When they go low, we go lower: extending the reach of collider experiments with low-level detector information

Grace E. Cummings

Brookhaven Colloquium, 22 April 2025

What is matter,

and how does it interact?

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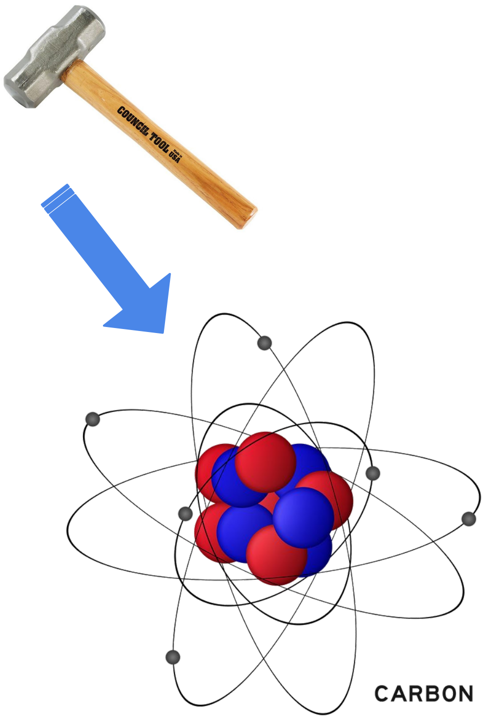

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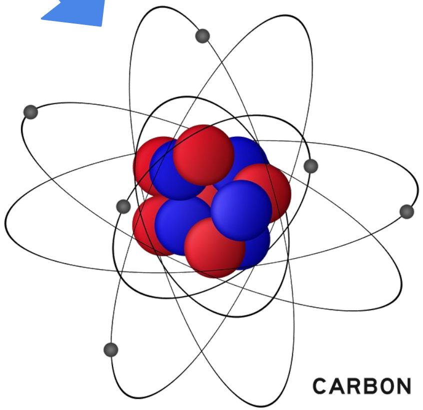
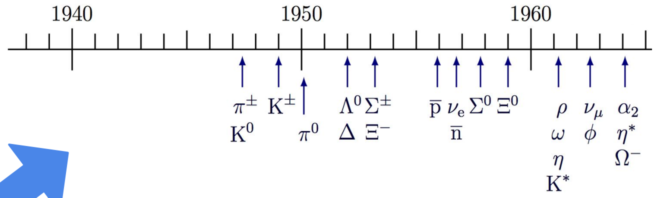
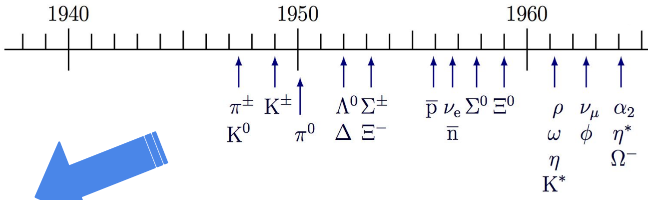


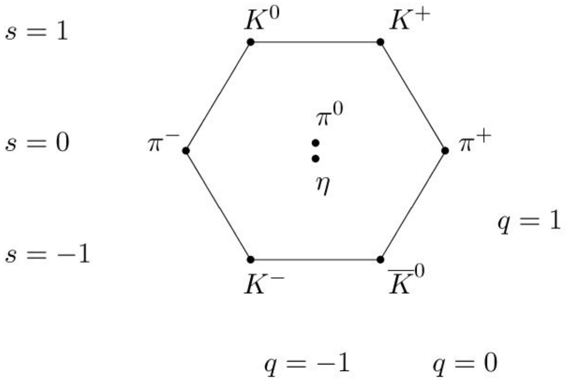


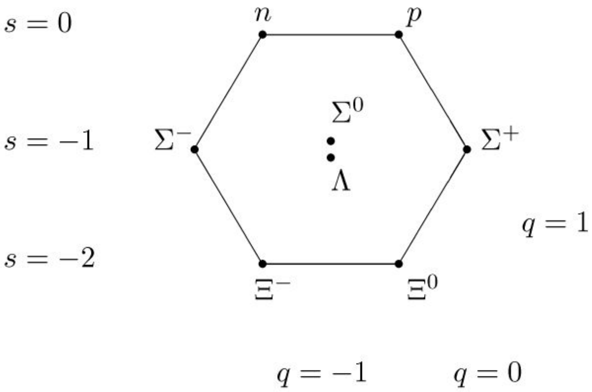
Hadrons and their substructure!

Detailed characterization of ..

Mass, Energy, Charge, etc..



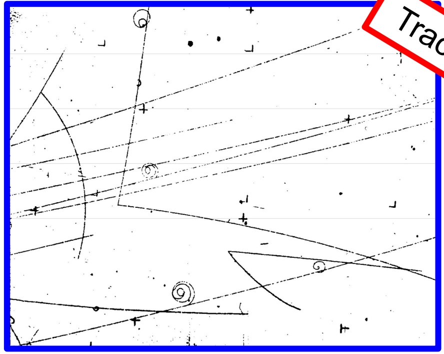




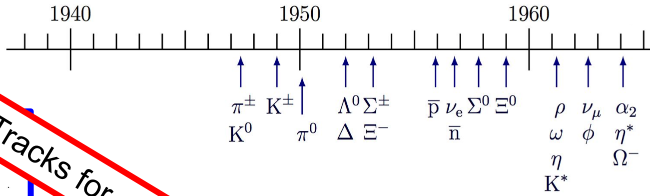
Quark-model emerges!

The “particle zoo” detectors - imaging detectors!

Bubble Chambers



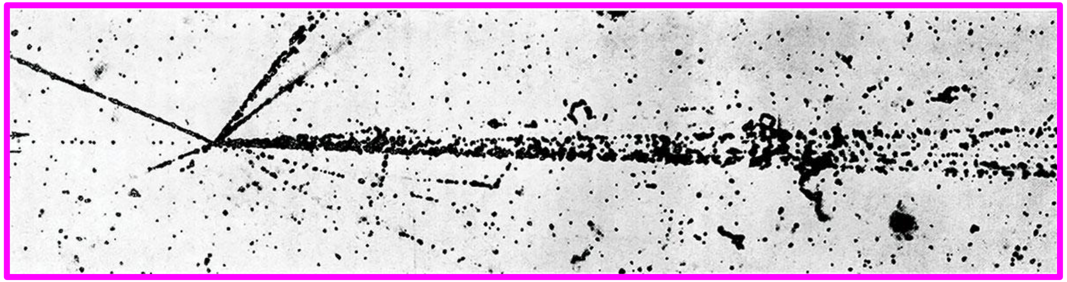
Tracks for momenta

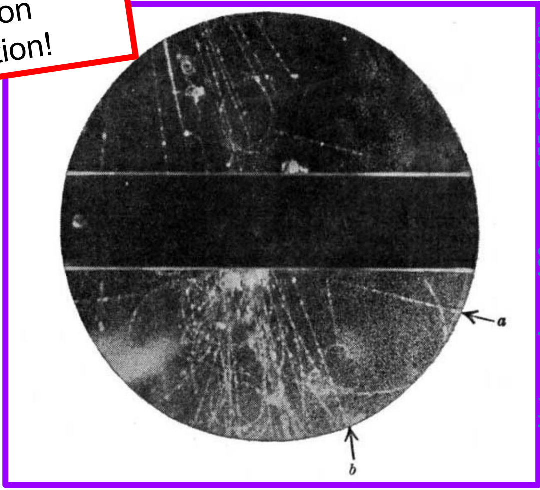


Cloud Chambers

Ionization information!

Nuclear Emulsions





Nature **volume 160**, pages 855–857 (1947)

Even more fundamental particles

Want higher mass?

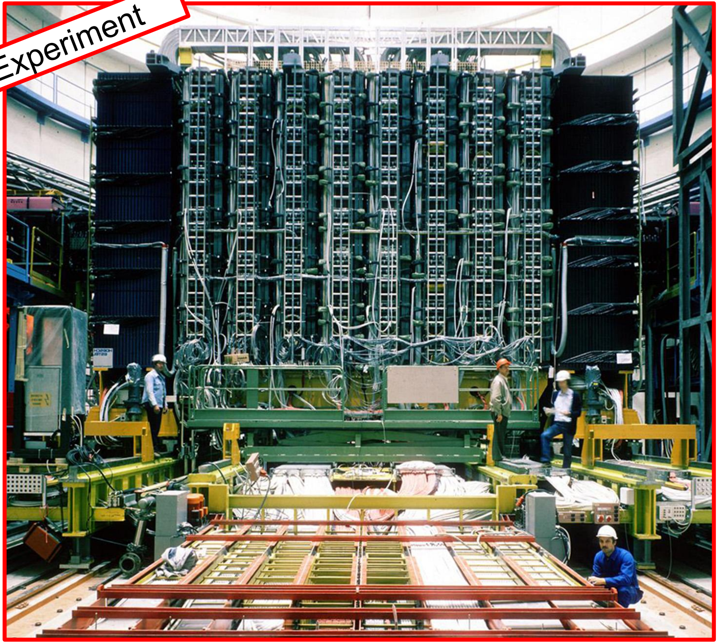
$$E^2 = \left(mc^2\right)^2 + (pc)^2$$

Need higher energy!

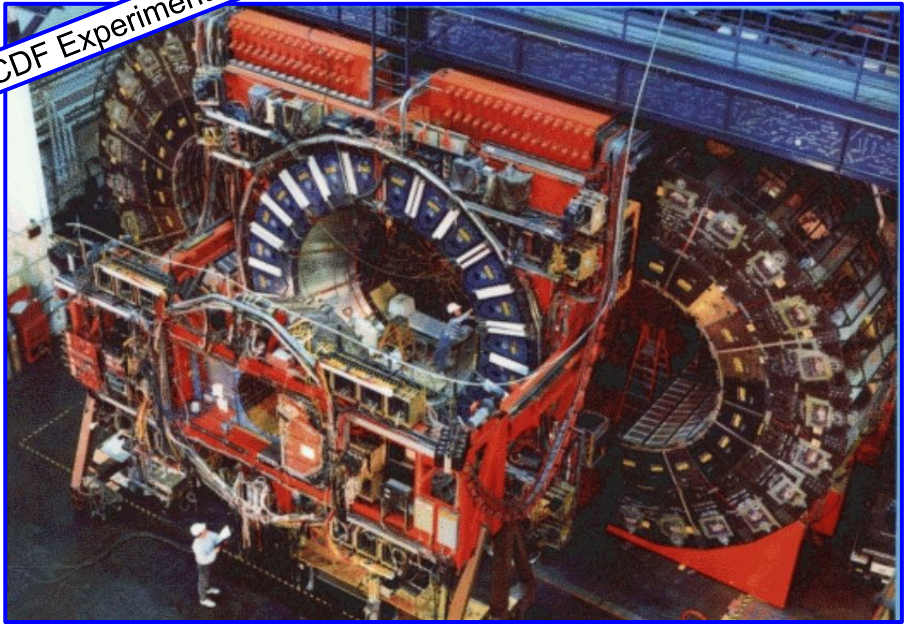
Larger energies → larger (layered!) detectors

Dedicated layers to measure different aspects of particles (energy, trajectories, etc.))

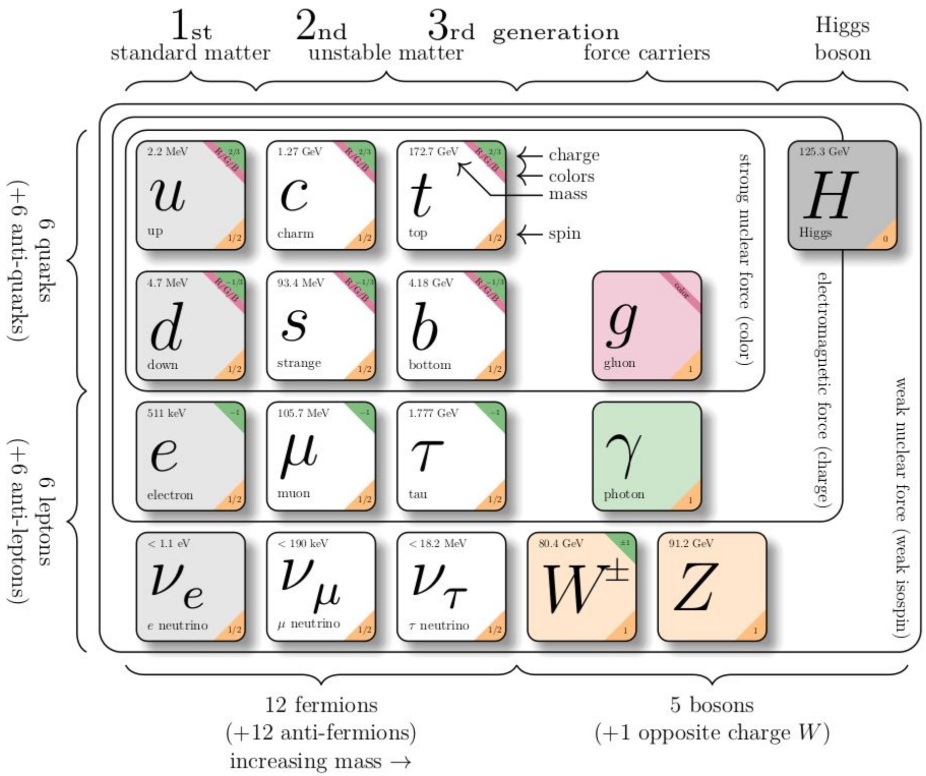
UA1 Experiment



CDF Experiment



Even more fundamental particles



Larger energies → larger (layered!) detectors

“Images” are different – information is compartmentalized, and compressed!

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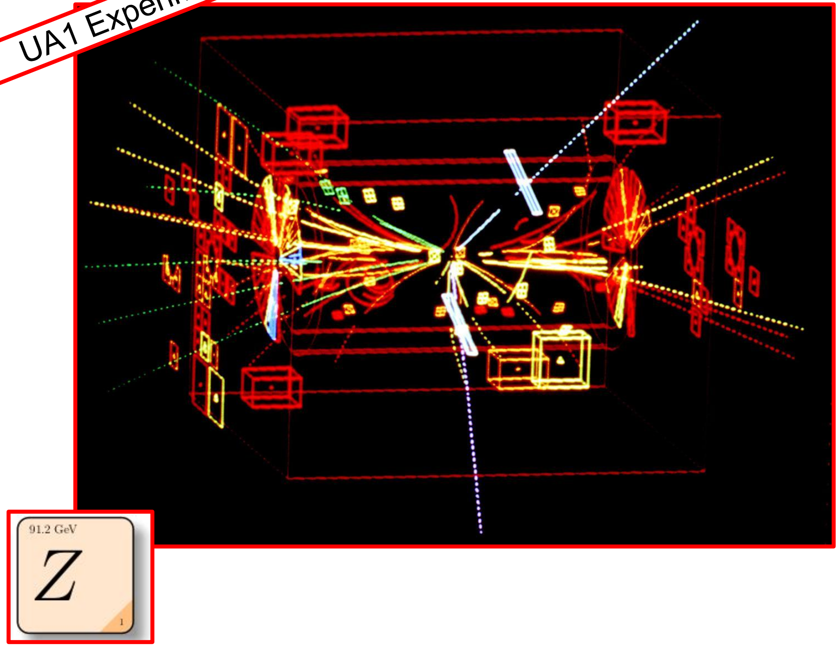
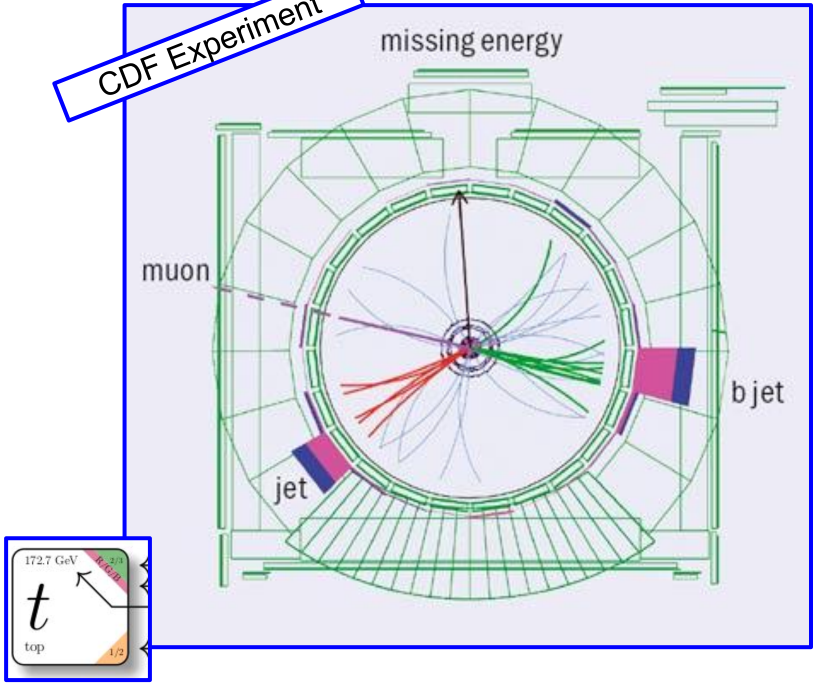


CDF Experiment



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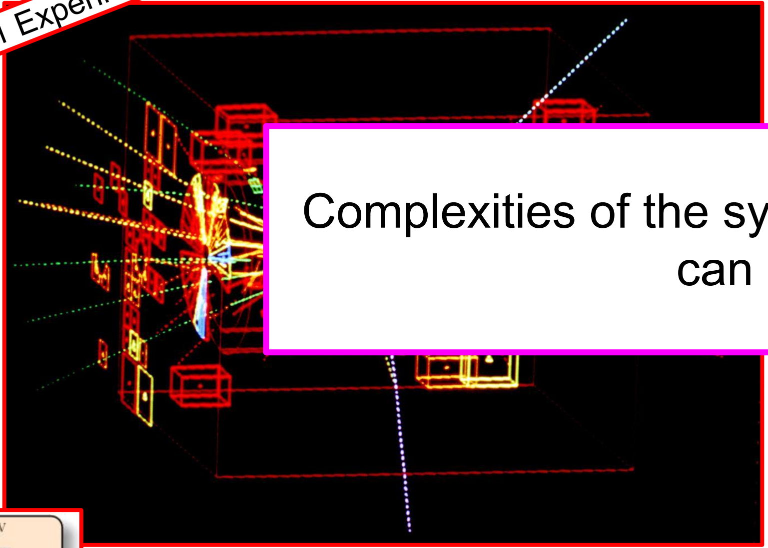
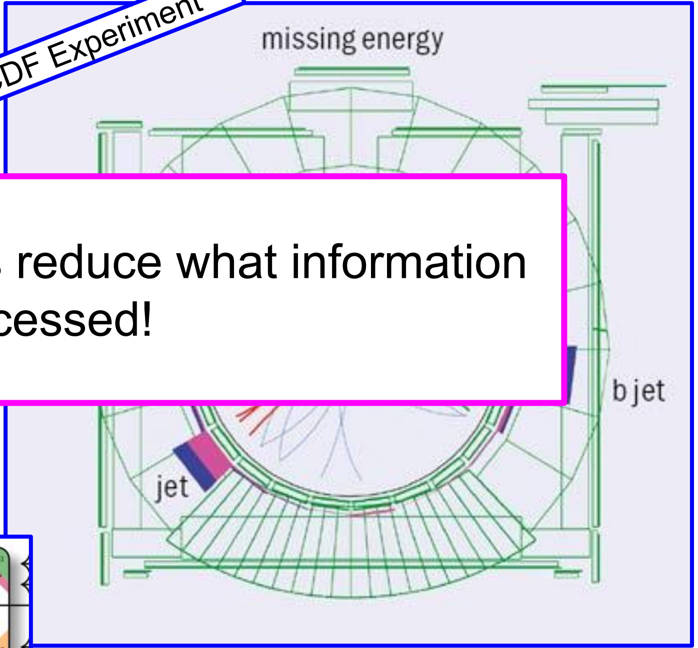
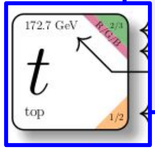


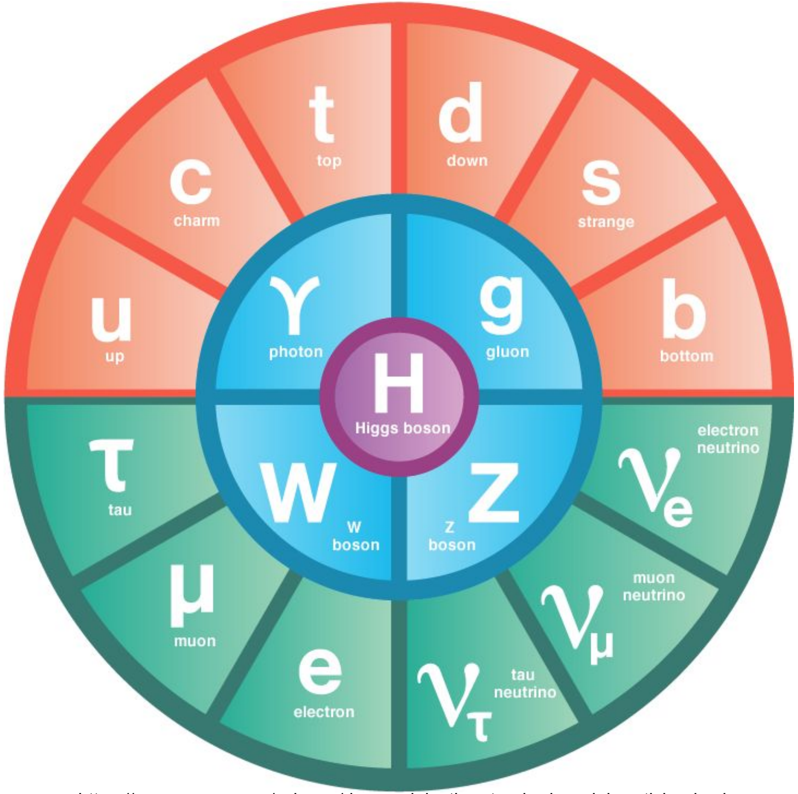
CDF Experiment





Complexities of the systems reduce what information can be accessed!

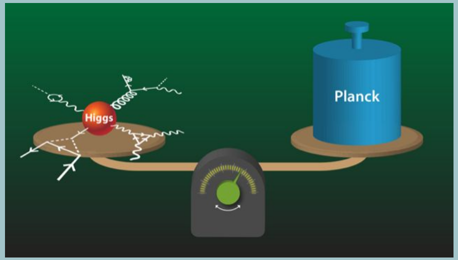
The Standard Model of Particle Physics



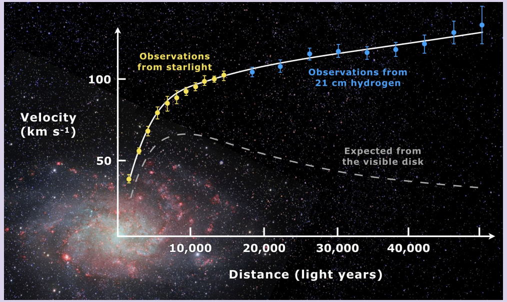
https://www.energy.gov/science/doe-explainsthe-standard-model-particle-physics

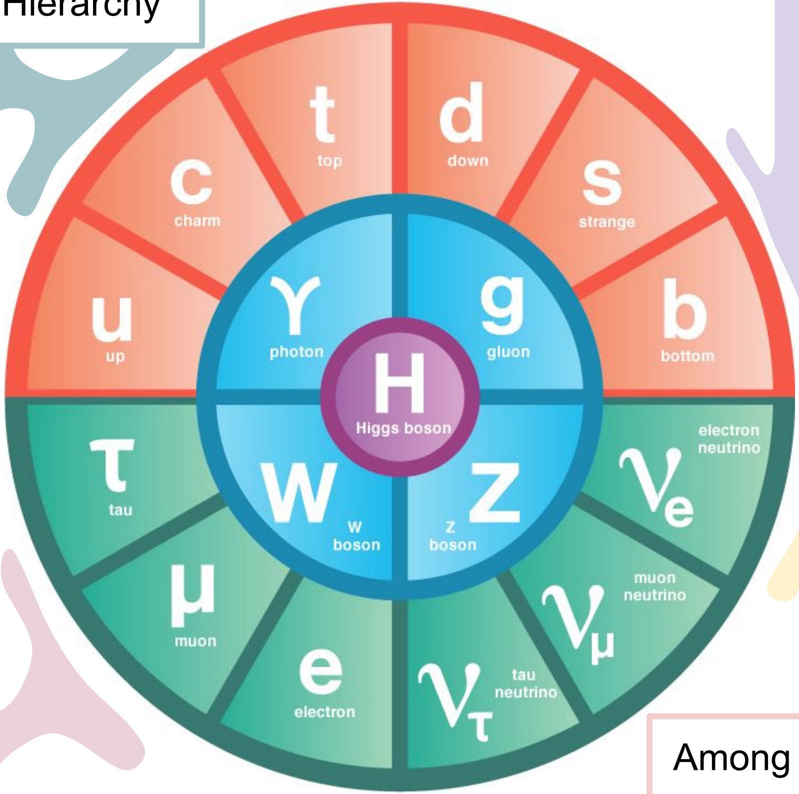
Standard Model's Standard Problems

Hierarchy

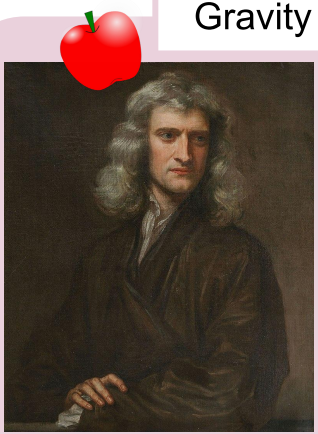


Dark matter

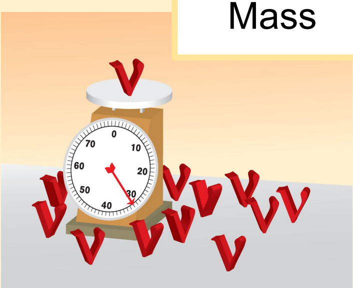




Gravity



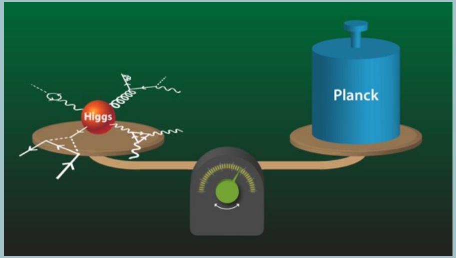
Neutrino Mass



Among others…

Standard Model's Standard Problems

Hierarchy



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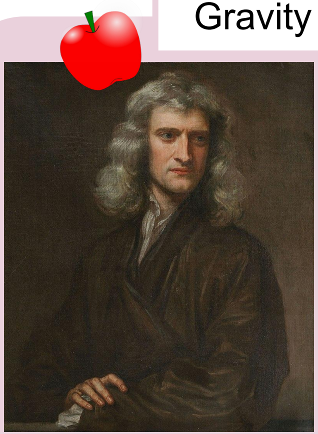

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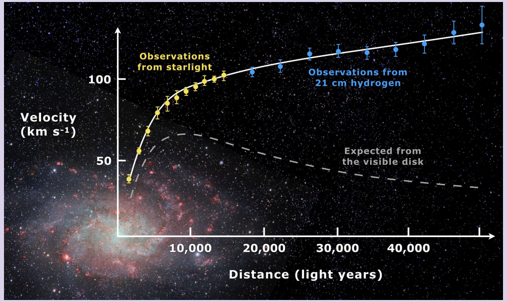
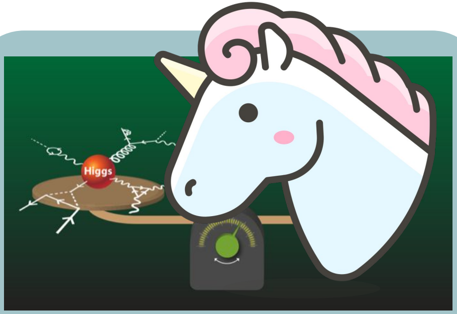


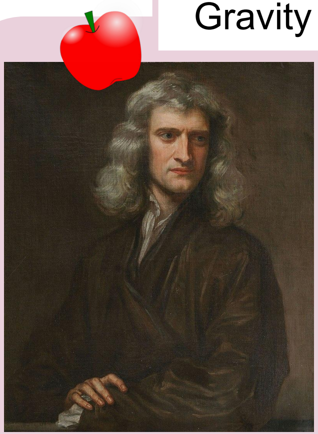
Are we leaving information on the table that would reveal new physics?

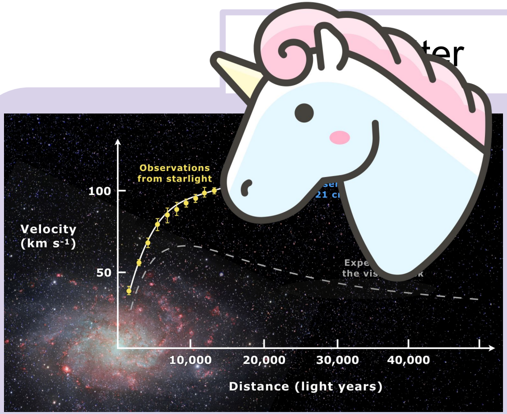
Standard Model's Standard Problems

Hierarchy



Gravity



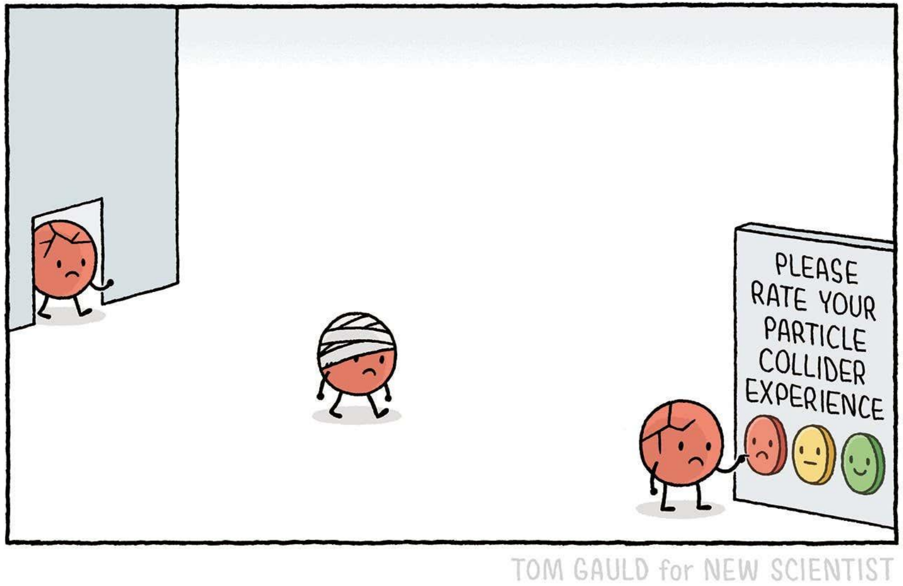


Are we leaving information on the table that would reveal new physics?

Today’s low-road

1. Machines of fundamental particle physics, today
    a. Large Hadron Collider
    b. Compact Muon Solenoid Experiment
2. Search for Heavy Stable Charged Particles
    a. CMS tracker as enabling technology
    b. Run 2 tracker-only analysis results
3. The future of the low-road
    a. Higgs Factories as future colliders
    b. Dual readout calorimetry

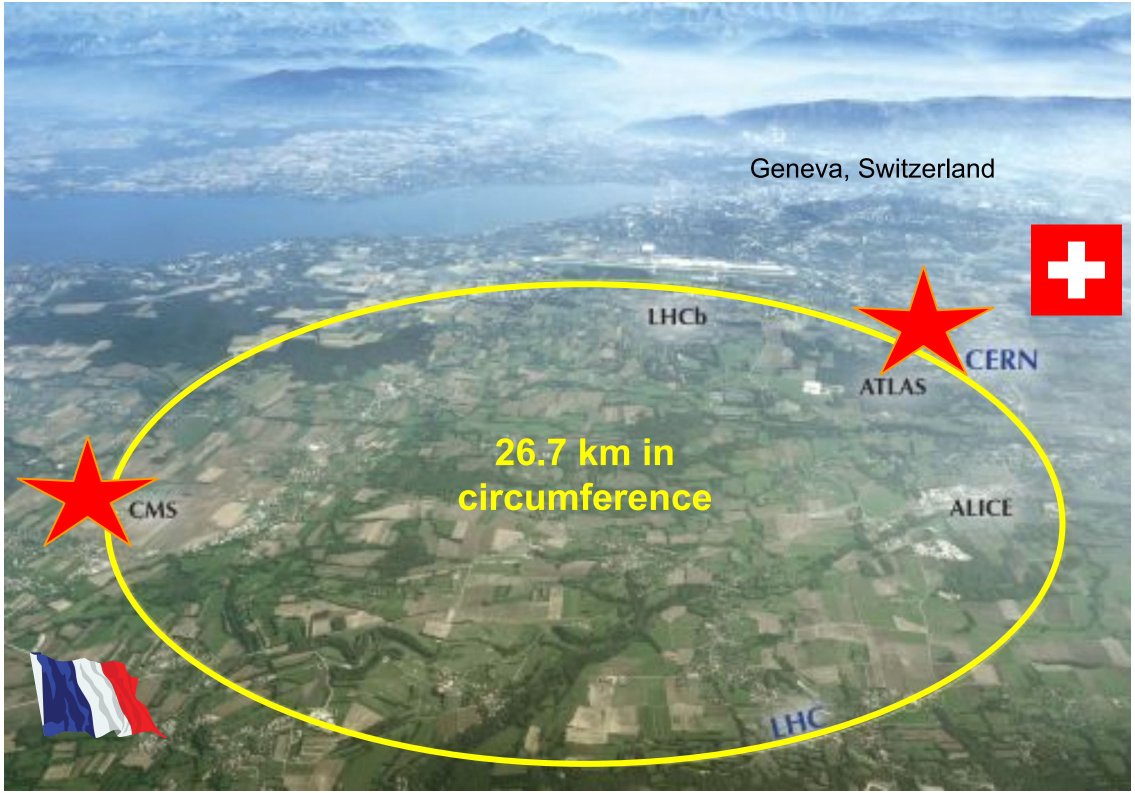
[prints]



The machines that make it possible

The Large Hadron Collider (LHC)

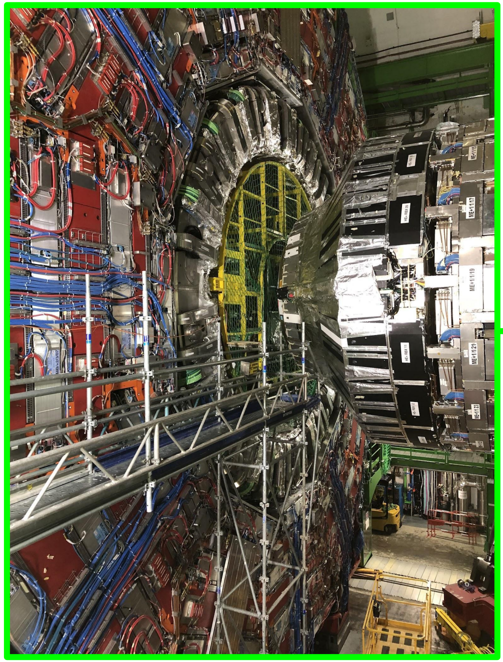
The heaviest things require ***colliders***

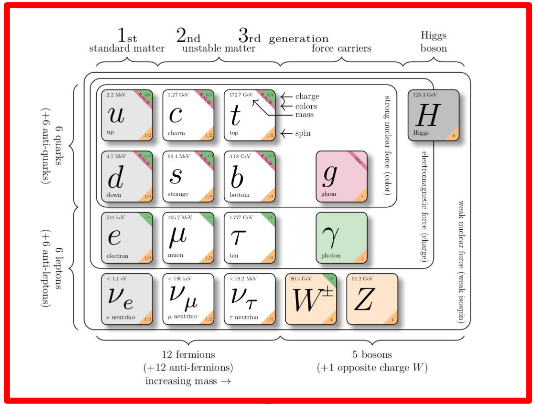


proton collider

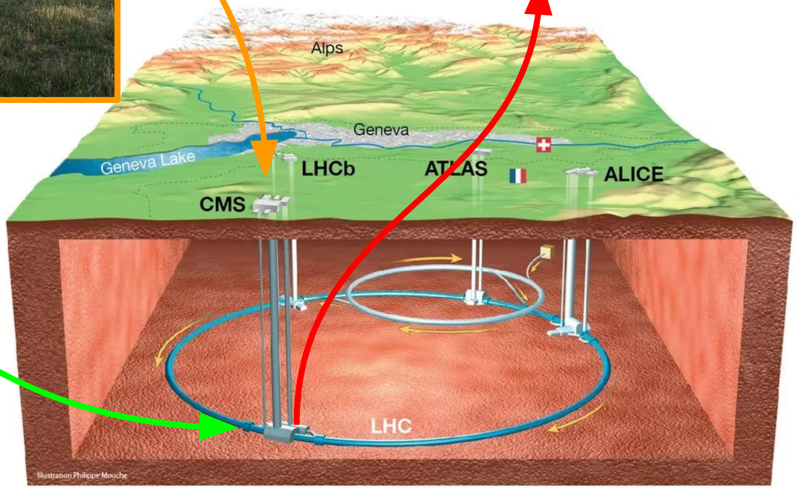
13 **TeV** - Run 2

CMS Experiment: General Purpose

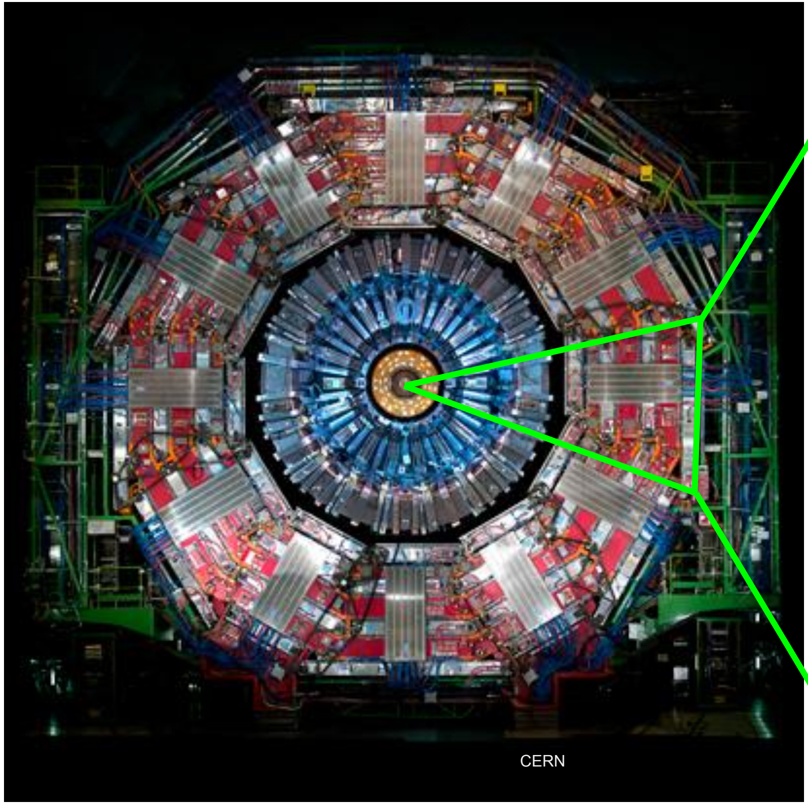


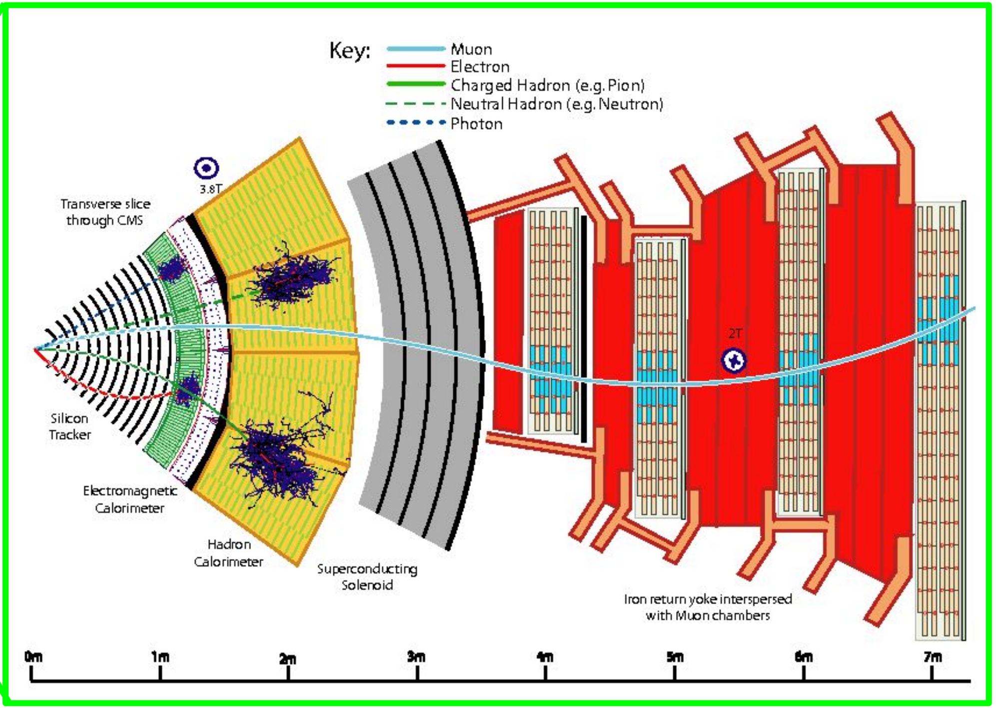


Designed to see everything!

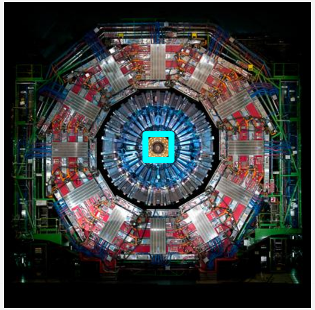


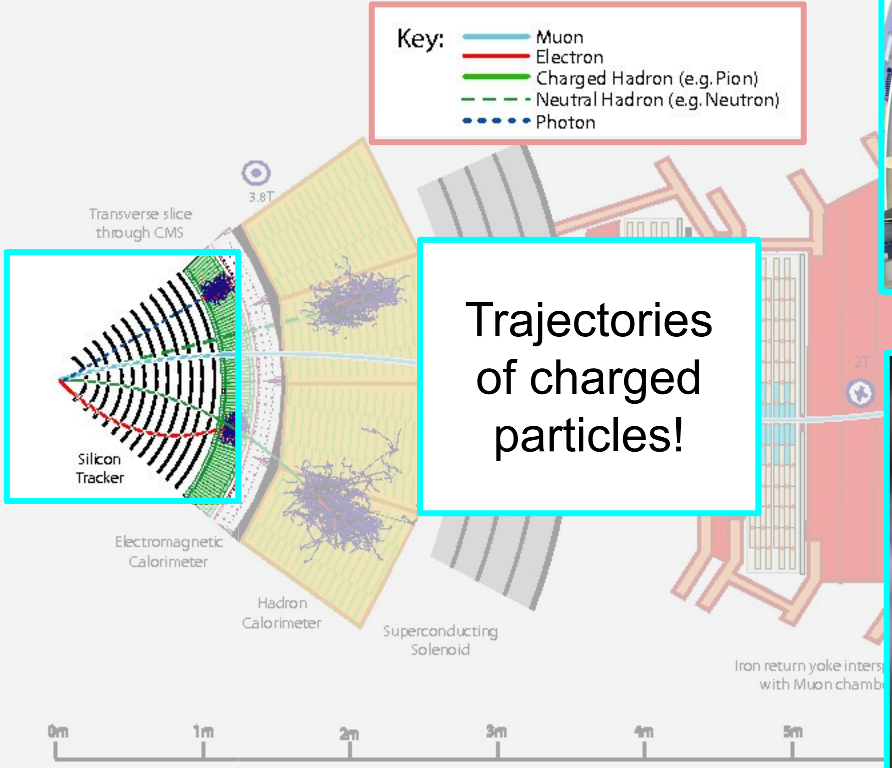
A Detailed Look: Slice of CMS



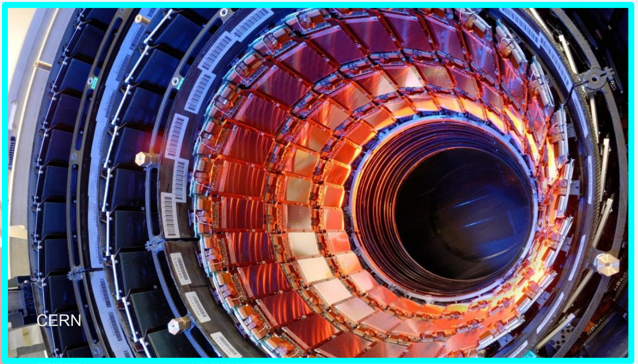


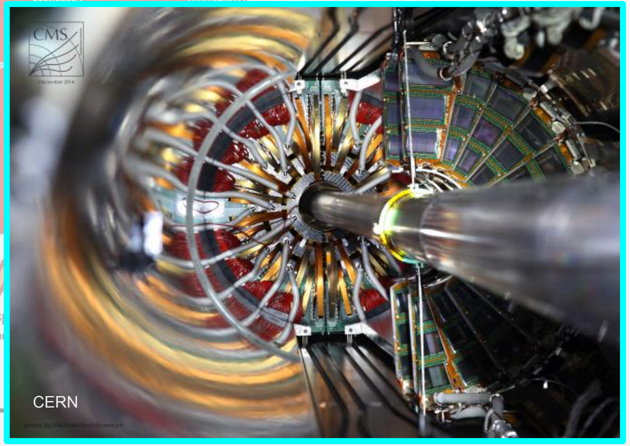
CMS at the LHC - Silicon Tracker



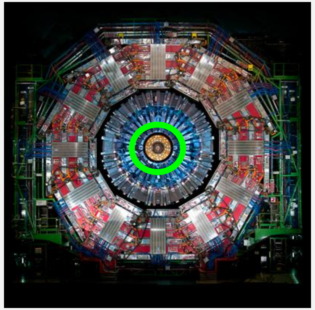


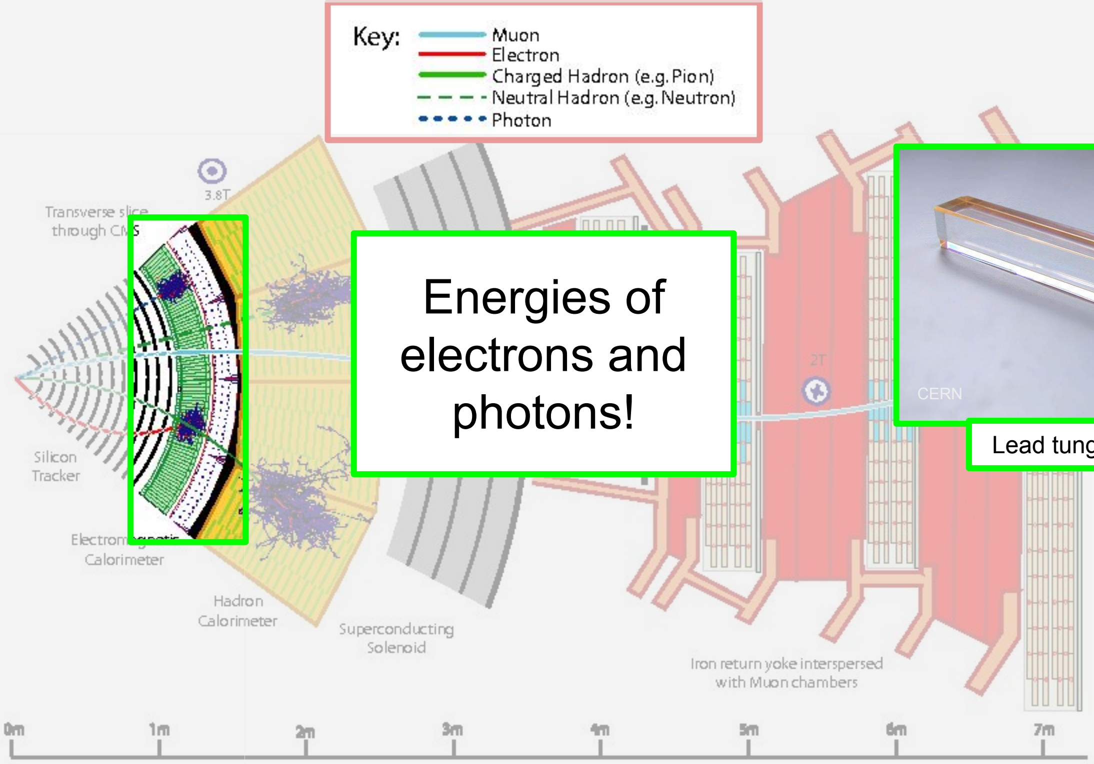
Trajectories of charged particles!





CMS - Electromagnetic Calorimeter (ECAL)

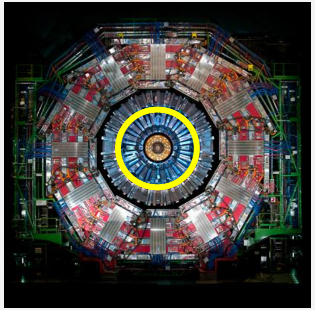


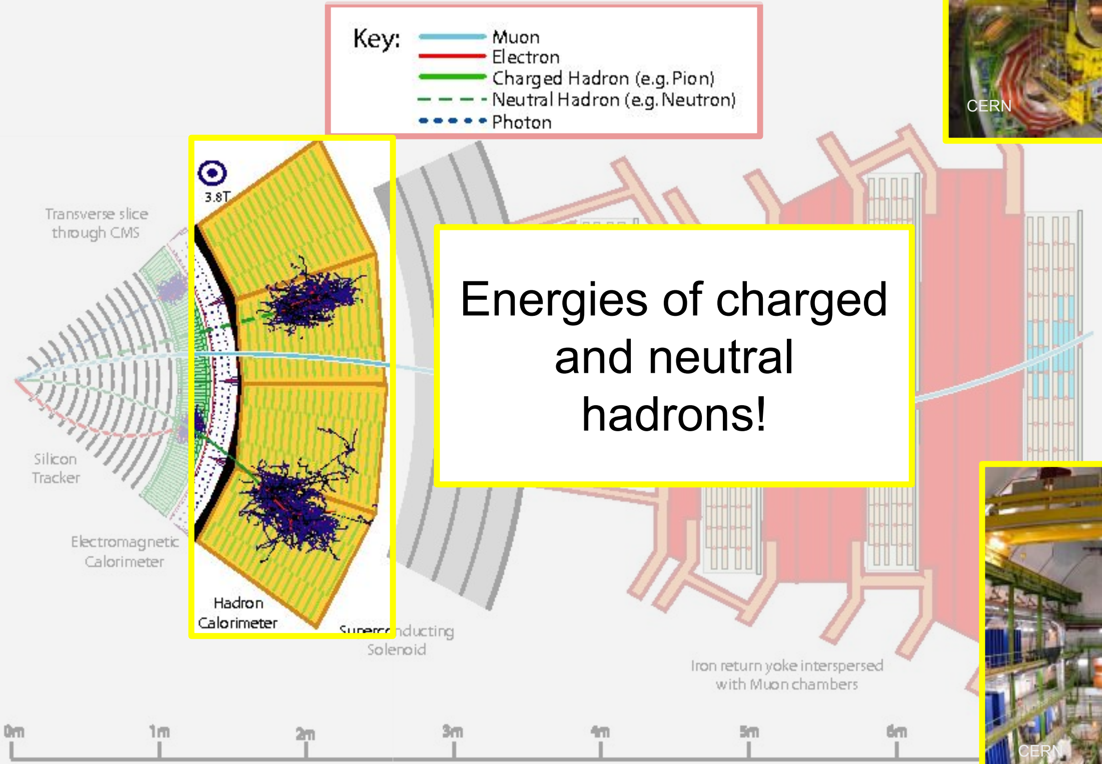


Energies of electrons and photons!

Lead tungstate crystal calorimeter

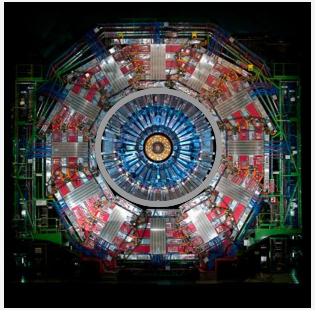
CMS - Hadron Calorimeter (HCAL)

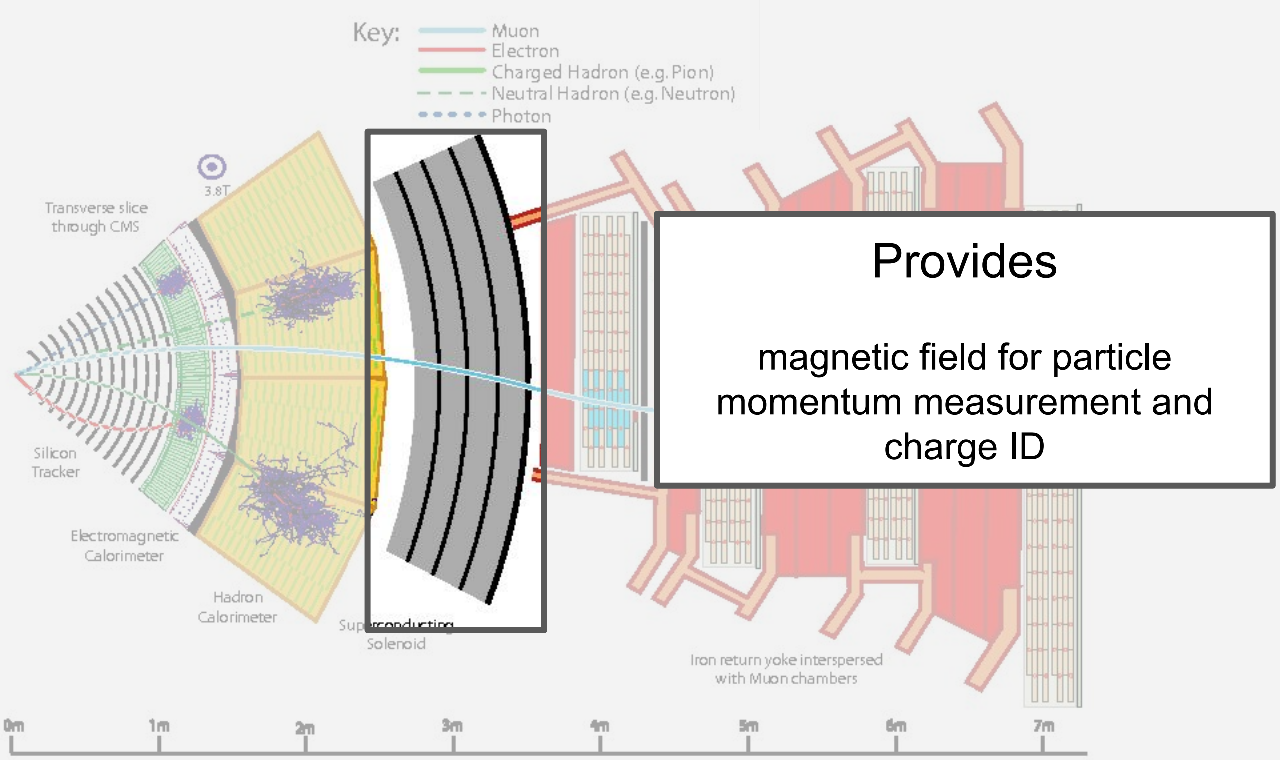




Energies of charged and neutral hadrons!

CMS at the LHC - Superconducting Solenoid

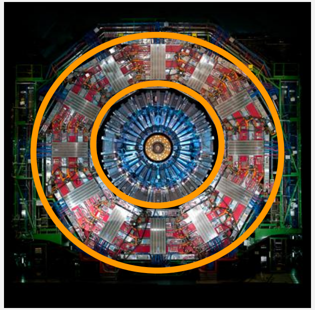


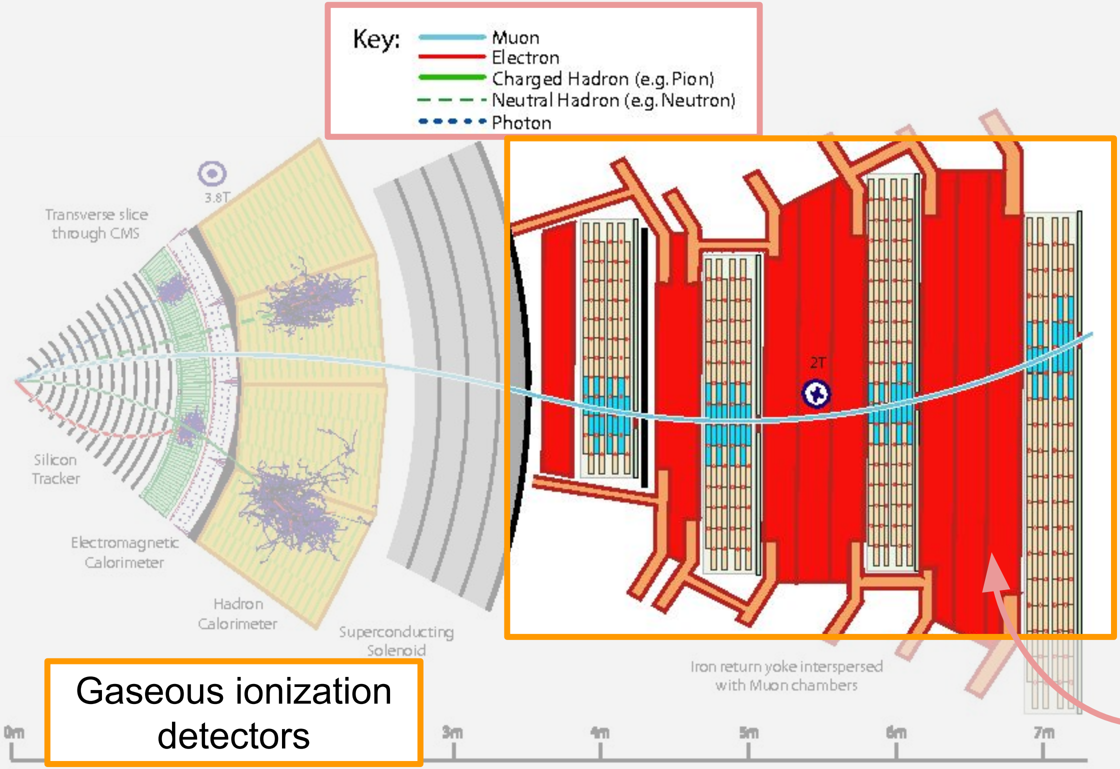


Provides

magnetic field for particle momentum measurement and charge ID

CMS at the LHC - Muon System and Flux Return





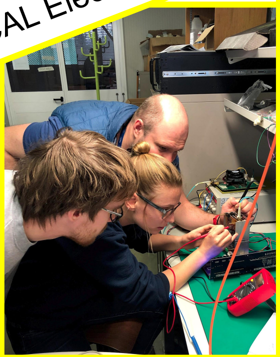
Gaseous ionization detectors

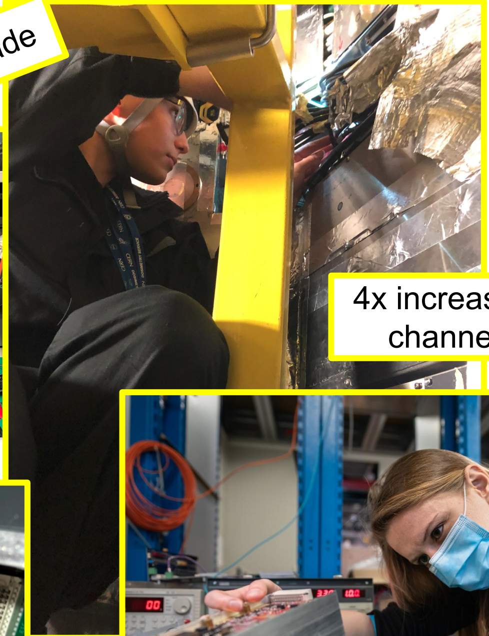
Muon trajectories and particle ID

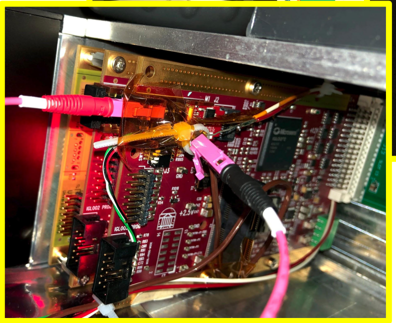
Iron for magnetic flux return

Electronics to read it all out!

HCAL Electronics upgrade



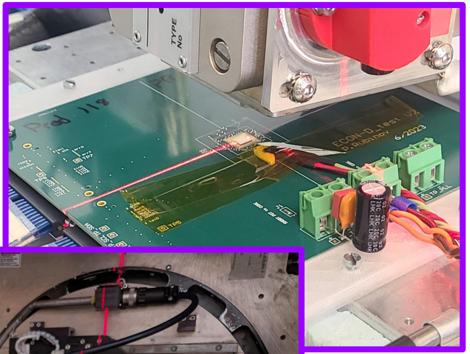


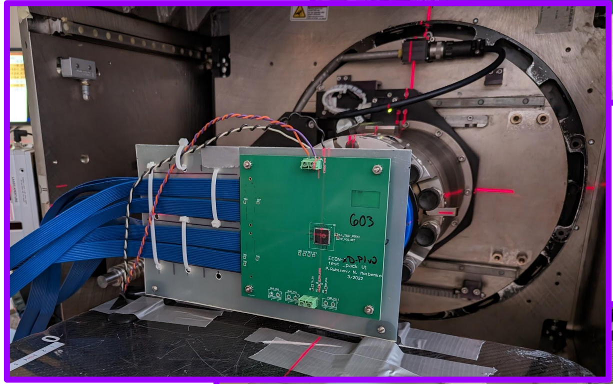


4x increase in channels

High Granularity Upgrade

6 million channels





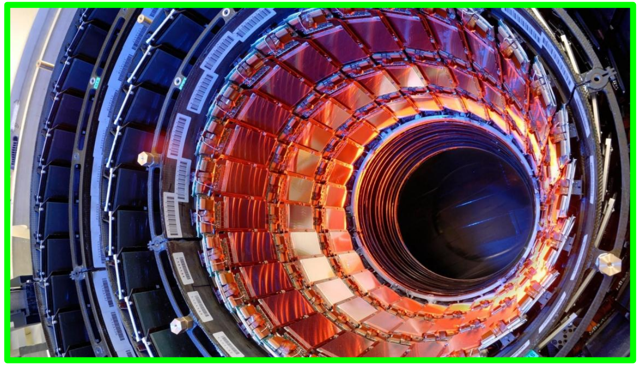
5 Pb/s → 50 Tb/s

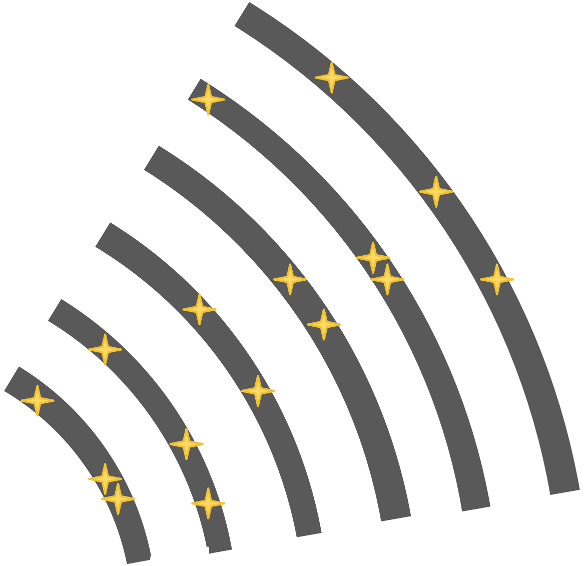
THE FIRST FEW TIMES EINSTEIN IMAGINED FLYING ALONGSIDE A BEAM OF LIGHT, HE DIDN'T HAVE ANY PARTICULAR INSIGHTS.

[xkcd: Beam of Light]

Search for Heavy Stable Charged Particles in the tracker

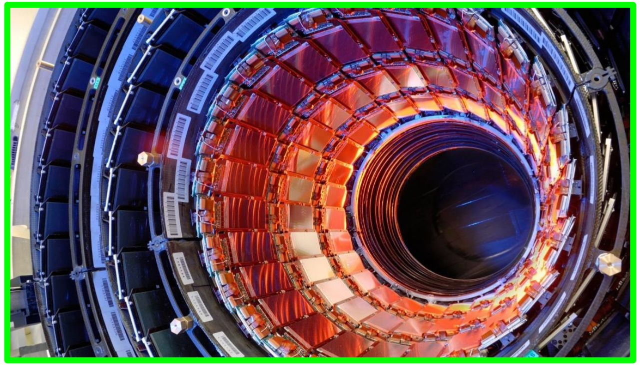
Closer look at tracker

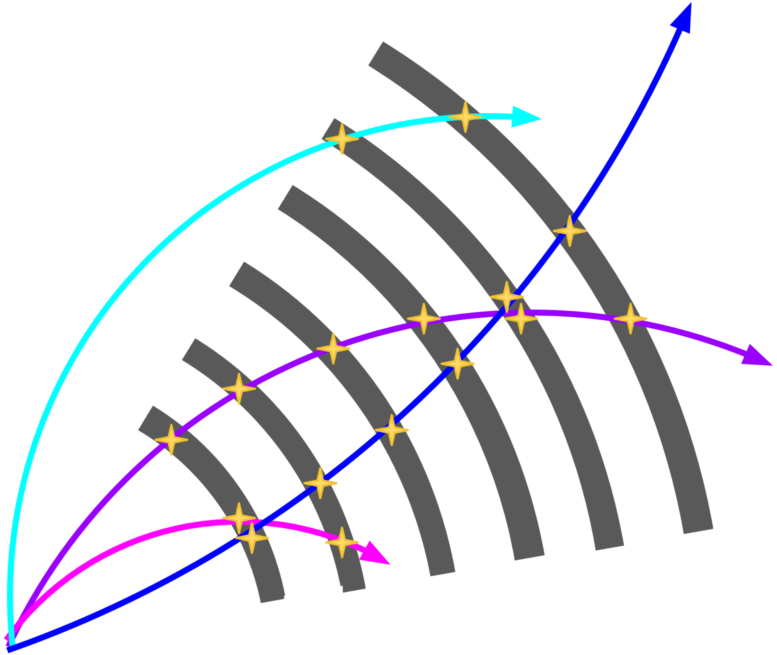




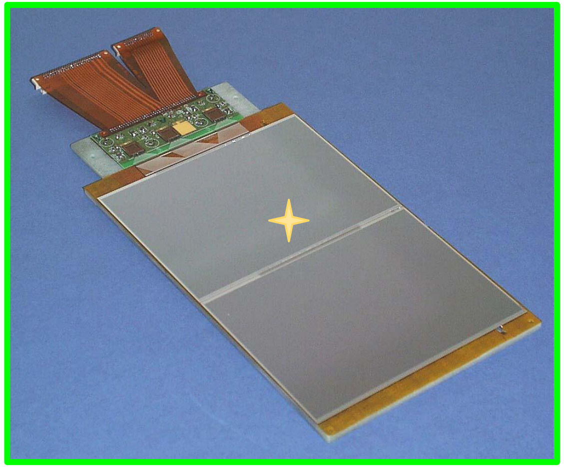
Closer look at tracker

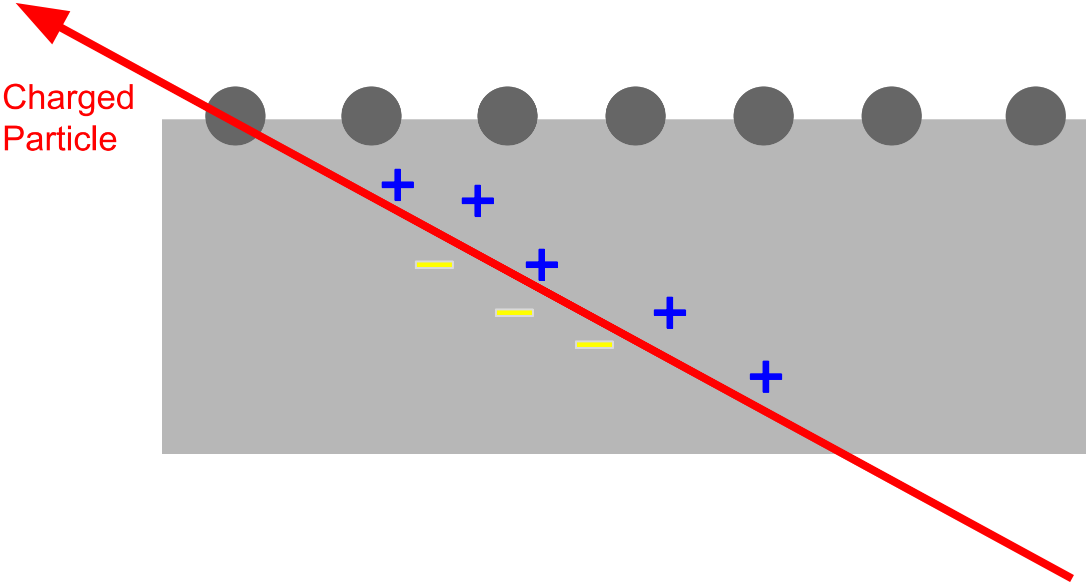
Elaborate game of connect the dots!



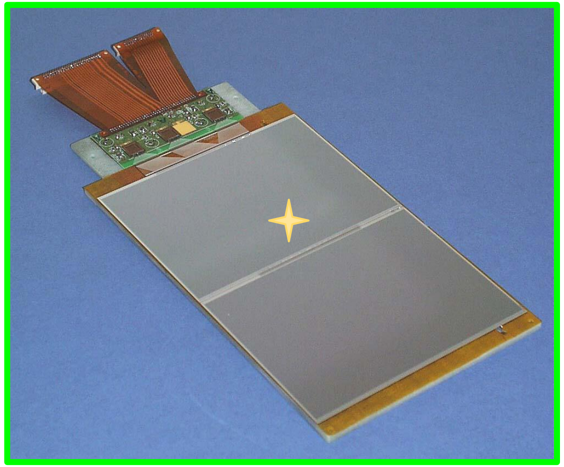


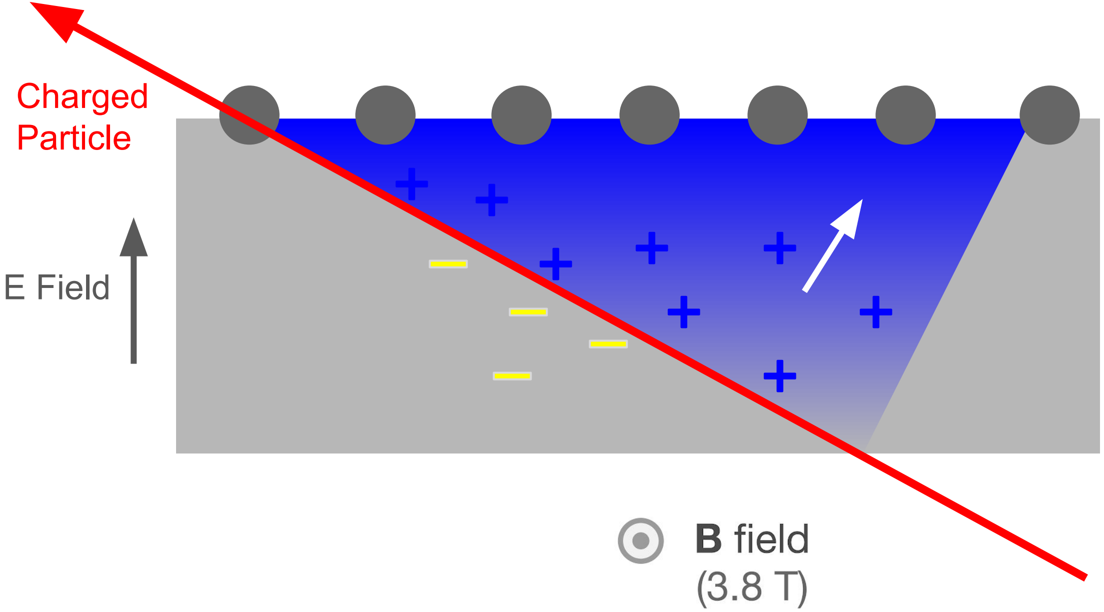
Making the dot





Making the dot





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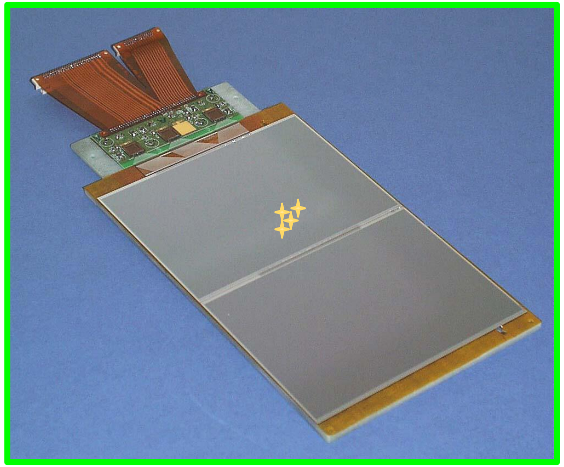

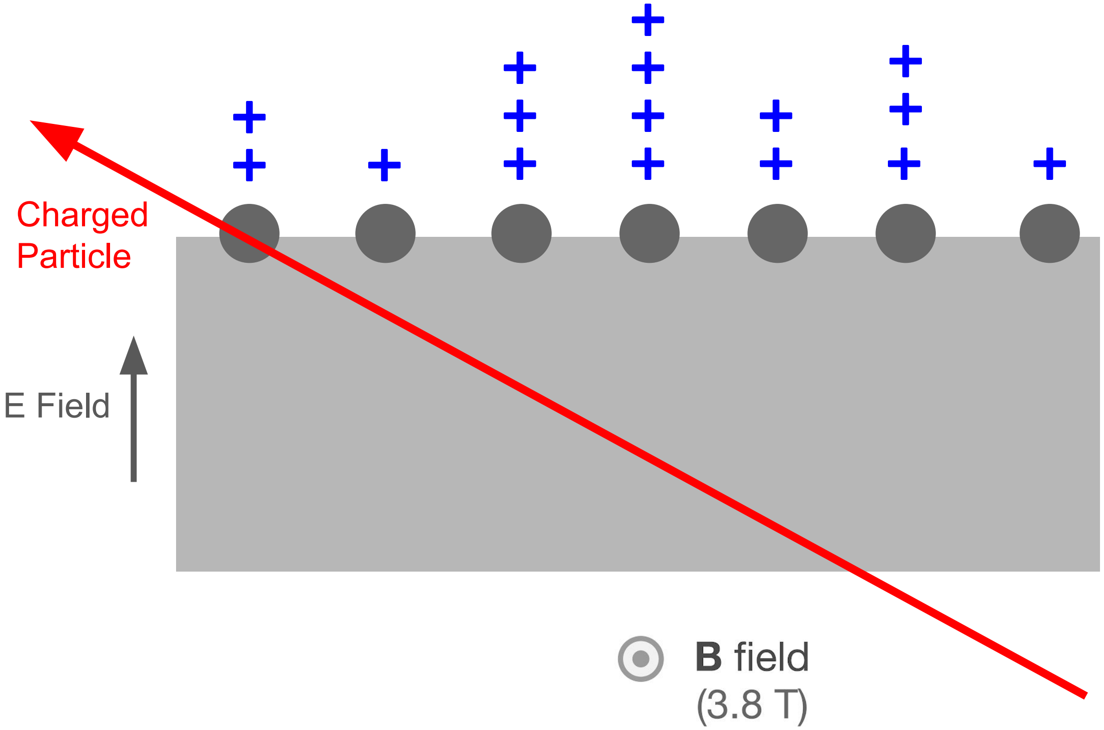

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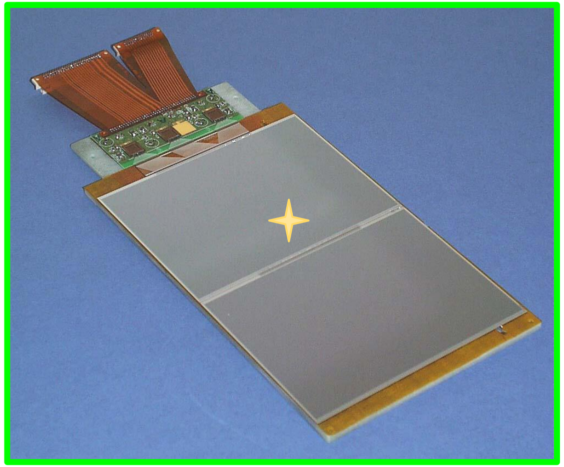
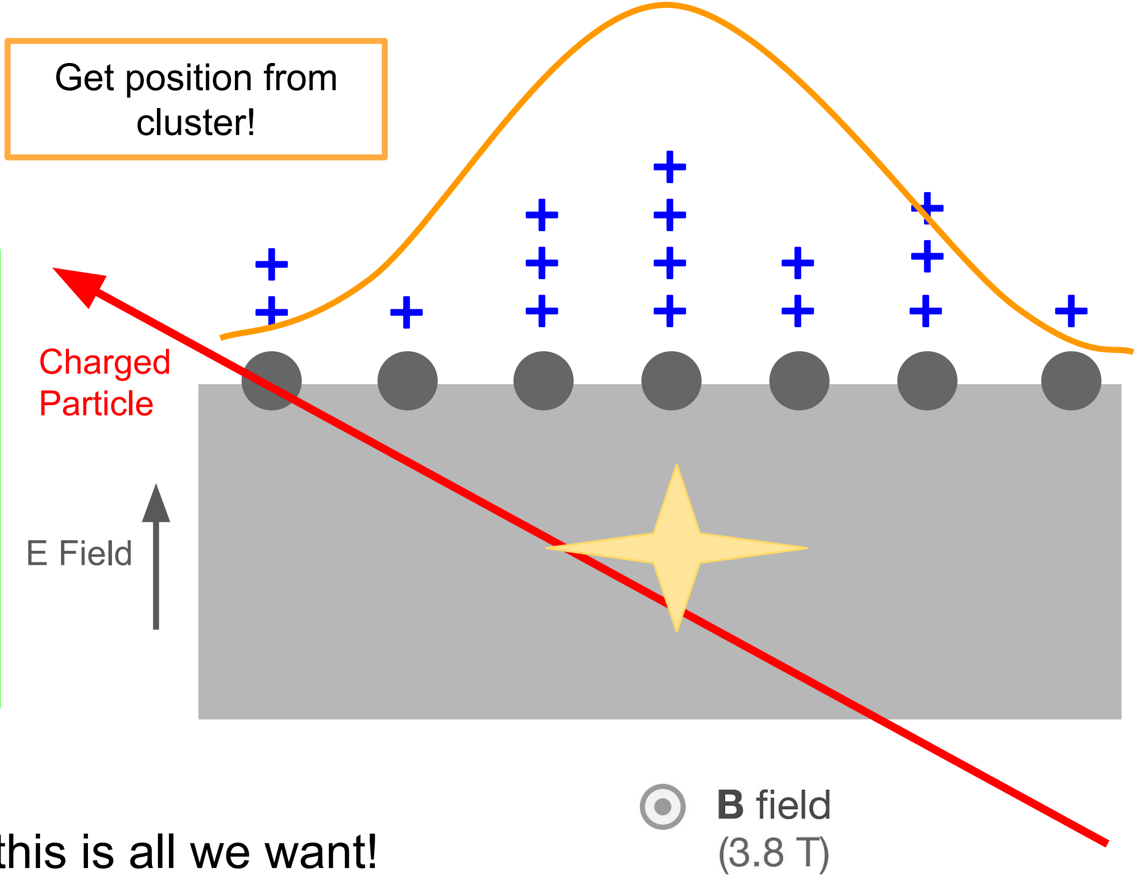
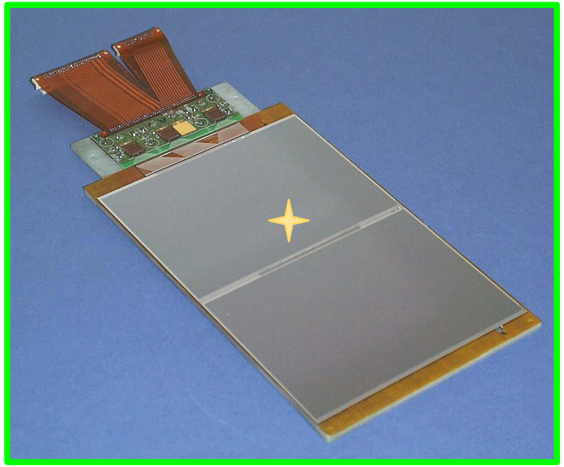
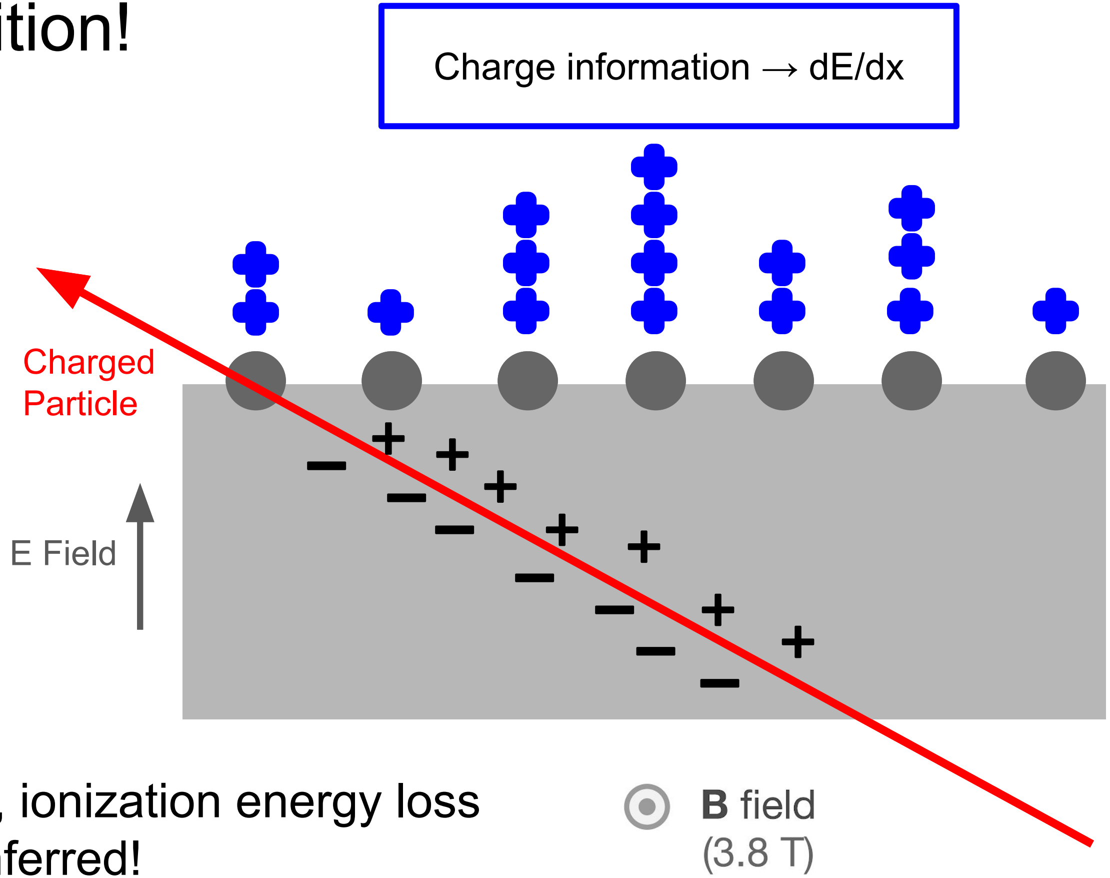




For most of CMS, this is all we want!

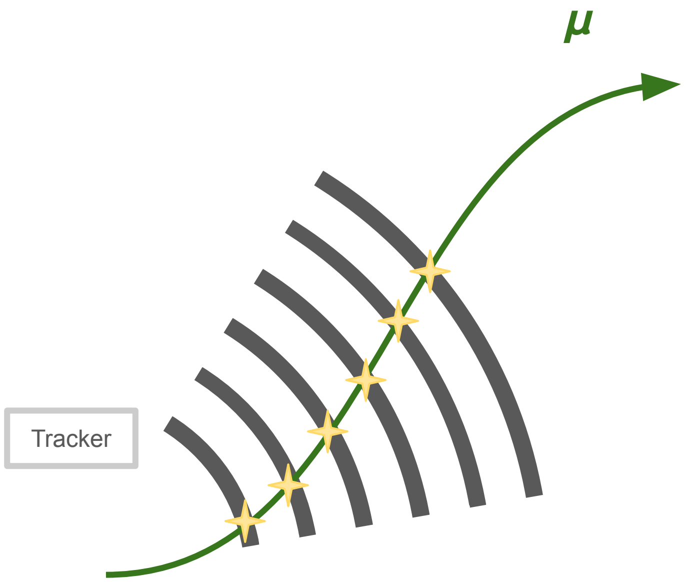
Much more than position!



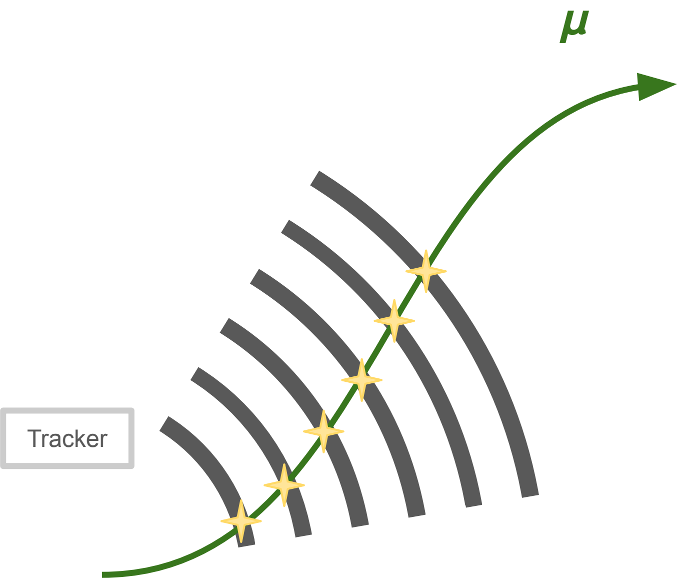


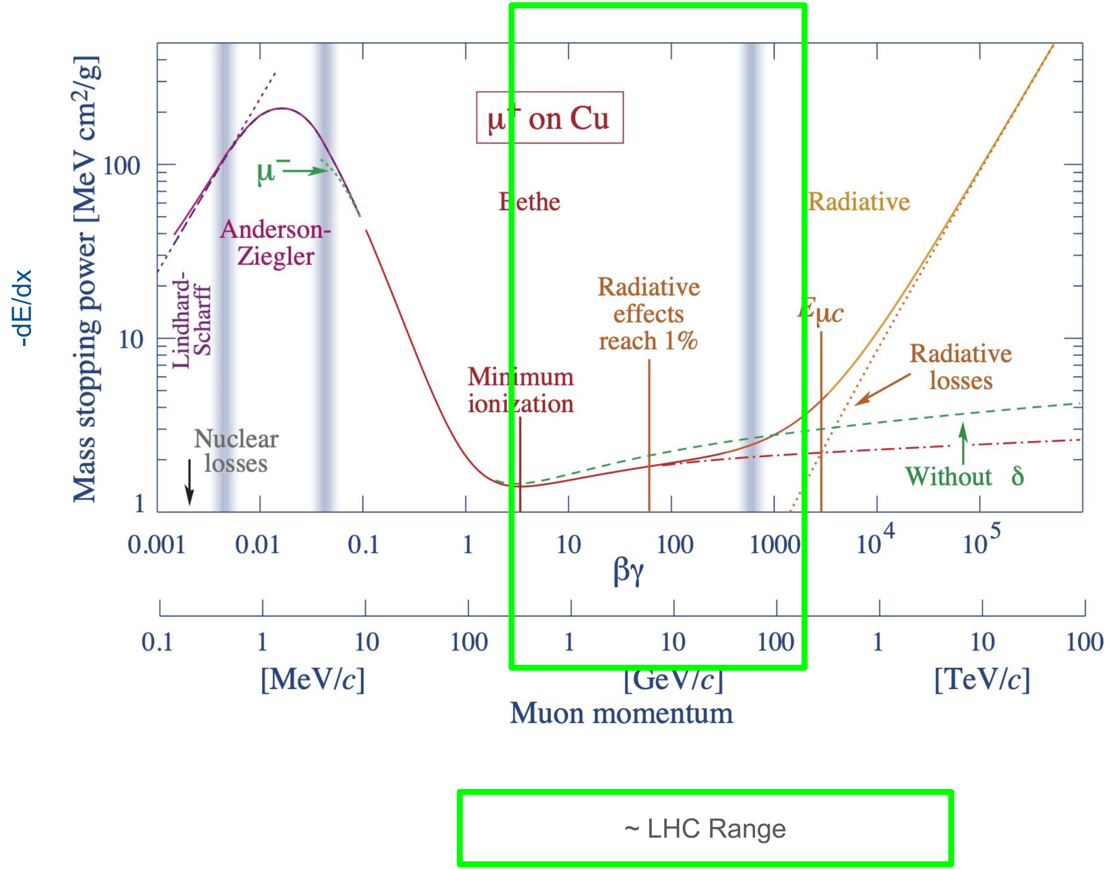
Charge readout is saved, ionization energy loss can be inferred!

A new lever

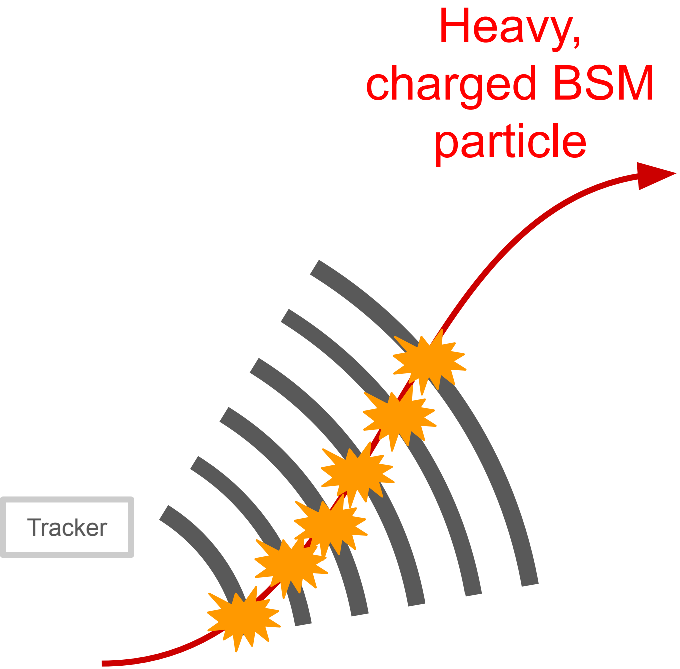


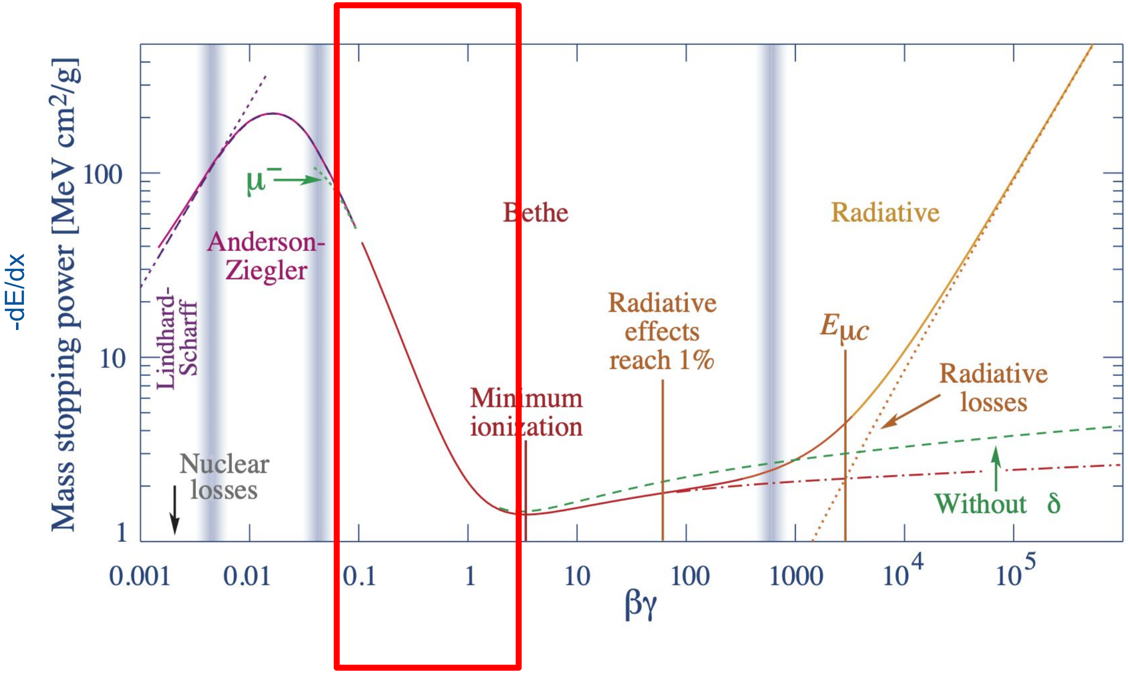
A new lever


μ
Tracker


-dE/dx
Mass stopping power [MeV cm²/g]
μ+ on Cu
μ−
Bethe
Radiative
Anderson-
Ziegler
Lindhard-
Scharff
Radiative
effects
reach 1%
Eμc
Radiative
losses
Minimum
ionization
Nuclear
losses
Without δ
βγ
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum
~ LHC Range

Clear signature of new physics



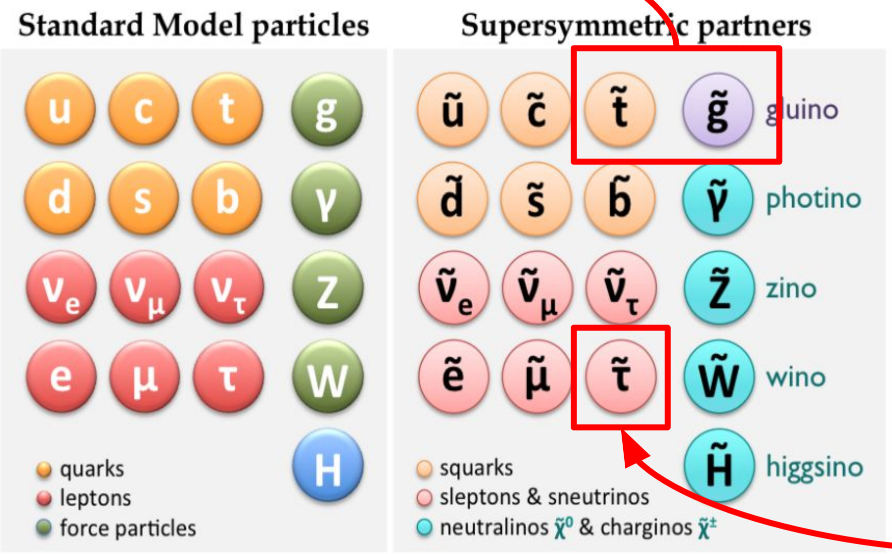


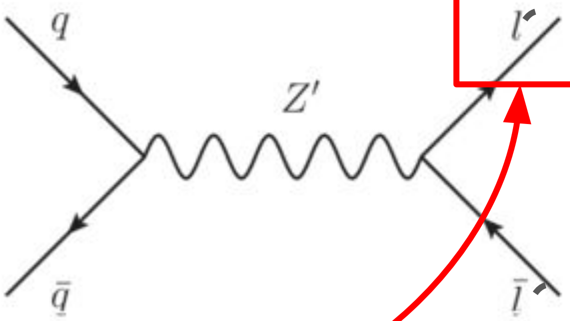
Anomalously high dE/dx for CMS!

Heavy Stable Charged Particles (HSCPs)

Heavy Stable(ish) Charged *Popularity*

Bound states w/ SM particles





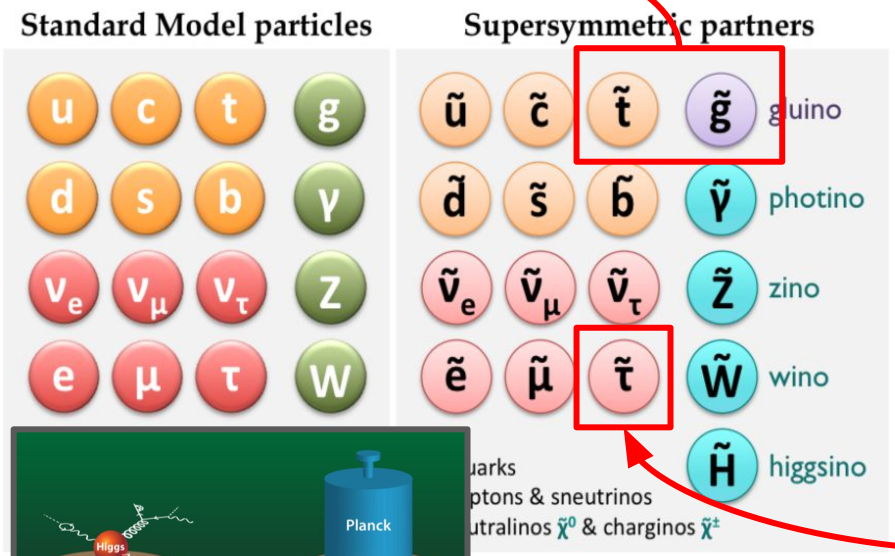
Just heavy and charged!

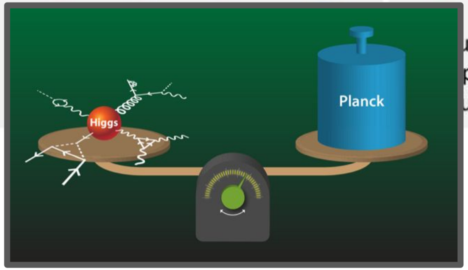
DOI:10.1007/JHEP03(2017)009

Heavy Stable Charged Particles (HSCPs)

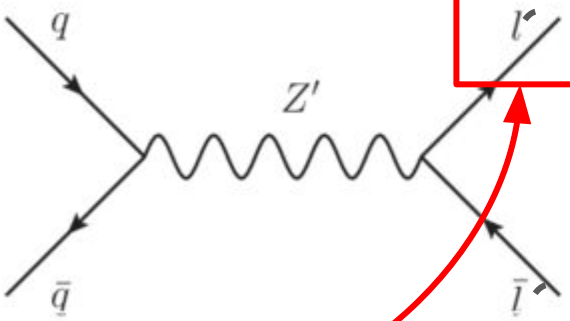
Heavy Stable(ish) Charged *Popularity*

Bound states w/ SM particles





Grand Unified Theories, etc..

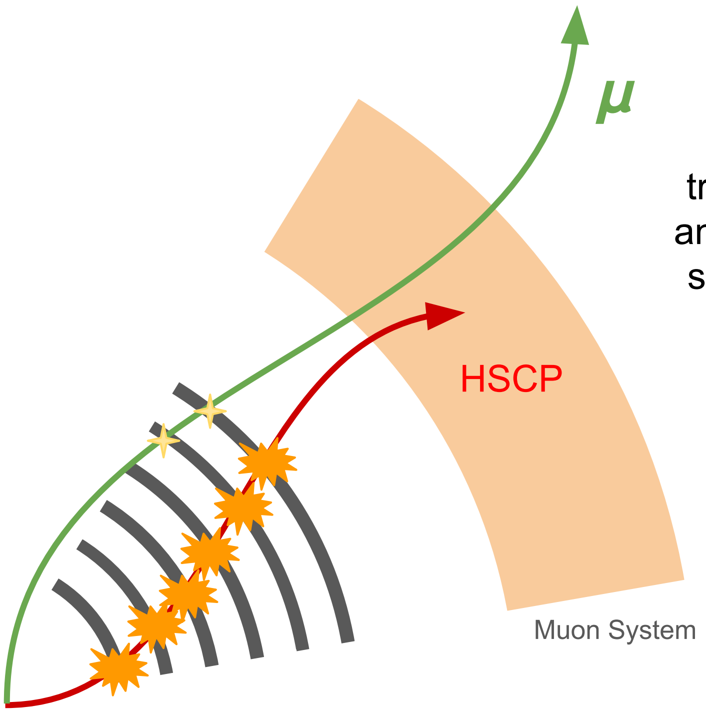


Just heavy and charged!

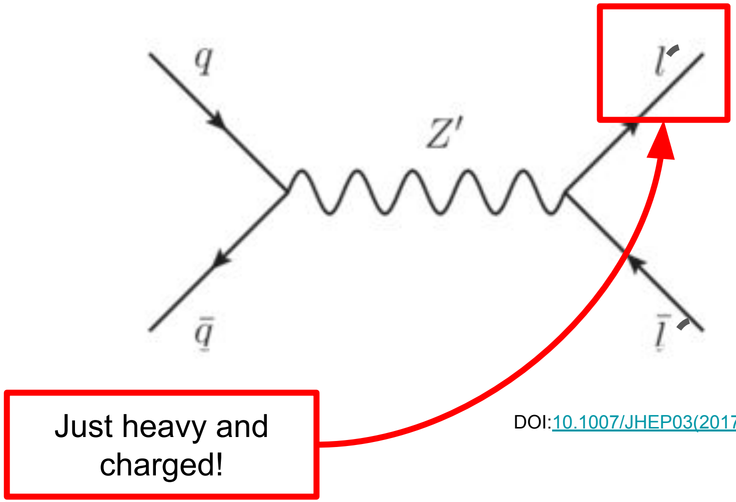
DOI:10.1007/JHEP03(2017)009

Heavy Stable Charged Particles (HSCPs)

Heavy Stable(ish) Charged *familiarity*

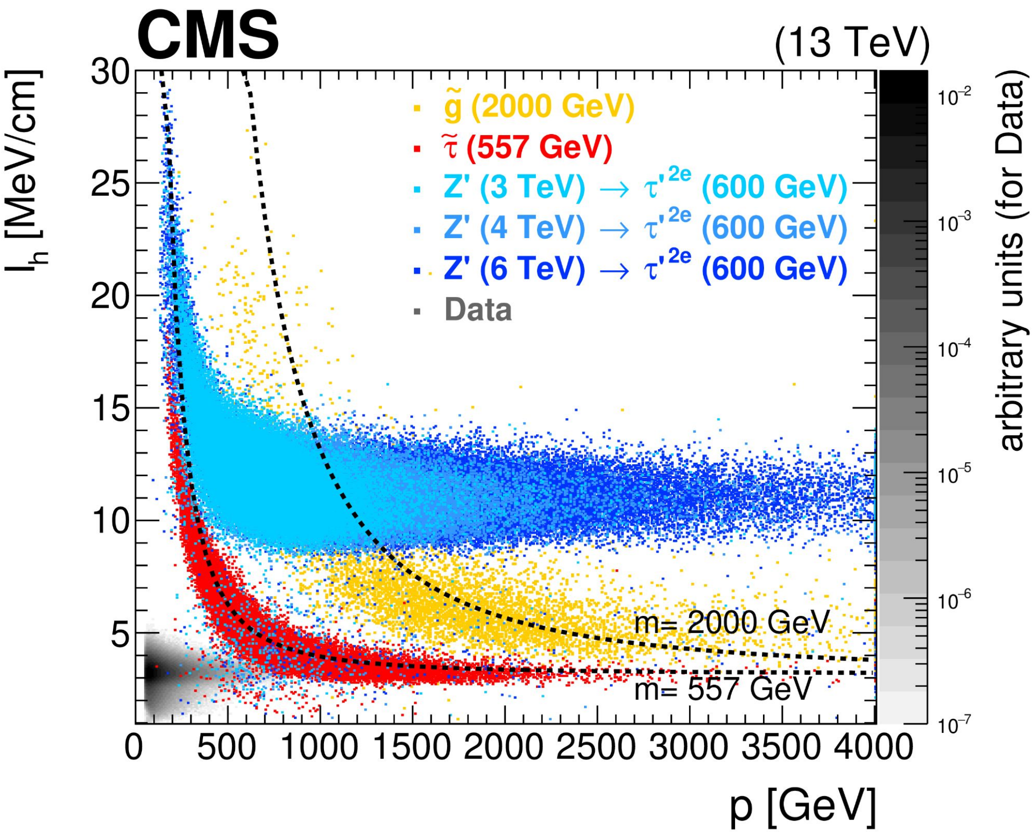


muon triggered analysis is sensitive



DOI:10.1007/JHEP03(2017)009

Ionization and mass



$$I_{\mathrm{h}} = \left(\frac{1}{N} \sum_{j}^{N} \left(\frac{\mathrm{d}E}{\mathrm{d}x_j} \right)^{-2} \right)^{-1/2}$$

"jth layer of the CMS tracker"

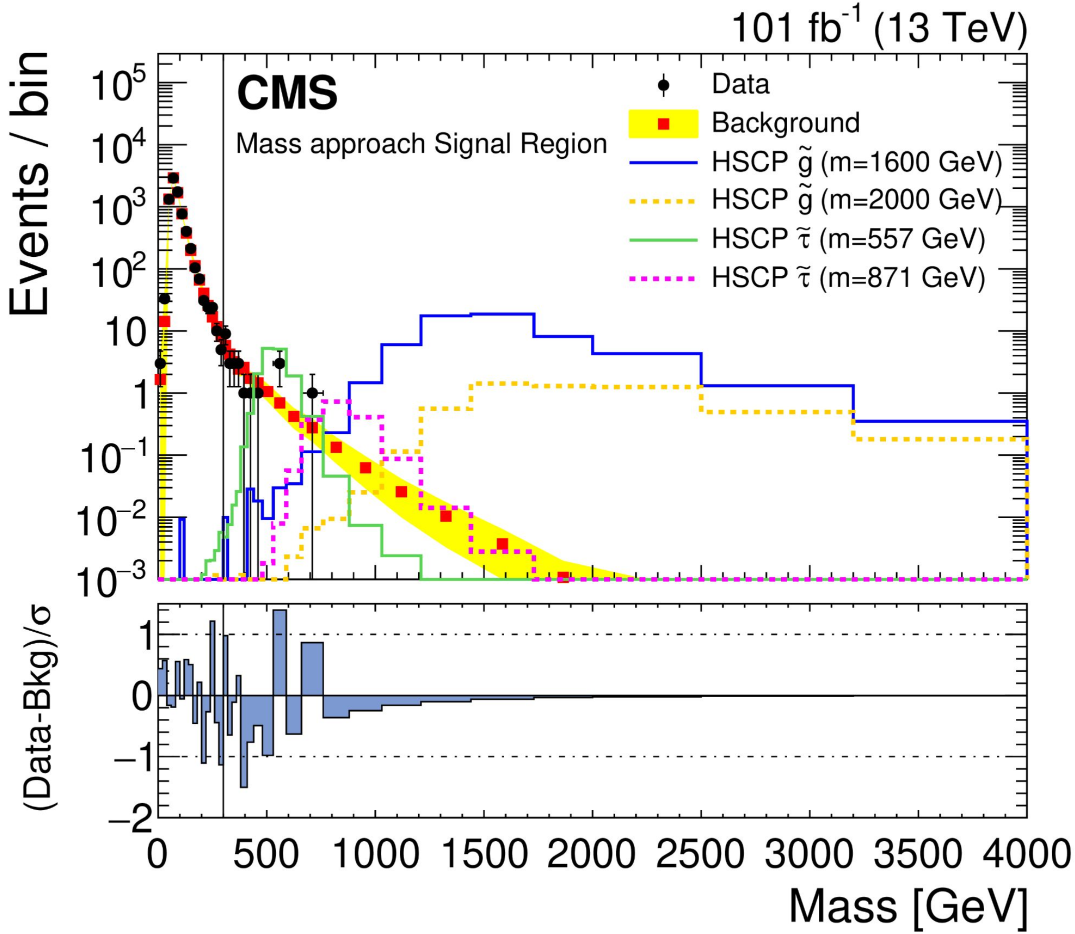
Mass reconstruction

$$I_{\mathrm{h}} = K\frac{m^2}{p^2} + C$$

Parameter (MeV/ cm)	Data 2017	Data 2018	Simulation 2017	Simulation 2018
K	2.54 ± 0.01	2.55 ± 0.01	2.50 ± 0.01	2.49 ± 0.01
C	3.14 ± 0.01	3.14 ± 0.01	3.18 ± 0.01	3.18 ± 0.01

Mass reconstruction

$$I_{\mathrm{h}} = K\frac{m^2}{p^2} + C$$



Mass reconstruction

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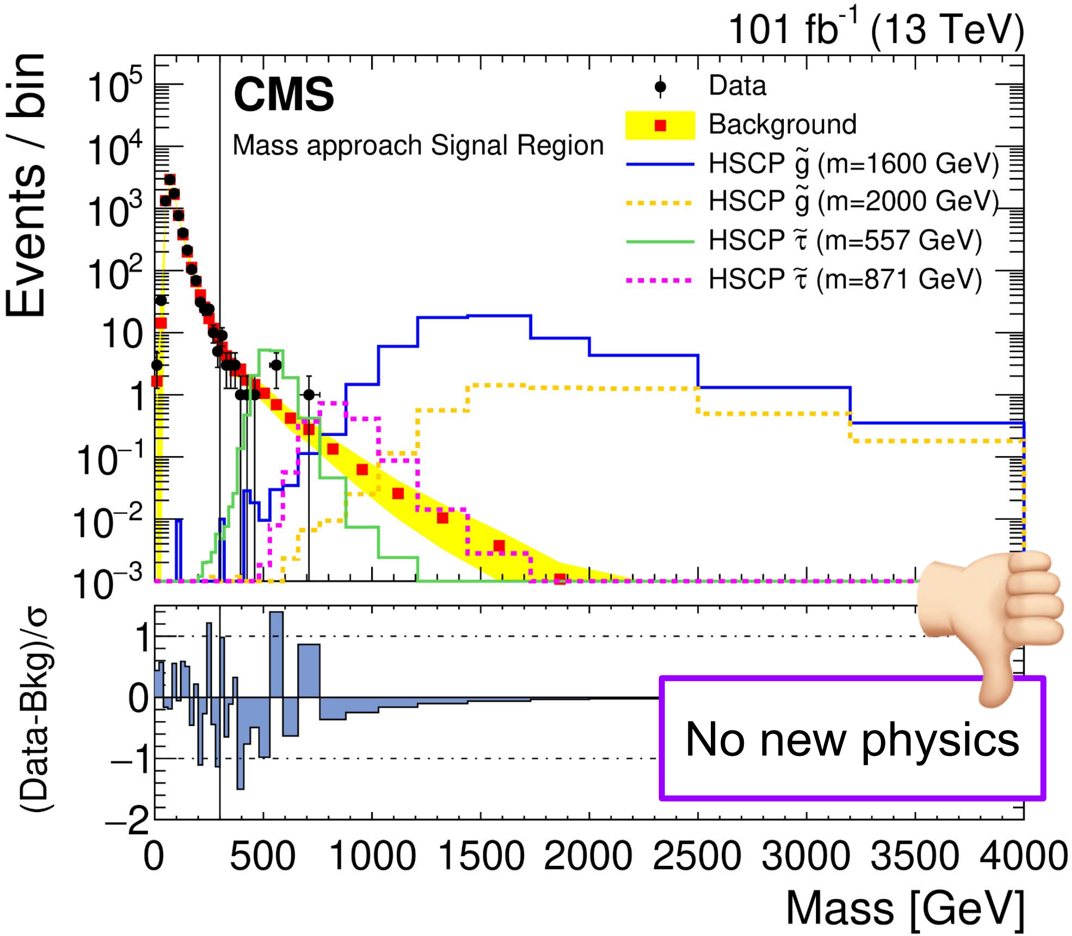
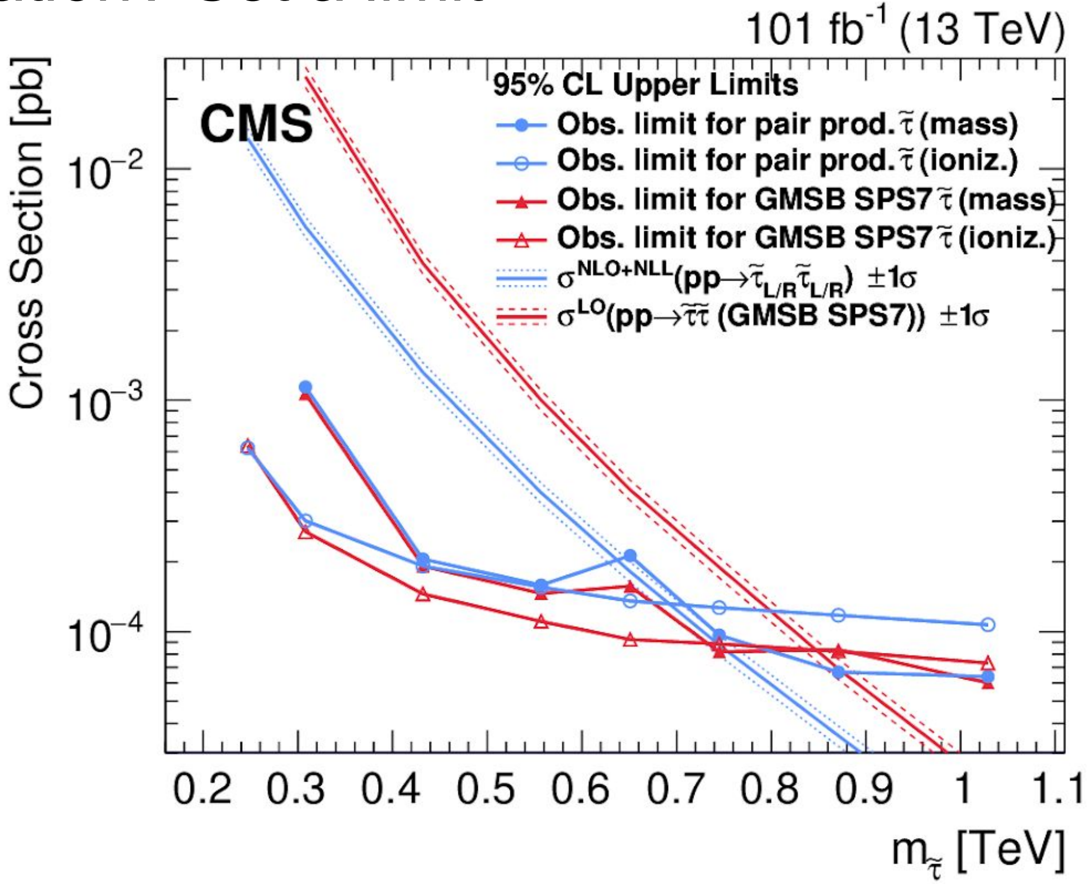
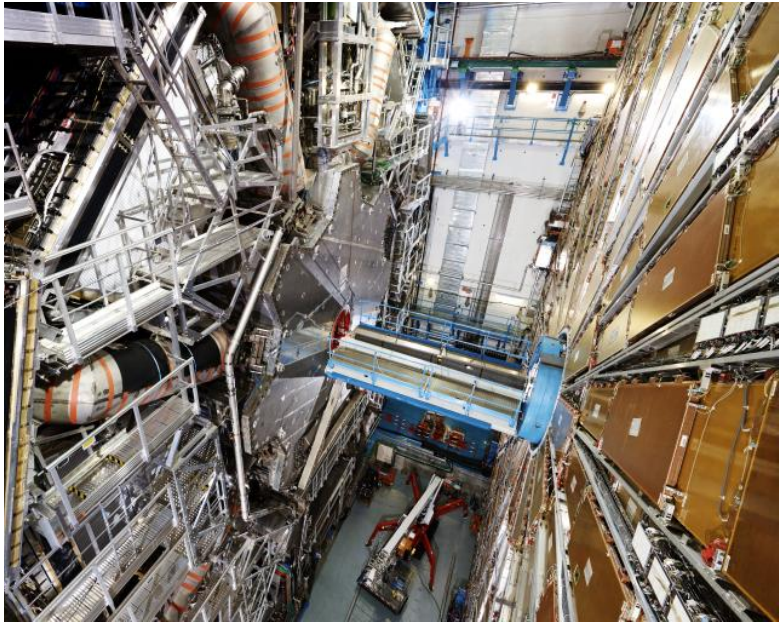


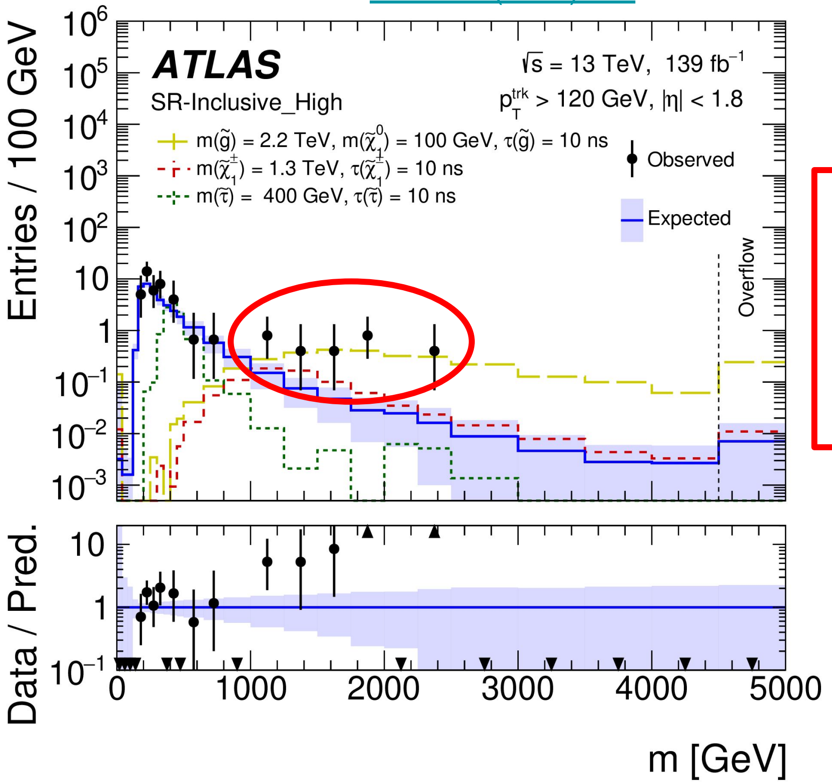
No Observation? Set a limit



Heavy Stable Charged Particles in ATLAS's Tracker

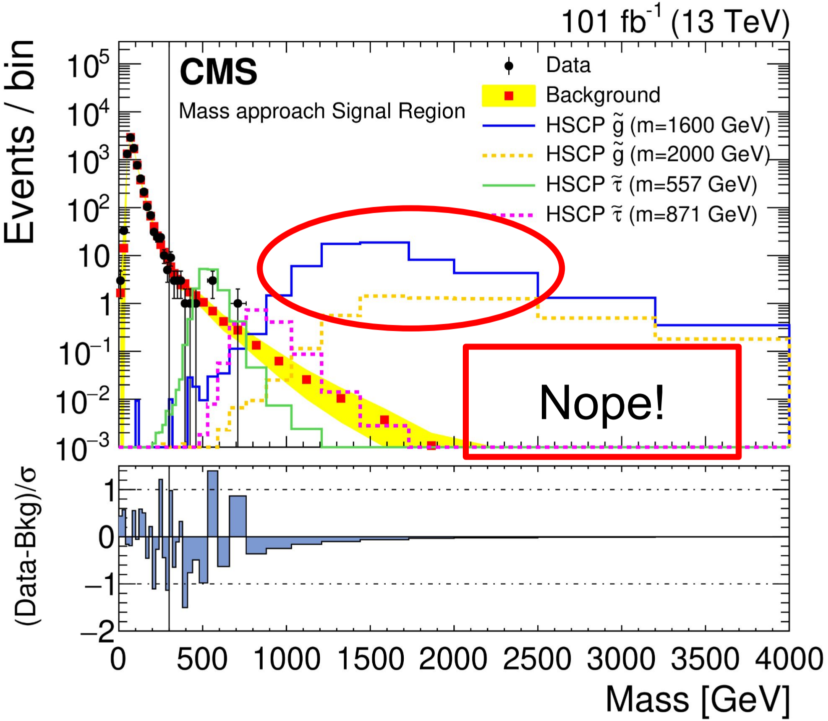


JHEP 06 (2023) 158

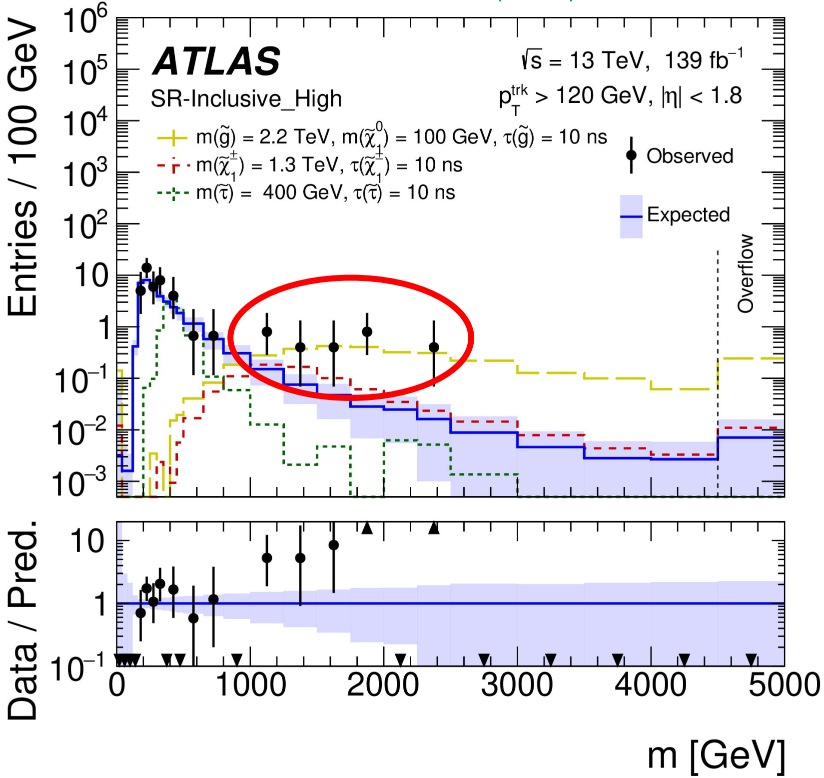


3.3σ excess!

Heavy Stable Charged Particles in ATLAS's Tracker

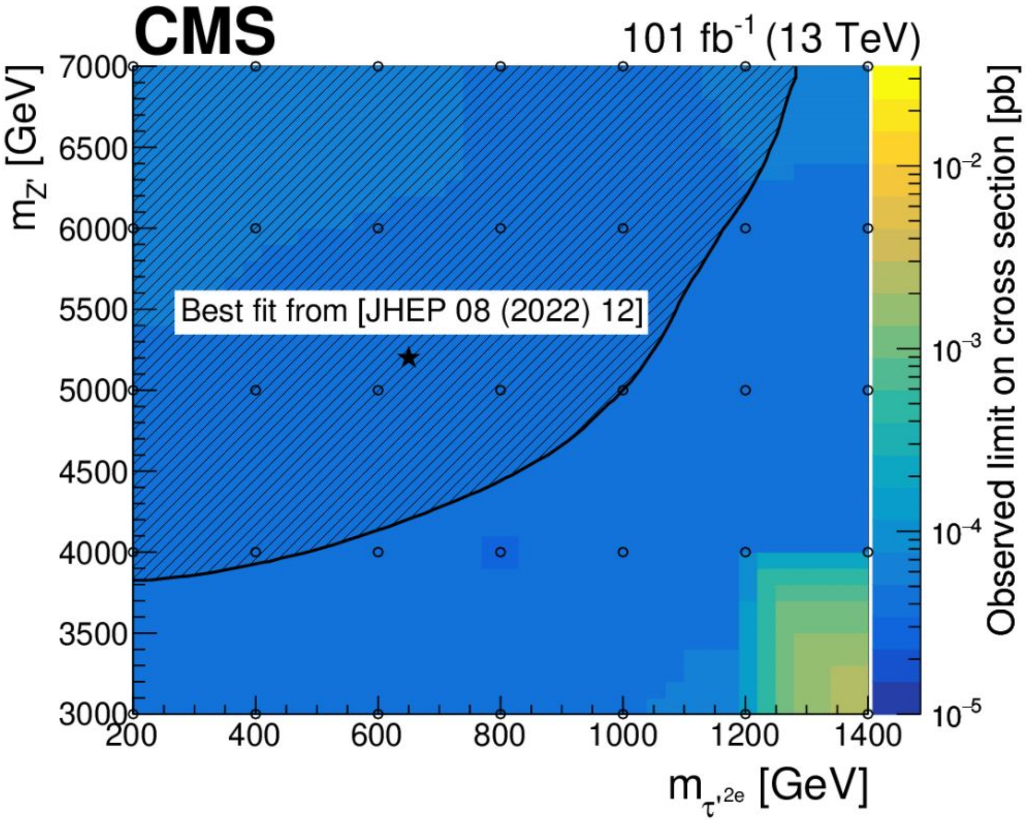


JHEP 06 (2023) 158



Results

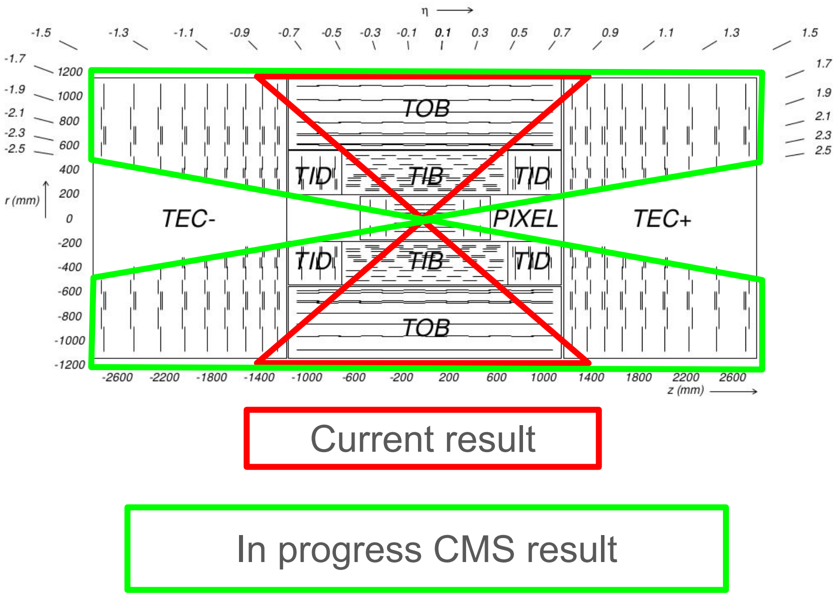
arXiv:2410.09164
CMS-EXO-18-002 figures



First ever limits on the multiply charged tau’ → excludes best fit to ATLAS excess

Future dE/dx in CMS

- Current work lays groundwork for tracker-only HSCP searches
    - New methods, new models
- Next Search(es)
    - Additional data acquisition paths
        - Current sensitivity could be dramatically improved for certain models
    - Expanding dE/dx reconstruction in tracker
    - Time-of-flight in the muon system
- High-Luminosity LHC
    - *farther*-forward dE/dx in silicon
        - High Granularity Calorimeter Upgrade
        - Pixel Upgrade
    - Time of flight w/ timing layers for HSCPs



Future dE/dx in CMS

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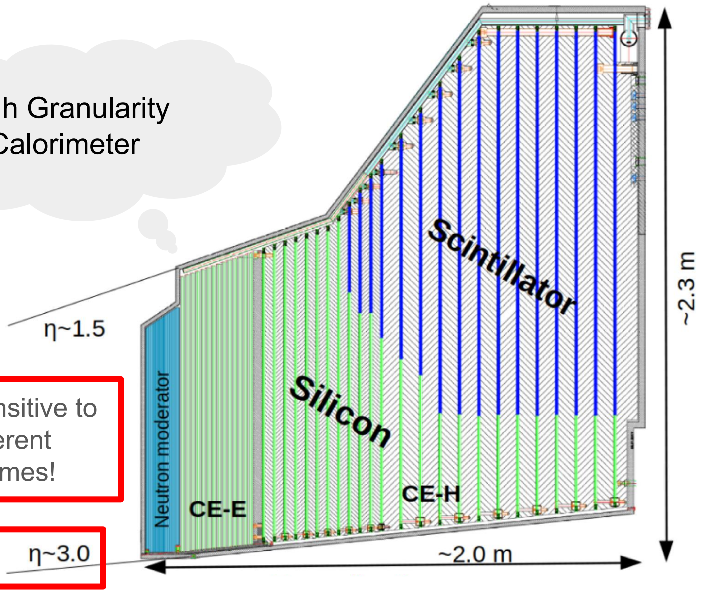
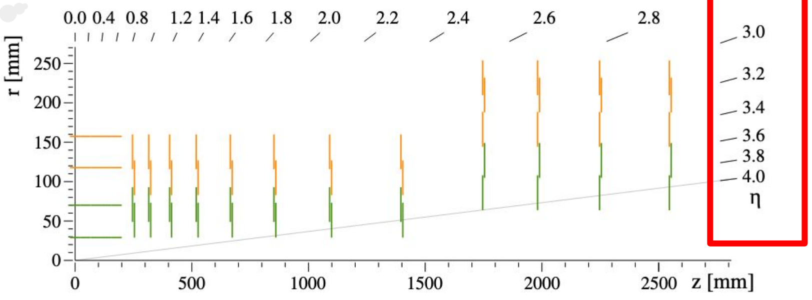
  - Time of flight w/ timing layers for HSCPs

High Granularity Calorimeter



And sensitive to different lifetimes!

Pixel Phase 2



Placard from now-closed metaphysical shop near my home in Humboldt Park, Chicago

The far-ish future of the low road

Placard from **now-closed** metaphysical shop near my home in Humboldt Park, Chicago

The far-ish future of the low road

A road we are on

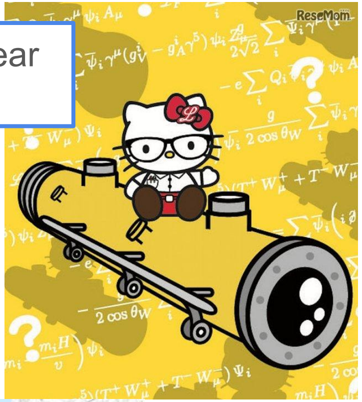
Exploring the Quantum Universe

Particle Physics Project Prioritization Panel (P5) prioritized…

A road we are on

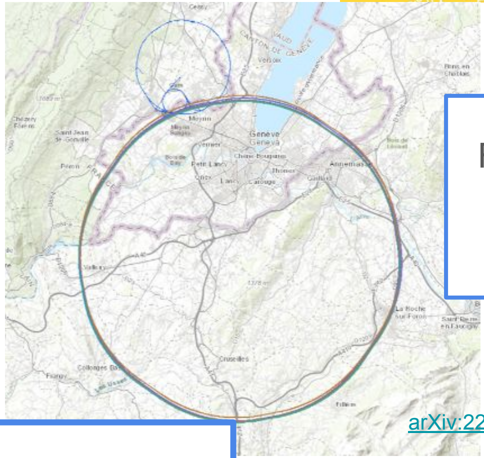
Exploring the Quantum Universe

International Linear Collider (ILC)



Particle Physics Project Prioritization Panel (P5) prioritized…

https://www.usparticlephysics.org/2023-p5-report/



Future Circular Collider e+e- (FCCee)

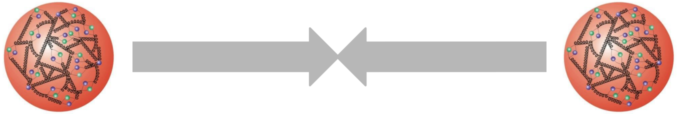
arXiv:2203.08310

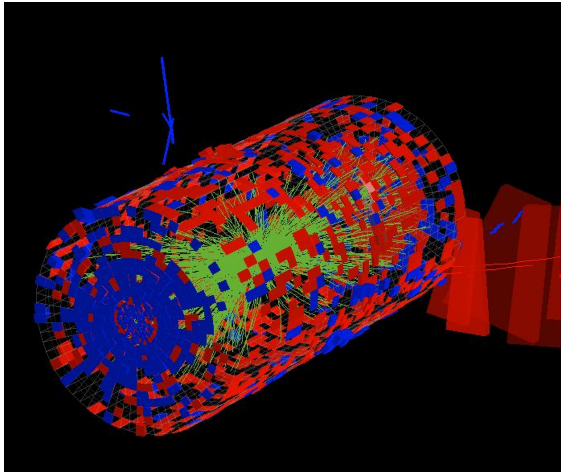
An offshore Higgs Factory!

electron/positron Higgs Factory

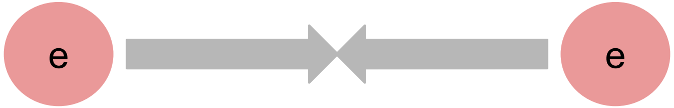
A completely different beast

Hadron Machines

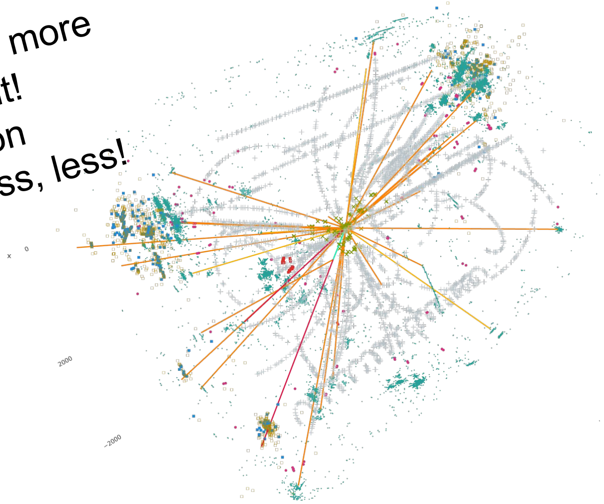




Lepton Machines

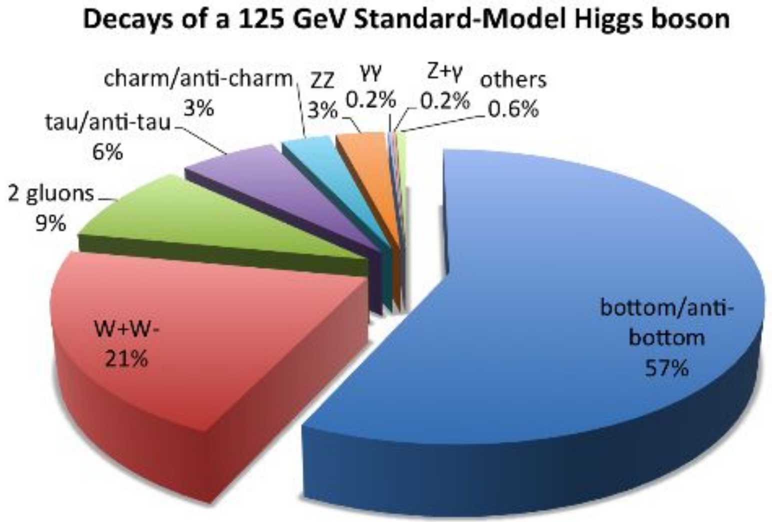


- Precision more important!
- Radiation hardness, less!



Precision calorimetry at a Higgs Factory

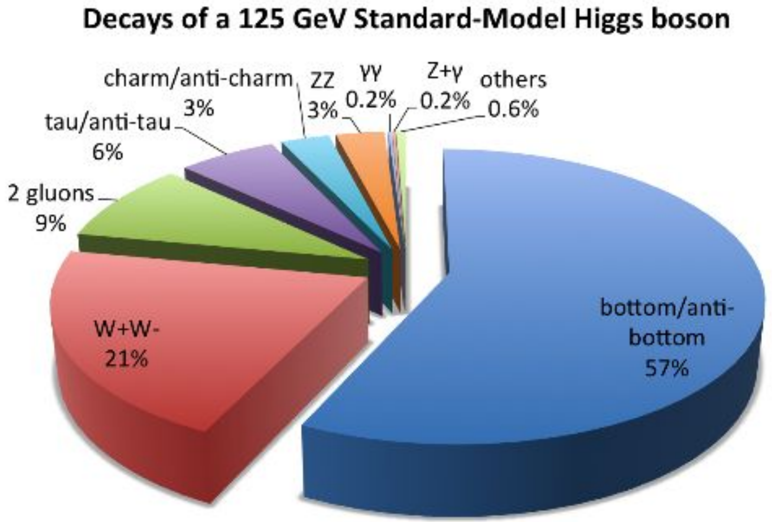
~% accuracy on all branching fractions!



Precision calorimetry at a Higgs Factory

Good Calorimeters!

~% accuracy on all branching fractions!

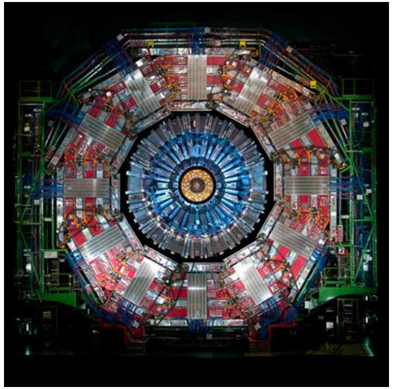


Precision coupling measurement → Tell apart hadronic decays of W and Z

Physics process	Measurands	Detector subsystem	Performance requirement
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E =$ $3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

Need 3-4% level hadronic energy resolution to separate!

A calorimeter designed with the Higgs in mind



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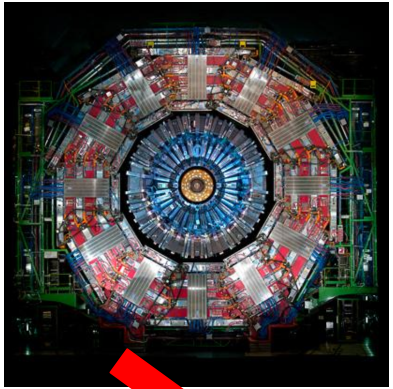
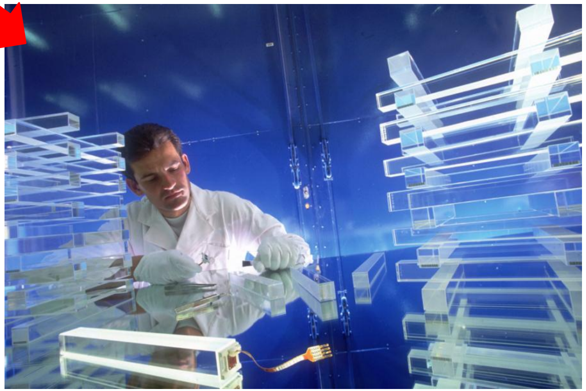


Dense crystals so entire deposition produces visible signature



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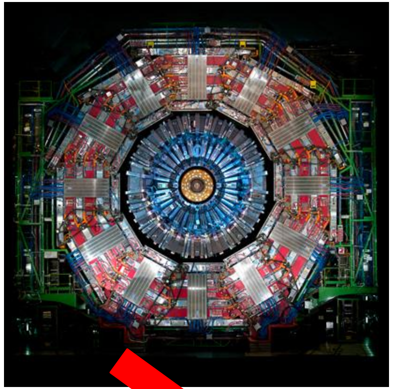

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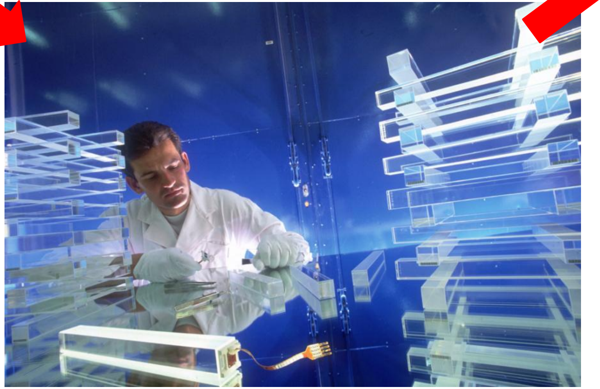
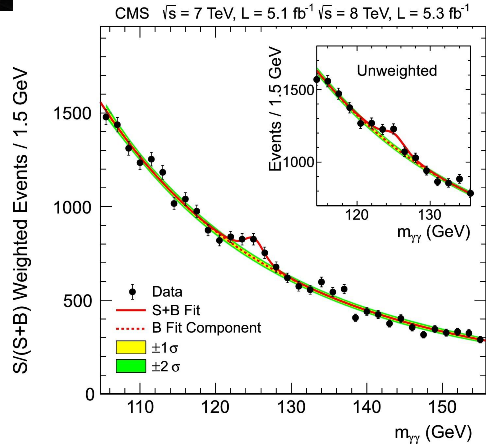
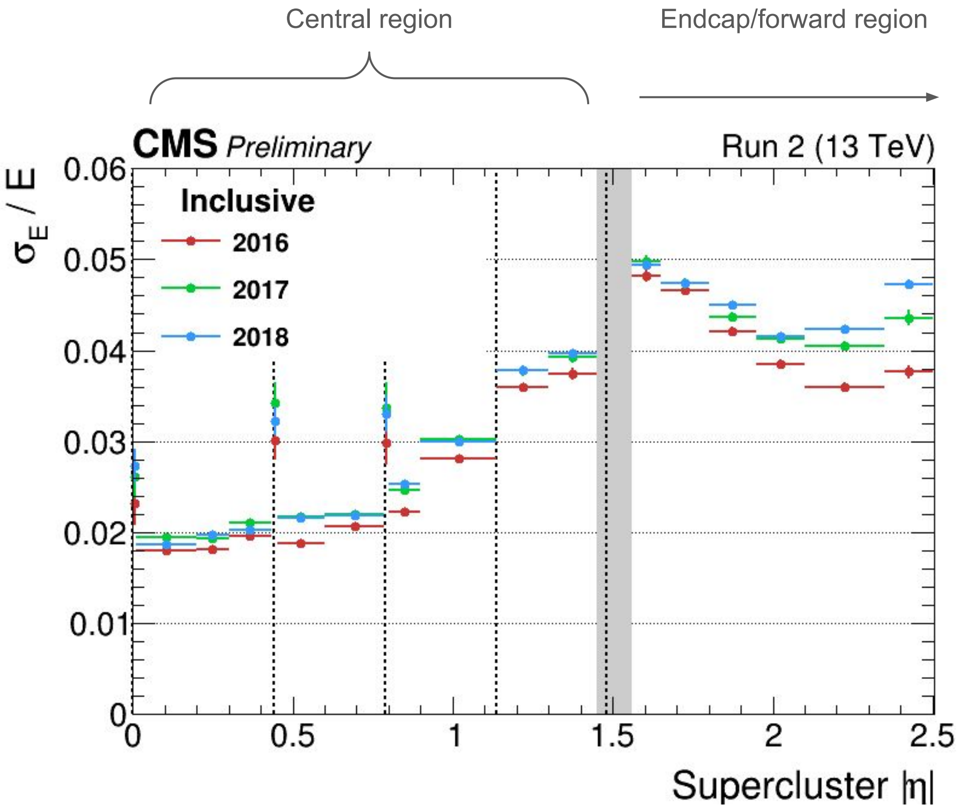


Projective and hermetic geometry -- precision calibration



Calorimetry that reaches these goals

arXiv:2403.15518v2
https://doi.org/10.22323/1.414.0337



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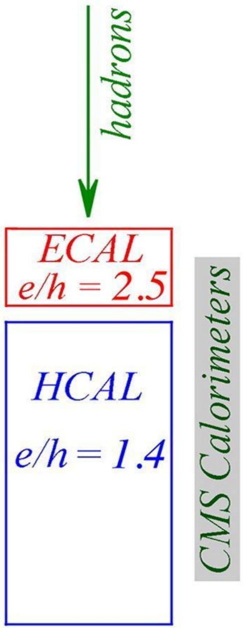
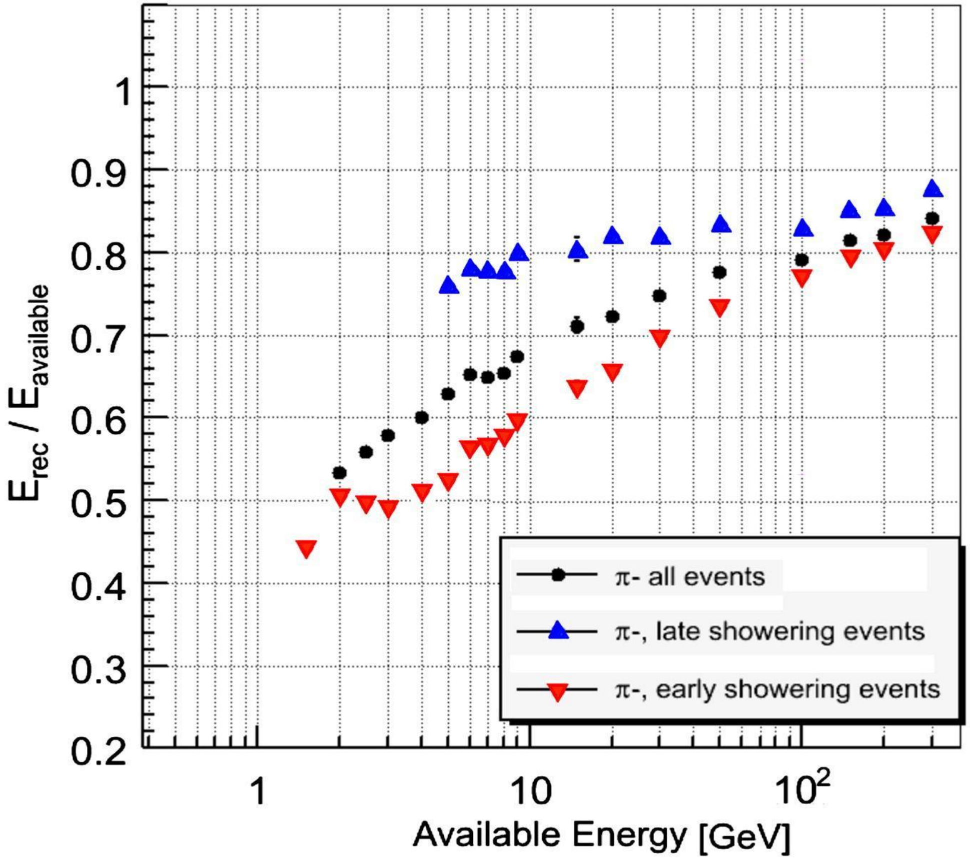
$H \to \gamma\gamma$	BR($H \to \gamma\gamma$)	ECAL	$\Delta E/E = \frac{0.20}{\sqrt{E(\text{GeV})}} \oplus 0.01$

Excellent resolution!

Drawback?

The CMS ECAL makes the CMS hadronic energy resolution *worse*





N. Akchurin, R. Wigmans, (2012) Nucl. Instr. and Meth. **A666** (80)

Hadronic energy deposition

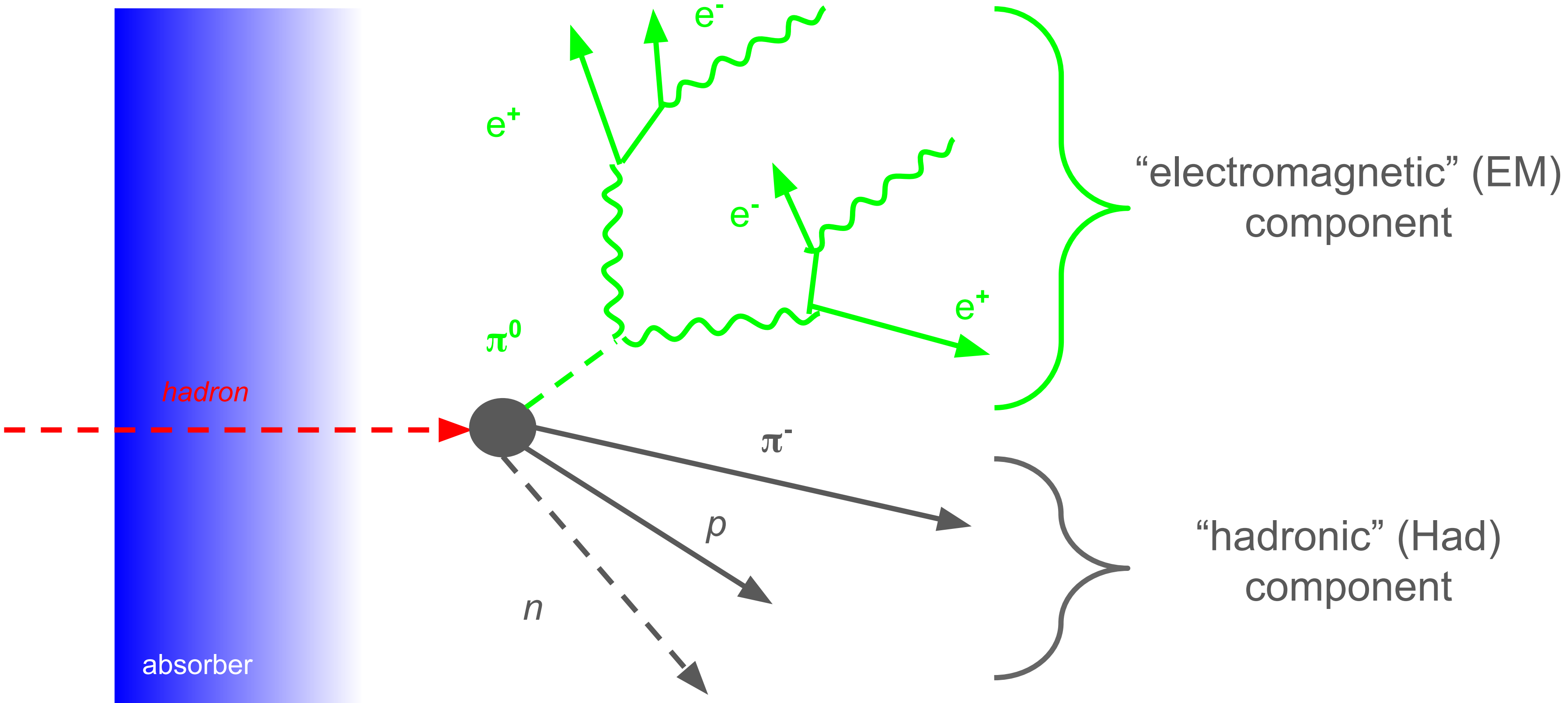
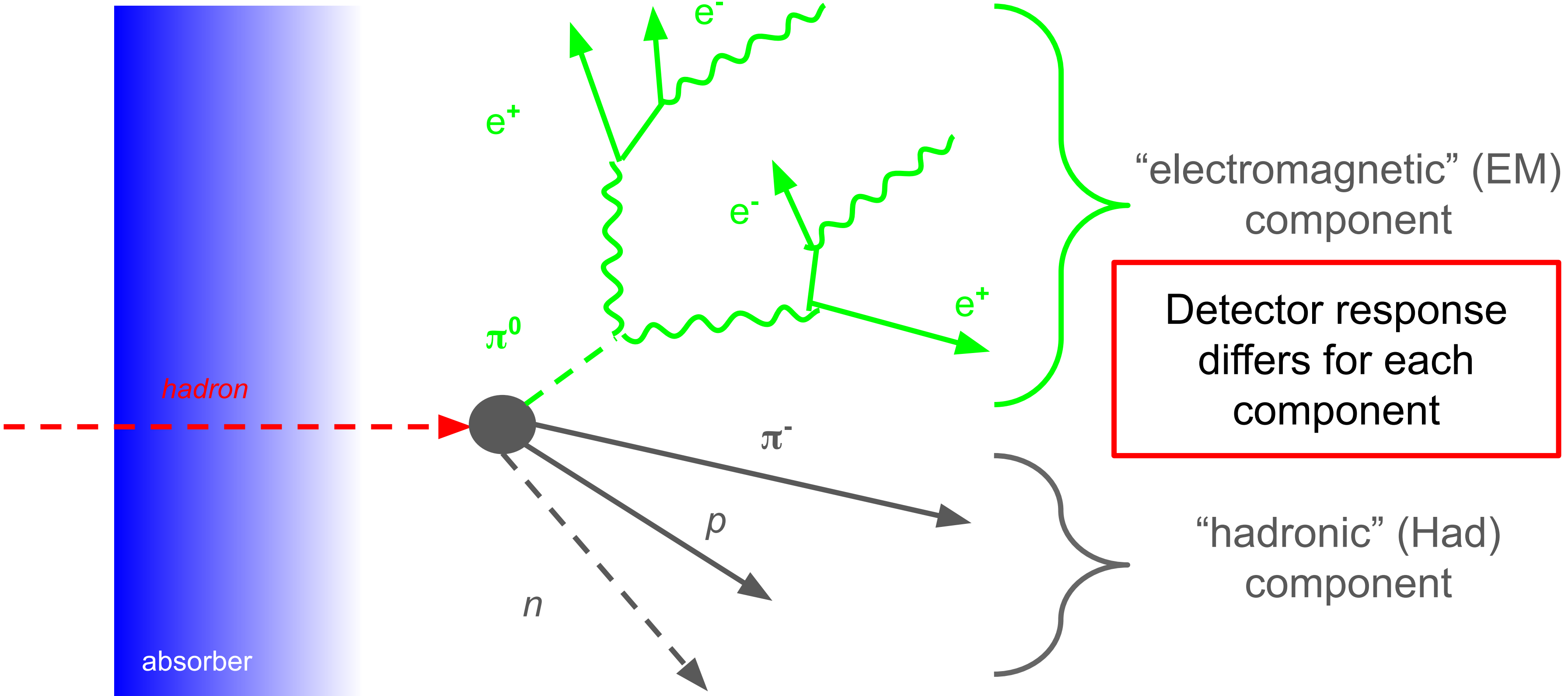


Figure adapted from Sehwook Lee 2019 *J. Phys.: Conf. Ser.* **1162** 012043

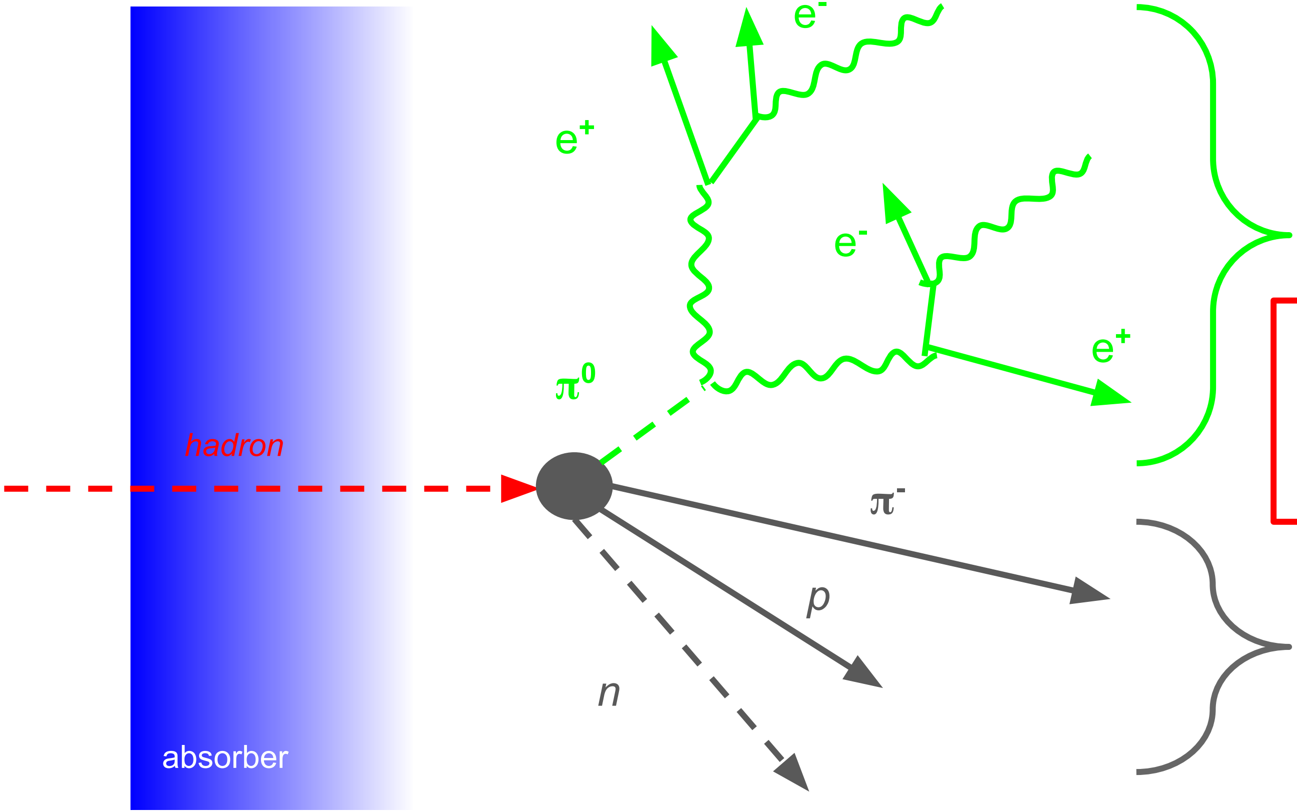
Hadron calorimetry is challenging



Detector response differs for each component

Figure adapted from Sehwook Lee 2019 *J. Phys.: Conf. Ser.* **1162** 012043

Hadron calorimetry is challenging



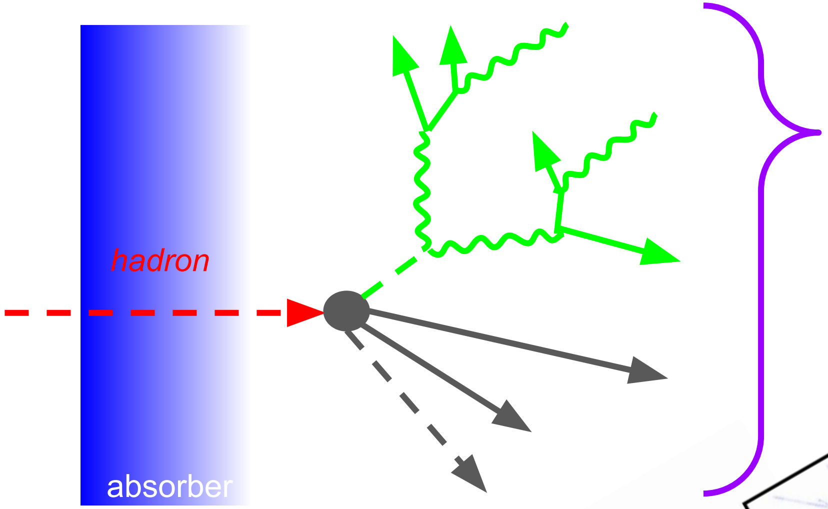
"electromagnetic" (EM) component

EM/Had ratio fluctuates event-to-event

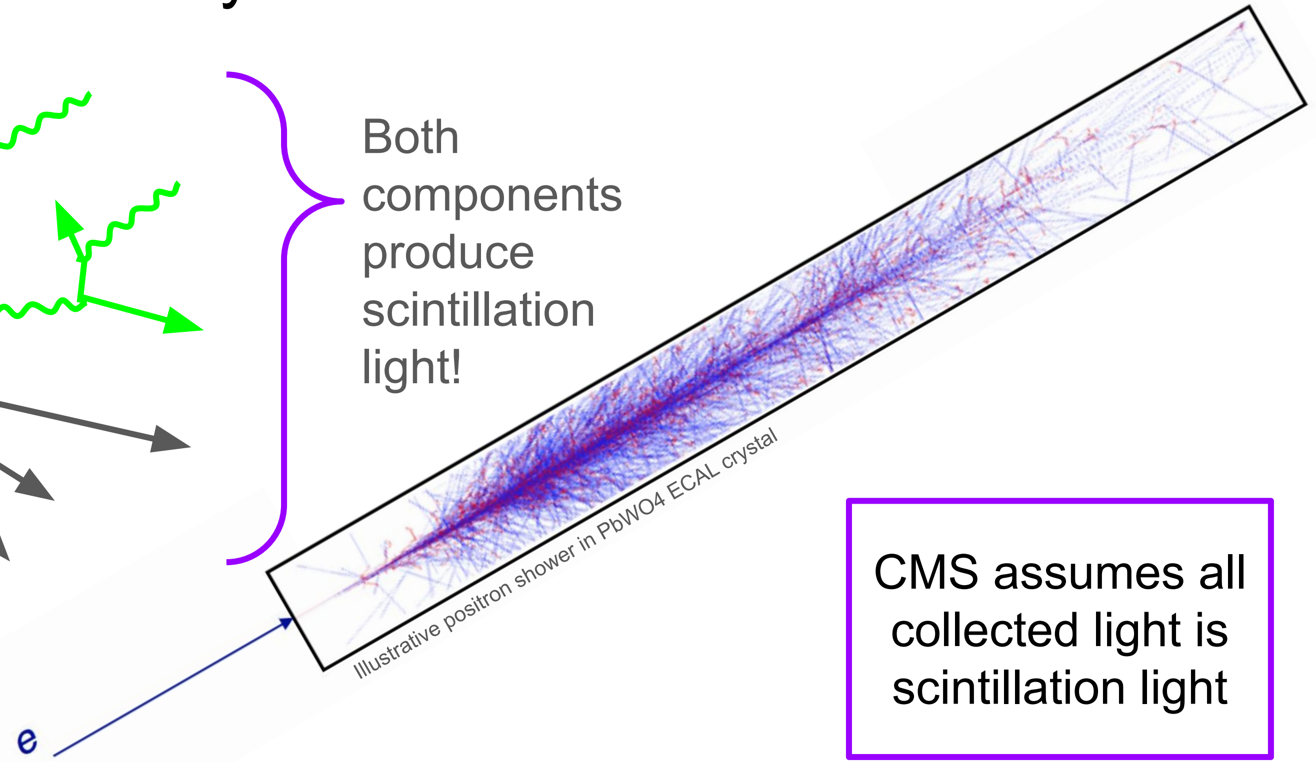
"hadronic" (Had) component

Figure adapted from Sehwook Lee 2019 *J. Phys.: Conf. Ser.* **1162** 012043

Hadronic showers in crystals



Both components produce scintillation light!

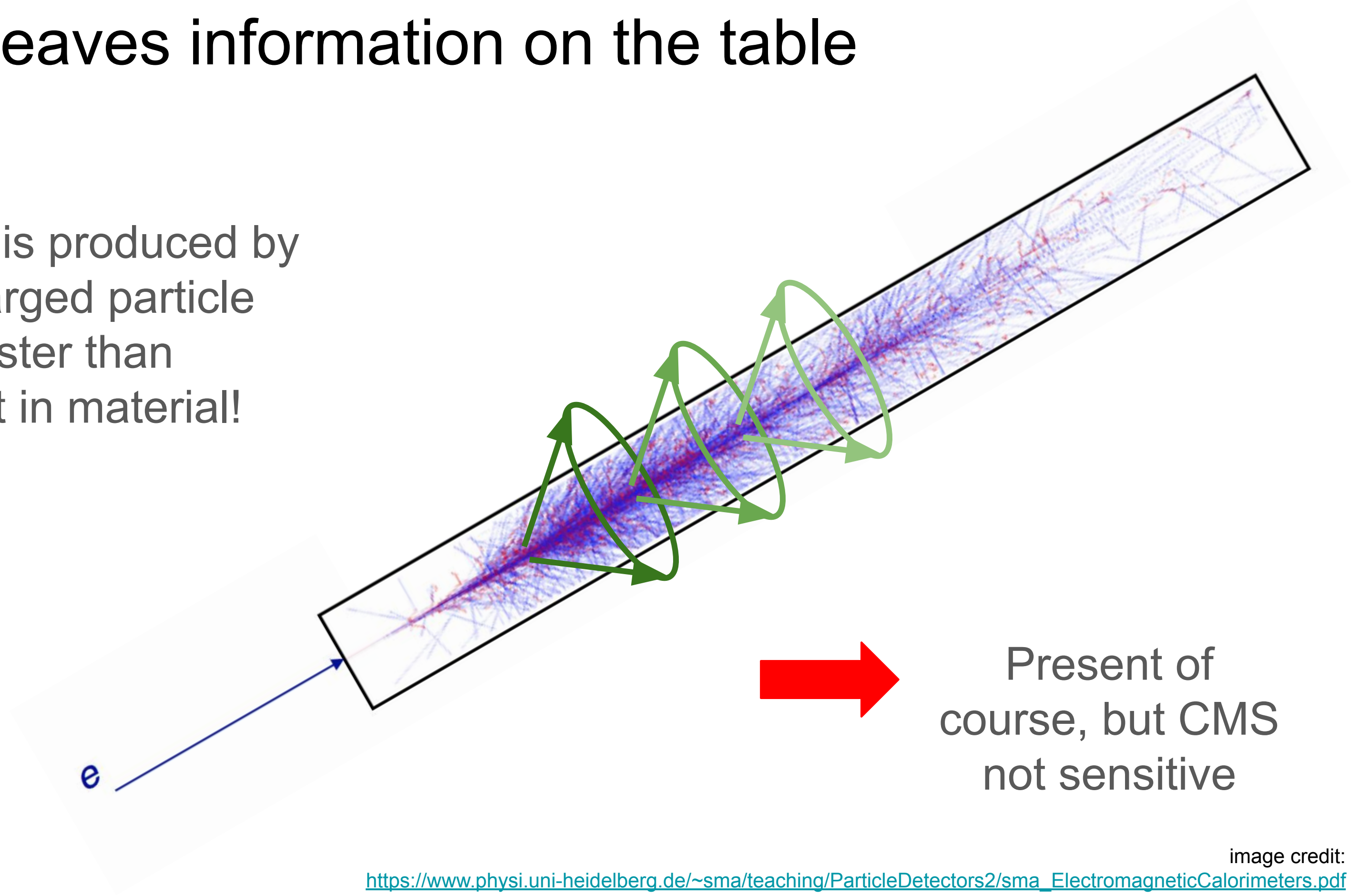


CMS assumes all collected light is scintillation light

image credit:
https://www.physi.uni-heidelberg.de/~sma/teaching/ParticleDetectors2/sma_ElectromagneticCalorimeters.pdf

CMS ECAL Leaves information on the table

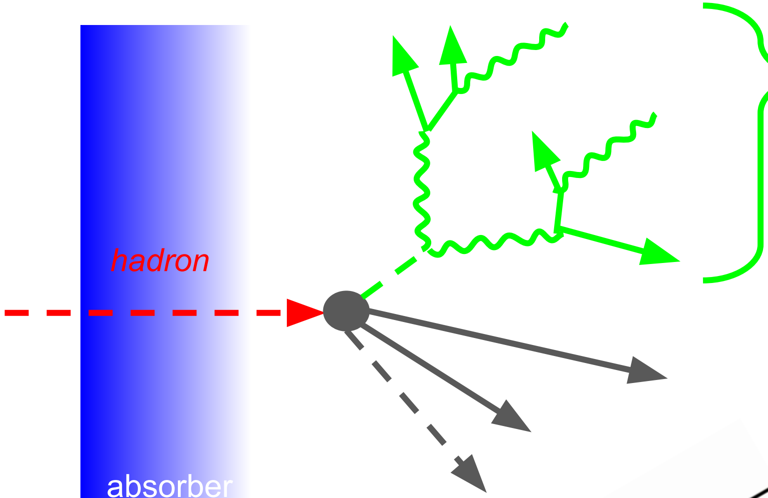
Cherenkov light is produced by relativistic charged particle moving faster than speed-of-light in material!



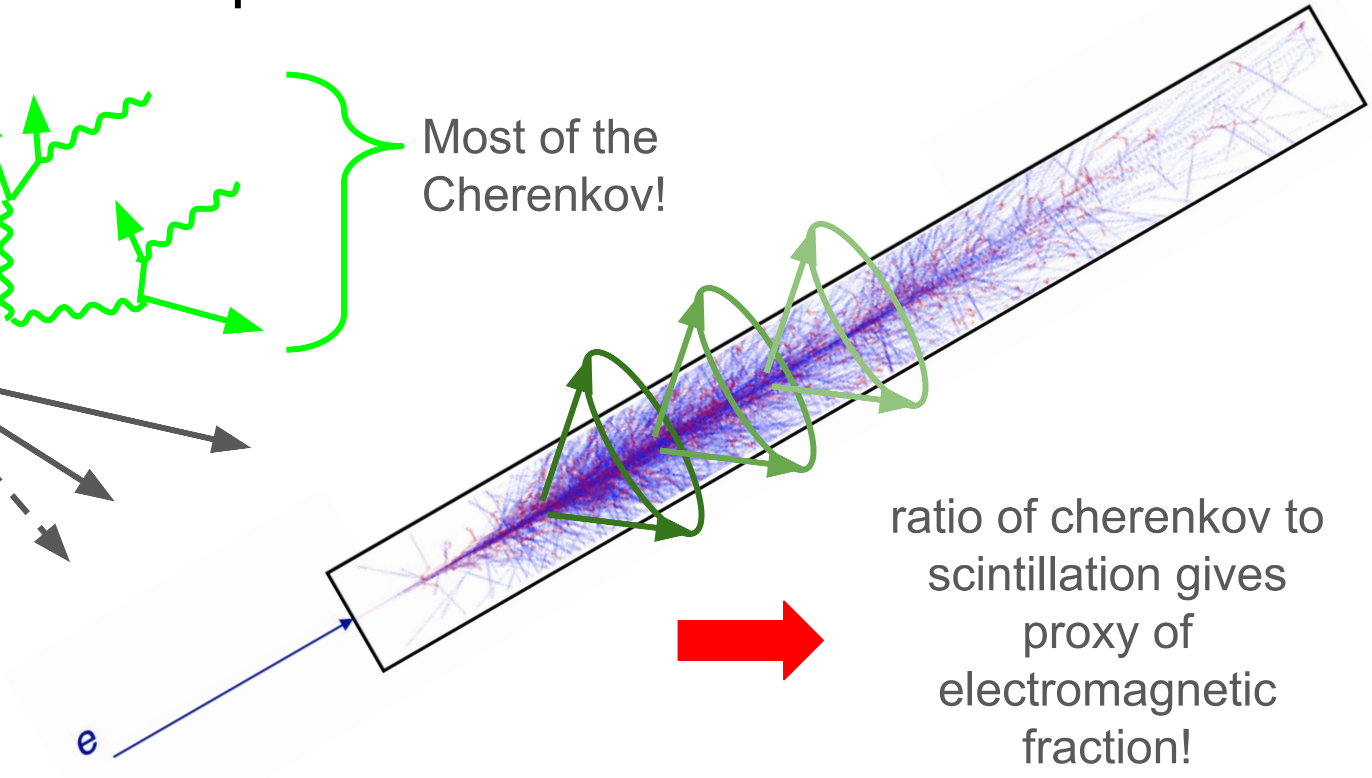
Present of course, but CMS not sensitive

image credit: https://www.physi.uni-heidelberg.de/~sma/teaching/ParticleDetectors2/sma_ElectromagneticCalorimeters.pdf

Dual-Readout technique



Most of the Cherenkov!

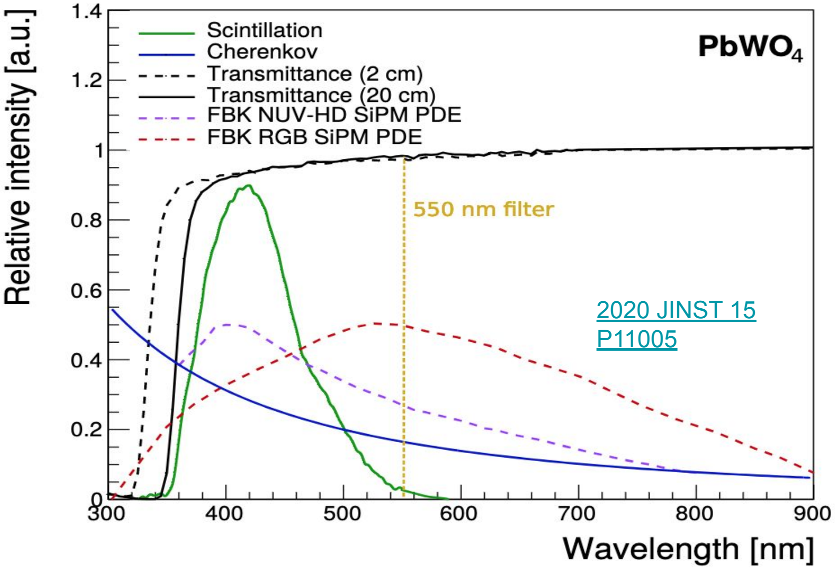


ratio of cherenkov to scintillation gives proxy of electromagnetic fraction!

image credit:
https://www.physi.uni-heidelberg.de/~sma/teaching/ParticleDetectors2/sma_ElectromagneticCalorimeters.pdf

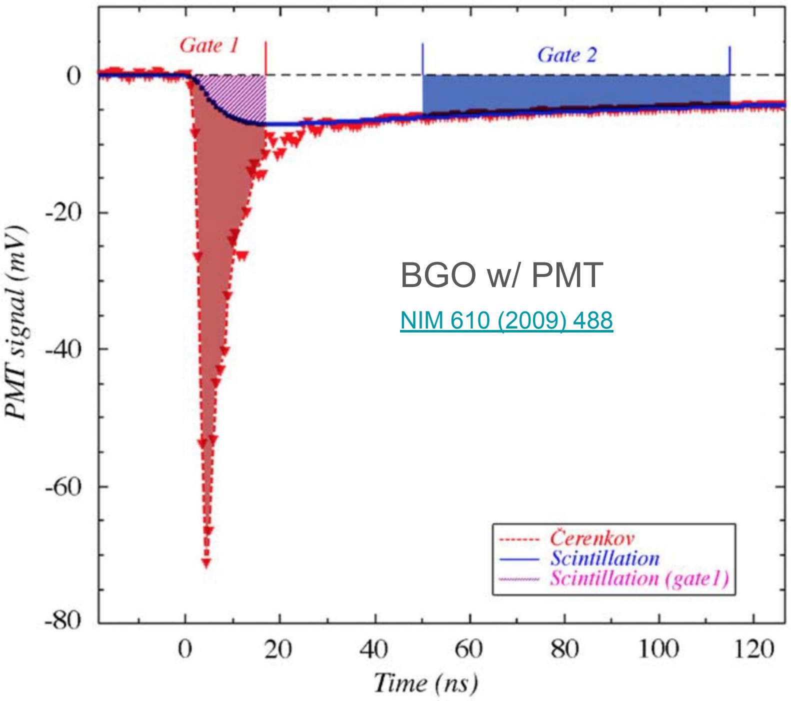
How to separate Cherenkov and Scintillation light

Wavelength



2020 JINST 15 P11005

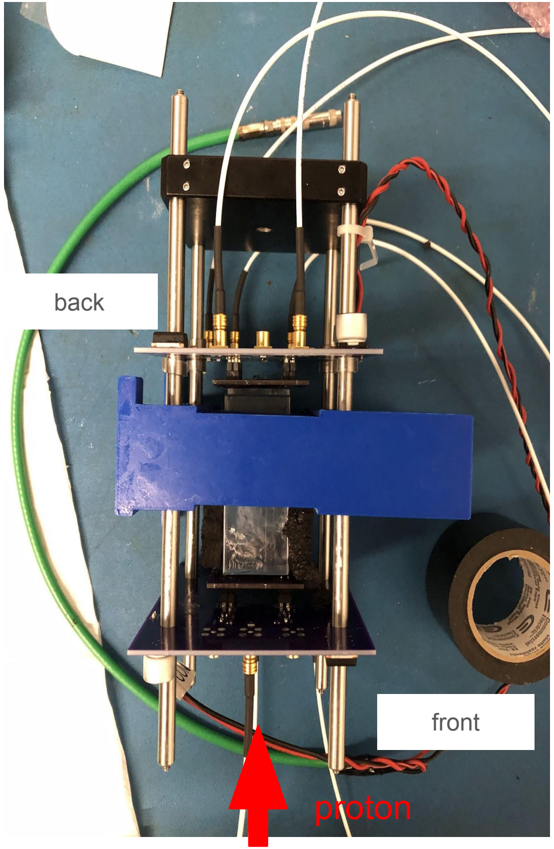
Time structure



BGO w/ PMT

NIM 610 (2009) 488

Initial Performance - Bismuth Germanate (BGO)



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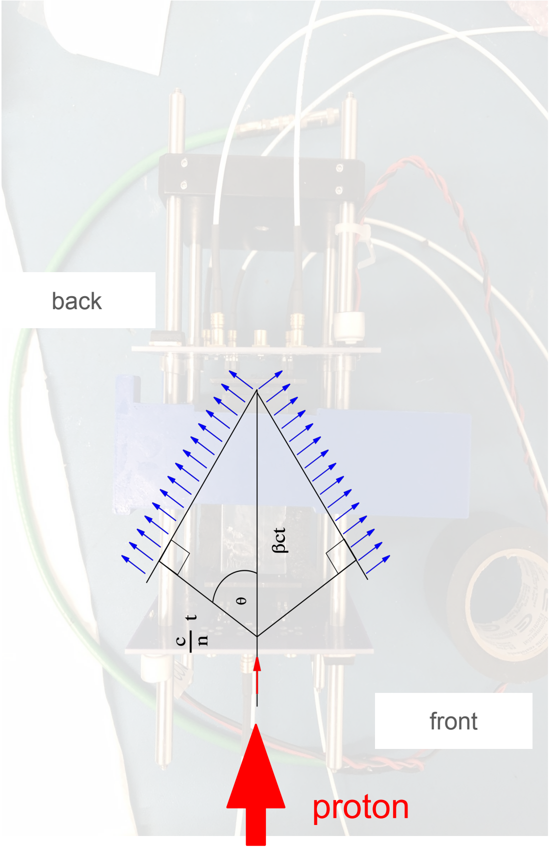
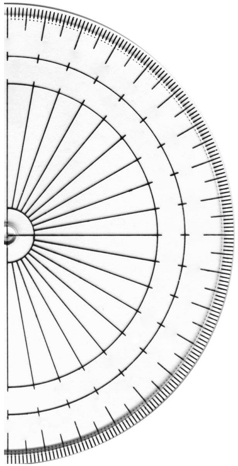
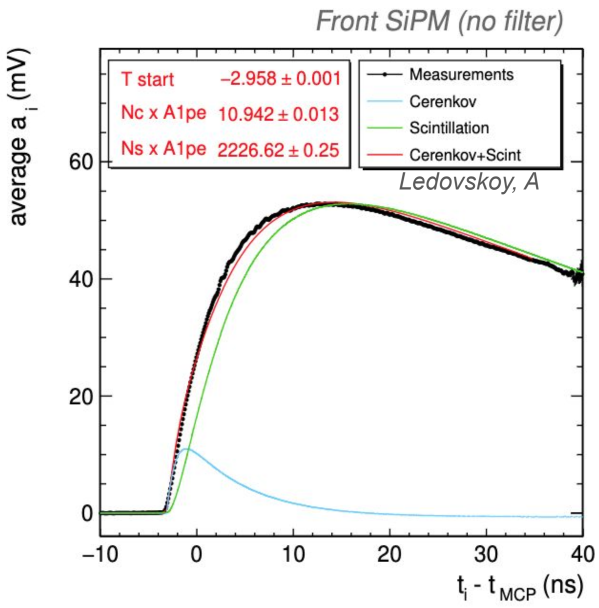


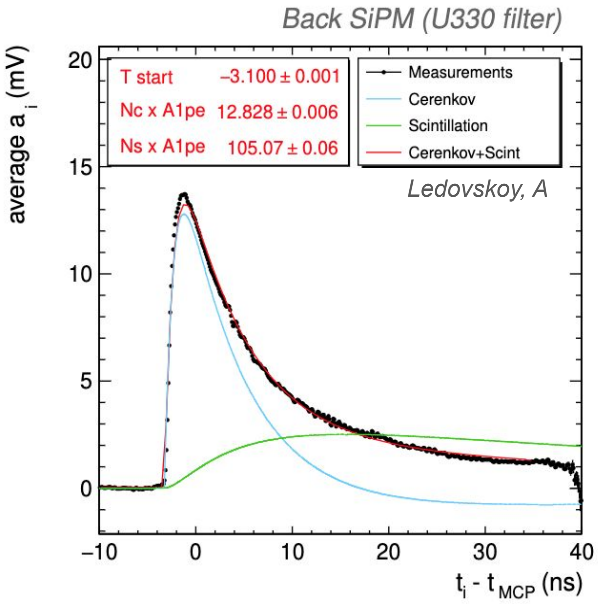
Strong angular dependence → handle for Cherenkov!

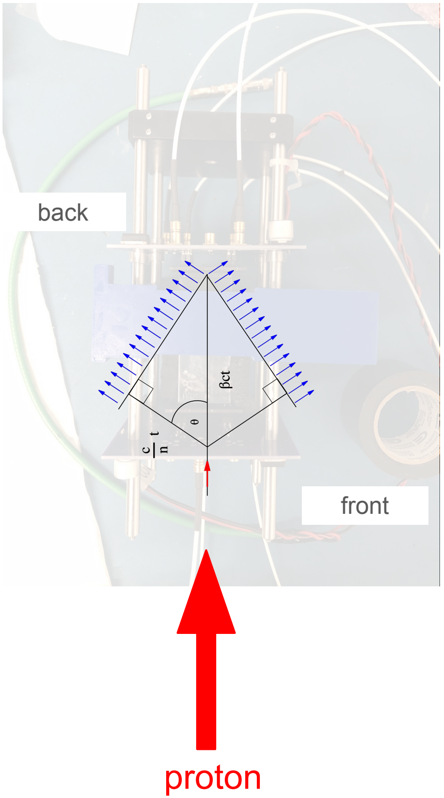


Initial Performance - Bismuth Germanate (BGO)

- Pulse shape analysis w/ proton data

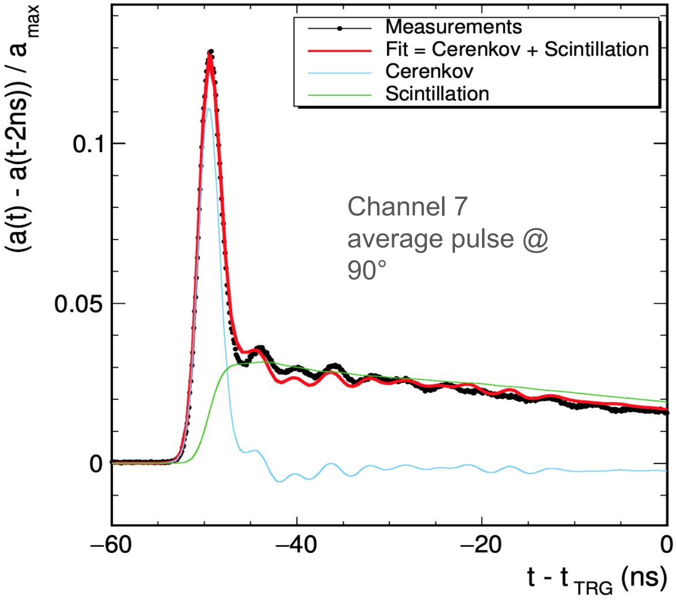




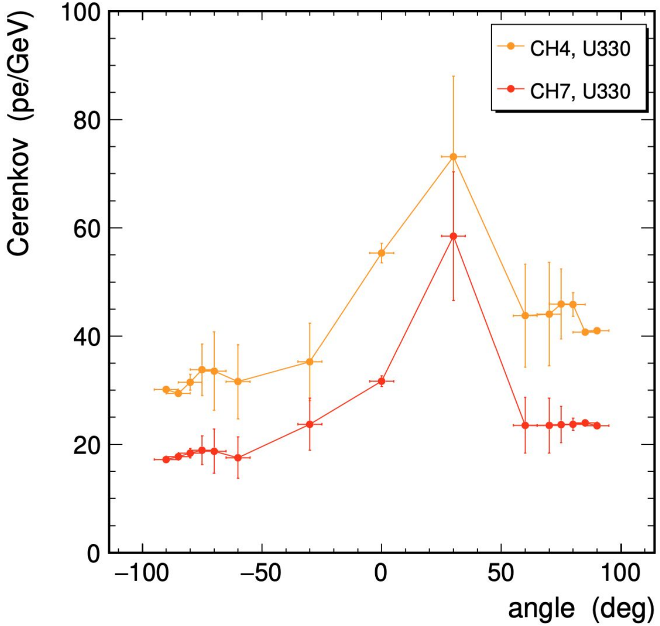


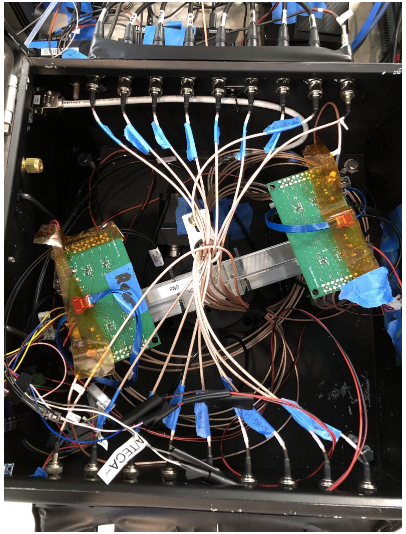
B. Hirosky CPAD Talk

BGO Analysis - electron data



*derivative of usual pulse!

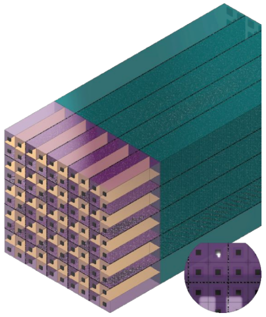


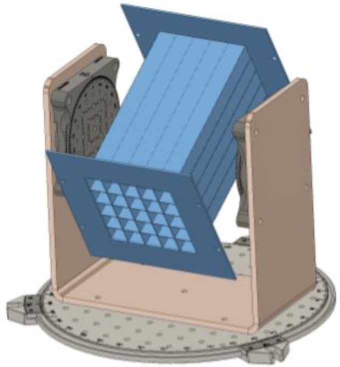


Comfortably exceeding the Cherenkov acceptance goals!

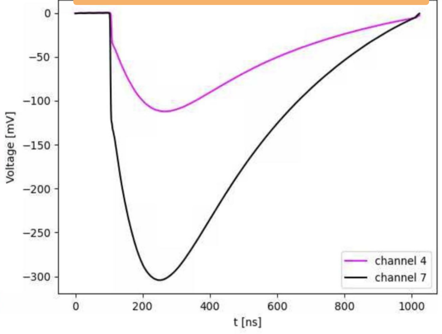
Next steps

- Build a matrix!
  - Complete containment of electrons
- Joint with hadron calorimeter for full hadronic energy resolution
  - Test of ultimate goal
- More materials
  - Lead Tungstate like CMS
  - Heavy scintillating glasses for homogenous HCALs
- More test beams
  - Last single crystal run next week!





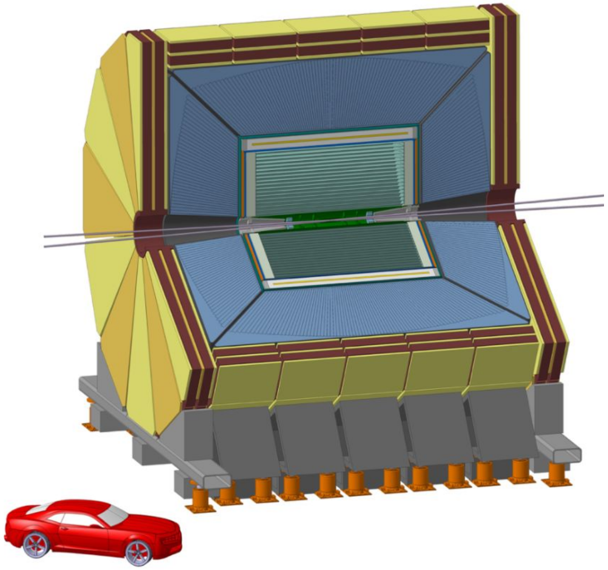
Heavy Glasses are promising!



In Summary

- Low-level decisions about detector readout directly impact physics reach
  - both Standard Model physics, and beyond the Standard Model reach
- Heavy Stable charged Particles in CMS
  - Run 2 CMS limits
  - First limits on doubly-charged tau' model
  - Last time some of these measurements will be available in CMS, make sure we do them
- Enabling hardware
  - New accelerators provide new challenges
  - Dual Readout crystals for precision measurements of the future

DR xtal calo new baseline for the IDEA detector concept for FCC-ee!



https://doi.org/10.22323/1.414.0337

back-up

Bethe-Bloch

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

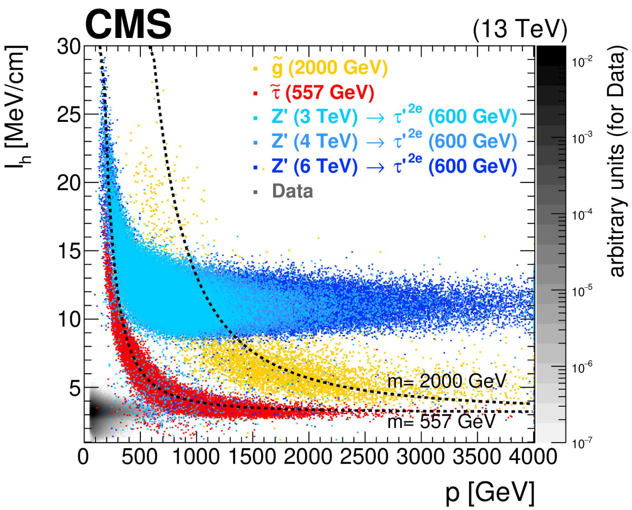
$$T_{\max} = \frac{2m_e c^2\,\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$

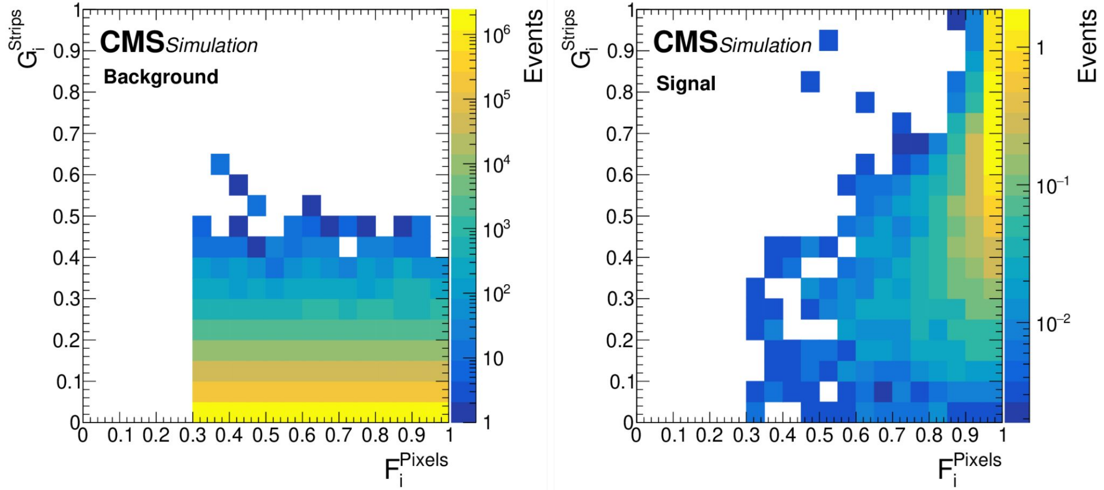
3 Different Ionization Variables

I_h	F_i^{Pixel}	G_i^{Strip}
dE/dx ‘Estimator’	dE/dx ‘Discriminator’	dE/dx ‘Discriminator’

$$I_h = \left(\frac{1}{N} \sum_j^N c_j^{-2} \right)^{-1/2}$$

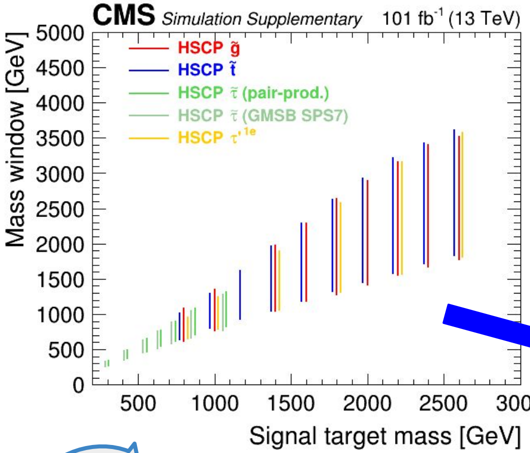
Probability something is “MIP” like

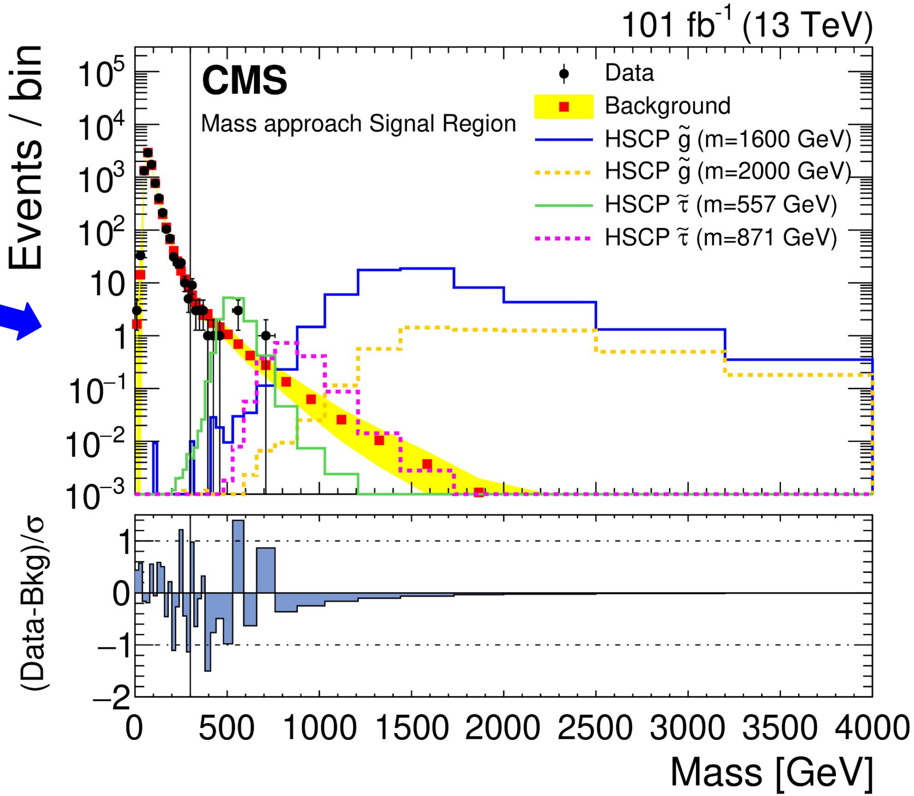


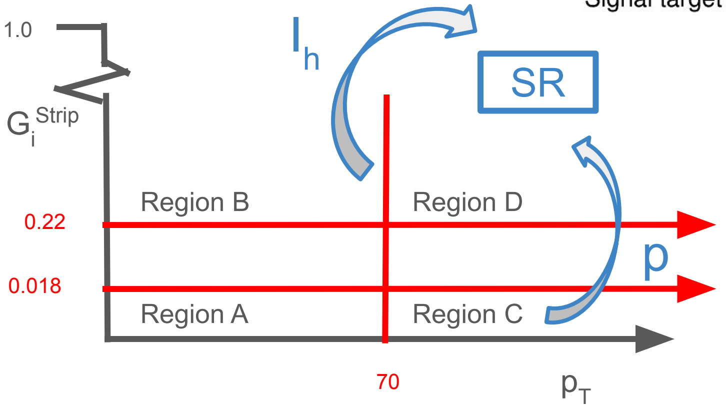


Search Strategy

arXiv:2410.09164
CMS-EXO-18-002 figures







HSCP Equations

$$m = p \times \sqrt{\frac{I_h - C}{K}}$$

Probability measured charge comes from MIP (template built for each sensor type)

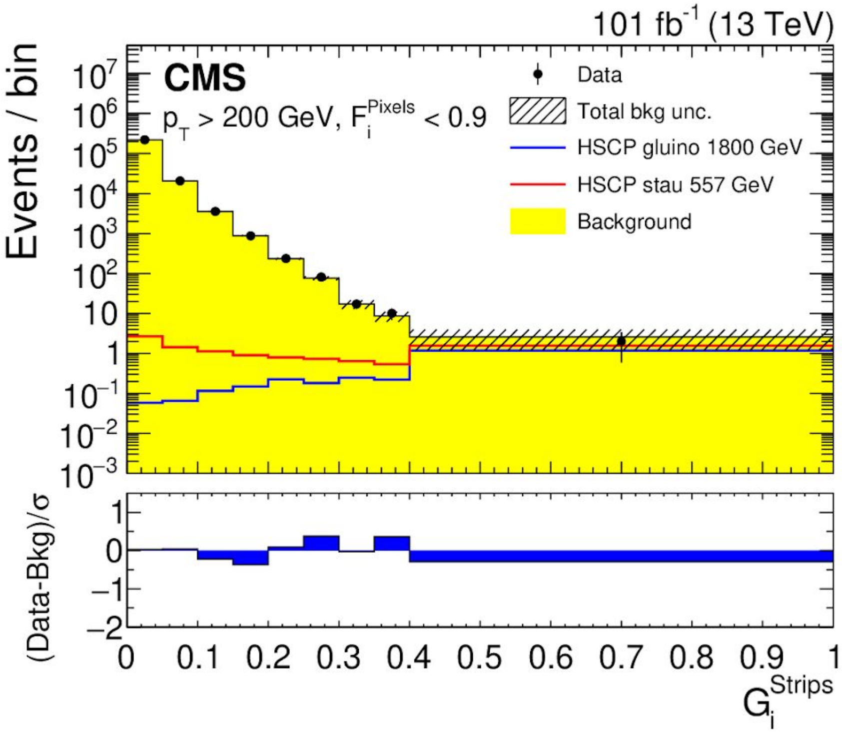
$$G_i^{Strip} = I_{as} = \frac{3}{N} \times \left(\frac{1}{12N} + \sum_{j=1}^{N} \left[P_j \times \left(P_j - \frac{2j-1}{2N} \right)^2 \right] \right)$$

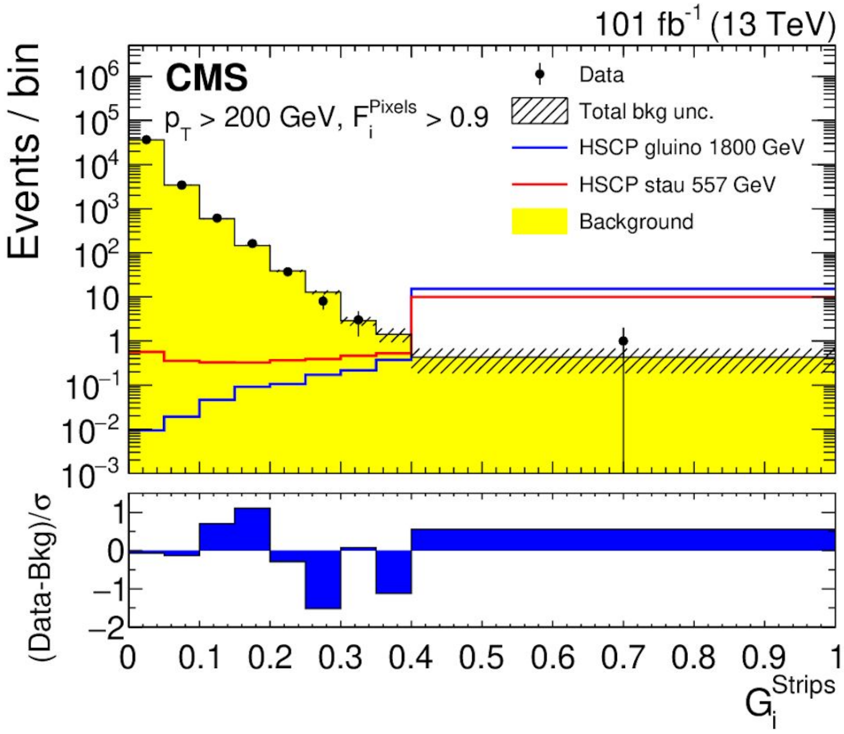
$$F_i^{Pixel} = 1 - Comb(probQ, noL1)$$

$$\beta_n = \alpha_n \sum_{m=0}^{n-1} \frac{[-ln(\alpha_n)]^m}{m!}$$

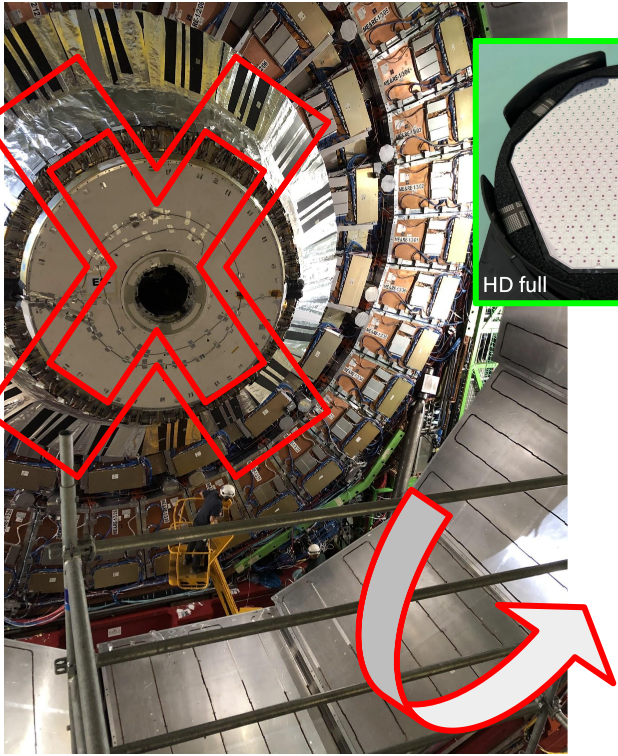
Combination scheme

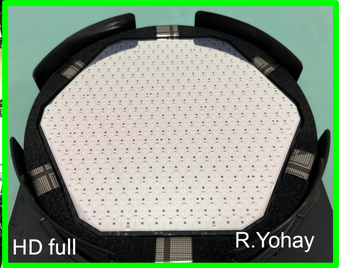
Ionization Method - Pass/Fail SR

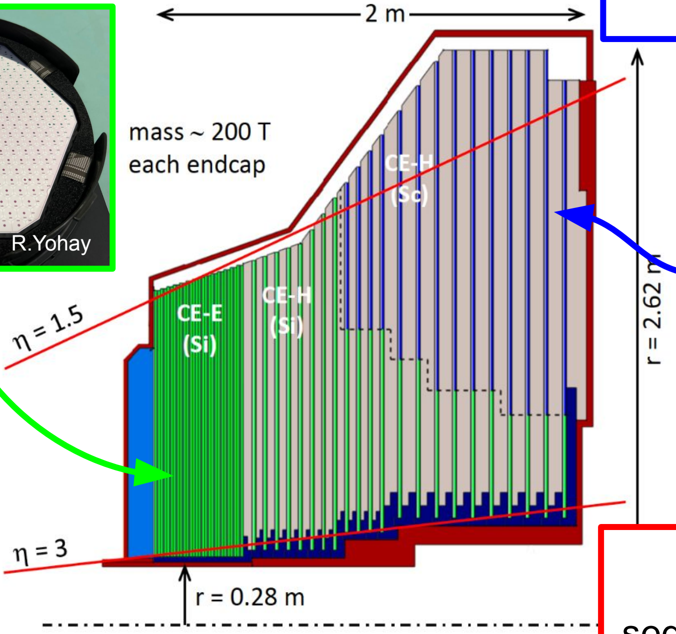




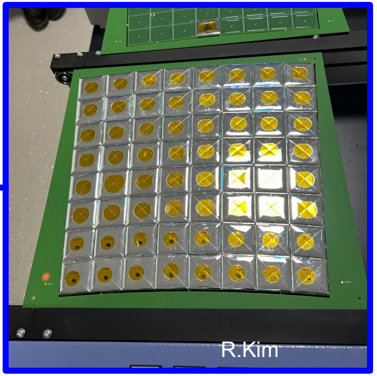
CMS *High Granularity* Calorimeter Endcap, HL-LHC







Plastic Scint Tiles



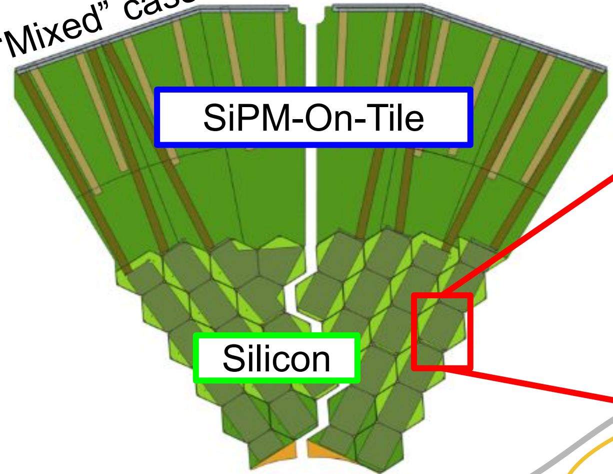
Silicon

47 layers of z-direction segmentation, ~30 ps timing in Silicon sections

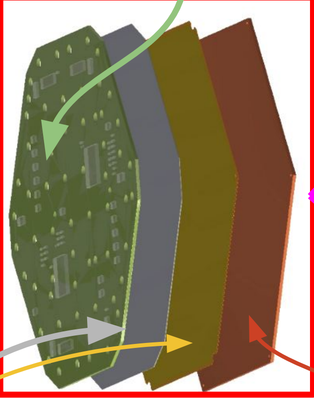
HGCAL front end data path

Raw Data:
6M Channels → 5 Pb/s, ~1M links*

“Mixed” cassette



Hexaboard with
HGCROC readout
ASICs



Silicon
Sensor

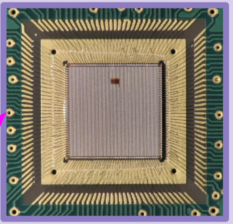
kapton

Cu/W absorber plate

HGROC: 1M Channels, trigger path → 300 Tb/s, **60k links***

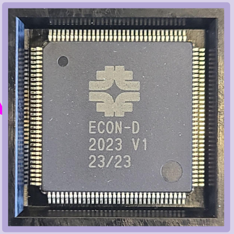
“**E**ndcap **CON**centrator”
On-detector data
compression

Trigger decision



ECON-T

7x compression
40 Tb/s, **9k links***



ECON-D

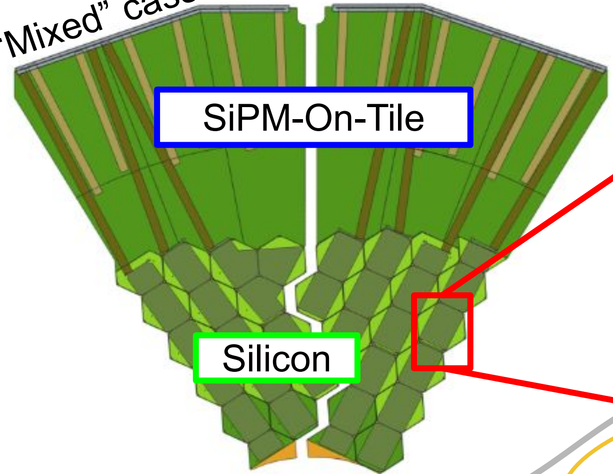
Concentrator Mezzanine

*Assumes 40 MHz rate and 50% link packing efficiency for 10.24 Gbps
**Assumes 750 kHz rate (trigger) and 50% link packing efficiency for 10.24 Gbps

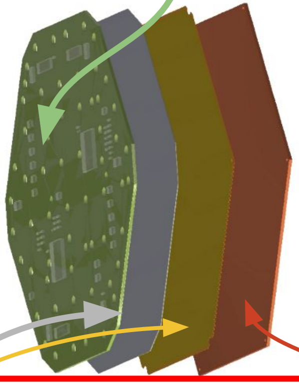
HGCAL front end data path

Raw Data:
6M Channels → 5 Pb/s, ~1M links*

“Mixed” cassette



Hexaboard with HGCROC readout ASICs



Silicon Sensor

kapton

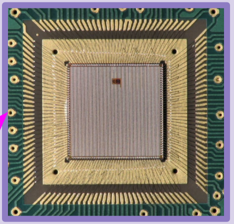
Cu/W absorber plate

HGROC: data path → ~144 Tb/s, **30k links****

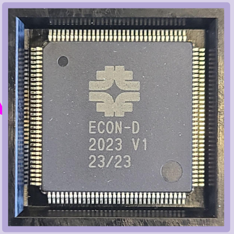
“**E**ndcap **CON**centrator” On-detector data compression

Trigger decision

accept



ECON-T



ECON-D

3x compression, **~9k links****

Concentrator Mezzanine

*Assumes 40 MHz rate and 50% link packing efficiency for 10.24 Gbps
**Assumes 750 kHz rate (trigger) and 50% link packing efficiency for 10.24 Gbps