# A TDR(*) calorimetry for FCC-ee?

❑ **(*) TDR = Two- (or three-) fold dual-readout**

Disclaimer: I have neither seen nor studied in detail the RD52 set up, and therefore am entirely ignorant of any hardware issues that the following proposal(s) may cause. The proposal(s) may thus be entirely flawed.

Principle of fibre DR calorimetry (RD52)

❑ **Fine grid of scintillating and Čerenkov fibres in Cu (Pb) absorber**
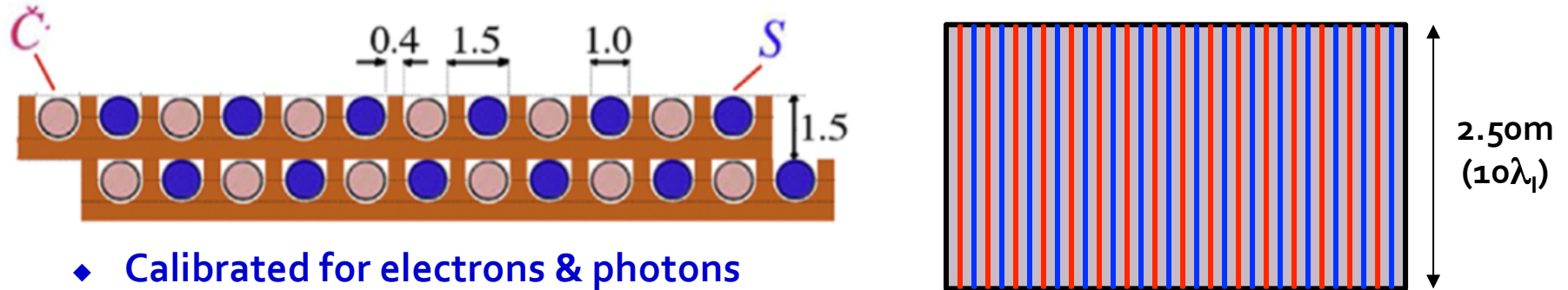
- ◆ **Calibrated for electrons & photons**
- ◆ **Different S & C responses to the hadronic part of a hadron shower**

$$S = \left[f_{EM} + \alpha_S \left(1 - f_{EM} \right) \right] E \ \text{ and } \ C = \left[f_{EM} + \alpha_C \left(1 - f_{EM} \right) \right] E$$

- ◆ **Two independent measurements of E and f_{EM}**

$$E = \frac{(1-\alpha_C)S - (1-\alpha_S)C}{\alpha_S - \alpha_C}, \quad E_{EM} = \frac{\alpha_S C - \alpha_C S}{\alpha_S - \alpha_C}, \ \text{ and } E_{HAD} = \frac{S-C}{\alpha_S - \alpha_C}.$$

❑ **Ultimate measurement of jet energy**

- ◆ **Self-calibrated for hadrons, once α_S and α_C are known.**

Jet energy resolution is not everything

- In e^+e^- collisions, jet energies can often be inferred from their directions
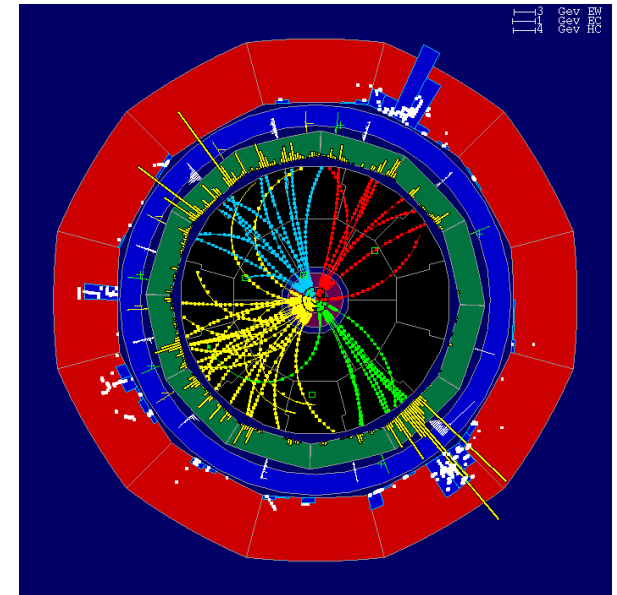 - Example: an $e^+e^- \to W^+W^- \to q\bar{q}q\bar{q}$ candidate in ALEPH
    - Four jets in the event and nothing else
    - Total energy and momentum are conserved
      - $E_1 + E_2 + E_3 + E_4 = \sqrt{s}$
      - $P_1^{x,y,z} + p_2^{x,y,z} + p_3^{x,y,z} + p_4^{x,y,z} = 0$
    - Jet directions ($\beta_i = p_i/E_i$) are very well measured

$$
\begin{bmatrix}
1 & 1 & 1 & 1 \\
\beta_1^x & \beta_2^x & \beta_3^x & \beta_4^x \\
\beta_1^y & \beta_2^y & \beta_3^y & \beta_4^y \\
\beta_1^z & \beta_2^z & \beta_3^z & \beta_4^z
\end{bmatrix}
\begin{bmatrix}
E_1 \\
E_2 \\
E_3 \\
E_4
\end{bmatrix}
=
\begin{bmatrix}
\sqrt{s} \\
0 \\
0 \\
0
\end{bmatrix}
$$

  - Jet energies determined analytically by inverting the matrix
    - With much better resolutions than the direct (Calo or PF) measurement
- Requires jet directions to be measured as best as possible
  - Hence, requires individual particle identification in jets (PF reconstruction)


Particle-flow concept in ECAL+HCAL experiment

❑ **Charged particles are bent in the magnetic field**

   ◆ **Their calorimetric deposits smear / bias the jet direction**
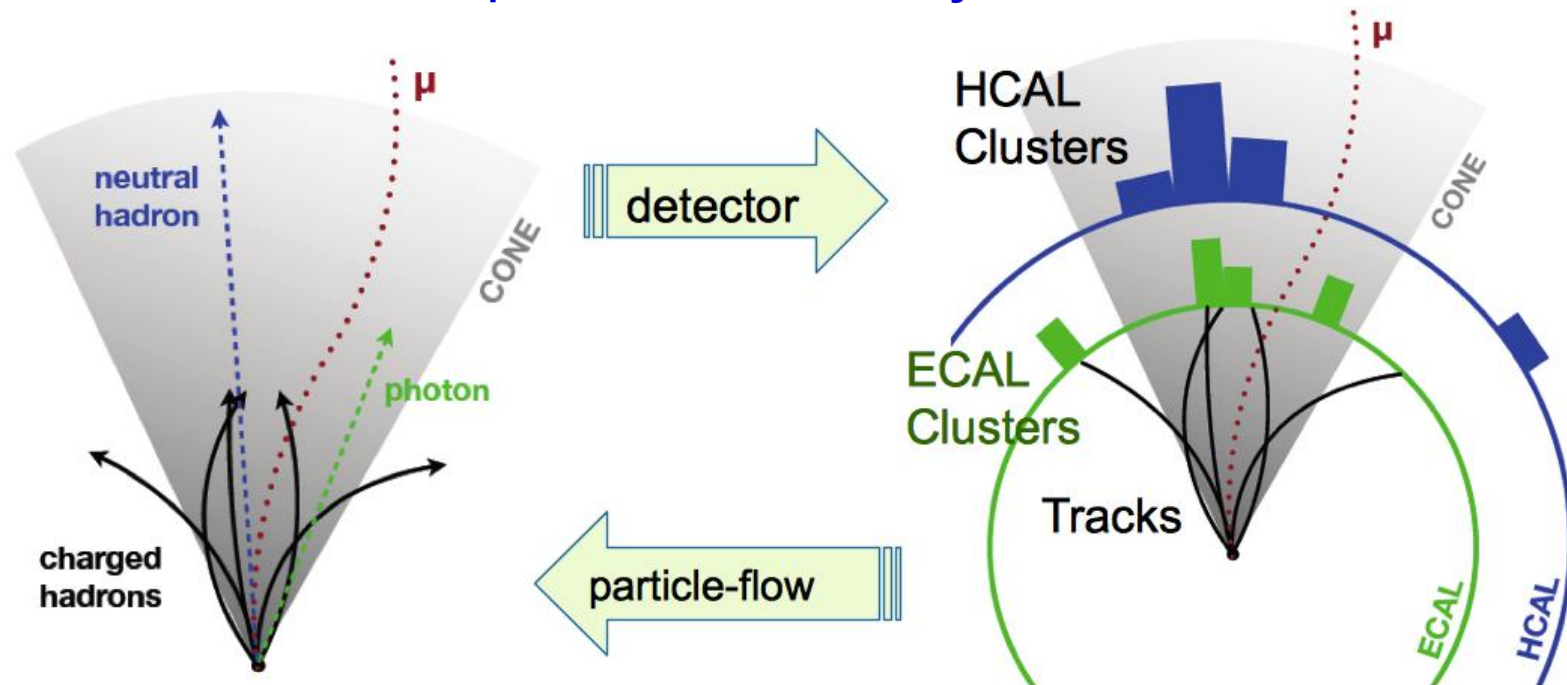
   ◆ **Requires the charged calo deposits to be identified as such**

      ● **And inclusively linked to the original track**

   ◆ **Original direction of charged hadrons is recovered**

      ● **The energies and directions of identified neutral deposits complete the jet**

# Particle-flow concept in ECAL+HCAL experiment

- ❑ **Jet angular resolution greatly improved**
  - ◆ **Up to a factor 4 for E = 50 GeV**
    - ● Improves in turn jet energy resolution (for constrained final states)
- ❑ **There are many other advantages of individual particle ID in jets**
  - ◆ **Tau exclusive decay identification**
    - ● Tau polarization
      - ➡ $\sin^2\theta_W$, $\alpha_{QED}(m_Z)$
    - ● Tau spectral functions
      - ➡ $\alpha_S(m_Z)$
  - ◆ **Jet substructure**
  - ◆ **Particle isolation**
  - ◆ **b- and c- jet tagging with b,c → e + X**
  - ◆ **Physics analysis simplicity**
    - ● With a list of (reco or gen) particles
  - ◆ **Demonstrated repeatedly with ALEPH and CMS data**
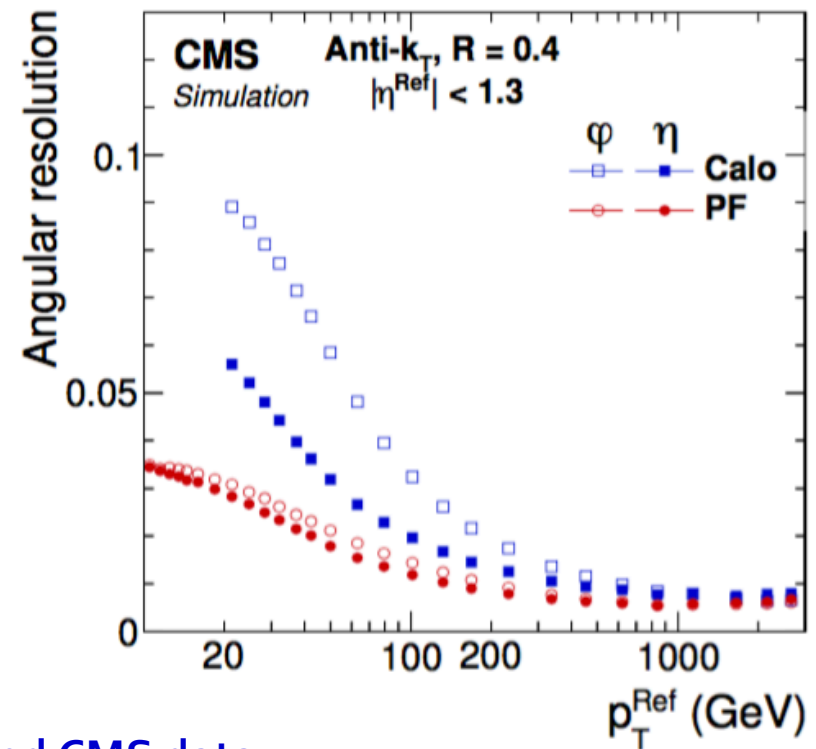
Particle identification in DR calorimetry ?

❏ **DR calorimetry was never designed to identify particles in jets**

◆ **Isolated particle identification seems to be a piece of cake:**
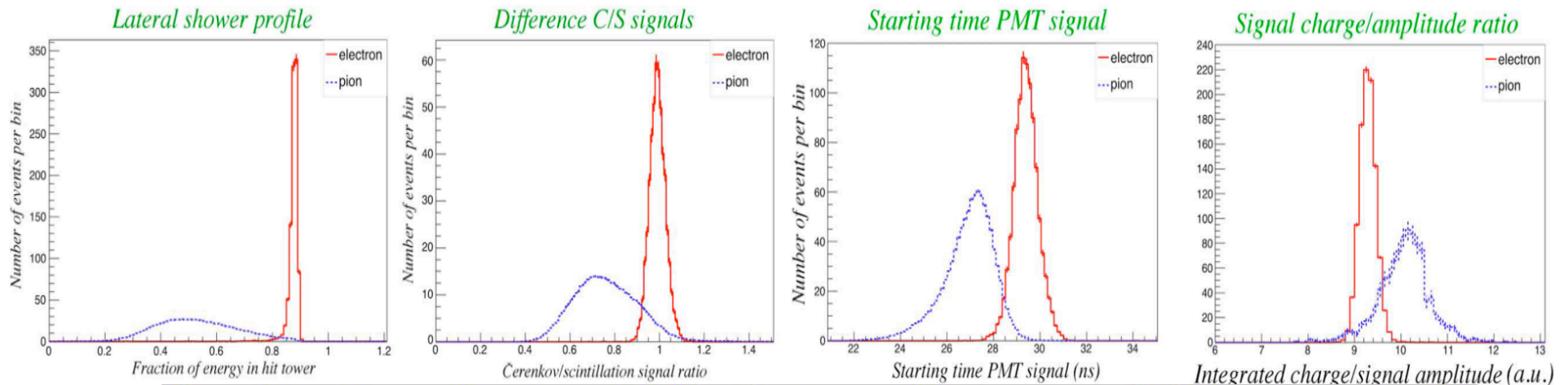
Combination of cuts: >99% electron efficiency, <0.2% pion mis-ID

◆ **Tiny detail**

- ● **Charged and neutral pions are almost never isolated**
- ● **Electrons in jets are not isolated either**

◆ **The absence of longitudinal segmentation merge e/γ and $\pi^{\pm}$ signals together**

◆ **The fine transverse granularity may help to recover some ID capability**

- ● **But it may as well often not be the case**

Example of a (very) simple jet

With longitudinal segmentation, single readout (CMS)
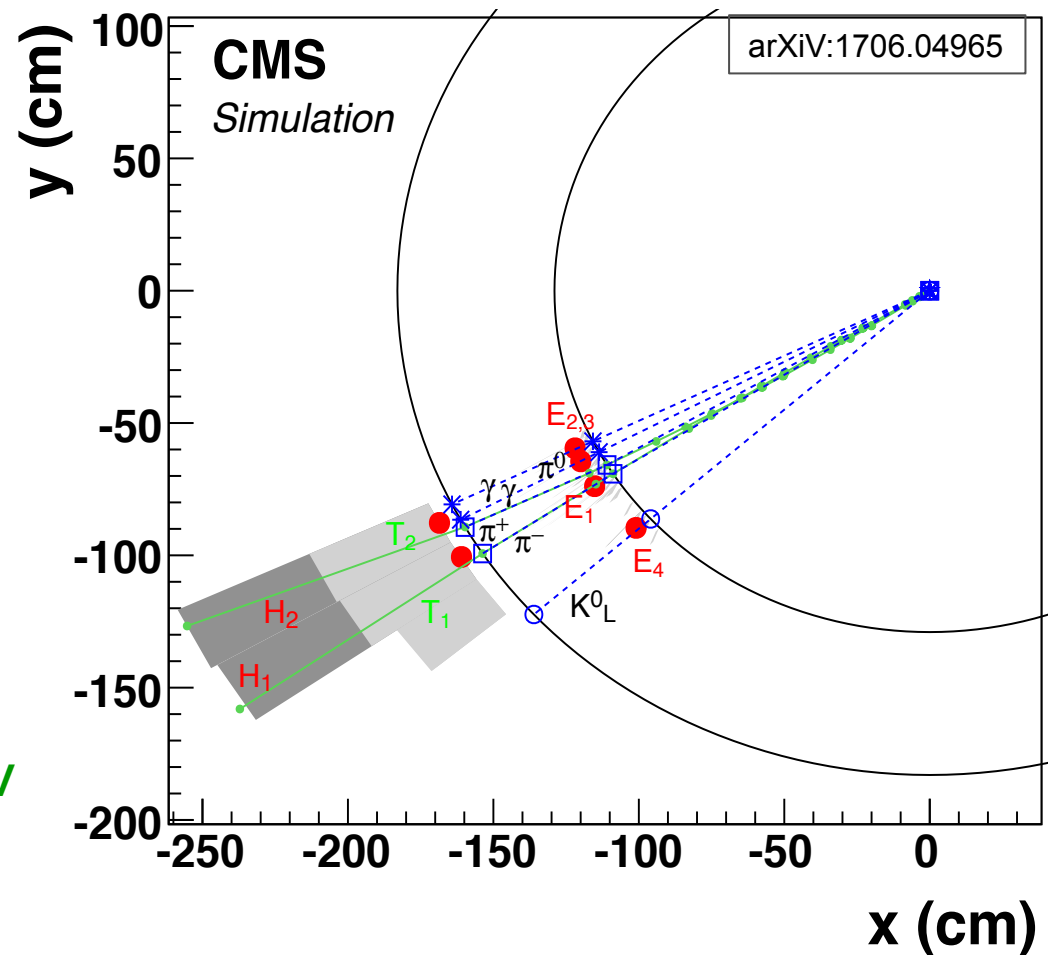
- The (x,y) view is not particularly enlightening

  - Gen jet content
    - π^+
    - π^-
    - $\pi^0 \rightarrow \gamma\gamma$
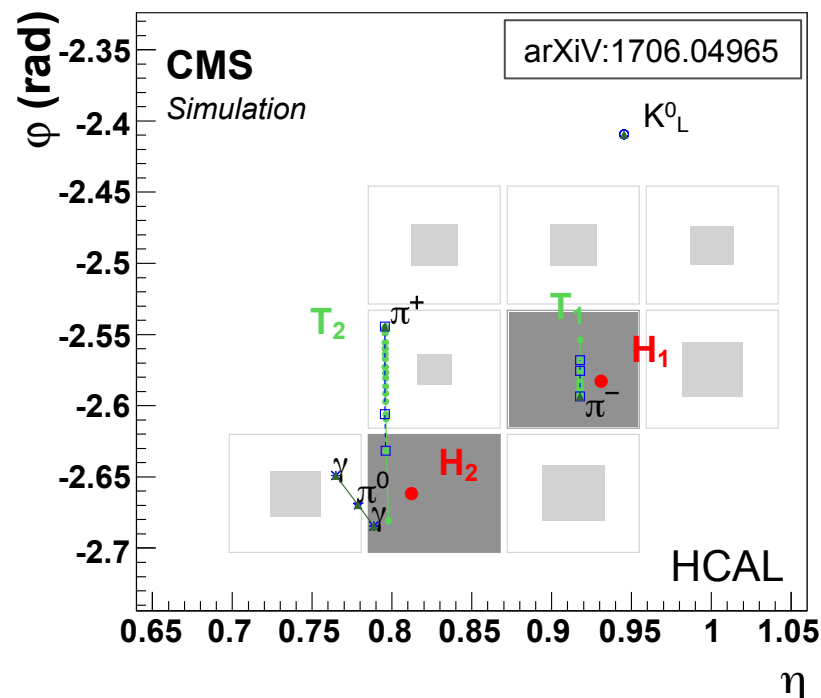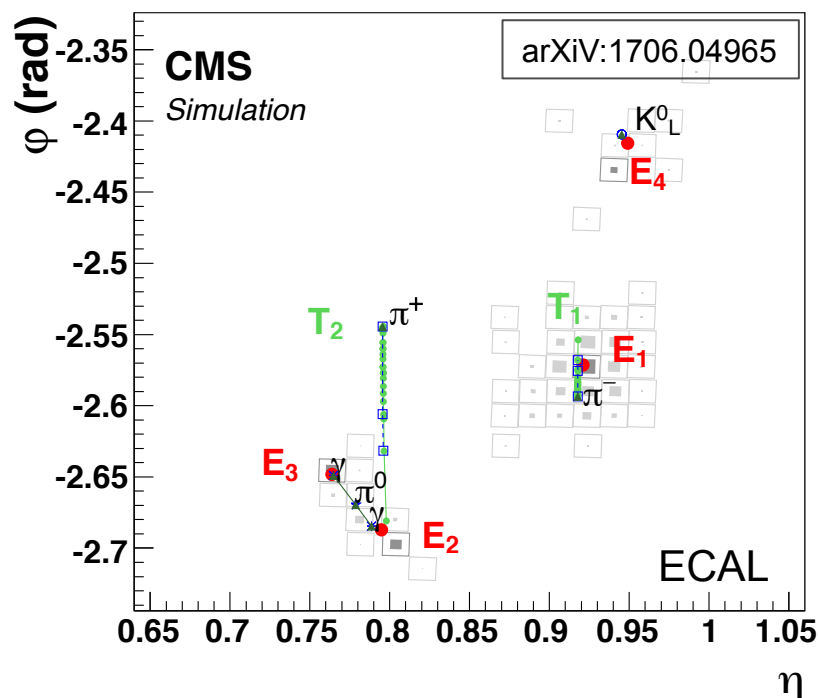   - K^0_L

  - Reco jet content
    - Two tracks
    - Four ECAL clusters
    - Two HCAL clusters

  - Jet energy is about 65 GeV

Example of a (very) simple jet

☐ **With longitudinal segmentation, single readout (CMS)**

◆ **The (η,φ) views from the ECAL and HCAL surfaces are more useful**


◆ **All five particles give their own, identified, well separated calo clusters**

- **Charged calo energy (E_1, H_1, H_2) is associated to charged tracks (T_1, T_2)**
- **Remaining ECAL clusters (E_2, E_3, E_4) give rise to photons**

◆ **Particle-Flow reconstruction is optimally at work**

Example of a (very) simple jet

□ **Without longitudinal segmentation, double readout calorimetry**

◆ **The (η,φ) views with EM and HAD energies are all mixed up**
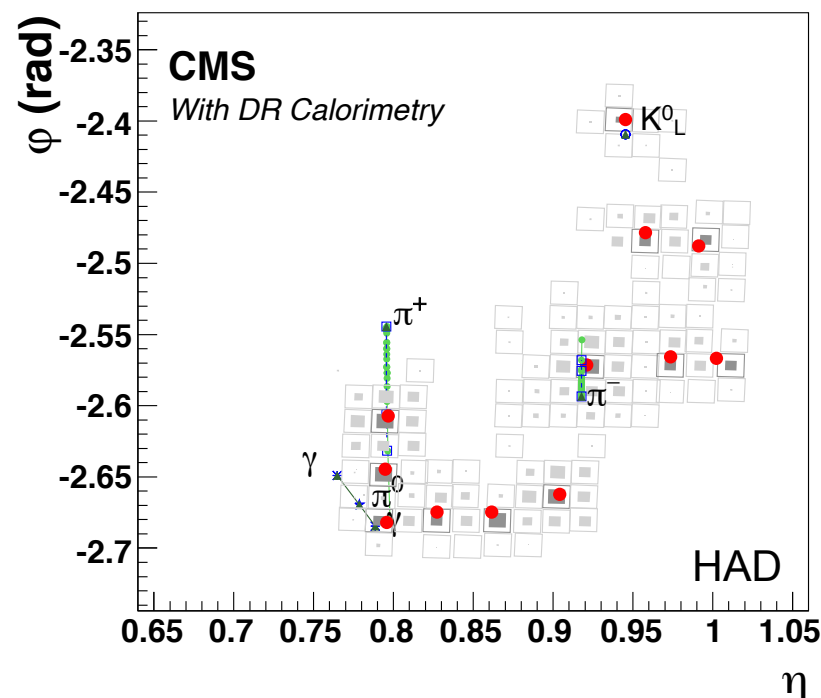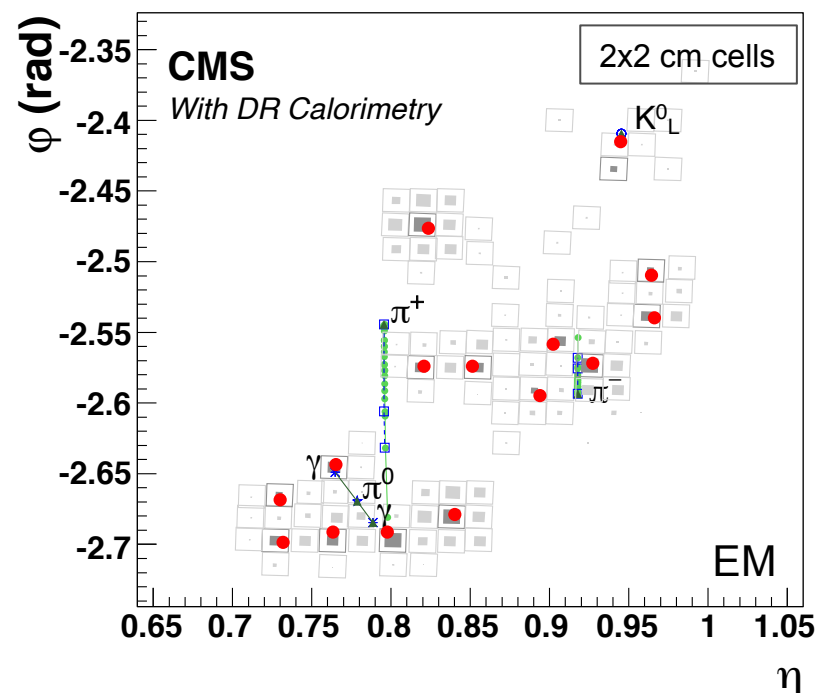
◆ **The EM fraction of the π+ merges with the photons from the π0**

● **The HAD fraction of the π+ prevents photons to be safely identified**

◆ **The EM fractions of the π+ and π− give rise to many EM clusters / HAD clusters**

● **Particle-Flow picture is confused / confusing**

How about timing ?

❑ **PMT signal starting time seems to be discriminating**
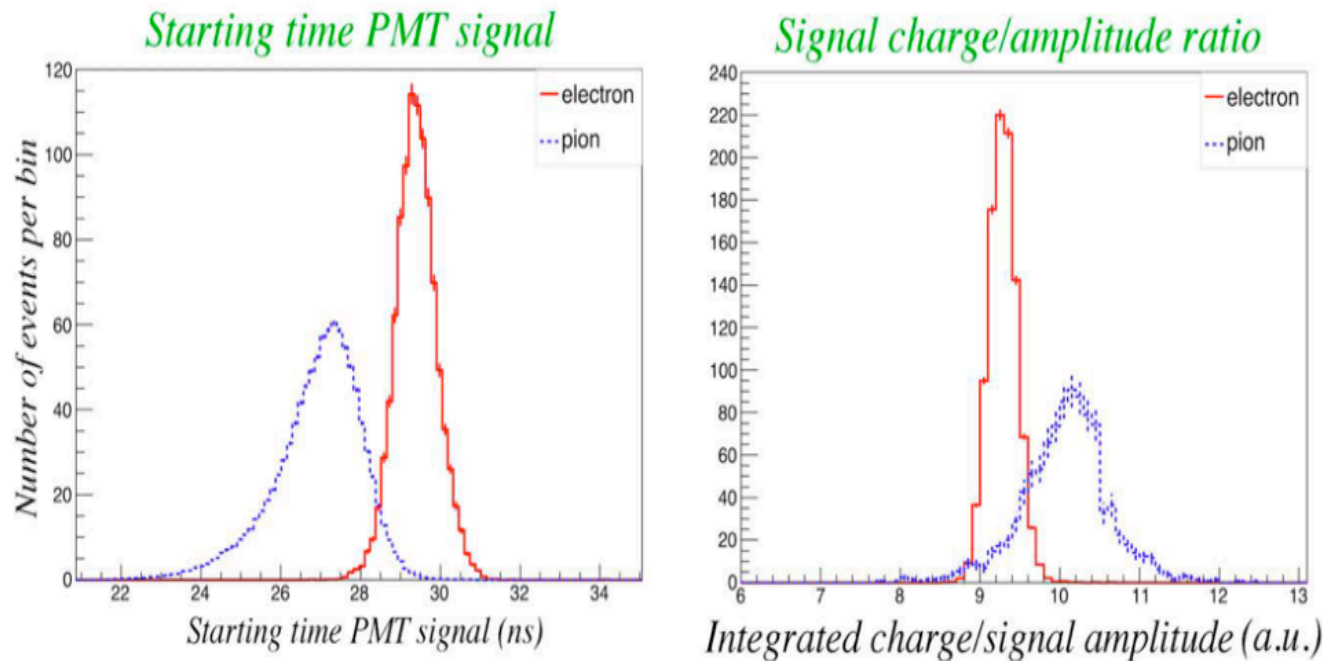
- ◆ **It is, however, not adapted for overlapping π^0 energy and π^+ EM fraction**
  - ● **The π^+ part always leads to an earlier starting time**
- ◆ **Full timing profile measurement would certainly help**
  - ● **Not practical in terms of event size (I am told)**
- ◆ **Signal charge / amplitude [not sure what that is] ratio suffers a similar problem**
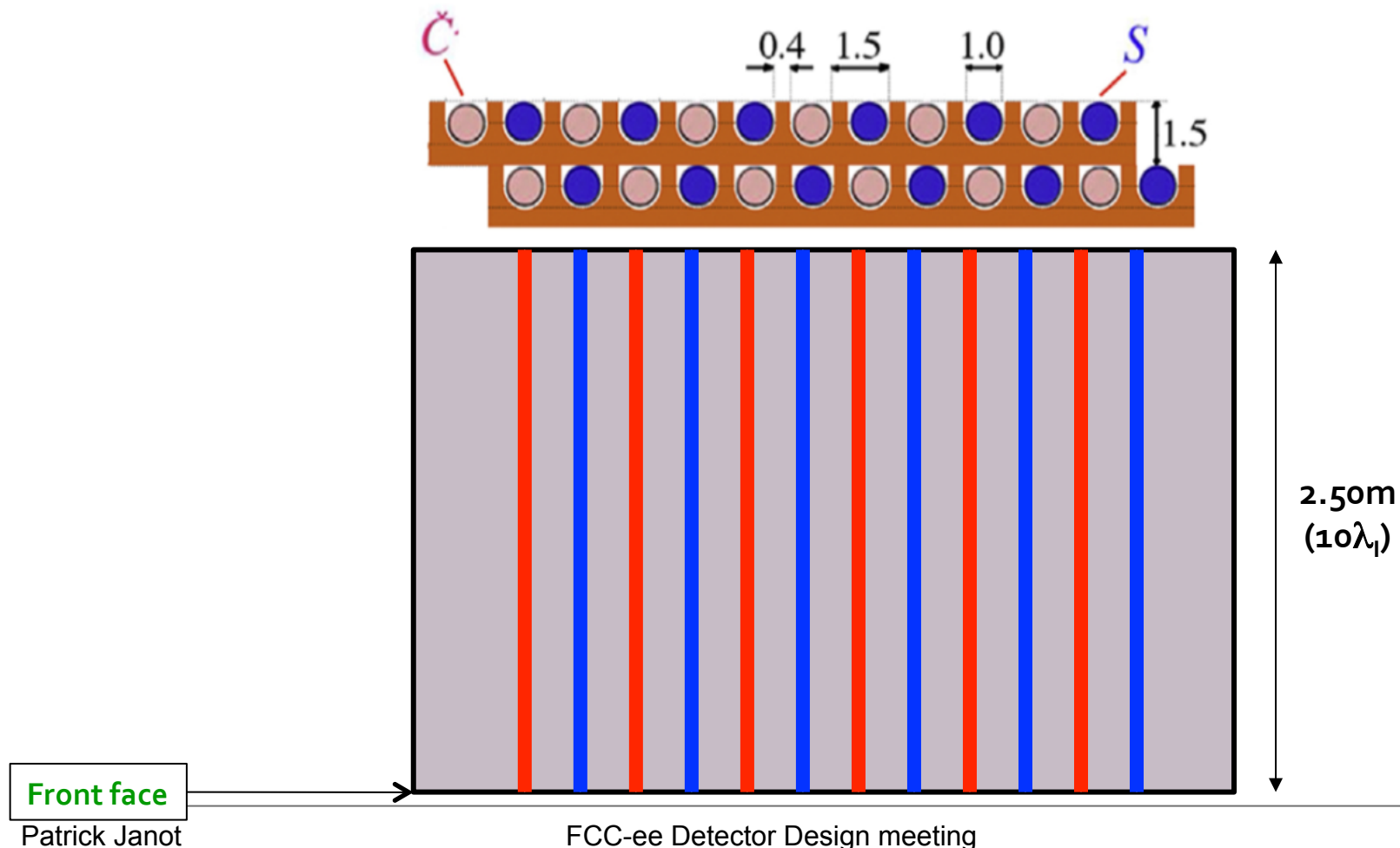
We need longitudinal segmentation !

❑ **Previous attempt with two compartments (ECAL and HCAL)**

   ◆ **Add crystal matrix (BGO / PbWO4) in front of the fibre DR calorimeter**

      ● **Requires timing filters to separate S and C light in crystals**

         ➡ **Photo-statistics reduction, nonlinearity, worse energy resolution**

      ● **Readout electronics between EM and HAD part**

         ➡ **Energy losses in the material, worse energy resolution**

         ➡ **Important design complication**

      ● **Different $\alpha_{S,C}$ in crystals and fibres**

         ➡ **Worse energy resolution**

         (esp. for early hadron showers)

      ● **Crystal are expensive**

❑ **Claim from R. Wigmans**

   ◆ **Any such two-compartment design will lead to performance degradation**

   ◆ **Corollary: PF reco will degrade DR performance**
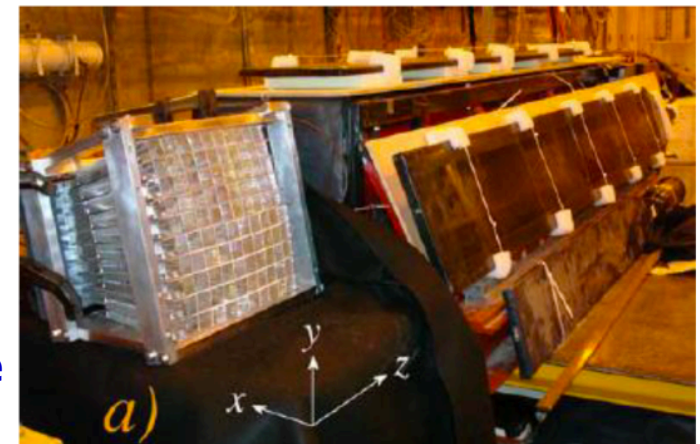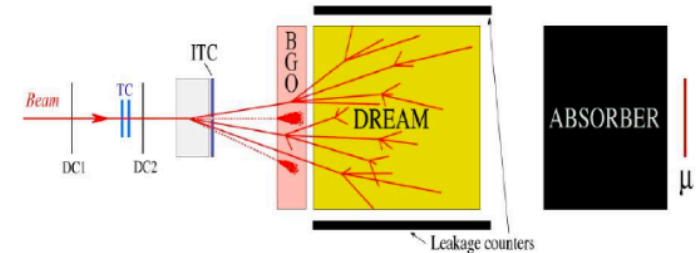
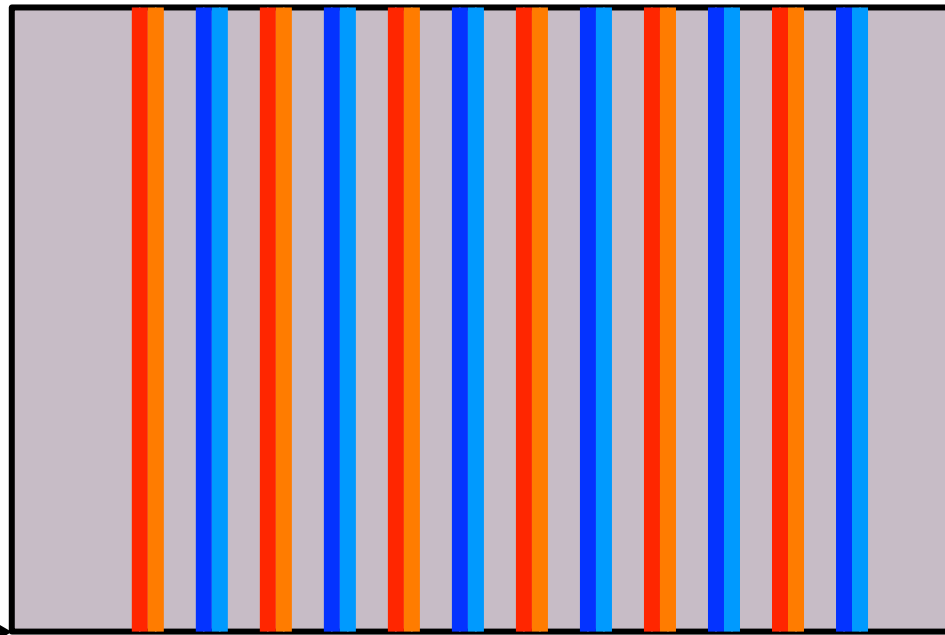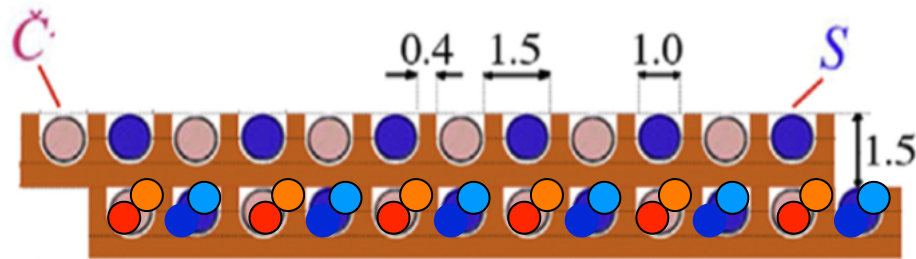# We need longitudinal segmentation !

❑ **Requirement: keep the one-compartment design**

We need longitudinal segmentation !

□ **Requirement: keep the one-compartment design**

◆ **But multiply the number of fibres by two**

We need longitudinal segmentation !

❑ **Requirement: keep the one-compartment design**

♦ But multiply the number of fibres by two, but the new ones are shorter by $1\lambda_I$

We need longitudinal segmentation !

❑ **Requirement: keep the one-compartment design**

   ◆ **But multiply the number of fibres by two, but the new ones are shorter by $1\lambda_I$**
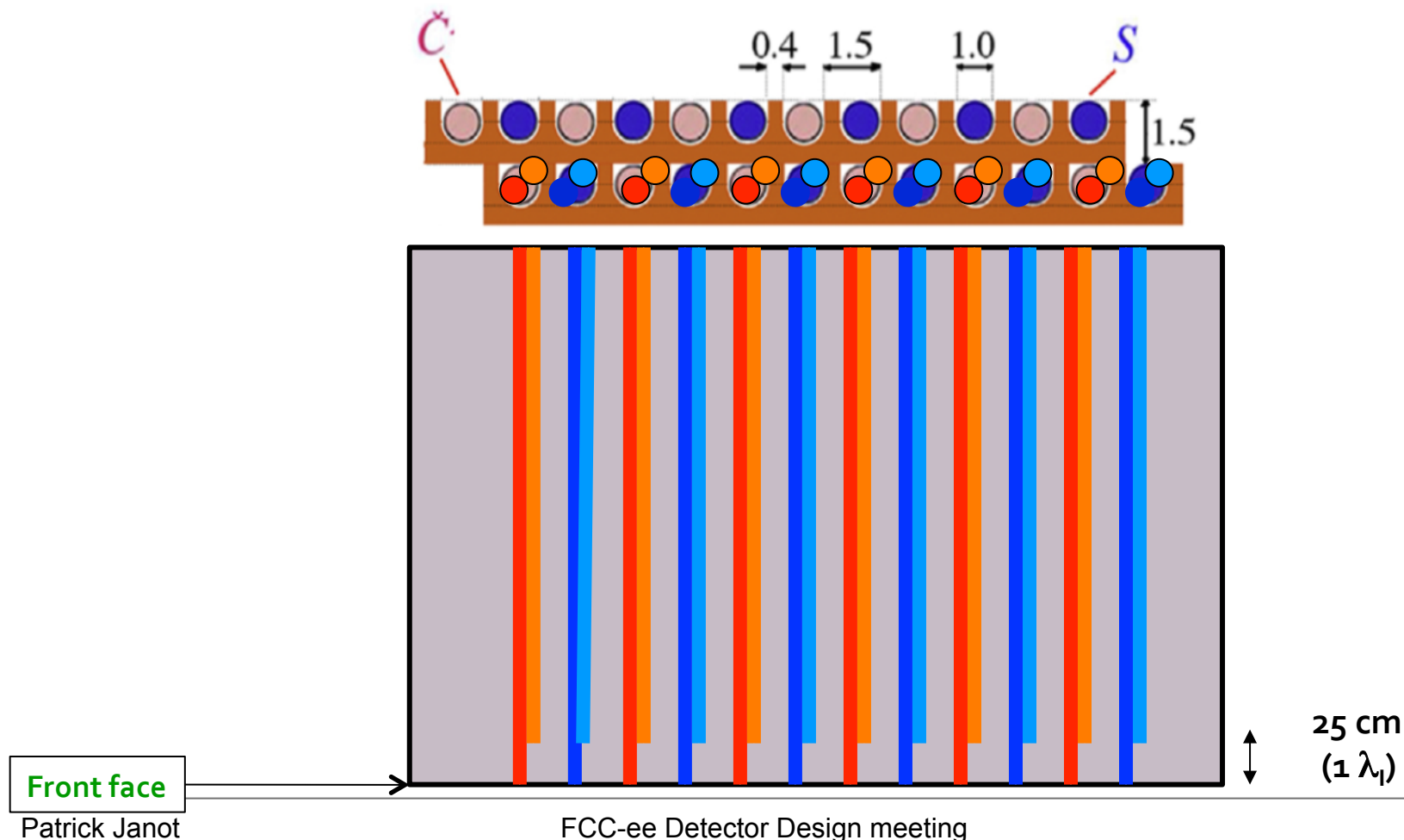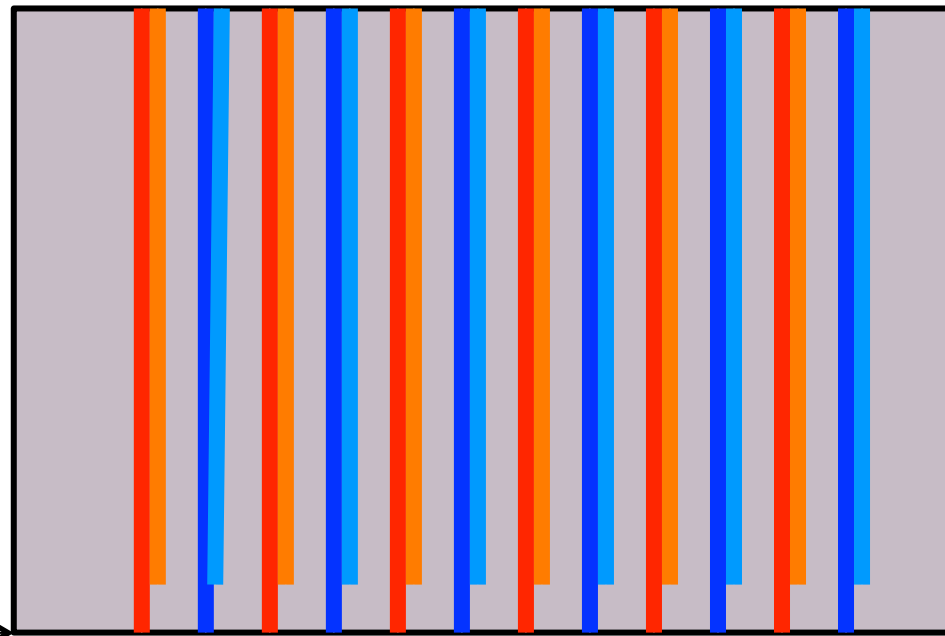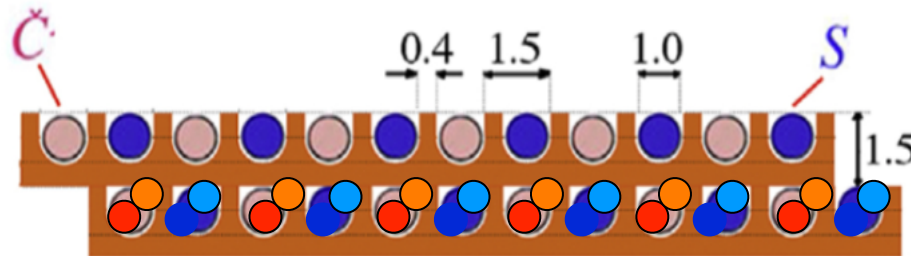
   ● **Read out separately C_{Long}, C_{Short}, S_{long} and S_{Short} : twofold dual readout**

Inspired from
CMS HF Calo
[Only Č fibres]

Front face

25 cm
($1 \lambda_I$)

And there was longitudinal segmentation !

- **The long fibres give the total energy (and the total f_{EM}), as before**
  - Richard is happy: the energy resolution is preserved
  - The design is unchanged.
  - The add'l cost is that of the fibres and their readout electronics
- **If 1 λ_I correspond to 25 X_0 or more (see next slide)**
  - Long – Short is equivalent to an ECAL compartment
    - And Short is equivalent to an HCAL compartment
- **Bonus: C_L-C_S and S_L-S_S give access to the ECAL EM/HAD fractions**
  - Enhances the e/γ ID and within jets with respect to simple ECAL/HCAL
- **Important requirement (different from CMS HF)**
  - Short and long fibres must be side by side
    - The same energy sample is measured
      - ➡ L-S is not subject to sampling fluctuations
  - Short and long fibres must have a uniform response (within 0.1%)
    - Detect photons of few 100 MeV merged with a 100 GeV hadron
  - Note: Read out L and L-S rather than L and S (L-S might be small wrt L & S)
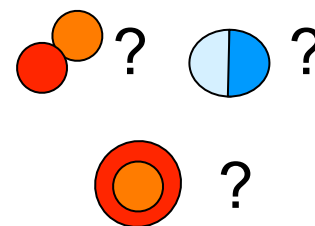
A small issue with Copper

❑ **Atomic and nuclear properties of Cu**

Copper (Cu)

Quantity	Value	Units	Value	Units
Atomic number	29			
Atomic mass	63.546(3)	g mole^{-1}		
Density	8.96	g cm^{-3}		
Mean excitation energy	322.0	eV		
Minimum ionization	1.403	MeV g^{-1}cm^2	12.57	MeV cm^{-1}
Nuclear collision length	84.2	g cm^{-2}	9.393	cm
Nuclear interaction length	137.3	g cm^{-2}	15.32	cm
Pion collision length	109.3	g cm^{-2}	12.20	cm
Pion interaction length	165.9	g cm^{-2}	18.51	cm
Radiation length	12.86	g cm^{-2}	1.436	cm
Critical energy	19.42	MeV (for e^-)	18.79	MeV (for e^+)
Molière radius	14.05	g cm^{-2}	1.568	cm
Plasma energy $\hbar\omega_p$	58.27	eV		
Muon critical energy	317.	GeV		
Melting point	1358.	K	1085.	C
Boiling point @ 1 atm	2835.	K	2562.	C

$$1 \; \lambda_\pi = 12.9 \; X_0$$

Makes the ECAL compartment thickness about 2 λ_π worth

Most hadron showers start in ECAL…
Not well adapted to Particle Flow

How about Lead ?

❑ **Atomic and nuclear properties of Pb**

Lead (Pb)

Quantity	Value	Units	Value	Units
Atomic number	82			
Atomic mass	207.2(1)	g mole^{-1}		
Density	11.4	g cm^{-3}		
Mean excitation energy	823.0	eV		
Minimum ionization	1.122	MeV g^{-1}cm^2	12.74	MeV cm^{-1}
Nuclear collision length	114.1	g cm^{-2}	10.05	cm
Nuclear interaction length	199.6	g cm^{-2}	17.59	cm
Pion collision length	137.3	g cm^{-2}	12.10	cm
Pion interaction length	226.2	g cm^{-2}	19.93	cm
Radiation length	6.37	g cm^{-2}	0.5612	cm
Critical energy	7.43	MeV (for e^-)	7.16	MeV (for e^+)
Molière radius	18.18	g cm^{-2}	1.602	cm
Plasma energy $\hbar\omega_p$	61.07	eV		
Muon critical energy	141.	GeV		
Melting point	600.6	K	327.5	C
Boiling point @ 1 atm	2022.	K	1749.	C

$$1 \, \lambda_\pi = 35.5 \, X_0$$

Can make the ECAL compartment
thickness about 0.7 λ_π worth

Few hadron showers start in ECAL…
Well adapted to Particle Flow

Calorimeter depth

- $\lambda_\pi \sim 20$ cm calls for a calorimeter depth of 2.50 m (Pb or Cu)
  - Other materials may reduce to less than 1.50m for $10\lambda_\pi$
    - Tungsten has $\lambda_\pi \sim 11.3$ cm $\sim 32\ X_0$
      - ➡ Drilling holes is extremely difficult
    - Gold has $\lambda_\pi \sim 11.5$ cm $\sim 35\ X_0$
      - ➡ We all know the price of gold... (16000 US$ / pound!)
    - Uranium $\lambda_\pi \sim 12.4$ cm $\sim 39\ X_0$
      - ➡ Price ~ 20 US$ / pound (Cu: 2.8, Pb: 1.1)
      - ➡ No idea of the difficulty of machining it
    - Other suggestions ?

- Another possibility is to limit the depth to $6\lambda_\pi$ (1.50m)
  - And to evaluate the hadronic energy leakage (next slide)
    - Note: Leakage is not expected to be large at FCC-ee energies
      - ➡ Typical jet energies ~45-100 GeV
        - Typical hadron energies below 20 GeV.

Evaluate the hadronic energy leakage

❑ **One may consider a threefold dual readout design**

Infer the energy leakage from the ratios Shortest/Short ?
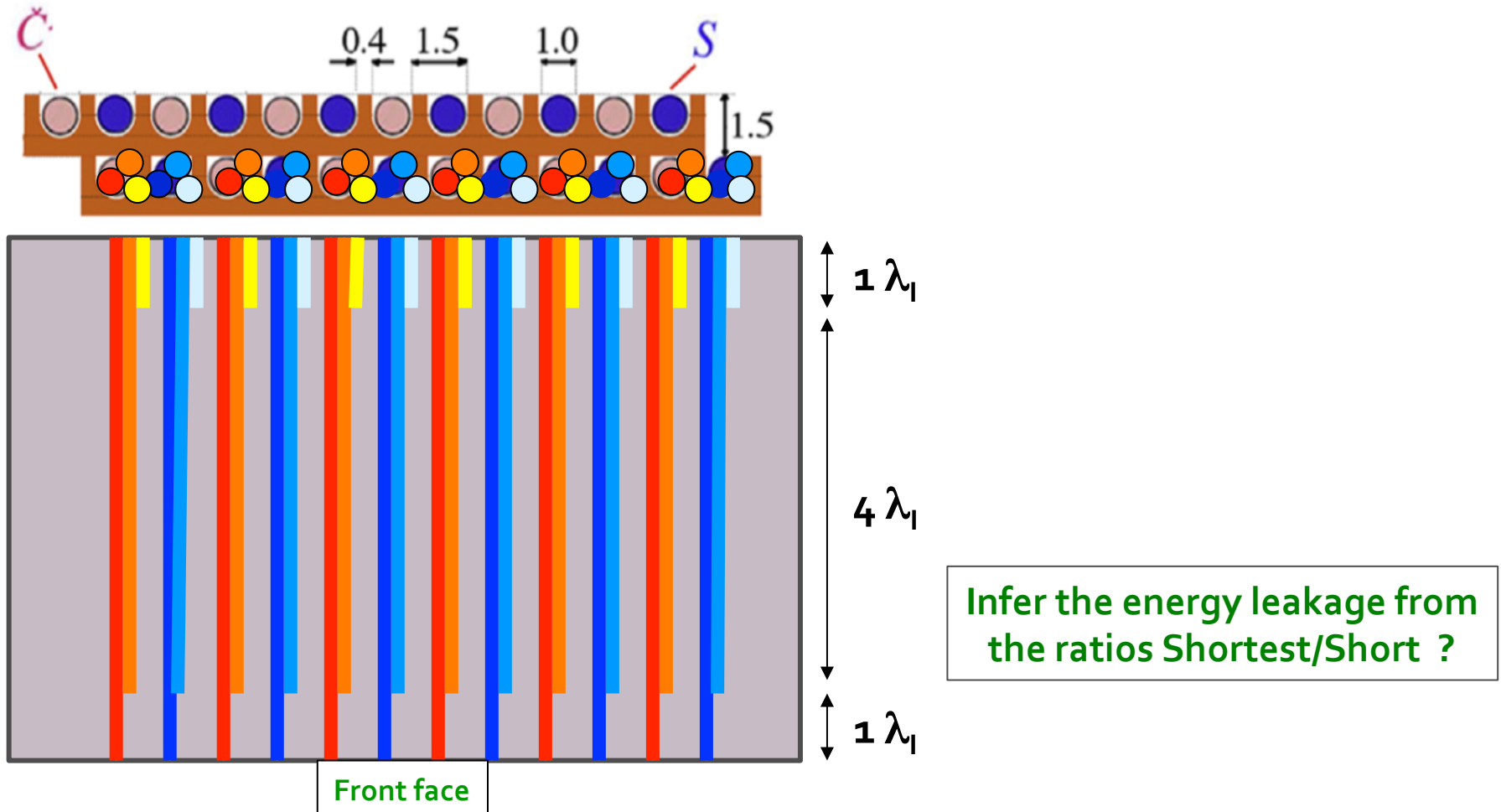
◆ **Might not be needed at FCC-ee energies**

Conclusion and outlook

- **At this point of the talk, flaws may have been identified**
  - ◆ **If so, just ignore the proposal…**
    - ● **And please accept my apologies for the waste of your time.**

- **If not, a <u>Lead</u> TDR calorimeter with long and short(est) fibres**
  - ◆ **May provide the required longitudinal segmentation for PF**
    - ● **Without degrading the intrinsic energy resolution**
    - ● **With almost no additional complication in the design**
  - ◆ **May provide additional rejection of hadrons in e/γ ID**
    - ● **By the measurement of f_{EM} in the ECAL section**
  - ◆ **Fibre response uniformity must be better than 1%**

- **Feasibility and performance must be assessed**
  - ◆ **With pne or several dedicated test-beam experiment(s)**
  - ◆ **With GEANT simulation and dedicated reconstruction**