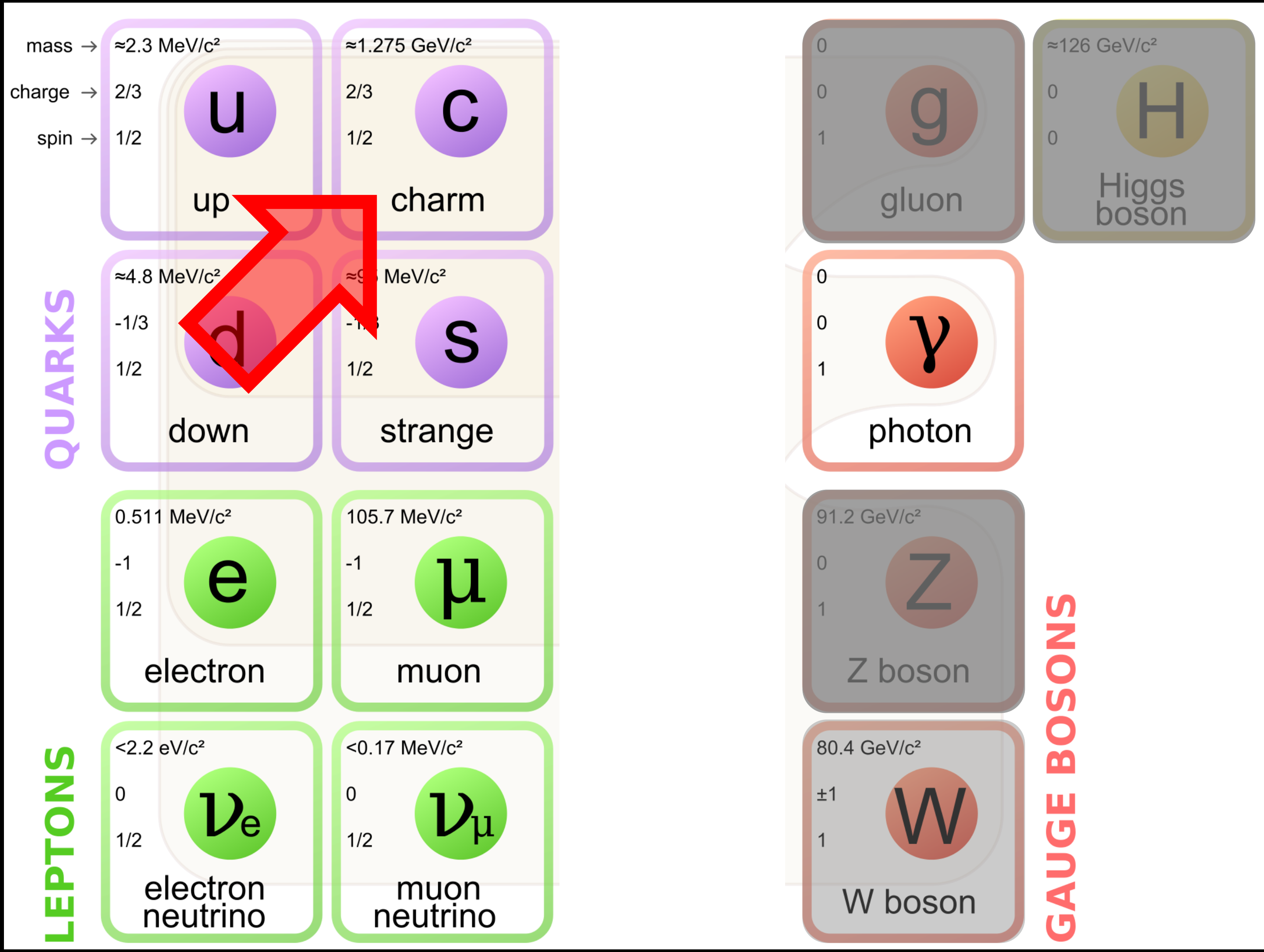
The Weinberg-Salam model



The Standard Model: 1974

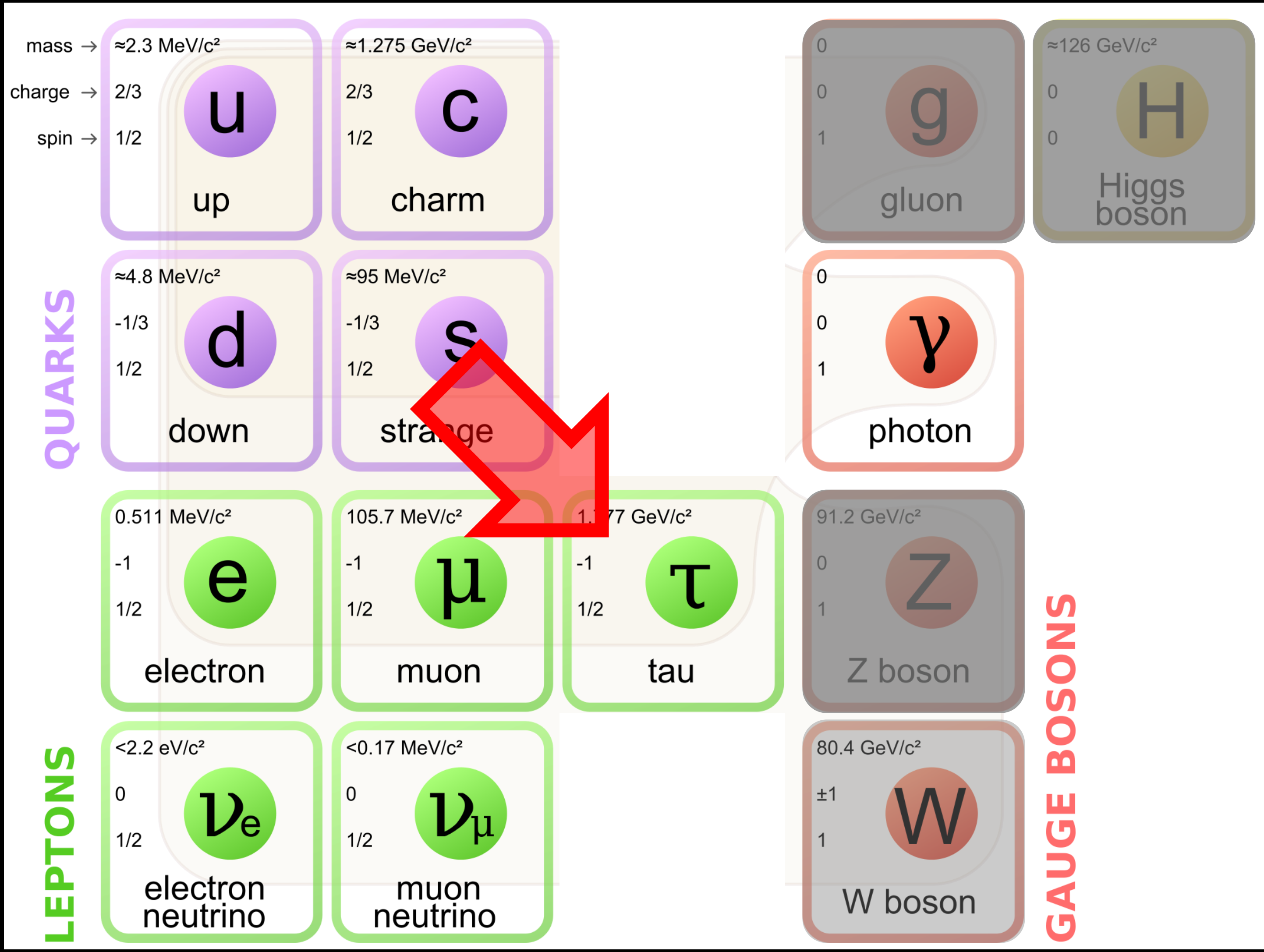
Burton Richter, SLAC

Sam Ting, Brookhaven

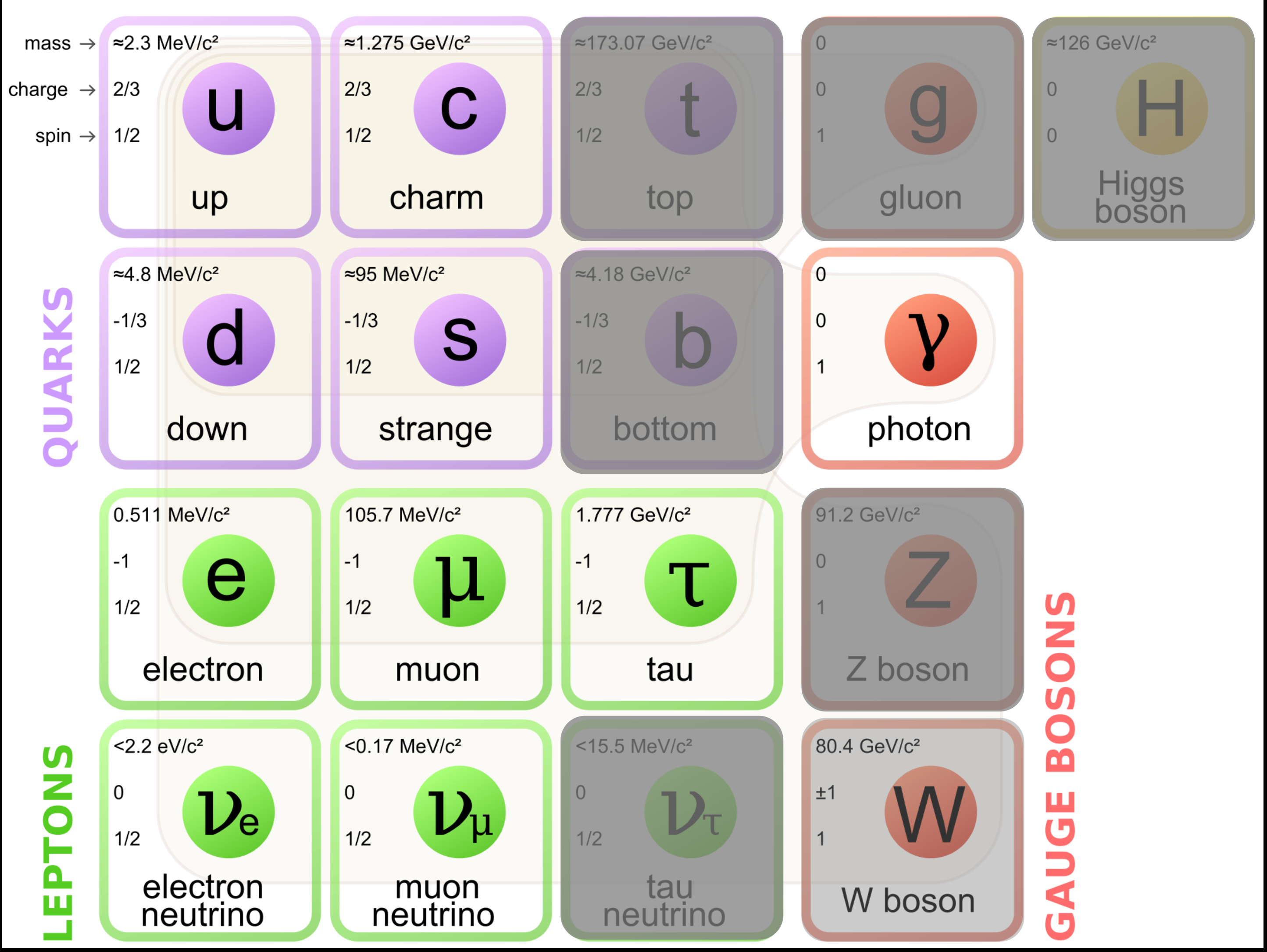


The Standard Model: 1976

Martin Perl,
SLAC

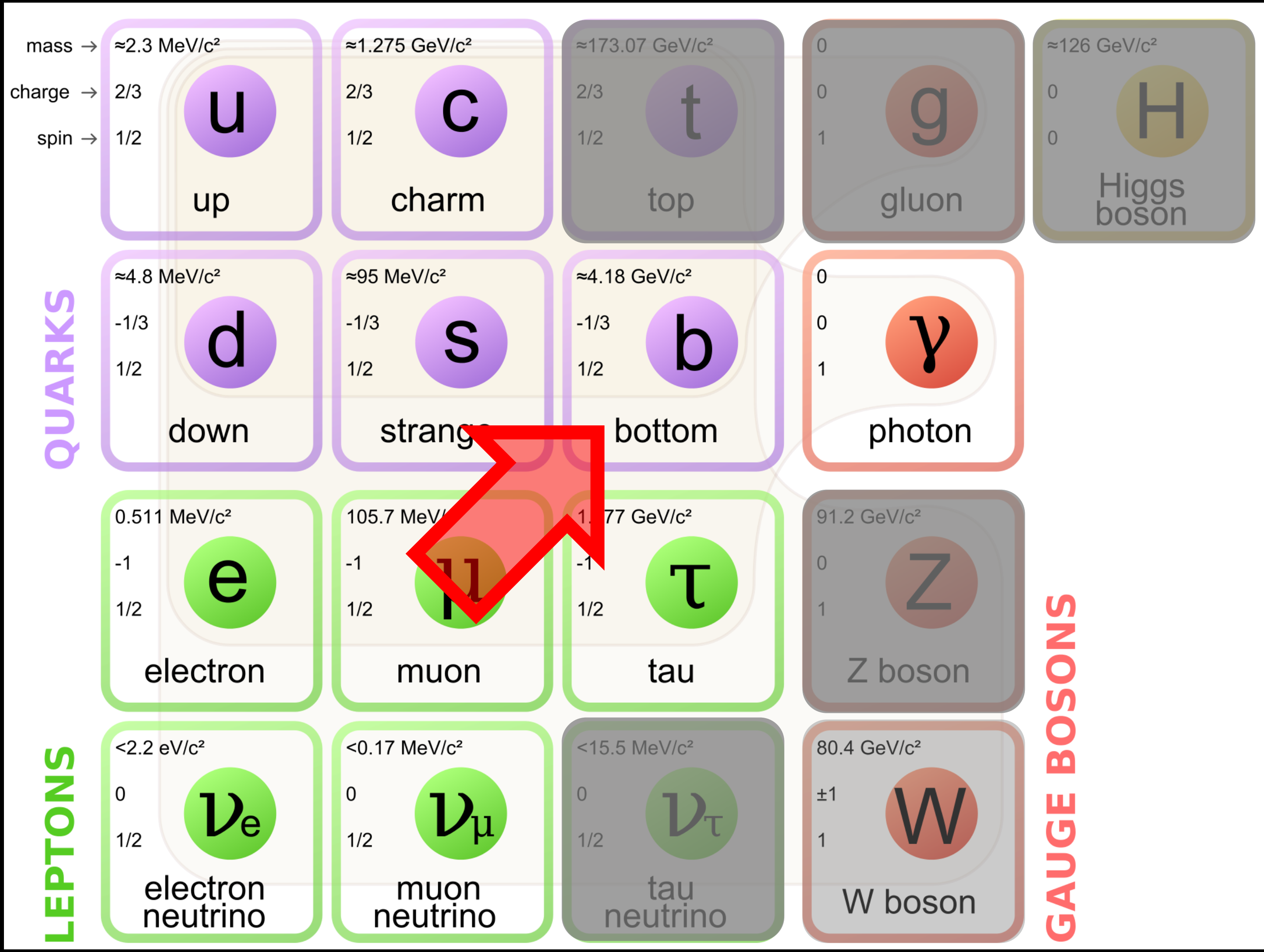


The Standard Model: 1976



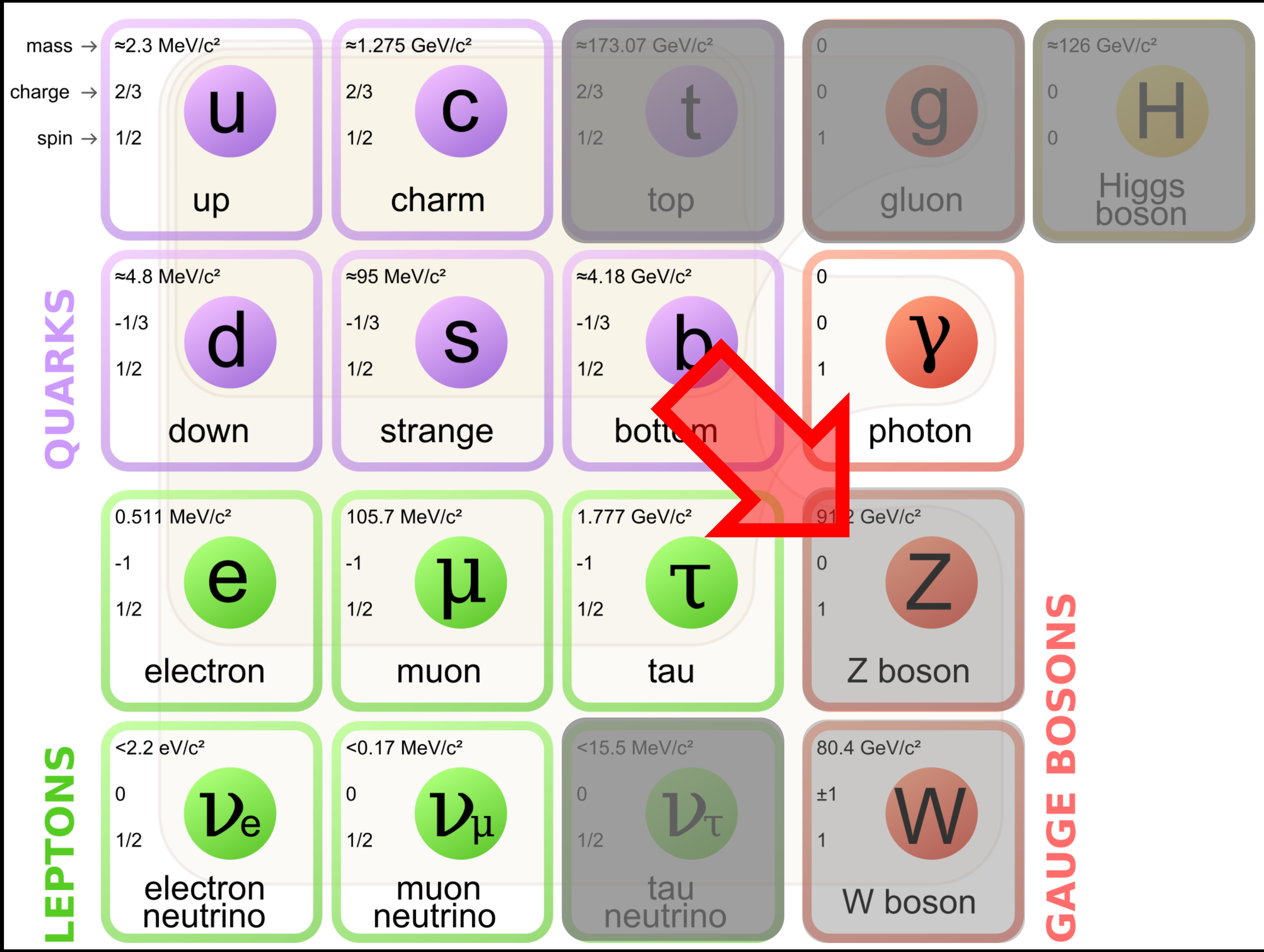
The Standard Model: 1977

Leon Lederman, Fermilab



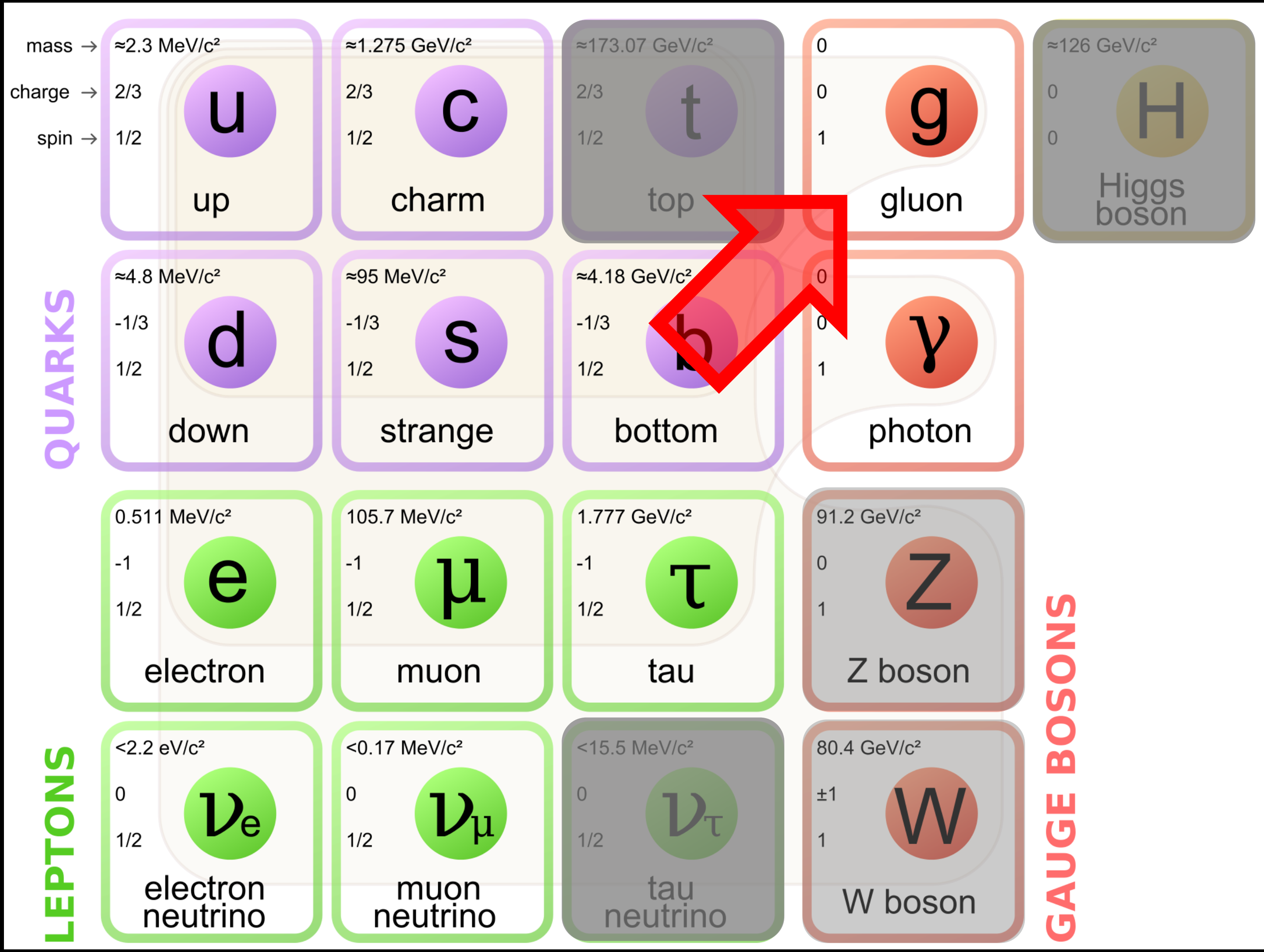
The Standard Model: 1978

Charles Prescott, Richard Taylor, SLAC



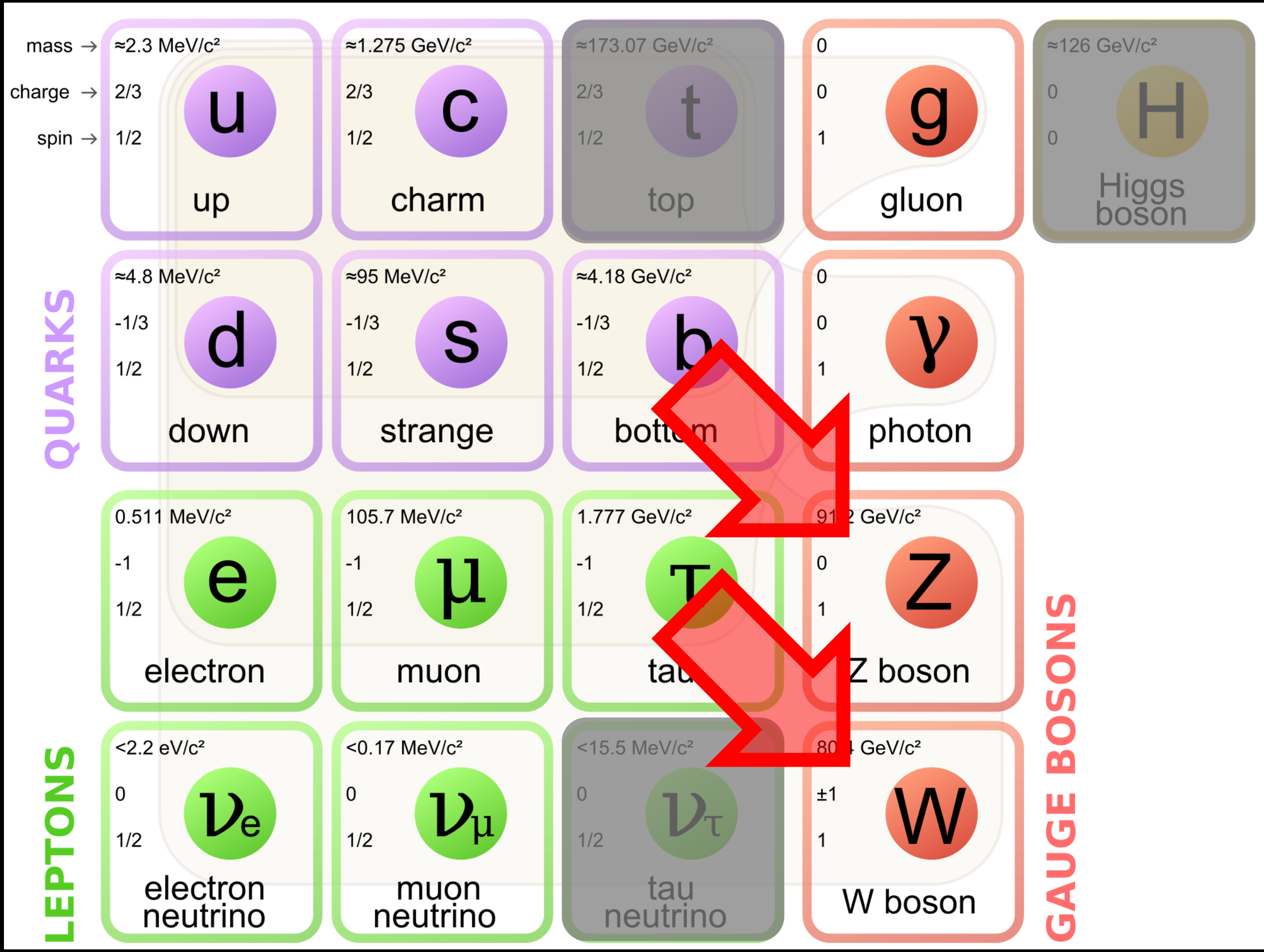
The Standard Model: 1979

PETRA, DESY



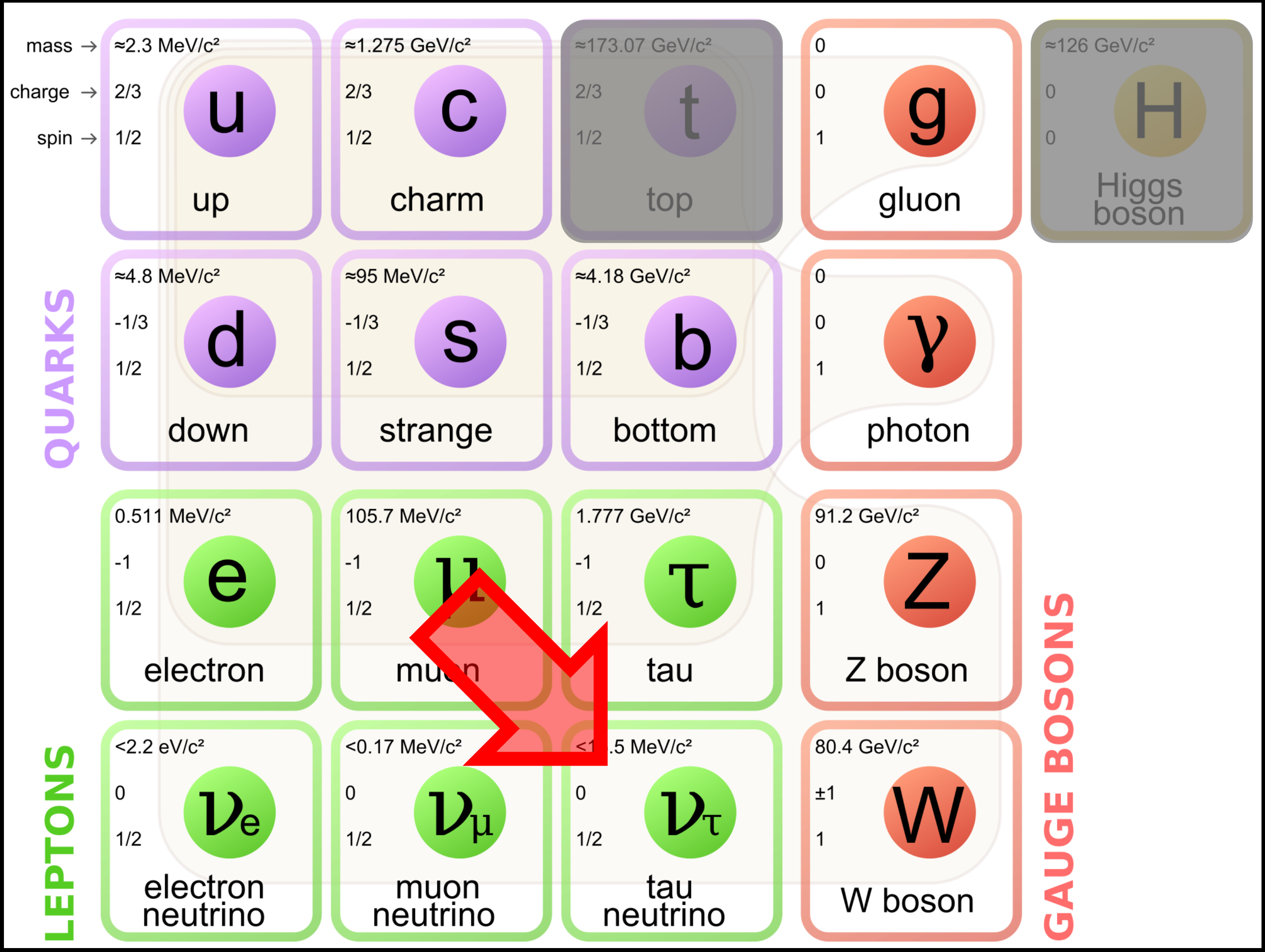
The Standard Model: 1983

UA1, UA2,
CERN



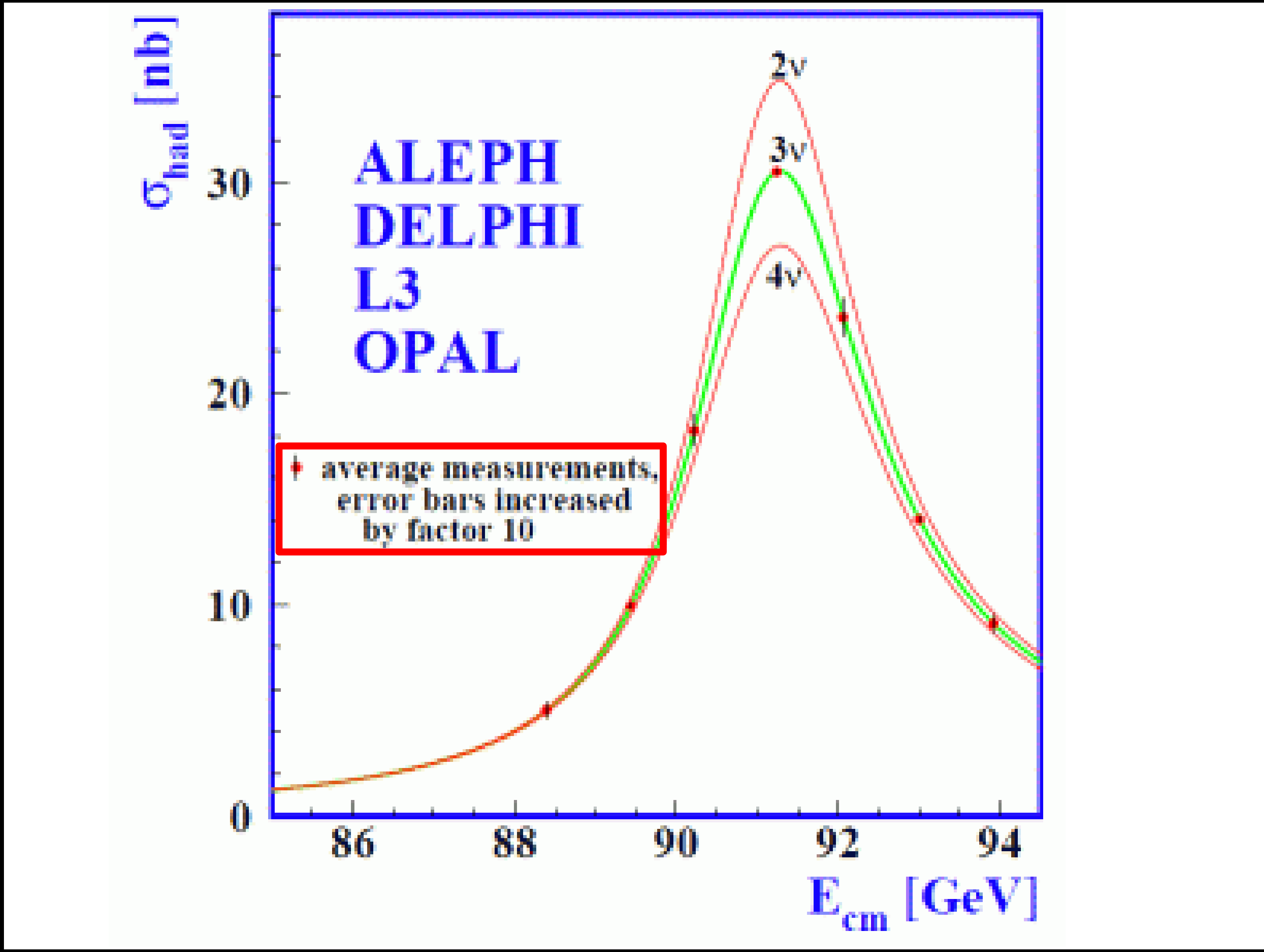
The Standard Model: 1989

LEP, CERN



The Standard Model: 1989

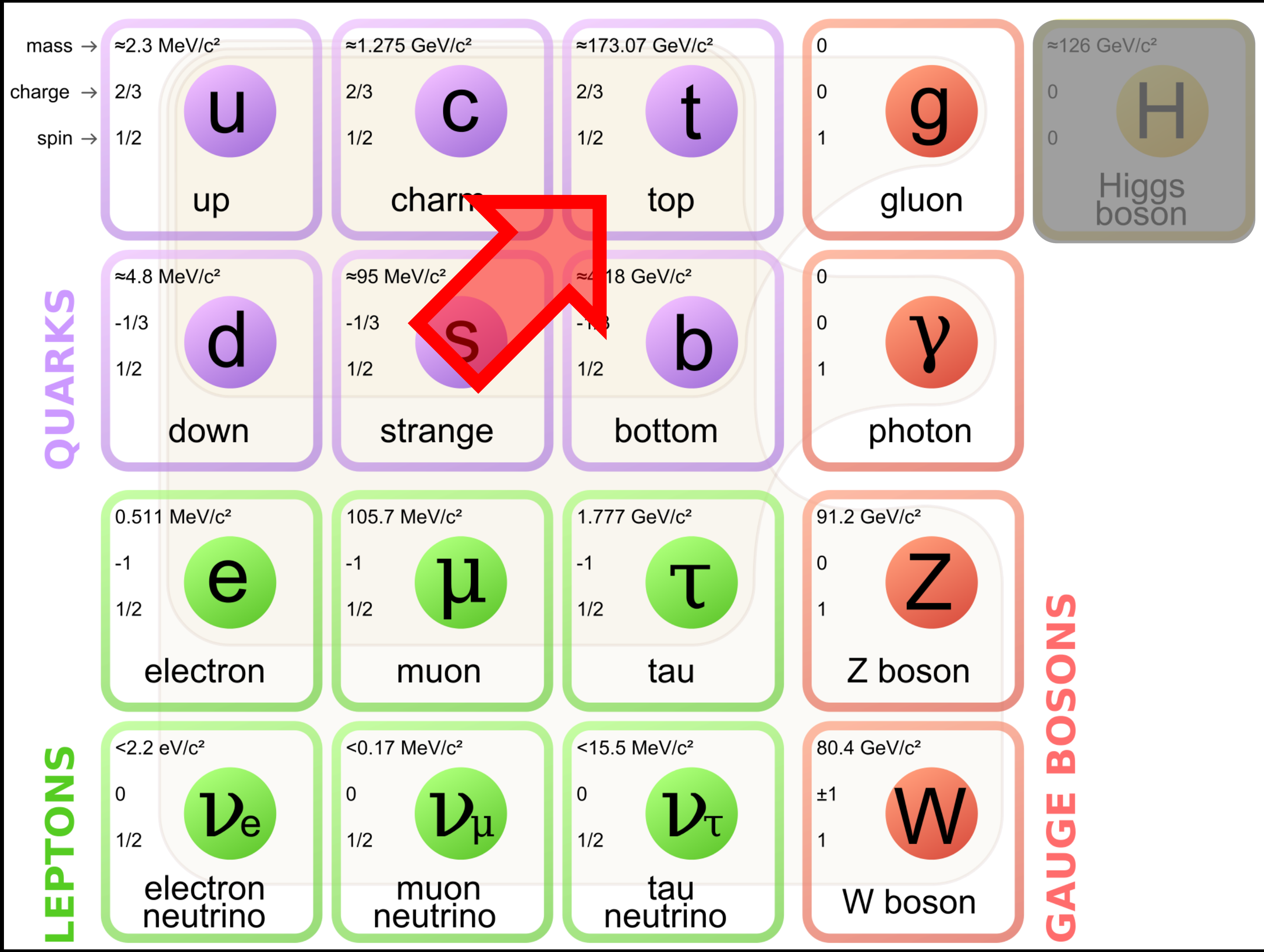
LEP, CERN



Also, proved that the lifetime of the Z-boson is consistent only with there being exactly three generations of light neutrino

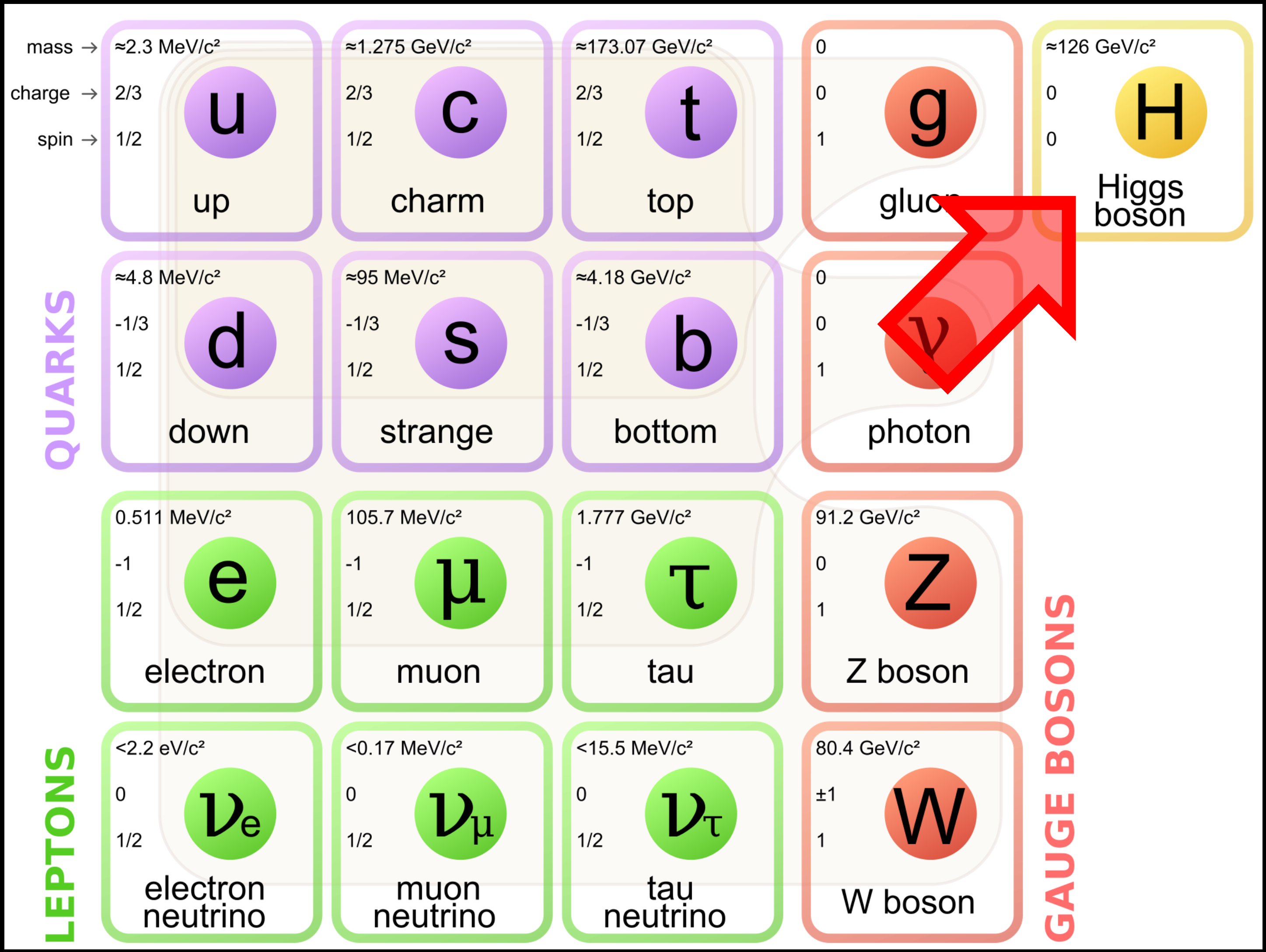
The Standard Model: 1995

Do, CDF, Fermilab

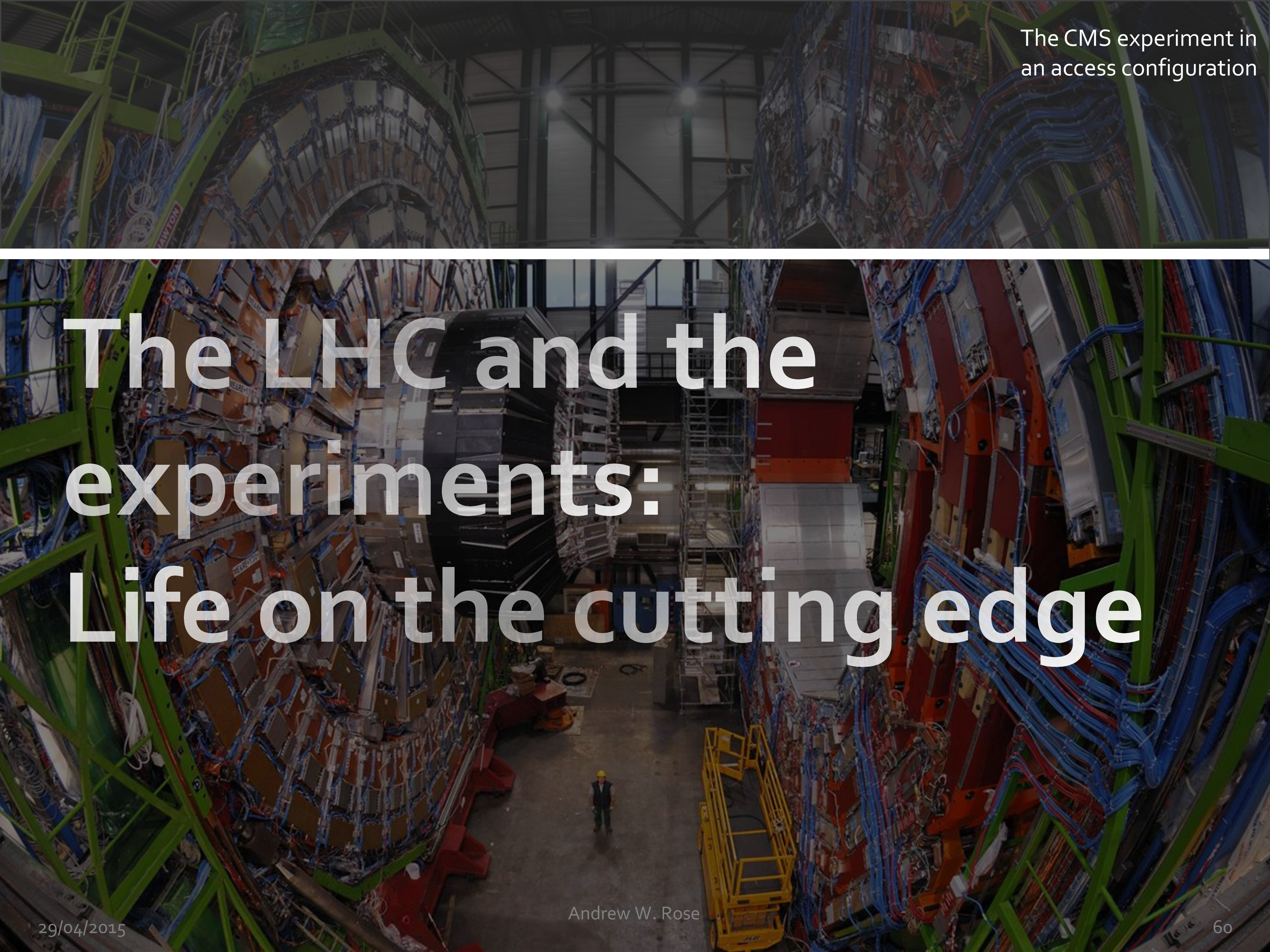


The Standard Model: 2012

CMS, ATLAS, CERN



The LHC and the experiments: Life on the cutting edge

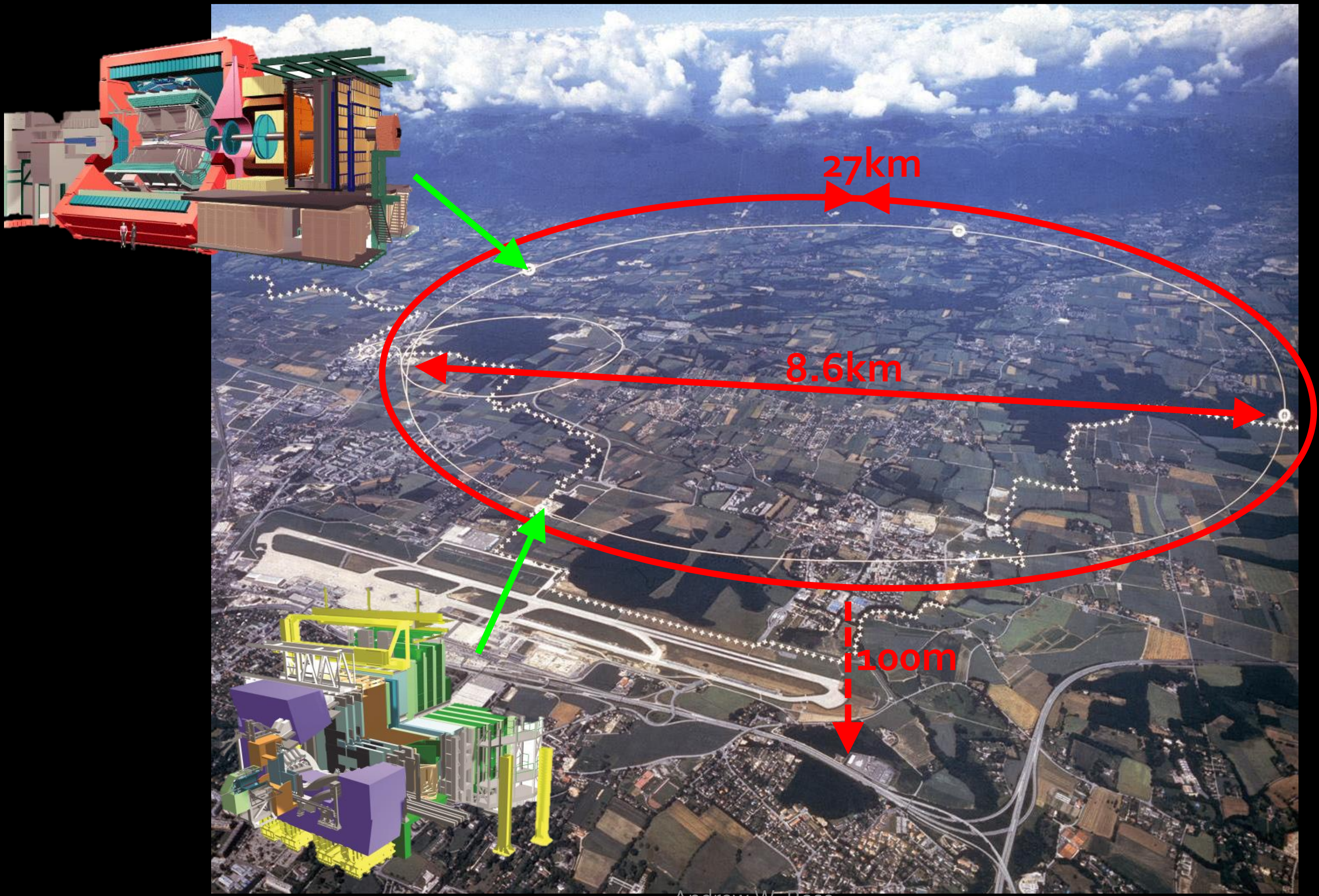


The CMS experiment in an access configuration

The LHC: Large Hadron Collider

The LHC: Large Hadron Collider

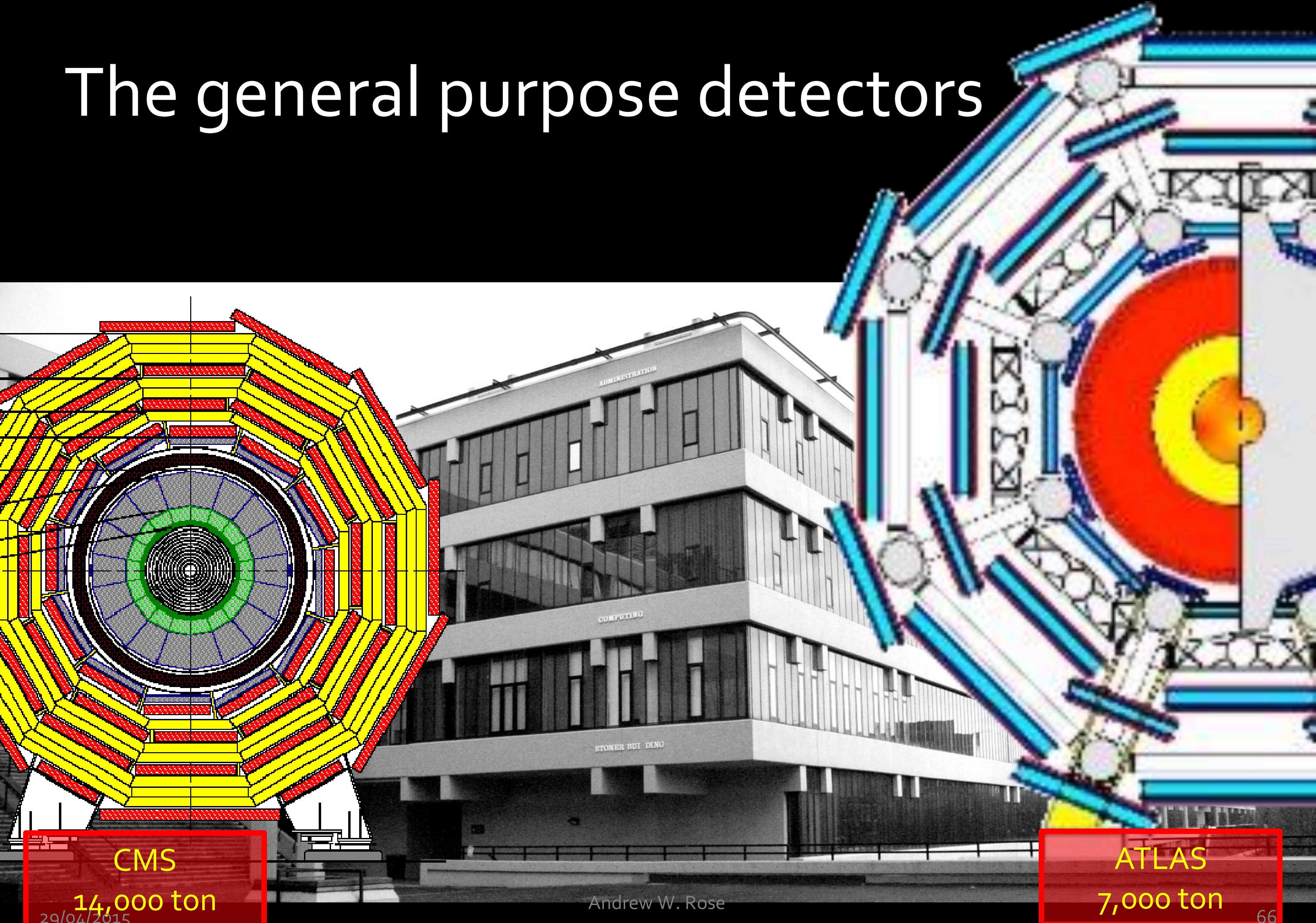
The LHC: Large Hadron Collider



The LHC: Large Hadron Collider

The general purpose detectors

The general purpose detectors

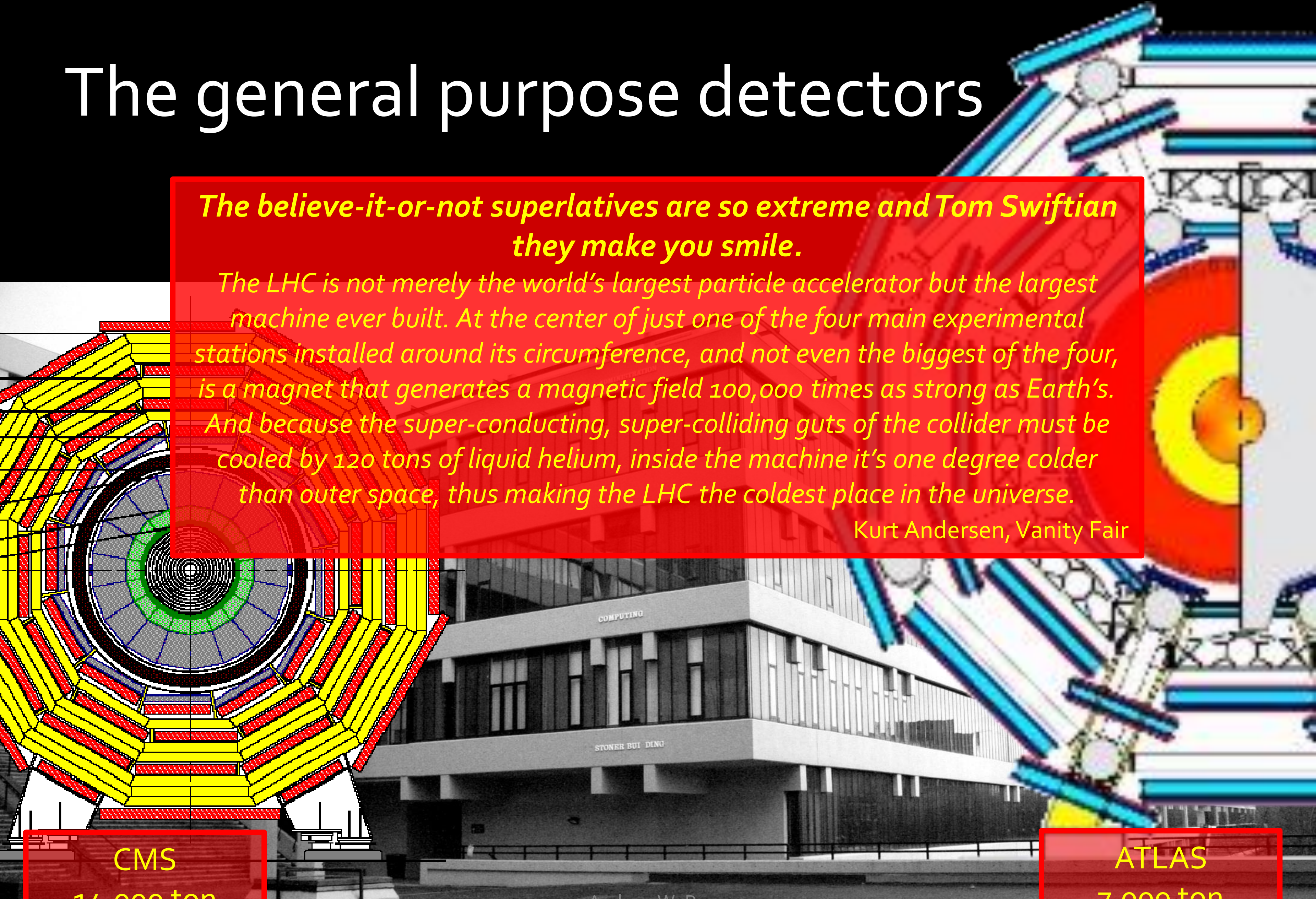


The general purpose detectors

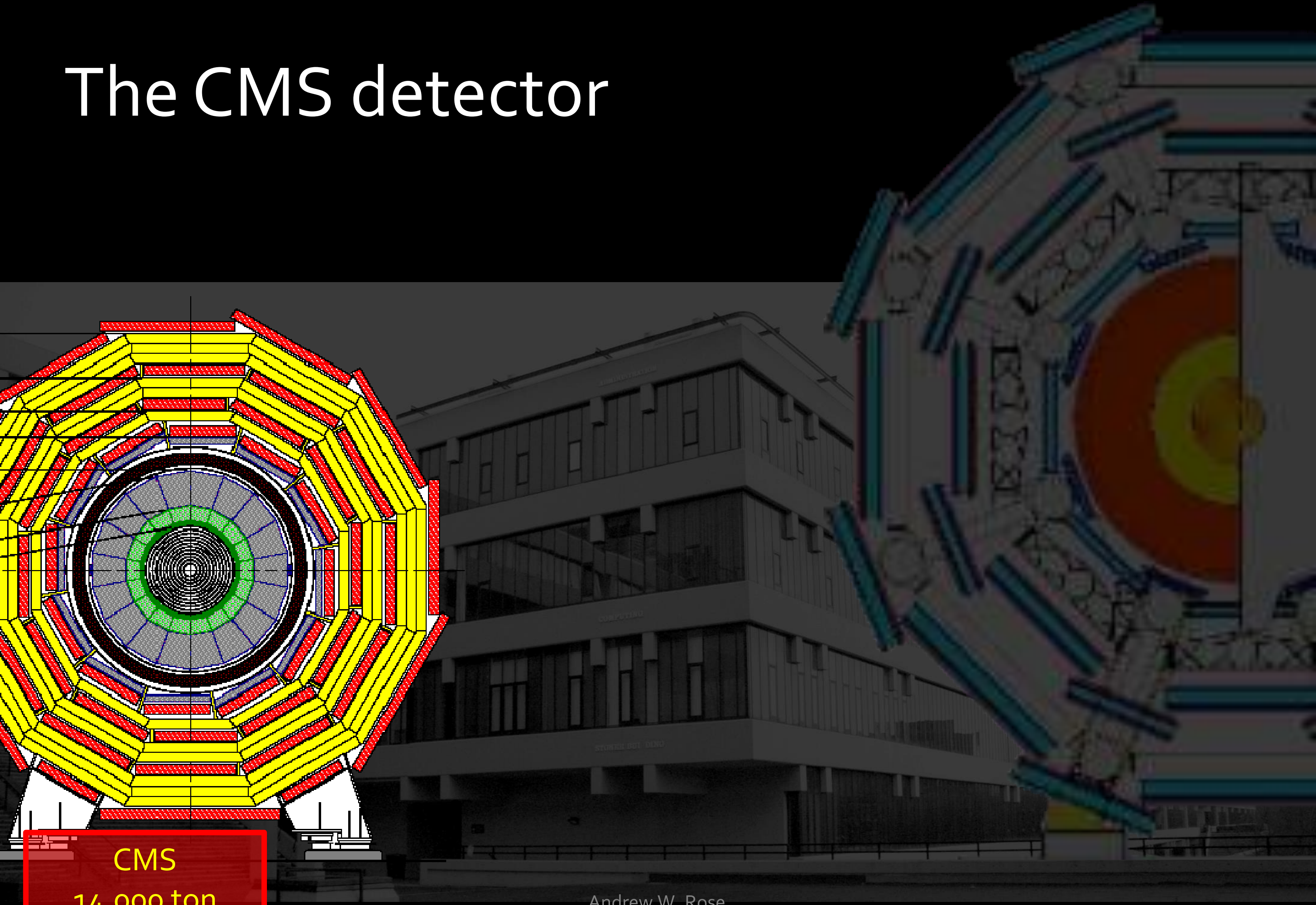
The believe-it-or-not superlatives are so extreme and Tom Swiftian they make you smile.

The LHC is not merely the world's largest particle accelerator but the largest machine ever built. At the center of just one of the four main experimental stations installed around its circumference, and not even the biggest of the four, is a magnet that generates a magnetic field 100,000 times as strong as Earth's. And because the super-conducting, super-colliding guts of the collider must be cooled by 120 tons of liquid helium, inside the machine it's one degree colder than outer space, thus making the LHC the coldest place in the universe.

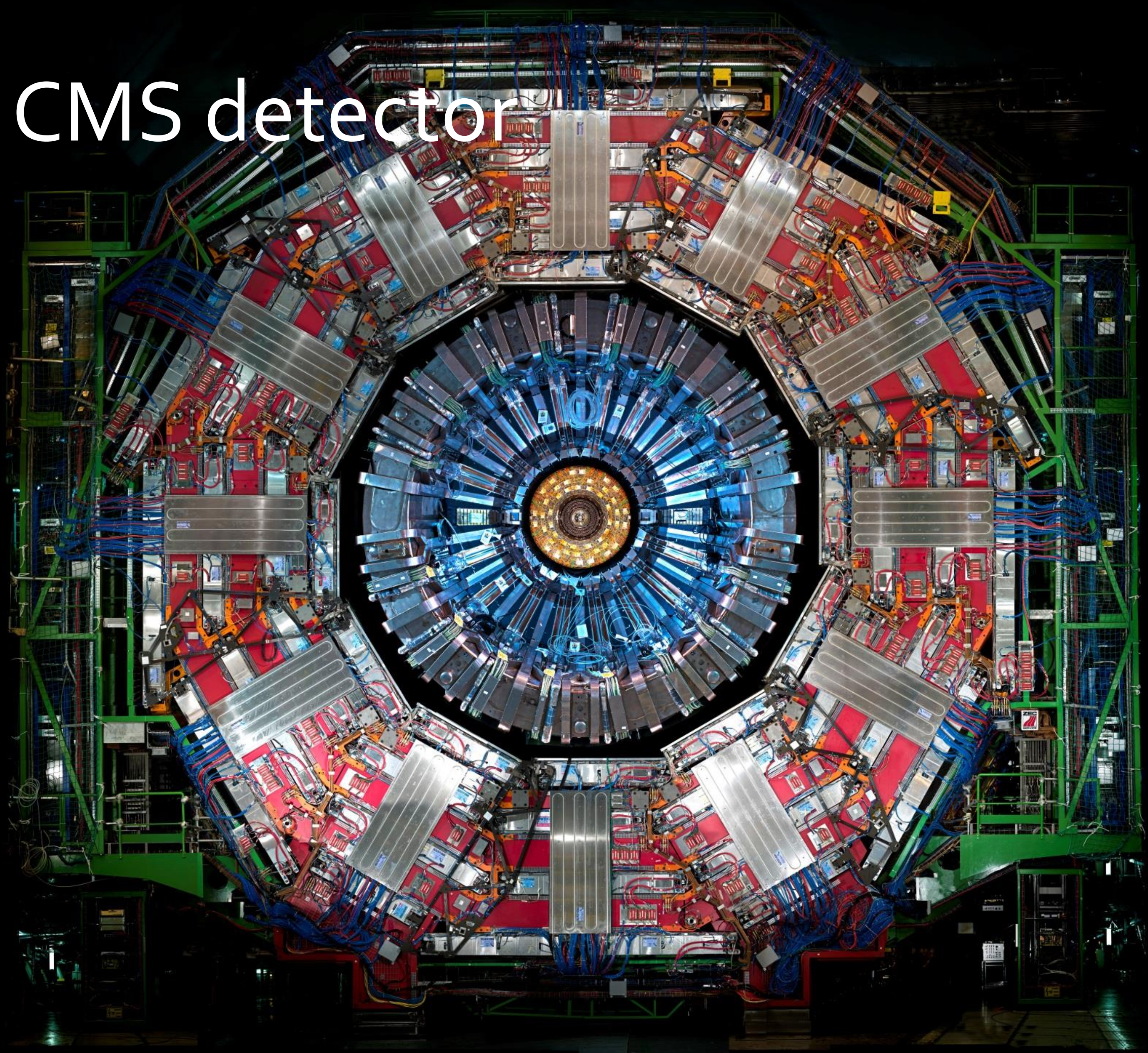
Kurt Andersen, Vanity Fair



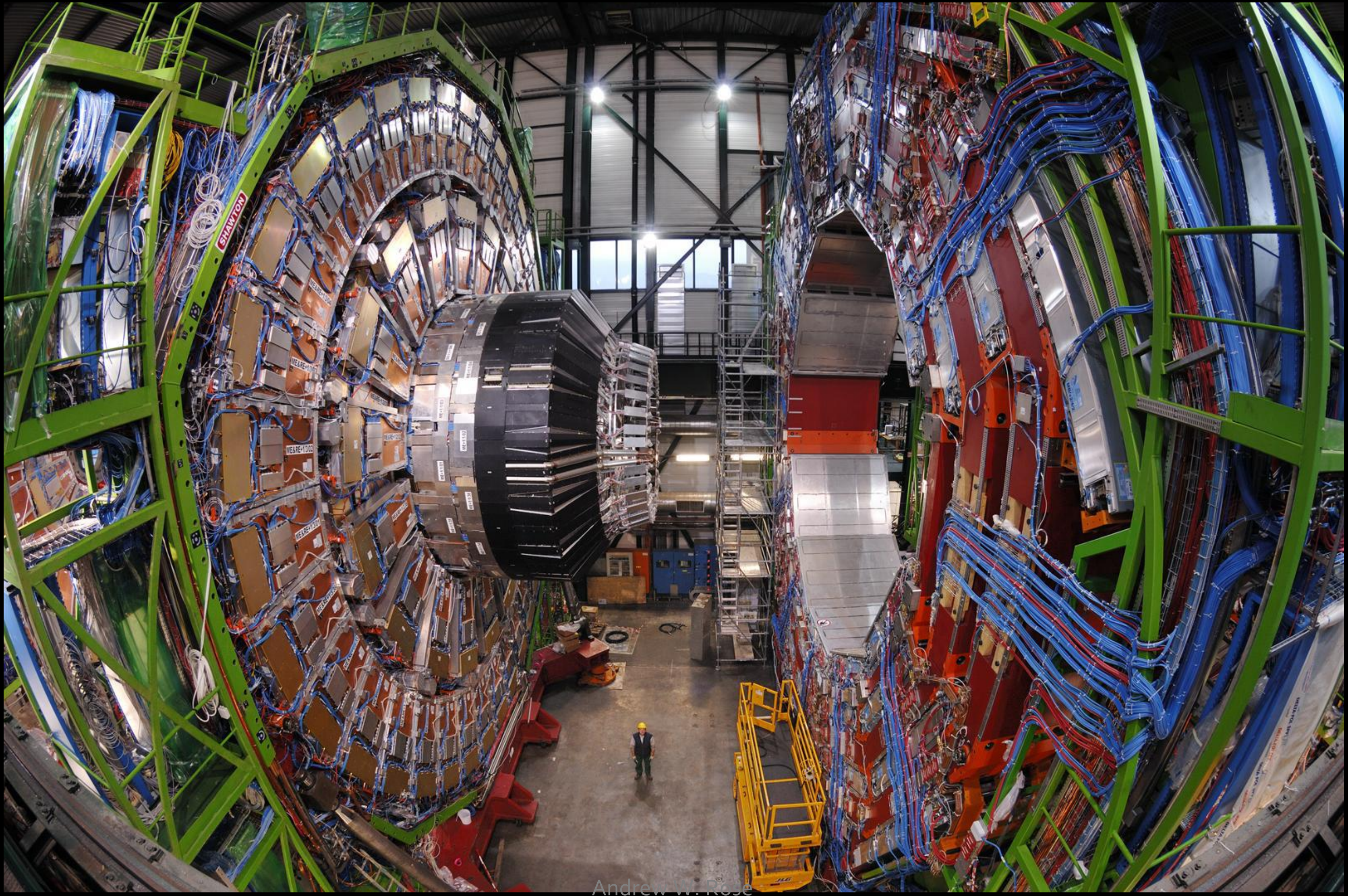
The CMS detector



The CMS detector



The CMS detector



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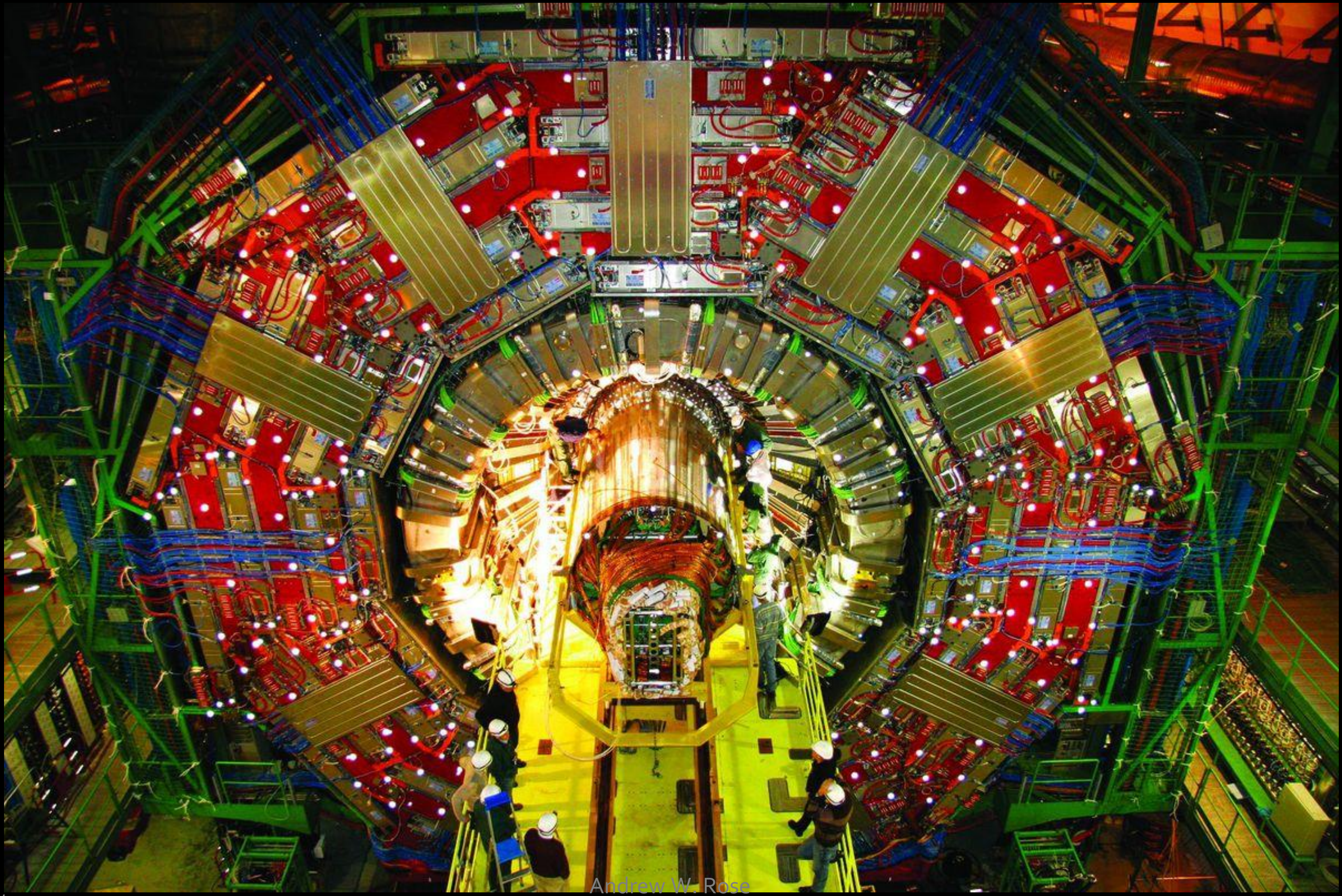

How to detect particles

How to detect particles

Minimal disruption

Maximal disruption

How to detect particles

Minimal disruption

- Tracking
- Measure precise position as particles pass through
- Join the dots to produce tracks
- Use B-field to provide curvature with which to measure momentum of charged particles

Maximal disruption

CMS Silicon Strip Tracker

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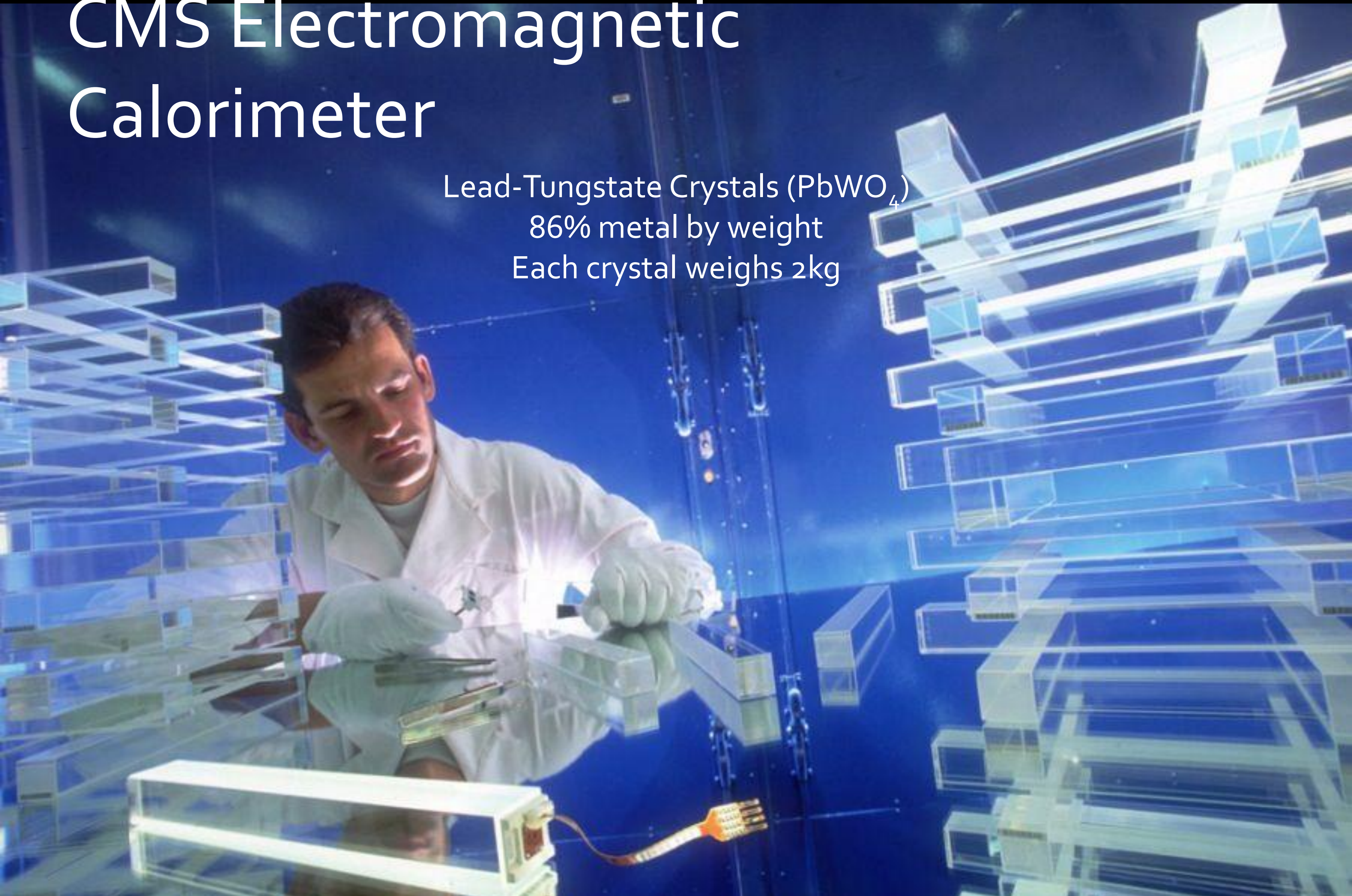
Maximal disruption

- Calorimetry
- Put a lot of material in the way
- Atomic and nuclear interactions force decay down to light particles including photons
- Measure the energy in the photons
- Proportional to the energy of the original particle

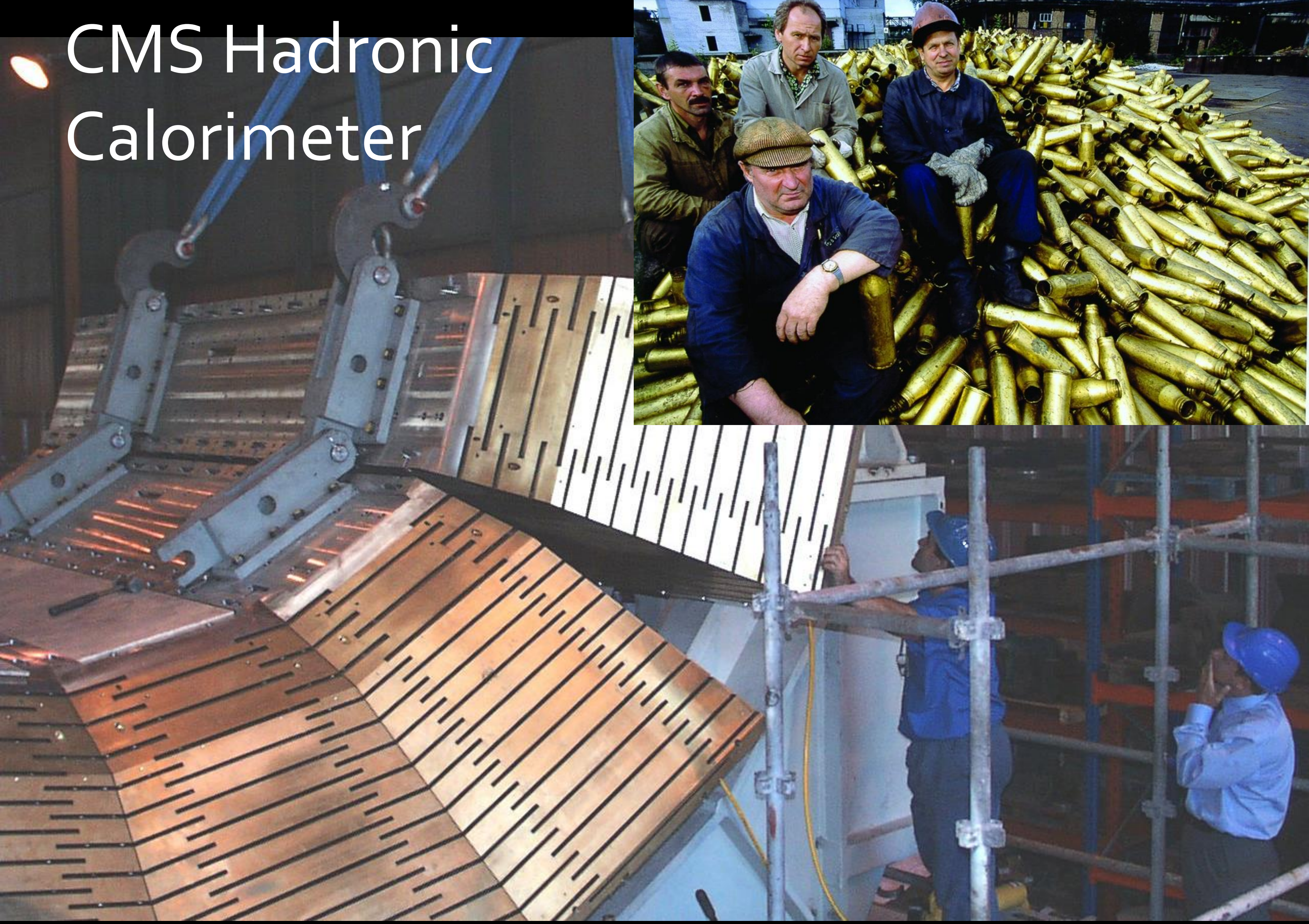
CMS Electromagnetic Calorimeter



Lead-Tungstate Crystals ($PbWO_4$)
86% metal by weight
Each crystal weighs 2kg

CMS Hadronic Calorimeter

CMS Hadronic Calorimeter



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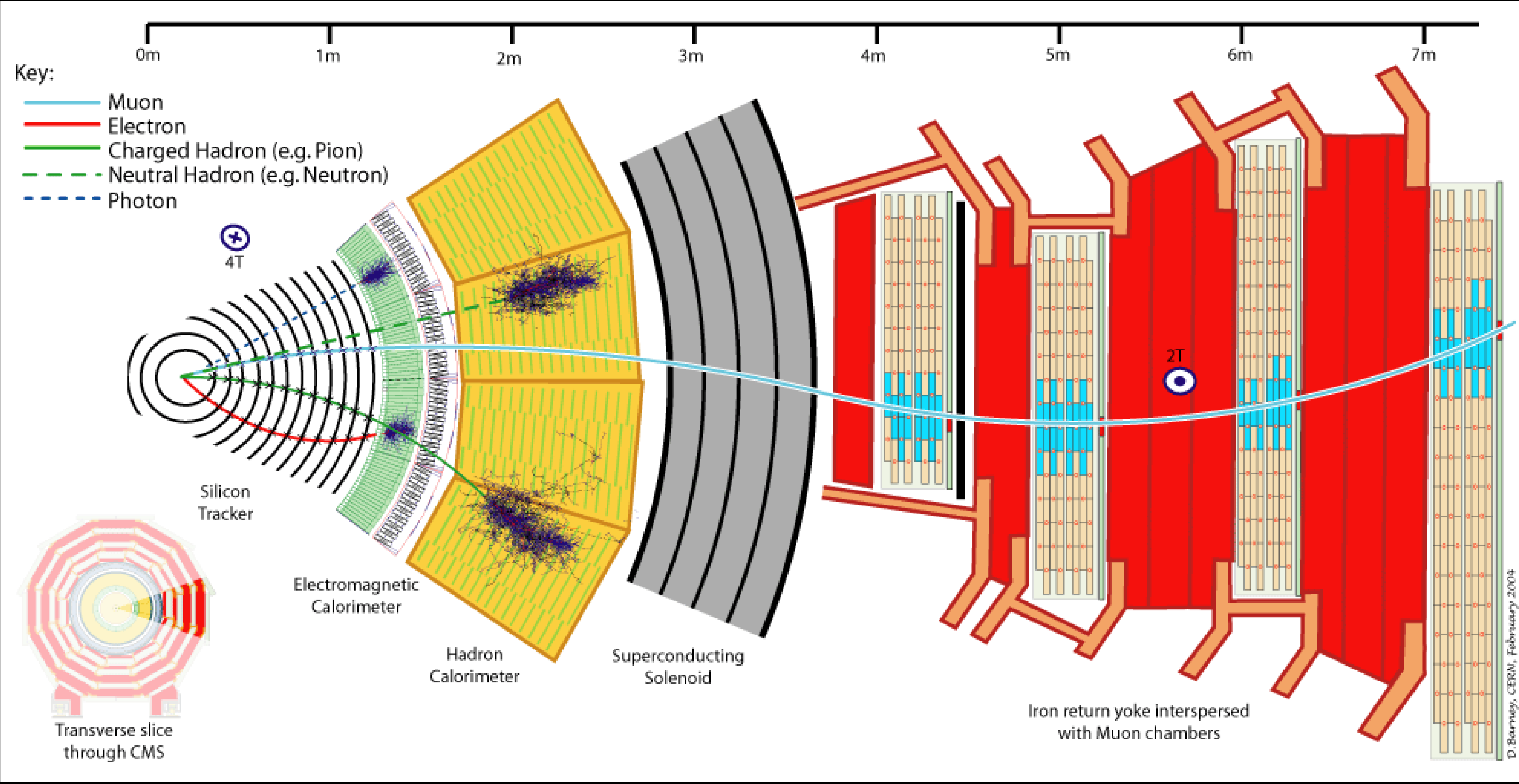
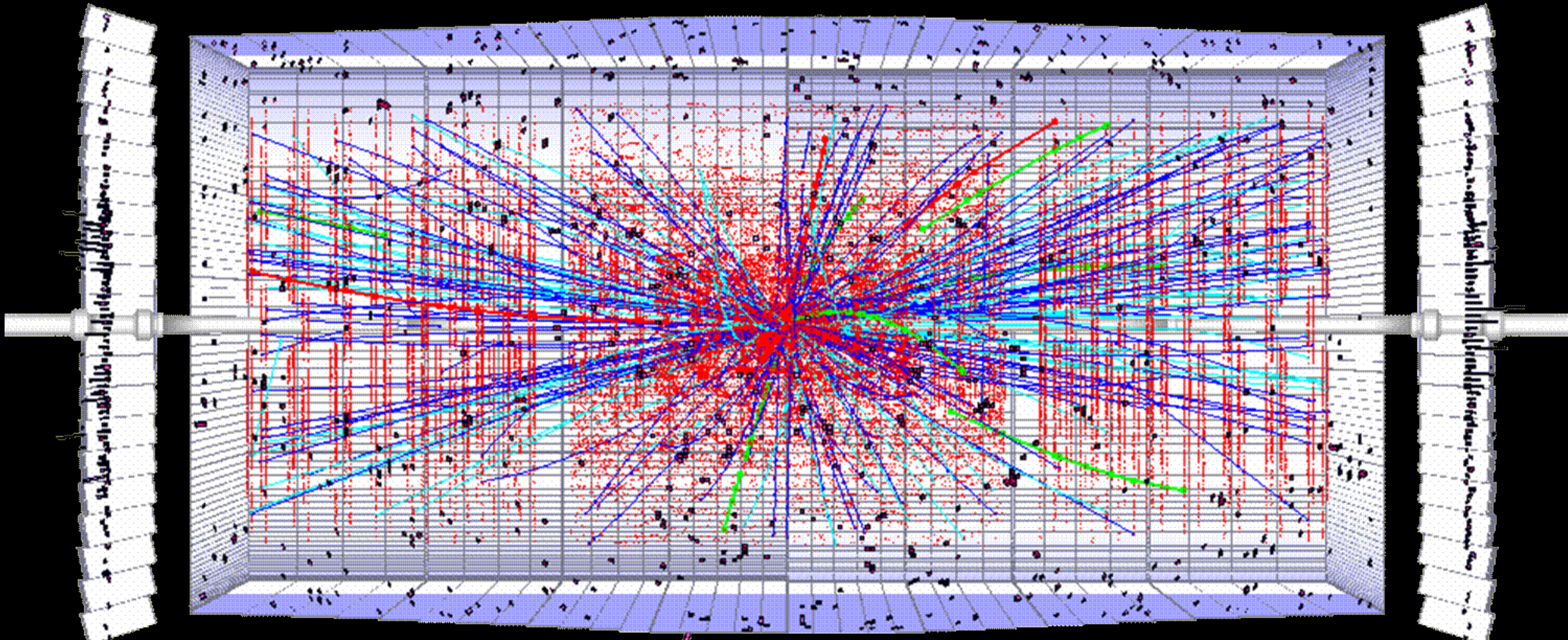
The CMS detector

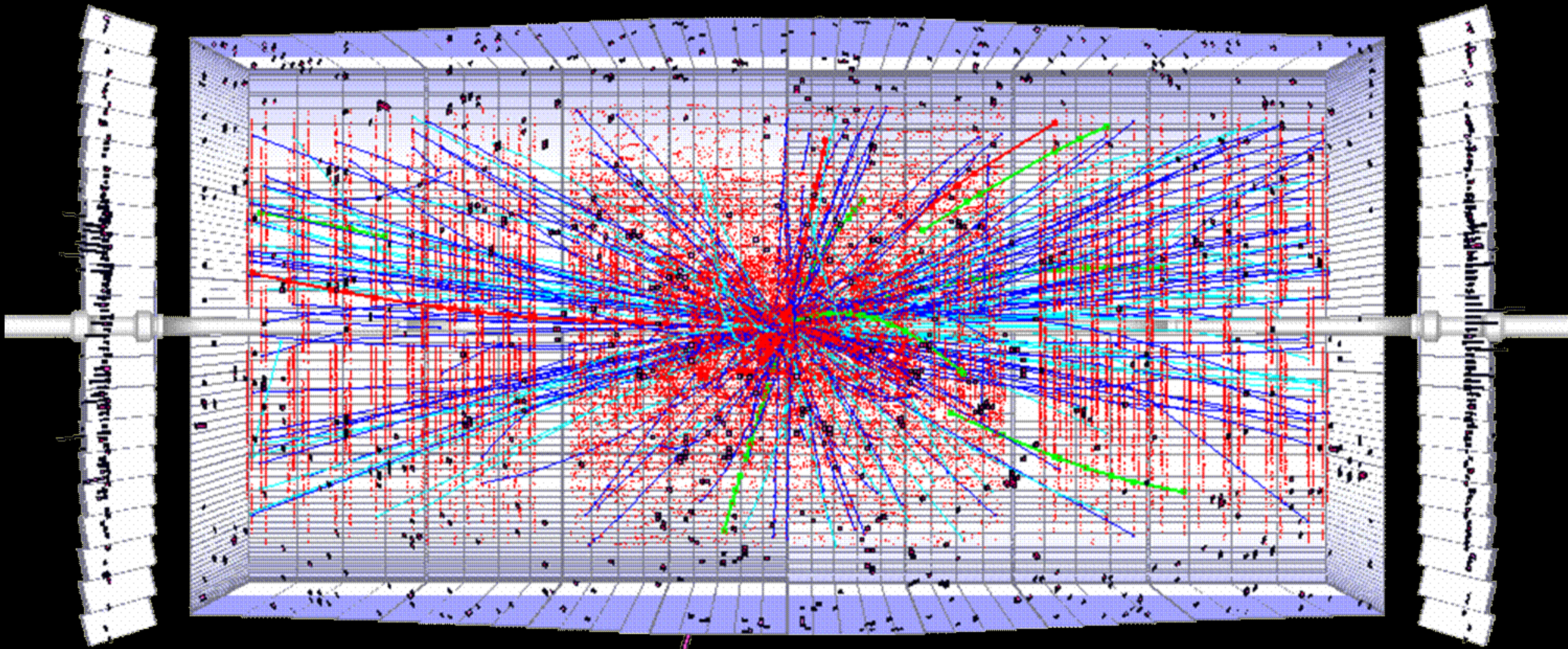


Just to keep things interesting…



L = $O(10^{34})$ $cm^{-2}s^{-1}$
~25 interactions/bx

Just to keep things interesting…



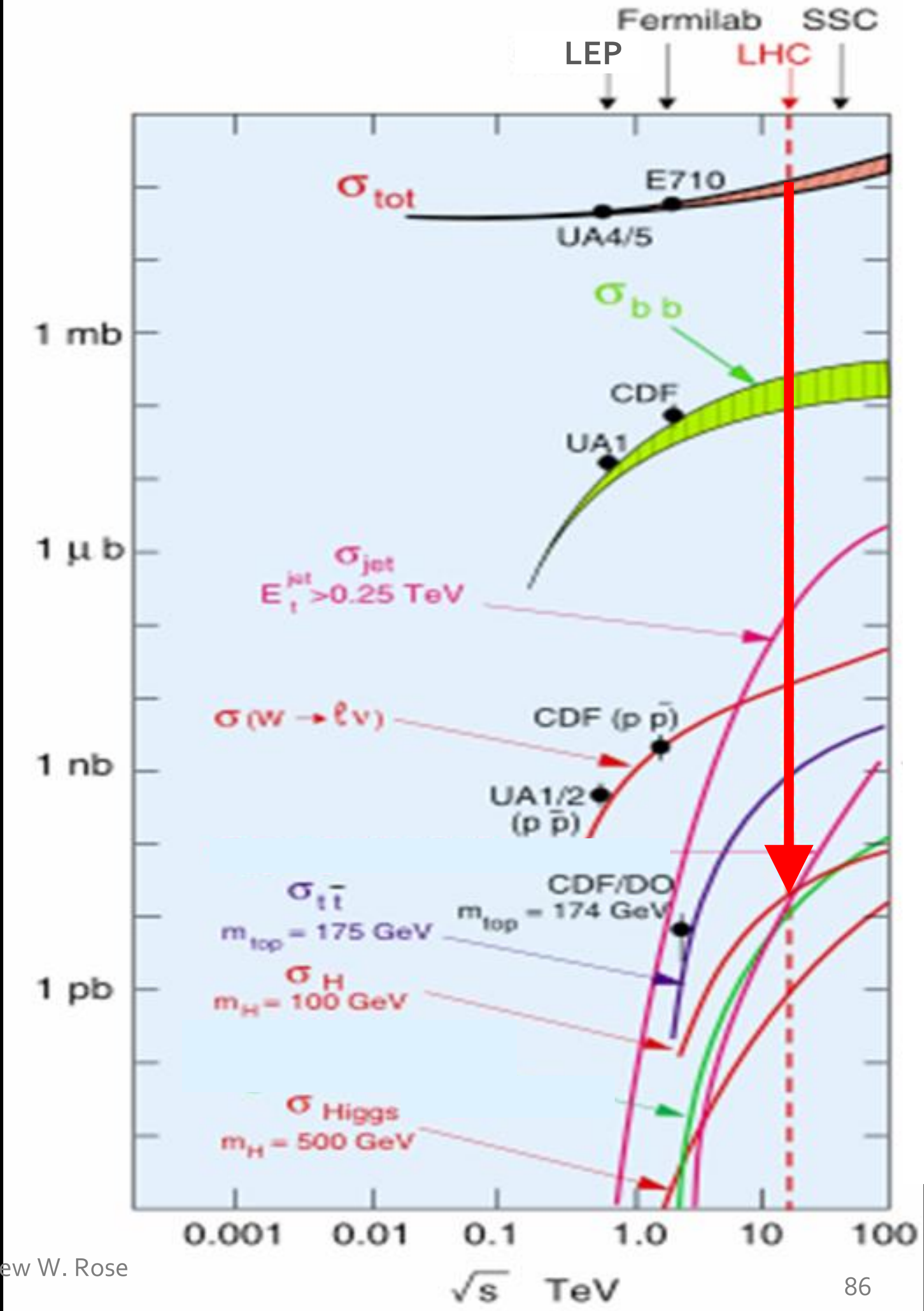
$L = O(10^{34})\ cm^{-2}s^{-1}$ × 40 million bx
~25 interactions/bx per second

Why would you do that?

Why would you do that?

Higgs Boson production is:

- Two order of magnitude lower than the top-quark
- Three orders of magnitude lower than W-boson
- **Ten orders of magnitude below the total interaction rate**



Why would you do that?

Higgs Boson production is:

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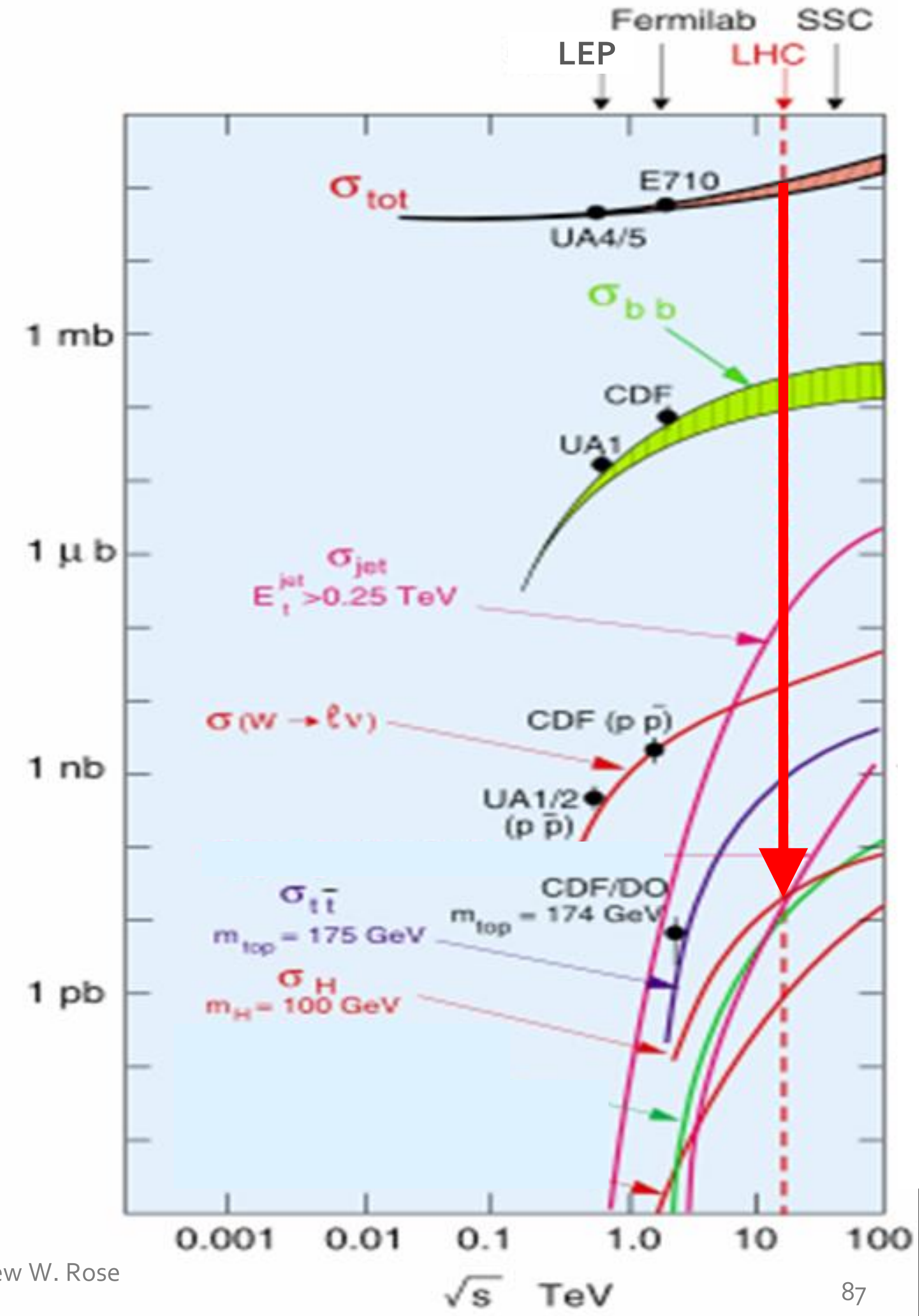
- Three orders of magnitude lower than W-boson
- **Ten orders of magnitude below the total interaction rate**

That is a needle in
a haystack the same mass as the
Empire State Building



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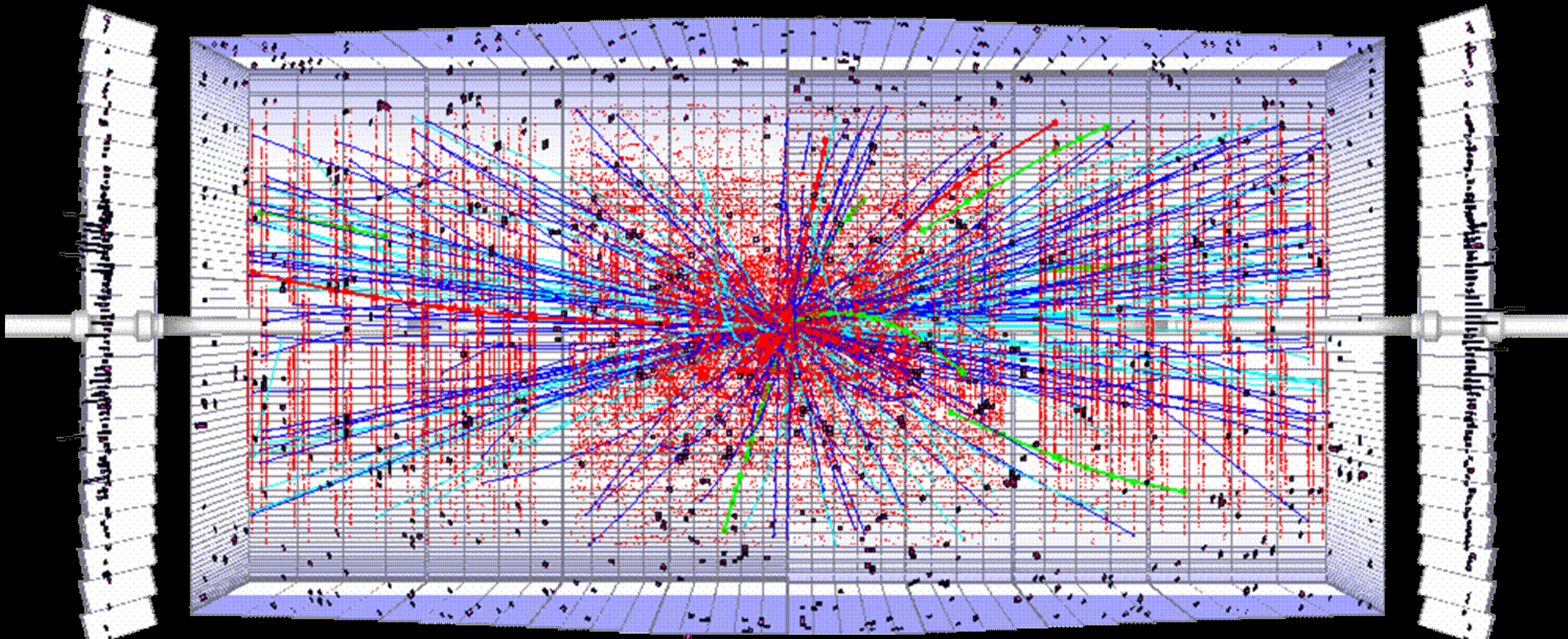
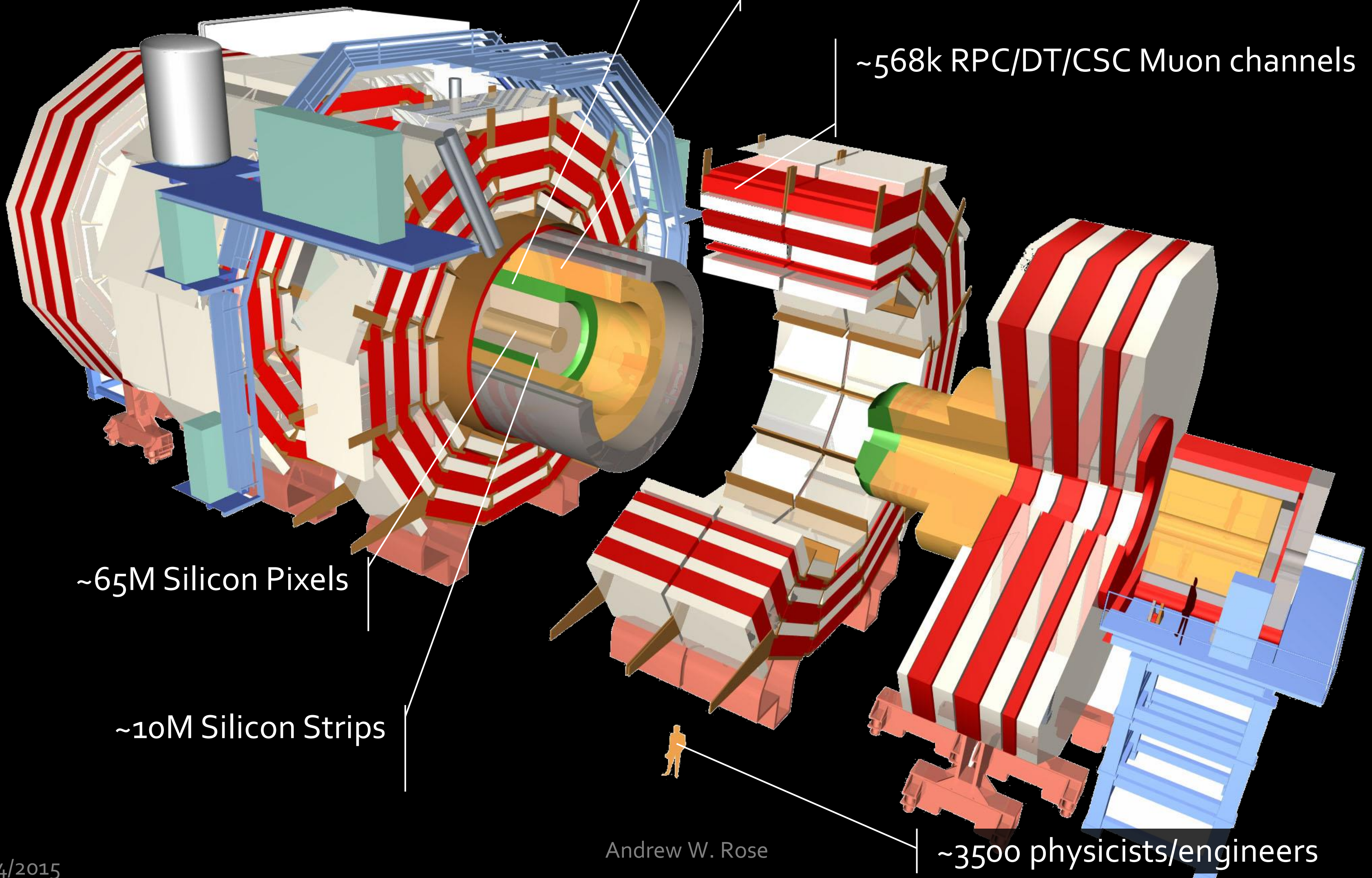


L = O(10^{34}) $cm^{-2}s^{-1}$ × 40 million bx
~25 interactions/bx per second

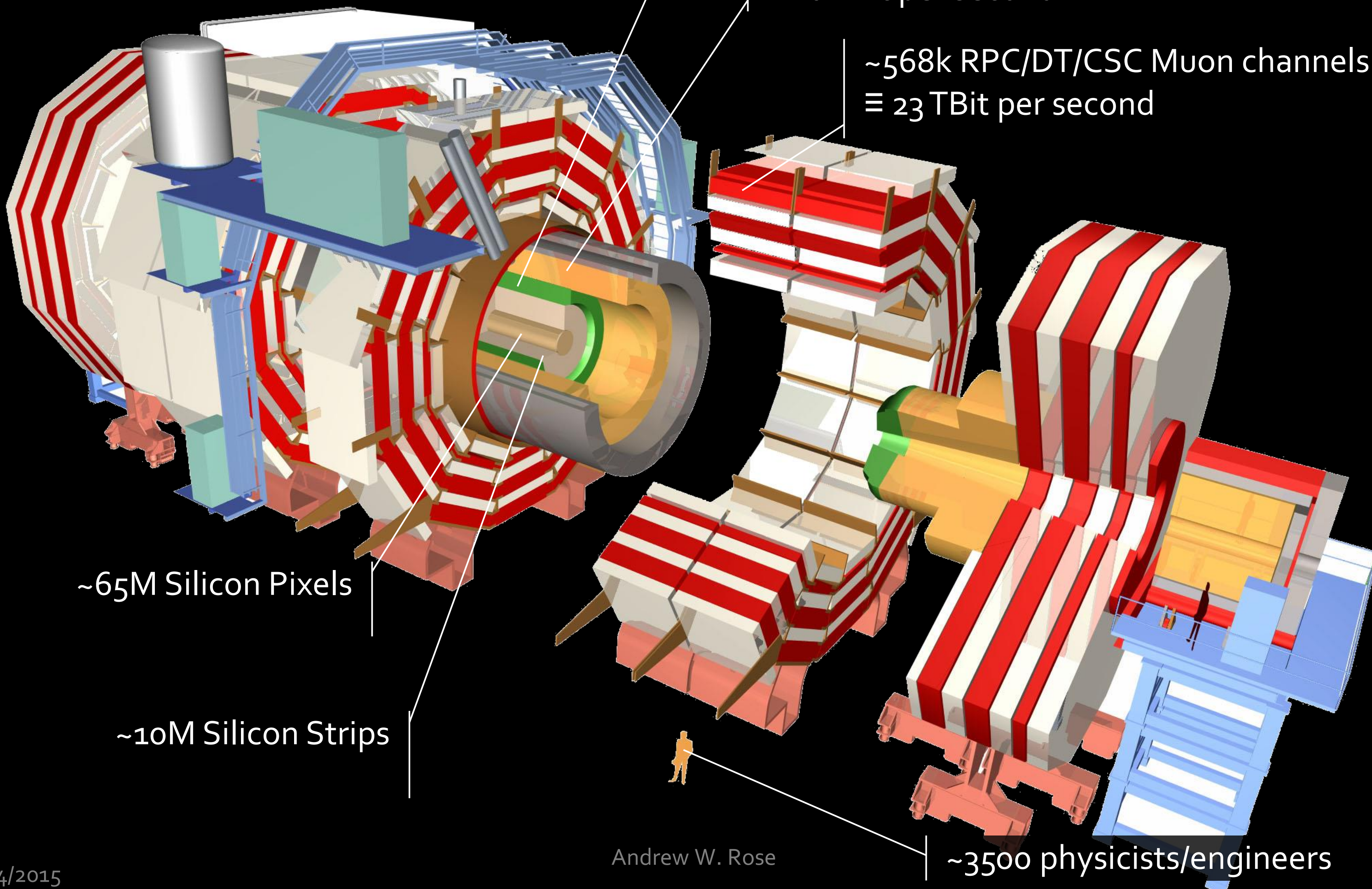
1 billion proton-proton interactions per second

The CMS detector



The CMS detector

Data rates before zero-suppression



The CMS detector

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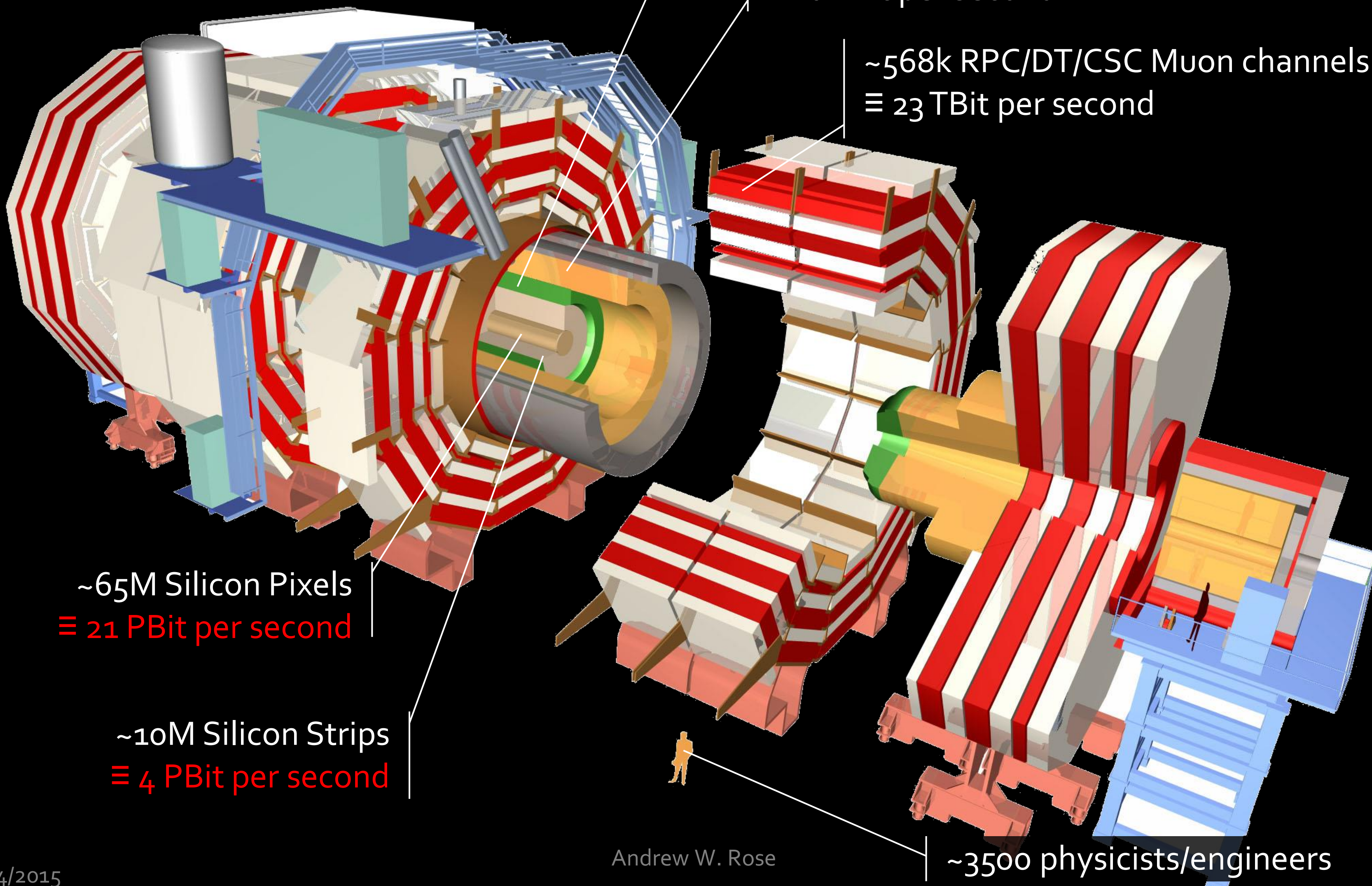
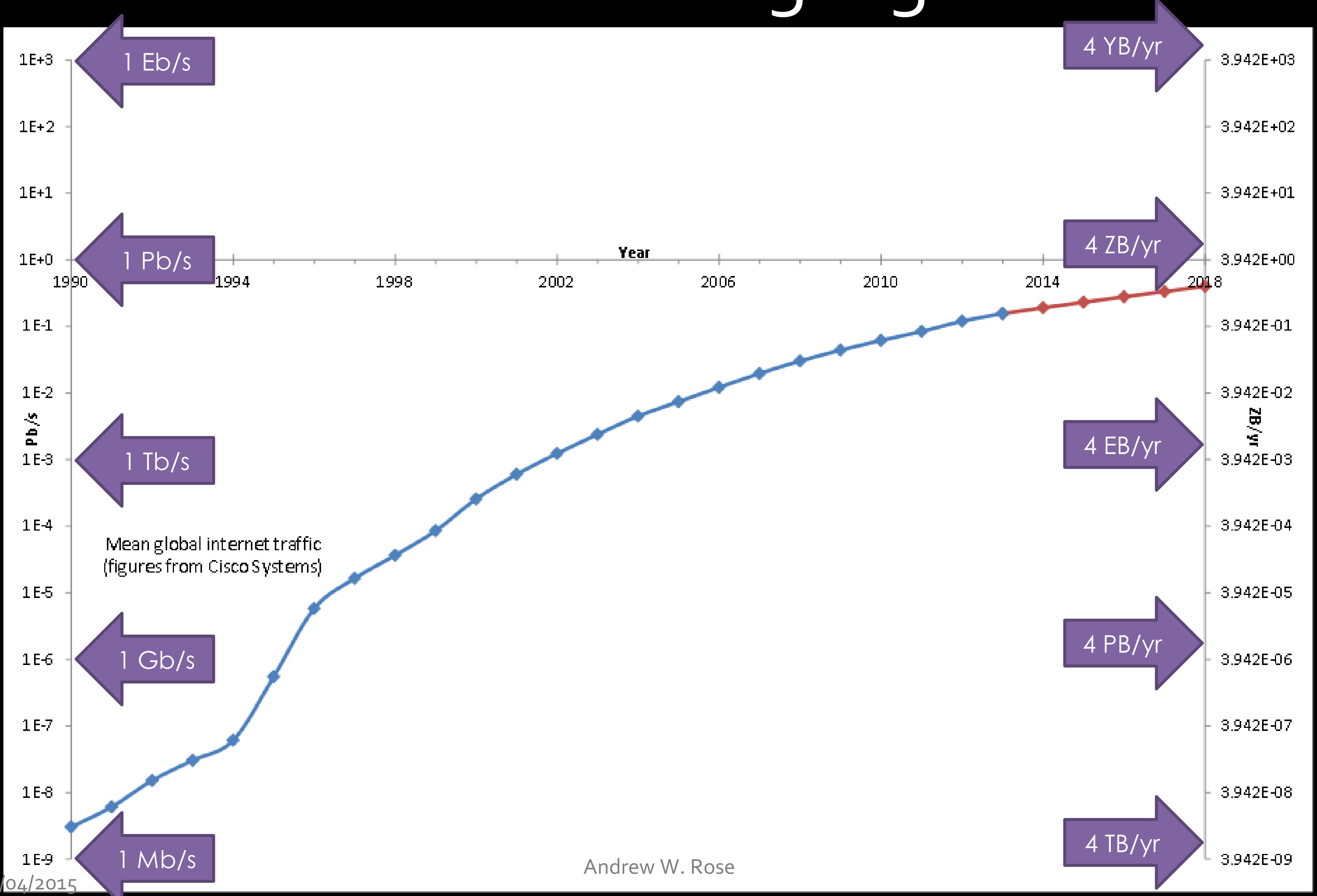
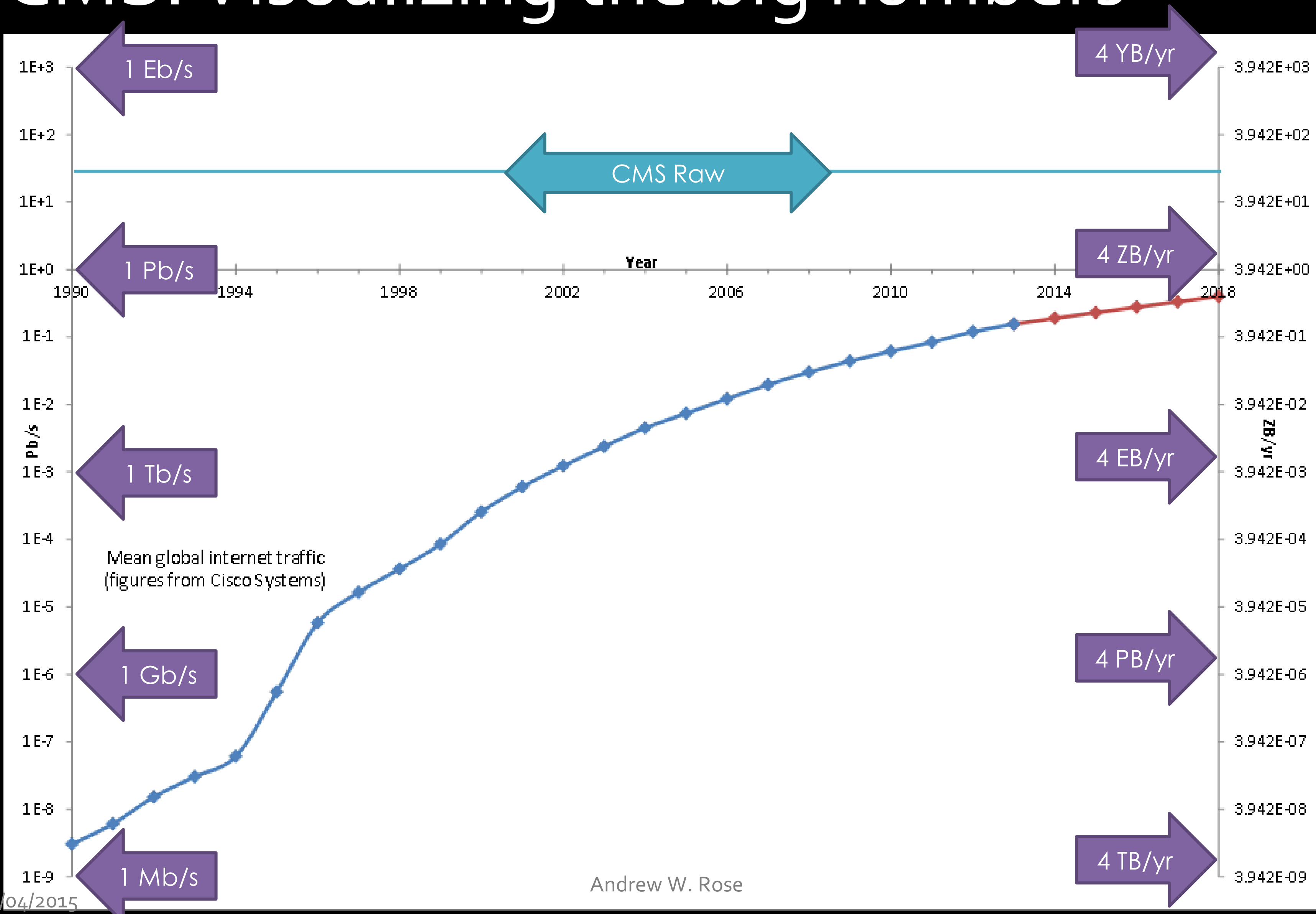


The Internet: Visualizing big numbers



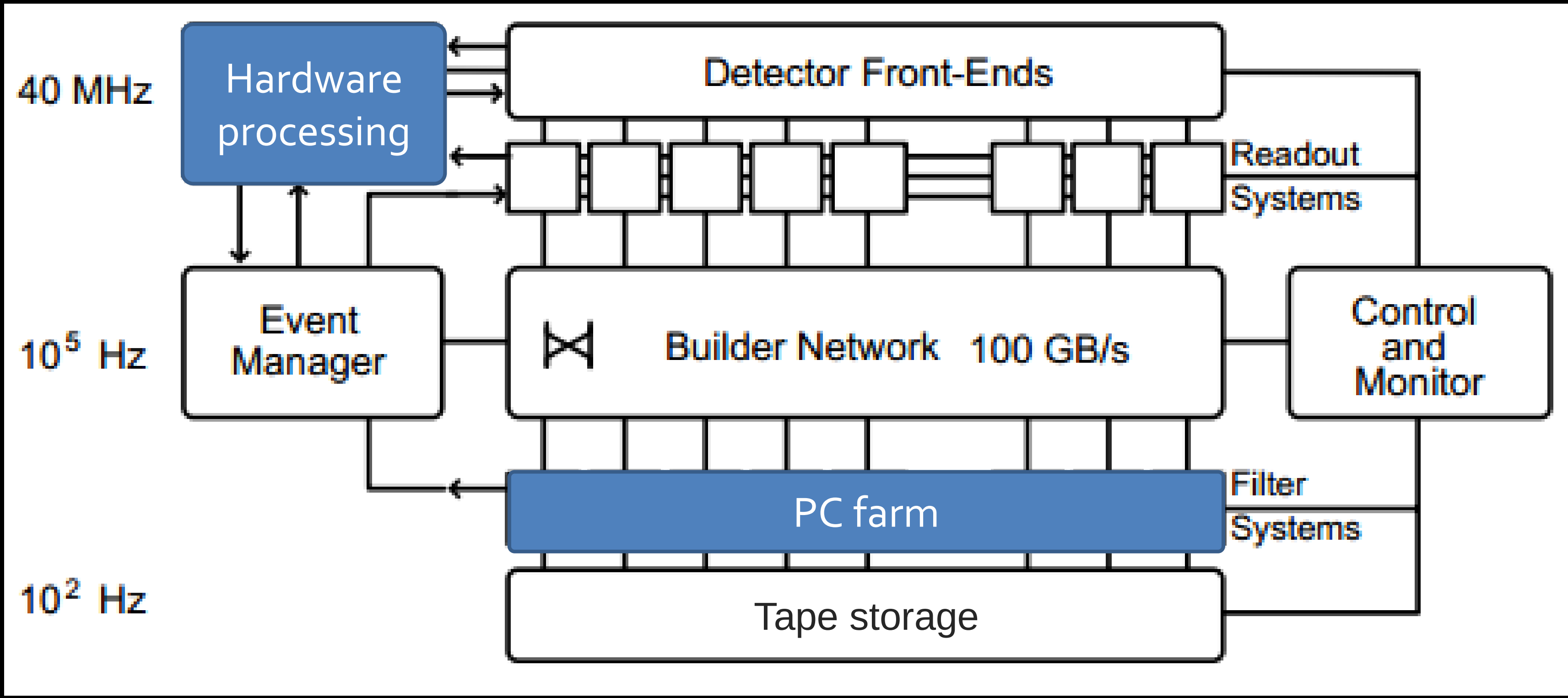
CMS: Visualizing the big numbers



How do you store O(Pb/s) data?

How do you store O(Pb/s) data?

Answer: You don't! You have to throw most of it away!



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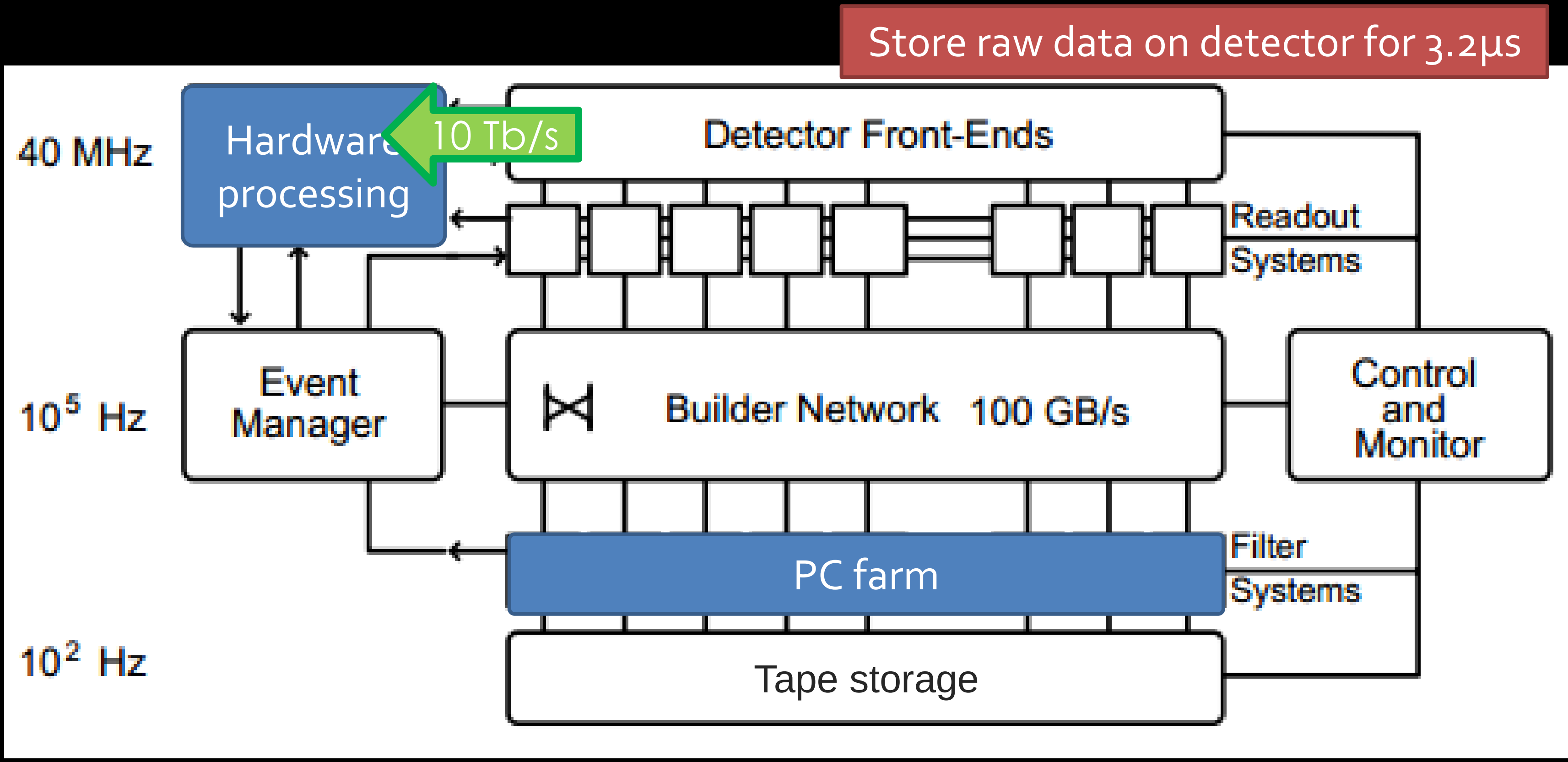
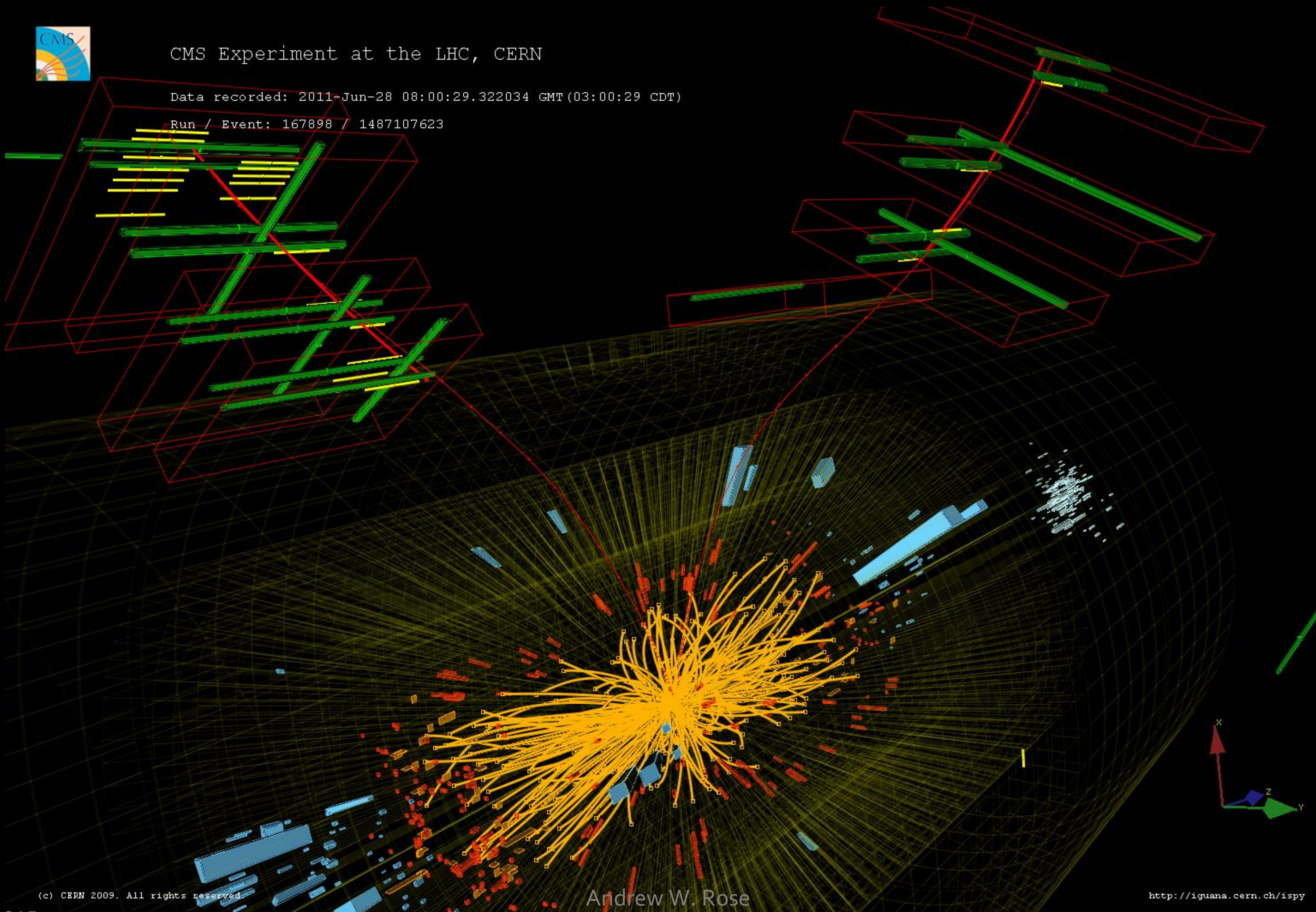
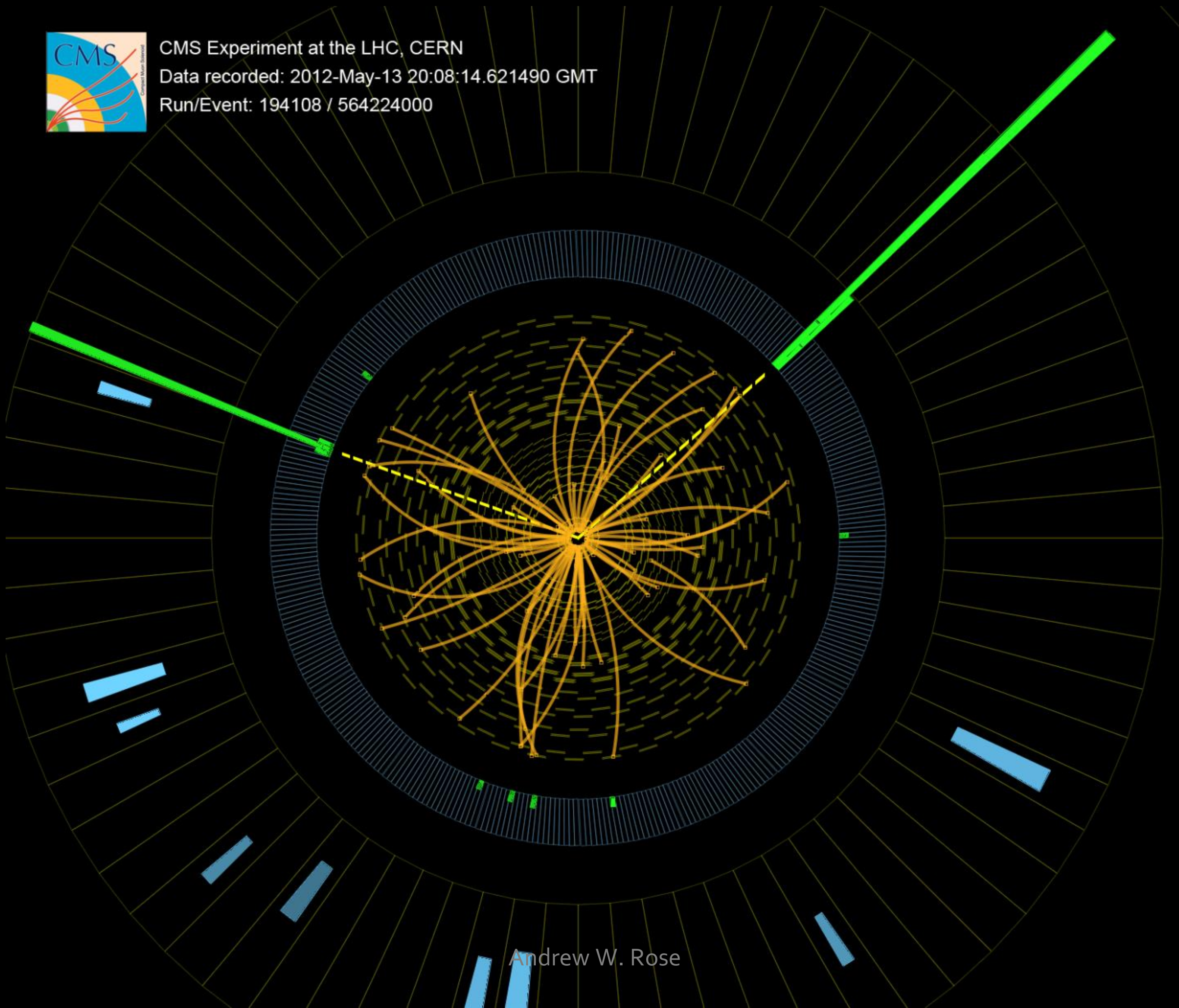


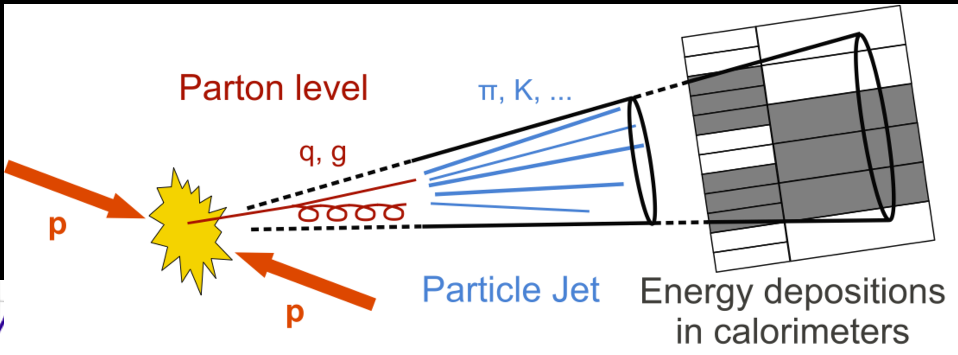
Muon Candidates: Join the dots

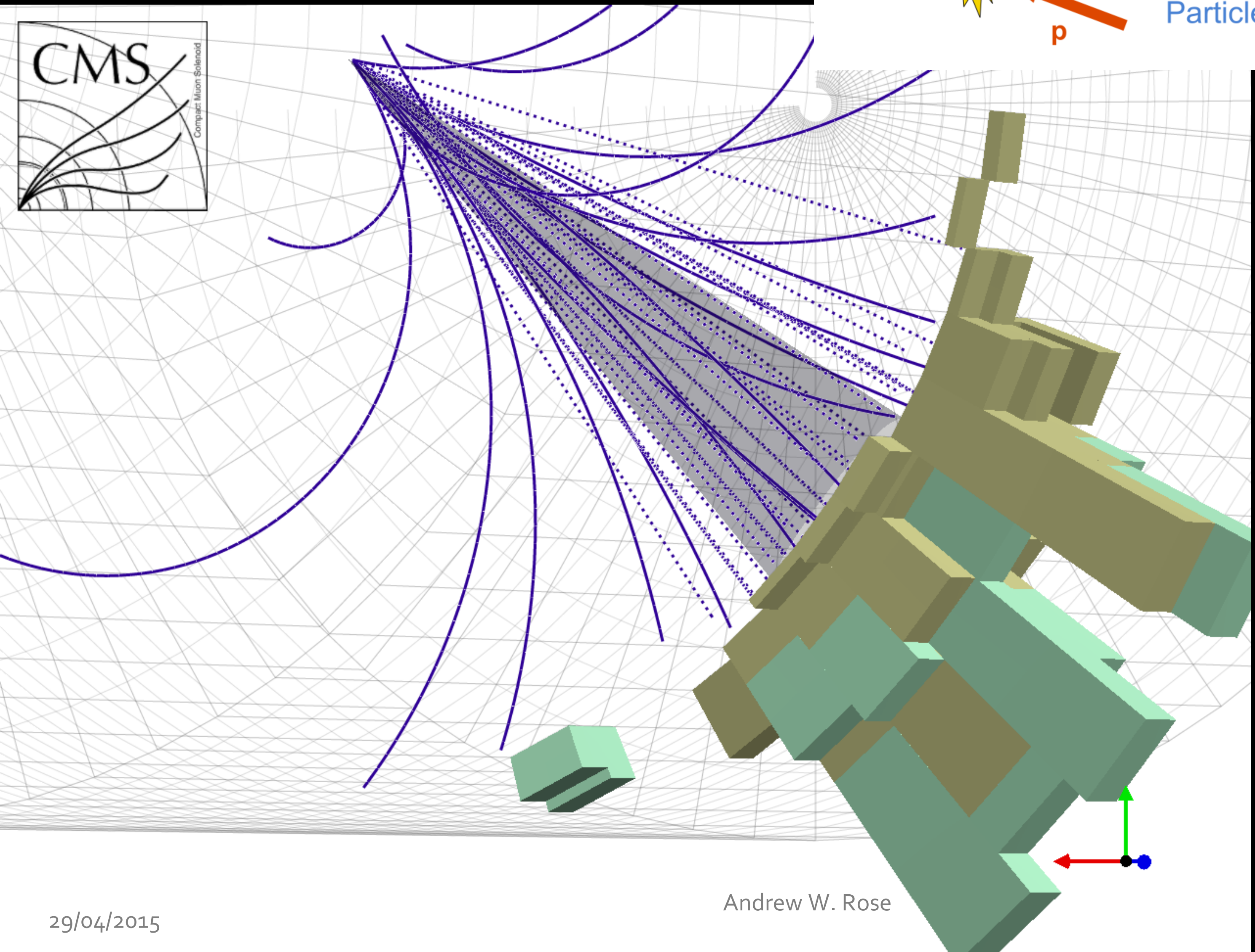


Electron/Photon Candidates: Spikes



Jet Candidates: A mess





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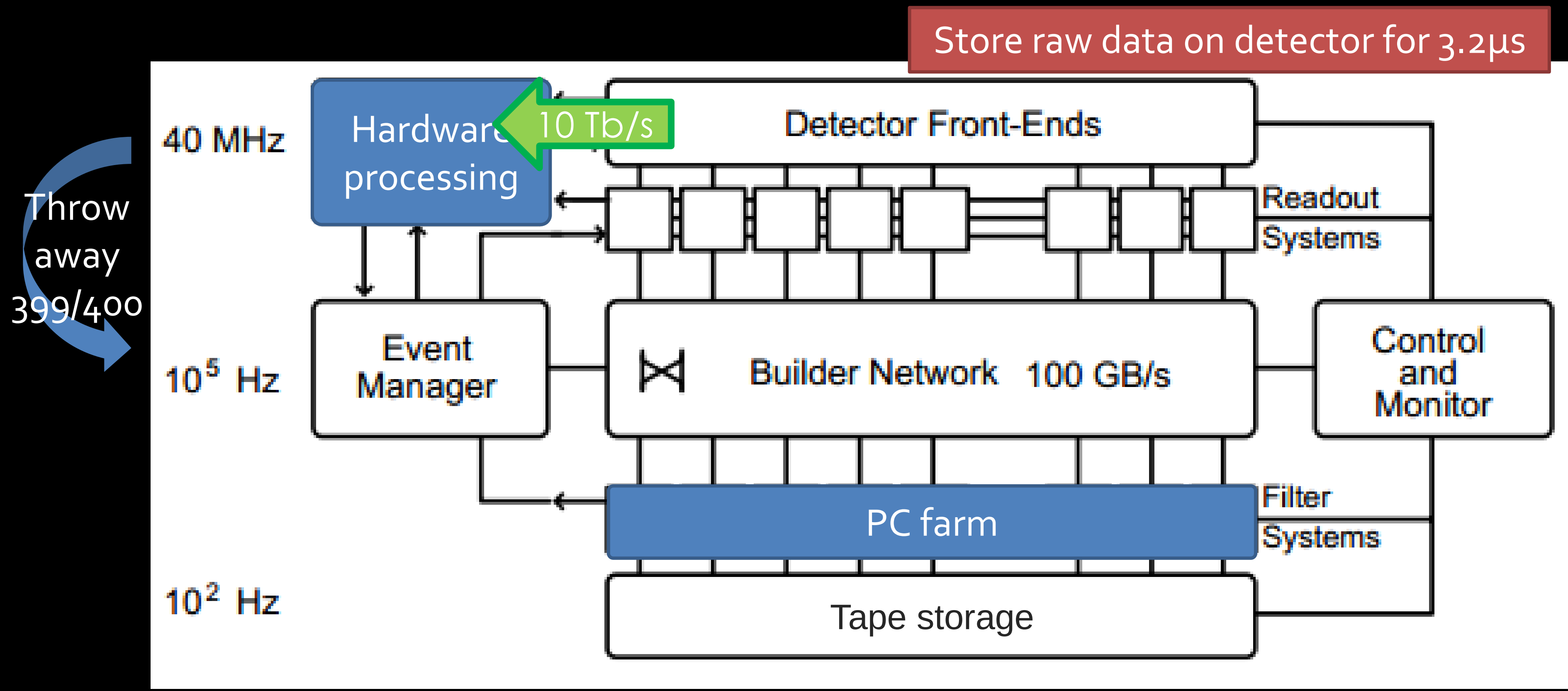
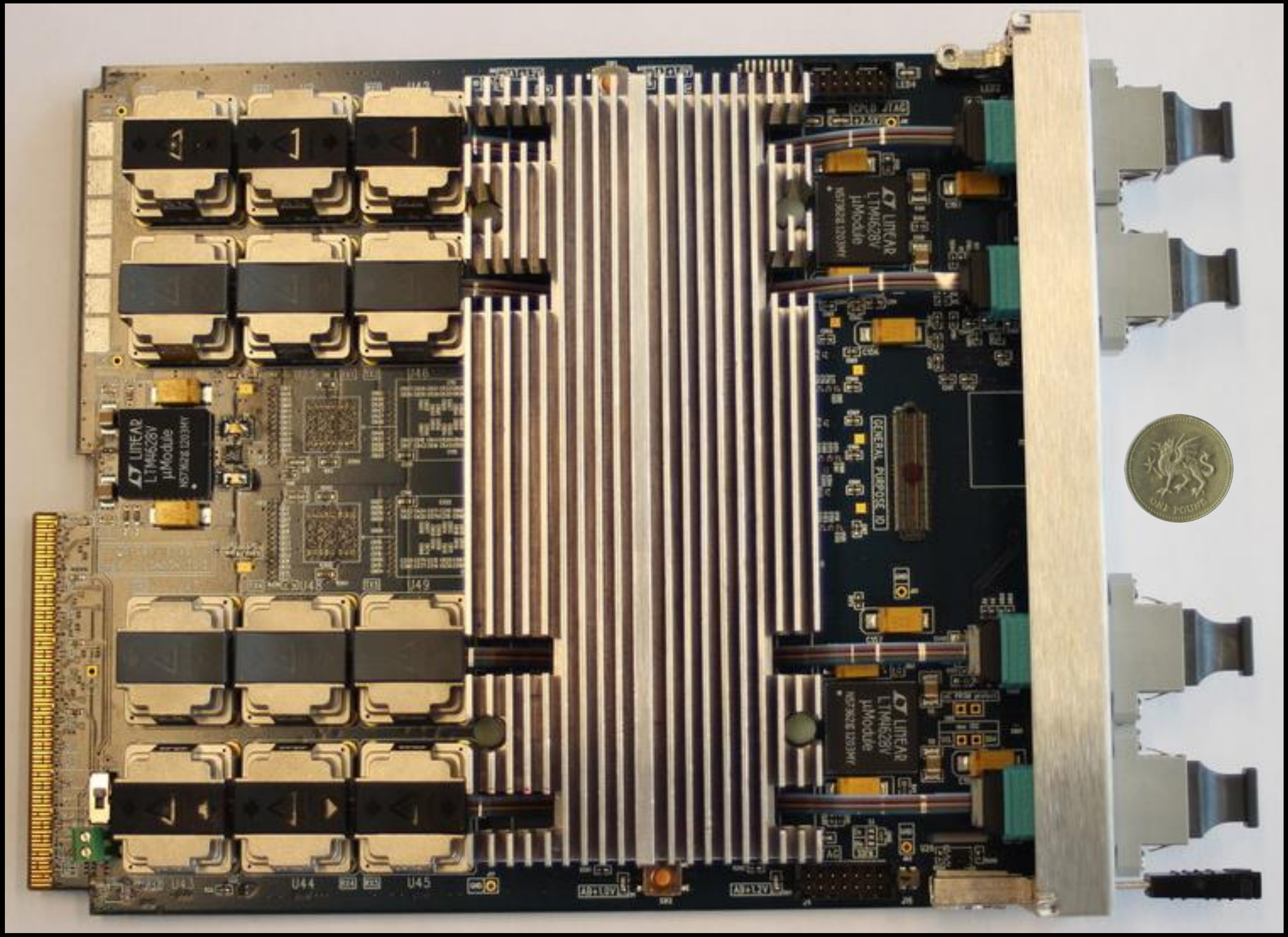


The Master-Processor, Virtex-7 (MP7)



Andrew Rose, Greg Iles

Imperial College London

72Tx+72Rx optical links @ 13Gbps = 0.9 + 0.9Tb/s signal processor

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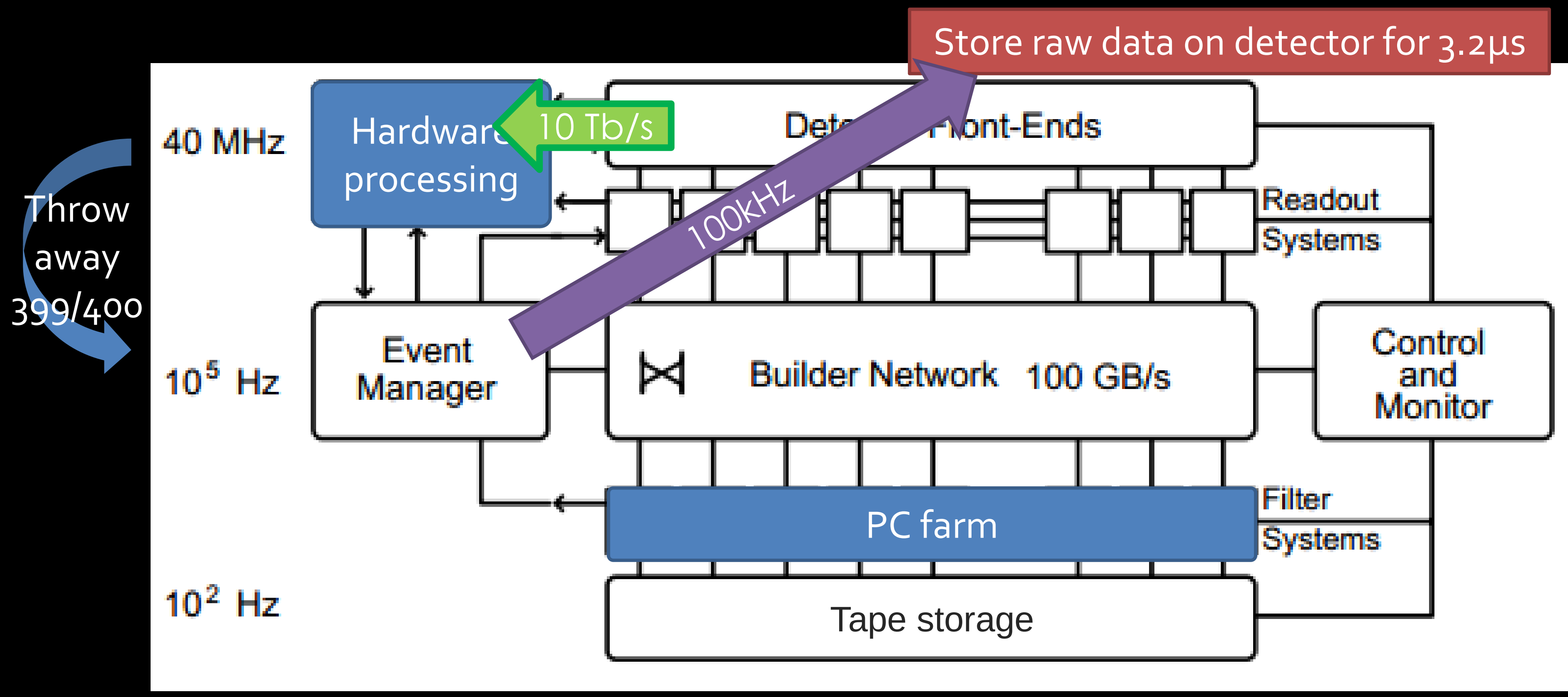

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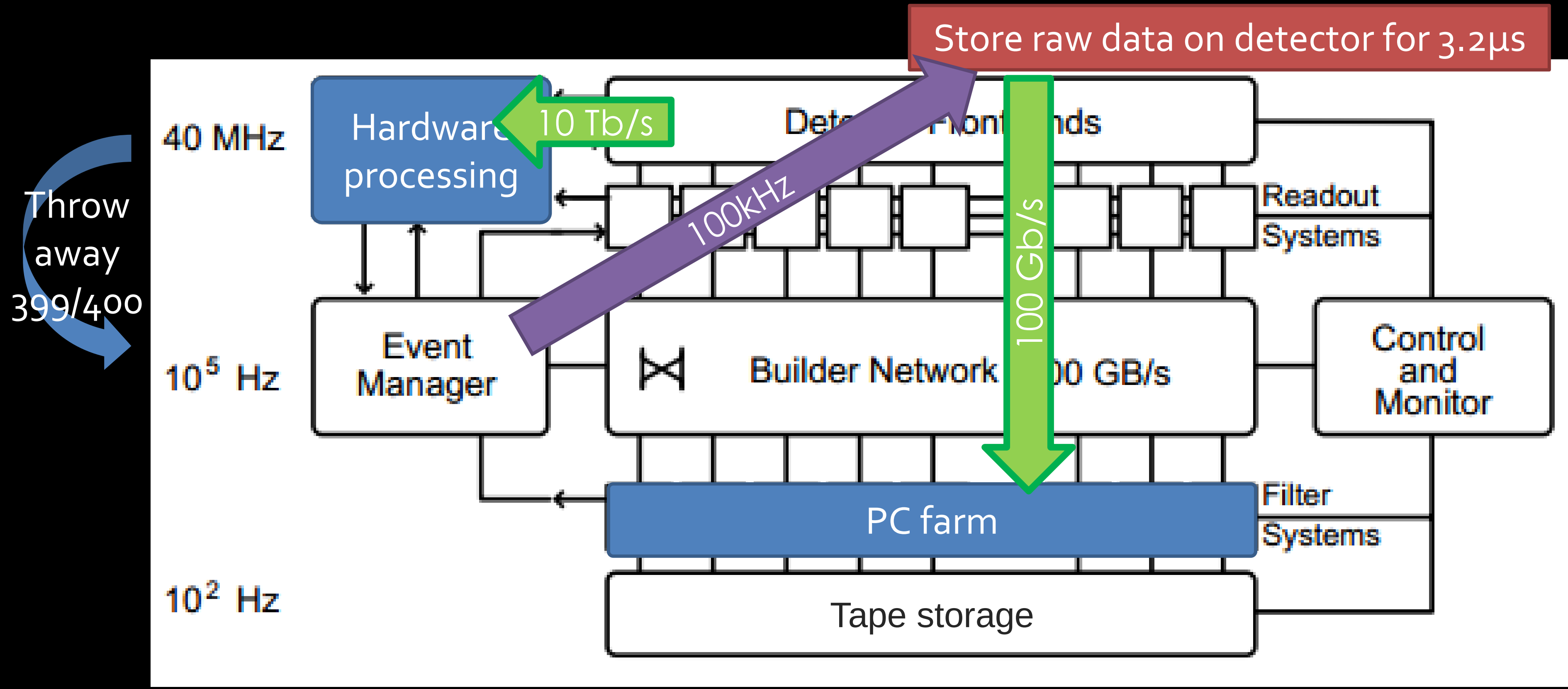

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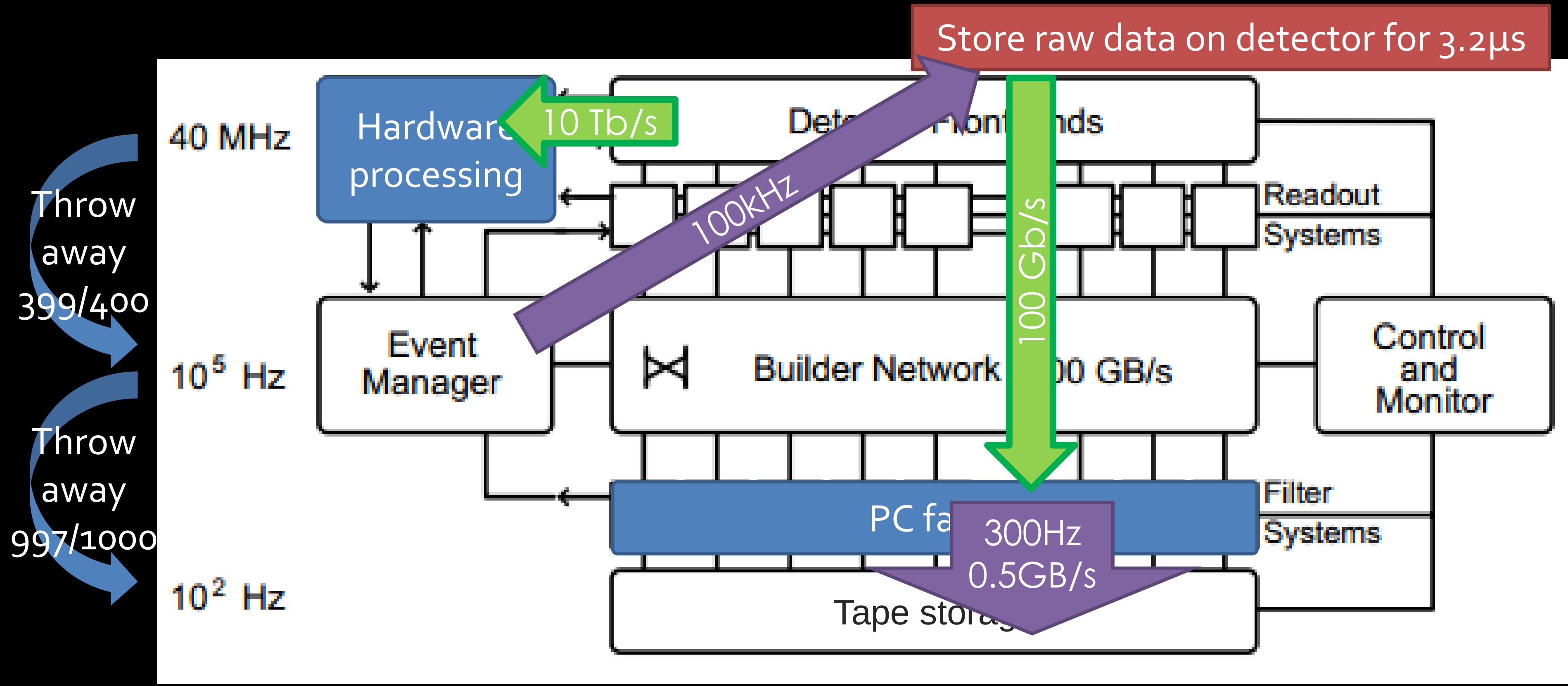

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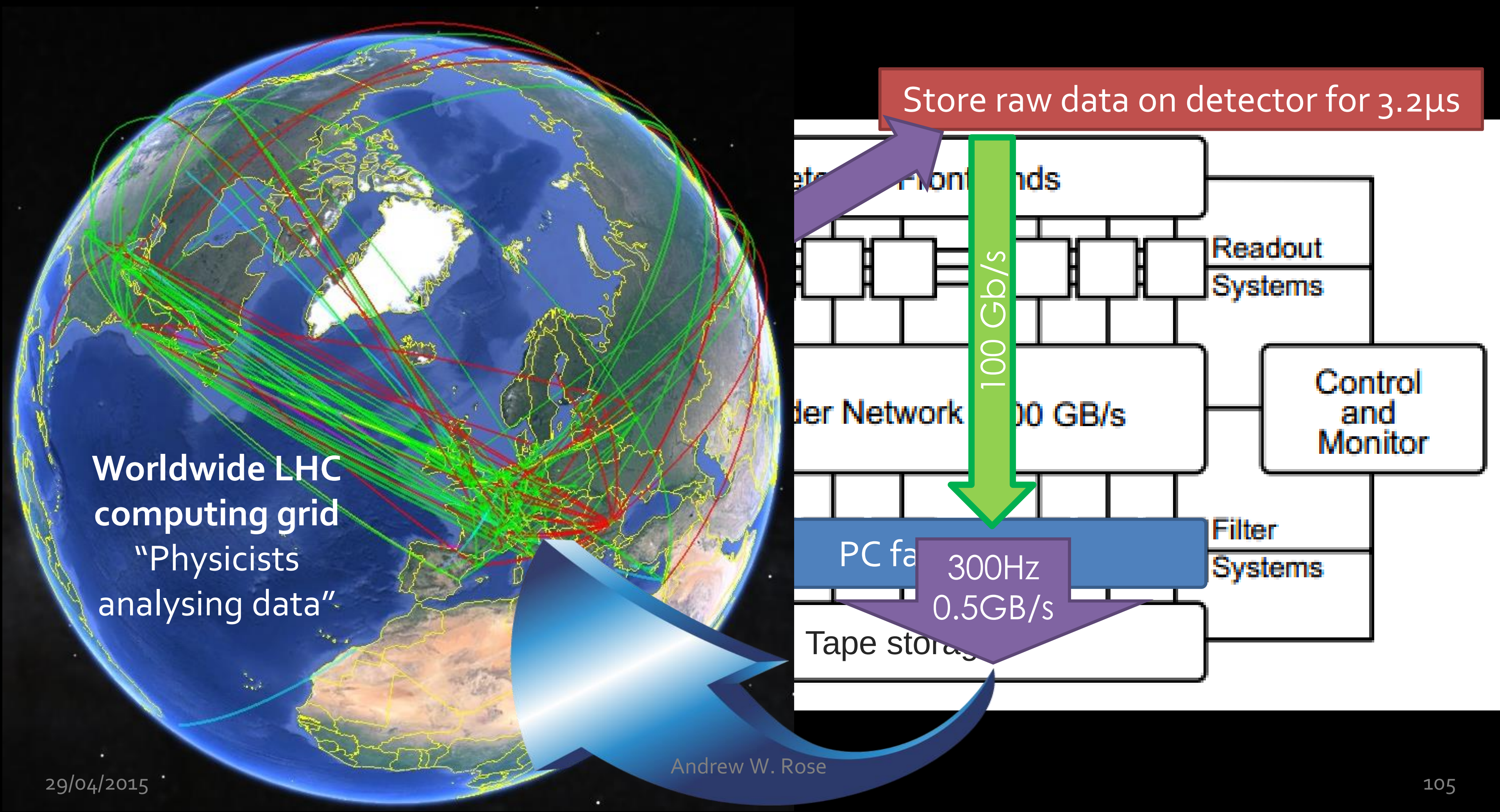
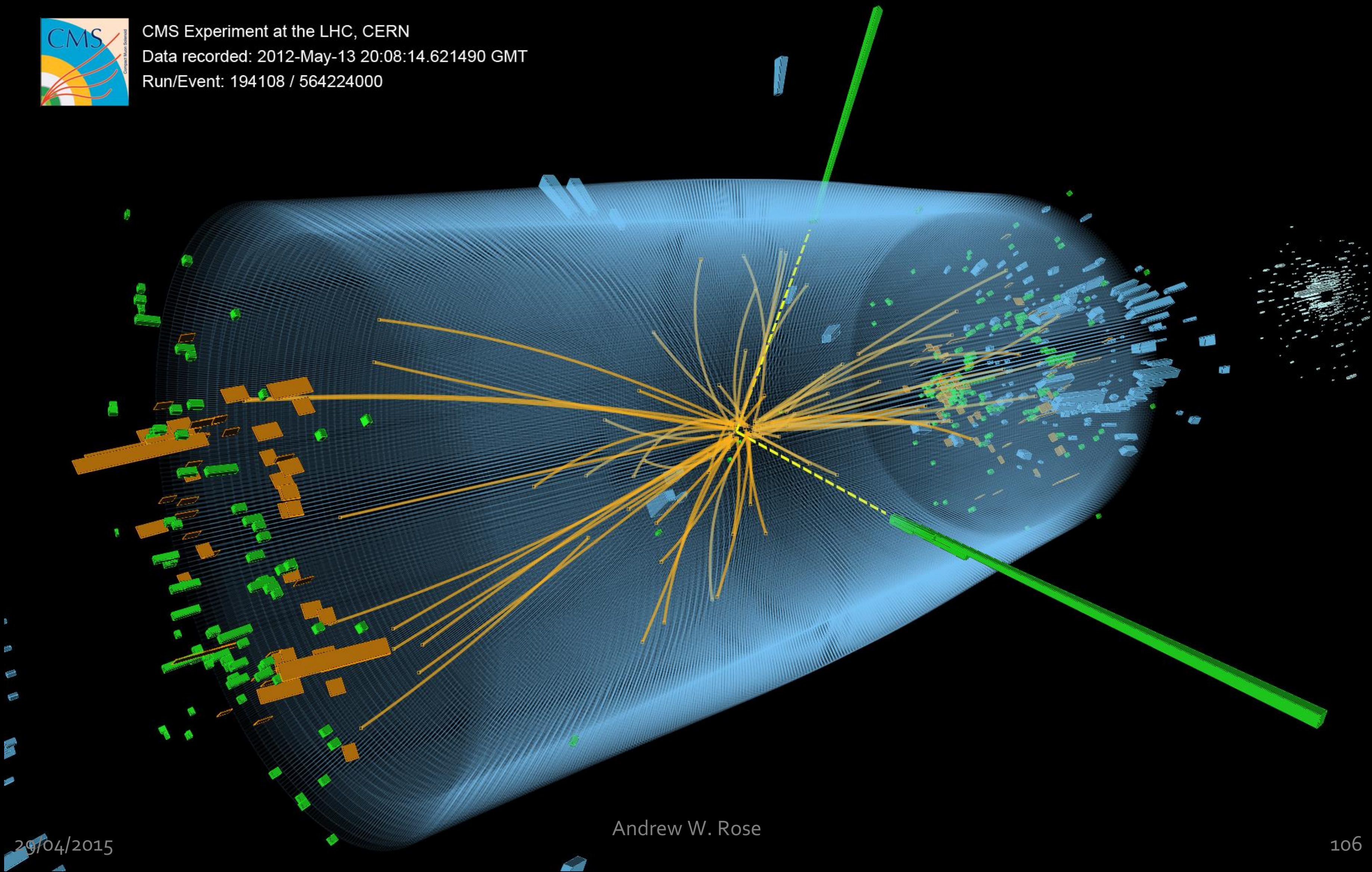
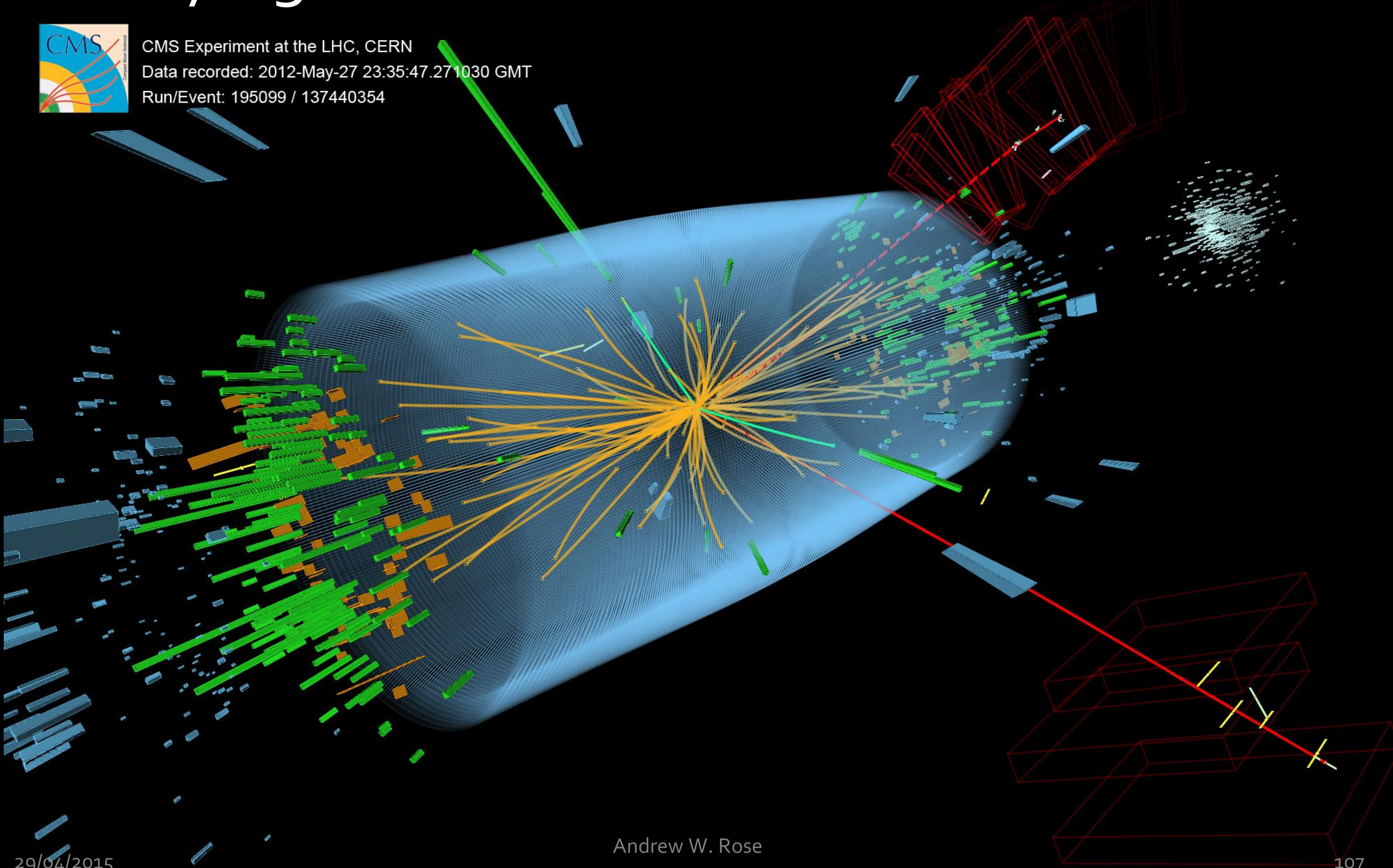


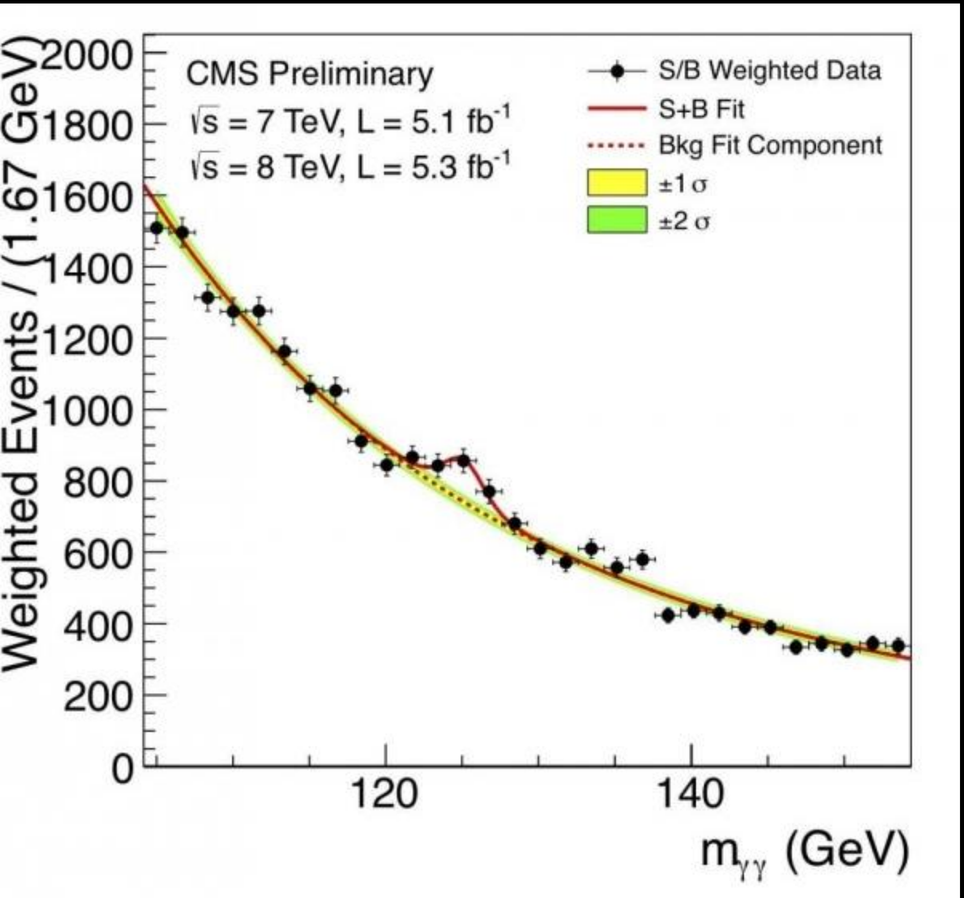
First observation of a 125GeV particle decaying to two photons



First observation of a 125GeV particle decaying to two Z-bosons



Congratulations – it's a boson



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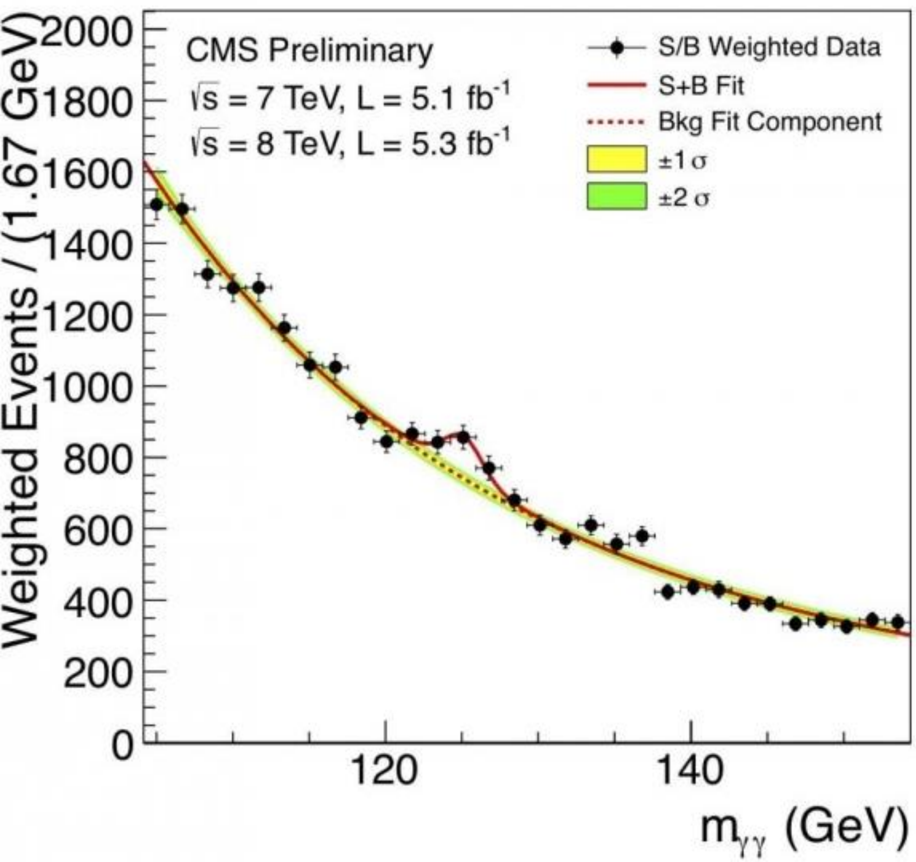

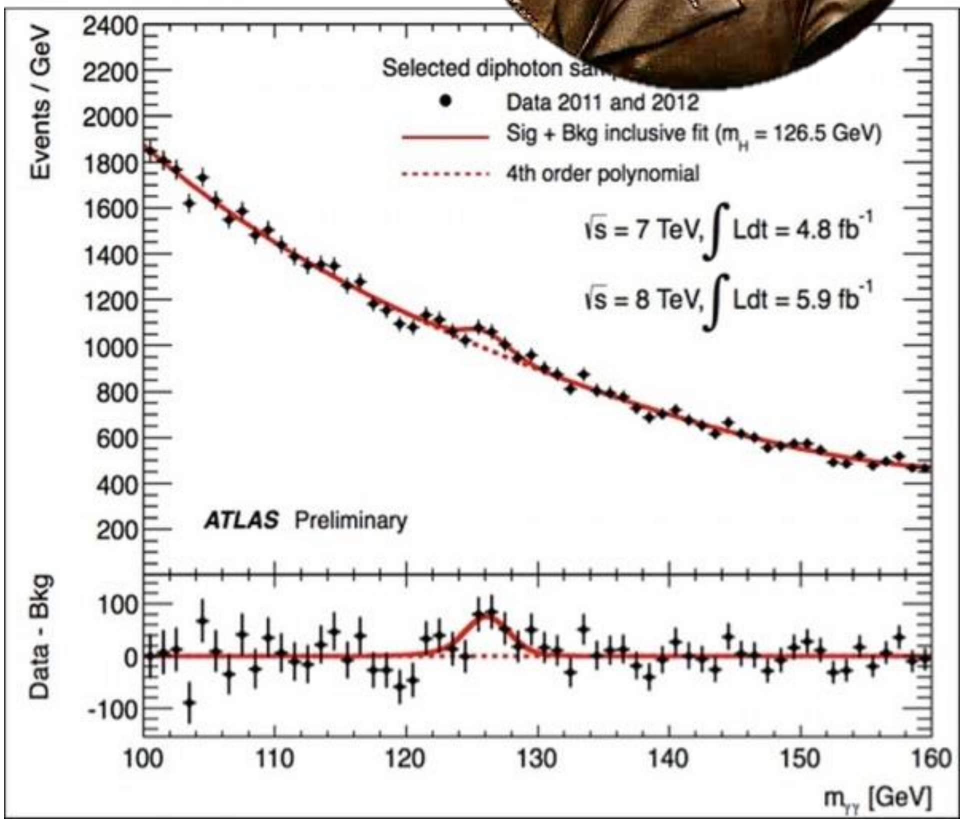

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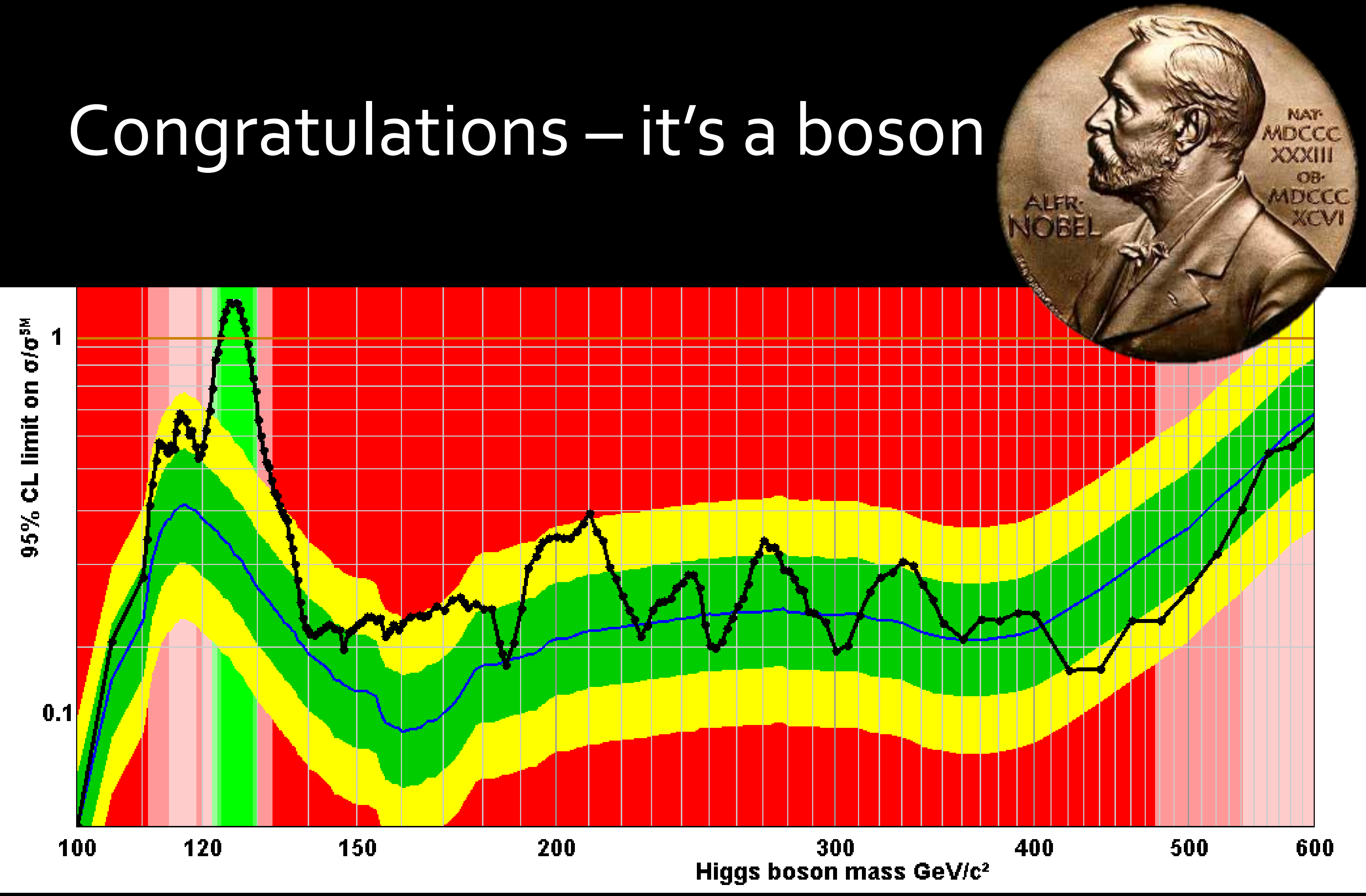


Collaboration publications (2008-2015)

- ATLAS: 3,321
- CMS: 3,070
- ALICE: 1,022
- LHCb: 992
- TOTEM: 52
- LHCf: 29

- TOTAL: 8,486

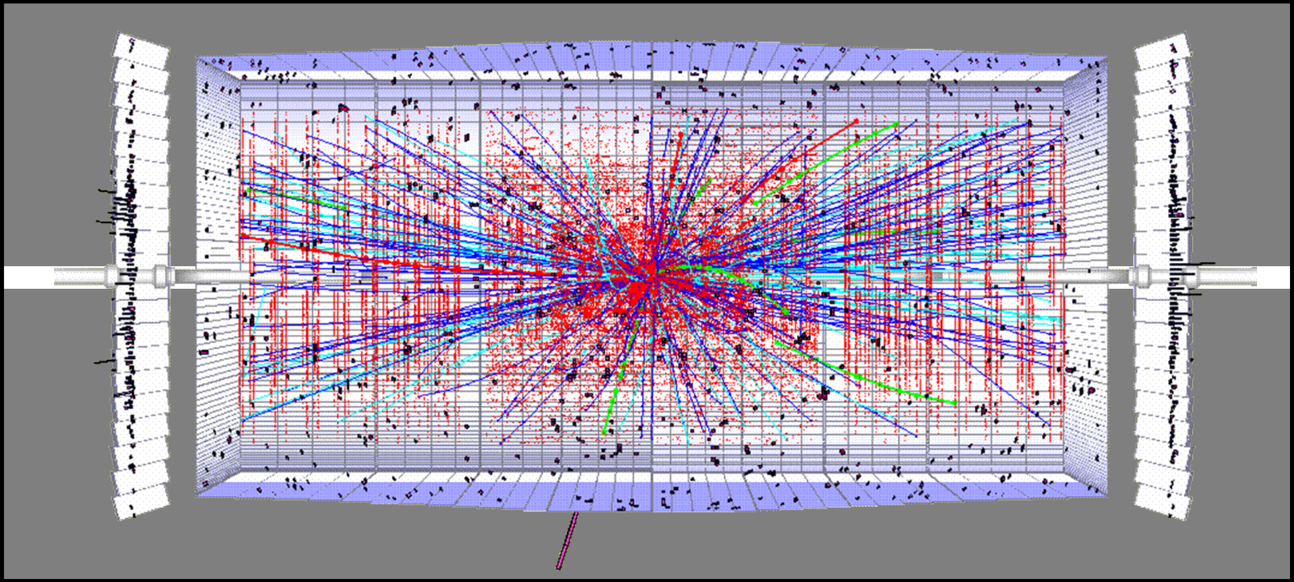
... and counting...

Metropolis, Fritz Lang, 1927
Set in the 2020's

The future

The HL-LHC

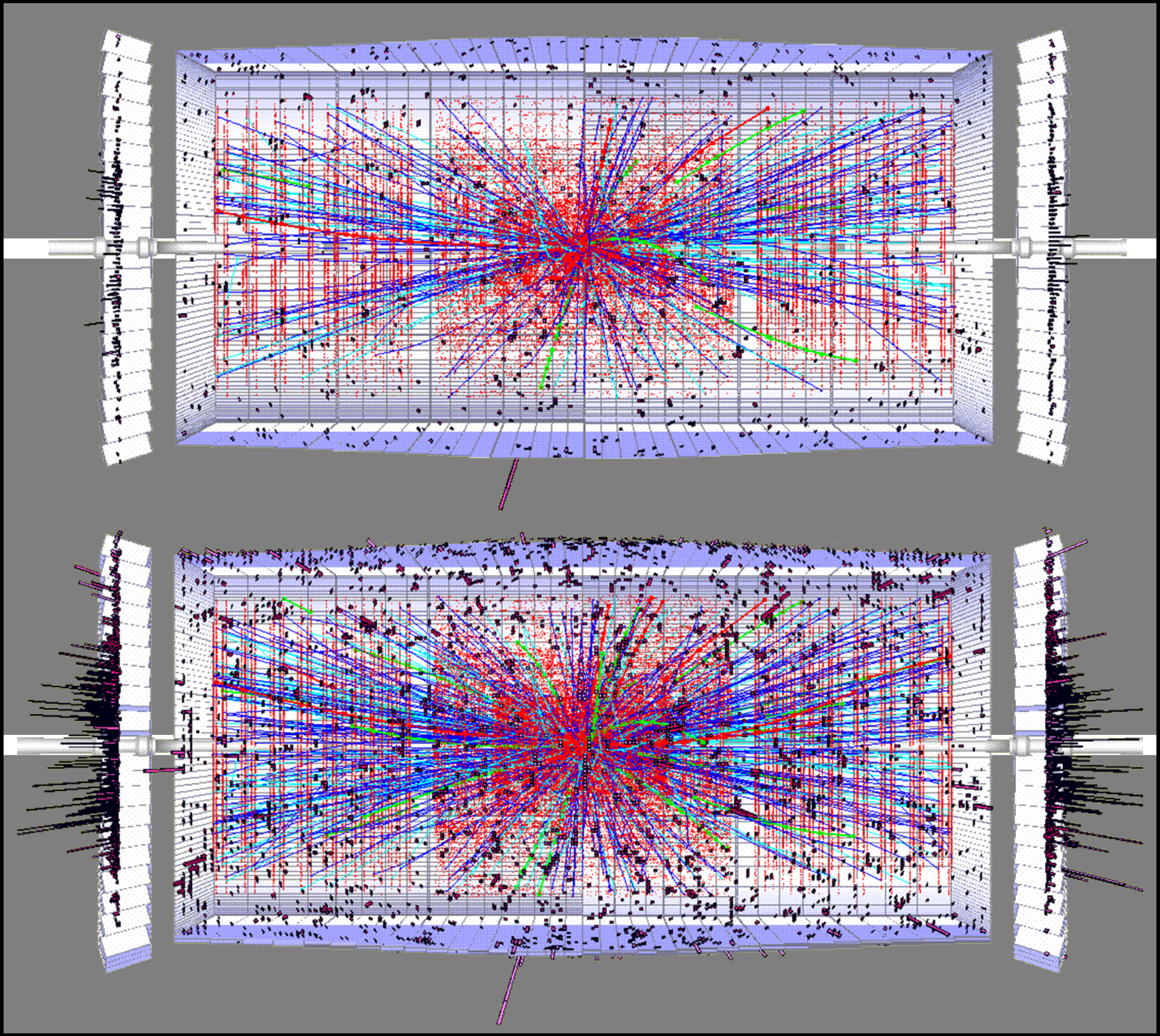
LHC Run-2
L = O(10^{34}) $cm^{-2}s^{-1}$
O(10) interactions/bx



The HL-LHC

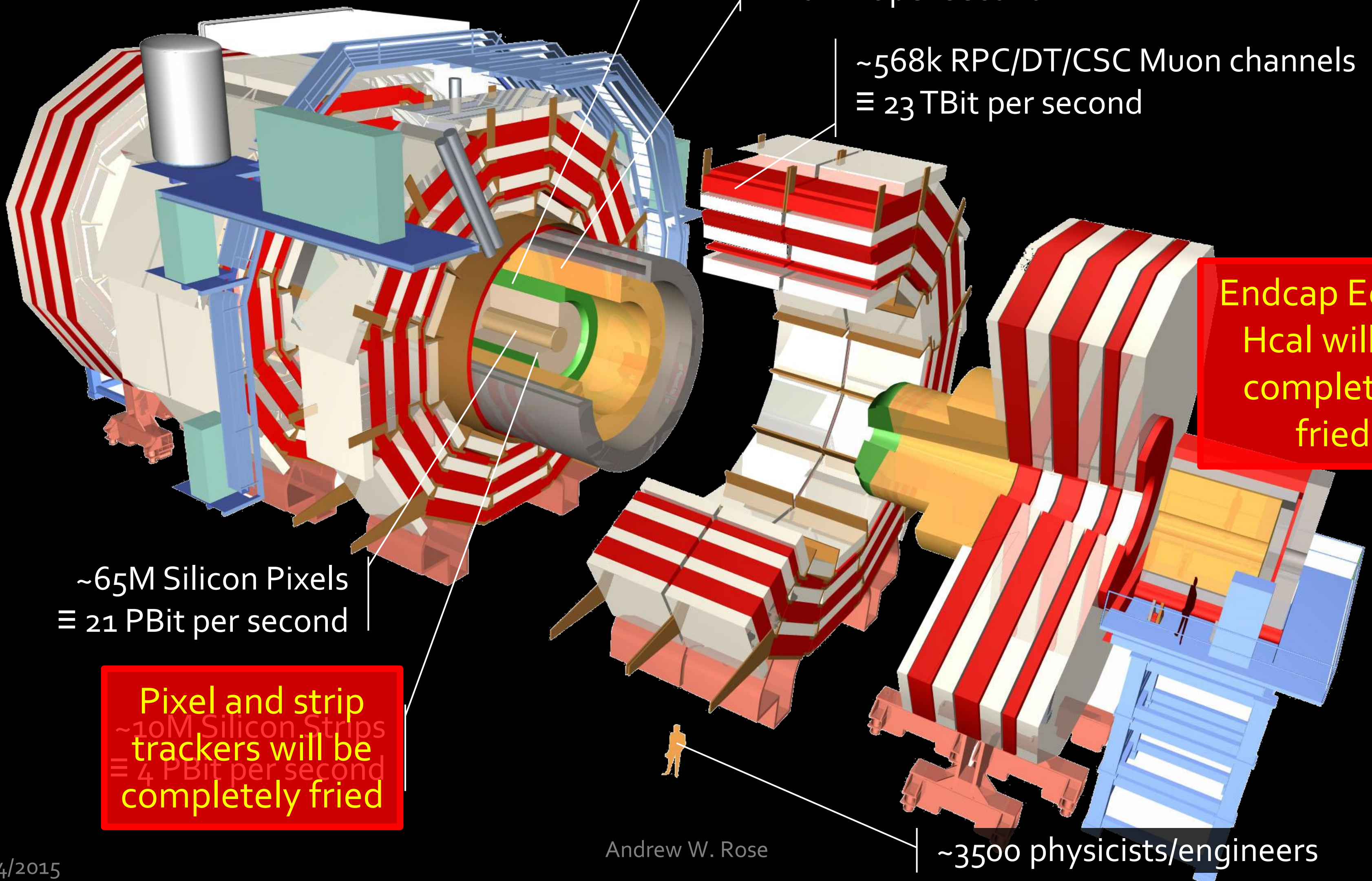
LHC Run-2
L = O(10^{34}) $cm^{-2}s^{-1}$
O(10) interactions/bx

LHC Run-3
L = O(10^{35}) $cm^{-2}s^{-1}$
O(100) interactions/bx



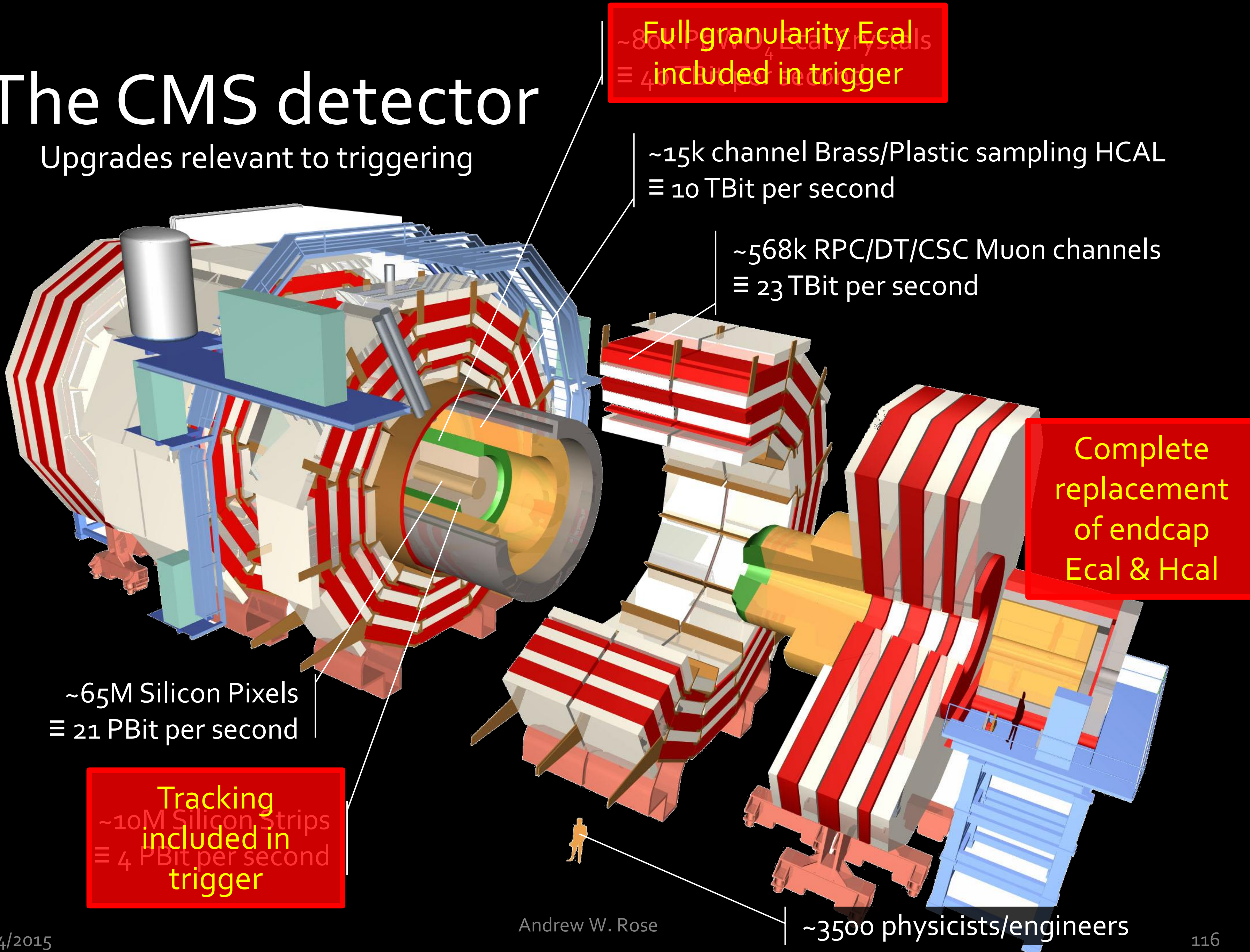
The CMS detector

Damage after Run-2

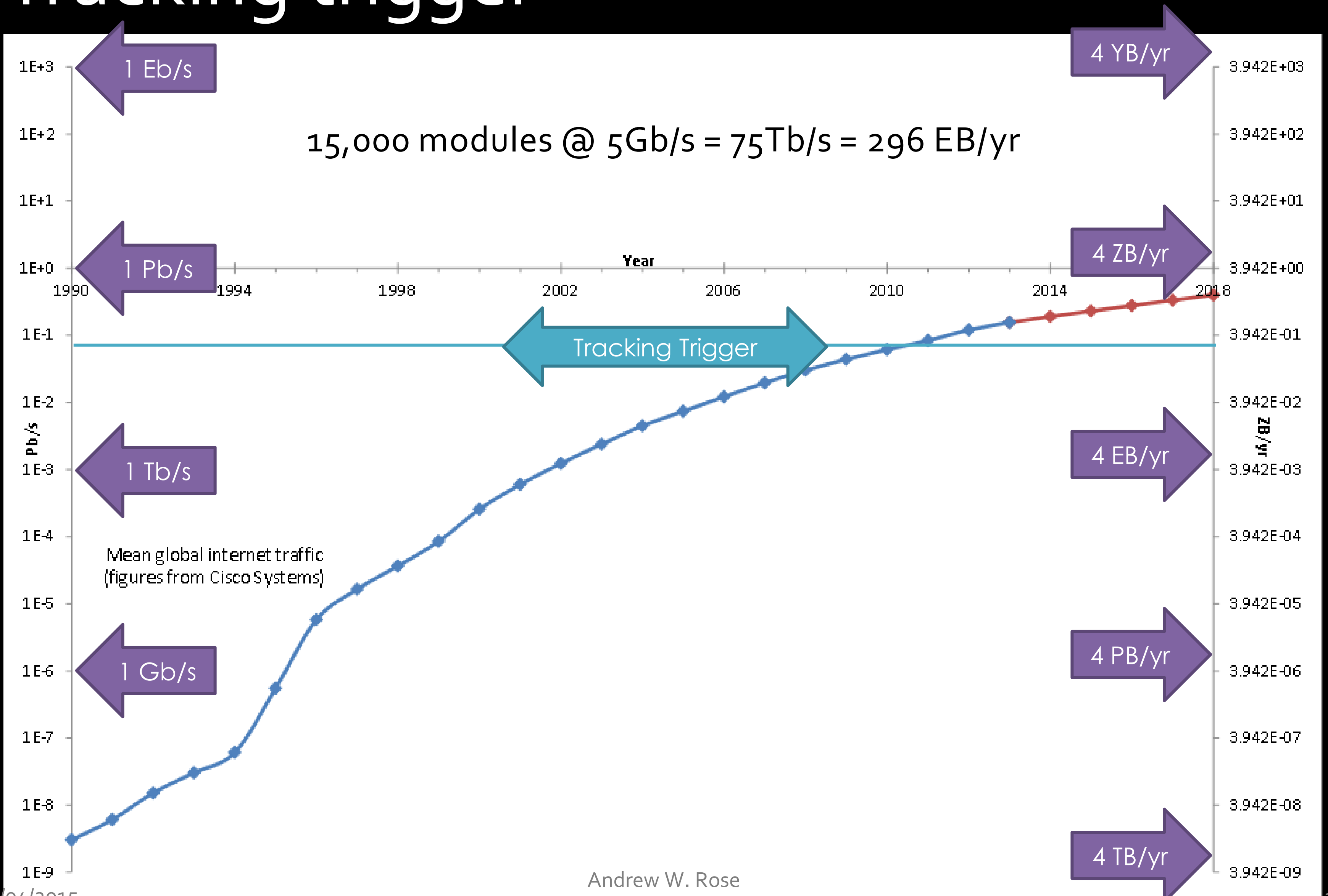


The CMS detector

Upgrades relevant to triggering

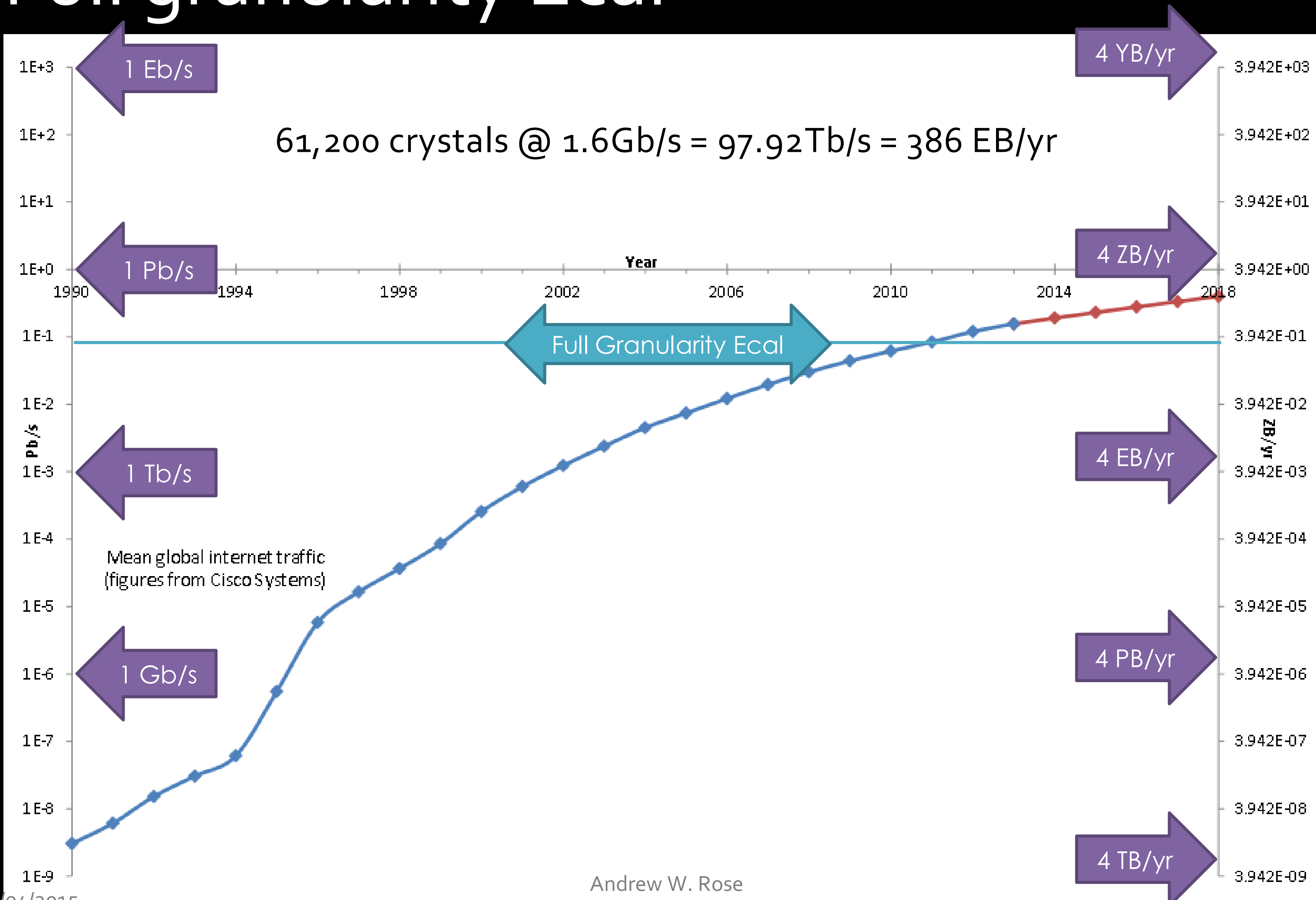


Big Data:
Tracking trigger

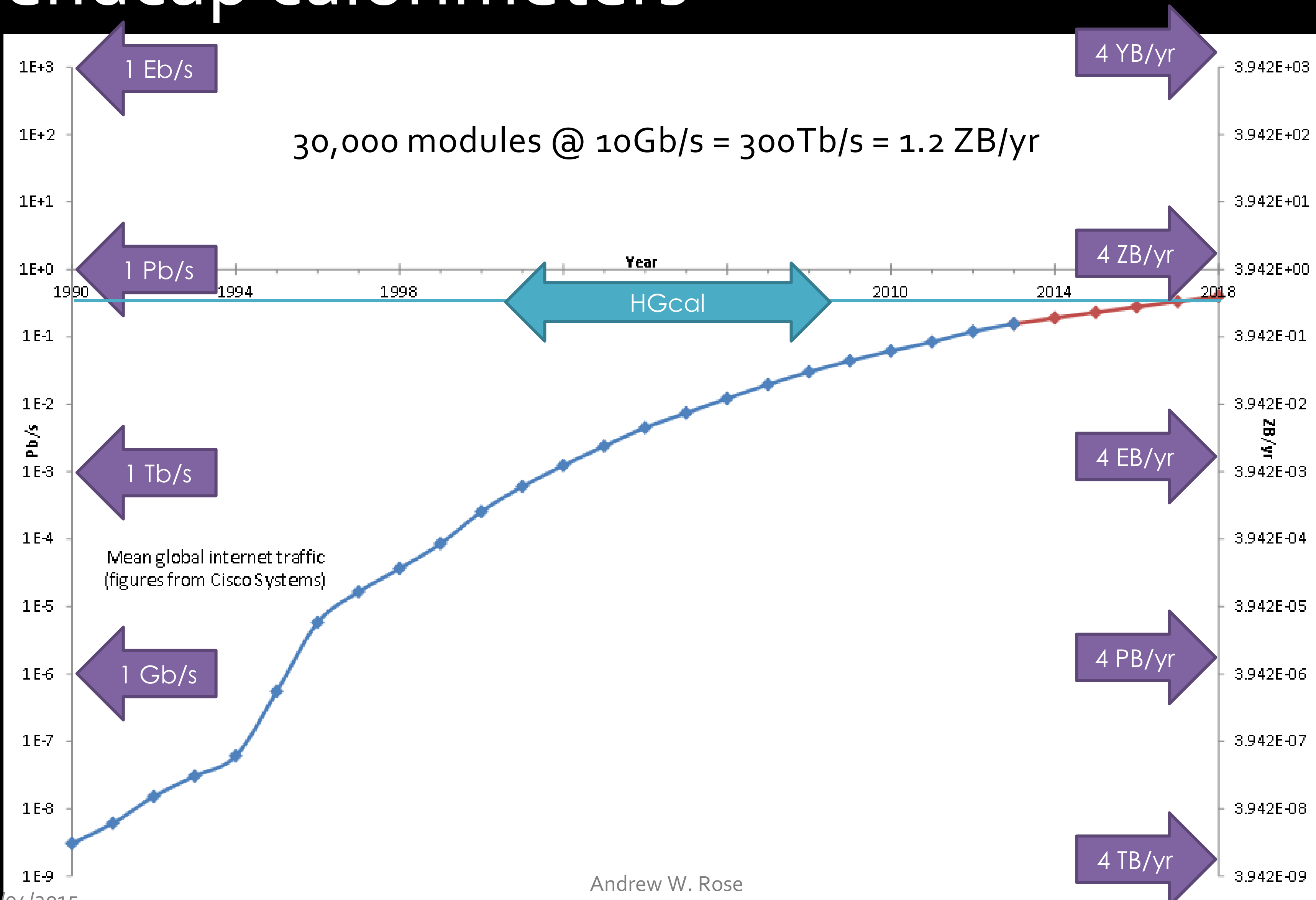


Andrew W. Rose

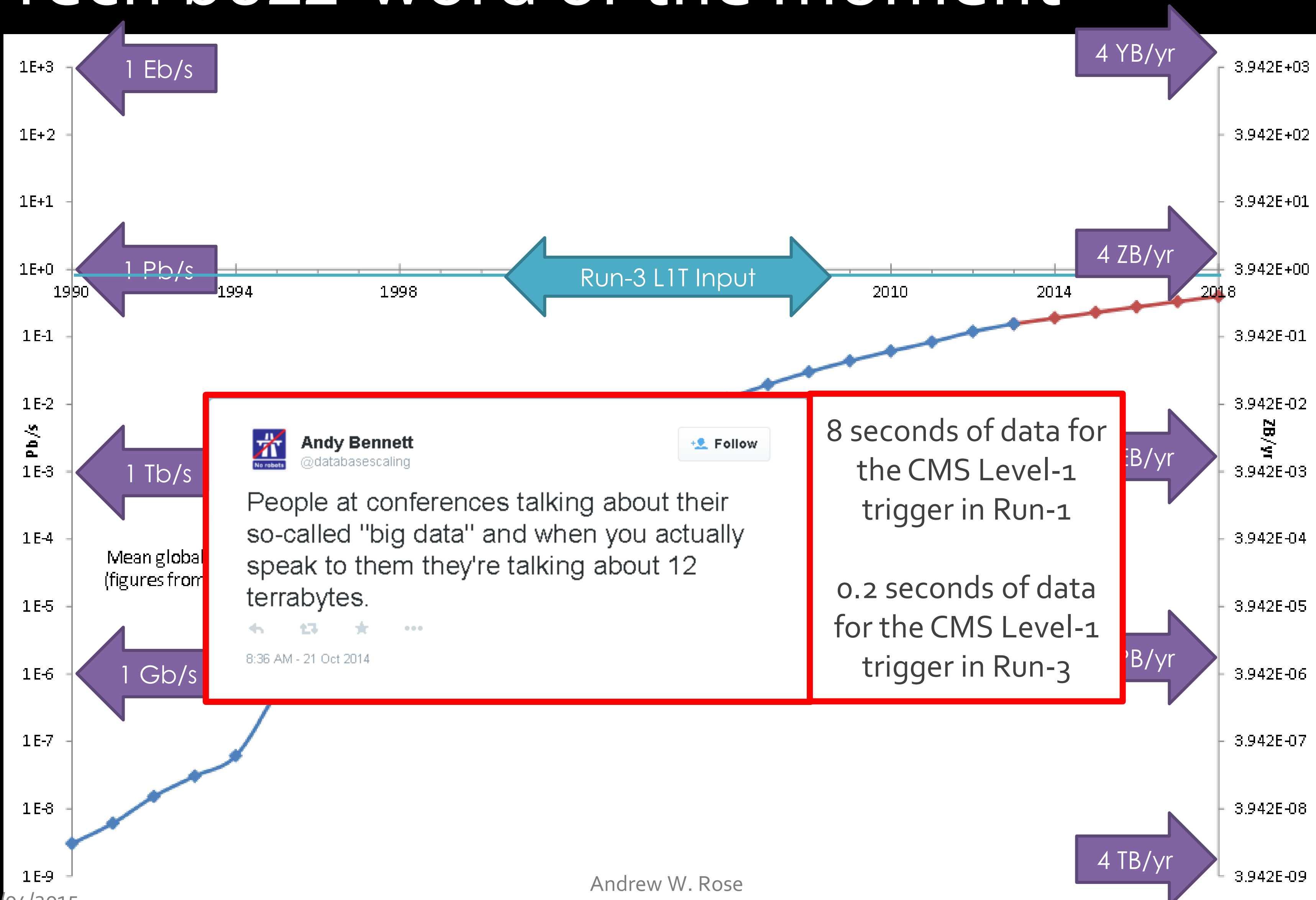
Big Data:
Full granularity Ecal



Big Data: High-granularity endcap calorimeters



Big Data:
Tech buzz-word of the moment

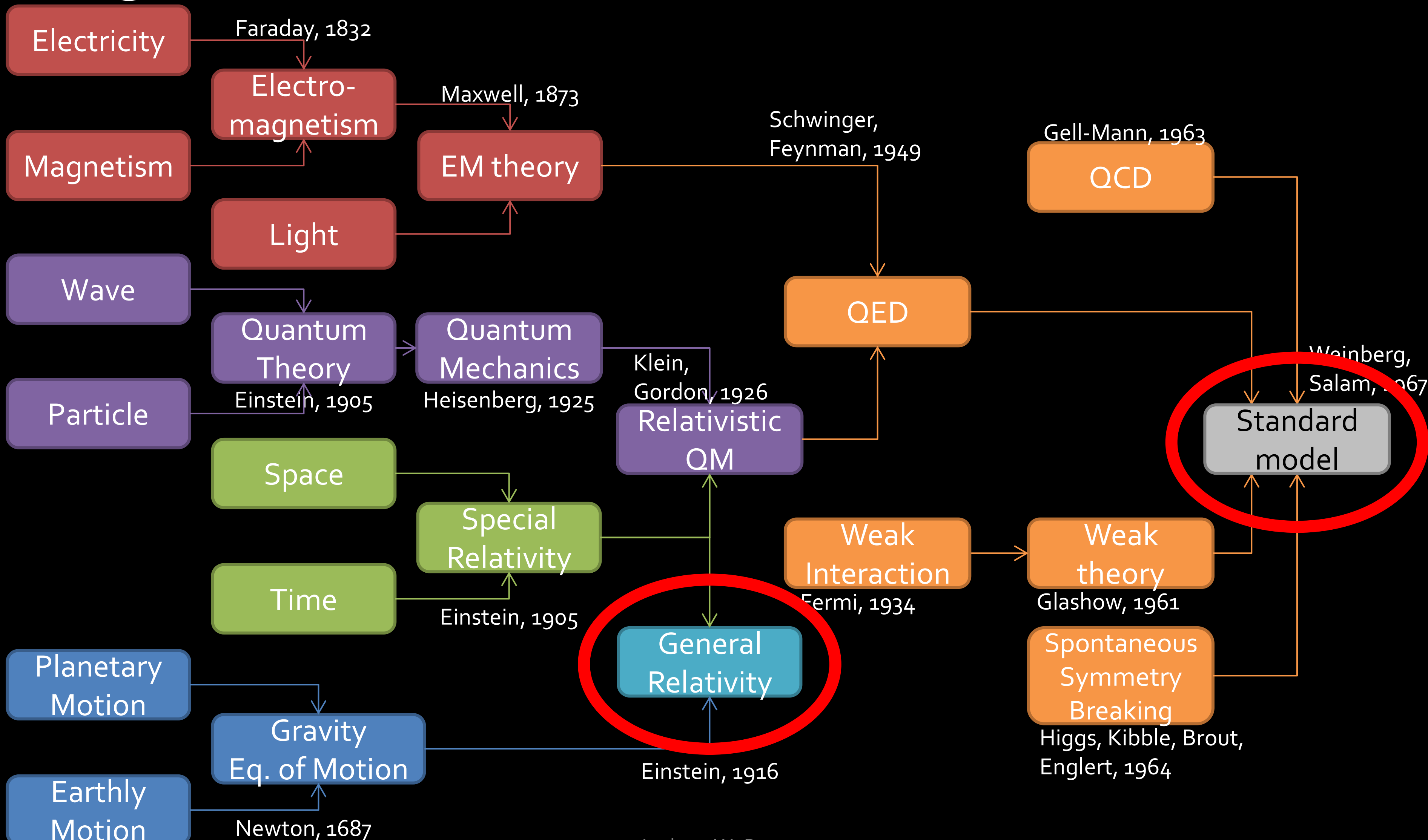


Again: Why would you do that?

Again: Why would you do that?

We are after an elegant, unified description of how the constituents of the universe interact (a “Theory-of-Everything” if you like…)

Again: Why would you do that?



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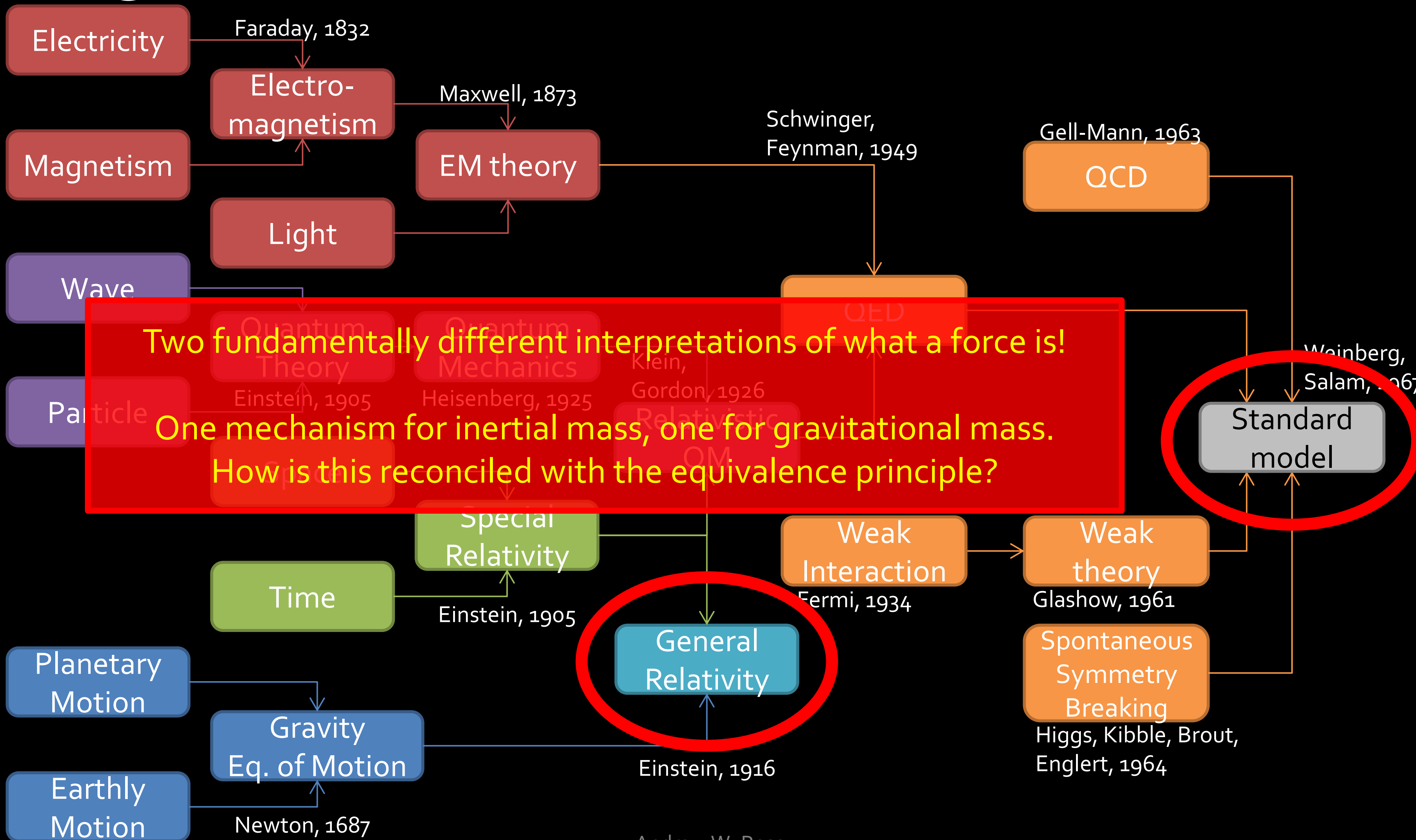

Two fundamentally different interpretations of what a force is!

One mechanism for inertial mass, one for gravitational mass.
How is this reconciled with the equivalence principle?

Again: Why would you do that?

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

General Relativity

Again: Why would you do that?

$$
\begin{gathered}
\mathcal{L}_{\mathrm{StandardModel}} = \\
-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\tfrac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
\tfrac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\tfrac{2M^2}{g^2} + \\
\tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - \\
W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\tfrac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2} g \tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2} ig[W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \tfrac{1}{2} g[W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ - \\
\phi^+ \partial_\mu H)] + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + \\
igs_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - ig \tfrac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \tfrac{1}{4} g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\tfrac{1}{4} g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+\phi^-] - \tfrac{1}{2} g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) - \tfrac{1}{2} ig^2 \tfrac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) + \tfrac{1}{2} ig^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w} (2c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- - \\
g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma\partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}_j^\lambda (\gamma\partial + m_u^\lambda) u_j^\lambda - \\
\bar{d}_j^\lambda (\gamma\partial + m_d^\lambda) d_j^\lambda + igs_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \tfrac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \\
\tfrac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\tfrac{4}{3} s_w^2 - \\
1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \tfrac{8}{3} s_w^2 - \gamma^5) d_j^\lambda)] + \tfrac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) e^\lambda) + \\
(\bar{u}_j^\lambda \gamma^\mu (1+\gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \tfrac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C^\dagger_{\lambda\kappa} \gamma^\mu (1 + \\
\gamma^5) u_j^\lambda)] + \tfrac{ig}{2\sqrt{2}} \tfrac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1-\gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1+\gamma^5) \nu^\lambda)] - \\
\tfrac{g}{2} \tfrac{m_e^\lambda}{M} [H(\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1-\gamma^5) d_j^\kappa) + \\
m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1+\gamma^5) d_j^\kappa] + \tfrac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C^\dagger_{\lambda\kappa} (1+\gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C^\dagger_{\lambda\kappa} (1 - \\
\gamma^5) u_j^\kappa] - \tfrac{g}{2} \tfrac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \tfrac{g}{2} \tfrac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \tfrac{ig}{2} \tfrac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \\
\tfrac{ig}{2} \tfrac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
\tfrac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + igs_w W^+_\mu (\partial_\mu \bar{Y} X^- - \\
\partial_\mu \bar{X}^+ Y) + igc_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + igs_w W^-_\mu (\partial_\mu \bar{X}^- Y - \\
\partial_\mu \bar{Y} X^+) + igc_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
\partial_\mu \bar{X}^- X^-) - \tfrac{1}{2} gM [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2} \bar{X}^0 X^0 H] + \\
\tfrac{1-2c_w^2}{2c_w} igM [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \tfrac{1}{2c_w} igM [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
igMs_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \tfrac{1}{2} igM [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0].
\end{gathered}
$$

Standard Model of Particle Physics

$$
R_{\mu\nu} - \frac{1}{2} R \, g_{\mu\nu} + \Lambda \, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}
$$

General Relativity

Back to the Greeks…

"Wisest is he who thinks he knows what he knows and never thinks he knows what he does not know"

(Often misquoted as "Wisest is he who knows what he does not know")

Socrates (470-399BC)

Again: Why would you do that?

1. What is the agent that hides the electroweak symmetry? Specifically, is there a Higgs boson? Might there be several?
2. Is the Higgs boson elementary or composite? How does the Higgs boson interact with itself?
3. Does the Higgs boson give mass to fermions, or only to the weak bosons? What sets the masses and mixings of the quarks and leptons?
4. What stabilizes the Higgs boson mass below 1 TeV?
5. Do the different behaviours of left-handed and right-handed fermions with respect to charged-current weak interactions reflect a fundamental asymmetry in the laws of nature?
6. What will be the next symmetry recognized in nature? Is nature supersymmetric? Is the electroweak theory part of some larger edifice?
7. Are there additional generations of quarks and leptons?

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Again: Why would you do that?

8. Why is gravity such a weak force? Why are the Planck scale and electroweak scale so different from each other? What prevents quantities at the electroweak scale, such as the Higgs boson mass, from getting quantum corrections on the order of the Planck scale? Is the solution supersymmetry, extra dimensions, or just anthropic fine-tuning?
9. Did particles that carry "magnetic charge" exist in some past, higher-energy epoch? If so, do any remain today?
10. Is the proton fundamentally stable or does it decay with a finite lifetime?
11. Is supersymmetry realized at TeV scale? If so, what is the mechanism of supersymmetry breaking? Does supersymmetry stabilize the electroweak scale, preventing high quantum corrections? Does the lightest supersymmetric particle (LSP or Lightest Supersymmetric Particle) comprise dark matter?
12. What is the mass of neutrinos? Are they Dirac or Majorana particles? Is mass hierarchy normal or inverted? Is the CP violating phase non-zero?

Again: Why would you do that?

13. Why has there never been measured a free quark or gluon, but only objects that are built out of them, like mesons and baryons? How does this phenomenon emerge from QCD?
14. Why is the strong nuclear interaction invariant to parity and charge conjugation?
15. Why is the experimentally measured value of the muon's anomalous magnetic dipole moment ("muon g-2") significantly different from the theoretically predicted value of that physical constant?
16. What resolves the vacuum energy problem? Why does the zero-point energy of the vacuum not cause a large cosmological constant? What cancels it out?
17. Is electroweak symmetry breaking an emergent phenomenon connected with strong dynamics? Is electroweak symmetry breaking related to gravity through extra space-time dimensions?

Again: Why would you do that?

18. What lessons does electroweak symmetry breaking hold for unified theories of the strong, weak, and electromagnetic interactions?
19. Does nature have more than four space-time dimensions? If so, what is their size? Are dimensions a fundamental property of the universe or an emergent result of other physical laws? Can we experimentally observe evidence of higher spatial dimensions?
20. Can quantum mechanics and general relativity be realized as a fully consistent theory? Does a consistent theory involve a force mediated by a hypothetical graviton, or a product of a discrete structure of space-time itself?
21. Is space-time fundamentally continuous or discrete? Is the space-time continuum a smoothing-over of quantum effects or is quantum mechanics emergent from continuum mechanics?

Conclusion

There are still a lot of unanswered questions before we have a theory of everything!

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So… I should probably get back to work

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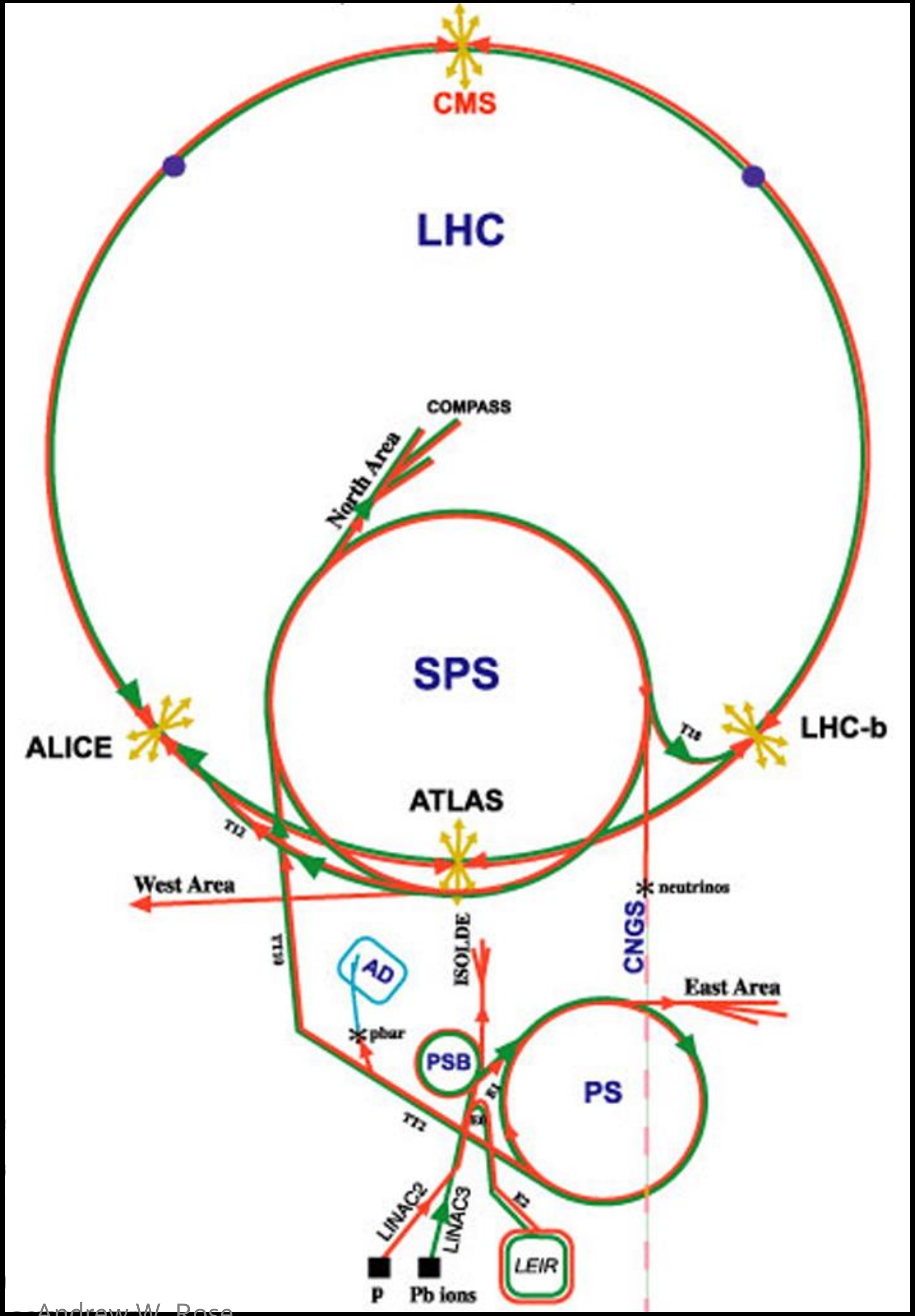
So… I should probably get back to work

Thanks for listening!

Spares

The LHC

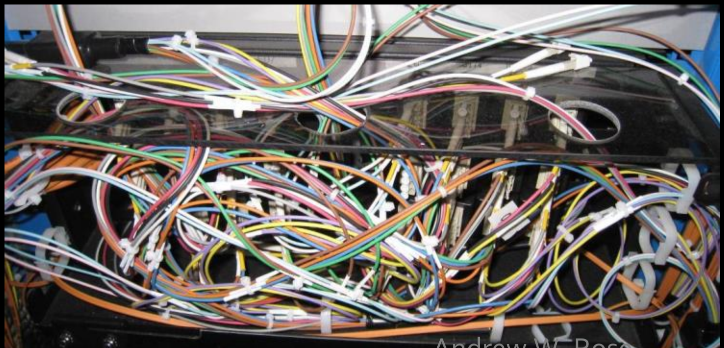


CMS
LHC
COMPASS
North Area
SPS
ALICE
LHC-b
ATLAS
T12
T18
West Area
neutrinos
CNGS
ISOLDE
T12
AD
pbar
PSB
East Area
PS
TT2
E1
E0
E2
LINAC2
LINAC3
LEIR
p
Pb ions

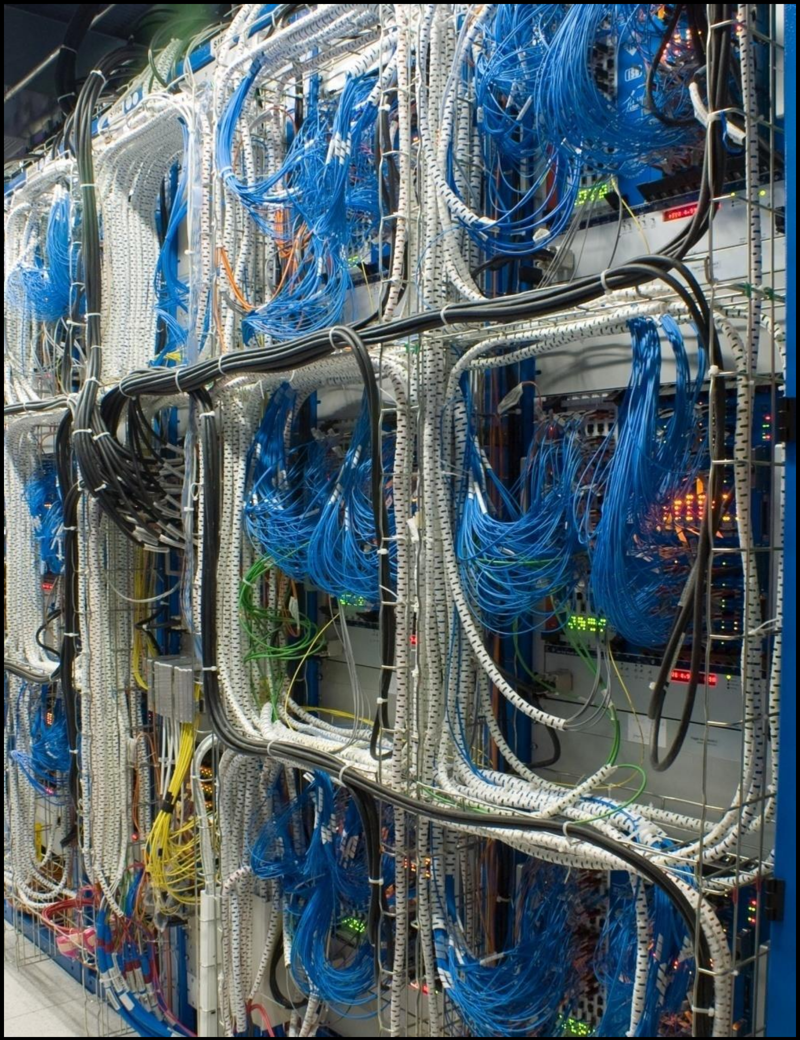
The tyranny of the links: Calorimeter trigger

RCT

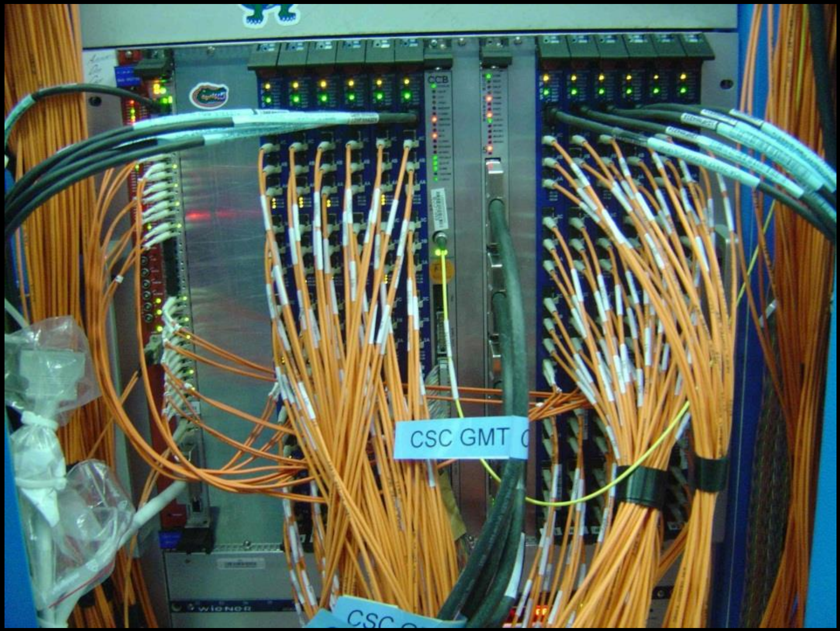
GCT



The tyranny of the links: Muon trigger



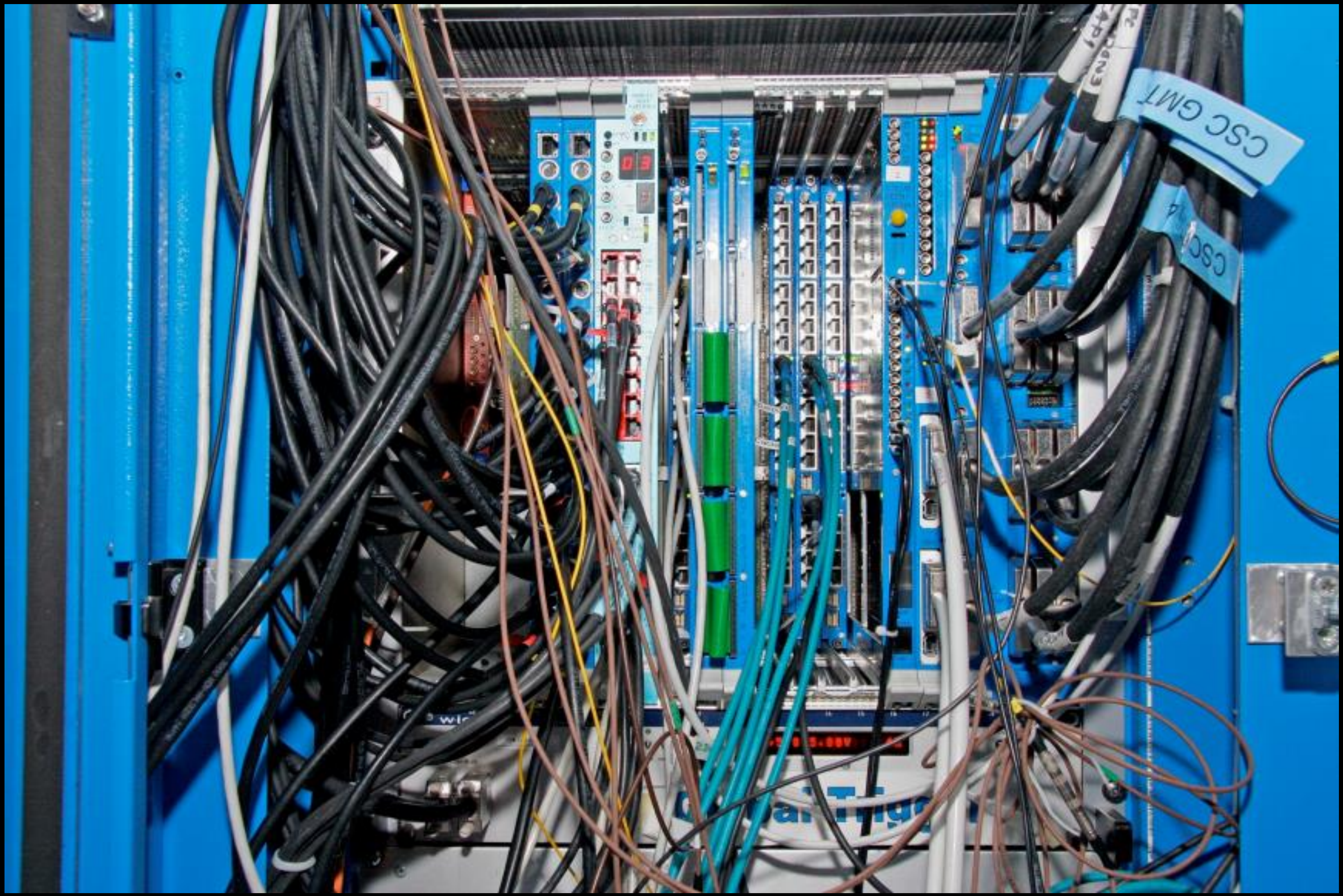
RPC Pattern Comparator



CSC Track-finder

DT Track-finder (aka the green salad or the green spaghetti forests)

The tyranny of the links: Global trigger



Abstract

The Standard Model of particle physics was finalized in the mid-1970s and is phenomenally successful at describing the world we see. The subsequent discoveries of the top quark, the tau neutrino, and most recently, the Higgs boson means that all the particles within the model have now been observed, crowning the earlier successes of the model. Despite this success, the Standard Model is lacking in several respects; some of which might be resolved trivially pending more data, and others which are far more profound.

The experiments at the LHC are at the energy-frontier in the ongoing quest to understand the universe we inhabit, but the task of finding and measuring the smallest and rarest objects in the universe poses its own unique challenges.

In this talk, I will give an overview of the standard model, some of the detectors and technology being used at the LHC, and finish with a discussion on what the future might hold for each.