TF1 Gaseous Detectors

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Silvia Della Torre

TF1 Gaseous Detectors Symposium

April 29th

https://indico.cern.ch/event/999799/

ECFA Detector R&D Roadmap TF1 Gaseous Detectors Symposium

Technologies: overview, limitations and perspectives.

- MPGD: GEM, Micromegas, THGEM, uRWELL, and other ongoing developments
- RPC, MRPC, and other ongoing developments,
- Drift chambers, straw tubes, TGC, CSC, and other wire chambers
- PID: TPC, TRD, RICH and other large area detectors

Future applications.

- Tracking and muon detection at future colliders
- TPCs at future lepton and lepton-hadron colliders (TPCs, drift chambers, large volume gaseous detectors)
- Nuclear physics applications (tracking, extremely low mass detectors, photon detection, TRD, neutron detection)
- Recoils imaging for DM, neutrino, and BSM physics applications (TPCs variations, optical readout)
- Semi-digital calorimetry (RPC, MPGD) at future colliders

Challenges and new developments.

- Detector stability (ageing, discharge issues) and rate capability: resistive electrodes
- Novel readout electrodes, optical readout, hybrids with ASICS
- Precise timing detectors
- IBF, photocathode stability and alternatives (including solid converters and nanotech)
- Precision manufacturing techniques (electrical and mechanical properties of detector components), additive manufacturing and new materials (low mass, radio-purity)
- Eco gas mixtures and mitigations procedures for GHG gas (recirculation, recuperation etc.)

Development tools and R&D environment.

- Electronics (front-end and DAQ) for gaseous detectors R&D
- Software tools for detector physics simulations
- Infrastructures – development, testing and production facilities
- Relations with industry
- Networking – collaborations, technology dissemination and training

Applications beyond fundamental research.

TF1 strategy and concerns

- Start from current technologies and their limitations, future perspectives
- Future applications (but with no focus on the experiments)
- Focus on generic R&D and the challenges: pushing current technologies to the limits and developing new techniques
- Focus on common infrastructure, tools and test facilities, relation with industries, networking for supporting detector R&D
- Applications beyond fundamental research

The panel is pushing more on the experiment-oriented R&D

- Promoting project-oriented R&D induces to focus on particular applications and paradoxically leads to restriction of possible fields of applications and size of developer/user community

ECFA R&D Input sessions➔ more focus on the projects and existing technologies.

- Many R&D were not presented (for example no-R&D presented in the future astro-particle neutrino experiments talk)

We aim to cover as many R&D as possible **(Matrix in preparation see backup)**
We invite you to contact us and the speakers of the symposium

TF1 questionnaire

TF1-gaseous detectors Questionnaire

Questions on national strengths (equal to all TFs):

1) Areas of particular national strength or of minimal **significant activity** within the topics covered by the Task Force 1 Gaseous Detectors

2) Current national **plans for strategic investment** relevant to this Task Force area

3) Significant **opportunities for seeking future resources**, particularly (though not only) through European schemes (also in synergy with other science areas) that should be considered when highlighting R&D priorities

Specific questions related to TF1 topics:

Please let us know:

1) If there are **topics not covered** in the proposed TF1 Symposium agenda
2) For a given topic in the agenda the **R&Ds you think are particularly relevant** for your community and for which future application
3) Any **suggestions to facilitate** detector R&D on the international level

Overlapping topics between TFs

- Gaseous detector as Active layer in sampling calorimeter (TF1 and TF6)

- **overlap with TF4 ➔ Keep technology issue in TF1**
  - Photon detectors, TPC, RICH in TF1 and TF4
  - dE/dx for PID - covered in TF1 and TF4
  - TRD for PID - covered in TF1 and TF4
  - RPC technologies used for ToF -> covered in TF1

- Additive manufacturing and new materials in TF1 and TF5

- Picosecond ASICs and fast discrimination -- interface area with electronics TF7

BACKUP

Notes about TF1 matrix and the input sessions:

https://indico.cern.ch/event/994685/

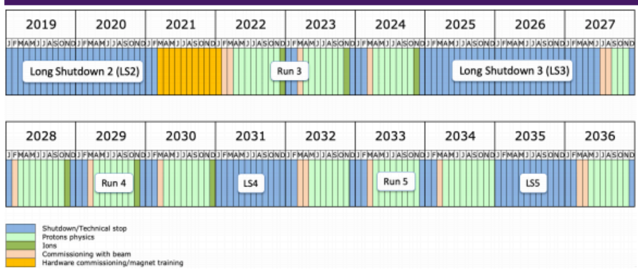
https://indico.cern.ch/event/994687/

Gaseous detectors at HL-LHC

Main Upgrade CMS/ATLAS in LS2/LS3, eco-gas studies on-going

HL-LHC Timelines

https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm



- HL-LHC will run from 2025-~ 2040
- Current schedule has shutdowns in 2031 (LS4) & 2035 (LS5)
  - In addition to end of year stops
- Detector construction typically 5+ years before shutdown for installation
  - R&D for LS4 (LS5) projects over next five (ten) years

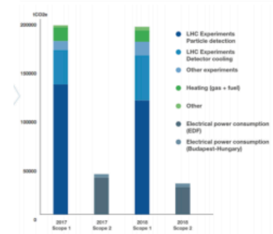
TF1: Gaseous Detectors (& Large Scale Tracking)

CMS: RPC, ATLAS: RPC/NSW, LHCb: RICH, μ-RWELL

- New gas mixture with lower environment impact
- Recuperation systems
- Detectors
  - RPCs, GEMs, MWPCs…
  - RICH Radiators: C_4F_{10}
- Cooling Systems
  - Move to NOVEC, CO_2

https://e-publishing.cern.ch/index.php/CERN_Environment_Report/index

GROUP	GASES	tCO_2e 2017	tCO_2e 2018
PFC	CF_4, C_2F_6, C_3F_8, C_4F_{10}, C_6F_{14}	61 984	69 611
HFC	CHF_3 (HFC-23), $C_2H_2F_4$ (HFC-134a), HFC-404a, HFC-407c, HFC-410a, HFC R-422D, HFC-507	106 812	96 624
	SF_6	10 192	13 087
	CO_2	14 612	12 778
TOTAL SCOPE 1		193 600	192 100



Source: CERN Environment Report 2017-18

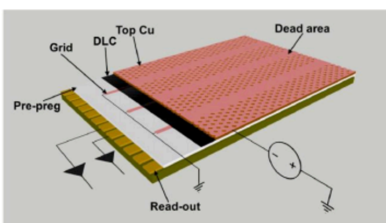
Main Upgrade LHCB in LS4 (LS5)

TF1: Gaseous Detectors (& Large Scale Tracking)

LHCb Upgrade II : Muon system

- Requirements

-Rates up to several MHz/cm^2 in the inner regions
-Efficiency > 95% within 25 ns
-Stability up to 6 C/cm^2 accumulated charge in 10 years of operation



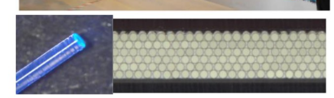
- R&D on μ-RWELL

-Single-amplification stage, spark-protected resistive MPGD based on a breakthrough technology suitable for large area planar tracking devices
-The detector is being characterized: gas gain ~ 10^4, rate capability ~10 MHz/cm^2, efficiency ~97%
- A design for the high rate has been found which is suitable for a simple industrialisation process

TF1: Gaseous Detectors (& Large Scale Tracking)

LHCb Upgrade II : Tracking System

- Requirements:
  - large scale, low cost: 30m^2 per layer, 12 layers
  - 70μm resolution in bending plane
- R&D:
- **Scintillating Fibre tracker**.
  - Radiation hard NOL fibres. > 35kGy
  - Cryogenic operation SiPMs.
  - SiPMs reduce active area, micro-lenses.
  - Time resolution to provide y-segmentation ?
- **Gaseous Solutions ?** No R&D currently



Gaseous detectors at HL-LHC

– R&D for LS4 (LS5) projects over next five (ten) years

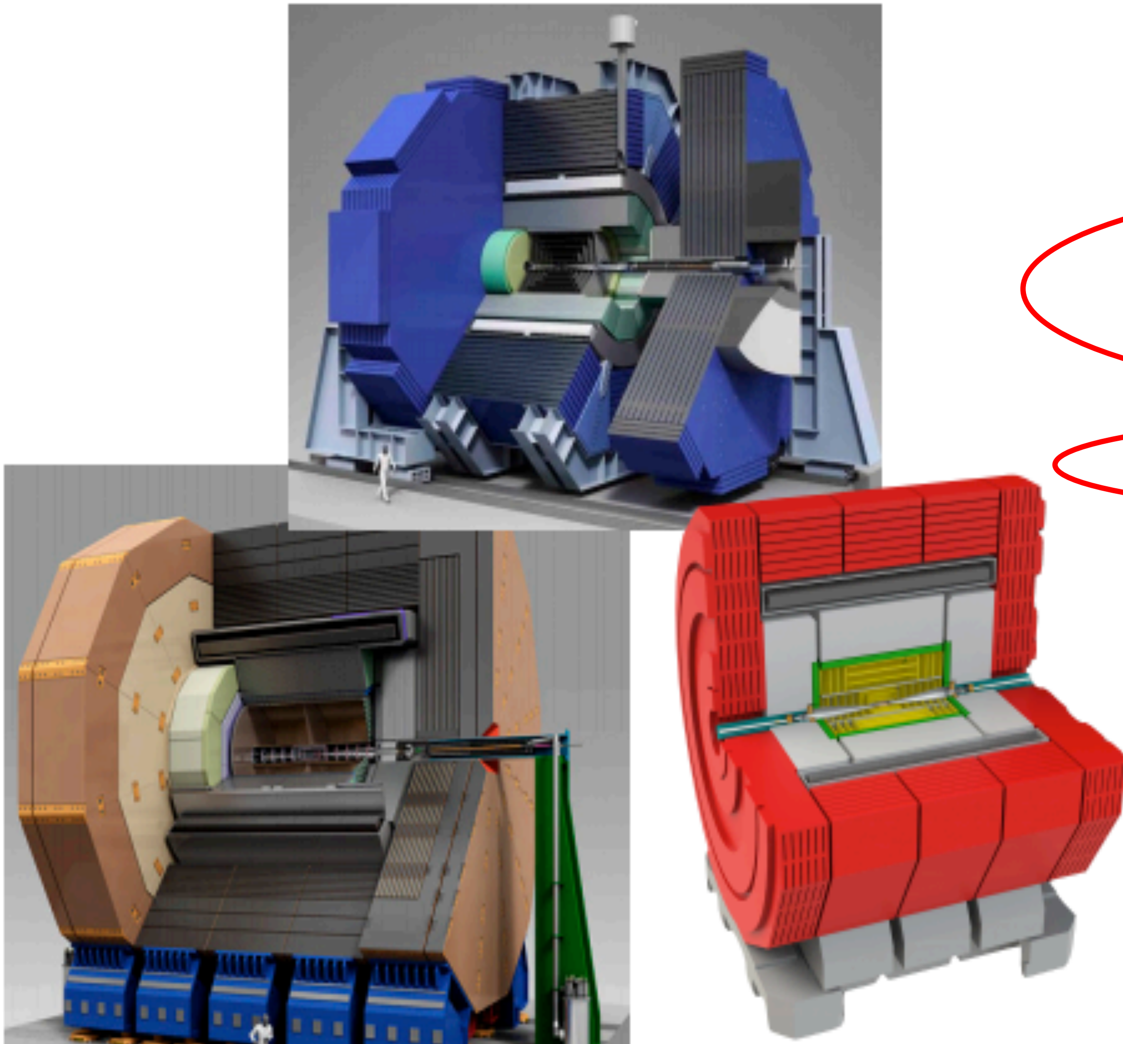
Application - Detector component	**Technology**	**Challanges**	**From the input sessions**
Inner tracker/PID	MRPC, multi-GEM, RICH	high spatial resolution, high rate/occupancy, fast/precise timing, radiation hardness, low mass	**LHCb:** option MPGD (instead of Scintillating Fibre tracker): requirements large area, low cost, high spatial resolution (70 um bending plane). RICH Radiators (C4F10): new eco-gas search
Muon trigger and tracking	Multi-GEM, resistive-GEM, Micromegas, micro-pixel Micromegas, RPC, RWELL, TSG, Drift chambers	stability, ageing, large area, low cost, space resolution, eco gases, spark-free	-Rates up to several MHz/cm2 in the inner regions -Efficiency > 95% within 25 ns -Stability up to 10 C/cm2 accumulated charge in 10 years of operation" **LHCb**: uRwell **Existing chambers remain** **Atlas**: RPC, Drift tubes, Micromegas, TRD, TSG ; **CMS:** RPC, Drift tubes, Triple-GEM, CSC. New gas mixture with lower environment impact

EW-Higgs-Top Factories (ee) linear colliders

The Linear Collider Detector Design - Main Features

Focusing on general aspects

MAX-PLANCK-INSTITUT FÜR PHYSIK



- A **large-volume solenoid** 3.5 - 5 T, enclosing calorimeters and tracking
- **Highly granular calorimeter systems**, optimised for particle flow reconstruction, best jet energy resolution *[Si, Scint + SiPMs, RPCs]*
- **Low-mass main tracker**, for excellent momentum resolution at high energies *[Si, TPC + Si]*
- **Forward calorimeters,** for low-angle electron measurements, luminosity *[Si, GaAs]*
- **Vertex detector**, lowest possible mass, smallest possible radius *[MAPS, thinned hybrid detectors]*
- **Triggerless readout** of main detector systems

EW-Higgs-Top Factories (ee) linear colliders

Application - Detector component	Technology	Challanges	From the input sessions
Inner tracker/PID	multi-GEM, Micromegas, GEM + pixel readout , InGrid (integrated Micromegas grid with pixel readout), Drift Chamber, RICH	high spatial resolution, high rate/occupancy, fast/precise timing, radiation hardness, low mass, 4D tracking, Drift Chamber transparency, cluster counting	**Significant beam-induced backgrounds:** In-time pile-up of hadronic background: granularity for topological rejection **CLIC (more challenging wr.t ILC):** - small Δtbunch (0.5 ns) results in out-of-time pile-up: **ns-level timing in many detector systems** - radiation environment and the particle density at Linear Colliders is benign compared to HL-LHC **- particle ID systems - improved flavour tagging with better π/K separation via TOF or other means** **TPCs**: Central challenge to reach high resolution in a robust way: controlling ExB effects, field distortions,eliminating ion backflow while keeping transparency. • Light materials, low-power readout to reduce required material for cooling: Advances in all "large-volume" technologies (**TPCs, Drift Chambers, RICH counters**) highly beneficial.

EW-Higgs-Top Factories (ee) linear colliders

Application - Detector component	Technology	Challanges	From the input sessions
pre-shower/EM CALO	GEM, THGEM RWELL, Micromega		
HADRON CALO	GEM, THGEM RWELL, Micromegas, MRPC	high granularity, radiation hardness, large volume, excellent hit timing	**(semi-) Digital hadron calorimetry** • Primary technology RPCs, also MPGDs: - Scalability to very large areas: ~ 10 000 m2, while keeping uniformity of response and avalanche properties. - Requires eco-friendly gas solutions to enable long-term operation of large systems - Adding few 10 ps-level time resolution for some layers: Highly compact, scalable MRPC layers
Muon trigger and tracking	GEM, THGEM, RWELL, Micromegas, RPC	stability, ageing, large area, low cost, space resolution, no greenhouse gases, spark-free	- similar requirements as for calorimeter, but coarser segmentation or strip-based readout

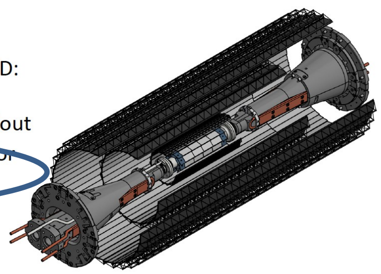
EW-Higgs-Top Factories (ee) circular colliders

Belle II Upgrade

Issues and options for Belle II upgrades for high luminosity I

- Robustness against machine backgrounds: many different sources (TF8)
  - From interaction region, from tunnel, from Interactions in nearby material
  - Very complex and tight space constraints in interaction region
- Very low material tracking; good space and time resolution (TF1, TF3, TF7)
  - Fast, high granularity, low mass replacement for current VXD: study of depleted CMOS MAPS; SOI sensors; thin strips
  - Faster and more radiation tolerant electronics for CDC readout
  - Replacement for drift chamber under study: CMOS MAPS for inner part; study of a TPC option
- New ideas: timing layers (TF3, TF7)
  - Possible use as TOF to improve PID performance
  - Provide track trigger in addition to or instead of CDC

- Small pixel pitch: 30x30 μm²
- Fast chip integration time: 25 ns (100 ns total integration time window)
- Thin material: 0.1% X_0 inner, 0.3-0.5% X_0 outer
- Low and homogeneous power consumption: < 200 mW/cm²
- Radiation hard: 100 Mrad TID, 10^{14} n_{eq} cm^{-2} NIEL



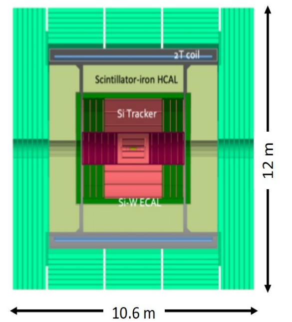
https://indico.cern.ch/event/895924/contributions/3968854/attachments/2102385/3560917/baudot-VXDupgrade-Belle2.pdf

FCC-ee

CDR: Two Complementary Detector Concepts

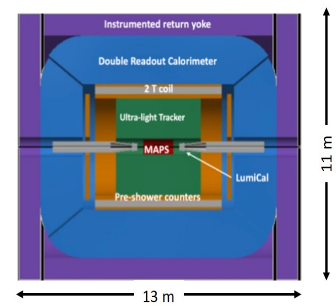
"Proof of principle concepts"
- Not necessarily matching (all) detector requirements, which are still being spelled out

CLD



- Based on CLIC detector design; profits from technology developments carried out for LCs (c.f. F.Simon's talk)
  - All silicon vertex detector and tracker
  - 3D-imaging highly-granular calorimeter system
  - Coil *outside* calorimeter system

IDEA



- New, innovative, possibly more cost-effective concept
  - Silicon vertex detector
  - Short-drift, ultra-light wire chamber
  - Dual-readout calorimeter
  - Thin and light solenoid coil *inside* calorimeter system

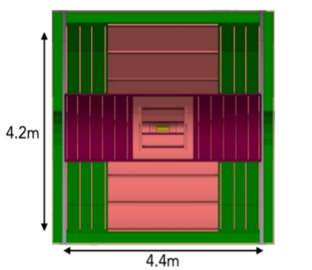
https://arxiv.org/abs/1911.12230, https://arxiv.org/abs/1905.02520 https://pos.sissa.it/390/

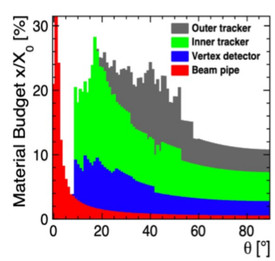
FCC-ee

Tracking

Two solutions under study

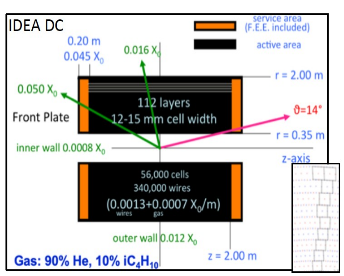
- CLD: All silicon pixel (innermost) + strips
  - Inner: 3 (7) barrel (fwd) layers (1% X_0 each)
  - Outer: 3 (4) barrel (fwd) layers (1% X_0 each)
  - Separated by support tube (2.5% X_0)

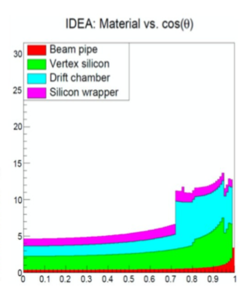




- IDEA: Extremely transparent Drift Chamber
  - GAS: 90% He – 10% iC_4H_{10}
  - Radius 0.35 – 2.00 m
  - Total thickness: 1.6% of X_0 at 90°
    - Tungsten wires dominant contribution
  - Full system includes Si VXTand Si "wrapper"

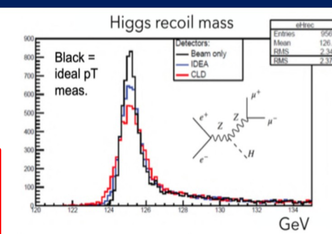
What about a TPC?
- Very high physics rate (70 kHz)
- B field limited to 2 Tesla
- Considered for CEPC, but having difficulties...



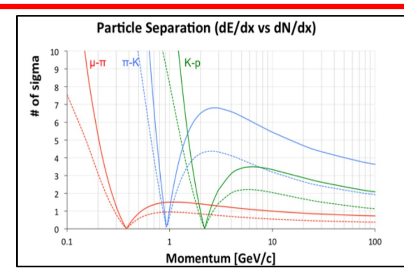


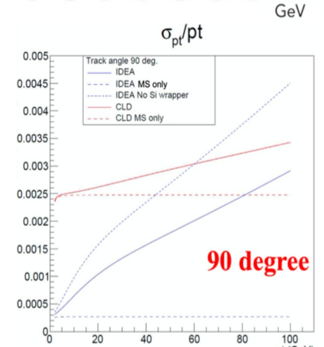
Drift Chamber

- For Higgs recoil mass analysis, both proposed tracker designs match well resolution from beam energy spread
- However, in general, tracks have rather low momenta ($p_T \lesssim 50$ GeV)
  - Transparency more relevant than asymptotic resolution



- Drift chamber (gaseous tracker) advantages
  - Extremely transparent: minimal multiple scattering and secondary interactions
  - Continous tracking: reconstruction of far-detached vertices (K^0_S, Λ, BSM LLPs)
  - Particle separation via dE/dx or cluster counting (dN/dx)
    - dE/dx much exploited in LEP analyses





EW-Higgs-Top Factories (ee) circular colliders: FCC-ee

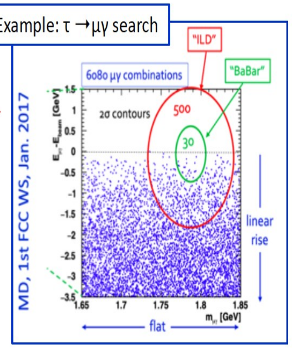
Calorimetry

- Several technologies being considered

Technology	ECAL	HCAL
CLD / CALICE-like	W/Si W/scint + SiPM	Steel/scint + SiPM Steel/glass RPC
IDEA / Dual Readout	Brass (lead, iron) / parallel scint + PMMA (C) fibres, SiPM	
Noble Liquid	Fine grained LAr (LKr) / Pb (W)	CALICE-like ?
Crystals	Finely segmented crystals (possibly DR)	Dual Readout fiber?

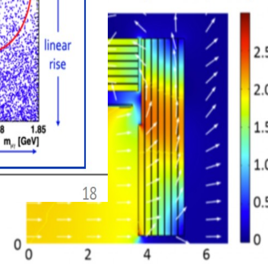
- Jet energy and angular resolutions via Particle Flow algorithm
  - Possibly augmented via Dual Readout
- Fine segmentation for PF algorithm and powerful γ/π^0 separation and measurement
- In particular for heavy flavour programme, superior ECAL resolution needed
  - $15\%/\sqrt{E} \rightarrow 8\%/\sqrt{E} \rightarrow 3\%/\sqrt{E}$
- Other concerns
  - Operational stability, cost, …
- Optimisation ongoing for all technologies
  - Choice of materials, segmentation, read-out, …

Example: $\tau \rightarrow \mu\gamma$ search



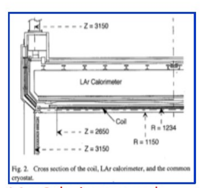
Solenoid Magnet and Muon System

er system (CLD)

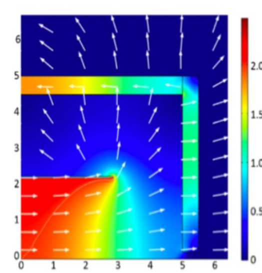


Thin solenoid inside calorimeter system (IDEA & LAr)

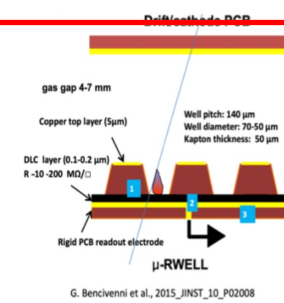
Must be **thin** and very **transparent**
- R&D ongoing



LAr: Calorimeter and coil in same cryostat (ATLAS style)



Muon system in instrumented return yoke
- 3-7 layers being considered: 3000-6000 m^2
- Proposed technologies
  - RPC (30×30 mm^2 cells)
  - Crossed scintillator bars
  - µRWell chambers (1.5×500 mm^2 cells)
    - Also for IDEA pre-shower detector
    - Ongoing R&D work

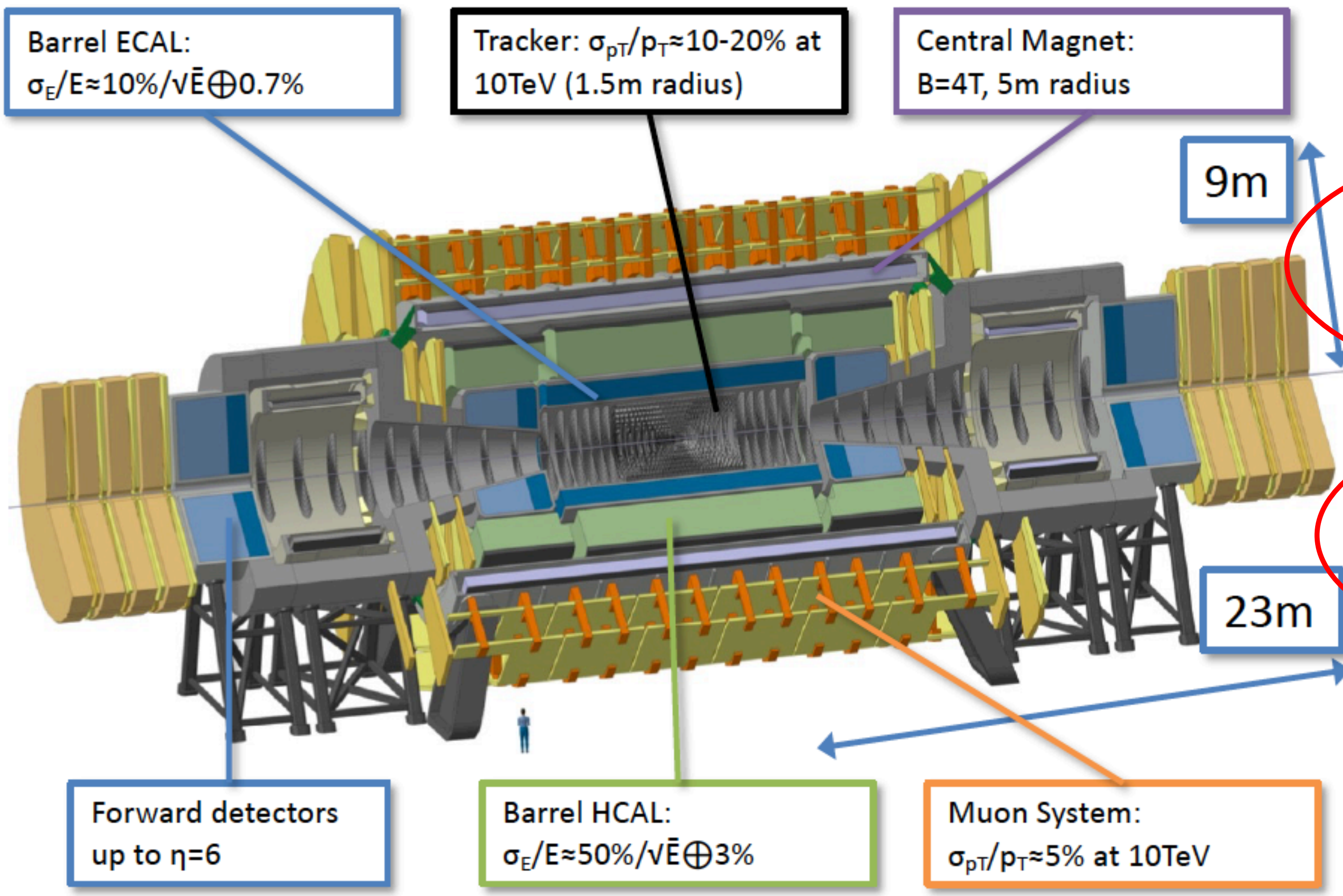


EW-Higgs-Top Factories (ee) circular colliders

Application - Detector component	Technology	Challanges	From the input sessions
Inner tracker/TPC/Drift chambers	multi-GEM, Micromegas, GEM + pixel readout , InGrid (integrated Micromegas grid with pixel readout), Drift Chamber, RICH	high spatial resolution, high rate/occupancy, fast/precise timing, radiation hardness, low mass, 4D tracking, Drift Chamber trasparency, cluster counting	**BELLEII Upgrade**: Replacement for drift chamber under study: CMOS MAPS for inner part or TPC option **FCC-ee:** **IDEA:** Extremely transparent (Radius 0.35 – 2.00 m) Drift Chamber (TPC non feasible due to high rate (70 kHz/cm2) and low B field --> considered at CEPC)
pre-shower/EM CALO	GEM, THGEM RWELL, Micromega, RPC		**FCCe**e Preshower: μRWell chambers
HADRON CALO	GEM, THGEM RWELL, Micromegas, MRPC	high granularity, radiation hardness, large volume, excellent hit timing	**FCCe**e CLD / CALICE-like: Steel/glass RPC
Muon trigger and tracking	GEM, THGEM, RWELL, Micromegas, RPC	stability, ageing, large area, low cost, space resolution, no greenhouse gases, spark-free	**Fcc-ee:** 3-7 layers being considered: 3000-6000 m2: RPC (30 × 30 mm2 cells) or μRWell chambers (1.5 × 500 mm2 cells)

High-energy hadron collider

A Possible FCC-hh Detector – Reference Design for CDR

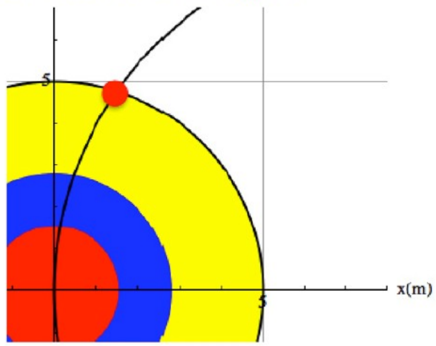


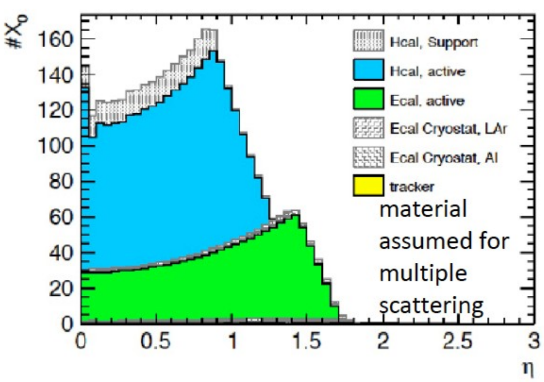
- Converged on **reference design for an FCC-hh experiment for FCC CDR**
- Goal was to demonstrate, that an **experiment** exploiting the **full FCC-hh physics potential** is **technically feasible**
  - **Input for Delphes physics simulations**
  - **Radiation simulations**
- However, this is one example experiment, other choices are possible and very likely → A lot of **room for other ideas, other concepts and different technologies**
- **In the following I will demonstrate the challenges for such an experiment – mostly independent of detector technologies chosen**

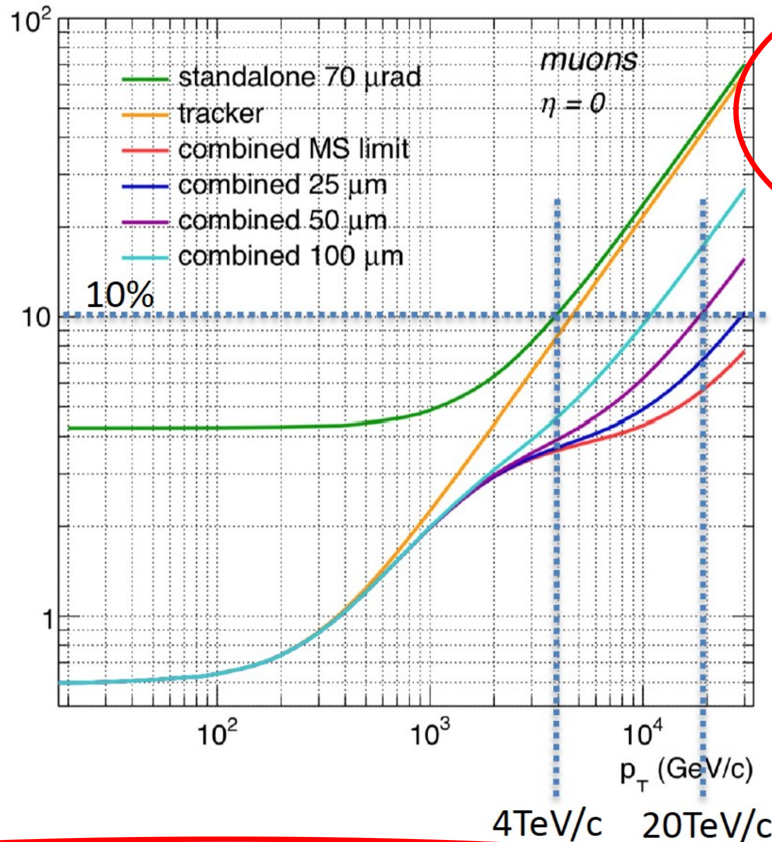
High-energy hadron collider

FCC-hh Muon System

p_t=3.9GeV enters muon system
p_t=5.5GeV leaves coil at 45 degrees





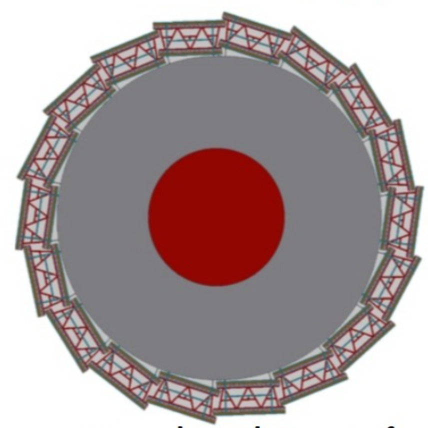


With 50µm position resolution and 70µrad angular resolution we find (η=0):

- ≤10% standalone momentum resolution up to 4TeV/c
- ≤10% combined momentum resolution up to 20TeV/c

Standalone muon performance not relevant, the task of muon system is **triggering and muon identification!**

Muon rate dominated by c and b decays → isolation is crucial for triggering W, Z, t!



Muon barrel: Rates of up to ~500Hz/cm^2 expected

Muon detection in forward region:

Excpected rates up to 500kHz for r > 1m

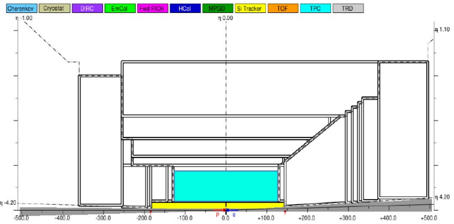
→ HL-LHC muon system gas detector technology will work for most of the FCC detector area (TF1)

High-energy hadron collider

Application - Detector component	Technology	Challanges	From the input sessions
Inner tracker	Micromegas, GEM, microRwell	high spatial resolution, good timing, radiation hard	
pre-shower/EM CALO	GEM, THGEM RWELL, Micromegas, FTM	high spatial resolution, high rate/occupancy, fast/precise timing, radiation hardness, 4D tracking	
HADRON CALO	GEM, THGEM RWELL, Micromegas, FTM	high granularity, radiation hardness, large volume, excellent hit timing, 4D tracking	
Muon trigger and tracking	GEM, THGEM, RWELL, Micromegas, RPC, FTM	stability, ageing, large area, low cost, space resolution, no greenhouse gases, spark-free, excellent hit timing	**Muon detection in forward region:** Expected rate in barrel 500 Hz/cm2. Excpected rates up to 500kHz for r > 1m . Position resolution requirments: 50µm position resolution and 70µrad angular resolution (for $\eta=0$) to get ≤10% combined momentum resolution up to 20TeV/c

Strong Interactions Experiments at Future Colliders

EIC – Tracking

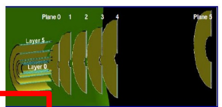


Detector Requirements

- Vertex (central): $\sigma_{xyz} \sim 20\mu m$, $d_0(z) \sim d_0(\varphi) \sim (20/p_T\ GeV + 5)\ \mu m$
- Resolution
  - central: $\sigma(p_T)/p_T \sim 0.05\% \cdot p_T \oplus 0.5\%$
  - fwd/bwd ($1<|\eta|<2.5$): $\sigma(p_T)/p_T \sim 0.05\% \cdot p_T \oplus 1\%$
  - fwd/bwd ($2.5<|\eta|<3.5$): $\sigma(p_T)/p_T \sim 0.1\% \cdot p_T \oplus 2\%$
- Material budget: $X/X0 \lesssim 5\%$
- Minimum p_T: 100 MeV/c pions, 135 MeV/c Kaons

All-silicon option

6-layer barrel, 5+5 disks



for back/forward regions
Option: light (Cr) GEMs for the most external disks

Sensor: MAPS with $\lesssim 20\mu m$ pitch, ...

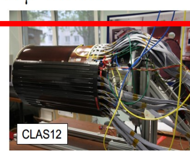
Needs new sensor to meet EIC requirements
⇨ consortium of EIC groups joined the ongoing sensor development effort for ALICE ITS3 (CERN)

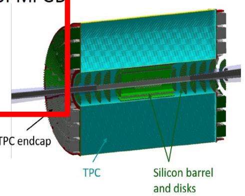
Hybrid option

silicon vertex + TPC (barrel), 7 silicon disks for back/forward

option 1: TPC + external layer of MPGD supports tracking + time

option 2: coaxial layers of μ–RWELLs

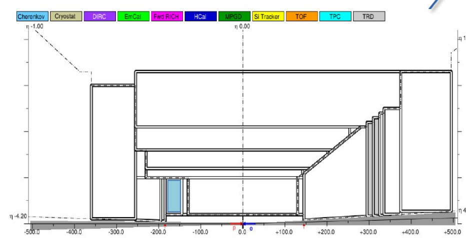




EIC – hadron ID

Requirements

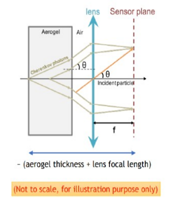
- $\pi^{\pm}, K^{\pm}, p^{\pm}$ separation over a wide range $|\eta| \leq 3.5$
- Resolution: $\pi/K \sim 3\text{-}4\,\sigma$, $K/p > 1\,\sigma$
- Momentum-η correlation a different PID technology
  - $-5 < \eta < 2$: $0.2 < p < 10$ GeV/c
  - $2 < \eta < 5$: **$0.2 < p < 50$ GeV/c**
- Hadron cut-off: B=1T ⇨ $p_T > 200$MeV, B=3T ⇨ $p_T > 500$MeV



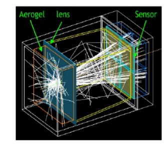
Backward

Reference: mRICH
(Modular RICH)

- **Aerogel** Cherenkov
- Focused by Fresnel lens
- e, π, K, p
- Sensor: SiPM / LAPPDs
- Adaptable to include TOF
- π/K separation
  ~ 3 σ @ 10 Gev/c

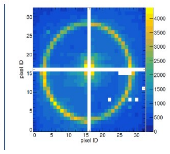


(Not to scale, for illustration purpose only)



Geant4 Simulation
With realistic material optical properties

2nd mRICH prototype was tested at Fermilab Test Beam Facility in June/July 2018



TOF with 2m lever arm, 2 options

- **LAPPD** (Large Area picos Photon Detector)
  - MCP, Cherenkov in window, 5-10 psec
- **LGAD** (Low Gain Avalanche Detector)
  - Silicon Avalanche, 25-35 ps
  - Accurate space point for tracking
  - Relevant also for central barrel

HBD (Hadron Blind Detector)

- Unfocussed CF_4 Cherenkov det.
- π-threshold ~ 4GeV
- New gain stage proposed to improve e/π separation

EIC – hadron ID

Requirements

- $\pi^{\pm}, K^{\pm}, p^{\pm}$ separation over a wide range $|\eta| \leq 3.5$
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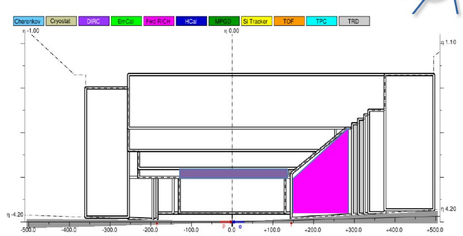
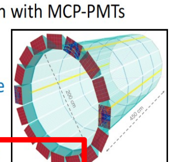


Barrel

Reference: hpDIRC (high performance DIRC)

- Quartz bar radiator, light detection with MCP-PMTs
- Fully focused
- π/K separation ~ 3 σ @ 6 Gev/c
- Reuse of BaBar DIRC as alternative



R&D e.g.: add timing to the DIRC

dE/dx from TPC, complementary

- expected resolution ~ STAR, sPHENIX

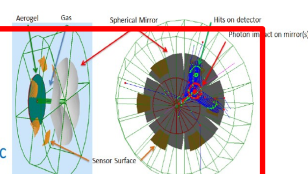
TOF (~ 1m lever arm)

- LGAD (Low Gain Avalanche Detector)

Forward

Reference: dRICH (dual RICH)

- Aerogel and C-F gas radiators
- Full momentum range
- Sensor: Si PMs (TBC)
- π/K separation ~ 3 σ @ 50 Gev/c



Windowless RICH

- Gaseous sensors (MPGDs), CF_4 as radiator and sensor gas
- Low p complements required (TOF with 2.5m lever arm/aerogel (mRICH)

HP-RICH (high-pressure RICH)

- Eco-friendly alternative to dRICH
- Ar @ 3.5 bar / 2 bar ↔ C_4F_{10} @ 1 bar / CF_4 @ 1 bar

EIC – Photon Detection Technologies

Photon Detection Technology critical for many PID devices

- High-gain: 10^5 - 10^6
- Small pixels with individual readout: O(1mm pitch)
- Good timing (even with small signals): $\lesssim$100ps (DIRC), $\lesssim$ 800ps (mRICH, dRICH)
- Tolerance to magnetic field (1.5 - 3 T) and radiation (up to $10^{11}\ n_{eq}/cm^2$)

Possible solution driven by detector performance and operational parameters, with cost optimizaton in mind

Viable candidates for EIC applications

- Multi-anode PMTs (MaPMTs)
- Commercial Microchannel-Plate PMTs (MCP-PMTs)
- Large-Area Picosecond Photodetectors (LAPPDs)
- Gaseous Electron Multipliers (GEMs) a for gas-only RICH
- Silicon PMs (SiPMs)

R&D needs

LAPPDs: very promising, but not yet suitable for EIC
⇨ need pixelization
⇨ Reduce sensitivity to B field

GEM-based photosensors (low-cost, radiation hard)

- Improve performance in the UV useful for gas-only RICH
- develop of photocathode sensitive in the visible region

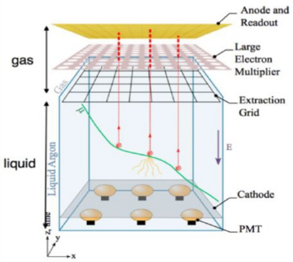
SiPM/SPAD: promising, quickly improving (driven mostly by automotive sector), cheap technology
⇨ can be operated up to 3T
⇨ Reduce sensitivity to neutron damage
⇨ Reduce DCR (presently too high for DIRC applications)
⇨ Increase fill factor

Strong Interactions Experiments at Future Colliders: EIC

Application - Detector component	Technology	Challanges	From the input sessions
Inner tracker/PID	Micromegas, GEM, microRwell, dual-RICH, high-pressure RICH	high spatial resolution, good timing, radiation hard , tolerance to magnetic field	- tracking barrel: **TPC** surrounded by MPGD or set of coaxial cylindrical MICROMEGAS or forward: 1 disk with GEMs with Cr electrodes - - hadron PID forward: **Dual-RICH** fluorocarbon gaseous RICH, **high pressure RICH** (Ar @ 3.5 bar / 2 bar n C4F10 @ 1 bar / CF4 @ 1 bar) - Photon Detection Technologies requirements: High-gain: 10^5 - 10^6 • high-resolution O(1mm pitch) • Good timing (even with small signals): ≲ 800ps (mRICH, dRICH) •Tolerance to magnetic field (1.5 - 3 T) and radiation (up to 10^11 neq/cm2): GEM-based photosensors (low-cost, radiation hard)
HADRON CALO	GEM, THGEM RWELL, Micromegas, FTM, RPC	high granularity, radiation hardness, large volume, excellent hit timing, 4D tracking	option RPC/DHCAL
Muon trigger and tracking	GEM, THGEM, RWELL, Micromegas, RPC, FTM	stability, ageing, large area, low cost, space resolution, no greenhouse gases, spark-free, excellent hit timing	

Neutrino Long Baseline

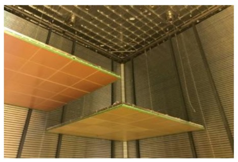
Anodes technologies: DP (double phase)

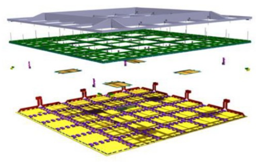


LEM S/N > 50 expectation

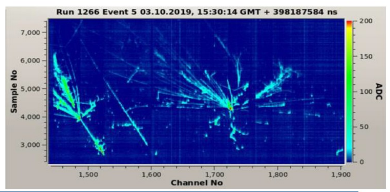
Solution tested in ProtoDUNE @ CERN
Needs more R&D to solve stability problems

Amplification in the gas difficult to stabilize !!

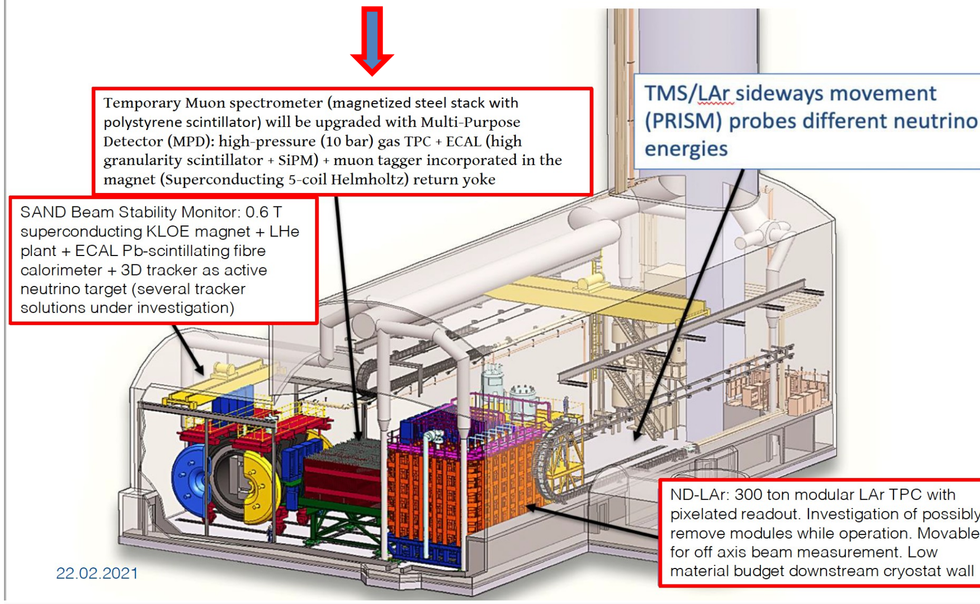




LEM : thick GEM technology



DUNE Near Detector complex



Temporary Muon spectrometer (magnetized steel stack with polystyrene scintillator) will be upgraded with Multi-Purpose Detector (MPD): high-pressure (10 bar) gas TPC + ECAL (high granularity scintillator + SiPM) + muon tagger incorporated in the magnet (Superconducting 5-coil Helmholtz) return yoke

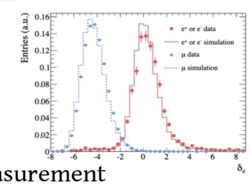
TMS/LAr sideways movement (PRISM) probes different neutrino energies

SAND Beam Stability Monitor: 0.6 T superconducting KLOE magnet + LHe plant + ECAL Pb-scintillating fibre calorimeter + 3D tracker as active neutrino target (several tracker solutions under investigation)

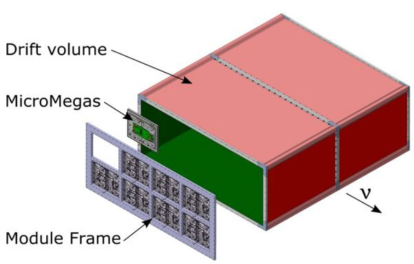
ND-LAr: 300 ton modular LAr TPC with pixelated readout. Investigation of possibly remove modules while operation. Movable for off axis beam measurement. Low material budget downstream cryostat wall

High-Angle Time Projection Chambers : HA-TPC

- ✓ Track reconstruction in 3D. Space point resolution around 800 μm
- ✓ Charge measurement
- ✓ Momentum measurement (<10% at 1 GeV/c)
- ✓ Particle identification by combining dE/dx with momentum measurement



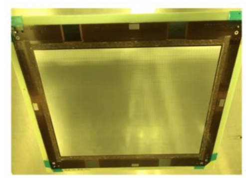
Low momentum of a few hundred MeV/c in the high angle and backward regions



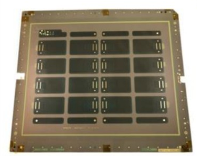
Parameter	Value
Overall x × y × z (m)	2.0 × 0.8 × 1.8
Drift distance (cm)	90
Magnetic Field (T)	0.2
Electric field (V/cm)	275
Gas Ar-CF_4-iC_4H_{10} (%)	95 - 3 - 2
Drift Velocity $cm/\mu s$	7.8
Transverse diffusion ($\mu m/\sqrt{cm}$)	265
Micromegas gain	1000
Micromegas dim. z×y (mm)	340 × 410
Pad z × y (mm)	10 × 11
N pads	36864
el. noise (ENC)	800
S/N	100
Sampling frequency (MHz)	25
N time samples	511

High-Angle Time Projection Chambers : HA-TPC

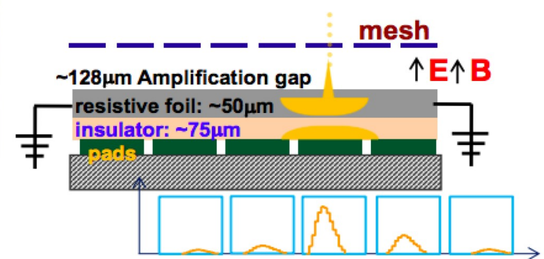
- 8 resistive MMs per volume



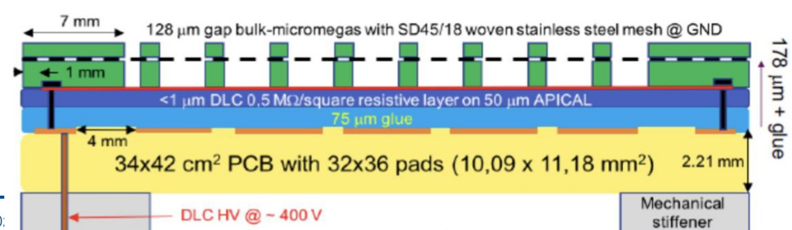
Bulk-micromegas side



Connector side



Resistive Micromegas technology chosen as baseline



Neutrino Long Baseline

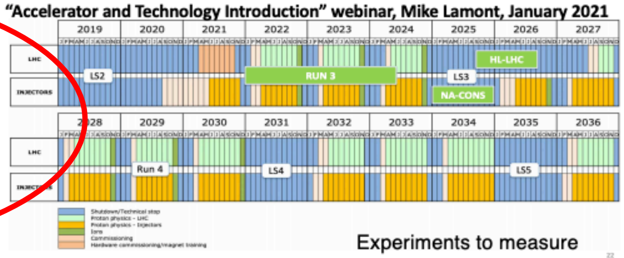
Application - Detector component	Technology	Challanges	From the input sessions
Inner tracker/PID	Micromegas, high pressure TPC, double-phase TPC	very large volume,radio purity	**DUNE Far Detector: LArTPC** Anodes technologies: DP (double phase): In the double phase detector the electrons are extracted from the liquid Ar to a gaseous Ar volume within a strong electric field of 2 to 3 kV/cm and undergo afterwards a charge amplification though Large electron multiplier (LEM) before the signal is readout at the segmented anode. **DUNE Near Detector (ND-GAr: High Pressure gas TPC (1t) + ECAL + magnet):** includes high pressure 10 bar gaseous Argon TPC **Hyper-Kamiokande** High-Angle Time Projection Chambers : HA-TPC with MICROMEGAS at anode amplification.
Muon tagging	GEM, RPC, Micromegas, Ionization chambers	stability, ageing, large area, low cost, space resolution	

Detector R&D requirements for future rare decay processes experiments (not colliders)

Integrated high-intensity Kaon programme at the SPS

Long-term programme in NA-ECN3 after NA-CONS (~2025)
Physics programme will be presented to PBC at the beginning of March (BSM session)
Programme extends from 2026 to ~2039

"Accelerator and Technology Introduction" webinar, Mike Lamont, January 2021



Experiments to measure $K \to \pi\nu\nu$ BRs at the SPS would require:

- $K^+ \to \pi^+\nu\nu$
  6x10^18 pot/year
  4x increase
- $K_L \to \pi^0\nu\nu$
  1x10^19 pot/year
  6x increase

increases with respect to

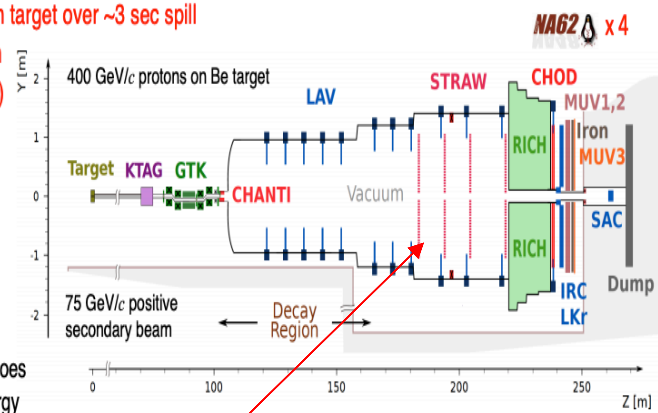
Multiple phases:
K^+ and K_L beams for precision measurement of $K \to \pi\nu\nu$
Study of other rare kaon decays, including K_L beam with tracking detector for $K_L \to \pi^0 l^+ l^-$
Data taking in dump mode to reach 10^{19} POT to search for FIPs

Phases order depends on factors like civil engineering and detector readiness.
K_L phase (KLEVER) probably involves civil construction, later stage

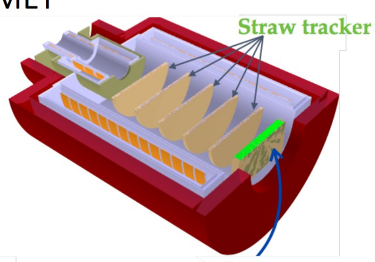
High-rate beam 1.3--2 10^{13} protons on target over ~3 sec spill
Unseparated secondary hadron beam
Challenging time resolution (20-40 ps)

K^+ phase

- Essential K^+ ID, momentum, space and time
- High-rate, precision tracking of pion
- Minimize material
- Highly efficient PID and muon vetoes
- Highly efficient and hermetic photon vetoes
- High-performance EM calorimeter (energy resolution, linearity, time, granularity)



COMET



"StrECAL" = Straw tracker and ECAL
To measure all delivered beam incl BG, vacuum-compatible tracker and calorimeter is employed
Straw = Planer/Low-mass, LYSO crystal
ECAL = High resolution / High density
Same concept as Phase-II detector = Prototype of Phase-II Final Detector

Ultra thin straw tube chambers operating in vacuum

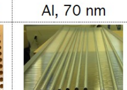
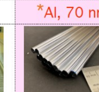
- 20μmT/10mmφ for Phase-I
- 12μmT/5mmφ for Phase-II
- Ar:C_2H_5=50:50
- Each "station" consists of 240(~500) straws ×2, 5(>6) stations for Phase-I (Phase-II)

STRAW detector

Straw chambers for 4x intensity

- **Main feature: Straw diameter ~5 mm**
- **Improved trailing-time resolution: ~6 ns (per straw), gaussian shape**
- **Smaller maximum drift time: ~80 ns**
- **Rate capability increased by factor 6-8, due to geometry and shorter drift**
- **Less space charge due to shorter drift time**
  - Ion clusters are faster → can use fast shaping
  - **Improved time resolution:**
    30 → 6 ns for single straw, 5 → 1 ns for track
- **Maintain efficiency > 98%**
- **Decreased straw wall thickness**: ~12 μm, with copper and gold plating, biggest contribution to material
- smaller gas volume: 2nd biggest contributor to material
- Position resolution (from leading edge time resolution) unchanged but can **increase number of straws per track** while maintaining low material budget
- Layout: 4 chambers, ~21000 straws
- **Material budget**: 1.7% → 1.1% X_0

Design study started
CERN and Dubna

	NA62	COMET Phase-I	New Straw
Straw Wall Thickness	36 μm	20 μm	12 μm
Straw Diameter	9.8 mm	9.8 mm	4.8 mm
Metal Deposition	Cu+Au, 70nm	Al, 70 nm	*Al, 70 nm
Photo			
Current Status	In Operation	Under Construction	Just Develope

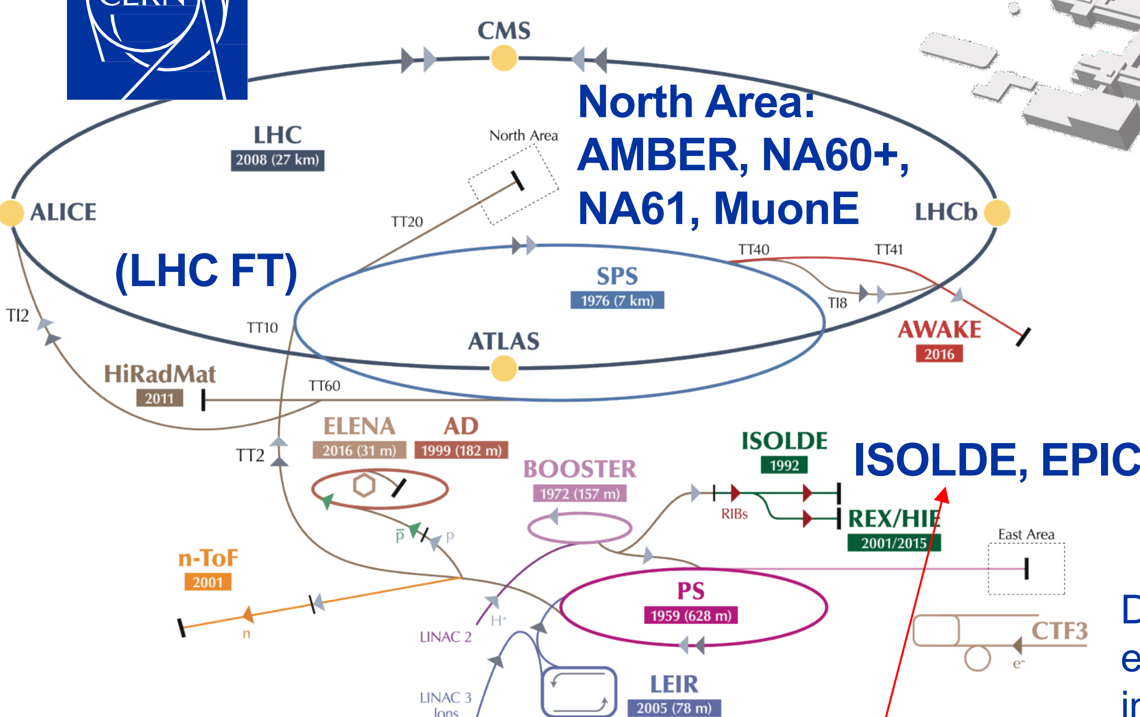
* Al for prototype: final straws will have 50 nm Cu + 20 nm Au like present stra

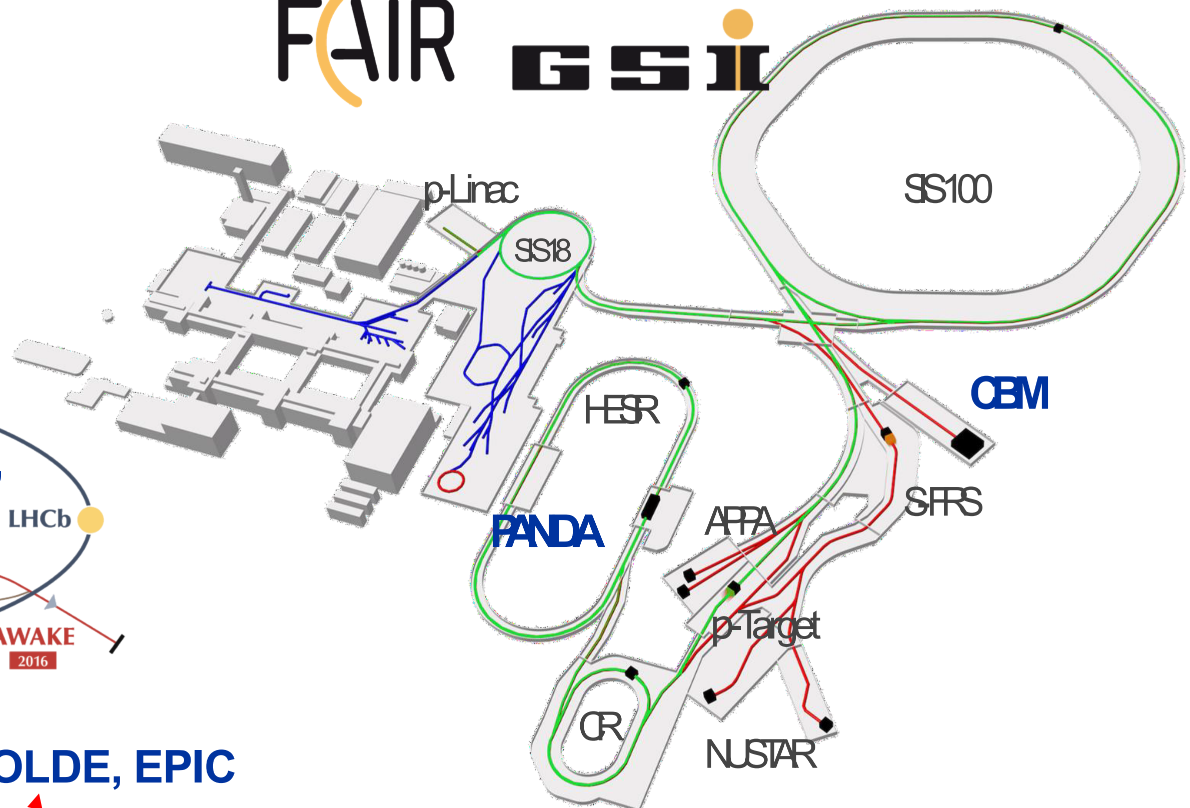
Detector R&D requirements for future rare decay processes experiments (not colliders)

Application - Detector component	Technology	Challanges	From the input sessions
Inner tracker/PID	Micromegas, THGEM, GEM, ACTIVE TPC, STRAW TUBES	high spatial resolution, occupancy, fast/precise timing, radiation hardness, low mass	**NA62** straw chambers with reduced diameter and material budget to increase rate capability (500 kHz/straw) and improved momentum resolution **Mu2e-II** Low-mass STRAW tracker **COMET** ultra-thin Straw tracker
Muon trigger and tracking	Micromegas, THGEM, GEM	stability, ageing, large area, low cost, space resolution, no greenhouse gases, spark-free, excellent hit timing	

Strong interaction at storage rings & fixed target

Overview on Facilities





Disclaimer: Not all existing facilities, projects and experiments covered today, partly still awaiting input and most probably inadvertently forgot some.

active targets (ACTAR-TPC, SPECMAT, ...)

- e.g. Micromega-based TPCs

Strong interaction at storage rings & fixed target

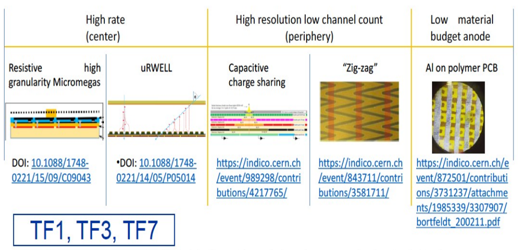
Contact: S. Levorato, INFN Trieste; J. Friedrich, TU München; V. Andrieux, U of Illinois; O. Denisov, INFN Torino

AMBER / CERN

- Detector R&D for many components planned, some examples
  - 0.5 – 2 m diagonal-sized MPGD based trackers study (MWPCs substitution)
  - Large size silicon tracker inside of polarised target (cryogenic environment)
  - R&D on MPGD based photon detectors after the RICH-1 hybrid THGEM+MM upgrade (1.4 m^2 2016)
  - R&D on high space resolution gaseous photon detectors for compact RICH approach
  - Active targets

Tracking

Technologies candidates under investigation



TF1, TF3, TF7

There are significant technological challenges in producing a large area mixed technologies detector

A combination of the ongoing technological R&Ds would most probably satisfy our requirements

0.5 – 2m diag size MPGD based trackers study (MWPCs substitution)

- For the running of the AMBER program, we evaluate the possibility to substitute of a part of MWPCs with MPGD based detectors
- The motivation is to substitute the structurally aged MWPC, to be able to optimize the acceptance coverage with a variable size detector. We would like to be able to cover both the high-rate central beam area and the external part of the aperture with a single detector taking advantage of the MPGDs anode flexibility
- The new detectors should be ready for the new trigger less DAQ and one of the possible R/O options could be the TIGER ASIC that was developed specifically to be used with MPGD detectors. Several other options like the VMM ASIC has to be investigated
- Presently small size prototypes are under test to validate the R/O and the production technics

❑ We would like to produce the first prototypes of a size ~55x55 cm^2 in 2022

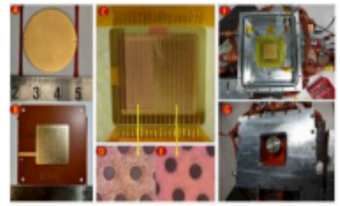
AMBER / CERN

R&D on MPGD based photon detectors after the RICH-1 hybrid THGEM+MM upgrade (1.4 m^2 2016)

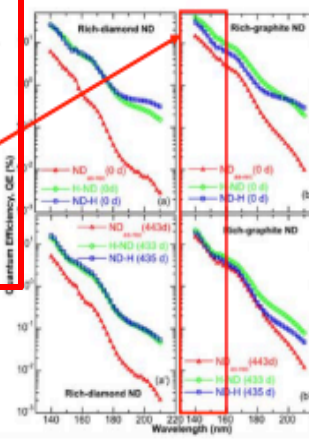
PID

New photoconverting material approach using Hydrogenated Diamond nano grains
Velardi et al., Diamond and Related Materials 76(2017)1 ;

Robust and efficient photoconverter never used for photon detectors of large size (~ m^2)



Being tested with THGEM based detector as replacement of CsI for RICH windowless approach (VUV)



RD51 Workshop on Gaseous Detector Contributions to PID 16-17 February 2021 https://indico.cern.ch/event/996326/
-MPGD-based photon detectors for the upgrade of COMPASS RICH-1 and beyond
Chandradoy Chatterjee
-Nanodiamond photocathode for MPGD-based single photon detectors at the future EIC
Daniele D'Ago

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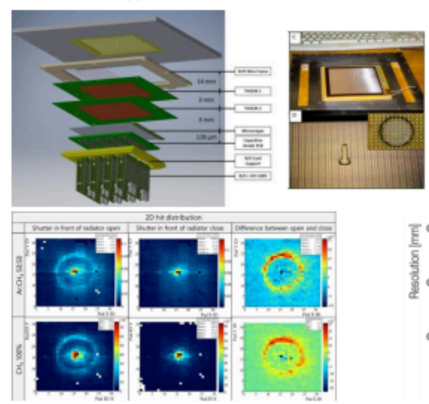
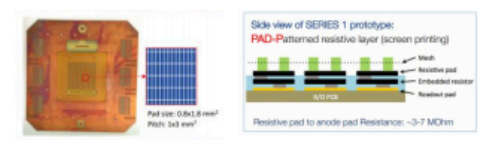
R&D on high space resolution gaseous photon detectors for compact RICH approach

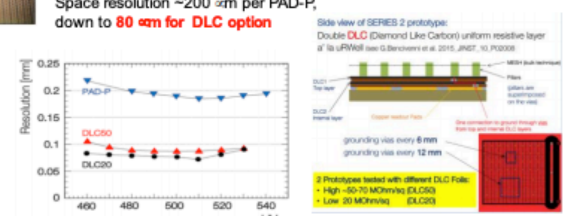
Prototype of modular scalable mini pad hybrid PD, INFN Trieste approach



Prototypes of modular scalable mini pad resistive MM INFN Roma Tre approach



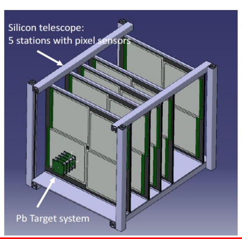
Space resolution ~200 µm per PAD-P, down to 80 µm for DLC option



Contacts: E. Scomparin, INFN Torino; G. Usai, U Cagliari

NA60+ / CERN

The NA60+ Silicon vertex telescope

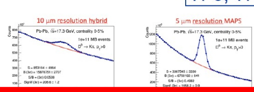


Use of state-of-the-art Monolithic Active Pixel Sensors

Motivation:

- Sensor thickness: few tens of microns of silicon
- New large area sensors (based on stitching):
  - No support under sensitive area → material budget <0.1% X_0
  - Stations with just few sensors → simpler mechanics
- Spatial resolution 5 µm or even better

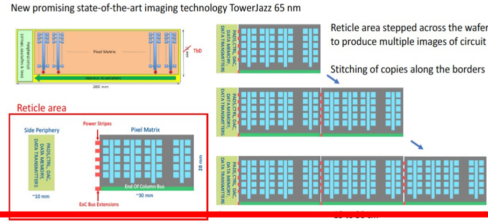
TF3, TF7



Stitching: new key idea for wafer-scale MAPS

Challenging R&D started, in synergy with ALICE experiment and with an aggressive schedule for the next 3 yrs

New promising state-of-the-art imaging technology TowerJazz 65 nm



Sensor of arbitrary size, just limited by wafer borders

NA60+ GEM-based muon tracker

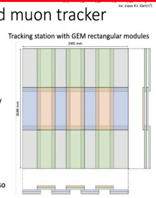
Motivation for GEMs:

- Position resolution 100-200 µm
- Good timing resolution (<10 ns)
- Rate capability (in NA60+ max 10 kHz/cm^2)
- Excellent radiation hardness
- Large area tracker 140 m^2
  ->Use components that can be mass produced by industry

Current foreseen geometry for GEM modules:

- ≈50x110 cm^2 rectangle (CMS, ALICE)
- ≈ 330 modules
- Baseline: one tracking layer per station

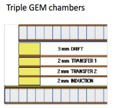
New emerging technologies for large scale trackers might also be considered → started contacts with RD51



- Staggering: ≈ 10 cm overlap in each direction
- Up to ≈20 cm between the layers

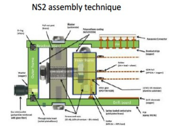
Proposed NA60+ GEM module

Triple GEM chambers



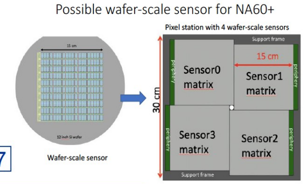
- Ar-CO$_2$ o Ar-CO$_2$-CF$_4$ mixtures
- 2D strip readout
  - 200 µm to 1 mm resolution
    → 0.8 mm to 3.5 mm pitch
  - Optional: pads in the innermost region, zig-zag strips, etc.
- VFAT3 or VMM3 readout

NS2 assembly technique



TF1, TF7

Possible wafer-scale sensor for NA60+



Strong interaction at storage rings & fixed target

Application - Detector component	Technology	Challanges	From the input sessions
Inner tracker/PID	Micromegas, THGEM, GEM, ACTIVE TPC, STRAW TUBES, MRPC for TOF	high spatial resolution, occupancy, fast/precise timing, radiation hardness, low mass	**ACTAR-TPC, SPECMAT:** ACTIVE TPC with MICROMEGA **AMBER TRACKING**: 0.5 – 2 m diagonal-sized MPGD based trackers study (MWPCs substitution): uRwell o resistive high granularity MICROMEGAS, reduced number of channel with zig-zag strips **AMBER Photon PID**: R&D on high space resolution gaseous photon detectors for compact RICH approach: - mini pad resistive MM - New photo-converting material approach using Hydrogenated Diamond nano grain **AMBER RICH:** gas radiator solution with eco-gas alternatives to C4F10"
Muon trigger and tracking	Micromegas, THGEM, GEM	stability, ageing, large area, low cost, space resolution, no greenhouse gases, spark-free, excellent hit timing	**NA60:** GEM based muon tracker

MUON COLLIDER

General requirements for the detector

- ✓ Track efficiency and momentum resolution – for feasibility and precision of many physics studies e.g. final states with leptons
- ✓ Good ECAL energy and position resolution for e/gamma reconstruction
- ✓ Good jet energy resolution
- ✓ Efficient identification of a secondary vertex for heavy quark tagging
- ✓ Other considerations (Missing Energy/MET, taus, substructure)

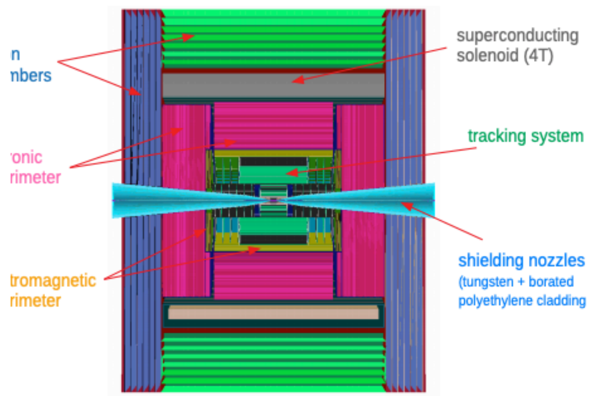
- ✓ Many ILC or CLIC considerations apply to Muon Collider detectors, although beam background conditions are different and much more challenging requiring a dedicated design for Muon Collider experiment: vertex/tracking – calorimetry – triggerless DAQ
- ✓ Detector design considerations should be driven by physics requirements and BIB considerations
- ✓ **Optimal design will very likely be different for different collision energies**

Detector @ $\sqrt{s}$ = 1.5 TeV – full simulation

available on github

CLIC Detector technologies adopted with important tracker modifications to cope with BIB
Detector design optimization at $\sqrt{s}$=1.5 (3) TeV one of the primary goals

B = 3.57 T to be studied and tuned



Vertex Detector (VXD)
- 4 double-sensor barrel layers 25x25μm²
- 4+4 double-sensor disks 25x25μm²

Inner Tracker (IT)
- 3 barrel layers 50x50μm²
- 7+7 disks ”

Outer Tracker(OT)
- 3 barrel layers 50x50μm²
- 4+4 disks ”

Electromagnetic Calorimeter (ECAL)
- 40 layers W absorber and silicon pad sensors, 5x5 mm²

Hadron Calorimeter (HCAL)
- 60 layers steel absorber & plastic scintillating tiles, 30x30 mm²

›ifferent stages of design depending on CoM energy

luite advanced conceptual design for Higgs factory, 1.5 TeV and 3 TeV

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TF1 Gaseous Detectors

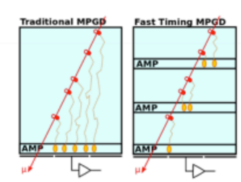
MPGDs or also improved RPCs, … for readout of high-granularity hadronic calorimeters and for muon detectors in high rate areas where high precision is required (eg endcaps, first station in barrel,…)

GOAL:
1. **First Muon Station(s)** with rad-hard, high spatial, time resolution and high rate-capability and two-track separation capable detectors; instrument large areas
2. **Instrumentation of active areas in sampling** (high-granularity) **Hadron Calorimeter**

- Study of hadronic shower interaction (absorber) with readout by gaseous detector as active detector
- Develop new calorimetric schemes (e.g. crystal absorber + photo-detection by MPGD)
- New gasmixtures for optimized operation and detection

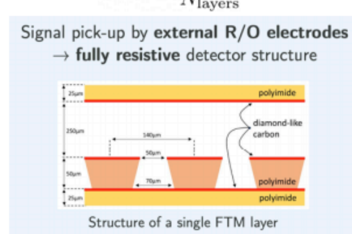
FTM Concept, design, performance

- Purpose of the fast timing MPGD (FTM): Improving on the time resolution of traditional MPGDs (~5ns) for MIP signals to ~500ps
- Jet energy resolution will scale 1/sqrt(number of jet particles)
- Working principle: Competition of arrival time of independent signals generated by fully decoupled drift+amplification layers



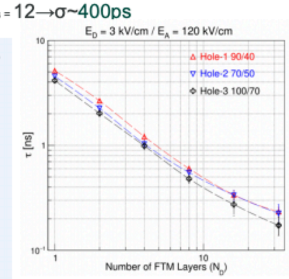
$$\sigma_{FTM} = \frac{\sigma_{layer}}{N_{layers}}$$

N_{layers} = 12→σ~400ps

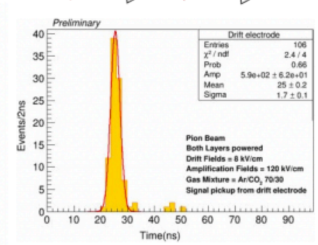


Structure of a single FTM layer

Prototypes undergoing tests in Bari, Pavia (Italy), Ghent (Belgium)



Simulated FTM time resolution for different n. of layers

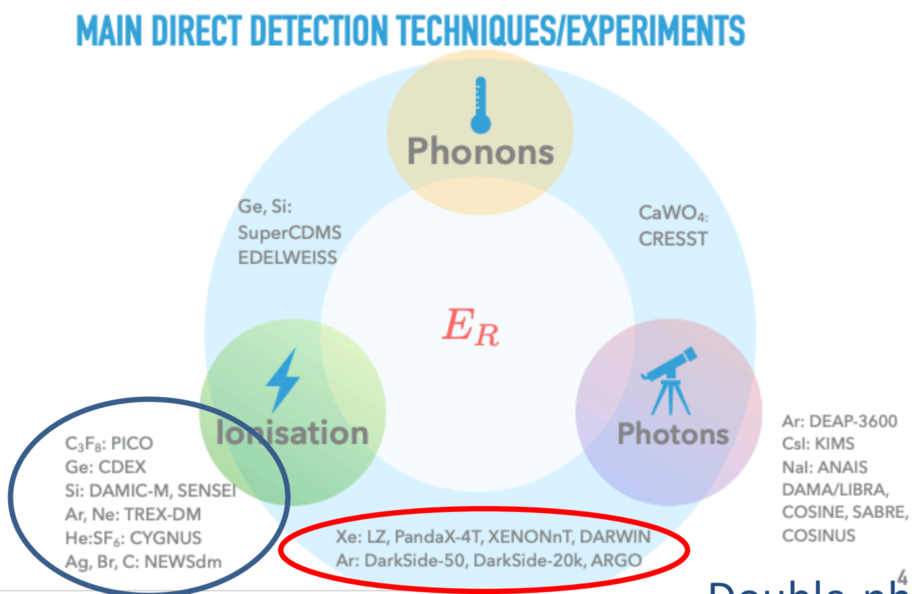


Measured two-layer time resolution at test beam

MUON COLLIDER

Application - Detector component	Technology	Challanges	From the input sessions
HADRON CALO	Micromegas, GEM + pixel readout , InGrid (integrated Micromegas grid with pixel readout), FTM, RPC	high granularity, radiation hardness, large volume, excellent hit timing, 4D tracking	High longitudinal and transversal granularity (~1cm2) High time resolution (few hundred of ps) to remove the BIB. High radiation hardness Gaseous detector (large area, high rate capabilities and spatial resolution, rad-hard) options considered for readout layers • **RPCs, GEM and Micromegas, Fast Timing MPGD (FTM).**
Muon trigger and tracking	GEM, THGEM, RWELL, Micromegas, RPC	no greenhouse gases, spark-free, high spatial resultion, fast/precise timing	Muon Station(s) with rad-hard, high spatial, time resolution and high rate capability and two-track separation capable detectors; instrument large areas: **RPC, MPGD**

Non-accelerator experiments for Dark Matter search



high pressure gas TPC equipped with MPGD readouts

Double-phase TPC

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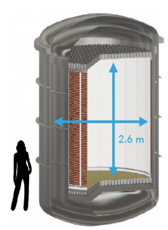
R&D FOR MULTI-TON SCALE NOBLE LIQUIDS: TPC DESIGN AND DETECTOR

- Demonstrate e-drift over large (>2.5 m) distances
  - high-voltage feed-throughs: must deliver 50 kV or more to the cathode (vacuum seal → cryofitting)
  - electrodes with large (>2.5 m) diameters: wire, mesh/ woven, micro-pattern
- reflective (and WLS in the case of Ar) coatings to optimise light collection efficiency
- cryostat design: stability; reduce the amount of material and hence gamma and neutron emitters close to the TPC

2.6 m tall Xe TPC demonstrator for DARWIN

Cryostat a la DUNE for Darkside-20K



DARWIN Ti cryostat (a la LZ)

2.6 m diameter Xe TPC demonstrator for DARWIN

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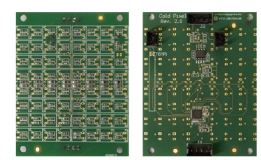
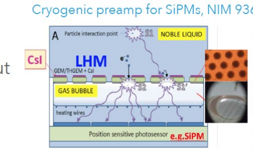
R&D FOR MULTI-TON SCALE NOBLE LIQUIDS: LIGHT AND CHARGE

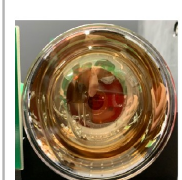
- Hybrid sensors: e.g., ABALONE, VSiPM, SIGHT
  - SiPM + Quartz + photocathode: reduced radioactivity compared to PMTs
  - lower DCR compared to SiPM arrays (photosensitive area difference)
- Cryogenic low-noise, low-radioactivity, low heat dissipation readout
- Bubble-assisted Liquid Hole Multipliers: local vapour bubble underneath GEM-like perforated electrode in LXe

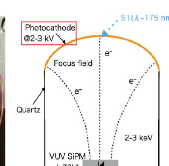


Cryogenic preamp for SiPMs, NIM 936, 2019

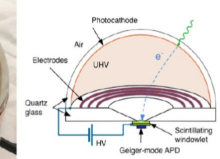


Liquid hole multipliers JINST 13, 2018





Hybrid photosensor: Hamamatsu XE5859



Hybrid photosensor: ABALONE; left (DARWIN R&D with SiPM); right: NIM 954, 2020

Non-accelerator experiments for Dark Matter search

Future Facilities	Application - Detector component	Technology	Challanges	From the input sessions
non-accelerator (Dark Matter search)	Tracking/PID	OpticalMPGD, Micromegas, GridPix, TPC	radio purity, cryogenic temperature,low presure, high presure, xenon procurement is challengin ◦ argon depleted in 39Ar underground wells ◦ both xenon and argon, storage and recuperation techniques	Ar, Ne: **TREX-DM** (TPC Rare Event eXperiment for Dark Matter) is intended to look for low mass WIMPs in the using light elements (Ne, Ar) as target in a high pressure TPC equipped with Micromegas readouts. **Cygnus:** multi-ton gas target (SF6:He, HeCF4) using TPC for Directional DM search, MPGD optical readout **Dual-phase TPC LXe** detectors: **PandaX-4T, LZ** **Dual-phase TPC LAr** detector **DarkSide -20k, Argo 200k** electrodes with large (>2.5 m) diameters: wire, mesh micro-pattern

Non-accelerator experiments on antimatter and neutron physics

Application - Detectorcomponent	Technology	Challanges	From the input sessions
Tracking/PID	OpticalMPGD, Micromegas, GridPix, TPC	radio purity, cryogenic temperature,low presure, high presure	**ELENA: Antimatter experiments:** **GBAR**: H+ free fall chamber surrounded by 6 faces of the surrounding cube, each face with a 60x60 cm2 triplet of Micromegas each with X and Y measurement. **ALPHA-g**: position sensitive particle detector, which provides information about antihydrogen annihilation location: TPC with MWPC amplification **ESS Neutron physics** Gd-deposited MPGD detectors Ongoing development based on GEM, VMM3 + SRS readout Requirements are: - position resolution of few 100 microns - several m2 detector, high rates