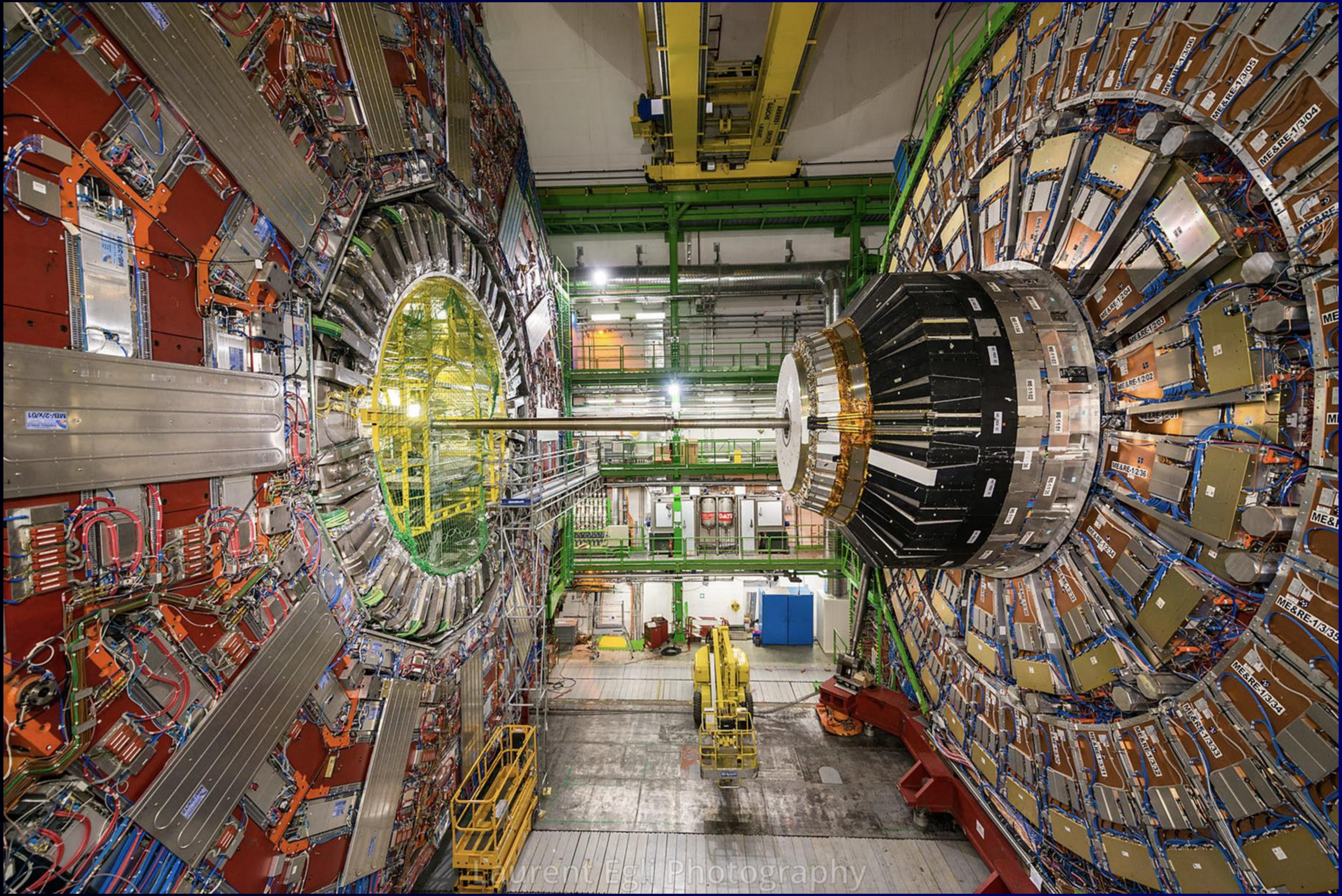


LHC and CMS

S. Nahn
PURSUE Undergraduate Summer Internship
June 5th, 2023

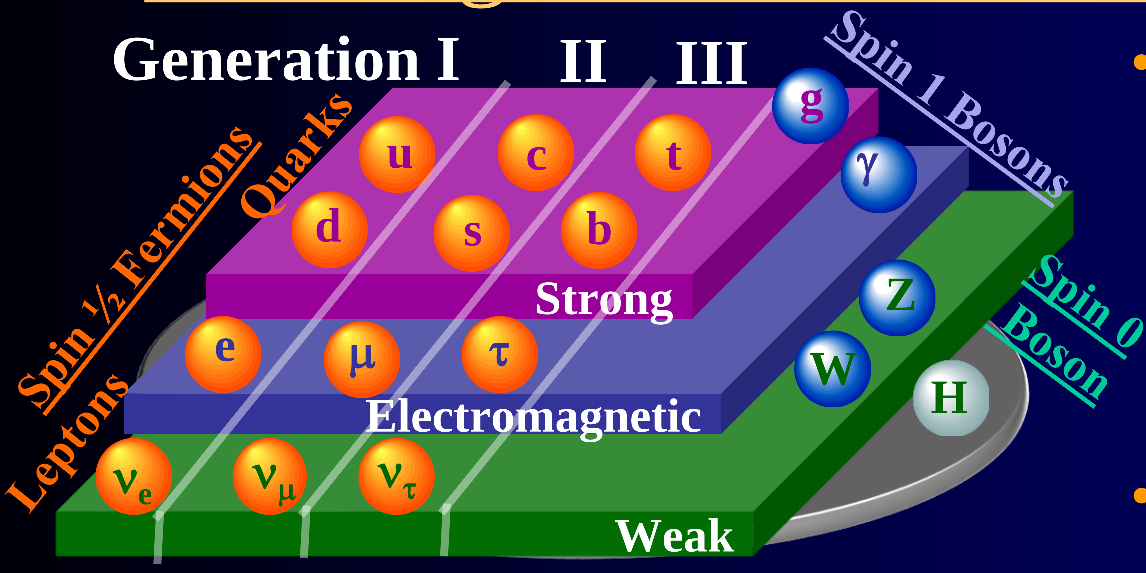
Meet the Detector Guy

- **Physics interests**
  - **EW and Higgs Physics**
- **Good at:**
  - **Programming clocks and VCRs**
  - **Herding Cats**
- **Problems with**
  - **Humility ☺**
  - **Herding Cats**
- **Eyes on**
  - **New Discoveries at the LHC**
- **Hobbies**
  - **Sailing, Soccer, Skiing, Music Appreciation**

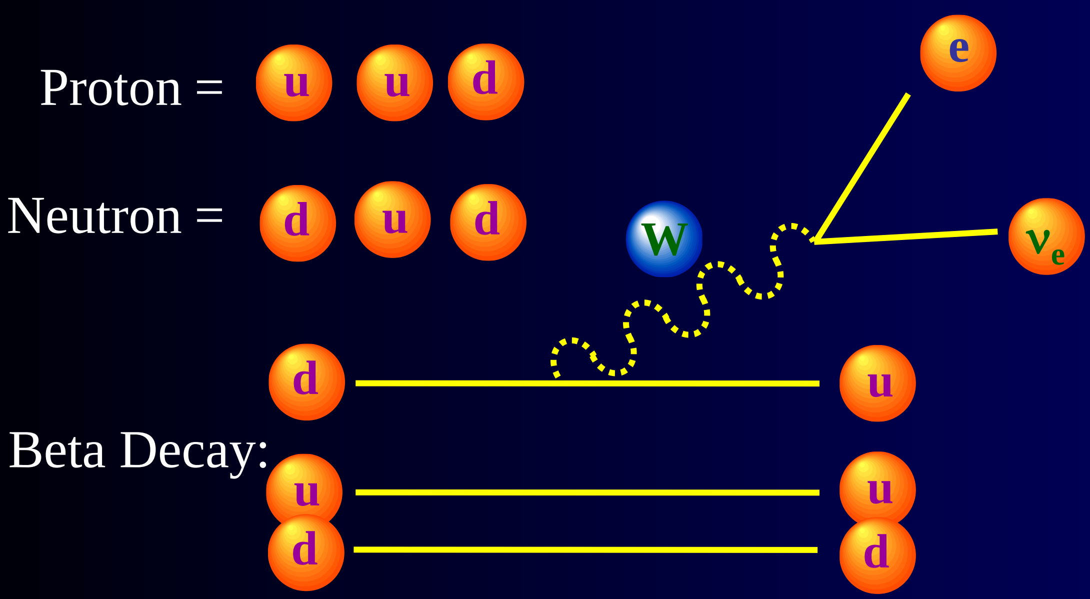
Subatomic Particles 101

In the interest of time, playing fast and loose with the subtleties. If you want details, go to Grad School

Building Blocks of Nature

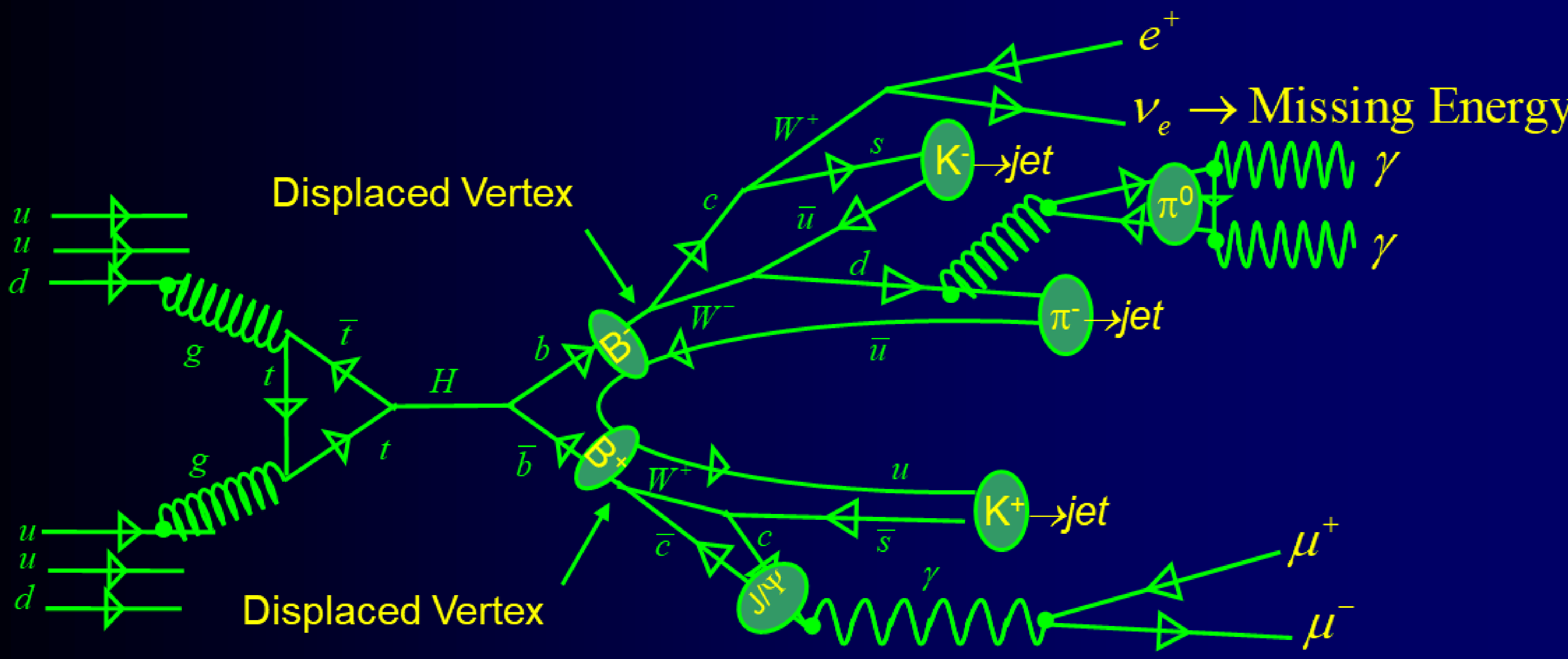


- **Beautiful symmetry**
  - **12 "things" in 3 sets of 2 pairs (+ anti-things mirror)**
    - **way easier than chemistry**
  - **3 types of interactions**
- **"Standard Model" (SM)= building particles and interactions from these items**
  - **Following certain rules**
  - **Very successful!**
    - **Meaning, hard to break!**



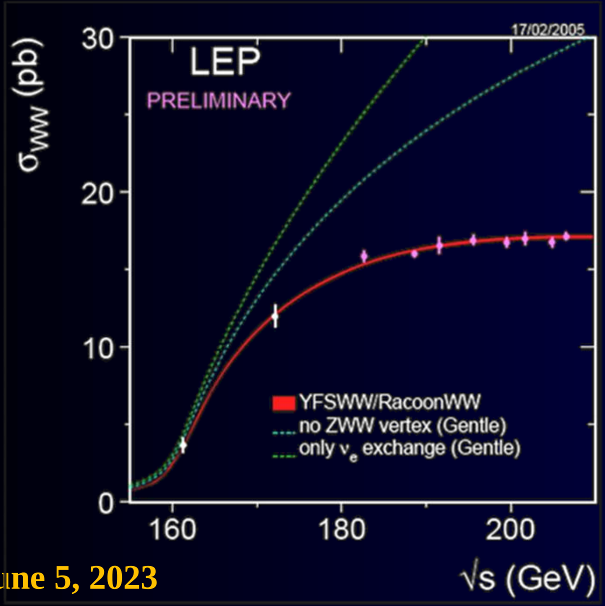
But can get complicated quickly

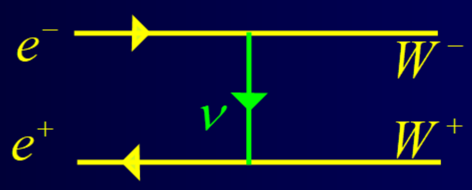
- **pp → H →bb**
  - **Leptons, Photons, “Jets” of Hadrons, Missing Energy, Secondary particles/vertices**

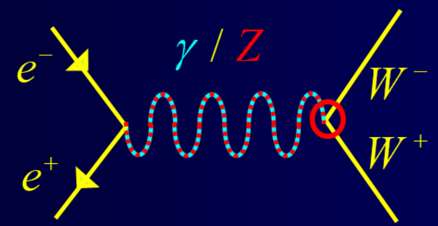


Rules → Discovery

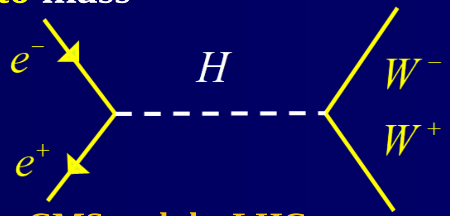
- **Symmetries imply Conserved Quantities (Noether's Theorem)**
    - **eg. Translation in space, time → Momentum, Energy conservation**
  - **Laws of motion must preserve these symmetries**
  - **Special type of Symmetry: Gauge symmetry**
    - **Sorta like measuring in feet rather than meters**
      - **You have the freedom to choose, and Nature doesn't care**
    - **Naïve mass term in Standard Model violate Gauge Invariant! Need a trick!**
- **Probabilities should not exceed 100% ("Unitarity")**







- **J=1 amplitudes cancel nicely**
- **J=0 amplitude also diverges**
  - **"wrong helicity" ~ *mass***
- **Need something to cancel with scalar coupling to mass**



You can't jus[t]

- **Pauli, Decembe[r]**

Original - Photocopie of
Abschrift/

Offener Brief an die Gruppe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4.
Gloriastra

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst
anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin
angesichts der "falschen" Statistik der N- und Li-6 Kerne, sow
des kontinuierlichen beta-Spektrums auf einen verzweifelten Au
verfallen um den "Wechselsatz" (1) der Statistik und den Ener
zu retten. Nämlich die Möglichkeit, es könnten elektrisch neu
Teilchen, die ich Neutronen nennen will, in den Kernen existie
welche den Spin 1/2 haben und das Ausschliessungsprinzip befol
sich von Lichtquanten ausserdem noch dadurch unterscheiden, da
nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutrone
müsste von derselben Grossenordnung wie die Elektronenmasse se
jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinui
beta- Spektrum wäre dann verständlich unter der Annahme, dass
beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittie
wird, derart, dass die Summe der Energien von Neutron und Elek
konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die
Neutronen wirken. Das wahrscheinlichste Modell für das Neutro
mir aus wellenmechanischen Gründen (näheres weiss der Ueberbri
dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein
magnetischer Dipol von einem gewissen Moment μ ist. Die Exper
verlangen wohl, dass die ionisierende Wirkung eines solchen Ne
nicht grösser sein kann, als die eines gamma-Strahls und darf
μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese I
zu publizieren und wende mich erst vertrauensvoll an Euch, lie
Radioaktive, mit der Frage, wie es um den experimentellen Nach
eines solchen Neutrons stände, wenn dieses ein ebensolches ode
10mal grösseres Durchdringungsvermögen besitzen würde, wie ein
gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein
wenig wahrscheinlich erscheinen wird, weil man die Neutronen,
sie existieren, wohl schon längst gesehen hätte. Aber nur wer
gewinnt und der Ernst der Situation beim kontinuierliche beta-
wird durch einen Ausspruch meines verehrten Vorgängers im Amte
Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt ha
"O, daran soll man am besten gar nicht denken, sowie an die ne
Steuern." Darum soll man jeden Weg zur Rettung ernstlich disk
Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich
persönlich in Tübingen erscheinen, da ich infolge eines in der
vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömm
bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer
untertänigster Diener

ges. W. Pauli

Physics Institute of
the ETH Zürich

Zürich, Dec. 4, 1930

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

Now it is also a question of which forces act upon neutrons. For me, the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), that the neutron at rest is a magnetic dipole with a certain moment μ. The experiments seem to require that the ionizing effect of such a neutron can not be bigger than the one of a gamma-ray, and then μ is probably not allowed to be larger than $e \cdot (10^{-13}\text{cm})$.

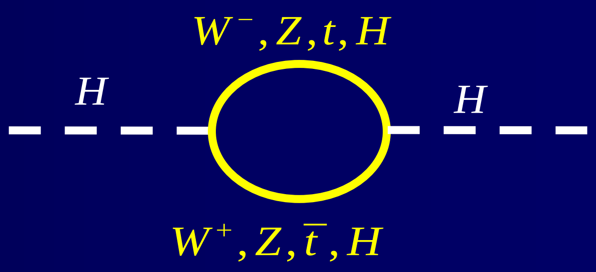
But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence for such a neutron if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray.

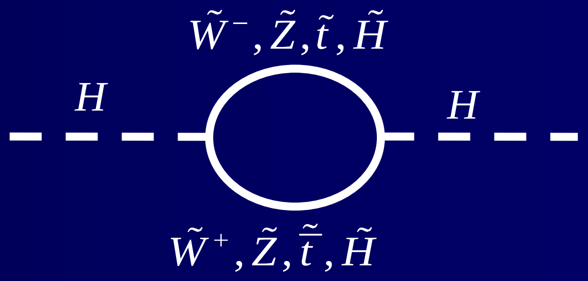
I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes." Therefore one should seriously discuss every way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble servant

signed W. Pauli

[Translation: Kurt Riesselmann]

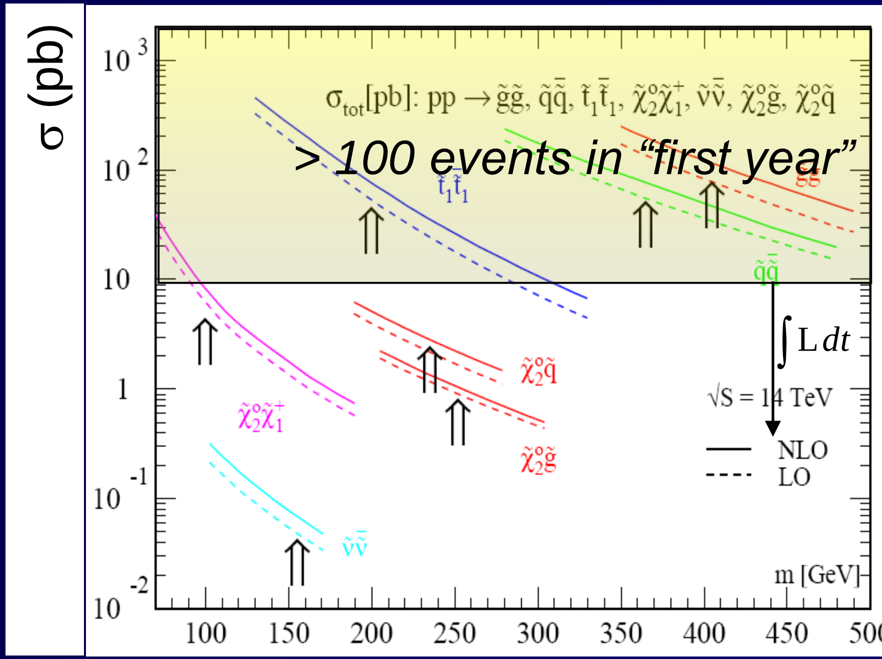
Higgs causes other problems





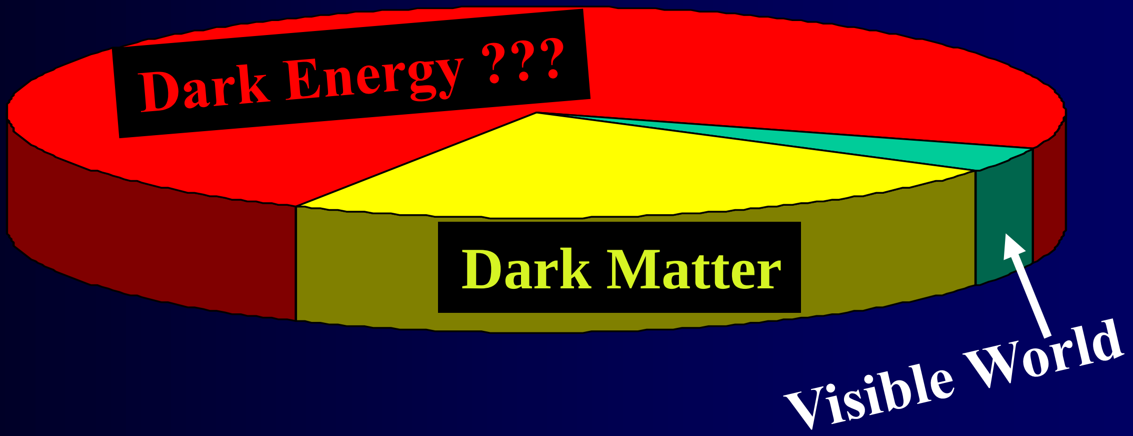
- **Electroweak Paradox**
  - **EW observables ⇒ light H**
  - **EW corrections ⇒ heavy H**

- **Supersymmetry: Eliminate large corrections without destroying EW theory**
  - **For each *particle*, a *sparticle* with opposite spin statistics**
    - **Fermions ⇒ Sfermions, Bosons ⇒ Bosinos ("Charginos","Neutralinos")**
  - **R parity**
    - **Conservation of sparticle #**
    - **Lightest sparticle stable**



Prediction from Prospino pre-LHC

The LHC is not only about the Higgs



Next new particle ?=? Dark Matter

And unify the strong and electroweak forces

Supersymmetry does this

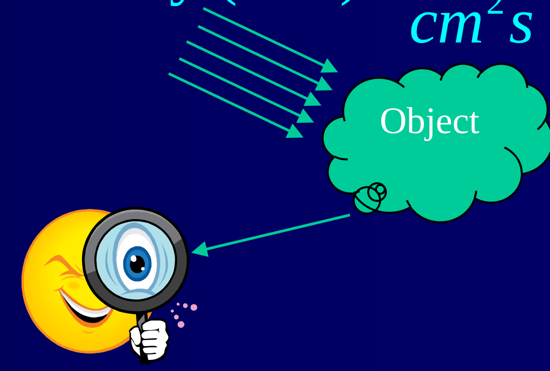
And cure further theoretical ailments

And … solve climate change?

The discovery process

How to probe Subatomic World

Luminosity (flux): $\frac{\#}{cm^2 s}$



- **Basic Recipe:**
  - **Send in a flux of particles**
  - **Measure what comes out vs (*E*nergy, angle, frequency …)**
- **Need High *E* to resolve small structures**

$\hbar c = 197 \text{ MeV fm} \quad p = 10 \text{ GeV} \rightarrow 0.02 \text{ fm}$

$\Rightarrow$ **Build Accelerators**

- **What to measure?**
  - **Rate/Scattering Cross Section:**
    - **Distributions in E,α…**
  - **Spectroscopy of Excited states**

Total Cross Section
Unit: $1 \text{barn} = 10^{-24} cm^2$

Rate

$$R(E, \alpha\ldots) = \mathrm{L}\,\sigma(E, \alpha\ldots)$$

Lumi

The accelerator

How to move a particle in a circle?

- **Electromagnetism!**

$$\vec{\mathbf{F}} = q\left[\vec{\mathbf{E}} + \left(\vec{\mathbf{p}} \times \vec{\mathbf{B}}\right)/m\right]$$

  - **Acceleration** $q\vec{\mathbf{E}} = \Delta\vec{\mathbf{p}} / \Delta t$
  - **Circular motion** $\dfrac{qpB}{m} = \dfrac{p^2}{mR} \Rightarrow \left|\vec{\mathbf{p}}\right| = qBR$

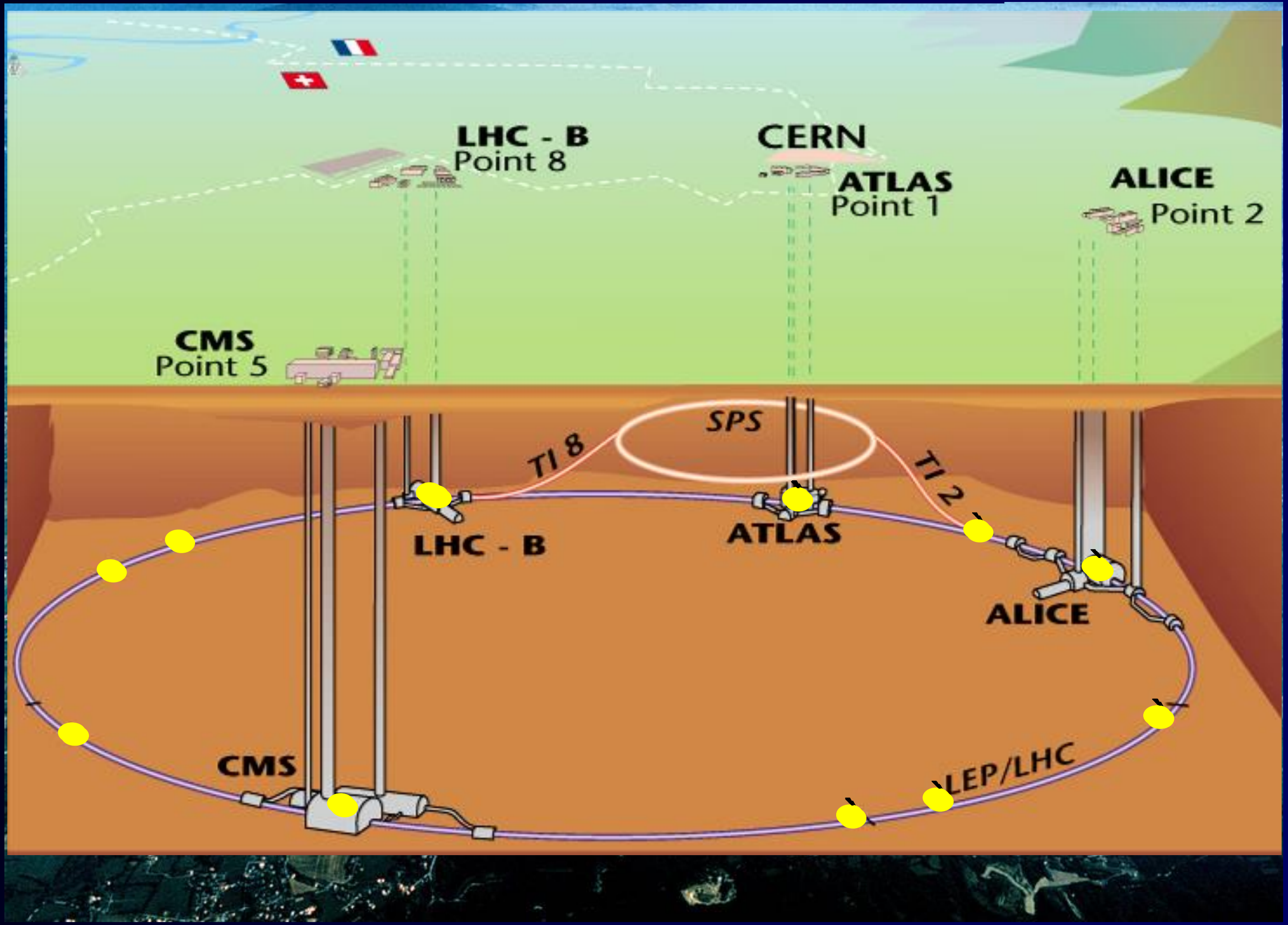
- **Have to ramp up *B* during acceleration to keep particles in the ring at fixed *R***
- **Need big *B*, big *R* to get highly energetic particles**

⇒ Large Storage Rings

Recycling: The Large Hadron Collider

Proton - Proton Collisions
Initially: 10^6 events/s, 7 TeV
Eventually: 10^9 events/s, 14 TeV

(Lead Ions
2.76 $\rightarrow$ 5.5
TeV/nucleon)



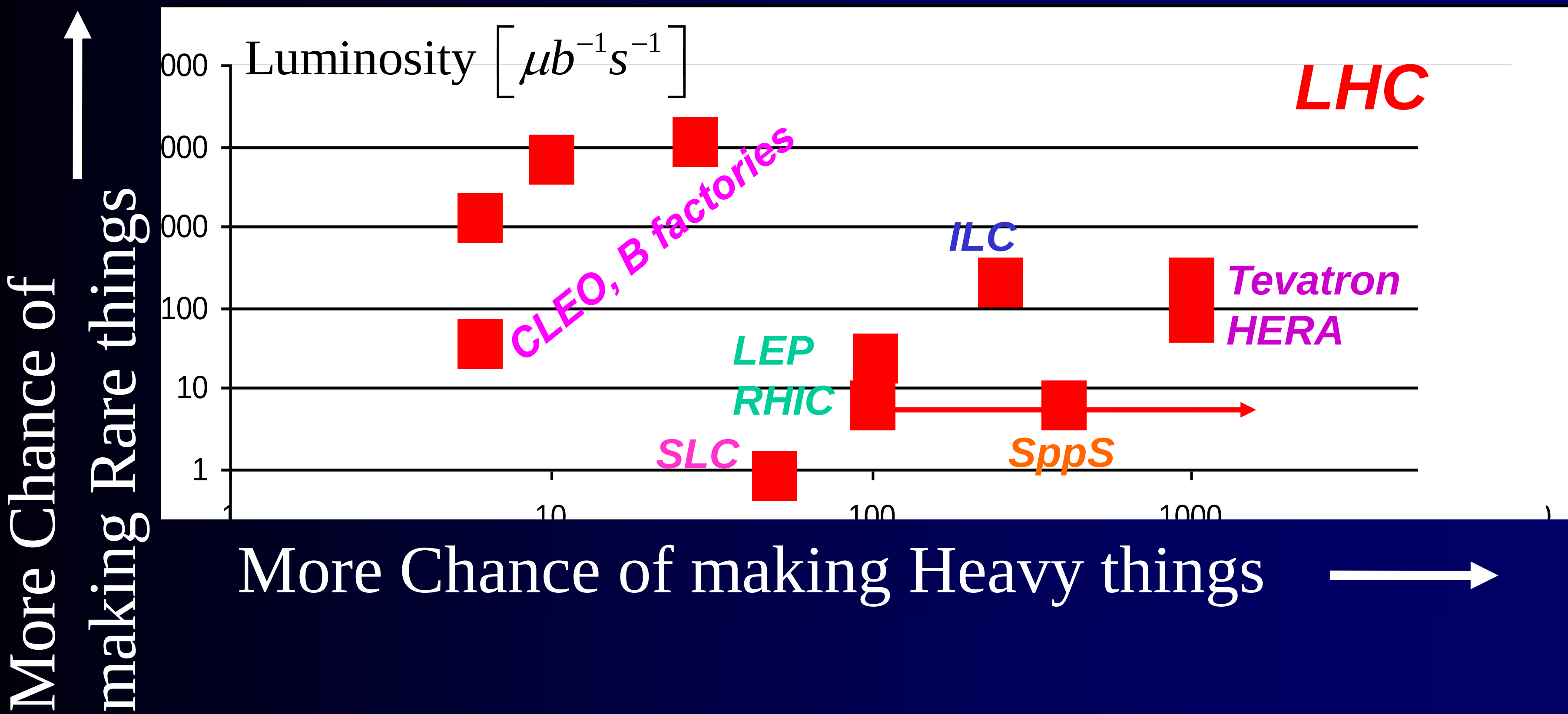
Superconducting Double Dipoles

$$|\vec{\mathbf{p}}| = 0.3BR = 7000\,GeV$$

$$B = \frac{7000}{0.3 \times 4300} = 5.5T \Rightarrow 8T$$

$$\approx 100{,}000 \times \text{Earth field}$$

A BIG Step



- **LHC has the reach in Luminosity and Energy to**
  - **Find the higgs** ✓
  - **Find more**

The detector

What is a detector?

- Many synchronous cameras looking at same event

- Rather complicated
  - ~ 100 "Mpix"
  - 40 MHz shutter speed
    - Real-time filtering

Detector Mission Statemennt

- **Goal: Measure observables, compare with theory**
  - **Cross sections** $\frac{d\sigma}{d\vec{\xi}}$ $\vec{\xi} = (E, p, \theta, \Omega\ldots)$
  - **Particle Properties**
    - ***m*, *Γ*, Branching Ratios, Spin, Parity …**
  - **Interactions and Couplings**
    - **ZWW ("Trilinear gauge") coupling, quark mixing matrix, …**
  - **Violations of the Standard Model**
    - **Parity or other symmetry violation, proton decay…**
- **Mandate for the Detector**
  - **Collect as precise data as possible**
    - **Resolution on** $(E, \vec{\mathbf{p}})$ and $(ct, \vec{\mathbf{x}})$
  - **Collect as much relevant data as possible**
    - **Cover all of 4π**
    - **Filter ("trigger") in face of limited bandwidth**
    - **Robustness in design and operation**

Measurements

- **Position: Follow trail left by ionization/Energy deposition**
  - **Intersections = Interaction vertices, decay vertices**
- **Energy/Momentum: Bend in $\vec{B}$, measure E via calorimeter**
- **Particle ID**
  - ***m* via *β*: Čerenkov effect, *dE/dx*, Time of Flight**
  - ***Q* from curvature, particle species from range**

Figures of Merit

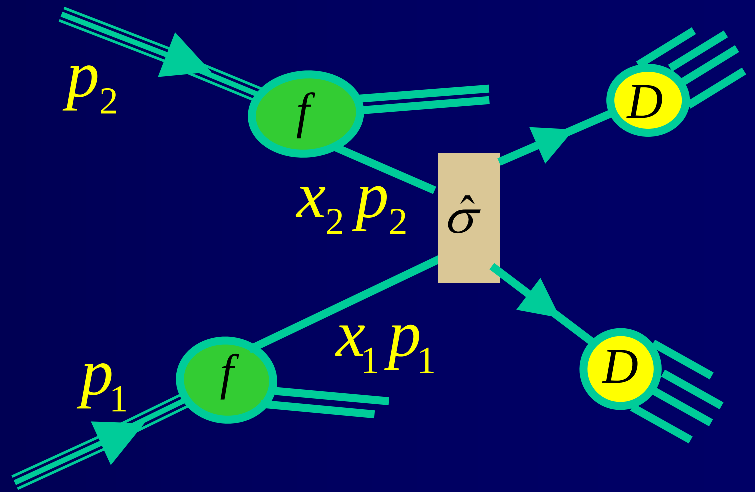
- **Resolution**
- **Response Time**
  - **Time needed to make signal after particle passage**
- **Dead Time**
  - **Minimum interval between successive detections**
- **Efficiency: Capability to see events**
  - **Acceptance (Geometrical) – how many events fall in fiducial volume**
  - **Intrinsic – how many in fiducial are triggered/reconstructed/recognized**

Particles vs Signatures

Theory		Experiment
$e^{\pm},\mu^{\pm},\gamma$	$\rightarrow$	$e^{\pm},\mu^{\pm},\gamma$
$\tau^{\pm}$	$\rightarrow W^{\pm}\nu_{\tau}$ $W^{\pm}\rightarrow l\nu_{l},qq$	$e^{\pm},\mu^{\pm},\nu$,jets
u,d,s,c	"Hadronize"	Tracks+jets, ID: p,π,K
b		" " + displaced vtx
t	$\rightarrow W^{+}b$	above, + $W^{\pm}\rightarrow l\nu_{l},qq$
ν	$\rightarrow$	$\varnothing$: Missing E,p

- **Complex!**
  - Reconstruct final state particles
  - Filter on intermediate invariant masses
  - Work back towards primary interaction

Hadron Kinematics



- **Energy set by PDFs** ***f(x)***

$$E_{CM}^2 = \left(x_1 p_1 + x_2 p_2\right)^2$$

- **Usually: Boosted along z**

$$p_1 = p_2 \text{ but } x_1 \neq x_2$$

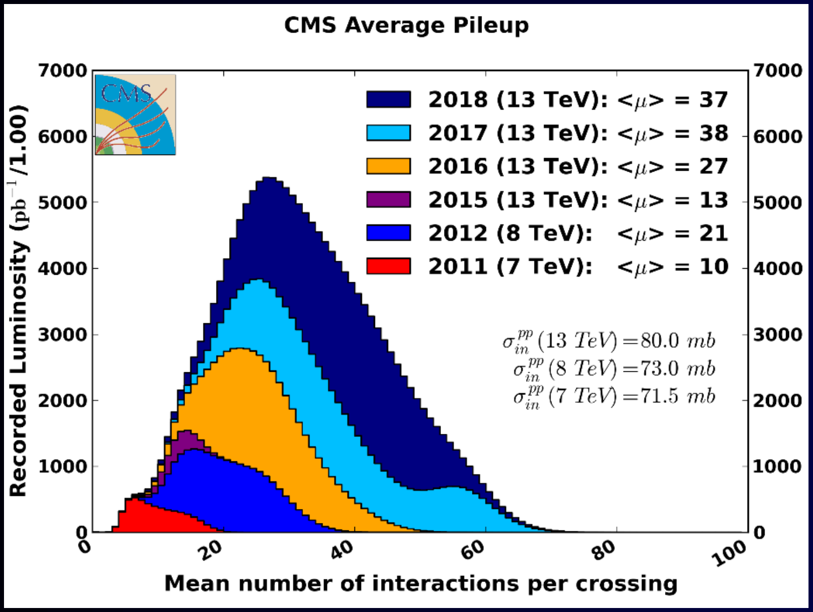
⇒ Use parametrization conducive to boosts along z

- **Rapidity:** $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) \quad y \in \left[-\infty, \infty\right]$
  - **Additive under boosts: Δy is invariant**
  - ***m*→0: Pseudorapidity** $\eta = \frac{1}{2}\ln\left(\frac{|\vec{\mathbf{p}}|+p_z}{|\vec{\mathbf{p}}|-p_z}\right) = -\ln\tan\left(\frac{\theta}{2}\right)$
- **Transverse Momentum: p_T**
  - **Transverse mass** $m_T = \sqrt{p_T^2 + m^2}$ **and Energy** $E_T = E\sin\theta$
- **Azimuth: ϕ**

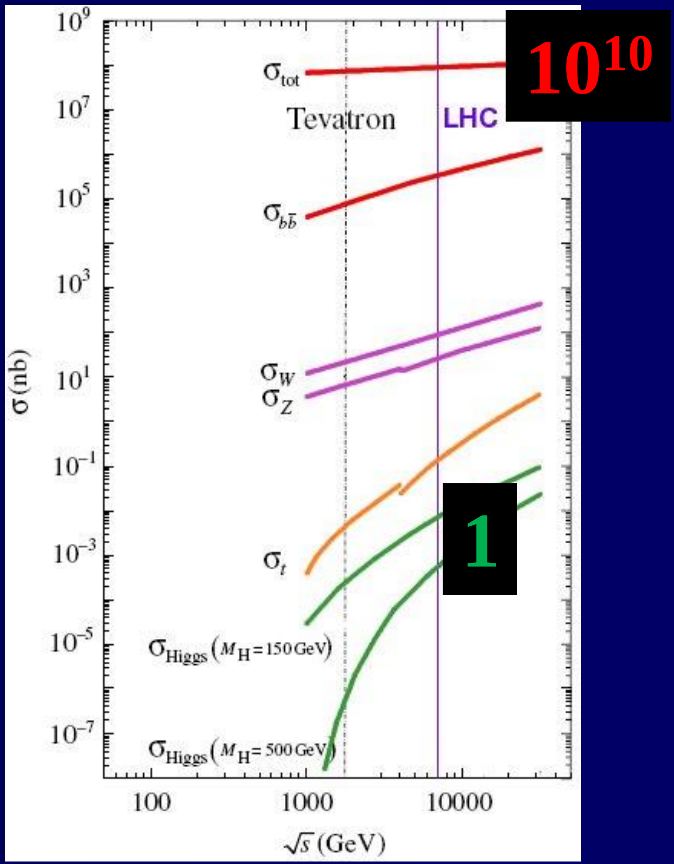
$$p^\mu = \left(m_T \cosh y, p_T \cos\phi, p_T \sin\phi, m_T \sinh y\right)$$

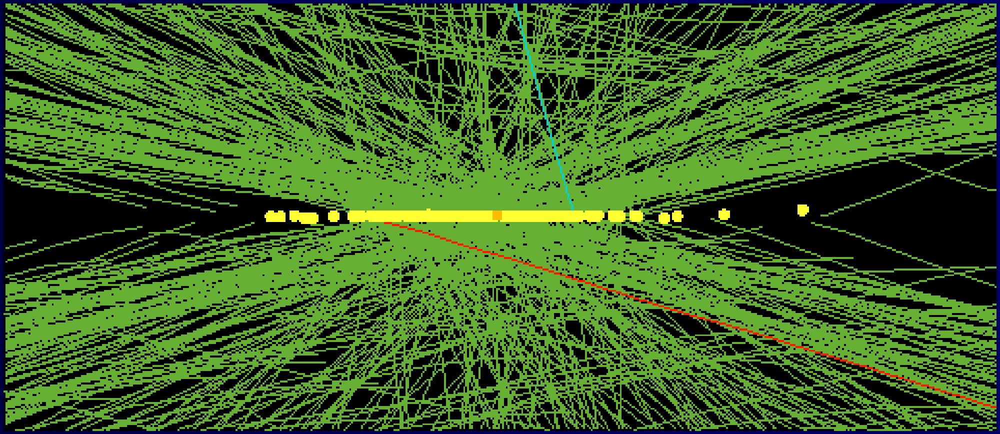
Multiple levels of haystacks

- **Interesting events swamped by mountain of uninteresting background**
- **Multiple interactions within same proton bunch crossing obfuscate the single "hard scatter" with "*pile-up*" events**



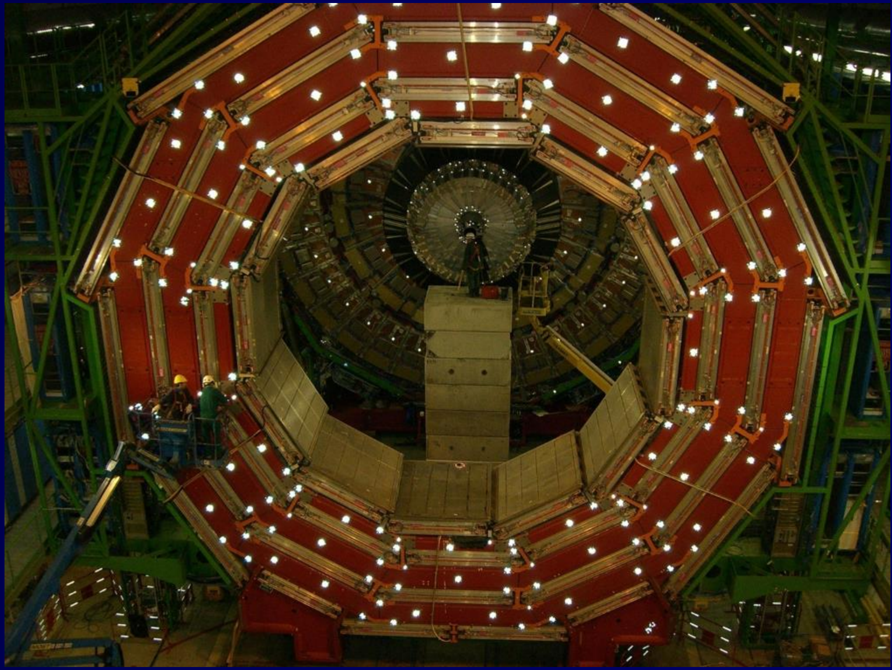
Flugge, Future Research in High Energy Physics
CERN Yellow Report CERN 94-04

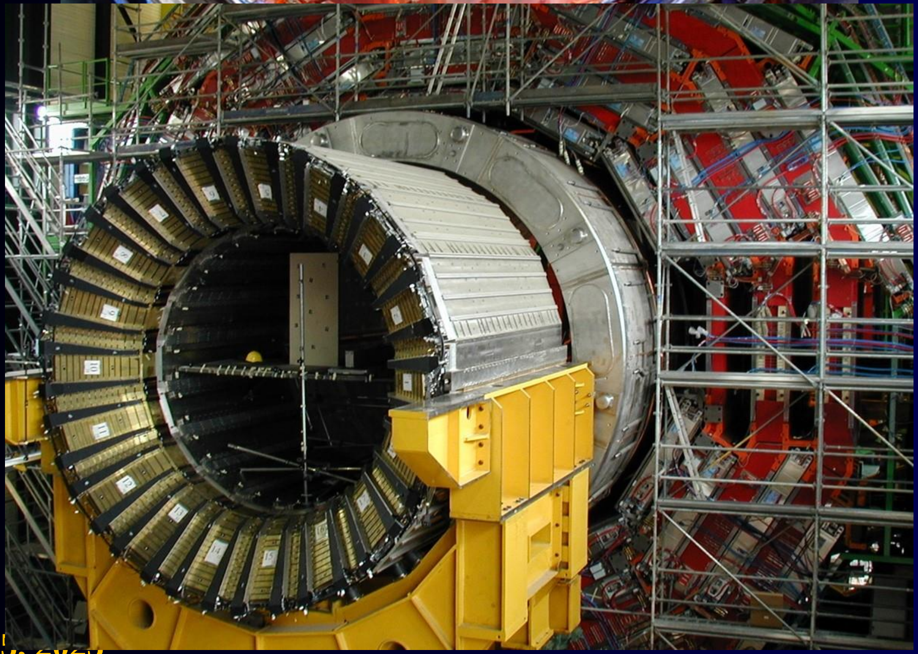




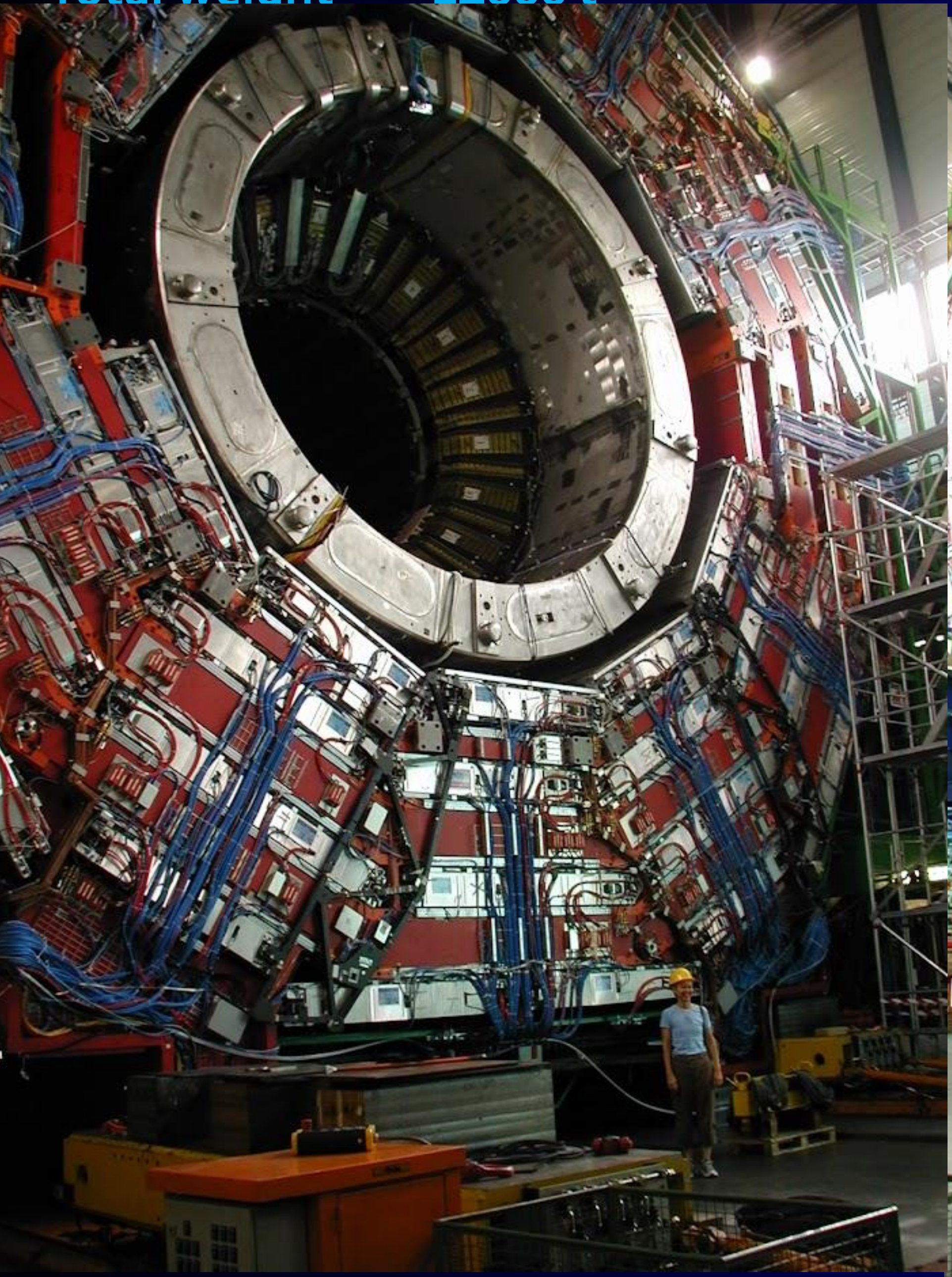
Questionable Detector Analogies

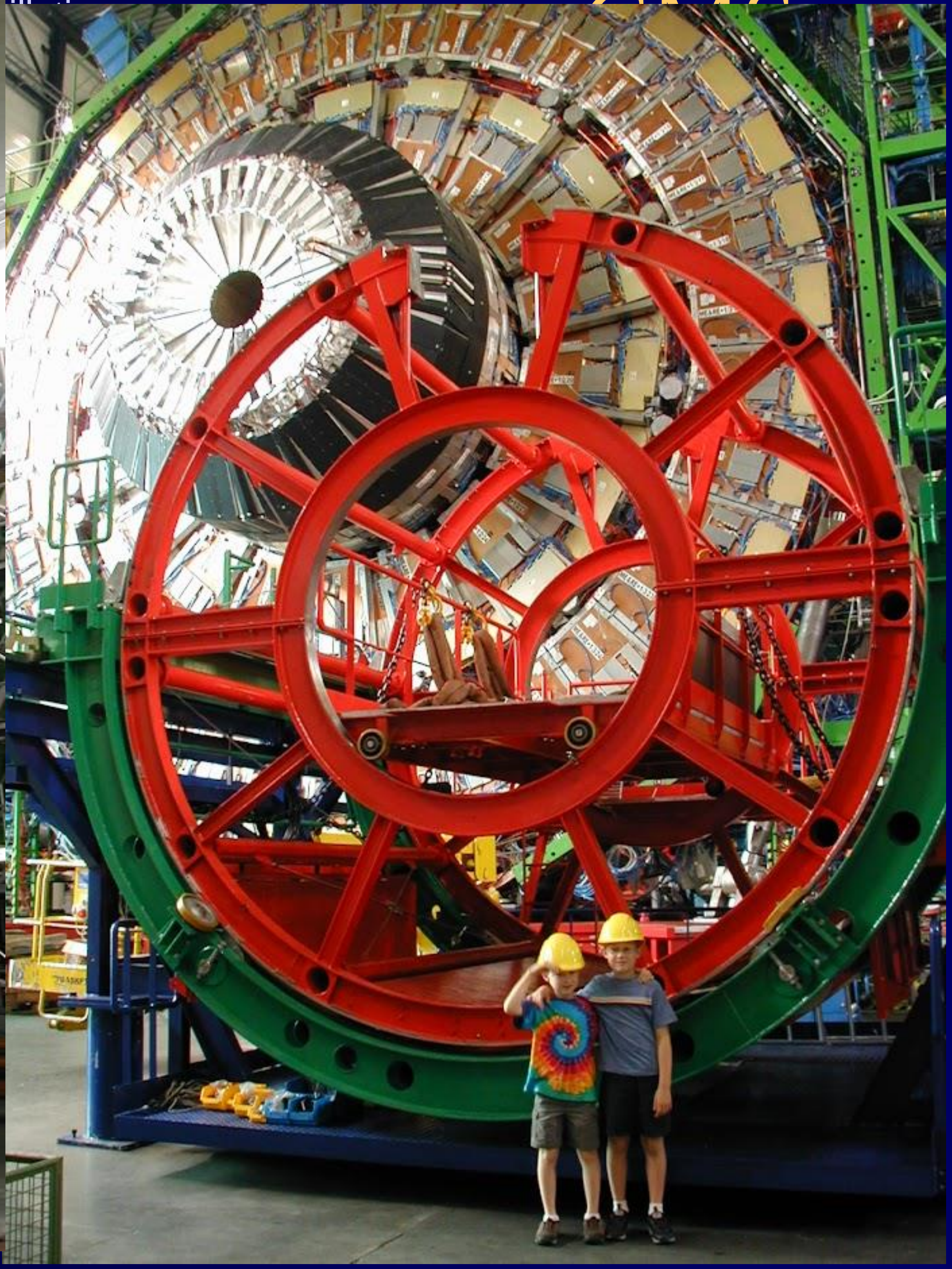
Questionable Detector Analogies

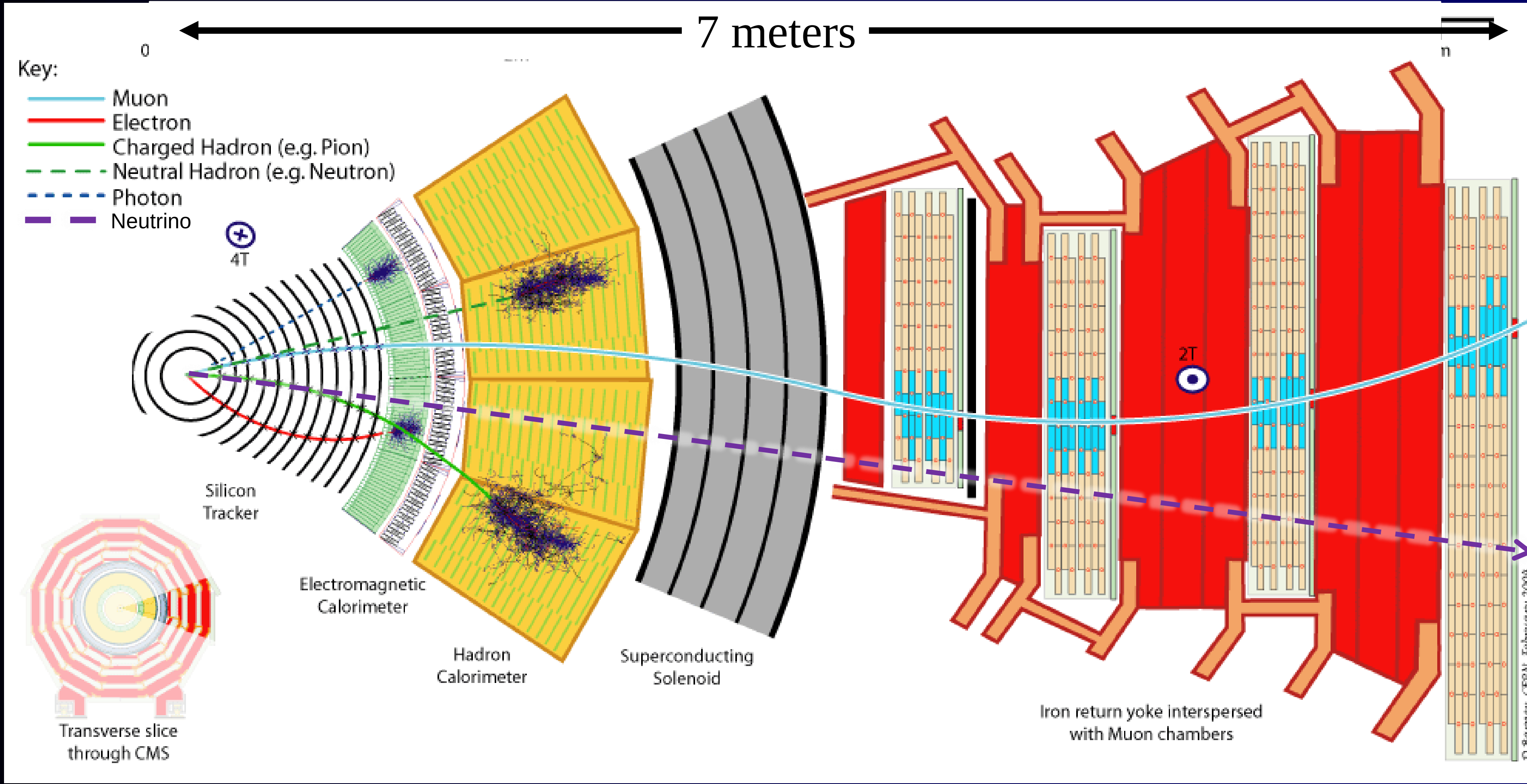




Total weight 14000 t







- **L1 Trigger samples Calorimeter and Muon content @ 40 MHz**
  - **Selects 1 of ~800 in 4 μs for further analysis → full detector readout**
- **High Level Trigger fully reconstructs event @ 50 – 100 kHz**
  - **Selects 1 of ~1000 for data storage → offline reconstruction and analysis**

~ scale…

But before HL LHC: Upgrade!

L1 Trigger/HLT/DAQ
- L1 40 MHz in/750 kHz out with tracking for PF-like performance
- HLT 7.5 kHz out

Barrel Calorimeters
- ECAL single crystal granularity in L1 Trigger with precise timing for e/γ at 30 GeV
- ECAL and HCAL new back-end electronics

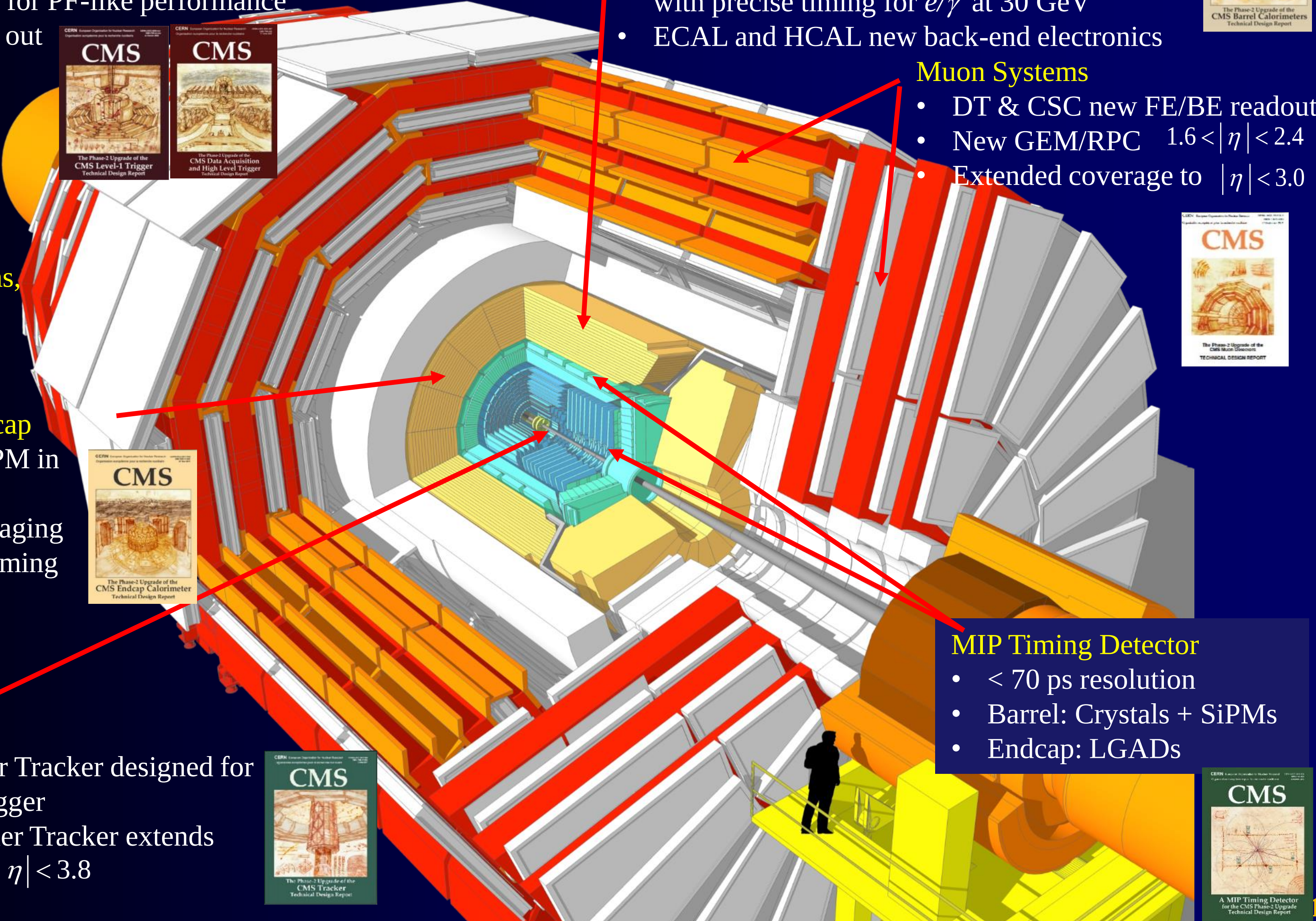
Muon Systems
- DT & CSC new FE/BE readout
- New GEM/RPC $1.6 < |\eta| < 2.4$
- Extended coverage to $|\eta| < 3.0$

Beam Radiation and Luminosity, Common Systems, Infrastructure

Calorimeter Endcap
- Si, Scint + SiPM in Pb-W-SS
- 3D shower imaging with precise timing

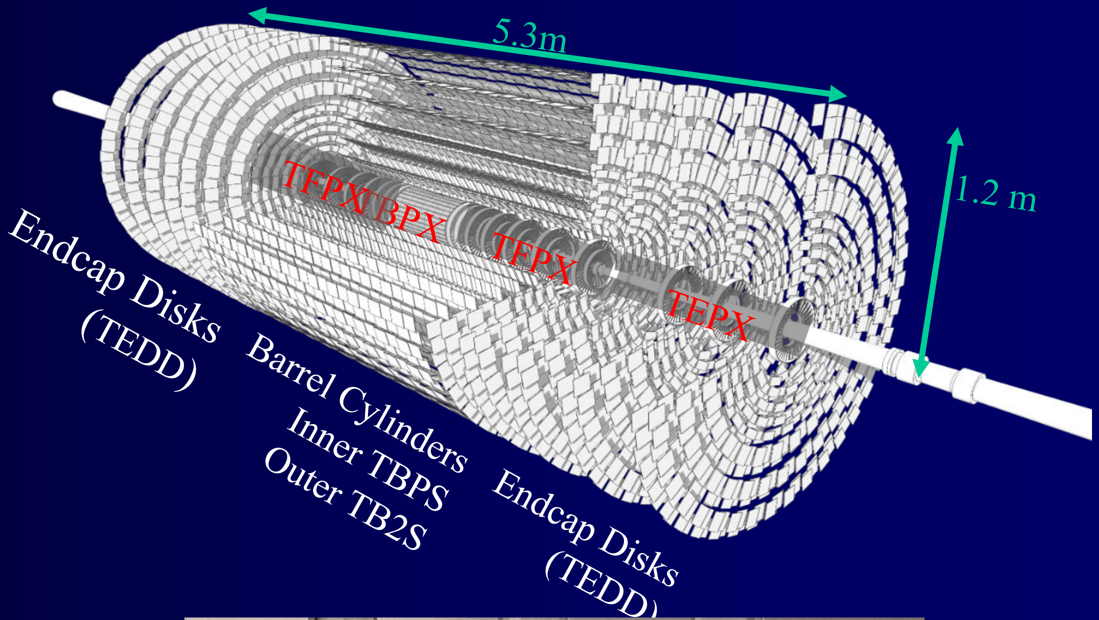
MIP Timing Detector
- < 70 ps resolution
- Barrel: Crystals + SiPMs
- Endcap: LGADs

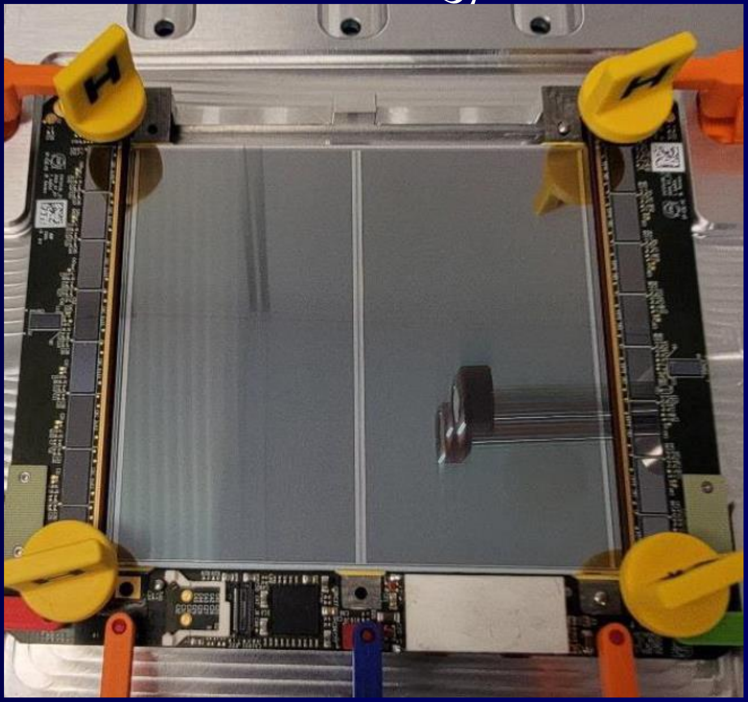
Tracker
- Si Strip Outer Tracker designed for L1 Track Trigger
- Pixelated Inner Tracker extends coverage to $|\eta| < 3.8$



New Tracker

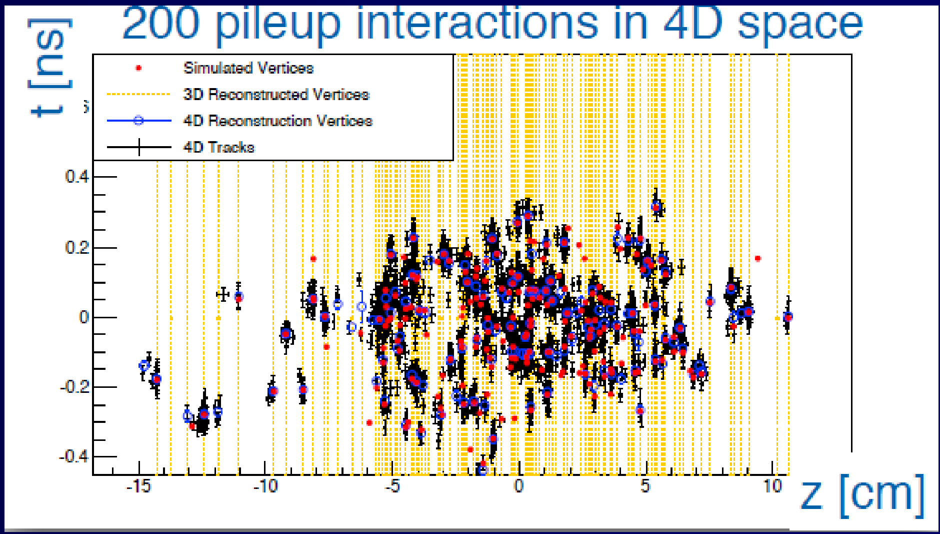
- **Current version doesn't survive HL LHC dose**
- **Features**
  - **~200 m^2 of Silicon!**
    - **×10 increase**
  - **Extended coverage**
  - **Increased granularity**
  - **Reduced multiple scattering**
  - **Tracking information in L1 Trigger**

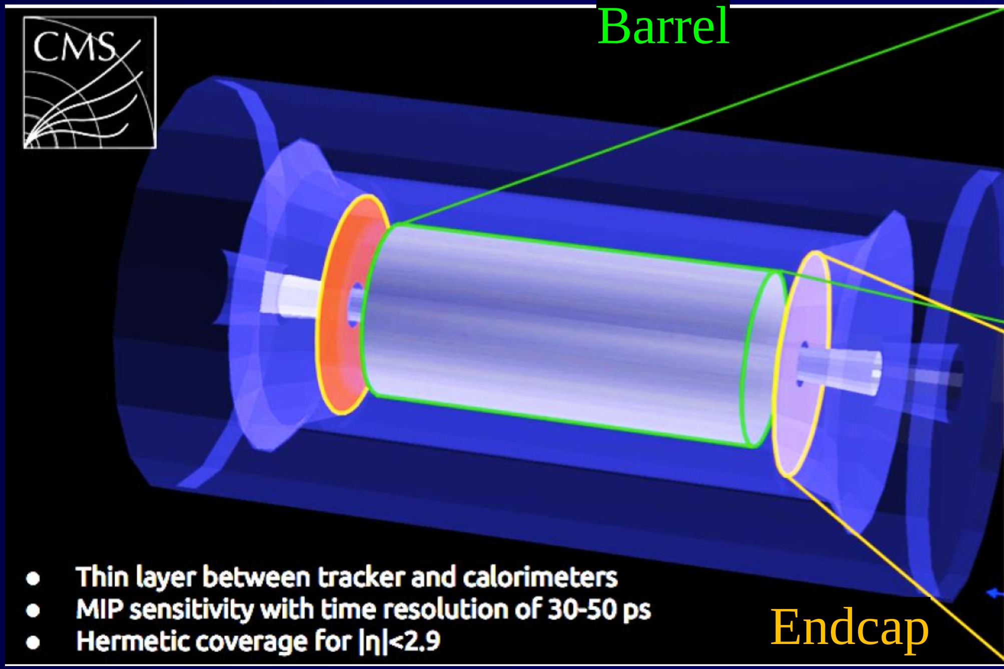




New Timing Layer

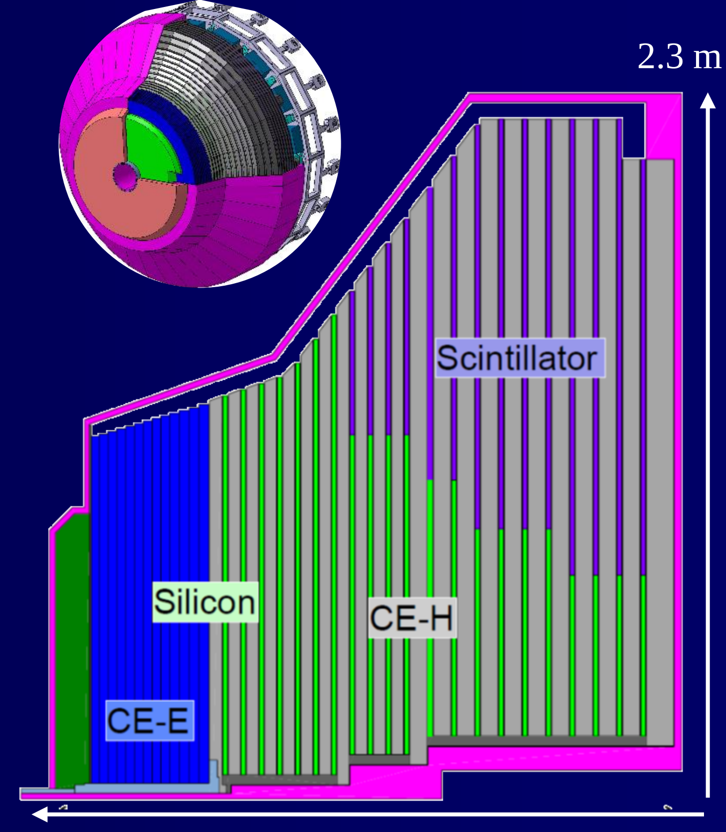
- **Defeat pile-up with separation in *time***
  - **Analogous to spatial separation in tracker**
- **Large coverage with ~ 30 ps timing resolution**
  - **Restores pile-up conditions to pre-HL LHC levels**
- **Font of innovation!**
  - **New handle for CMS**
  - **Extremely valuable for Particle ID in Heavy Ions, for instance**
    - **First step towards "Quantum Worldline Detector" ;)**



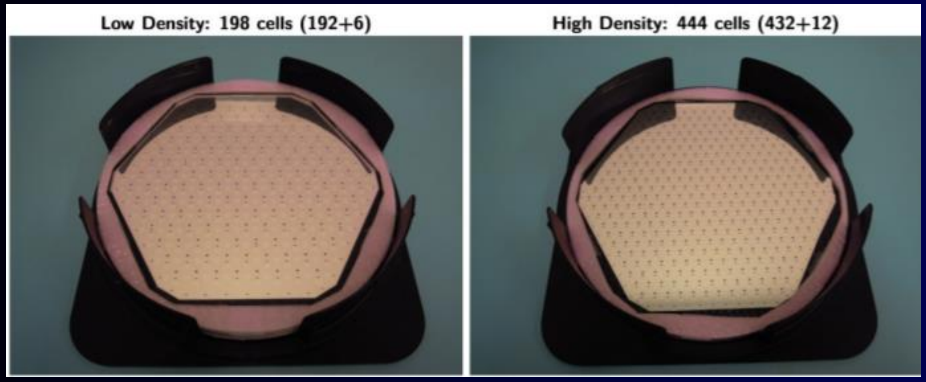


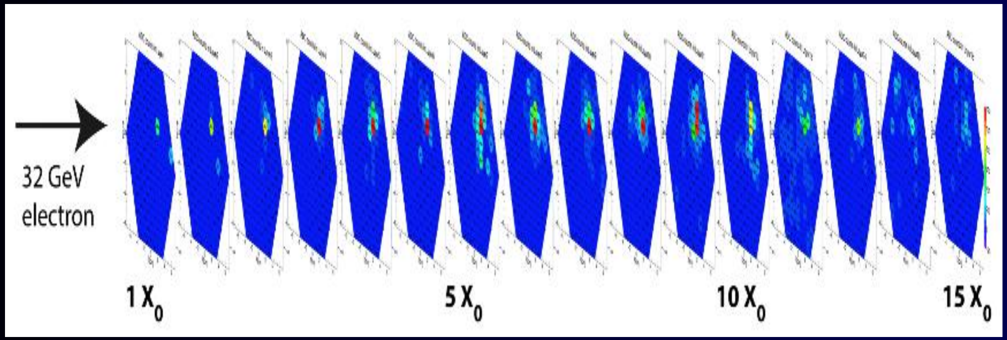
New Endcap Calorimeter

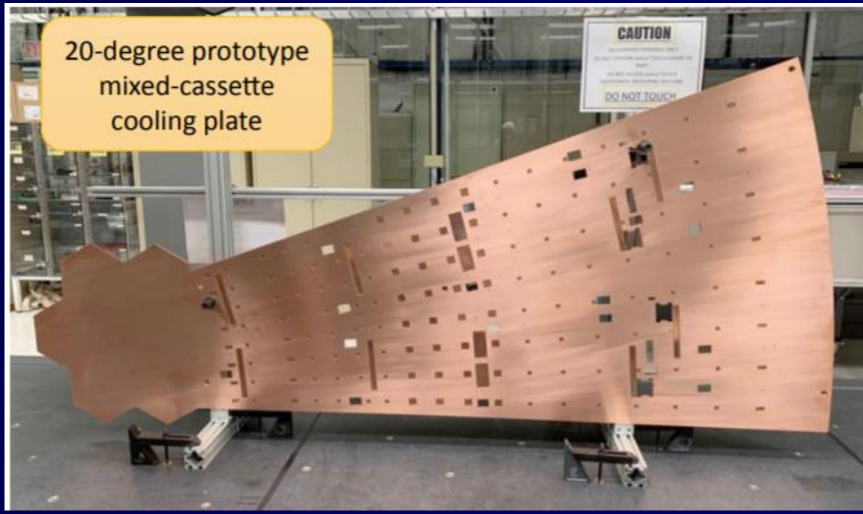
- **Current version doesn't survive dose**
- **Novel "Imaging Calorimeter"**
  - **Highly segmented (×250) 4-D jet image**
    - **Silicon section in high radiation area**
    - **Scintillator (cheaper!) in lower radiation area**



2.2 m

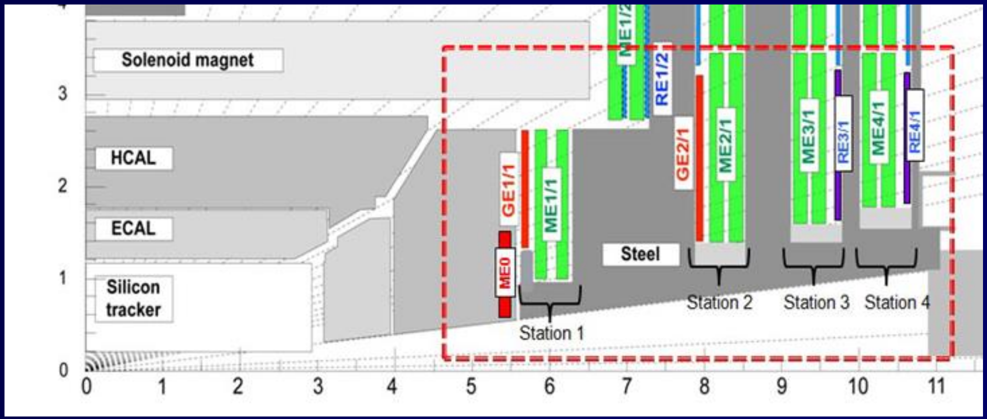






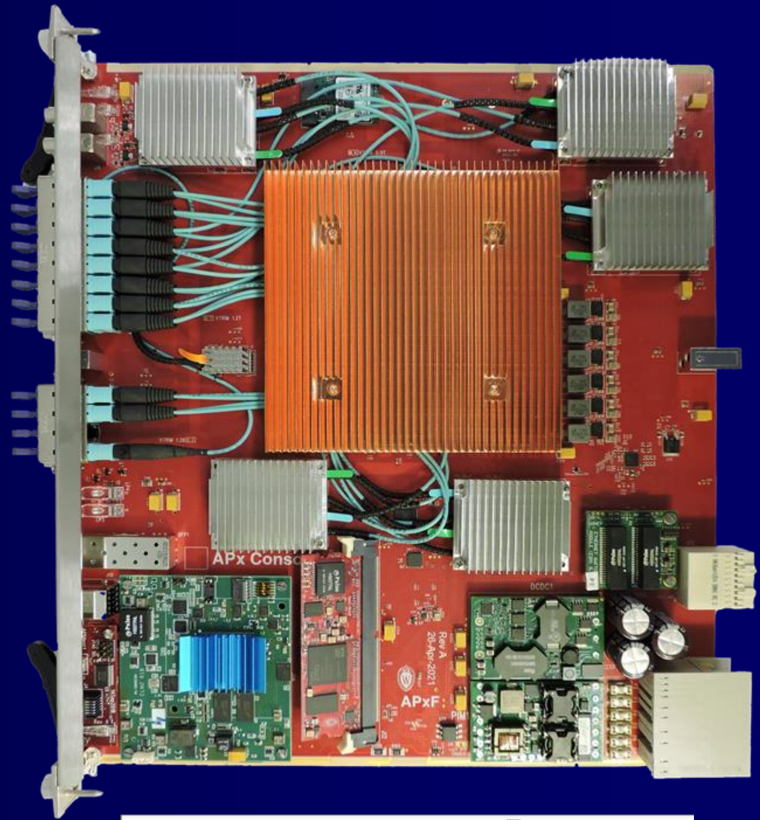
New Muon Systems

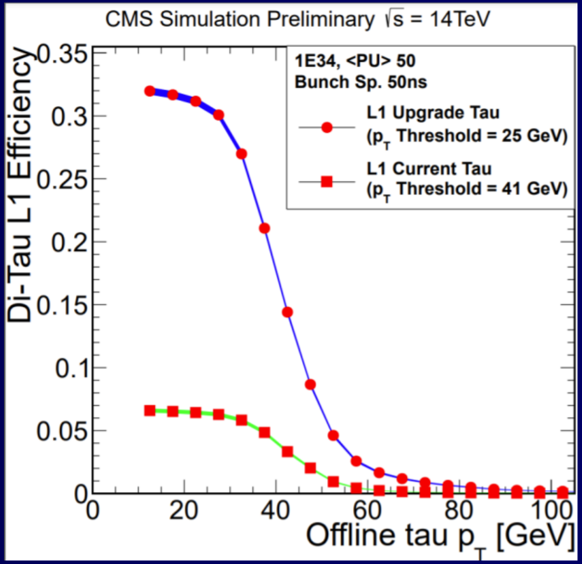
- **New GEM and RPC detectors deployed to increase coverage**
  - **GEM GE 2/1 installed and running in 2023!**



New Electronics

- **Coping with ×5-7 collision rate**
  - **Physics/sec: L1 rate 100 → 750 kHz**
  - **Background/sec: decision time 4 → 12 μs**
- **Level 1 Trigger (L1T)**
  - **High bandwidth optics brings new/more info into Powerful FPGAs**
    - **Longer decision time ⇒ complex algorithms with multiple detectors**
  - **New! C++ ⇒ FPGA algorithms**
    - **Exploits scientist creativity!**
- **Muons, Calorimeter Backend**
  - **Increased bandwidth to keep up with L1A rate**

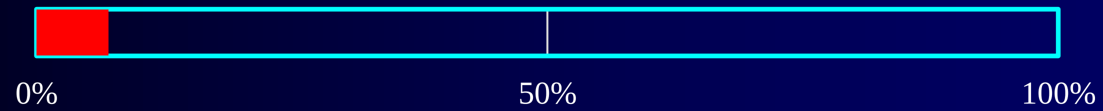




Excellent times at the LHC, and more to come

- **Last 13 years the LHC has been a prolific source of results on a broad spectrum of questions addressable at colliders**
  - **Testing the Standard Model at higher and higher precision, including the resolution of a 50 year old outstanding question**
  - **Constantly pushing the boundaries of where *Physics beyond the Standard Model* may hide**
- **Success resulted from excellent accelerator and detector performance**
  - **The only way to lose at the LHC is to not be able to play the game**
- **There is a lot more to do**
  - **(Very!) Challenging Upgrades employing cutting edge technologies**
  - **Analyzing the 95% of the data to come – results for the next 20 years!**
    - **Up next: The computing challenge to turn data into results!**

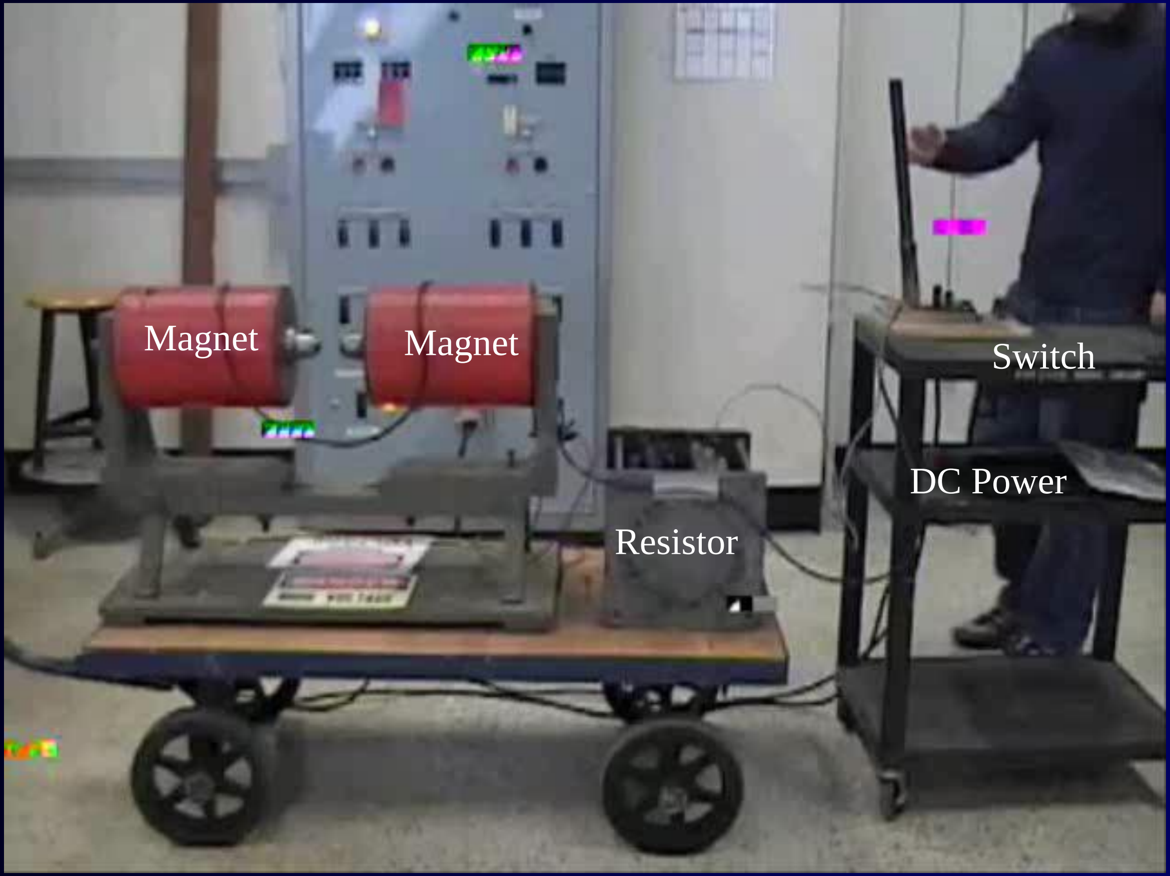
Accumulated LHC Luminosity



An assortment of older slides

Rain Delay, 2008

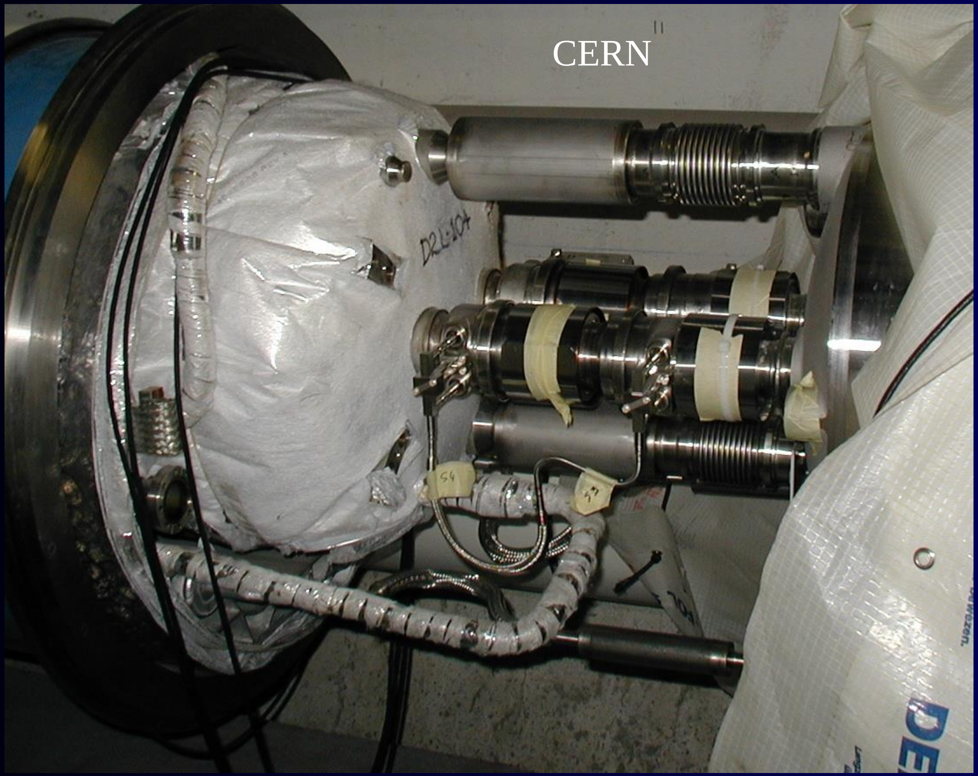
MIT Technical Services Group – Classical E&M demo



- **Above: 12 H solenoid at 30 A $\Rightarrow$ 5.4 kJ**
- **LHC Dipoles: 154 × 0.11 H at 9 kA $\Rightarrow$ 690,000 kJ**

A Series of Unfortunate Events

- **Arc: He at 1.9K ⇒ Insulation vacuum (Room Temp)**
- **Relief Valves overwhelmed - 30 tons on Vacuum Barriers**
  - **Moved tons by ~meter**
- **Cost one year, initial running at 7 TeV (½ design)**



LHC reloaded

The Collaboration

5385 Members | 2104 Authors | 239 institutes | 54 countries

A. Tumasyan, W. Adam, J. W. Andrejkovic, T. Bergauer, S. Chatterjee, M. Dragicevic, A. Escalante Del Valle, R. Frühwirth, M. Jeitler, N. Krammer, L. Lechner, D. Liko, I. Mikulec, P. Paulitsch, F. M. Pitters, J. Schieck, R. Schöfbeck, M. Spanring, S. Templ, W. Waltenberger, C.-E. Wulz, V. Chekhovsky, A. Litomin, V. Makarenko, M. R. Dawish, E. A. De Wolf, X. Janssen, T. Kello, A. Lelek, H. Rejeb Sfar, P. Van Mechelen, S. Van Putte, N. Van Remortel, F. Blekman, E. S. Bols, J. D'Hondt, J. De Clercq, M. Delcourt, H. El Faham, S. Lowette, S. Moortgat, A. Morton, D. Müller, A. R. Sahasransu, S. Tavernier, W. Van Doninck, P. Van Mulders, D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, L. Favart, A. Grebenyuk, A. K. Kalsi, K. Lee, M. Mahdavikhorrami, I. Makarenko, L. Moureaux, L. Pétré, A. Popov, N. Postiau, E. Starling, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer, D. Vannerom, L. Wezenbeek, T. Cornelis, D. Dobur, J. Knolle, L. Lambrecht, G. Mestdach, M. Niedziela, C. Roskas, A. Samalan, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, A. Bethani, G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, ... [illegible]