Noise & Geometry Studies and π^0 Rejection

Noise Considerations

Inclined Cells – Projective Cells

π^0 Rejection

Noise Considerations

- **FCC-ee Physics Program:**
  - Measurement down to very low energies (γ's down to 300 MeV)
    - For comparison: Noise term for ATLAS LAr calorimeter: ~300 MeV
  - Particle flow profits from single particle (MIP) tracking also inside the calorimeter
- **→ New calorimeter concepts have to optimize electronics noise**
- **Two approaches**
  - **Warm electronics:** ATLAS EM-calorimeter like:
    - **Advantages:** Maintainability of front-end electronics (no active components inside the cryostat), upgradeability, possibility to adapt calorimeter to new requirements (e.g. LHC was designed for $L=10^{34}cm^{-2}s^{-1}$, HL-LHC will go up to $L=7x10^{34}cm^{-2}s^{-1}$).
    - **Disadvantages:** Long transmission lines (attenuation), high-density signal feedthroughs
  - **Cold electronics:** ATLAS HEC-calorimeter or DUNE like:
    - **Advantages:** Much shorter transmission lines, cold preamplifiers have less serial noise (~$(kT)^{1/2}$ → temperature), one optical fibre can carry signal of 100's of channels
    - **Disadvantages:** No possibility to repair or upgrade

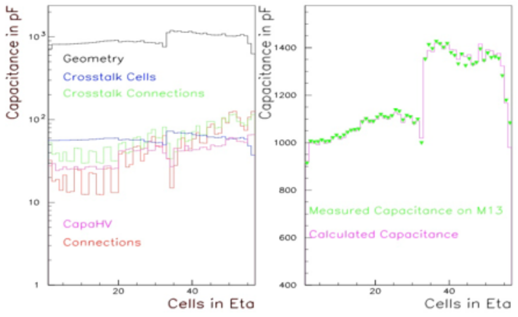
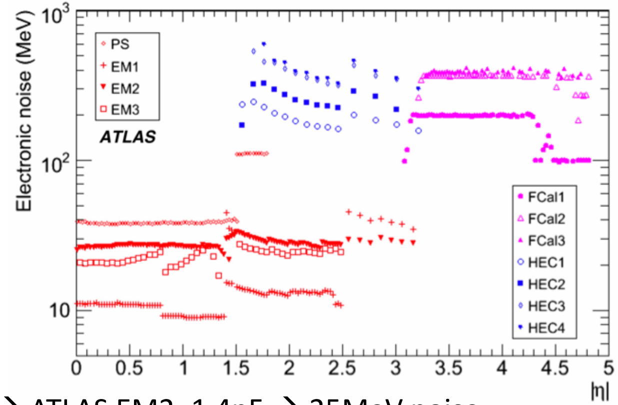


Figure 10: Left: expected contributions to cell capacitances as a function of η. Right: Total expected capacitance as a function of η and comparison with measurements done on M13 module. The agreement is very fair.

→ ATLAS middle cells (EM2): ε_r x 1nF = 1.4nF



→ ATLAS EM2: 1.4nF → 25MeV noise

Noise Considerations

- **Will show here my scaling for the ATLAS-like warm electronics**
  - Smallest cell sizes (2 double gaps) in the strips, Δθ=0.0025: C_d = 5.0 pF
  - Other layers (4 double gaps), Δθ=0.01: $C_d \approx$ 35 pF (+ capacitance to shields of signal traces)
  - Serial noise dominates, it is proportional to the capacitance C: with ATLAS-like electronics reached 25/1400 MeV/pF = 0.018 MeV/pF
  - Shaping-time constant τ_s=45ns, could use longer shaping time (e.g. τ_s=100ns)
    - → could gain another factor 1.5 or 2 due to longer shaping times
  - Sampling fraction in FCC-ee strips layer is factor 1.6 worse than in ATLAS (smaller LAr gaps)
  - Estimate 50% higher signal attenuation than in ATLAS due to PCBs
  - **→ C_d = 5.0 pF: 0.018MeV/pF x 5pF /2.0 x 1.5 x 1.6 = 0.11 MeV (!)**
  - Those layers with shields of signal traces crossing will have higher capacitance (to be optimized) → **expect up to 200pF capacitances**
    - → **still only ~5MeV of noise**
- **D. Fournier did estimates for DUNE-like cold electronics (potentially factor ~2-5 better) – see talk later today**

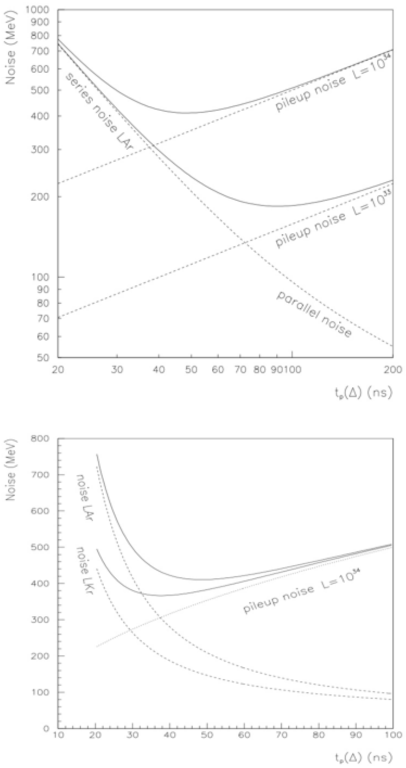


Figure 8: *Total noise in a 3 x 7 tower of the EM calorimeter, as a function of the overall peaking time (5-100%) to the triangle : $t_p(\Delta)$ (details in footnote 14 ; the parallel noise has been doubled for clarity ; pileup from [13]). The optimum is σ_{opt} = 420 MeV at $t_{opt}(\Delta)$ = 47 ns with LAr compared to 370 MeV at 36 ns for LKr.*

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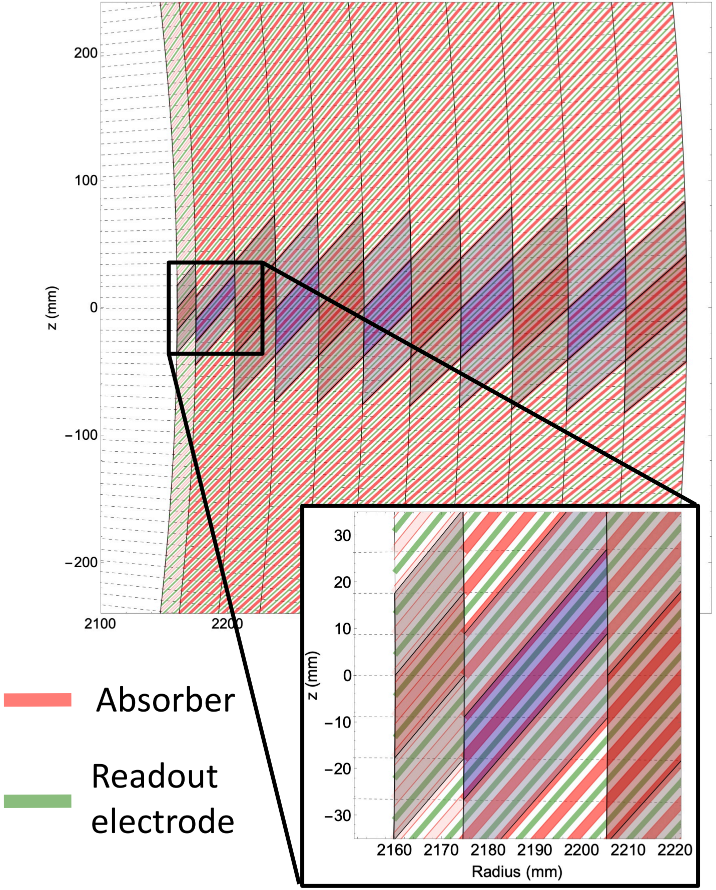
Geometry Considerations

Adopted geometry proposed by Ronic Ciche in the Dec. meeting (link) – all parameters still to be optimized with performance optimization

- No Pb/W in the first compartment = presampler (PS) → used to compensate for lost energy upstream
- 1536 absorbers in 2π, flat, no step-increase with r.
- r_i=2160mm, r_o=2560mm, inclination of absorbers at r_i is α_i=50.381°
- 11 longitudinal compartments, particle traverses 2 absorbers in 1st comp., 4 in all others
- Cells line up in projective towers in θ and ϕ, add 2 double gaps in the PS and strips (1st and 2nd longitudinal compartment) and 4 double gaps in each other layer
  - Strips (2nd comp.): Δϕ x Δθ = 8.2mrad x 2.5mrad = 17.8mm x 5.4mm
  - Other compartments: Δϕ x Δθ = 16.4mrad x 10mrad = 36mm x 22mm$|_{r=2205mm\ (3rd\ comp.)}$
- Readout with 7-layer PCB (FR4), 1.2mm thick
- Next pages: tried several absorber compositions and thicknesses, different absorber materials (Pb/W), different active material (LAr/LKr)



LAr with Pb Absorbers

- LAr as active aterial
- Absorber (t = 2mm): 1.4mm Pb, 0.2mm glue, 0.4mm stainless steel

Absorbers	Length (mm)	Radius (mm)	LAr gap (mm)	$\langle X_0 \rangle$ (mm)	ΔL (mm)	Δr (mm)	Δr (X_0)	Accum. X_0	f_{sampl}
0	0	2160.	1.21718	-	-	-	-	-	0.275538
2	23.0979	2174.8	1.26442	19.0567	23.0979	14.8018	0.776728	0.776728	0.165411
6	70.2646	2205.47	1.36089	19.4726	47.1667	30.6687	1.57497	2.35169	0.175812
10	118.794	2237.62	1.46015	20.0332	48.5292	32.1537	1.60502	3.95671	0.186247
14	168.773	2271.35	1.56237	20.6049	49.9787	33.7222	1.63661	5.59332	0.196721
18	220.295	2306.73	1.66775	21.1882	51.5222	35.3812	1.66985	7.26317	0.207239
22	273.462	2343.87	1.7765	21.784	53.1672	37.1383	1.70485	8.96802	0.217809
26	328.384	2382.87	1.88883	22.3928	54.9221	39.0021	1.74173	10.7097	0.228435
30	385.18	2423.85	2.00499	23.0155	56.7963	40.982	1.78062	12.4904	0.239125
34	443.981	2466.94	2.12526	23.653	58.8002	43.0884	1.82169	14.3121	0.249884
38	504.926	2512.27	2.24991	24.306	60.9452	45.3328	1.86508	16.1771	0.260719
42	568.17	2560.	2.37926	24.9756	63.2442	47.7283	1.911	18.0881	0.271637

→ 18.1 X_0

LAr with Pb Absorbers

- LAr as active aterial
- Absorber (t = 2mm): 1.8mm Pb, 0.1mm glue, 0.1mm stainless steel

Absorbers	Length (mm)	Radius (mm)	LAr gap (mm)	$<X_0>$ (mm)	ΔL (mm)	Δr (mm)	Δr (X_0)	Accum. X_0	f_{sampl}
0	0	2160.	1.21718	–	–	–	–	–	0.317843
2	23.0979	2174.8	1.26442	140.735	23.0979	14.8018	0.105175	0.105175	0.158756
6	70.2646	2205.47	1.36089	16.51	47.1667	30.6687	1.85758	1.96276	0.168823
10	118.794	2237.62	1.46015	16.9973	48.5292	32.1537	1.89169	3.85445	0.178933
14	168.773	2271.35	1.56237	17.495	49.9787	33.7222	1.92753	5.78198	0.189091
18	220.295	2306.73	1.66775	18.0036	51.5222	35.3812	1.96523	7.74721	0.199303
22	273.462	2343.87	1.7765	18.5237	53.1672	37.1383	2.00491	9.75212	0.209575
26	328.384	2382.87	1.88883	19.0561	54.9221	39.0021	2.0467	11.7988	0.219913
30	385.18	2423.85	2.00499	19.6015	56.7963	40.982	2.09075	13.8896	0.230322
34	443.981	2466.94	2.12526	20.1607	58.8002	43.0884	2.13724	16.0268	0.240811
38	504.926	2512.27	2.24991	20.7345	60.9452	45.3328	2.18634	18.2132	0.251384
42	568.17	2560.	2.37926	21.3239	63.2442	47.7283	2.23826	20.4514	0.26205

→ 20.5 X_0

LKr with Pb Absorbers

- LKr as active aterial
- Absorber (t = 2mm): 1.8mm Pb, 0.1mm glue, 0.1mm stainless steel

Absorbers	Length (mm)	Radius (mm)	LKr gap (mm)	$\langle X_0 \rangle$ (mm)	ΔL (mm)	Δr (mm)	Δr (X_0)	Accum. X_0	f_{sampl}
0	0	2160.	1.21718	–	–	–	–	–	0.420707
2	23.0979	2174.8	1.26442	75.3403	23.0979	14.8018	0.196467	0.196467	0.227289
6	70.2646	2205.47	1.36089	14.9402	47.1667	30.6687	2.05277	2.24923	0.24046
10	118.794	2237.62	1.46015	15.2791	48.5292	32.1537	2.10443	4.35366	0.253552
14	168.773	2271.35	1.56237	15.6205	49.9787	33.7222	2.15884	6.5125	0.26657
18	220.295	2306.73	1.66775	15.9647	51.5222	35.3812	2.21621	8.72872	0.279524
22	273.462	2343.87	1.7765	16.3119	53.1672	37.1383	2.27676	11.0055	0.292421
26	328.384	2382.87	1.88883	16.6623	54.9221	39.0021	2.34074	13.3462	0.305267
30	385.18	2423.85	2.00499	17.0162	56.7963	40.982	2.40841	15.7546	0.318069
34	443.981	2466.94	2.12526	17.3738	58.8002	43.0884	2.48007	18.2347	0.330836
38	504.926	2512.27	2.24991	17.7354	60.9452	45.3328	2.55606	20.7908	0.343574
42	568.17	2560.	2.37926	18.1012	63.2442	47.7283	2.63675	23.4275	0.356289

→ 23.4 X_0

LAr with W Absorbers

- LAr as active aterial
- Absorber (t = 2mm): 1.8mm W, 0.1mm glue, 0.1mm stainless steel

Absorbers	Length (mm)	Radius (mm)	LAr gap (mm)	$<X_0>$ (mm)	ΔL (mm)	Δr (mm)	Δr (X_0)	Accum. X_0	f_{sampl}
0	0	2160.	1.21718	–	–	–	–	–	0.317843
2	23.0979	2174.8	1.26442	140.735	23.0979	14.8018	0.105175	0.105175	0.105664
6	70.2646	2205.47	1.36089	10.6734	47.1667	30.6687	2.87337	2.97855	0.112816
10	118.794	2237.62	1.46015	11.0038	48.5292	32.1537	2.92205	5.90059	0.120056
14	168.773	2271.35	1.56237	11.3422	49.9787	33.7222	2.97317	8.87376	0.127391
18	220.295	2306.73	1.66775	11.689	51.5222	35.3812	3.02689	11.9006	0.134824
22	273.462	2343.87	1.7765	12.0447	53.1672	37.1383	3.08338	14.984	0.142364
26	328.384	2382.87	1.88883	12.4099	54.9221	39.0021	3.14282	18.1268	0.150015
30	385.18	2423.85	2.00499	12.7852	56.7963	40.982	3.20542	21.3323	0.157786
34	443.981	2466.94	2.12526	13.1712	58.8002	43.0884	3.2714	24.6037	0.165682
38	504.926	2512.27	2.24991	13.5686	60.9452	45.3328	3.34101	27.9447	0.173712
42	568.17	2560.	2.37926	13.9781	63.2442	47.7283	3.4145	31.3592	0.181882

→ 31.4 X_0

LKr with W Absorbers

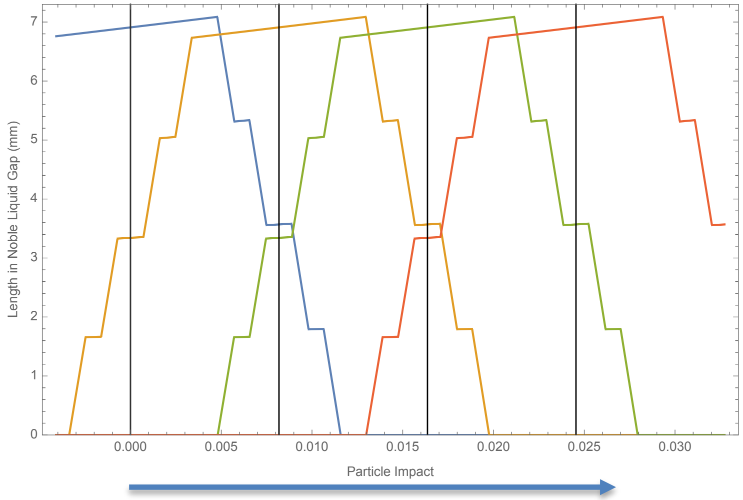
- LKr as active aterial
- Absorber (t = 2mm): 1.8mm W, 0.1mm glue, 0.1mm stainless steel

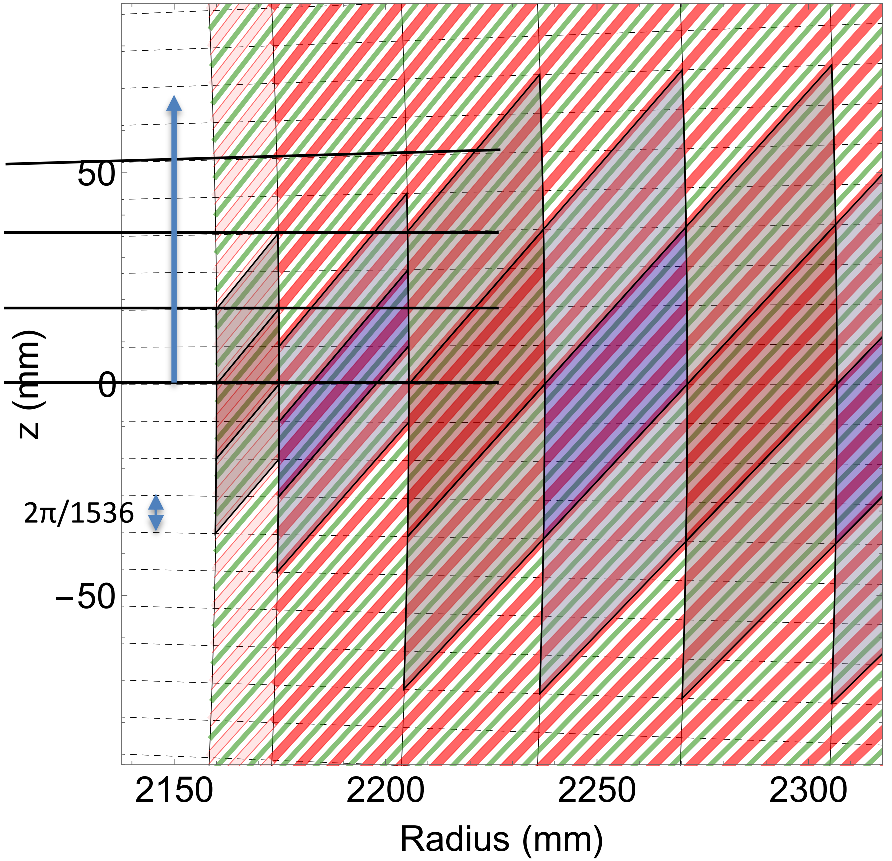
Absorbers	Length (mm)	Radius (mm)	LKr gap (mm)	$\langle X_0 \rangle$ (mm)	ΔL (mm)	Δr (mm)	Δr (X_0)	Accum. X_0	f_{sampl}
0	0	2160.	1.21718	–	–	–	–	–	0.420707
2	23.0979	2174.8	1.26442	75.3403	23.0979	14.8018	0.196467	0.196467	0.155515
6	70.2646	2205.47	1.36089	9.99452	47.1667	30.6687	3.06855	3.26502	0.165417
10	118.794	2237.62	1.46015	10.2571	48.5292	32.1537	3.13478	6.3998	0.175366
14	168.773	2271.35	1.56237	10.5235	49.9787	33.7222	3.20447	9.60428	0.185367
18	220.295	2306.73	1.66775	10.794	51.5222	35.3812	3.27787	12.8821	0.195427
22	273.462	2343.87	1.7765	11.0688	53.1672	37.1383	3.35523	16.2374	0.20555
26	328.384	2382.87	1.88883	11.3482	54.9221	39.0021	3.43686	19.6742	0.215743
30	385.18	2423.85	2.00499	11.6324	56.7963	40.982	3.52308	23.1973	0.226013
34	443.981	2466.94	2.12526	11.9219	58.8002	43.0884	3.61423	26.8116	0.236365
38	504.926	2512.27	2.24991	12.2167	60.9452	45.3328	3.71073	30.5223	0.246807
42	568.17	2560.	2.37926	12.5173	63.2442	47.7283	3.81299	34.3353	0.257345

→ 34.3 X_0

Track-Length of a MIP in Inclined Cell

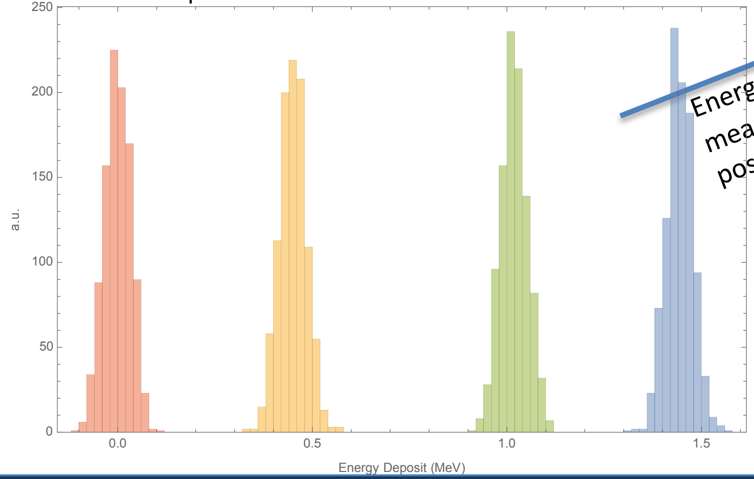
- Track-length of a projective MIP inside active material in one cell (2 double-gaps)
- ~7mm track length in one cell, but track in 2-3 consecutive cells (13.7mm in one layer)
- Energy deposit of a MIP
  - LAr: 2.105 MeV/cm
  - LKr: 3.281 MeV/cm
- Needs to be divided by sampling fraction f_{sampl} to get energy in the EM scale
  - → 0.7 cm x 2.105 MeV/cm / 0.17 = 8.7 MeV (MIP signal in strips)



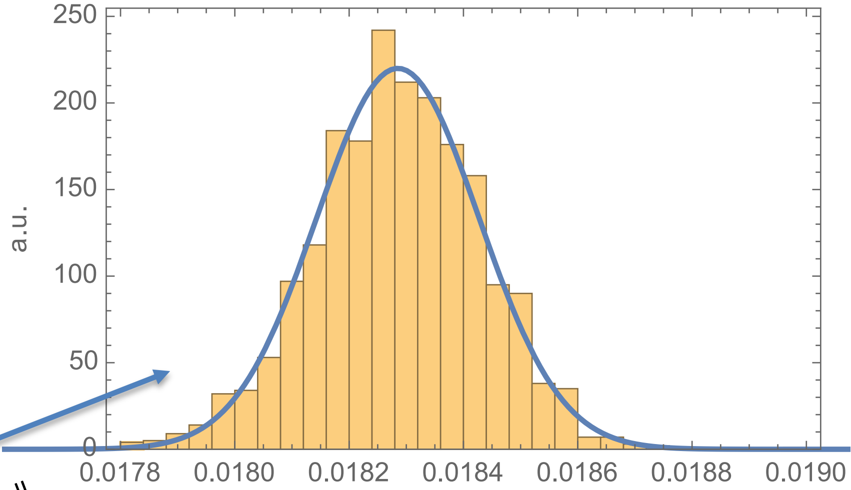


Position Measurement

- Interpolating energy deposit of neighbouring cells allows to measure exact position of a MIP
- For projective cells the resolution would be cell-size / √12
- Cell size assumed here: 2 x 2π/1536 = 8.2mrad
- Cell noise assumed in the following:
  - σ_{noise} = 0.2MeV → 0.2MeV x f_{sampl} = 0.034MeV in EM scale, f_{sampl} = 0.17



Energy weighted mean between cell positions



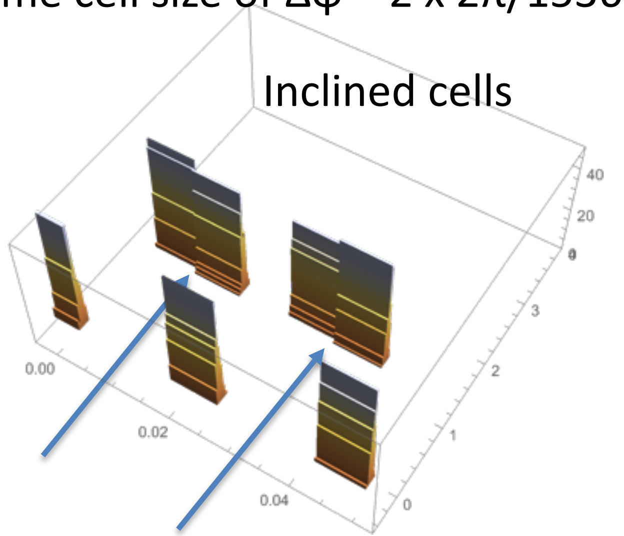
Measured particle impact (rad)

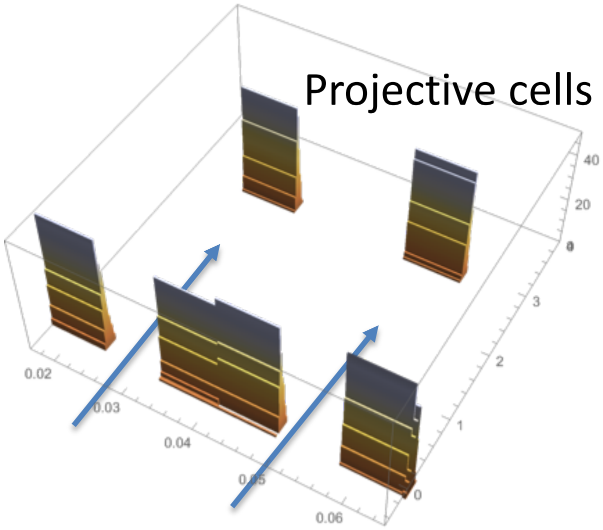
σ_{meas} = 0.14mrad
Cell size / √12 = 2.36mrad

→ **Inclined cells are a factor 16 better than projective cells**

2-Particle Identification → π^0 Rejection

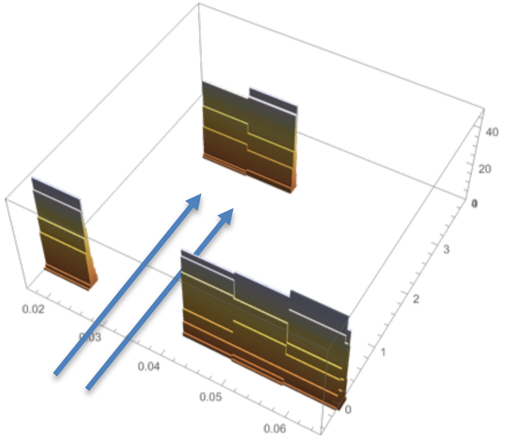
- Position resolution is important for particle flow
- But for π^0 rejection the capability to reconstruct two close-by MIPs or starting showers as two particles is more important
- Below energy deposit in 7 consecutive cells of two particles of 24.5mrad distance in inclined cells (left) and ϕ-projective cells (right),
  - same cell size of $\Delta\phi = 2 \times 2\pi/1536$

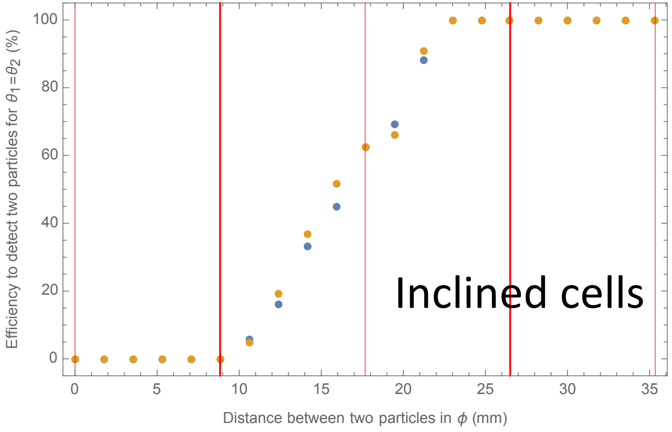


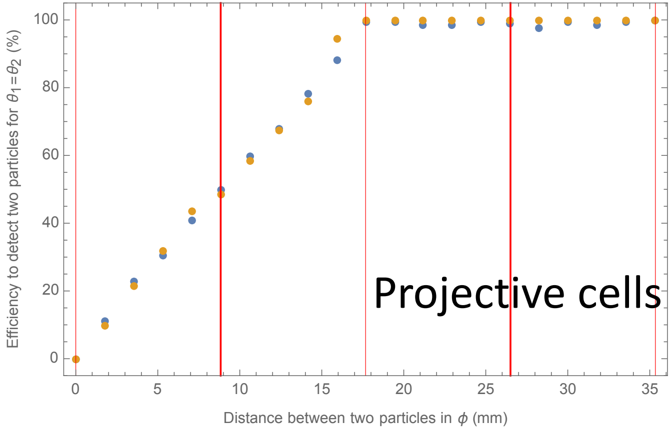


Two Single MIPs

- Separation of two single MIPs with distance *d*
- Projective cells: separation possible if two MIPs hit 2 neighbouring cells → 100% efficiency if
  - *d* = cell-size = 2π/1536 rad = 8.2mrad = 17.8mm
- Inclined cells: More difficult, energy always distributed in neighbouring cells → neural network
  - 100% efficiency for *d* > 22mm

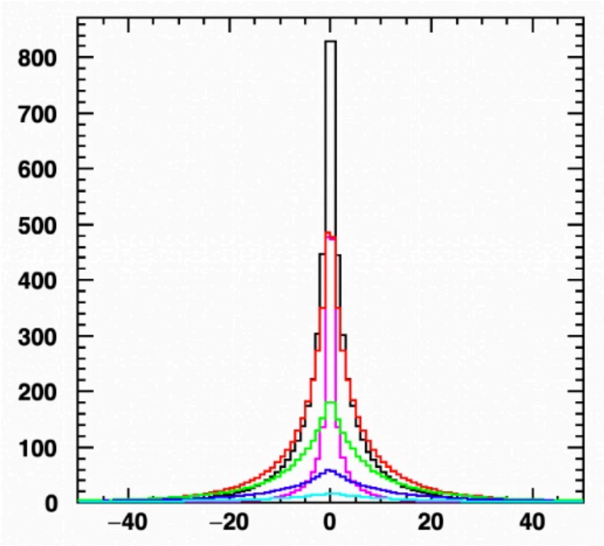






More Realistic Case – Starting Showers

- In reality photons will have started to shower in the cryostat walls + tracker (> $1X_0$) → showers with very narrow width (see presentation by M. Dam in Dec.)
- → For the following studies I assumed shower width of 4mm in the strips layer
- → Now signal in two neighbouring cells cannot be interpreted as 2 particles anymore!
- → Training neural networks (with Mathematica 12)

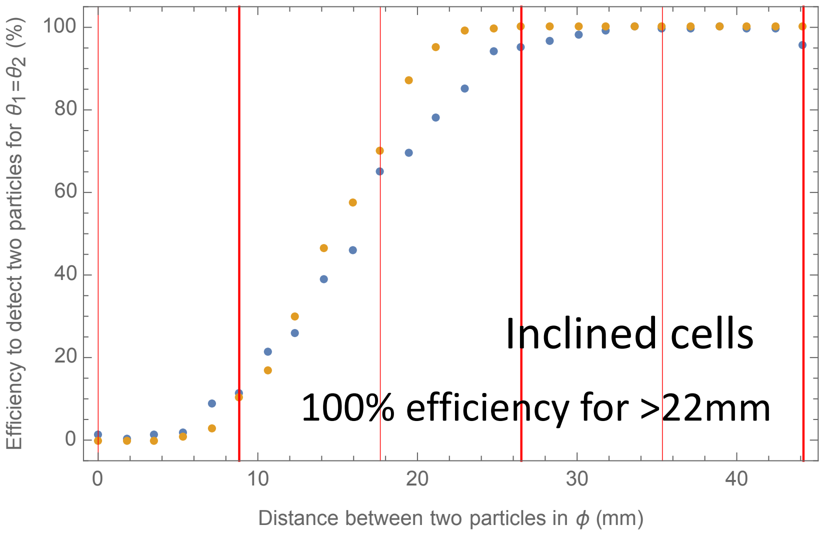


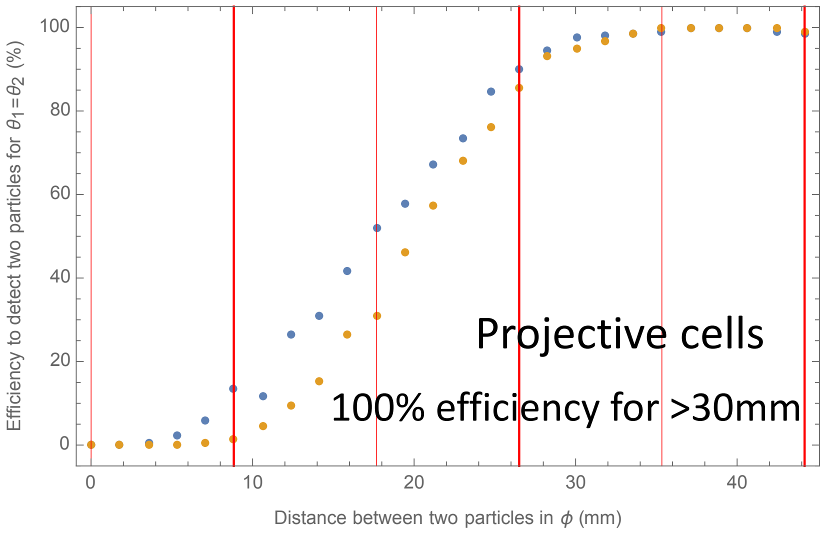
Transverse shower development in 5 first 10 layer deep (~3 X_0) samplings. Largely inside 5 mm in first 2 samplings (until shower max at $6X_0$)

Plot by M. Dam (link)

Separation in ϕ of Two Starting Showers

- Training with 3 x 50000 (0, 1, 2 showers) random events. Showers with 1 – 6 MIPs (random)
  - Noise per cell 0.2 MeV
- Curves are for 1 MIP (blue) and 3 MIP-showers (orange)
  - For both cases the efficiency to identify events with 1 shower only is > 99.5%
- Curves below are obtained for a separation in ϕ only.
- Much finer segmentation (~1/3) in θ (cell-size: 5.4mm) → 100% eff. for Δθ > 10mm ($\pi^0 \rightarrow \gamma\gamma$, $E_{\pi 0}$ < 60GeV)

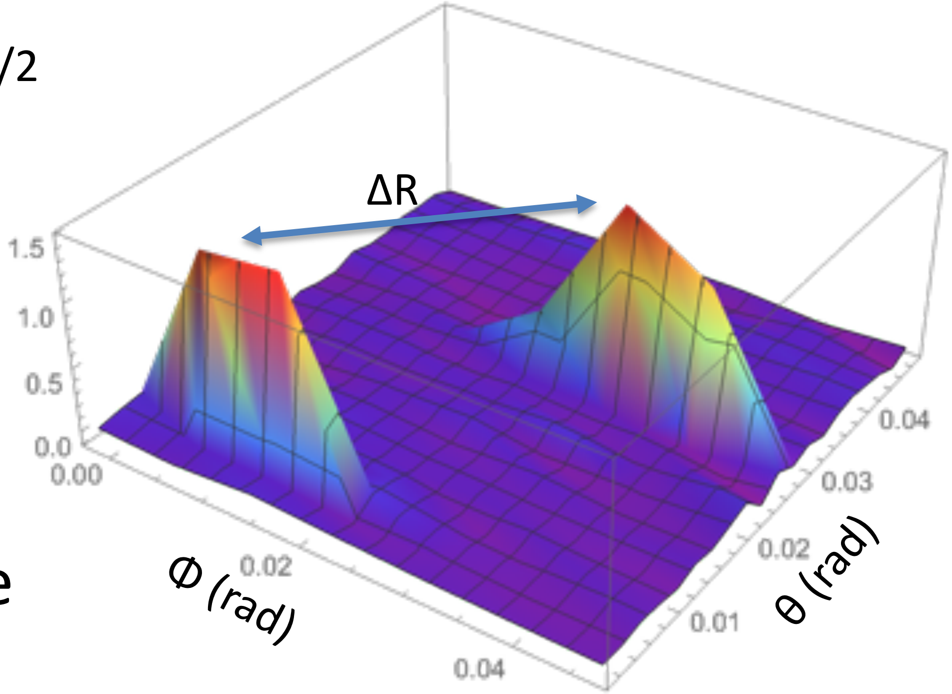




Next Steps

- → Need to calculate efficiency for 2D separation in θ and ϕ: $\Delta R = (\Delta\phi^2+\Delta\theta^2)^{1/2}$
- 2D neural network → but this might be beyond the capacity of Mathematica
  - First attempts limited by statistics
- Probably necessary to move to full-sim FCC-SW

2 showers of 3 MIPs



Conclusions

- Noise values extrapolated for ATLAS-like warm read-out electronics
  - C_d = 5pF and $\sigma_{noise} \approx 0.2$ MeV seems possible in the strips (if no shields in this long. compartment)
- Inclined geometry is clearly an advantage for position resolution
- Inclined geometry also prevails for π^0 rejection