Les detecteurs du futur

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École polytechnique - Palaiseau

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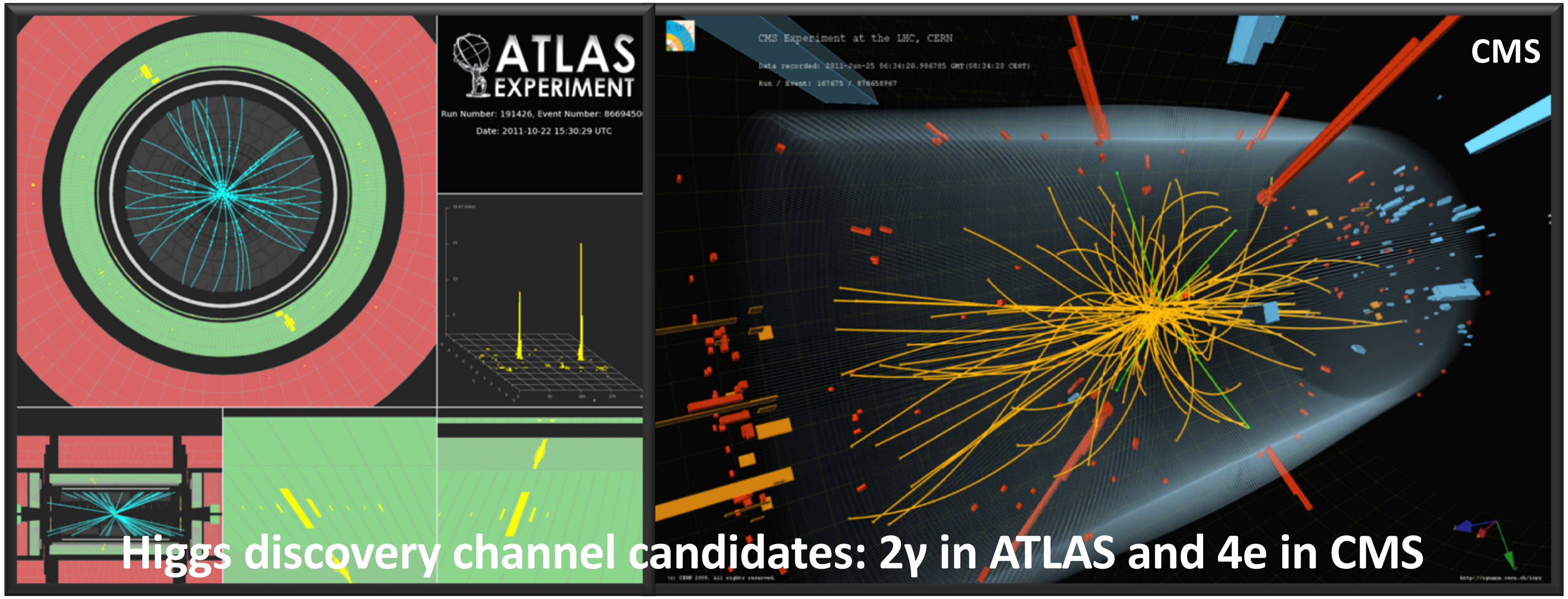
Calorimeters

Measure energy and identify e/γ, measures charged and neutral hadron energy and identify jets (τ, q, g), measure missing transverse energy (ν, BSM) provide trigger information, can also provide position, direction and Time of Flight information with various precisions

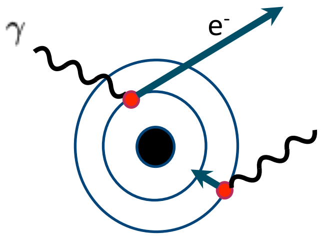


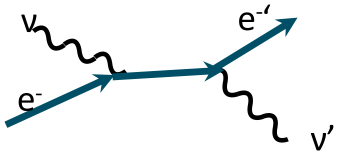
Higgs discovery channel candidates: 2γ in ATLAS and 4e in CMS

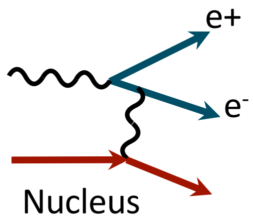
Photon interactions and electron energy loss* in matter

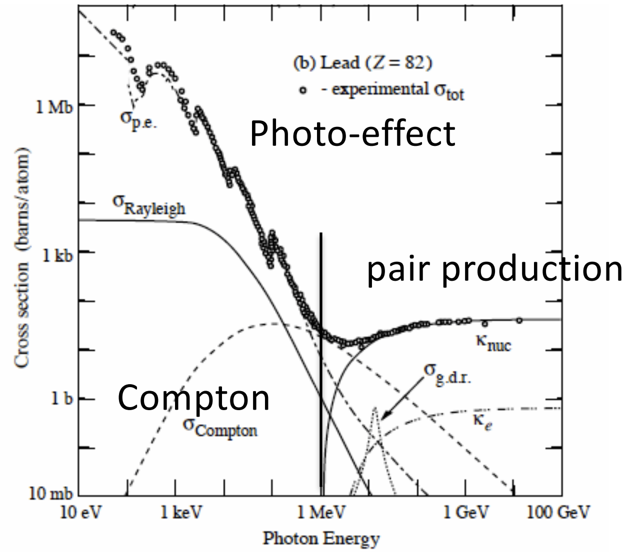
Photon interactions in matter are mostly

Photo-electric effect, Compton scattering, pair production







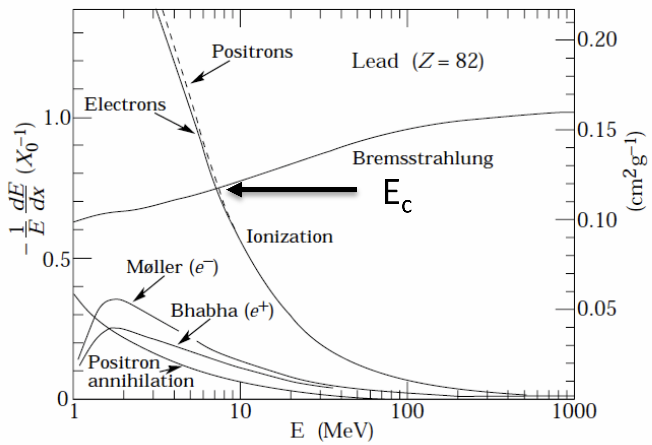


- In calorimeters photon pair production is dominating ($E \geq 1$ MeV)
  - Mean free path $\lambda = (9/7)\, X_0$, $I(x) = I_0\, e^{-(7/9(x/X0))}$
- Electron energy loss is dominated by Bremsstrahlung down to E_c:
  - $dE/dx \propto Z^2E/m_e^2$, $E(x) = E_0e^{-x/X0}$
  - Energy loss is 63% after 1 X_0

Main parameters are radiation length $X_0 \simeq 183\ A/Z^2$ g cm^{-2}

and critical energy $E_c \simeq 610$ MeV/$(Z + 1.24)$[1)]

Favored materials in calorimeters have high Z

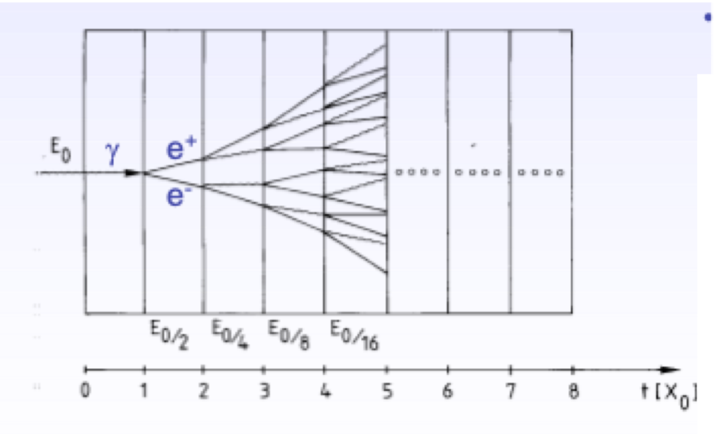


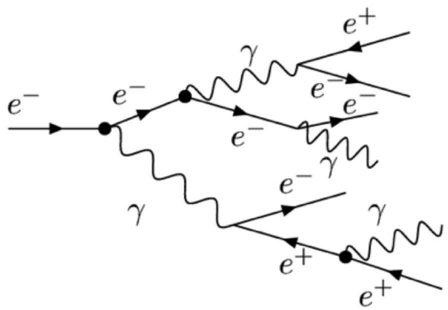
1) *For solid and liquid*

Electromagnetic (EM) shower cascade

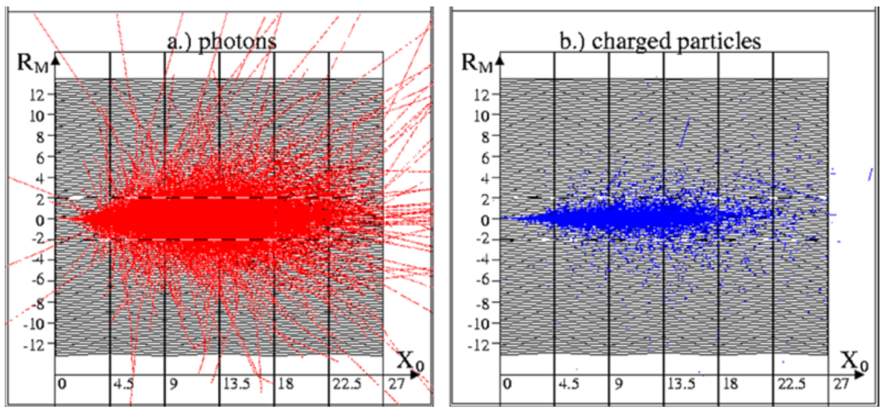
Photon interactions, direct or from incident e bremsstrahlung, leads to a e/γ cascade

- Primary γ with E_0 energy have a 54% probability to produces e^+e^- pair in a layer of 1 X_0
  - On average, each has $E_0/2$ energy If $E_0/2 > E_c$, they then lose energy by Bremsstrahlung
- In next layer X_0, charged particle energy decreases to $E_0/(2e)$
  - Bremsstrahlung with an average energy between $E_0/(2e)$ and $E_0/2$ is radiated
    - Radiated γs produce again pairs
- After n radiation lengths $N_{particles} \simeq 2^n$ with average energy $E \simeq E_0/2^n$
  - Showers continues until E becomes ≤ $E_c \simeq 610\ \mathrm{MeV}/(Z + 1.24)$[1], $n_{max} = \ln(E_0/E_c)/\ln(2)$, $N_{total} = 2E_0/E_c$
    - For a 50 GeV electrons in Pb: $N_{total} \simeq 14000$ and $n_{max} \simeq 13\ X_0$





Simulation of a 100 GeV electron shower in Liquid Krypton

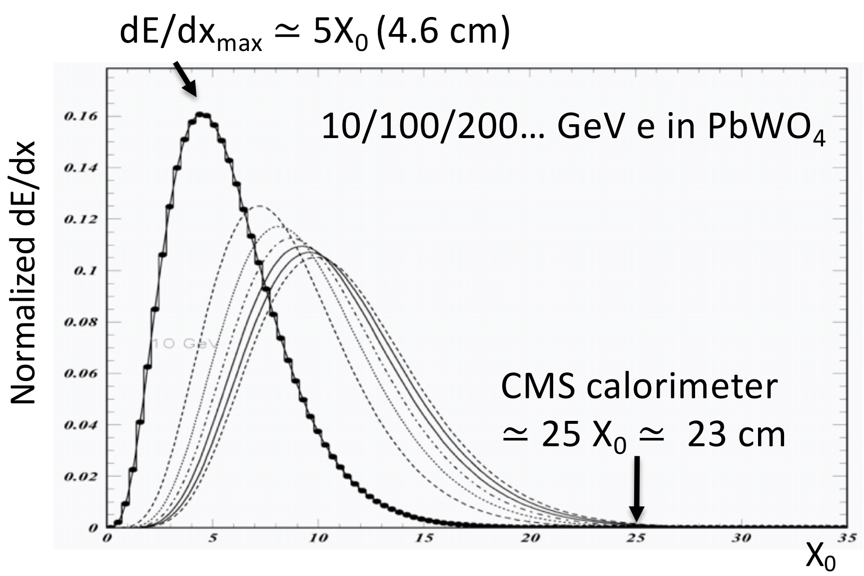


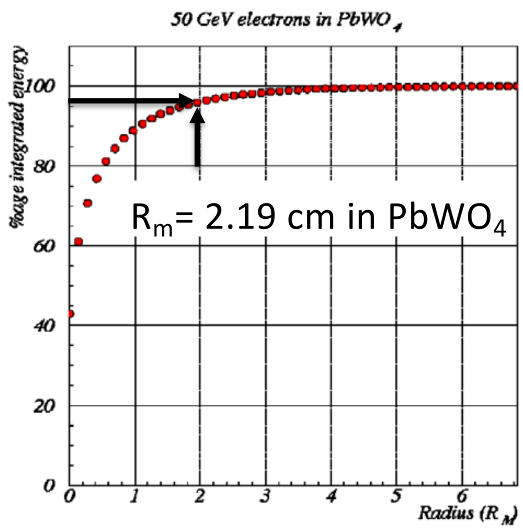
1) For solid and liquid

Electromagnetic (EM) shower properties

Shower spatial development:

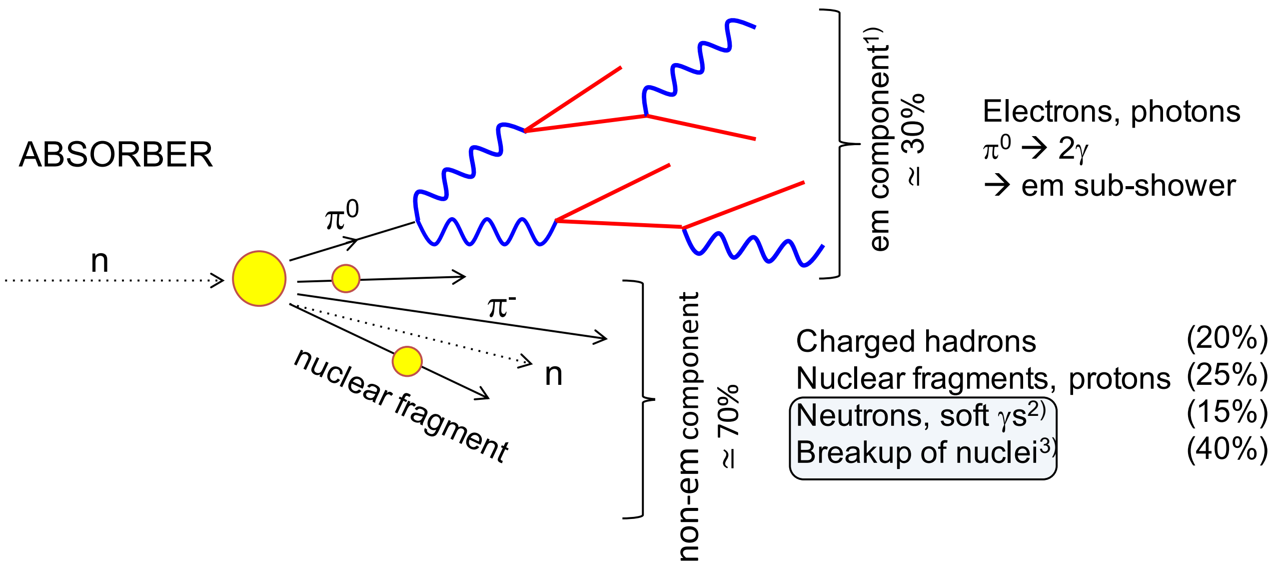
- Longitudinal energy deposit is governed by material radiation length
  - Energy deposit peaks at $n_{max} \simeq \ln(E_0/E_c)/\ln 2$
  - Typically 25 X_0 are required for adequate shower containment at LHC energy
- Transverse size is characterized by Moliere radius R_M defined as the radius of the cone containing 95% of the shower energy
  - $R_M = 21.2 \text{ MeV } X_0/E_c = 0.035X_0(Z+1.24)$



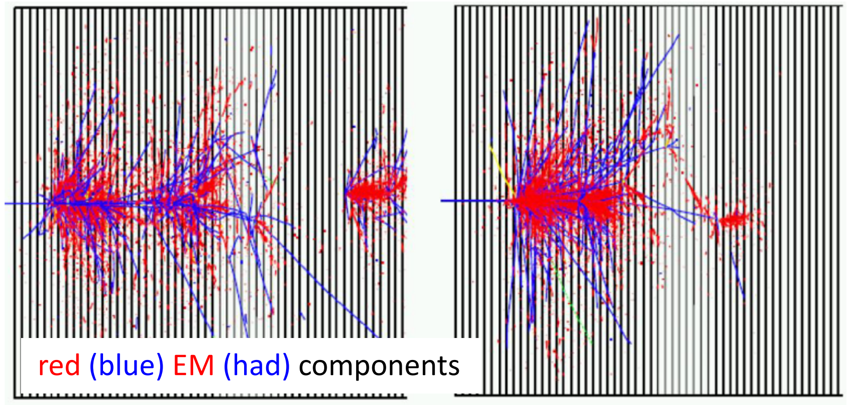


Hadronic shower cascade

Hadron nuclear interaction involve several processes the shower development is driven by the mean free path: Interaction Length $\lambda_I = A/(N_A\sigma_{total}) \simeq (35/\rho)\,A^{1/3}$ cm



Two examples



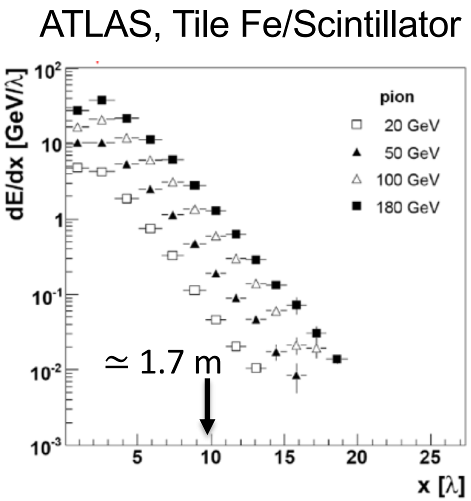
Hadronic showers are not uniform (as EM)
substantial fraction of energy is not measured limiting energy resolution

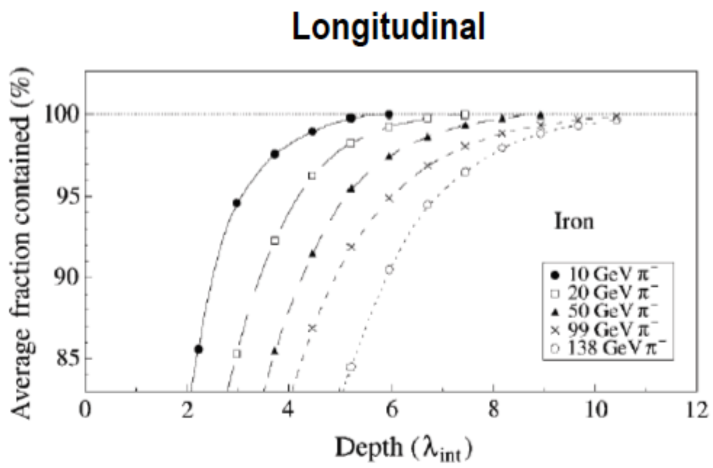
1) *Increase with energy and depends on material, typically 30(50)% at 10(100) GeV*
2) *Late component needs large integration time window O(μs) to be measured*
3) *Depends on material ex. Pb(Fe) invisible energy is 34(21)%*

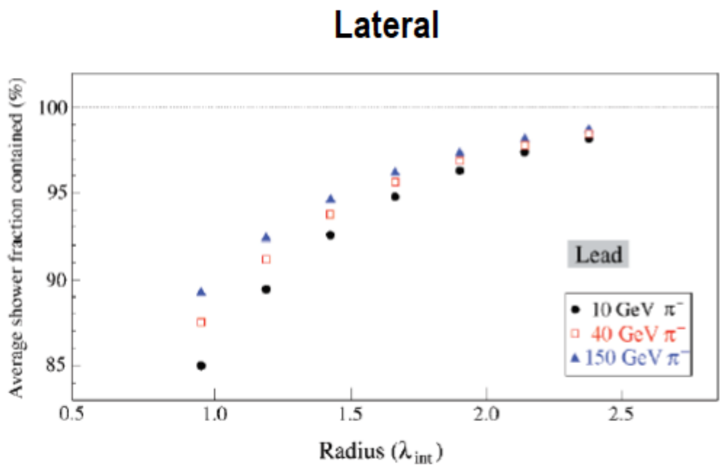
Hadronic shower properties

Shower spatial development[1)]:

- Longitudinal profile
  - dE/dx peak close to 1st interaction, dominated by EM component, fall-off $\simeq$ exponential with λ_I
  - Typically 10 λ_I for adequate shower containment at LHC energy
- Transverse size as an EM core and a Halo from lower energy particles
  - 95% containment within $\simeq$ 1.5 λ_I (ex. 1.5 $\lambda_I \simeq$ 26 cm in Pb compared to 2 cm for EM in $PbWO_4$)





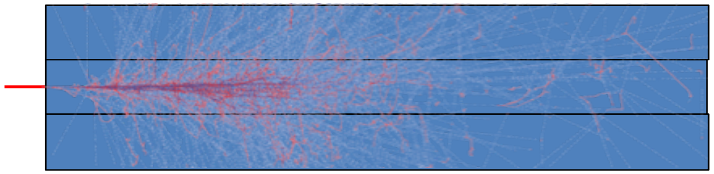


Hadronic calorimeter sections are much longer than EM ones

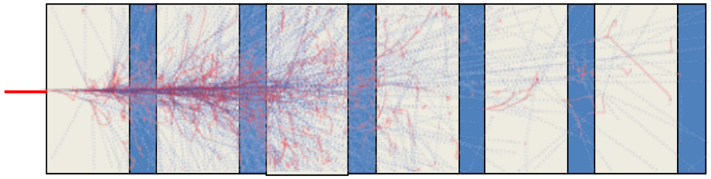
1) *Longitudinal and transverse profile discriminate e/γ and hadron showers for particle ID*

Calorimeter designs: two main concepts but several designs

- Homogenous calorimetry: the absorber is also the active material
  - All released energy is measured, providing best stochastic contribution to energy resolution
  - Compact enough for EM shower measurement (not for had. showers in collider experiments)
  - Doesn't allow fine longitudinal segmentation



- Sampling calorimetry: alternate absorber and sensitive layers
  - Only fraction of released energy is measured, depending on geometry
    - Fluctuations limit energy resolution
  - It is compact suitable both for EM and Had. Calorimetry
  - It can be segmented both in longitudinally and transverse plan
    - Several possible designs depending on sensitive element technology



- Several technologies are possible for sensitive elements
  - Ionization noble liquid (Ar, Xe, Kr), Silicon-sensors, Gas detectors
  - Scintillation in organic/inorganic(crystals) materials
  - Cerenkov light in quartz…

Electromagnetic energy resolution

Relative energy resolution is parameterized as: $\sigma(E)/E = S/\sqrt{E} \oplus N/E \oplus C$

- Stochastic term S: signal statistical fluctuations
  - Ideally in homogenous calorimeters (EM) $\sigma(E)/E$ (stochastic) $= 1/\sqrt{N_{particle}} = \sqrt{(Q/E)}$, Q energy to produce γ/e[1)], typically $S \simeq 1 - 3\ \%$
  - In sampling calorimeters fluctuations are depending on sampling fraction (energy deposited in active layer over total energy)
    - $S \simeq 2.7\%\ \sqrt{(d(mm)/f_{samp})}$, d active layer thickness, f_{samp} fraction of total energy deposited to energy deposited in active layers, typically $S \simeq 10 - 20\ \%$
- Noise term N: electronics noise, spurious signal from collision pile-up and activation effects
- Constant term C: detector inhomogeneities, calibration, fluctuations in longitudinal energy containment, dead material in front of calorimeter

Optimization can depend on experimental conditions, ex. pile-up effect on noise term and physics priorities, ex high mass particles dominated by constant term

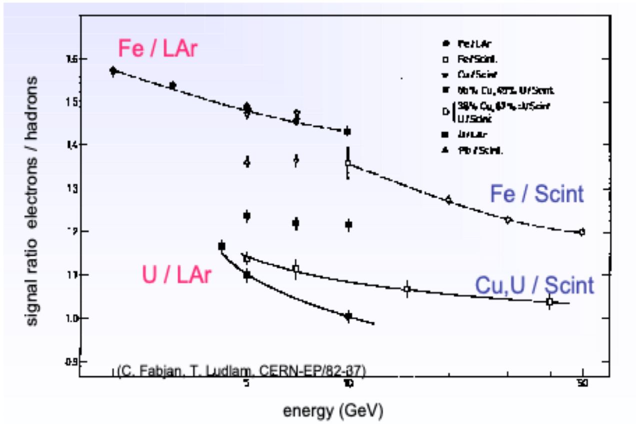
1) $Q \simeq 3.6, 30, 100$ eV in Si, Gas and Scintillators

Hadronic energy resolution

Due to ≠ efficiency for EM and Had. components hadron response is not linear with E

To improve linearity & resolution, e/h response should be close to 1 "compensation"

- Adjustment of sensitivity to EM and had. components through design parameters
  - Sampling design/fraction, ex educed EM sensitivity high(low) Z absorber(active material)
  - Increased sensitivity to non had. (neutrons & soft photons) with scintillators with H, U absorber, long time windows
- Dual readout design, measure energy in material Cerenkov(Scintillating) differently sensitive to EM(hadron) energy deposit in
- Fine segmentation to weight EM and hadron components event by event in software reconstruction



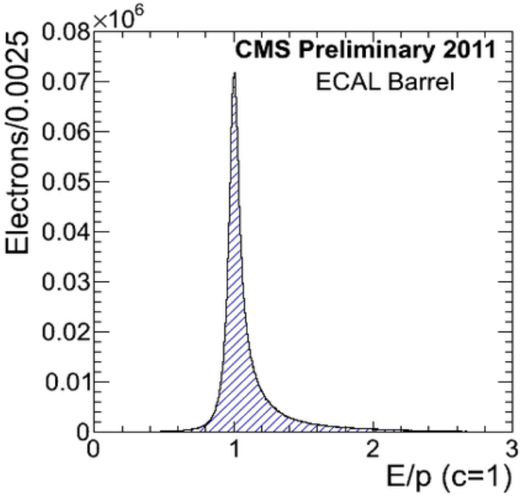
Calorimeter designs: usual material parameters

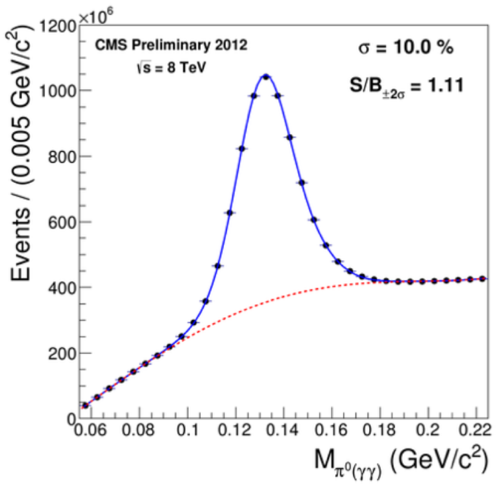
	Z	ρ (g.cm^{-3})	E_c (MeV)	X_0 (cm)	λ_{int} (cm)
Air				30 420	~70 000
Water				36	84
$PbWO_4$		8.28		0.89	22.4
C	6	2.3	103	18.8	38.1
Al	13	2.7	47	8.9	39.4
L Ar	18	1.4		14	84
Fe	26	7.9	24	1.76	16.8
Cu	29	9	20	1.43	15.1
W	74	19.3	8.1	0.35	9.6
Pb	82	11.3	6.9	0.56	17.1
U	92	19	6.2	0.32	10.5

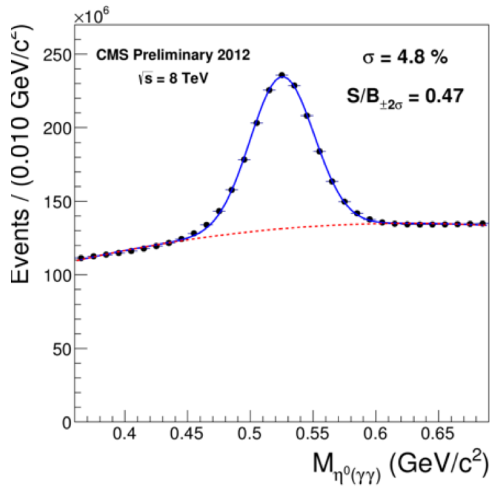
Energy calibration

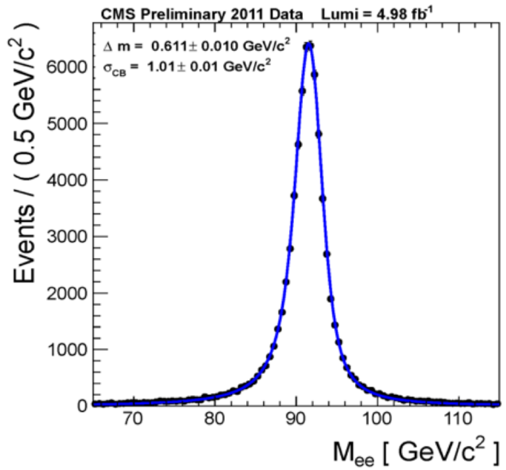
Accurate calibration across the entire detector is also critical for energy resolution

- Intercell calibration with muons[1] (≃ Minimum Ionizing Particles, small S/N)
- Relative ring calibration from Φ-symmetry (≃ days)
- Use electron E(calorimeter)/P(tracker)[2] distribution for EM
- Use back to back jets for hadron calorimeters
- Absolute calibration from particle mass measurement (≃ week(month) π(Z/W))
- Monitor operation conditions and aging of detector components under irradiation





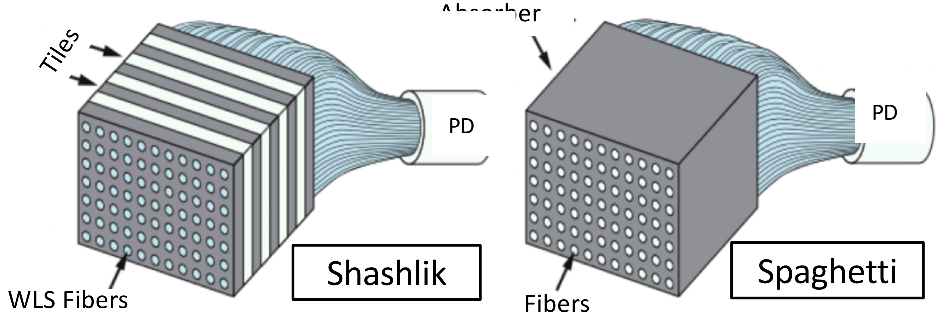


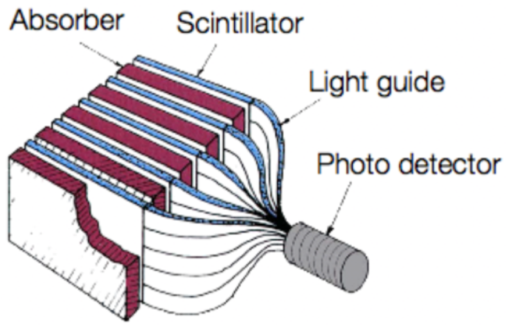


1) *Pre-calibration can be done with cosmic at commissioning time*
2) *Tracker resolution for electrons better than em up to few GeV (depending on B-field)*

Current calorimeters: typical designs versus technology

- Scintillating/Cerenkov
  - Homogenous
    - Crystals EM-CAL
  - Sampling
    - Crystal/Scintillator/Cerenkov in shashlik (EM-CAL) (tiles + WLS fibers) or spaghetti designs (fibers) (possibly both EM-CAL/HCAL)
    - Scintillator in tiles (HCAL)
- Liquid noble gas
  - Sampling
    - ECAL and HCAL with longitudinal and transverse segmentation
- Silicon Technologies
  - Sampling
    - ECAL high granularity
- Gas technologies
  - Sampling
    - HCAL high granularity





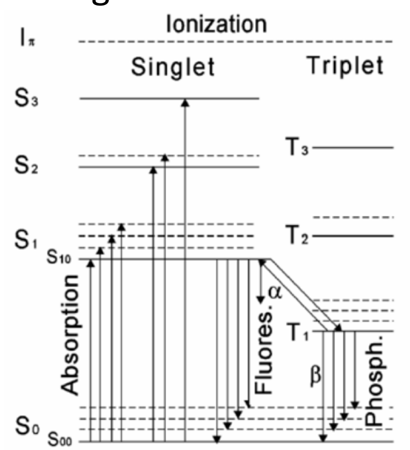
HCAL tile design example, also design
for liquid noble gas and high granularity calorimeters

Calorimeters: scintillation/Cerenkov technologies

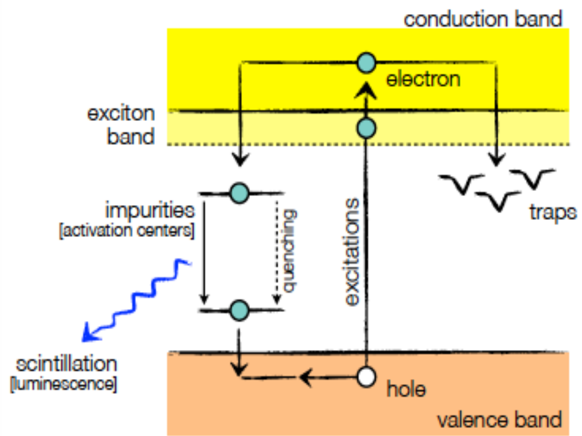
Scintillation mechanism

- Electrons are excited to high energy levels in organic scintillator or to conduction band in inorganic crystals
    - Organic scintillator directly de-excite with γ-emission
    - In crystals electrons recombine in bandgap with intermediate levels created by doping in the crystal lattice (impurities) that eventually de-excite with γ-emission
- γ-emission can be fluorescence fast O(ns) and/or phosphorescence O(up to hours)
- Signal increases with energy[1)]
    - Light in UV (100-350 nm) and visible range (350 – 500) nm
- Fast rise time allows precise ToF measurement
- Decay time must be short to avoid dead time

Organic scintillators

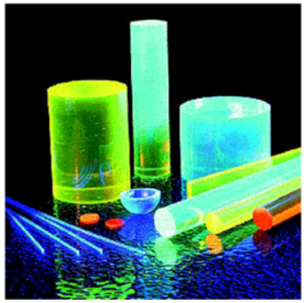


Inorganic crystals



1) *Fraction of energy loss going into γ can be rather small ex. 200 γ 3 eV for a 1 MeV particle in $PbWO_4$*
2) *Requires a shift between absorption and emission spectra*

Calorimeters: scintillation/Cerenkov technologies



Scintillating materials

- Organic: plastic, liquid
  - Very fast response O(ns)
  - Primary emission in UV (100-350 nm), wave length shifting to visible included in material
  - Relatively low density (light yield)
  - Relatively low radiation tolerance
- Inorganic: crystals (ex NaI(TI), Csi(TI), CSI(NA), BGO, BaF_2, LYSO, LuAG, CeF_3, YAG…)
  - High density, light yield, maximum in visible range
  - Strong temperature dependence
  - Relatively good radiation tolerance (not all)
  - Decay time can be long in some cases
- Noble gases (He, Ne, Ar, Krypton, Xenon, Krypton) are also scintillators, but mostly used to measure electrons from ionization fluorescence is purely atomic
  - Fast response O(10 ns)
  - Light is in UV
  - Relatively low density, eg light yield (can be increased with pressure in gas)
  - Need cryogeny operation for liquids
- Scintillating glasses (ex. Ce doped with Li or B)
  - Low light yield but improved sensitivity to neutron through doping

Calorimeters: some crystal and noble gas scintillating properties

Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [μs]	Photons/MeV
NaI	3.7	1.78	303	0.06	$8 \cdot 10^4$
NaI(Tl)	3.7	1.85	410	0.25	$4 \cdot 10^4$
CsI(Tl)	4.5	1.80	565	1.0	$1.1 \cdot 10^4$
$Bi_4Ge_3O_{12}$	7.1	2.15	480	0.30	$2.8 \cdot 10^3$
CsF	4.1	1.48	390	0.003	$2 \cdot 10^3$
LSO	7.4	1.82	420	0.04	$1.4 \cdot 10^4$
$PbWO_4$	8.3	1.82	420	0.006	$2 \cdot 10^2$
LHe	0.1	1.02	390	0.01/1.6	$2 \cdot 10^2$
LAr	1.4	1.29 *	150	0.005/0.86	$4 \cdot 10^4$
LXe	3.1	1.60 *	150	0.003/0.02	$4 \cdot 10^4$

Calorimeters: some organic scintillator properties

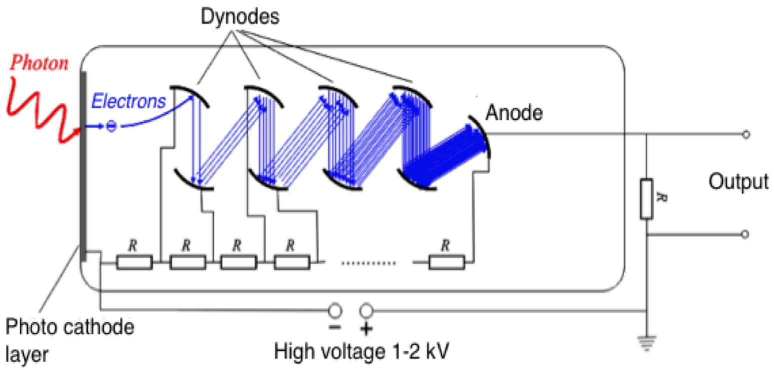
Scintillator material	Density [g/cm³]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [ns]	Photons/MeV
Naphtalene	1.15	1.58	348	11	$4 \cdot 10^3$
Antracene	1.25	1.59	448	30	$4 \cdot 10^4$
p-Terphenyl	1.23	1.65	391	6-12	$1.2 \cdot 10^4$
NE102*	1.03	1.58	425	2.5	$2.5 \cdot 10^4$
NE104*	1.03	1.58	405	1.8	$2.4 \cdot 10^4$
NE110*	1.03	1.58	437	3.3	$2.4 \cdot 10^4$
NE111*	1.03	1.58	370	1.7	$2.3 \cdot 10^4$
BC400**	1.03	1.58	423	2.4	$2.5 \cdot 10^2$
BC428**	1.03	1.58	480	12.5	$2.2 \cdot 10^4$
BC443**	1.05	1.58	425	2.2	$2.4 \cdot 10^4$

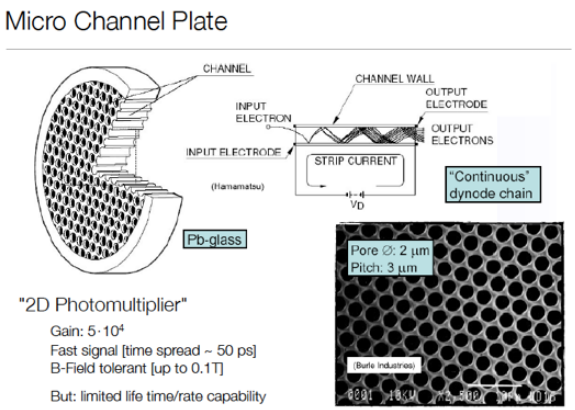
* Nuclear Enterprises, U.K.
** Bicron Corporation, USA

Calorimeters: Photo-detectors

Photo-detectors convert photons to photons-electrons for readout (photo-electric effect)

- Photo-Multipliers (sensitive to B-field)
  - Photon are converted in photo-cathode and accelerated to dynodes into vacuum to produce secondary emission, fast signal 50 ps
  - Quantum efficiency[1)] is O(10-30) % depending on WL and photocathode, high gain 10^4 to 10^7
    - Can cover UV to visible wavelengths
  - Several designs, multi-anode, flat, micro channel plate (MCP) can provide large area with small pad size O(mm) for higher rates and position resolution



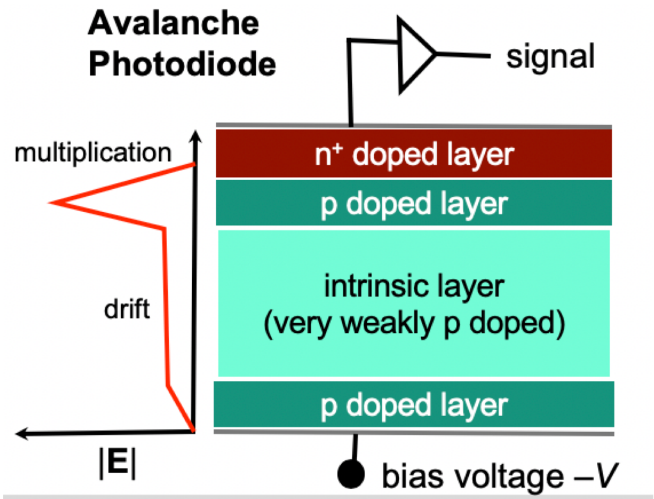


1) *Also referred to as Photon Detection Efficiency PDE = $N_{pe} / N_{photons}$*

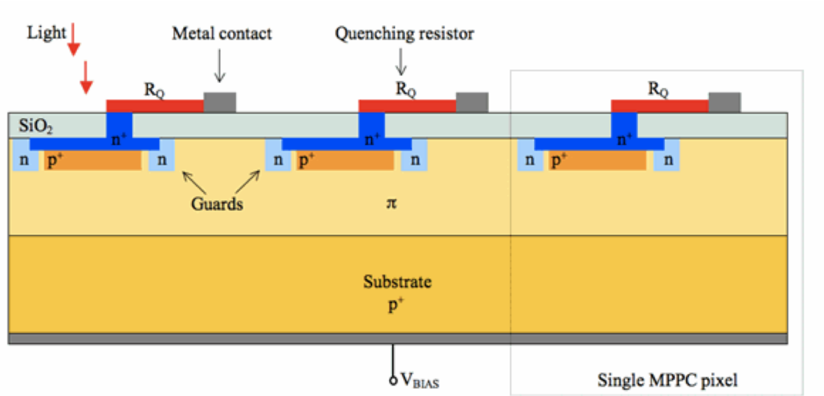
Calorimeters: Photo-detectors

- Silicon devices: Avalanche PhotoDiodes, Si-PhotoMultipliers (insensitive to B-Field)
  - APDs are reverse bias diodes with multiplication of primary ionization trough high E-field
  - SiPM[1)] are arrays of pixelized APDs operated in Geiger mode with $V_{bias} > V_{breakdown}$ and current quenching
    - Work in binary mode, can detect single photo-electrons
    - High granularity pixel few 10x10 μm^2
    - High gain 10^5 to 10^7
    - Quantum efficiency is ≥ 30% mostly in visible range

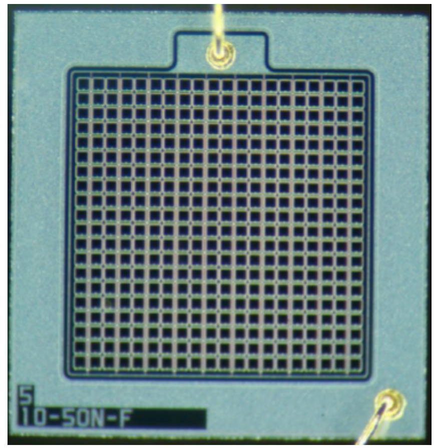
APD



SiPM



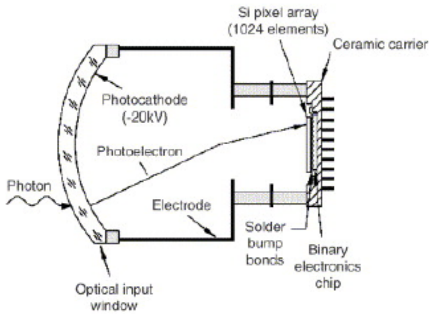
HPK SiPM

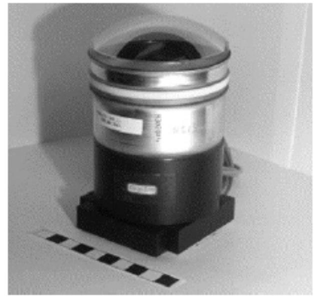


1) Also referred to as Mutli Pixels Photon Counters (MPPC)

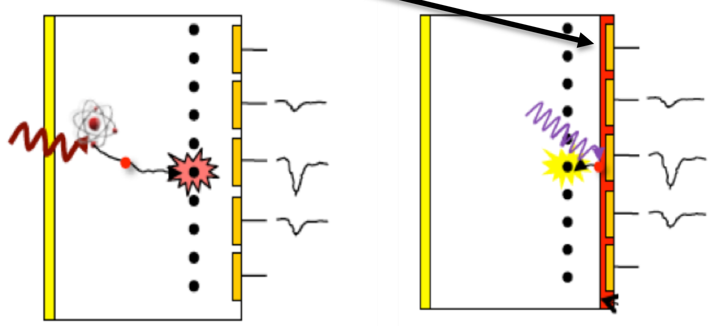
Calorimeters: Photo-detectors

- Hybrid Photo Diode
  - Photoelectrons produced in photocathode are accelerated toward APD





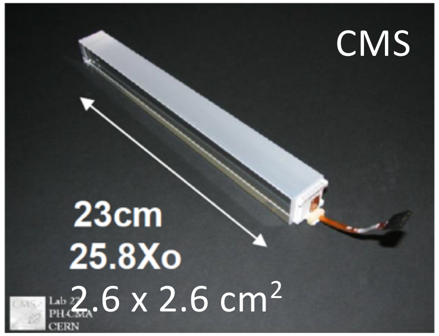
- Gaseous photodetectors
  - Photo-sensitive material added to Gas or coating with photocathode
  - window produce electrons signals triggering an avalanche

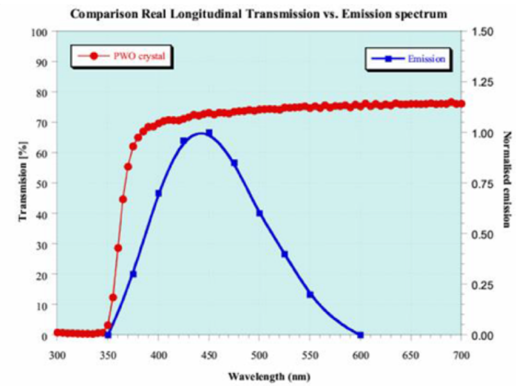


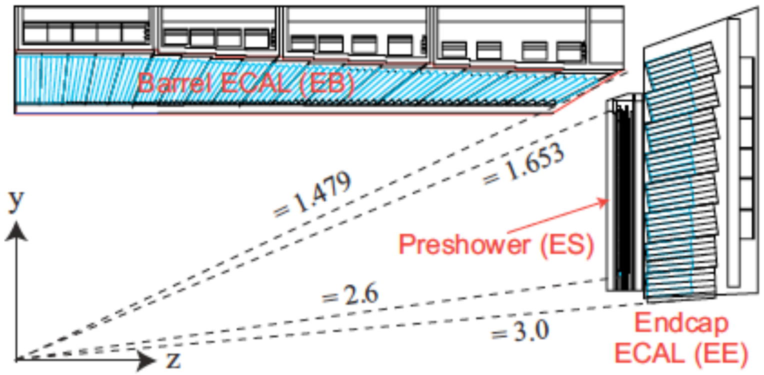
Homogenous Crystal Calorimeter: CMS ECAL design

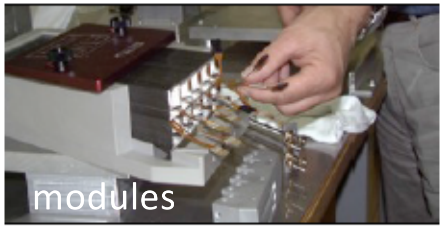
CMS ECAL $PbWO_4$ crystals[1)]

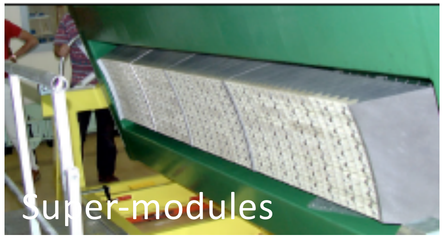
- ρ = 8.3 g/cm^3, X_0 = 0.89 cm, R_M = 2.2 cm
- Emission 80% in ≤ 15 ns, decay time in < 40 ns
- Wavelength 450 nm (blue)
- Signal 150 γ/MeV
- Readout with APDs(VPTs)[1)] in barrel(endcaps)

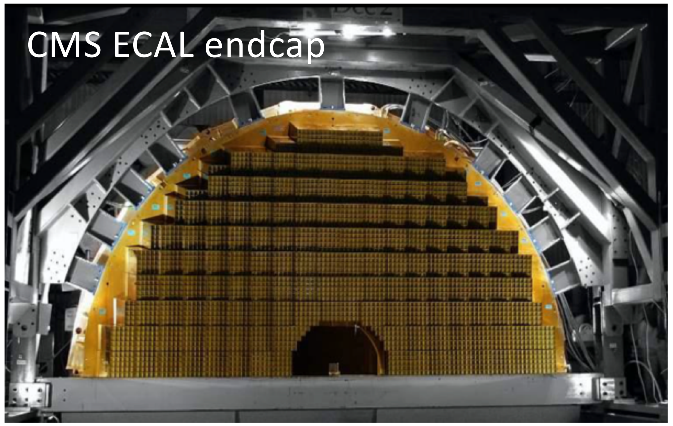










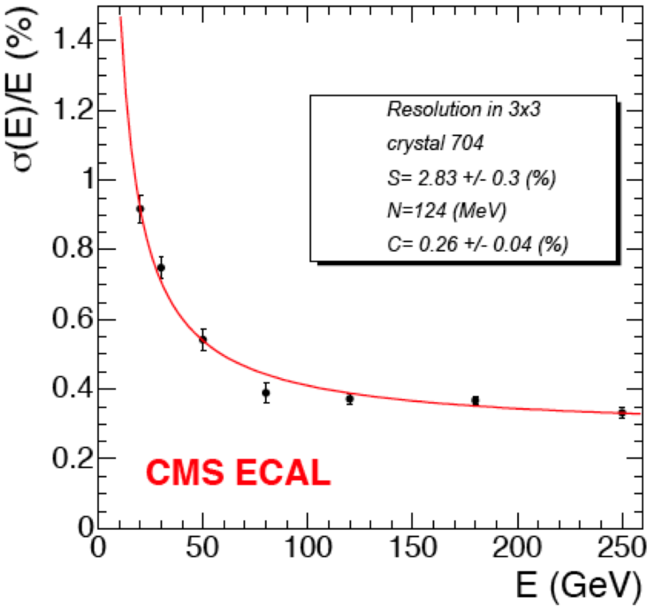


61(15)k crystals barrel(endcaps), 67(23) tonnes coverage to η = 3

1) *APD development with good PDE at HPK was crucial since* $PbWO_4$ light yield is relatively small, *VPT (PMT) would be sensitive to barrel B-field*

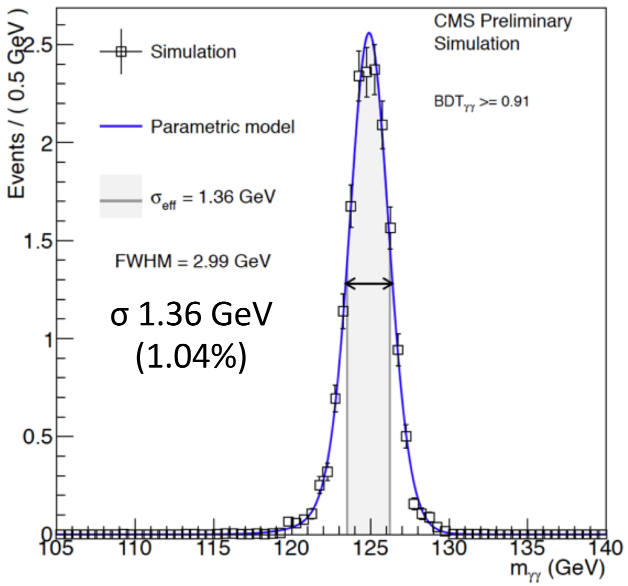
Homogenous Crystal Calorimeters: CMS ECAL resolution

e test beam energy resolution



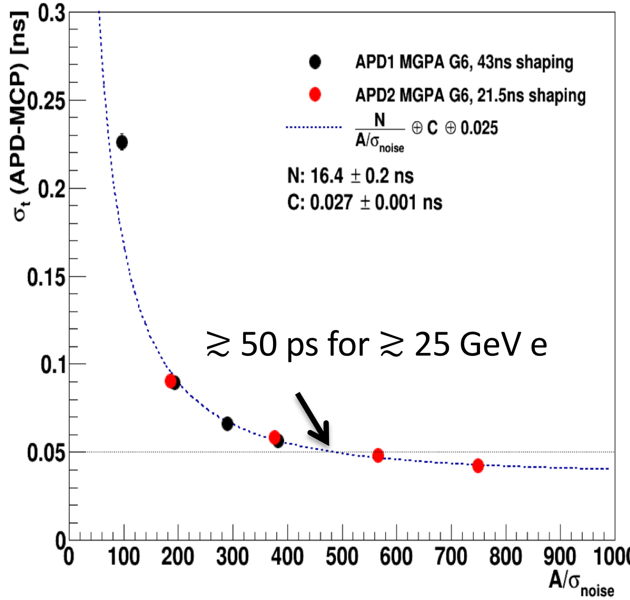
σ(E)/E = 2.8 % /√E ⊕ 124 (MeV)/E ⊕ 0.26%

Higgs mass resolution



$$\frac{\sigma_{m_{\gamma\gamma}}}{m_{\gamma\gamma}} = \frac{1}{2}\left(\frac{\sigma_{E_{\gamma_1}}}{E_{\gamma_1}} \oplus \frac{\sigma_{E_{\gamma_2}}}{E_{\gamma_2}} \oplus \frac{\sigma_{\vartheta_{\gamma\gamma}}}{\tan\frac{\vartheta_{\gamma\gamma}}{2}}\right)^{1)}$$

Time resolution[2)]

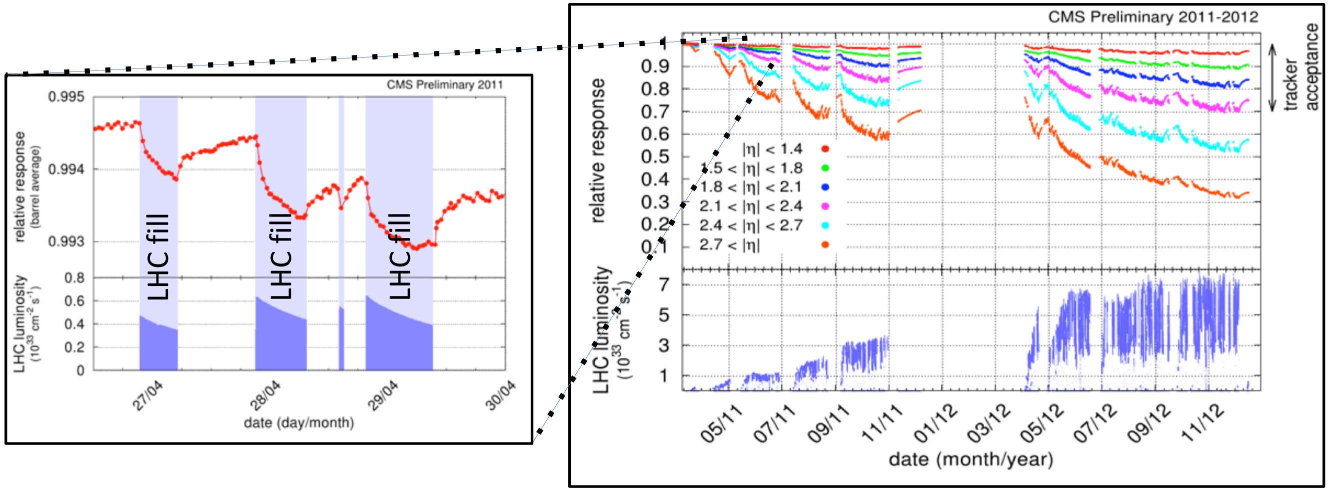


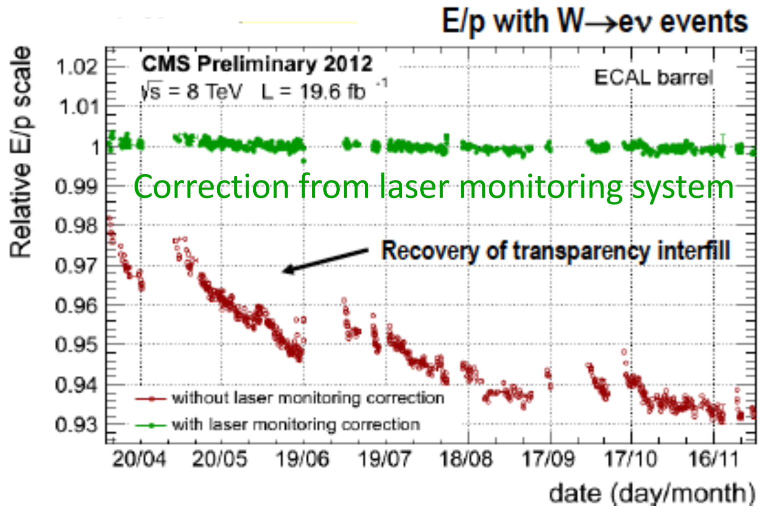
1) *Pointing term in mass resolution relies on efficient vertex-id with charged tracks, this will degrade at high pile-up*
2) *Can be exploited in conjunction with MIP timing detector to associate*

Homogenous Crystal Calorimeters: CMS ECAL radiation tolerance

$PbWO_4$ transparency changes due to colour-centre formation[1)] (not damage to scintillation)

- Electromagnetic damage is fast and spontaneously recovered at room temperature in O(hours)



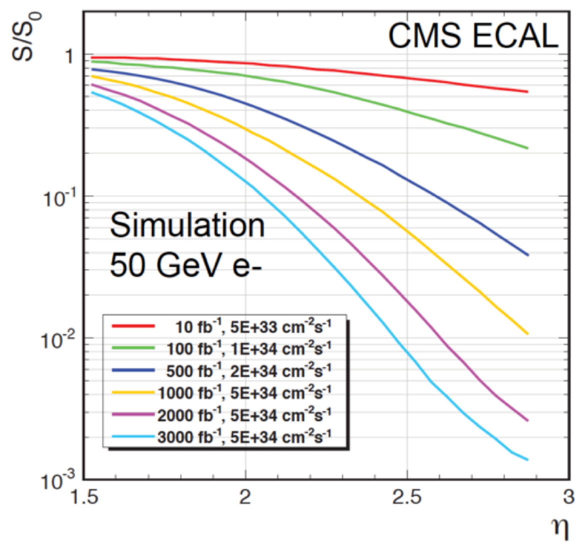


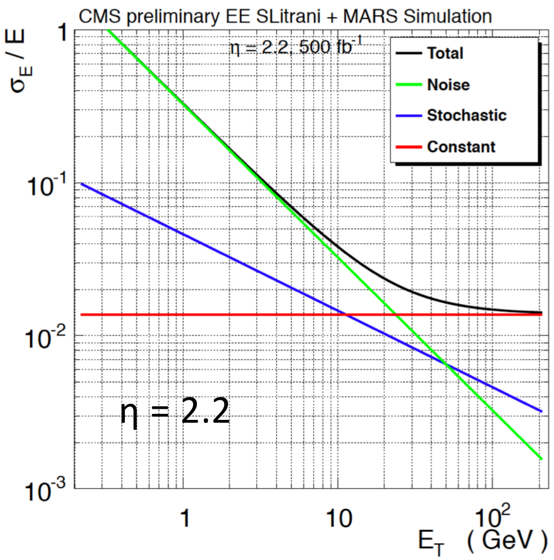
1) Light transmitted to initial light is ∝ exp [-μ(λ)L], μ attenuation length (m⁻¹), λ wave length, L path length in material

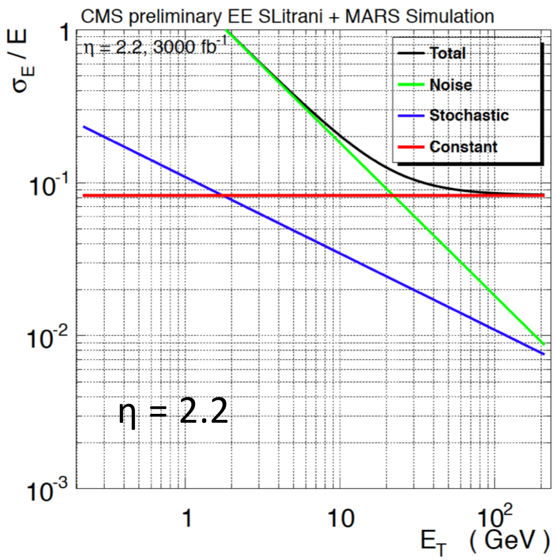
Homogenous Crystal Calorimeters: CMS ECAL radiation tolerance

$PbWO_4$ transparency changes due to colour-centre formation[1)] (not damage to scintillation)

- Electromagnetic damage is fast and spontaneously recovered at room temperature in O(hours)
- Hadronic damage causes permanent (at room temp.) and cumulative defects





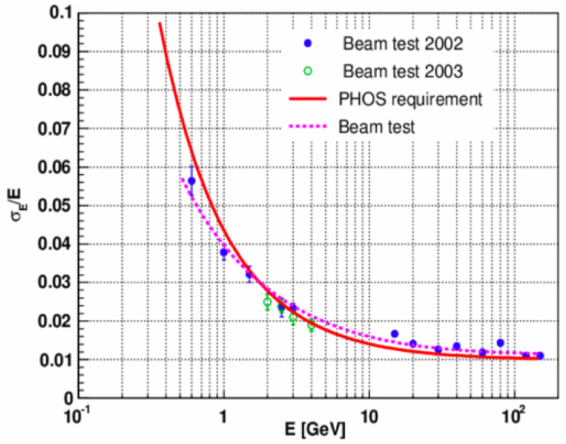


Radiation tolerance to $\simeq$ 10 Mrad, 50% light yield loss acceptable for energy resolution (barrel)[2)]
temperature will be lowered to -8° to compensate increase of dark current noise in APDs
endcaps need replacement for HL-LHC

1) *Light transmitted to initial light is $\propto$ exp [-μ(λ)L], μ attenuation length (m^{-1}), λ wave length, L path length in material*
2) *More recent crystal LYSO are about x 10 more radiation hard can be considered for O(100) Mrad*

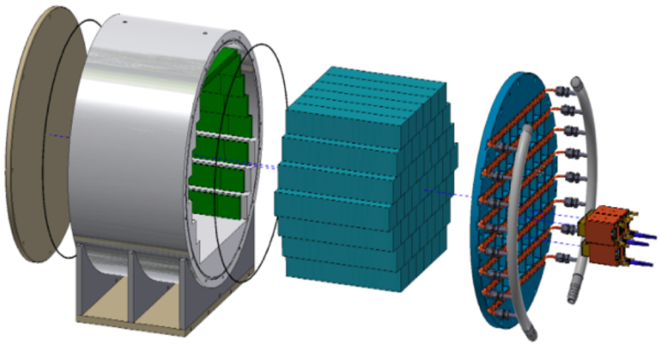
Homogenous Crystal Calorimeters: other examples

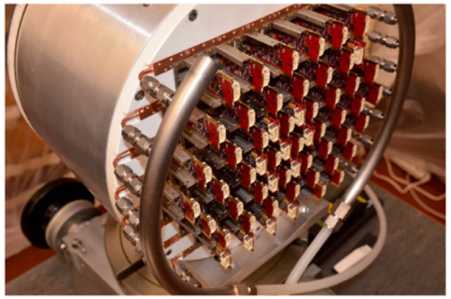
ALICE PHOS (CMS-like)
18k $PbWO_4$ crystals 22 × 22 × 180 mm^3
Readout with APDs, $\sigma(E)/E = 3.3\%/\sqrt{E} \oplus 1.1\,\%$

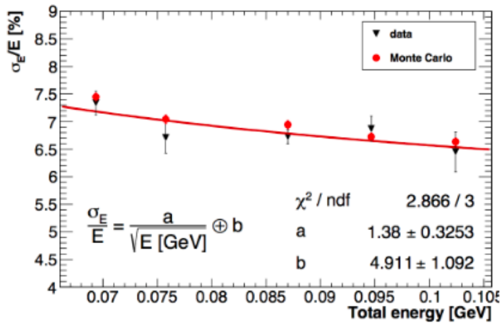


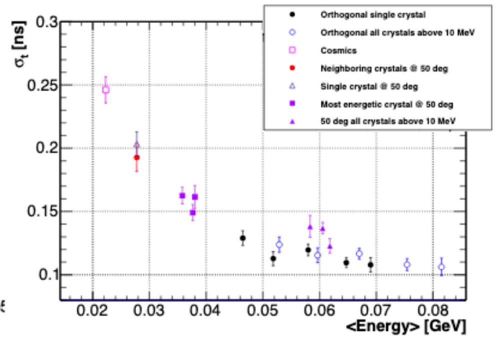
Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/E^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16\text{–}18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998

Mu2e future LFV experiment at FNAL (2021) 674 CSI crystals (low energy electrons) good timing for ToF position measurment





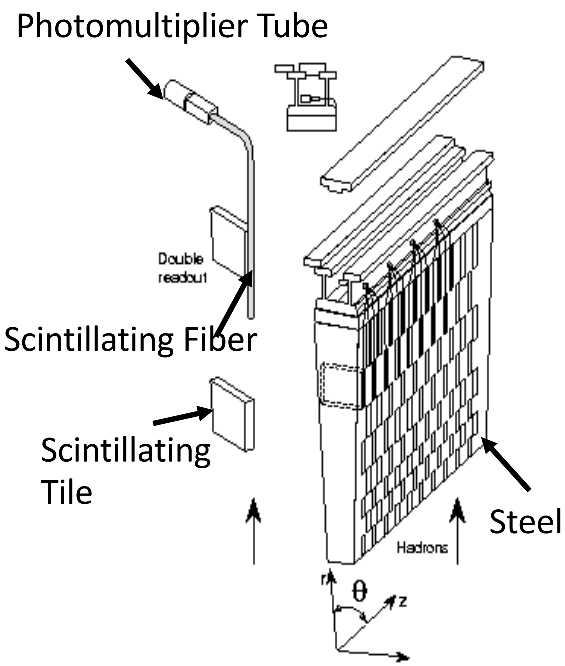




Organic scintillator calorimeters: ATLAS-CMS HCAL tile design

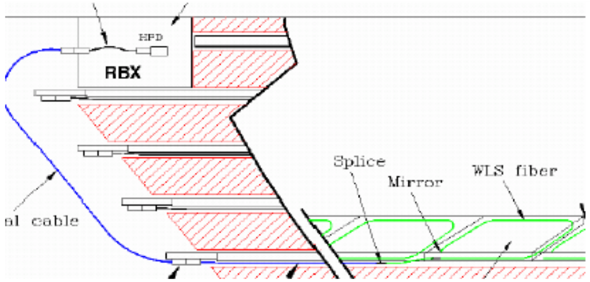
ATLAS HCAL tile calorimeter[1)] (barrel $\eta < 1.5$)

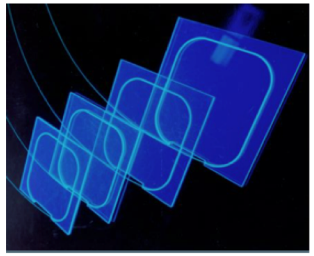
- Iron/scintillator tiles barrel + PMTs
- 500 kch in vertical arrangement



CMS HCAL tile calorimeter barrel and endcaps

- Brass/plastic scintillator tiles + WLS fiber + HPDs,
- 7 kch in horizontal arrangement in barrel





1) *Similar design for LHCb*

Organic scintillator calorimeters: ATLAS-CMS HCAL tile design

No compensation e/h fraction about 1.4 in both ATLAS and CMS

ATLAS 64 layers: 3 mm scint. / 14 mm iron

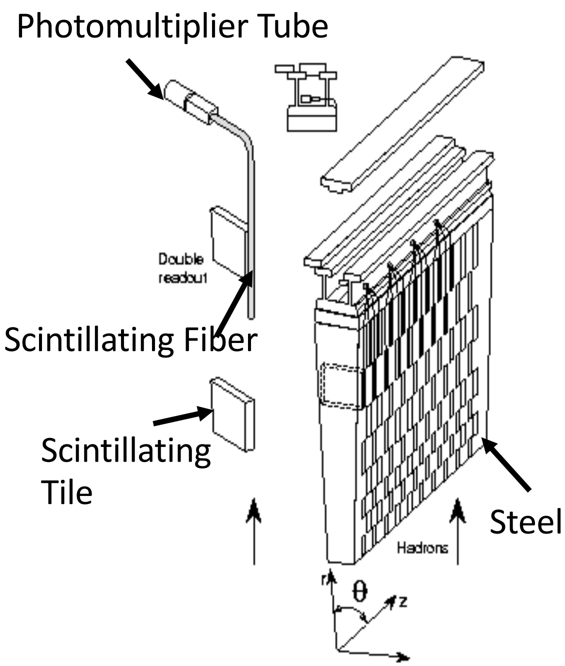
$\sigma_{\pi}(E)/E= 53((42)\%/\sqrt{E} \oplus 5.7(2)\%$ HCAL(HCAL+ECAL)

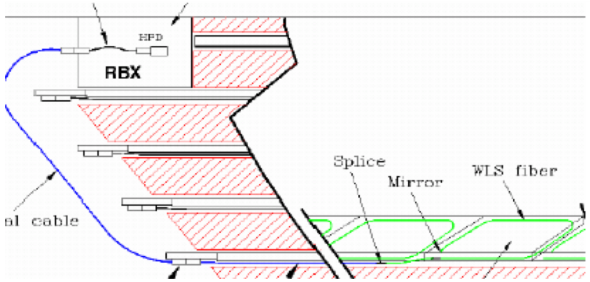
$\sigma_{Jet}(E)/E= 60\%/\sqrt{E} \oplus 3\%$ HCAL(HCAL+ECAL)

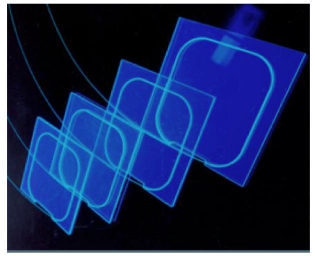
CMS 16 layers 3.4 cm scint. / 5 cm brass

$\sigma_{\pi}(E)/E= 94(83)\%/\sqrt{E} \oplus 4.5\%$ HCAL(HCAL+ECAL)

$\sigma_{Jet}(E)/E= 125\%/\sqrt{E} \oplus 3.3\%$ HCAL(HCAL+ECAL)





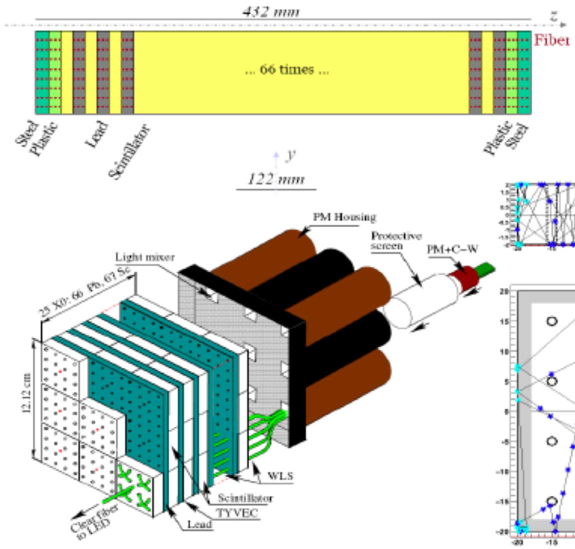


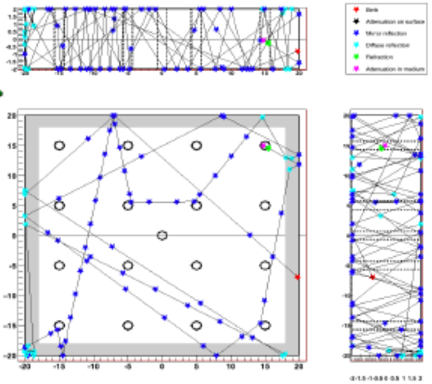
Hadron resolution improved by 15% using transverse granularity for e/h weighting according to cluster energy and density

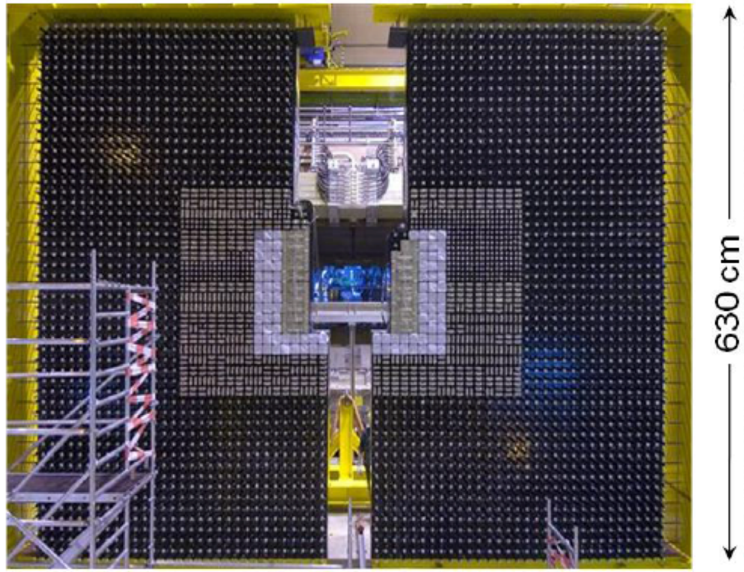
4 depths segmentation introduced in Phase 1 upgrade with replacement of HPD readout by SiPM

Organic scintillator calorimeters: LHCb ECAL shashlik design

3312 module of 67 4 mm scintillator tiles, interleaved with 2 mm lead plates[1]
readout with wavelength shifting fibres running through plates to PMTs
$\sigma(E)/E \simeq 9\,\%/\sqrt{E} \oplus 1\,\%$







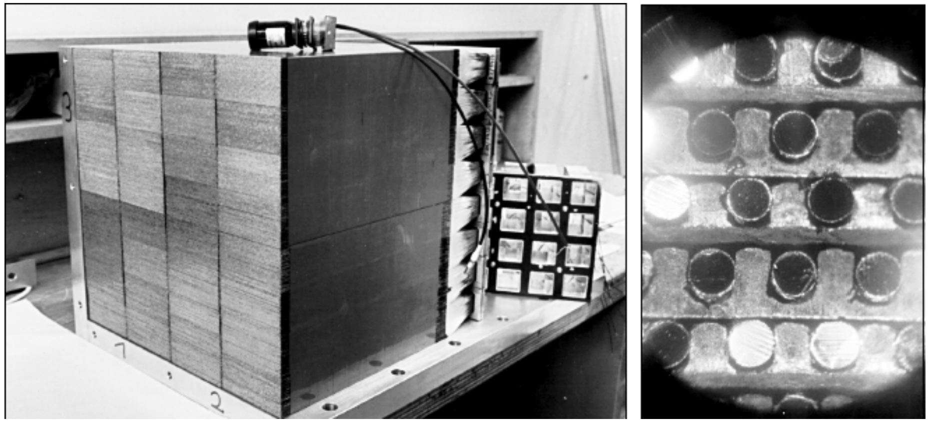
1) *Moliere radius ~ 36 mm*

Organic scintillator calorimeters: ECAL-HCAL spaghetti design

SPACAL ECAL-HCAL at H1 HERA DESY

- Pb / 0.5(1) mm Plastic scintillating fibers with volume ratio of 2.3/1 (3.4/1) in ECAL(HCAL)
- Readout with PMTs

$\sigma_{EM}(E)/E \simeq 7\ \%/\sqrt{E}$



KLOE ECAL at Frascati Φ-factory

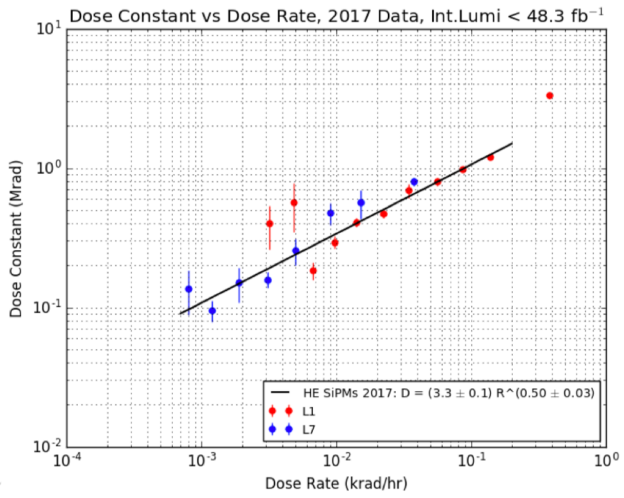
- Pb / 1 mm Plastic scintillating fibers with volume ratio of 42/48
- Readout with PMT

$\sigma_{EM}(E)/E \simeq 5.7\%/\sqrt{E}$

Organic scintillator calorimeters: radiation tolerance

As for crystals, radiation damage affect light transmission[1], not scintillation
It is a complex process depending on scintillator components, with
annealing behavior that can depend on environment condition (presence of oxygen, nitrogen)
it depends not only of Total Integrated Dose (TID) but also of instantaneous rate

Light yield ∝ exp(-TID/D), loss is higher at smaller rates
CMS measurement[2] dose constant D $\simeq$ 3.3 $R^{0.5}$, R instantaneous rate



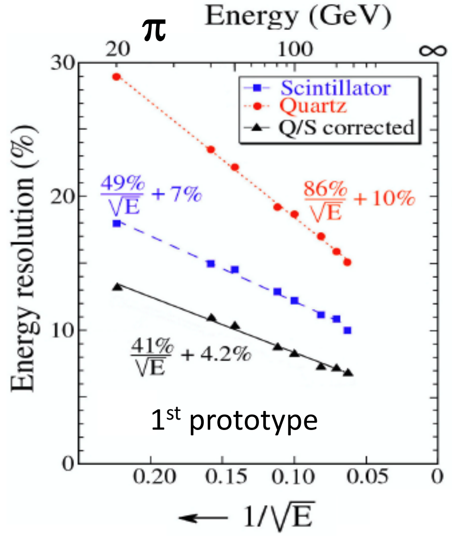
- In CMS HCAL tile calorimeter a light yield drop of 60 % after $\simeq$ 500 kad (4500 fb^{-1}) was shown to have little impact on jet energy resolution
  - This is geometry dependent, eg path length of light to WLS fibers
- Light yield can be improved with short path
- LHCb is considering 3 Mrad radiation tolerance for the tracker scintillating fibers upgrade

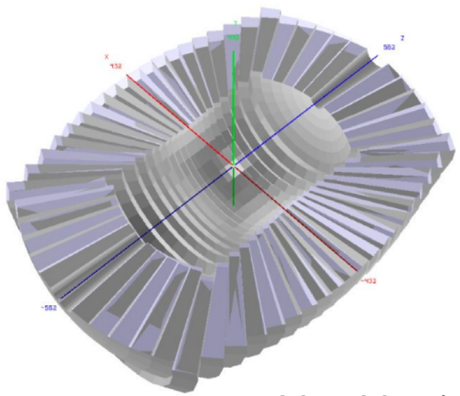
1) *WLS and clear fibers for light guide can also be affected by aging*
2) *Substantial aging of the readout HPDs was also observed with no systematic behavior (eg. large spread)*

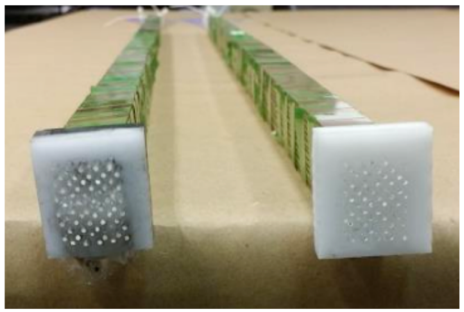
Crystals/Scintillating/Cerenkov calorimeters: future experiments

IDEA proposal for FCC-ee and CepC based on DREAM concept

- Spagetthi calorimeter alternating scintillating and Cerenkov fibers
  - Cerenkov light almost exclusively produced by EM component (80% of non EM shower components is non relativistic)
    - $(e/h)_S = 1.3$; $(e/h)_C = 4.7$
- 1 mm fibers Scint/Cerenkov, 1.5 mm pitch in Pb or Cu absorber readout with SiPMs
  - 10^8 fibers 2m long (assembly challenge)
  - Longitudinal segmentation options:
    - staggered ≠ length fibers, precise timing measurement



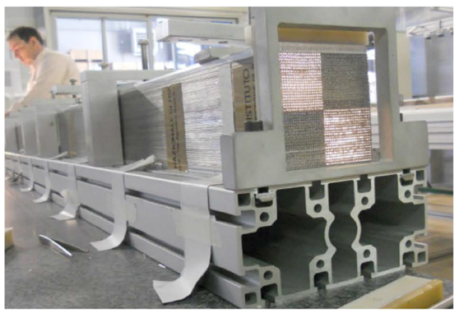




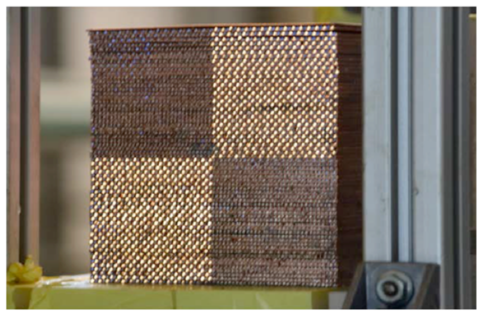
32 + 32 scint./cerenkov fibers protoype

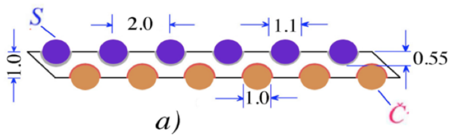
$\sigma(E)/E \simeq 10(30)\%/\sqrt{E} + 1\%$ for $e/\gamma(\pi)$

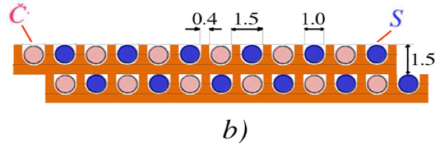
Pb



Cu



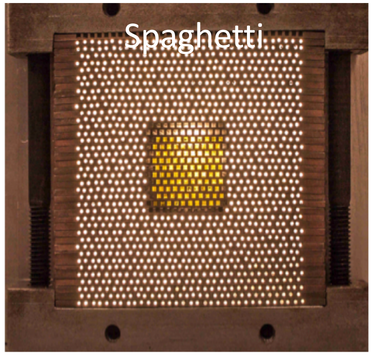




Crystals/Scintillating/Cerenkov calorimeters: future experiments

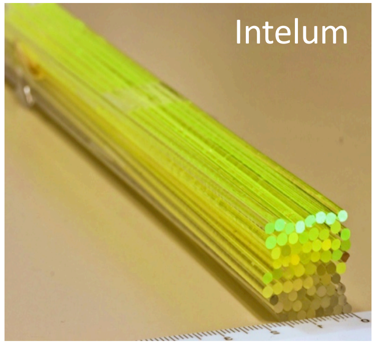
LHCb Phase-2 upgrade sampling electromagnetic crystal calorimeter

Radiation tolerance $\simeq$ 300 MRad, time resolution $\simeq$ 50 ps



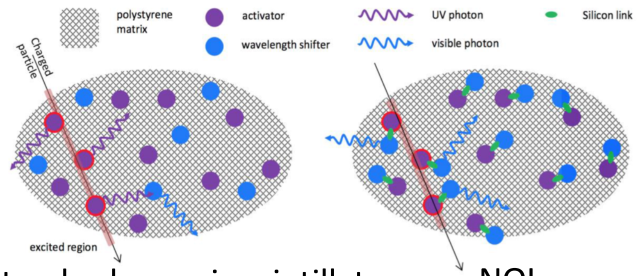
Generic development of a Time Imaging Calorimeter (TICal) in synergy with PET application

Homogenous crystal fibers calorimeter with $\simeq$ 10 ps, could provide some segmentation



Crystals/Scintillating/Cerenkov calorimeters: R&D

- Best performance in energy and time resolutions with heterogenous designs or materials
  - Several option for crystals (LSO/LYSO/YAG/GAGG…), investigation of nano-crystals (ex. quantum dots)
- Improved light transport for radiation tolerance*
  - Currently O(1/100/1000) Mrad for organic/crystals/quartz materials in existing typical experiment configurations
  - Study new material, ex. Nano-structure Organo-silicon Luminophor
- Production of organic scintillators by 3D printing



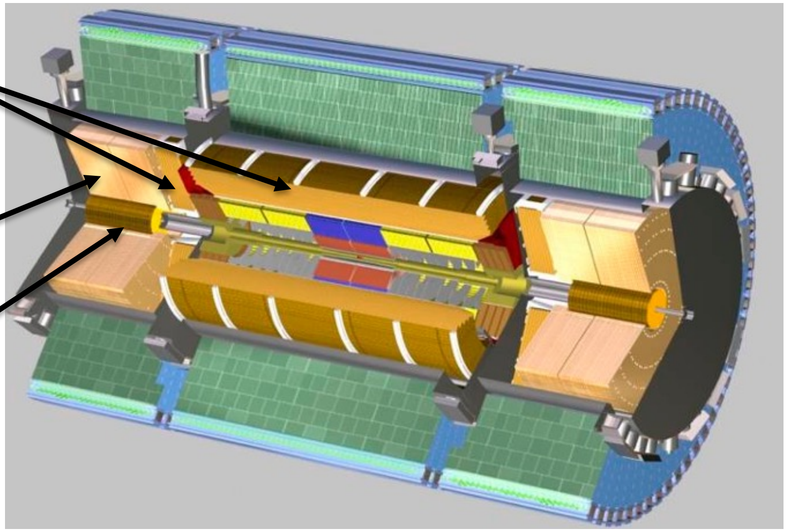
SiPMs is a commercial product used in several imaging applications outside HEP: PET, LIDAR…
- Recent developments in CMOS process to integrate digital electronics, could be ultrafast and allow photon counting
- Also developments in process/material/design to improve
  - Quantum Efficiency in UV to exploit very fast Cerenkov and cross-luminescence materials
  - SPTR from O(100) ps to O(10) ps (interest for PET/LIDAR)
  - Dark Current Rate increase with irradiation
    - Drives time resolution after 1000 fb^{-1} in CMS barrel timing layer

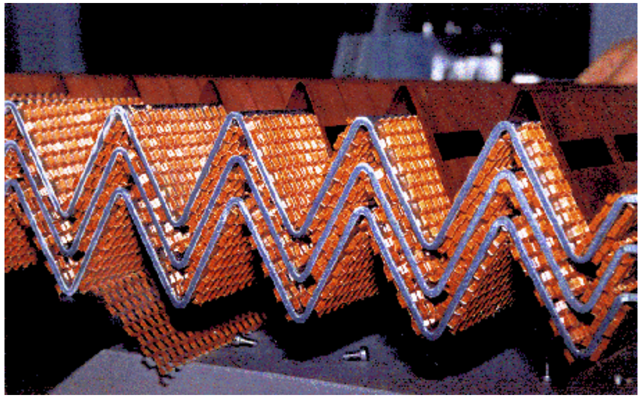
** CERN RD18: https://crystalclear.web.cern.ch/crystalclear*

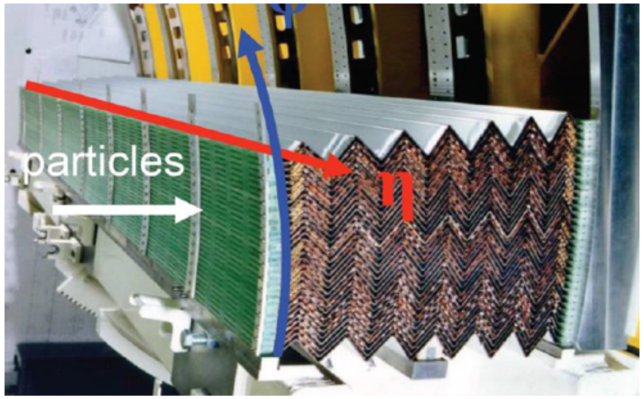
Noble gas calorimeters: ATLAS Liquid Argon

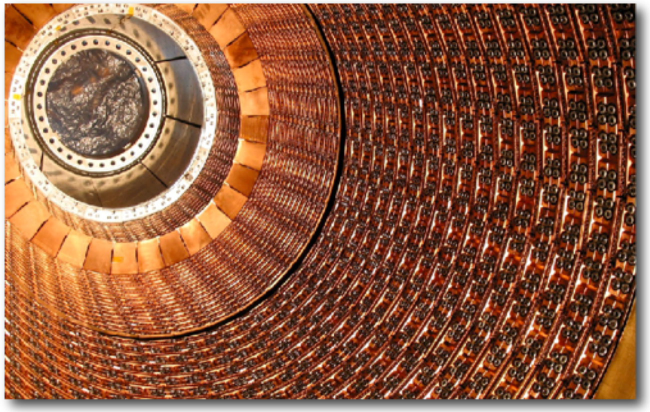
- Barrel and Endcaps in "Accordion" design to avoid cracks
  - ECAL barrel η < 1.5 (endcaps 1.5 < η < 3.2) Pb absorber 1-2 mm thick[1)], 110(64) kch in 3 depths
  - HCAL endcaps with Cu absorber, 5.6kch in 2 wheels (depths)
- Forward ECAL(HCAL)
  - 3.1 < η < 4.9: LAr tubes in W(Cu) absorber, 3.6 kch in three modules (depths)

Immersed in LAr at -183°





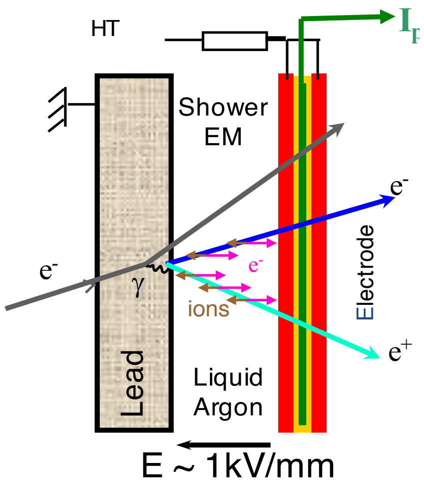


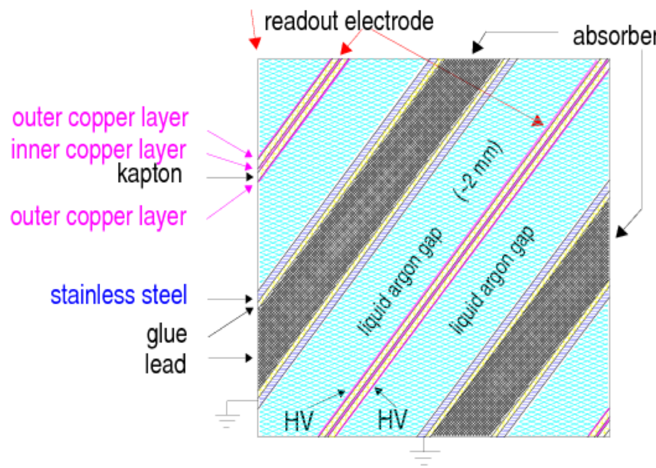


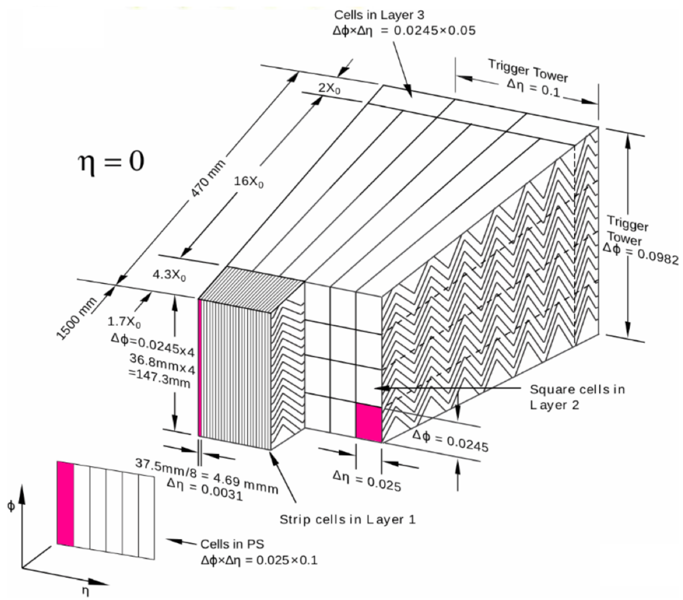
1) Challenge for uniformity/tolerances/mechanical stability (constant term in energy resolution)

Noble gas calorimeters: ATLAS Liquid Argon

- Measure ionization signal: 5×10^6 e^-/GeV deposit
- Relatively deep 47 cm to reach 25 X_0
- Relatively slow (450 ns drift time)
- Insensitive to radiation (but not to particle flux in forward direction)



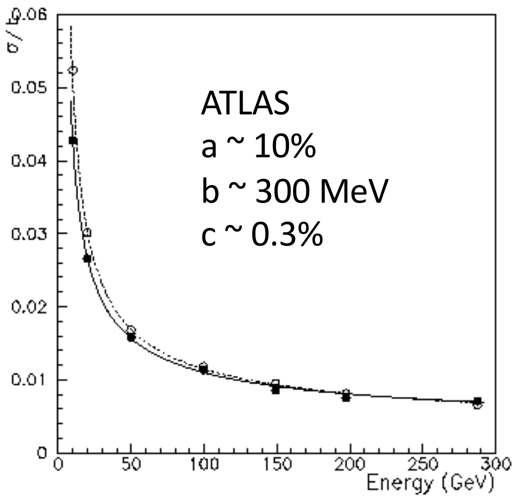


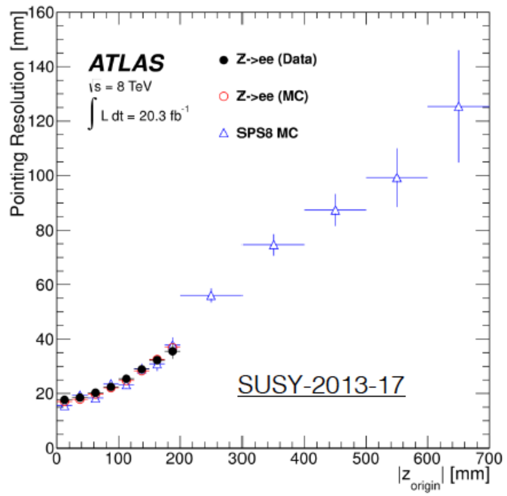


Finer granularity in 1st section for $\pi_0 \rightarrow \gamma\gamma$ versus prompt γ ID through shower shape

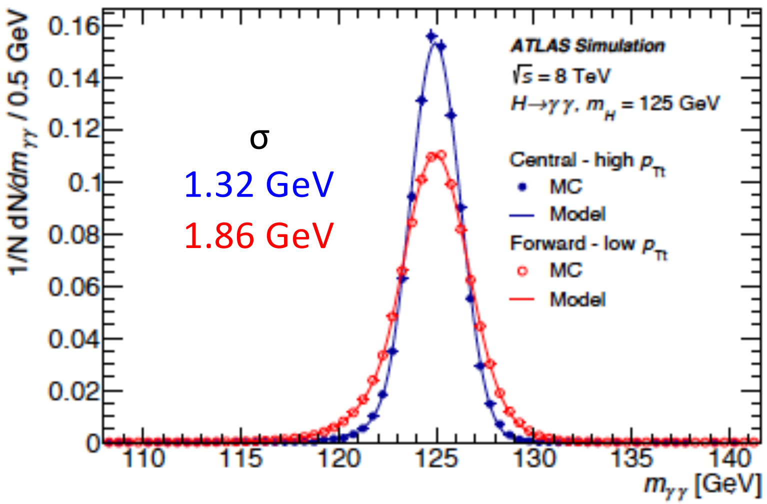
Noble gas calorimeters: ATLAS LAr EM resolution

Barrel σ(E)/E = 10%/√E ⊕ 300 MeV ⊕ 0.3%





Pointing resolution 60 mr/√E

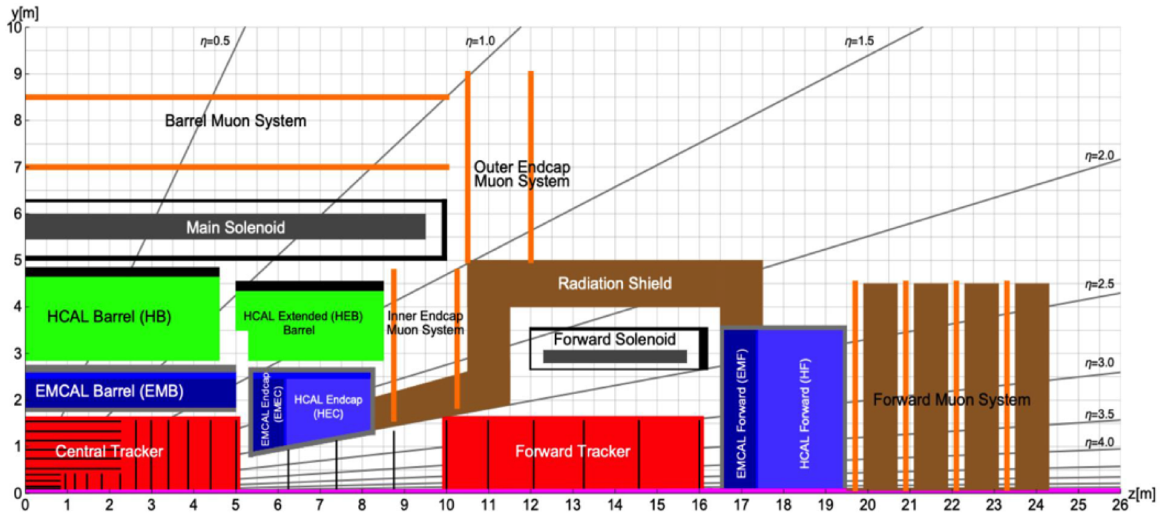


Higgs mass resolution

Time resolution is relatively high O(100) ps

Noble gas calorimeters: concept for future h-h calorimeters

30 X_0 - 12 λ and extension to η = 6 for energy boost, extreme radiation tolerance

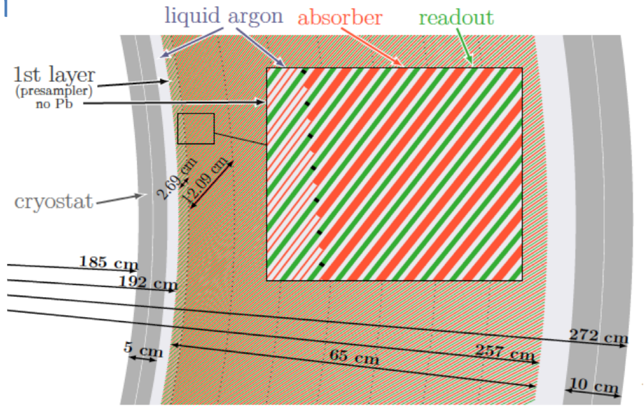


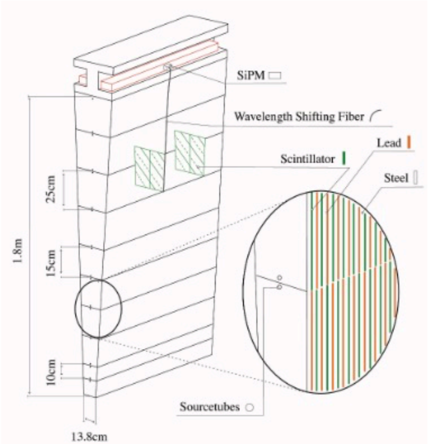
	η_{min}	η_{max}	a	c	$\Delta\eta$	$\Delta\phi$	Fluence	Dose	Material
Unit			$\%\sqrt{\text{GeV}}$	%			cm^{-2}	MGy	
EMB	0	1.5	10	0.7	0.01	0.009	5×10^{15}	0.1	LAr/Pb/PCB
EMEC	1.5	2.5	10	0.7	0.01	0.009	3×10^{16}	1	LAr/Pb/PCB
EMF	2.5	4	10	0.7	0.025	0.025			LAr/Cu/PCB
	4	6	30	1	0.025	0.025	5×10^{18}	5000	LAr/Cu/PCB
HB	0	1.26	50	3	0.025	0.025	3×10^{14}	0.006	Sci/Pb/Fe
HEB	0.94	1.81	50	3	0.025	0.025	3×10^{14}	0.008	Sci/Pb/Fe
HEC	1.5	2.5	60	3	0.025	0.025	2×10^{16}	1	LAr/Cu/PCB
HF	2.5	4	60	3	0.05	0.05	5×10^{18}	5000	LAr/Cu/PCB
	4	6	100	10	0.05	0.05	5×10^{18}	5000	LAr/Cu/PCB

Noble gas calorimeters: R&D future h-h experiments

- Liquid Argon calorimeter is the unique technology that can sustain expected radiation up to 5×10^{18} neq/cm^2 and 500 Grad
  - Straight inclined structure design with 8 longitudinal segmentation $\Delta\eta \times \Delta\varphi \simeq 0.01(0.025) \times 0.01(0.025)$ in ECAL(HCAL) /10 ATLAS
  - Engineering challenge to develop multilayer PCB electrodes, and high density feedthrough for readout outside the cold volume
  - Interest in low mass composite cryostat
- Silicon HGC could be an alternative up to $\eta \simeq 2.5$
  - Could provide precise timing measurement for pile-up mitigation
- Scintillating tile + WLS + SiPM can sustain radiation for barrel Had. Calo.
  - Similar vertical design as current ATLAS with x4 granularity increase

Lar Calo. concept



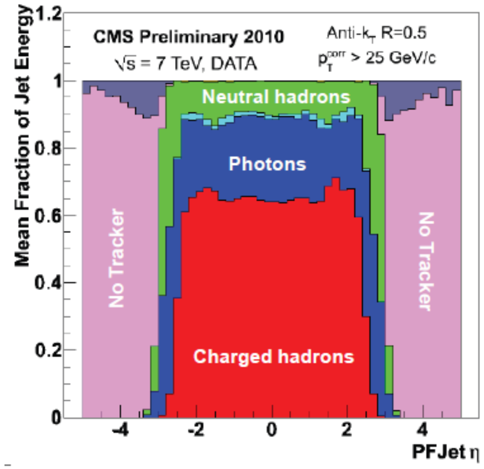


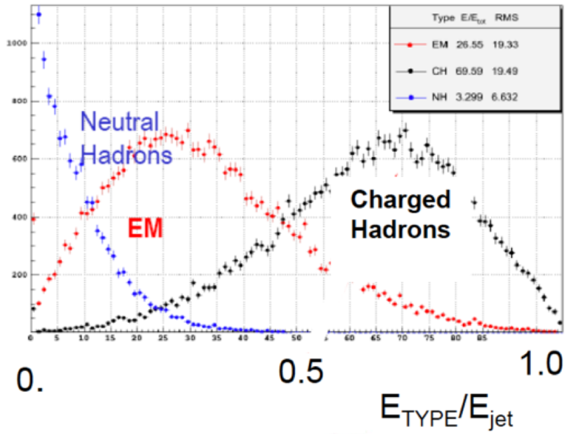
Tile Calo. concept

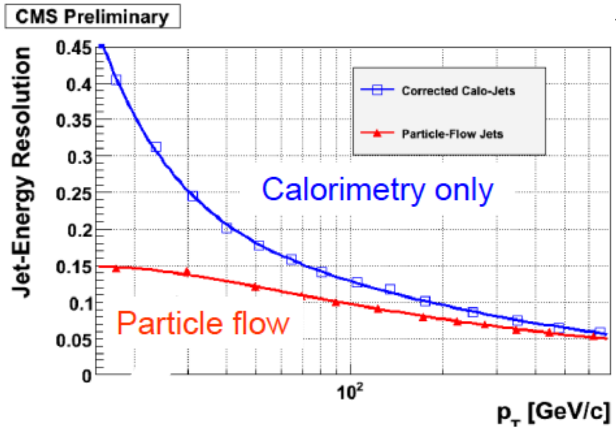
High Granularity Calorimeters: CMS HGC

Particle Flow concept for Jet energy reconstruction

- 65% of the jet energy is in charged hadrons
  1) Remove energy associated with tracks (better resolution up to 100 GeV)
- 25% of the jet energy is in photons
  2) Remove energy associated with γ, best measured by ECAL
- 10% remaining from neutral hadrons measured by HCAL







P-Flow efficiently used in current CMS to compensate relatively poor hadron calorimetry resolution
benefit limited by overlaps of energy deposits in calorimeters
high granularity also allows pile-up mitigation, improves pointing performance for neutrals

High Granularity Calorimeters: CMS HGC overall design

CALICE concept adapted to the CMS endcap requirements

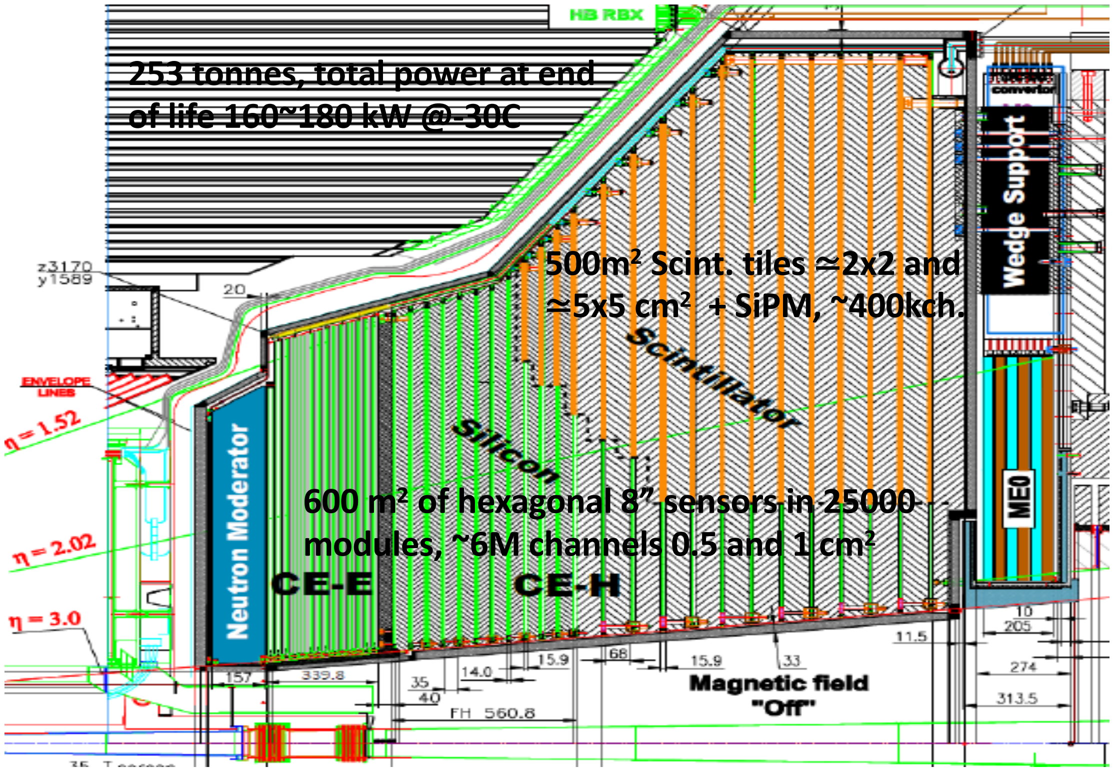
- Electromagnetic (CE-E) is 28 layers of Silicon sensors in W/Pb absorber (26 X_0 - 1.7 λ)
- Hadronic (CE-H) is 22 layers: 8 silicon + 14 silicon/scint. tiles at high/low η in stainless steel absorber (9 λ)

	CE-E	CE-H	
	Si	Si	Scintillator
Area (m^2)	368	215	487
Channels (k)	3916	1939	389
Si modules (Tileboards)	16 008	8868	(3960)
Partial modules	1008	1452	–
Weight (t)	23	205	
Si-only planes	28	8	
Mixed (Si+Scint) planes		16	

Largest fluence and doses at 3000 fb^{-1}

- 10^{16} 1 MeV neq/cm^2 Max for Si-sensors
- 5 x 10^{13} 1 MeV neq/cm^2 for SiPM 5 x 10^{13}
- 0.3 Mrad for scintillators

Operation at -30°

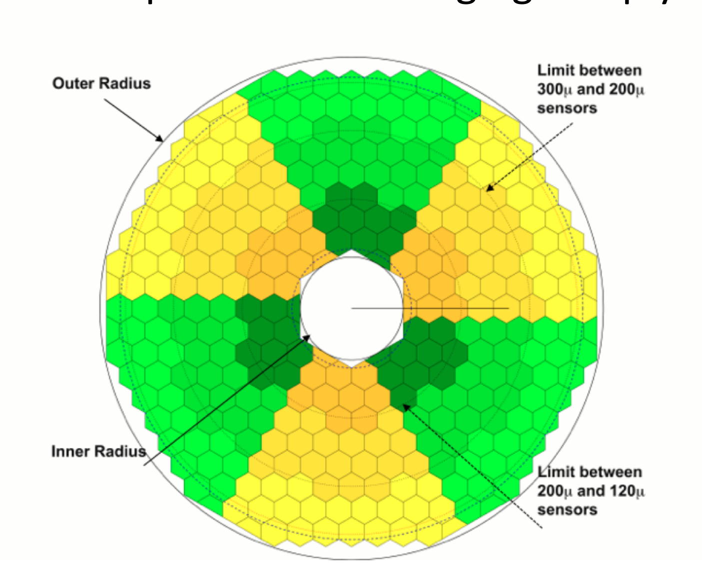


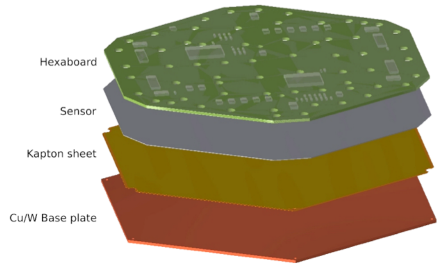
Limit between Silicon and Scintillating tiles + SiPMs is driven by radiation tolerance

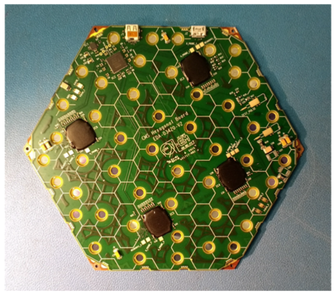
High Granularity Calorimeters: CMS HGC components

- 8’’ hexagonal sensors (1st experience in HEP)
  - 300, 200 and 120 μm thick and pad size selected for performance and to maintain S/N after irradiation (capacitance ≃ 50 pF)
- Scintillating tiles 2x2 and 5x5 cm^2
- FE ASIC designed to achieve 50 ps time resolution
- Assembly in wedge cassettes
  - Complex geometry at edges to avoid too many shapes
  - Also complex readout optimization of optical link BW usage as occupancies are changing steeply with radius

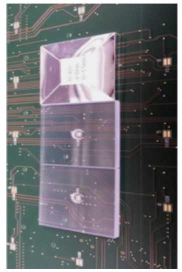
Active thickness (μm)	**300**	**200**	**120**
Area (m^2)	245	181	72
Largest lifetime dose (Mrad)	3	20	100
Largest lifetime fluence (n_{eq}/cm^2)	0.5×10^{15}	2.5×10^{15}	7×10^{15}
Largest outer radius (cm)	≈180	≈100	≈70
Smallest inner radius (cm)	≈100	≈70	≈35
Cell size (cm^2)	1.18	1.18	0.52
Initial S/N for MIP	11	6	4.5
Smallest S/N(MIP) after 3000 fb^{-1}	4.7	2.3	2.2

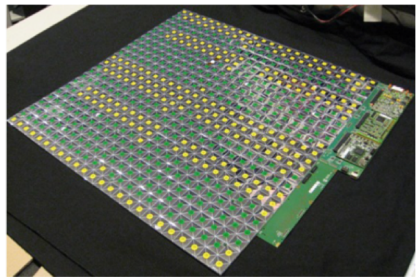


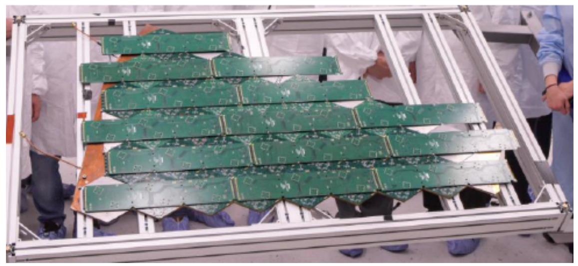




3 x 3 cm^2 scintillating tiles + SiPMs
24 x 24 tile array (Calice)



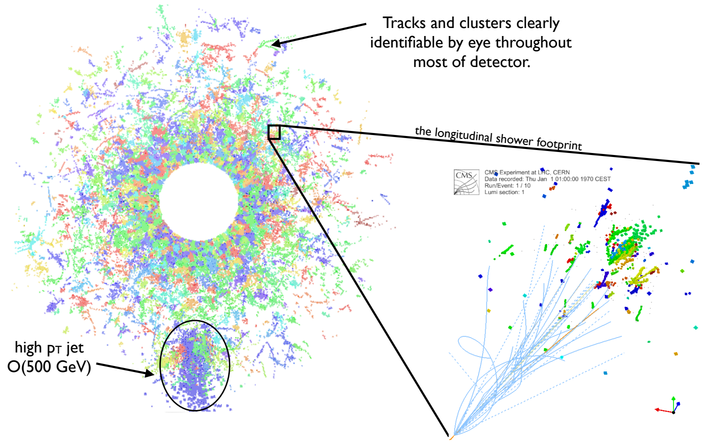




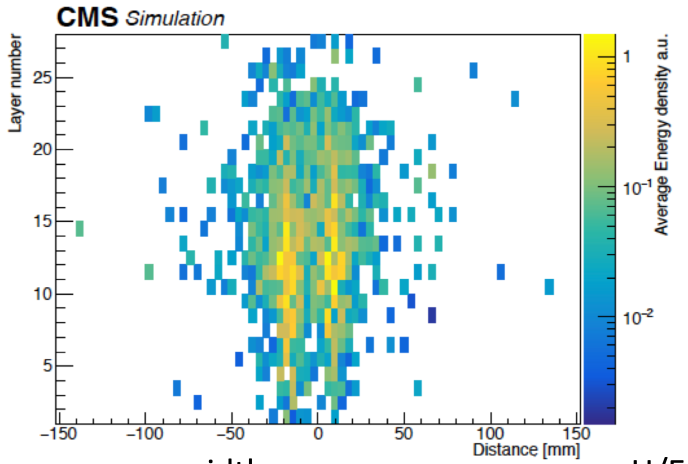
Cassettes with mother PCB board

CMS HGC: Hadronic and Jet performance

140 pile-up event

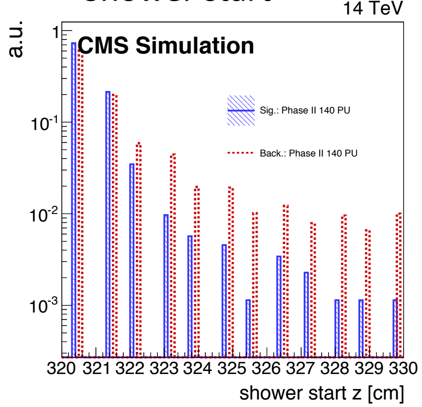


Two γ separated by 3 cm

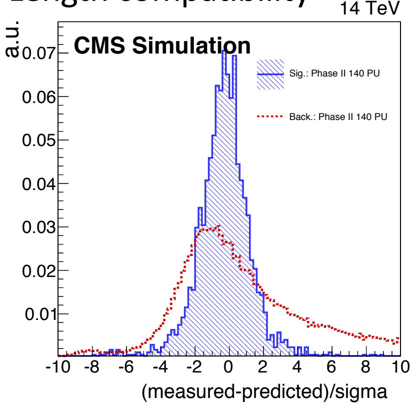


Signal/background

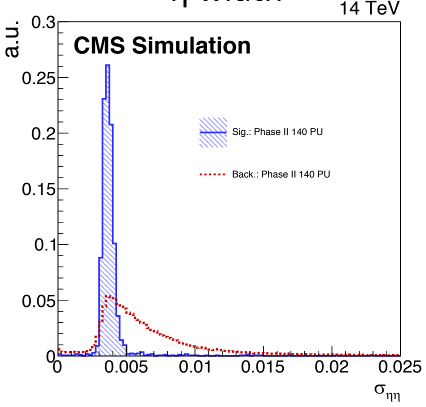
Shower start



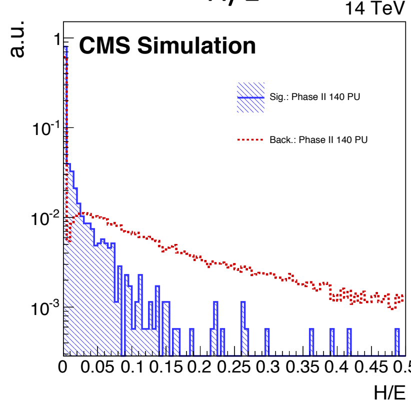
Length compatibility



η width



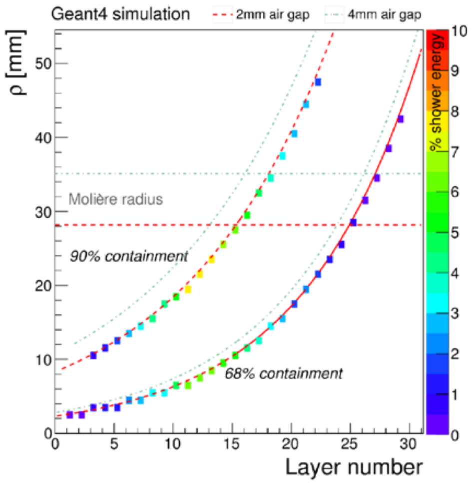
H/E

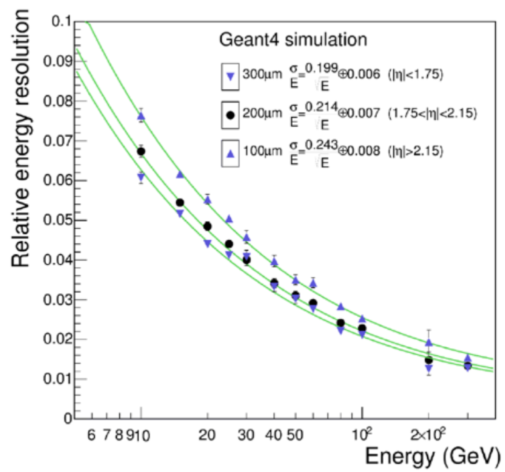


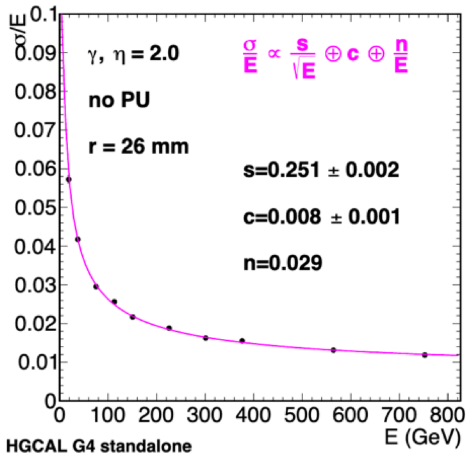
Software is not yet available to fully exploit benefit of the 3D topology at high pile-up

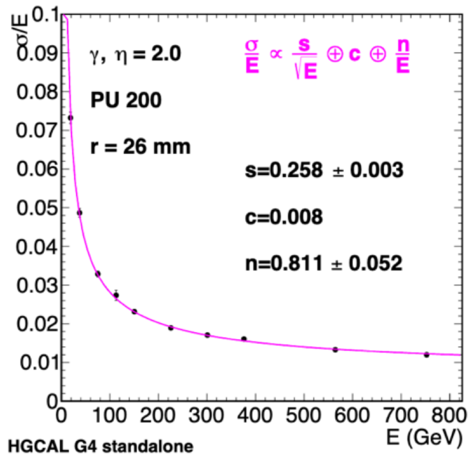
High Granularity Calorimeters: CMS HGC performance

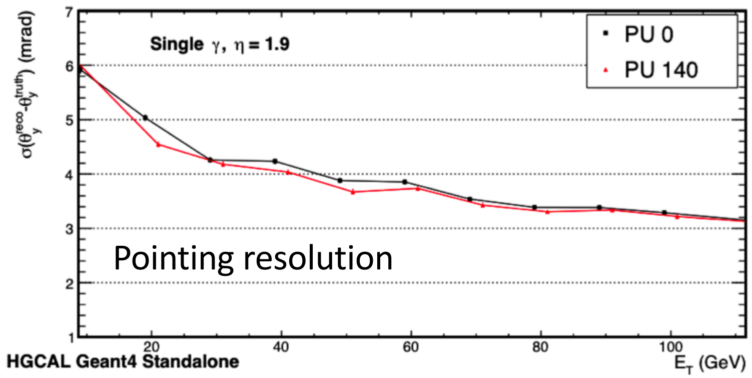
Moliere radius is relatively large (compactness challenge (air gap)) but shower topology compensate











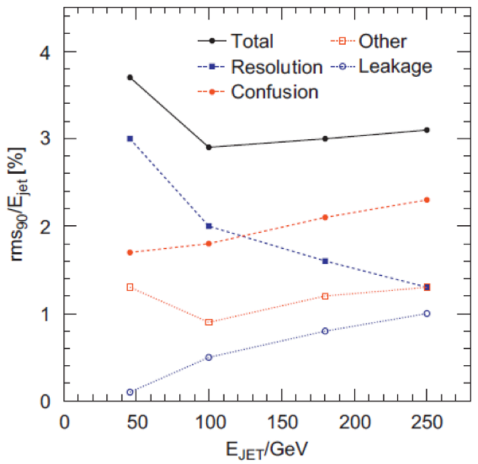
High Granularity Calorimeters: CALICE for e-e colliders

At e-e colliders, studies of Higgs width, VBF, top production strongly relies on high rate hadronic decays and require W/Z discrimination (10 GeV)

Goal for calorimetry is a hadron resolution of 30-40%/√E for a jet $\sigma(E)/E \simeq 3\%$

Granularity optimized to reduces particle association confusion contribution to resolution

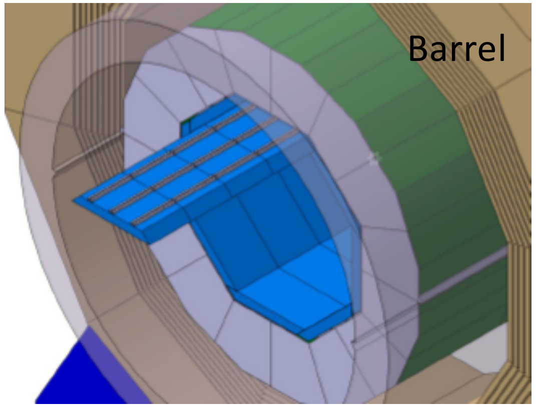
ILD HGC configuration	Electromagnetic section	Hadronic section options	
Active Layer/Absorber	Si / W	Scint. tile + SiPM /Steel	Glass RPC / Steel
Number of layers	30	48	48
Cell size (cm x cm)	0.5 x 0.5	3 x 3	1 x 1
Readout	analog	analog	semi-digital
Depth number of X_0/Λ_{int}	24 X_0	5 Λ_{int}	5 Λ_{int}
Number of channels ($x10^6$)	100	8	70
Total area	2500	7000	7000

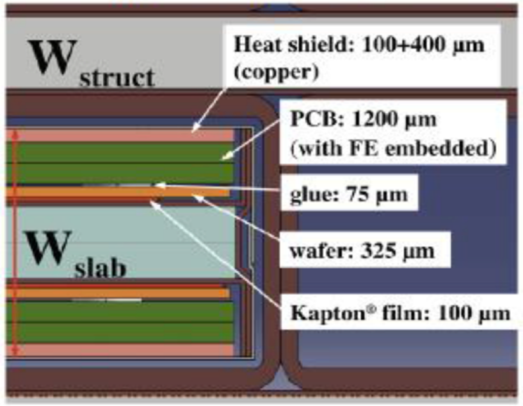


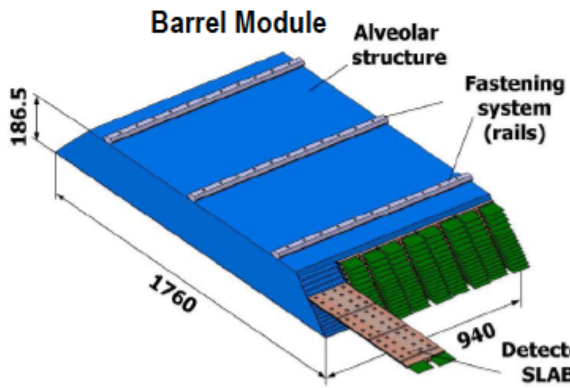
Scale of the detector is a challenge

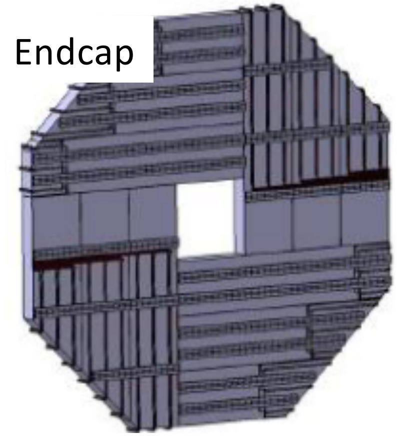
CALICE Si/W + AHCAL prototype: $\sigma(E)/E$ (e/γ)≃16%/√E ⊕ 1% and $\sigma(E)/E$ (π) ≃ 44%/√E ⊕ 2%

High Granularity Calorimeters: CALICE Si/W ECAL design

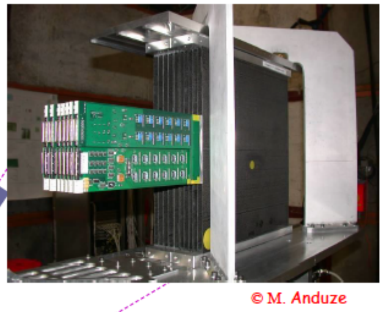


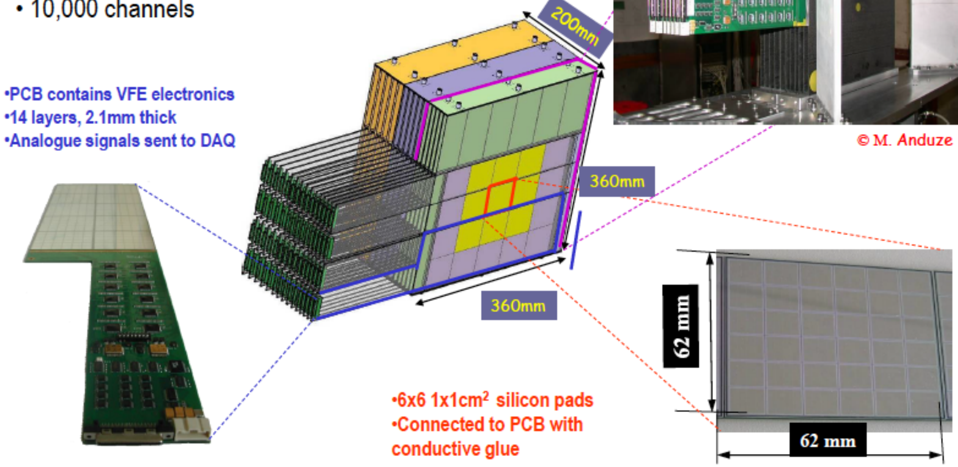


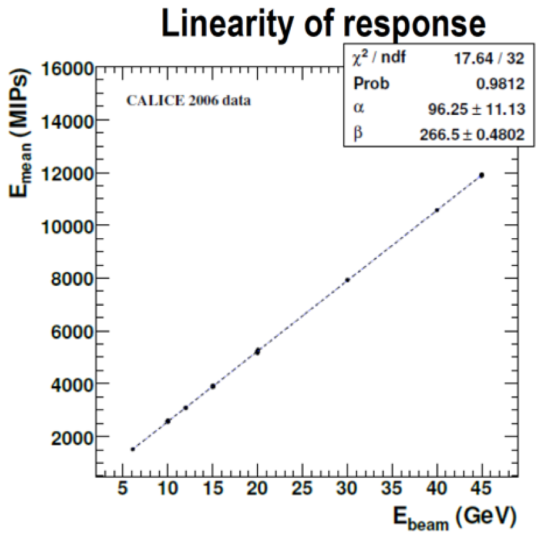


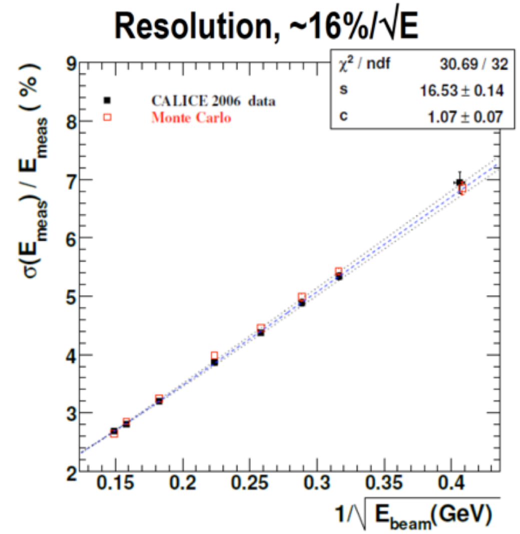


- 30 layers of variable thickness Tungsten
- Active silicon layers interleaved
- Front end chip and readout on PCB board
- Analog signals sent to DAQ
- 10,000 channels





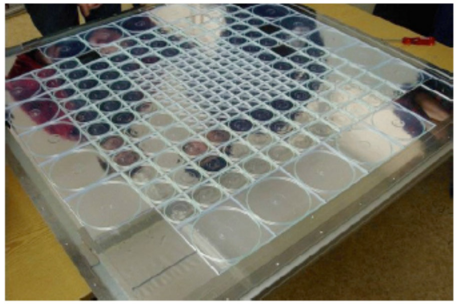


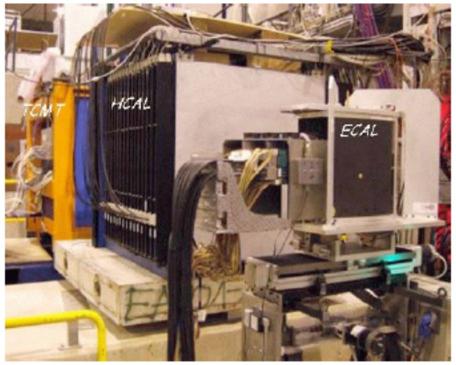


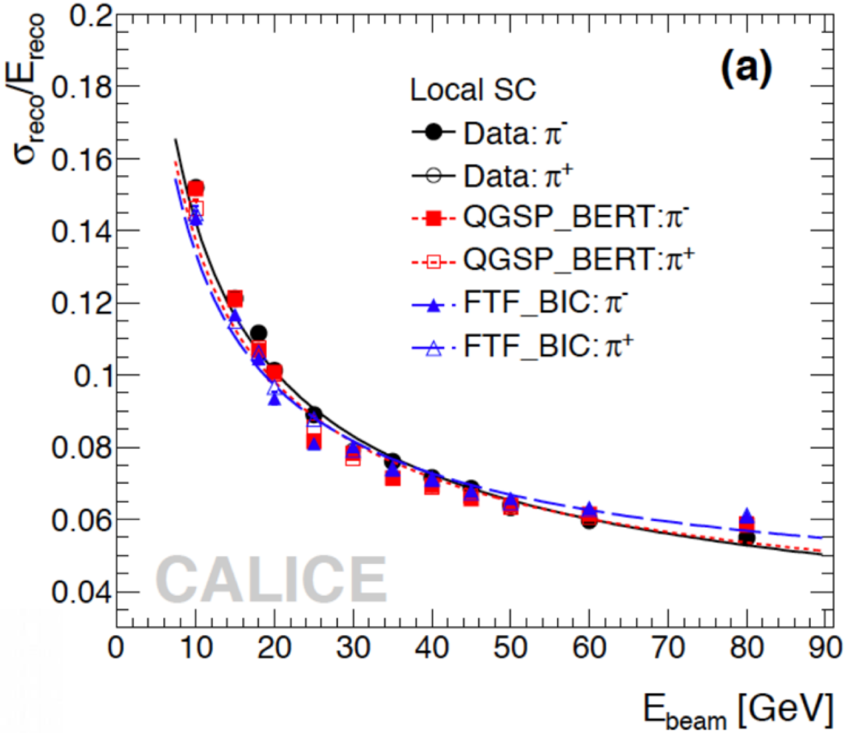
High Granularity Calorimeters: CALICE AHCAL/DHCAL design

AHCAL 1m^3 prototype 38 layers

- Scintillator Tiles+WLS+SiPMs (.5 cm)
- Stainless steel absorber (1.6 cm)



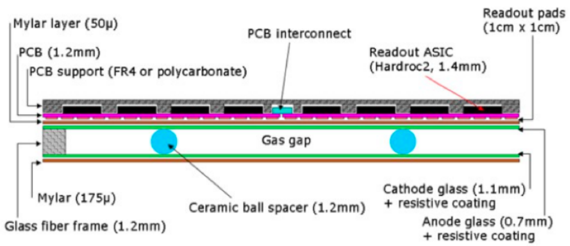


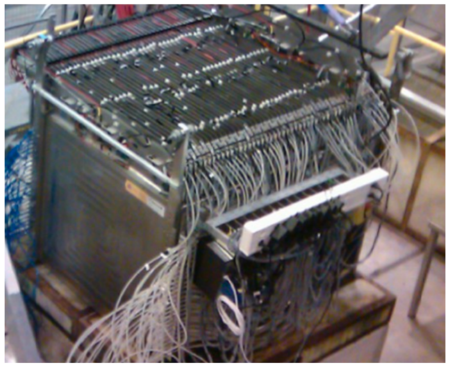


AHCAL ≃ 44%/√E after software compensation

SDHAC 1m^3 prototype 50 layers

- Resistive Plate Chambers as sensitive element
- particle counting with 3 energy thresholds

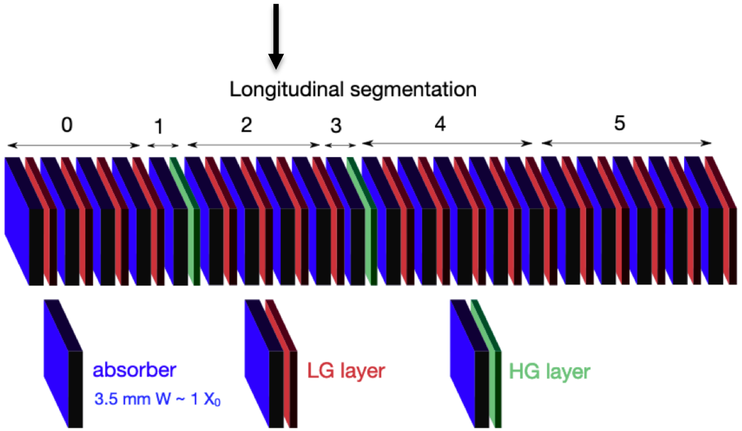


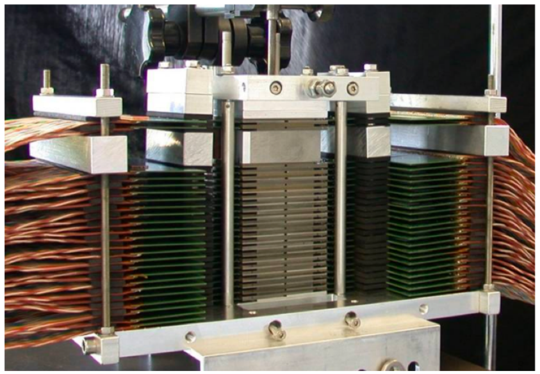


High Granularity Calorimeters: HGC R&D for e-e experiments

CMOS Monolithic sensors can be an alternative to planar pad sensors

- The step further in granularity would allowing particle counting
- ALICE FoCAL project (LS3): 20 layers Si/W mixed design, Si-pads 1 cm^2 (LG) and MAPs 30 x 30 μm^2 (HG)





First prototype of MAPs calorimeter

- 20 layers, 4 x 4 cm^2 MIMOSA MAPs
- Next prototype with ALICE ALPIDE in preparation
- Could be a unique tool to improve shower simulation

Calorimeter summary

ECAL Homogenous

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	16–$18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998

ECAL Sampling

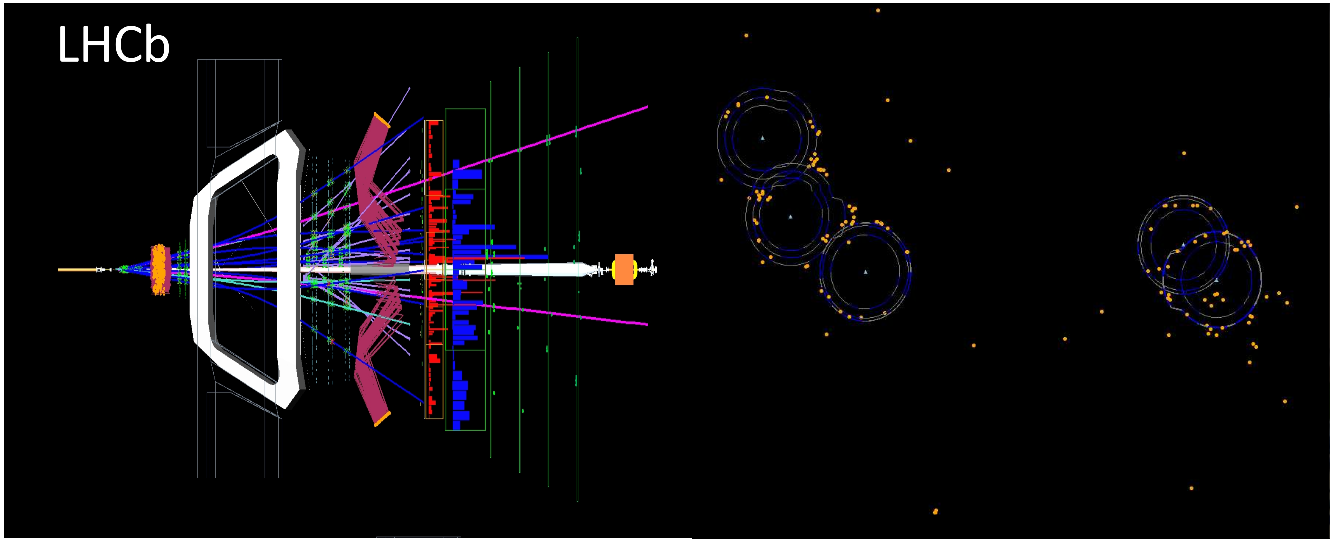
Scintillator/depleted U (ZEUS)	20–$30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	20–$30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

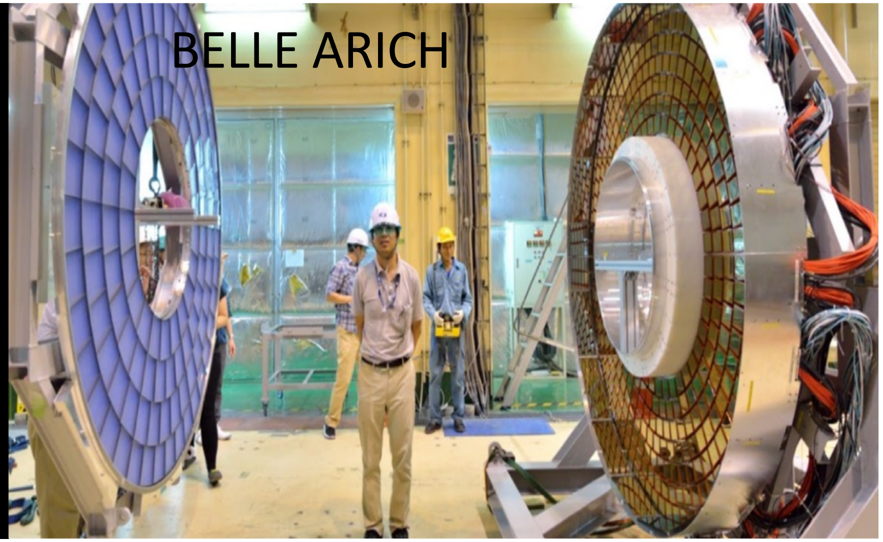
HCAL Sampling

Experiment	Active Material	Absorber	e/h	Single π resolution (GeV)
H1	LAr	Steel	1.1–1.3	$50\%/\sqrt{E} \oplus 2\%$
ZEUS	Scintillator	Uranium	1.0	$35\%/\sqrt{E}$
CDF (central)	Plastic scintillator	Steel	1.4	$50\%/\sqrt{E} \oplus 3\%$
DØ	LAr	Uranium	1.1	$45\%/\sqrt{E} \oplus 4\%$
ATLAS (barrel)	Scint. tiles + WLS	Iron	1.36	$42\%/\sqrt{E} \oplus 2\%$
CMS (barrel)	Scint. tiles + WLS	Brass 70(30)% Cu(Zn)	1.4	$83\%/\sqrt{E} \oplus 4.5\%$

Cherenkov detectors

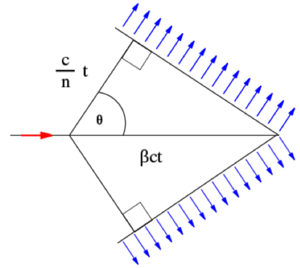
Measure β for particle identification
can also provide Time of Flight
Largely used in Flavor and Heavy Ion experiments





Cherenkov detectors: process

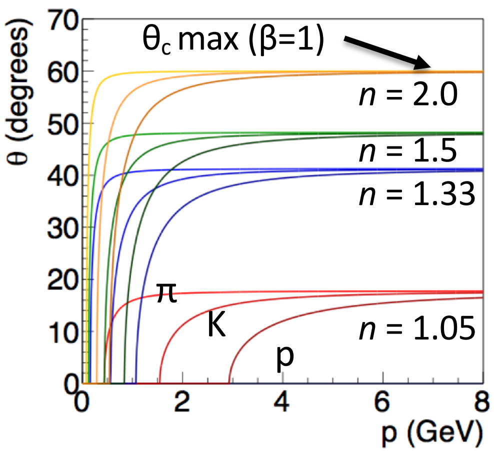
Emission of photons by a charged particle with $\beta > 1/n$, n material refraction index

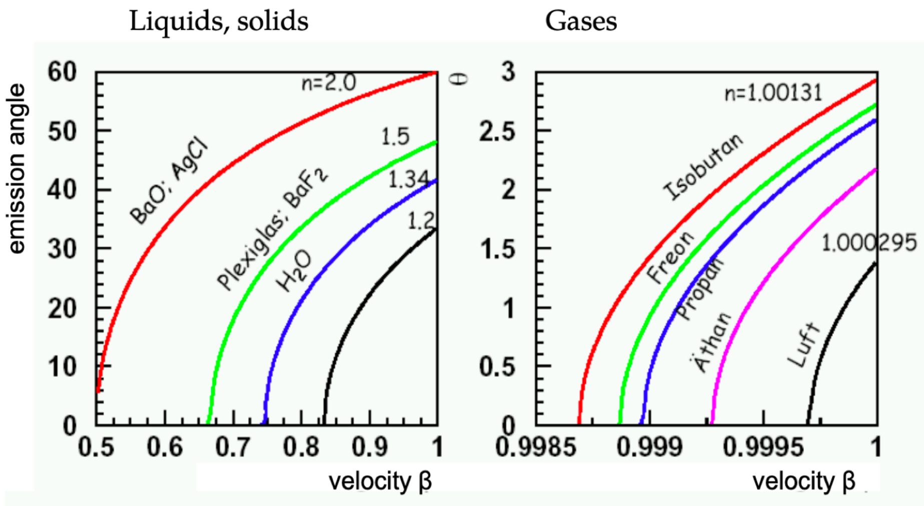


- Light is emitted at angle θ_c with $\cos\theta_c = 1/(n\beta)$
  - Can be measured in transparent material to provides mass particle identification in combination with momentum measurement ($p = \beta\gamma mc$)
- $d^2N_\gamma/d\lambda dx \propto (\sin^2\theta_c)/\lambda^2$, λ = wave length, $dN_\gamma/dx \propto (\sin^2\theta_c)(\lambda_2 - \lambda_1)/\lambda_2\lambda 1$
  - $N_\gamma \simeq 490(1150) \sin^2\theta_c$ cm^{-1} for [400,700] nm visible range (including UV > 200 nm)
  - eg relatively small $\simeq$ few to 100 per cm in visible from low to high n materials[1)]

Material	n	Threshold β
Diamond	2.42	0.41
ZnS (Ag)	2.37	0.42
PbF_2	1.8	0.56
Glass	1.46–1.75	0.57–0.68
Scintillator	1.58	0.63
Plexiglass	1.48	0.68
Water	1.33	0.75
Aerogel	1.025–1.075	0.93–0.976
Pentan*	1.0017	0.9983
CO_2*	1.00043	0.9996
He*	1.000033	0.99997

* gas at standard temperature and pressure (STP)

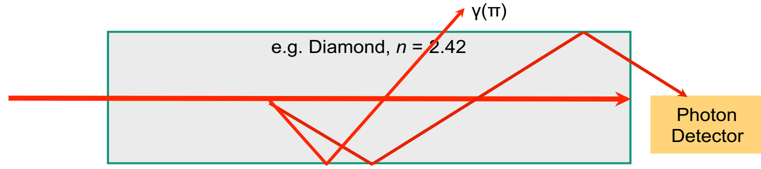


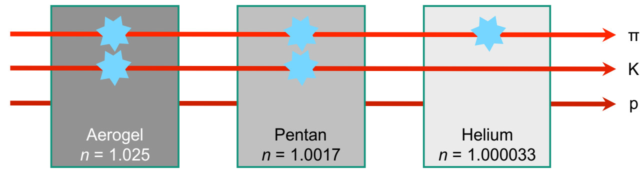


1) favors higher n materials for precision timing measurement

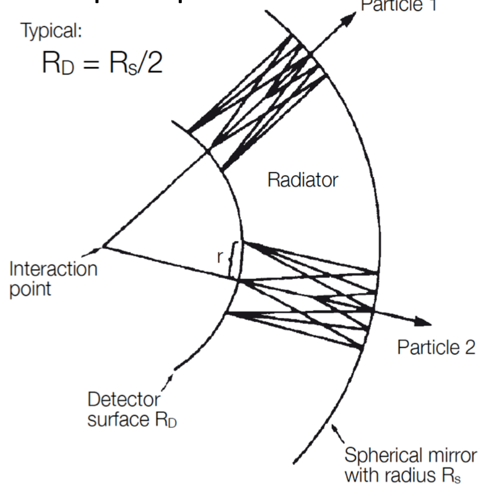
Cherenkov detectors: measurement[1)]

- Differential detection, narrow measurement window
  - eg. θ_c limited by total reflection angle
- Threshold detection
  - Combine materials in serie with different n so that different particles do not cross threshold $\beta > 1/n$ in all materials
    - ex. light in 1, 2, 3 for π, in 1,2 only for K and none for p
- Angle detection through device optics
  - RICH (Ring Imaging Cherenkov)
    - Short radiator, focusing not needed (referred as proximity focusing)
    - Long radiator (gas) focusing with a spherical mirror (possible expansion improvement with a second planar mirror toward readout)
  - DIRC (Detection of Internally Reflected Cherenkov light)
    - Need total reflection (ex quartz material)

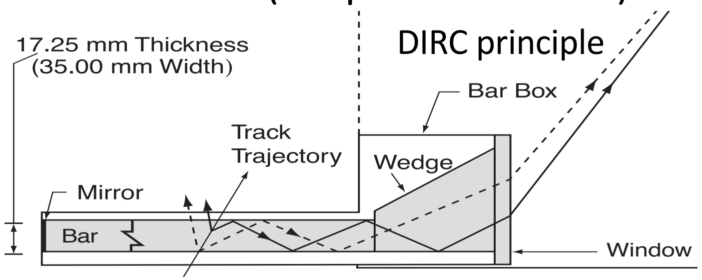




RICH principle



DIRC principle



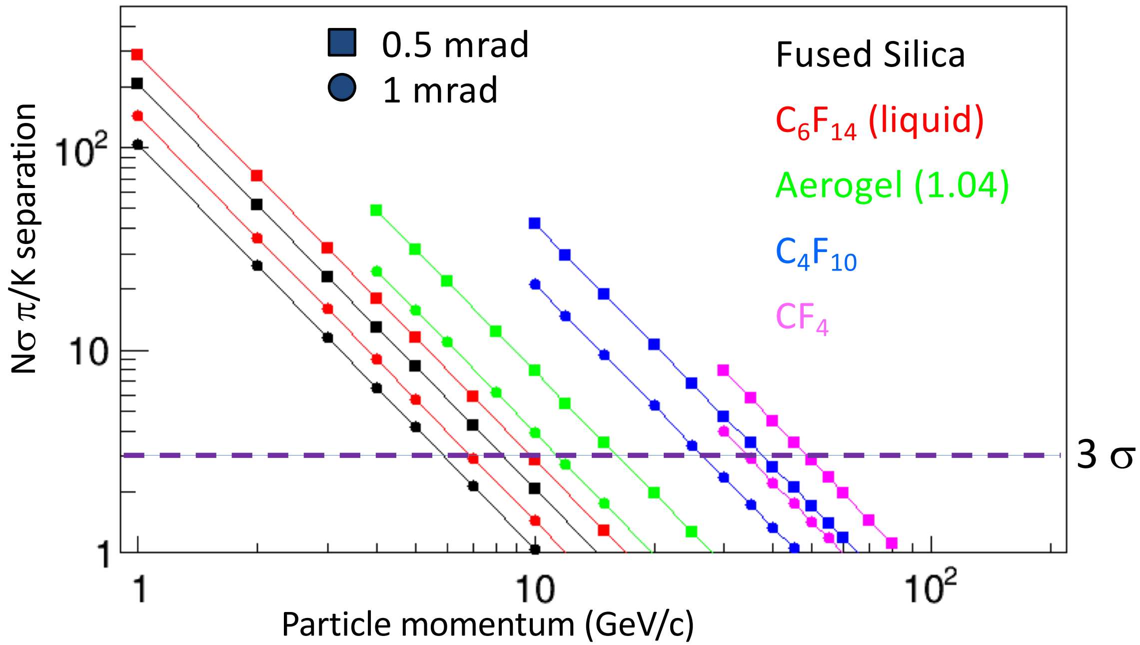
1) Experiments can use hybryd systems with different radiators and focusing

Cherenkov RICH: resolution

Resolution usually expressed in number of σ for π/K separation

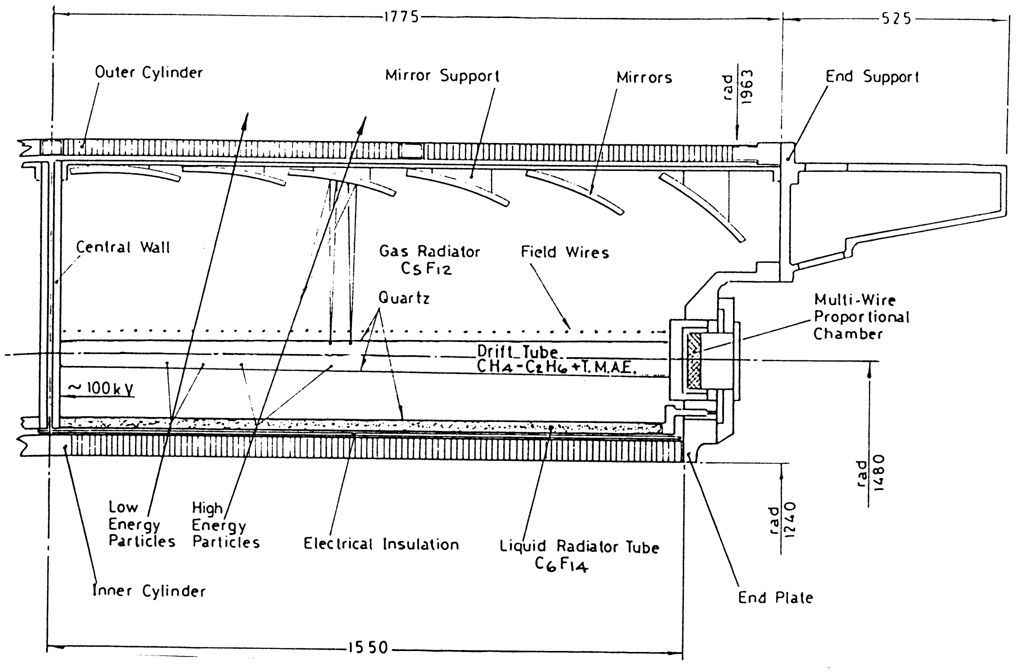
$$N_\sigma \approx \frac{\left|m_1^2 - m_2^2\right|}{2P^2\sigma[\theta_c(tot)]\sqrt{n^2-1}}$$

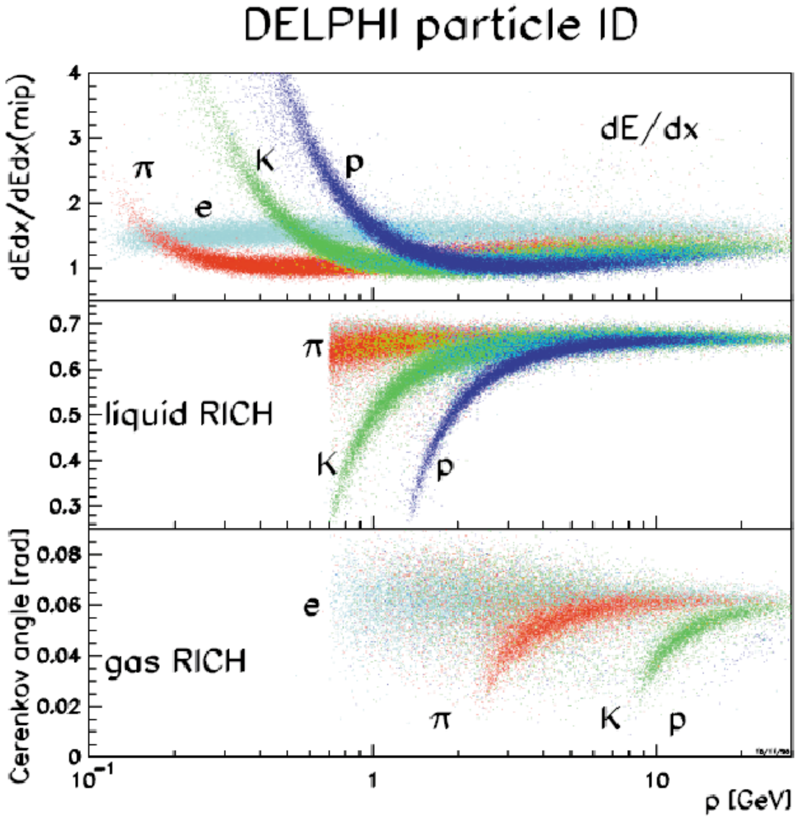
- Low n material
  - Favor higher momenta
  - But need more expansion space for θ resolution



Cherenkov RICH: DELPHI design

Two stages, liquid (C_6F_{14}) and gas (C_5F_{12}) w/o and w focusing, readout in MultiWire Proportional Chambers with TMAE photo-converter vapor[1)] in gas mixture

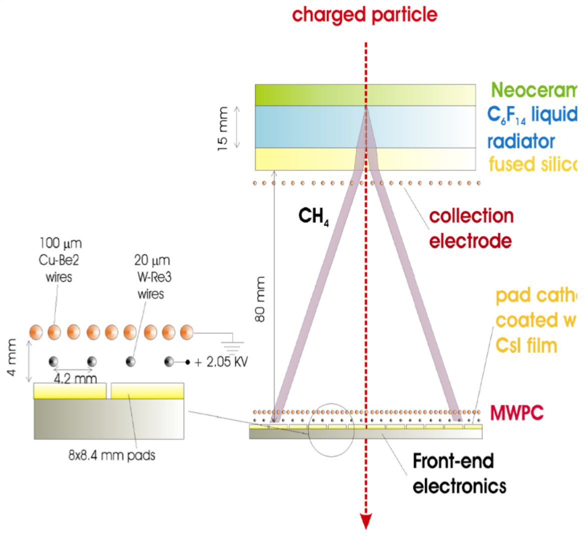


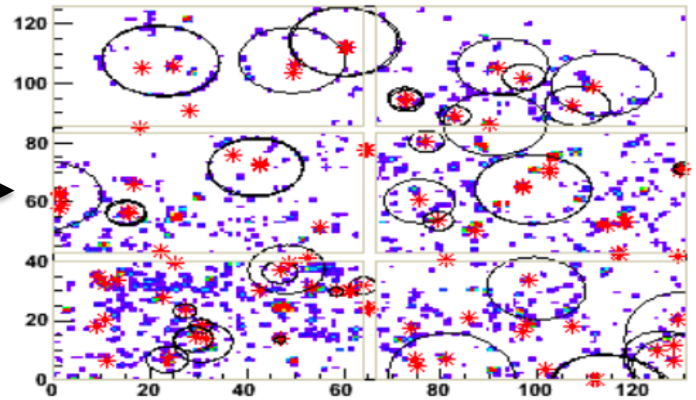


1) Conversion in the UV range, uneasy operation due to chemical properties

Cherenkov radiation: ALICE HMPID RICH design

- Liquid C_6F_{14} radiator[1)] proximity focusing for momentum range 1 -6 GeV
- Readout with MWPC with CsI photo-cathode coating allows to collect UV signal (25% QE)
  - Largest scale of CsI photocathode in HEP
  - The incident MIP impact position is also measured and matched to a track

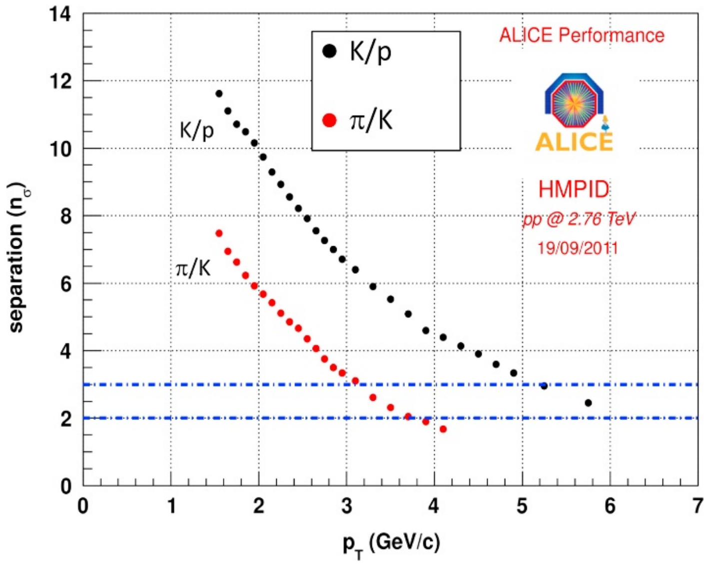


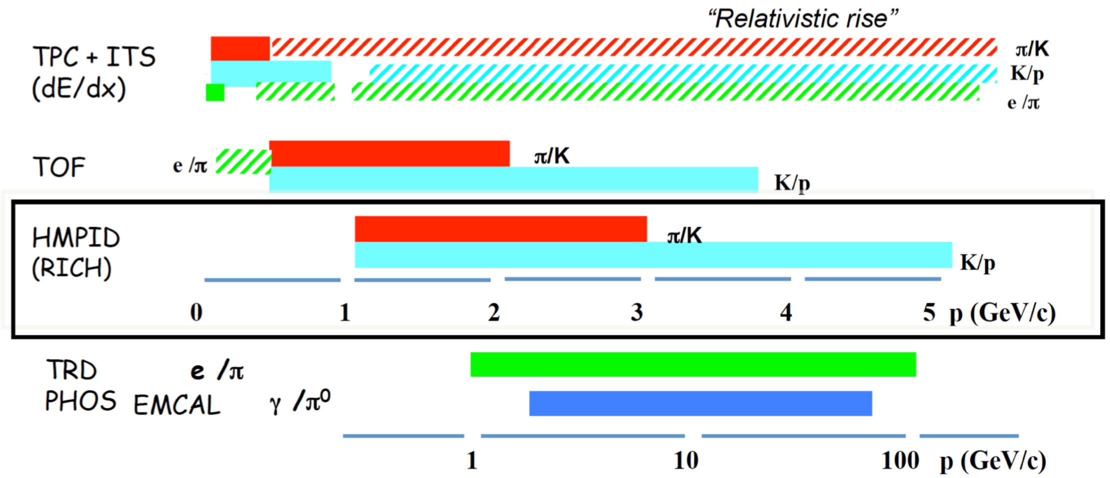


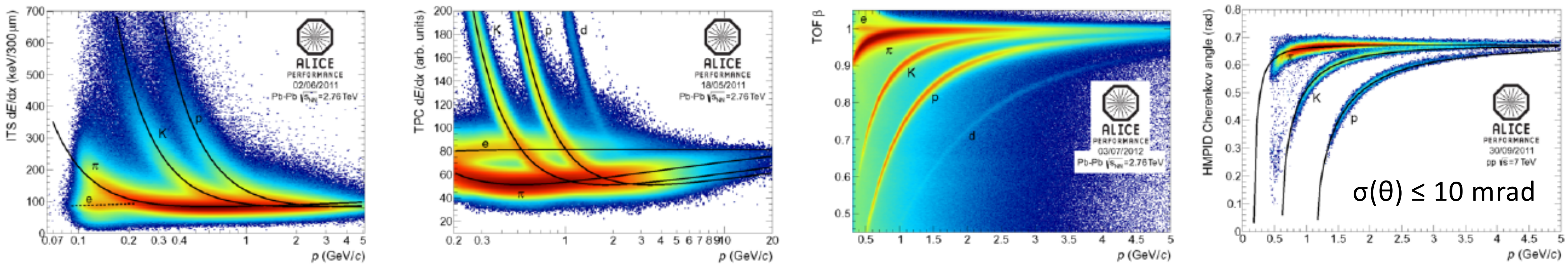
Event in one chamber

1) n = 1.29 at 179 nm UV (β threshold 0.77)

Cherenkov radiation: ALICE HMPID RICH performance

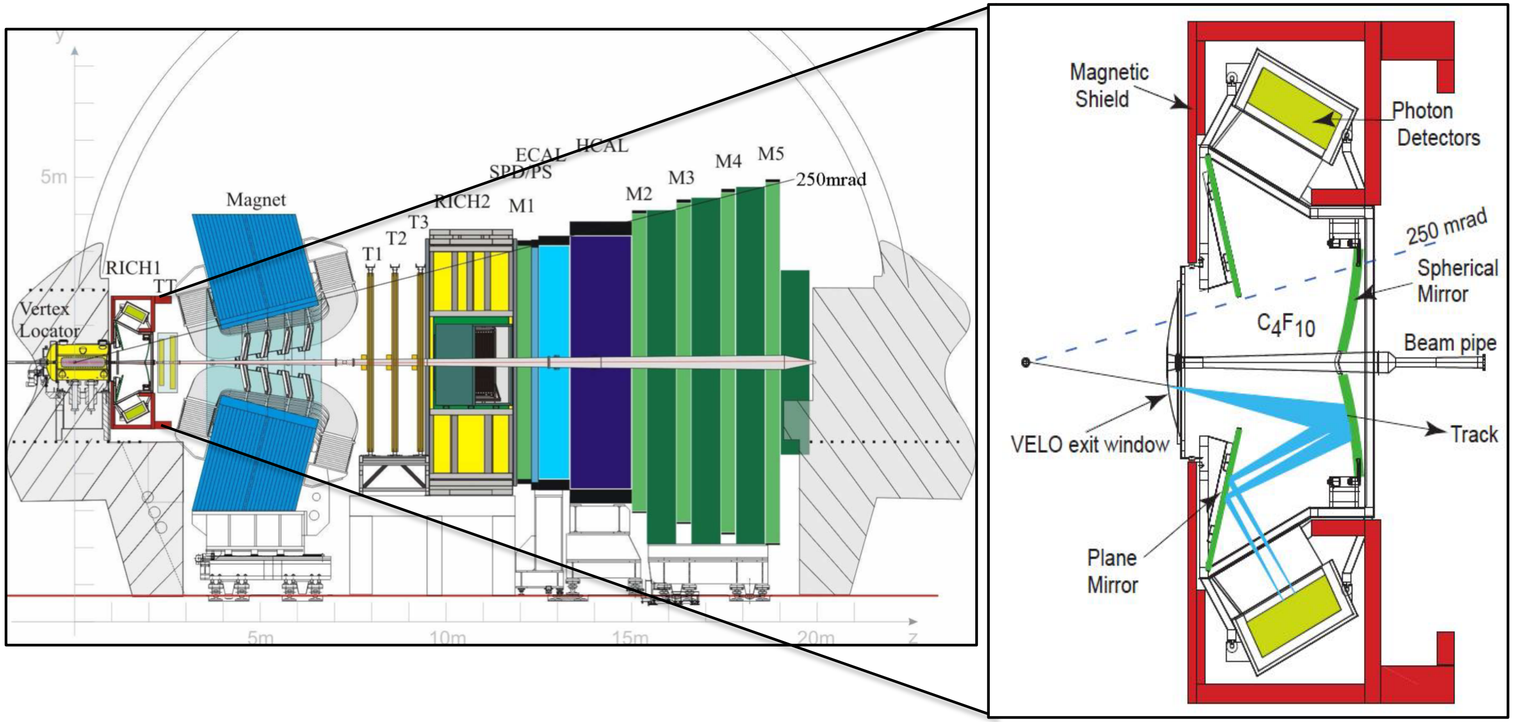






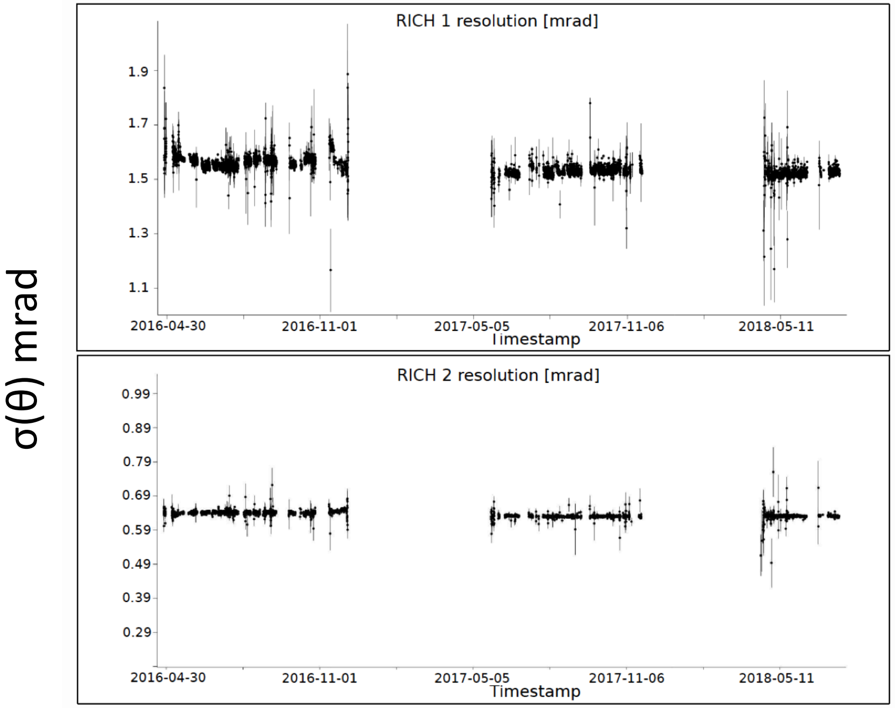
Cherenkov RICH : LHCb focusing design

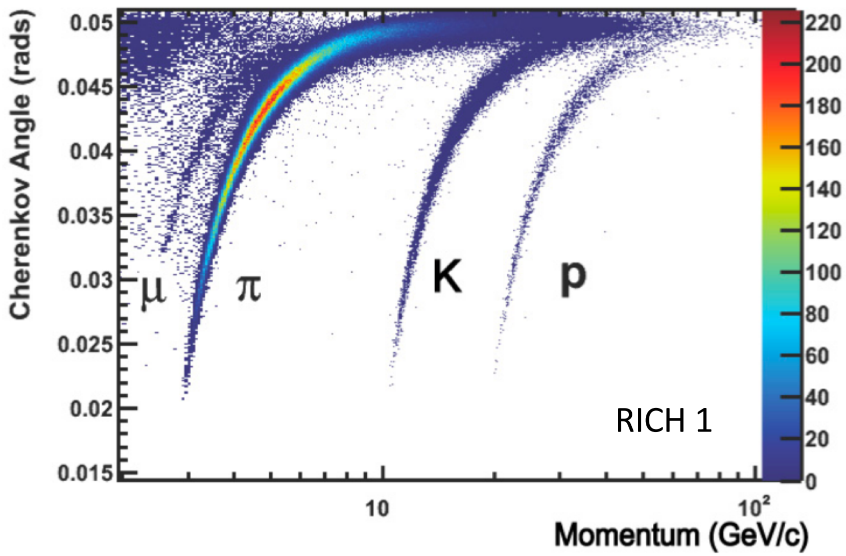
- RICH 1: C_4F_{10} gas radiators for 1 - 60 GeV range
- RICH 2: CF_4 gas radiator for 30 - 100 GeV range
- Similar focusing geometry and readout with hybrid PMTs →



Cherenkov radiation: LHCb RICH performance

Thorough calibration and monitoring is required to control refraction index (temperature, pressure, composition of gas mixture) and alignment stabitility[1],
absolute calibration can be done with mass of decays

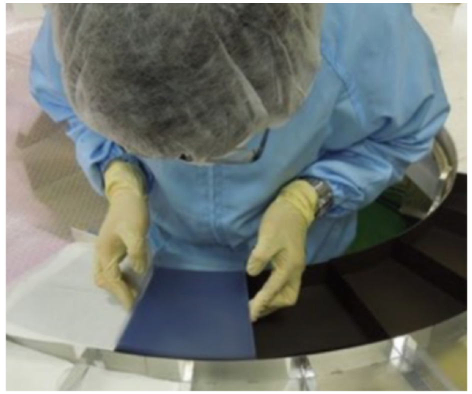


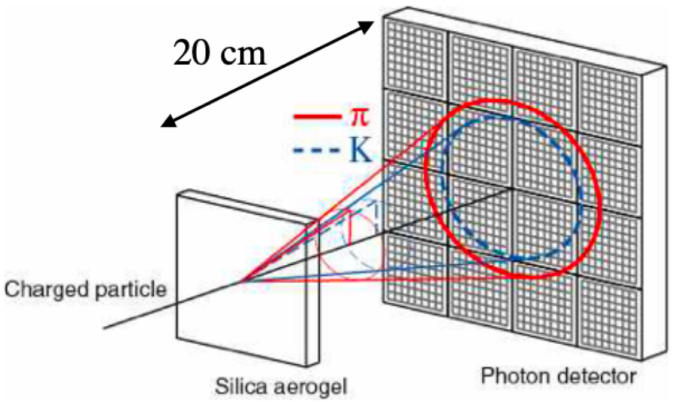


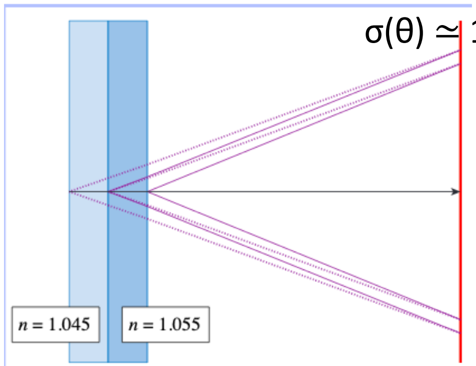
1) Applies to other RICH devices

Cherenkov detectors: Belle ARICH endcap

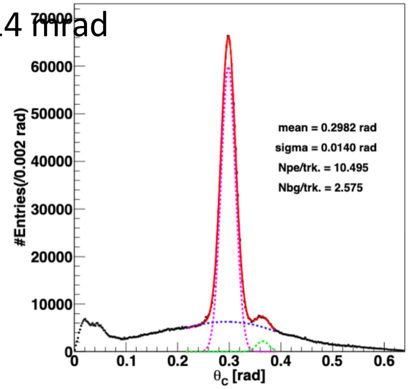
- Silica aerogel radiator (new material)
  - Goal 4σ π/K separation at 4 GeV
  - Limited space of 30 cm with 20 cm expansion length
- Focusing with two layers each 2 cm $n_1(n_2) = 1.045(1.055)$
- Readout with 5 mm resolution 30% QE HPDs



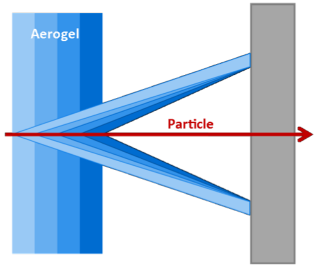


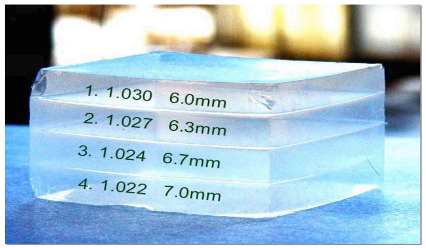


σ(θ) ≃ 14 mrad



Belle-II upgrade

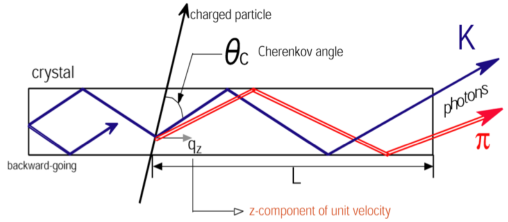


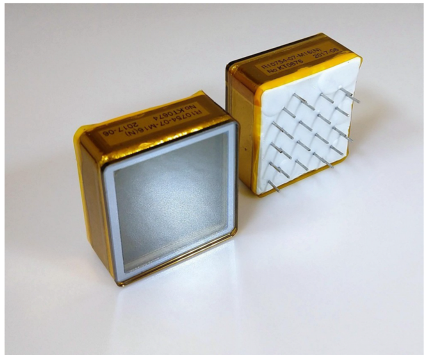


Future RICH detectors: BELLE-II RICH upgrade

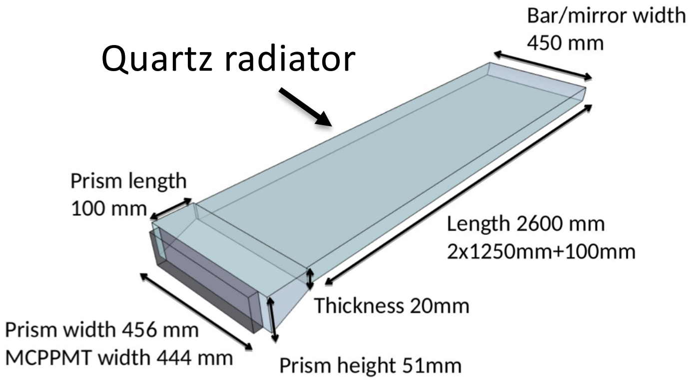
Time of Propagation design in Barrel

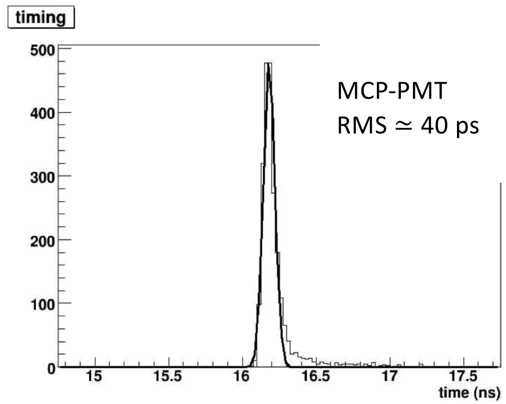
- Extension of the DIRC design developed for the BABAR experiment w/o expansion volume to the photo-detectors due lack of space
- The ID is based on the photon time of arrival (earlier for lighter particles) detected in MCP-PMTs (needs particle impact parameter on radiator)
- Target resolution $\simeq$ 80 ps (50 ps (SPTR[2])) $\oplus$ 50 ps (electronics) $\oplus$ 50 ps (clock)

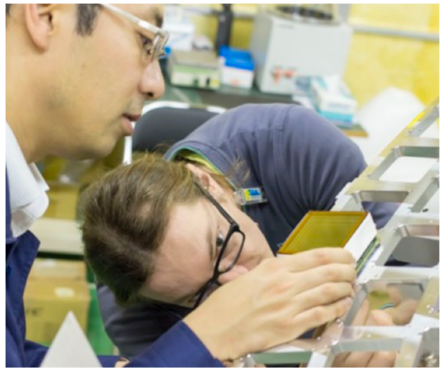




MicroChannel Plate PMT







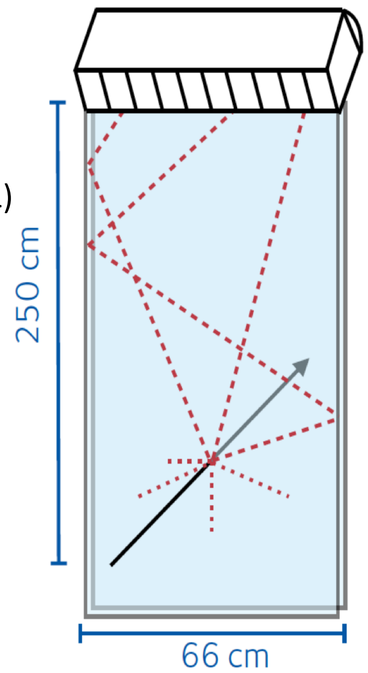
Commissioning of the detector is on-going

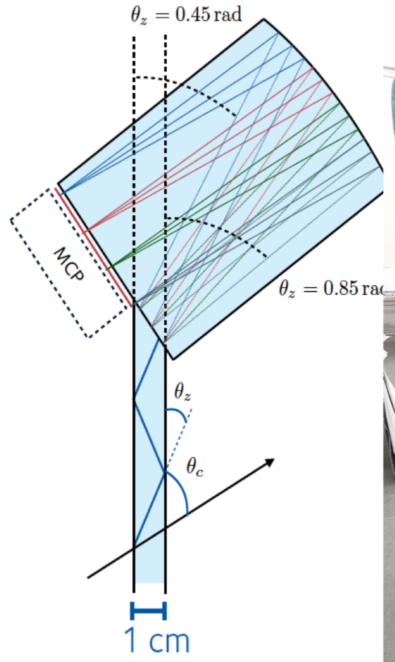
1) Single Photon Time Resolution of MCP-PMT

Future RICH detectors: LHCb TORCH upgrade for HL-LHC

Time of Reflected Cerenkov Light Rich

- Quartz bar radiator and focusing on MCP-PMT[1)]
  - Target id in the range 2 -10 GeV combining Cherencov angle and TOF measurements with σ(ToF) ≃ 15 ps, (≃ 70 ps SPTR & ≃ 30 γ/track)
  - MCP demonstrated to achieve ≃ 35 ps
  - TORCH ½ full size prototype tested in 5-8 Gev π/p beam achieved SPTR of ≃ 90 ps



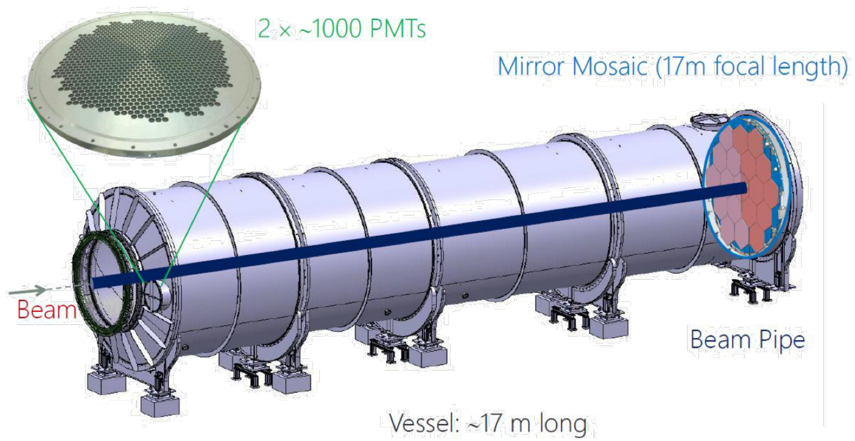


Wall of 18 elements in front of RICH2

1) R&D in new rich material radiator (photonic crystals nano-structure) and MCP-PMT to improve SPTR

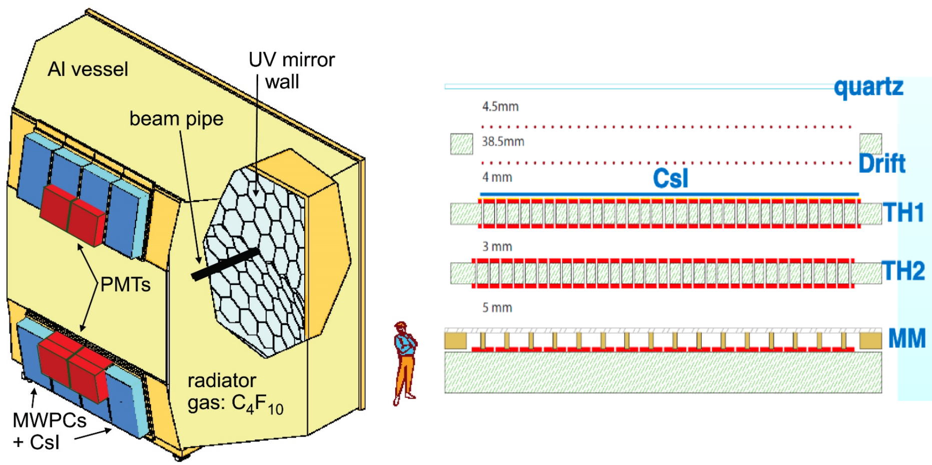
Cherenkov detectors: other examples

NA62 RICH



- Momentum range 15-35 GeV/c
- Neon radiator 200 m^3 in 17 m long cylindrical vacuum tank
- Readout with 2000 PMTs (16mm, 8 active)
- Mirror alignment ~30 mrad
- Single photon resolution: ~140 mrad

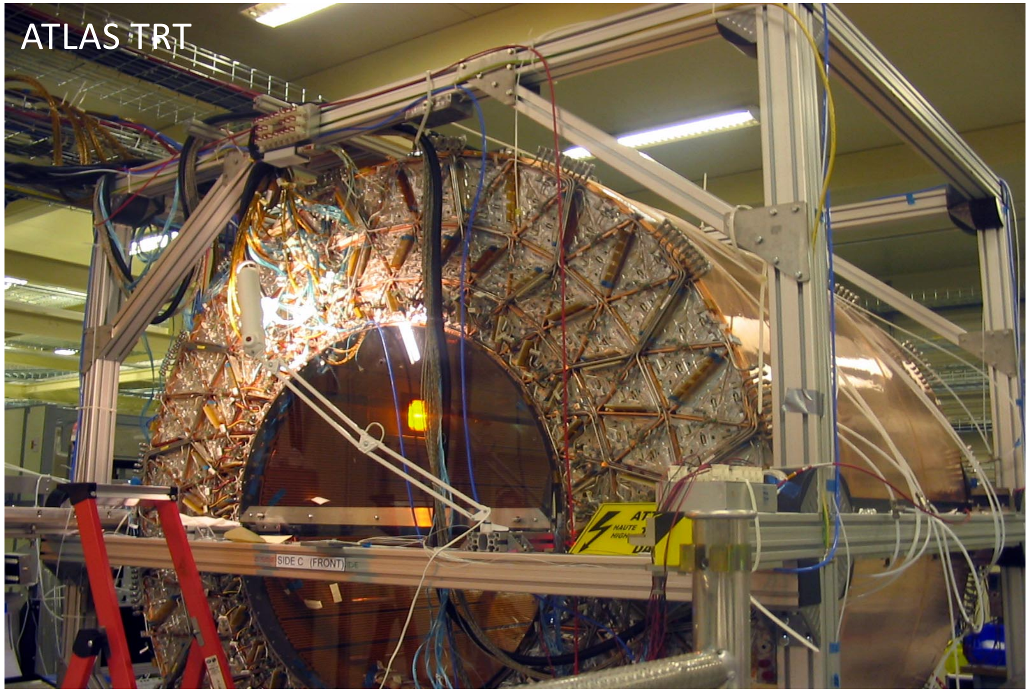
COMPASS RICH

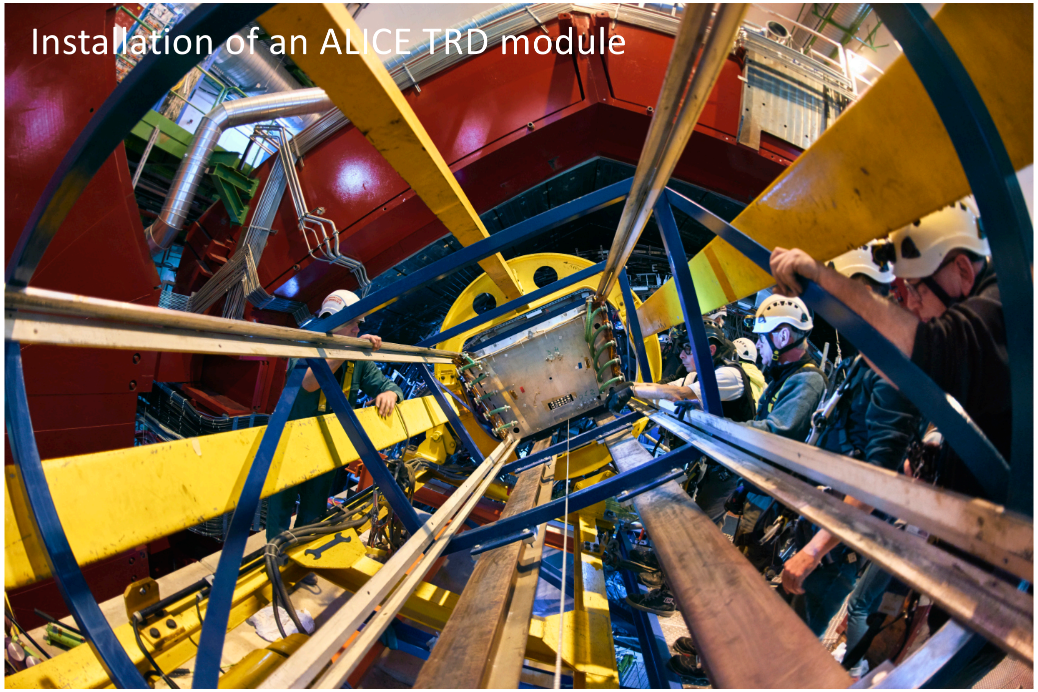


- C_4F_{10} radiator detector
- Central part readout with MaPMTs and MPGD (THGEM + MM) with CSI photocathode coating

Transition Radiation Detectors

e^- / e^+ identification ($\geq$ GeV)





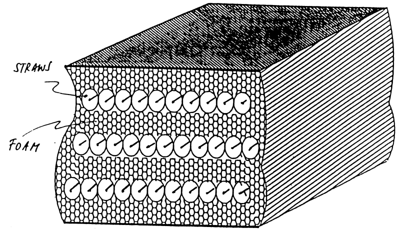
Transition Radiation: process and measurement

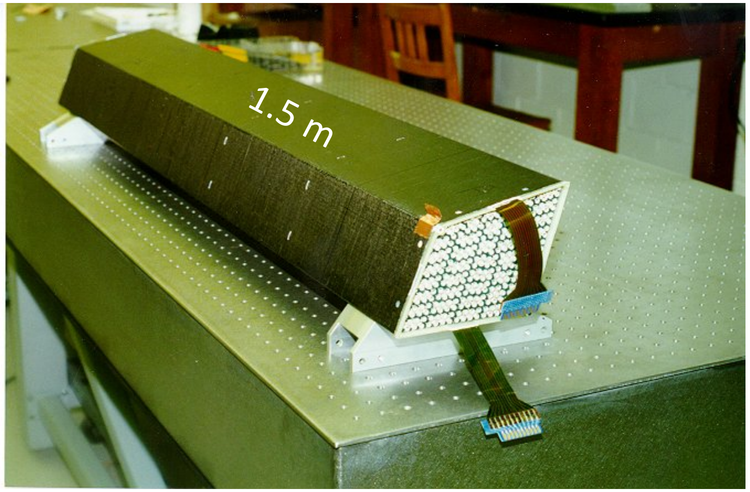
- Radiation from charged particle crossing the boundary of materials with different dielectric constants
  - Total emitted energy is $\propto \alpha\gamma\omega_p$, $\alpha = 1/137$, γ Lorentz factor, ω_p material property
    - Only e^- and e+ have high enough γ to emit transition radiation
    - Number of photons is small (emission angle is also small $\propto 1/\gamma$)
      - Radiators must be stack of transition, with low z to avoid re-absorption of photons
    - Radiation wave length is in the X-ray domain 1 - 10's keV
      - Gas detectors are well suited, sensitive to
  - Identification relies on different energy loss measured for e^-/e^+ compared to π
    - (dE/dx (ionization) + dE/dx (TR)) / dE/dx (ionization)

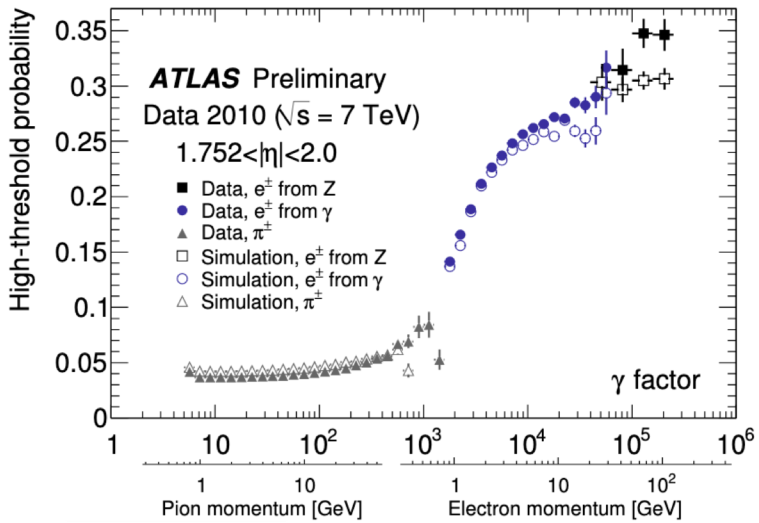
Material	Luft	He	Li	Al	Polyethylen	Polypropylen	Mylar	Rohacell
$\hbar\omega_p$ (eV)	0.71	0.26	13.8	32.8	20.53	20.51	24.6	23.09

Transition Radiation Detector: ATLAS TRT

- Transition Radiation Tracker
  - Straw tubes (4 mm)[1)] are embedded in polymer fiber (19 mm) foam radiator
  - X-rays from transition radiation are converted through photo-electric effect in straw tube gas mixture
  - Tracks cross 35 to 40 straws



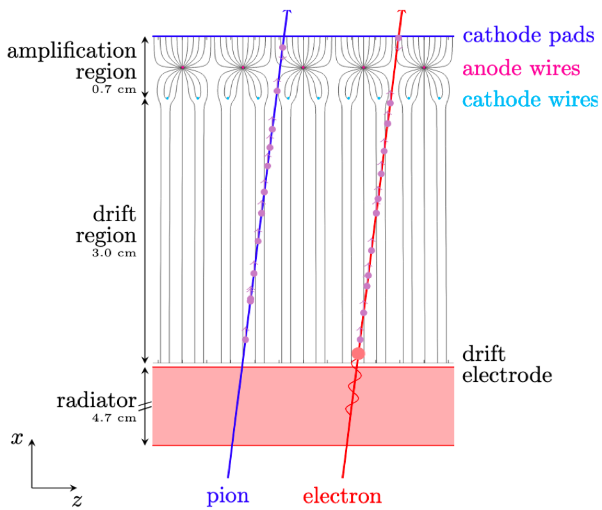


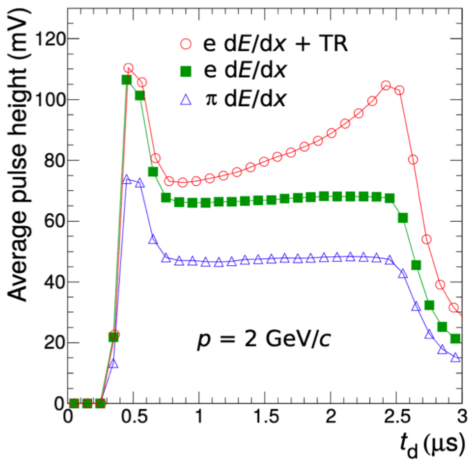


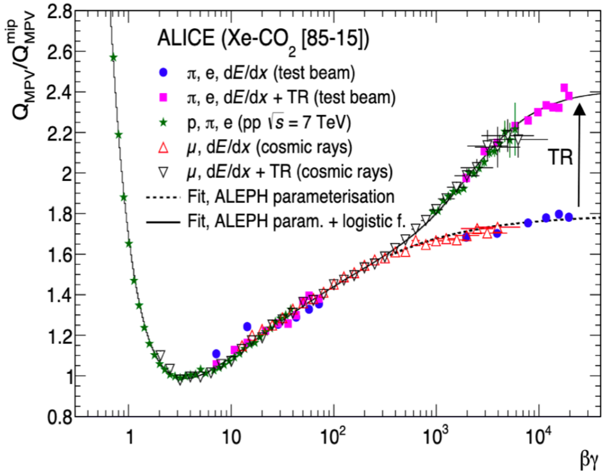
1) Tracking hit resolution $\simeq$ 120(140) μm barrel(endcaps)

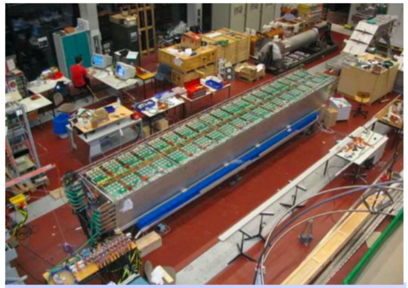
Transition Radiation Detector: ATICE TRD

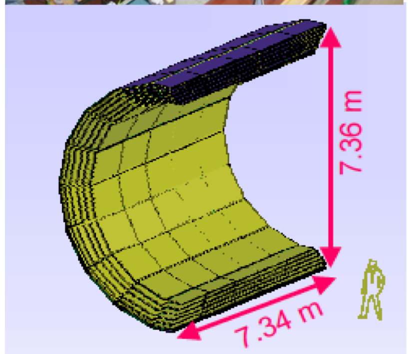
- Transition Radiation Detector
  - 6 layers MWPC chambers MWPC chambers with Xe based gas mixture
    - High Z to have short X-ray absorption length
  - Radiator is propylene fibers mats sandwiched in Rohacel (foam)

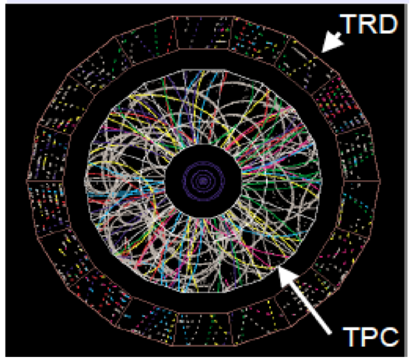












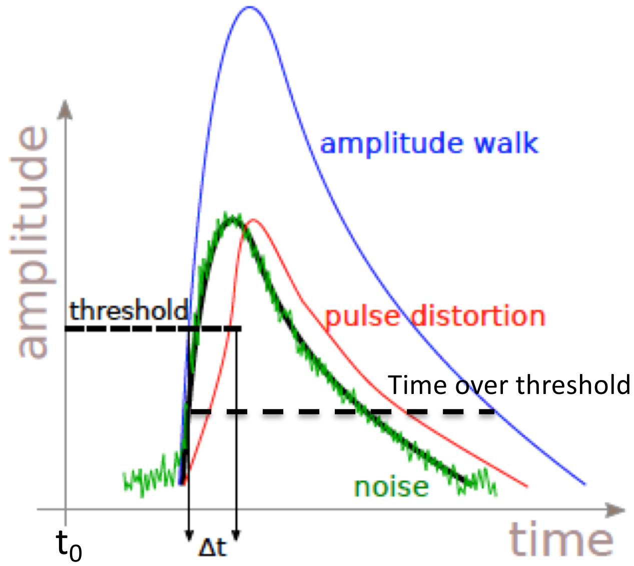
Minimum Ionizing Particle Timing Detectors

Measure time of arrival of charged particle with precision ≤ O(100) ps
Can provide collision time stamp, particle ID, position
and pileup mitigation in association of track to vertices

MIP Timing Detectors: resolution parameters

$$\sigma_t = \sigma_{sign} \oplus \sigma_{elec} = \sigma_{sign} \oplus \sigma_{time\text{-}walk} \oplus \sigma_{noise} \oplus \sigma_{TDC} \oplus \sigma_{clock}$$

- σ_{sign} = detector signal fluctuations
- $\sigma_{time\text{-}walk}$ = amplitude of signal
  - time-walk is corrected by amplitude measurement usually from pulse Time over Threshold
- $\sigma_{noise} \simeq \tau_{rise}/(S/N)$ (τ_{rise} signal development)
- σ_{TDC} = digitization precision (number of TDC bits)
- σ_{clock} = t_0 reference precision



MIP Timing Detectors: ALICE ToF MRPC detector for PID

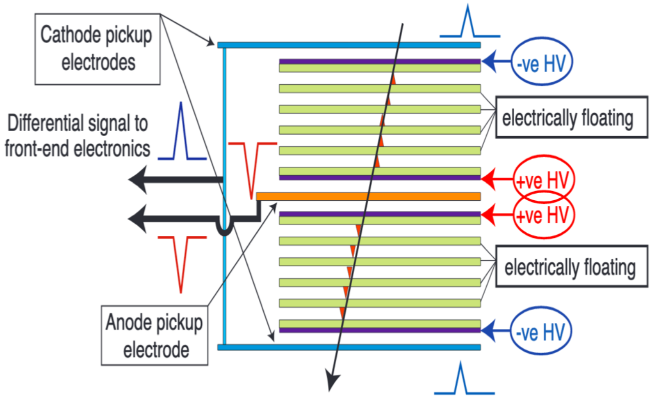
For a relativistic particle with momentum p flying over a length L

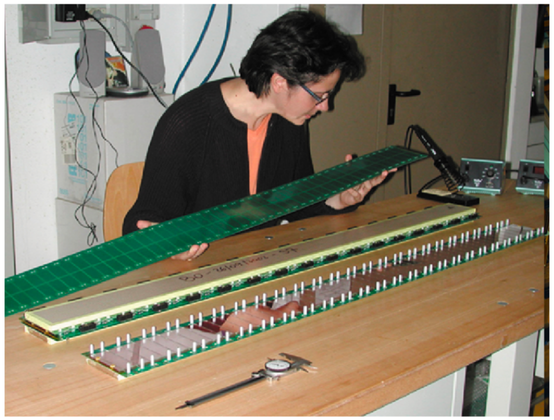
$m^2 = p^2/c^2[(c^2t^2/L^2)-1]$ and ToF contribution to mass resolution is $\sigma(m)/m = \gamma^2 \sigma(t)/t$

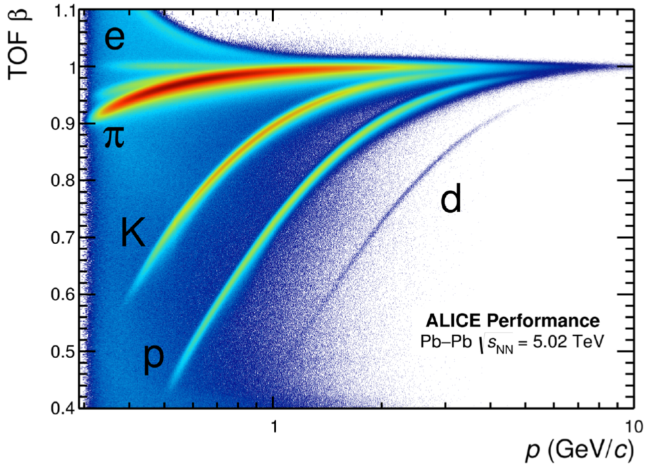
- A 10% mass resolution for a 5 GeV proton flying and 5 m requires $\sigma(t) = 40$ ps
- Particle ID is qualified by n $\sigma(t)$ separation = $(t_1-t_2)/\sigma(t) = (Lc/2p^2)(m_1^2 - m_2^2))/\sigma(t)$
- 3σ separation of a 5 GeV proton from a Kaon requires $\sigma(t) = 70$ ps

140 m^2 cylindrical detector located around the TPC and TRT systems with $\sigma(t) = 60$ ps[1)]

- Two stack of multi-gap resistive plate chambers, 120 x 7.4 cm^2
  - 5 x 250 µm gap/stack (much smaller than regular RPC 2 mm gap), ad size 3.5 x 2.5 cm^2



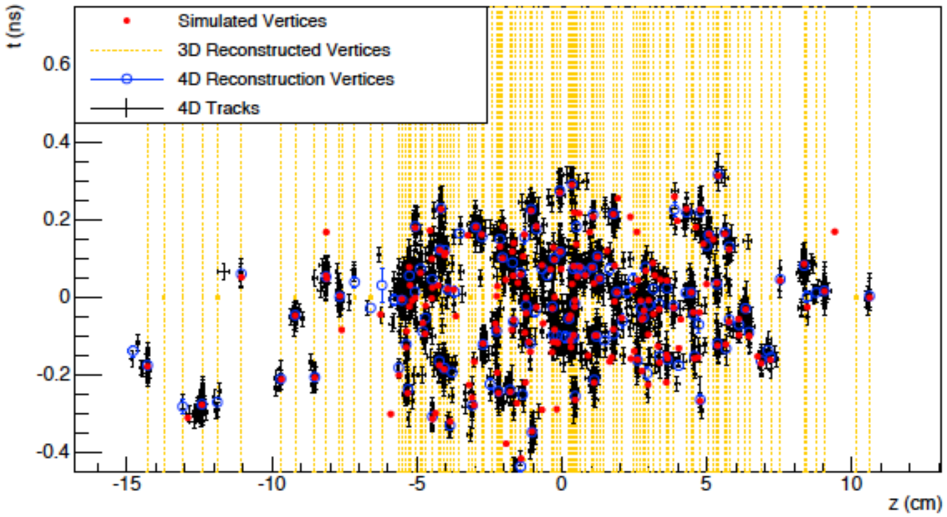




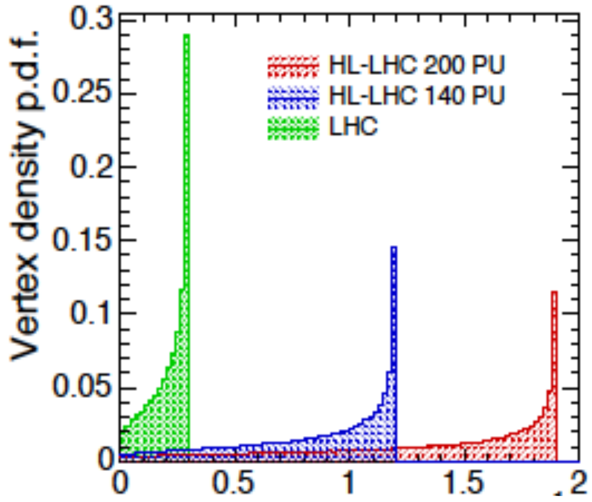
1) ≃ 150 ps per RPC gap, with 20 ps NINO chip resolution, 30 ps TDC and beam spot size 14 ps

MIP Timing Detectors: pile-up mitigation at HL-LHC

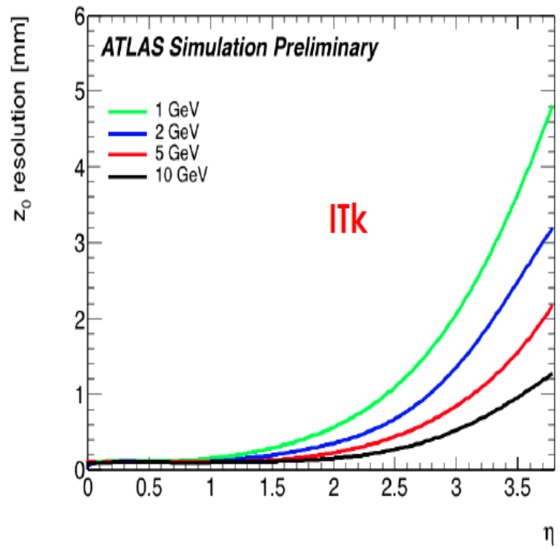
200 p-p collisions (pile-up) in a BC



Vertex density (mm^{-1})



Track z-precision



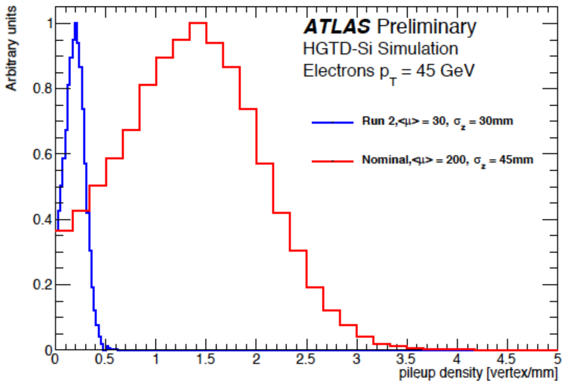
- Tracking efficiency is not affected by pile-up
- However track z-precision ≃ O(10) µm to ≃ O(1) mm increasing with P_t ↘ and η ↗

Track association to vertices is degraded by collision pile-up

MIP Timing Detectors: pile-up mitigation at HL-LHC

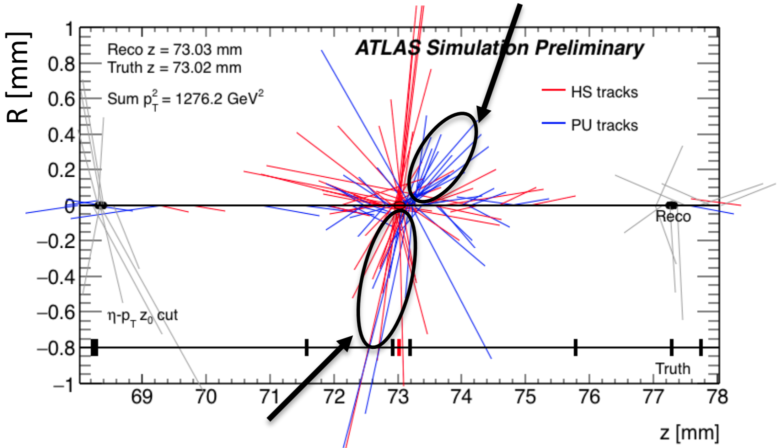
Total pile-up and pile-up density effects

Distribution of the pile-up density



13 % of merged vertices

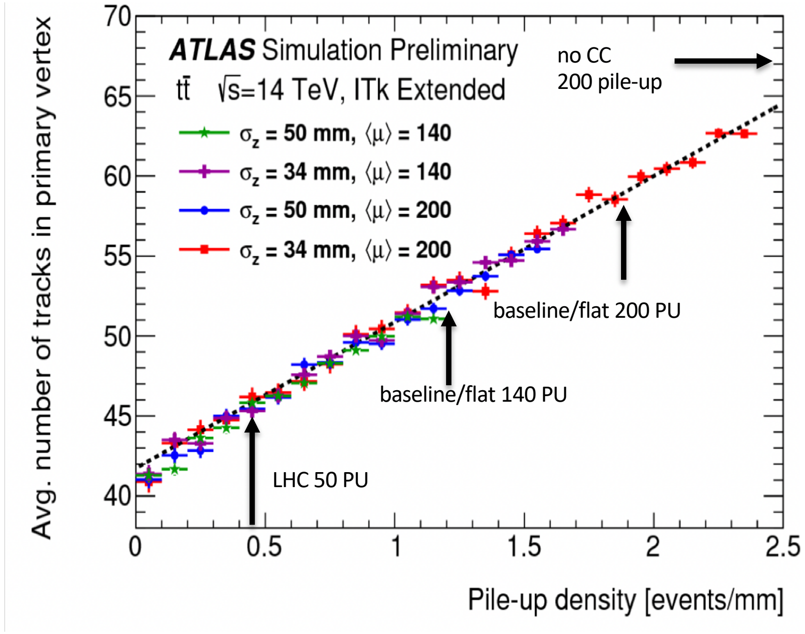
Pile-up jets, fake missing transverse energy are affected both by total and PU density

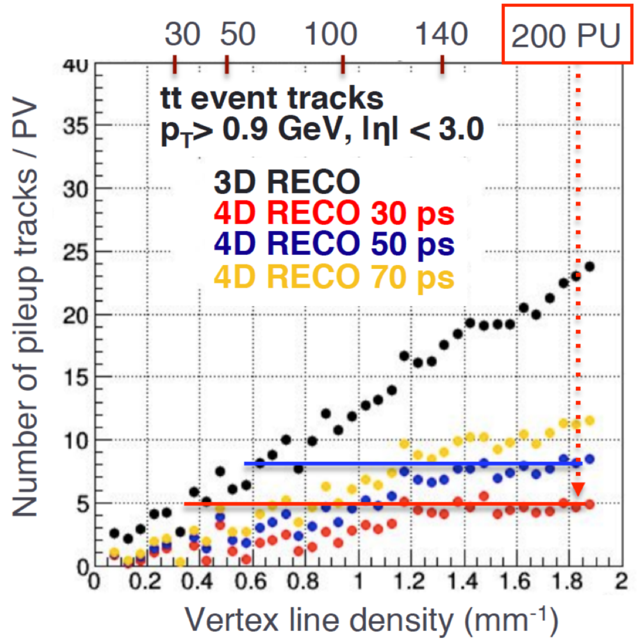


b-tagging & lepton isolation are mostly affected by pileup density

MIP Timing Detectors: pile-up mitigation at HL-LHC

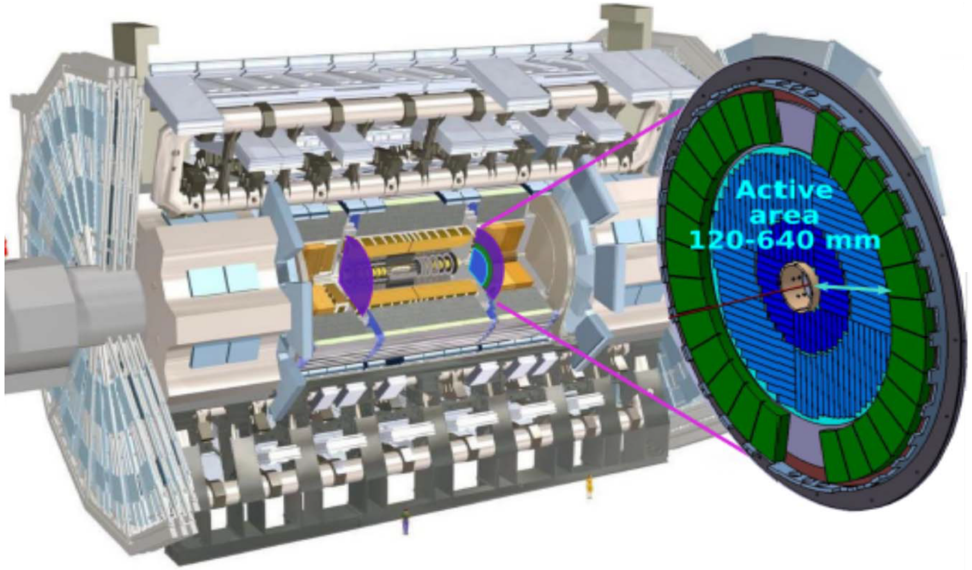
MIP timing detector precision pile-up mitigation figure of merit
is recovery of low pile-up track contamination in association to primary vertex





Time of Flight with 30 - 50 ps precision can disentangle tracks
from close by collisions occurring at different time to recovering an effective pile-up ≃ 50

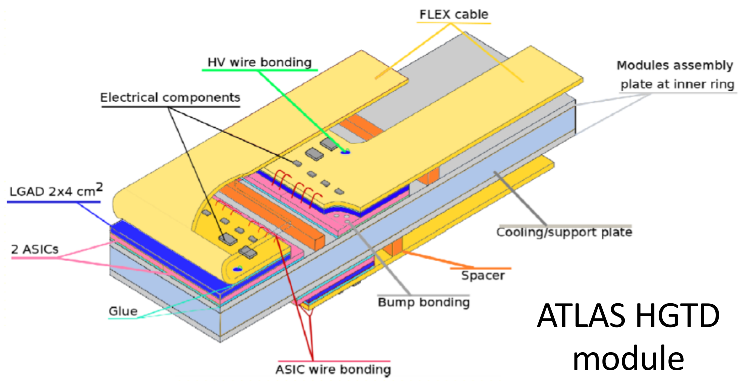
MIP Timing Detectors: ATLAS HGTD



Pad size	1x1 mm^2
Detector capacitance	2pF
Total dose in the electronics	500- 600 MRad
Neutron dose in the electronics (n/cm^2)	5 10^{15}
Total power available per area	100 mW/cm^2
Collected charge (1 MIP) for a LGAD gain of 10	4.6fC
Noise from Landau fluctuations	25ps
(preamplifer+discri)	
iome walk contribution	< 10 ps
TDC binning	20 ps
TDC range	1.2ns up to 3ns
Dynamic range wo/wi PreShower	20/600 MIPs

Two double sided layers 2.4 < η < 4 in front of Calorimeter endcap (r_{active} = 12 - 64 cm), z < 75 mm

- 2(3) hits per track for R >(<) 30 cm
  - 30 ps resolution per track after irradiation
- LGADs 1.3 x 1.3 mm^2 pads, 6.3 m^2, 3.54 Mch
- Fluence and TID 4000 fb^{-1}
  - up to 4 x 10^{15} 1 MeV neq/cm^2 and 400 MRad
- Operation at -30°
- Inner ring replaceable



ATLAS HGTD module

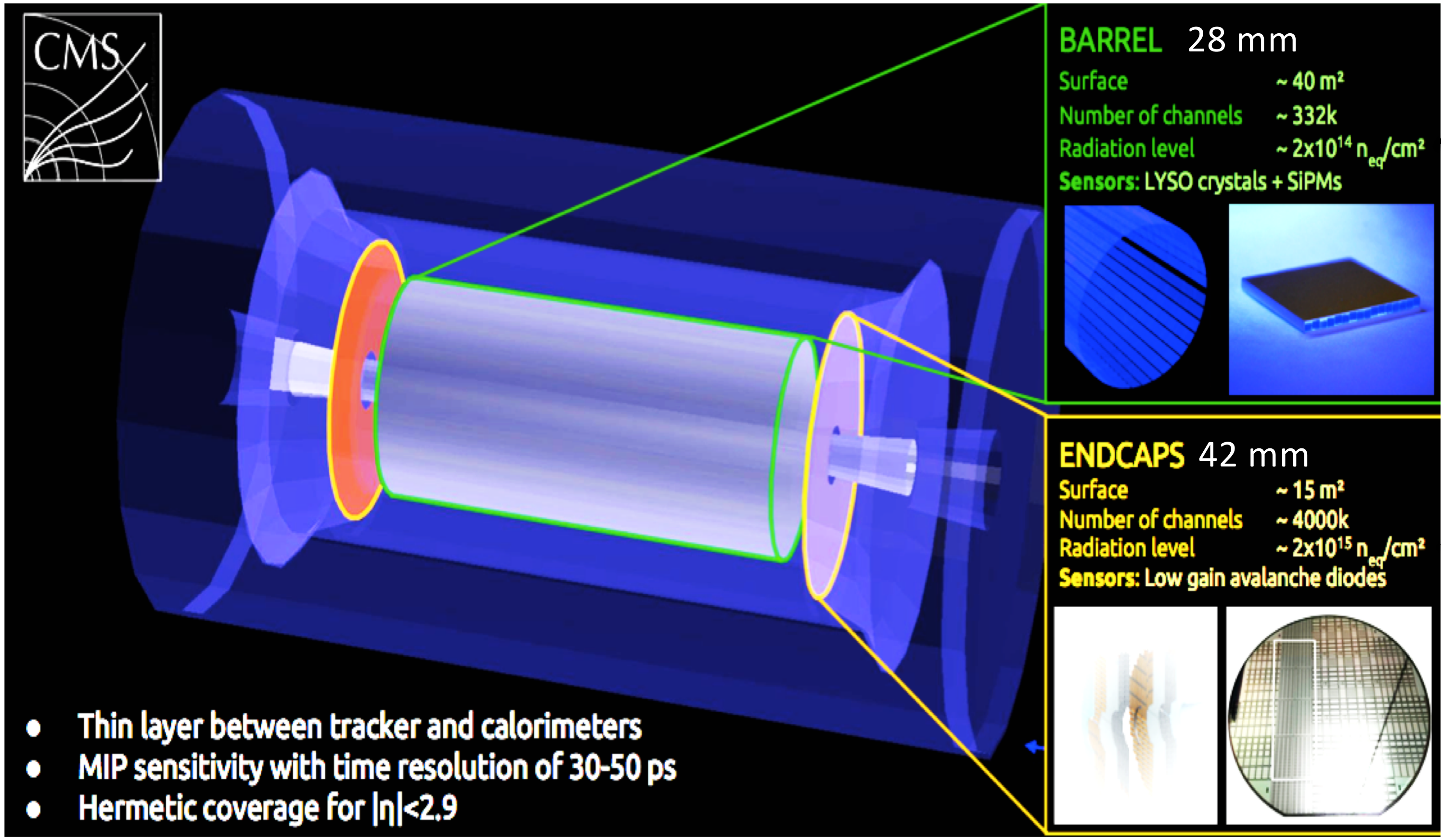
MIP Timing Detectors: CMS MTD

Barrel layer (28 mm) in Tracker volume

- Lyso bars 56 mm x 3 x 3 mm^2, readout both ends with 2 SiPM 3 x 3 mm^2, 30(40) ps before(after) irradiation

Endcap 2 layers (42 mm each) in front of Calo. Endcap (42 mm), 1.6 < η < 3

- LGAD 1.3 x 1.3 mm^2 pads, 30(40) ps per track before(after) irradiation

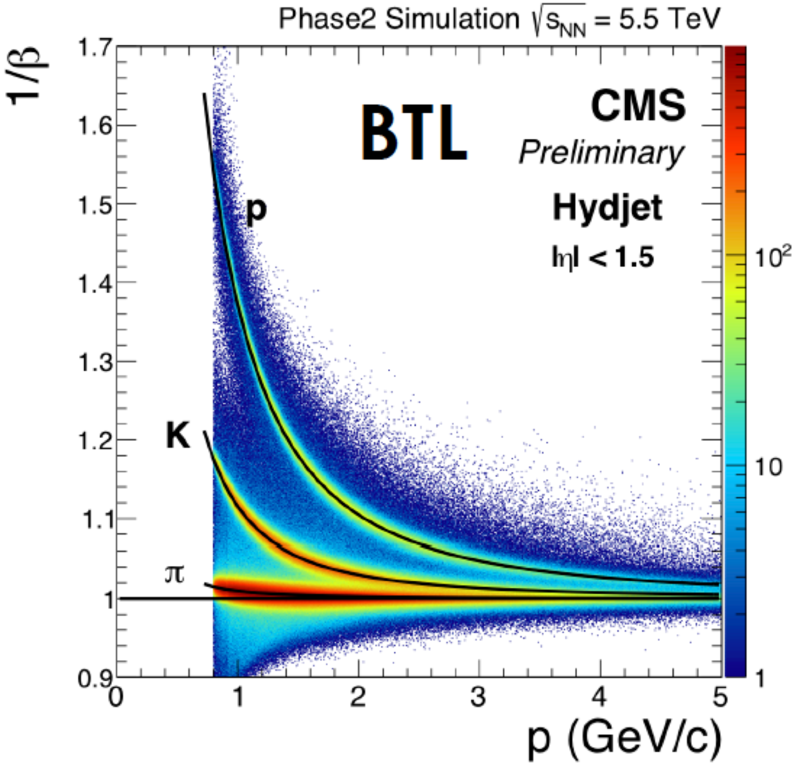


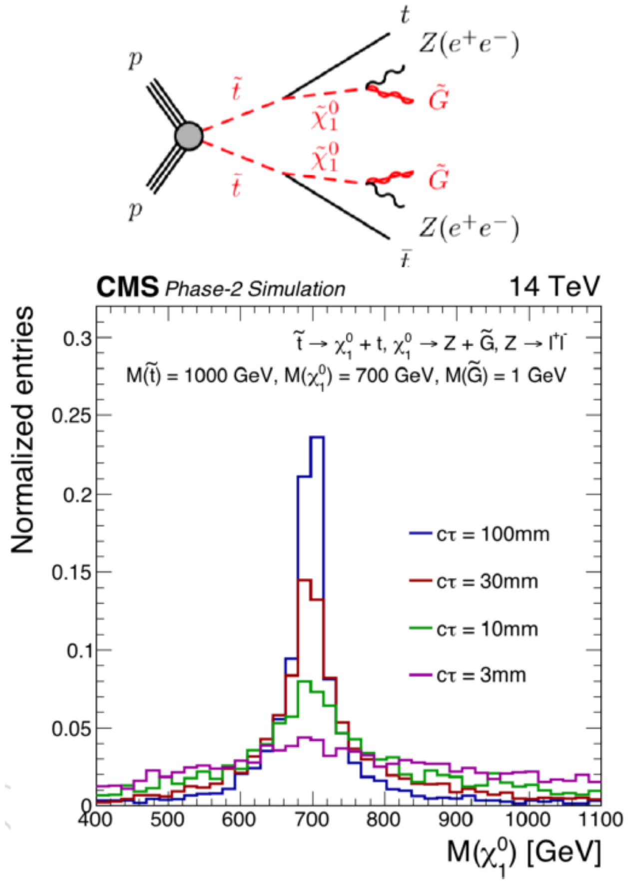
For 3000 fb^{-1}
TID = 2.5 MRad

For 3000 fb^{-1}
TID = 70 MRad

MIP Timing Detectors: CMS MTD particle ID

π/K separation up to 2.5 GeV and K/p up to 5 GeV
Enable long lived particle mass measurement

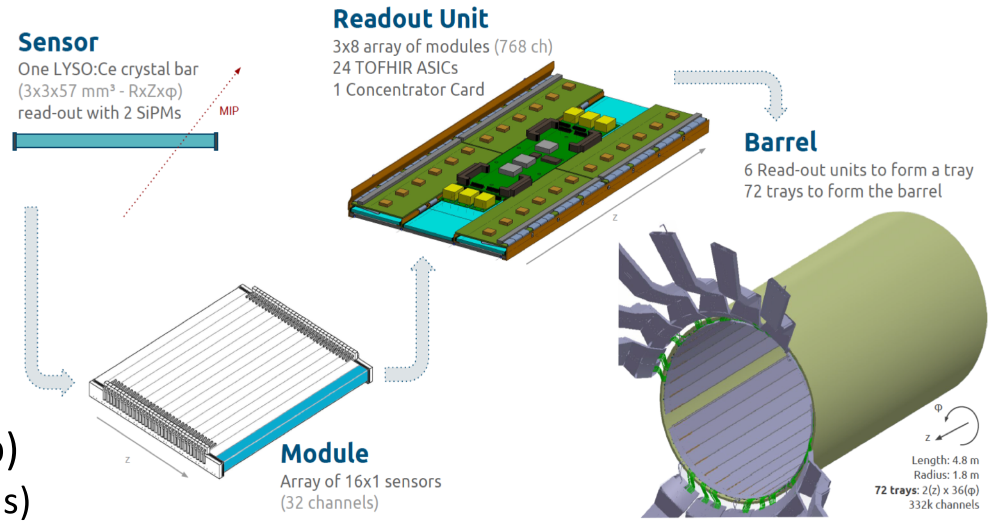


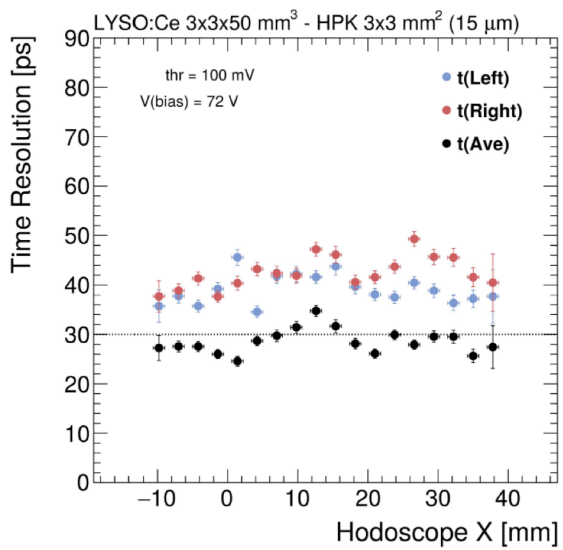


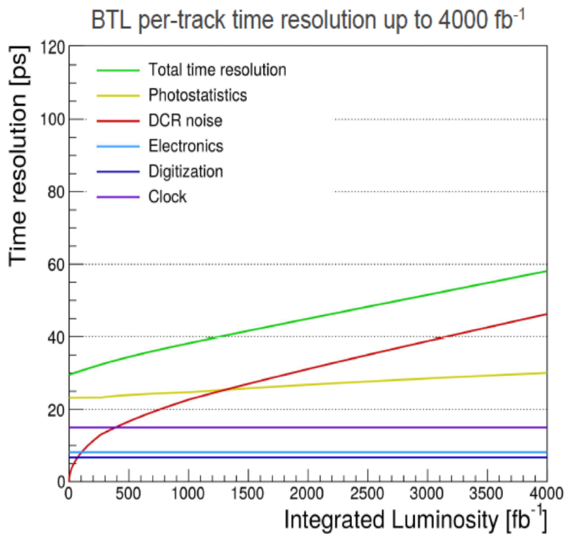
MIP Timing Detectors: CMS crystal barrel layer

- LYSO Crystals + SiPMs
  - $\sigma_{photo} = \sqrt{[(\tau_{rise}\tau_{decay})/N_{pe}]}$
    $= \sqrt{[(\tau_{rise}\tau_{decay}{}^{1)})/(E_{dep}.LY.LCE.PDE)]}$
  - σ_{DCR} SiPM Dark Current Rate noise dominates resolution after 1000 fb-1
  - Operation at -30°, with annealing period during year end technical stops for SiPM DCR recovery[2)]
  - ASIC,TOFHIR 130 nm technology (base on TOFPET chip)
    - Pulse peak time 15 ns (threshold 5 to 50 photoelectrons)
    - TDC bin 20 ps, $\sigma_{TDC} \simeq$ 6 ps
    - DCR noise filtering
    - $\sigma_{noise} \leq$ 20 ps

$\sigma_t \simeq$ 30(50) ps before(after) irradiation





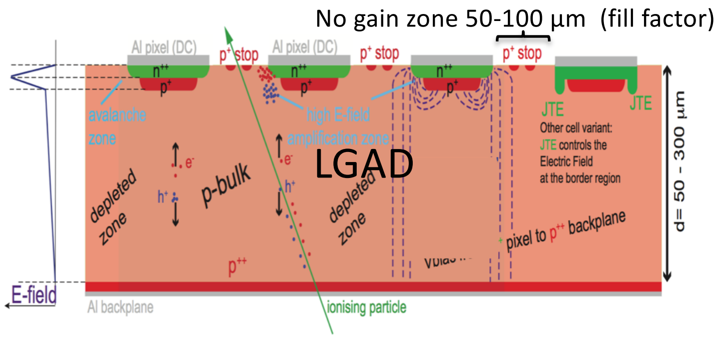


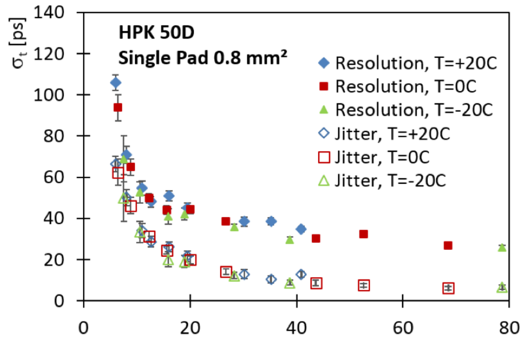
1) *Lyso:* $\tau_{rise} \simeq$ 100 ps $\tau_{decay} \simeq$ 40 ns
2) *Improving DCR is a R&D topic for SiPMs*

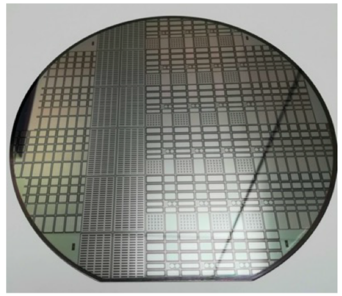
MIP Timing Detectors: ATLAS and CMS LGAD sensors

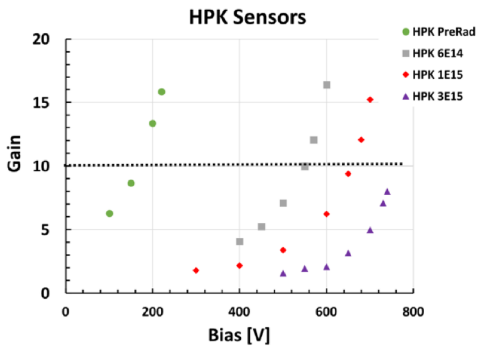
Low Gain Avalanche Diodes are n-in-p Si-sensors with a p-implant below the readout electrode to provide low amplification of primary signal (as in APD process)

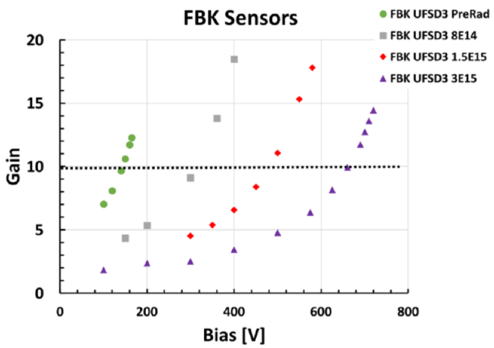
Landau fluctuation limit: $\sigma_{sign} \simeq 25$ ps for 50 $\simeq$ µm thick, 1.3 x 1.3 mm^2 pad sensors

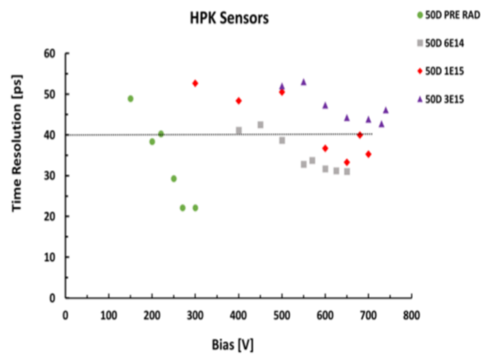


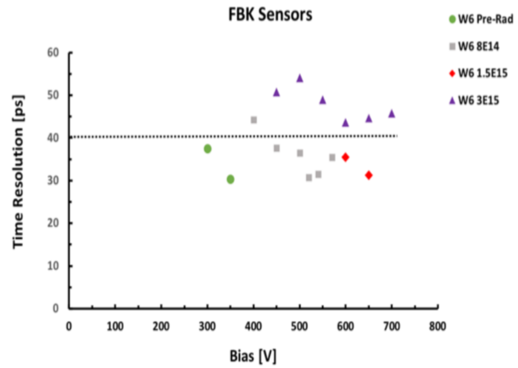












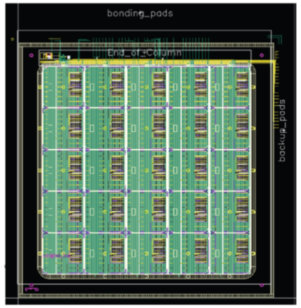
after irradiation, gains[1)] 10 - 20 can be maintained at high voltage with $\sigma_{(t)} \leq 40$ ps up to 3 x 10^{15} 1MeV neq/cm^2

1) at G $\simeq$ 15 for 50 µm thickness the signal is $\simeq$ 8 fC (50000 e$^-$) with τ_{rise} $\simeq$ 500 ps

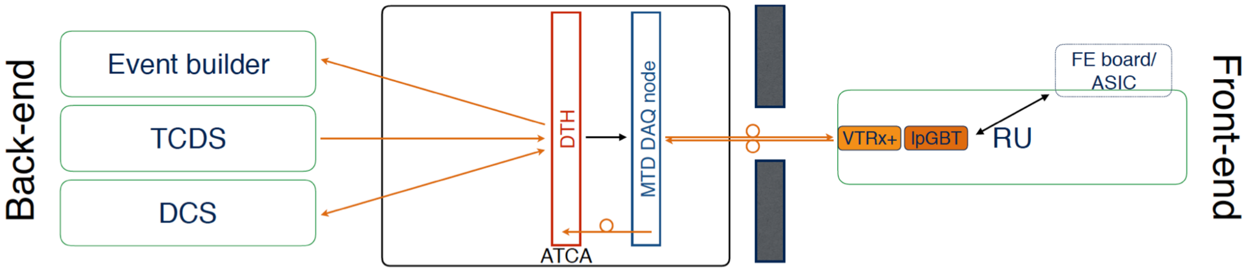
MIP Timing Detectors: ATLAS and CMS LGAD sensors

- Front End ASIC
  - ATLAS- CMS similar design
    - 130(65) nm ASIC technology ATLAS(CMS), Time of Amplitude for timing measurement and Time over Threshold for amplitude measurement
    - $\sigma_{noise} \leq 30$ ps, first prototype ASIC test encouraging
    - TDC bin 20 ps, $\sigma_{TDC} \simeq 6$ ps
    - Power consumption $\simeq$ 200-300 mW/cm^2 ($\simeq$ 1-1.2 W/ASIC) depending on technology

ATLAS ALTIROC chip



- Clock distribution
  - Target σ_{clock} = 10-15 ps with regular distribution of encoded clock filtered in LpGBT ASIC
  - Particle calibration $\simeq$ 5 ps in $\leq$ 0.1(1) s per channels and 0.4(4) ms per ASIC depending on radius
  - Different source of jitter, random and deterministic, preliminary test results encouraging
  - Alternative investigated with direct clock distribution to FE fan-out chip



Encoded (regular) clock distribution scheme

MIP Timing Detectors: ALICE Fast Interaction Trigger

Trigger timing detector for installation in LS2

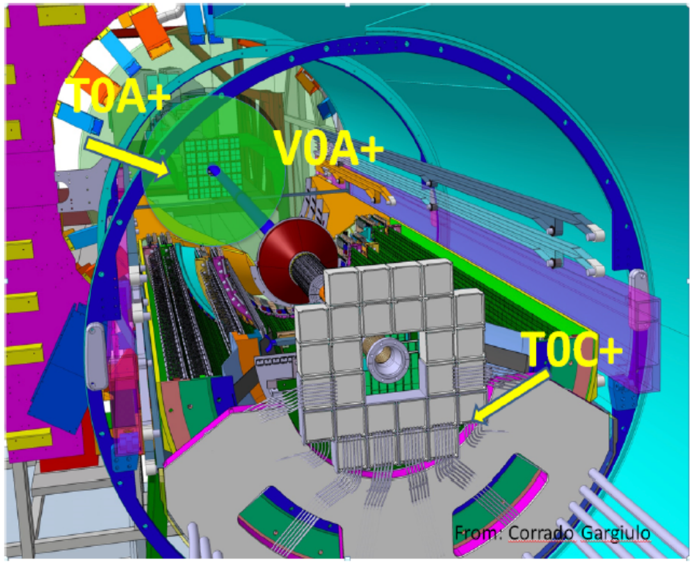
Two arrays of 28 Cerenkov quartz modules with MCP-PMT readout T0A(T0C) at +370 (-82) cm from IP

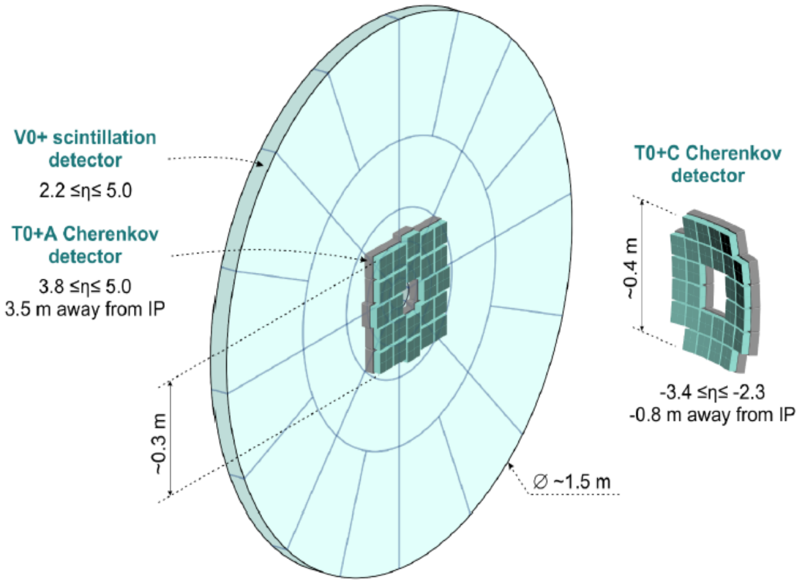
T0C with concave shape, 82 cm radius to equalize ToF

T0A(T0C) made of 24(28) modules, each consisting of 4 quartz Cerenkov radiators 2 cm thick

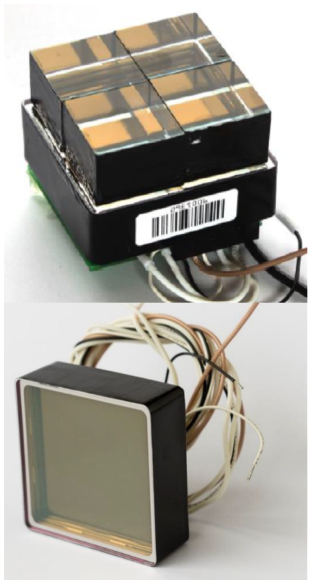
readout by a MCP-PMT, large photocathode 53 x 53 mm^2 and 64 channels

$\sigma(t) \simeq 33$ ps achieved in full prototype test





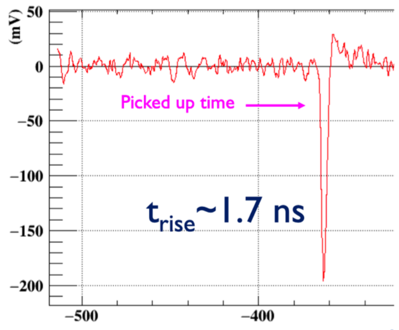
Cerenkov module
And MCP-PMT

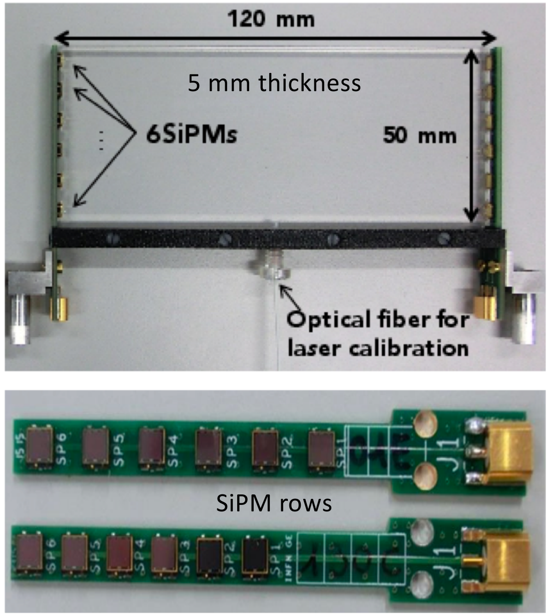


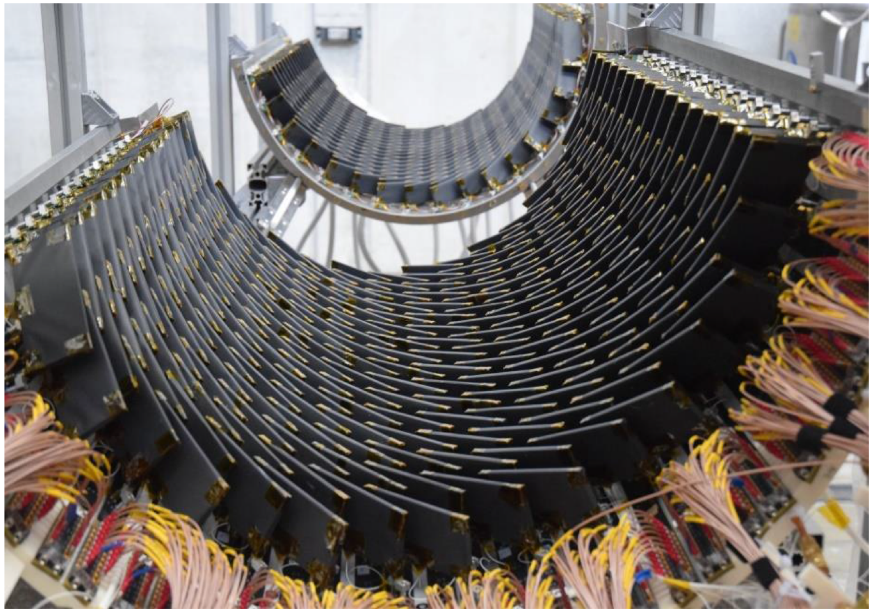
MIP Timing Detectors: MEG-II positron Timing Counter

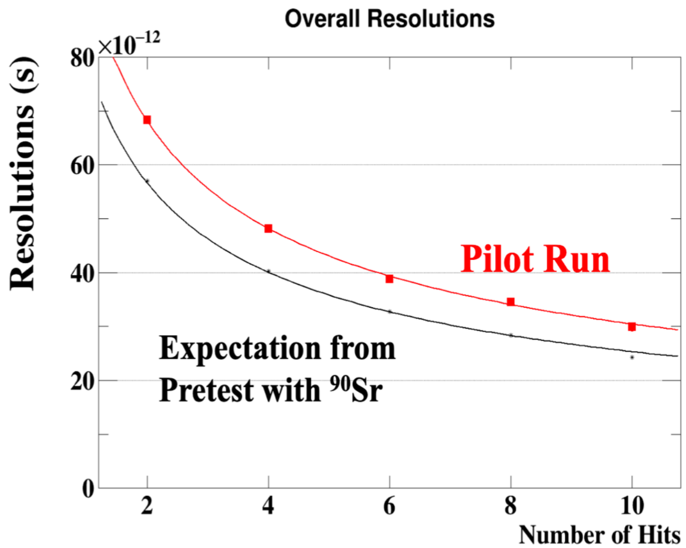
Measure ToF of 50 MeV e^+ with ≤ 40 ps precision

- 2 x 256 scintillating tiles of 5 x 5 x 12 cm^3, rise time 0.35 ns
- Readout on each side with 6 SiPMs (avoid impact point effect)
- Geometry provide multiple measurement for improved resolution (average of 9 hits)
  - $\sigma(t) = [\sigma(\text{counter}) \oplus \sigma(\text{electronics}) \oplus \sigma(\text{inter-counter})]/\sqrt{\text{Nhit}}$
  - σ(counter) ≃ 70(80) ps resolution with readout for 4(5) cm width
  - σ(inter-counter) laser plus track calibration ≃ 50 ps



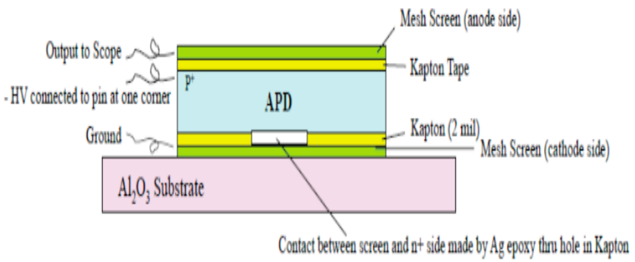




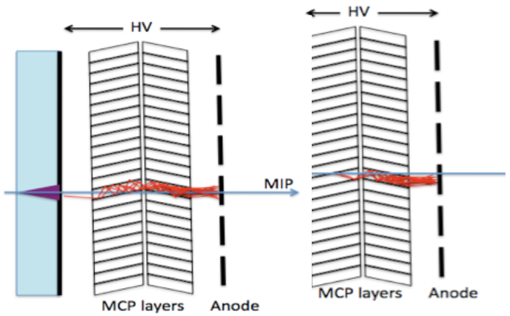


MIP Timing Detectors: R&D

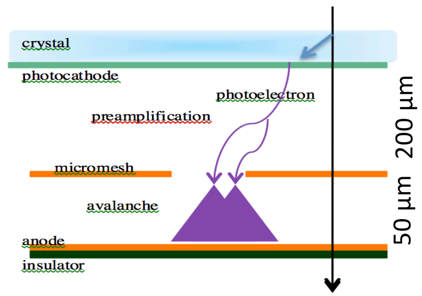
- LGAD
  - Higher fill factor, improve efficiency, and allow pixel size detector devices
    - AC coupling RSD design and/or trench techniques between pixels as developed for SiPM
  - Higher radiation tolerance, process depth/level/nature of doping implant, wafers content (C)
  - Higher resolution, thinner and smaller pads (improve S/N)
- Other technology R&D:
  - HyperFastSilicon deep depleted APDs
    - $\sigma_t \simeq 10$ ps, limited radiation tol. $\leq 10^{13}$ neq/cm^2
  - MCP-PMT with cerenkov radiator and photocathode referred to as Large Area Picosecond Photo Detectors
    - $\sigma_t \simeq 10$ ps - rate & rad. tol. capability to be evaluated (back ion flow) - alternative secondary emission
  - Micro-Megas with Cerenkov radiator & photocathode
    - rate & rad. tol. Capability to be evaluated (back ion flow) - alternative photocathode on mesh



High gain APDs 2 x 2 mm^2



Cerenkov radiator + MCP-PMT
LAPPD



Photocathode + MicroMegas

Some topics not covered but essential that require progress for future detectors

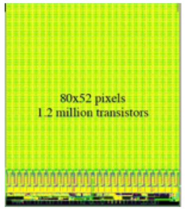
electronics, data transfer, mechanical structures, cooling and services, trigger and data acquisition

Electronics: front end ASICs

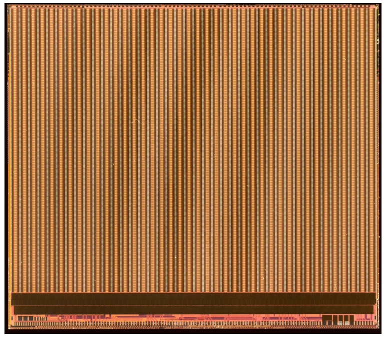
67 ASIC chips are being developed with various complexity for LHC upgrades

- RD53 for HL-LHC pixel upgrades is an ex. of ATLAS and CMS collaboration, likely the most complex chip

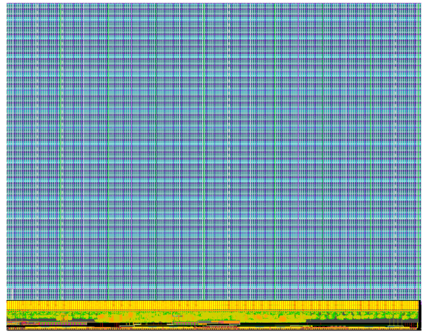
≃ pixel size/6 and x 10 transistors at each step



CMS pixel chip 250 nm CMOS
80 x 52 pixels, 100 x 150 μm^2
7.9 x 9.8 mm^2, 1.2 x 10^6 transistors
2005 →



FEI4 ATLAS IBL 130 nm CMOS
80 x 336 pixels, 50 x 250 μm^2
20 x 19 mm^2, 80 x 10^6 transistors
2010 →

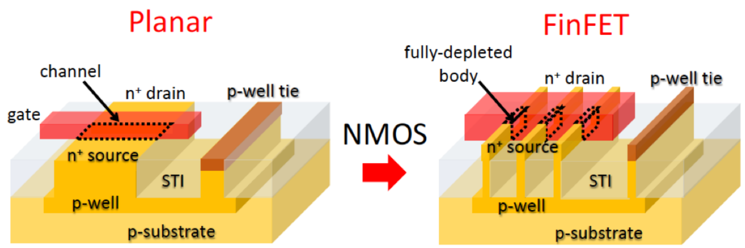


RD53 ATLAS/CMS 65 nm CMOS
384 x 400 pixels, 50 x 50 μm^2
21.6 x 19 mm^2, 700 x 10^6 transistors
2019

Next generation of vertex detectors will be ≥ 4 more pixels and x 10(30) in rates (radiation tolerance) at h-h colliders

Long lead time to develop radiation tolerance in 65 nm O(Grad) and large cost, technology choice is not straightforward

- 28 nm technology investigation started
- FinFET process in industry at 7 nm and prototypes at 5 nm



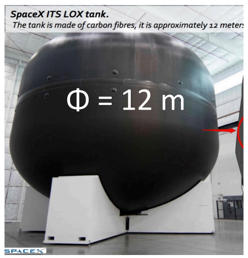
Other components: data transfer, back end electronics

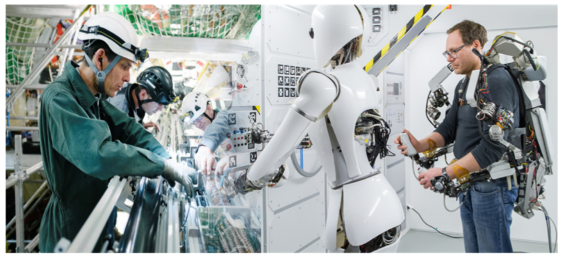
- Data transfer bandwidth x 10 will be needed at hh-colliders with much higher radiation tolerance
  - Silicon photonics for optical conversion and multiple amplitude modulation can provide high bandwidth
  - Wireless transmission, could allow ion-detector data reduction ex. for trigger readout of trackers
- Back-end electronics
  - Progress are driven by commercial applications, bandwidth and power of FPGA are increasing allowing development of reconstruction algorithms in firmware so far only implemented at computing level

Lightest mechanical structures and improved cooling will improve performance

- ≤ -40° cooling (current CO_2 limit) to increase radiation tolerance; pipes embedded in sensitive elements for hh-colliders and airflow cooling for linear ee-colliders to reduce % X_0
- New material ex. Carbon composite with graphene and Carbon nanotubes, CFRP with new resins… can reduce mass, and new fabrication process (3D printing…)
- Low mass cryostats for LAr and detector magnets will also reduce mass
- Automated manipulation will be needed for maintenance in high irradiation environment

Mu3e CMOS MAPs
Kapton structure
0.1% X_0/layer





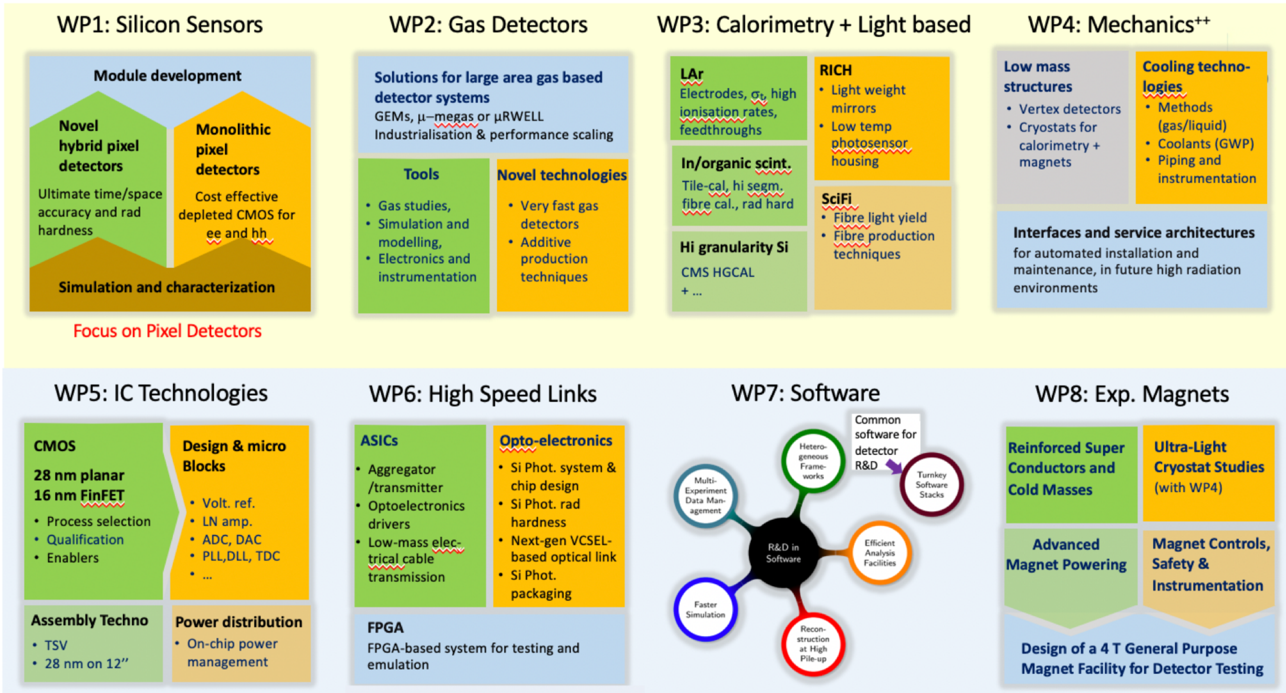
Outlook

Outlook: CERN strategic R&D program https://cds.cern.ch/record/2649646

Past and current CERN RD international programs have been efficient to provide technologies needed

gather/form expertise, develop tools/protocols for simulation/qualification, ease access to material science/industry partners

C. Joram VIC2019: https://indico.cern.ch/event/716539/



8 Work Packages proposed to federate efforts starting in 2020 for 4-5 years

technology/detector, common ancillary components, magnets, software

Also broader European programs: AIDA++ (HEP synergy) - ATTRACT (technology synergy across fields)

Outlook: R&D trends for future detectors

- Generic technology R&D is mandatory to improve base performance, trends are:
  - Evolution to smaller scale of components, eg. deep sub-micron microelectronics, nano-materials…
    - Higher granularity, resolutions, radiation tol., precision timing is a new paradigm for all devices
  - Development of hybrid/integrated components, eg. integrated functionalities, merged technologies…
  - Development of new fabrication process, ex. 3D printing
- Detectors designs then need to be optimized to needs of experiments (no universal detectors)
  - Considering global performance and resources, requiring thorough effort of simulation
- Technologies are mostly developed for commercial or other scientific fields
  - Partnerships with material science labs and industry (imaging, microelectronics…) become increasingly important with mutual benefit to develop ultimate performance devices
    - Technology progress outside HEP are fast, needing thorough tracking
    - HEP remains single owner of the radiation tolerance constraints
- International R&D programs are essential to gather & form deep expertise needed, to help resourcing

e-e collider experiments could enter design engineering R&D phase , ≃ 5 years toward production
Future h-h collider detectors require a leap in rates and radiation capabilities
strong technology R&D effort is need now