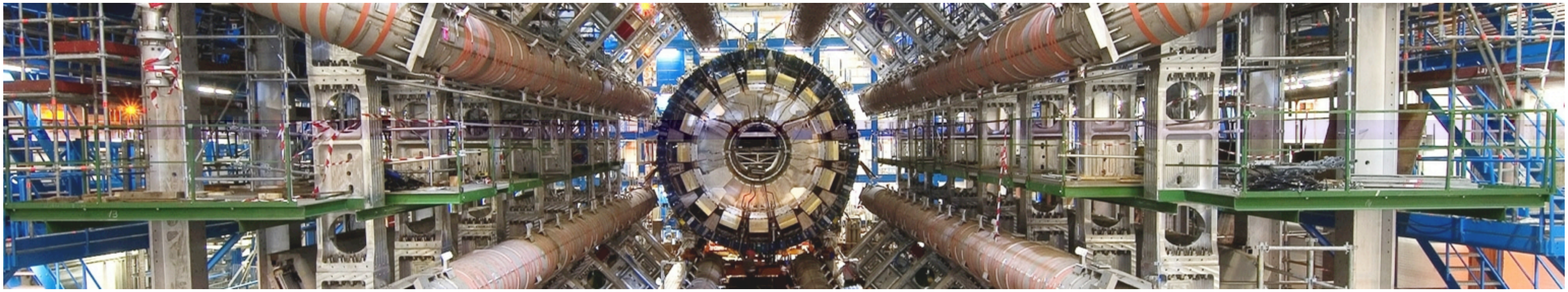

Event Reconstruction and Particle Identification

Part One

Jason Nielsen

Santa Cruz Institute for Particle Physics

University of California, Santa Cruz

Hadron Collider Physics Summer School

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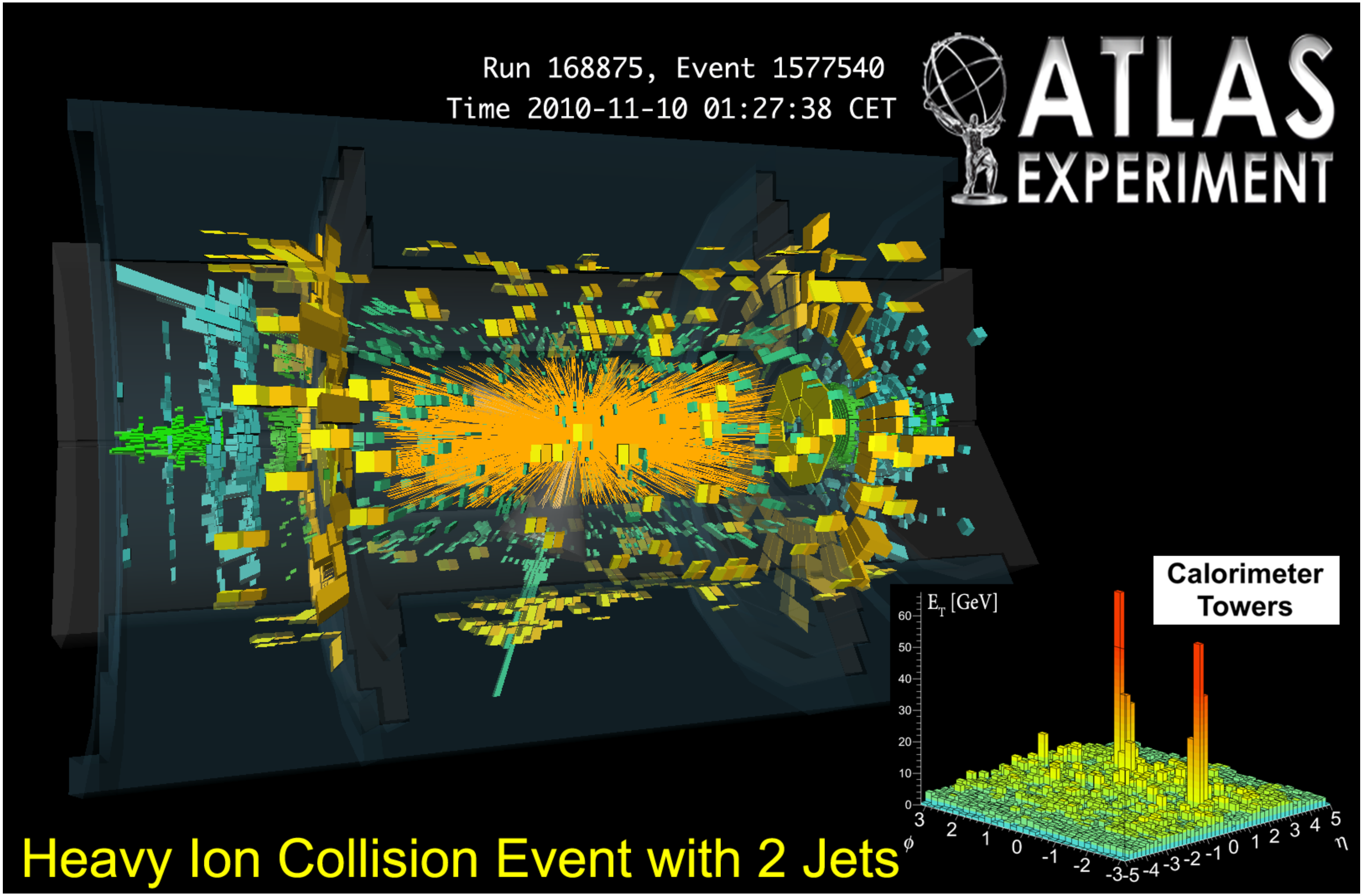
Challenge of Event Reconstruction

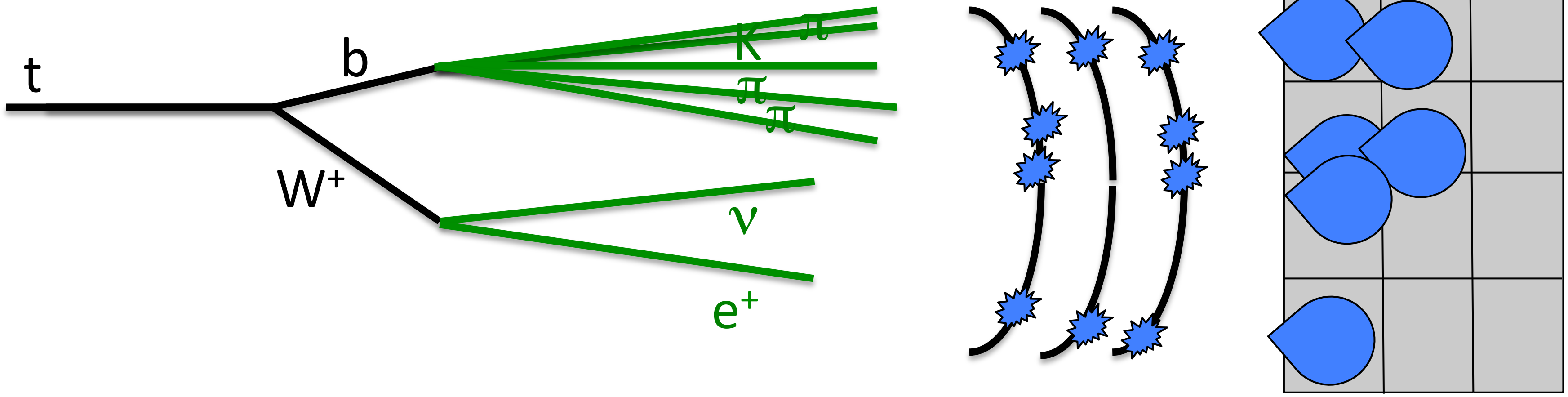


Philosophy of Event Reconstruction

"QUARKS. NEUTRINOS. MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM!"

- High-energy colliders probe interactions on tiniest spacetime scales
- But particle lifetimes limit our experimental reach
- Two parts of reconstruction:
  - Use detector hits to track and catalog particles' passage
  - Recreate final and intermediate states of interaction
- Depend on prior knowledge of particle interactions
- Practical approach: no epistemological discussions!

Forward Evolution from “Parton-Level”

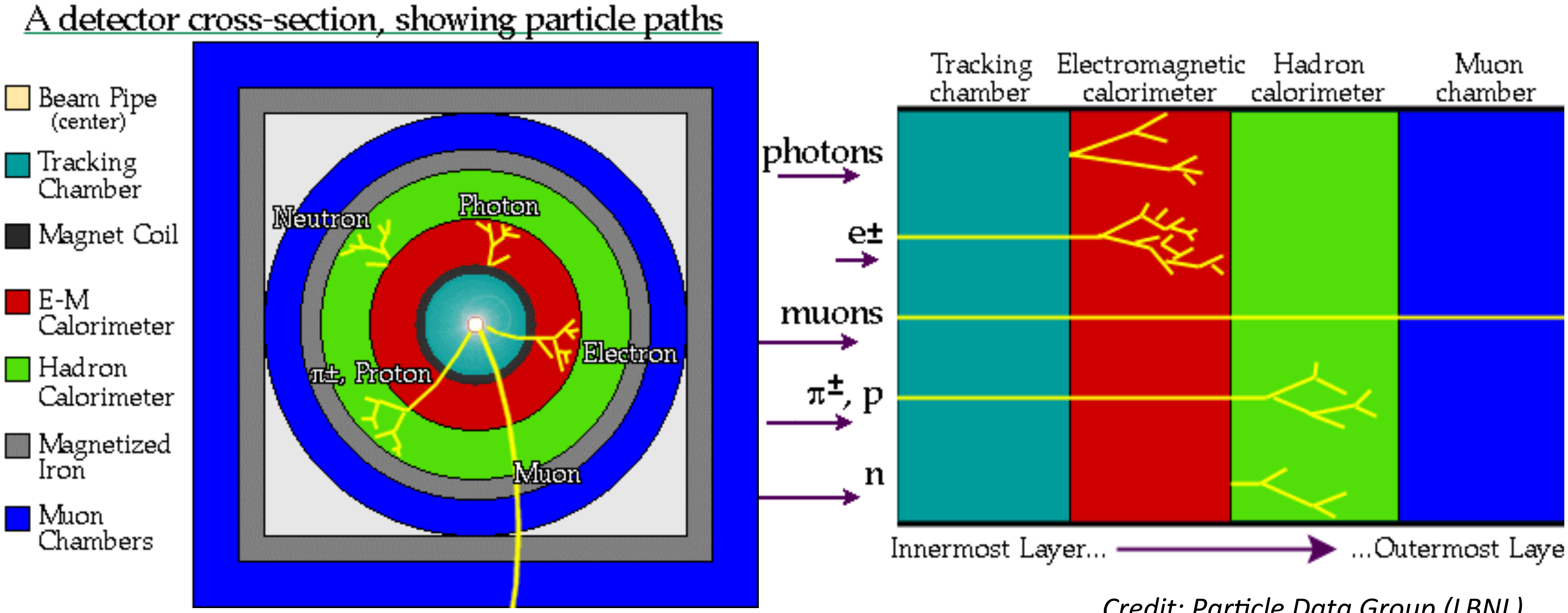


- “Parton-level” or “hard process” (in MC)
  - Typically what you see in a Feynman diagram (“quarks and leptons”)
  - Time evolution through radiation and hadronization to reach…
- “Particle-level” (or “hadron level”) (in event generators)
  - Color-neutral final state particles that reach detector material
  - These particles may or may not create…
- “Detector-level” hits in tracking detectors and calorimeters
  - These are specific to the experiment or the simulation, including efficiency

Reconstruction from "Detector-Level"

- "Detector-Level" hits are read out from detector to storage
  - List of silicon strips on which significant charge was deposited, and possibly the amount of charge that was collected
  - List of tracker straws, and the time when the charge was collected
  - List of calorimeter cells with amount of charge collected
- Hits are translated into low-level objects used for reconstruction
  - Clusters of silicon pixel and strip hits, representing one particle's impact
  - Clusters of calorimeter cells, intended to representing one particle's deposit
  - Global translation from local coordinate systems to global coordinates
- Reconstruction algorithms combine these objects into tracks and calibrated calorimeter clusters
- Subsequent algorithms identify "physics objects" as combinations of tracks, clusters, and vertices
  - These "physics objects" are intended to match the "particle-level" constituents of an interaction

Particle Identification



Credit: Particle Data Group (LBNL)

- Charged particles leave tracks due to ionization energy loss
- Photons and electrons shower in EM calo due to bremsstrahlung
- Hadrons deposit energy in EM+HAD calorimeters
- Muons and neutrinos typically escape the experiment

Outline of these 3 Lectures

Lecture 1 (Monday): particle interactions with detector material

- Charged particle interactions at a physical level
- dE/dx, Cherenkov radiation, transition radiation, time of flight
- Examples from hadron collider experiments

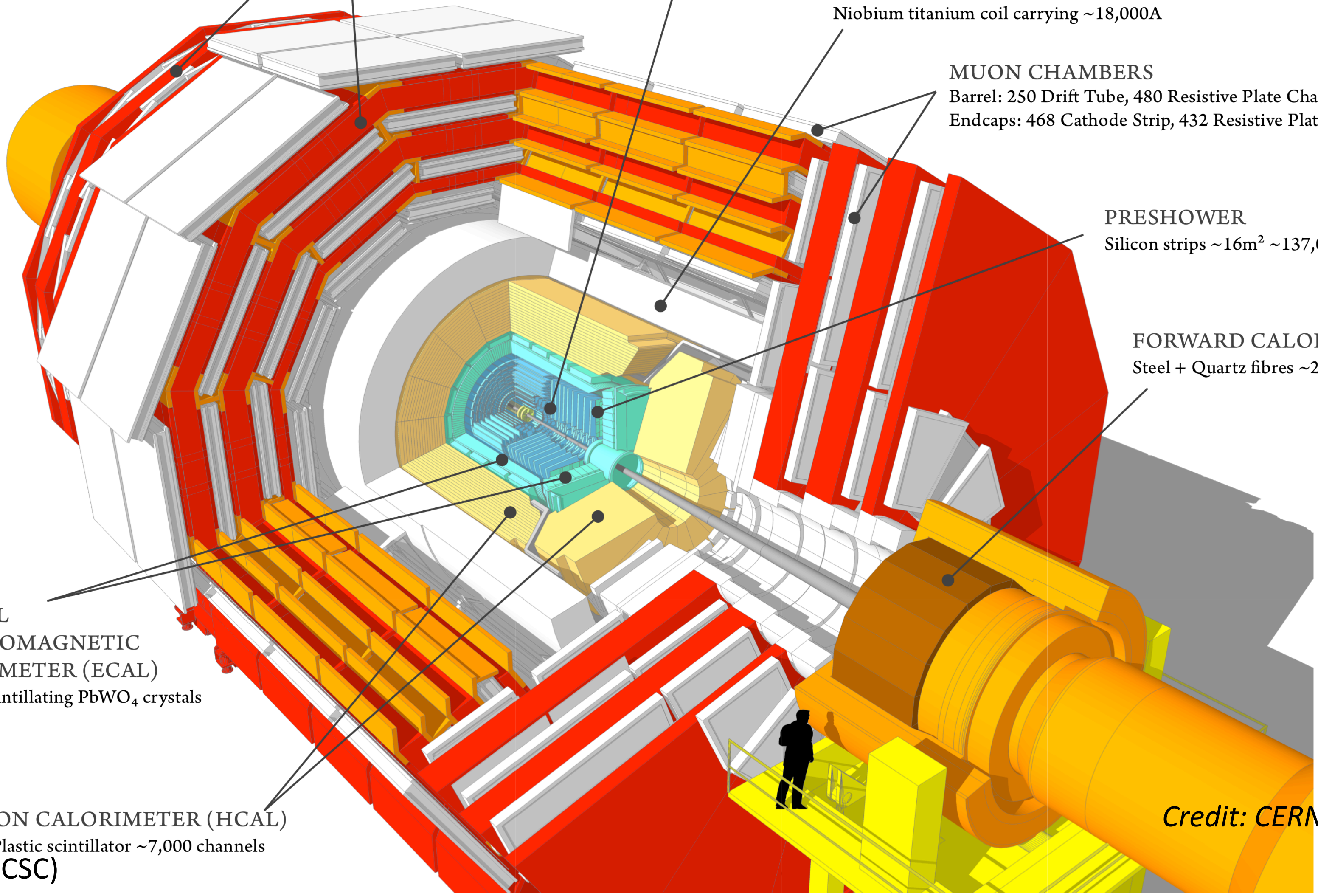
Lecture 2 (Thursday): particle identification algorithms

- Neutral particle identification
- Practical identification approaches and efficiency measurements
- Particle flow algorithms in theory and practice

Lecture 3 (Friday): advanced particle ID for complex signatures

- Jet clustering, jet tagging, missing E_T calculations
- Tau lepton identification
- W boson and top quark tagging

CMS Experiment



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm) ~16m^2 ~66M channels
Microstrips (80x180 μm) ~200m^2 ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
Silicon strips ~16m^2 ~137,000 channels

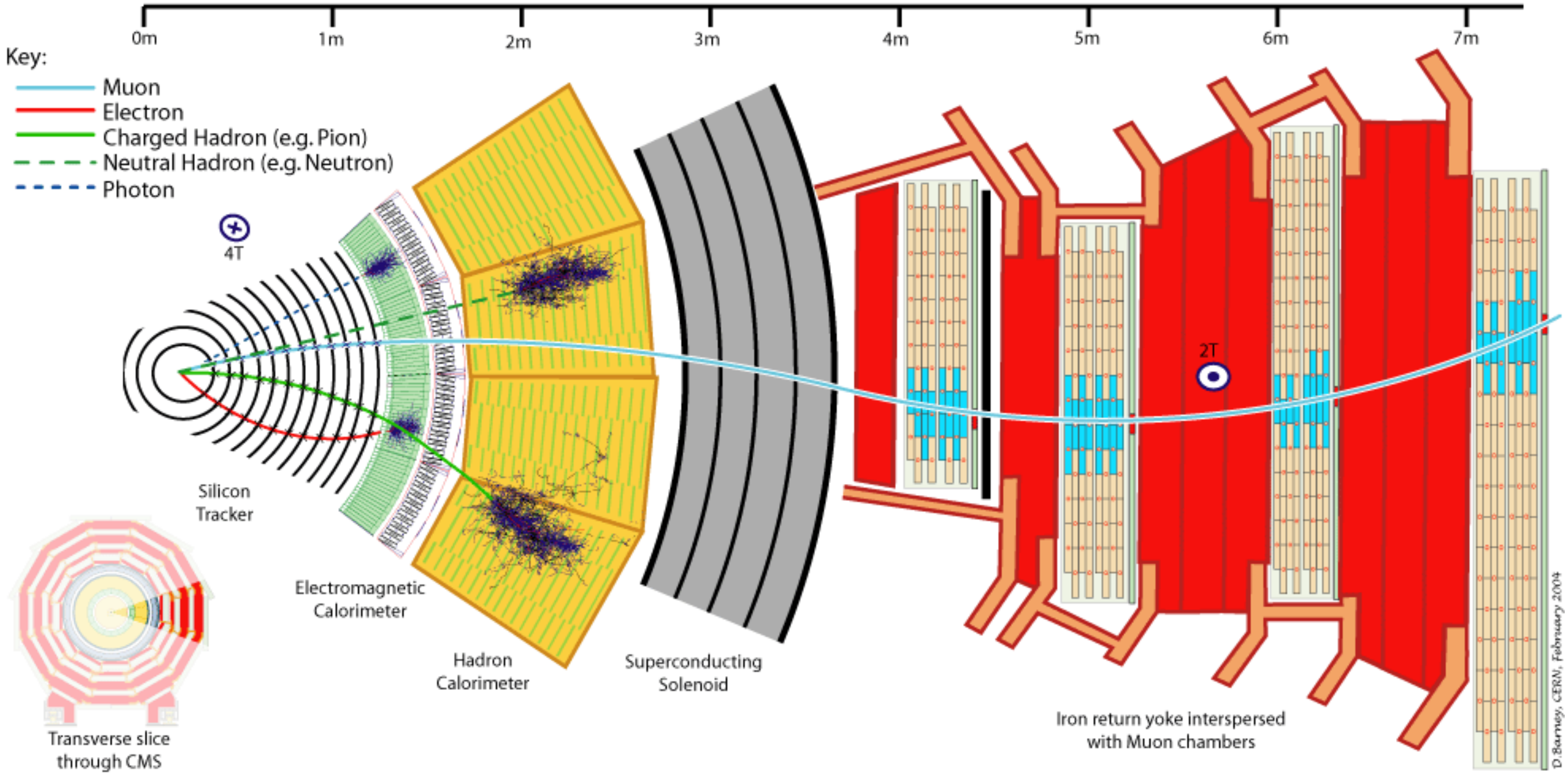
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

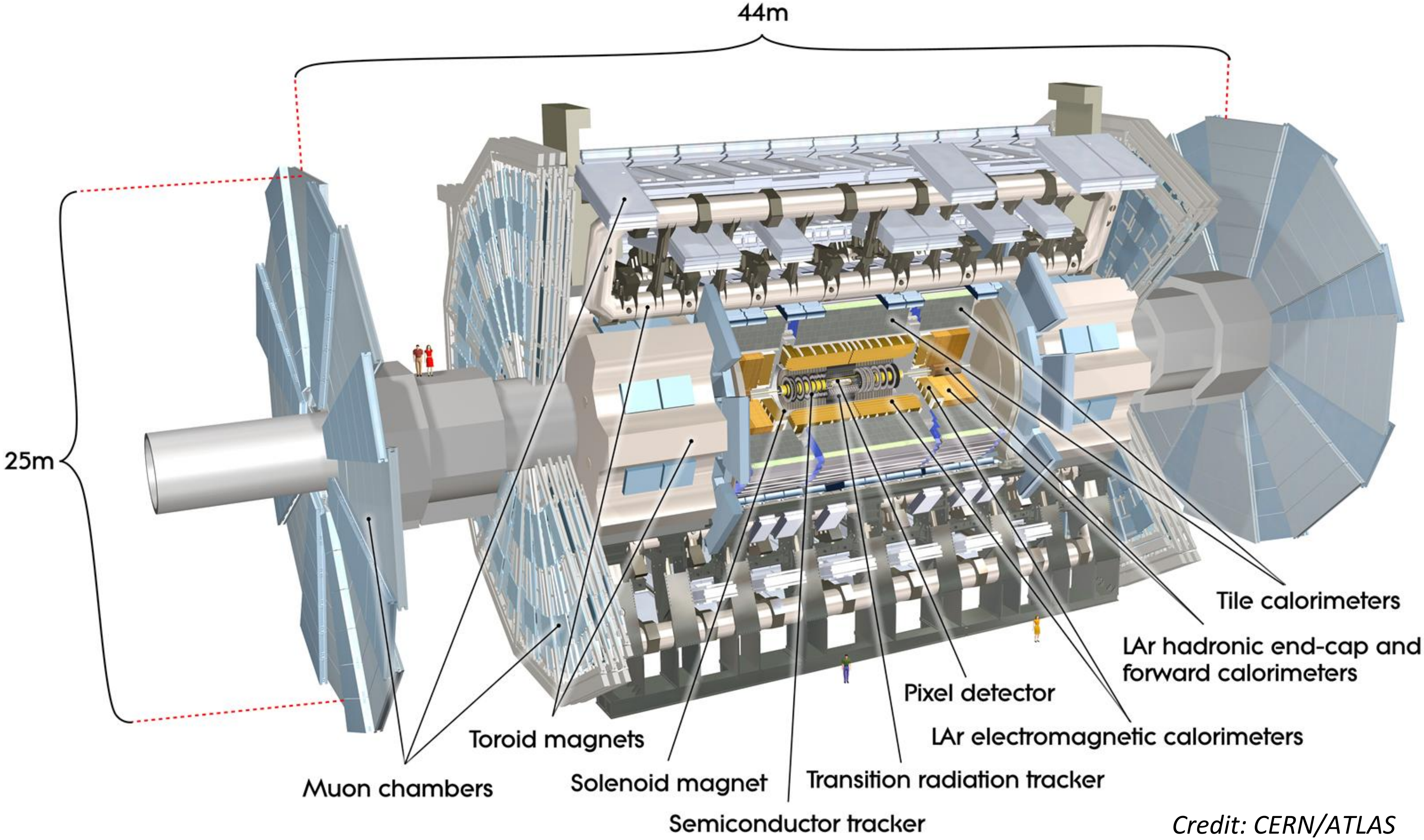
Credit: CERN/CMS

Particles' Passage through CMS



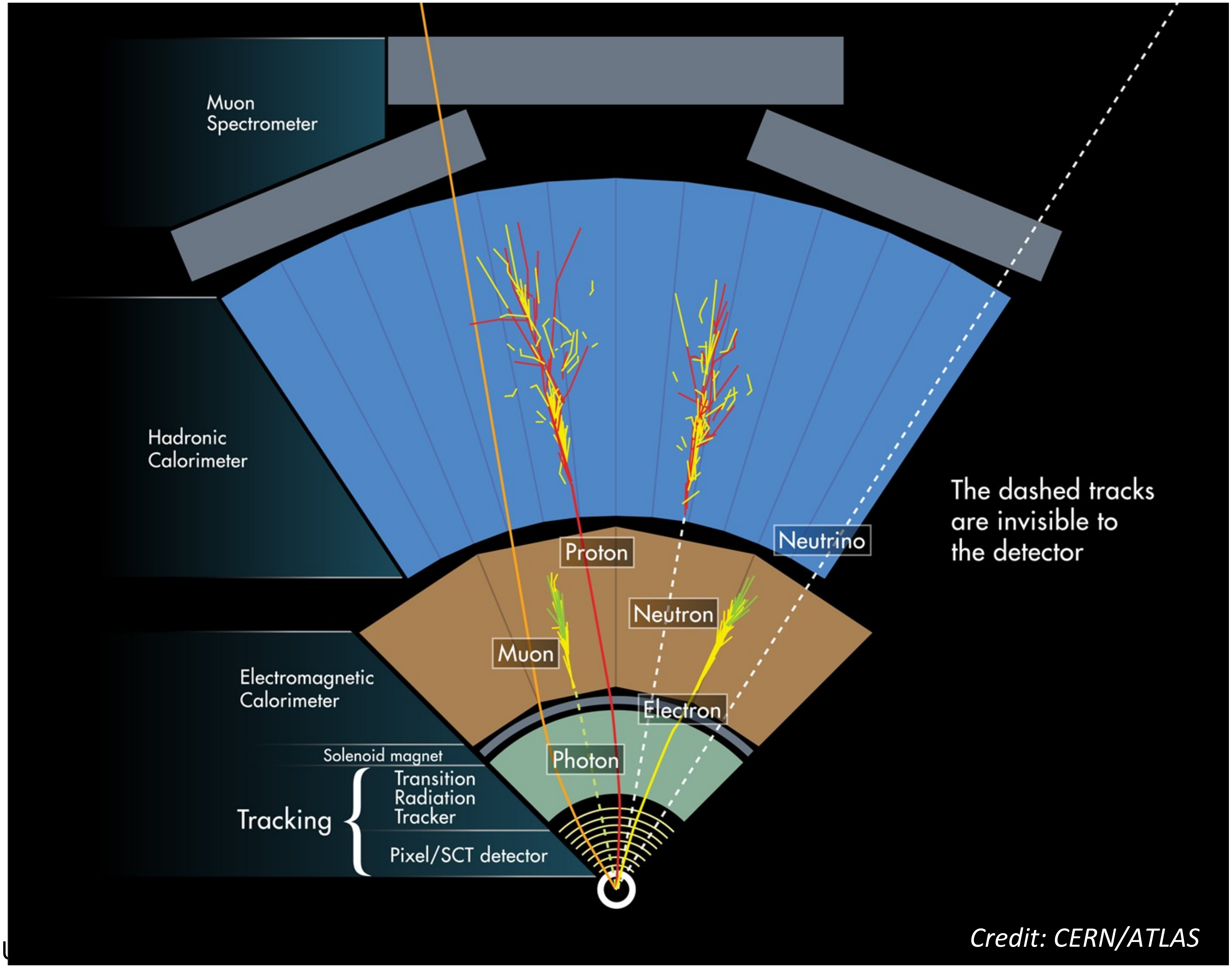
Credit: CERN/CMS/D. Barney

ATLAS Experiment



Credit: CERN/ATLAS

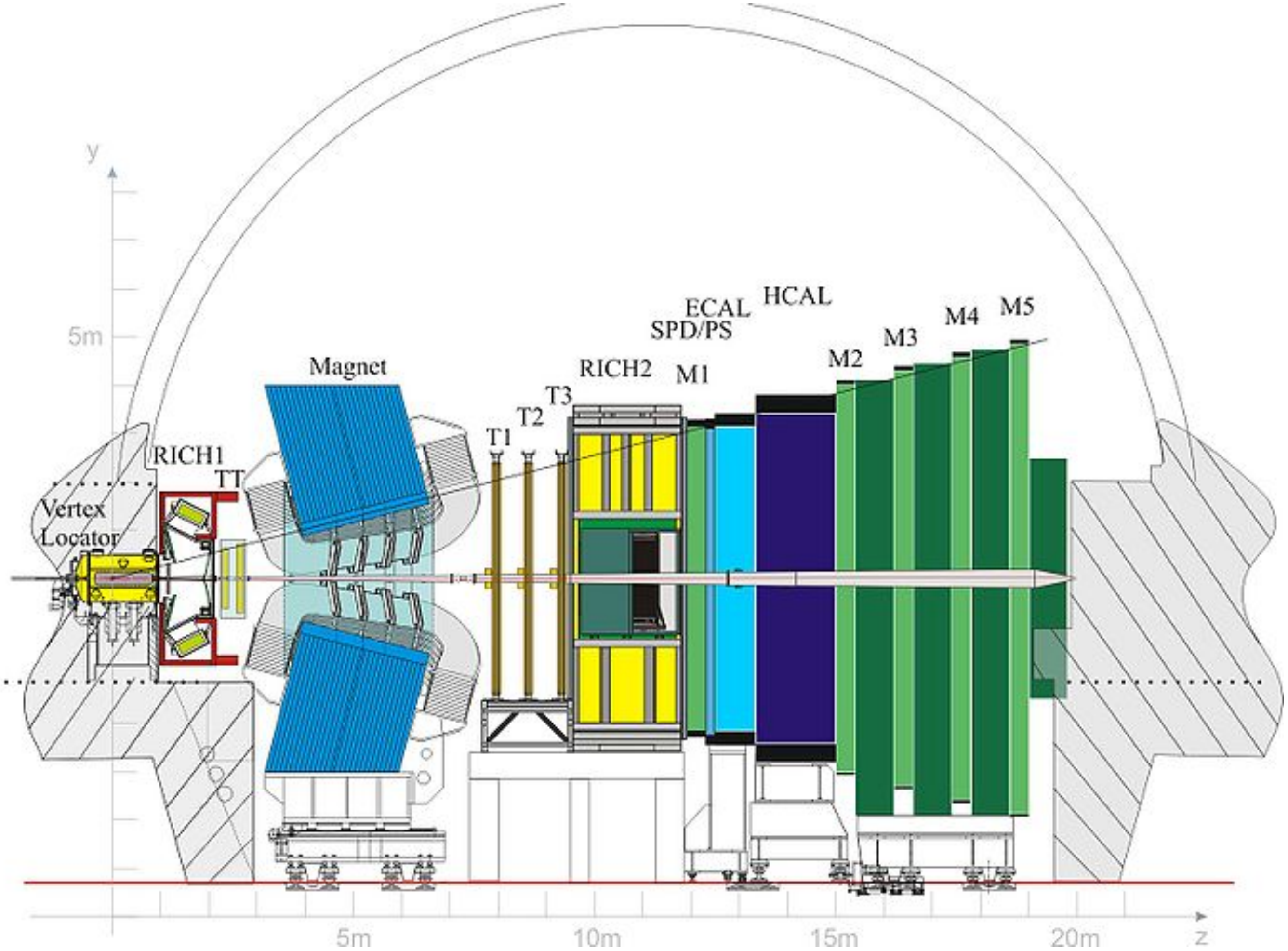
Particles' Passage through ATLAS



The dashed tracks are invisible to the detector

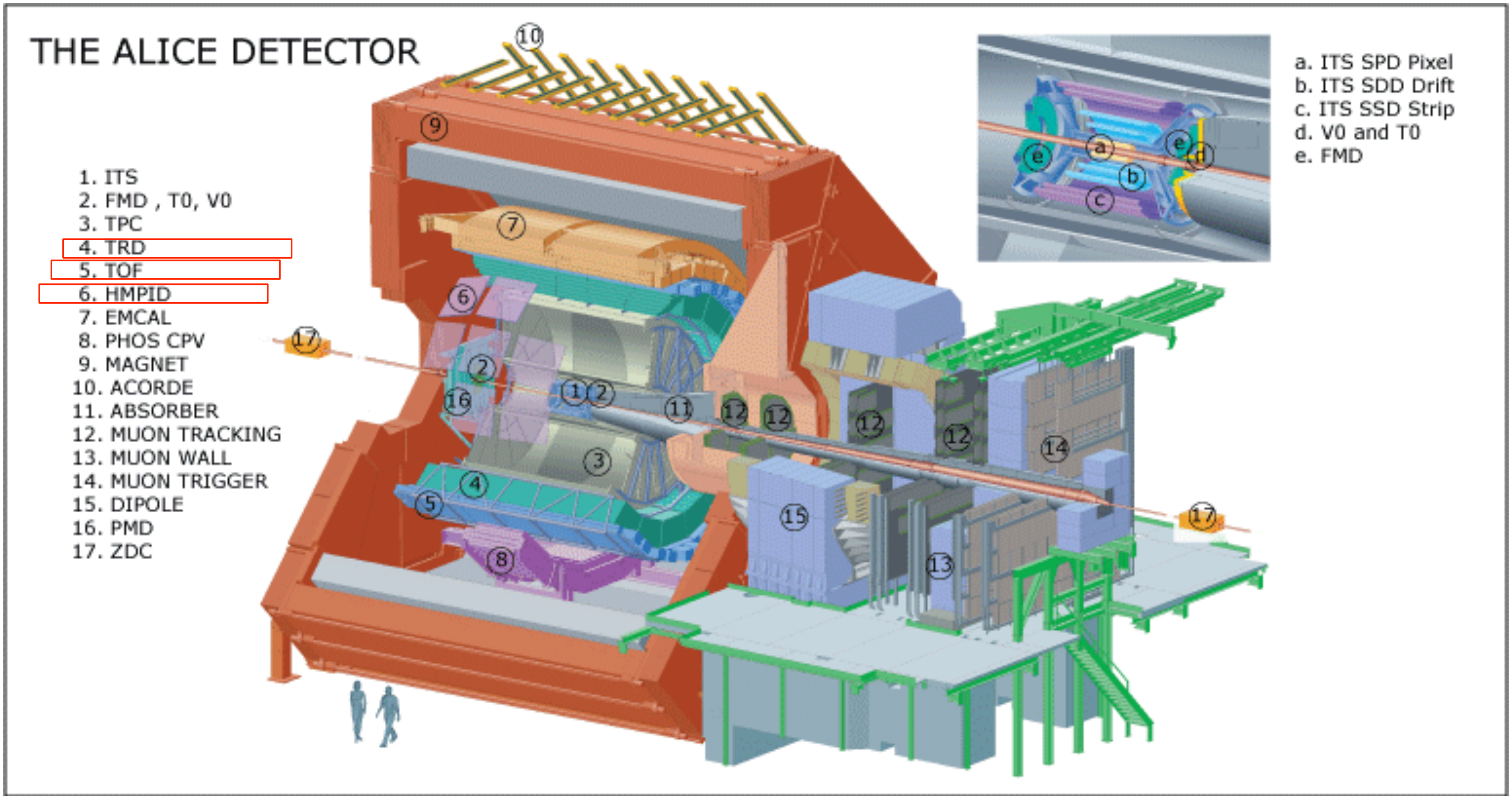
Credit: CERN/ATLAS

LHCb



Credit: CERN

ALICE



Credit: CERN

What is Particle ID?

- A particle's quantum numbers distinguish it from other particle species: electric charge, weak hypercharge, spin, mass
- For the most part, our particle ID differentiates particles based on their mass, which is unique to each charged particle species!
  - Electrons vs. muons (essentially the same quantum numbers, except for m)
  - Pions vs. kaons vs. protons
  - Many of the interaction differences are in fact just mass differences
- Typical detector measurements focus on energy or momentum
  - Momenta of charged particles in magnetic spectrometer
  - Energy of particles in destructive calorimeter measurements
- Special consideration is needed to infer the particle mass
  - Could depend on full knowledge of 4-momentum
  - Could consider interactions that are especially sensitive to the velocity of relativistic particles or the related Lorentz γ factor

Outline for Today

- Today: focus on charged particle identification via radiative energy loss mechanisms associated with electromagnetic interactions
  - All of these approaches are sensitive to particle's β or γ factors
  - All have been used in hadron collider experiments for purposes of PID

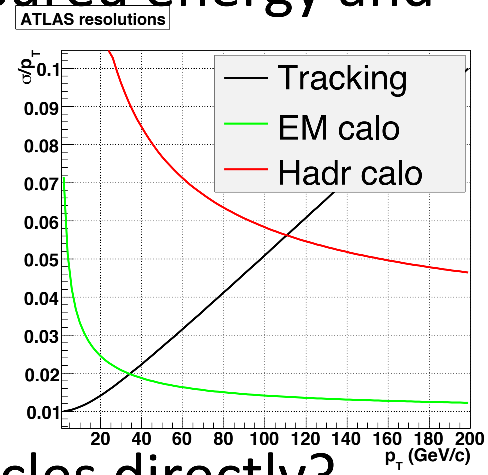
- Ionization energy loss through interactions with atomic electrons in material: "dE/dx"
- Cherenkov radiation from superluminal particles: particle counting and angular measurements
- Transition radiation emitted as particles pass through a boundary between materials with different refractive indices
- Time-of-Flight (TOF) measurements and technical challenges

Particle ID via Energy & Momentum

- If the goal is to calculate m, why not use the measured energy and momentum?

$$\delta(m) = \frac{1}{2}\sqrt{(2\delta E)^2 + (2\delta p)^2}$$

  - Energy resolution is not good enough at low E
  - Momentum resolution is not good enough at high p
  - Remember that we need mass resolution < 100 MeV



- Or what about measuring the velocity of the particles directly?
  - Rewrite defn. of γ to find

$$\beta = \frac{1}{\sqrt{\left(\frac{mc}{p}\right)^2 + 1}} \quad \text{and} \quad \beta = \frac{v}{c} = \frac{L}{tc} \quad \text{to give} \quad m = \frac{p}{c}\sqrt{\frac{c^2t^2}{L^2} - 1}$$

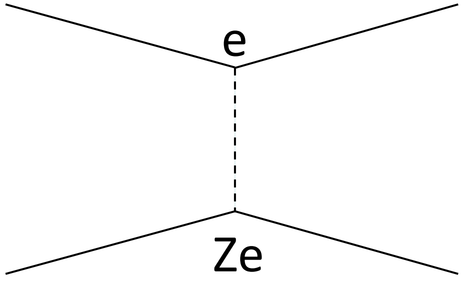
- We will return eventually to the Time-of-Flight measurements, acknowledging the strict requirement on timing resolution δt/L

Charged Particle Energy Loss

- Three main mechanisms for energy loss from relativistic particles
- “dE/dx”: ionization energy loss w/ virtual photons absorbed
  - In non-relativistic region, rate of energy loss falls as $1/\beta^2$
  - In relativistic regime ($\beta\gamma>4$), energy loss rises as $\ln(\beta\gamma)$
  - Measurement of energy loss sum can be converted to measurement of $\beta\gamma$
- Cherenkov radiation: real photons emitted at characteristic angle
  - Emission occurs at all frequencies (energies) democratically
  - Angle of emission can be converted to measurement of β
  - Becomes more difficult to separate particle types as β approaches 1
- Transition radiation: real photons emitted at interface
  - Energy of the photons depends directly on $\beta\gamma$
  - Small number of photons emitted: α photons per transition
  - TR saturates at some γ_{max} dependent on distance between interfaces

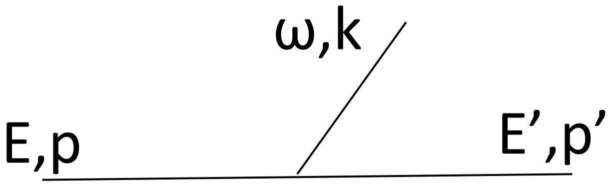
Electromagnetic Interactions Dominate

- Charged particle interactions dominated by electromagnetic interactions (large cross section process)
  - Electromagnetic vs. weak force couplings, atomic cross section
  - Strong interaction range is too short, limited to nuclear cross section
- For the purposes of energy loss in detector material, we consider the cross section of a charged particle scattering on atom
  - Scattering from charges in the nucleus
  - Emitted (virtual) photons from the fields of the charged particle are most often absorbed by atomic electrons



- Happy conclusion: soft EM interactions deposit enough energy in detector but do not (usually) affect the particle's momentum vector

Soft Electromagnetic Interactions



- Emission of photons in a dispersive medium, characterized by $\mu\epsilon = n^2$

$$E = E' + \omega \quad \text{and} \quad p = p' + k$$

so that $\omega = v \cdot k$

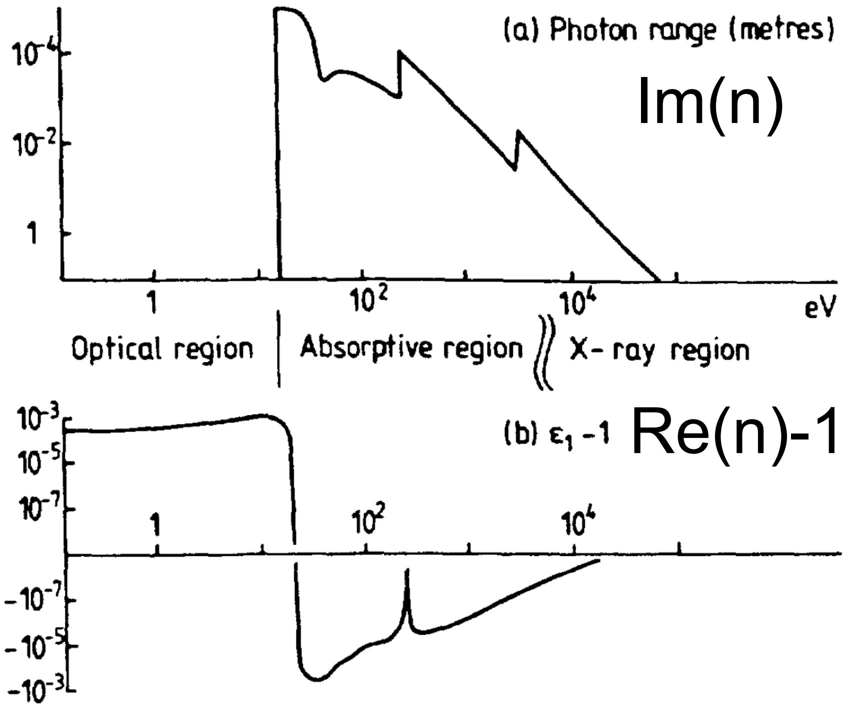
- Dispersion relation in real material $k^2 = \mu\epsilon \left(\frac{\omega}{c}\right)^2 \left[1 - i\left(\frac{4\pi\sigma}{\omega\epsilon}\right)\right]$
  - A material with free electrons ("plasma") has imaginary σ.
  - Photons with $\omega > \omega_p$ have real k, satisfy wave equation, and can propagate.
  - Otherwise there is a damping term, characterized by skin depth
- Gives rise to two kinds of radiation by charged particles
  - Real emission is Cherenkov radiation
  - Virtual emission (with damping) can still interact with atoms in material

Energy Loss and Emitted Radiation

- Dispersion relation recast in terms of refractive index n (or ε)
  - Frequency-dependent behavior
- At frequencies below the absorption region, n>1 and medium is transparent: optical
- In the absorption region, imaginary part is large, and range is short (dE/dx ionization energy loss)
- At high frequencies (X-ray), there is little absorption, and n<1. Some emission can still occur: TR

$$k^2 = \mu\epsilon\left(\frac{\omega}{c}\right)^2\left[1 - i\left(\frac{4\pi\sigma}{\omega\epsilon}\right)\right]$$

$$n = \frac{w}{k}$$



Argon at normal density (*Allison & Wright)*

Spectrum of Energy Loss: dE/dx

- Elastic collisions of relativistic particles with atomic electrons
- Usually expressed as the mean energy loss: <dE/dx>
- Each scatter transfers to target

$$\Delta\epsilon \sim \Delta p_T^2/2m \sim (2\alpha/bv)^2/2m$$

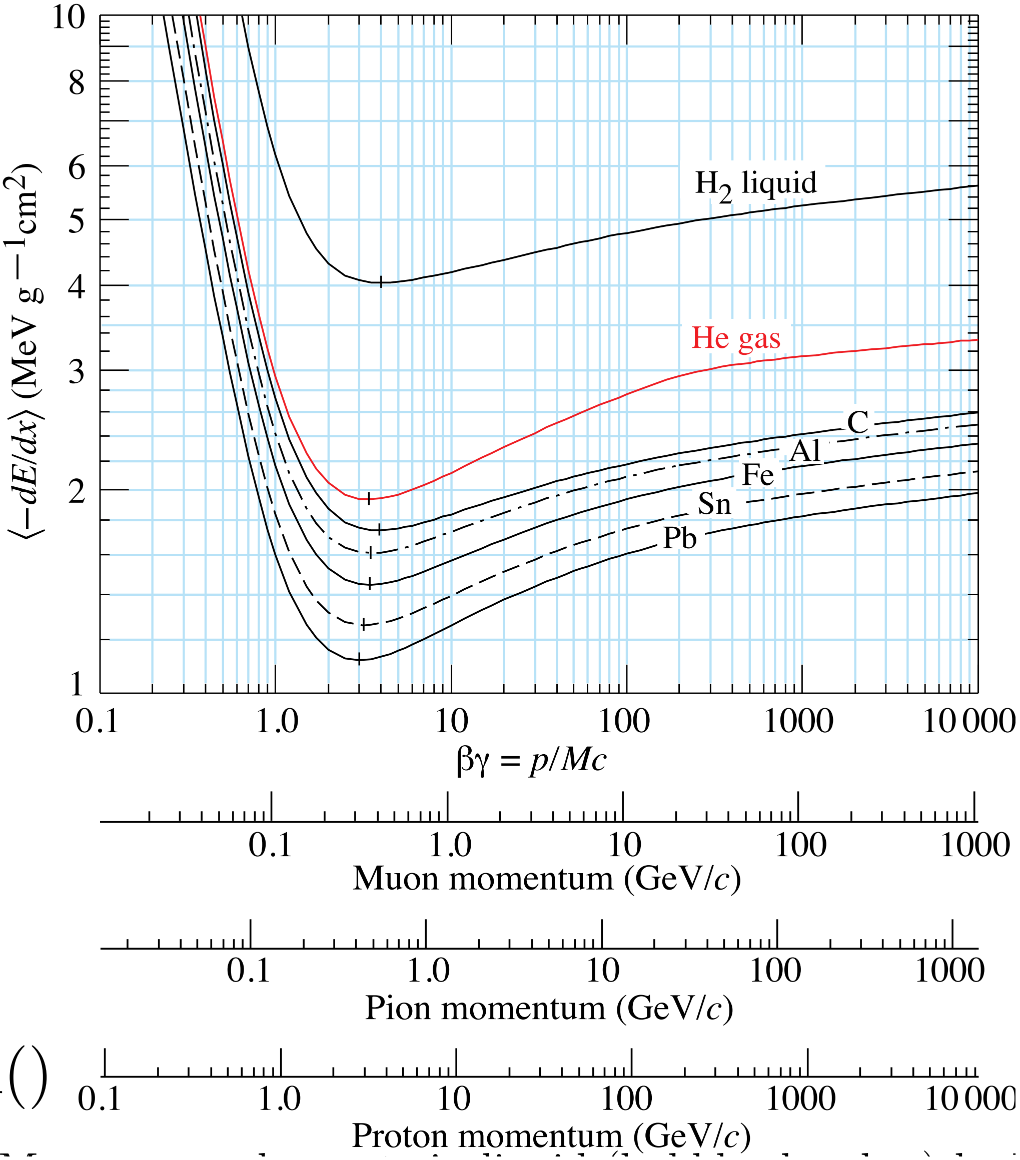
- Integrate over impact param.

$$d\epsilon \sim \frac{\alpha^2}{mv^2}\left[\ln(b_{\max}/b_{\min})\right]$$

- Sum over all collisions

$$\frac{dE}{d(\rho x)} \sim \left(\frac{NZ}{A}\right) d\epsilon \qquad \text{or}$$

$$\frac{dE}{d(\rho x)} \sim \left(\frac{NZ}{A}\right) \alpha^2 \lambda_e \left(\frac{1}{\beta^2}\right) \ln()$$

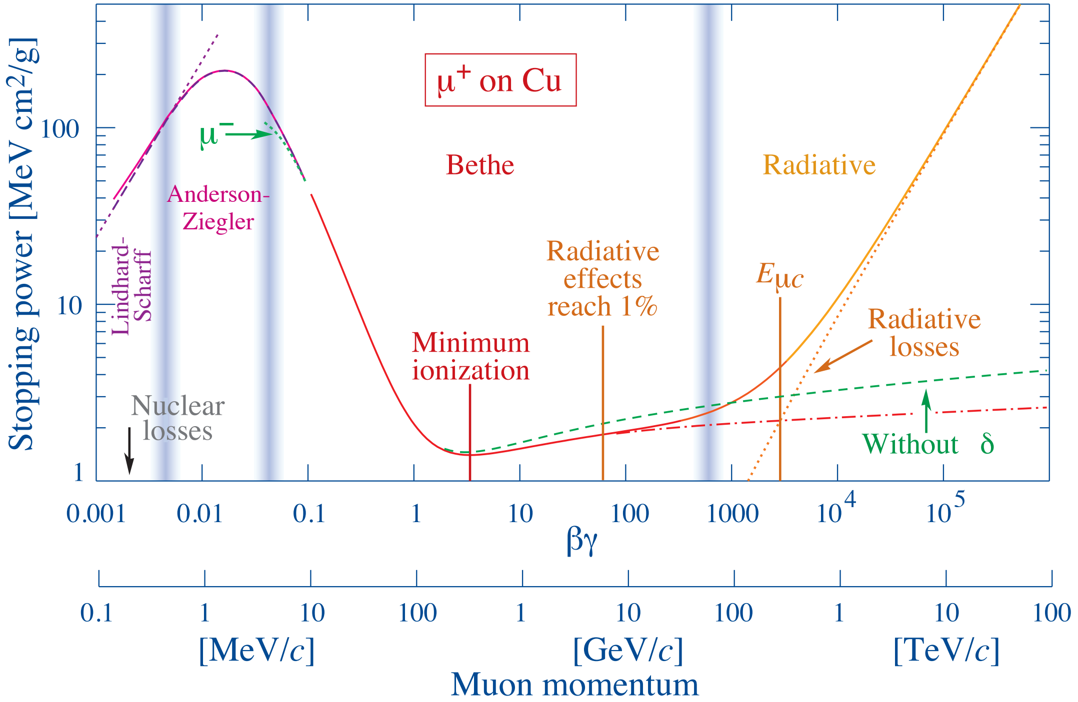


Bethe-Bloch Calculation

- Full quantum mechanical calculation is found in many places

$$\langle dE/dx\rangle \sim \frac{ze}{\beta^2}\left(\ln\frac{\sqrt{2m_ec^2E_{\max}}\beta\gamma}{I}-\frac{\beta^2}{2}-\frac{\delta}{2}\right)$$

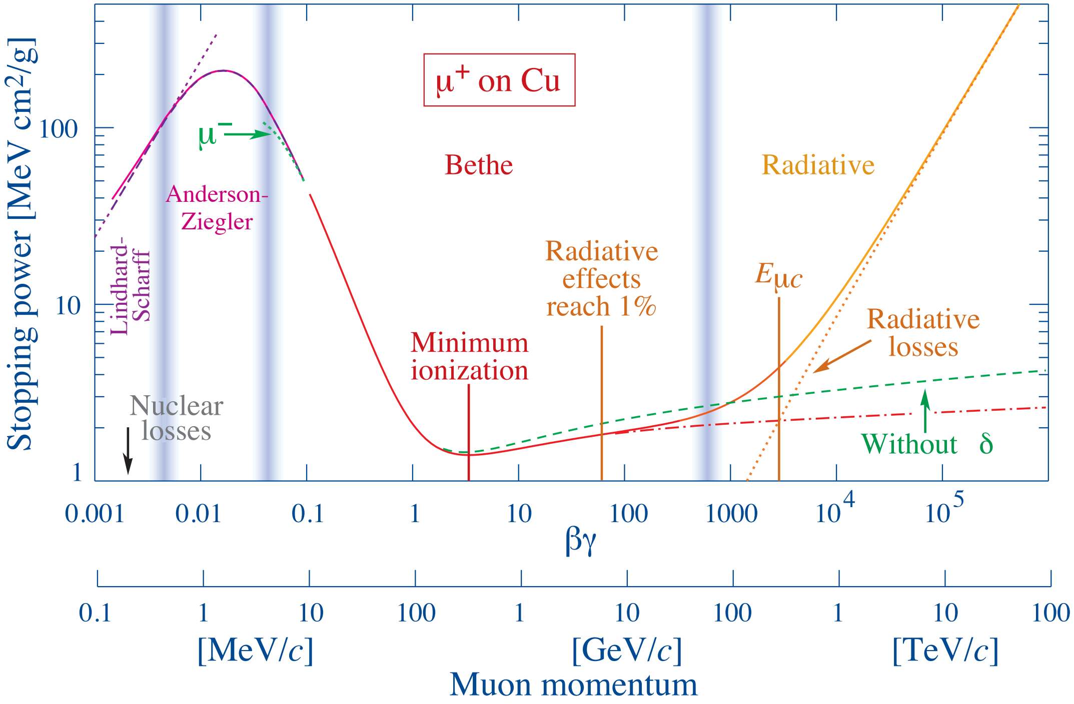
- Note the logarithmic rise with γ (relativistic rise) and the density effect correction (dependent on βγ)



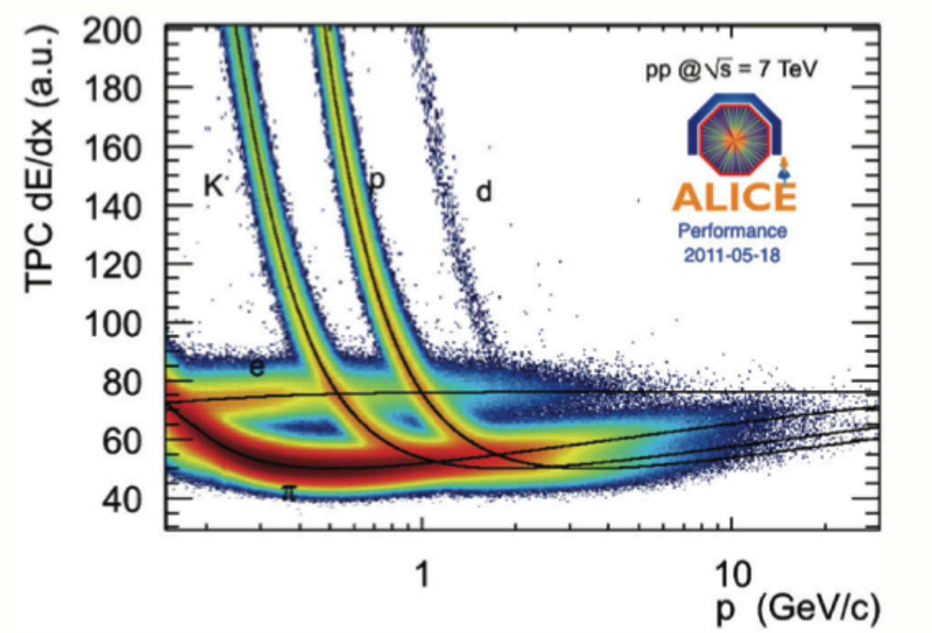
- Bethe regime: ionization energy loss dominates
- Strong dependence on b, weak dependence on γ
  - Limited at high γ
  - Useful for PID when βγ <≈ 3
- At very high βγ, radiative energy losses dominate

Minimum Ionizing Particles

- According to simplified form $dE/d(\rho x) \sim 1/\beta^2$, minimum mean energy loss <dE/dx> occurs at $\beta=1$ (ignoring relativistic rise)
  - Typical rules-of-thumb: 1.5 MeV/(g/cm^2) for Z/A=1; muon loses 1.2 GeV/m in a thick iron absorber like the CMS return yoke or the ATLAS TileCal
- Ionization energy loss remains roughly constant at high momentum
- MIP serves as standard candle for detector design
  - Energy transferred to atomic electrons, inducing charge in detectors
- Ensure sufficient signal by using dense materials
  - Subject to limitations on scattering angles



dE/dx in Gaseous Detectors



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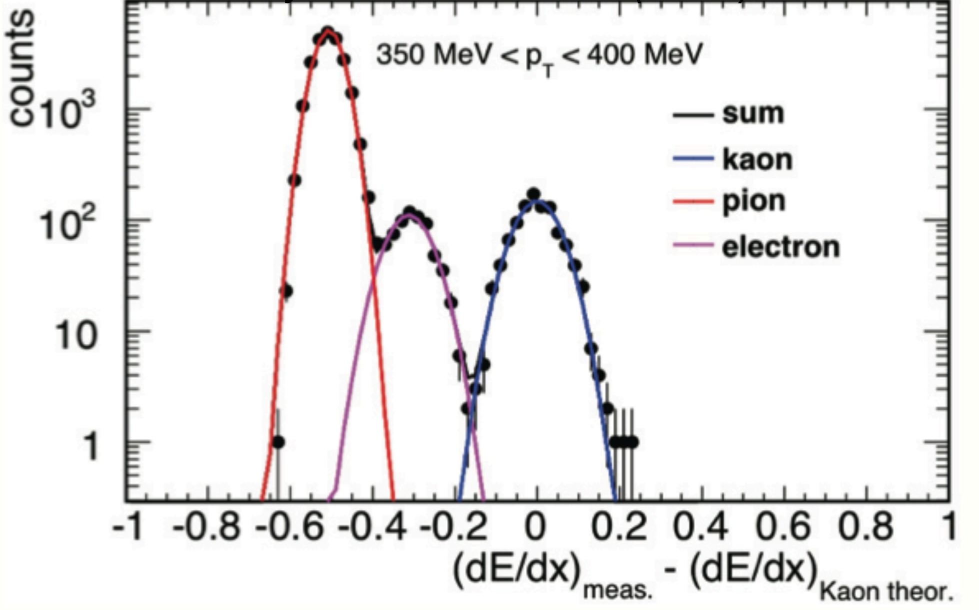
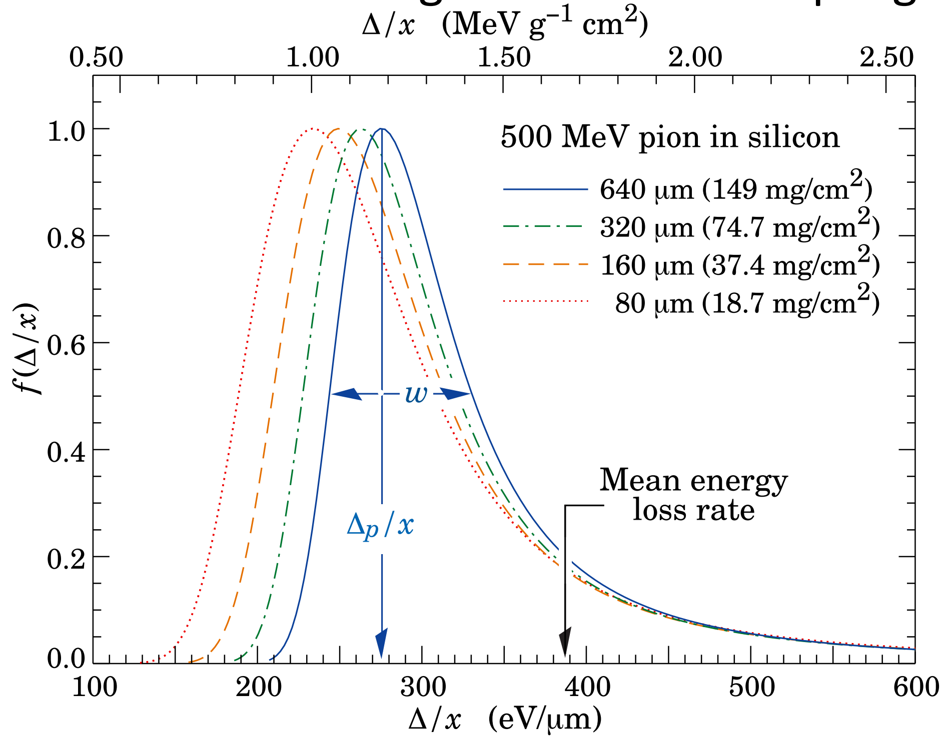
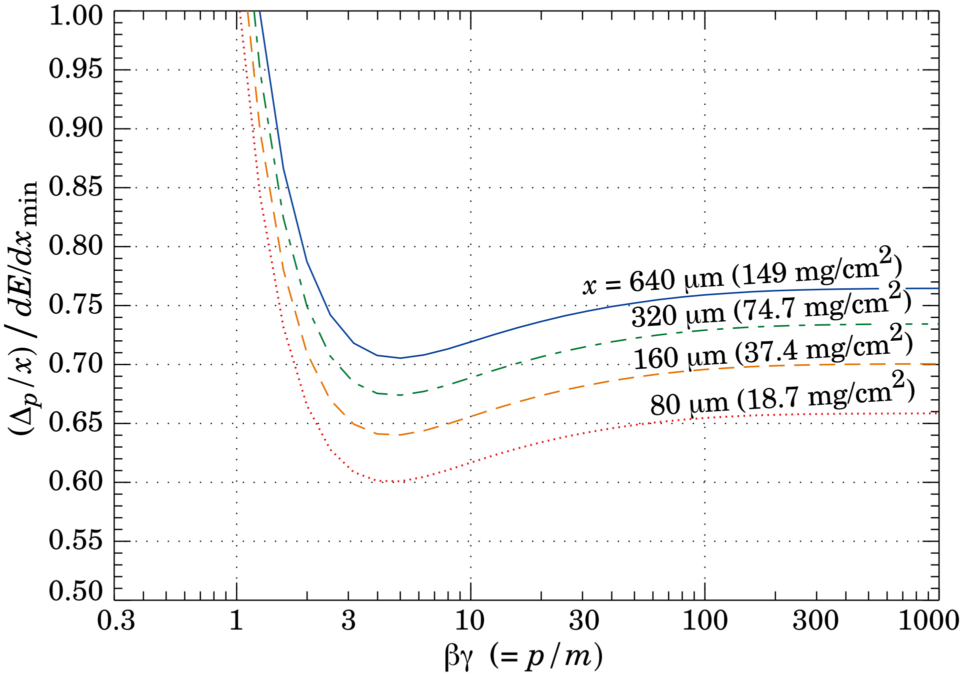


- Must assume that total ionization is proportional to energy loss
- Large number of measurements ensures good dE/dx resolution
  - ALICE TPC samples ionization up to 159 times for each track
  - Mean free path for relativistic particles is approx. 300 μm in Ar
- Calibrated energy loss distributions allow effective measurement of βγ for each particle, combined with p to allow PID

dE/dx in Silicon Detectors

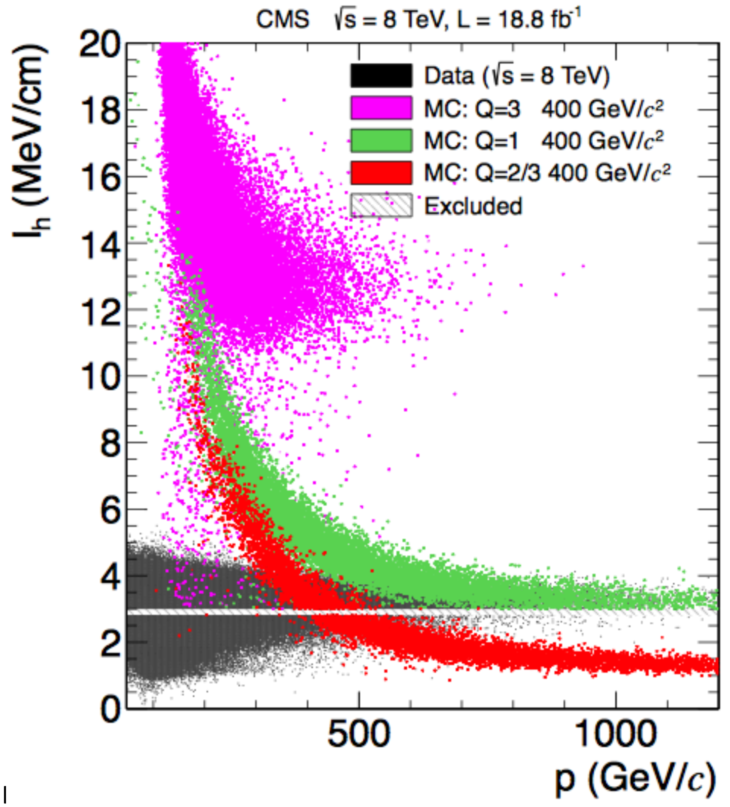
- Band gap in silicon is only 3.6 eV, so many more electrons are produced than in gaseous detectors, but usually fewer samplings
- Characteristic Landau distribution of energy loss
  - 90% of collisions result in energy loss less than the mean (<dE/dx>)
  - Most Probable Value of energy loss is more commonly used for calibration
  - Need a large number of sampling to approach the distribution

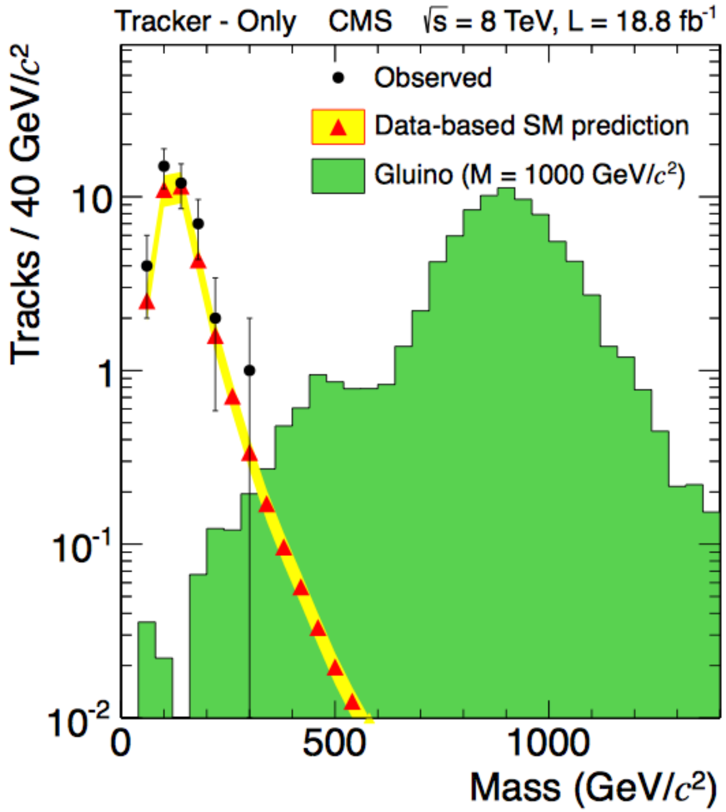




Example of dE/dx in New Particle Searches

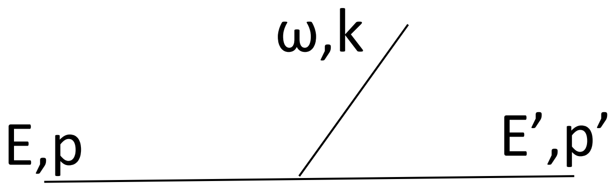
- CMS search for heavy stable charged particles (HSCP/CHAMP)
  - Could be a new lepton with q≠1e and coupling only through U(1)
- Two striking detector signatures for these particles
  - Long time of flight, as measured with CMS muon system (skip for now)
  - If charge is unusual (i.e. ≠1e), then anomalous dE/dx measurements





Cherenkov Radiation

- Fields of charged particle interact with dispersive medium (n≠1)
  - Instead of Huygens construction, try alternative particle-based derivation



$$E = E' + \omega \quad \text{and} \quad p = p' + k$$

so that $\omega = v \cdot k$

  - Dispersion relation gives $k^2 - \frac{n^2\omega^2}{c^2} = 0 \rightarrow k = \frac{\omega n}{c}$
  - And then the angle is defined by $\frac{k}{n} = \beta k \cos\theta_c$

$$\cos\theta_c = \frac{1}{n\beta}$$

  - In this Cherenkov regime (low energy), the permittivity ε is real, and so is n. (This is not true for dE/dx.) If v<c, then no radiation *in continuous medium*.
  - Note that photons are *effectively* constrained to this angle of emission

Cherenkov Radiation: Frequency and Direction

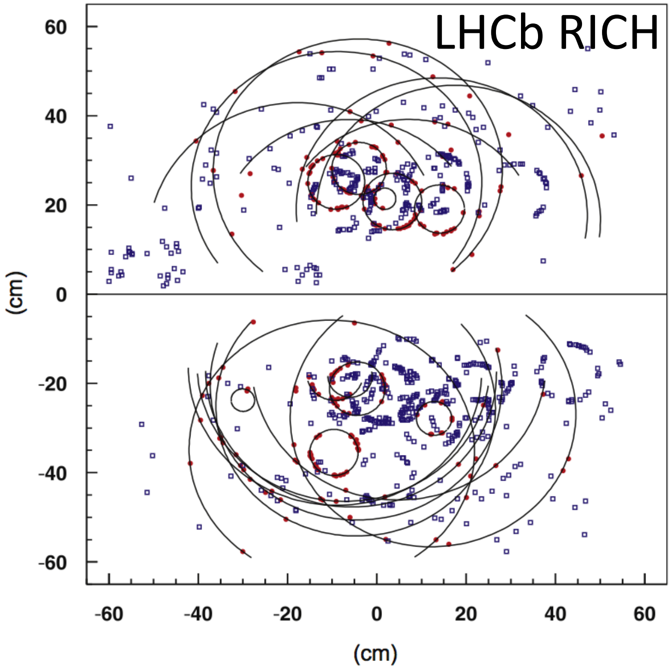
- Both frequency and direction are set by the particle β, index of refraction, and length of radiator (full derivation in Green's book)

$$\frac{d^2 N_c}{d\omega d\cos\theta} = \frac{\alpha}{c}\left(\frac{\sin\delta}{\delta}\right)^2 \sin^2\theta \frac{L^2}{\lambda}$$

  - Where δ is phase difference (Fraunhofer) $\delta = \left(\frac{1}{n\beta} - \cos\theta\right)\frac{\pi L}{\lambda}$
  - If the radiator length L is long, then (sinδ/δ) gives a delta function at a single characteristic Cherenkov angle; otherwise there is a spread in cosθ.
- Other relations
  - Cherenkov angle $\theta_c \sim \frac{1}{\gamma^2_{\mathrm{threshold}}} - \frac{1}{\gamma^2}$
  - Maximum Cherenkov angle $\theta_c^{\mathrm{max}} = 1/\gamma_{\mathrm{threshold}}$
  - Maximum number of photons $N_c^{\mathrm{max}} \sim 1/2\gamma^2_{\mathrm{threshold}}$

Practical Cherenkov Detectors

- Cherenkov detector fall into two main classes:
  - Threshold detectors: measure intensity (number) of particles above some β
  - Imaging detectors: measure angles of emitted photons, in addition to number
  - Both types have been used in LHC experiment (following pages)
- Ring-Imaging Cherenkov detectors focus photons emitted in radiator
  - Photons with common emission angle form rings on focal plane



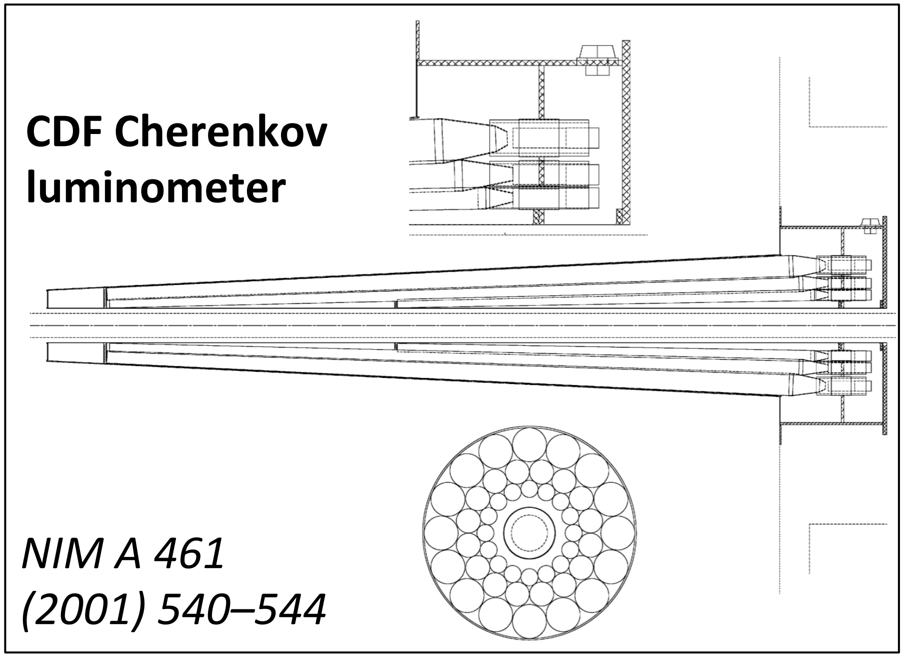
- Challenge to reconstruct overlaps
- Separation power between particles:

$$P_{\theta_c} = \frac{c^2}{2p^2 \langle \sigma_{\theta_c} \rangle \sqrt{n^2 - 1}} \left| m_1^2 - m_2^2 \right|$$

  - This favors ultra-low n radiators (high-temperature gases and even aerogel)

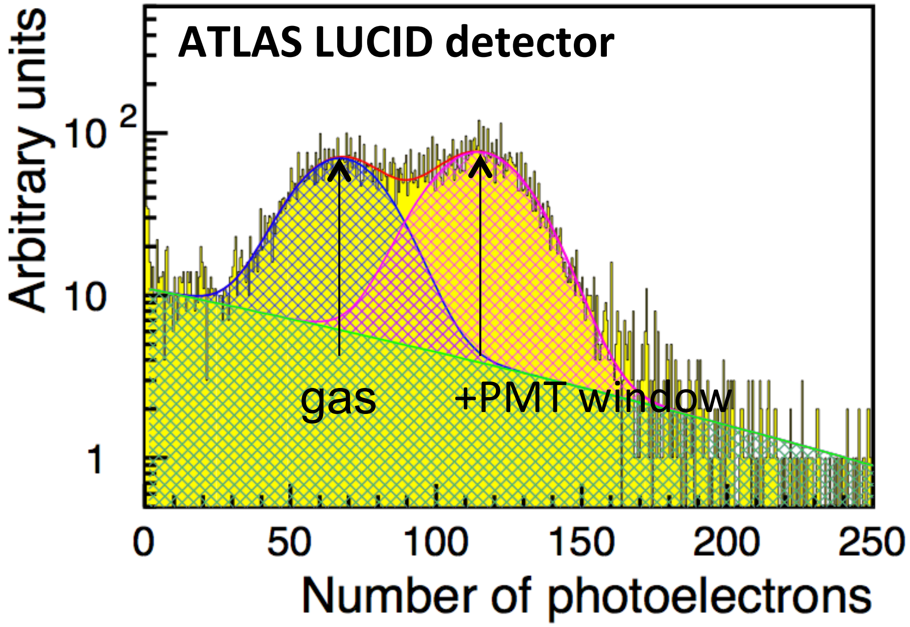
Cherenkov Detectors for Counting

- Particles with $\beta>1/n$, above Cherenkov threshold, yield a narrow single-particle peak in the light output (no Landau fluctuations)
- Number of particles can be translated to number of interactions per bunch crossing and then to inst. luminosity
- This approach is limited by saturation of the counter occupancy



CDF Cherenkov luminometer

NIM A 461 (2001) 540–544

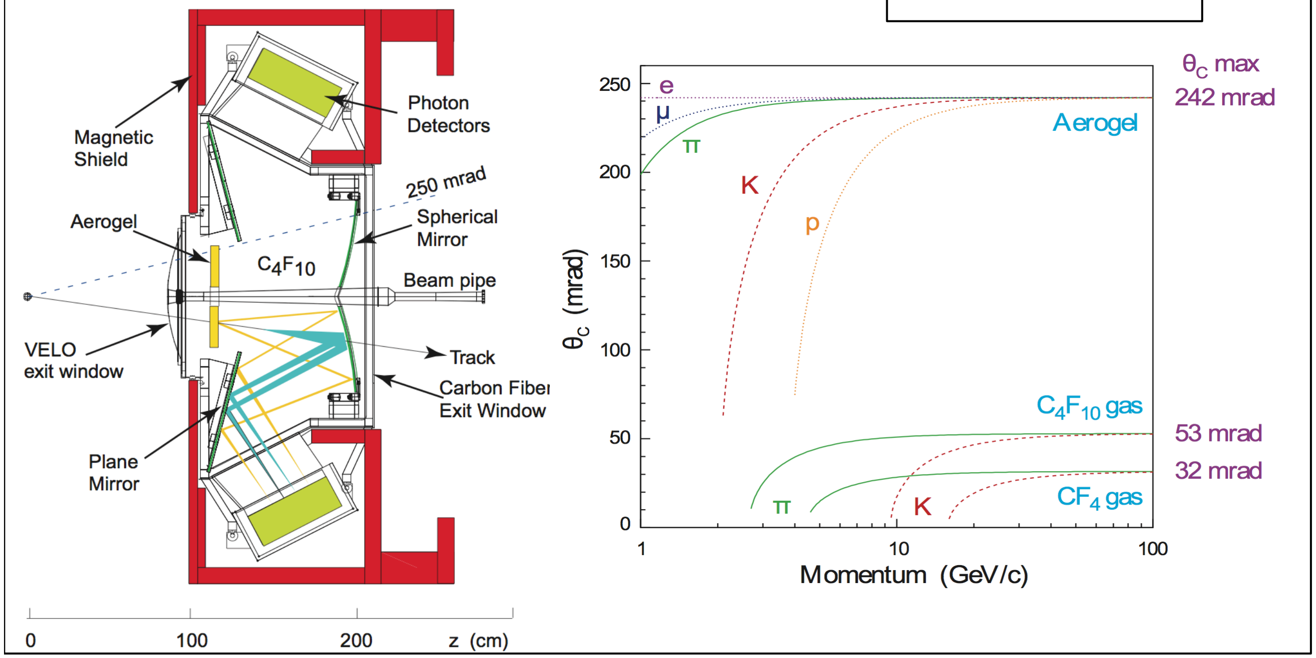


ATLAS LUCID detector

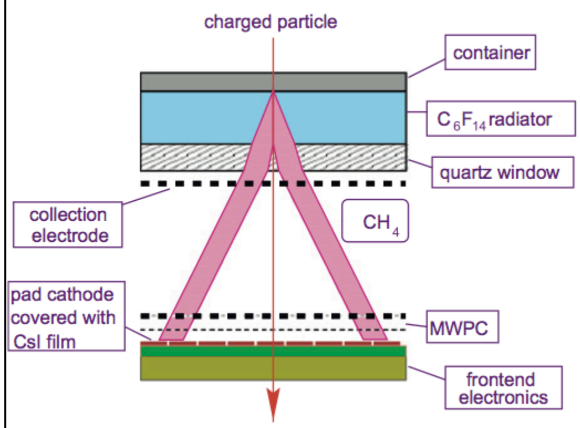
Cherenkov Detectors for PID

- Ring Imaging Cherenkov detectors measure number of photons and Cherenkov angle, from which mass is calculated
  - Special optics focus all photons emitted at a common angle to a point
- K/π separation over a wide momentum range (up to 50 GeV)
  - Separation at high momentum requires very small n: $\cos\theta_c = 1/\beta n$

LHCb RICH



ALICE HMPID

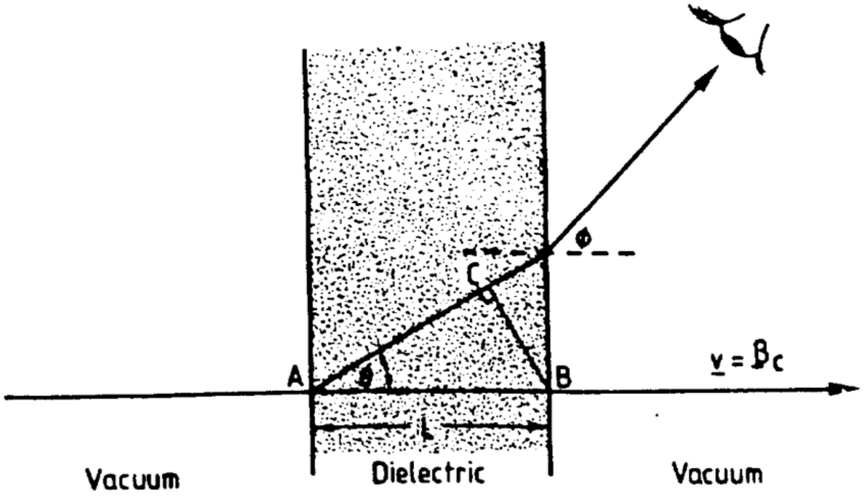


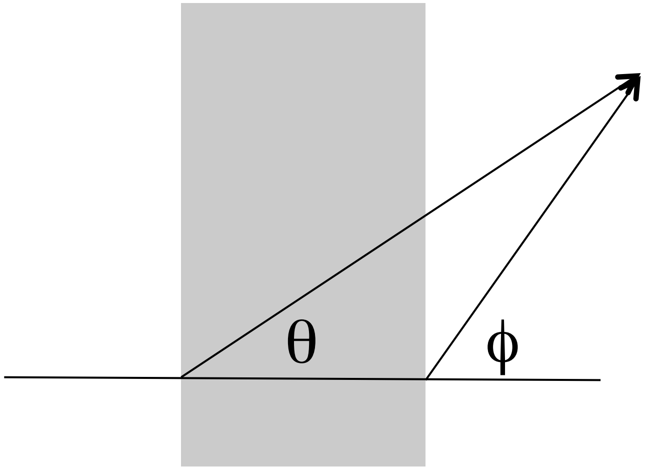
Transition Radiation

- For very short radiator length L, diffractive effects allow radiation at sub-threshold β with real (but small) emission angles
  - Diffraction broadening to achieve this implies very high frequencies
  - The very high frequencies are interesting – a striking experimental signature
- Transition radiation from a thin radiator scales as γ, not β
  - Makes it a uniquely valuable approach for PID at high momentum
  - Unfortunately the rate of emission is much lower than for Cerenkov radiation
  - Experimental challenge to implement thin foils and high-Z gas for absorption
- J.D. Jackson: "the fields must reorganize themselves as the particle approaches and passes through the interface. In this process, some pieces of the fields are shaken off as transition radiation."
  - In more detail, D. Green suggests thinking of an image charge approaching boundary and then changing direction as the particle passes through

Transition Radiation Coherence

Allison & Wright





- Optical path length difference varies as

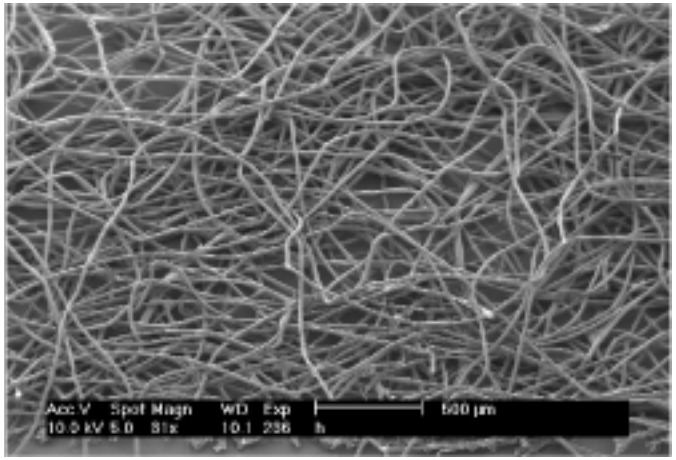
$$\delta = \frac{\omega L}{2c}\left(n\cos\theta - \frac{1}{\beta}\right)$$

- Diffraction peak is centered on Cherenkov angle 1/βn
- Angular width of the emitted radiation is Δθ~λ/L
  - Since we are looking for the broadened distribution, small L are required
  - There is some minimum L required to avoid destructive interference

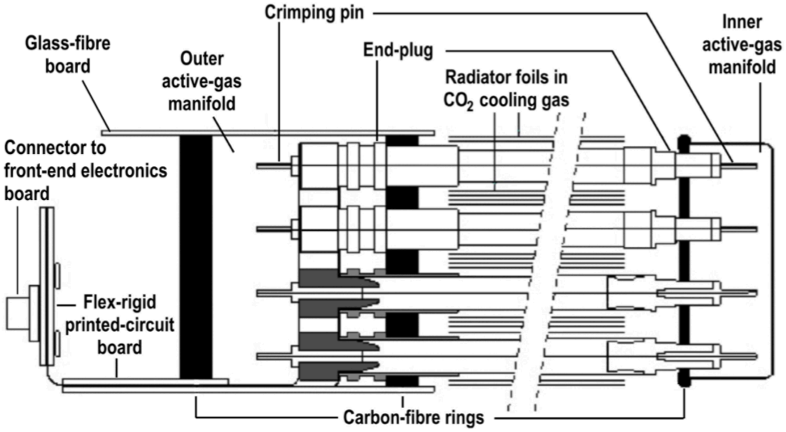
Tuning TR Detector Parameters

- What is the right foil thickness and number of foils?
- Use some rules-of-thumb that come from full derivation:
  - Number of photons $N_{\mathrm{TR}} \sim \alpha$ (yes, that α!)
  - Energy of emitted photons
    $$E_\gamma \sim \hbar\omega \sim \gamma\hbar\omega_p/3$$
  - Typical emission angle $\langle\theta_c\rangle \sim 1/\gamma$
- For typical γ factors of 1000, emission is in keV (X-ray) regime
- To avoid destructive interference, need foils > O(10 μm) thick
- Since each foil yields on average α photons, need $1/\alpha$ foils to collect at least 1 photon
  - Unfortunately we can't simply add more foils, because they are not transparent to the X-ray radiation emitted

ATLAS TR Tracker (TRT) Design



- Transition radiators: fiber mats in barrel, planar foils in endcap detectors
  - Orientation of cylindrical fibers not crucial
  - Fiber mats are simple for construction
- TR (and dE/dx from simple ionization) read out in gas-filled straw tubes
  - Tubes interspersed with radiating foils (15µm thickness)
  - Tubes operate in high-gain regime (10^4)
  - Only issue is high occupancy because each straw tube extends length of detector



- Even 6 keV photons interact via photoelectric effect: use high-Z gas like Xenon to maximize the interaction cross section
- Read out ToT for each straw as well as “high-threshold” bit for TR

“High Threshold” e/π Separation

- Since electrons have higher γ for a given momentum, expect more detected TR than for pions
  - High threshold set at 6 keV; compare to typical TR photon energy 6-15 keV
  - Low threshold is 300 eV for dE/dx
  - HT fraction limited by # of TR photons
- Turn-on of TR seen for electrons
  - γ=1000 gives 6 keV TR photons
  - Non-zero pion probability due to Landau fluctuations in dE/dX; slight rise with γ due to relativistic rise
- We’ll see in next lecture how this information is used for e/γ PID

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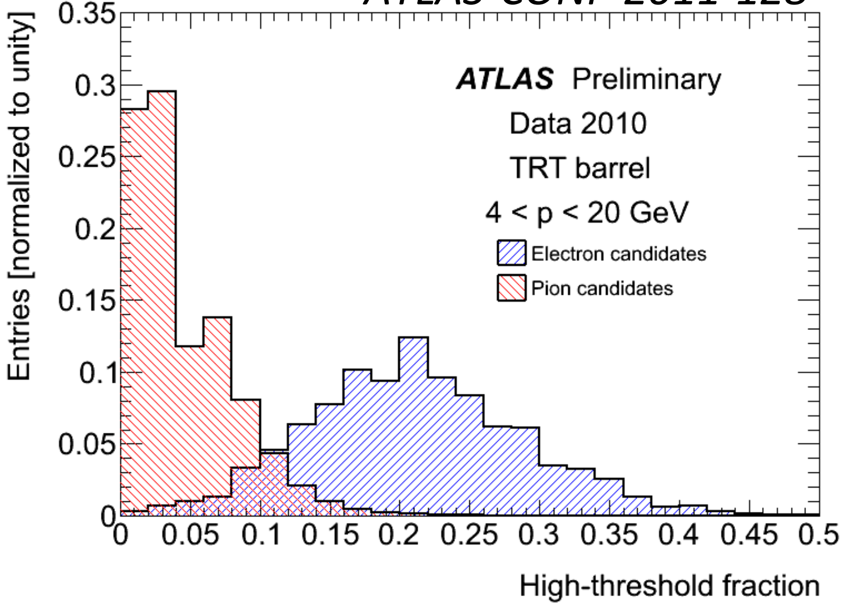

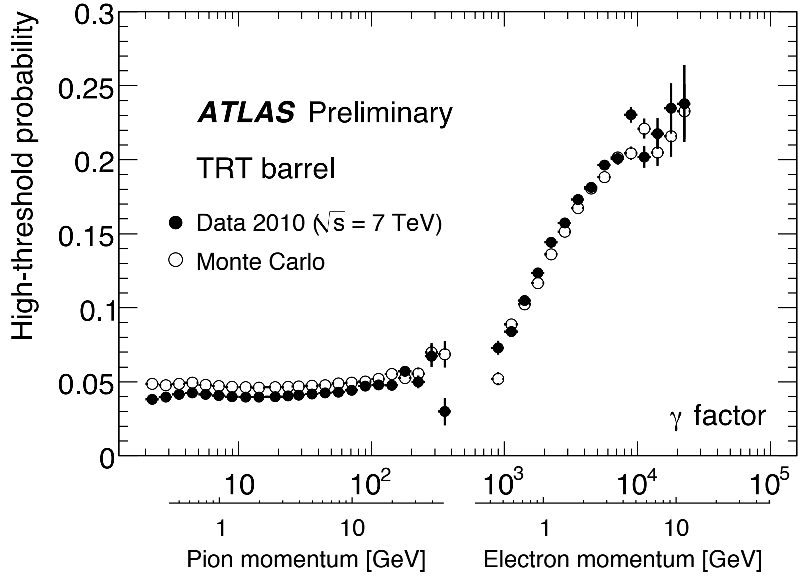

Time of Flight Principles

- If particles have the same (or known) momenta, their masses can be distinguished by using β to calculate γ ≈ p/m

$$\beta = \frac{v}{c} = \frac{L}{tc} \qquad \text{but also} \qquad \beta = \sqrt{1 - \frac{1}{\gamma^2}} \cong 1 - \frac{1}{2\gamma^2}$$

- This allows us to solve for t in terms of L and p:

$$t = \frac{L}{c}\left(1 + \frac{1}{2\gamma^2}\right) \cong \frac{L}{c}\left(1 + \frac{m^2}{2p^2}\right)$$

- And to distinguish the flight times for two particles of mass m_1, m_2

$$\Delta t \cong \frac{L}{c}\left(\frac{m_1^2 - m_2^2}{2p^2}\right)$$

  - Strict requirements on time resolution, due to practical limits on L/p^2
  - This is due to the fact that all particles' β values tend to 1 at high p

Fast Detectors and Electronics

- Typical required time-of-flight resolution: O(100 ps)
  - For K/π separation with p = 1 GeV and L = 1 m, need Δt=100 ps
- Physical processes in detectors occur on typical timescale O(ns):
  - Plastic scintillator fluorescence mechanism is typical O(ns)
  - Electron drift time in Resistive Plate Chamber gaps is O(ns)
  - Charge mobility in silicon: 300μm in O(10 ns)
  - The overall width in time of the collected charge is not as important as an absolute measurement of where the distribution is in time.

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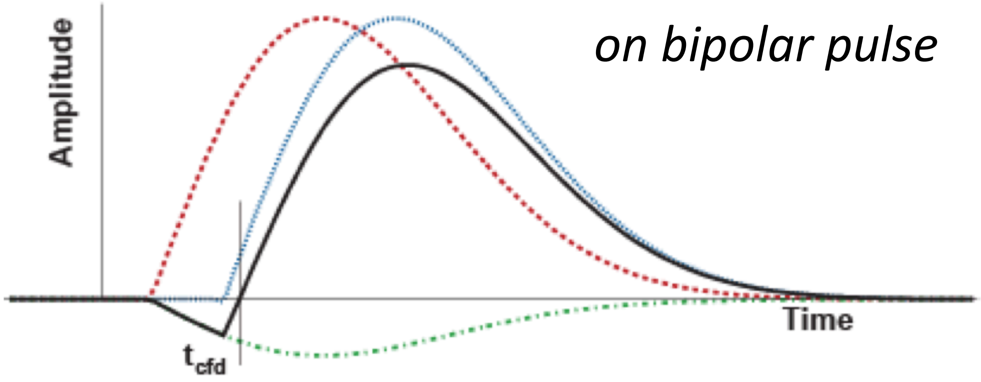
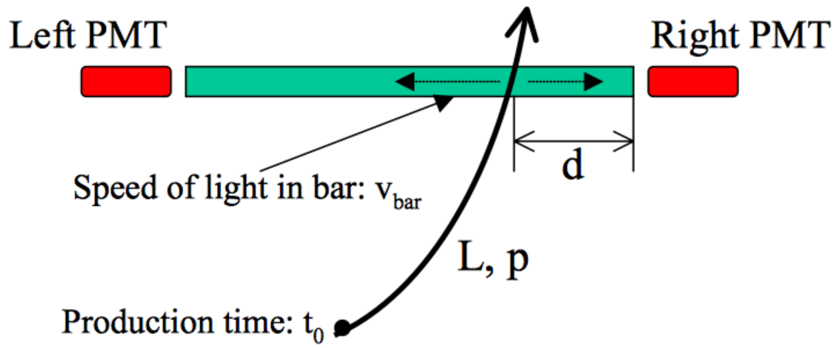


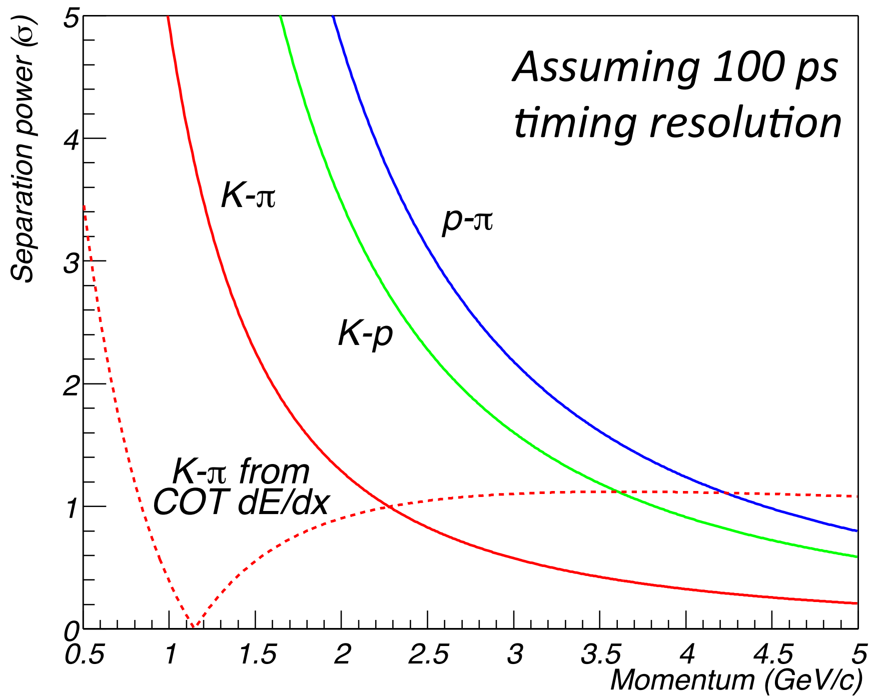
Constant Fraction Discriminator on bipolar pulse

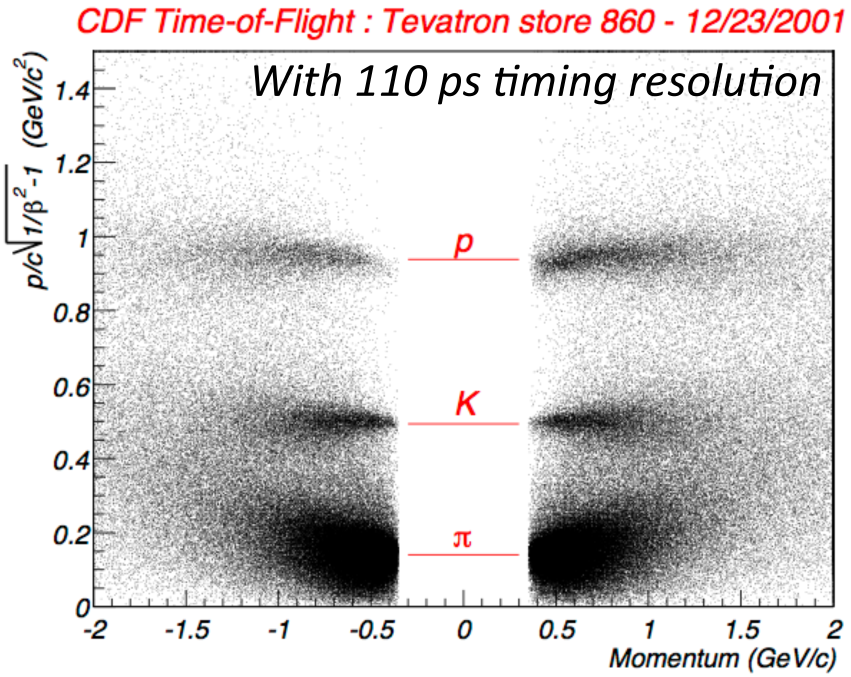
TOF Detector at CDF

- Provided K/π separation for flavor tagging in B-mixing analysis
- Cylindrical array of scintillator bars located at r=1.4 m

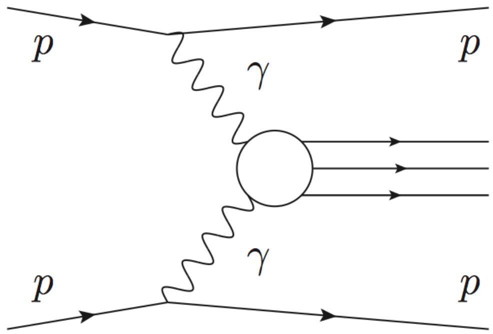
$$t = t_{\text{hit}} - \frac{d}{v_{\text{bar}}} - t_0$$



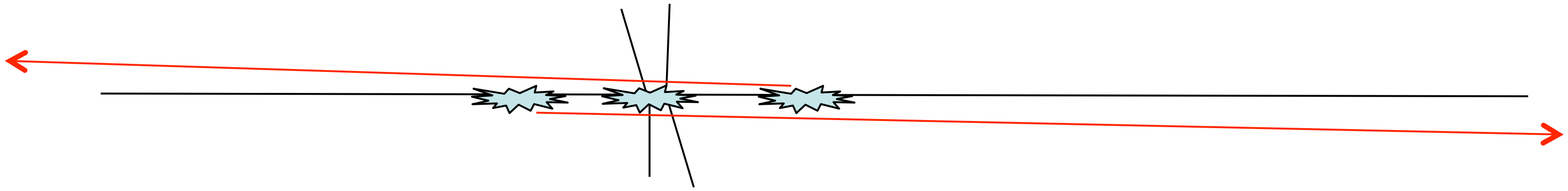




TOF for Forward Detectors at LHC



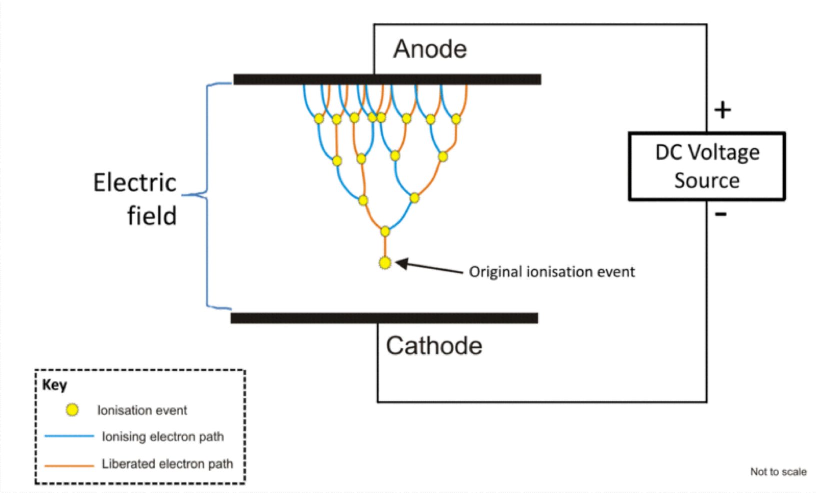
- Targeting diffractive physics, including Higgs
- Must tag proton remnants at very low angle
  - Proposed detectors lie 220 m from IP
- At this distance, it becomes difficult to know which proton belongs to which central event back at the IP
  - At highest event rates, there may even be accidental coincidences

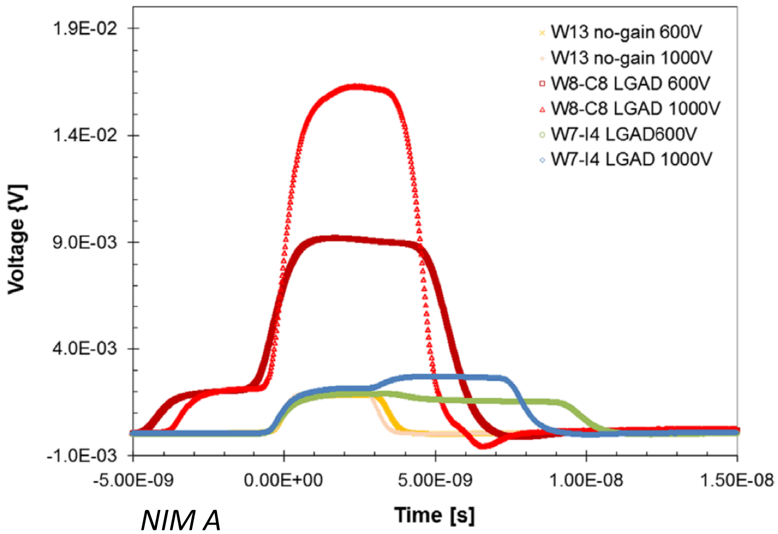


- Precision TOF can give the location over the PV in z
  - For z-vertex separation of 3 mm, need 10 ps timing resolution
- Proposed detectors include finely-segmented readout or extra silicon detectors for precision position measurements

Recent TOF advances: Fast Silicon Detectors

- Silicon detectors are unity gain; depend on thickness to generate sufficient ionization signal
- Carrier mobility and depletion depth limit timing resolution
- New idea to realize silicon detectors with gain, like gaseous detectors
  - Depends on high electric field, carefully shaped to avoid field breakdown near implanted structures
- With increased gain (now at 14x), can reduce detector thickness and improved timing resolution
- Proposed for forward detectors at LHC, providing time and position

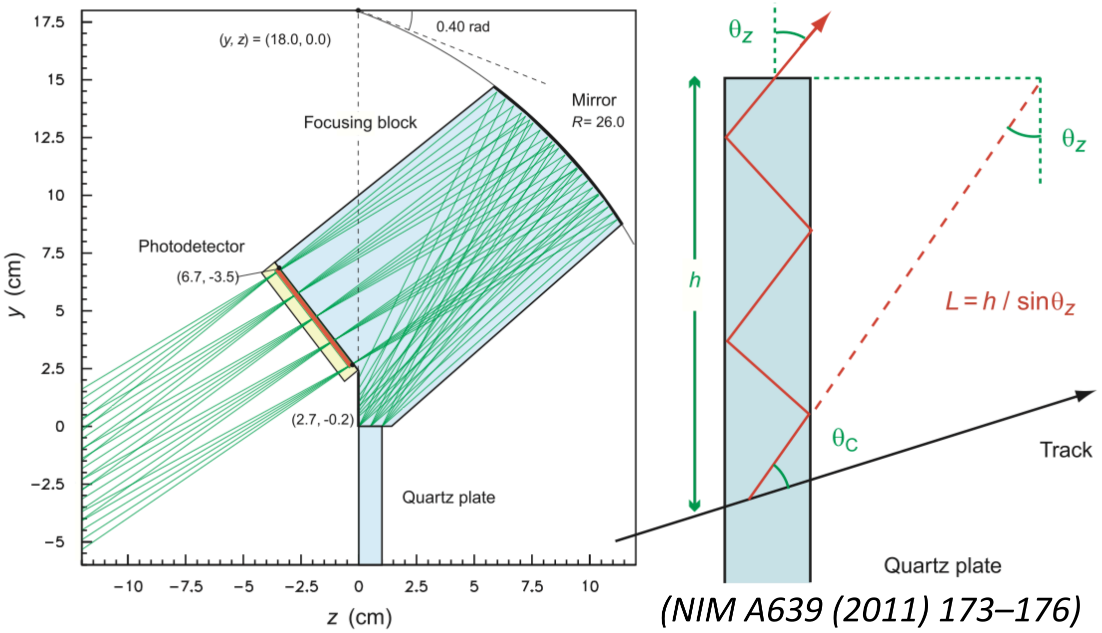




NIM A
http://dx.doi.org/ 10.1016/j.nima.2014.05.006

Future: TOF + Cherenkov?

- Leverage extremely fast Cherenkov emission into a TOF system
  - TORCH detector for LHCb upgrade and HPS detectors for CMS
- Benefits of Cherenkov-based PID and TOF-based PID combined



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- Or use combined system to improve TOF measurement with instantaneous radiation mechanism

Summary of Today's Topics

- Event reconstruction: unwinding detector-level to particle-level
- Charged particle identification is really "mass calculation"
- Charged particles interact electromagnetically with material
  - dE/dx: virtual photons ionize atomic electrons
  - Cherenkov radiation: real photon emission when v > c/n; sensitive to b
  - Transition radiation: real photon emission sensitive to g
  - Note: these techniques are used only for charged particle ID, since they depend on electromagnetic interactions with material
- Time-of-flight measurements for particle ID and vertex association
  - These also depend on material interactions of charged particles
- Practical examples of detectors sensitive to these interactions in hadron collider experiments at Fermilab and CERN

Plan for Tomorrow

- Neutral particle ID techniques (γ ,π^0, K, Λ,…)
  - V0 identification with tracking detectors
  - Photon vs. Electron shower shapes
  - Converted photon reconstruction
  - Isolation requirements and calculations
- Muon reconstruction
  - Combined reconstruction and measurements
  - Punch-through and charge mis-identification
- Measurements of particle ID efficiencies and fake rates
  - Tag-and-probe methods
  - "Matrix methods"
- Introduction to Particle Flow algorithms
  - Practical examples and results from particle flow

Guide to Further Reading

- W.W.M. Allison and P.R.S. Wright, "The Physics of Charged Particle Identification," in *Formulae and Methods in Experimental Data Evaluation, Vol. 2* (EPS: CERN, 1984) (Oxford preprint archived at http://cds.cern.ch/record/146109/)
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- Dan Green, *The Physics of Particle Detectors*, Cambridge Univ. Press, 2000.
- *The CERN Large Hadron Collider: Accelerator and Experiments*, JINST Vol. 3, August 2008.