Detector design concept of the EIC

Vertex Detectors & Calorimeters

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Inspired by presentations from D. Cockerill, S. Easo , T. Hemmick, A. Kiselev, A Papanestis, D. Petyt, O. Tsai

Outline

- Introduction
  - Foundations & motivation for the EIC program
  - Basics of Deep Inelastic Scattering and DIS kinematics
- EIC accelerator and detector requirements
- Building blocks of EIC multipurpose detector
  - Tracking detectors
  - Vertex reconstruction
  - Calorimeters
  - Detectors for Particle Identification
- Summary and Tutorial

Outline: Tracking & Vertex Detectors

- Silicon Trackers as vertex detectors
- Momentum measurements
  - Energy loss
  - Momentum reconstruction
- Momentum resolution
  - Resolution for a measured track
  - Effects of multiple scattering

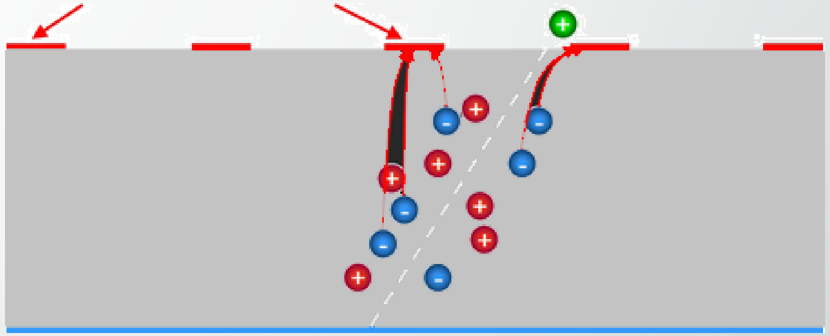
Vertex Detectors: Si

- Vertex detectors are trackers, but:
- Fine(r) spatial resolution (< 50 μm) and close to interaction

Gas detectors → Silicon detectors

- Design considerations:
  - Close to interaction region (beam) → radiation damage
  - Material budget (to minimize losses)
  - Reconstruction (higher track/hit density)
  - Price

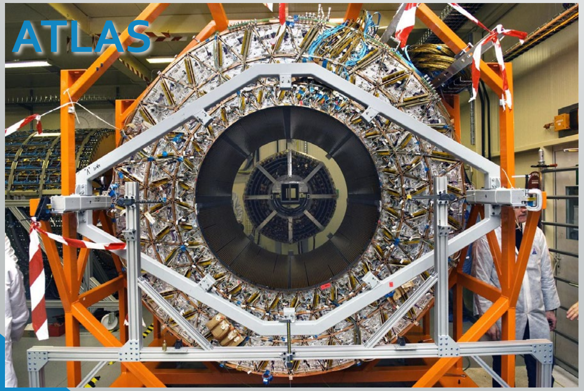
Operation Basics



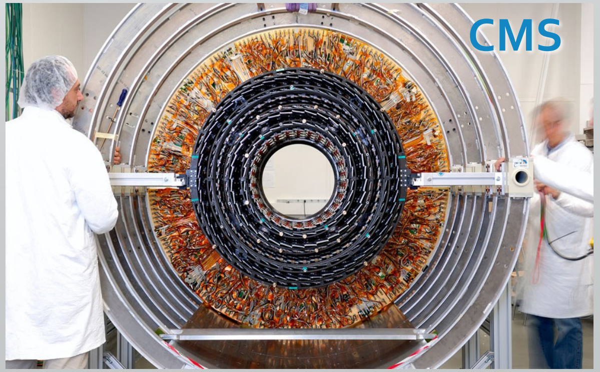
- Semiconductor acts as ionization chamber
- Propagating charged particles creates electron/ hole pairs
- Charges drift& recorded by closest electrode
- Electrode location == hit

Gas vs. Si Detectors

- Gas Detectors
  - 26 eV needed to produce e/ion pair
  - ~100 e/ion pairs per cm
  - Amplification ~10^6
  - Typical noise > 3000 e-
  - Material budget: lowest
  - Cost: low
  - Typical resolution: ~ $100\mu m$



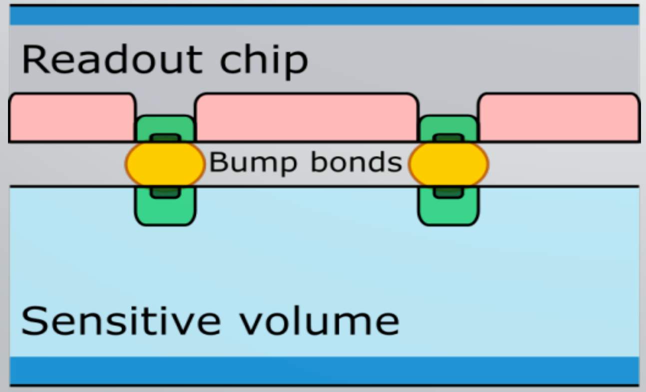
- Silicon Detectors
  - 3.65 eV needed to produce e/hole pair
  - 10^6 e/h pairs per cm (scale to size ~ 100 μm)
  - No intrinsic amplification (typically)
  - Typical nose ~100e- (pixels) ~1000e- (strips)
  - Material: higher (particularly support)
  - Cost: high
  - Resolution: 1-$10\mu m$



Pixel Sensors

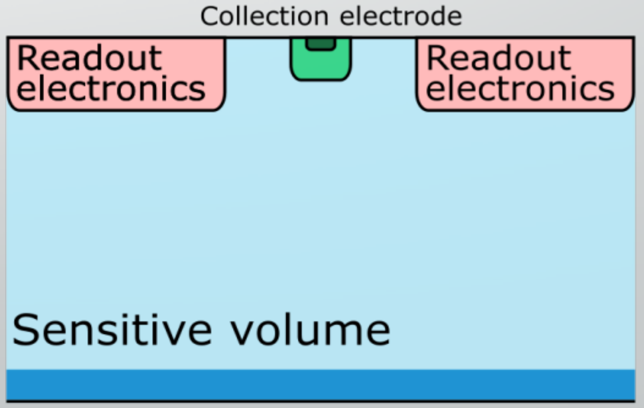
Hybrid pixels:

- Sensitive volume and readout electronics on separate chips
- Electronics bump-bonded to each pixel
- Most commonly used in silicon vertex trackers
- Radiation tolerant and fast (but high material)
- Example: ATLAS/Pixel CMOS



Monolithic Active Pixel Sensors (MAPS):

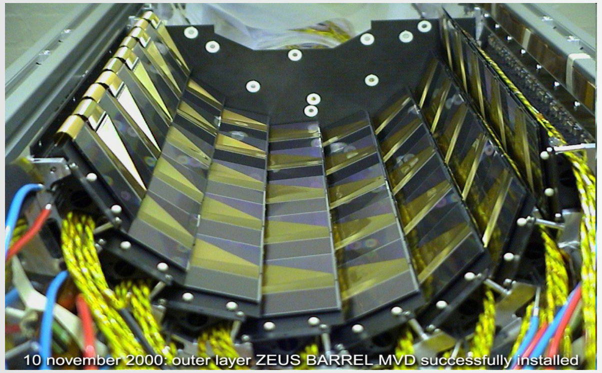
- Sensitive volume and readout electronics on same chip
- Made using commercial CMOS technology
- Thin and high granularity
- Slower
- Example: STAR-HFT/Pixel



Si Detector Examples

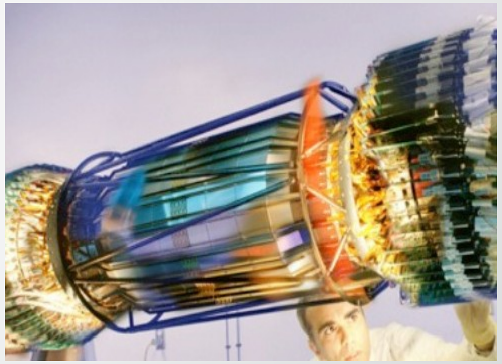
- Semiconductor detector: strips, pixels (DEPFET, MAPS,CMOS)

ZEUS vertex

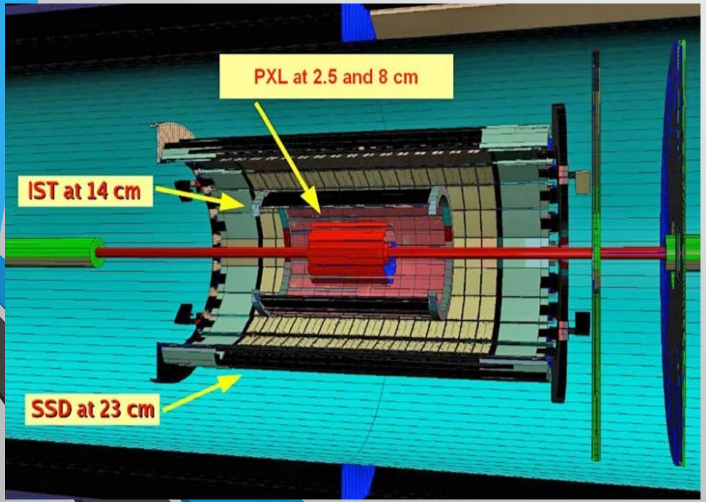


BELLE-2 pixels

BABAR vertex

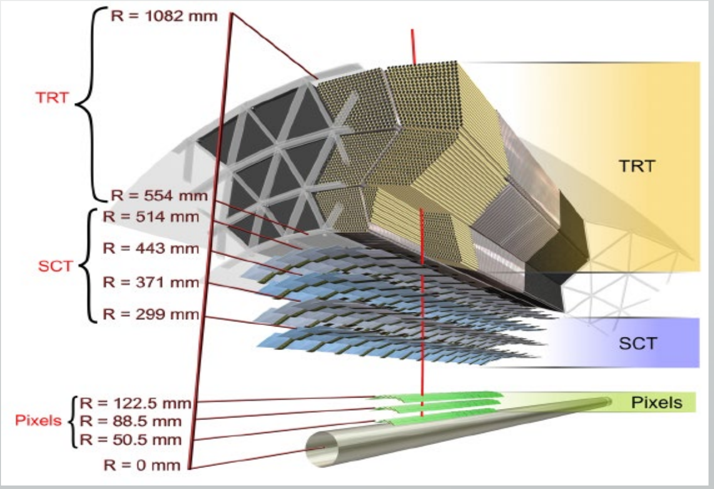


STAR HFT



CMS Si-tracker

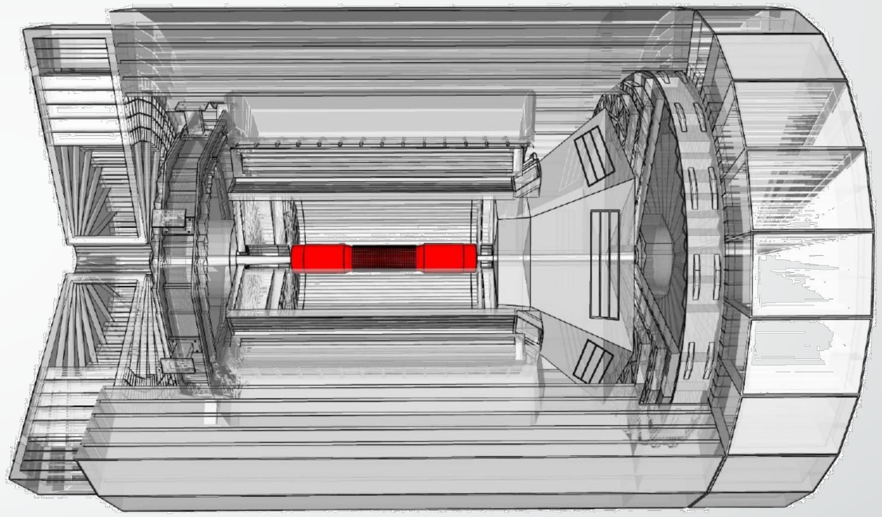
ATLAS Si-tracker

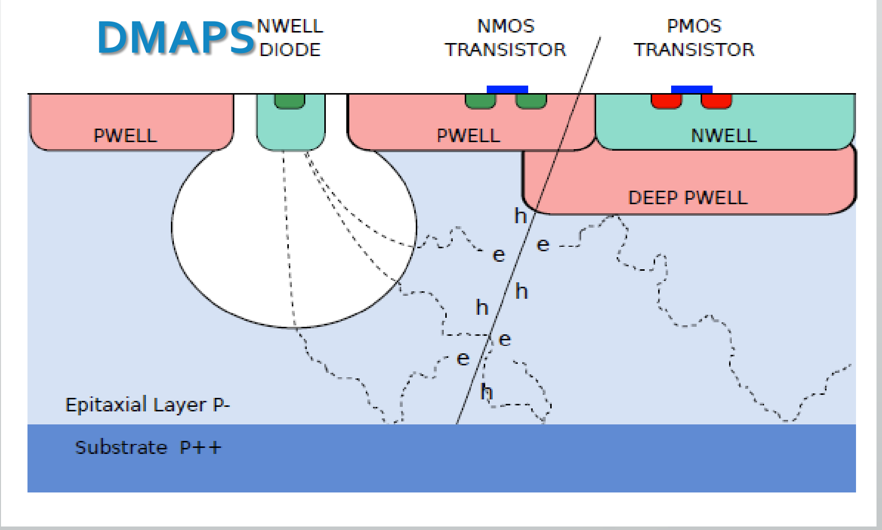


Si Tracker for EIC

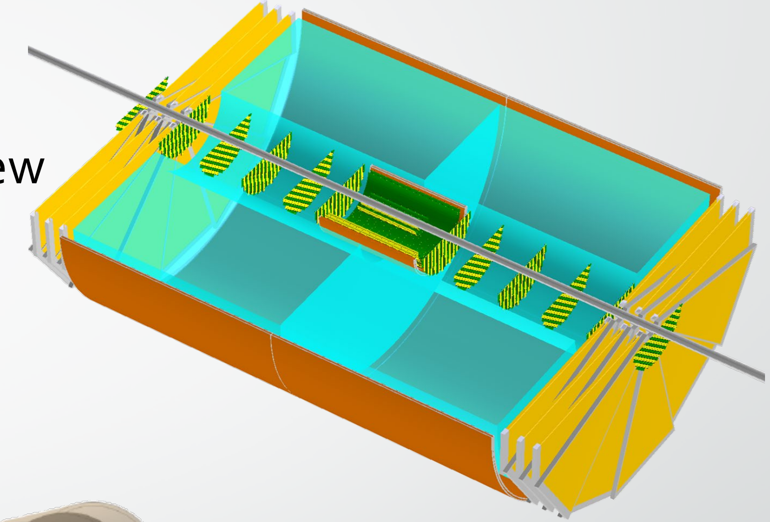
eRD25 & EIC Si Consortium

- Requirements: Spatial resolution: ~5 μm (20 μm pixel pitch), material budget: < 0.3% X/Xo per layer, Integration time ~2 μs, low power consumption
- Multiple technologies were considered: hybrid pixel, Si strips, Low Gain Avalanche Detectors (LGAD), MAPS.
- Consensus on technology of choice: MAPS/DMAPS
- A dedicated EIC MAPS sensor is desired solution → generic R&D

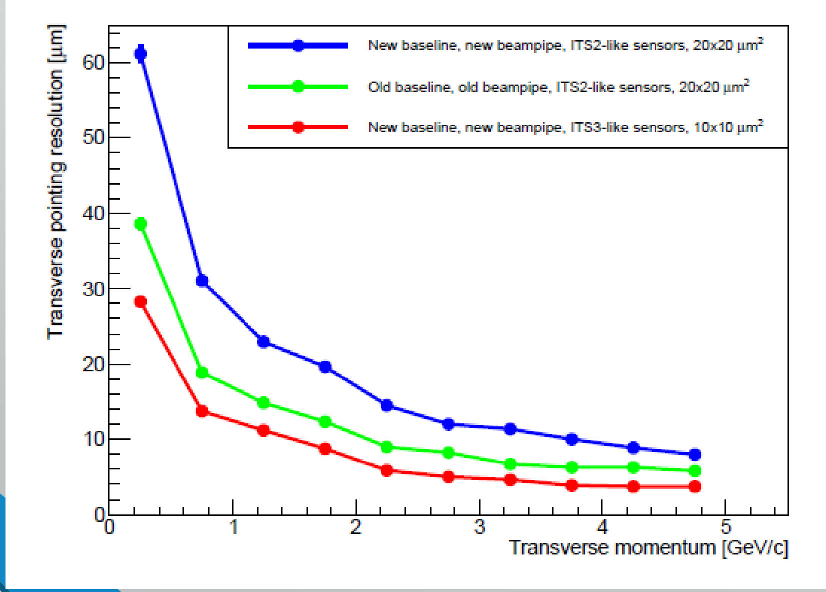


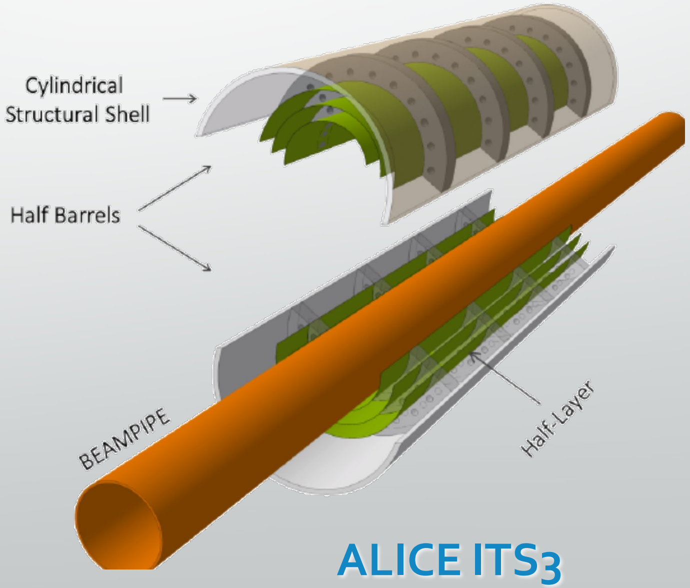


EIC Si Tracker Developments

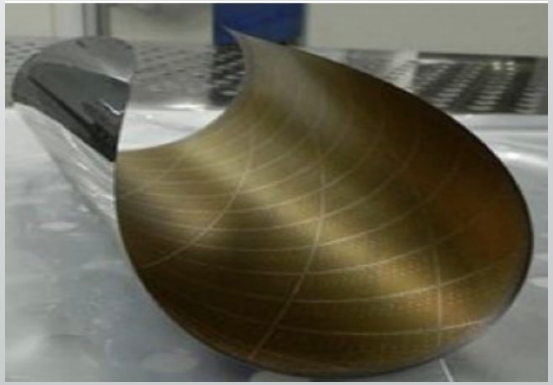


- Close collaboration with ALICE-ITS3 collaboration to develop new generation MAPS sensors (leverage on a large effort at CERN)
- EIC sensor development will take–off ITS3 design later
- Projected pointing resolution:

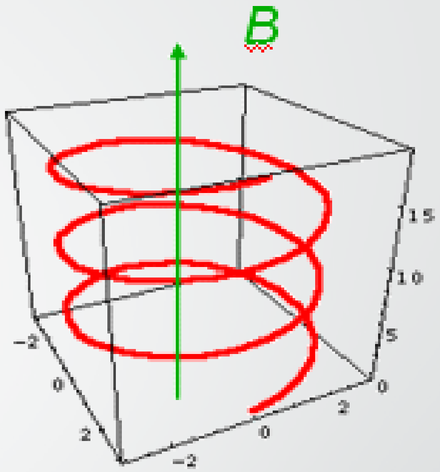




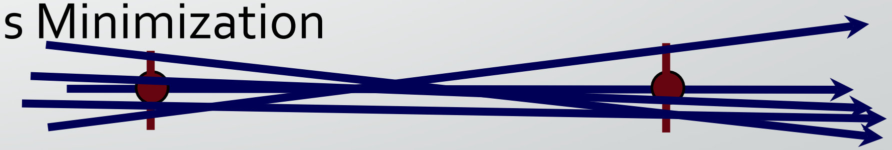
ALICE ITS3



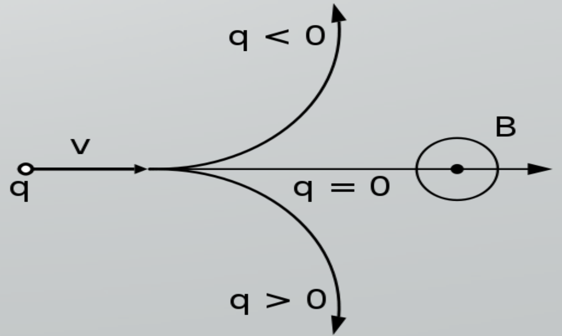
Detectors to Physics: Tracking



- Tracking basics: building trajectory
  - 1D straight line as staring model; 2 layers → perfect fit (no uncertainty)
  - Use staring line model and extrapolate
  - The further you extrapolate the bigger the error
  - Adjust your model as the number of hits grows
  - Track parameters are extracted typically by Least-Squares Minimization



- Next steps
  - Extrapolate track back to the point of origin
  - Reconstruct primary vertex → track impact parameters; refits
  - Reconstruct decay vertices

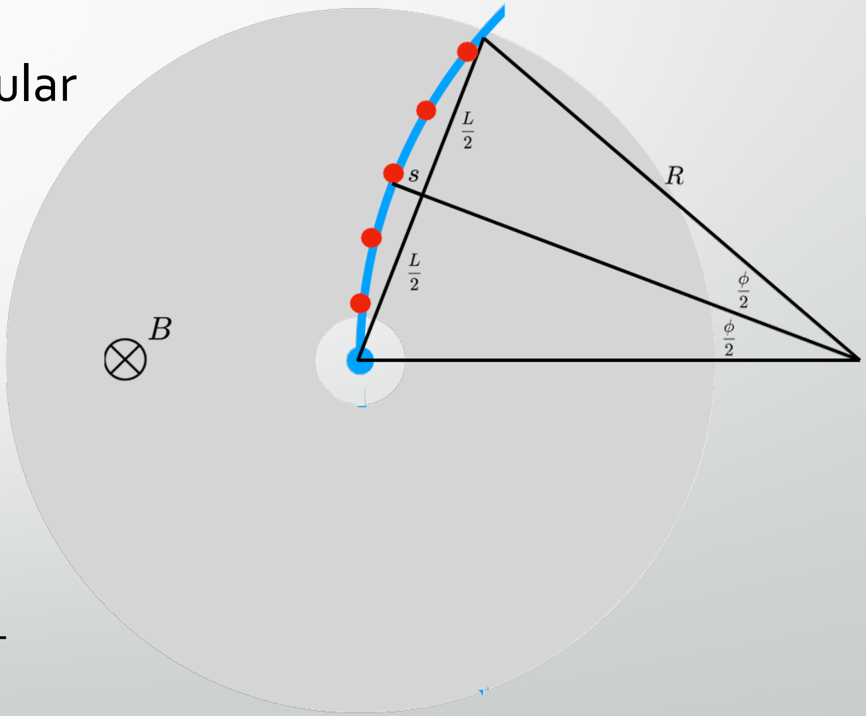


Detectors to Physics: Tracking

- Tracking fitting (solenoidal field)
  - Lorentz force $F_L = q\,\vec{v} \times \vec{B}$; with constant B-field: circular motion in transverse plane:

$$p_\mathrm{T}\,[\mathrm{GeV}] = 0.3B\,[T]\;\; R\,[m]$$

$$s = R - R\cos\frac{\phi}{2} \approx R\frac{\phi^2}{8} \qquad \phi = \frac{L}{R}$$



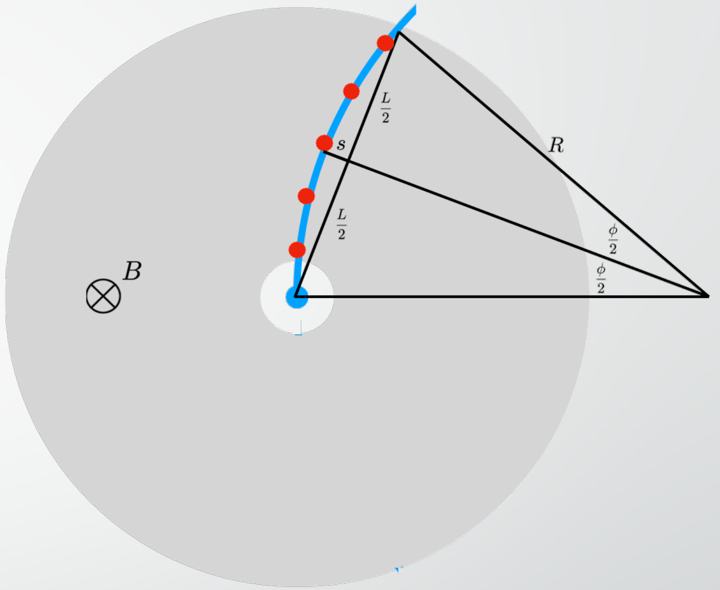
  - Thus: $\dfrac{\Delta p_\mathrm{T}}{p_\mathrm{T}} = \dfrac{\Delta R}{R} = \dfrac{\Delta\phi}{\phi} \approx \dfrac{\Delta s}{L^2} \cdot \dfrac{8p_\mathrm{T}}{B}$

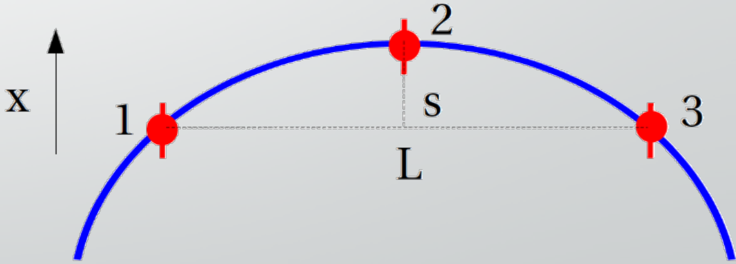
- Glückstern, 1963: $\dfrac{\sigma(p_T)}{p_T} = \dfrac{\sigma(x)\cdot p_T}{0.3BL^2}\sqrt{\dfrac{720}{N+4}}$

Tracking: Momentum Resolution

Assume that your tracking is provided by 3 layers only with equal 1D spatial resolution σ_x

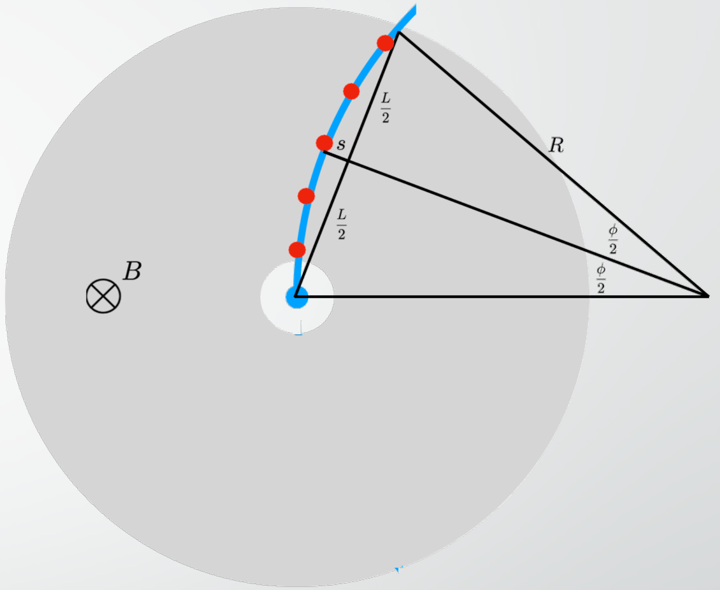
- *What is the momentum resolution in terms of* σ_x*?*





$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(x)\cdot p_T}{0.3BL^2}\sqrt{\frac{720}{N+4}}$$

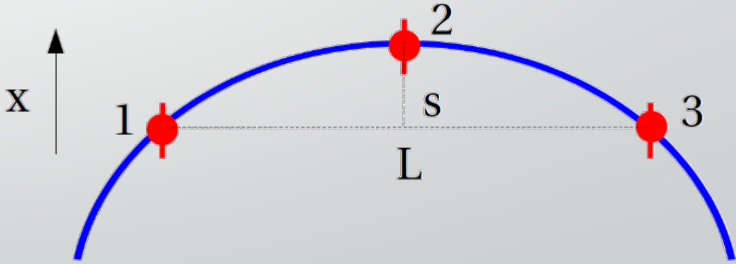
Tracking: Momentum Resolution



Assume that your tracking is provided by 3 layers only with equal 1D spatial resolution σ_x

- *What is the momentum resolution in terms of σ_x?*

- Since we have relation $\frac{\Delta p_T}{p_T} = \frac{\Delta_s\, 8\, p_T}{0.3BL^2}$, we need to find uncertainty in sagitta
- From pure geometry $s = x_2 - \frac{x_1+x_2}{2}$, then



$$\Delta_s = \sqrt{\sigma_x^2 + \frac{\sigma_x^2}{4} + \frac{\sigma_x^2}{4}} \quad \text{and} \quad \frac{\Delta p_T}{p_T} = \frac{\sigma_x \sqrt{96}\, p_T}{0.3BL^2}$$

$$\boxed{\frac{\sigma(p_T)}{p_T} = \frac{\sigma(x) \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{N+4}}}$$

Detectors to Physics: Tracking

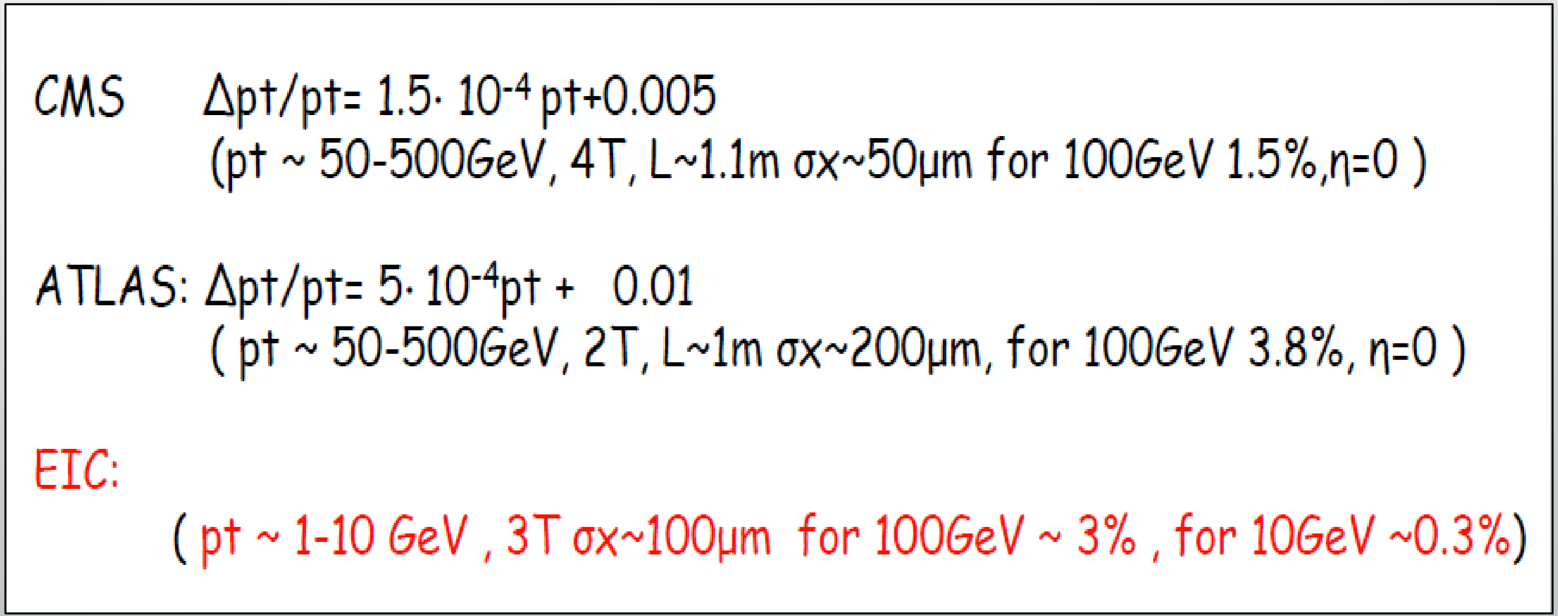
- So, for layered trackers: momentum resolution:

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(x)\cdot p_T}{0.3BL^2}\sqrt{\frac{720}{N+4}}$$

Worsens with p_T Improves with B

Worsens with σ_x Improves with L

- Examples:



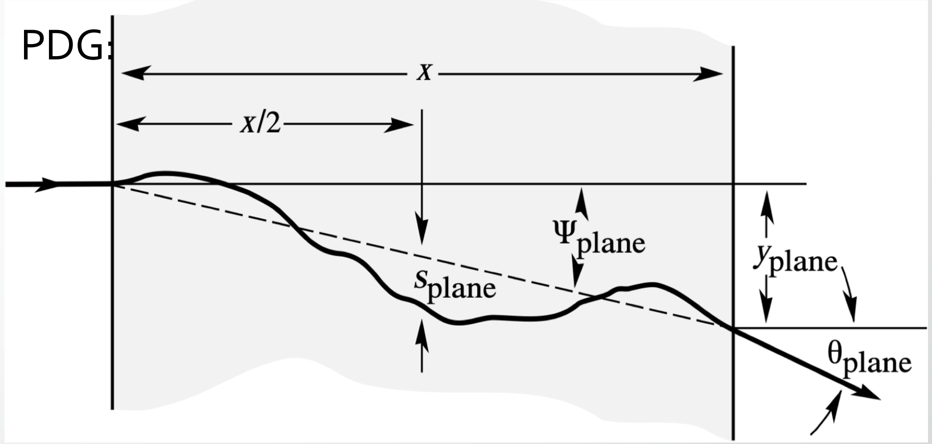
CMS Δpt/pt= 1.5· 10^{-4} pt+0.005
(pt ~ 50-500GeV, 4T, L~1.1m σx~50μm for 100GeV 1.5%,η=0)

ATLAS: Δpt/pt= 5· 10^{-4}pt + 0.01
(pt ~ 50-500GeV, 2T, L~1m σx~200μm, for 100GeV 3.8%, η=0)

EIC:
(pt ~ 1-10 GeV , 3T σx~100μm for 100GeV ~ 3% , for 10GeV ~0.3%)

Multiple Scattering

- Reality is more complicated: Multiple Scattering
  - Changes the trajectory of charged particle
  - The smaller the momentum, the higher the effect
  - Depends on distance and density of a material

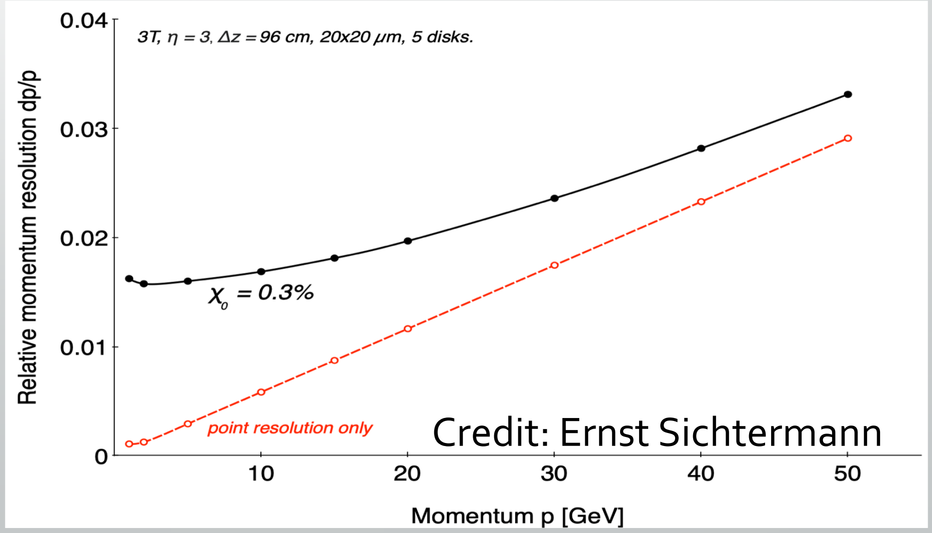


$$\Delta\phi \approx \frac{14\,\text{MeV}}{p}\sqrt{L/X_0} \qquad p = \frac{p_{\text{T}}}{\tan\theta}$$

$$\left.\frac{\Delta p_{\text{T}}}{p_{\text{T}}}\right|_{\text{m.s.}} \approx \frac{14\,\text{MeV}}{p}\sqrt{\frac{L}{X_0}}\cdot\frac{R}{L} = \frac{14\,\text{MeV}}{p}\sqrt{\frac{1}{LX_0}}\frac{p_T}{eB}$$

- Thus:

$$\frac{\Delta p_{\text{T}}}{p_{\text{T}}} = a\cdot\frac{p_{\text{T}}}{BL^2} \oplus b(\theta)\cdot\frac{1}{B\sqrt{LX_0}}$$



Credit: Ernst Sichtermann

Summary: Momentum Resolution

- Momentum resolution includes two terms:

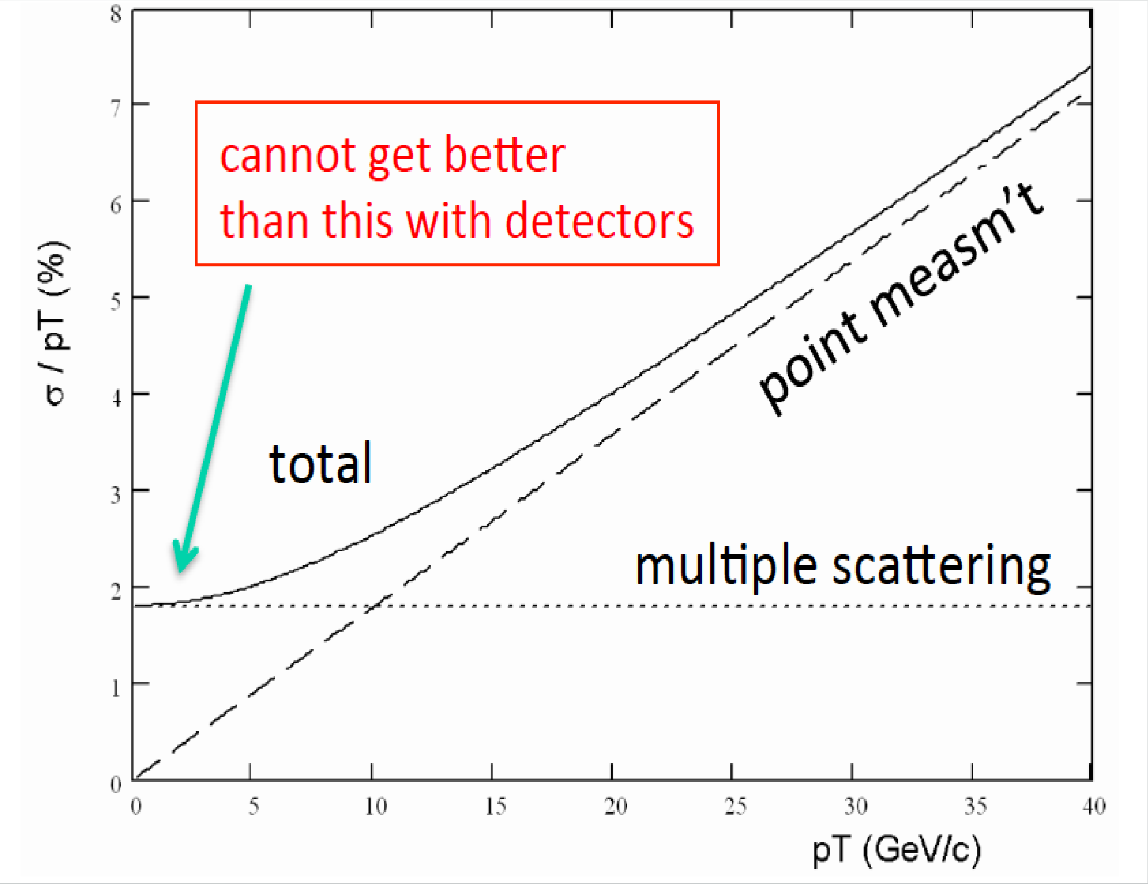
$$\left(\frac{\sigma_{p_T}}{p_T}\right)_{Total} = \sqrt{\left(\left(\frac{\sigma_{p_T}}{p_T}\right)_{mes}\right)^2 + \left(\left(\frac{\sigma_{p_T}}{p_T}\right)_{m.s.}\right)^2}$$

- Position (or "measurement) resolution:

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(x)\cdot p_T}{0.3BL^2}\sqrt{\frac{720}{N+4}}$$

- Multiple Scattering:

$$\left.\frac{\Delta p_{\mathrm{T}}}{p_{\mathrm{T}}}\right|_{\mathrm{m.s.}} \approx \frac{14\,\mathrm{MeV}}{p}\sqrt{\frac{1}{LX_0}}\frac{p_T}{eB}$$



Tracking: Wrapping Up

EIC Tracking options:

- Vertex detector:
  - MAPS
- Central tracker:
  - TPC, All-silicon, µMEGAs, Straw tube tracker
- Endcap trackers: Large-area GEMs
  - µMEGAs, µ RWELL, GEM-TRD
- Forward & backward trackers:
  - MAPS, high resolution GEMs
- Close-to-beamline instrumentation (was not discussed today)

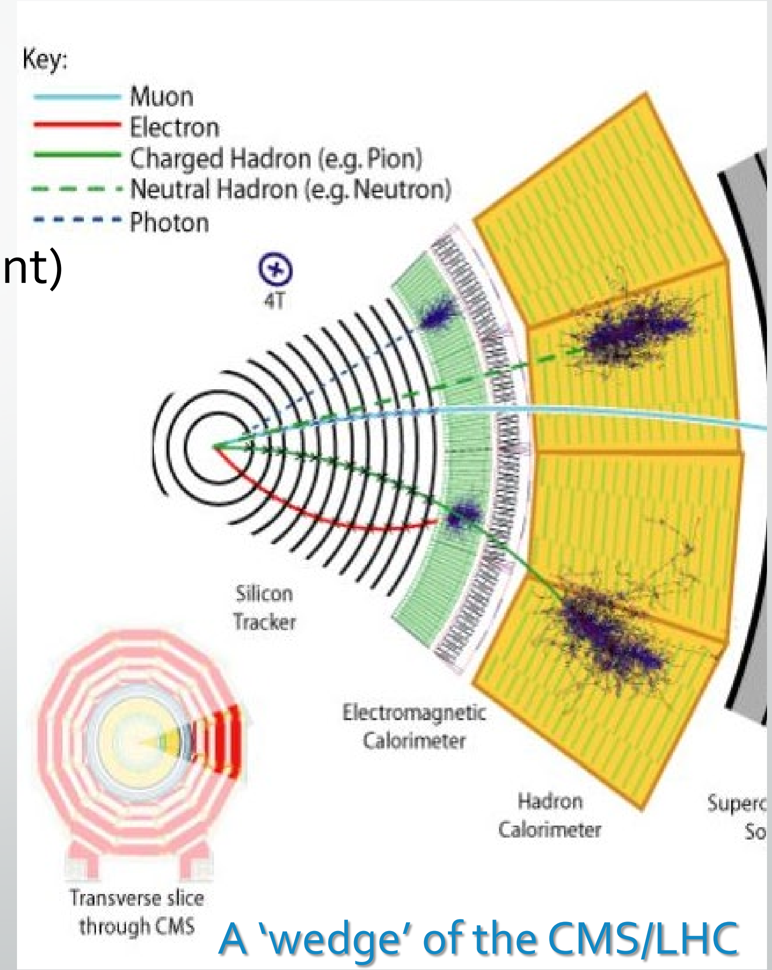
Outline: Calorimeters

- Introduction to calorimetry
- Know your technology options:
  - Calorimeter types
  - Examples of calorimeters
  - Properties and design considerations
- Energy resolution
- Clustering & energy reconstruction
- Particle Flow algorithm

Calorimeters

- All calorimeters measure particle energy through
  - Stopping the particle
  - Converting the energy into something detectable (light, current)
  - Basic mechanism: EM and hadronic showers
  - The measured output is ~proportional to the particle energy

- Calorimeters also provide location of the stopping
  - Showers are relatively well localized
  - Calorimeters are segmented
- If collision vertex is known → neutral particle direction



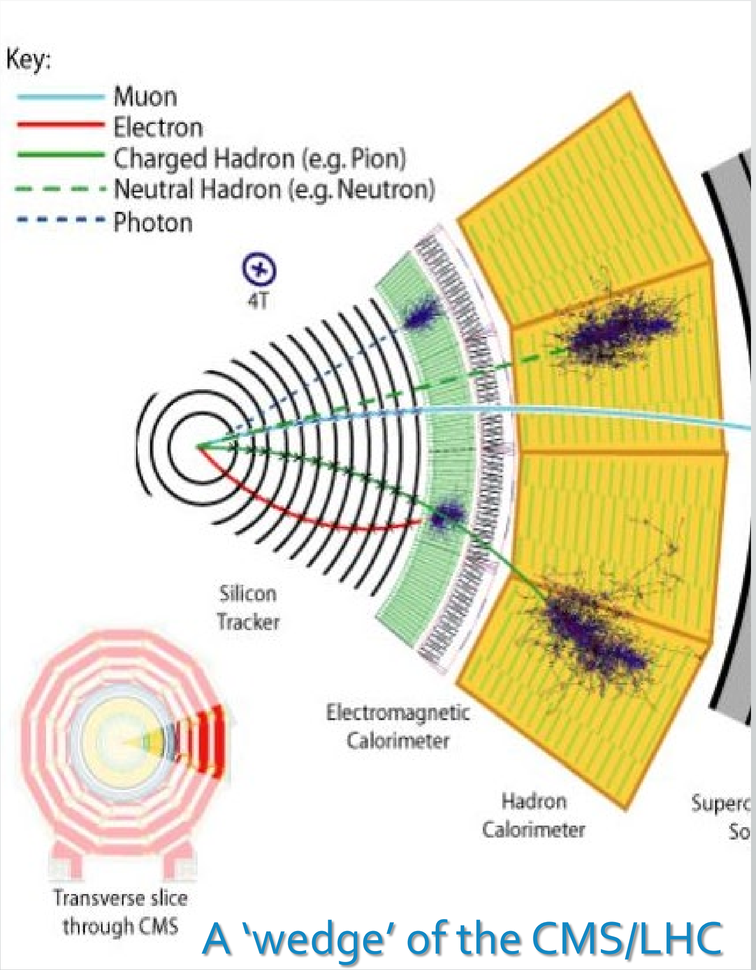
A ‘wedge’ of the CMS/LHC

Calorimeter Types

- Calorimeters are typically divided into dedicated electromagnetic and hadronic detectors

- Electromagnetic calorimeters:
  - $e^{\pm}$ and photons
  - $e^{\pm}$ could be matched to tracks

- Hadronic calorimeters:
  - charged hadrons: $\pi^{\pm}, K^{\pm}, p$
  - neutral hadrons: n, K_L^0
  - charged hadrons could be matched to tracks

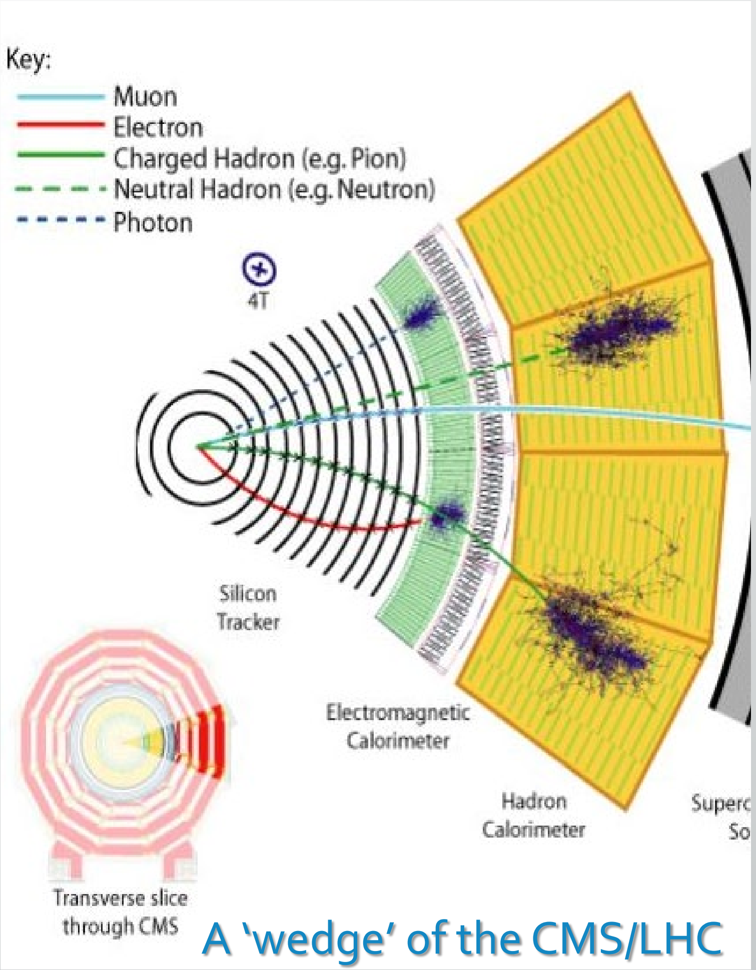


A ‘wedge’ of the CMS/LHC

Calorimeter Uses

- Energy measurements:
  - Particle energy E absorbed in calorimeter
  - Extracted signal is proportional to E
- Particle Identification:
  - Energy deposit patterns
  - Stopping location
  - Track matching (for charged particles)

- Combination of calorimeter and tracking information* is the foundation for *Particle Flow* algorithm



A ‘wedge’ of the CMS/LHC

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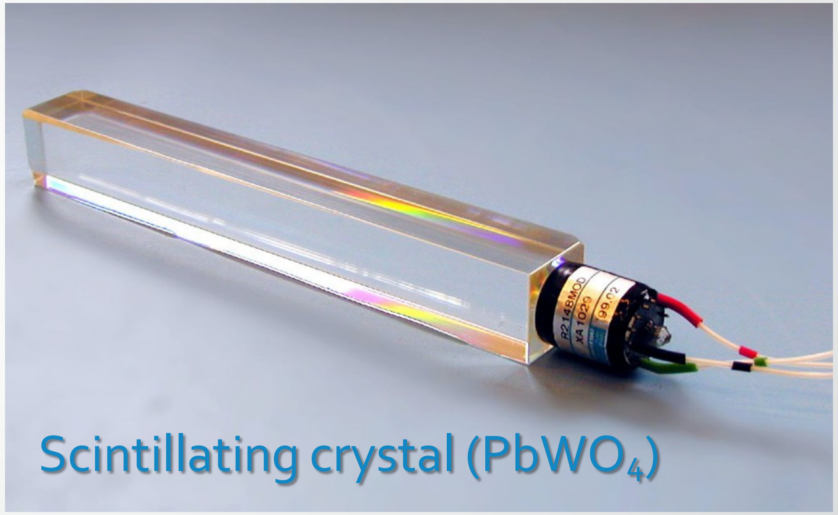
* and other subsystems if any

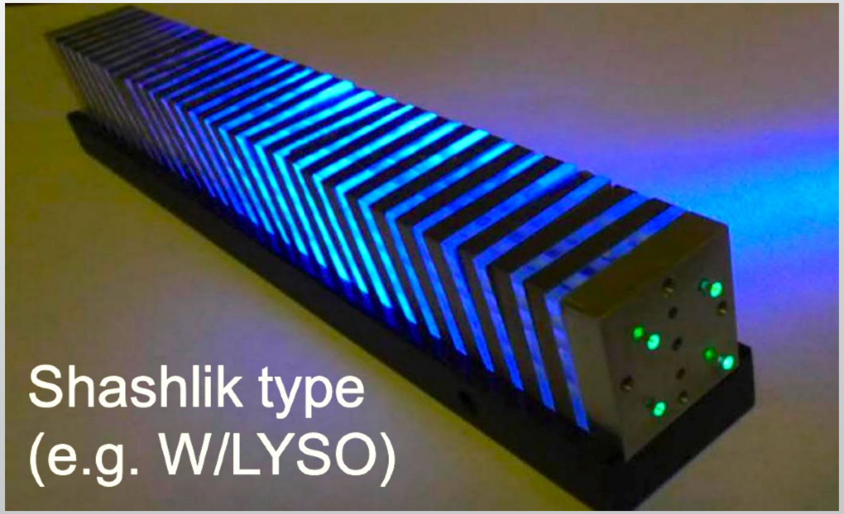
Calorimeter Classification

- Homogeneous:
  - Single medium for absorber and detector
    - Liquefied noble gases (Kr,Xe,Ar)
    - Organic liquid scintillators
    - Dense organic crystals

- Sampling:
  - Layers of passive absorber and active material
    - Absorbers: Lead, Tungsten, Copper
    - Active material: Scintillator/Si/Ar



Scintillating crystal ($PbWO_4$)



Shashlik type
(e.g. W/LYSO)

Calorimeter Classification

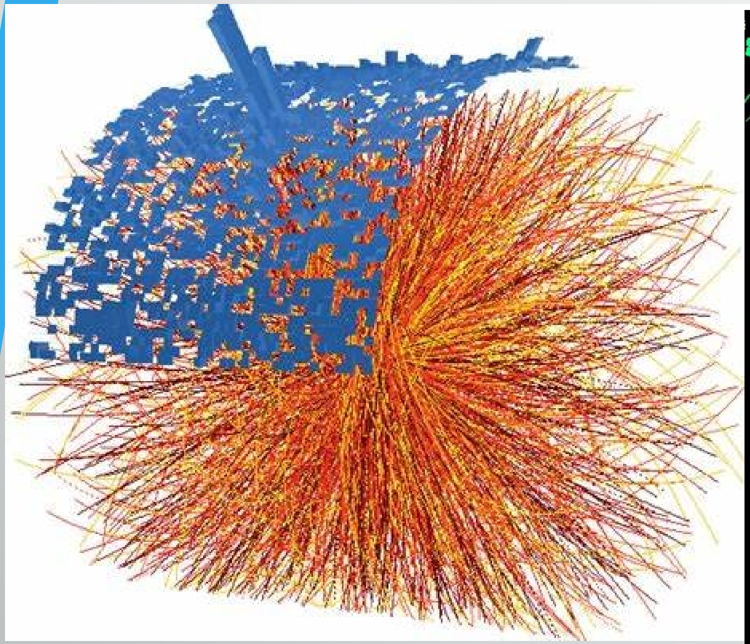
- Homogeneous:
  - Pros: optimal energy resolution
  - Cons: very expensive
  - Used exclusively used for electromagnetic

Signal	Active medium
Scintillation Light	$PbWo_4$, BGO, BaF_2, CeF_3,…
Cherenkov Light	Lead glass
Ionization signal	Liquid Nobel gasses (Ar, Kr, Xe)

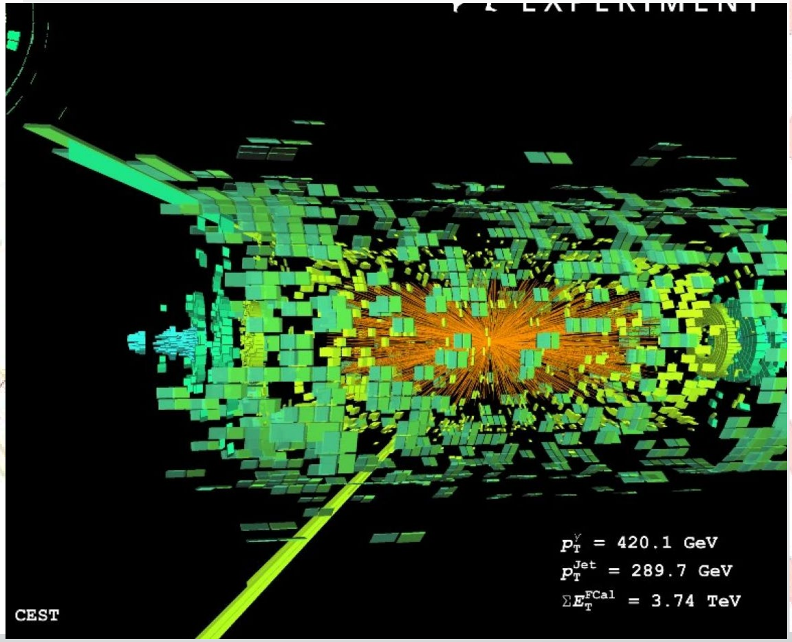
- Sampling:
  - Pros: compact, cheaper (more passive material)
  - Cons: only part of E is recorded; fluctuations
  - Used for EM and hadron calorimetry

Absorber	Active medium
Fe	Plastic scintillator
Pb	Si Detectors
U	Gas Detectors

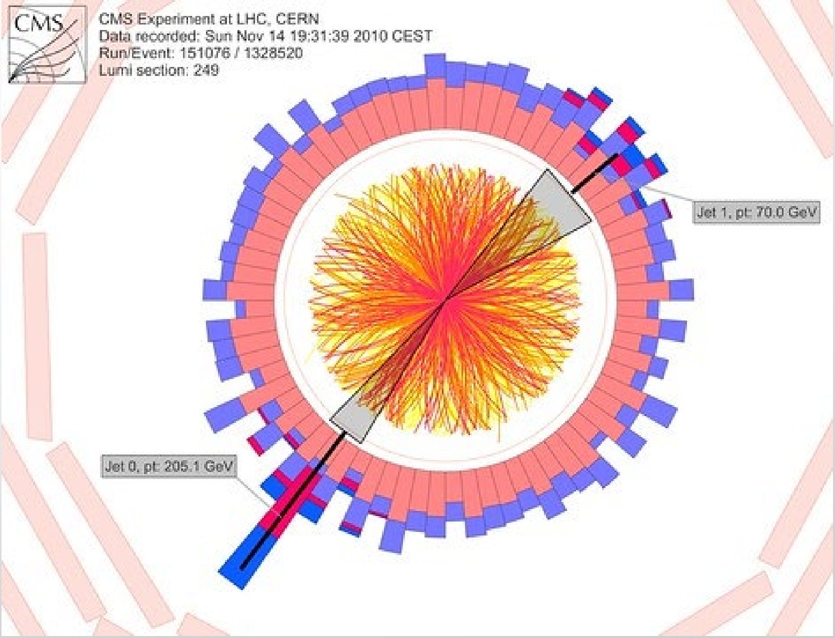
Calorimeter Event Displays



ALICE



ATLAS

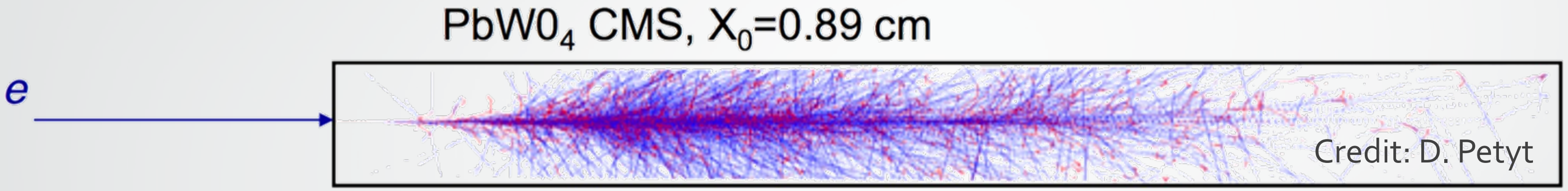


CMS

Central PbPb Event at 5 TeV

Calorimeter Showers

- **Electromagnetic shower:** X_0 – radiation length, energy reduced by $1/e$



Energy loss:

$$E < E_c$$

Ionization

- Photoelectric effect
- Compton scattering

$$E_c = \frac{610\ \text{MeV}}{Z + 1.24}$$

$$E > E_c$$

Electron bremsstrahlung

- e± → γ

Photon pair production

- $\gamma \rightarrow e^+ + e^-$

Controlled by X_0

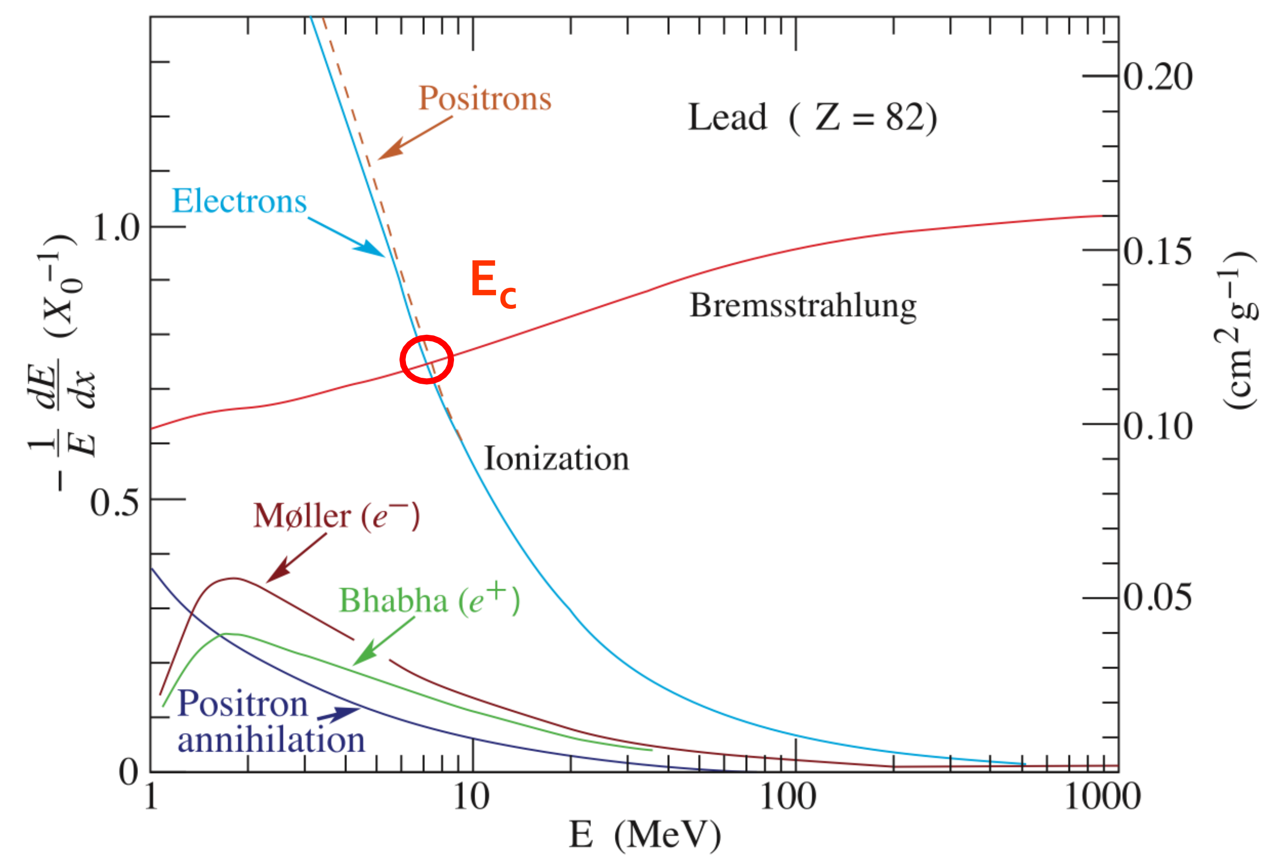
$$X_0 \sim \frac{1}{Z^2}$$

→ compact calorimeters need dense media

Critical Energy

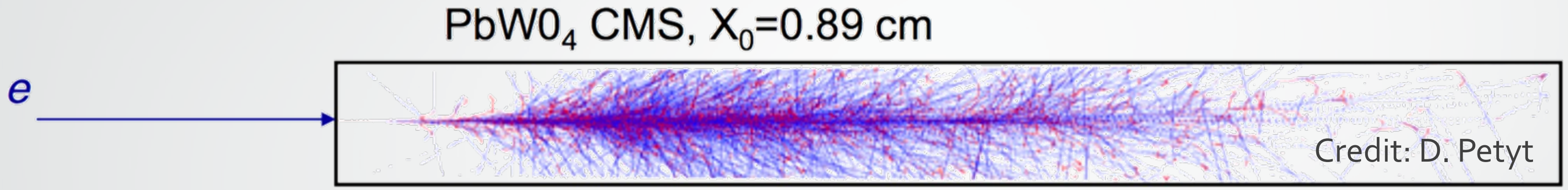
- Electron and photon interactions with material:
  - Higher E: dominated by bremsstrahlung (electrons) and pair production (photons) → shower multiplicity grows exponentially
  - Lower E: dominate by ionization → shower is "dying out"
- Critical energy, E_c: ionization and radiation processes contribute equally

Fractional energy loss per radiation length



Calorimeter Showers

- Electromagnetic shower:



Credit: D. Petyt

Above E_c:

$$E = E_0 e^{-x/X_0}$$

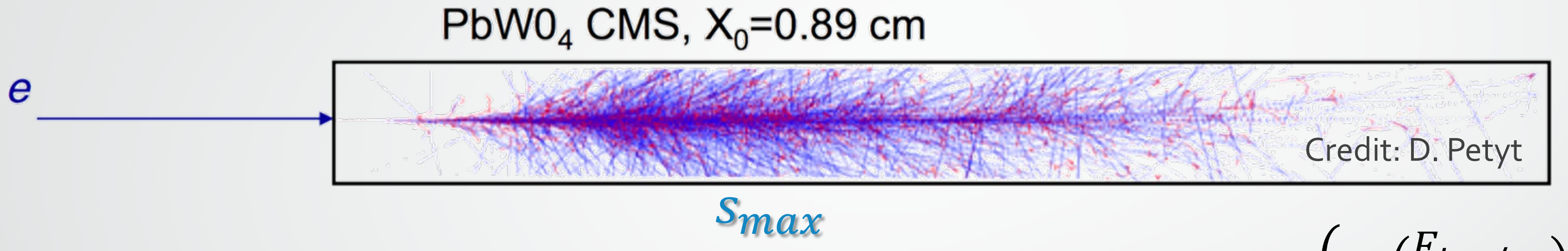
- Electrons lose energy via bremsstrahlung with characteristic path length X_0
- Photons convert to lower energy electrons via pair production

with characteristic path length ${}^{9}/_{7}\, X_0$

- Shower multiplication and development

Calorimeter Showers

- Electromagnetic shower:



Credit: D. Petyt

$$s_{max} = \begin{cases} ln\left({}^{E_{inc}}/_{E_c}\right) - 0.5 \text{ for } e^{\pm} \\ ln\left({}^{E_{inc}}/_{E_c}\right) + 0.5 \text{ for } \gamma \end{cases}$$

At critical energy E_c:

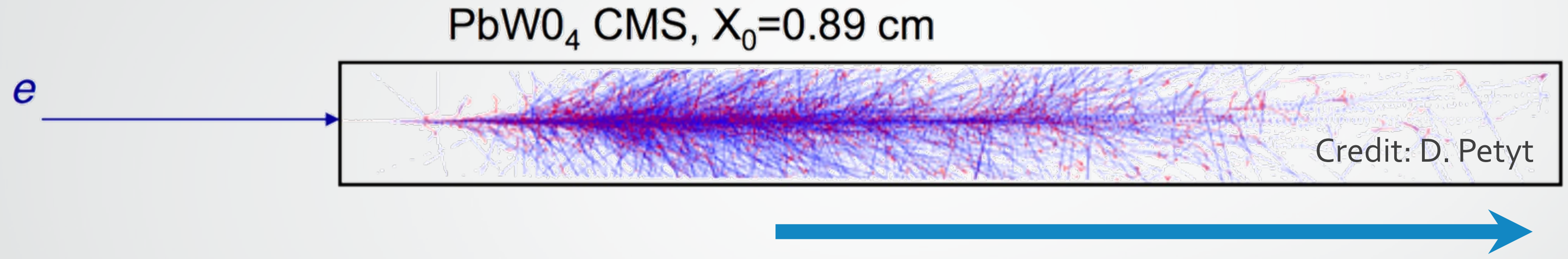
- Average particle energy $\sim E_c$
- Ionization losses are similar to bremsstrahlung and pair production
- Peak particle multiplicity reached → position of shower maximum: s_{max}

- s_{max} depends logarithmically on incident particle energy: $s_{max} \sim ln\left({}^{E_{inc}}/_{E_c}\right)$

  (CMS example: $s_{max} \sim 5X_0$ for a 10 GeV electron in PbWO$_4$)

Calorimeter Showers

- Electromagnetic shower:



Credit: D. Petyt

Below E_c:

- Ionization losses dominate over bremsstrahlung and pair production losses
- Slow decrease in number of shower particles
- Electrons and positrons range out

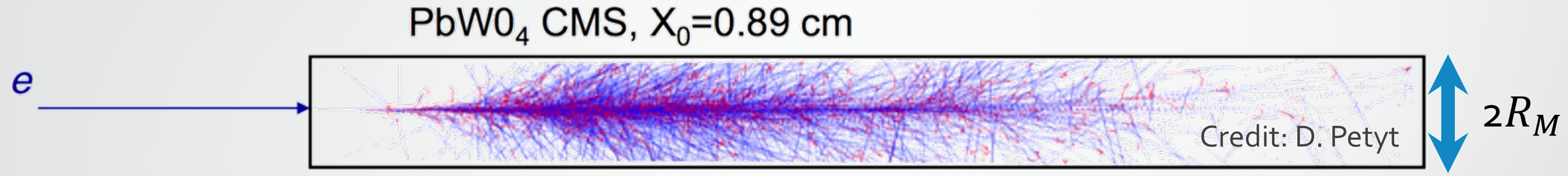
FABlAN & LUDLAM (1982)

- Longitudinal shower containment depends on energy $L(95\%) = (s_{max} + 0.08Z + 9.6)\ [X_0]$

  (CMS example: 100 GeV electron in $PbWO_4$ crystal contained within $\sim 20X_0$)

Calorimeter Showers

- Electromagnetic shower:



Credit: D. Petyt

Lateral shower development

- Described by Moliere radius (R_M): 90% of shower is contained in a cylinder of radius R_M

$$R_M = 21.2MeV\frac{X_0}{E_c}$$

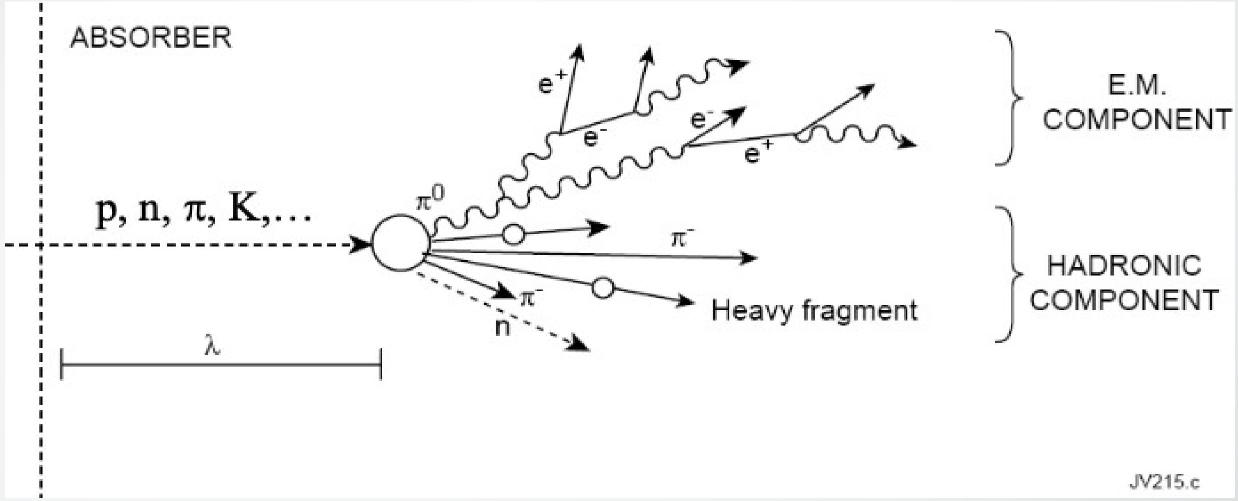
CMS example:

Crystal length: 23cm ($25X_0$) – minimizes end "leakage"

Crystal cross-section: 2.2cm ($\sim R_M$) – maximizes granularity (while lateral "leakage" is minimized by summing energy over 3x3 crystals)

Calorimeter Showers

- Hadronic shower:



Shower development

- Determined by interaction length λ_I of the detector medium
- λ_I is a mean free path between inelastic collisions

$\lambda_I \sim A^{1/3}$ (16.7 cm in Pb)

multiparticle production

$\pi^{\pm}, \pi^0, K$

nuclear breakup

spallation neutrons, protons

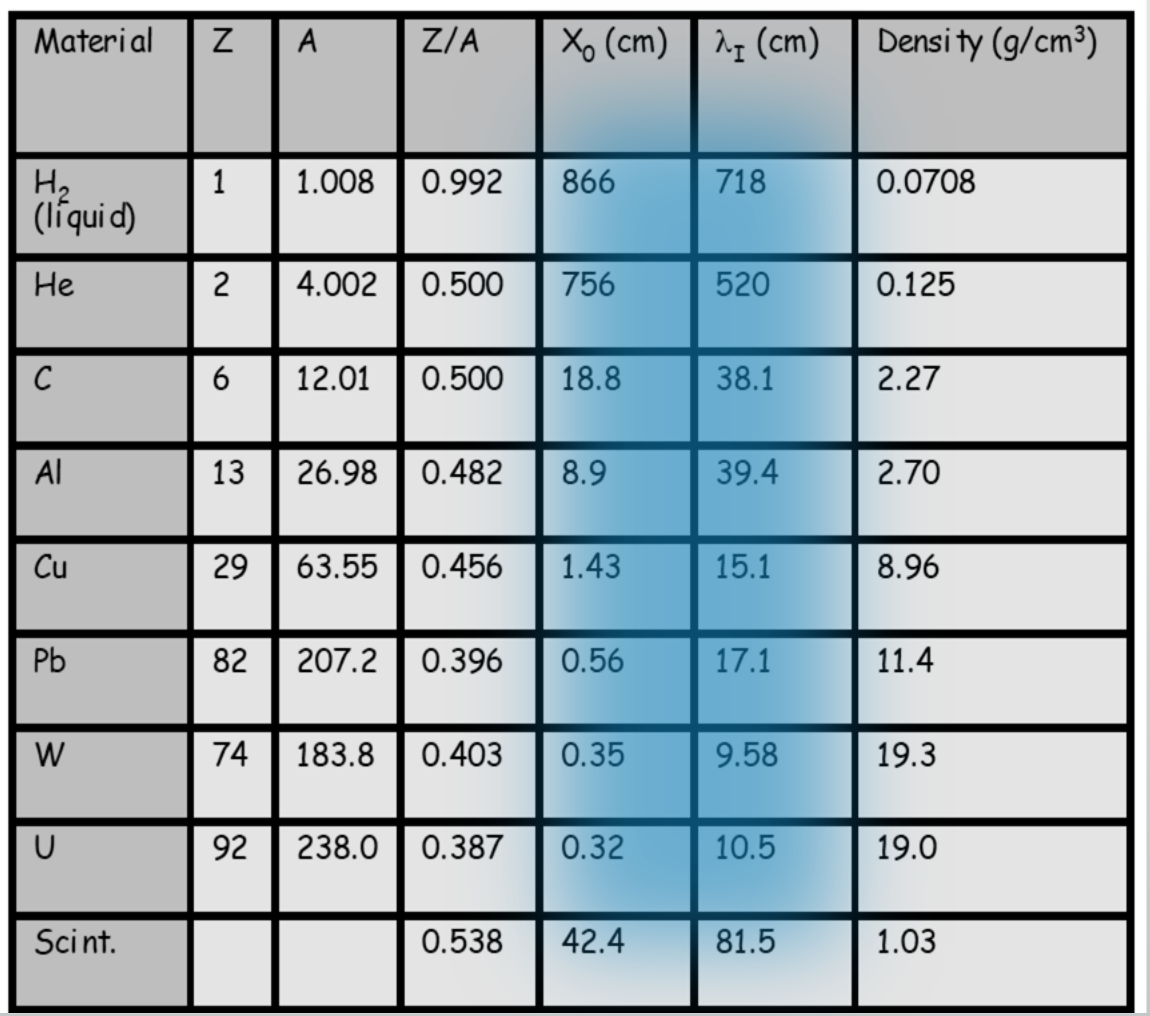
electromagnetic component

$\pi^0 \rightarrow \gamma\gamma$

Calorimeter Showers

- Radiation length X_0 (electromagnetic) vs. interaction length λ_I (nuclear)

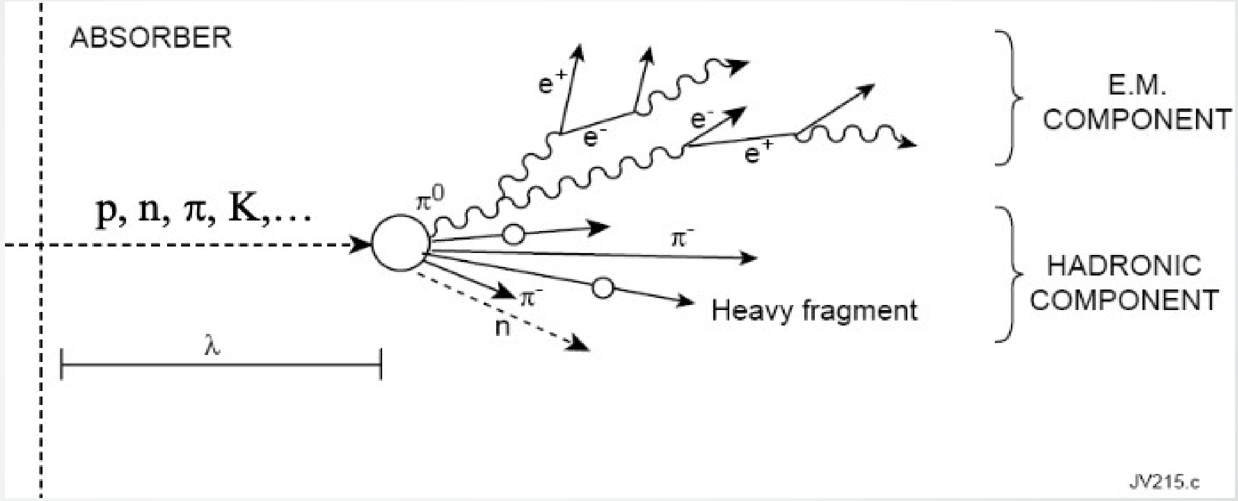
- For most absorbers, $\lambda_I \gg X_0 \rightarrow$
    - HCals are typically much bigger than ECal (to fully contain the hadronic shower)
    - HCals are always placed after ECals



Material	Z	A	Z/A	X_0 (cm)	λ_I (cm)	Density (g/cm^3)
H_2 (liquid)	1	1.008	0.992	866	718	0.0708
He	2	4.002	0.500	756	520	0.125
C	6	12.01	0.500	18.8	38.1	2.27
Al	13	26.98	0.482	8.9	39.4	2.70
Cu	29	63.55	0.456	1.43	15.1	8.96
Pb	82	207.2	0.396	0.56	17.1	11.4
W	74	183.8	0.403	0.35	9.58	19.3
U	92	238.0	0.387	0.32	10.5	19.0
Scint.			0.538	42.4	81.5	1.03

Calorimeter Showers

- Hadronic shower:

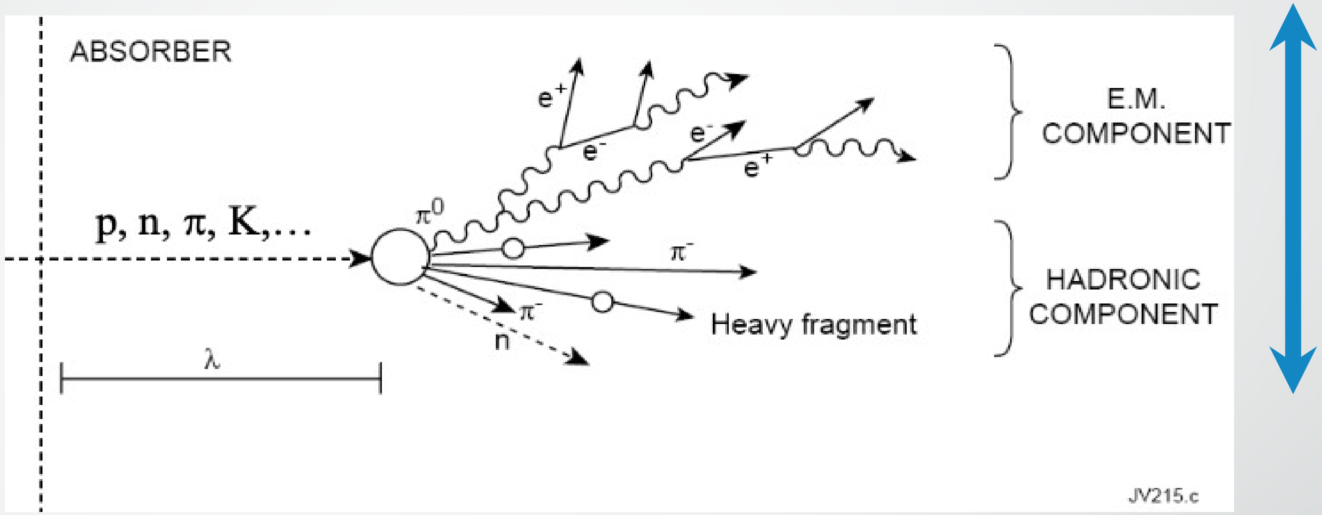


Shower development

- EM component is most significant at the beginning of the shower; falls-off exponentially
- Longitudinal containment:
  - 90% of hadronic shower from 100 GeV pion contained in $\sim 10\lambda_I$ (1.7m of Pb)
  - Peak in shower profile at $\sim 1\ \lambda_I$

Calorimeter Showers

- Hadronic shower:



Shower development

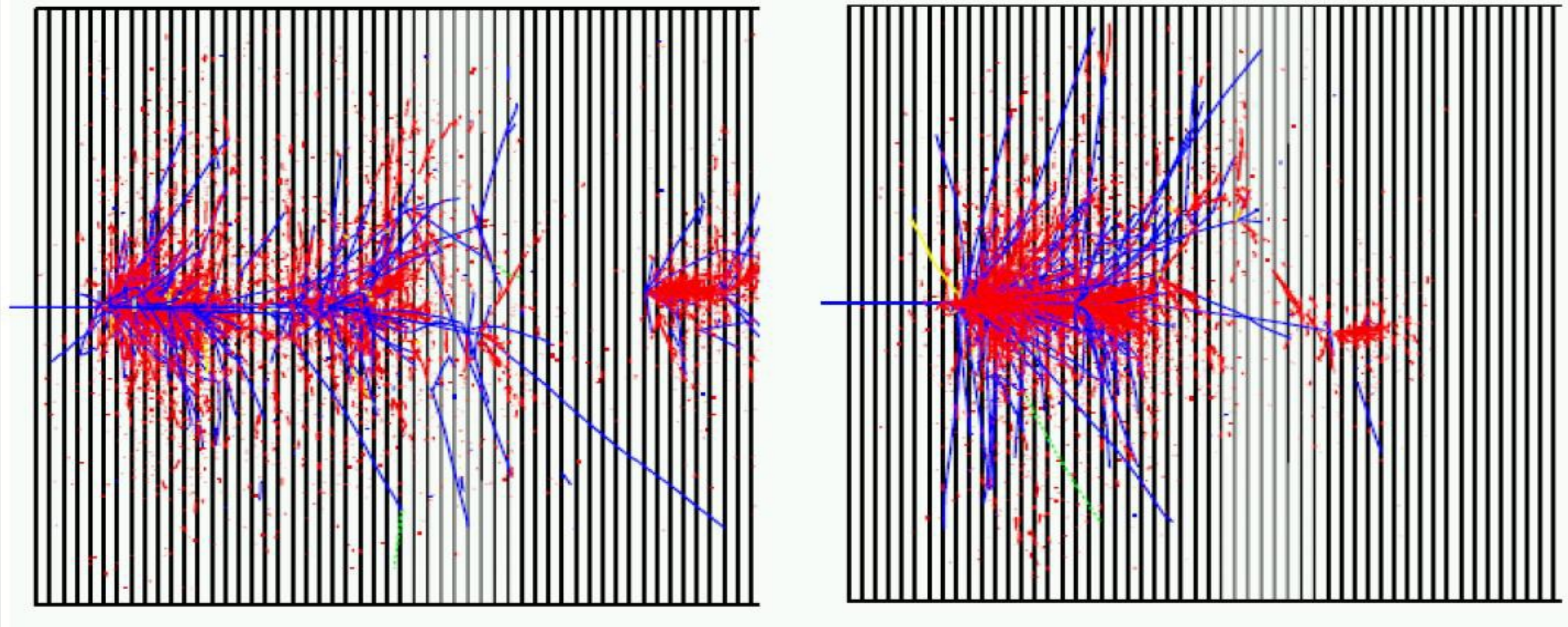
- EM component is most significant at the beginning of the shower; falls-off exponentially
- Lateral containment:
  - Hadron showers are larger and broader than EM showers
  - 90% containment of hadronic shower from 100 GeV pion is within $\sim 1\ \lambda_I$ (17cm of lead)

→ reflected in larger dimensions of HCals are generally bigger than ECals

Credit: D. Petyt

Hadronic Cascades

- Simulations of hadron showers:



Red - EM component   Blue – charged hadrons

- Unlike electromagnetic showers, hadron showers do not show a uniform deposition of energy throughout the detector medium

Designing a Calorimeter

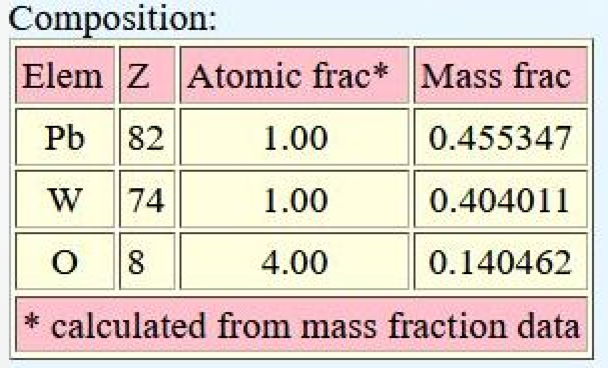
- Shower max: $S_{max} = ln\left(\frac{E}{E_c}\right) \pm 0.5[X_0]$ (E is the incident particle energy)
- Critical energy: $E_c = \frac{610\ MeV}{Z+1.24}$
- Longitudinal shower containment at 95% level is $L(95\%) = (s_{max} + 0.08Z + 9.6)\ [X_0]$

Let's determine basic characteristics for ECal based on PbWo4 and Lead Glass crystals for electron of 10 GeV and 100 GeV

PbWo4

E_c = 9.64 MeV (for e^-)

X_o = 0.8903 cm



Composition:

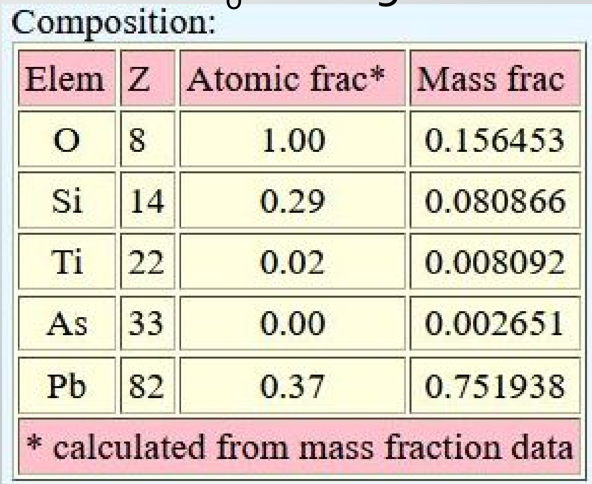
Elem	Z	Atomic frac*	Mass frac
Pb	82	1.00	0.455347
W	74	1.00	0.404011
O	8	4.00	0.140462

* calculated from mass fraction data

Lead Glass

E_c = 10.41 MeV (for e^-),

X_o = 1.265 cm



Composition:

Elem	Z	Atomic frac*	Mass frac
O	8	1.00	0.156453
Si	14	0.29	0.080866
Ti	22	0.02	0.008092
As	33	0.00	0.002651
Pb	82	0.37	0.751938

* calculated from mass fraction data

Designing a Calorimeter

Let's determine basic characteristics for ECal based on PbWo4 and Lead Glass crystals for electron of 10 GeV and 100 GeV

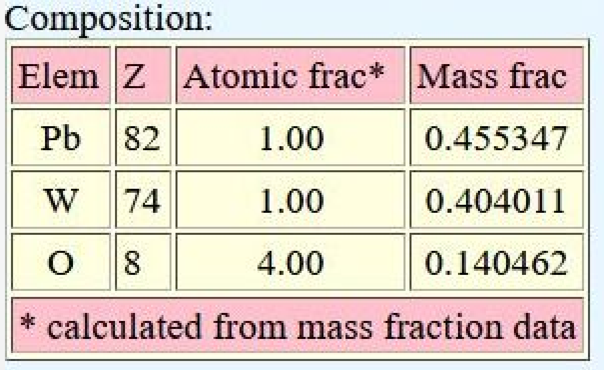
- For PbWO4
  - $Z_{eff}\,(PbW04) = (82 \times 0.455 + 74 \times 0.404 + 4 \times 0.14) = 67.76$
  - S_{max} (10 GeV e)= $\ln(10000/9.64) - 0.5 = 6.45\,[X_0]$
  - $S\_\mathrm{max}(100\ GeV\ e) = \ln(100000/9.64) - 0.5 = 8.74\,[X_0]$
  - $L(95\%, 10\ GeV\ e) = 6.45 + 0.08 \times 67.76 + 9.6 = 21.47[X_0] \sim \boldsymbol{19\ cm}$
  - $L(95\%, 100\ GeV\ e) = 8.74 + 0.08 \times 67.76 + 9.6 = 23.76[X_0]\ \sim\boldsymbol{21cm}$

- For Lead Glass
  - $Z_{eff}\,(Lead\ Glass) = (8 \times 0.15 + 14 \times 0.08 + 22 \times 0.008 + 33 \times 0.002 + 82 \times 0.752) = 64.22$
  - S_{max} (10 GeV e) = ln (10000/10.41) - 0.5 = 6.37 [X_0]
  - S_{max} (100 GeV e)= ln (100000/10.41) - 0.5 = 8.67 [X_0]
  - $L(95\%, 10\ GeV) = 6.37 + 0.08 \times 64.22 + 9.6 = 21.10[X_0] \sim\boldsymbol{27\ cm}$
  - $L(95\%, 100\ GeV) = 8.67 + 0.08 \times 64.22 + 9.6 = 23.40[X_0] \sim\boldsymbol{29.6\ cm}$

PbWo4

E_c = 9.64 MeV (for e^-)

X_o = 0.8903 cm



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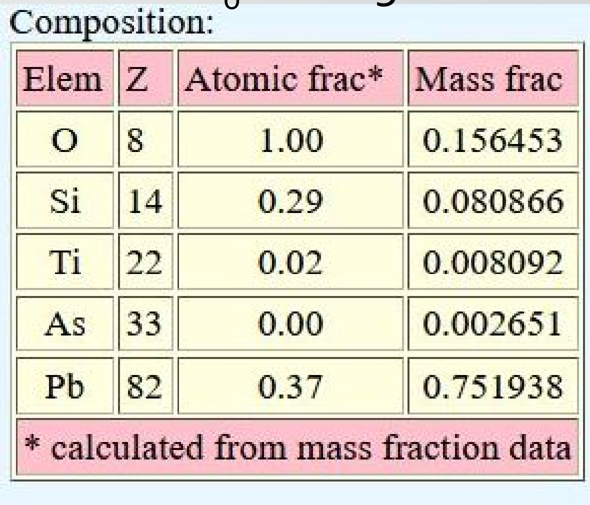

Composition:

Elem	Z	Atomic frac*	Mass frac
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Si	14	0.29	0.080866
Ti	22	0.02	0.008092
As	33	0.00	0.002651
Pb	82	0.37	0.751938

* calculated from mass fraction data

Calorimeter Resolution

Calorimeter Resolution:

- Stochastic term:
  - photon statistics, sampling fluctuations
- Constant term:
  - non-uniform detector response
  - channel-to-channel mis-calibration
  - longitudinal leakage
- Noise term:
  - Electronic noise

Parameterized as follows:

Constant term

$$\left(\frac{\sigma_E}{E}\right) = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

Stochastic term Noise term

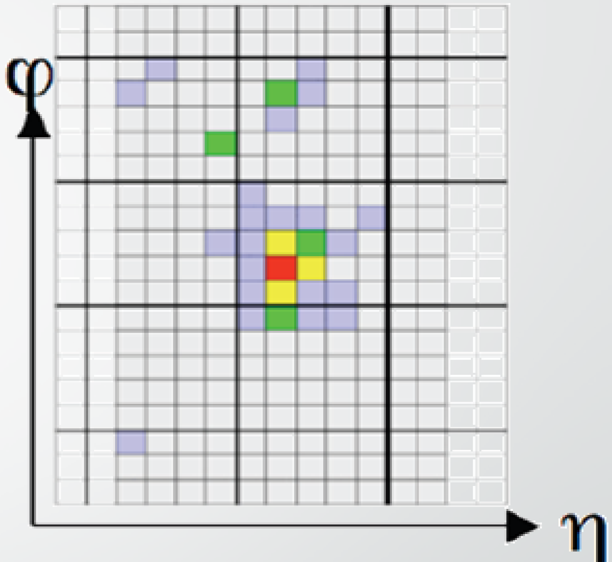
Resolution improves with energy (up to the constant term)

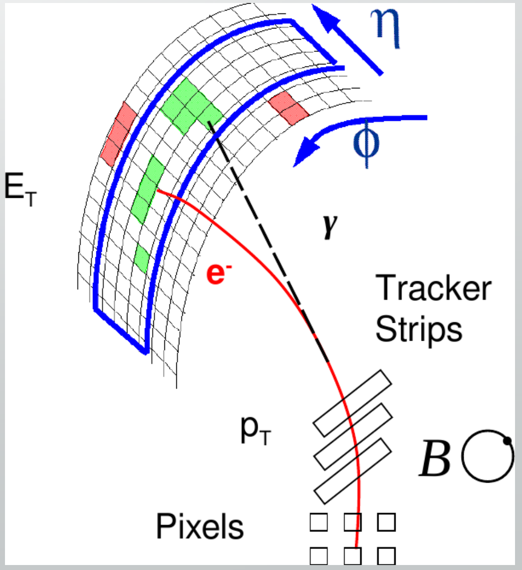
Detector to Physics

Cluster Reconstruction

- After readout of energy deposited to the calorimeter by the incident particles, clustering techniques are often employed for energy reconstruction and PID
- Clustering algorithm groups individual channel energies; many implementations
- Common clustering approach: scan calo cells for local maximum (usually with a predefined threshold) then build a cluster around
- Variations include fixed window/fixed cone size or dynamic cluster building (above certain thresholds)
- Next – multivariate cluster corrections: improve energy determination by employing event information (i.e. showering/ non-showering, proximity to dead regions)

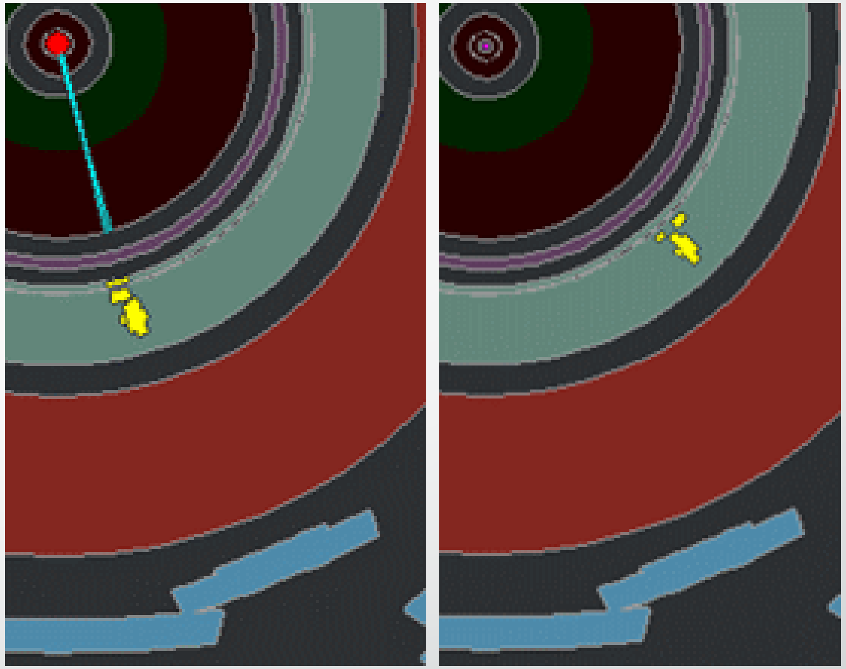
(HIN data usually require some form of data-driven pedestal subtraction)





Detector to Physics: Particle ID

Electrons vs. Photons vs. Jets



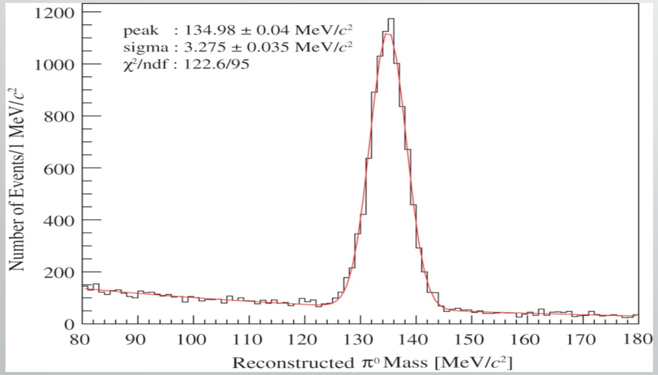
- Global analysis (Particle Flow algorithm)
- Energy deposit in EM calorimeter
  - Energy nearly completely deposited in ECal
  - No energy in HCal (hadronic leakage)
- Cluster shape check
  - narrow" e/γ vs "broad" mainly jets
  - substructure: $\pi^0 \rightarrow \gamma\gamma$
- "Track back"
  - electrons has a track pointing to the cluster
  - Photons do not (but mind photon conversion)
- Momentum measurement for e: combination of tracking and calorimeter information

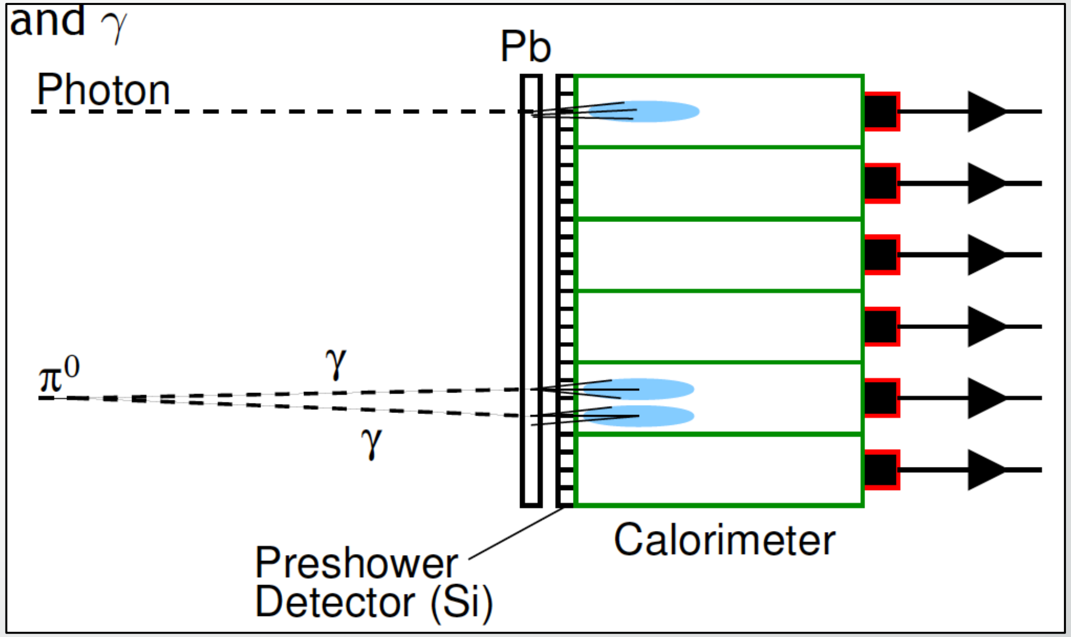
Detector to Physics: π^o ID

- Neutral pion measurement/suppression is allowed through ECal measurements. Decay channel:

$$\pi^0{-}{>}\gamma\gamma$$

- Decay photons are detected by Ecal, providing energy and *location*; together with primary vertex location one can build 4-momenta for invariant mass technique

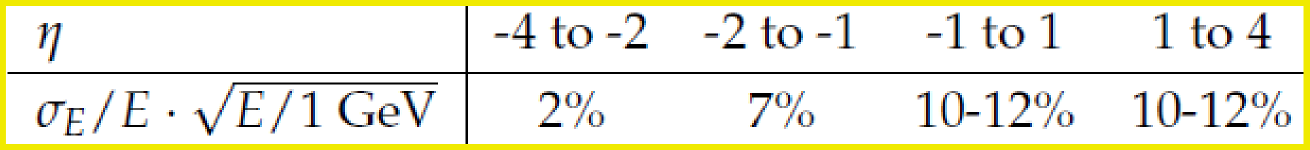




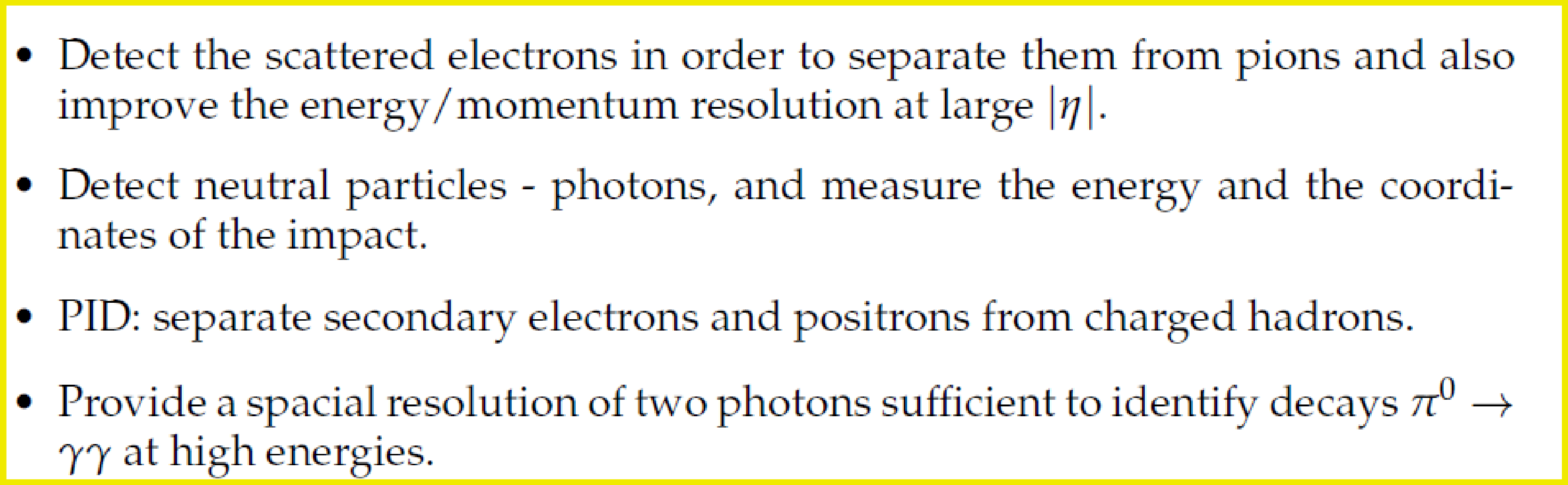
For large boosts/small opening angles: ECal is combined with high granularity Preshower

Calorimeters for EIC

- General design considerations:
  - (high) resolution, especially for ECAL
  - (high) granularity (for particle ID and position measurement)
  - Compact and hermetic
- YR requirements for EIC ECal



η	-4 to -2	-2 to -1	-1 to 1	1 to 4
$\sigma_E/E \cdot \sqrt{E/1\ \mathrm{GeV}}$	2%	7%	10-12%	10-12%

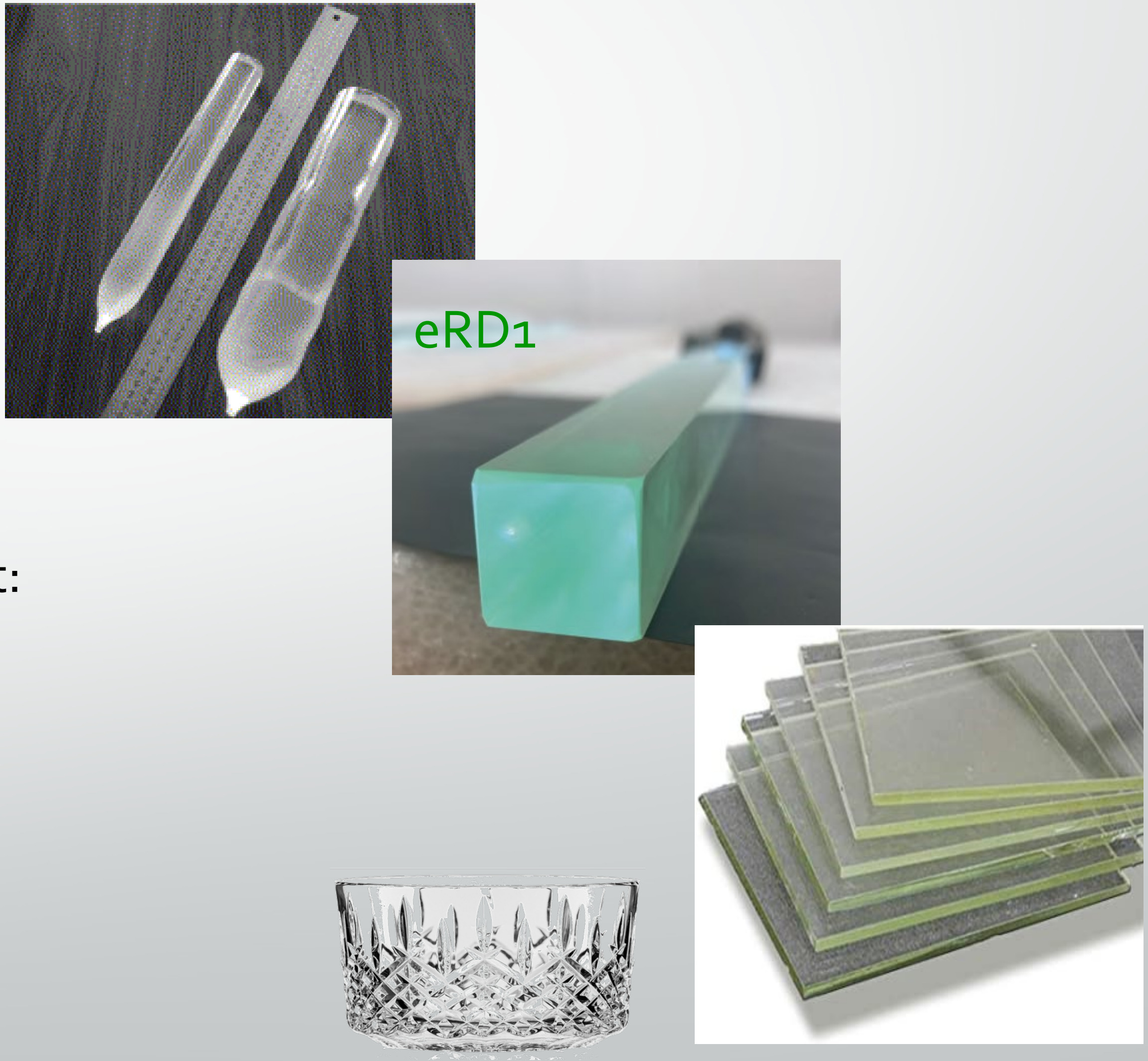


- Detect the scattered electrons in order to separate them from pions and also improve the energy/momentum resolution at large $|\eta|$.
- Detect neutral particles - photons, and measure the energy and the coordinates of the impact.
- PID: separate secondary electrons and positrons from charged hadrons.
- Provide a spacial resolution of two photons sufficient to identify decays $\pi^0 \rightarrow \gamma\gamma$ at high energies.

EIC ECal Options

Homogeneous

- **PbWO4**: well-established technology. High resolution, compactness, radiation hardness
- **Scintillating glass**: a new, cheaper material. Expected resolution ~ PbWO4. Cheaper. But: less dense, needs more space
- **Lead glass**: uses Cherenkov light, typical resolution of $a \sim 6\%$. But: less dense, needs more space

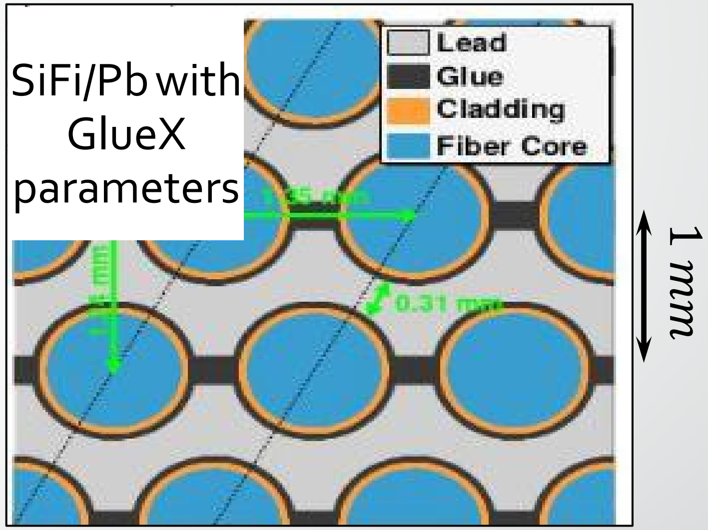


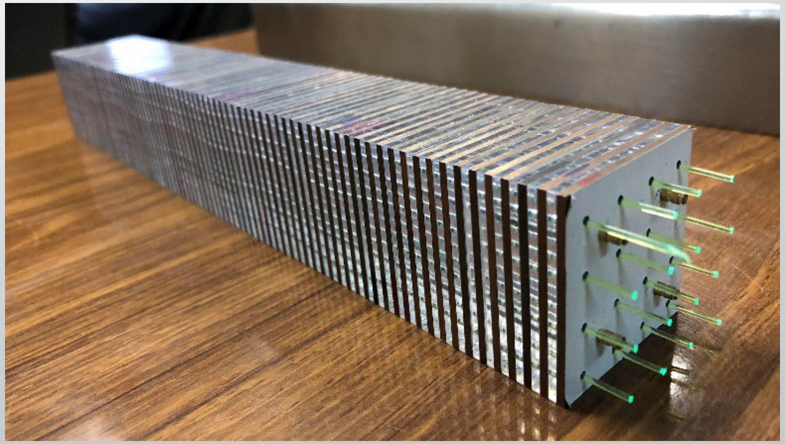
EIC ECal Options

Sampling

- **Pb/ScFi** or **W/ScFi**: fibers are embedded into a heavy material. Established technology. Resolution varies between 6-15%

- **Shashlyk** - a stack of absorber and scintillator plates. The light is collected by fibers passing through the plates. Widely used technology. Resolution varies between 5-15%.



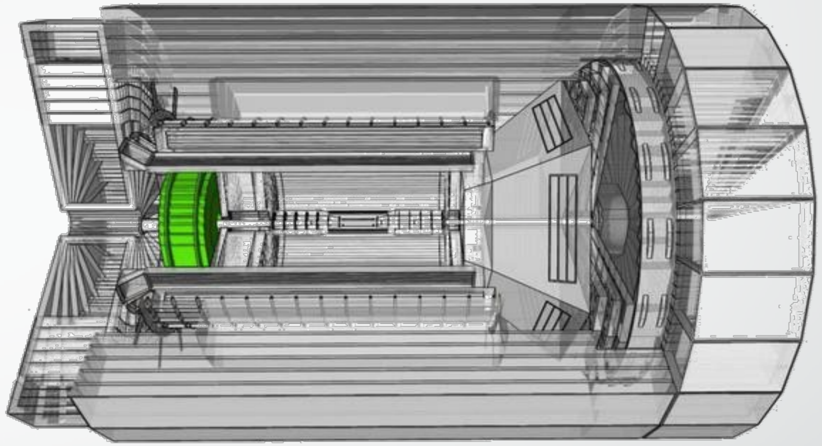


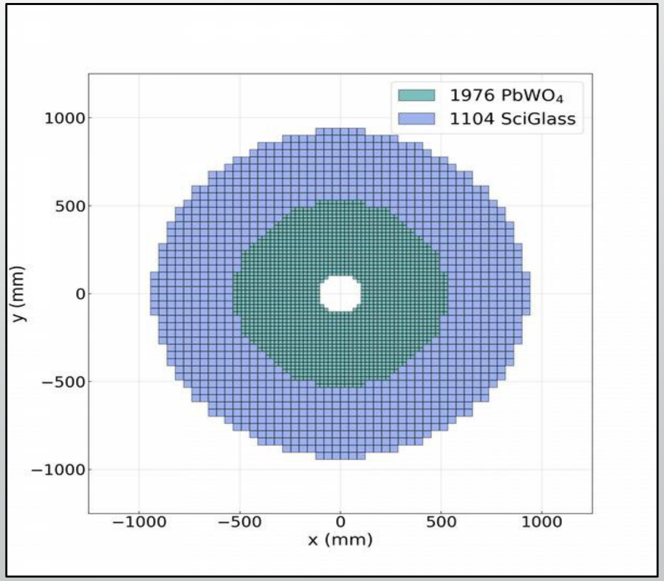
Hybrid Options Explored: Electron side

- Electron “end cap” -- most demanding resolution requirements
- Hybrid approach: a mix of new and old technologies

- Crystal only option for General Purpose EIC detector needs ~7600 ($2x2x20$ cm^3) PWO4 modules → Weight: 5-6 tons!

- Possible Hybrid PWO4+ SciGlass option
  - 1976 ($2x2x20$ cm^3) Crystal modules
  - 1104 ($4x4x40$ cm^3) Glass modules

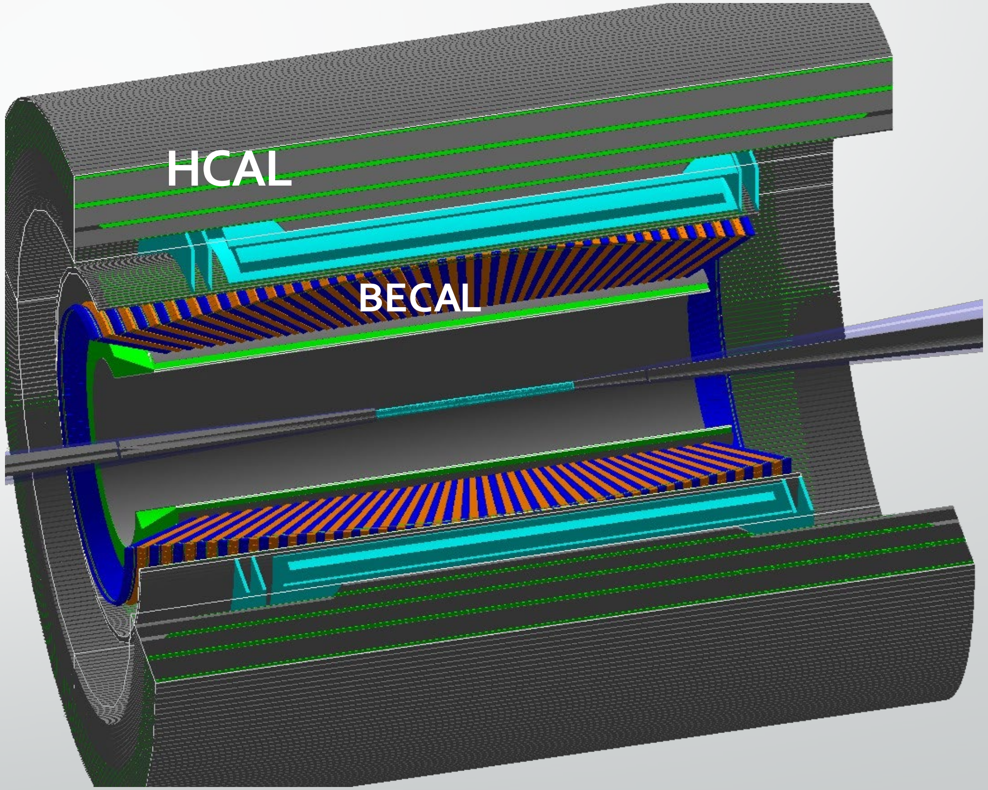




Options Explored: Central Region

- Another hybrid approach: a mix of new and old technologies
- ECal: Sci-Glass calorimeter
- 4 × 4 × 45.5 cm partially projective towers

- HCal: Fe-Sci Tile Calorimeter
- Re-use sPHENIX outer HCal
- Read-out upgrade with new SiPMs

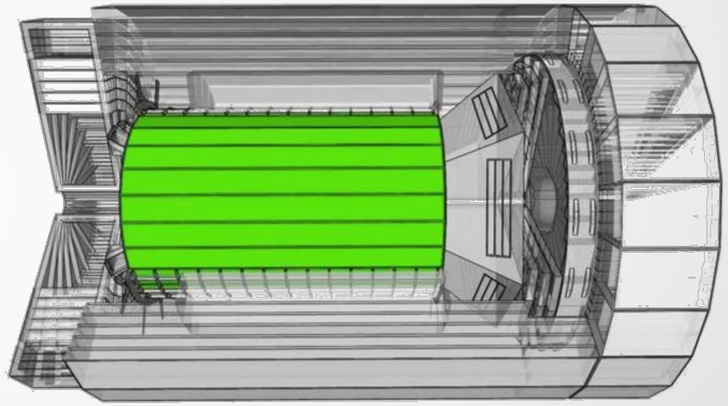


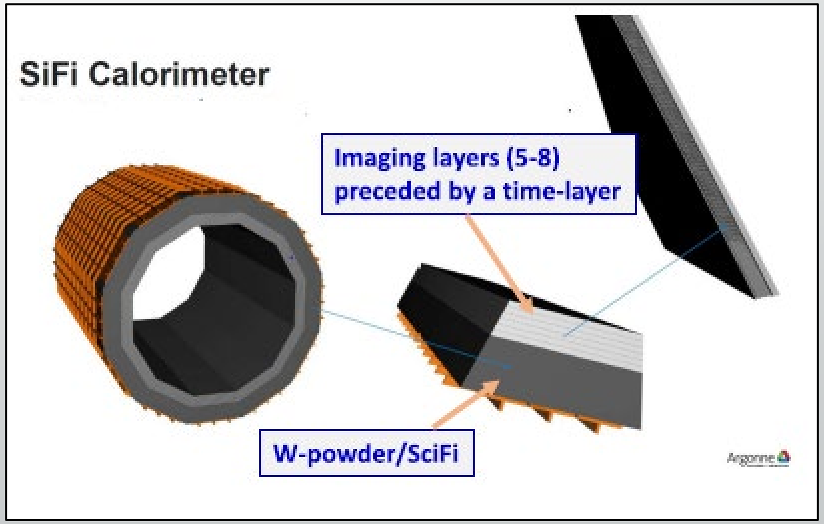
Options Explored: Central Region

Hybrid imaging calorimeter

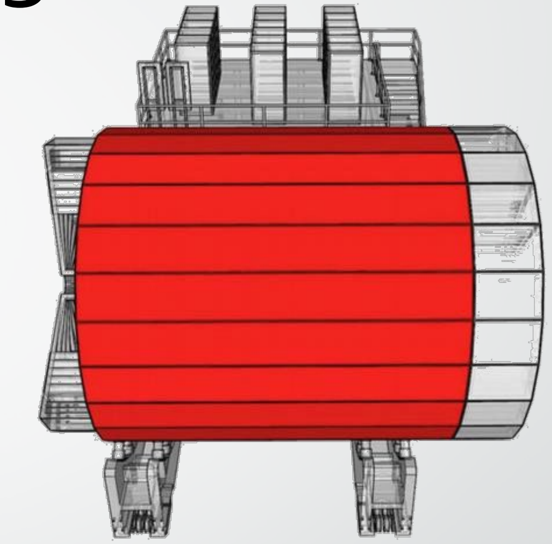
- Inside→out
  - LGAD timing layer to help PID
  - Imaging calorimeter based on monolithic silicon sensors
  - W/SciFi (starting configuration is based on GlueX)

- Silicon pixel sensors: AstroPix (developed for NASA, off-the shelf)
  - Energy resolution:~2% within dynamic range (20keV to ~a few MeV)





Options Explored: Central Region

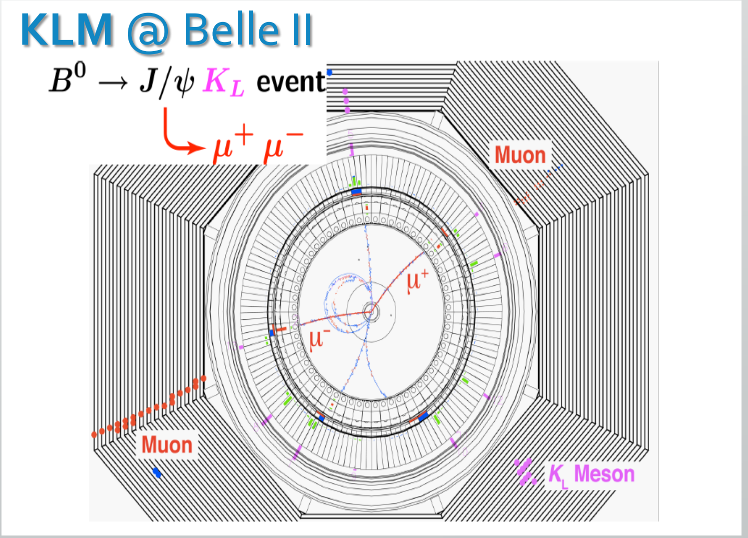


KLM-type calorimeter

- Based on optimized design of Belle KLM device
- Goal to detect K_L^0 and muons
- Belle II studies:
  - high efficiency and purity for muons above ~ 0.6 GeV
  - good angular resolution (~ 2 deg) for the K_L^0

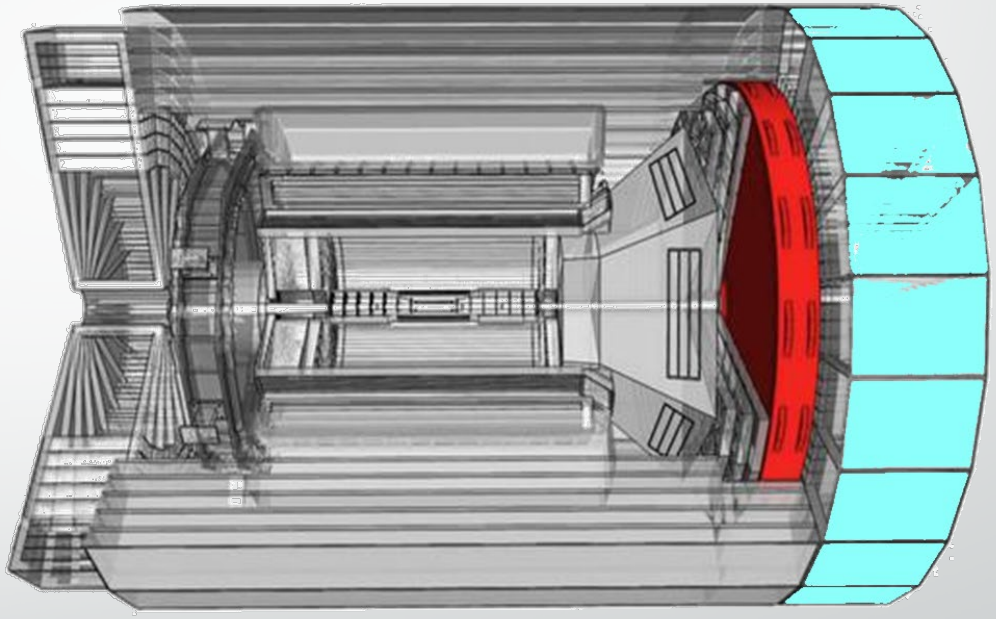
Possible realization:

- layers of ~20mm Fe and~ 5 mm plastic scintillator in 10x10 cm^2 cells
- Could reuse STAR BEMC Scintillator mega-tiles with SiPM readout
- Each layer ~80 tiles; 5-7 layers



Options Explored: Forward

- Another mix: a system of W/SciFi + Fe/Sc
- ECAL: W/ScFi ECAL
  - Compact, high resolution
  - Similar technology is used for sPHENIX
- HCal : Fe/Sc
  - Latest tests: $\sim 30\%/\sqrt{E}$ + small constant term
  - Similar   to STAR Forward HCal upgrade longitudinally separated Fe-Sci tile calorimeter



ECal options: 18 X0 / 23 X0. Could reuse PHENIX

HCal options: Fe/Sc of 20 mm Fe and 3 mm plastic; needs $\sim 6-7\,\lambda$ total

Calorimeters: Wrapping Up

- Calorimeters are crucial parts for Nuclear (and Particle) Physics detectors
  - Provide energy measurements of electrons/photons, jets and (neutral) hadrons
  - Aid/provide PID capabilities
- Several design choices available for each of the EIC generic detector regions: backward, central, forward
  - No straightforward "right" or "wrong" choices
  - Optimization is crucial for desired performance