Technology Inventory
or
The Quest For Complementarity

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Much material taken shamelessly from too many people to be mentioned here.

BROOKHAVEN
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Outline

1. Magnet
2. Si-Tracking (3D)
    - 2.1. MAPS
    - 2.2. Alternatives to MAPS
3. Non-Si Tracking
    - 3.1. MPGDs
    - 3.2. Scintillating Fiber Tracker
    - 3.3. Mini-Drift Detector
    - 3.4. GridPiX/miniTPC
    - 3.5. Drift Chambers
    - 3.6. Straw Tracker
    - 3.7. TPCs
4. Calorimetry
    - 4.1. Trends
    - 4.2. EM Calorimetry
    - 4.3. Hadron Calorimetry
5. Muons
6. Particle ID
    - 6.1. ToF with Si sensors
    - 6.2. LGAD
    - 6.3. SPAD
    - 6.4. hpDIRC
    - 6.5. xpDIRC
    - 6.6. RICH Detectors
    - 6.7. Photosensors
        - 6.7.1. SiPM
        - 6.7.2. Digital SiPM
        - 6.7.3. LAPPD/HRPPD
    - 6.8. Transition Radiation Detectors
7. Novel Ideas
    - 7.1. Nanowires
8. Take Away Message

MAGNET

Magnet

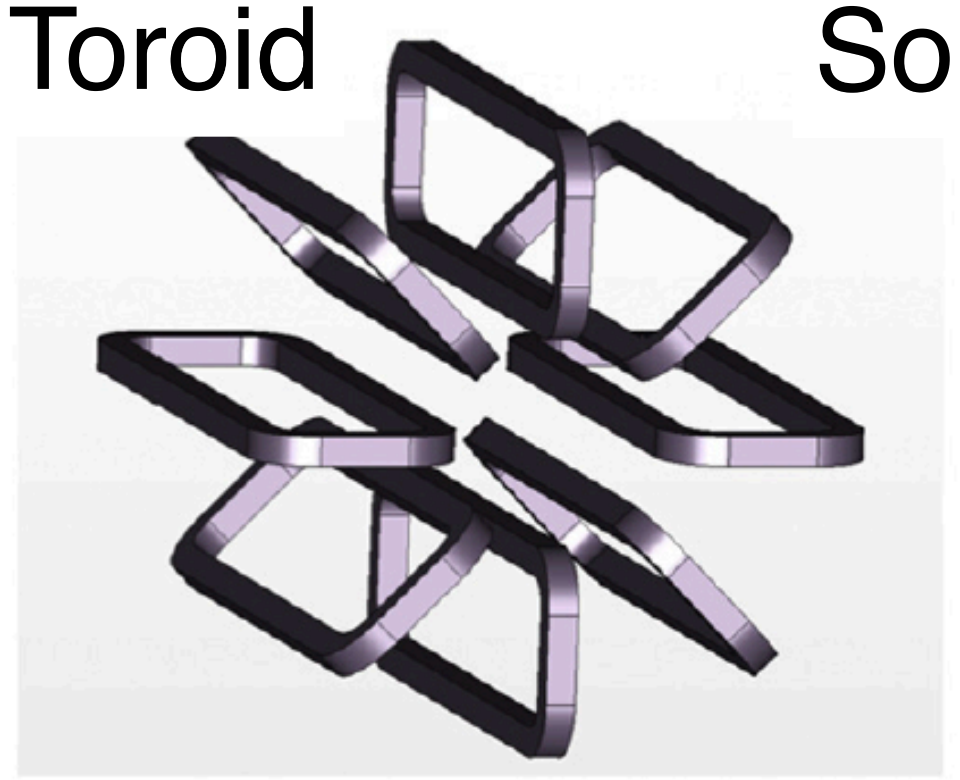
$$\mathbf{F} = q(\mathbf{E} + \mathbf{v}\mathbf{B}) \rightarrow r = p_T/qB \rightarrow (\delta p/p) \approx p_T/BR^2$$

R = radius of the volume, where the particle track is reconstructed.

Strong field and/or large R

- Pro: improved resolution
- Cons: confines low p_T particles at smaller radii

Toroid



Solenoid

Solenoids

- Conceptually simple and very effective: cost ~ LR^2B^2 (large R → better $(\delta p/p)/\$$)

Toroid

- In theory ideal for a 4π detector. No need for iron yoke and no field along the axis of the beams that could disturb the beam dynamics
- Not the most popular because of the difficulty of making in practice anything resembling an ideal toroid. Also coils (=material) close to beam pipe.

Magnet

Source: CERN/WP8, Snowmass, ECFA

Choices:

- size (R, L) and B
- place the coil in front of the calorimeter system or behind the electromagnetic or hadronic calorimeter:
  - behind calorimeter → larger magnets → larger cost
  - in front of the calorimeters → have to be ultra-thin and optimally represent $< 1\ X/X_0$

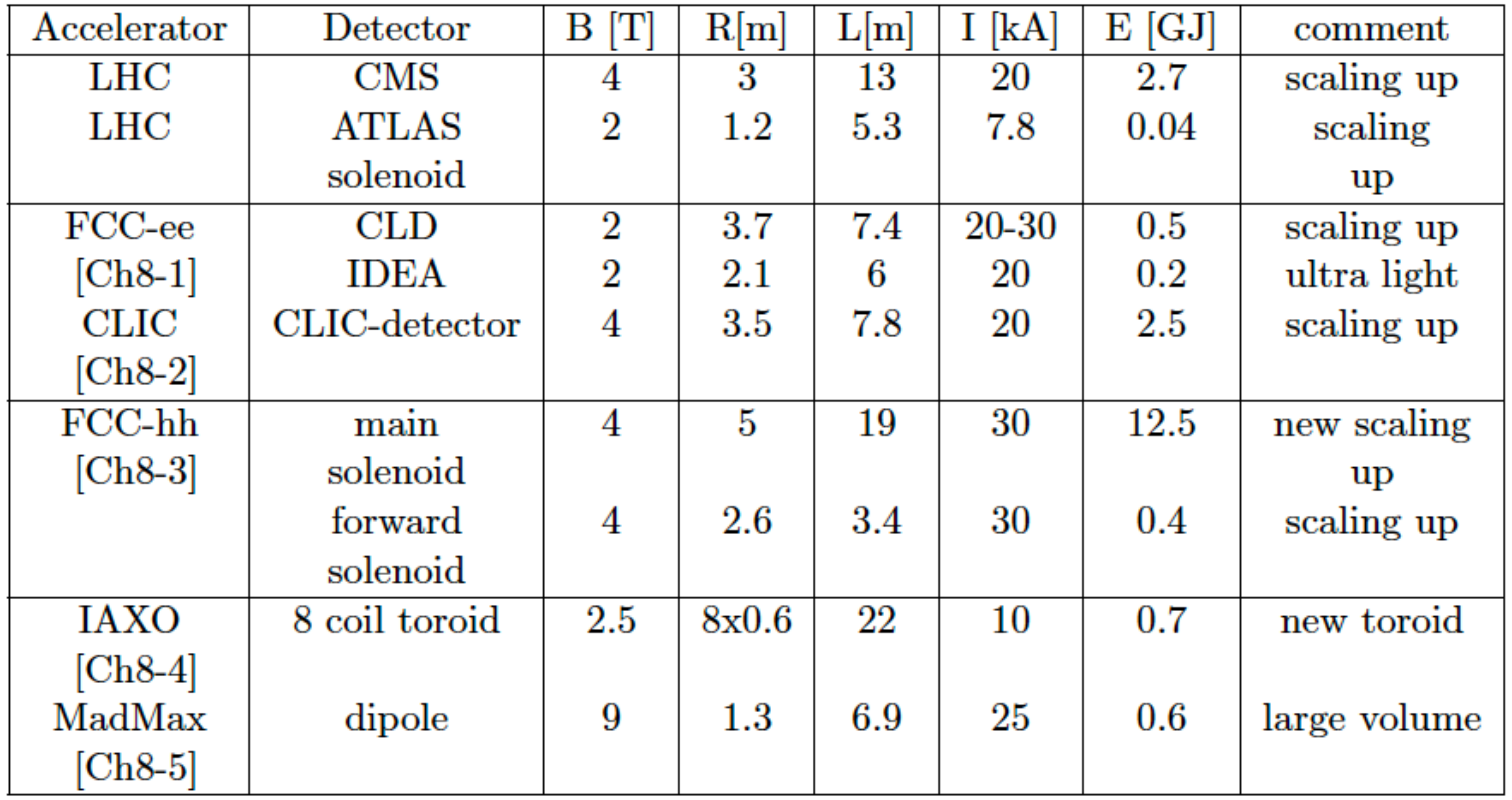
R&D:

- Thin conductors based on Al/Cu/NbTi together with a cryostat made from an Al honeycomb structure could achieve this goal (verified). R&D on dedicated conductors and prototyping is needed.
- In the long term, the development of HT superconductors for coils and current leads would remove the need for He temperatures and allow operation at 30-40 K.
- Some detector proposals use dual solenoids instead of iron yokes for shielding of the field but R&D for assemblies of EIC sizes still has to be performed.
- Development of quench protection, energy extraction and high voltage designs for coils with high energy/mass ratios also needed.

Magnet

Source: CERN/WP8, Snowmass, ECFA

Examples of magnets for future experiments that represent the engineering and R&D challenges:



Accelerator	Detector	B [T]	R[m]	L[m]	I [kA]	E [GJ]	comment
LHC	CMS	4	3	13	20	2.7	scaling up
LHC	ATLAS solenoid	2	1.2	5.3	7.8	0.04	scaling up
FCC-ee	CLD	2	3.7	7.4	20-30	0.5	scaling up
[Ch8-1]	IDEA	2	2.1	6	20	0.2	ultra light
CLIC [Ch8-2]	CLIC-detector	4	3.5	7.8	20	2.5	scaling up
FCC-hh [Ch8-3]	main solenoid	4	5	19	30	12.5	new scaling up
	forward solenoid	4	2.6	3.4	30	0.4	scaling up
IAXO [Ch8-4]	8 coil toroid	2.5	8x0.6	22	10	0.7	new toroid
MadMax [Ch8-5]	dipole	9	1.3	6.9	25	0.6	large volume

CERN: Magnet R&D (WP 8) on advanced powering, 4-T facility, instrumentation

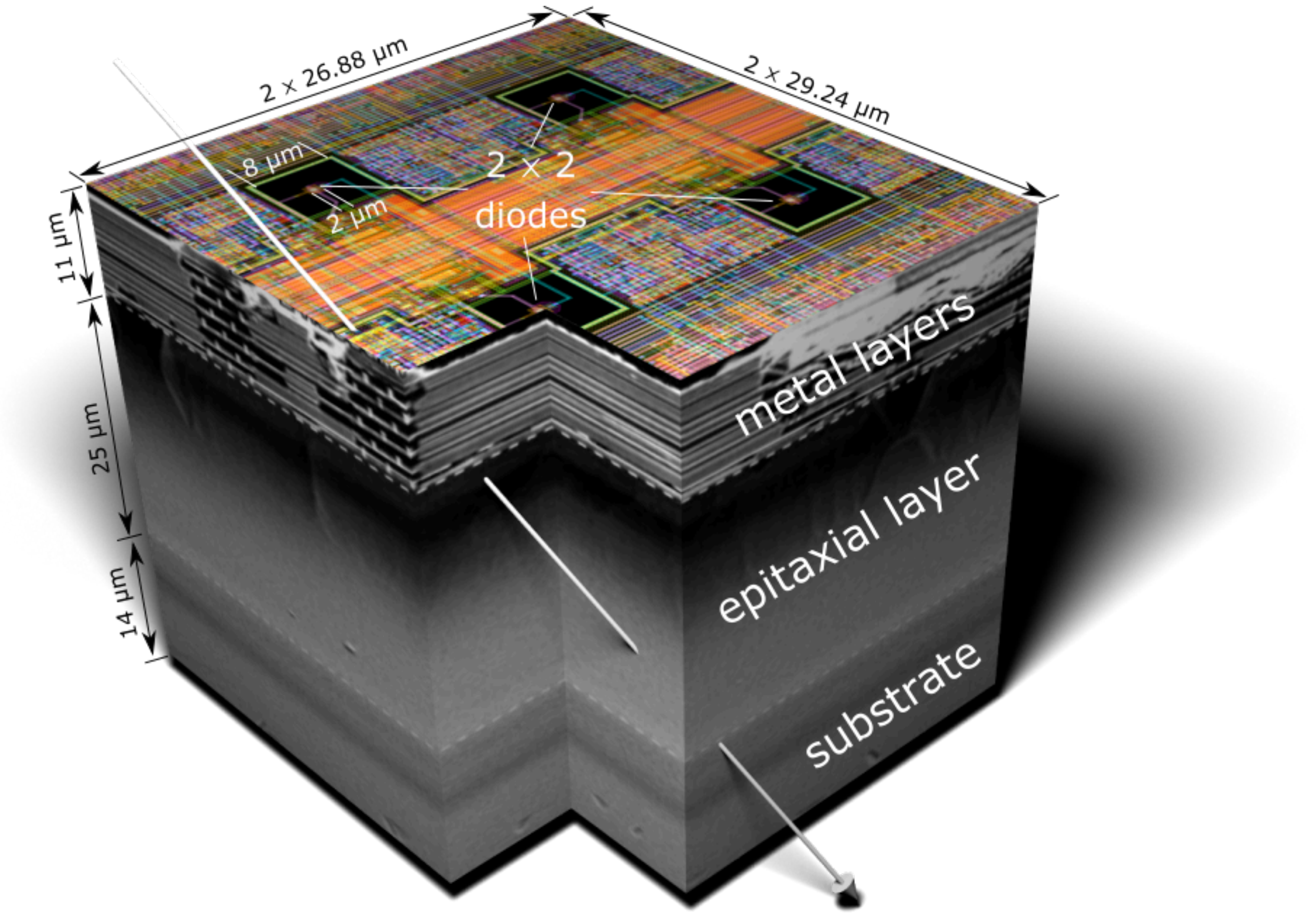
Reality check: anything but low X/X_0 coils is probably beyond a 2nd EIC detector's timeframe - expect no miracles.

Si-Tracking (3D)

Tracking - Silicon Based Detectors

Physics requirements:

- high spatial resolution $\leq 5\ \mu m$ (vertex $\leq 3\ \mu m$)
- very low material budget (lesson from EPIC)
- air cooling: power consumption < 20 mW/cm^2
- < 2 μs integration time

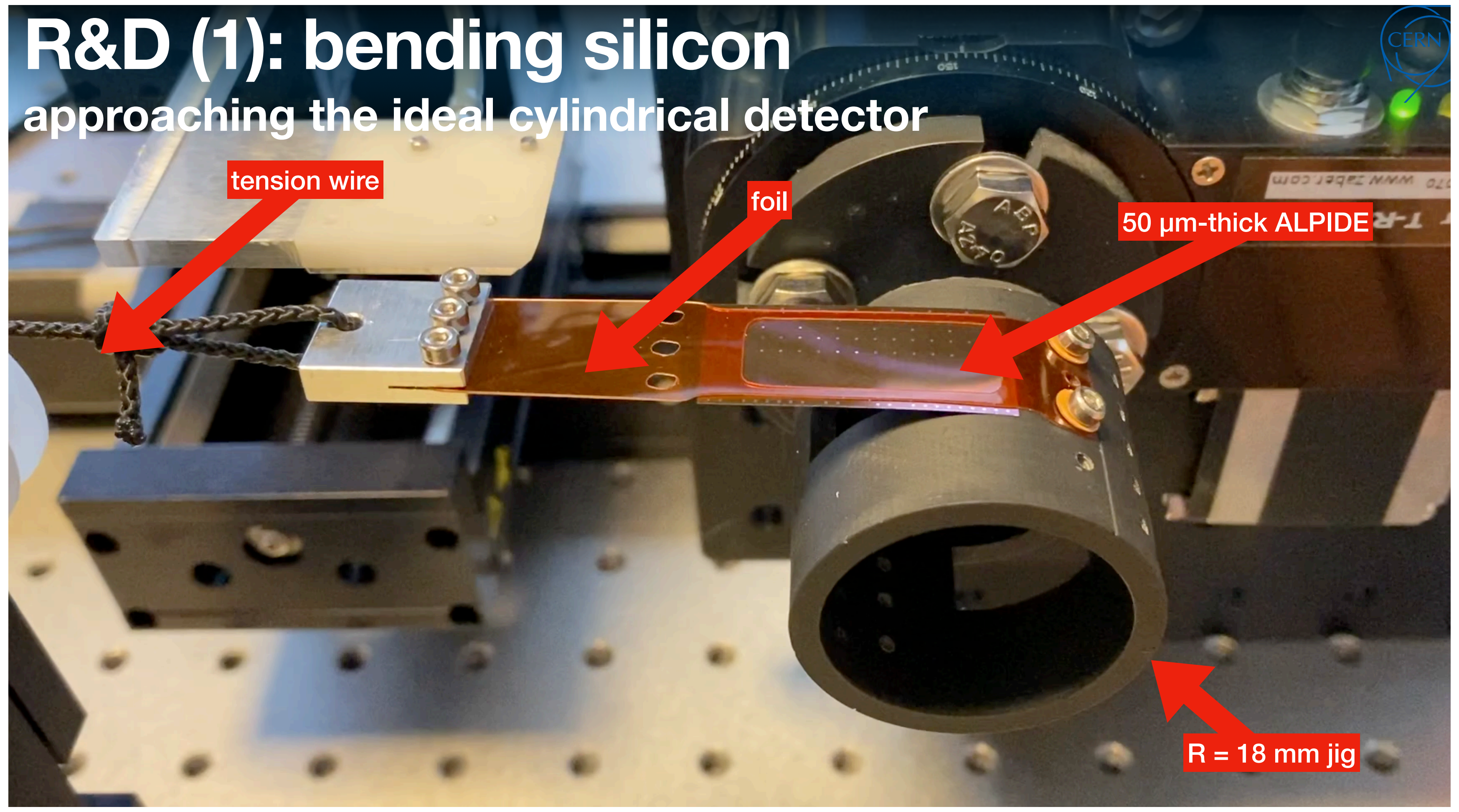


EIC/ePIC:

- Consensus that technology of choice is MAPS (used in ALICE, STAR, to be implemented in ePIC, CBM, LHCb, and Mu3e)
- None of the existing MAPS sensors (e.g. Alpide) meets all of the requirements
- EIC Si Consortium joined forces with ALICE/ITS3 collaboration developing novel MAPS sensor
- Goal is to develop Large-area, wafer-scale, stitched sensors bent around beam pipe using latest 65 nm MAPS technology
- EIC sensor development needs to fork-off later to develop an ITS3-derived sensor for outer layers (non stitched wafer-scale sensors)

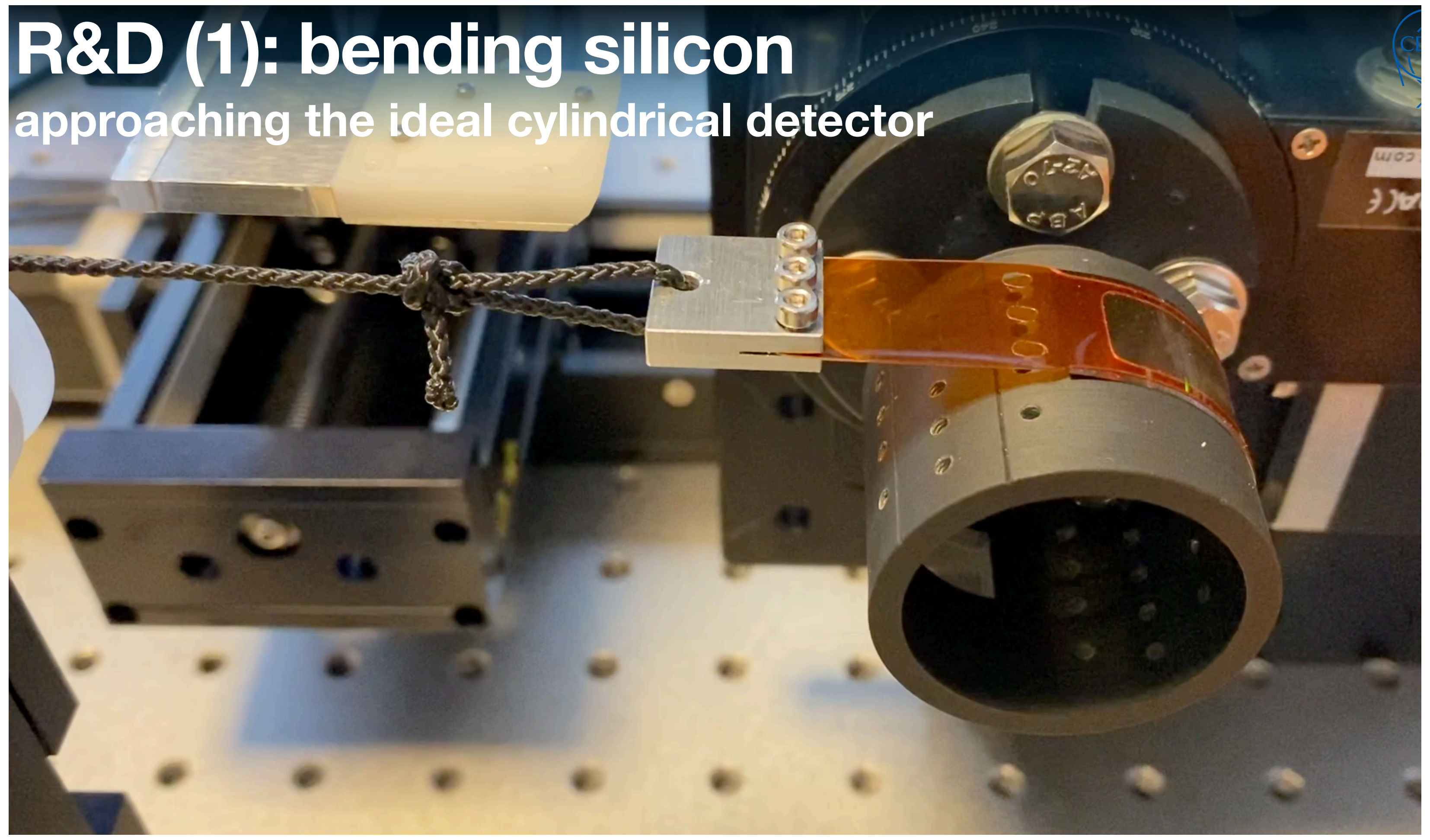
MAPS

- Silicon sensors manufactured using mainstream CMOS technologies
  - MAPS are especially suited for applications requiring low-mass and excellent position resolution
    - Very small pitches yielding the best position resolution achieved so far
  - Signal readout circuit integrated into the sensitive element
    - 50 μm thickness = the sensitive volume, a high-resistive epitaxial layer, the analog front-end (amplifier, discriminator), the readout electronics
    - minimise multiple scattering, leading to further position and momentum resolution improvements.
- ITS3
  - More advanced technology: 180 nm → 65 nm
  - Push technology: thinner, large sensors through stitching, less power consumption (air cooling)
  - Massive effort at CERN (~30 FTEs)



R&D (1): bending silicon

approaching the ideal cylindrical detector



R&D (1): bending silicon

approaching the ideal cylindrical detector

Bending 20 μm silicon

MAPS

- ITS3 not perfect
  - integration time ~5-10 μs (ALICE seeks low power: $t_{\mathrm{int}} \propto 1/(W/\mathrm{cm}^2)$)
  - timing precision ~OK for EIC but much room for improvement
  - geometry/coverage affected by foundary limitations
- R&D
  - Stitching techniques must be developed to provide large area sensors, which are vital in building low mass large area trackers.
  - Thickness of the MAPS is the ultimate limit to the device's scattering material, and new designs must allow novel advances in post-processing techniques.
  - MAPS with reduced granularity and very low power consumption in very large area detectors for tracking and calorimetry applications (compete with MPGD)
  - Improve designs to reach ultimate timing precision of ~ 100ps in different processes
- Who?

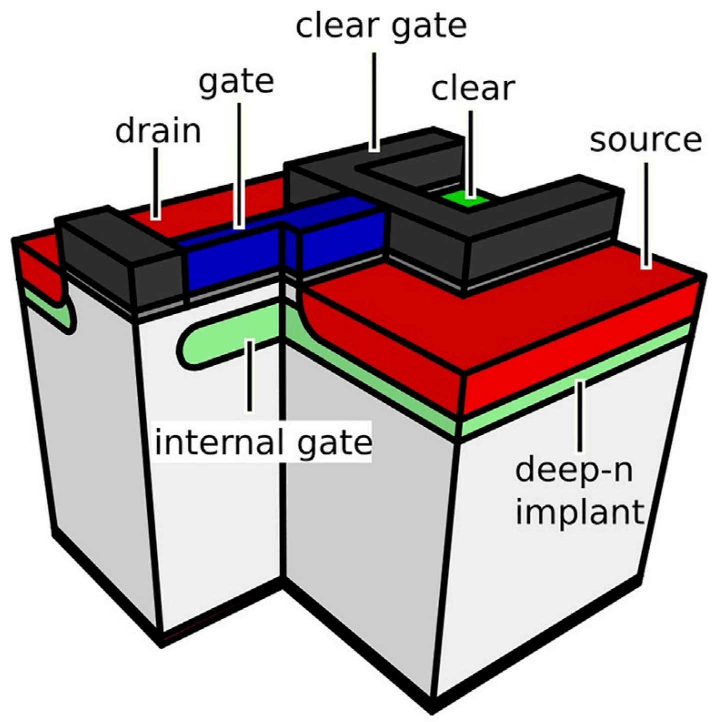
Alternatives to MAPS

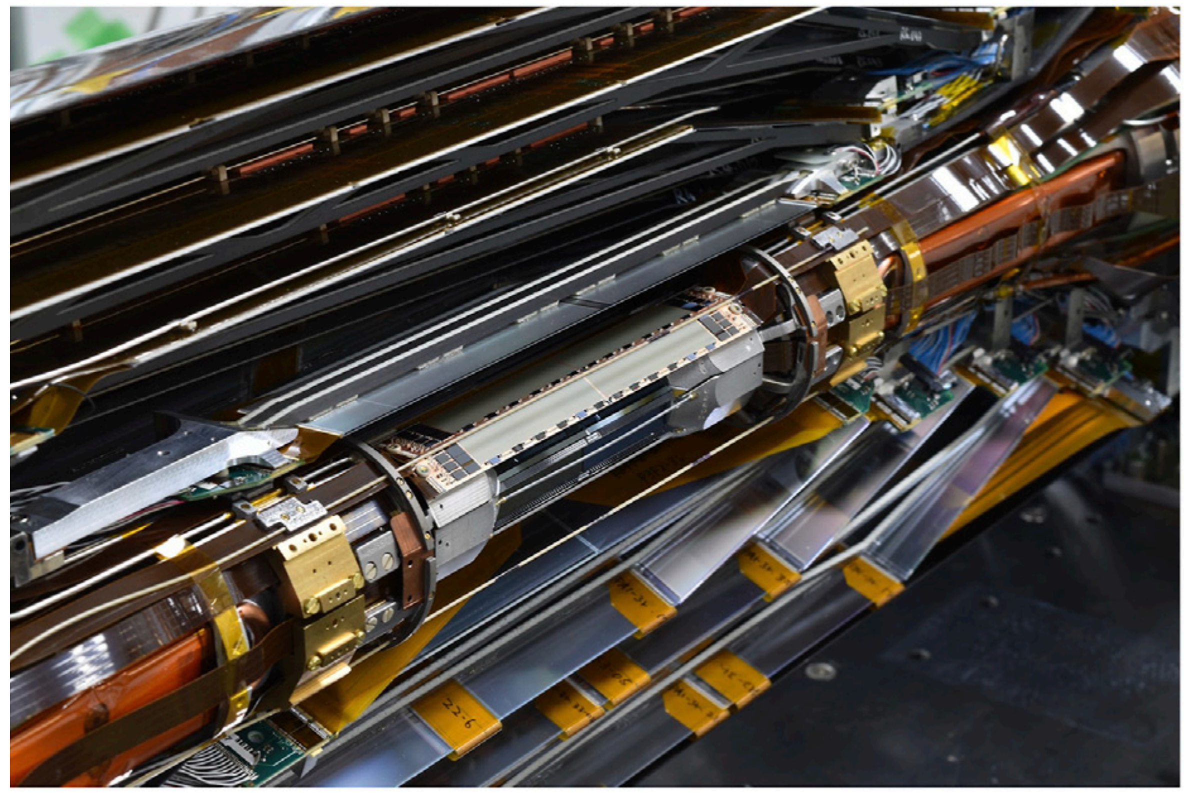
Source: Belle-II, Andricek et al., Front. Phys. 10:896212, ECFA, Snowmass

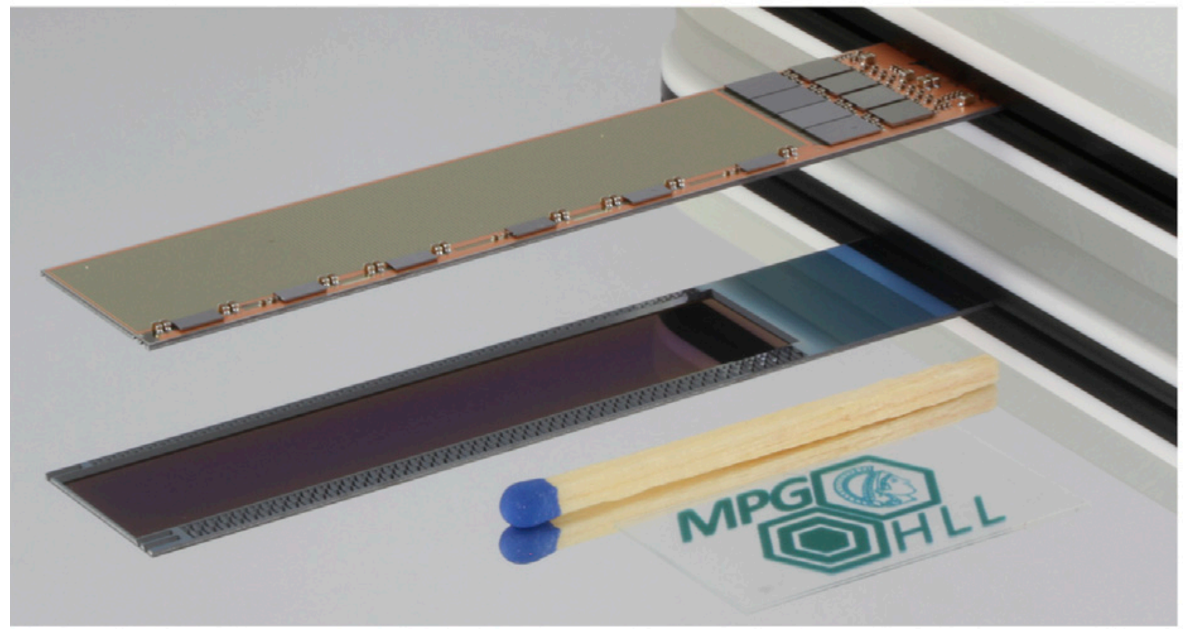
- Alternatives to (D)MAPS include those with split charge amplification and readout sectors: DePFET, FPCCD (ILC, Fine Pixel CCD), MONOPIX (targets radiation hardness), MALTA
- DePFET
  - active pixel sensor combining sensor and first amplification stage
  - MOSFET built on a high resistivity n-doped silicon wafer
  - used by Belle II, planetary science mission BepiColombo, ATHENA satellite
  - Belle-II:
    - fully depleted sensor is thinned to 75 µm thickness
    - module = array of 256x768 pixels of 55x50 µm^2

	Belle II
Frame thickness	525 µm
Sensitive layer	75 µm
Switcher thickness	500µm
Cu layer	only on periphery
Total	0.21 %X0

DePFET:

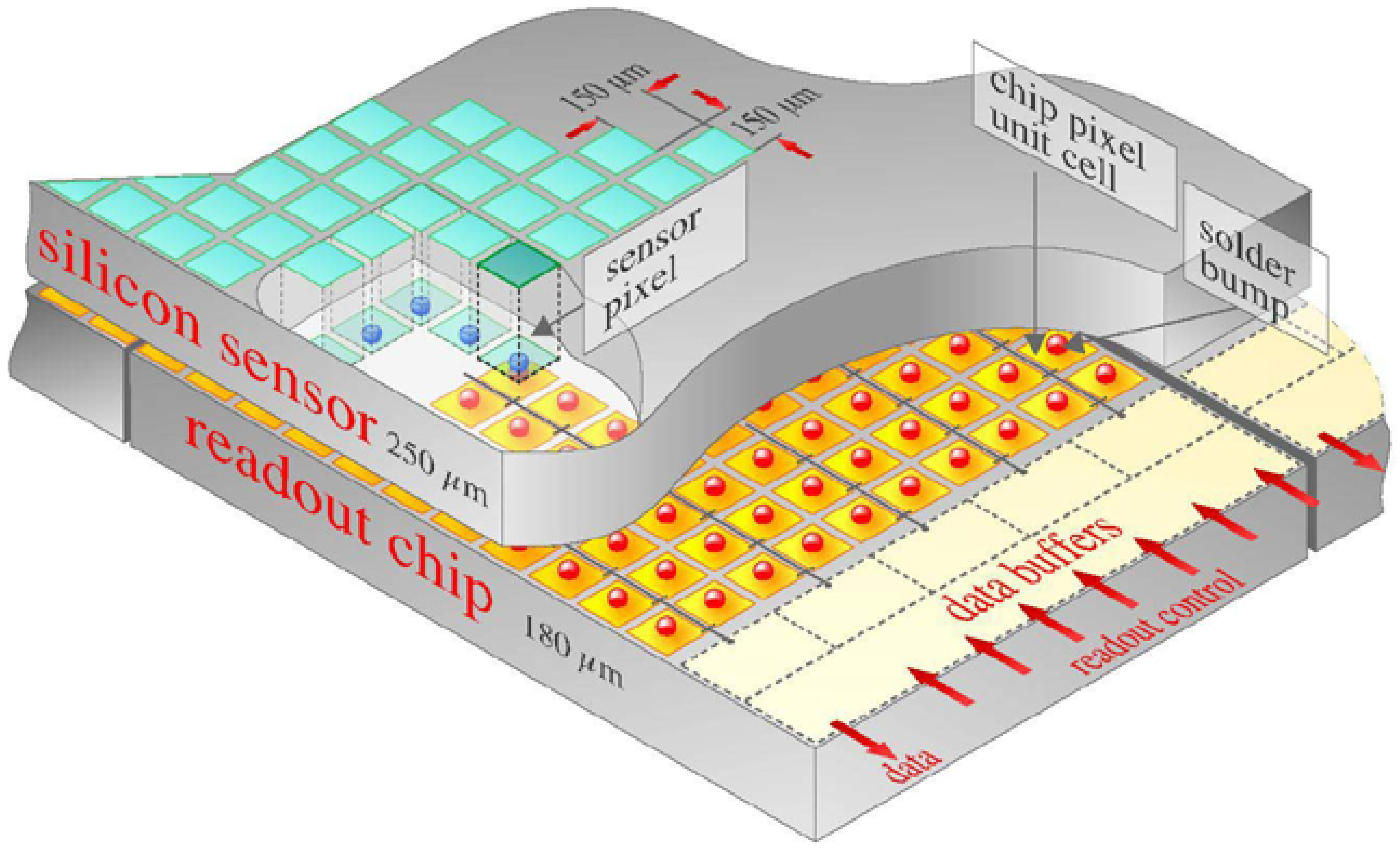






Are Hybrids an Alternative?

Hybrid = sensor + ASIC bonded



- Key technology for HL-LHC and FCC-hh
- Goals/Parameters:
  - Timing resolution 10 to 50ps
  - Pixel pitches 25 to 50µm
  - Fluences up to 10^{17} neq/cm^2/y
  - Max hit rate up to 20 G/cm^2/s
- X/X_0 ~ 0.5-2% acceptable for HEP
- Known example in EIC community: LGAD
- Hybrid are more radiation hard than MAPS, thicker, and have faster timing

Si Tracker

Reality check:

- MAPS/CMOS pixel sensors are the future for EIC detectors
  ➡ No other technology maps to EIC requirements like MAPS
- Experience in the community (STAR, ALICE, Si Consortium)
- HEP interest due to good match with FCC-ee might turn out beneficial
- Unclear if a next generation ITS3/EIC can be developed for D2 in time unless we start very soon (requirements)
- Independent: Stitching techniques must be developed to keep mass low
- Key is (as we leaned the hard way) to keep $(X/X_0)_{\text{layer}} \leq 0.1\ \%$

Of high interest (also R&D needed):

- MAPS with reduced granularity, very low power consumption for large area detectors
- MAPS with reduced granularity and excellent timing (EIC generic R&D)

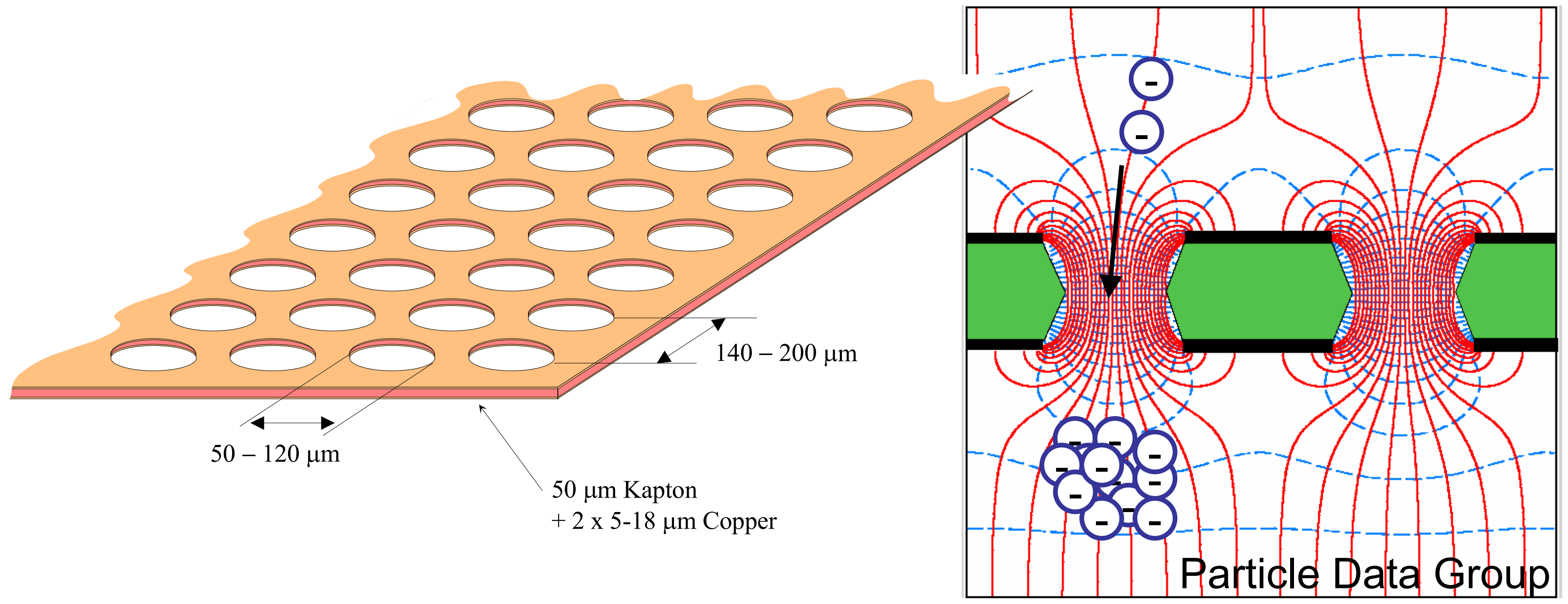
Non-Si Tracking

MPGDs

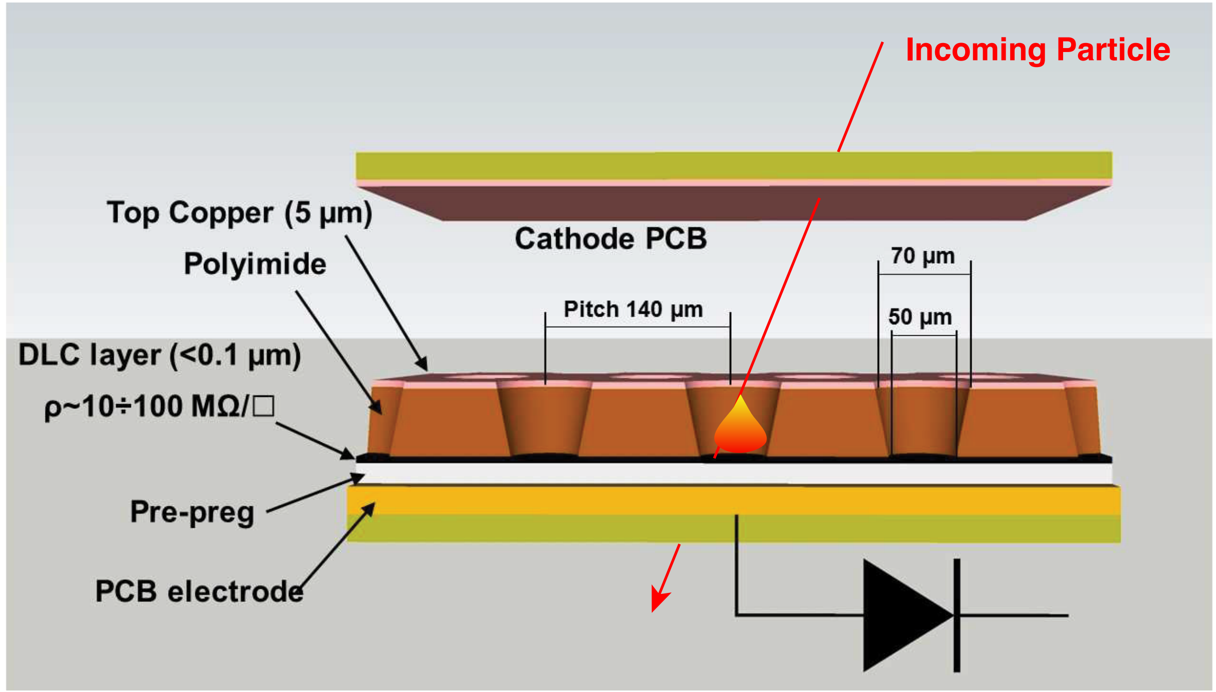
- Micro Pattern Gaseous Detectors (MPGDs) are primary choice for cost effective instrumentation of large areas with minimal detector material.
  - gas avalanche devices with order O(100 µm) feature size, enabled by modern photolithographic techniques.
- Critical in the past: RD51
- CERN MPGD Workshop often key supplier
- NP more active on MPGDs than HEP (EIC, FRIB, RHIC)
- Current MPGD technologies include
  - Gas Electron Multiplier (GEM)
  - Micro-Mesh Gaseous Structure (MicroMegas)*
  - Thick GEMs (THGEMs), also referred to as Large Electron Multipliers (LEMs)
  - Resistive Plate WELL (RPWELL) and its
  - GEM-derived architecture (µRWELL)*
  - the Micro-Pixel Gas Chamber (µ-PIC)
  - integrated pixel readout (InGrid).

*ePIC

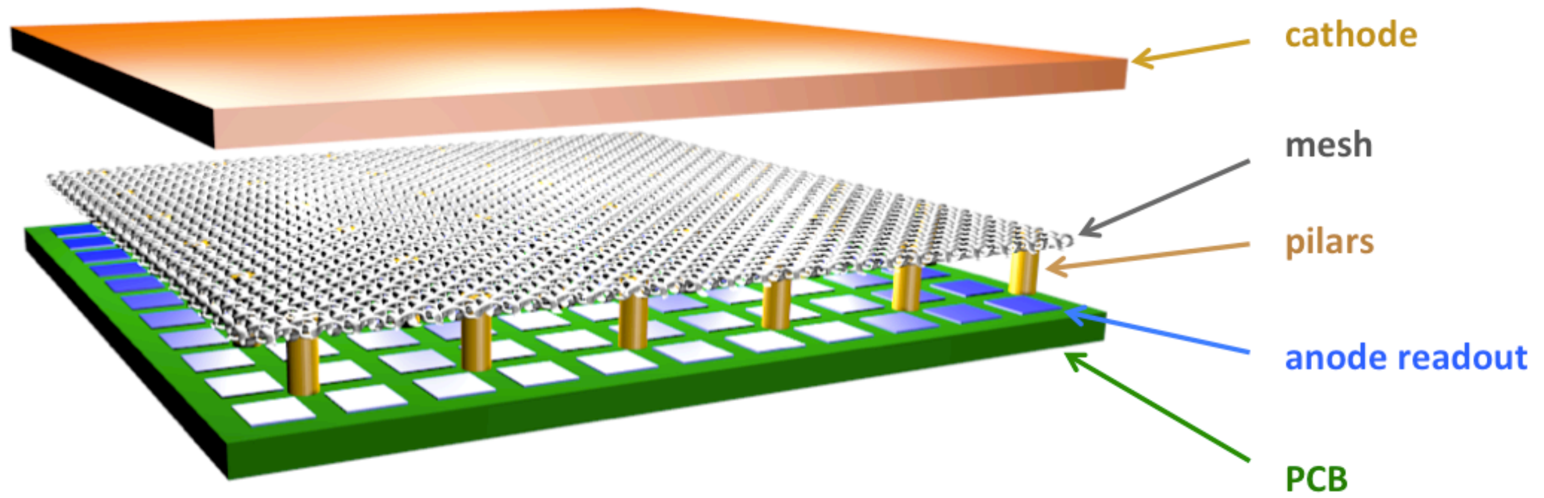
GEM



µRWell

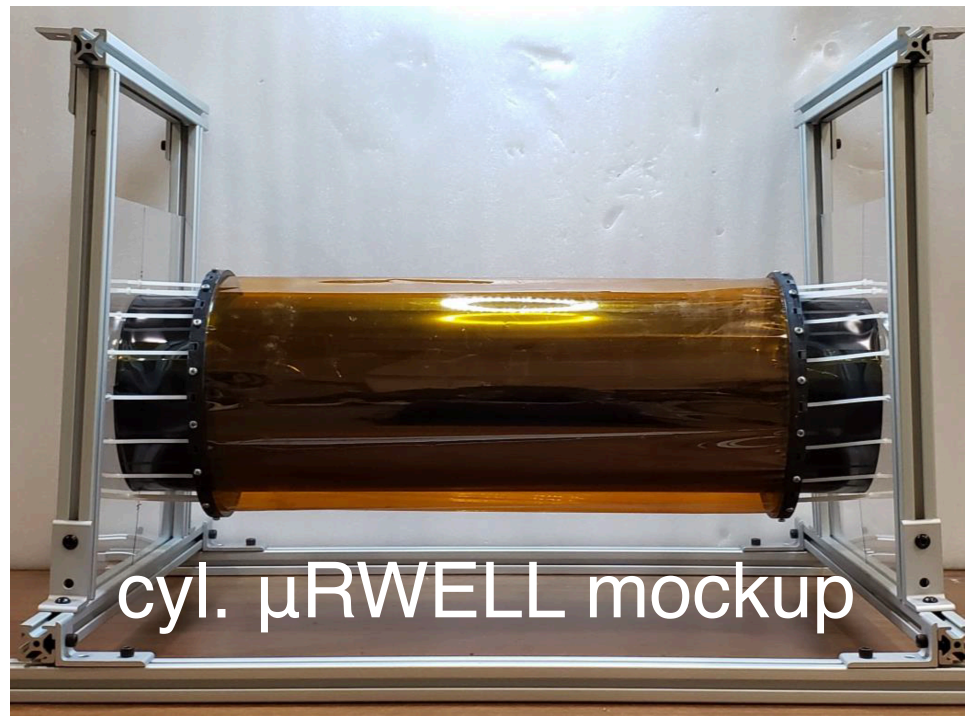


MMG



MPGDs

- MPGDs provide a flexible go-to solution whenever particle detection with large area coverage, fine segmentation, and good timing is required.
- R&D needed for curved/cylindrical applications and large area solutions (homogeneity, stability)



Reality check:

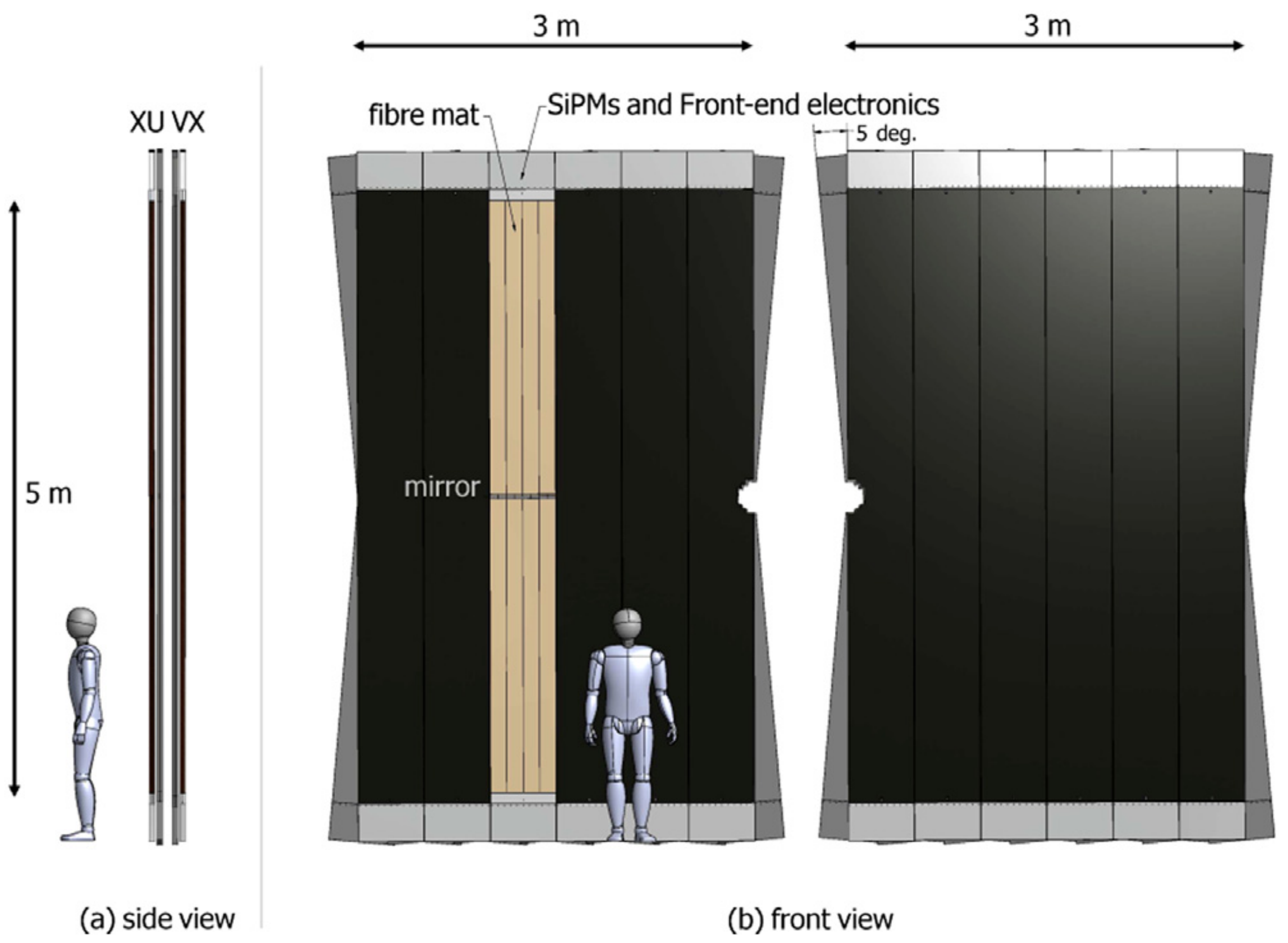
- MPGDs are here to stay. Many potential application (tracking, muon, …)
- Benefit from MPGD expertise in EIC community
- MMG and µRWELL increasingly favored over GEM
- Experience from ePIC (R&D prototypes) invaluable for D2

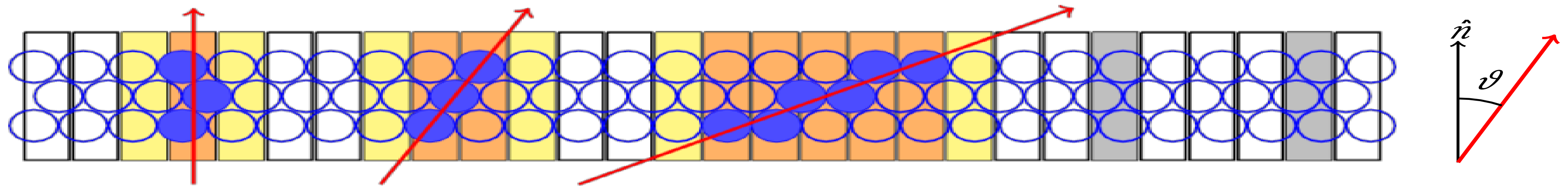
Scintillating Fiber (SciFi) Tracker

Source: LHCb

- Deployed by LHCb upgrade, PERDaix, Mu3E
- 4-6 layers of 250 μm fibers (stereo angles or xy)
- Read out by SiPM
- Achieve 100 μm resolution at overall low mass

  $$X/X_0 < 1\,\%$$
- Provides vector ⇒ improve pattern recognition





Reality check:

- Definitely something to look into benefiting from long time efforts and experience at LHCb (e.g. winding machine)
- Solid alternative to miniTPC

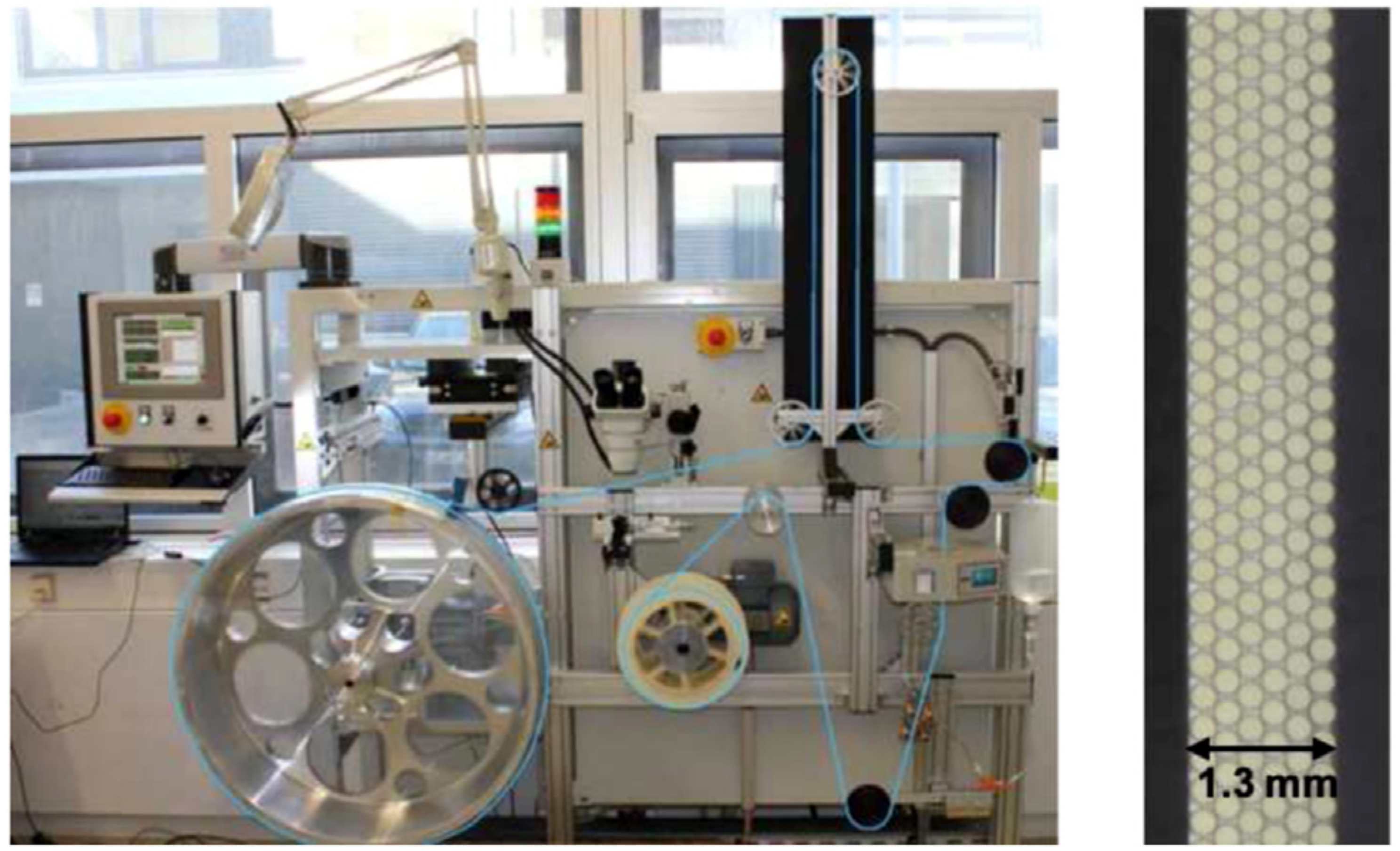


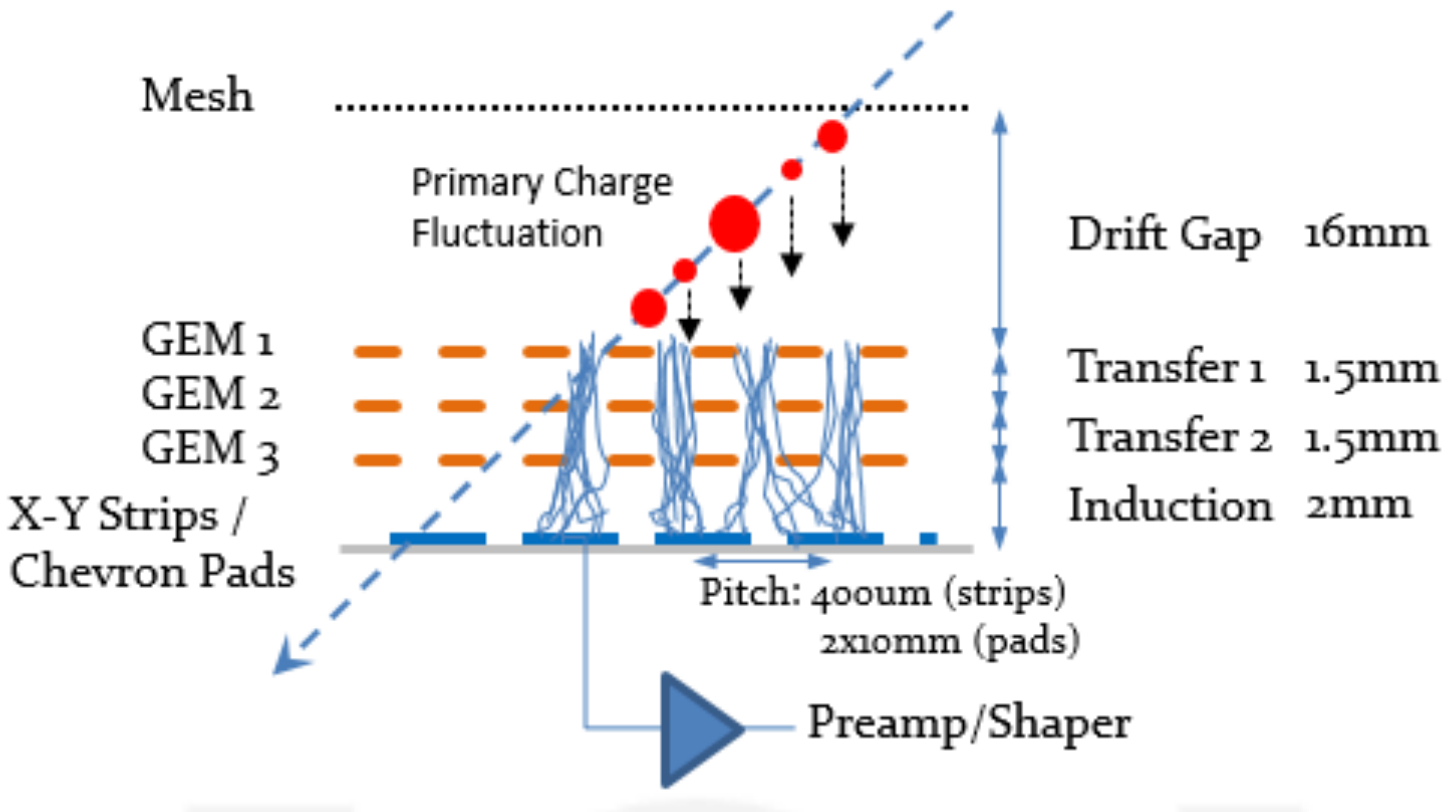
Fig. 3. Left: picture of the custom designed mat winding machine. Right: cross section of a fibre mat.

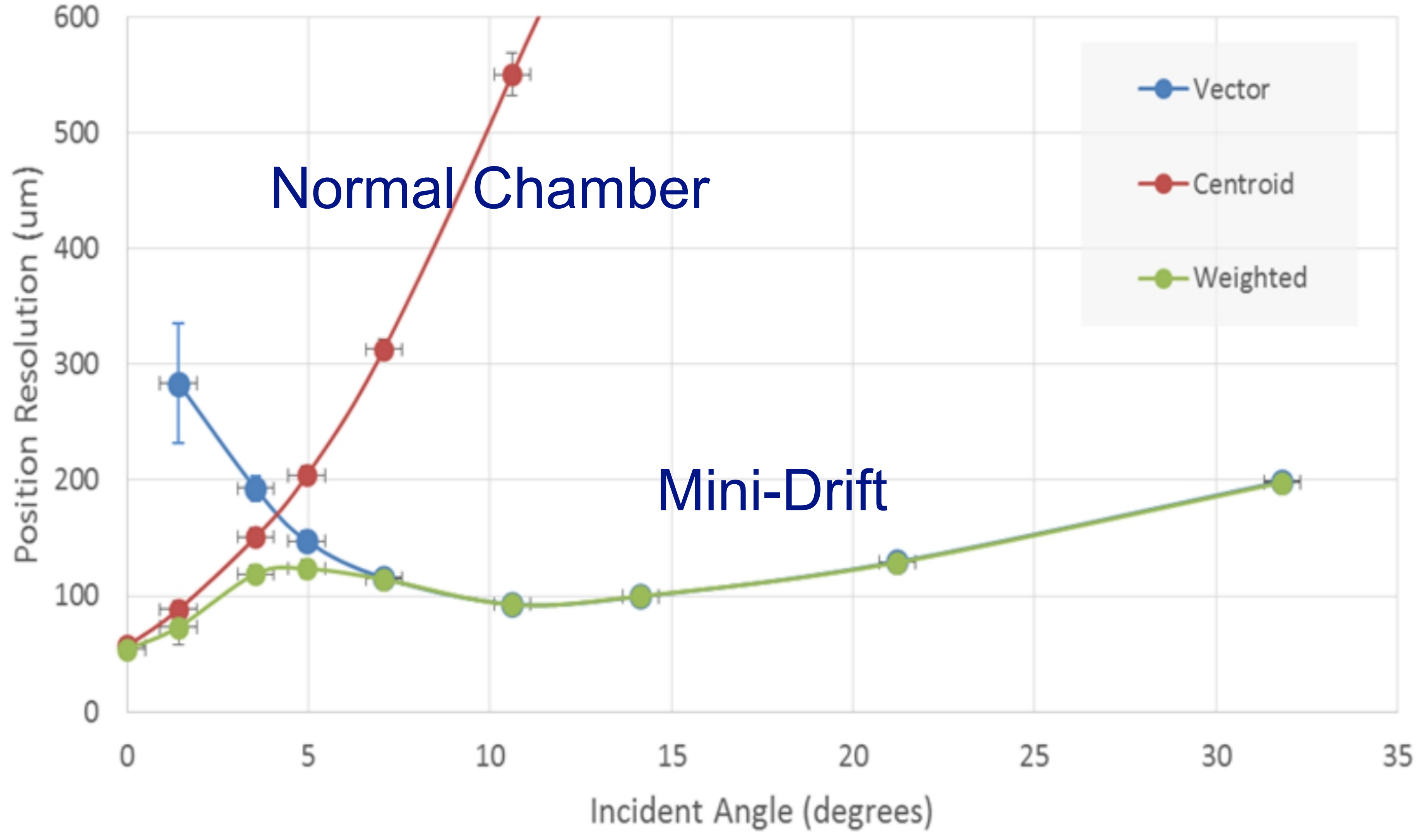
Mini-Drift GEM Detector aka miniTPC

- Basic idea: instead of single layer MPGD have a small draft region
- Position and arrival time of the charge deposited in the drift region is measured on the readout plane allowing reconstruction of track (vector) traversing the chamber improving patter recognition
- Typically GEM but other MPGD will do
- Prototypes tested in eRD6 (ZigZag pattern pad plane)

Reality check:

- Definitely something to consider.
- Could be crucial for pattern recognition
- Experience in EIC community (eRD6)
- Needs R&D for optimization - X/X_0

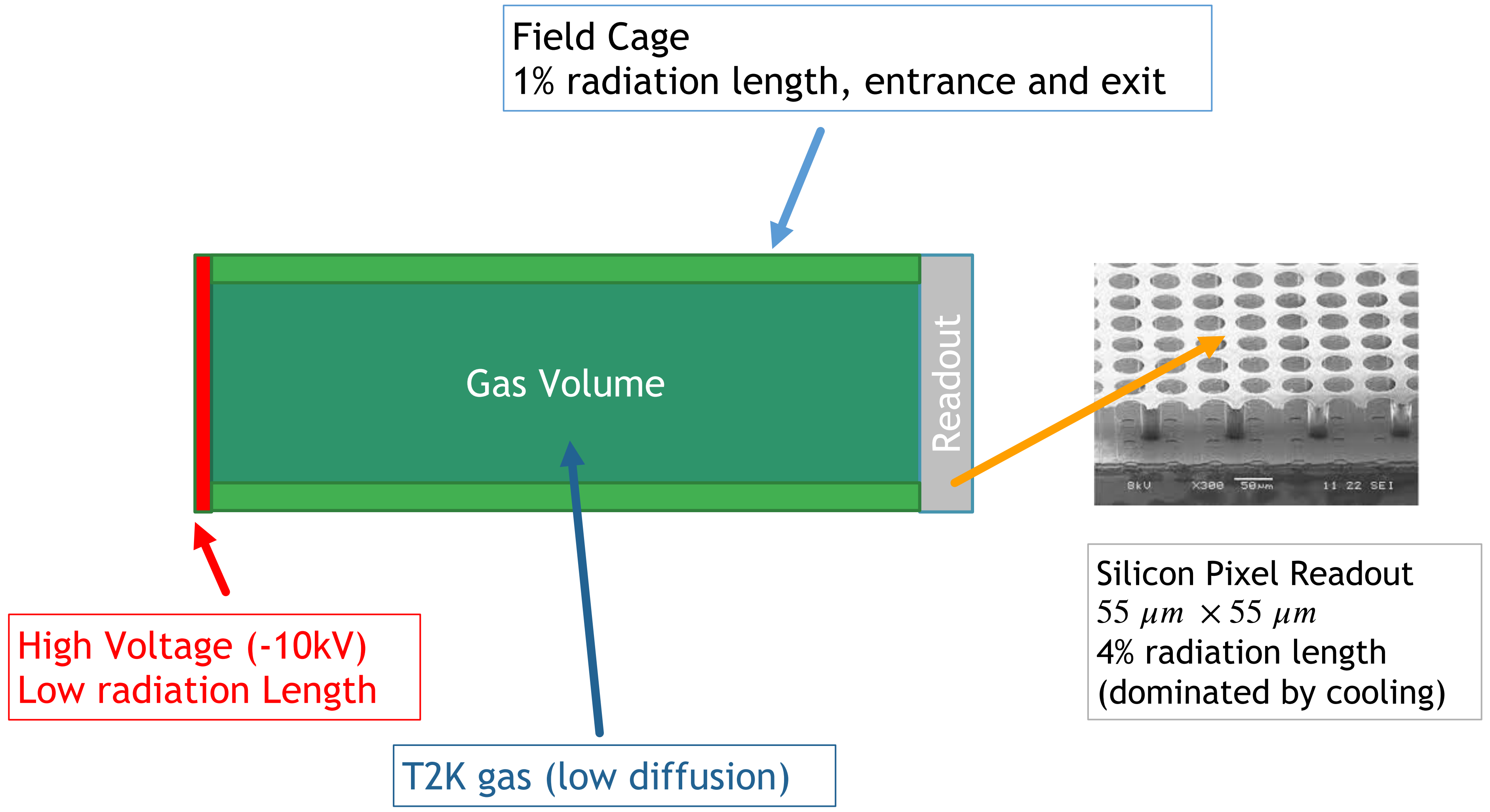




IEEE Transactions on Nuclear Science 63.3 (June 2016), pp. 1768–1776

GridPIX aka miniTPC

- Basic idea: Small ΔR TPC with Si Pixel readout on one endcap
  - PID ($\pi - K - p$) from 100 MeV/c to 800 MeV/c
  - Tracking with large number of hits (pattern recognition)
  - Works only in barrel (field!)
- GridPIX
  - Avalanche grid in front of 55 x 55 μm$_2$ pixels.
  - >90% efficiency for single electrons.
  - Small area is not particularly expensive: 1800 chips (order/produce/test 3600) = $716k
  - Careful: 1.2-5.4 kW of power
  - Services bulky: Gas, power, cooling
  - Realistic X/X_0?



Reality check:

- Very compelling for D2
- Provided tracking an dE/dx (compare with ToF/AC-LGAD)
- Excellent Pattern recognition
- Less sensitive to backgrounds
- Generic R&D ongoing
- Need to see concrete prototype

Drift Chambers

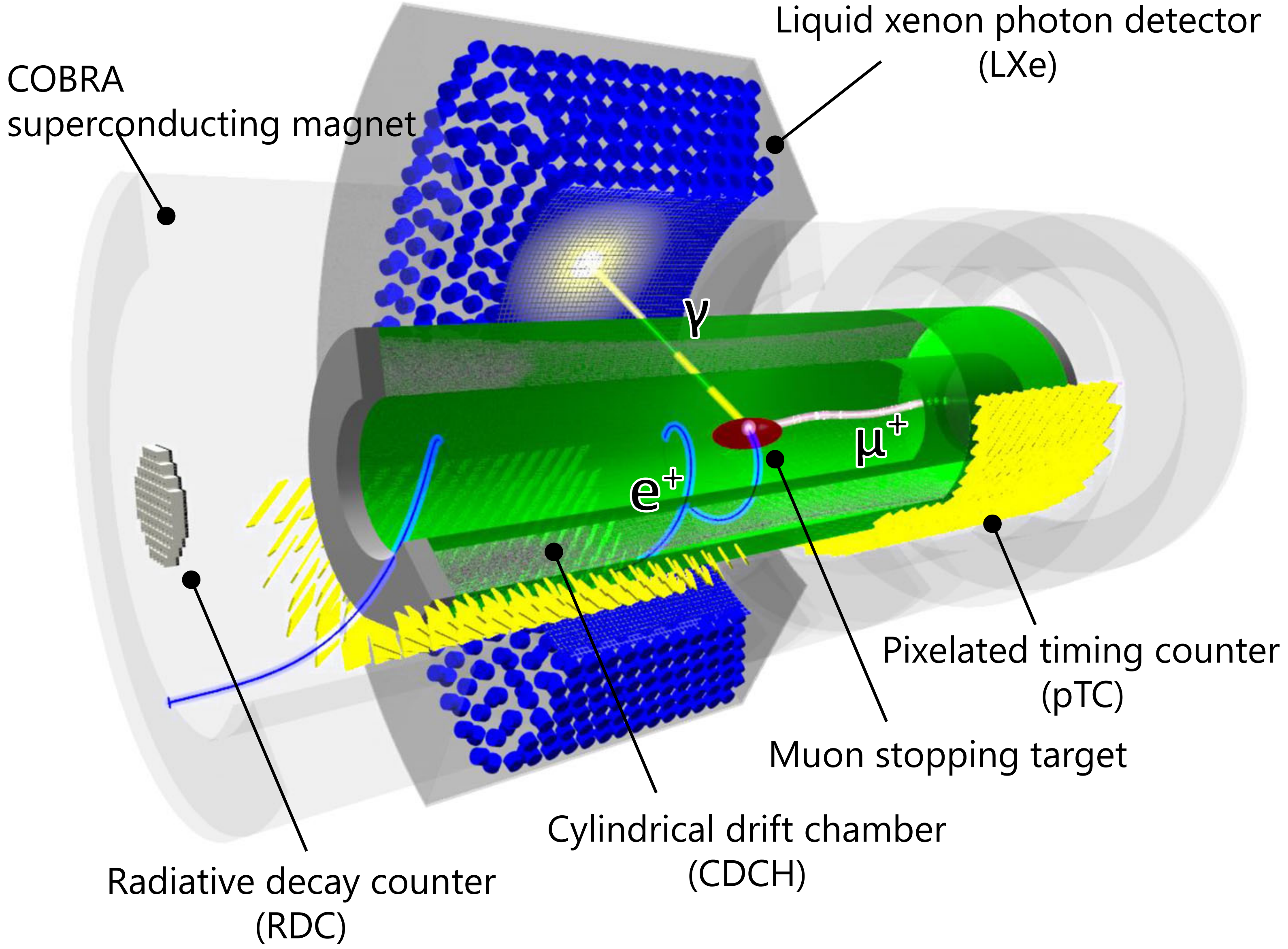
Source: MEG2, Snowmass, ECFA

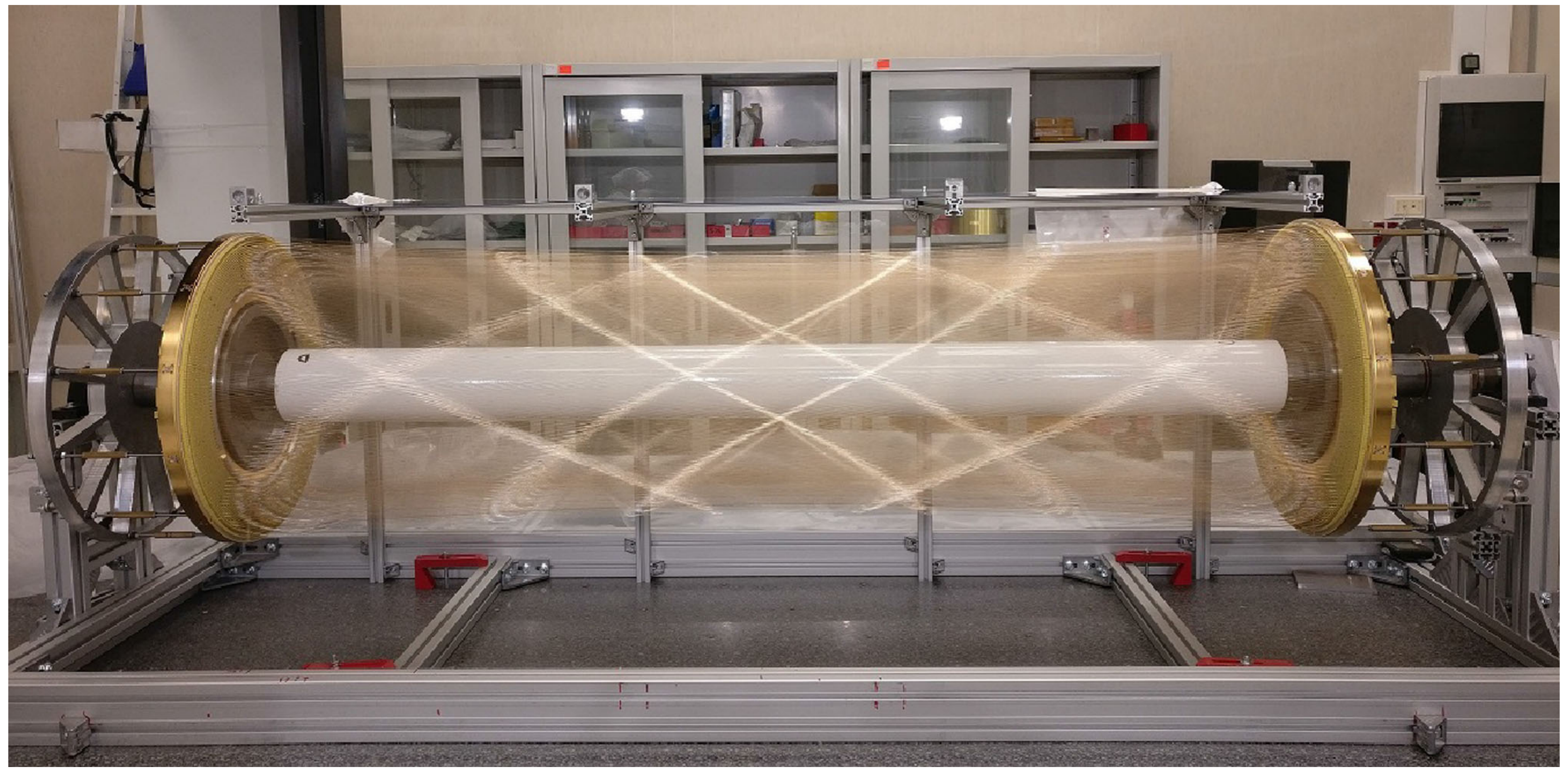
- Think twice if you consider this being old technology
- Huge progress thanks to KLOE and MEG2 drift chambers
  - Low radiation length thanks to novel approach for wiring and assembly procedures.
  - Total amount of material in radial direction, towards the barrel calorimeter is of the order of 0.016 X_0.
  - ~0.05 X_0 in the forward and backward directions, including the end-plates instrumented with front-end electronics.
    - obtained thanks to an innovative system of tie-rods, which redirects the wire tension stress to the outer end-plate rim
  - High granularity, all stereo, cylindrical drift chamber filled with helium based gas mixture. Resolution ~ 100 μm
- FCC-ee/IDEA: inspired by MEG2 a large-volume extremely-light drift chamber surrounded by a layer of silicon detector

Reality check:

- Compelling but w/o expertise in community and R&D it is hard to see this as a viable alternative. X/X_0 might still be too much.

MEG2





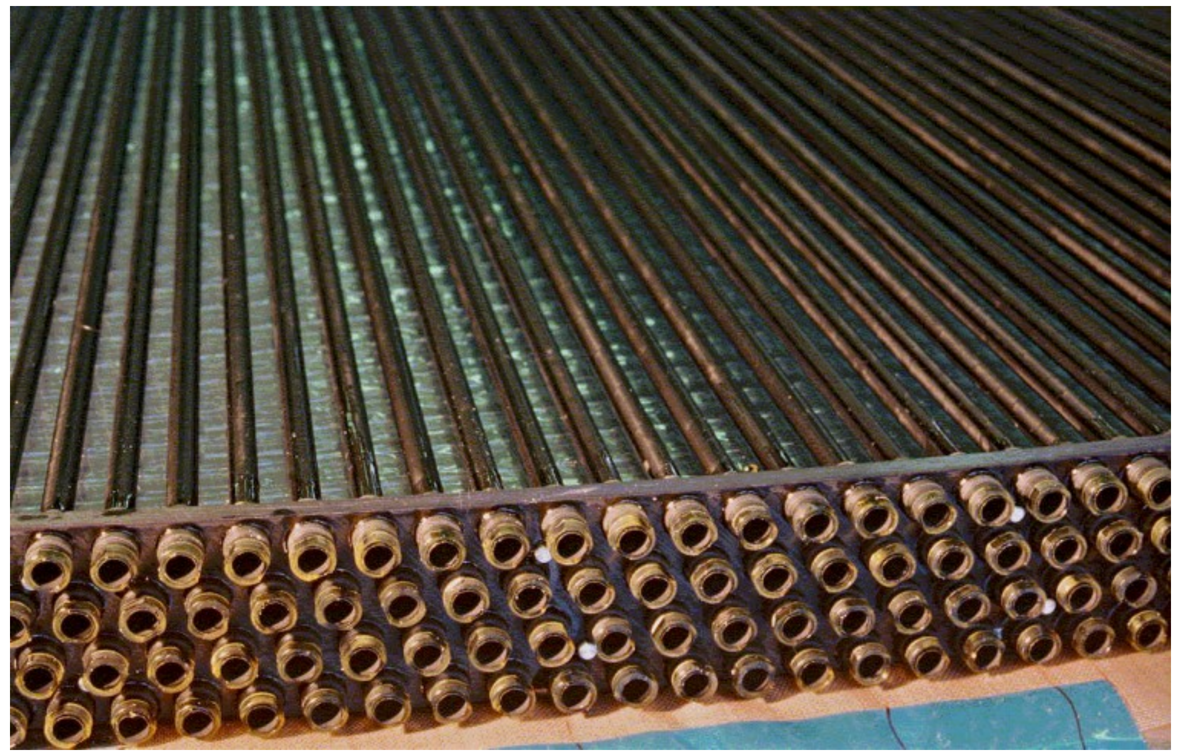
Eur. Phys. J. C (2018) 78:380

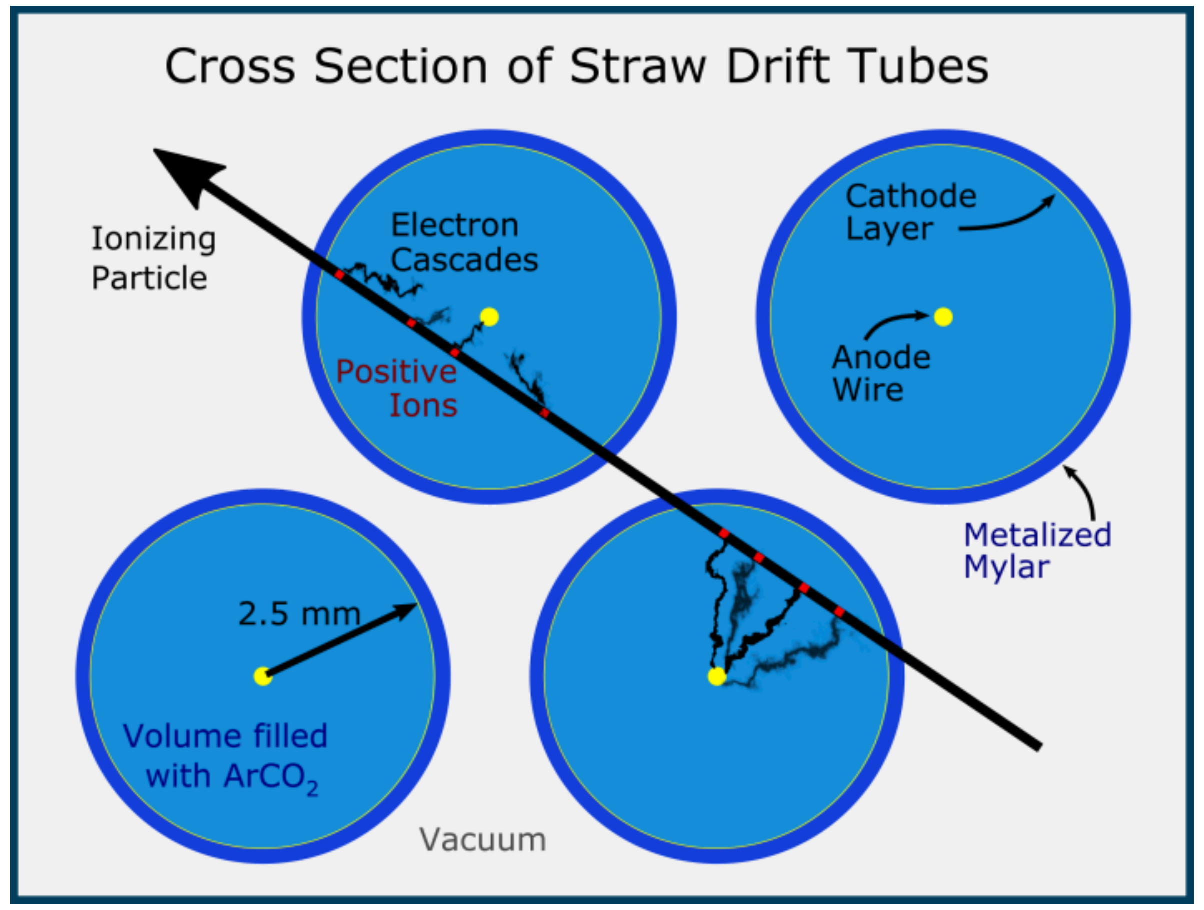
Straw Tracker

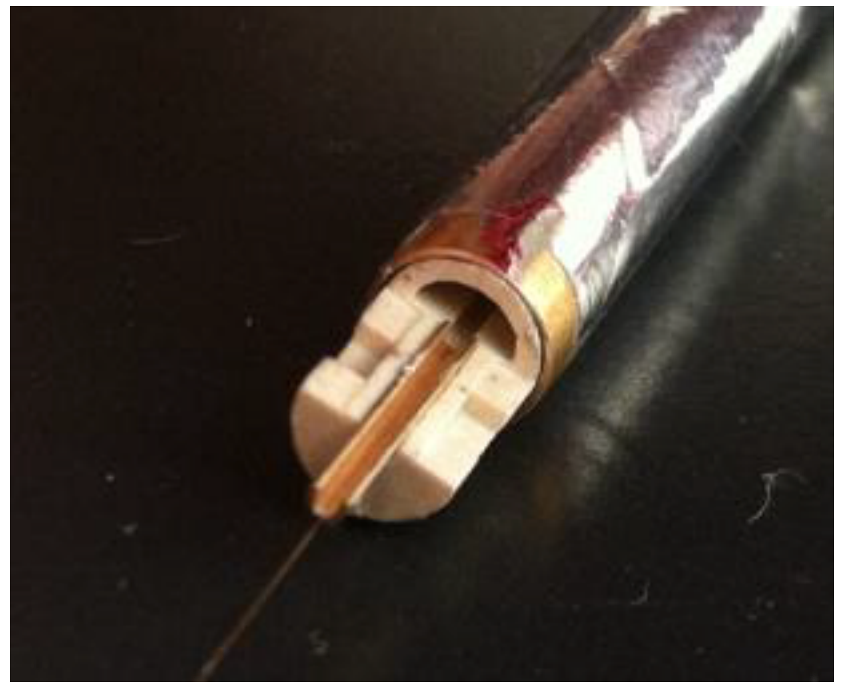
- Self-supporting straw tubes with thin anode wire and an aluminised mylar cathode wall
- Offers a combination of short drift time, low mass, and high spatial resolution tracking by using long (a few meters) and small diameter (< 1 cm) straws, arranged in planar layers and mounted in a hexagonal array.
- Examples:
  - DELPHI, HERA-B, FINUDA, COMPASS, LHCB, ATLAS, NA62, PANDA, g-2
  - NA62: state of the art 0.45% X/X_0. New construction techniques of ultrasonic welding to close the straw
  - PANDA - 10mm diameter and 1.5m length tubes, made of a 27 μm thick mylar foil 1.2% X/X_0, spatial resolution 150 μm.

Reality check:

- Exists, works, …
- Not necessarily better, easier than other solutions (MPGDs, Scintillating Fibres)

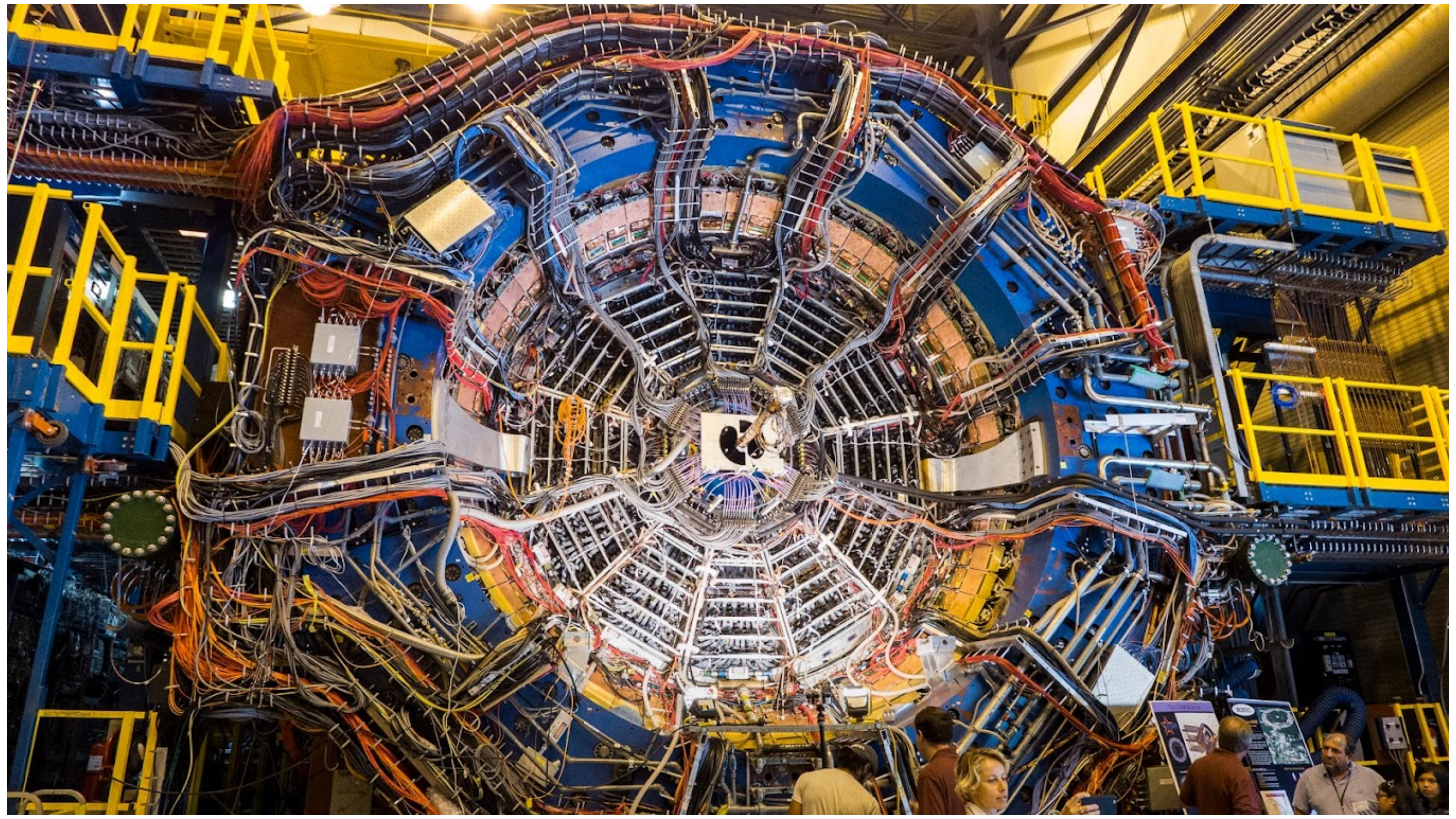


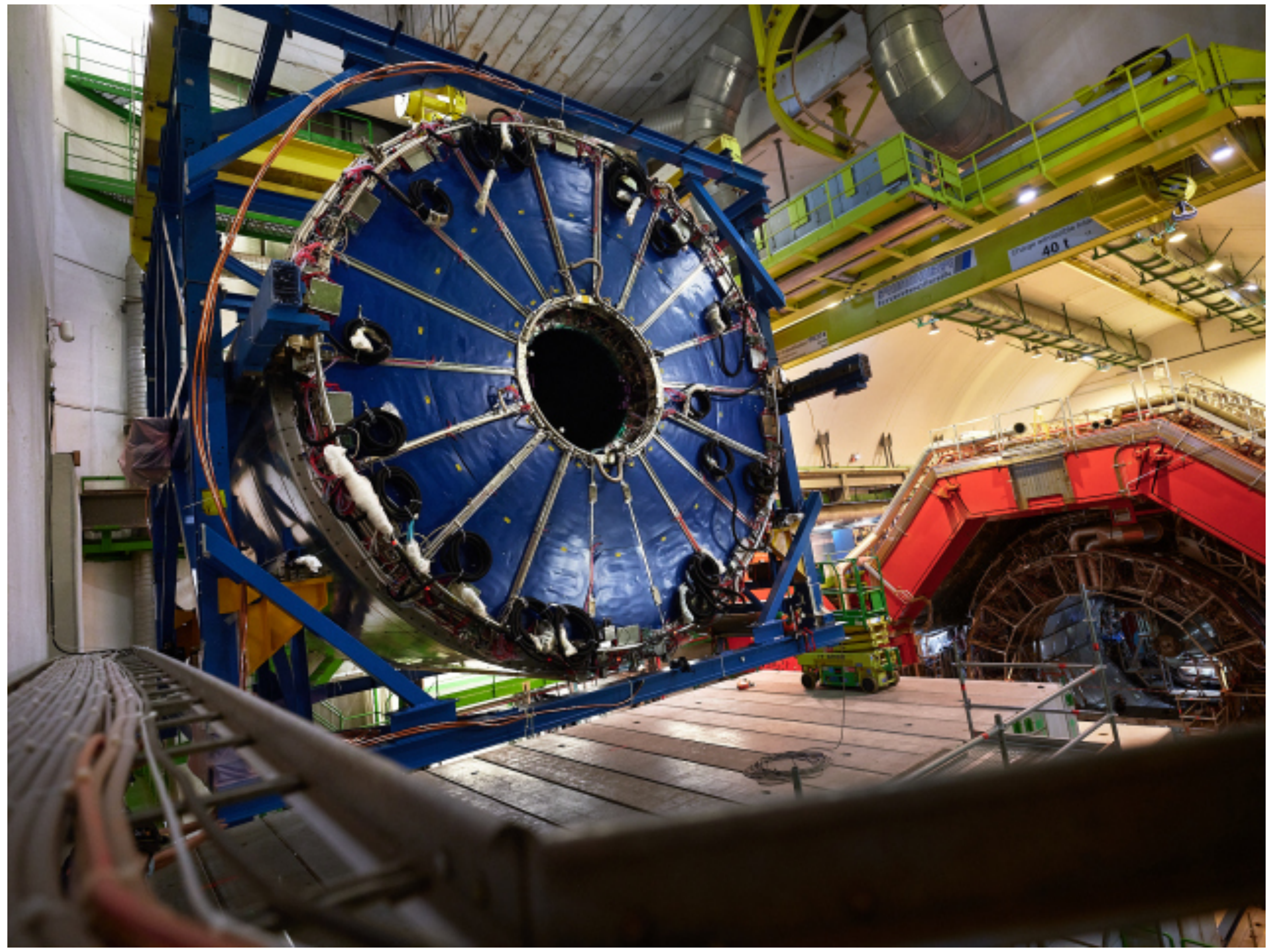




TPCs

Source: STAR, ALICE





Beyond a mini-TPC:

- Original EIC concepts contained a TPC (see YR) but dropped at the end.
  - too much material in endcap(s)
  - resolution cannot compete with Si tracker
- Every new TPC concept (ILC TPC, FCC-ee) considers MPGD readout (GEM, MMG, μRWell) or Gridpix.
- None solves the endcap X/X_0 issue

Reality check:

- Many of us know what a wonderful device a TPC is. It might just not be cut-out for the EIC (famous last words)

Calorimetry

Calorimetry

Electromagnetic Calorimetry

- Physics requirements:
  - σ_E/E very low where tracking is insufficient (EIC typically $|\eta| > 3$): 1.5 % - 10%
  - good γ separation ($\pi_0 \to \gamma\gamma$)
  - Most important: e/h ~ 10^4 over wide p_T range (DIS: $e' \to x, Q^2, y$)

Hadronic Calorimetry

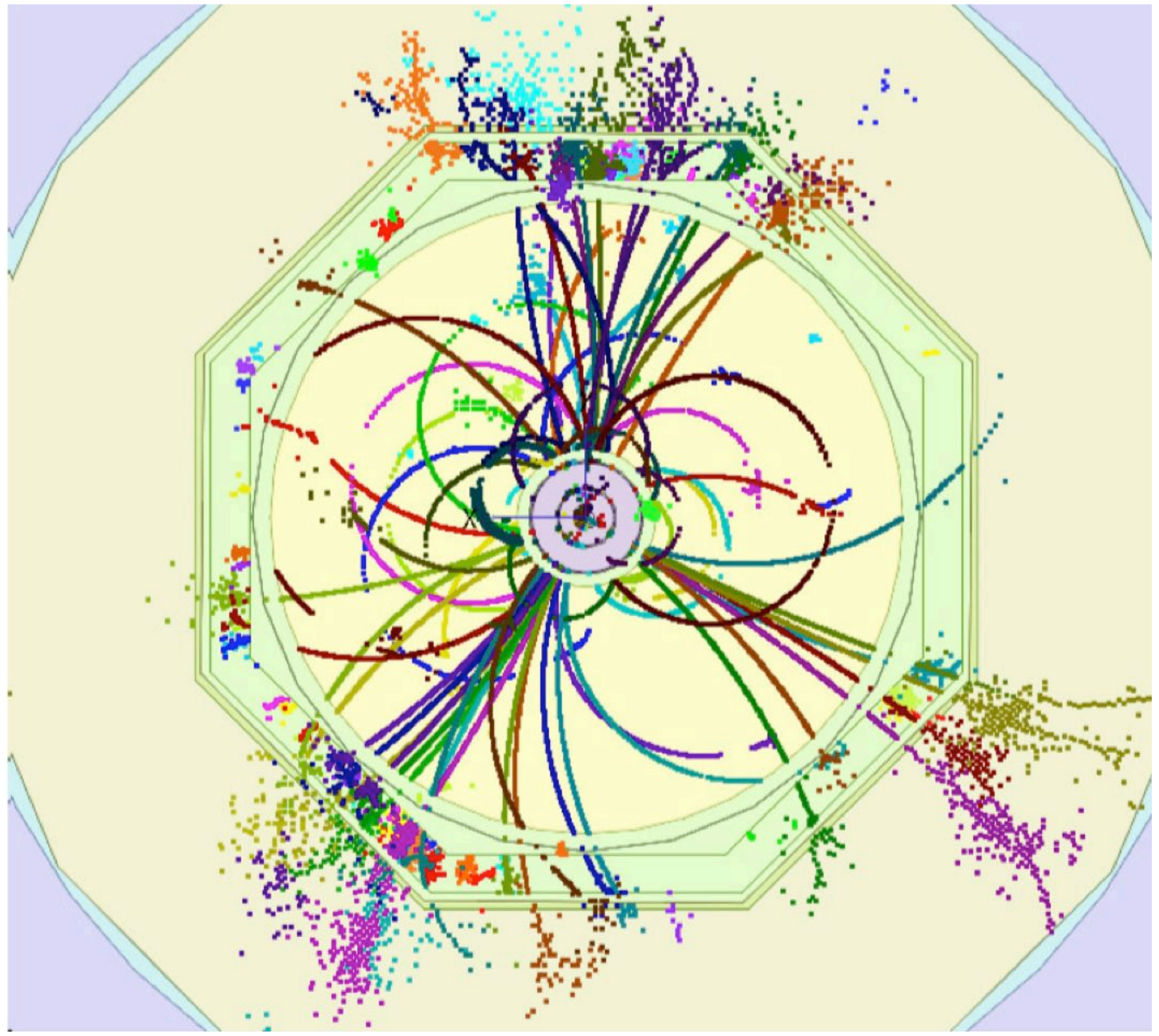
- Importance/Need
  - Forward region (p-going): high
  - Central: need debatable (neutral hadrons)
  - Backward: not really needed (as of yet)
- Physics Requirements
  - Forward: as good as one can push technology $\sigma_E/E < 40\,\%$, Central: ~70%-100%

Calorimeter Trends

Source: CERN R&D, Snowmass, ECFA

To reach the highest resolution

- Highly granular calorimetry
- Dual Readout (DR)
- Particle Flow Analysis (PF)



Goals:

- Multidimensional (5D), providing shower position, time, energy, and a detailed look at shower constituents via combination of PF techniques, materials with intrinsically good time or energy resolution, or DR techniques.

Issues:

- Massive R&D support is needed to achieve these goals.
- Scaling to tens of millions of channels while maintaining the required quality is a huge challenge.
- Electronics must be developed to allow new features such as fast timing without significantly adding to the power budget or cooling load.
- Cost are enormous

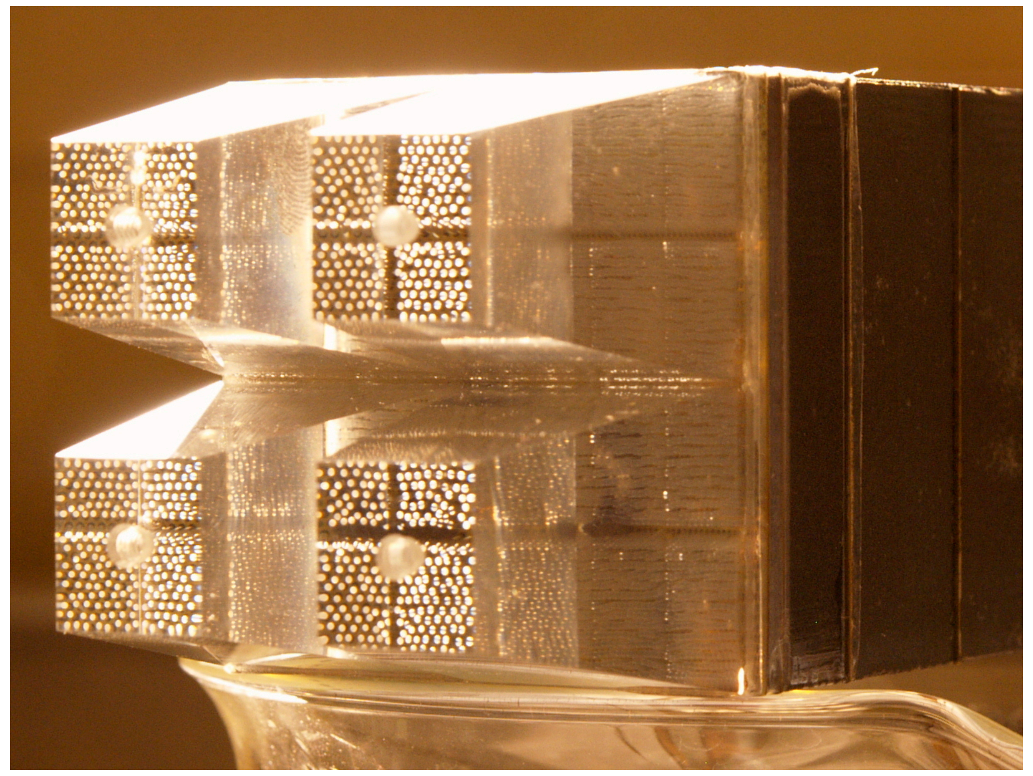
Reality check: cost of full fledged 5D calorimetry is beyond capabilities of NP funding a 2nd detector. We need a different, more pragmatic approach

EM Calorimetry

EM Calorimeter can be divided into

- Sampling calorimeters, that allow the realisation of fast and highly granular devices at affordable costs. They can provide an energy resolution of $\mathcal{O}(5-10\%)/\sqrt{E}$
- Homogeneous calorimeters, that often have higher costs and a lower granularity (and often a slower response) but a much better energy resolution, $\mathcal{O}(1-3\%)/\sqrt{E}$

- Homogeneous
  - Scintillating Glass (SciGlass)
  - Crystal ($PbWO_4$)
  - Lead Glass
- Sampling
  - Imaging (Astropix) Sampling Pb/Sci Calorimeter
  - Tungstate-Scintillating Fiber Calorimeter (WSciFi)



EM Calorimetry

Parameter ======= Material	Density (g/cm^3)	Rad. Length (cm)	Moliere Radius (cm)	Decay time (ns)	Light Yield (γ/MeV)	dLY/dT (%/°C)	Rad. Hard. (krad)
NaI(Tl)	3.67	2.59	4.13	245	41000	-0.2	1--2
CsI(Tl)	4.51	1.86	3.57	1220	60000	0.4	1
CsI	4.51	1.86	3.57	35 6	1600 400	-0.6 -1.4	1
BaF_2	4.89	2.03	3.1	650 0.9	16000 2000	-1.9 0.1	>50
CeF_3	6.16	1.70	2.41	30	2800	~0.1	>100
(BGO) $Bi_4Ge_3O_{12}$	7.13	1.12	2.23	300	8000 4000	-0.9 -1.6	>1000 (recovery
(PWO) $PbWO_4$	**8.3**	**0.89**	**2**	**30 10**	**40 240**	**-2.5**	**>1000**
SciGlass	3.7-4.5	2.2-2.8	2--3	20-50	500-2000	None	>1000

- Smaller Moliere radius allowing higher granularity
- Smaller radiation length allowing smaller longitudinal size
- Smaller constant term contribution to energy resolution, mainly due to non-uniformity and gaps, to readout and noise.
- To achieve convergence to good energy resolution one often need ~20 radiation lengths (PbWO4 or SciGlass) and sometimes more (CsI)
- Other key factors
  - small decay time
  - high light yield
  - radiation hardness

- PbWO4 in terms of resolution and suitability still unmatched
  - Constant factor is an issue (1% needed, only achieved with std. PMs)
  - Improve readout: SiPM → HRPPD, other?
  - expensive, few good vendors

- SciGlass is a great (inexpensive) alternative
  - Similar to lead glass but exhibit much higher light yield
  - Crystal need to be longer than $PbWO_4$ (~45 cm vs ~24 cm)
  - considered for ePIC but more R&D and prototyping is needed

Hadron Calorimetry

ePIC: Common Fe/Sc sampling

Limitations:

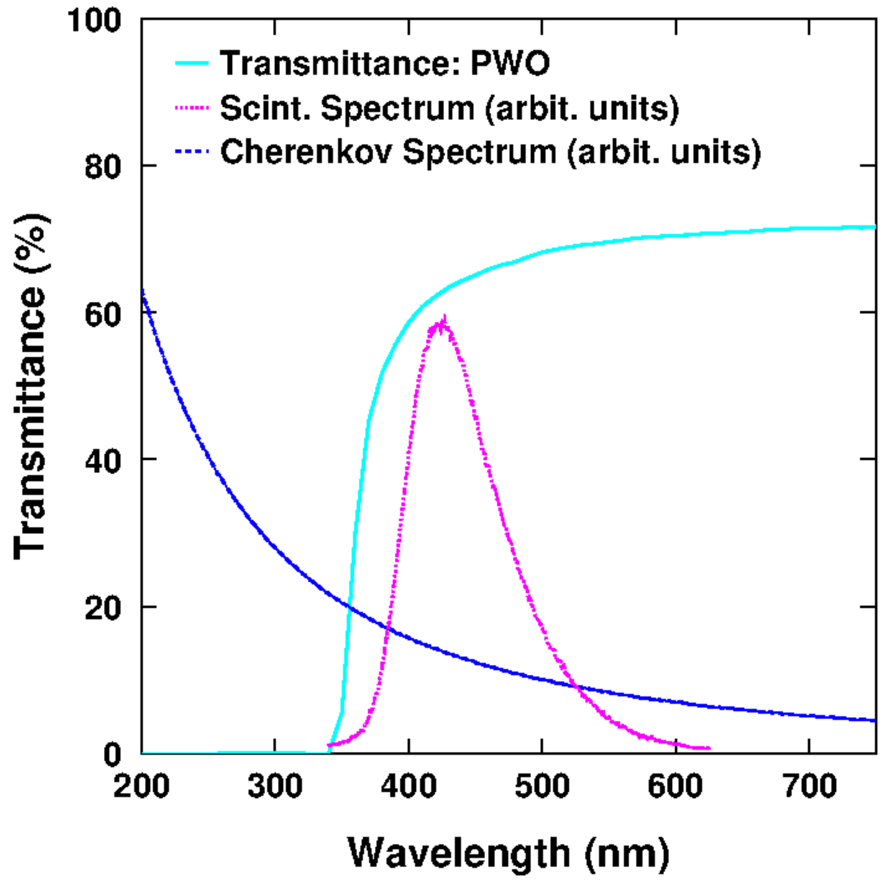
- “Invisible" contributions to the hadronic energy deposition, such as nuclear excitation: calorimeter is said to be “non-compensating”
- Hadronic energy measurements are compromised by the fluctuations in the EM fraction by those of the “invisible” components

Note:

- Non-compensating calorimeters offer higher degrees of freedom to optimize cost or segmentation
- Compensating calorimeters, that require a fixed sampling fraction and specicial choices of absorber and active medium, but have a much better energy resolution ($\sim 30\,\%/\sqrt{E}$ versus $\sim > 50\,\%/\sqrt{E}$).

R&D and potential improvements

- PF algorithms (software)
- Dual Readout, DR
  - based on the measurement of all energy deposits through two different processes:
    - scintillation produced by all ionising particles
    - Cherenkov light emission, produced only by relativistic charged particles
- Combination of the two signals strongly improves-shower energy measurements.
- EIC was and is supporting R&D on CSGlass to distinguish and measure both components (also SBIR)



Calorimetry

Reality check:

- There is no silver bullet
- Improvements are tedious through continuing R&D of light collection and other factors
- EMCAL: R&D and careful evaluation of design to reduce the constant factor (→1%)
- LAPPDs/HRPPDs as readout (➟ LHCb) needs to be looked at (adds timing)
- CSGlass has huge potential and R&D should be supported
- DR to improve hadronic calorimetry could be key to bring hadron calorimetry in the fwd region in the $\sim 30\,\%/\sqrt{E}$ range → needs more R&D

Muons

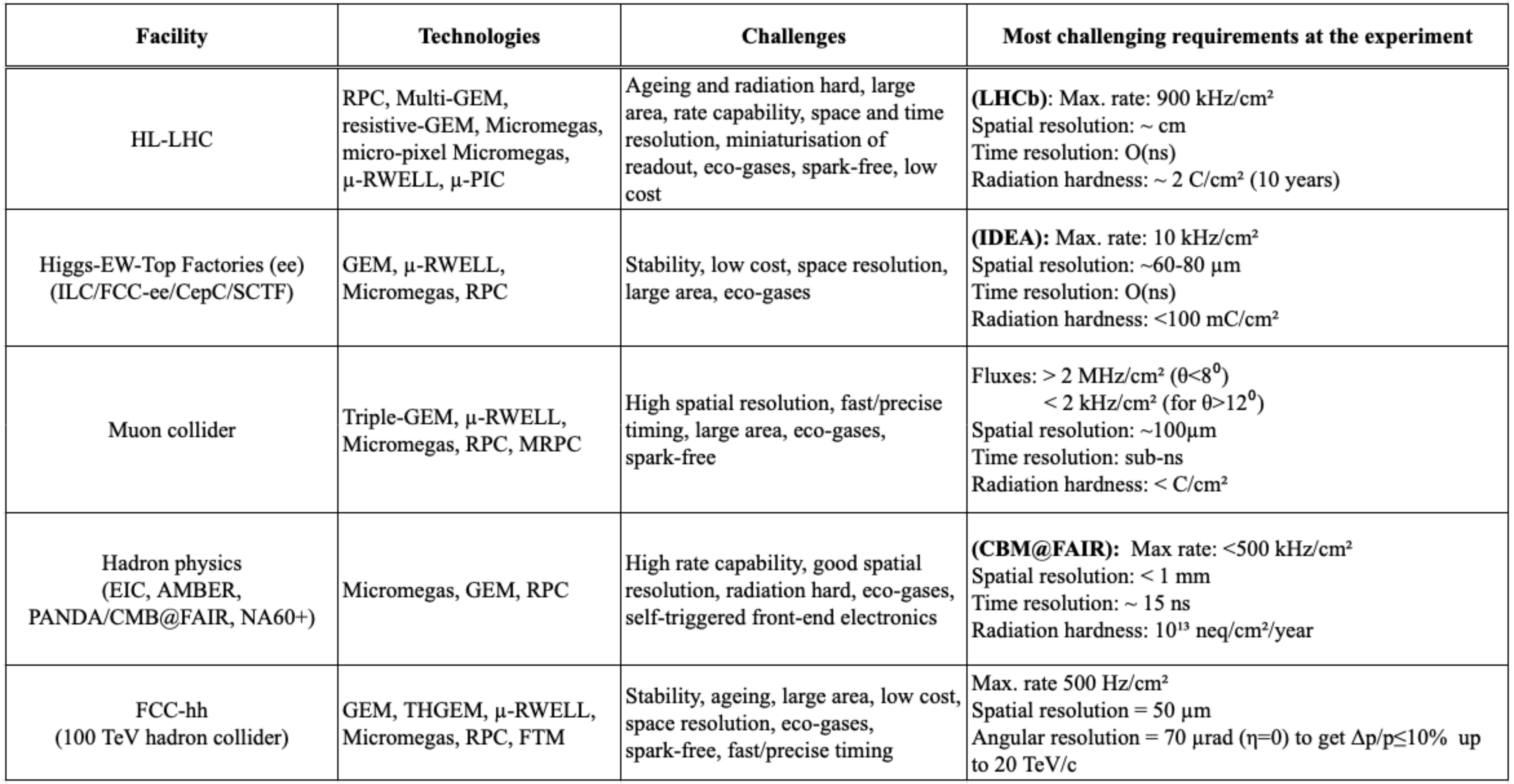
Muons

- $\mu^{\pm}, \mu^{+}\mu^{-}$ are a compelling alternative to electrons (except e')
- Requirements not defined yet
- Like many general-purpose collider detectors we need a μ-Tagger not a μ-Tracker relying on the inner tracking detectors for their momentum measurements
- Muon systems do not pose significant challenges at the EIC
- Layers of gaseous detectors embedded in a steel (return yoke) are the primary choice for cost-effective, large-area coverage and high detection efficiency.
- Optional precision nanosecond-level timing also helps to reduce uncorrelated beam-induced backgrounds, while improving the sensitivity for heavy long-lived particle searches

Muon Detection

- RPCs
  - ATLAS: new RPCs with small gap size (1 mm), High Pressure Laminate (HPL) electrodes with reduced resistivity, and the latest generation of front-end electronics ASICs (noise < 4000 e)
- MPGDs: GEM, MMG, μRWell
  - with precise spatial resolution could be an interesting tool also for studying long-lived particles

Main drivers for muon systems at future facilities



Facility	**Technologies**	**Challenges**	**Most challenging requirements at the experiment**
HL-LHC	RPC, Multi-GEM, resistive-GEM, Micromegas, micro-pixel Micromegas, μ-RWELL, μ-PIC	Ageing and radiation hard, large area, rate capability, space and time resolution, miniaturisation of readout, eco-gases, spark-free, low cost	**(LHCb)**: Max. rate: 900 kHz/cm^2 Spatial resolution: ~ cm Time resolution: O(ns) Radiation hardness: ~ 2 C/cm^2 (10 years)
Higgs-EW-Top Factories (ee) (ILC/FCC-ee/CepC/SCTF)	GEM, μ-RWELL, Micromegas, RPC	Stability, low cost, space resolution, large area, eco-gases	**(IDEA):** Max. rate: 10 kHz/cm^2 Spatial resolution: ~60-80 μm Time resolution: O(ns) Radiation hardness: <100 mC/cm^2
Muon collider	Triple-GEM, μ-RWELL, Micromegas, RPC, MRPC	High spatial resolution, fast/precise timing, large area, eco-gases, spark-free	Fluxes: > 2 MHz/cm^2 ($\theta<8^0$) < 2 kHz/cm^2 (for $\theta>12^0$) Spatial resolution: ~100μm Time resolution: sub-ns Radiation hardness: < C/cm^2
Hadron physics (EIC, AMBER, PANDA/CMB@FAIR, NA60+)	Micromegas, GEM, RPC	High rate capability, good spatial resolution, radiation hard, eco-gases, self-triggered front-end electronics	**(CBM@FAIR):** Max rate: <500 kHz/cm^2 Spatial resolution: < 1 mm Time resolution: ~ 15 ns Radiation hardness: 10^{13} neq/cm^2/year
FCC-hh (100 TeV hadron collider)	GEM, THGEM, μ-RWELL, Micromegas, RPC, FTM	Stability, ageing, large area, low cost, space resolution, eco-gases, spark-free, fast/precise timing	Max. rate 500 Hz/cm^2 Spatial resolution = 50 μm Angular resolution = 70 μrad (η=0) to get $\Delta p/p \leq 10\%$ up to 20 TeV/c

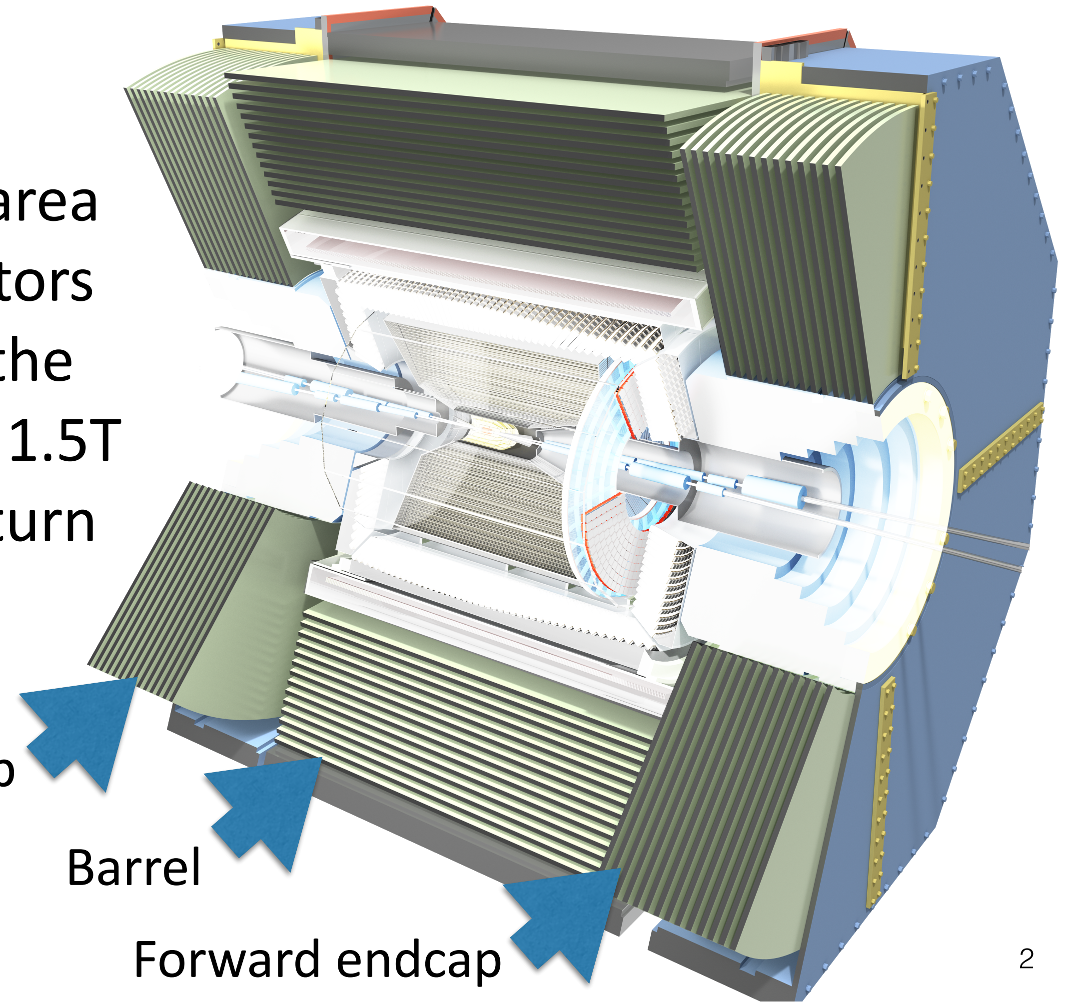
Muons

Source: Belle-II

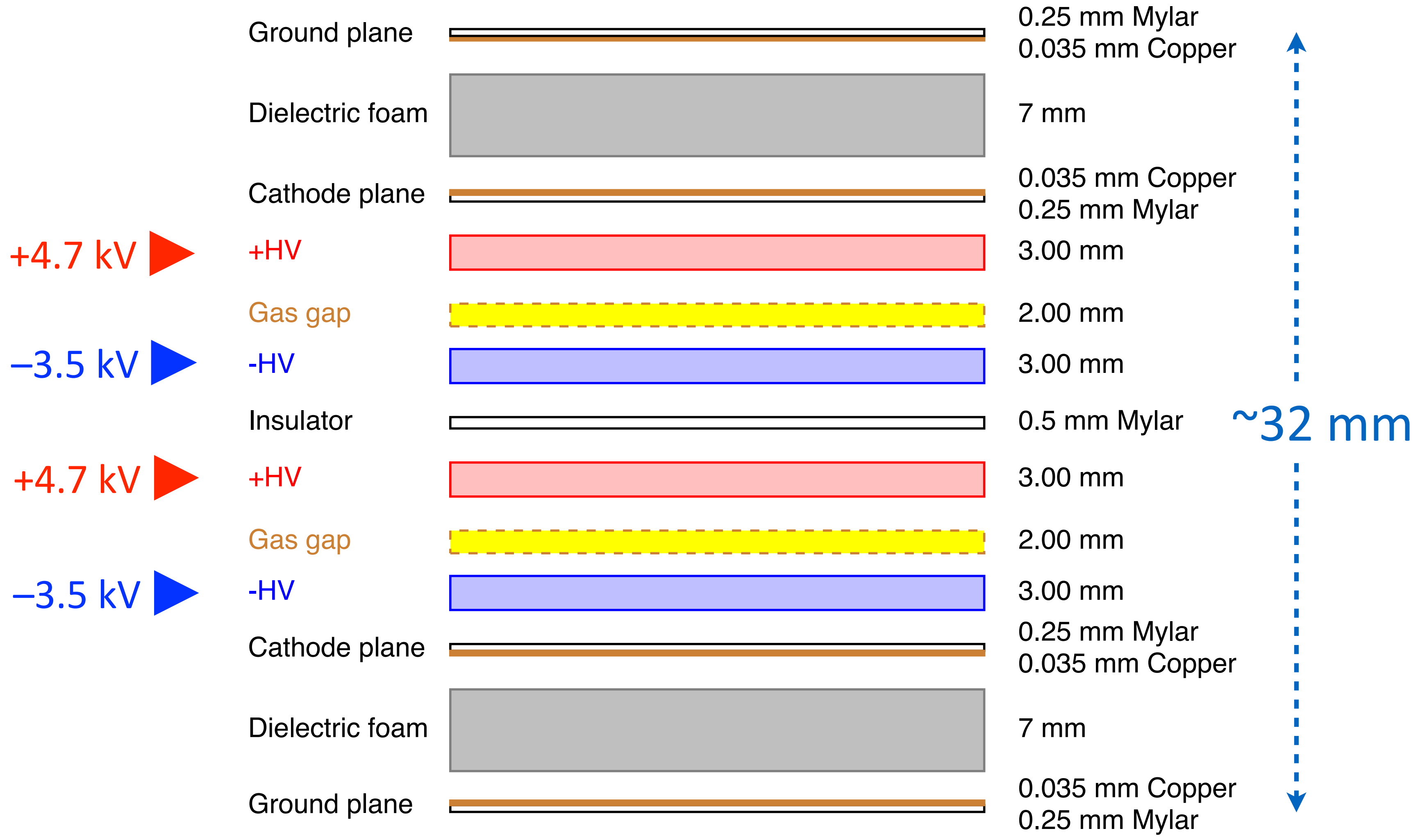
Example (Belle-II)

The KLM (“K_L–Muon detector”)

consists of large-area thin planar detectors interleaved with the iron plates of the 1.5T solenoid’s flux return yoke.



Belle Resistive Plate Counter



Reality check:

- Not a significant challenge
- Could benefit from MPGD expertise in EIC community
- Critical Interplay between HCALs and muon detectors/taggers

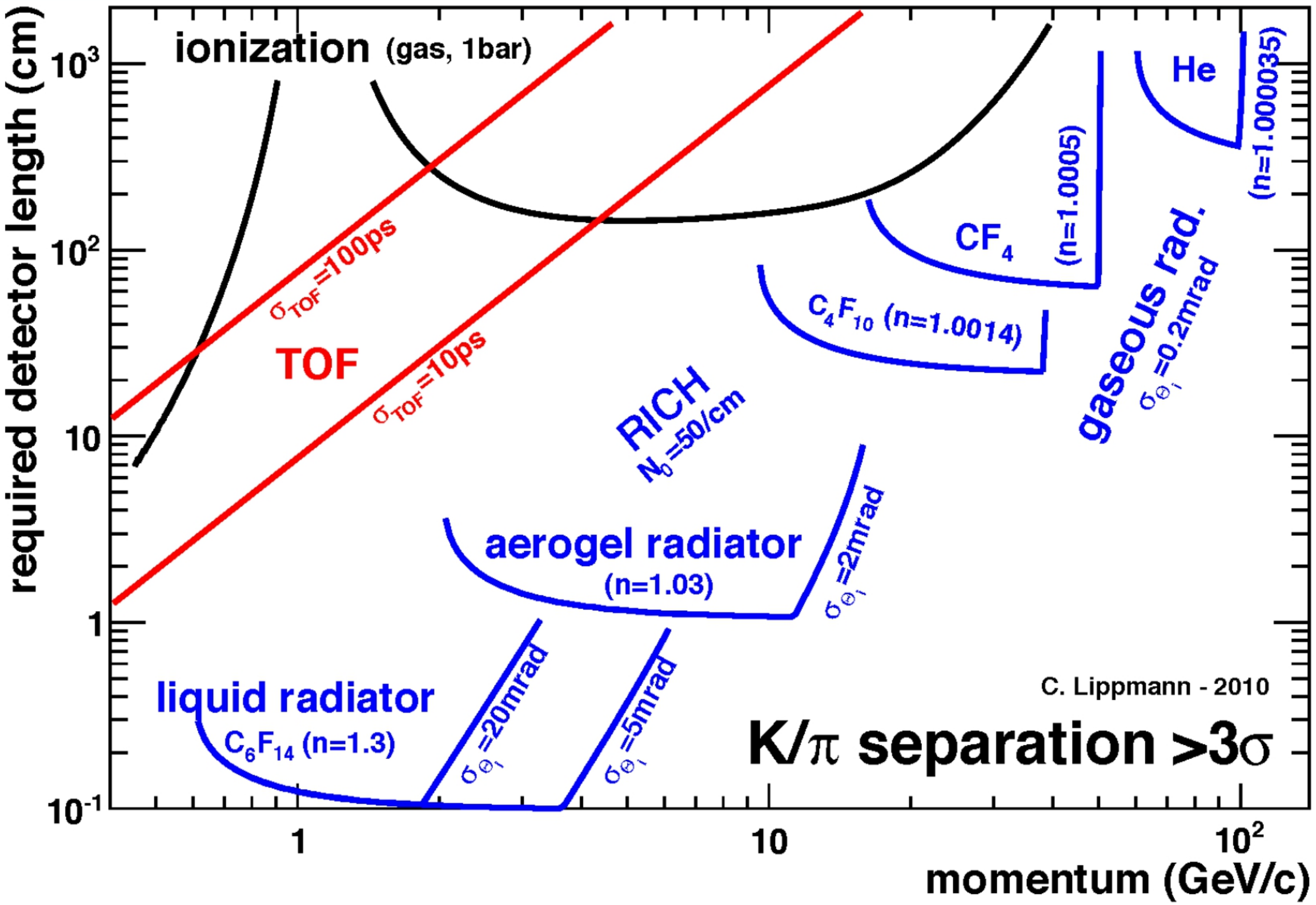
Particle ID

Particle ID

talk about e/h later

Requirements

- Excellent PID (3σ) π/K/p (btw 3σ isn’t so much!)
  - forward: up to 50 GeV/c
  - backward: up to 7 GeV/c
  - central: up to 8 GeV/c (up to 10 GeV/c on wishlist)
- Need more than one technology to cover the entire momentum ranges at different rapidities
- PID needs are more demanding then at most collider detector



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talk about e/h later

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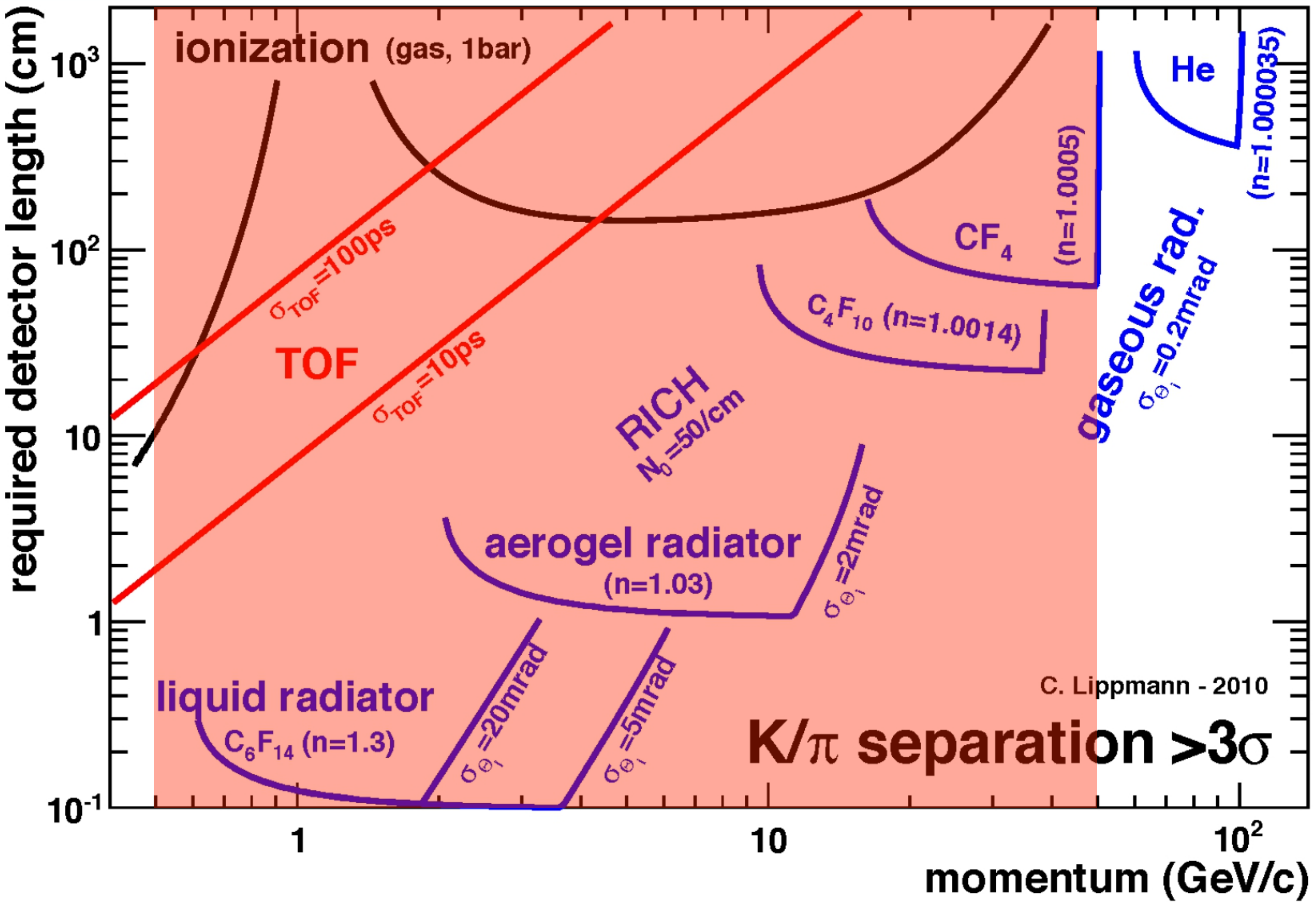

Fwd: ToF+aerogel RICH+gaseous RICH

Particle ID

talk about e/h later

Requirements

- Excellent PID (3σ) π/K/p (btw 3σ isn't so much!)
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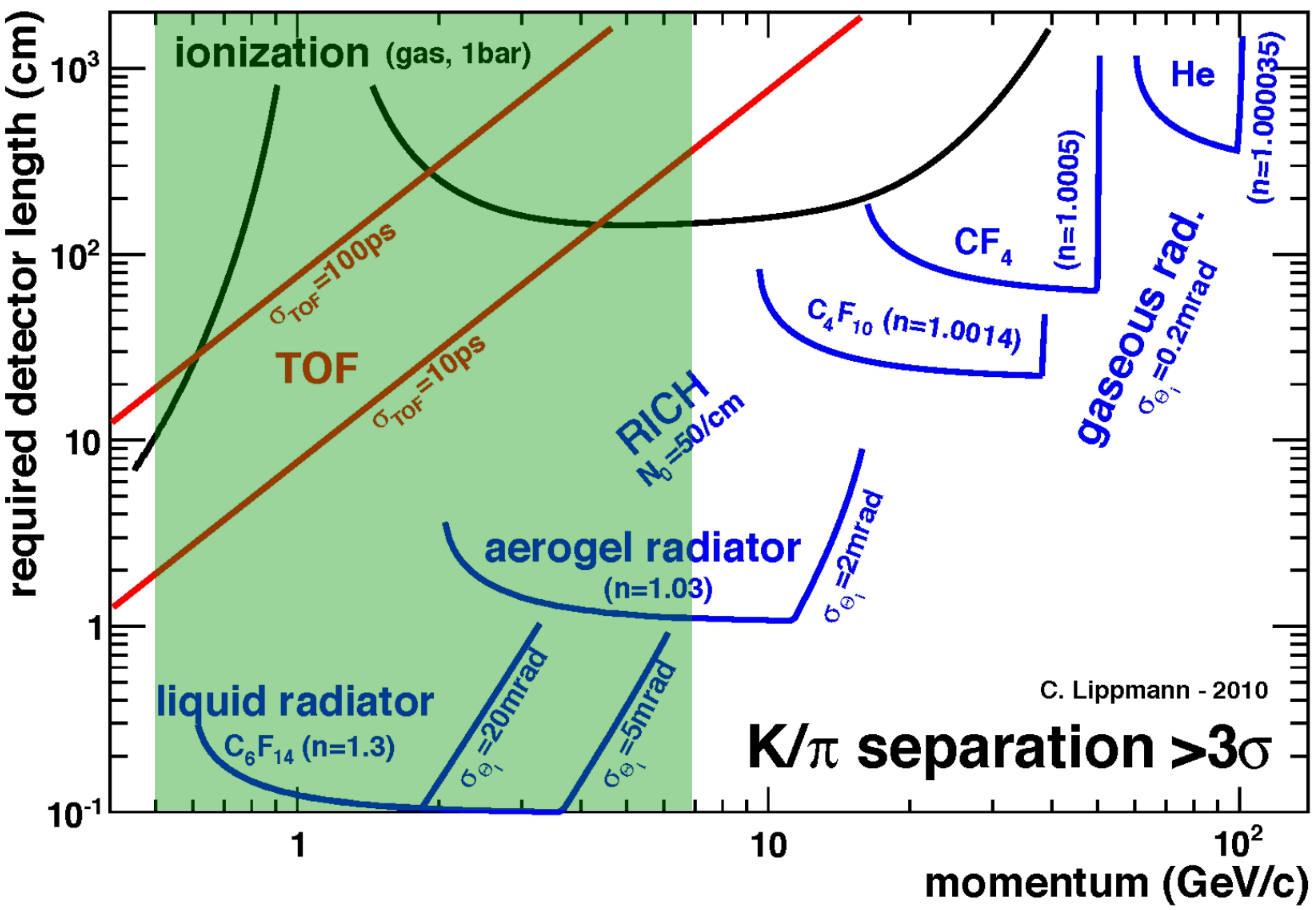

Fwd: ToF+aerogel RICH+gaseous RICH

Bkwd: ToF+aerogel RICH

Particle ID

talk about e/h later

Requirements

- Excellent PID (3σ) π/K/p (btw 3σ isn’t so much!)
  - forward: up to 50 GeV/c
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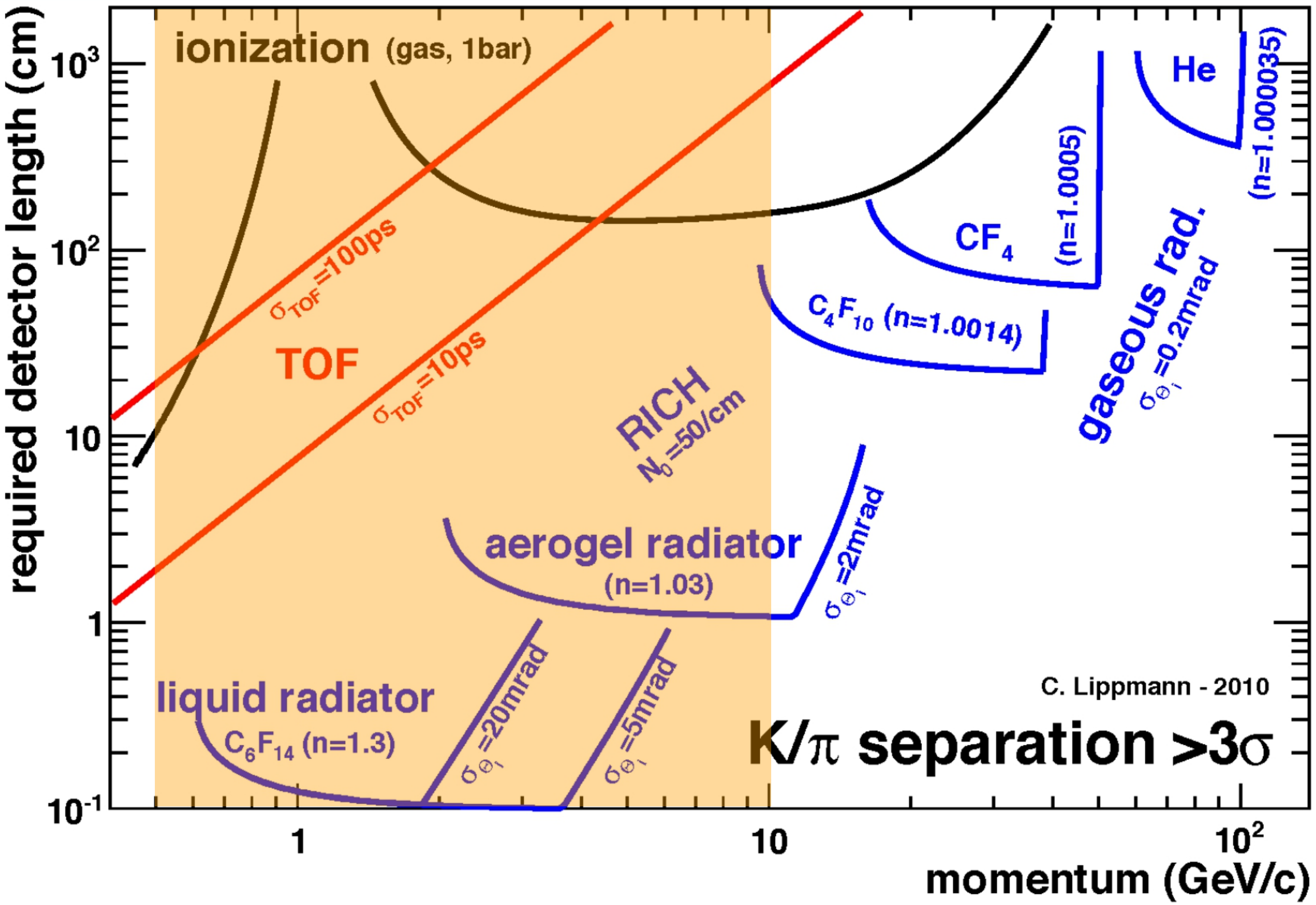


Fwd: ToF+aerogel RICH+gaseous RICH

Bkwd: ToF+aerogel RICH

Central: ToF+ (RICH, DIRC,?)

Particle ID

- ToF
  - Two technologies are evolving
    - Si based pixel detectors - also adds to tracking (buzzword = 4D sensors)
    - LAPPD based - also adds to photo-dection in RICHs
- Aerogel RICH
  - Modular RICH, proximity focusing RICH (ePIC, Belle-II)
  - Readout options: LAPPD/HRPPDs, MC-PMTs
- Gaseous RICH
  - Combination with aerogel common (ePIC, HERMES, LHCb)
  - Readout options: SiPM, LAPPD/HRPPDs
- Solid RICH
  - high performance DIRC (ePIC, Panda, BaBar)
  - Readout: SiPM, LAPPD/HRPPDs, MC-PMTs

ToF with Si Sensors

Fantastic overview: CERN seminar by Werner Riegler (2021)

Issues

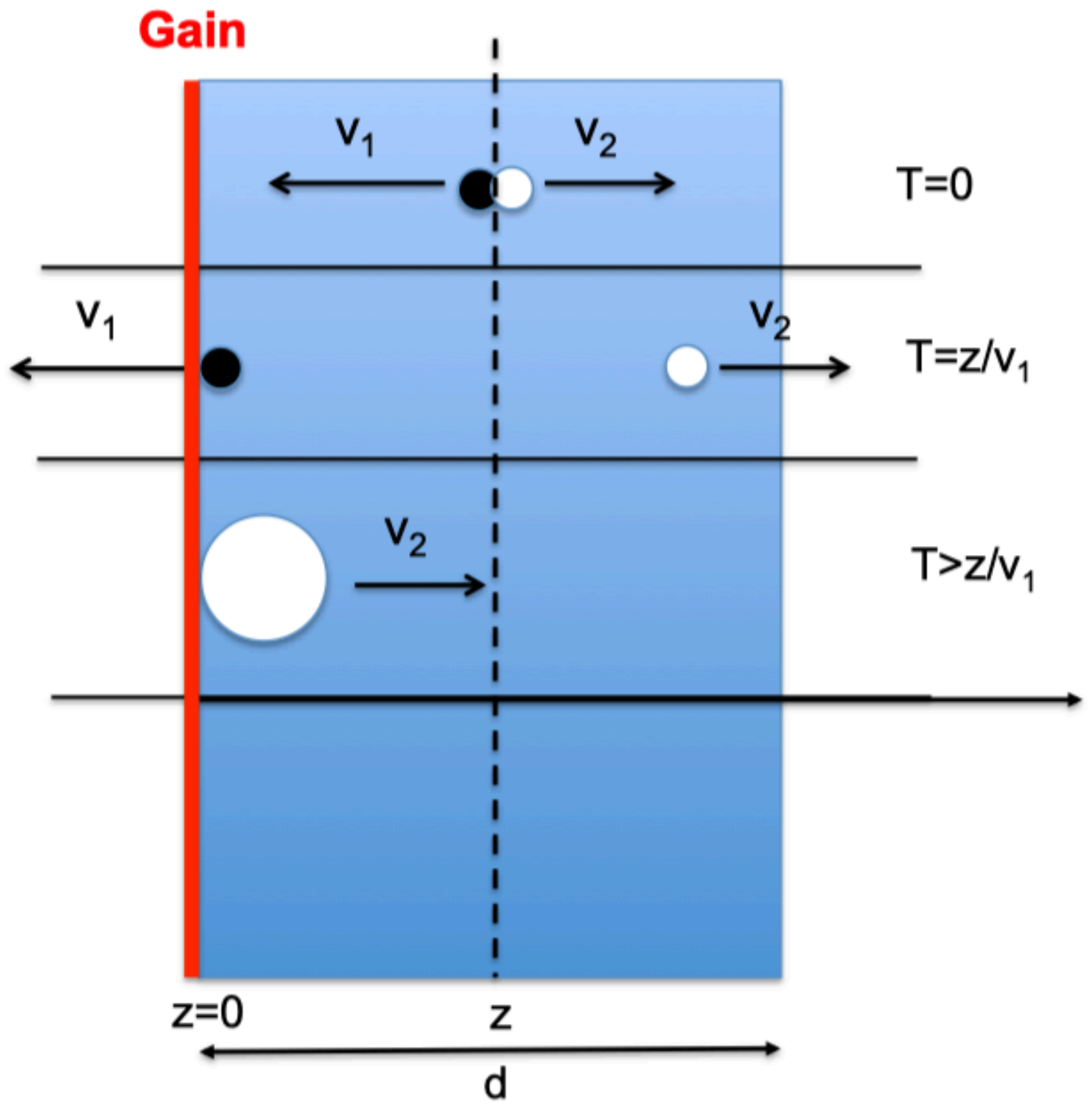
- Good time resolution demands thin sensors
- Thin sensors give small charge and large capacitance i.e. unfavorable S/N
- Capacitance can be reduced by making the pixels small
- If the pixel size ~ sensor thickness, the field fluctuations start to dominate … and there will be many channels …

MAPS

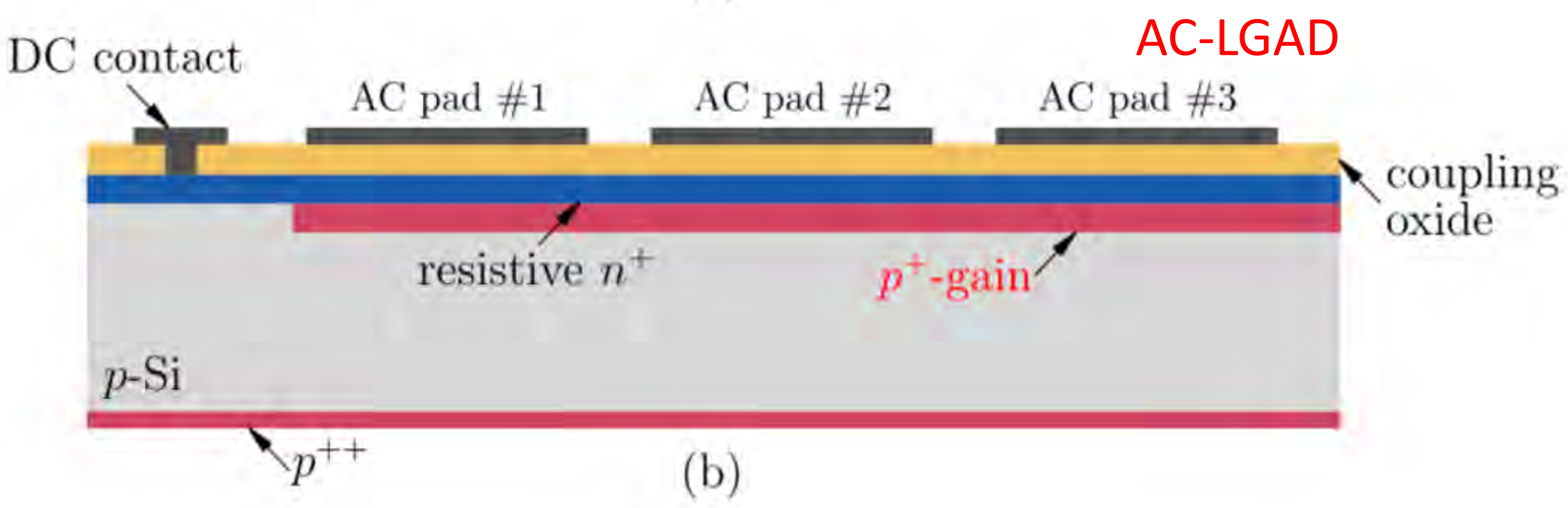
- needs fast amplifiers and good S/N
- extreme demands on performance of the amplifiers, resulting in significant power consumption
- Simulations show that ~400 ps is achievable
- R&D needed (generic EIC R&D likely not enough to develop chip with these performance parameters)
- Even if available ~400 ps is not enough

ToF with Si Sensors: LGAD

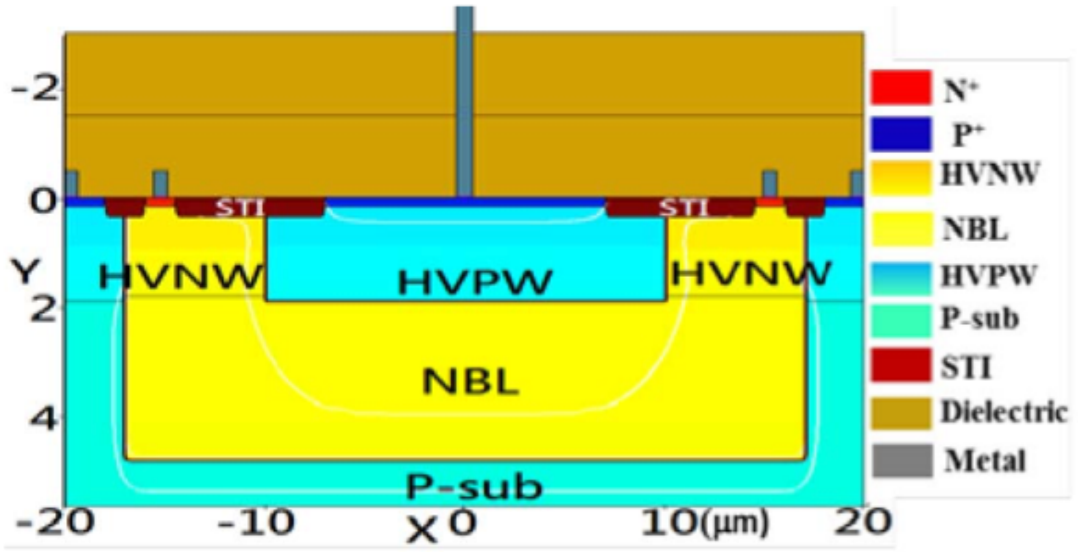
- Low Gain Avalanche Diode Sensor (Hybrid)
    - Issues: fill factor, heat
- Several modifications have been proposed
    - analog-coupled AC-LGADs: signal sharing between electrodes, used to obtain the simultaneous 30 ps and up to 5 μm resolutions (ePIC pick)
    - "Deep-Junction" DJ-LGAD: formed by abutting thin, highly-doped p+ and n+ layers geared towards 100% fill factor
    - "Double Sided LGADs" DS-LGADs: adding a readout layer to the p-side of the LGAD structure, which allows one to also measure signals from the slower-drifting holes. Aim to simultaneously measure not only the position and time, but also the angle of passing tracks. Dramatically reduce the complexity of detector modules.



- An e-h pair is produced at position z
- The electron arrives at z=0 at time T=z/v1
- The electron multiplies in high field in layer at z=0
- The holes move back to z=d inducing the dominant part of the signal



ToF with Si Sensors



Others

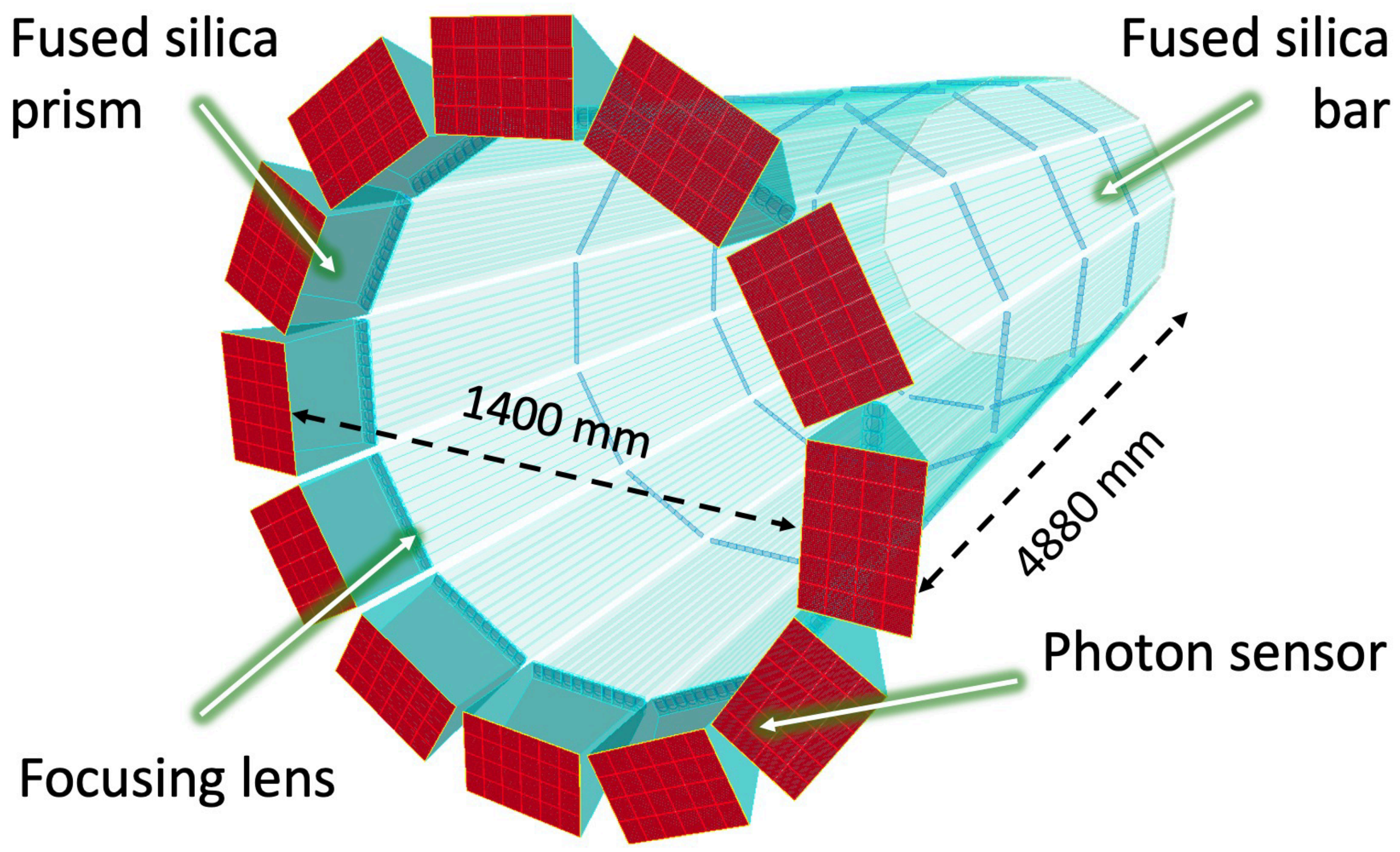
- Single Photon Avalanche Diodes (SPAD)
  - below 20 ps, many derivatives
  - considered for ALICE3
  - btw: SiPMs consist of an array of ~1000 SPADs
- SiPM typically in conjunction with L(Y)SO:Ce crystals
  - used for CMS timing layers
  - 35-60 ps is expected
- MCP-PMTs in conjunction with Cherenkov based detectors

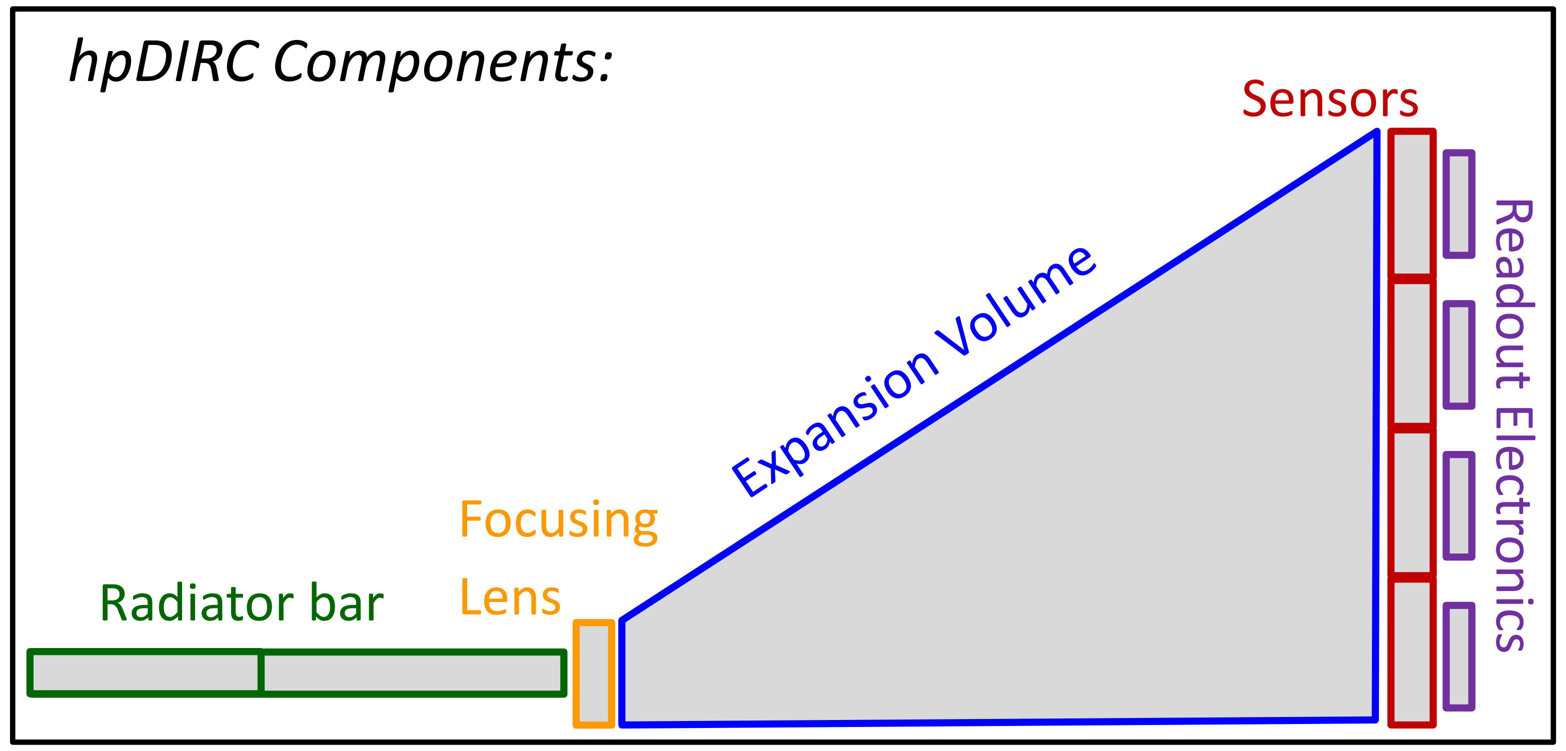
Reality check:

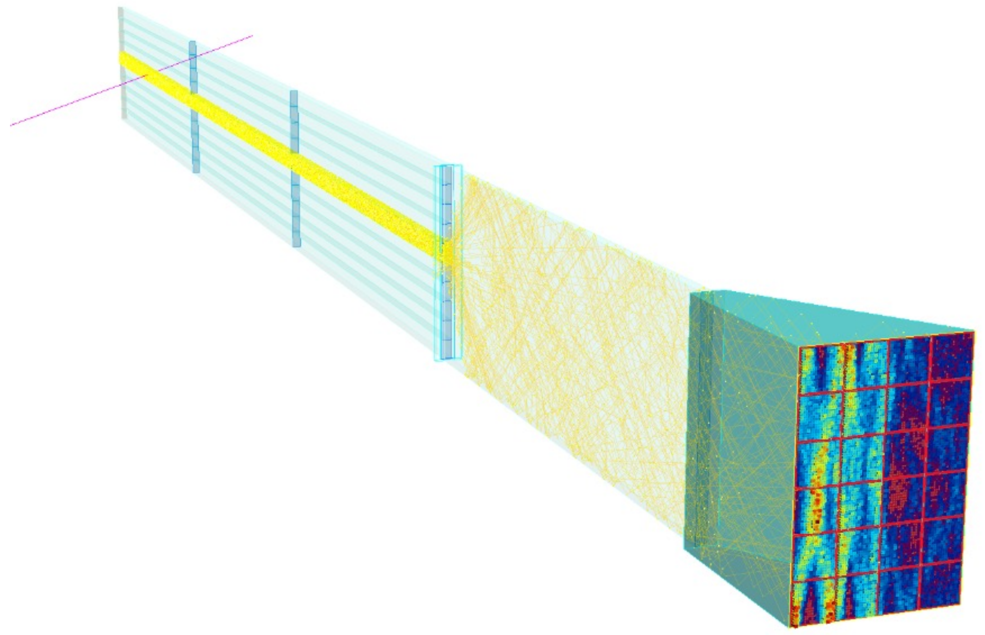
- LGAD technology is main stream and EIC has available expertise (BNL/HEP/IO, UCSC, …). More experience will be gained via ePIC. Any other Si solution seems too far away even for D2 and/or does not get required resolution of ~30ps.

DIRC ➟ hpDIRC

- Detection of Internally Reflected Cherenkov Light
- DIRC pioneered by BaBar, later Belle-II and PANDA
  - extremely compact PID device for barrel and endcap regions facilitating space for calorimeters and tracking detectors.
  - DIRCs cover the momentum region below 6-7 GeV/c
- hpDIRC (ePIC)
  - Fast focusing DIRC, utilizing high-resolution 3D (x,y,t) reconstruction
  - Radiator/light guide: narrow fused silica bars (radius/ length flexible)
  - Innovative 3-layer spherical lenses
  - Compact fused silica prisms as expansion volumes
  - Fast photon detection: small-pixel MCP-PMTs and high-density readout electronics
  - Detailed Geant4 simulation: ≥ 3 s.d. π/K separation at 6 GeV/c, ≥ 3 s.d. e/π separation at 1.2 GeV/c



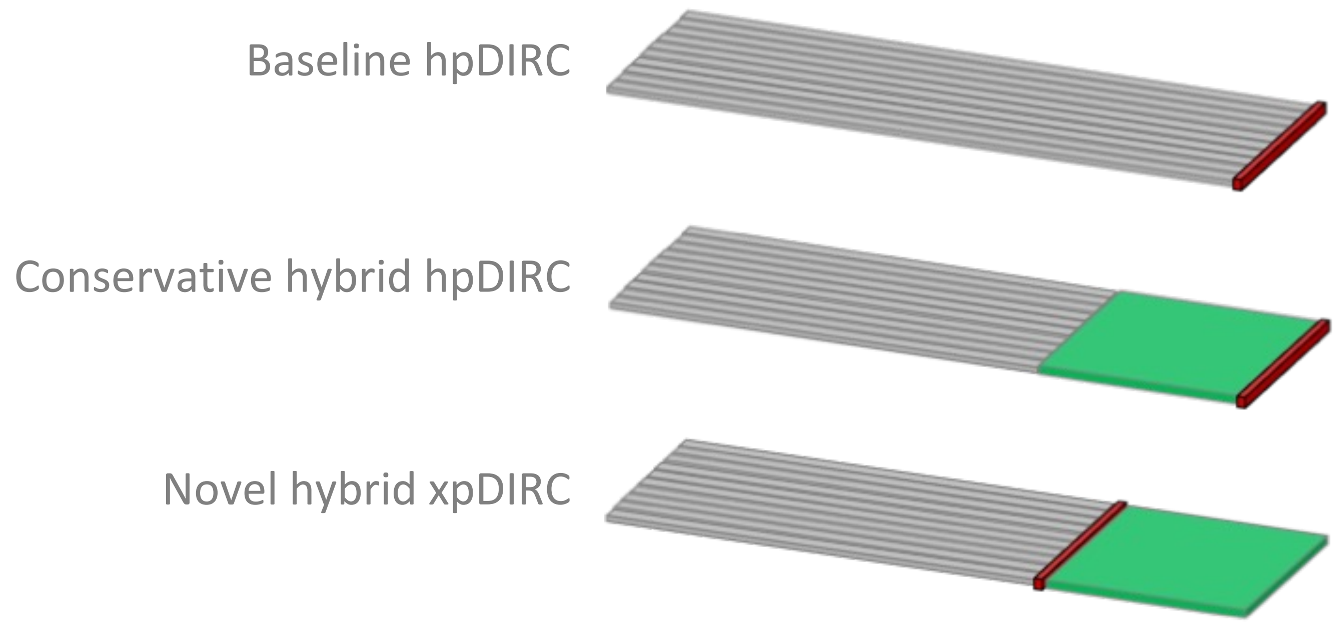




hpDIRC ➟ xpDIRC

- Room for improvement and optimization
  - Novel hybrid optics
  - Thinner bars for low-mass DIRC
    - ~40% reduction in mass benefits the EMCal
  - Improved e/π performance at low momentum
  - MC-PMTs ➟ SiPM ➟ HRPPDs
  - Better timing (ToF capability?)
  - Many challenges, needs lots of R&D

Ongoing generic EIC R&D
Note, we are in our own, no interest in HEP



Reality check:

- No good alternatives known (to me). RICH is out since sensors would be aligned with B field unless one chooses CsI + MPGDs which becomes thick!
- Improvements look promising and feasible in D2 time frame
- Cannot extend p range much beyond 6 GeV/c

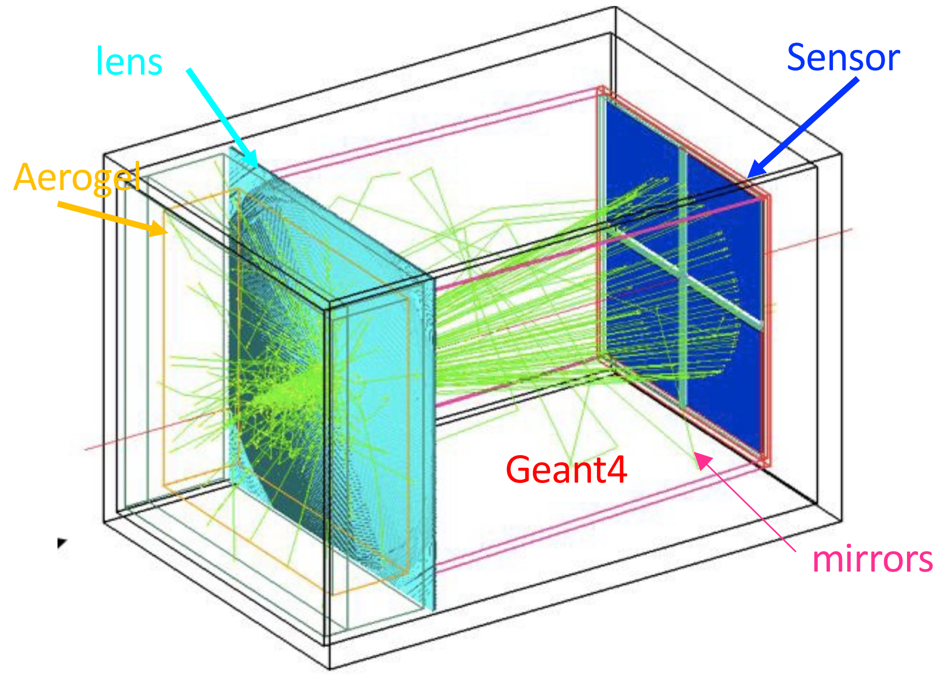
Novel hybrid xpDIRC: bar-lens-plate configuration
Plate serving as pre-expansion volume may allow smaller prism, decrease material budget and improve integration

RICH Detectors

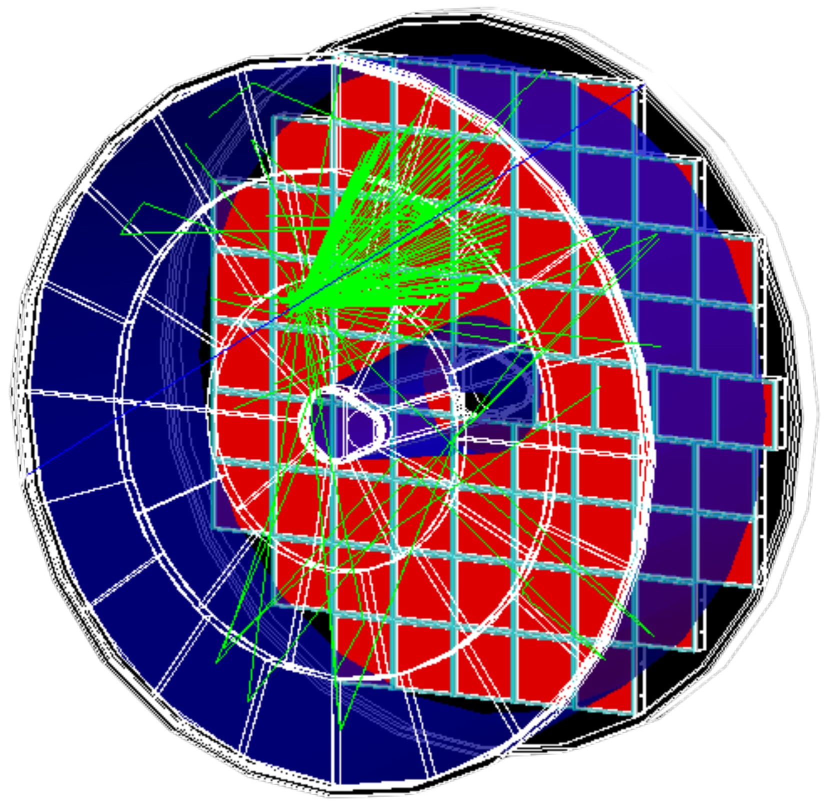
- In general RICH (aerosol and gaseous) detectors are established technology
- EIC: modular RICH, proximity focussing RICH, dual RICH
- Devil is in the detail
  - Aerogel quality, specifications, provider
  - Critical: photons/ring N_γ
  - Integration
- Big Issues
  - Photosensors
  - Future of fluorocarbons

Reality check:
- There is a lot of expertise in the EIC community
- The issue are photosensors (see next slides)
- Ban of fluorocarbons is a real danger for D2

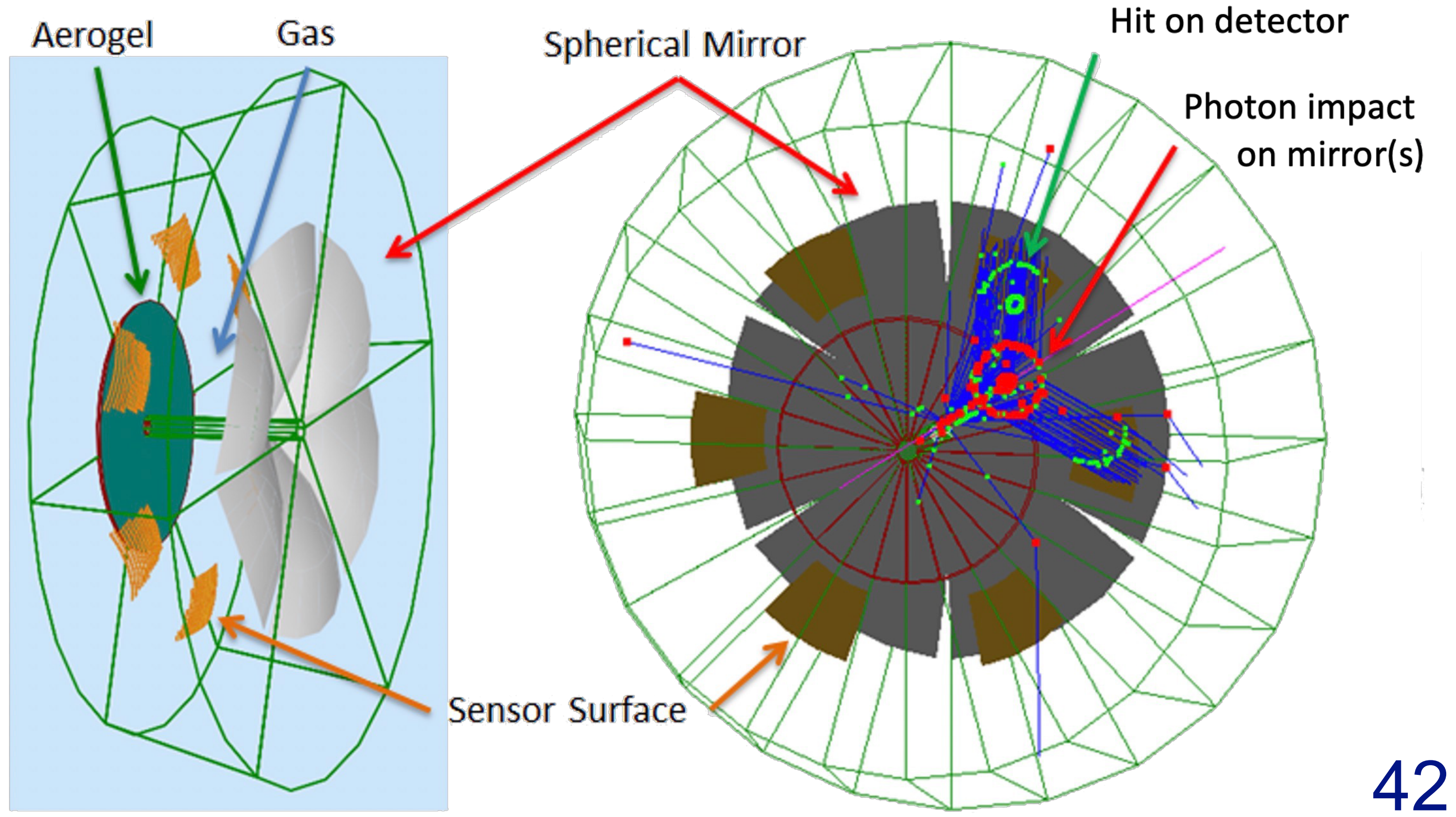
mRICH



pfRICH



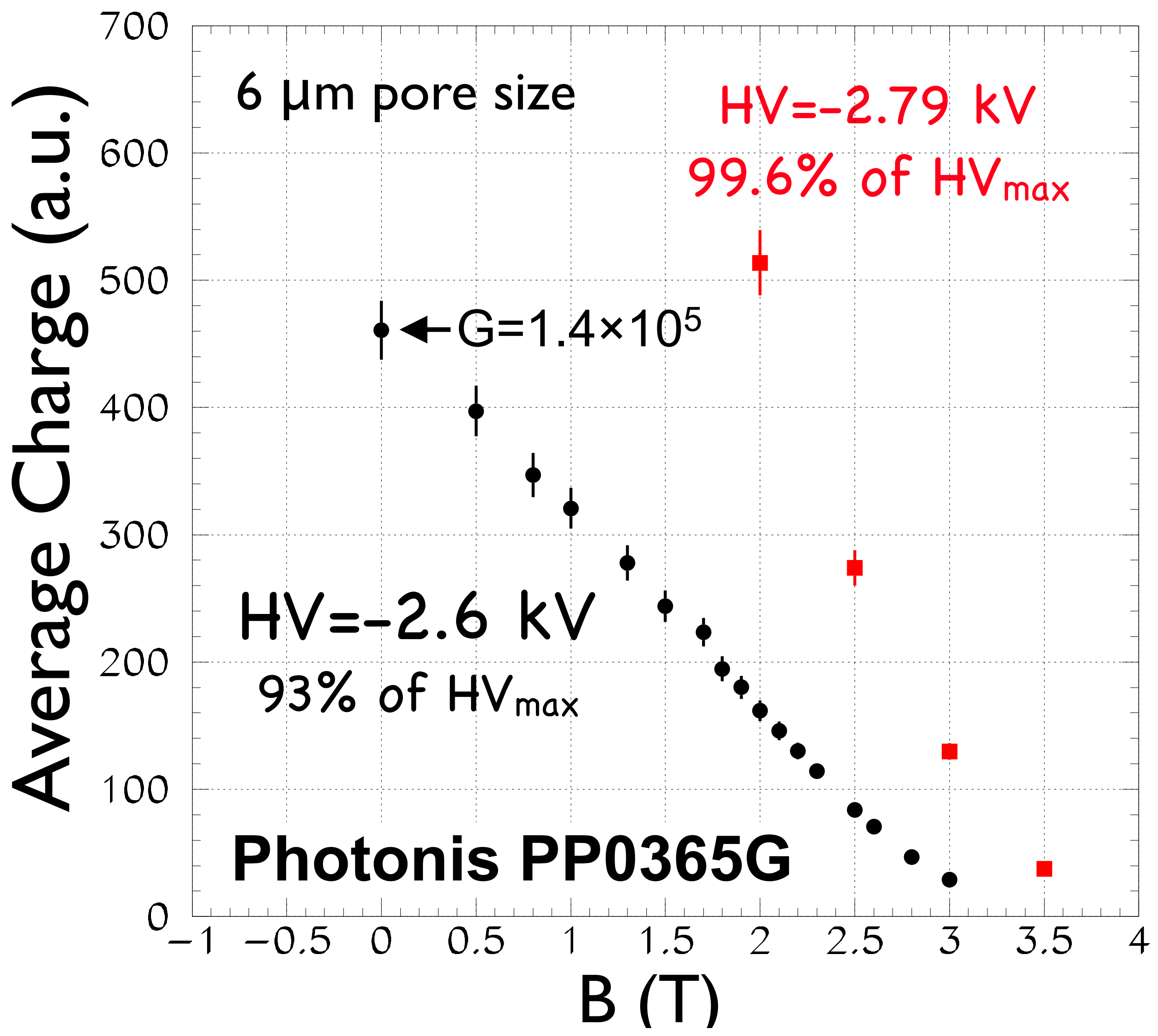
dRICH

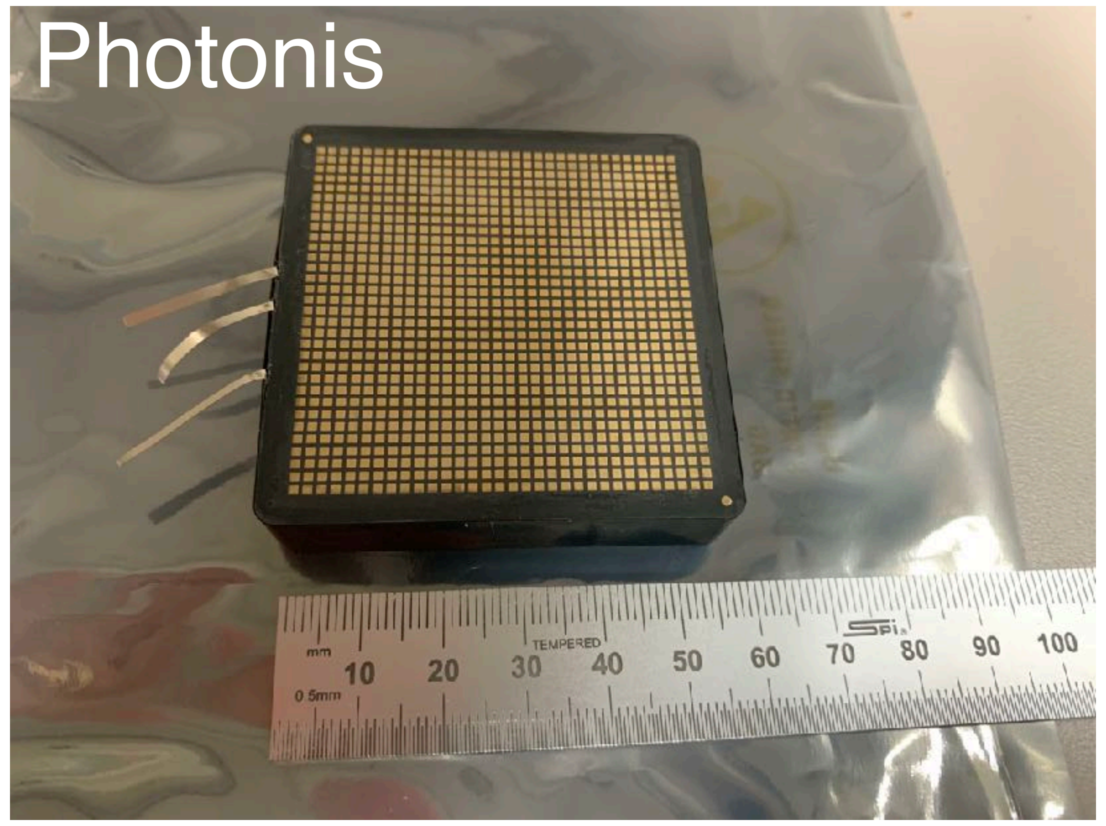


Photosensors

- 2nd detector requires highly-pixilated photodetectors working at ~3 T. This problem is most critical for RICH detectors and is not fully solved yet.
- No-Can-do
  - Everything CsI (O_2, H_2O sensitivity, aging, maintenance)
  - Novel photocathode based on NanoDiamond (ND) particles coupled to MPGD (e.g. THGEM) did not work out (solid state expertise?)

- MCP-PMTs
  - On market: Photonis/Photek
  - Not very tolerant to magnetic fields (angle!)
  - Characterization of performance in eRD14
  - No collaboration with vendor
  - Very expensive

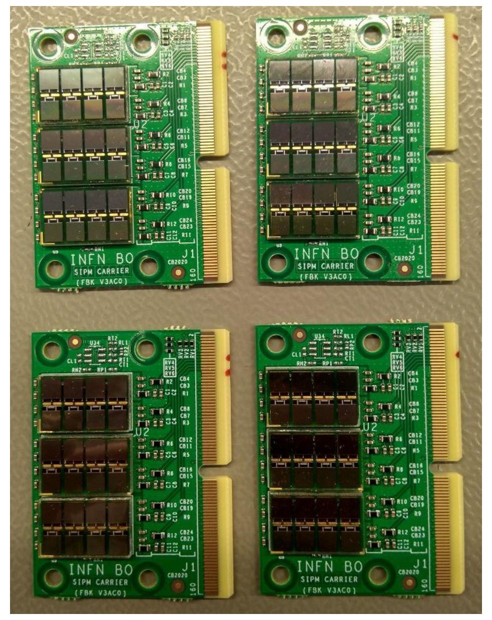




eRD14

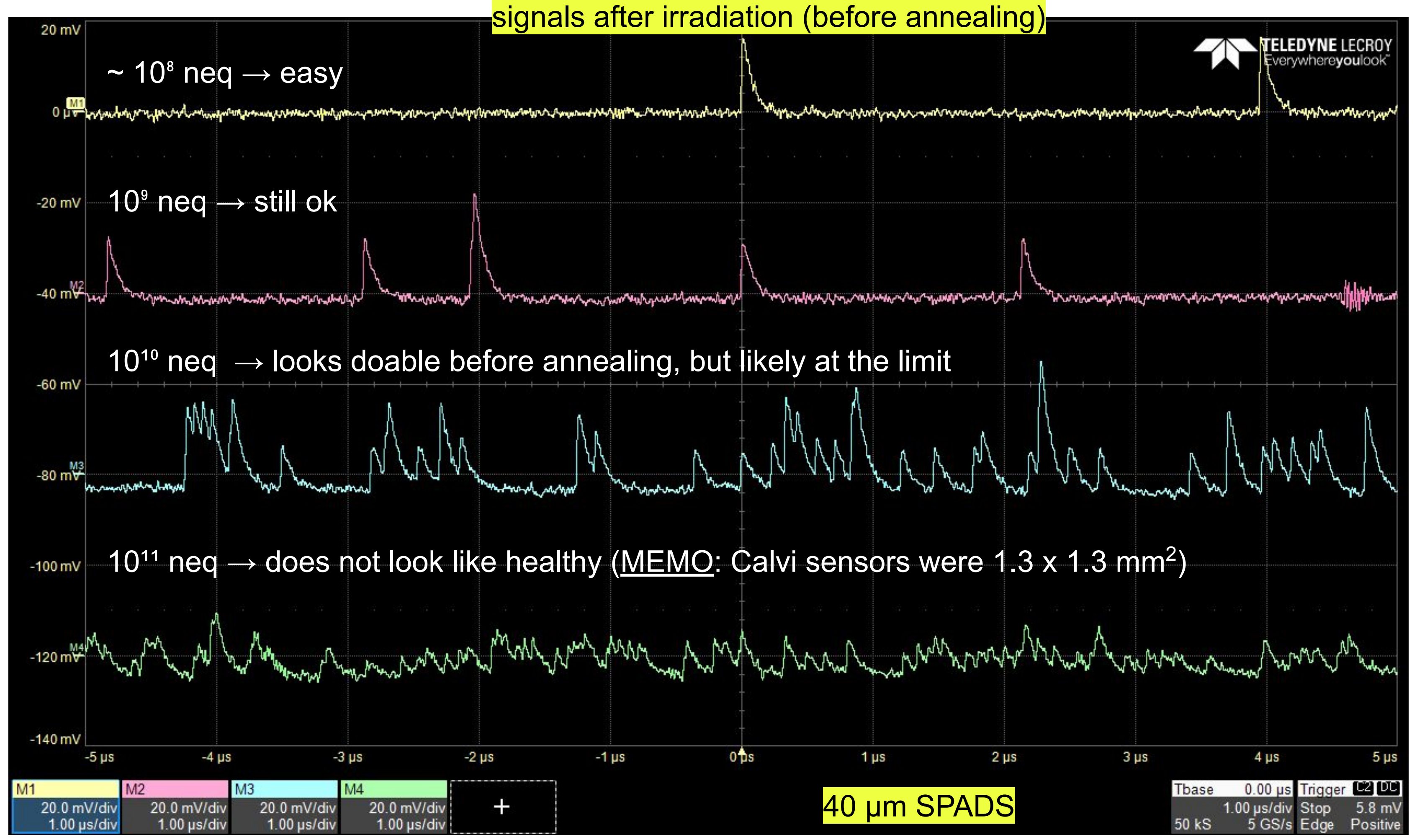
Photosensors: SiPM

- SiPM
  - Pros: high photon efficiency, good time resolution, insensitive to magnetic field
  - Cons: large dark count rates (data rate!), not radiation tolerant
  - 10^{11} (1-MeV) neq/cm at dRICH sensor location reached after 10 years



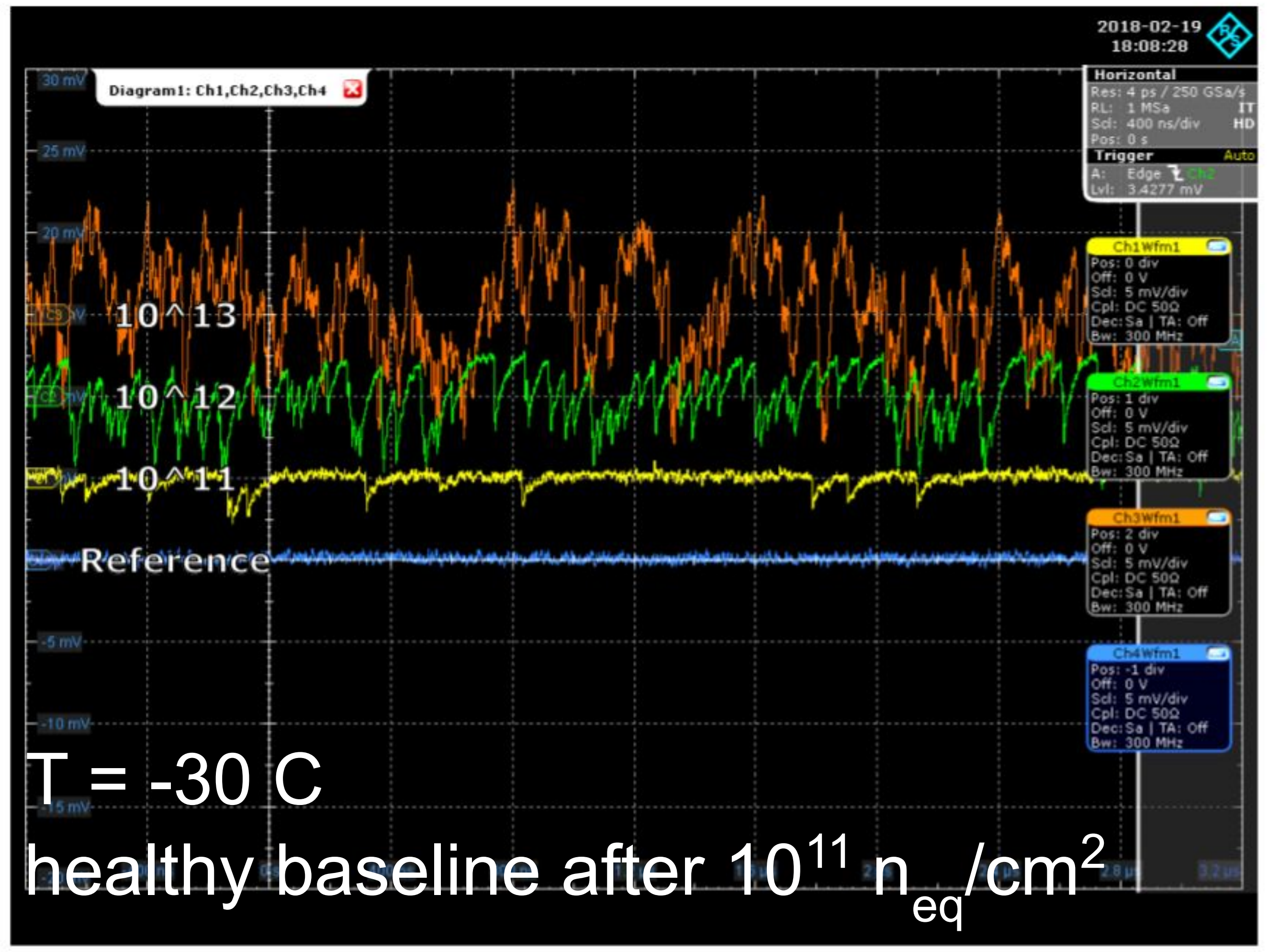
Courtesy R. Preghenella

signals after irradiation (before annealing)



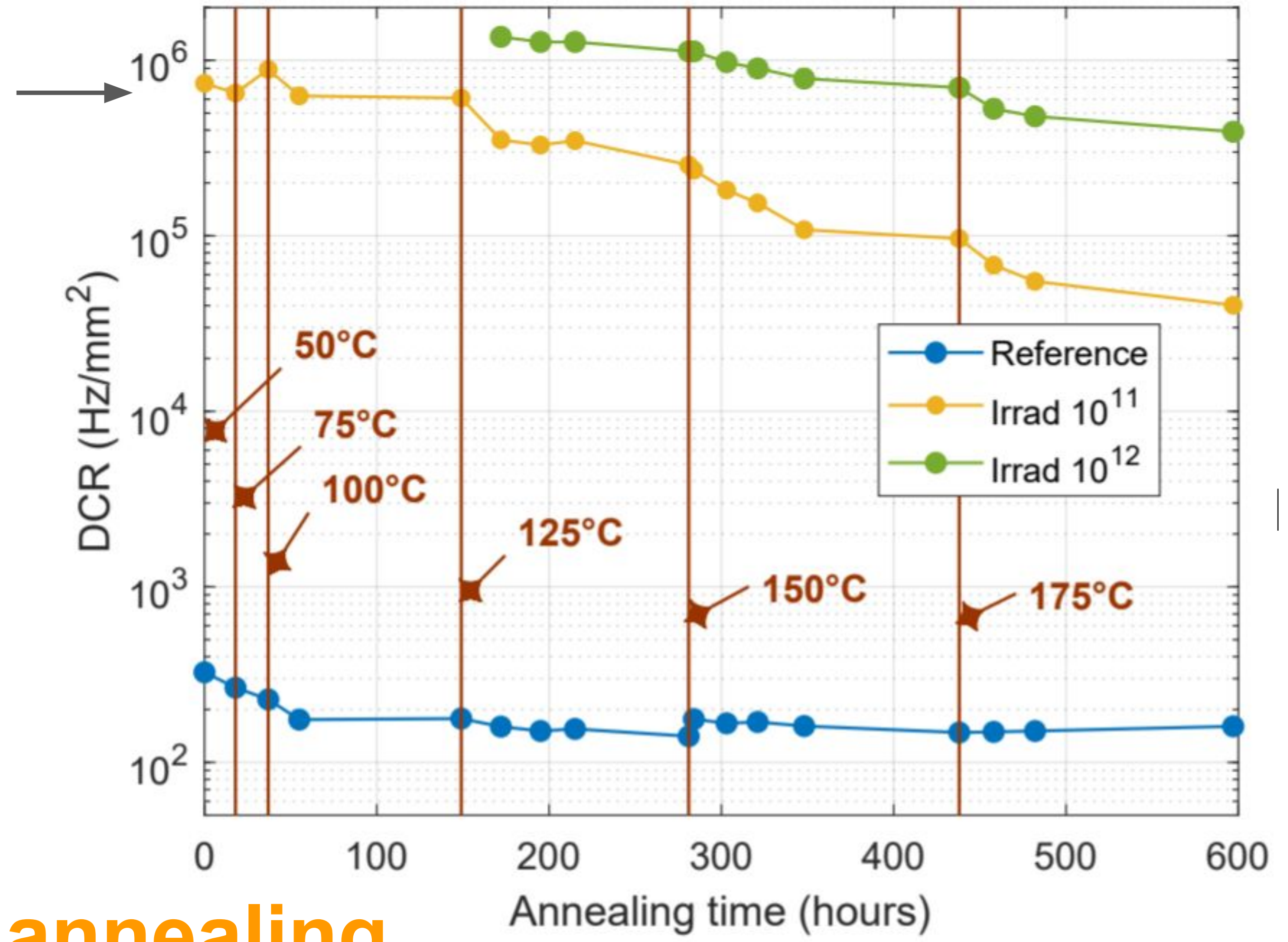
40 µm SPADS

Calvi, NIM A 922 (2019) 243



T = -30 C

healthy baseline after 10^{11} n_{eq}/cm^2



annealing

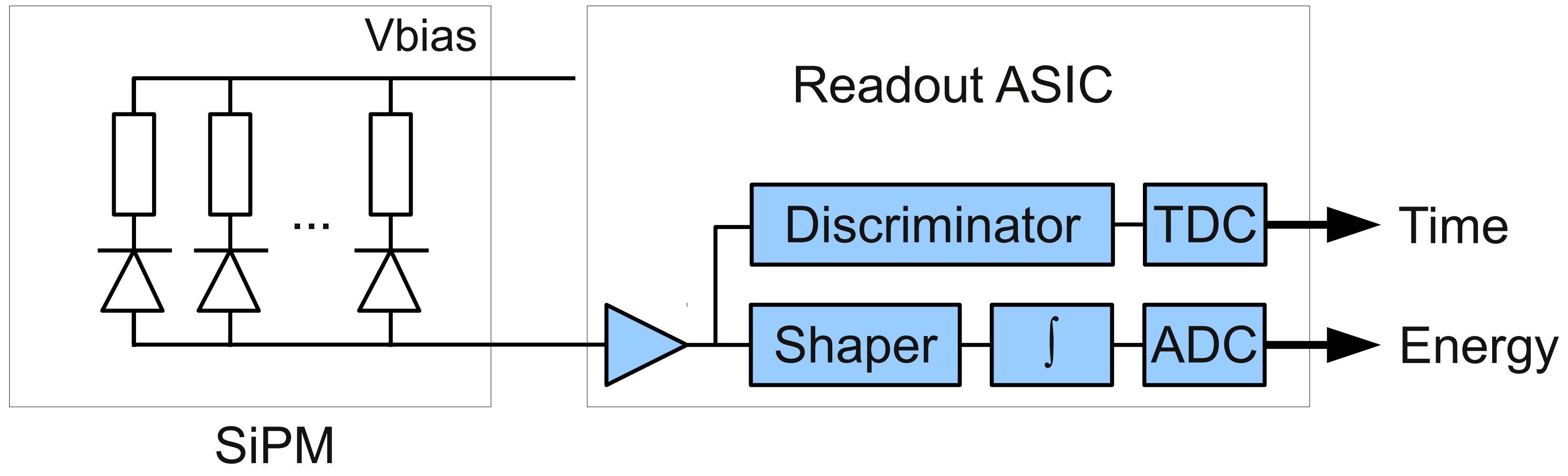
- Mitigation:
  - Cooling ($T < -30°$) & annealing cycles ($T > 120°$), anneal-in-place needed ➟ infrastructure nightmare
  - Variations in devices from different providers ➟ detailed characterization
  - Lots of synergy with efforts in Italy (INFN) & collaboration with FBK
  - Unclear how to modify SiPM design to achieve better radiation hardness

Photosensors: Digital SiPM

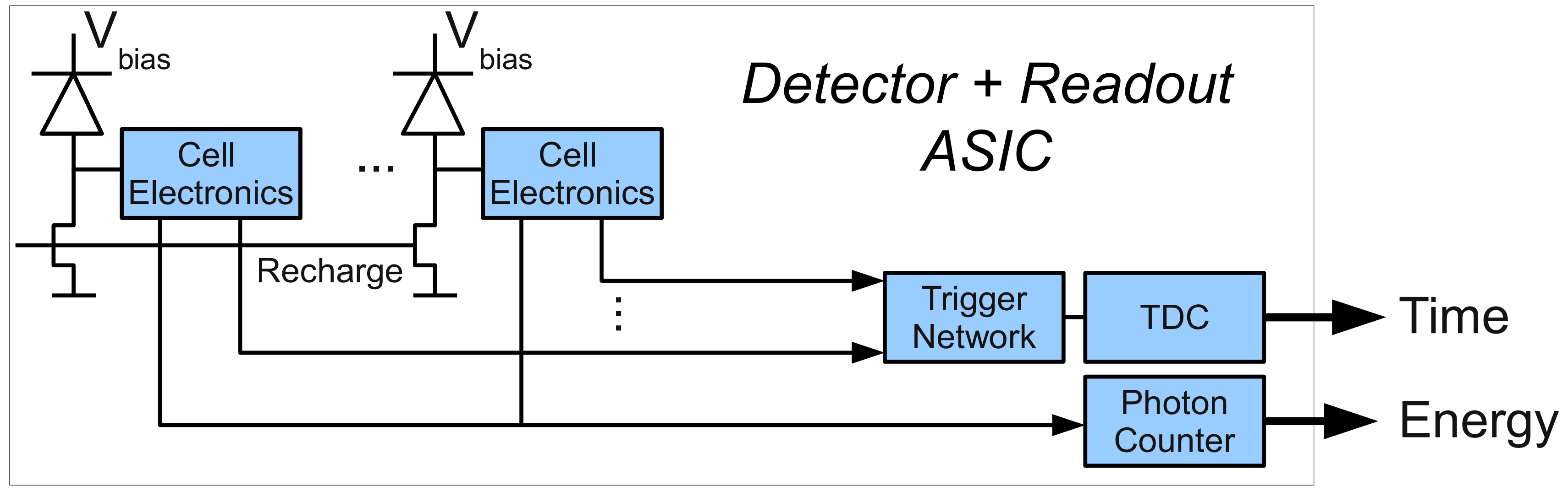
In the analog SiPM the SPAD (microcell) signals are summed up and the positron emission time is estimated via leading edge discrimination. In the multi-digital SiPM the timestamp of every photon detected is recorded with its own time to digital converter (TDC).

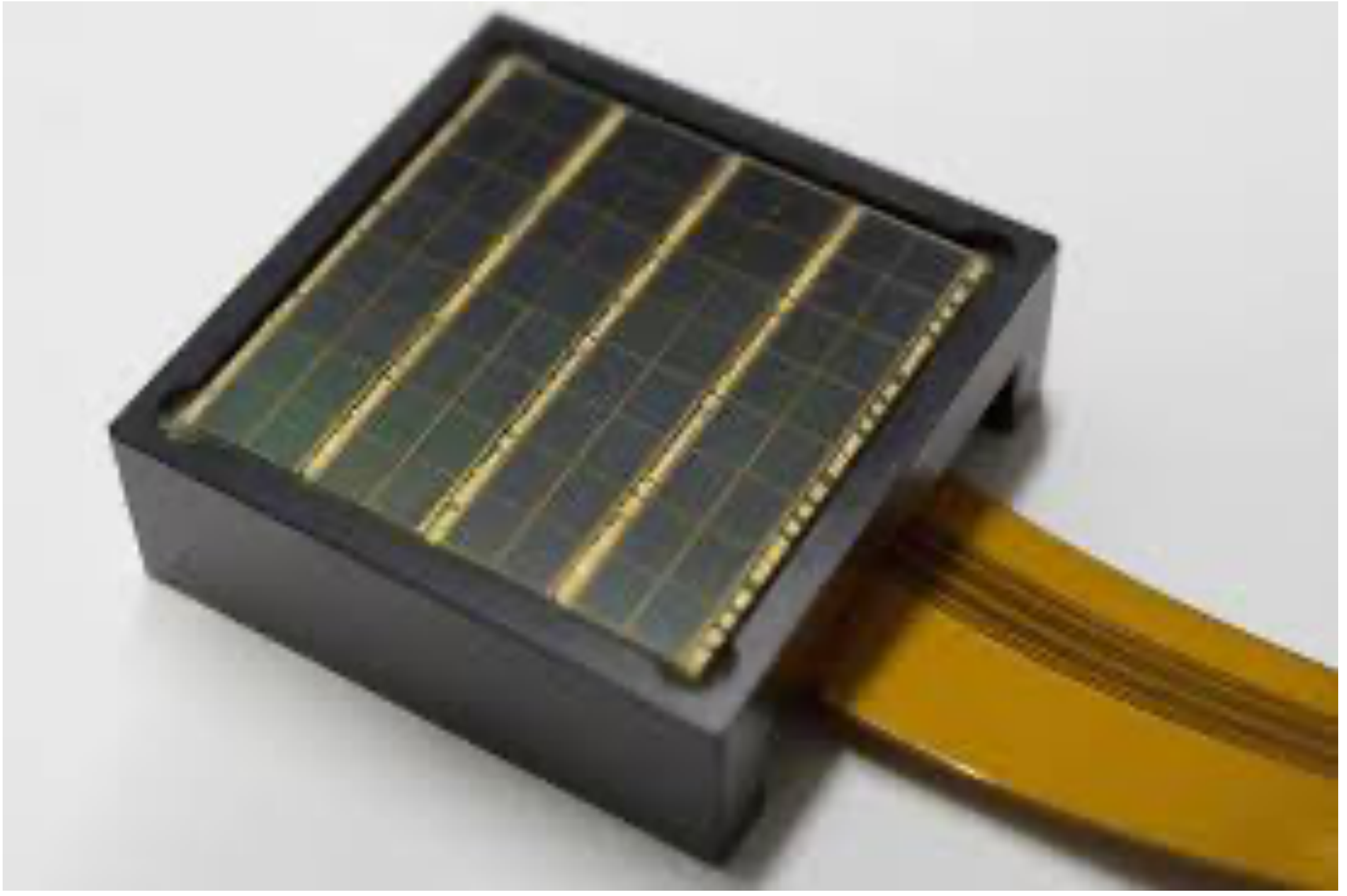
- Efforts by Philips ~2009, also 3DSiPM and Smart SiPMs
- Less sensitive to noise and defects
- Provides the digital counting of photons and precise detection time
- Enabled by CMOS technology
  - Pros: allows for additional circuitry comprises active quenching and recharge circuits, pulse combining and counting logic, and a time-to-digital converter. Also disconnection of defective SPADs,
  - Cons: CMOS SPADs are less sensitive
  - Cons: Reduced light-sensitive area
- Commercially available - R&D ongoing (HEP, PET)

Analog Silicon Photomultiplier Detector



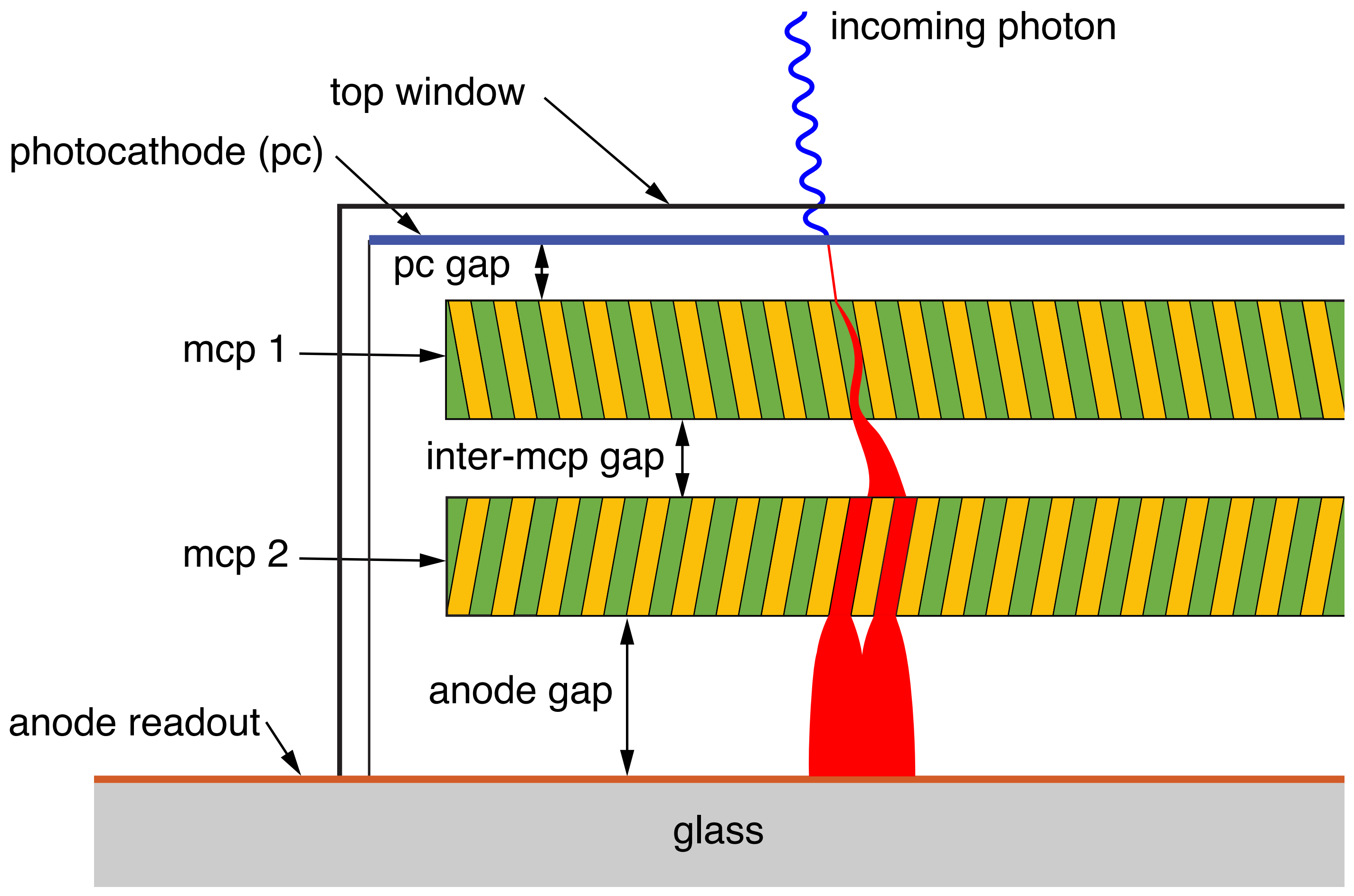
Digital Silicon Photomultiplier Detector



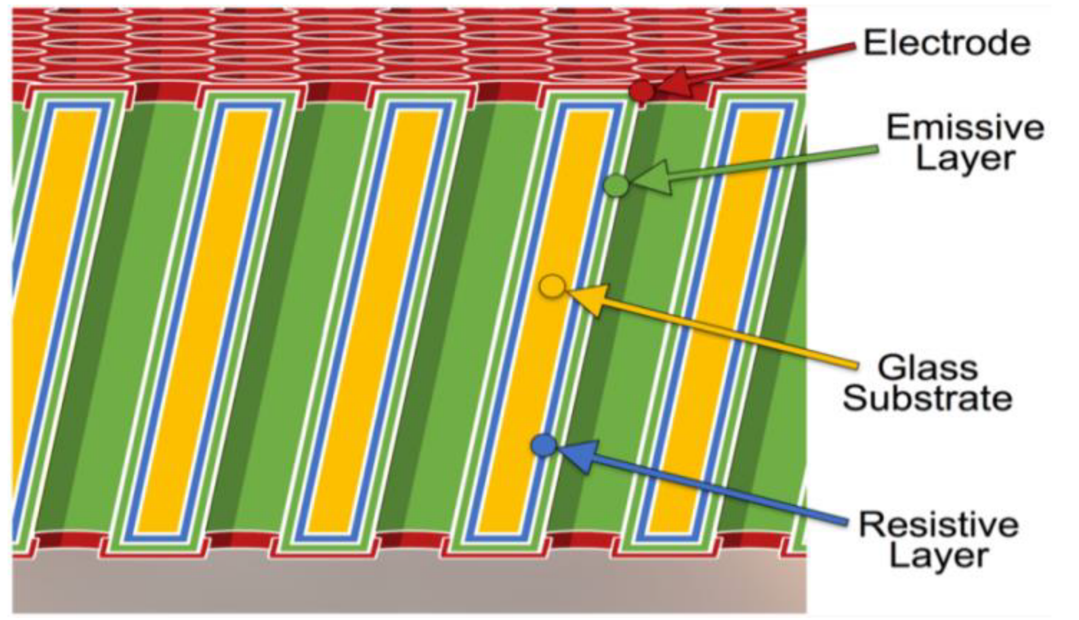


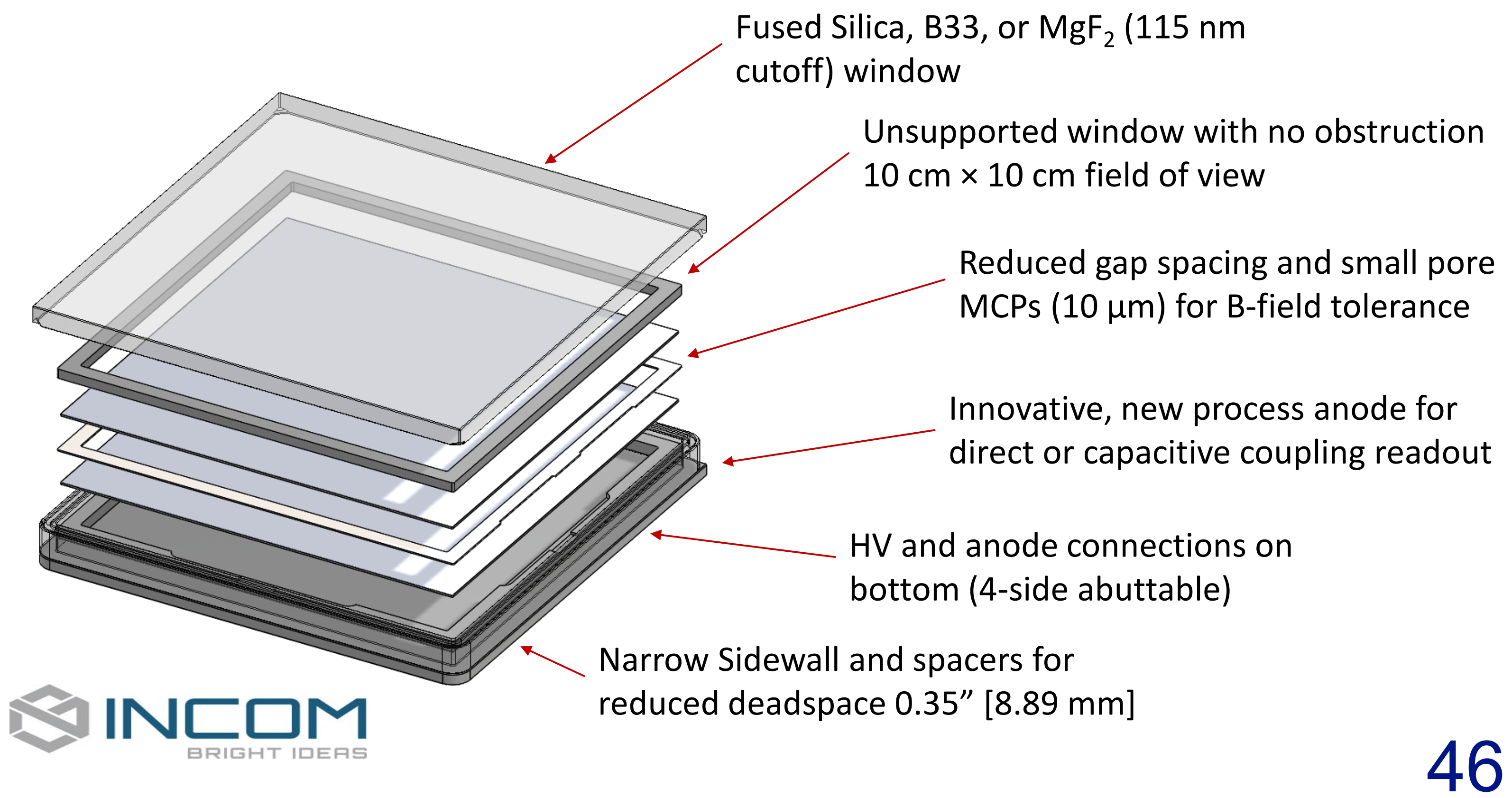
Photosensors: LAPPD

- LAPPD/HRPPD potential solution for EIC
  - Photon detector **+** ~10 ps ToF detector at the same time
- Large-Area Picosecond PhotoDetector (LAPPD)
  - Microchannel plate (MCP) based large area picosecond photodetector
  - Original LAPPD-Collaboration (HEP), now INCOM (Gen-II)
  - Promising but still not fully applicable for EIC needs
    - good but not sufficient field resilience
    - no pixelization
- High-Resolution Picosecond PhotoDetector (HRPPD)
  - Novel multi-anode direct readout
  - In development by manufacturer (INCOM) with PED support by EIC project
  - Reduced gap spacing for improved timing resolution and B-Field tolerance, better tilability



ALD+ glass substrate MCP: cross section





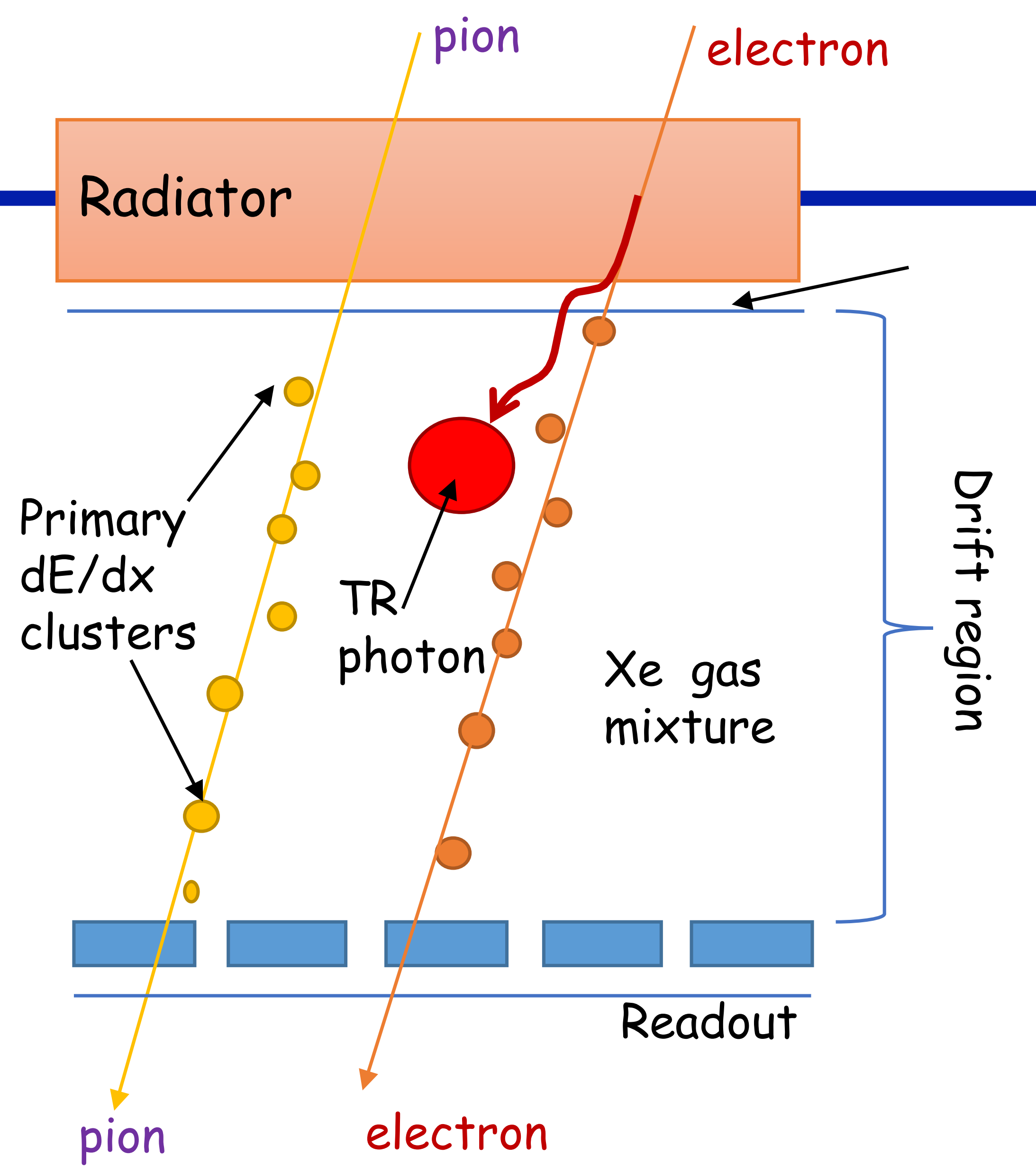
Photosensors

Reality check:

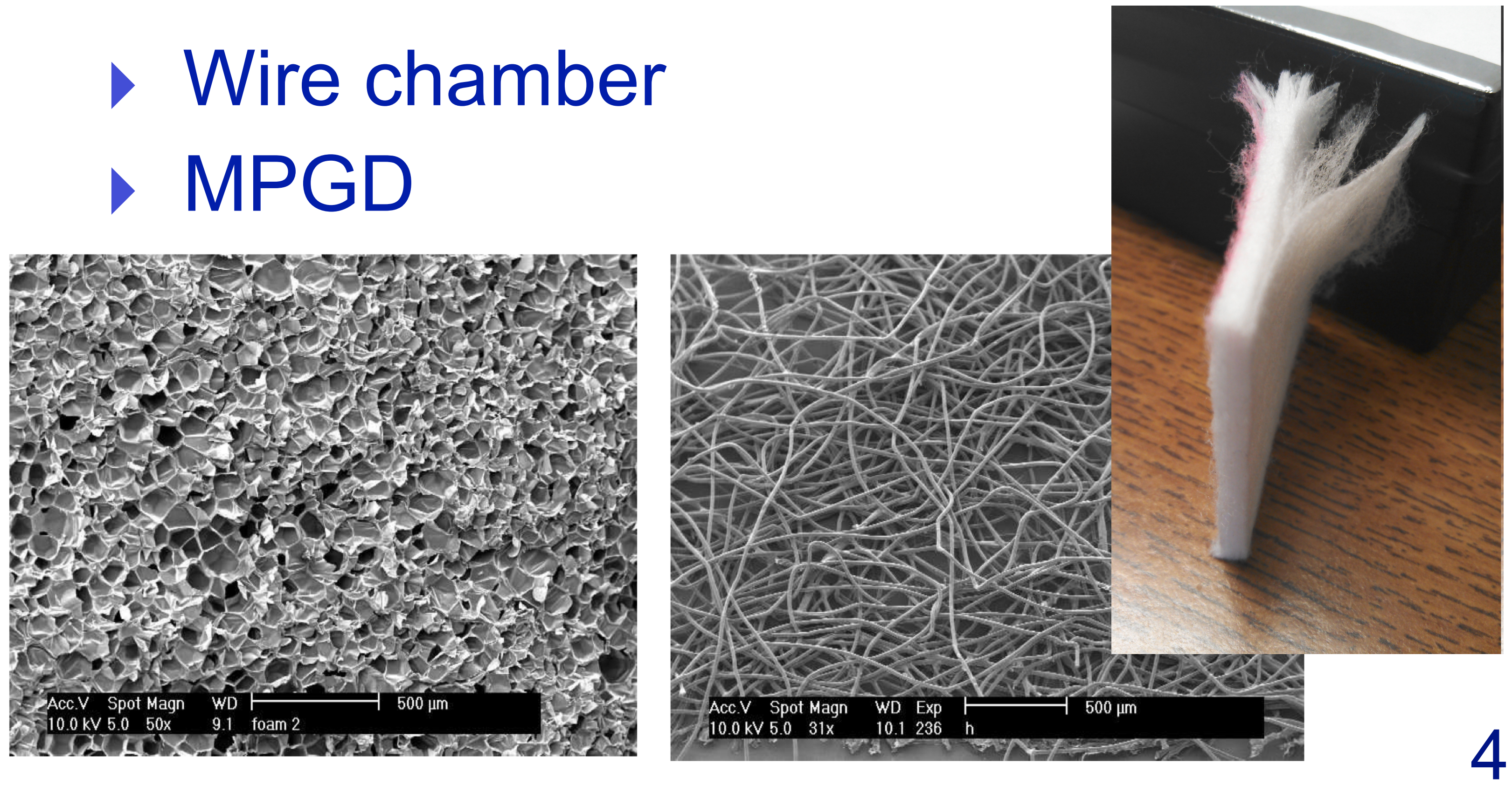
- LAPPD/HRPPD could become the go-to technology for Cherenkov detectors providing also ToF info. Next years will show.
- SiPM radiation hardness & dark currents
  - Industry has little interest
  - R&D for more radiation hard SiPM is a huge effort (beyond EIC resources)
  - Mitigation techniques are not very compelling
- Digital SiPM developemnt should be followed - promising
- MCP-PMTs - expect no big changes on the long term

Transition Radiation Detectors

- What if e/h from EMCALs and other PID detectors is not enough ($< 10^4$)?
- Transition radiation detector (TRD)
  - γs radiated when charged particle crosses the boundary between vacuum and a dielectric layer
  - number of photons emitted per boundary is small
  - photons are emitted close to the track $\theta \sim 1/\gamma_{h/e}$
  - typical energy is in the keV range
  - low Z material preferred to keep re-absorption small $\propto Z^5$
- TRDs notorious for not working well and rarely to specs, need lots of calibration and are thick
  - doesn't mean one cannot do better
- EIC concept: combine tracking with TRD



- Radiator
  - stacks of CH_2 foils
  - fibre materials, fleece
  - polymethacrylimide or polypropylene foams
- Readout
  - Wire chamber
  - MPGD



TRD for EIC

- R&D since 2018 (eRD22) - continued in FY23 generic program
- MPGD tracker and TRD
    - e/π separation (for E > 2 GeV)
    - provide a track segment for tracking
- Micromegas prototype at Vanderbilt and µRWELL prototype at JLab
    - single amplification structure MPGD replaces stack of original 3 GEM foils
- Ongoing tests for tests with different Xe/Kr/CO_2-based gas mixtures
- Continue to search and test different types of radiators
- Low X/X_0 is crucial

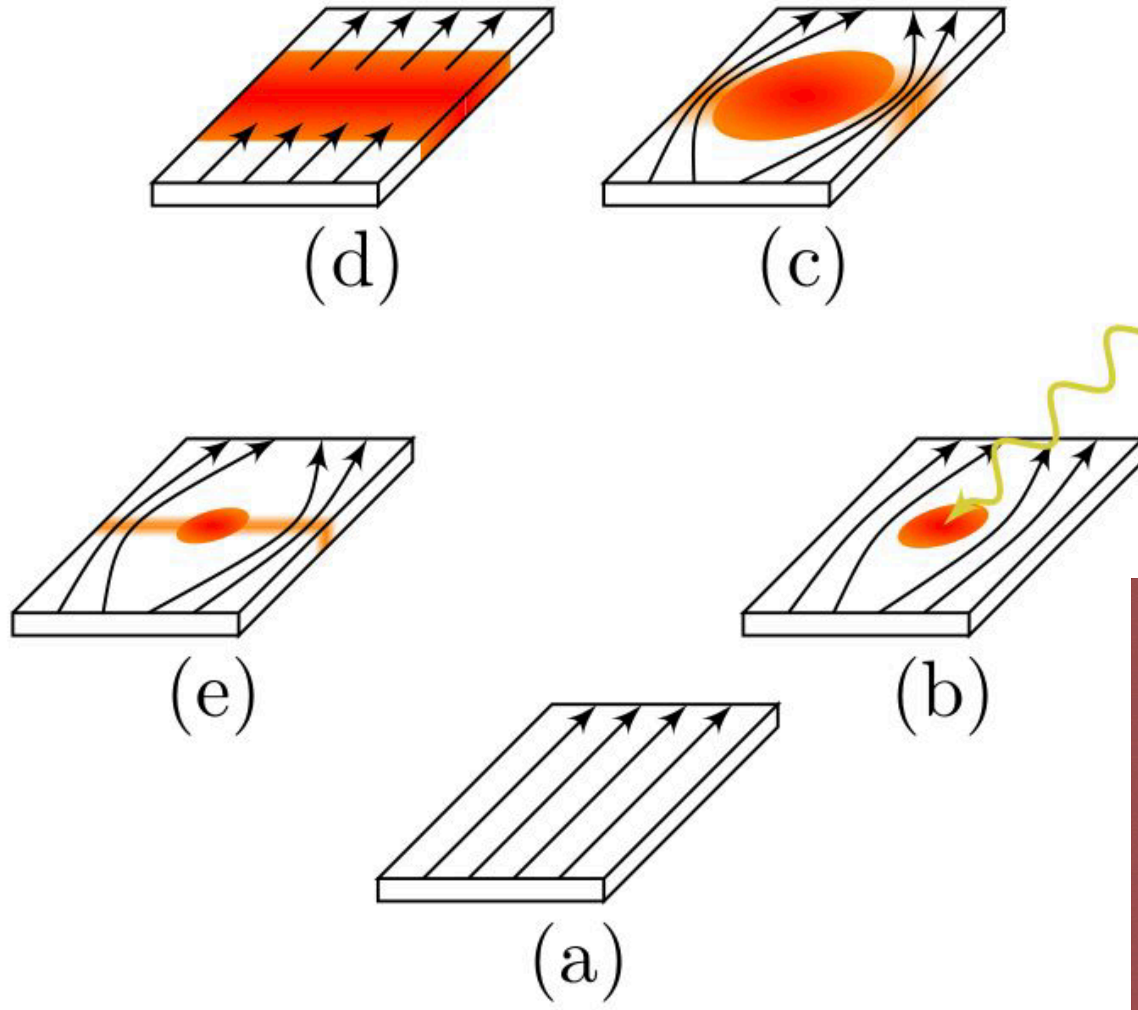
Reality check:

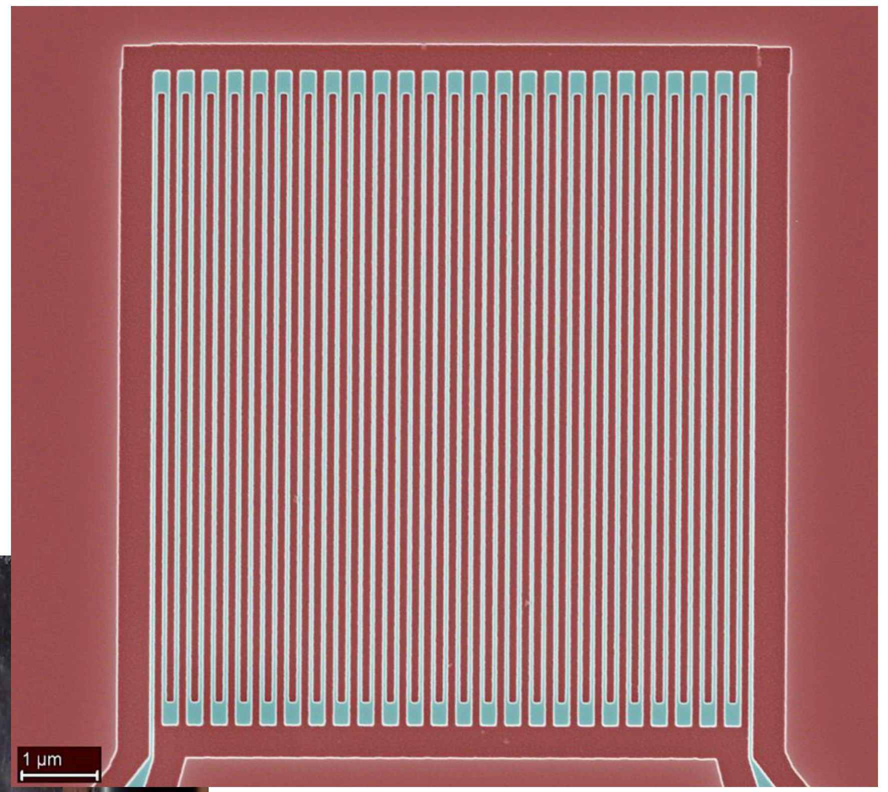
- **If** D2's EMCals do not achieve required e/h (electron purity) at good efficiency this would be the natural (only?) way out. Addresses mostly e' if D2 decides for muon detection.

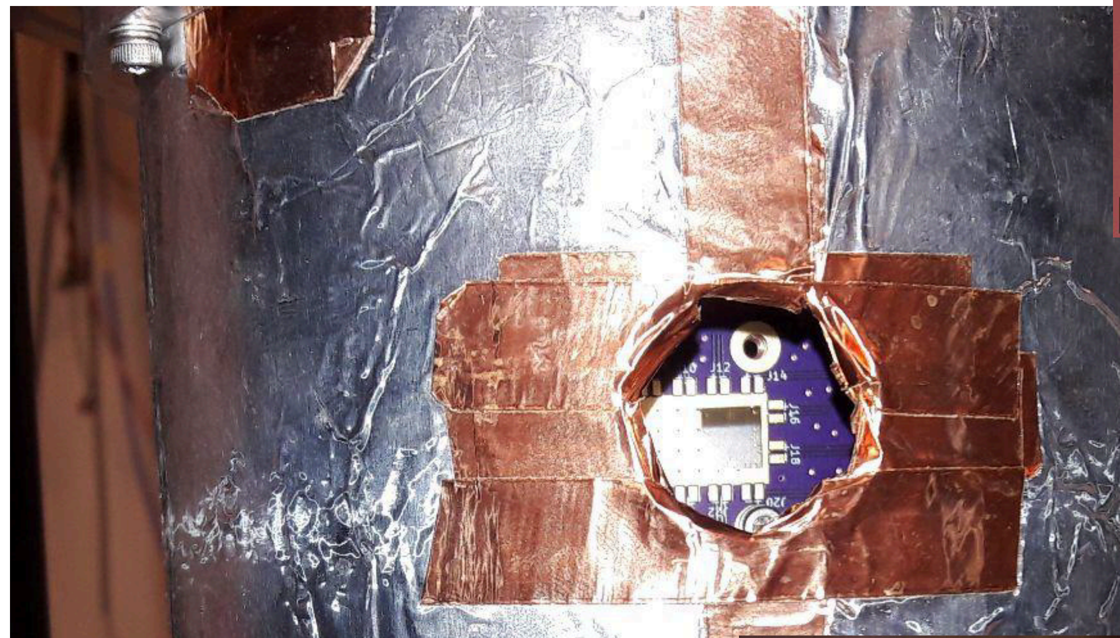
Novel Ideas

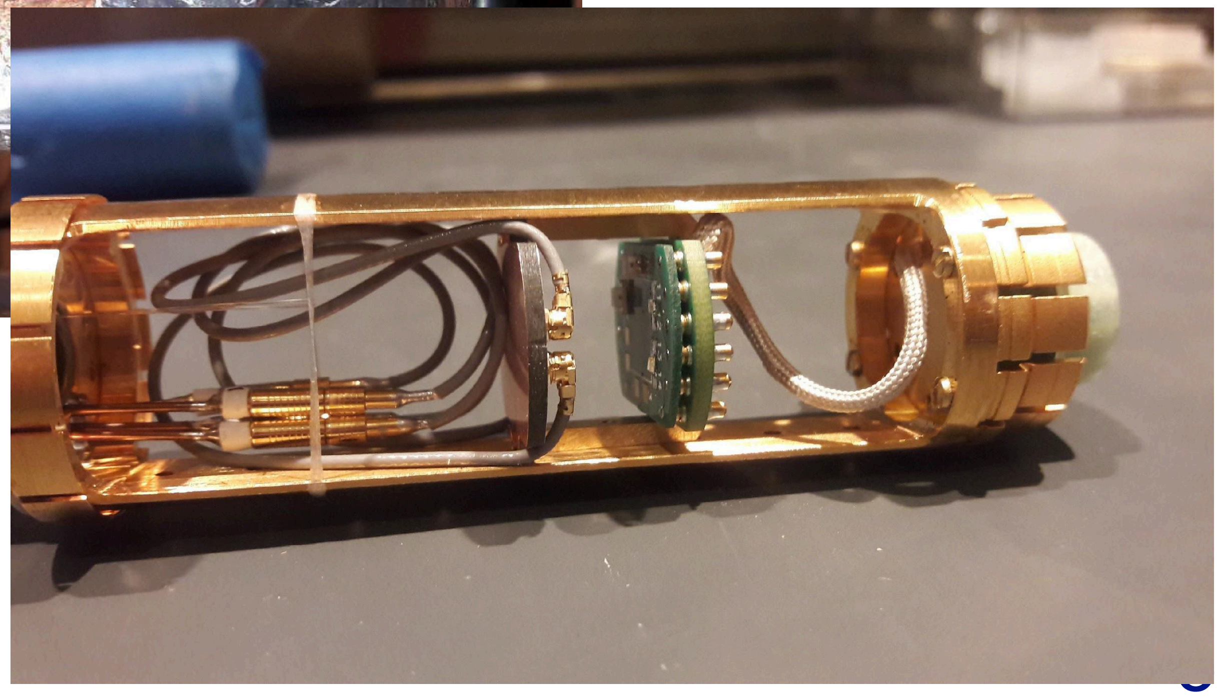
Nanowires

- Superconducting Nanowire Single Photon Detectors (SNSPD)
  - a thin (4 nm) and narrow (100-250 nm) superconducting nanostrip
  - current-biased just below its critical current
  - Absorption of a photon generates a resistive domain in the superconducting nanostrip (breaks cooper pair), which leads to transient voltage signal that can be detected.
- Almost too good to be true
  - Photon energy thresholds as low as ~100 meV
  - Timing jitter 20–40 ps easily achieved (current record 3 ps)
  - Reset times can be as low as 5-10 ns (potentially <1 ns in the future) ➟ GHz count rate
  - Pixels on the order of 10x10 μm^2 to 30x30 μm^2
  - High detection effciencies, approaching 100% for UV to near-IR
  - Low dark count rates (5-10 Hz)
- Generic EIC R&D program (eRD28) also intensive HEP R&D









Nanowires

- However
  - Need to increasing the area (using 300mm wafers and larger)
  - Increase pixel size
  - Superconducting electronics for data processing (ongoing)
  - Any application of these sensors with severe cryogenic requirements in large accelerator-based detectors would require an extensive R&D program.
- Potential Applications at the EIC
  - Far forward detectors and superconducting magnet beamline detector
    - e.g. B0, ZDC (photon part)
  - In Roman Pot Configurations (low Q^2!)
  - Also a photon (or electron) detector for compton polarimeter which can operate at high rate and last the lifetime of the EIC

Reality check:

- Needs lots of R&D but do not brush away as too futuristic
- Likely decades away for use in central detectors but could be a compelling candidate for auxiliary detectors
- … and we have expertise in the EIC community

Take Away Message

- Many technologies we have developed in the generic R&D program are now used in ePIC and available for D2
  - R&D program was finite in terms of funding and scope
- Many technologies were never looked at. Luckily others did!
- There is a large inventory of complementary technologies with few exceptions (MAPS, DIRC)
- There is no silver bullet - all have pros and cons
- Need to expand used technologies to new frontiers (e.g. MPGDs by far not exploited)
- New technologies could open the door for new groups in a second detector
- The efforts needed for R&D are getting larger and longer - can we keep up?