

### LHC and CMS

S. Nahn PURSUE Undergraduate Summer Internship June 5<sup>th</sup>, 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

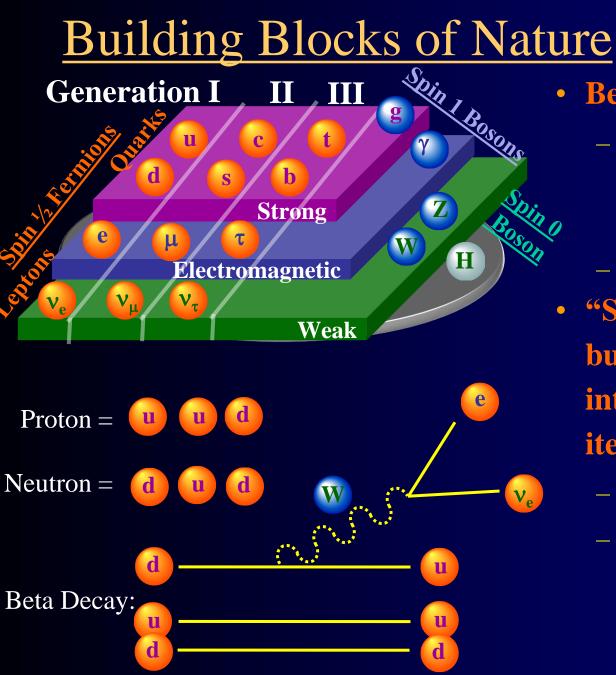


## Subatomic Particles 101

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

June 5, 2023

PURSUE - FNAL CMS and the LHC

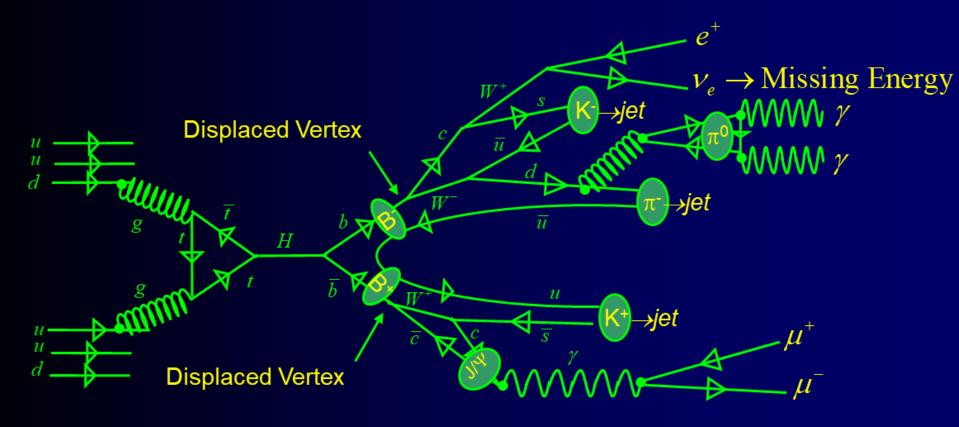


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- Beautiful symmetry
  - 12 "things" in 3 sets of 2 pairs (+ anti-things mirror)
    - way easier than chemistry
  - 3 types of interactions
- "Standard Model" (SM)= building particles and interactions from these items
  - Following certain rules
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

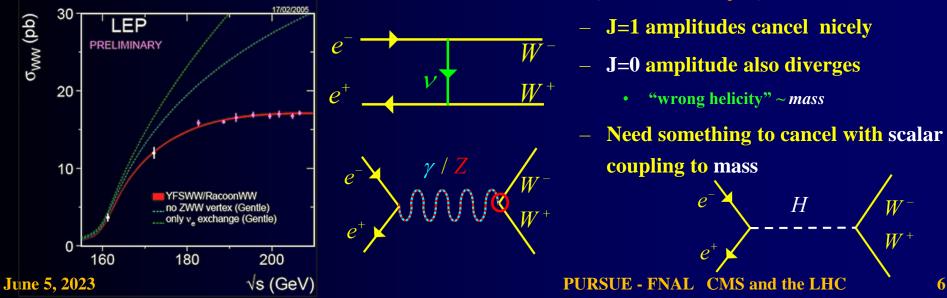
### But can get complicated quickly

- $pp \rightarrow H \rightarrow bb$ 
  - Leptons, Photons, "Jets" of Hadrons, Missing Energy, Secondary particles/vertices



## $\frac{\text{Rules} \rightarrow \text{Discovery}}{\text{Rules}}$

- Symmetries imply Conserved Quantities (Noether's Theorem)
  - eg. Translation in space, time → Momentum, Energy conservation
  - Laws of motion <u>must preserve</u> 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")





### • Pauli, Decembe

Hyrical - Plotocopie of Absobrist

Zirich, 4.

Gloriastra

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

Abschrift

Physikalisches Institut der Eidg. Technischen Hochschule Zurich

#### Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollet ansuhören bitte, Ihmen des näheren aussinendersetsen wird, bin angesichte der "falschen" Statistik der N- und Li-6 Kerne, sow des kontinuisrlichen bete-Speitrums auf einen verweifelten Au verfallen um den "wechenlasts" (1) der Statistik und den Ener zu retten. Nämlich die Möglichkeit, es könnten elektrisch neu Teilchen, die ich Neutronen nemmen will, in den kernen azistie welche den Spin 1/2 heben und des Ausschlieseungsprinsip befoliste von lächtquanten zuszerden noch dadurch unterscheiden, das wiedet alt lächtgeschwindigkeit laufen. Die Hasse der Neutrone misste mit lächtgeschwindigkeit laufen. Die Hasse der Neutrone misste wen derselben Grössenordnung wie die Elektronermasse se jesenfalle nicht grösser als 0,00 Frotonermasses- Des kontinui bete-Speitrum wire dann verständlich nuter der Annahme, dass i bete-Zerfall mit den bleitron jeweils noch ein Neutron und bleit Konstant ist.

Num handelt es sich weiter derum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutro mir aus wellenmechanischen Gründen (näheres weise der Ueberbri dieser Zeilen) dieses zu sein, dass das ruhende Meutron ein marnetischer Dhol von einem gesissen Moment Arist. Die Experverlanen wohl, dass die ionisierende Wirkung eines solchen Ner nicht grösser sein kann, els die eines gamma-Strahls und dauf ( Ar wohl nicht grösser sein als e  $\cdot (10^{-5} \text{ cm})$ .

Ich traue mich vorlüufig aber nicht, etwas über diese I su publisieren und wende mich erst vertrauensvoll an Buch, lie Radicaktive, mit der Frage, wie es um den experimentellen Mach eines solchen Neutrons stände, wenn dieses ein ebensolches oder Maal grösseres Durchdringungsverwögen besitzen würde, wie ein grünsstrahl.

Ich gebe su, das- mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, u die exististen, wohl schon löngst gesehen hätte. Aber nur wer genümst und der Ernst der Situation bein kontinnigrliche betawird durch einen Aussprach weines wrehrten Vorgingers im Ante-Herrn Debye, beleuchtet, der mir Mürzlich in Prissel gesagt het "O, daran soll man am besten gar nicht denken, sowie an die ne Steuern." Darum soll man jeden Weg sur Retung ernstlich disk Also, liebe Radioaktive, prüfet, und richtsta- Ledder kann ich personlich in Tübingen erweheinen, da sch infolge eines in der vom 6. sum 7 Des. in Zurich stattfindenden Balles hier unabköm bin.- Hit vielen Orügeen an Buch sowie an Herrn Baek, Raer untertänigster Diemer

ges. W. Pauli

Physics Institute of the ETH Zürich

#### 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  $\mu$ . 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  $\mu$  is probably not allowed to be larger than e • (10<sup>-13</sup> 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

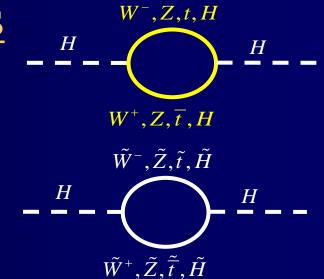
signed W. Pauli

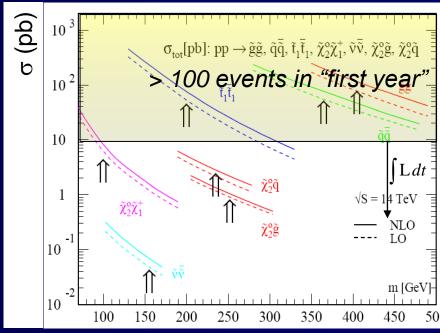
#### [Translation: Kurt Riesselmann]

## Higgs causes other problems

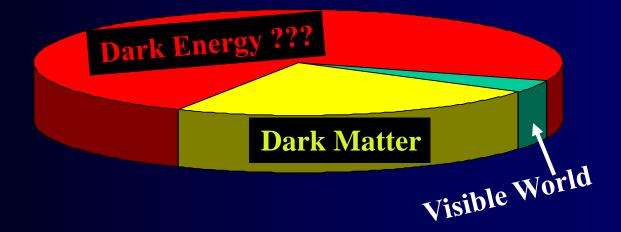
- Electroweak Paradox
  - **EW** observables  $\Rightarrow$  light H
  - **EW** corrections  $\Rightarrow$  heavy **H**

- 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





### 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?



### How to probe Subatomic World Luminosity (flux):

- Basic Recipe:
  - Send in a flux of particles
  - Measure what comes out vs
    - (Energy, angle, frequency ...)
- Need High *E* to resolve small structures  $\hbar c = 197 \text{ MeV fm}$   $p = 10 \text{ GeV} \rightarrow 0.02 \text{ fm}$  $\Rightarrow$  Build Accelerators
- What to measure?
  - Rate/Scattering Cross Section: Rate
    - Distributions in E,α...
  - Spectroscopy of Excited states

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

Object

 $R(E,\alpha...) = L\sigma(E,\alpha...)$ 



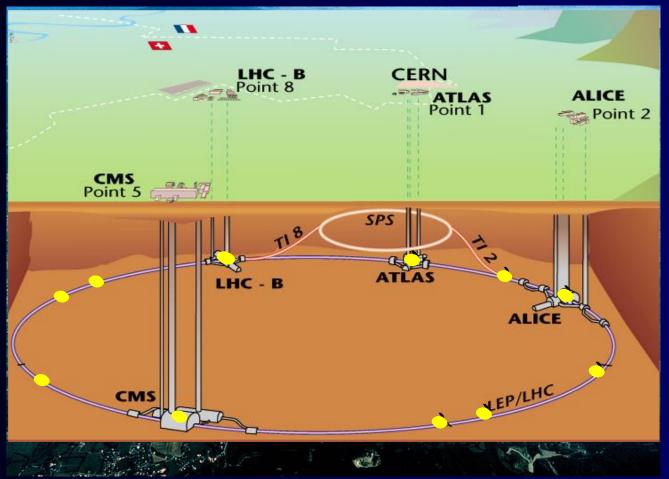
### How to move a particle in a circle?

 Electromagnetism!  $\vec{\mathbf{F}} = q | \vec{\mathbf{E}} + (\vec{\mathbf{p}} \times \vec{\mathbf{B}}) / m |$ - Acceleration  $q\vec{\mathbf{E}}$  = *qpB* **Circular motion**  $|\vec{\mathbf{p}}| = qBR$  $p_R$ 1/1

- 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

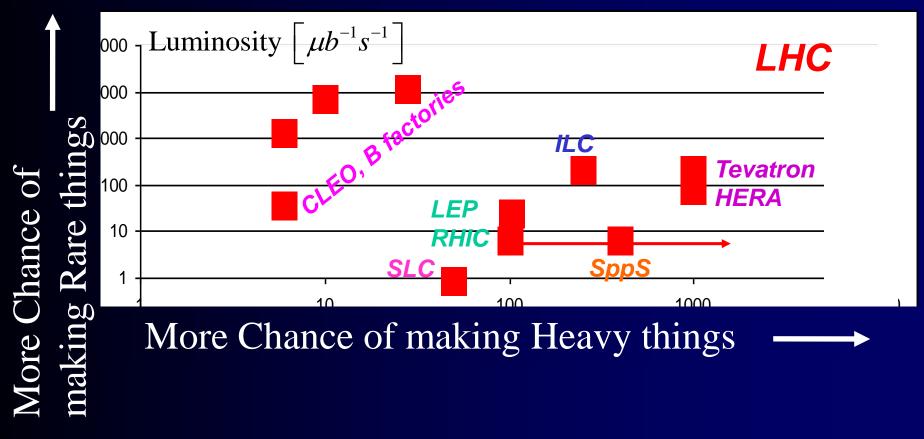
Proton - Proton Collisions Initially: 10<sup>6</sup> events/s, 7 TeV Eventually: 10<sup>9</sup> events/s, 14 TeV (Lead lons 2.76 → 5.5 TeV/nucleon)





Superconducting Double Dipoles  $|\vec{\mathbf{p}}| = 0.3BR = 7000 \, GeV$   $B = \frac{7000}{0.3 \times 4300} = 5.5T \Rightarrow 8T$  $\approx 100,000 \times Earth field$ 

## A BIG Step



LHC has the reach in Luminosity and Energy to

 Find the higgs ✓
 Find more

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### What is a detector?

Many synchronous cameras looking at same event



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

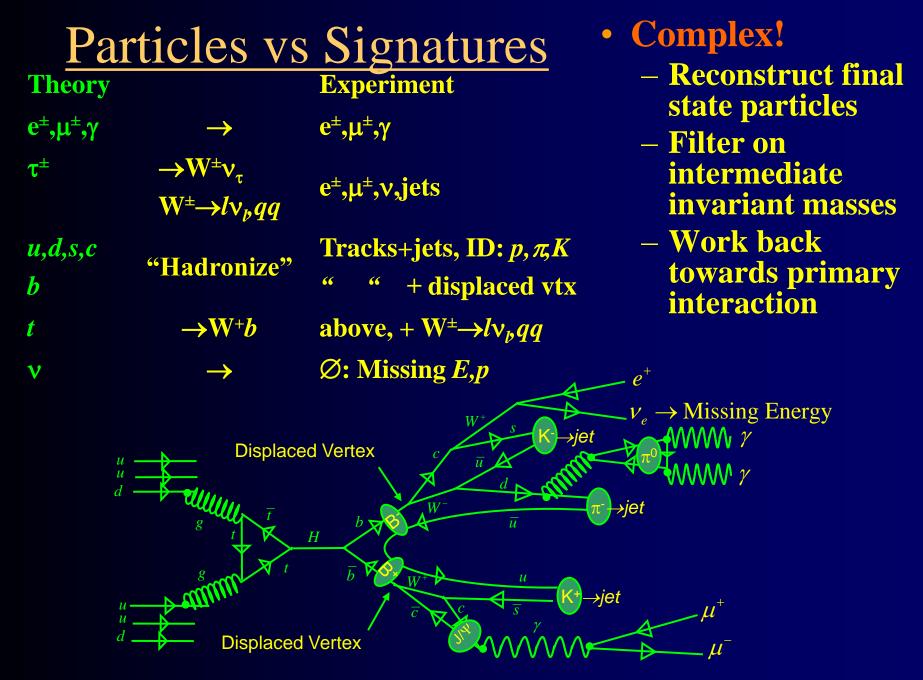


### **Detector Mission Statemennt**

- **Goal:** Measure observables, compare with theory  $\frac{d\sigma}{d\vec{\xi}} \quad \vec{\xi} = (E, p, \theta, \Omega...)$ 
  - Cross sections
  - 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  $4\pi$
    - Filter ("trigger") in face of limited bandwidth
    - Robustness in design and operation

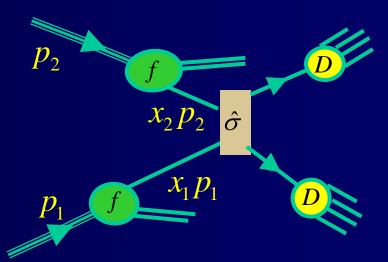
### **Measurements**

- Position: Follow trail left by ionization/Energy deposition
  - Intersections = Interaction vertices, decay vertices
- Energy/Momentum: Bend in  $\dot{\mathbf{B}}$ , measure E via calorimeter
- Particle ID
  - *m* via  $\beta$ : 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



## Hadron Kinematics

• Energy set by PDFs  $f(x_i)$   $E_{CM}^2 = (x_1 p_1 + x_2 p_2)^2$ • Usually: Boosted along z  $p_1 = p_2$  but  $x_1 \neq x_2$ 



 $\Rightarrow$  Use parametrization conducive to boosts along z

- <u>**Rapidity</u>**:  $y = \frac{1}{2} \ln \left( \frac{E + p_z}{E p_z} \right)$   $y \in [-\infty, \infty]$ </u>
  - Additive under boosts:  $\Delta y$  is invariant
  - *m*  $\rightarrow$  0: Pseudorapidity  $\eta = \frac{1}{2} \ln \left( \frac{|\vec{\mathbf{p}}| + p_z}{|\vec{\mathbf{p}}| p_z} \right) = -\ln \tan \left( \frac{\theta}{2} \right)$

### • <u>Transverse Momentum</u>: p<sub>1</sub>

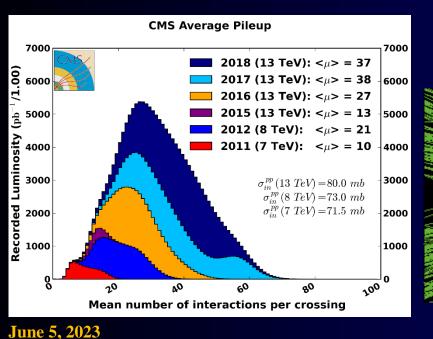
- Transverse mass  $m_{\rm T} = \sqrt{p_{\rm T}^2 + m^2}$  and Energy  $E_{\rm T} = E \sin \theta$ 

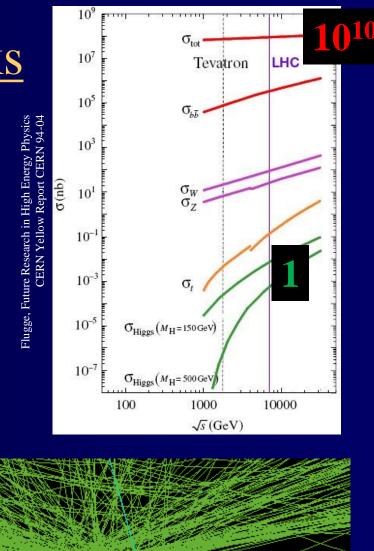
<u>Azimuth:</u> φ

$$p^{\mu} = (m_{\rm T} \cosh y, p_{\rm T} \cos \phi, p_{\rm T} \sin \phi, m_{\rm T} \sinh y)$$

## 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





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### **Questionable Detector Analogies**

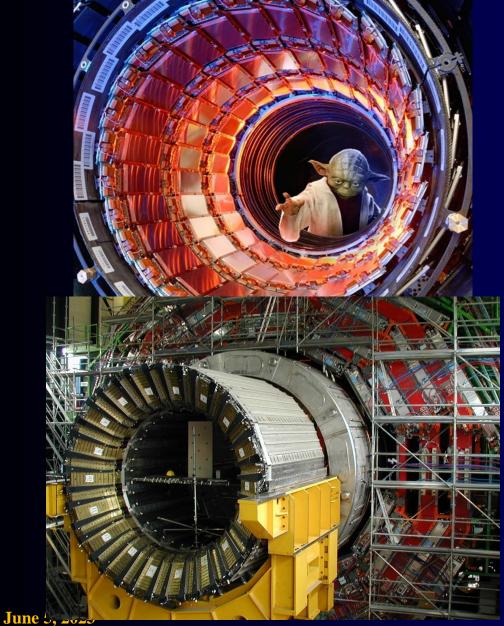






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### **Questionable Detector Analogies**





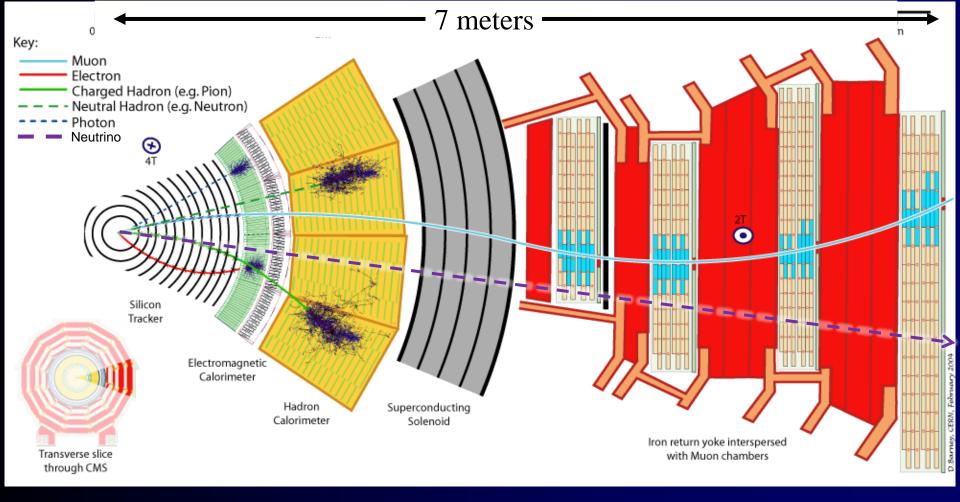
### Total weight 14000 t

-

And the second

1. ·





- L1 Trigger samples Calorimeter and Muon content @ 40 MHz
  - Selects 1 of ~800 in 4  $\mu$ s for further analysis  $\rightarrow$  full detector readout
- High Level Trigger fully reconstructs event @ 50 100 kHz

— Selects 1 of ~1000 for data storage → offline reconstruction and analysis
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## But before HL LHC: Upgrade!

#### L1 Trigger/HLT/DAQ

 L1 40 MHz in/750 kHz out with tracking for PF-like performance

CMS

CMS

CMS

CMS

• HLT 7.5 kHz out

Beam Radiation and Luminosity, Common Systems, Infrastructure

#### Calorimeter Endcap

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

#### Tracker

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

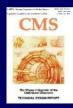
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#### **Barrel Calorimeters**

- ECAL single crystal granularity in L1 Trigger with precise timing for  $e/\gamma$  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  $|\eta| < 3.0$



CMS

The Phase-2 Upgrade of CMS Barrel Calorin

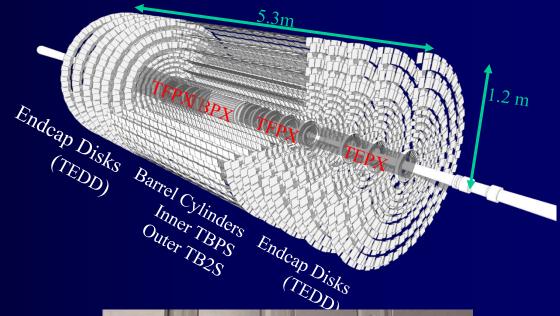
#### MIP Timing Detector

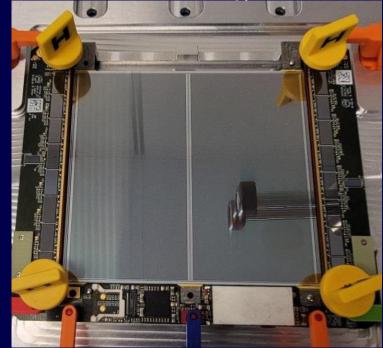
- < 70 ps resolution
- Barrel: Crystals + SiPMs
- Endcap: LGADs



## New Tracker

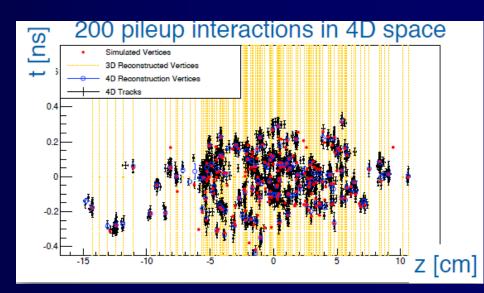
- Current version doesn't survive HL LHC dose
- Features
  - ~200 m<sup>2</sup> of Silicon!
    - ×10 increase
  - Extended coverage
  - Increased granularity
  - Reduced multiple scattering
  - Tracking information in L1 Trigger

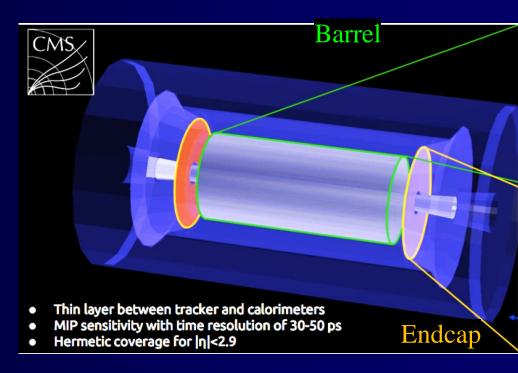




## New Timing Layer

- 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" ;)

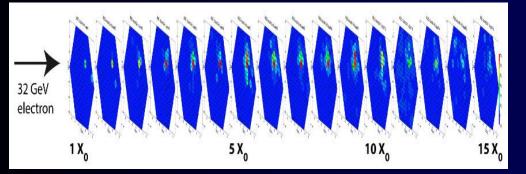


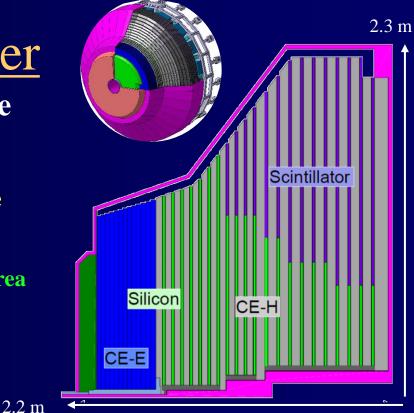


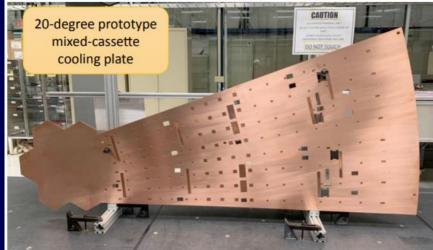
### New Endcap Calorimeter

- 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





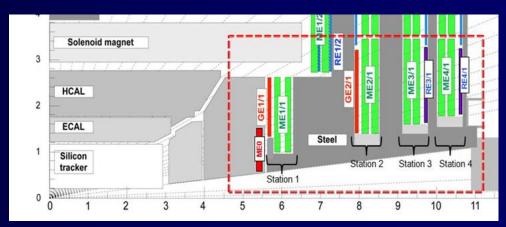




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### New Muon Systems

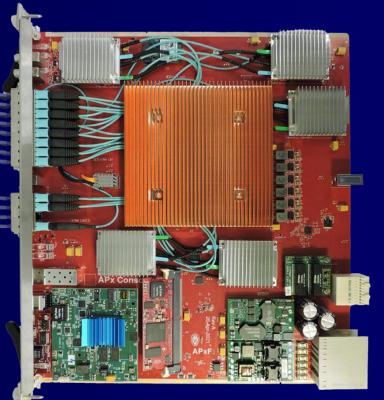
- New GEM and RPC detectors deployed to increase coverage
  - GEM GE 2/1 installed and running in 2023!

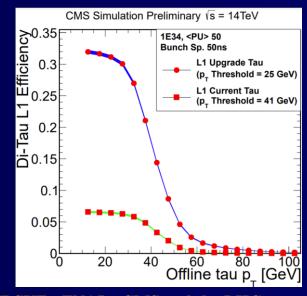




### New Electronics

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

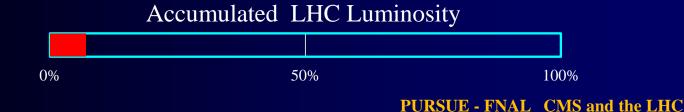




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### Excellent times at the LHC, and more to come

- 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!



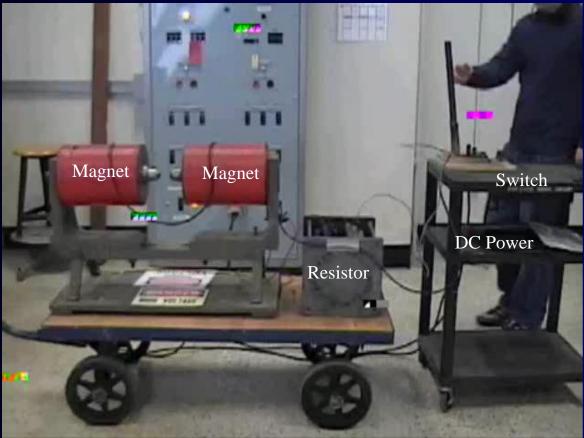
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LHC

### An assortment of older slides



MIT Technical Services Group – Classical E&M demo



- Above: 12 H solenoid at 30 A  $\Rightarrow$  5.4 kJ
- LHC Dipoles:  $154 \times 0.11$  H at  $9 \text{ kA} \Rightarrow 690,000$  kJ

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### 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 (<sup>1</sup>/<sub>2</sub> design)







## The Collaboration

# 5385210423954MembersAuthors institutescountries

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Samalan, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, A. Belhani, G. Bruno, F. Bury, C. Caputo, P. David, C. Delaer I. S. Donertas, A. Giarmanco, K. Jaffel, Sa. Jain, V. Lematre, K. Mondal, J. Prisciandaro, A. Taliercio, M. Tekishyn, T. T. Tran, P. Vischia, S. Wertz, G. A. Alves, C. Hensel, A. Moraes, W. L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbourisson, W. Carvalho, J. Chinelato, E. M. Da Costa, G. G. Da Silveira, D. De Jesus Damiao, S. Fonseca De Souza, D. Matos Figueiredo, C. Mora Herera, K. Mota Amanio, L. Mundim, H. Nogima, P. Rebelio Teles, A. Santoro, S. M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo, A. Vilela Pereira, C. A. Bernardes, L. Calligaris, T. R. Fernandez Perez Tomei, E. M. Gregores, D. S. Lemos, P. G. Mercadante, S. F. Novaes, Sandra S. Padula, A. Aleksandrov, G. Antchev, R. Hadjiska, P. laydjev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov, A. Dimitrov, T. Ivanov, L. Litov, B. 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