DRD6.2 : Calorimétrie à liquide noble

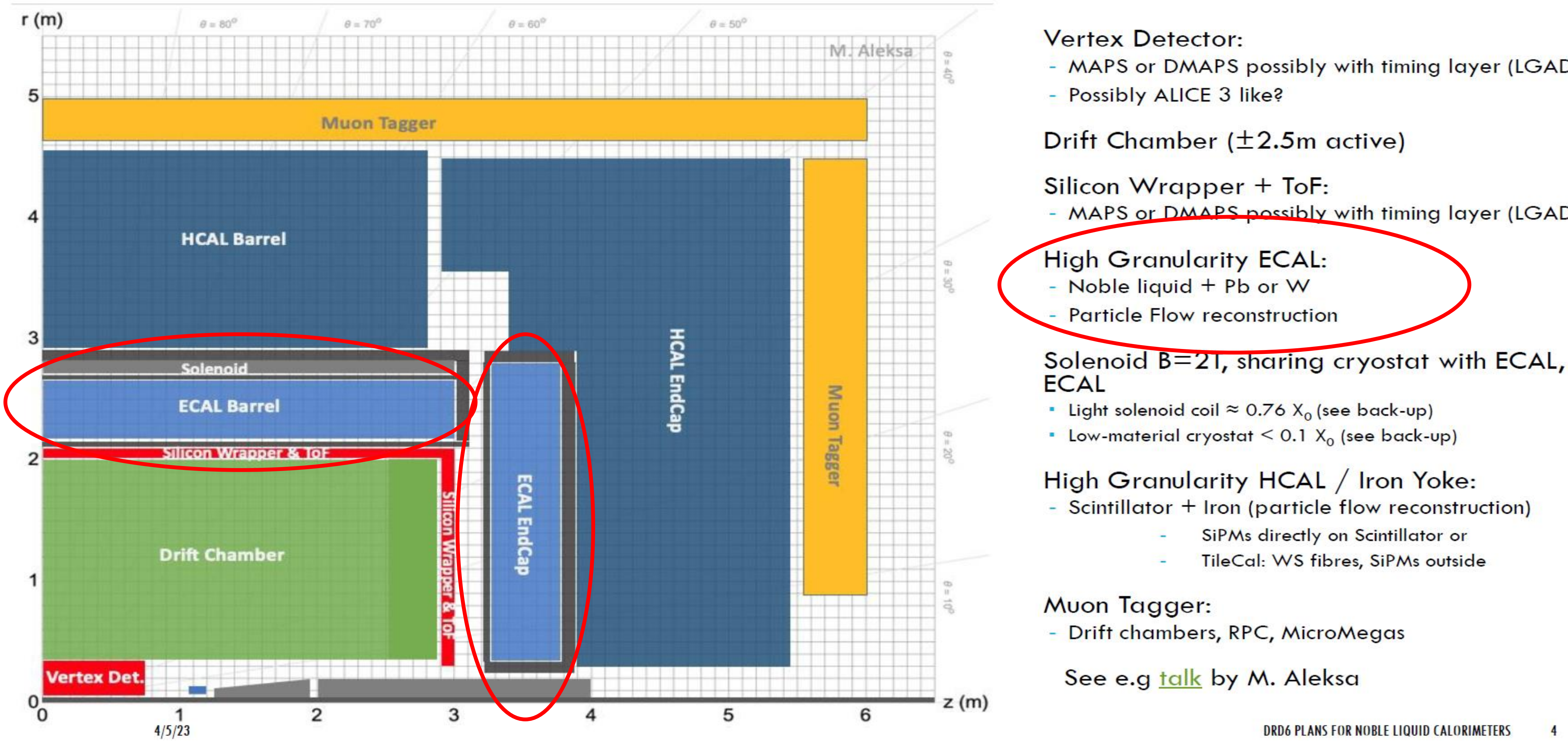
L. Poggioli

- Introduction
- Besoins en calorimétrie pour FCC-ee
- Résultats
- Axes de R&D

Sources

- M. Selvaggi, FCC week, Londres, 06/2023
- N. Morange 2nd DRD Calorimetry community meeting, CERN, 04/2023
- J. Faltova & N. Nikiforou, ECFA WG3: Topical workshop on calorimetry, PID and photodetectors, CERN, 05/2023

FCC-ee détecteur avec liquide noble (1 des 3 détecteurs baseline)



Vertex Detector:
- MAPS or DMAPS possibly with timing layer (LGAD)
- Possibly ALICE 3 like?

Drift Chamber (±2.5m active)

Silicon Wrapper + ToF:
- MAPS or DMAPS possibly with timing layer (LGAD)

High Granularity ECAL:
- Noble liquid + Pb or W
- Particle Flow reconstruction

Solenoid B=2T, sharing cryostat with ECAL, outside ECAL
- Light solenoid coil ≈ 0.76 X_0 (see back-up)
- Low-material cryostat < 0.1 X_0 (see back-up)

High Granularity HCAL / Iron Yoke:
- Scintillator + Iron (particle flow reconstruction)
  - SiPMs directly on Scintillator or
  - TileCal: WS fibres, SiPMs outside

Muon Tagger:
- Drift chambers, RPC, MicroMegas

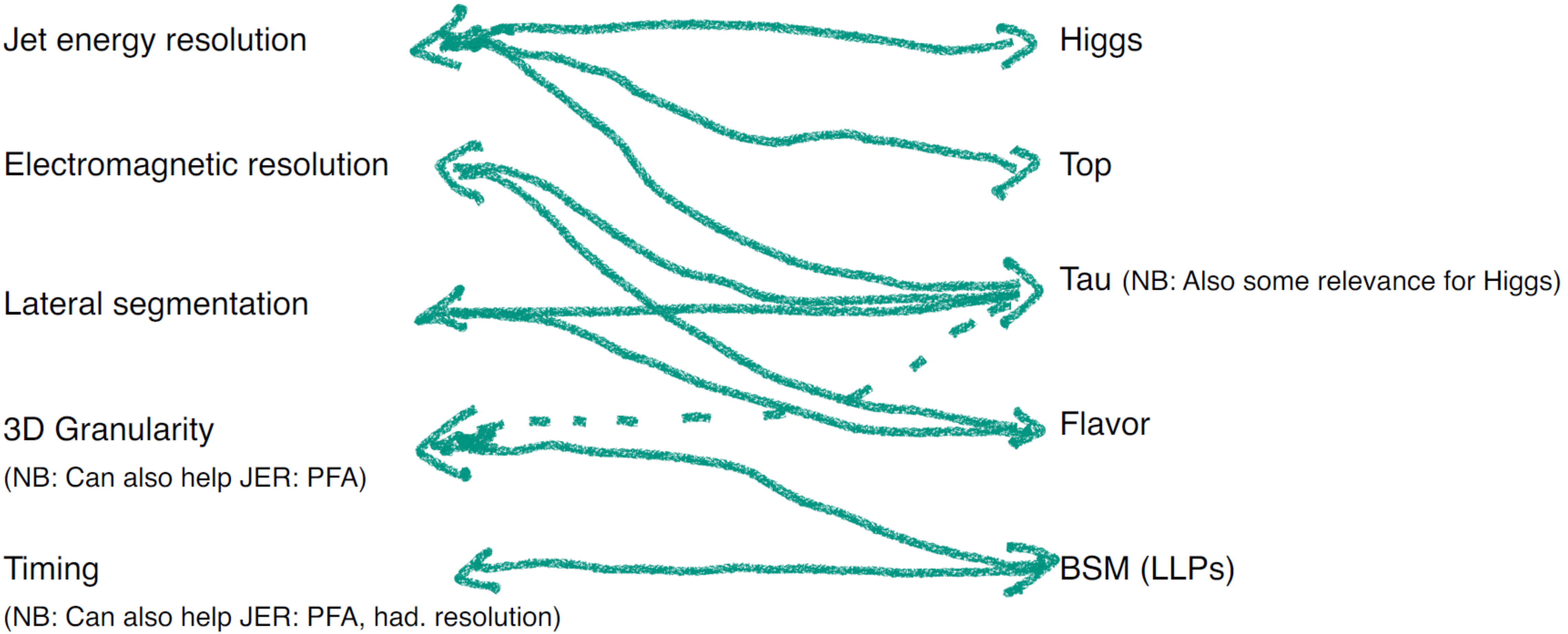
See e.g talk by M. Aleksa

4/5/23 DRD6 PLANS FOR NOBLE LIQUID CALORIMETERS 4

Attributs calorimètres vs Physique

F. Simon
ECFA WG3

- The main performance criteria for a Higgs Factory calorimeter system:



Jet energy resolution

Electromagnetic resolution

Lateral segmentation

3D Granularity
(NB: Can also help JER: PFA)

Timing
(NB: Can also help JER: PFA, had. resolution)

Higgs

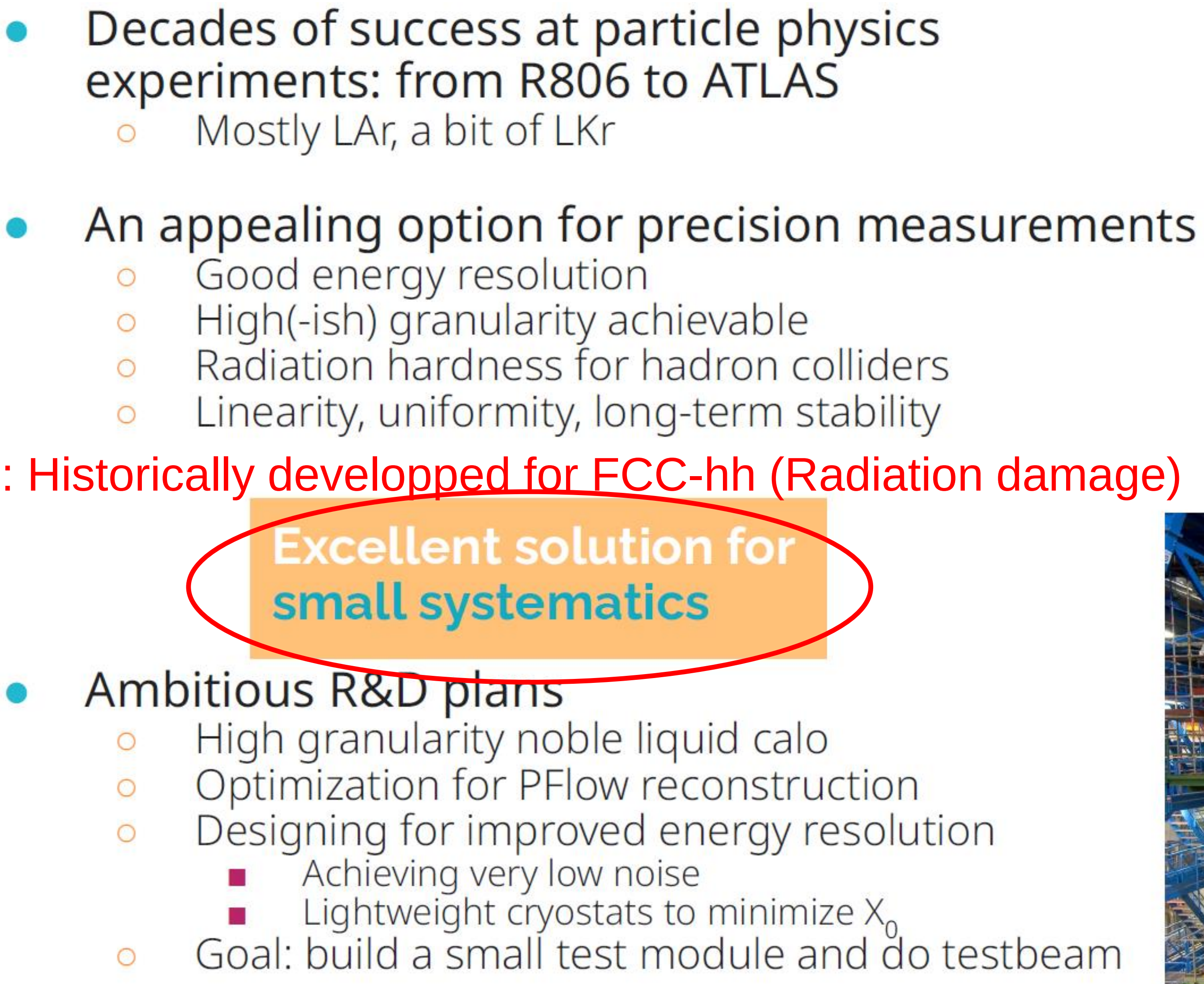
Top

Tau (NB: Also some relevance for Higgs)

Flavor

BSM (LLPs)

Historique

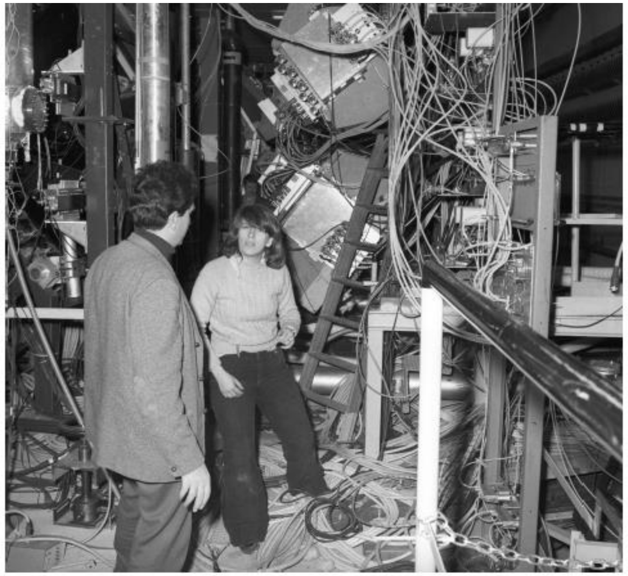


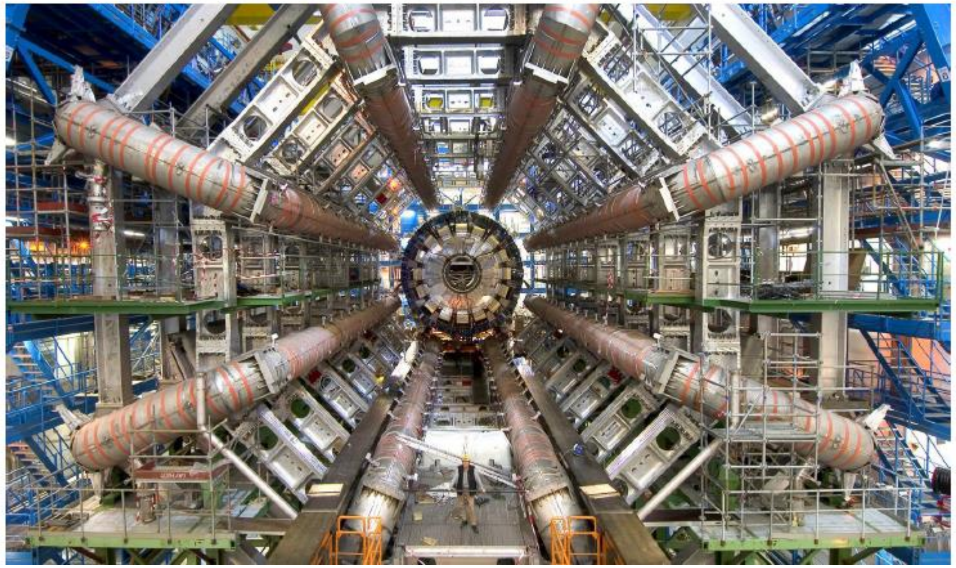
- Decades of success at particle physics experiments: from R806 to ATLAS
  - Mostly LAr, a bit of LKr
- An appealing option for precision measurements
  - Good energy resolution
  - High(-ish) granularity achievable
  - Radiation hardness for hadron colliders
  - Linearity, uniformity, long-term stability

NB: Historically developped for FCC-hh (Radiation damage)

Excellent solution for small systematics

- Ambitious R&D plans
  - High granularity noble liquid calo
  - Optimization for PFlow reconstruction
  - Designing for improved energy resolution
    - Achieving very low noise
    - Lightweight cryostats to minimize X_0
  - Goal: build a small test module and do testbeam





Instituts participants/intéressés

A Growing Collaboration

Areas of interests of the groups are still evolving

CERN

IJCLab
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

Brookhaven
National Laboratory

CHARLES UNIVERSITY

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

APC

LPNHE
PARIS

ARIZONA

STONY BROOK UNIVERSITY

NEVIS LABORATORIES
COLUMBIA UNIVERSITY

TECHNISCHE UNIVERSITÄT DRESDEN

ÚSTAV EXPERIMENTÁLNEJ FYZIKY SAV, v. v. i. · 1969

THE UNIVERSITY OF TEXAS AT AUSTIN

ΩMEGA
Microelectronics

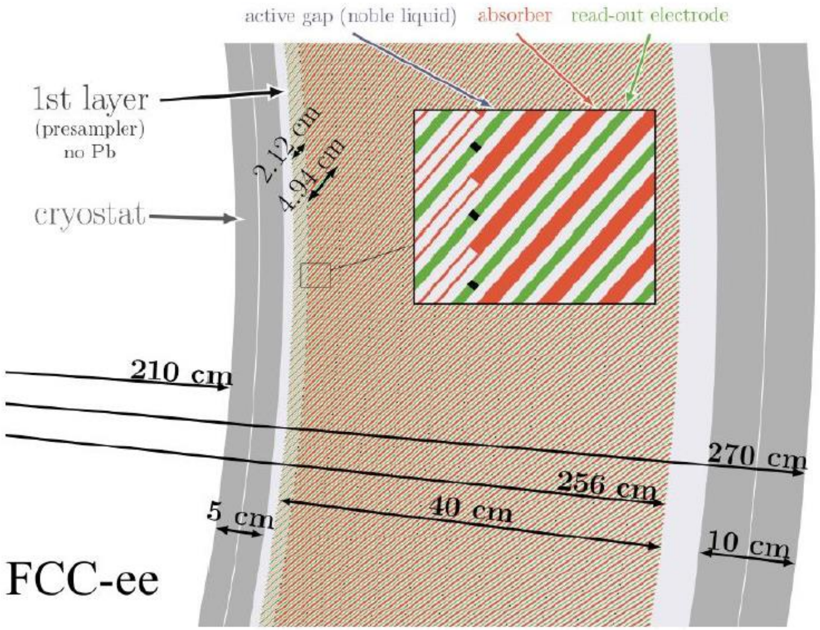
Conveners DRD6.2: N. Morange (IJCLab), M. Aleksa (CERN), M-A. Pleier (BNL)

Concept : PCBs droits pour les électrodes

Design driven by readout electrodes

Baseline (conservative) FCCee ECAL barrel design

- 1536 **straight inclined** (50°) 1.8mm **Pb** absorber plates
- Multi-layer PCBs as readout electrodes
- 1.2 – 2.4mm **LAr** gaps
- 40cm deep (22 X_0)
- $\Delta\theta$ = 10 (2.5) mrad for regular (strip) cells, $\Delta\phi$ = 8 mrad,
  12 longitudinal layers
- **Solid aluminum** cryostat
- Implemented in FCC Fullsim

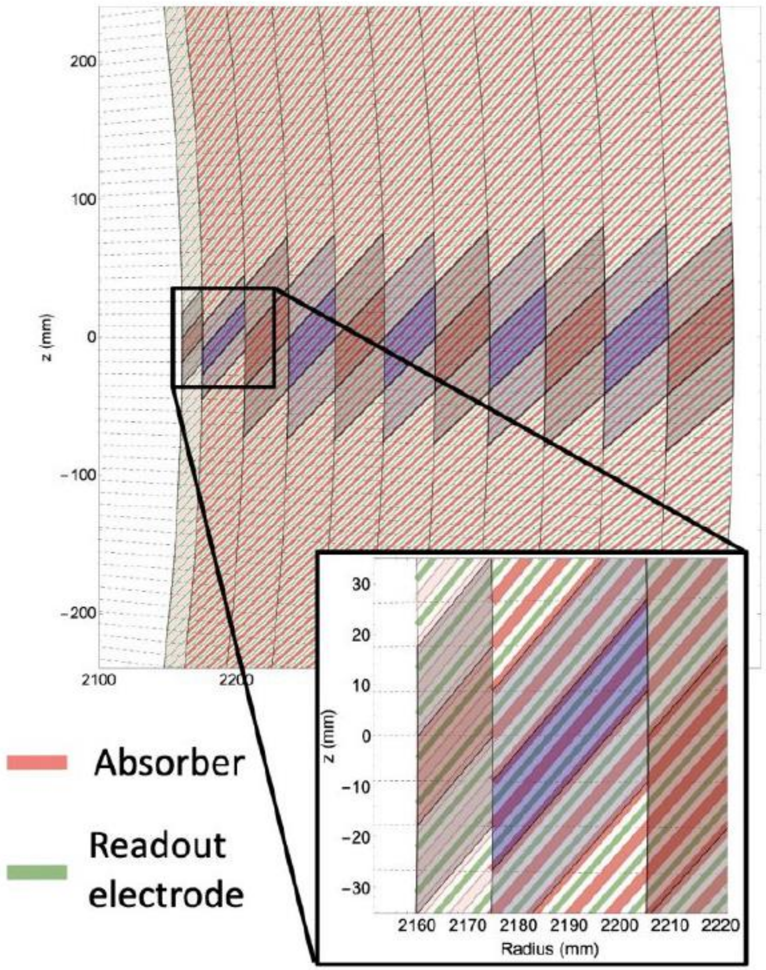


Lots of room for optimization and improvements

- Haute granularité (latérale & longitudinale) : # cellules au moins 10 x ATLAS
- PCB: Permet de sortir les signaux

Géométrie & Segmentation

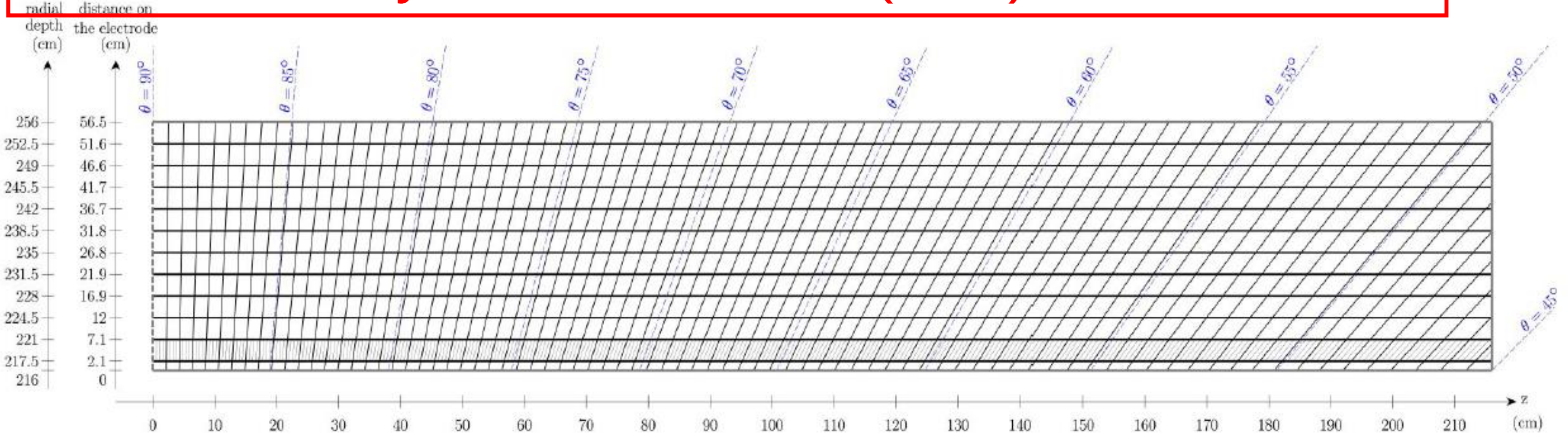
Transverse

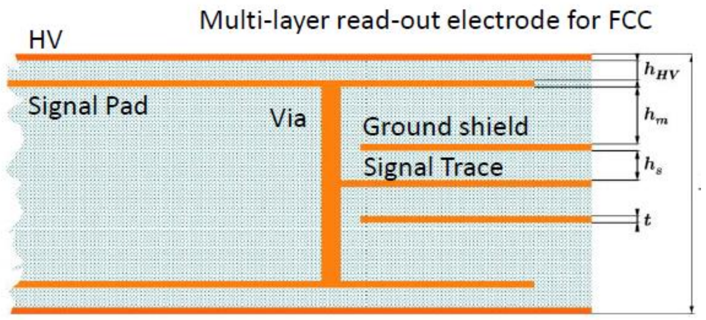


Longitudinal

- Exemple : 12 segments en profondeur (ATLAS 3)

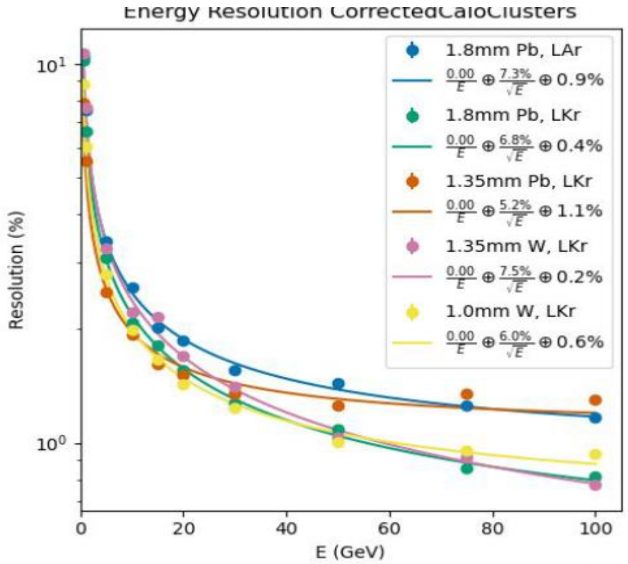
-> Pour Analyse Particle Flow (PFA)





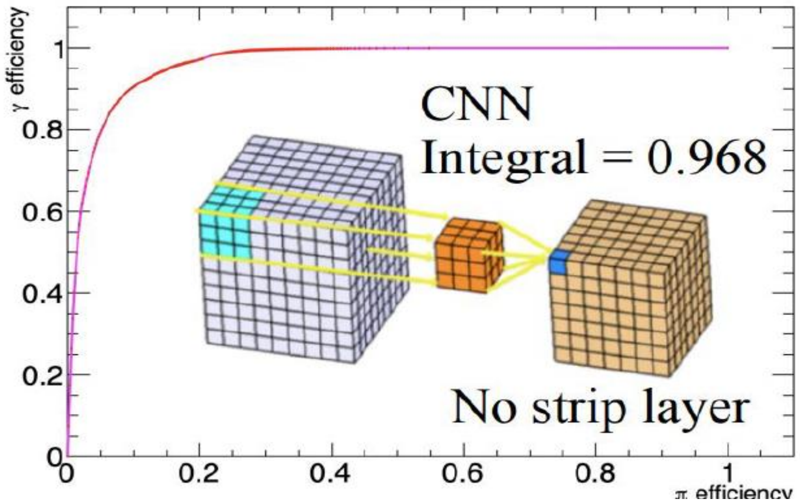
Performances

Résolution en énergie (e, γ)
- 7-8% $E^{-1/2}$ LAr
- 5% $E^{-1/2}$ LKr

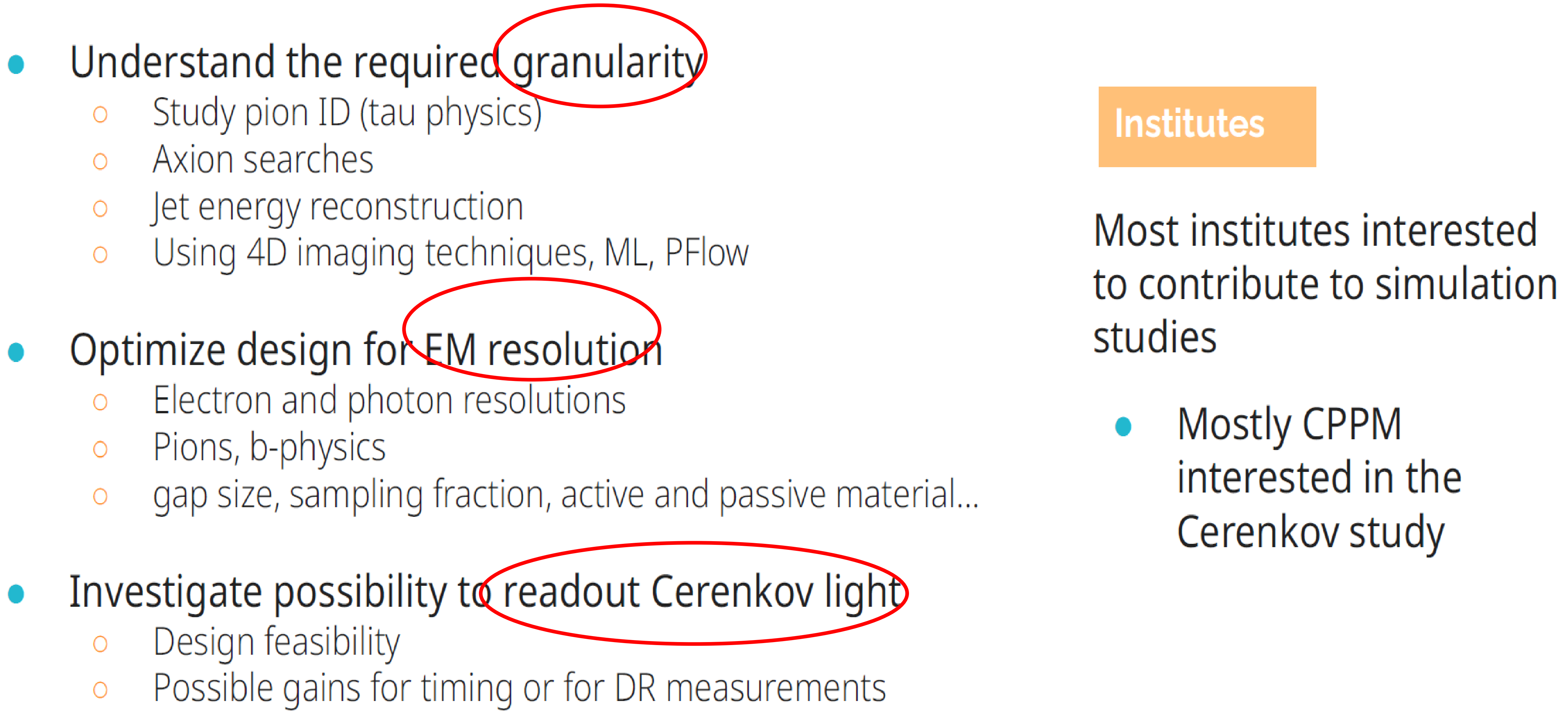


- Full simulation integrated in FCC software chain is a big asset
- First EM physics studies performed in 2022
  - Many more can be performed
  - Can guide LAr/LKr, granularity...
- Next major step will be addition of some HCAL in simulation, along with PFlow algorithms
  - Then can look at all physics performance metrics
- Performance in endcaps also has never been looked at
- Many opportunities for software development
  - Clever ML techniques for clustering / PID ?

En cours



Axes d’étude performances



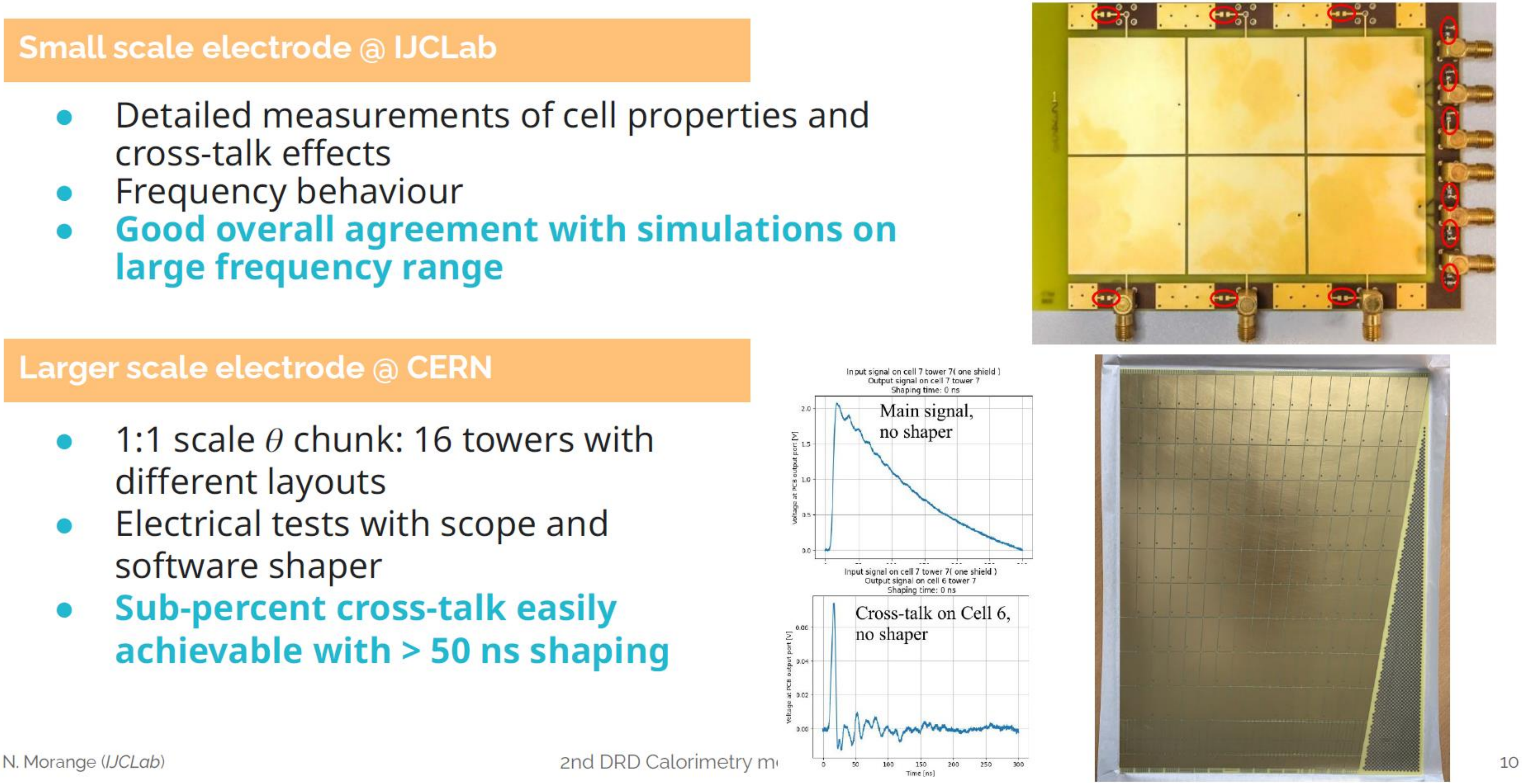
- Understand the required granularity
    - Study pion ID (tau physics)
    - Axion searches
    - Jet energy reconstruction
    - Using 4D imaging techniques, ML, PFlow
- Optimize design for EM resolution
    - Electron and photon resolutions
    - Pions, b-physics
    - gap size, sampling fraction, active and passive material…
- Investigate possibility to readout Cerenkov light
    - Design feasibility
    - Possible gains for timing or for DR measurements

Institutes

Most institutes interested to contribute to simulation studies

- Mostly CPPM interested in the Cerenkov study

Prototypes électrodes : Statut



Small scale electrode @ IJCLab

- Detailed measurements of cell properties and cross-talk effects
- Frequency behaviour
- **Good overall agreement with simulations on large frequency range**

Larger scale electrode @ CERN

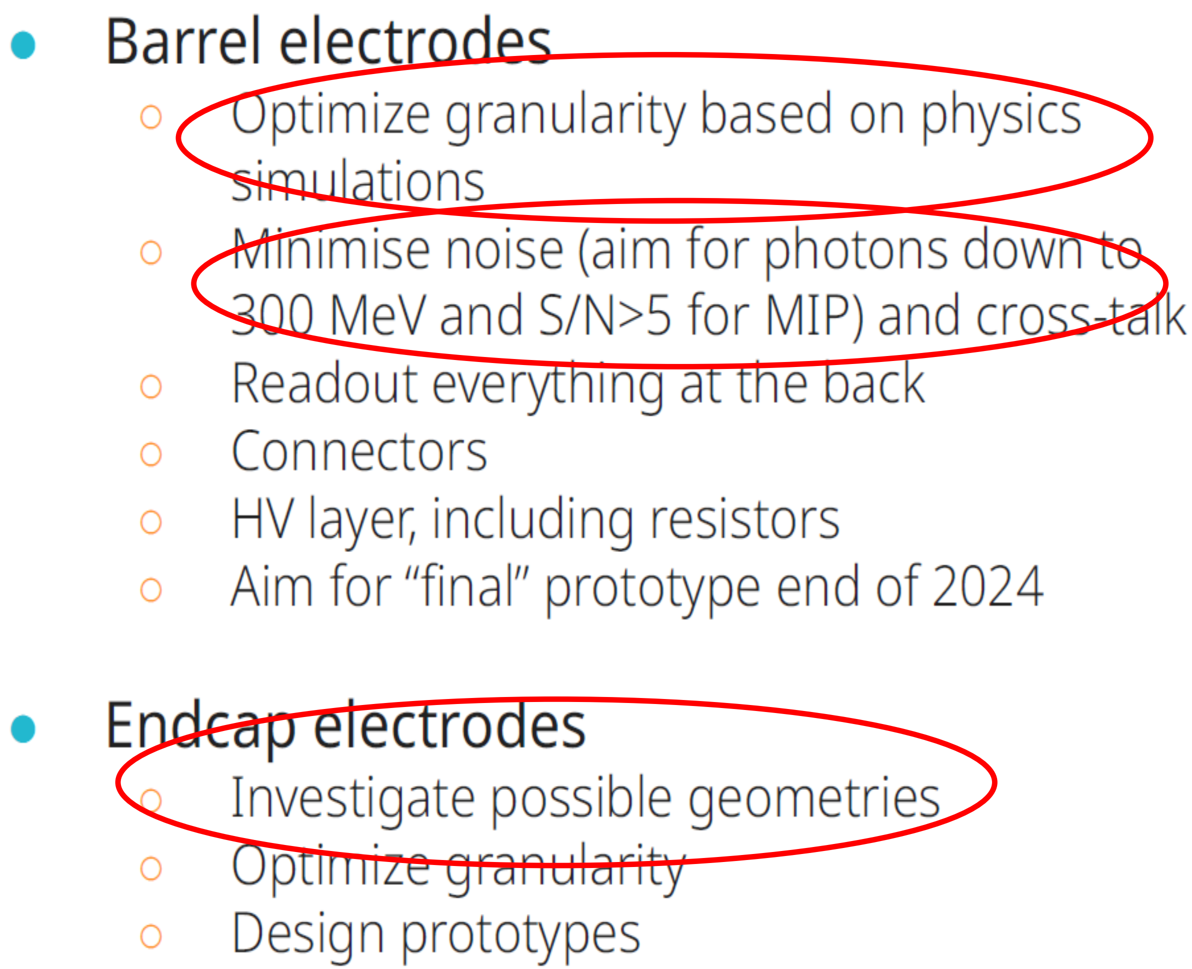
- 1:1 scale θ chunk: 16 towers with different layouts
- Electrical tests with scope and software shaper
- **Sub-percent cross-talk easily achievable with > 50 ns shaping**

N. Morange (*IJCLab*)

2nd DRD Calorimetry m

10

Electrodes : Plan de travail



- Barrel electrodes
  - Optimize granularity based on physics simulations
  - Minimise noise (aim for photons down to 300 MeV and S/N>5 for MIP) and cross-talk
  - Readout everything at the back
  - Connectors
  - HV layer, including resistors
  - Aim for “final” prototype end of 2024
- Endcap electrodes
  - Investigate possible geometries
  - Optimize granularity
  - Design prototypes

Institutes

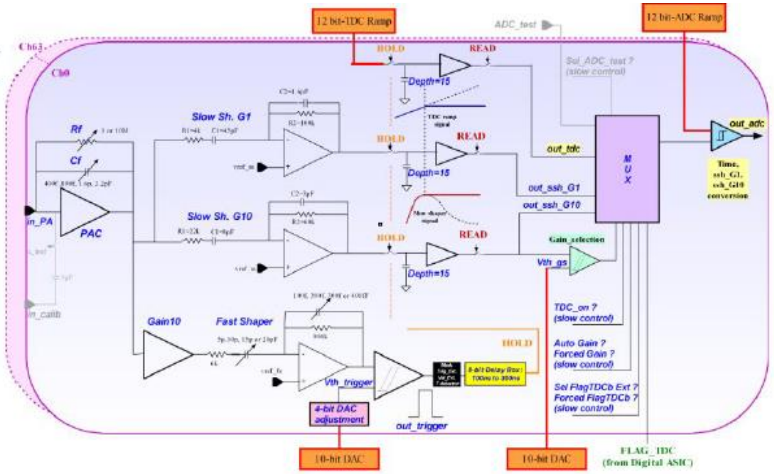
- Barrel: CERN, IJCLab
- Endcaps: Arizona
- Also: BNL, Stony Brook

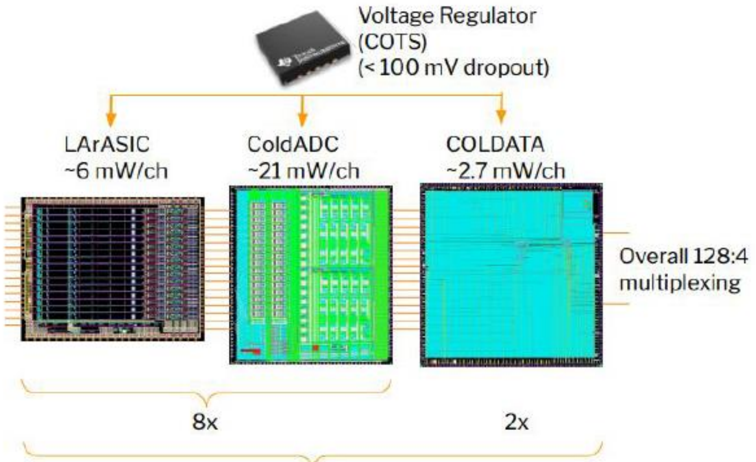
Electronique de lecture

- Warm Frontend electronics option
  - Requirements similar to other calos
  - Requires work on cables inside the cryostat
- Cold Frontend electronics option
  - Very appealing option
  - Needs dedicated work
  - How much can we put in the cold ? Preamp, ADC, multiplexer ? Optical conversion ?
  - Power consumption is a huge challenge
- Backend electronics and DAQ
  - Requirements not yet defined

$$N \sim C_d \sqrt{\frac{4kT}{g_m \tau_p}}$$

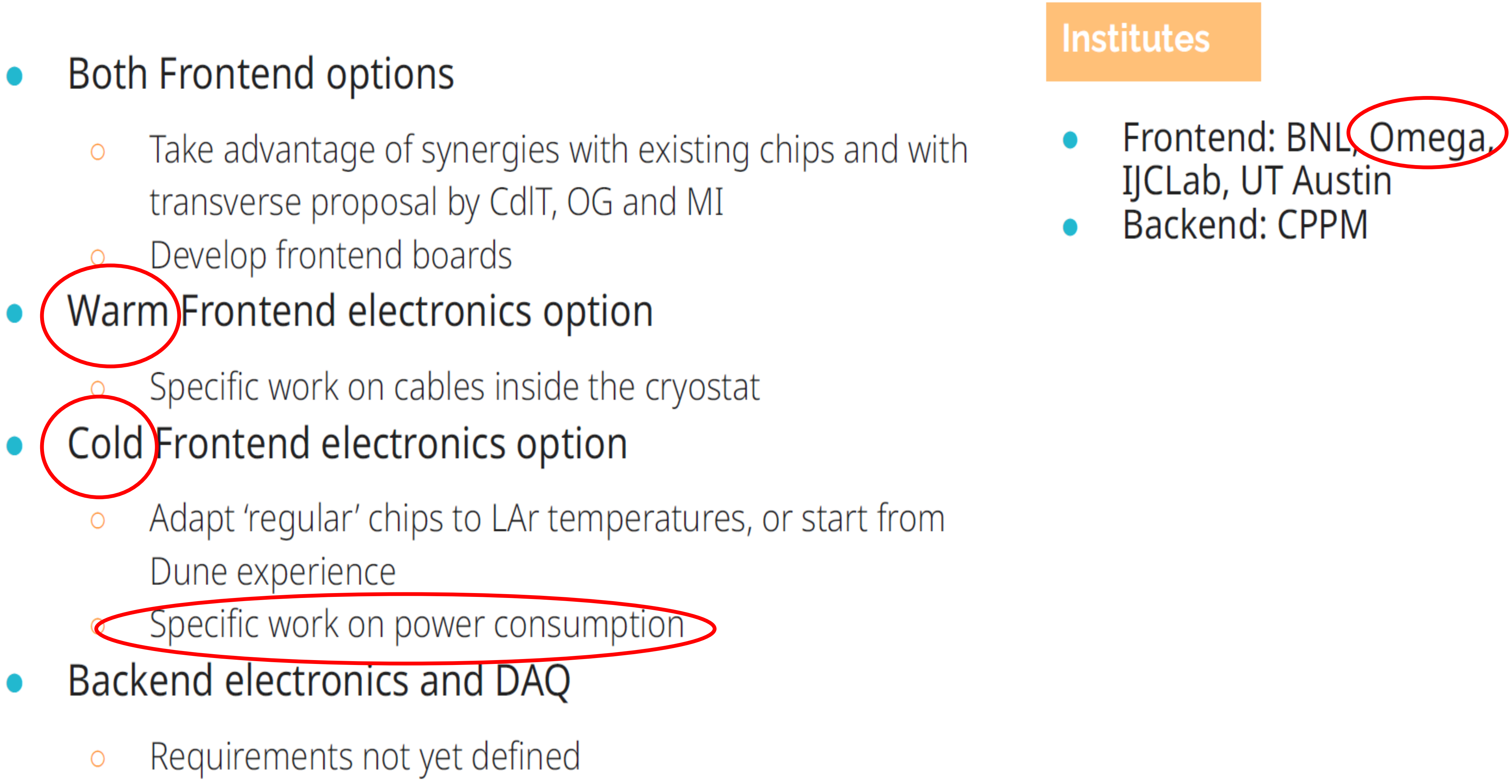
SKIROC





Dune horizontal drift front-end chips

Electronique de lecture : Plan de travail



- Both Frontend options
  - Take advantage of synergies with existing chips and with transverse proposal by CdIT, OG and MI
  - Develop frontend boards
- Warm Frontend electronics option
  - Specific work on cables inside the cryostat
- Cold Frontend electronics option
  - Adapt 'regular' chips to LAr temperatures, or start from Dune experience
  - Specific work on power consumption
- Backend electronics and DAQ
  - Requirements not yet defined

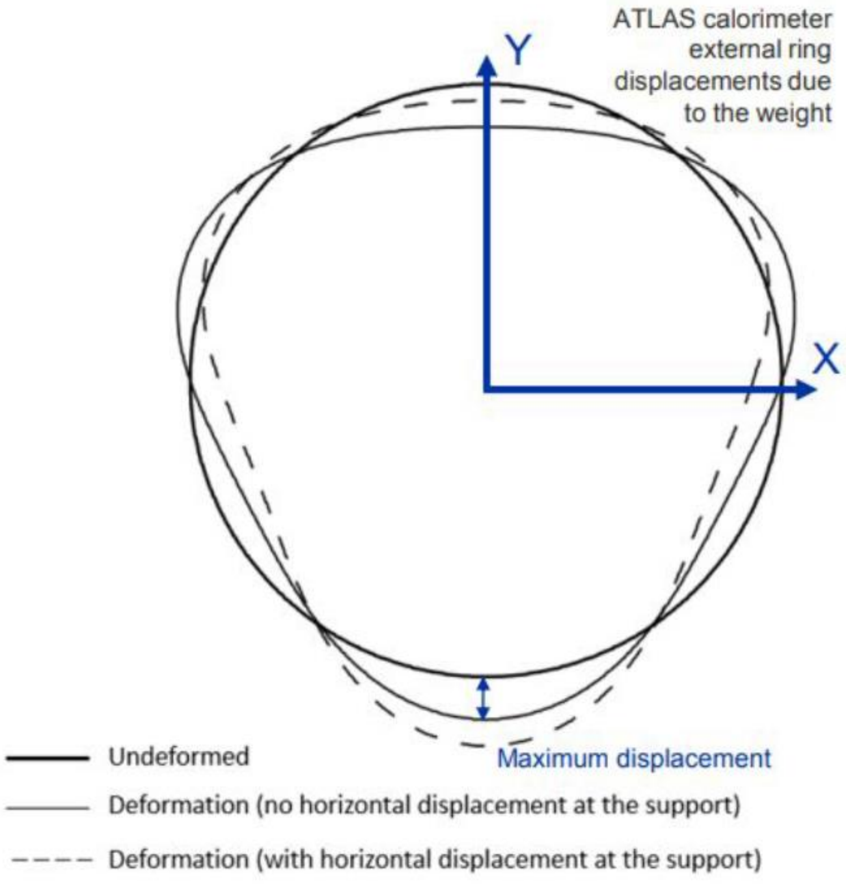
Institutes

- Frontend: BNL, Omega, IJCLab, UT Austin
- Backend: CPPM

Etudes mécaniques

Small systematics require highly uniform and stable calorimeter

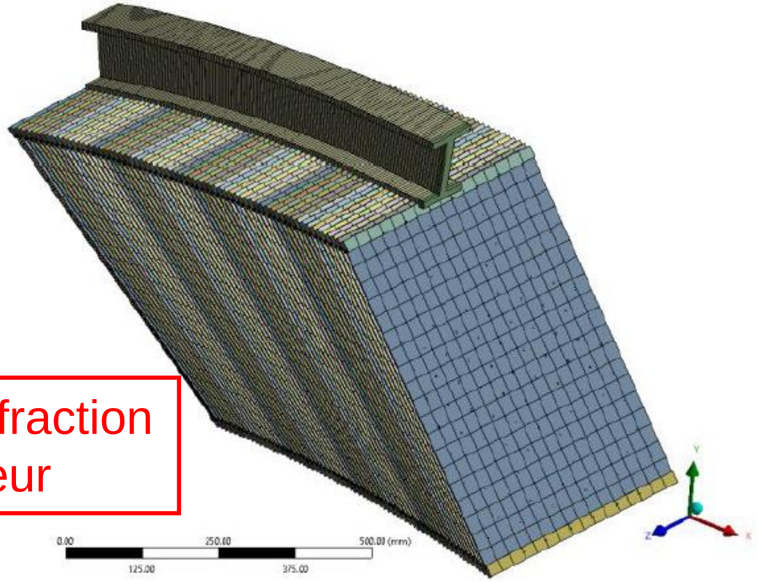
- Studies just starting
  - Identifying what are our requirements and learning from ATLAS
  - First FEM studies
- Overall challenge: make the whole structure rigid enough, while keeping light on support structures
- Lots of room for new ideas

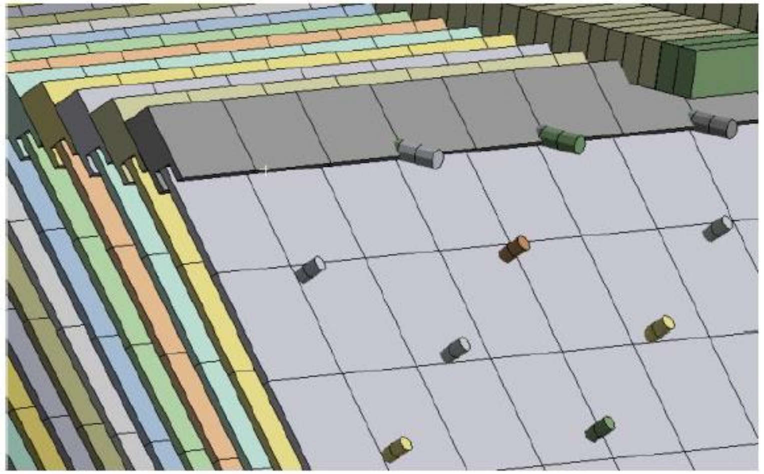


Absorbeurs & Espaceurs

- Basic absorber design directly inspired from ATLAS
  - Can we do better ?
  - Thickness, tolerances…
- Simpler because no accordion bending
- New idea of trapezoidal absorbers
  - Can it be done, with what tolerances ?
  - Need iterations with industry
- ATLAS spacers: honeycomb
  - Including variable size in the endcaps
- Spacers: can we instead 3D-print pillars to be placed regularly ?

Pour garder sampling fraction constante vs profondeur





Résumé

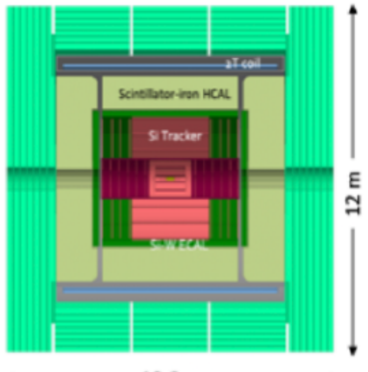
- Avantages liquides nobles
  - Parfaitement adapté à mesures de précision / FCC-ee (faibles systématiques)
  - Gratuit : ~ OK pour FCC-hh
  - Compromis idéal (?) pour granularité, EM résolution énérgie, résolution HAD
  - Expertise existante, eg au Labo (autres groupes français impliqués)
- Timescale
  - Echéances proches (2027-2028)
  - Le moins 'avancé' des projets R&D calorimètre
  - Prototype en faisceau test asap essentiel
    - Assemblage & Test à chaud en 2027
    - Tests à froid & Test beam en 2028
- Contributions possibles intéressantes, gratifiantes et valorisantes
  - Mécanique, Electronique, simulation de physique, software

Backup

Concepts détecteurs

F. Sefkow,
Cracow, 01/2023

CLD

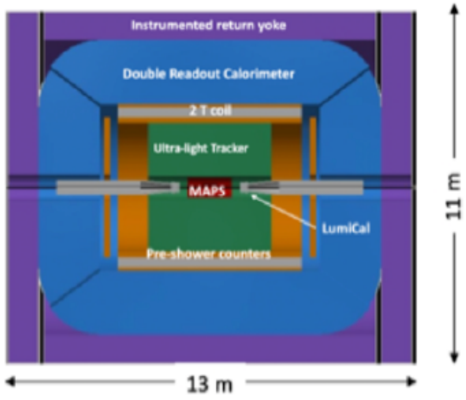


CALICE
inside

CALICE based ECAL

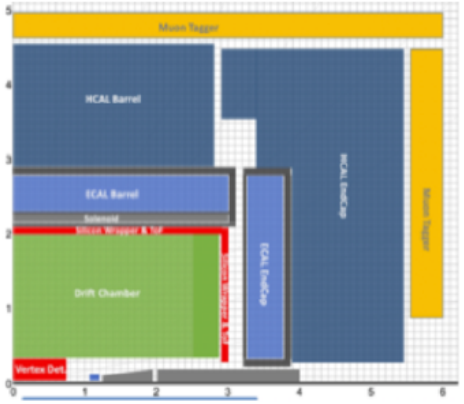
- Well established design
  - ILC -> CLIC detector -> CLD
- Engineering needed to make able to operate with continous beam (no pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations?
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - …
- Robust software stack
  - Now ported (wrapped) to FCCSW

IDEA



- Less established design
  - But still ~15y history: 4th Concept
- Developed by very active community
  - Prototype construction / test beam compains
  - Italy, Korea,…
- Is IDEA really two concepts? Or will it be?
  - w, w/o crystals
- Software under active development
  - Being ported to FCCSW

Noble Liquid ECAL based



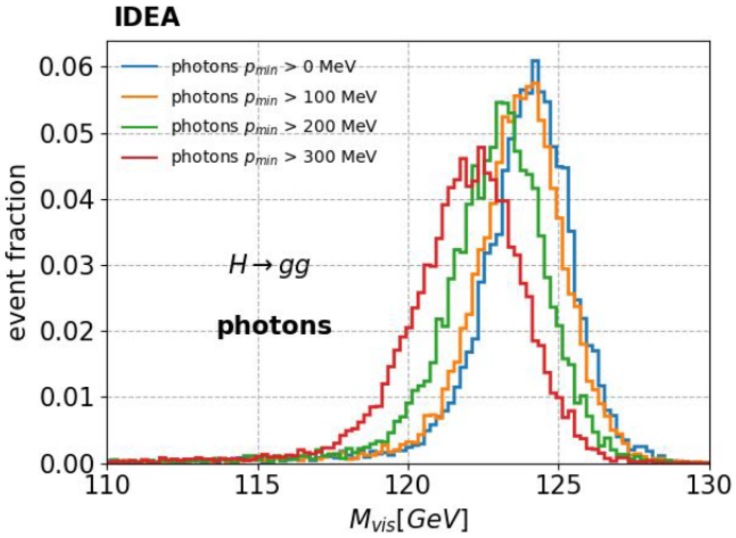
- A design in its infancy
- High granul Noble Liquid ECAL is the core
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies
- Full simulation of ECAL available in FCCSW

Mogens Dam

Detector Concepts | Felix Sefkow | January 2023

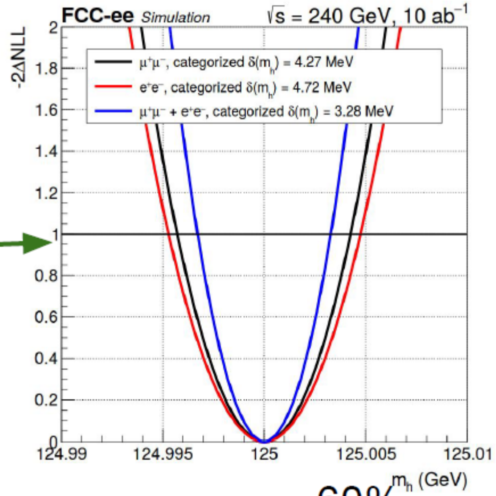
ECAL : electron/photon reconstruction

- many flavor physics benchmarks: $B_s \to D_s$ K, $B_0 \to \pi^0 \pi^0$, $B_s \to K^* \tau \tau$ ..
- put stringent requirements on ECAL performance, both resolution and granularity:
  - soft π^0 ECAL resolution is a must (e.g crystal) AND low X_0 material in front
  - for boosted π^0 granularity required (τ decays)
- High momentum prompt photon $H \to \gamma\gamma$, ALPs
- ECAL granularity resolution needed for efficient brem recovery (and low X_0 tracker)



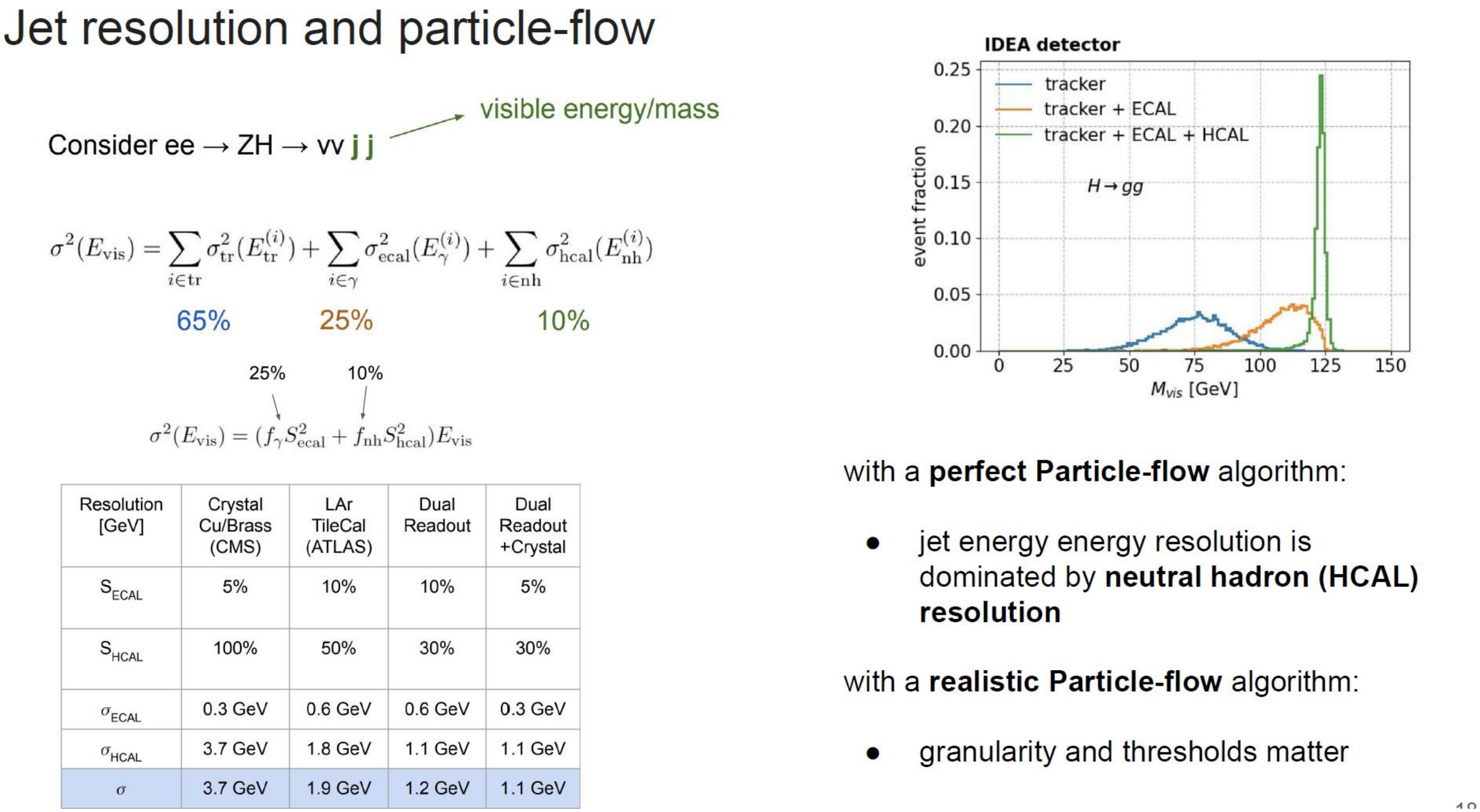
Low energy photons content from π^0
(in particular for $H \to$ gg)

Z(ee) channel improves m_H precision



ECAL granularity and resolution needed for efficient brem recovery → 60% improvement vs standalone tracking

Jet resolution & Particle flow



Jet resolution and particle-flow

Consider ee → ZH → νν **j j** → visible energy/mass

$$\sigma^2(E_{\text{vis}}) = \sum_{i\in\text{tr}} \sigma^2_{\text{tr}}(E^{(i)}_{\text{tr}}) + \sum_{i\in\gamma}\sigma^2_{\text{ecal}}(E^{(i)}_{\gamma}) + \sum_{i\in\text{nh}}\sigma^2_{\text{hcal}}(E^{(i)}_{\text{nh}})$$

65% 25% 10%

$$\sigma^2(E_{\text{vis}}) = (\overset{25\%}{f_{\gamma}} S^2_{\text{ecal}} + \overset{10\%}{f_{\text{nh}}} S^2_{\text{hcal}}) E_{\text{vis}}$$

Resolution [GeV]	Crystal Cu/Brass (CMS)	LAr TileCal (ATLAS)	Dual Readout	Dual Readout +Crystal
S_{ECAL}	5%	10%	10%	5%
S_{HCAL}	100%	50%	30%	30%
σ_{ECAL}	0.3 GeV	0.6 GeV	0.6 GeV	0.3 GeV
σ_{HCAL}	3.7 GeV	1.8 GeV	1.1 GeV	1.1 GeV
σ	3.7 GeV	1.9 GeV	1.2 GeV	1.1 GeV

with a **perfect Particle-flow** algorithm:

- jet energy energy resolution is dominated by **neutral hadron (HCAL) resolution**

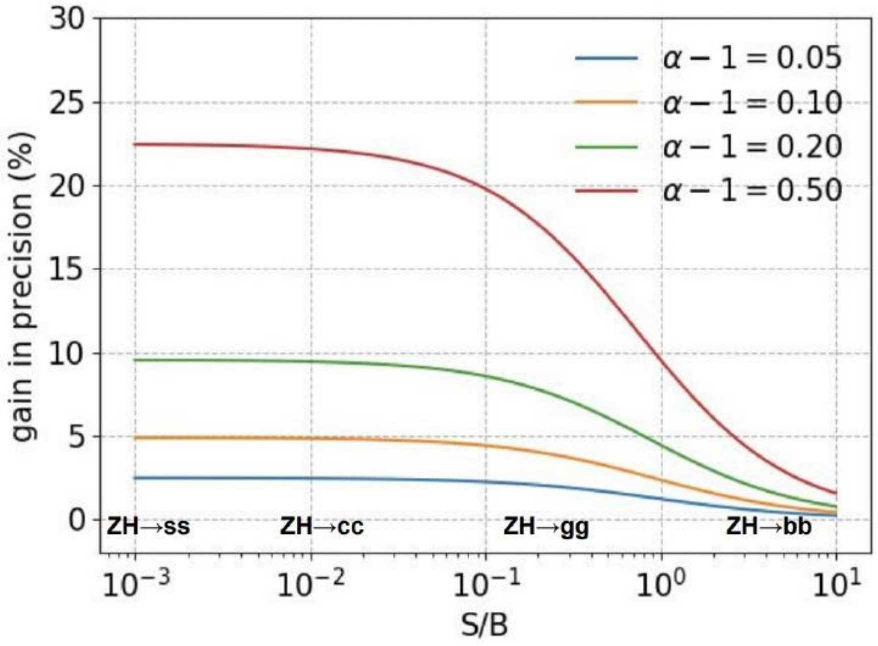
with a **realistic Particle-flow** algorithm:

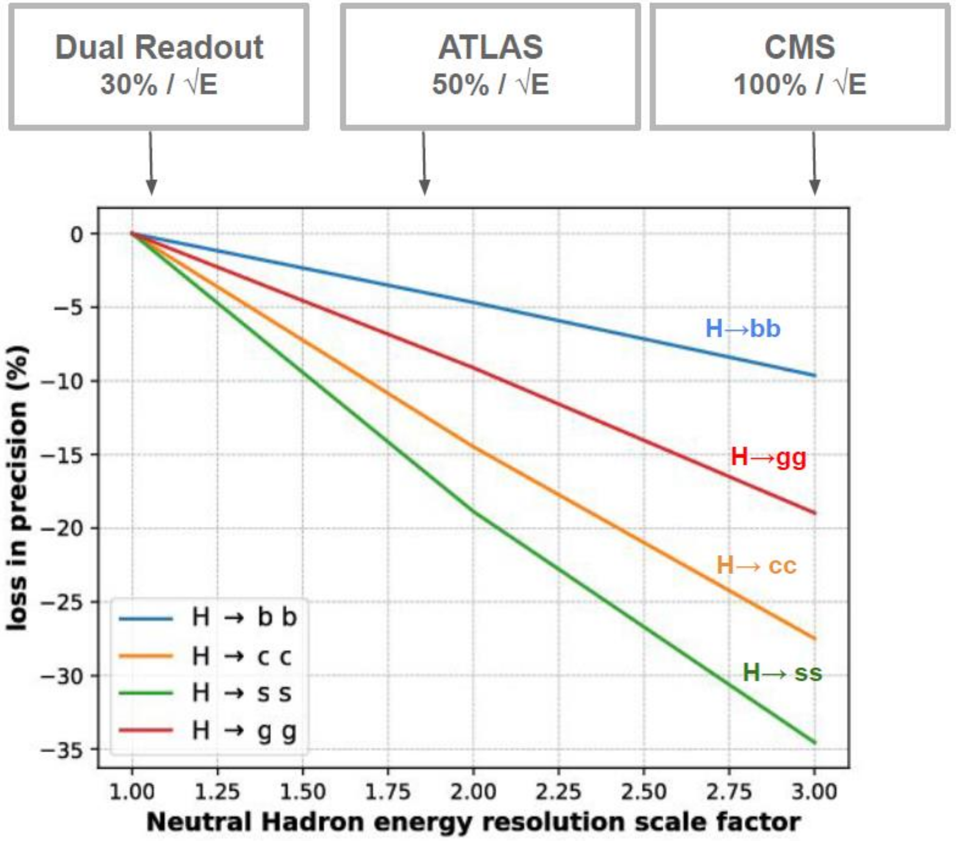
- granularity and thresholds matter

HCAL and jets: Higgs hadronic final states

Largest gain from JER expected for S/B << 1:

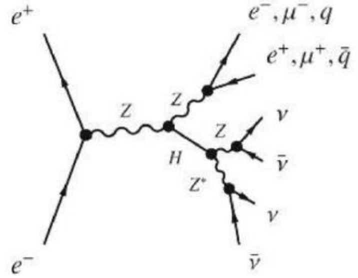
If relative improvement **α**, expect √**α** increase in precision





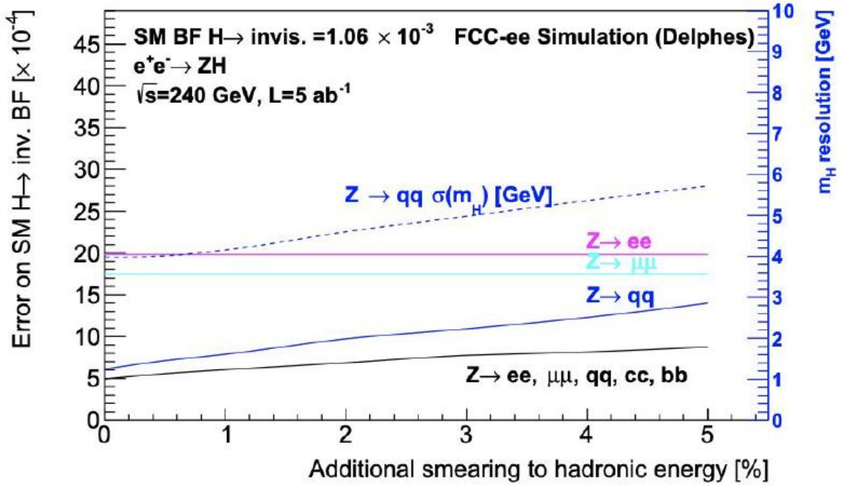
Observe less degradation than expected, studies will have to be repeated with full simulation

HCAL and Jets

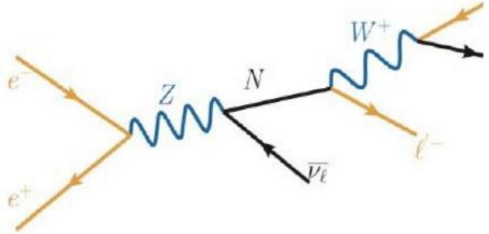


see L. Portales (wed.)

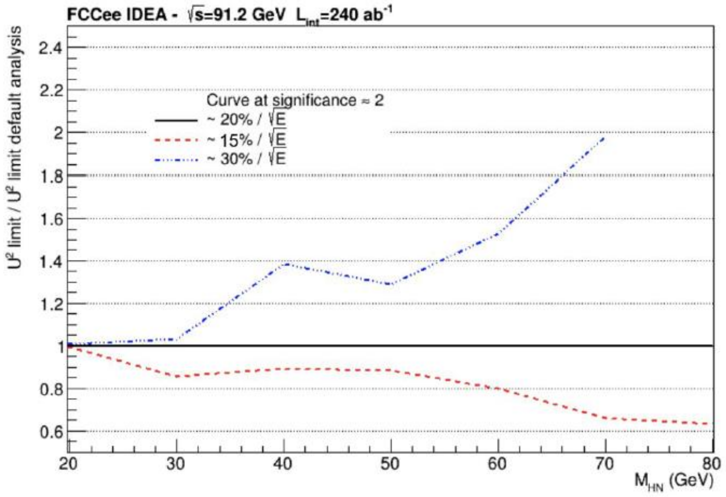
H→ invisible



sizable impact of JER on Z→qq channel
offset by Z→ll channel at large smearings



HNLs → μqq prompt final state
reconstruct visible mass



sizable impact of JER

see S. Williams, N. Valle (wed.)

Besoins transverses : Software

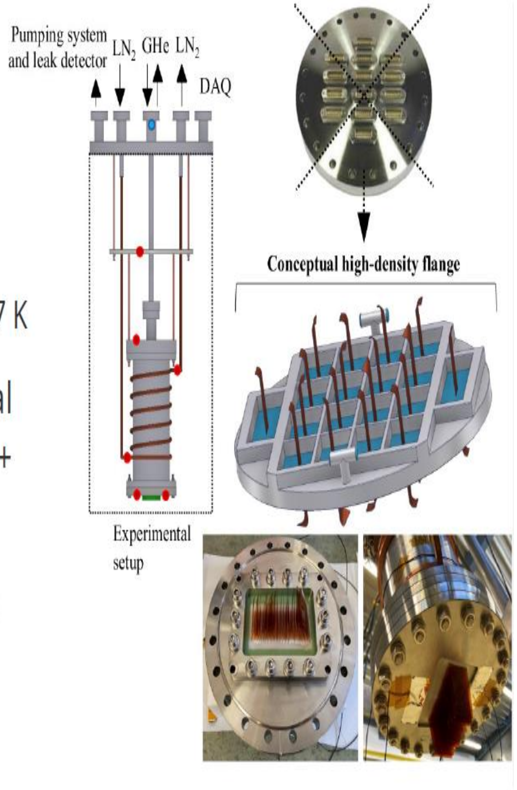
- Materials
- Photodetectors, Electronics and DAQ
- Testbeam Facilities
- Detector Physics, simulation, algorithm and software tools
- Industrial Connections and technological transfer

- Particle Flow Algorithms:
  - mentioned in 17/23 proposals (also in non-native PF-calorimeters)
  - High-granularity ⇔ PFA
- Geant4 Simulation:
  - needed to optimise detector design and interpret data
- Machine (Deep) Learning
  - widely used to reconstruct complicated final states
  - thoughts to have on-board intelligence in FE elx
  - used to optimize detectors?
- Common test beam software?
  - what about a “plug-n-play” SW for data acquisition? Eudaq?

Cryostats & Feedthroughs

Feedthrus

- Factor of 10-15 more channels wrt ATLAS (ECAL barrel with ~2 M channels)
- Innovative connector-less feedthroughs
  - High density flange
  - Higher area dedicated to signal extraction
  - 20 000 wires per feedthrough
  - Leak and pressure (3.5 bar) tests at 300 and 77 K
- Identified a solution surviving several thermal cycles (G10 structure with slits + indium seal + Epo-Tek glued Kapton strip cables)
- To be done: design and test a full flange (not covered)



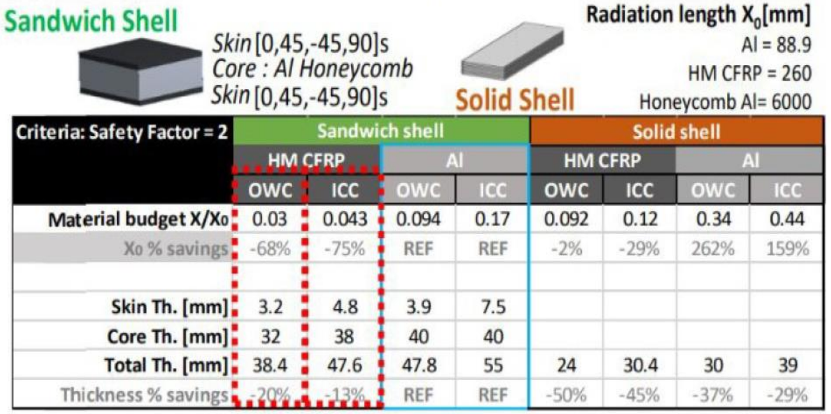
Cryostat

- Carbon fiber materials for low material cryostat
  - Sandwich of Carbon Fibre Reinforced Polymer (CFRP) shell and Al honeycomb

    → Very low X_0 (10% compared to Al solid)
- Ongoing R&D at CERN
  - CFRP / metal interfaces, sealing methods

NASA cryotank

Sealing with Belleville washers



Sandwich Shell

Skin [0,45,-45,90]s
Core : Al Honeycomb
Skin [0,45,-45,90]s

Solid Shell

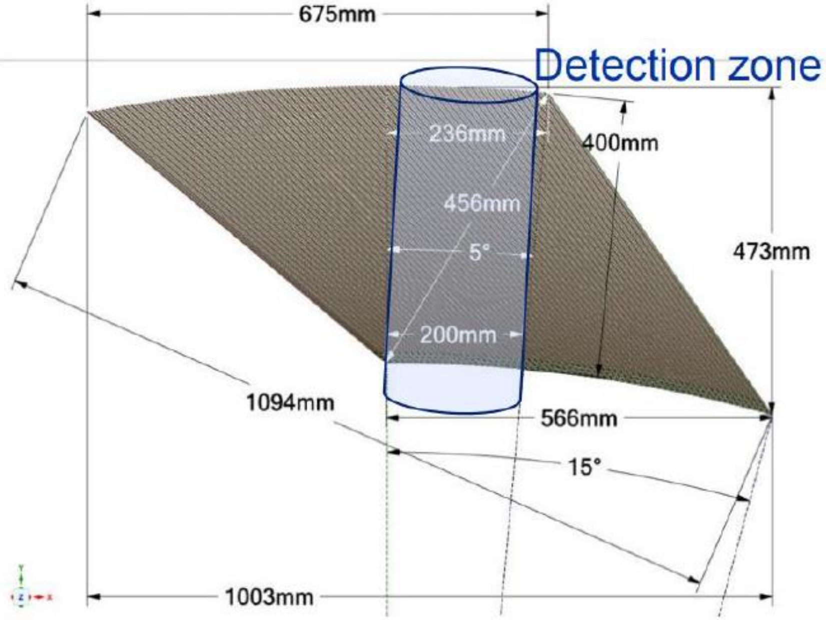
Radiation length X_0[mm]
Al = 88.9
HM CFRP = 260
Honeycomb Al= 6000

Criteria: Safety Factor = 2	Sandwich shell				Solid shell			
	HM CFRP		Al		HM CFRP		Al	
	OWC	ICC	OWC	ICC	OWC	ICC	OWC	ICC
Material budget X/Xo	0.03	0.043	0.094	0.17	0.092	0.12	0.34	0.44
Xo % savings	-68%	-75%	REF	REF	-2%	-29%	262%	159%
Skin Th. [mm]	3.2	4.8	3.9	7.5				
Core Th. [mm]	32	38	40	40				
Total Th. [mm]	38.4	47.6	47.8	55	24	30.4	30	39
Thickness % savings	-20%	-13%	REF	REF	-50%	-45%	-37%	-29%

Vers un prototype

Workplan

- Absorbers
  - Find best compromise in feasibility, between thickness, rigidity, support structures
  - Prototypes in 2024 and 2025
- Small module
  - Requires to put everything together
  - Design in 2024 and 2025
  - Assemble and test at warm temperatures in 2027
  - Cold tests and testbeam in 2028
- Infrastructure
  - Use of common tools (EUDAQ...) would facilitate the integration in a testbeam facility
  - Strong testbeam expertise from some institutes



Institutes

- Absorbers: CERN
- Most institutes interested to contribute to testbeam
- Contributions in construction not yet discussed

Attention: No SPS operation in 2026 & 2027 No PS operation between 2026 & mid-2027