Advances in Detector Technology

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Introduction

- ✱ Discoveries are limited by detector advances
  - – Must keep pace with moving scientific frontiers, and accelerators
  - – Detectors can rejuvenate accelerator programs

- ✱ Large challenges posed by future scientific opportunities
  - sLHC
  - ILC
  - Super B
  - Neutrinos
  - Dark Matter
  - Astro

  $\left.\right\}$ many common challenges

- ✱ Many promising technologies advancing
  - – Impossible to do justice - apologies for biases and omissions

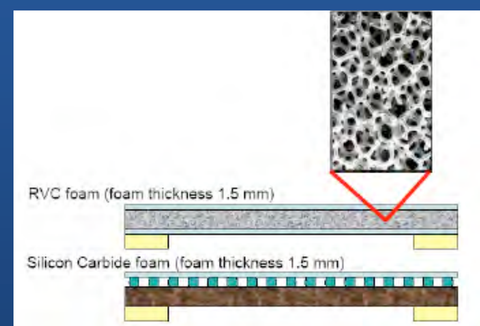
Challenges

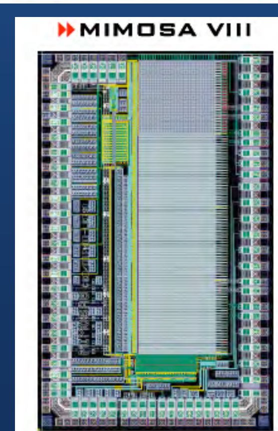
* Precision - energy, momentum, time, space
* Speed/Occupancy
* Radiation Hardness/Background Rejection
* Power/Cooling
* Cost

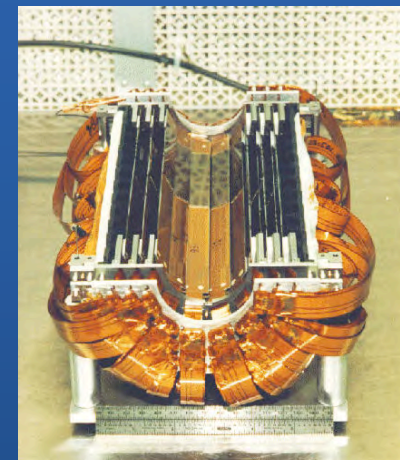
* Progress presented in several recent major conferences
  – IEEE Nuclear Science Symposium, Dresden, October, 2008
  – TIPP09, Tsukuba, March, 2009
  – 11th Pisa Meeting, May, 2009

Enabling Advances

- Segmentation
  - 10-300 μm Si pixels, Si Cal, MPGDs
- Speed & Power
  - Faster electronics, lower noise
- Integration
  - Microelectronics, mechanics
- Materials
  - Sensor, rad hard, robust, thin
- Radiation immunity
  - Understanding, design, annealing

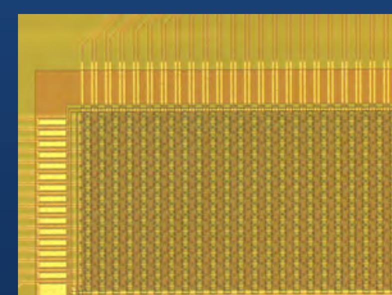




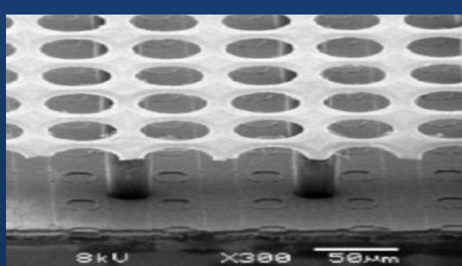


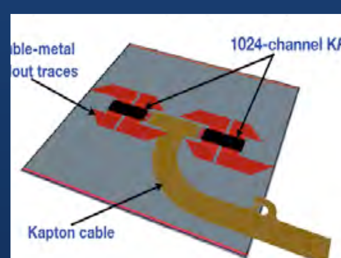
307 Mpixel SLD vxd3

LC - Maintain segmentation with increased speed



16x128 DEPFET-Matrix



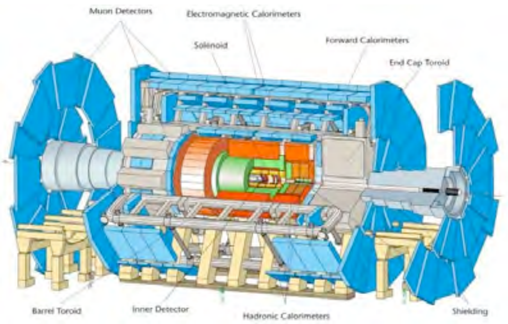


The Enterprise

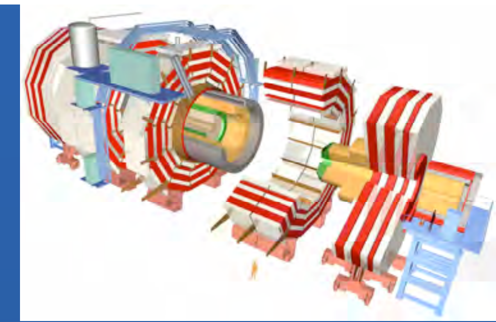
- Applications
  - Colliders
    - Vertex
    - Tracker
    - Calorimeter
    - PID, incl. muon
  - Dark Matter Detectors
  - Neutrinos
  - Ground-based Particle Astro
  - Space

- Core Technologies
  - Silicon
  - Gas
  - Crystals
  - Liquids
  - Readout, Electronics
  - Services, Power, Cooling, Support, Materials
  - Metrology
  - Trigger, DAQ

$\left.\begin{matrix} \\ \\ \\ \end{matrix}\right\}$ Parallel Advances

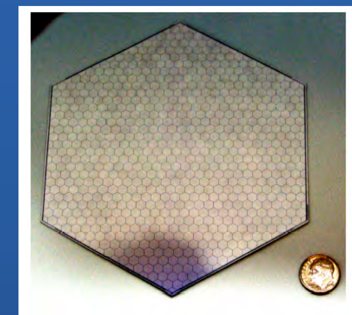


ATLAS and CMS

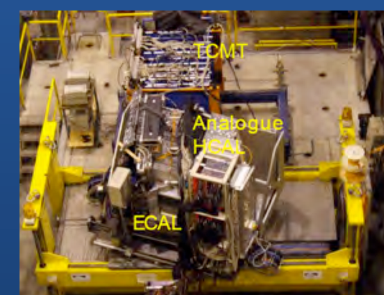


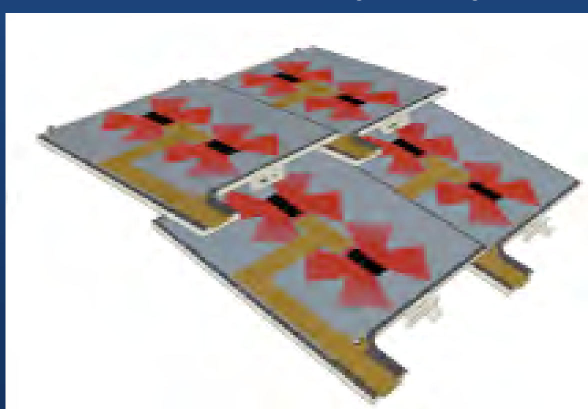
- Successful Construction & Commissioning established critical lessons for future
- Upgrades for increased LHC luminosity
  - 10^{35} for sLHC at end of decade (shutdown ~2017)
- Inner trackers
  - Complete replacement (even for lower luminosity due to accumulated radiation)
  - Radiation damage limits
  - Increased rate (eg. ATLAS TRT)
  - Improved granularity - for pattern recognition
- Other systems will need some upgrades, esp. electronics

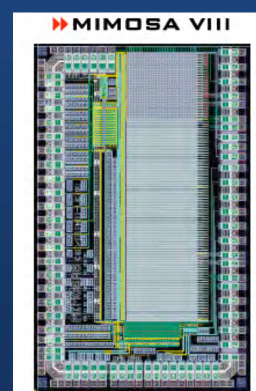
Linear Collider Detectors

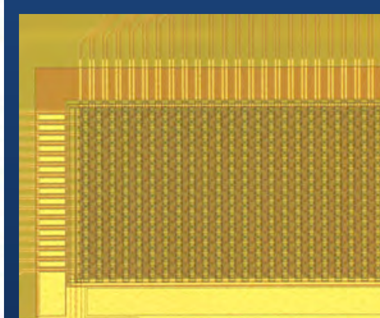


- Goals - exceptional precision and time stamping
  - Bunch train is ~3000 bunches over 1 msec (ILC)
- Vertex detectors
  - < 4 μm precision w/ ~20 μm pixels
- Trackers
  - $\sigma(1/p) \sim \textit{few} \times 10^{-5}$
- Calorimeter
  - 3-4% $\sigma(E_{jet})/E_{jet}$ for $E_{jet} > 100$ GeV







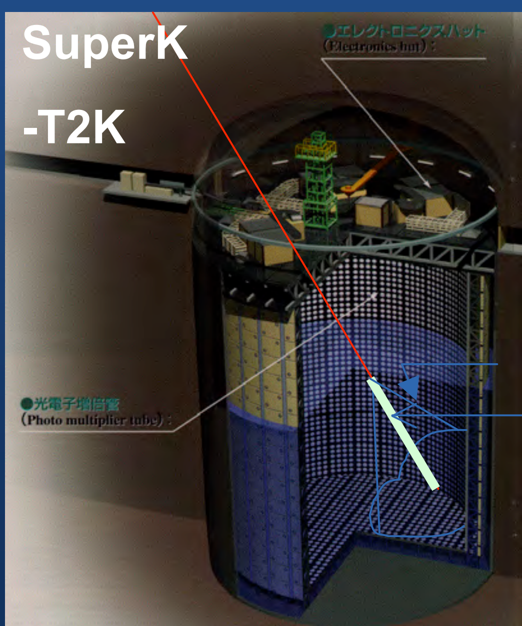


Heavy Flavor Experiments

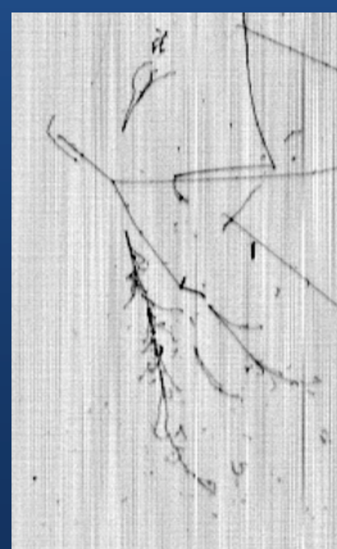
- LHC-b
  - Radiation - rad-hard vertex locator
- Super B
  - Reduce scattering in tracker - thinner
  - Endcap crystals - radiation
  - Endcap PID
- NA62 ($K^+ \rightarrow \pi^+ \nu \bar{\nu}$)
  - giga-tracker
  - RICH
- MEG ($\mu \rightarrow e \gamma$)
  - Liquid Xe Calorimeter
    - purity, cal response, calibration

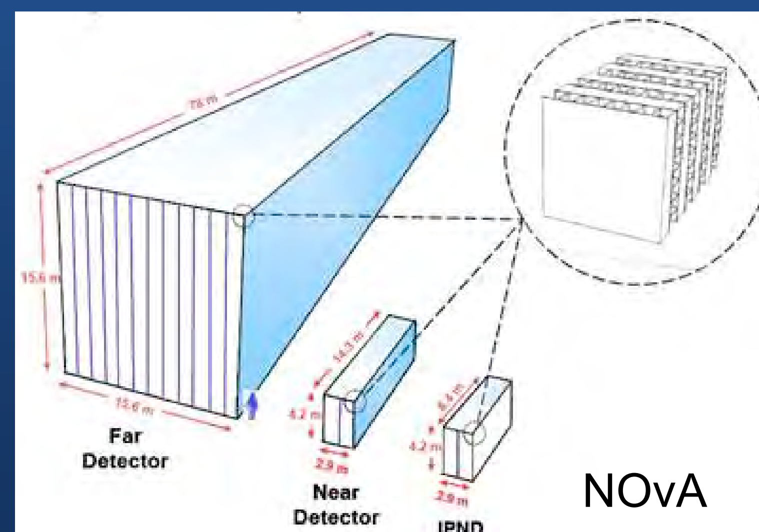
Neutrinos

- Current and recent advances
  - MPPC (SiPMs) at T2K
  - NOvA (seg. Liquid Scintillator)
- Future (toward the ~MegaTon detector)
  - Large liquid argon - tracking
  - New PMTs (low cost) - H_20 Ch



Cherenkov
Charged particle





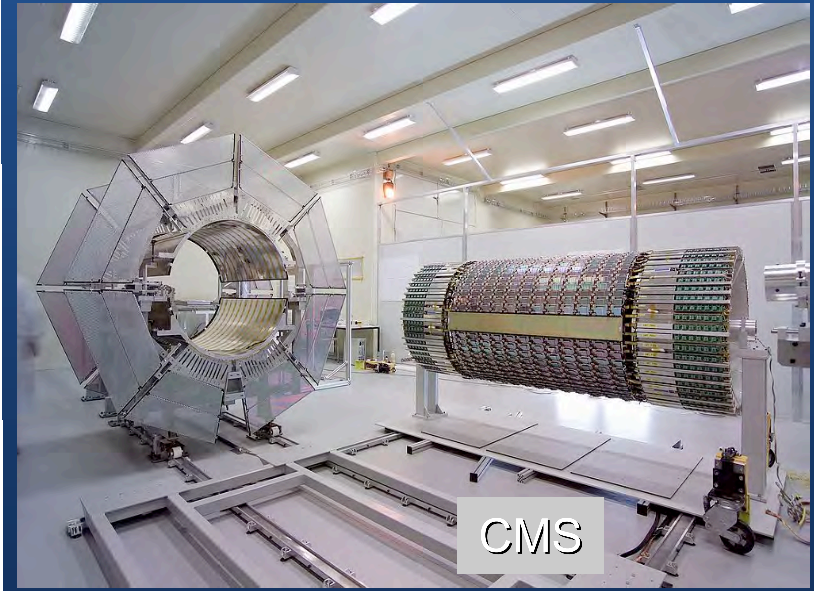
Direct Dark Matter Detection

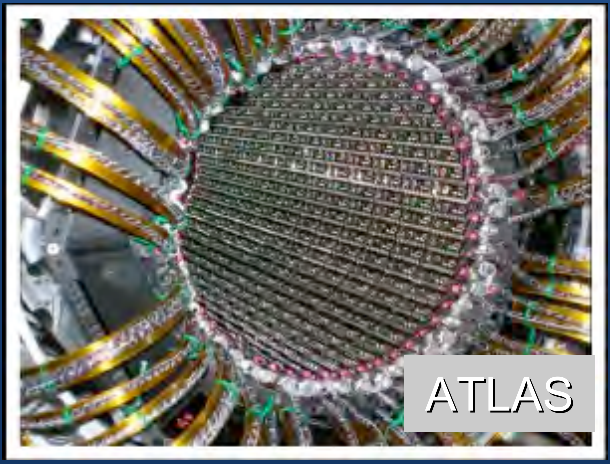
- large mass
- low energy threshold (a few keV)
- background suppression
  - deep underground
  - passive shield
  - low intrinsic radioactivity
  - gamma background discrimination

- Signatures
  - Ionization
  - Scintillation
  - Phonons

Silicon

* Construction/commission experience of LHC and Fermi
* Future challenges
  – Increased rate and radiation at sLHC
  – Increase precision for ILC and B factories
  – Specialize applications, such as NA62 Gigatracker

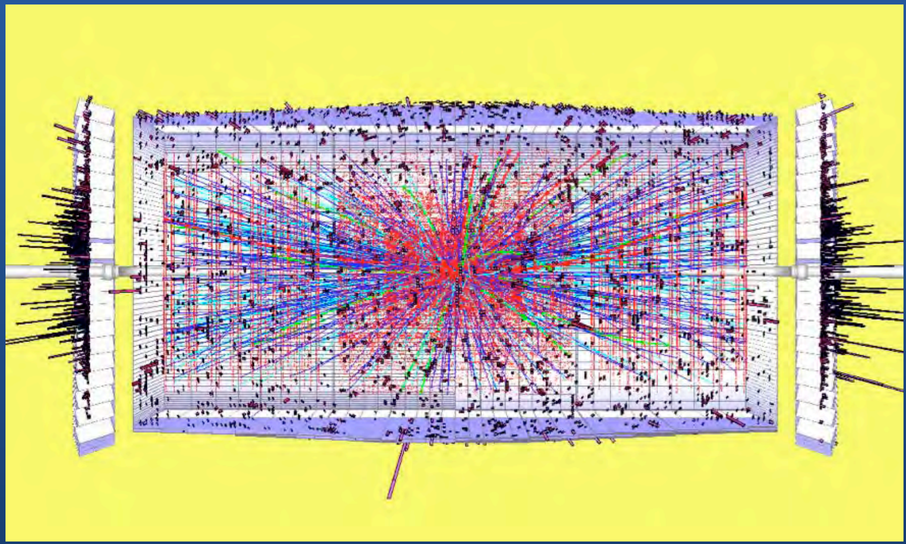




sLHC Tracking

- ✱ Intense Radiation Levels
  - – 10^{16} /cm^2 @ 5 cm (~400 MRad)
  - – 10^{15} /cm^2 @ 20 cm (~40 MRad)
  - – 2×10^{14} /cm^2 @ 50 cm (~10 MR)

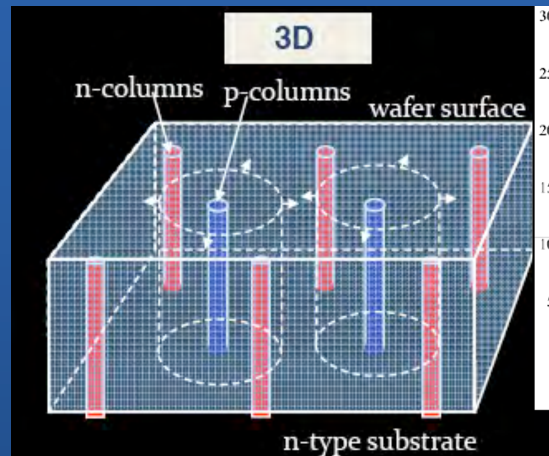
  (dictates technology for tracker)
- ✱ R > 20 cm
  - – Silicon Strips (> 60 cm)
  - – Pixels (20 - 60 cm)
- ✱ R< 20 cm
  - – New technologies

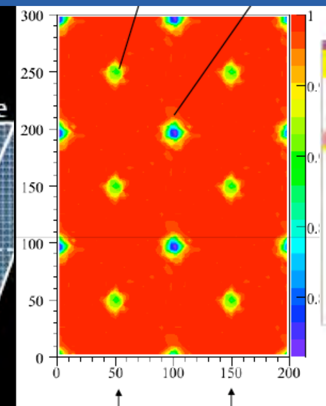


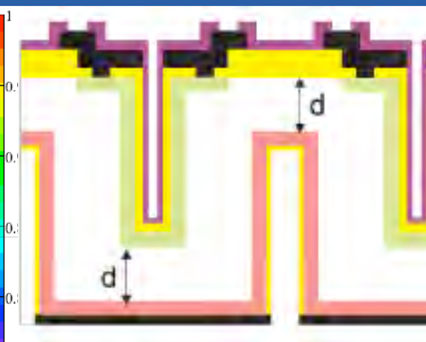
- 300-400 events/crossing
- ~ 10000 particles in $|\eta| \leq 3.2$
- mostly low p_T tracks

sLHC Inner Tracking (R<20cm)

- ATLAS Candidates:
  - Planar
  - 3D-silicon
  - Diamond
  - GOSSIP (Gas Pixel)



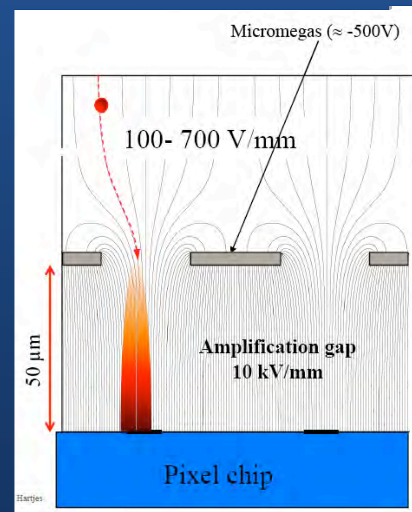


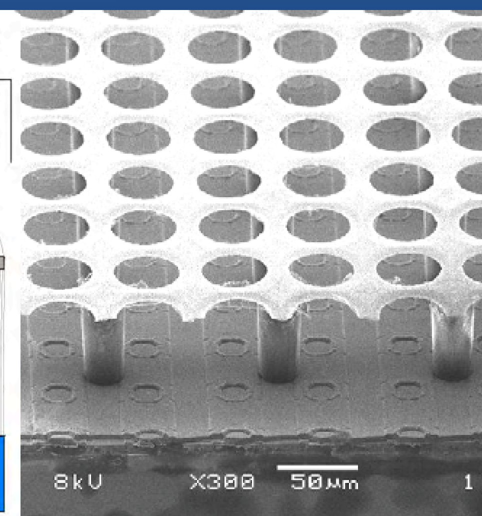


3D- Double Type Columns

technology	Planar silicon	3D silicon	Diamond	Gossip
possible pos resolution (um)	< 10	< 10 ?	~ 14 (polycryst)	~20
resolution for inclined tracks	reasonable	reasonable	reasonable	mediocre
charge collection time (ns)	< 6	20 - 35	2	20 - 80
mass including cooling	pretty high	pretty high	medium	low
life time in SLHC (3000 fb-1)	20 - 50%?	~ 50%	~ 50%	> 100% poss
production technology	well known	difficult	difficult	much R&D
bias voltage control	easy	easy	easy	critical
ease of operation	reasonable	reasonable	relaxed	critical
cooling	critical	less critical	relaxed	relaxed
additional services	NO	NO	NO	HV + gas
additional DAQ channels	NO	NO	NO	probably
track efficiency	100%	>95%?	98-100%	98%
costs	75 - 300 €/cm2	150 - 300 €/cm2	~ 1000 €/cm2 ?	20-30 €/cm2
size of coll. (ATLAS institutes)	>10	10	6	2
approved R&D?	yes	yes	Yes	near submit

ATLAS F. Hartjes





GOSSIP

EPS HEP 09 talks - S. Palestini, C. Civinini, G. Pellegrini

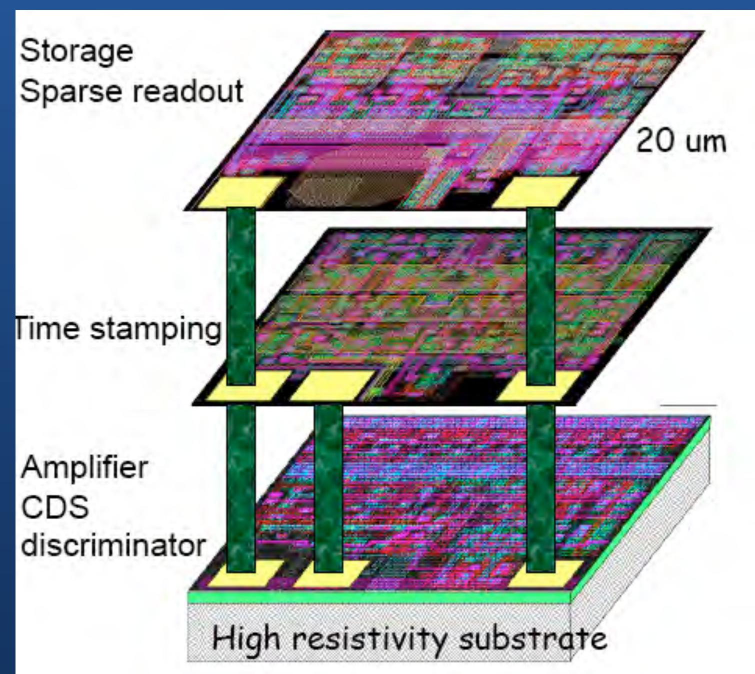
Silicon for Linear Collider

vertex sensors

- ∗ **Excellent spacepoint precision (** < 4 microns **)**
- ∗ **Superb impact parameter resolution (** 5µm ⊕ 10µm/(p $\sin^{3/2}\theta$) **)**
- ∗ **Transparency** (~0.1% X_0 per layer)
- ∗ **Track reconstruction (** find tracks in VXD alone **)**
- ∗ **Sensitive to minimal bunch crossings (** <150 = 45 µsec for ILC)
- ∗ **EMI immunity**
- ∗ **Power Constraint** (< 100 Watts)

<u>Concepts under Development</u>

- ∗ **Charge-Coupled Devices (CCDs)**
  - **Build on 307Mpx of SLD ⇒ Column Parallel CCDs, FPCCD (slow!)**
- ∗ **Monolithic Active Pixels – CMOS**
  - **MAPs, FAPs, Chronopixels, 3D-SOI**
- ∗ **DEpleted P-channel Field Effect Transistor (DEPFET)**
- ∗ **Silicon on Insulator (SoI)**
- ∗ **Image Sensor with In-Situ Storage (ISIS)**
- ∗ **HAPS (Hybrid Pixel Sensors)**

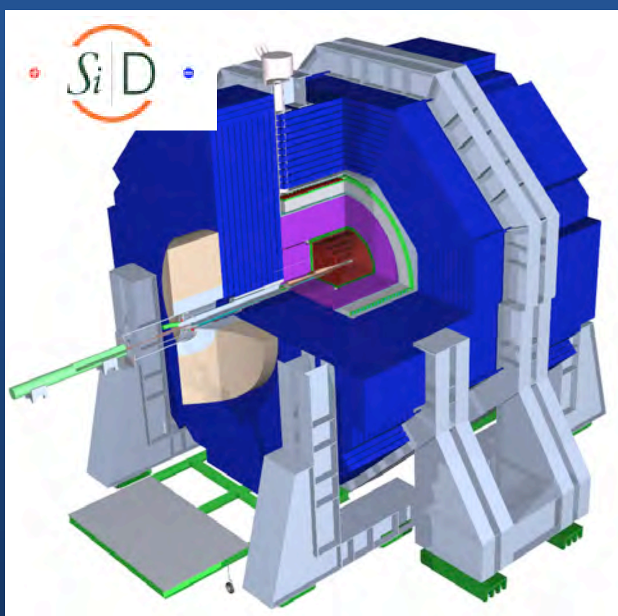


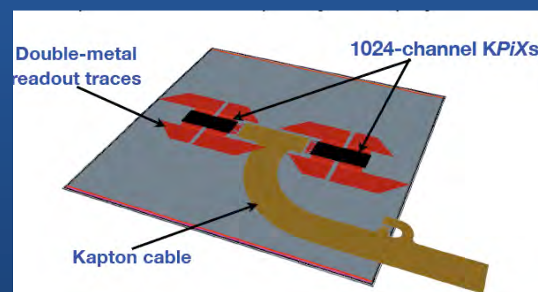
3D concept - Yarema

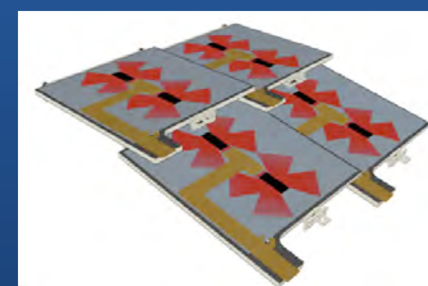
EPS HEP 09 talk - R. De Masi

Silicon for Linear Collider
tracker

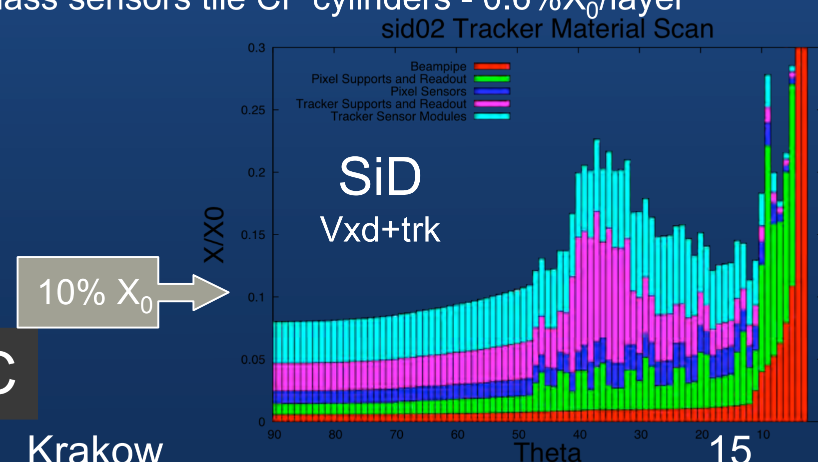
* Superb resolution allows small tracking volume
  – <1% σ_p/p at 100 GeV
* Fast - robust to backgrounds
* Requires very low mass support (passive cooling)







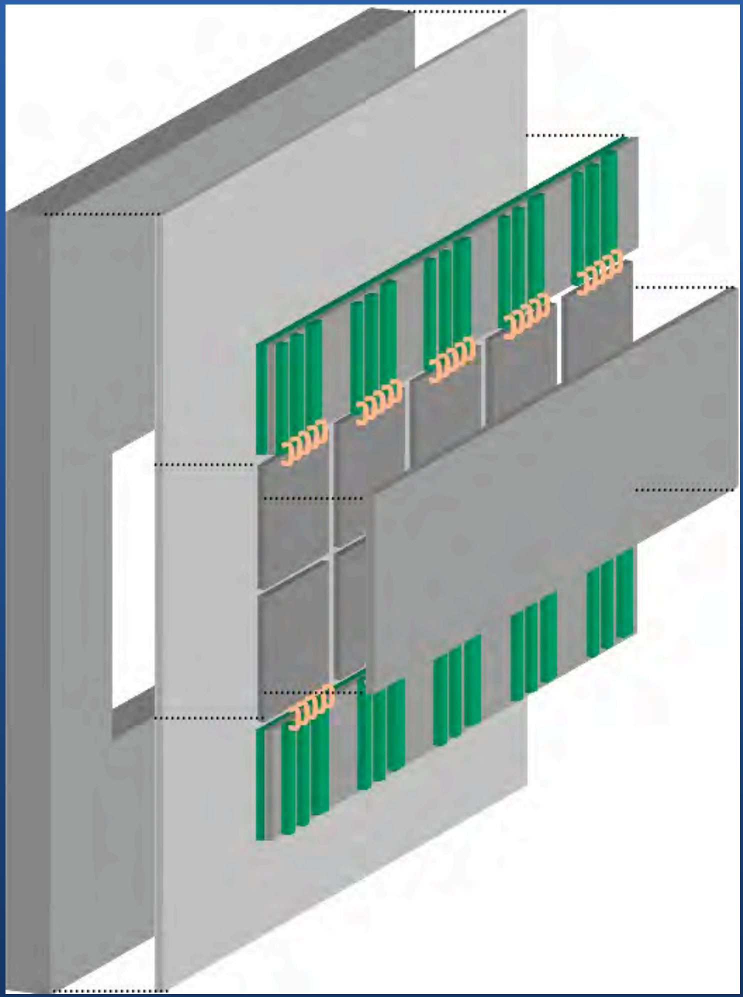
Modular low mass sensors tile CF cylinders - 0.6%X_0/layer



ALSO - SiLC - Silicon envelope for TPC

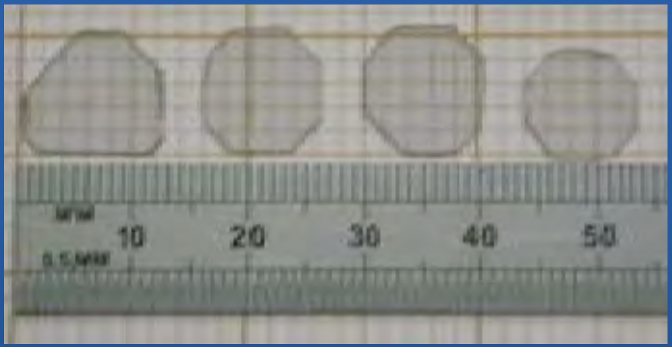
NA62 Gigatracker

- Three silicon pixel sensors
  - Precise direction & timing
  - ~ GHz rate
  - 1.5 MHz/mm^2 maximum
  - In vacuum
- Two readout options
  - Constant Fraction Discriminator (CFD) with complex pixel circuitry
  - Time Over Threshold (TOT) with simple, low power pixel circuitry
- Prototypes of analog for options in CMOS 0.13 μm passed tests

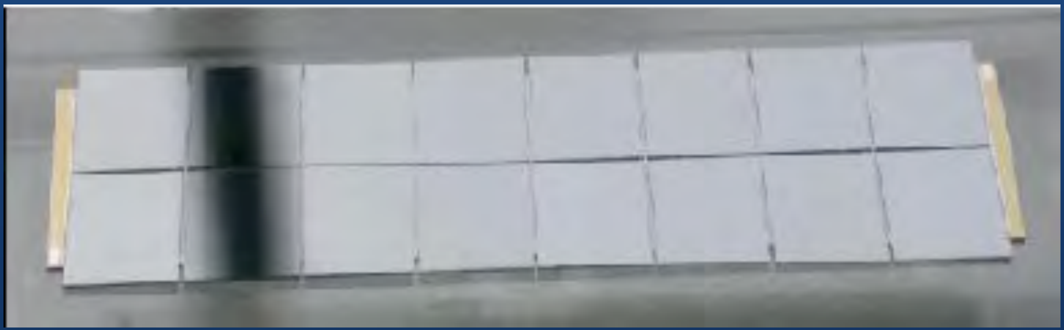


Diamond

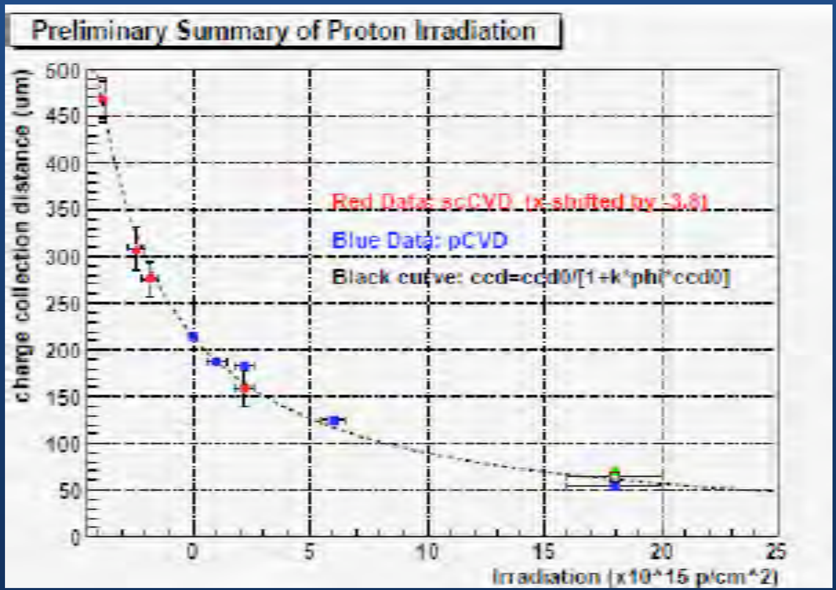
Polycrystalline



- ✱ Advantages over silicon
  - Larger bandgap
  - Smaller dielectric constant
- ✱ Single Crystal (> 12 cm, 2 cm thick) polycrystalline (few cm^2)
- ✱ Experience as radiation monitors
- ✱ Candidate for LHC inner tracking

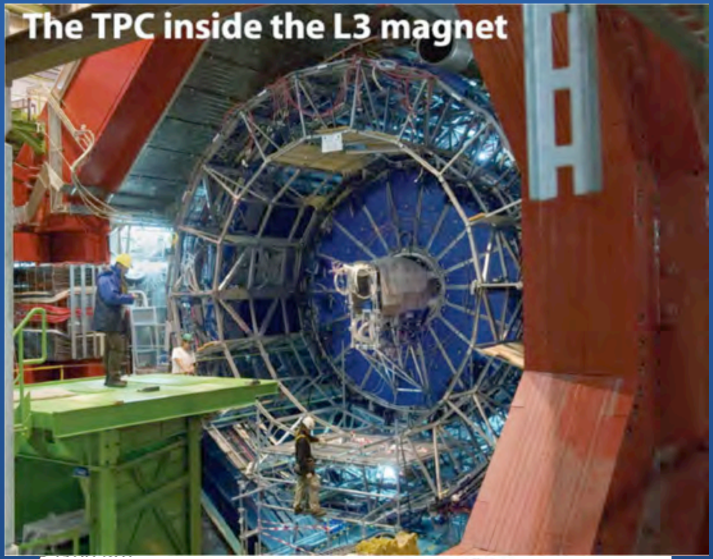


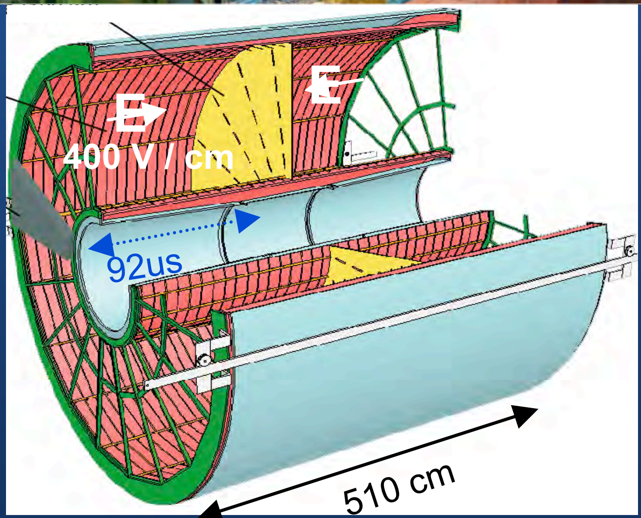
16 chip ATLAS Module of single crystal



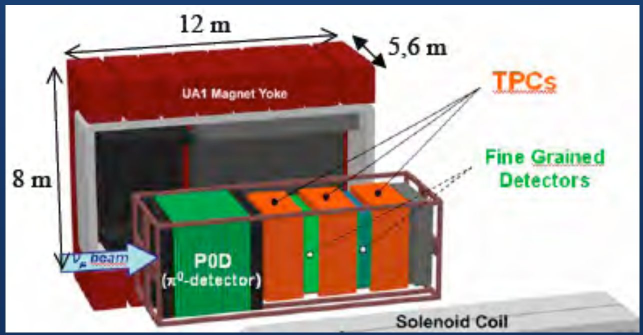
Gas Detectors

- ALICE TPC
  - Largest - 2466 mm Rout,
    2 x 2500 mm drift
- Micro Pattern Gas Detectors (MPGDs)
  - GEMs
  - MicroMegas
  - Timepix(CMOS)/Ingrid
- T2K Near Detector
  - Largest TPC equipped with MPGDs

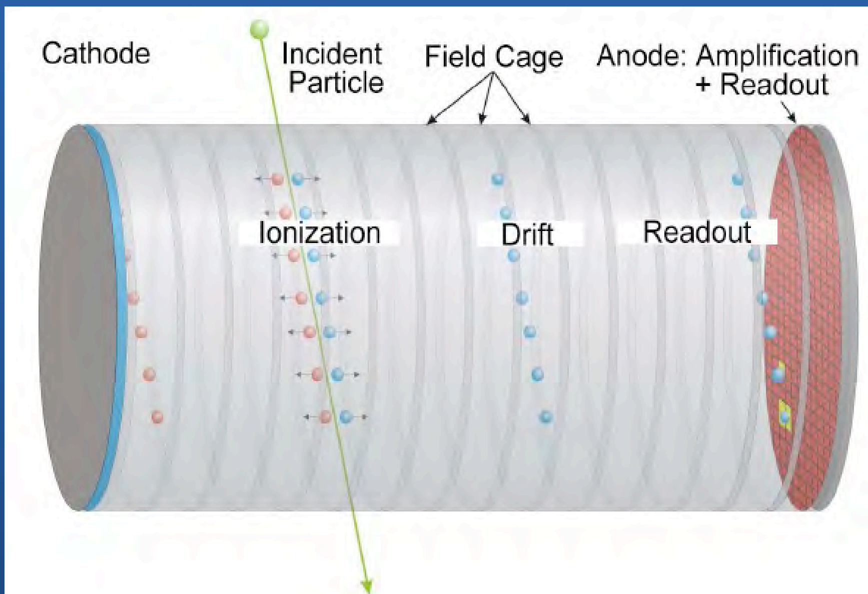




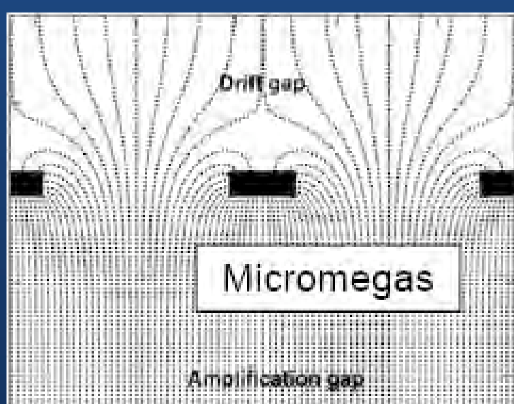
EPS HEP 09 talk - A. Matyja



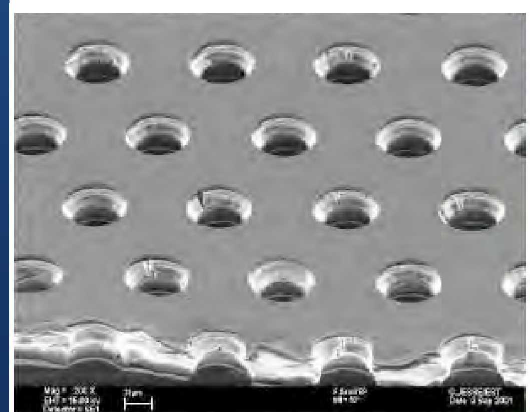
Linear Collider TPC w/MGPDs

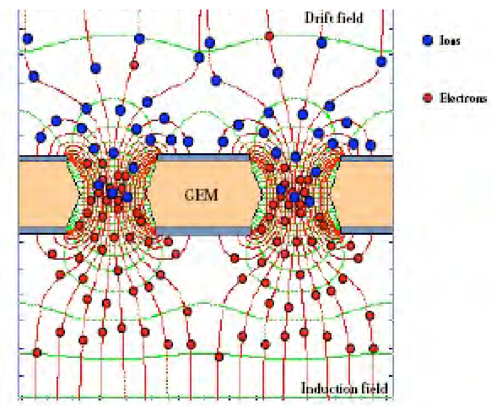


MicroPatternGasDetector
MPGD
not limited by **E** x **B** effects



Gas Electron Multiplier GEM

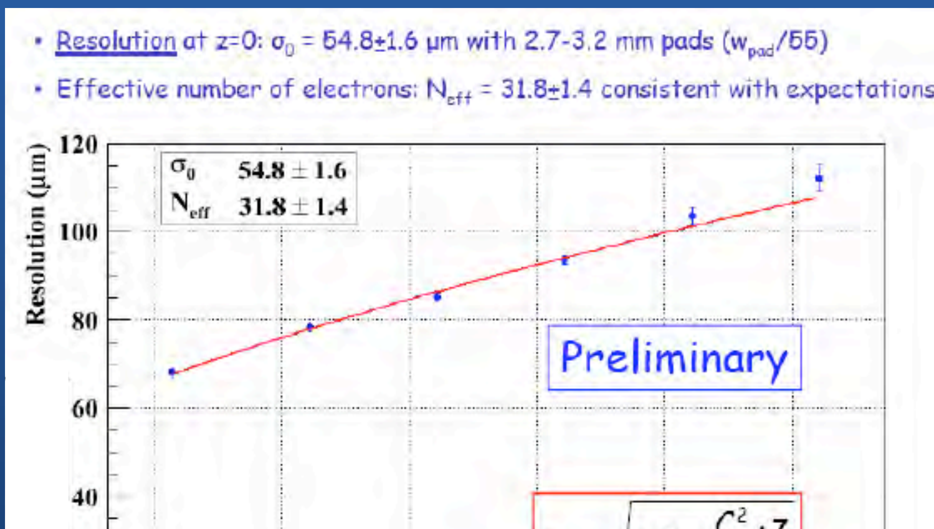


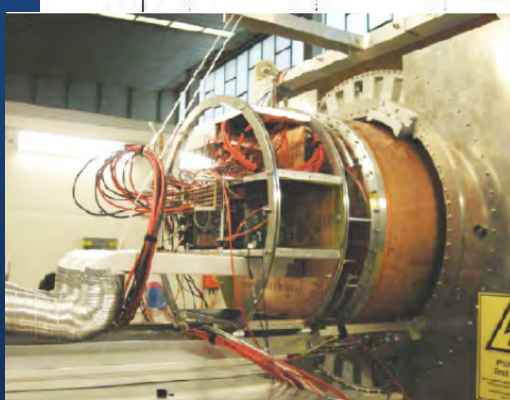


EPS HEP 09 talk - K. Dehmelt

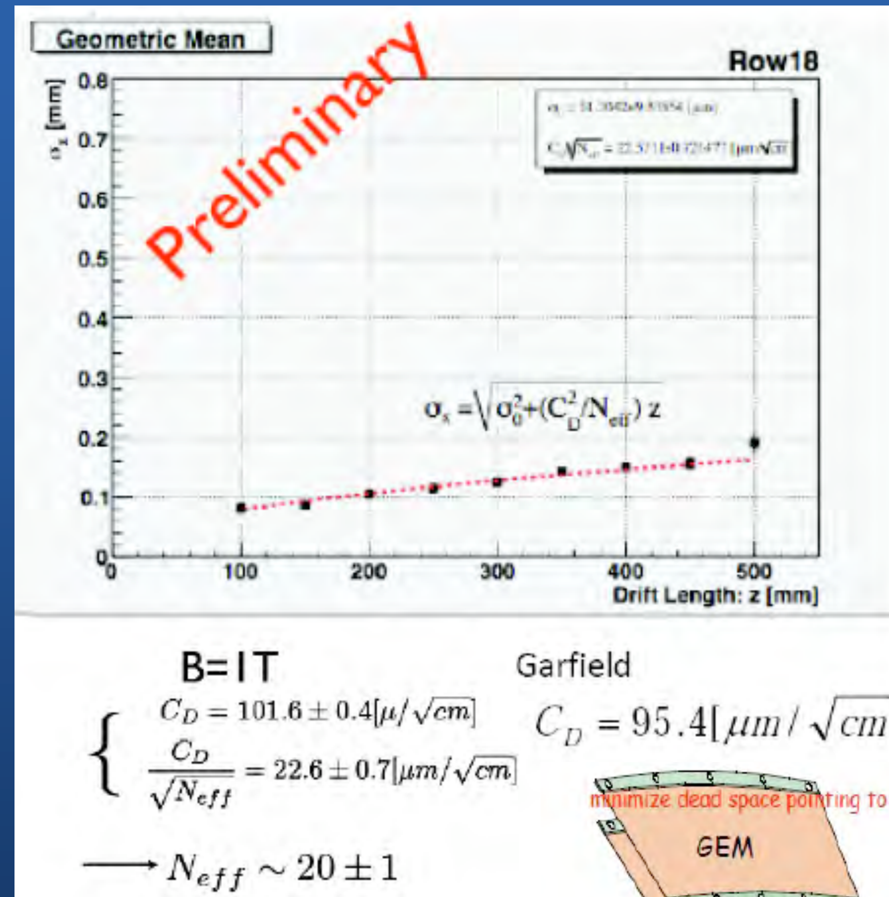
Linear Collider TPC

✱ DESY Beam Test

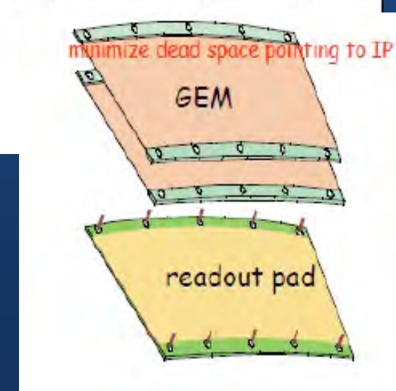




MicroMeGas
5 GeV electrons,
1 Tesla

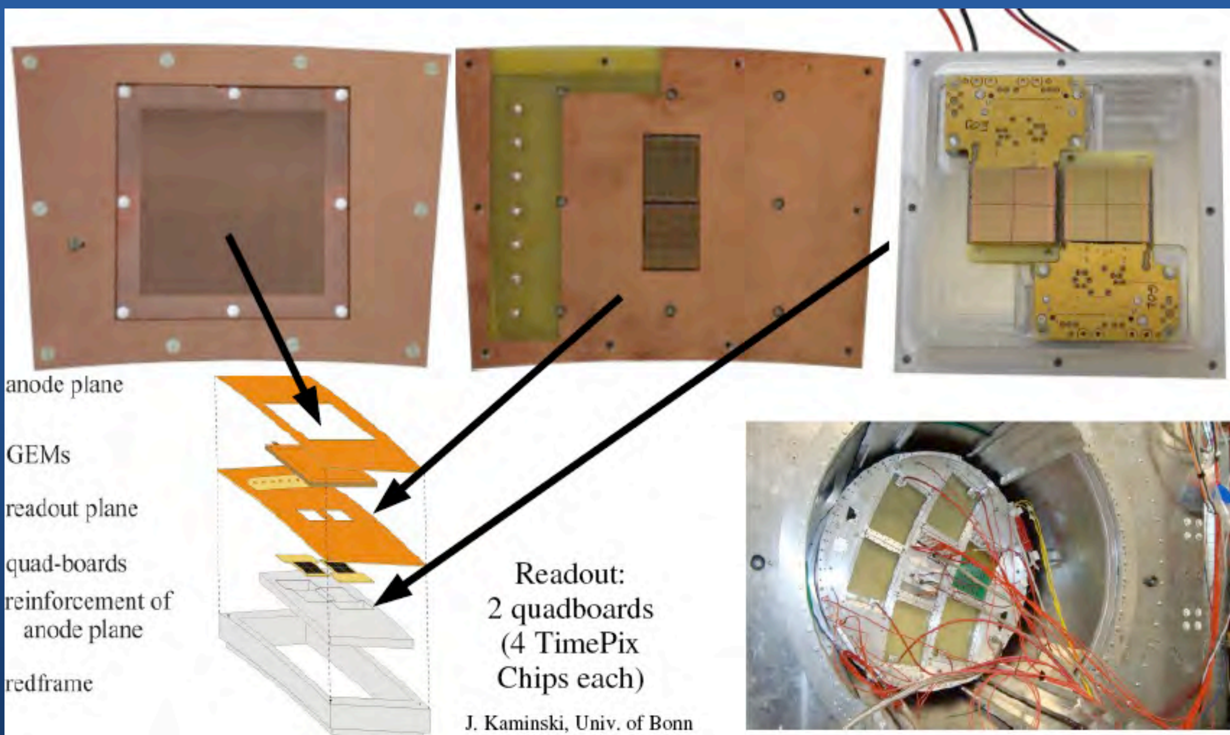


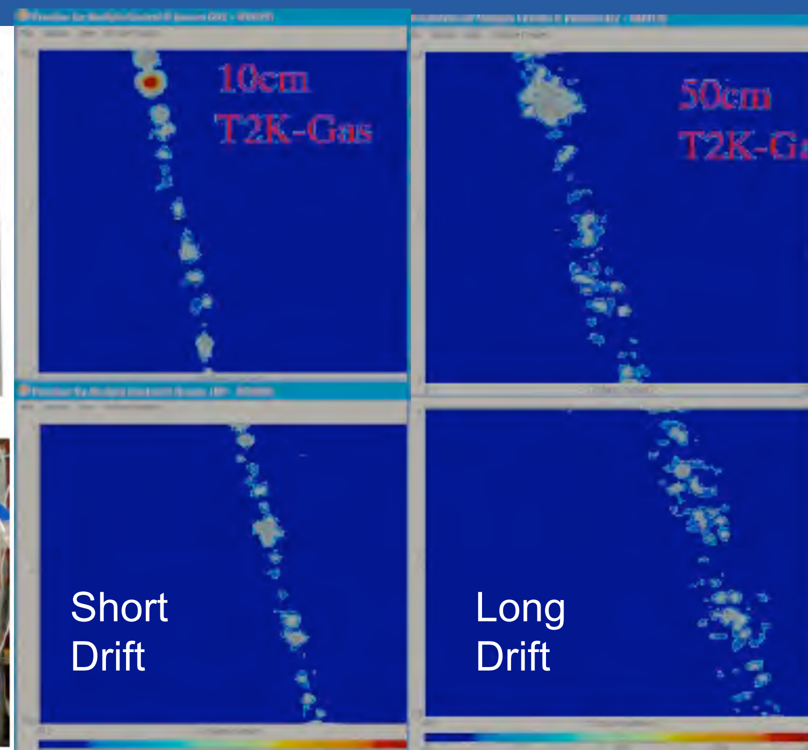
Double GEMs



Linear Collider TPC

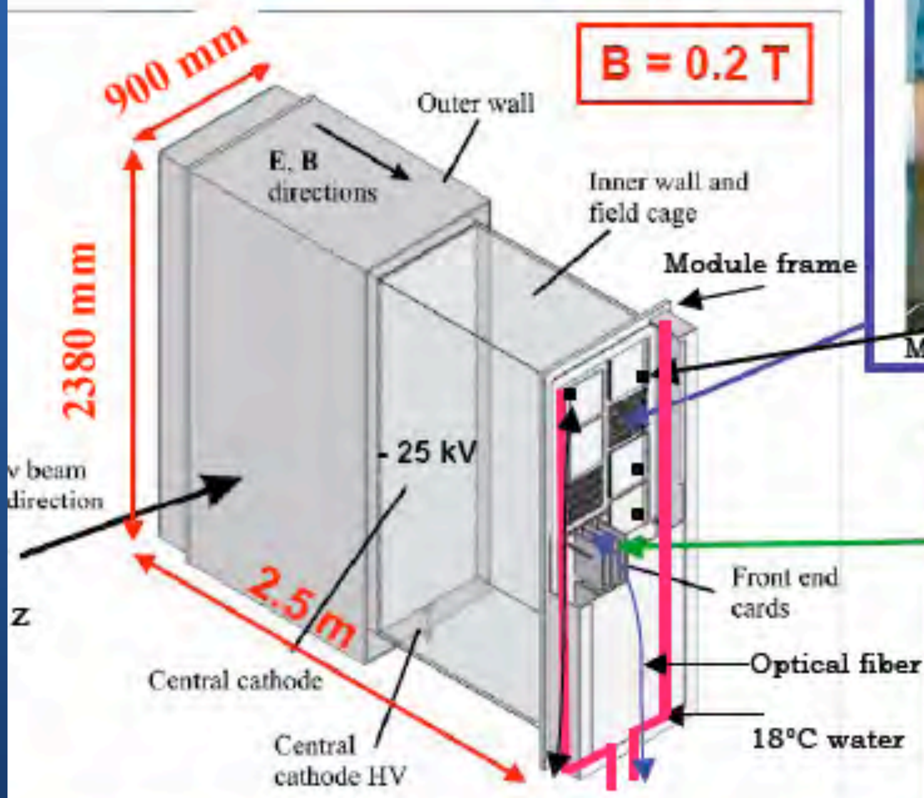
- ✱ Triple GEM structure with Timepix readout



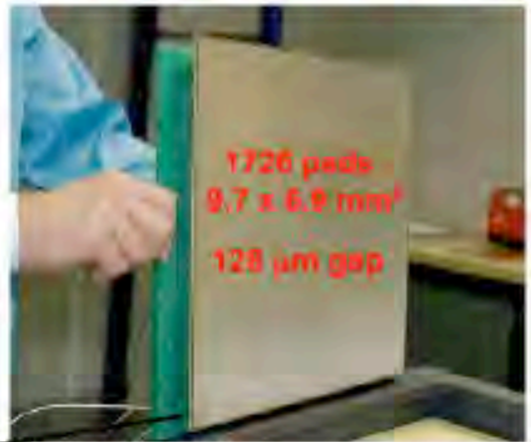


J. Kaminiski, Univ. of Bonn

The T2K/TPCs : the largest TPCs equipped with MPGDs



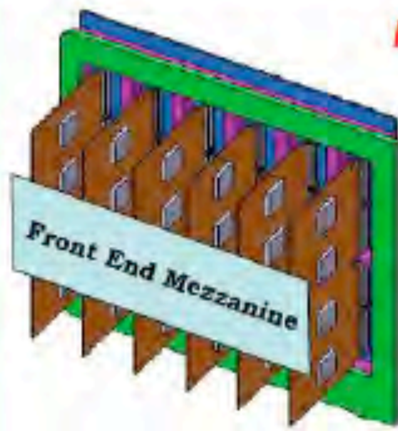
36 x 34 cm² « Bulk » MicroMegas



12 modules per Readout plane

Total of 72 modules

FEE based on the ASIC AFTER



6 FECs + 1 FEM per module

Total of
1728 ASICs
432 FECs
72 FEMs

72 modules for ~9 m² active area
~120k electronic channels

With On-detector FEE cooling mechanicals

EPS HEP 09 talk - Claudio Giganti

A. Delbart

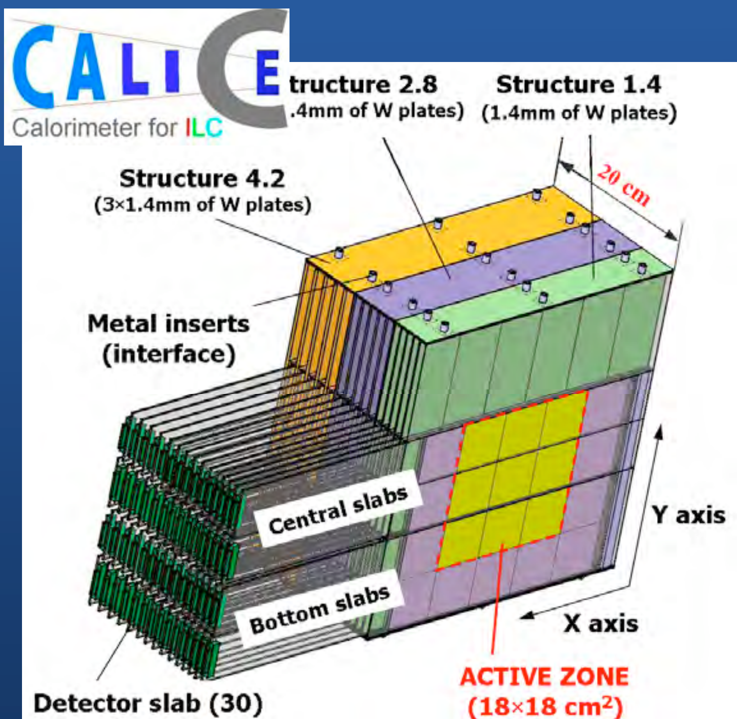
Calorimetry

- ✱ Electromagnetic Calorimetry
  - – Silicon-Tungsten
  - – Scintillator strips
  - – Crystals
  - – Liquid Xe (MEG)
- ✱ Hadron Calorimetry
  - – Particle Flow
  - – Dual Readout

Electromagnetic Calorimetry

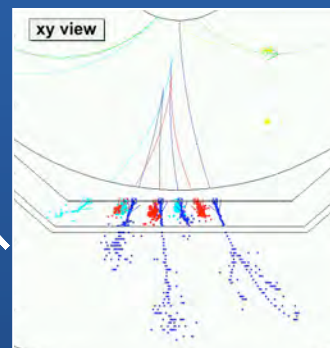
Silicon-Tungsten for Linear Collider

- High granularity needed for Particle Flow Analysis

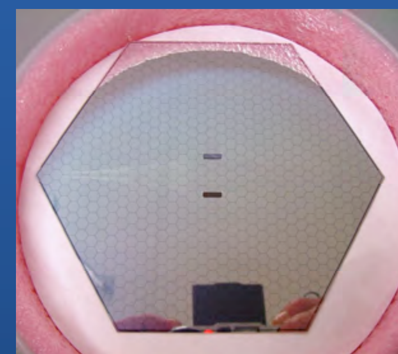


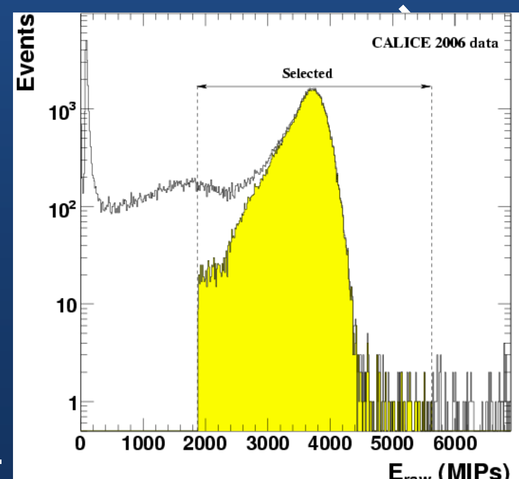
Test Beam Program	
	2006 - DESY/CERN
	2007 - CERN
	2008 - FNAL

→ building Technolog. Prototype



EPS HEP 09 talk - C. Carloganu

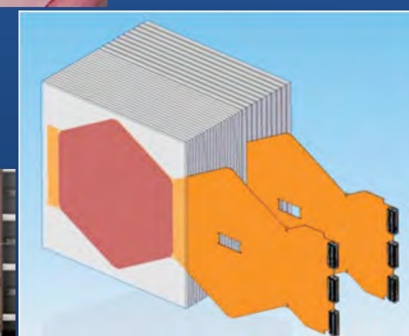




SiD

1024

13mm² pixels handled by KPiX

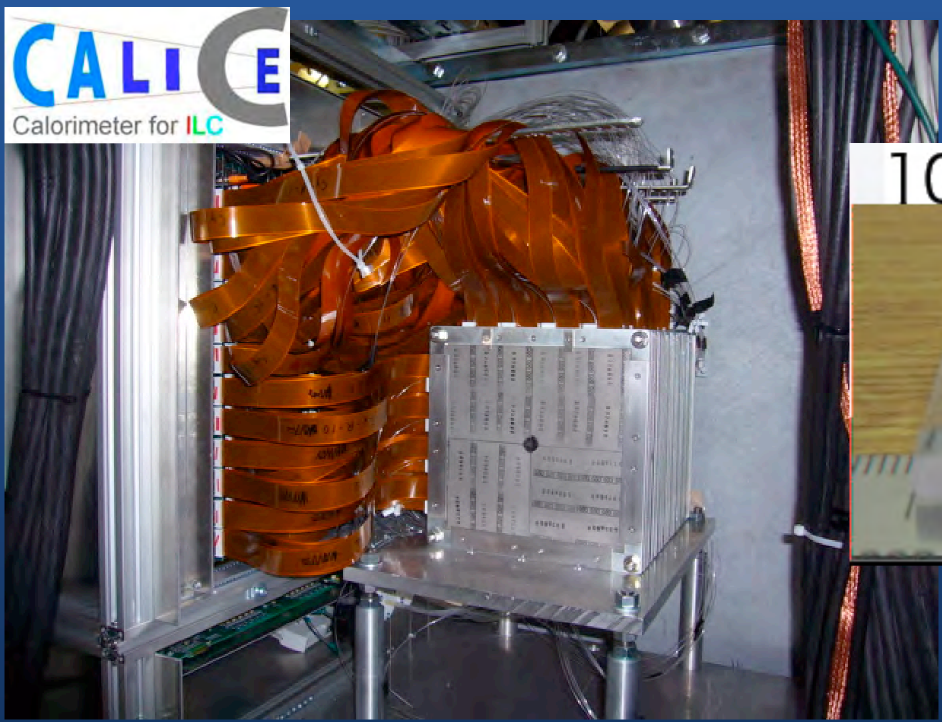


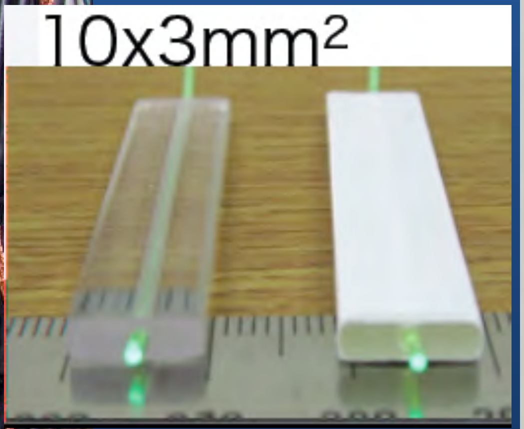
Working toward stack with 13mm² Pixels & MAPS version

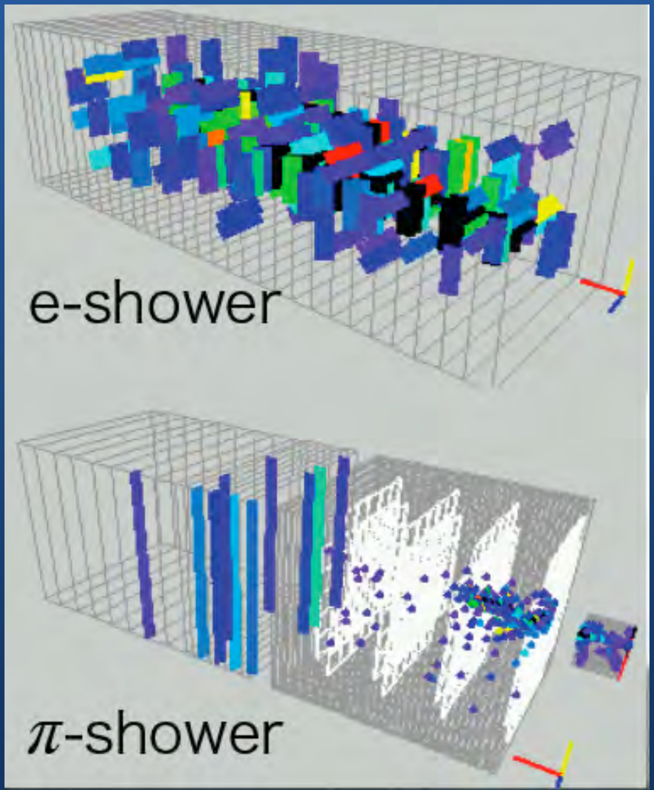
Electromagnetic Calorimetry

Scintillator Strips w/ MPPC* for Linear Collider

- ✱ 3-5 mm strips for high granularity needed for Particle Flow
- ✱ Tested at DESY & Fermilab







* Multi-Pixel Photon Counters

Electromagnetic Calorimetry

Crystals

Crystal Calorimeters in HEP

Date	75-85	80-00	80-00	80-00	90-10	94-10	94-10	95-20
Experiment	C. Ball	L3	CLEO II	C. Barrel	KTeV	*BaBar*	BELLE	CMS
Accelerator	SPEAR	LEP	CESR	LEAR	FNAL	SLAC	KEK	CERN
Crystal Type	NaI(Tl)	BGO	CsI(Tl)	CsI(Tl)	CsI	CsI(Tl)	CsI(Tl)	$PbWO_4$
B-Field (T)	-	0.5	1.5	1.5	-	1.5	1.0	4.0
r_{inner} (m)	0.254	0.55	1.0	0.27	-	1.0	1.25	1.29
Number of Crystals	672	11,400	7,800	1,400	3,300	6,580	8,800	76,000
Crystal Depth (X_0)	16	22	16	16	27	16 to 17.5	16.2	25
Crystal Volume (m^3)	1	1.5	7	1	2	5.9	9.5	11
Light Output (p.e./MeV)	350	1,400	5,000	2,000	40	5,000	5,000	2
Photosensor	PMT	Si PD	Si PD	WS[a]+Si PD	PMT	Si PD	Si PD	APD[a]
Gain of Photosensor	Large	1	1	1	4,000	1	1	50
σ_N/Channel (MeV)	0.05	0.8	0.5	0.2	small	0.15	0.2	40
Dynamic Range	10^4	10^5	10^4	10^4	10^4	10^4	10^4	10^5

Future crystal calorimeters in HEP:

PWO for PANDA at GSI

LYSO for a Super B Factory, Mu2e and CMS Endcap Upgrade

PbF_2, BGO, PWO for HHCAL

R. Zhu

11/18/2008 ILC Workshop 2008, Ren-yuan Zhu, Caltech 3

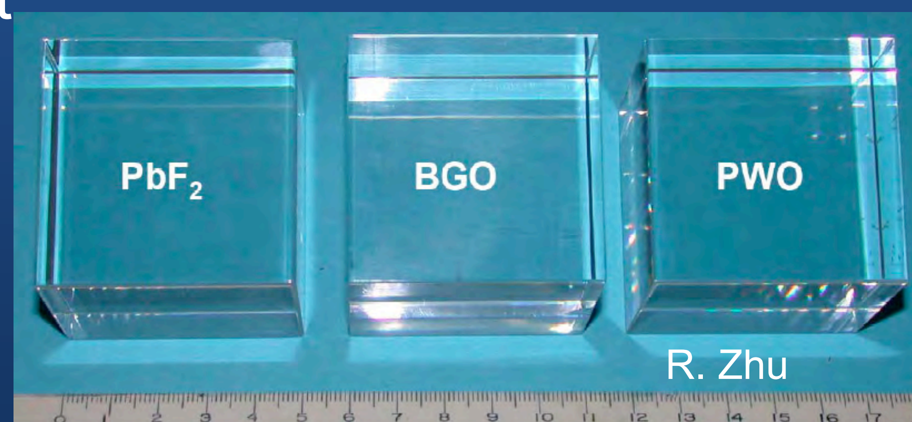
Electromagnetic Calorimetry

Crystals

- Rad Hard for SuperB, Mu2e, CMS Endcap upgrade
  - LYSO favored
  - Large light, low noise

($Lu_{2(1-x)}Y_{2x}SiO_5$: Ce - Cerium doped Lutetium Yttrium Orthosilicate)

- Recent Application - Homogenous <u>HCAL</u> -dual readout
  - For large volume, cost-effective UV transparent material crucial.
  - Three candidates evaluated.
  - Initial investigation favors scintillating PbF_2.



Electromagnetic Calorimetry

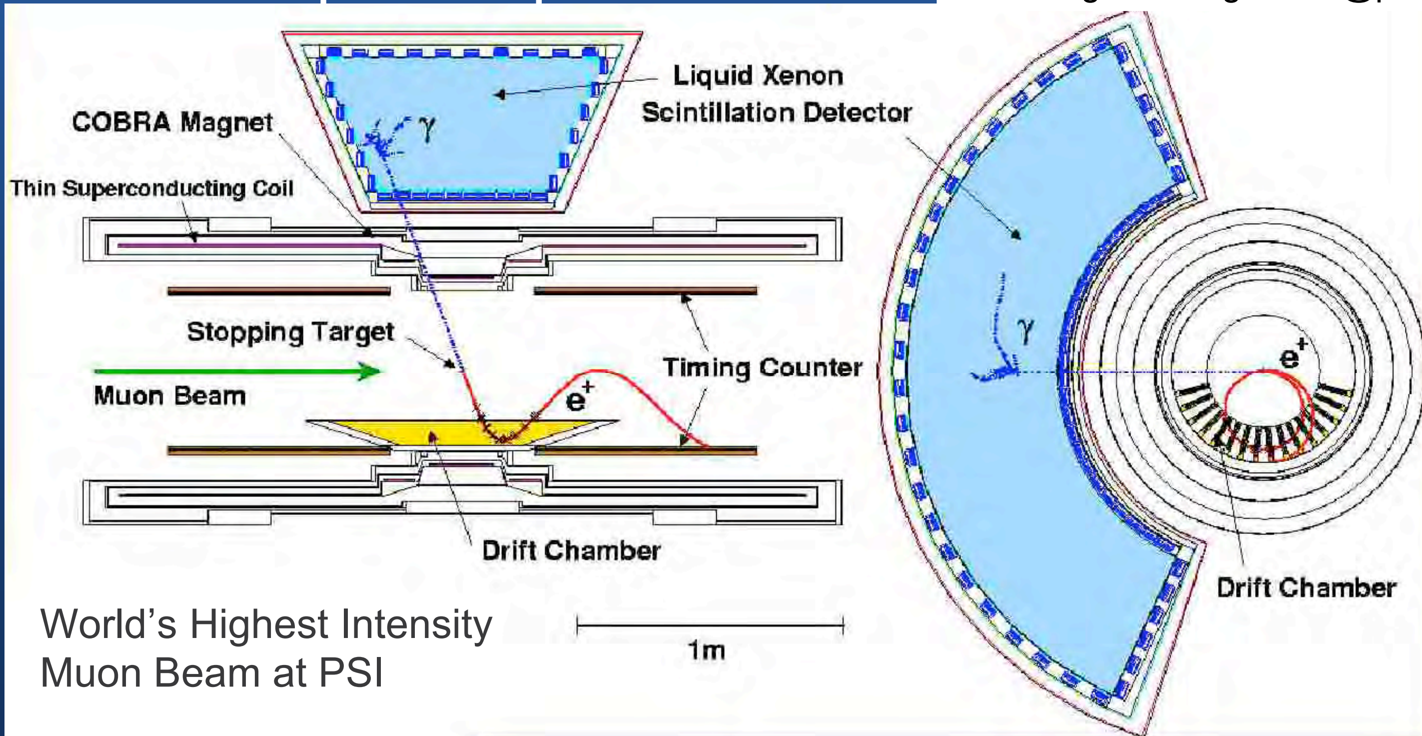
Liquid Xenon - MEG

* 800 liters of LXe
  - 846 PMTs
* Nearing start of new run with improved performance

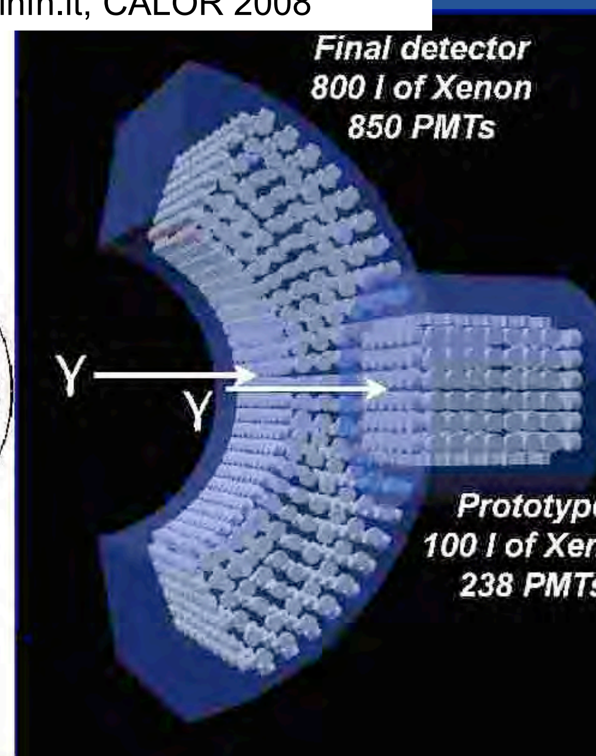
Table 1. Summary of liquid xenon detector resolution

Measurement	Resolution (FWHM)
γ Energy (on 55 MeV)	4.8
γ Position (mm)	15.0
γ Time (nanosecond)	0.15

giovanni.gallucci@pi.infn.it, CALOR 2008



World's Highest Intensity
Muon Beam at PSI

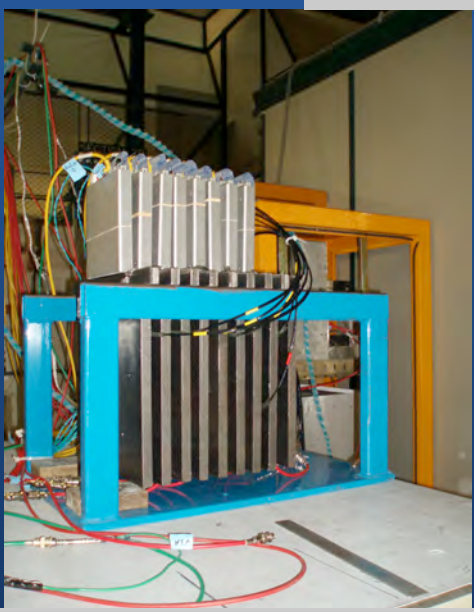


Hadronic Calorimetry

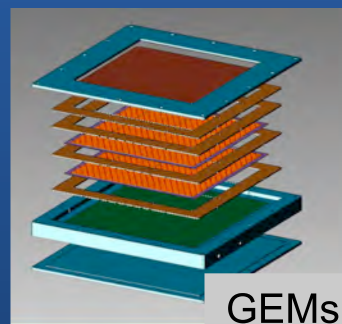
Particle Flow for Linear Collider

- Particle Flow demands high granularity
- Intense test beam program

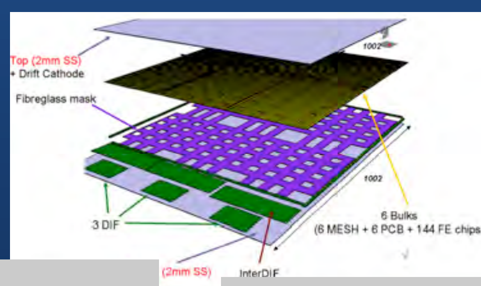
DIGITAL



Small RPC calorimeter in the
Fermilab test beam
Fully containing Hcal under construction



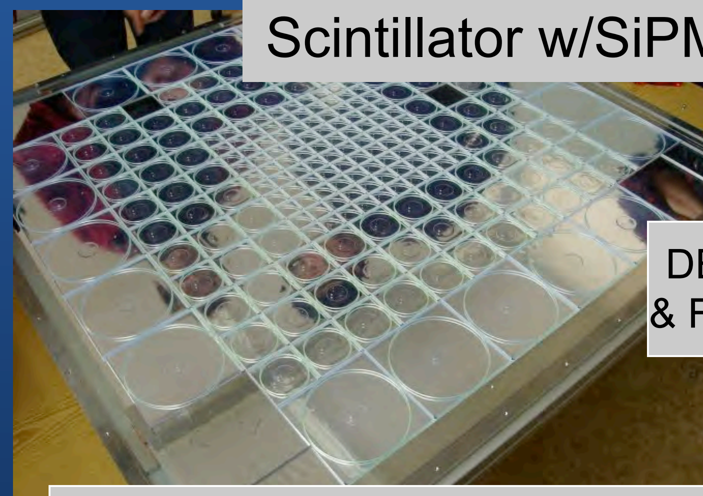
GEMs



MicroMeGas

ANALOG

Scintillator w/SiPM



DESY, CERN, & Fermilab tests

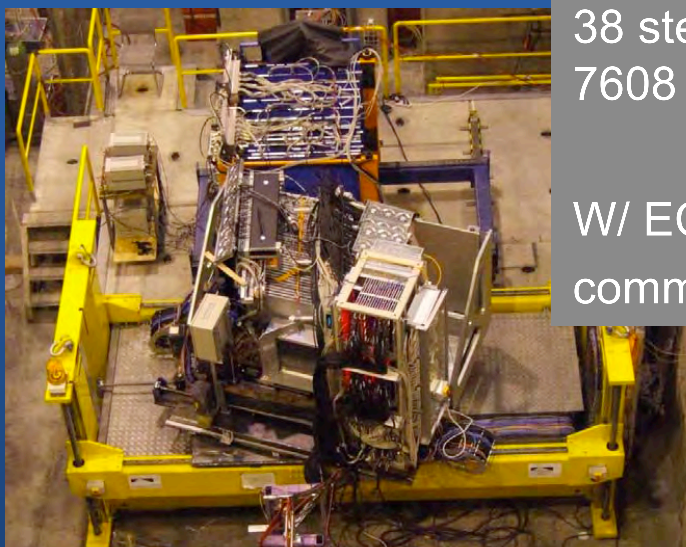
One of 38 layers
of the prototype

EPS HEP 09 talk - J. Cvach

CALICE Scintillator Tests

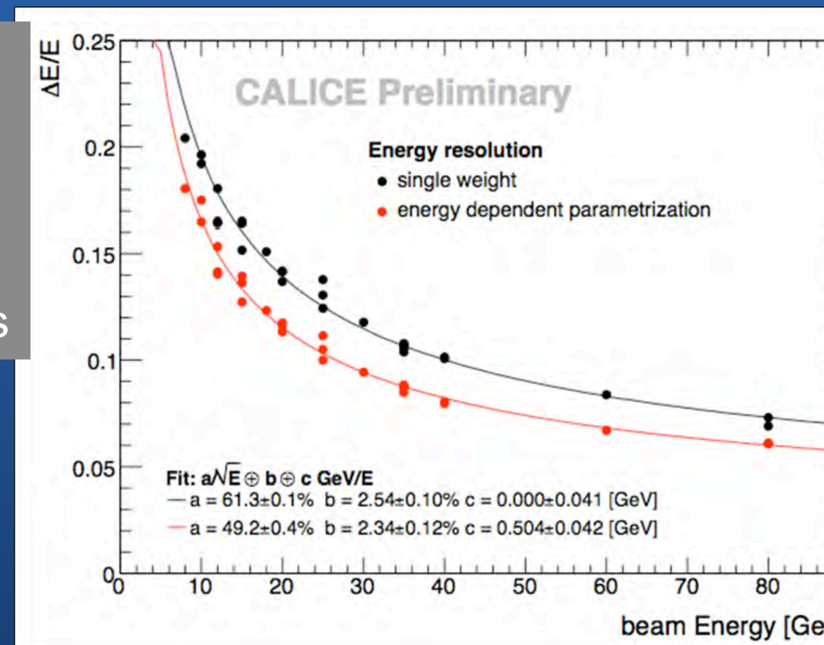
Particle Flow for Linear Collider

✱ CERN 2006-07, FNAL 2008-09



38 steel layers (2cm), 4.5λ
7608 tiles with SiPMs

W/ ECAL and TCMT
common readout electronics



✱ CALICE's conclusions:

- The SiPM technology has proven to be robust and stable
- The calibration is well under control
- The performance is as expected and understood
- Strong support for predicted PFLOW performance

CALICE Digital HCAL Tests

Particle Flow for Linear Collider

✱ Small glass RPC module tested in Fermilab beam

20 x 20 cm^2 RPCs (based on two different designs)
1 x 1 cm^2 readout pads
Up to 10 chambers → 2560 readout channels
Complete readout chain as for larger system
Detailed tests with cosmic rays & in Fermilab beam
(μ, 120 GeV p, 1 – 16 GeV π^+, e^+)

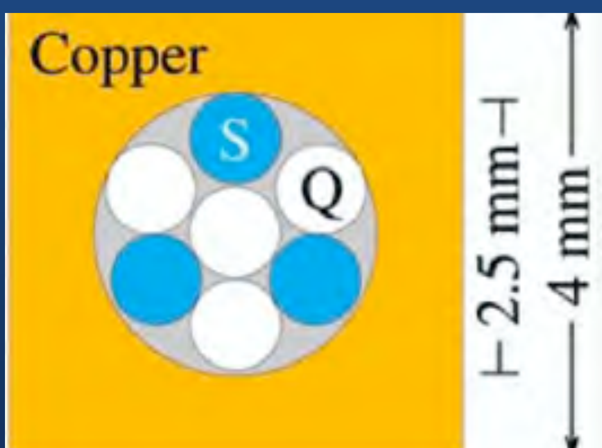
✱ 1m^3 prototype under construction

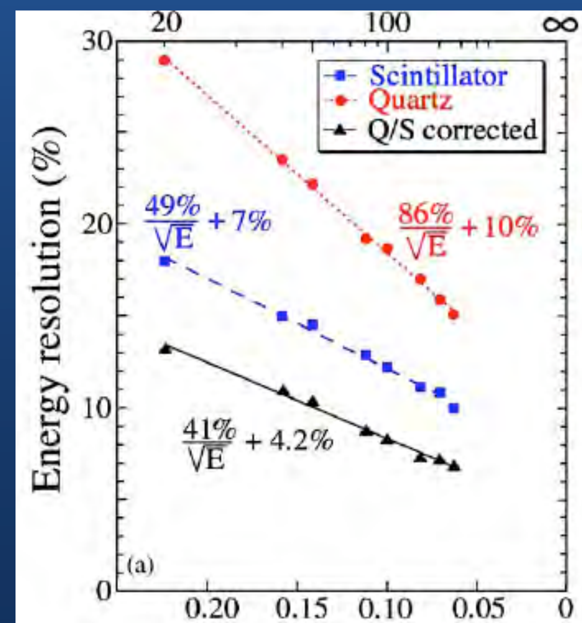
Cosmic ray tests for each chamber
Fermilab test beam with μ, $\pi^\pm$, $e^\pm$
hadronic shower MC model comparison
analog HCAL (CALICE) comparison
Construction completed in CY 2009
Data analysis in 2010/2011

Hadronic Calorimetry

Dual Readout

- Fluctuations in hadronic shower
  - Nuclear binding energy losses & π^0 energy variations
- Measure separately the EM shower component
  - DREAM Collaboration measured in HE calorimeter
  - Correct for EM fraction event by event (Q/S method)
- What resolution with combined signals?
  - DREAM leakage limited

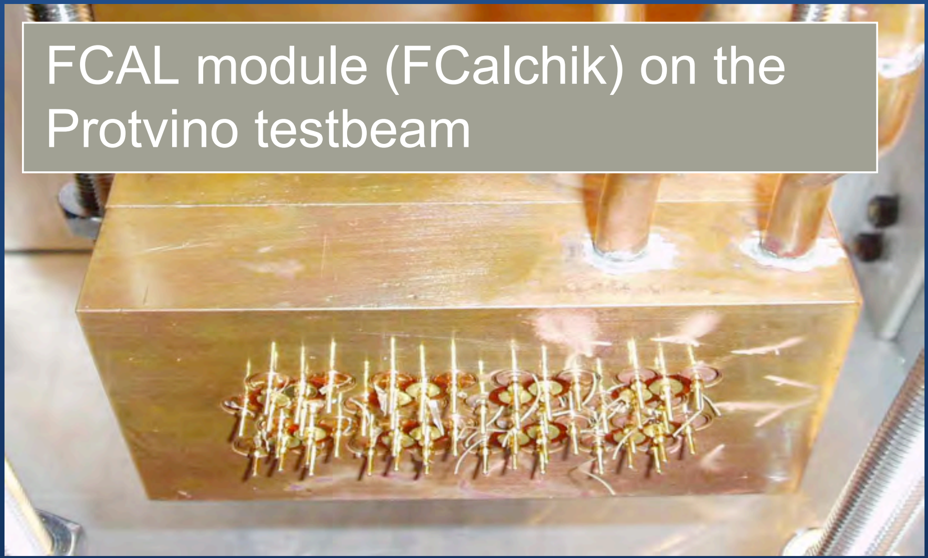




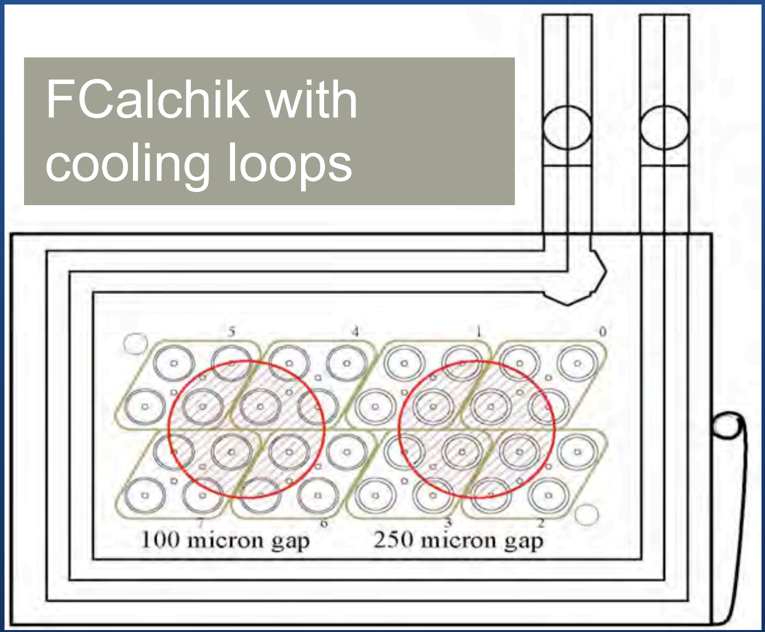
sLHC Calorimetry

Confronting the Radiation Challenge

* ATLAS Forward Calorimeter
  - LAr boiling, inter-electrode ion build-up, HV resistor voltage drop
  - Two possible solutions
    - Warm calorimeter in front of current FCAL
    - New FCAL - smaller gaps and increased cooling



FCAL module (FCalchik) on the Protvino testbeam



FCalchik with cooling loops

Particle ID

- Crucial role in many experiments
  - BaBar, Belle, LHC-b
- Future Needs
  - Belle II, INFN SuperB, NA62
- Key Technologies
  - Radiators
    - Quartz (fused Silica) - polishing
    - Silica aerogel - improved transmission, mulit-index tiling
  - Photodetectors
    - Hybrid PD
    - MCP-PMT
    - MPPC

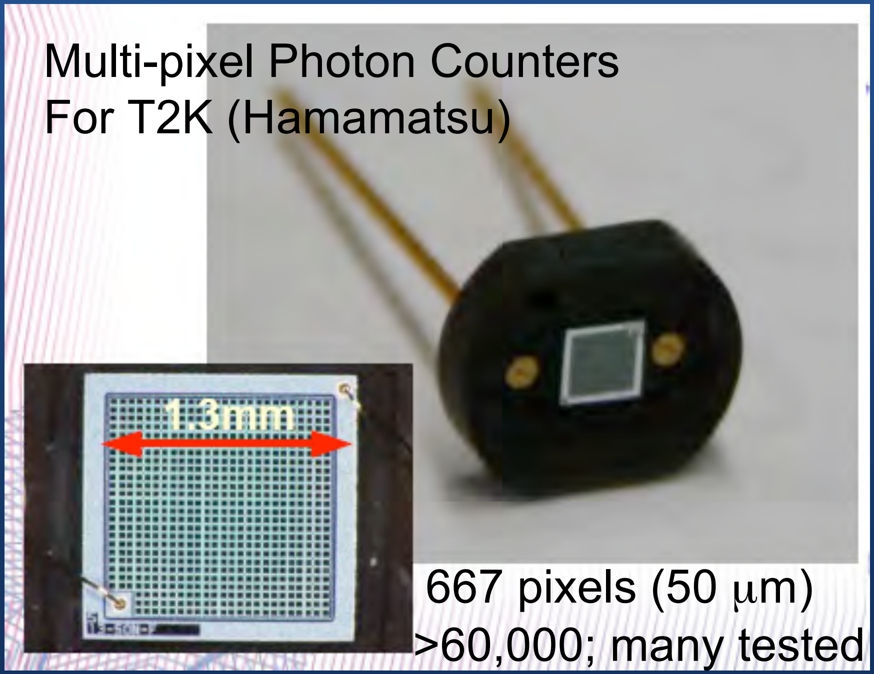
Novosibirsk Aerogel


144ch HAPD

EPS HEP 09 talk - Z. Dolezal

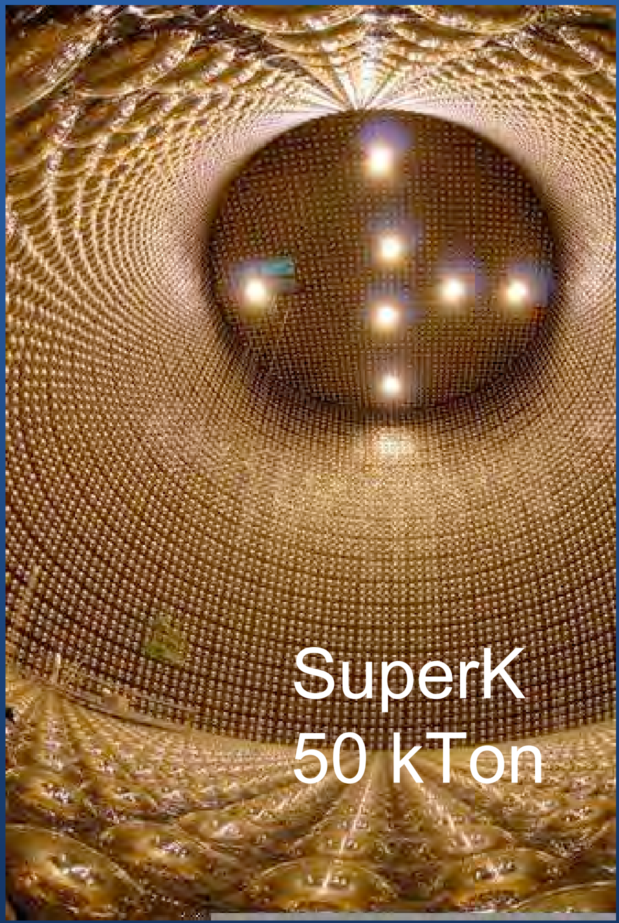
MPPCs, SiPMs

- Single photon sensitive devices built from an avalanche photodiode (APD) array on common Silicon substrate.
- Many attractive properties
  - Extremely compact
  - B-field immune
  - Good timing
  - Gain and QE competitive with PMT
- Many investigations

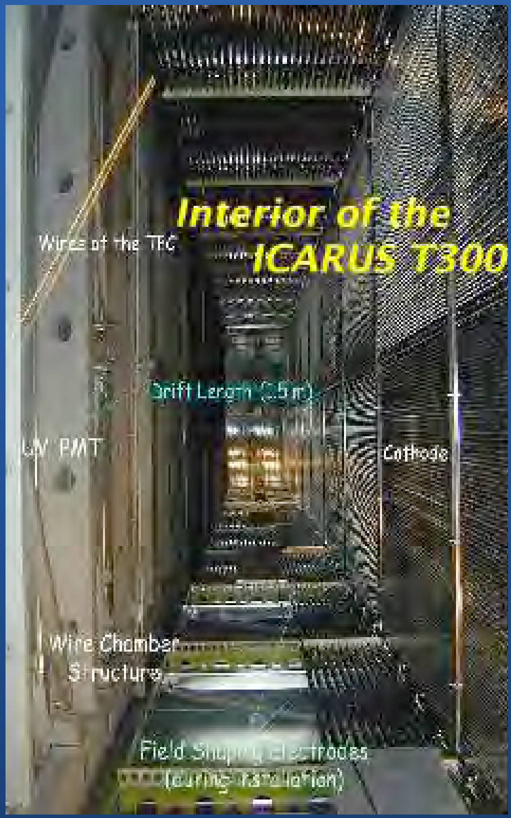


Megaton Detectors for Neutrinos

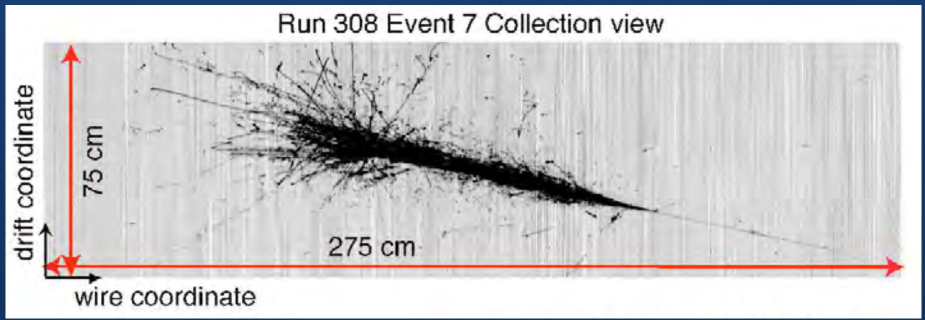
- SuperK proves performance of water Cherenkov
- Future goal - 1 MTon
- Challenges
  - Costs
  - PMTs (increased QE)
  - Readout Electronics
  - New photosensors
  - Harden against accident
- T2K develops MPPC (SiPM)



Liquid Argon for Neutrinos



- ICARUS demonstrated potential
- Promising technique for future experiments
  - Low threshold
- Goal - scale up to ~100kTon
- Challenges
  - Purification
  - Cold, low noise electronics, signal mplex
  - Vessel - design, design, materials, insulation
  - Siting
  - Costs



Neutrinoless Double Beta Decay

✱ Several 100-200 kg detectors being developed

– Challenge to minimize backgrounds

– CUORE

- 203 kg ^{130}Te
- 988 TeO_2 bolometers
- Follows 11 kg ^{130}Te CUORICINO

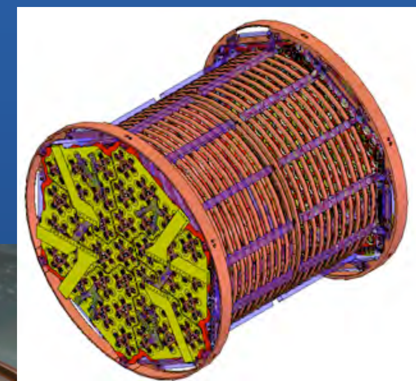
– EXO-200

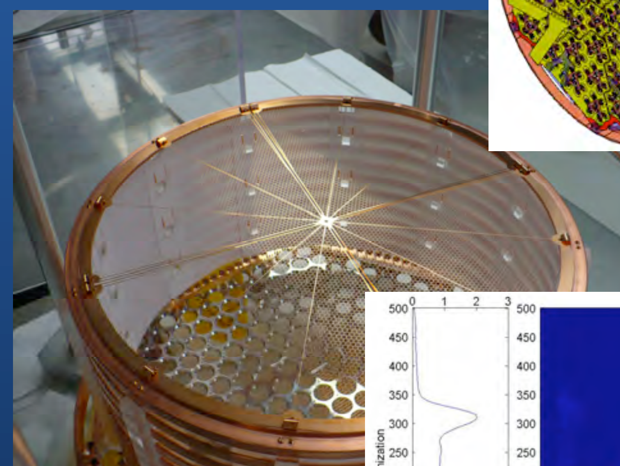
- 200 Kg ^{136}Xe
- Measure ionization and scintillation plus Ba tag

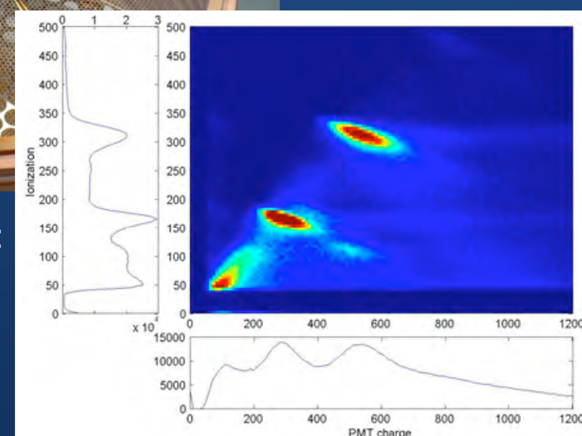
– Majorana

- Goal: 120 kg of ^{76}Ge

EXO-200
LXe Field Cage
& Readout Planes



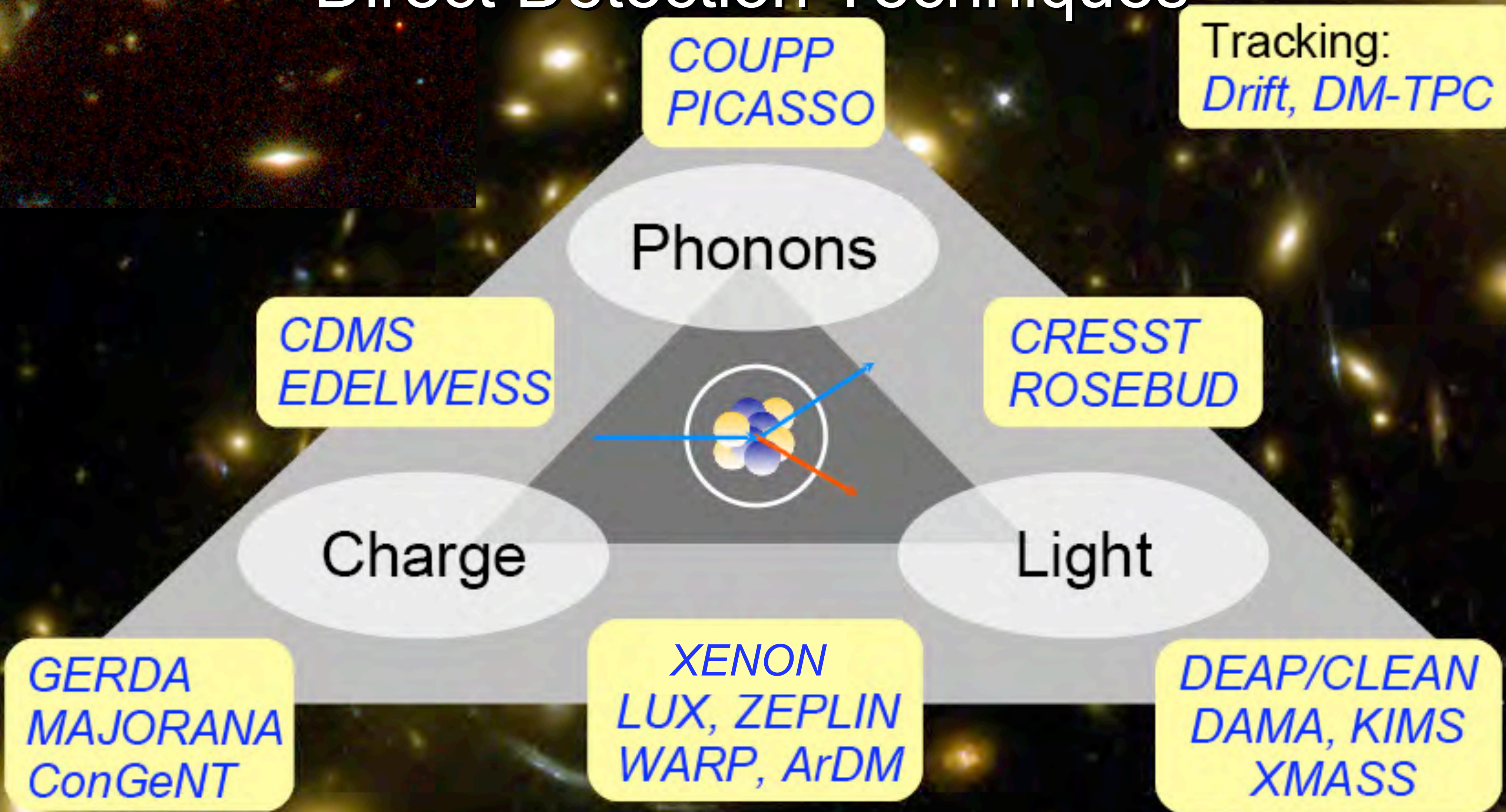




R&D -Ionization & Scintillation:
$\sigma(E)/E$ = 3.0% @ 570 keV
or 1.4% @ $Q_{\beta\beta}$

Will add Ba tagging

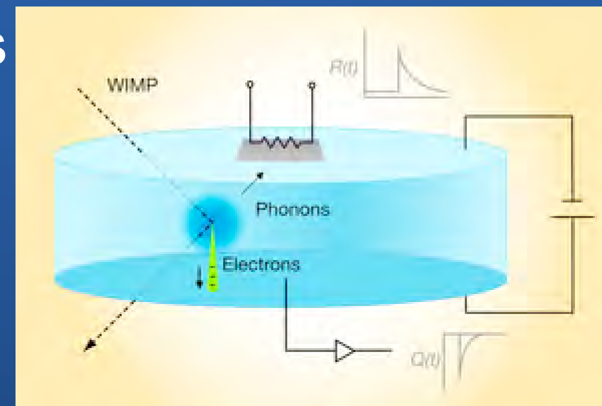
Dark Matter
Direct Detection Techniques

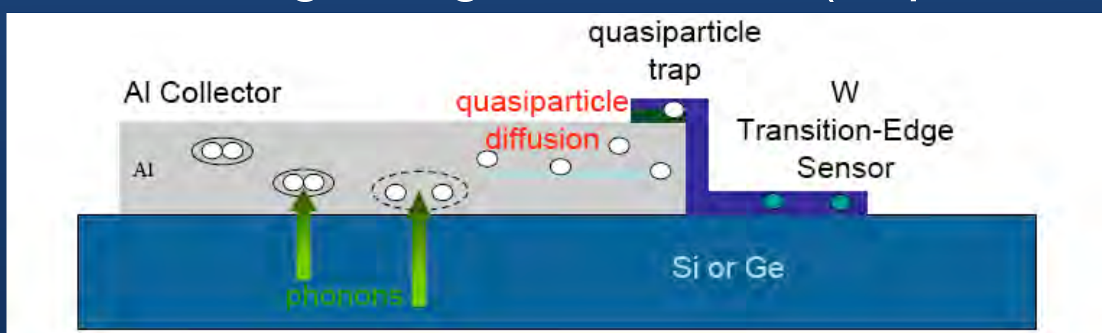


M. Schumann

Bolometers for DM Detection

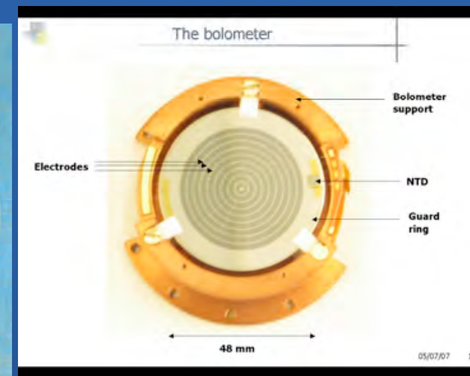
* CDMS
  – Phonon/Charge detection with ZIP detectors
    - Electric field pulls charge to sensitive amplifier
    - Phonons break Cooper pairs in thin superconducting Al layer, heating transition-edge sensor & causing change in resistance.
    - Readout elements highly segmented, and relative timing of ionization and phonon signals provide good event localization.
  – Operated 5 kg in Soudan
  – Planning 25 kg in SNOLAB (SuperCDMS)

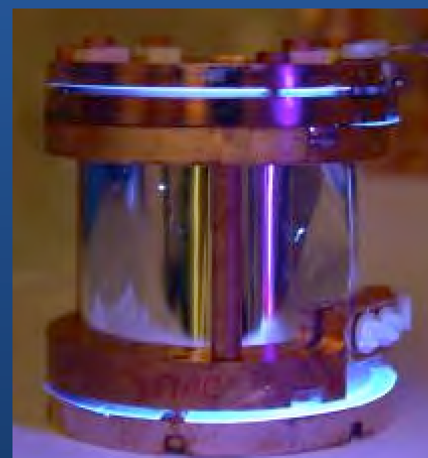




Bolometers, cont.

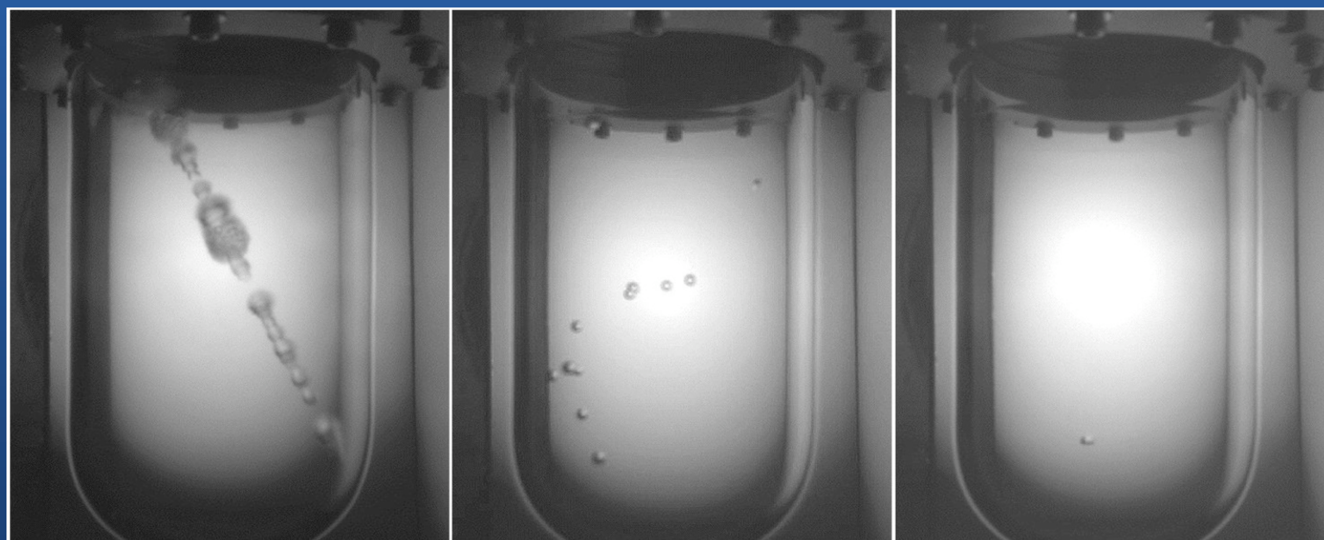
- EDELWEISS
  - Ge/NTD
  - Ge/NbSi
  - Ge/Interdigit
    - 30 kg operating
- CRESST-II
  - ~ 300 g $CaWO_4$ crystal
    - Gran Sasso
- ROSEBUD
  - BGO
  - LiF (n-mon)
  - Sapphire





Warm Liquid Dark Matter Detector

- COUPP
  - Room Temp Bubble Chamber, CF_3I, 2 kg tested



A CCD camera takes pictures at 50 Hz. Chamber triggers on appearance of bubble in the frame.

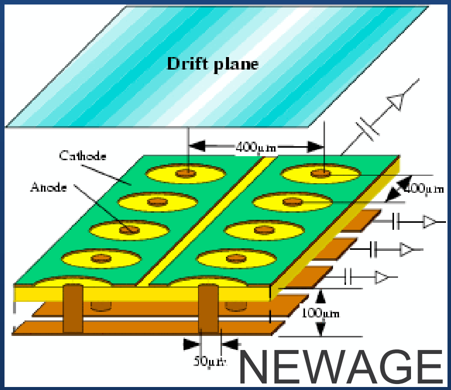
Single bubble DM signature.

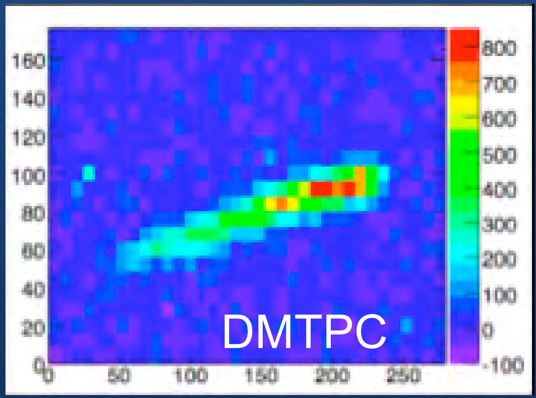
  - New 20 and 60 kg chambers will go underground in 2010

Directional Dark Matter Detectors

- ✱ Low pressure TPCs favored
  - CS_2 - spin-dependent interactions
  - CF_4 and ^3He - spin-independent interactions

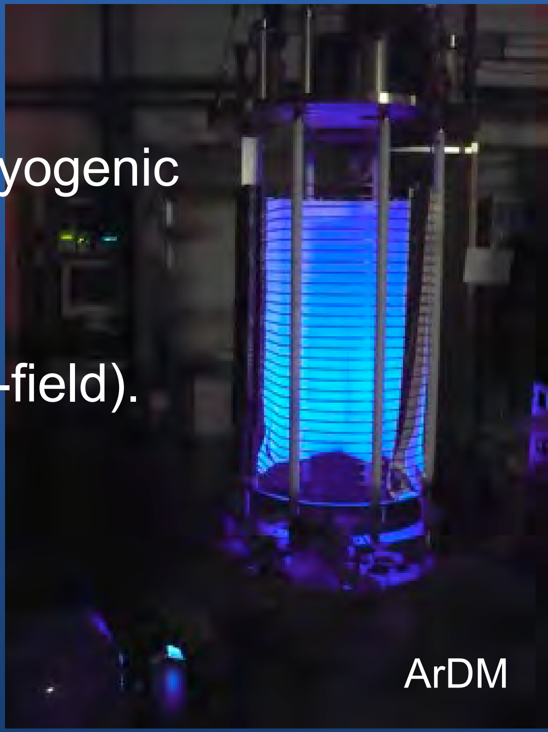
- ✱ Wire chamber readout
  - DRIFT-II
  - Two 1m^3 (CS_2) modules underground
- ✱ MPGDs
  - NEWAGE, MIMAC
- ✱ PMT and CCD readout
  - DMTPC (CF_4)





Noble Liquid Dark Matter Detectors

- ✱ Many Attractive Features
  - – Low cost, easy to obtain, dense target material.
  - – Easily purified due to freeze out of contaminants at cryogenic temperatures.
  - – Very small electron attachment probability.
  - – Large electron mobility (Large drift velocity for small E-field).
  - – High scintillation efficiency.
  - – Possibility for large, homogenous detectors.



- ✱ Problem - ^{39}Ar, ^{85}Kr.

  - – See Elena Aprile's talk for R&D on noble liquids

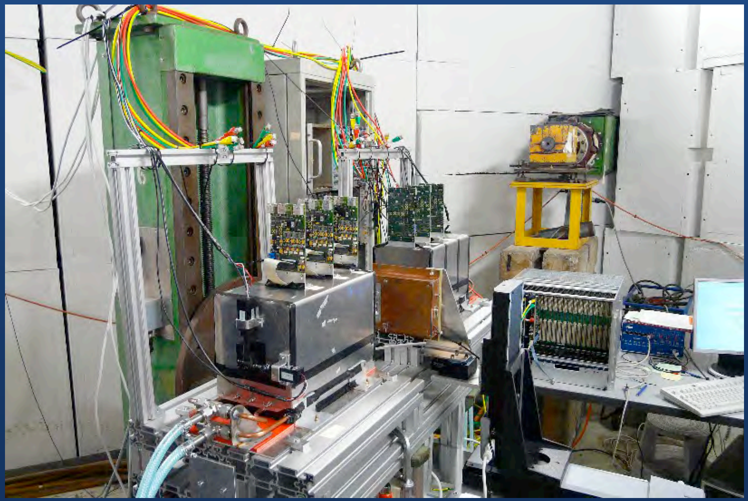
Test Beams

* Needed for detector development

as well as in many other phases of HEP experiment

eg. prototype testing, calibrations, etc.

* Laboratory support of test beams very important



Conclusion

* Discoveries in HEP vitally depend on advances in detector technology
* Challenges are huge
  – speed, granularity, radiation, exotic materials, etc.
* Many efforts confronting these challenges
* Critical that the efforts are well funded
* Technology will continue to advance, with important emerging capabilities critical to future discoveries
  - with timescales dependent on the level of financial support

■ ■ Don’t forget the test beams

Acknowledgements

* E. Aprile, M. Breidenbach, A. Bevan, K. Dehmelt, M Demarteau B. Fleming, G. Gratta, D. Hitlin, J. Jaros, G. Rakness, J. Repond, F. Sefkow, A. Seiden, D. Strom, F. Taylor, J. Timmermans, D. Wark, A. White