Applications of Detector Technology

DPF2019

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Introduction

- An overview* of detector technologies as applied to a variety of experiments

- A technology/functionality approach:
  - Position measurement
  - Time measurement
  - Energy measurement
  - Particle ID measurement
  - Innovation/new ideas

- Perspectives on how technologies have moved us forward in our abilities to study physics.
- R&D Organizational Issues

*Note: this is personal selection; any mistakes are mine.

ECFA Detector Panel Report

P. Allport, A. Cattai, S. Dalla Torre, D. Eckstein, E. Koffeman,
L. Linssen, L. Serin, A. Straessner

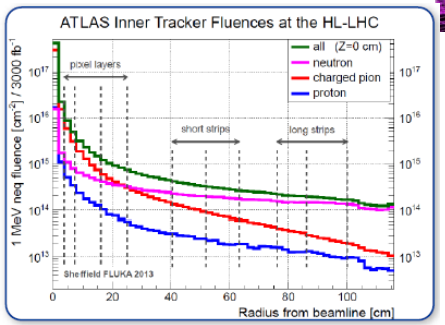
The ECFA Detector Panel
(http://ecfa-dp.desy.de/ - ecfa-dp@desy.de)

Most promising future R&Ds	**# answers (380 total)**
Precision timing	210
Precise position resolution	63
Precise energy measurements	25
Radiation Hardness	29
CMOS HV-MAPS monolithic	24
High granularity imaging calorimetry	21
Artificial intelligence / Machine Learning	16
Fast (tracker) triggers (online)	16
High rate capability	14
Low power consumption in detector systems/electronics,	14
4D tracking	14

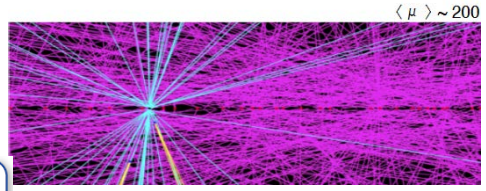
?? NO Quantum Information Science listed ?:?

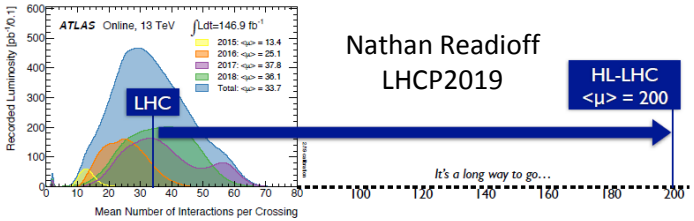
Position Measurement

LHC – High Luminosity Upgrades
14 TeV, 5 x 10^{34} cm^{-2} s^{-1}, <μ> =200
∫L.dt = 3-4 ab^{-1},
~10^{16} (1 MeV n eq)/cm^2



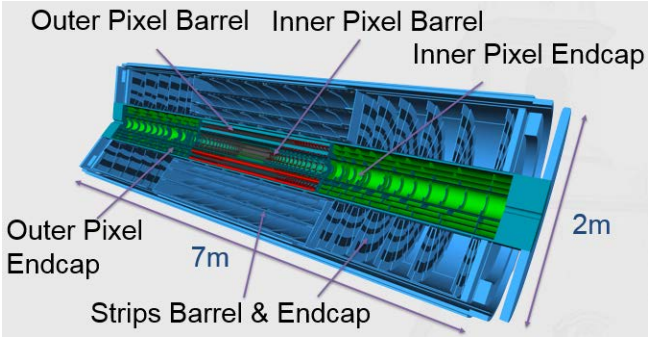
I. Dawson, P. S. Miyagawa, *ATLAS Upgrade radiation background simulations*



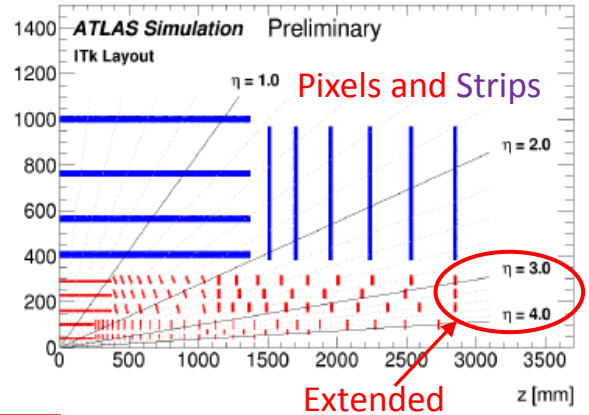


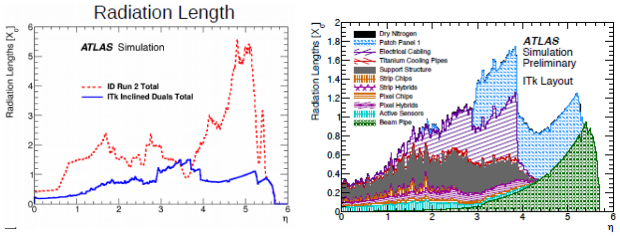
Nathan Readioff
LHCP2019

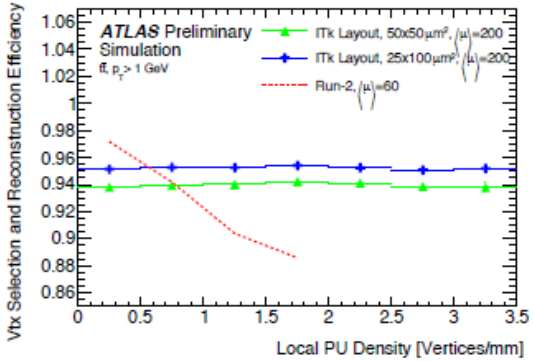
ATLAS Inner Tracker (Itk)



Barrel strip pitch 75.5μm
Pixel pitch 50 x 50 or 25 x 100 μm^2

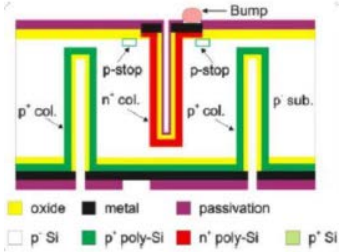




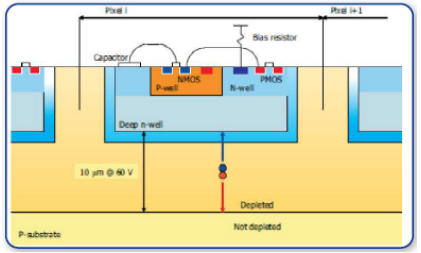


RD50 Silicon Detectors for HL-LHC

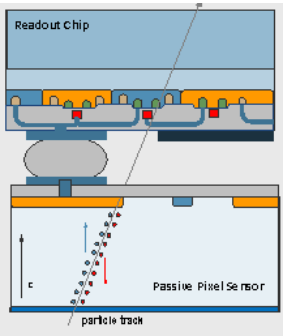
3D

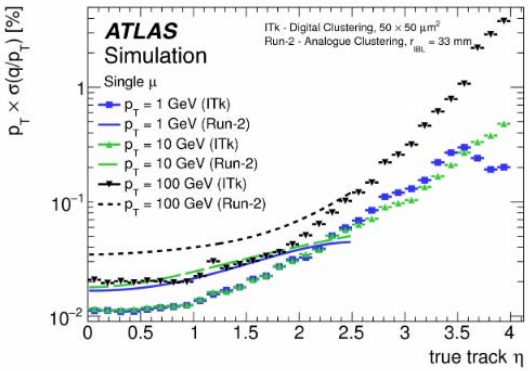


HV-CMOS



RD53 readout chip

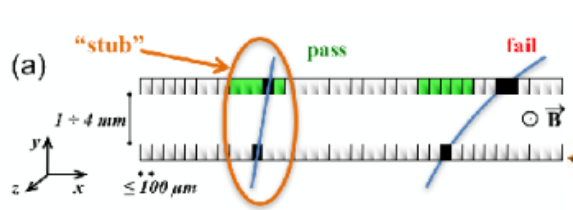


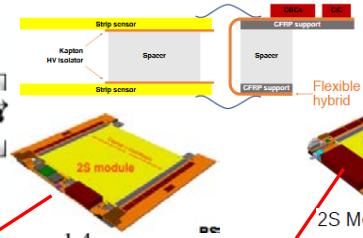


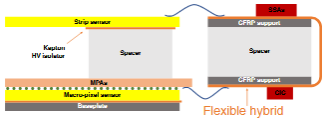
M.Mandurrin CTD/WIT 2019

CMS Tracker Upgrade

Position Measurement





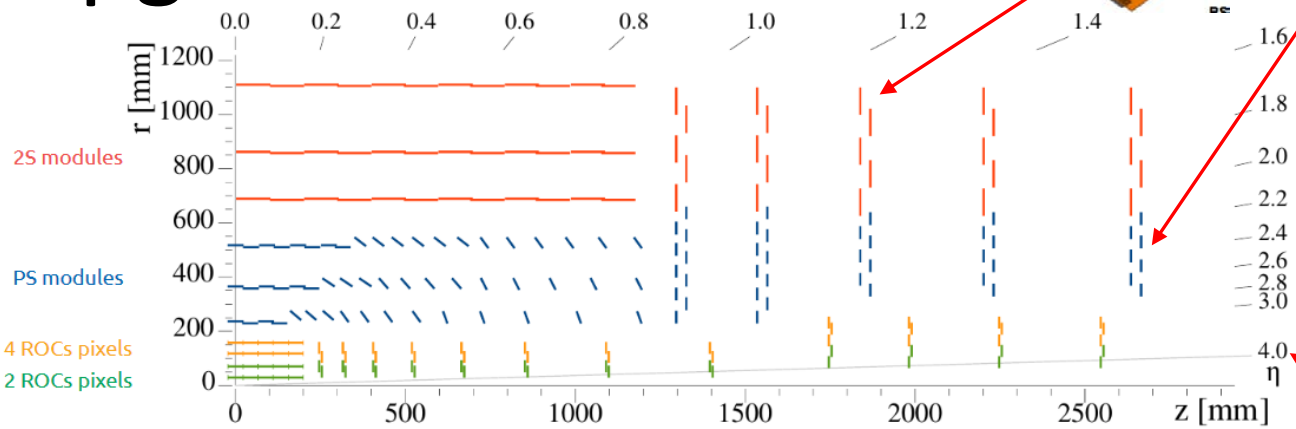


2S Modules

- Two strip sensors with 5 cm x 90 μm strips
- Sensor is 10x10 cm² large → two sets of strips

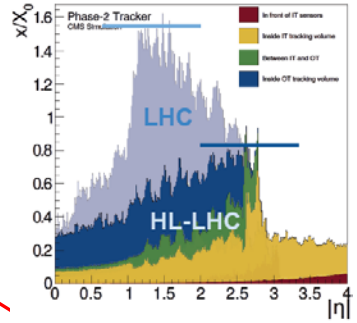
PS Modules → Module with one (Macro-)Pixel and one strip sensor

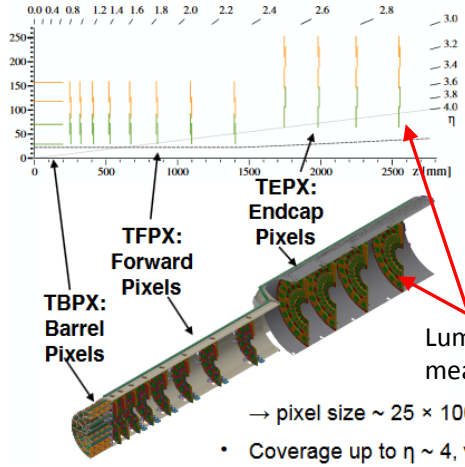
- Sensor size: 5x10 cm²
- Strips: 2.5 cm x 100 μm
- Macro Pixels: 1.5 mm x 100 μm

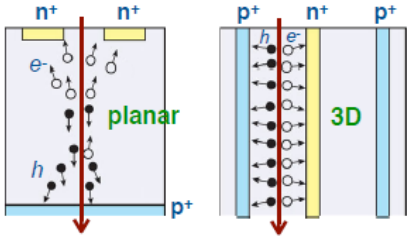


https://doi.org/10.1016/j.nima.2018.11.023.

Significant material profile reduction



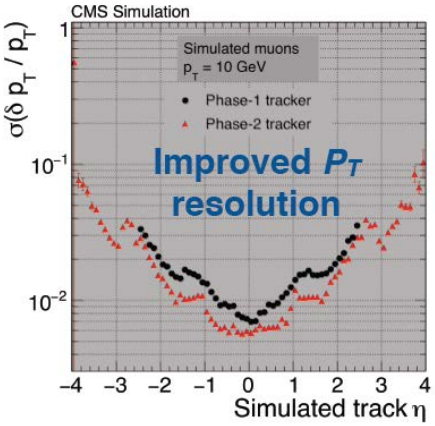


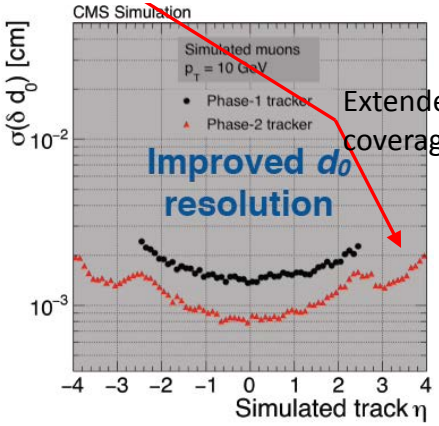


Luminosity measurement

→ pixel size ~ 25 × 100 μm² or 50 × 50 μm²

- Coverage up to η ~ 4, with ~4.9 m² active area
- 4 barrel layers, 8 small disks, 4 large discs per side





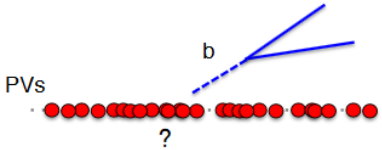
Extended coverage

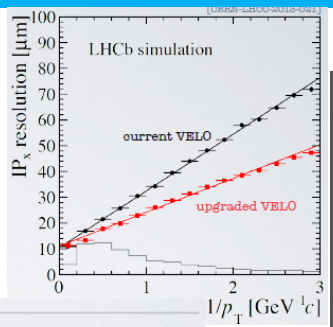
G. Sgauzzoni, VCI2019

LHCb Vertex Locator (VELO) Upgrade(s)

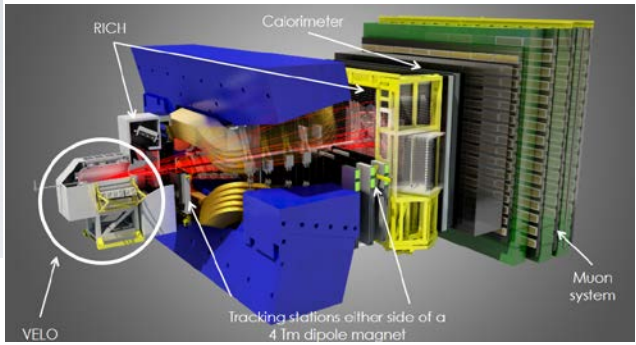
Position Measurement

The issue – mis-associated PV's





Present VELO



VELO Upgrade I (for Run 3):

Luminosity 4×10^{32} cm^{-2}s^{-1} -> 2×10^{33} cm^{-2}s^{-1}

No hardware trigger – 40 MHz r/o (was 1 MHz)

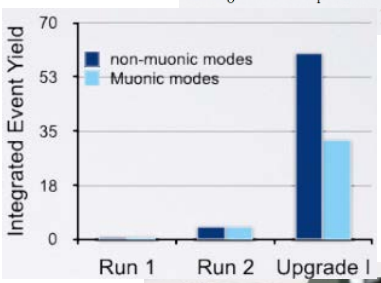
41M pixels, 3.5 mm from beam

Micro-channel cooling

VELOPix ASIC derived from TimePix3

130nm CMOS, 55x55 μm pixels;

Sensor: Hamamatsu n-on-p 200μm

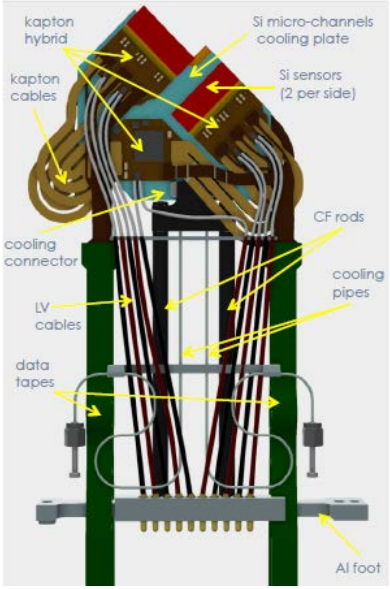


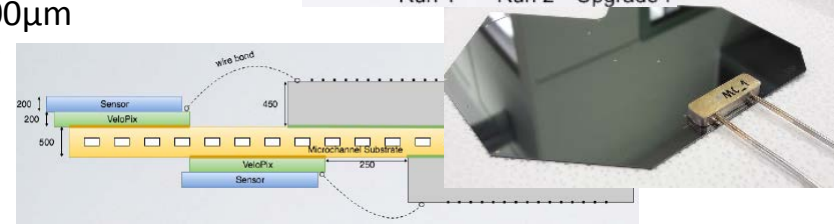
VELO Upgrade II:

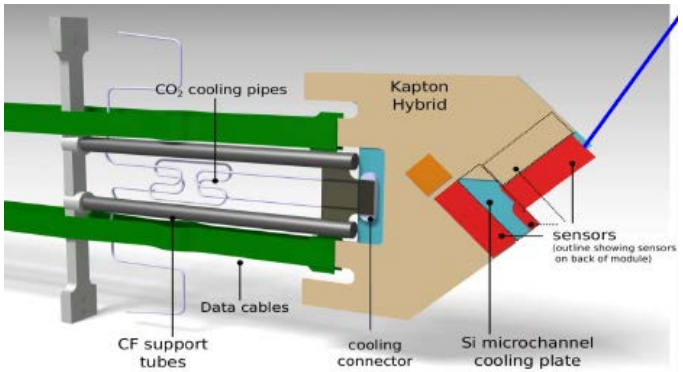
Add 100ps timing for pixels

HL-LHC 50 PV/bunch

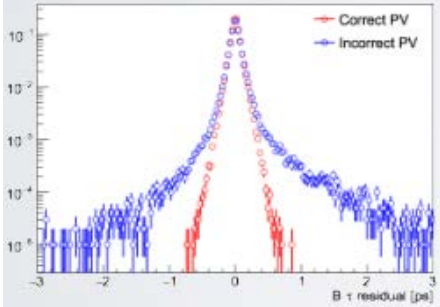
and 2 < η < 5 acceptance







Direct degradation to proper times resolution from mis-associated primary vertices.



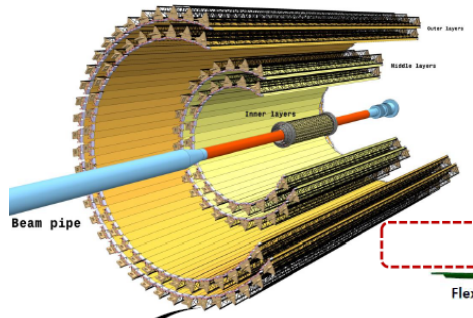
Recovered with O(100ps) timing measurements of pixel hits.

ALICE Inner Tracker Upgrade

Position Measurement

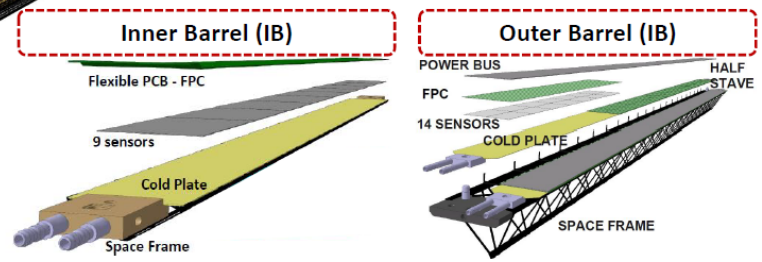
New ITS layout

ALICE

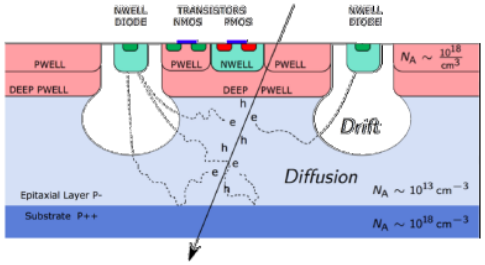


- 7 layers of Monolithic Active Pixel Sensors (MAPS)
  - 3 Inner Layers (Inner Barrel)
  - 2 Middle + 2 Outer layers (Outer Barrel)
- Total area: $\sim 10\ m^2$
- $|\eta|$ coverage: $|\eta| < 1.22$
- r coverage: $22 - 400\ mm$

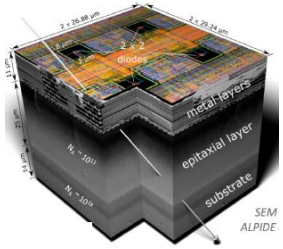
Run 3



ALPIDE is the core of the new **ITS**



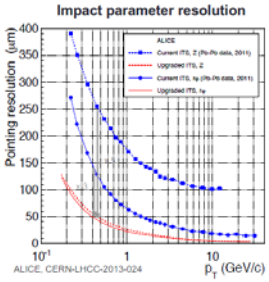
Monolithic CMOS 180nm



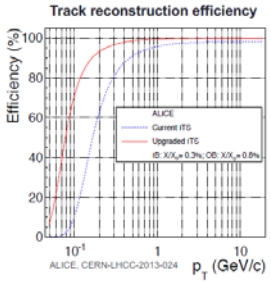
Material budget: 1.1% X_0 → 0.3% X_0 (inner layers)
Pixel size: 50x425 μm^2 → ~30x30 μm^2
Closer to the vertex (first layer radius): 39 mm → 22 mm

Inner Barrel Production completed and all layers assembled

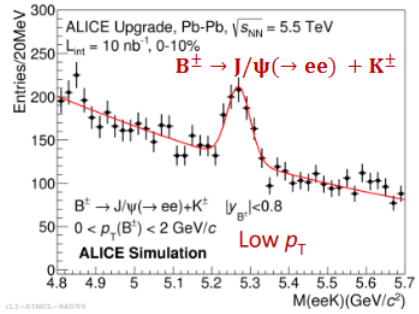
Goals: - high precision QGP studies esp. at low Pt
- heavy flavor and quarkonia



Improved impact parameter resolution

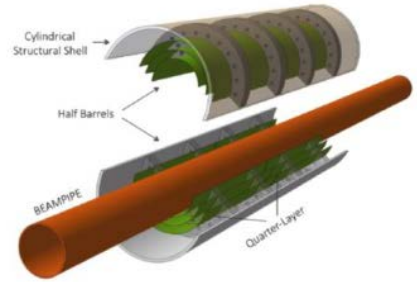


High standalone tracking efficiency



3 layers of stitched CMOS MAPS sensors of up to 508 cm² with 56 M pixels (30 x 30 μm²)

Run 4



near-term realization of this technology in a running experiment will revolutionize vertexing

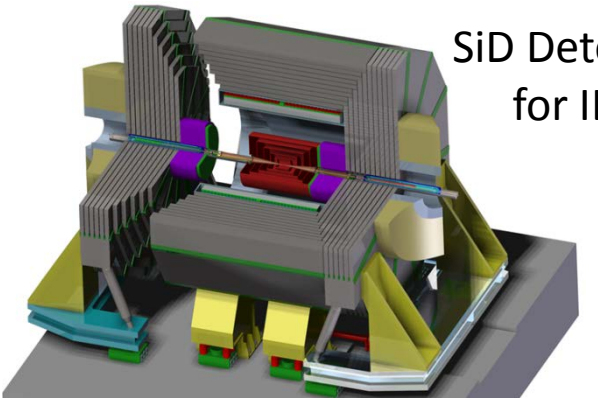
Ultra-thin chip (<50 um): flexible with good stability

Ultra thin (< 30μm) wafer-scale CMOS sensors.
Few μm spatial resolution.

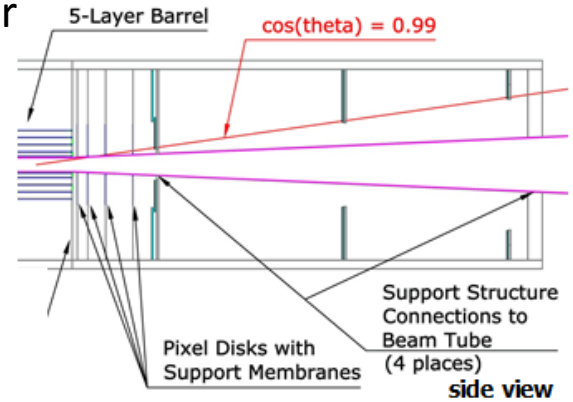
ALICE-PUBLIC-2018-013

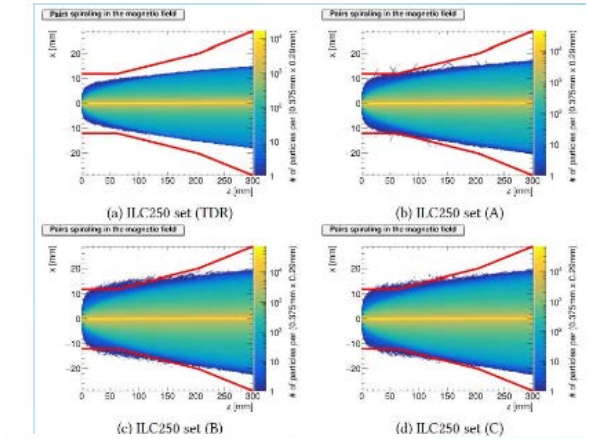
Position Measurement

Vertex detector

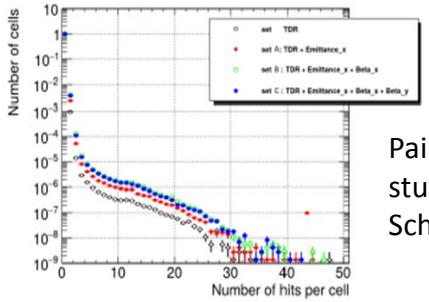


SiD Detector for ILC





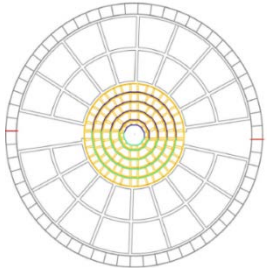
Occupancy for SiVertexBarrel wrt to tot # cells



Pair envelope study – Anna Schuetz (DESY)

Very challenging requirements

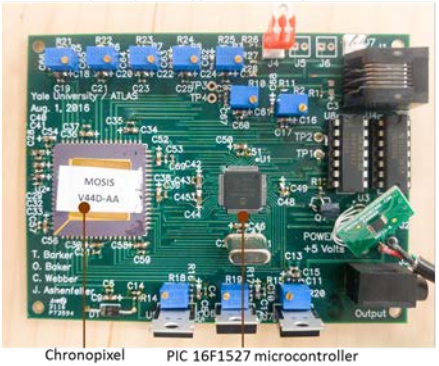
- **< 3 μm hit resolution**
- Feature size ~20 μm
- ~0.1% X_0 per layer material budget
- < 130 μW / mm^2
- Single bunch time resolution



Preliminary ideas for mechanical design. Power pulsing, forced air cooling

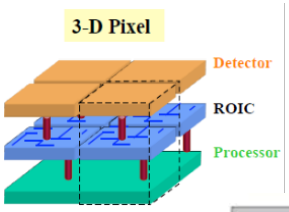
Chronopixel - Oregon, Yale

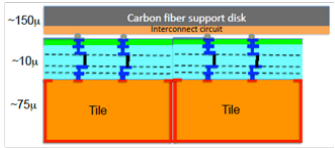
Chronopixel prototype 3 development board



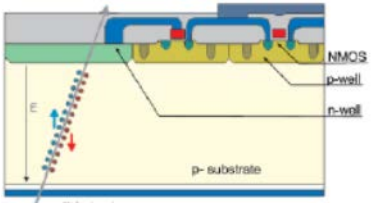
- monolithic CMOS design
  90 nm feature size,
  7 μm epitaxial layer
  280 μm thick chip
  10 ohm·cm
  manufactured by TSMC
- store up to 2 hits per pixel, 12 bit per timestamps
- 25 μm pixel pitch
- implements 6 sensor diode options

Vertically Integrated ("3D")



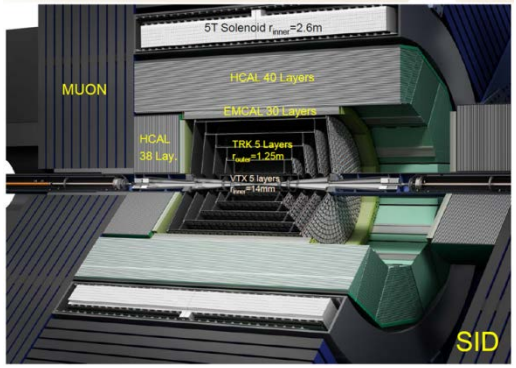


HV CMOS



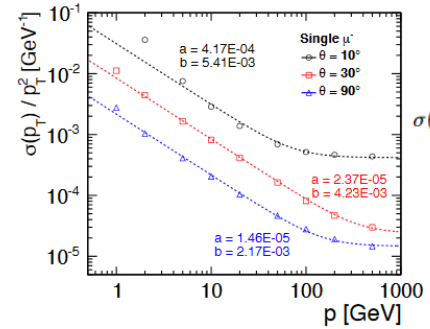
Position Measurement

SiD Detector for ILC Main Tracker

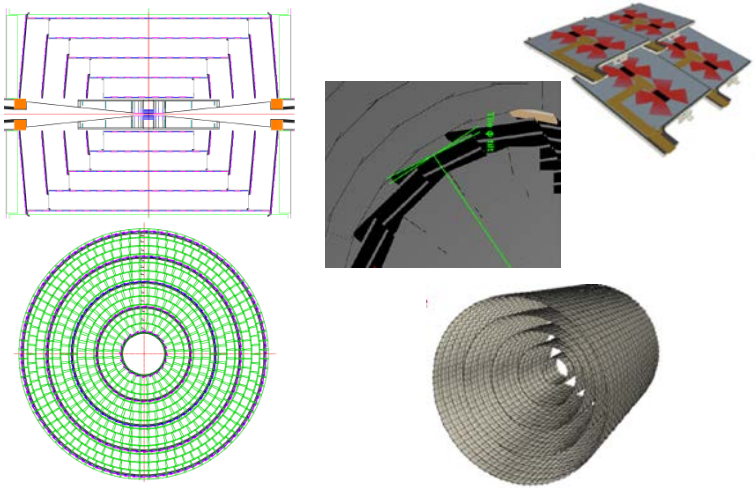


Baseline

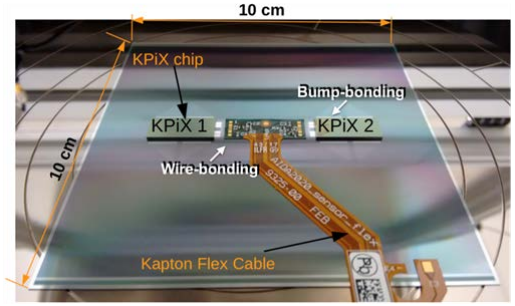
- All Silicon Tracker
  - Using Silicon micro-strips
    - 25 μm pitch / 50 μm readout
    - v2 sensor prototype July 2017*
- 5 barrel layers / 4 disks
- Tracking unified with vertex detector
  - 10 layers in barrel
- Gas-cooled
- Material budget < 20% X_0 in the active region
- Readout using KPiX ASIC
  - Same readout as ECAL
  - Bump-bonded directly to the module



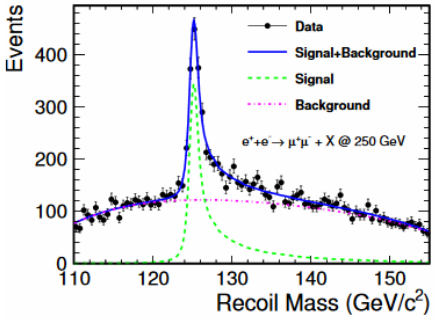
$$\sigma(p_T)/p_T^2 = a \oplus \frac{b}{p \sin\theta}$$



Beam tests ongoing - DESY



Physics goal



Excellent momentum resolution to obtain the best possible recoil mass measurement

Goal – full prototype test: sensor + kPix + cables

MAPS/Pixel tracker option

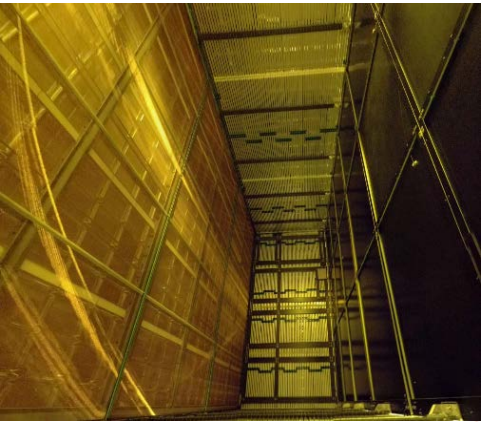
kPixM – optimized for tracker, 40μm x 500μm pixels. Position resn. < 14μm,
S/N >20

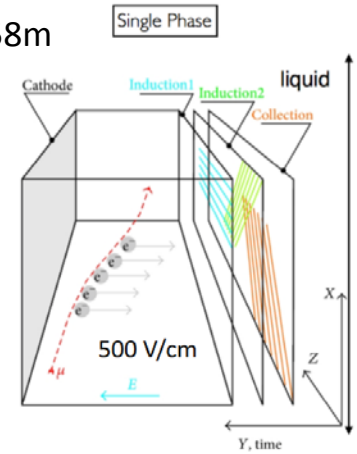
- Pixel tracker option and alignment methods (Bristol)
- Carbon fiber structures for low material, integrated services (Oxford, Lancaster, Liverpool)

Position Measurement

Single phase

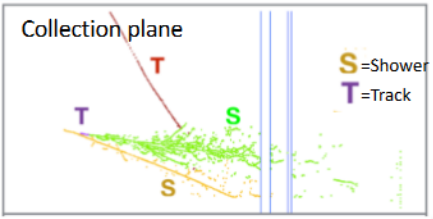
Active volume of 12m x 15m x 58m





Ionization charges drift horizontally and are read out with wires

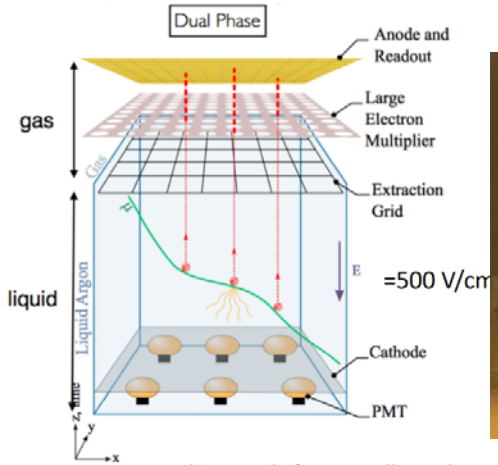
- No signal amplification in liquid
- 3.6 m maximum drift
- Read out by APAs



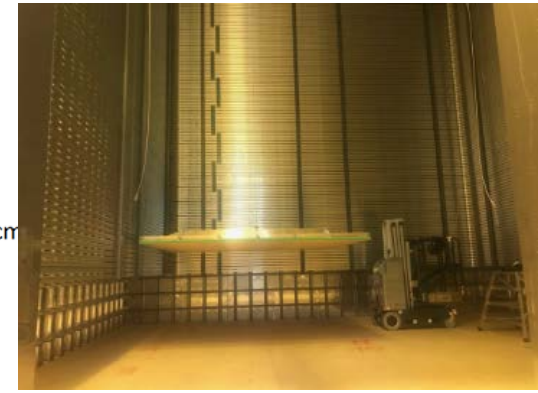
topology consistent with $\pi^0 \rightarrow \gamma\gamma$

- Automated PANDORA Reconstruction

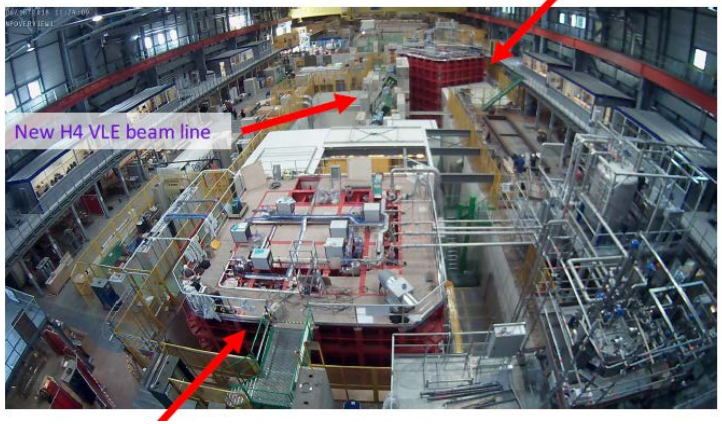
Dual phase



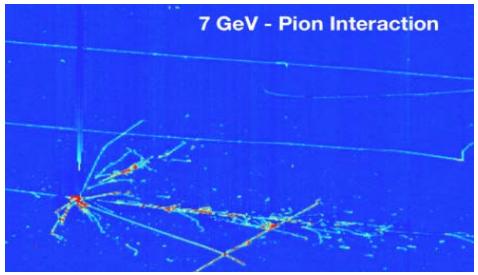
- Ionization charges drift vertically and are read out on PCB anode
- Amplification of signal in gas phase by LEM
- 12 m maximum drift
- Access through chimneys on top



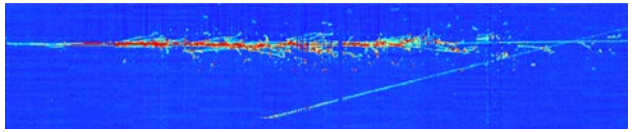
ProtoDUNEs hosted at CERN in a new facility



Beam-initiated event



Muon w/brem-initiated EM shower



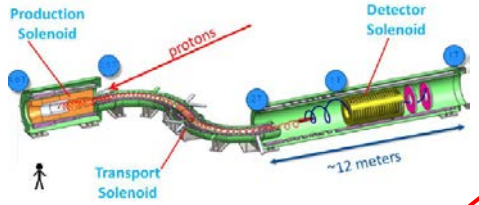
Christos Touramanis, VCI 2019

Stefan Söldner-Rembold

Mu2e

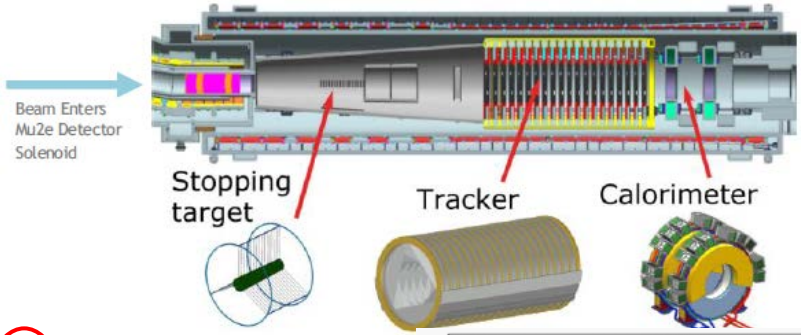
Position Measurement

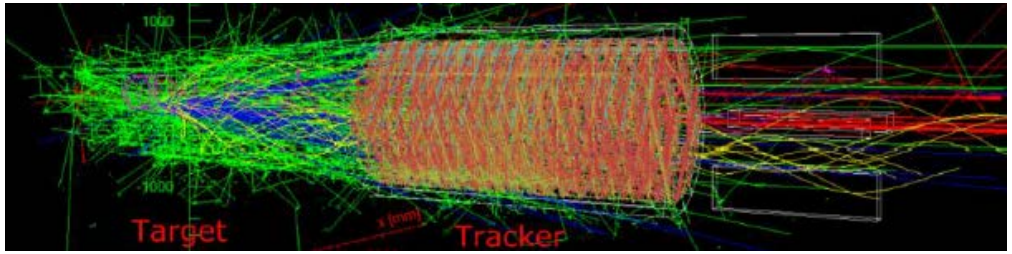
Lepton flavor violation



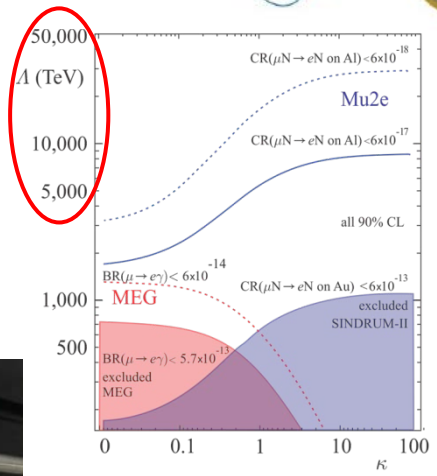
10^4 improvement!

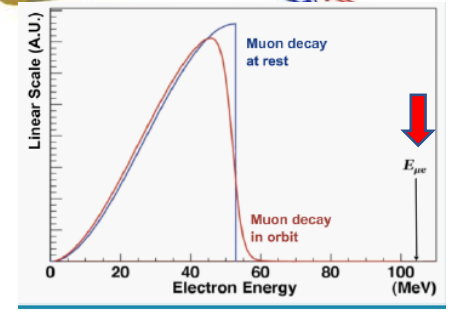
$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z)) \to e^- + N(A,Z)}{\Gamma(\mu^- + N(A,Z)) \to \text{all muon captures}} < 8\times 10^{-17} \text{ @ } 90\% \text{ C.L.}$$

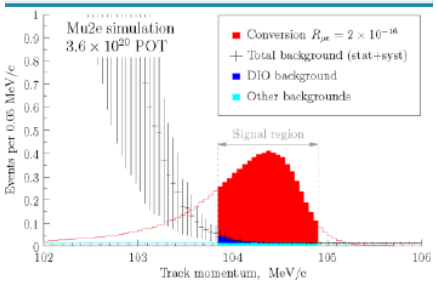




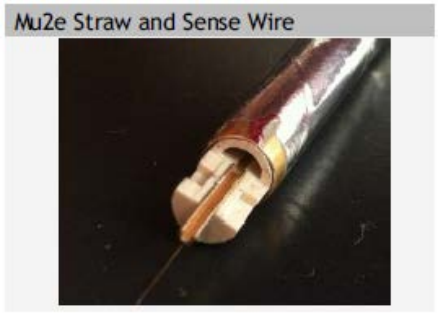
Tracker must measure momentum with better than 0.2% resolution to separate conversion electrons from normal muon decay products





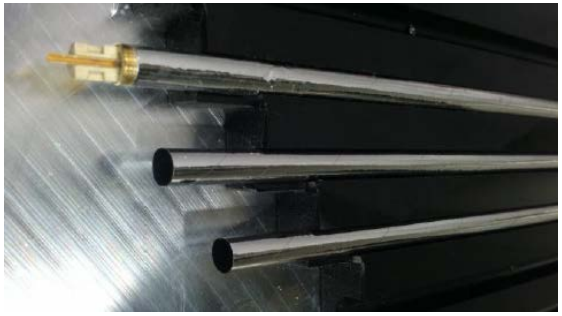


Mu2e TDR

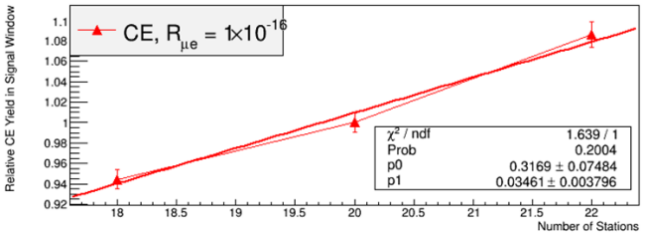


Low mass metalized Mylar
~20K straws, 5mm

Kate Ciampa, Fermilab 2018

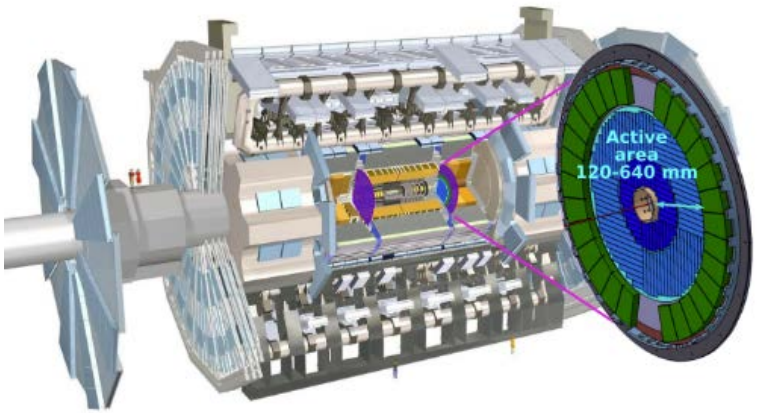


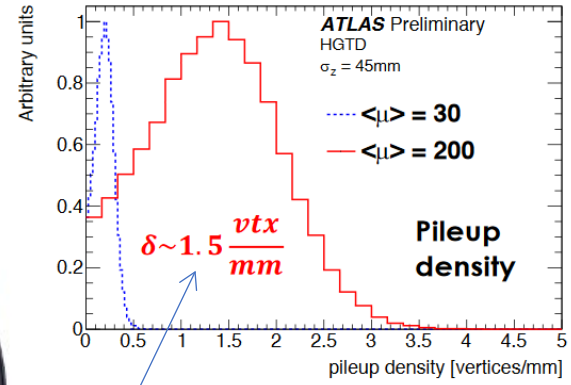
Straws (15μm) account for only about half of the active detector mass, comparable to the drift gas inside



Time Measurement

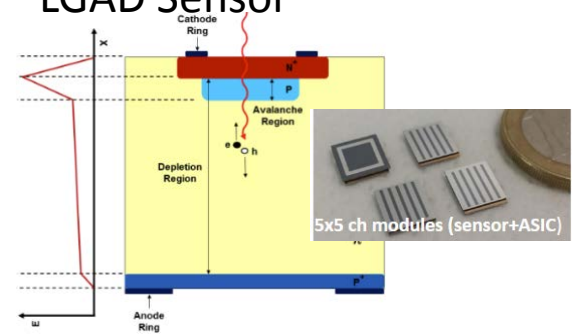
ATLAS High Granularity Timing Detector



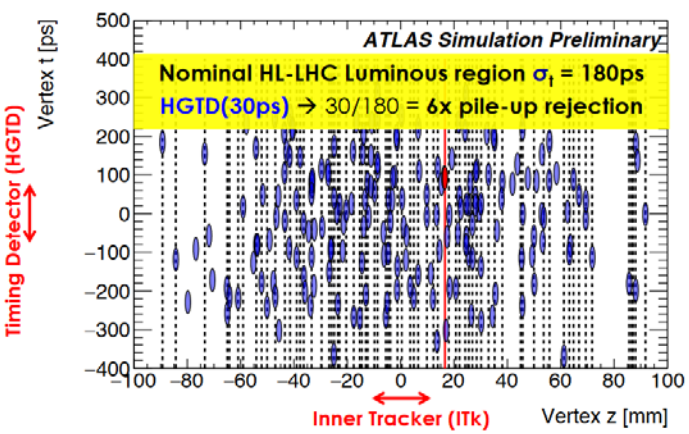


PU density comparable to longitudinal impact parameter resolution of tracker – esp. for forward angles

LGAD Sensor



Precision timing:
Short rise time (thin)
Large signal
Low noise

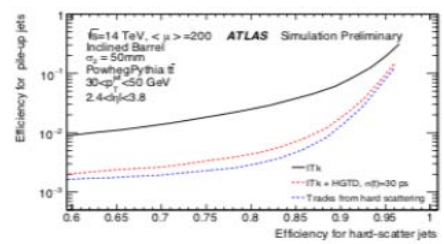


Require Δt ~30ps
35ps achieved so far

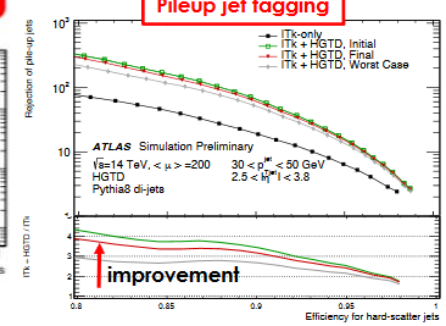
Occupancy < 10%
1.3mm x 1.3mm pixels

After 5 x 10^{15} n/cm^2
Δt ~40-50ps

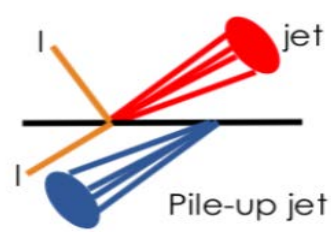
forward pile-up suppression



Pileup jet tagging



VBF final states



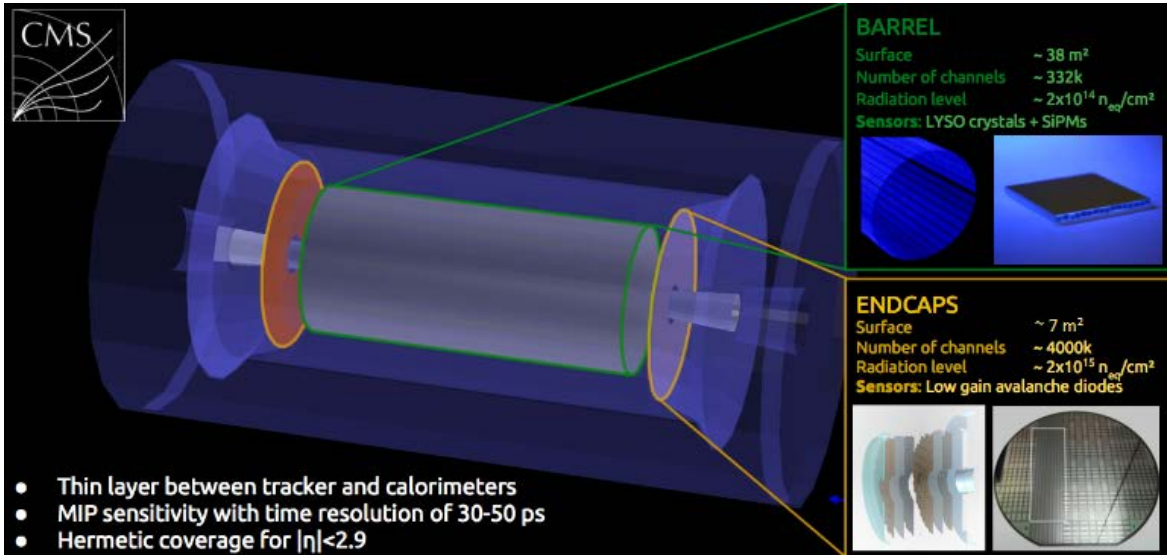
e.g. Higgs -> invisible analysis
Use correct VBF jet in q/g tagging.

VCI 2019, Bengt Lund-Jensen; A. Schwartzman, ICHEP2018

Time Measurement

CMS MIP Timing Detector

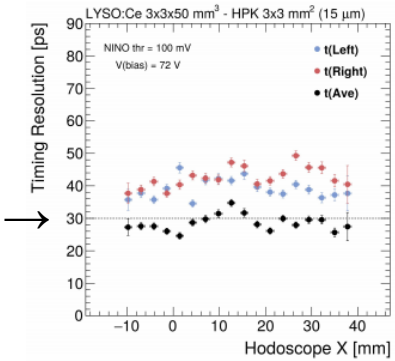
LYSO-Ce + SiPM



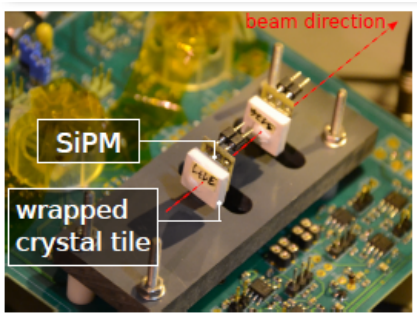
Test beam results (LYSO-Ce)

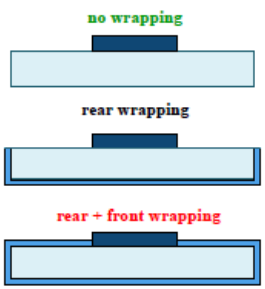
LGAD

30ps →

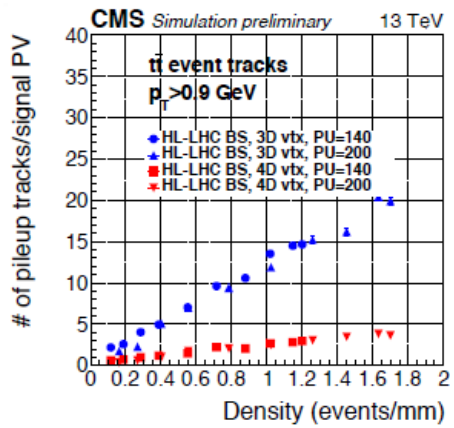


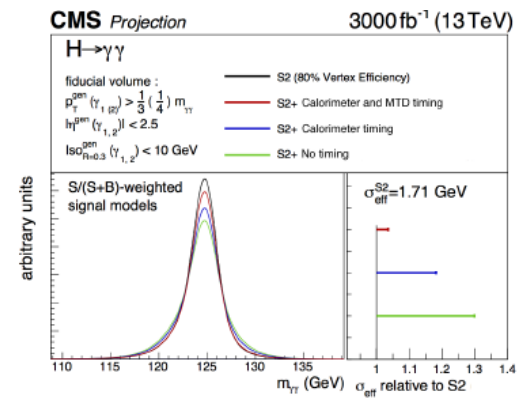
Crystals in test beam





CMS MTD TP: CERN-LHCC-2017-027





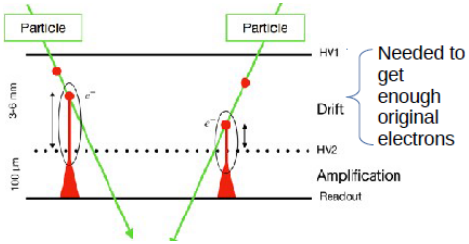
Wrapping -> better time resolution

L. Masetti CTD/WIT Valencia

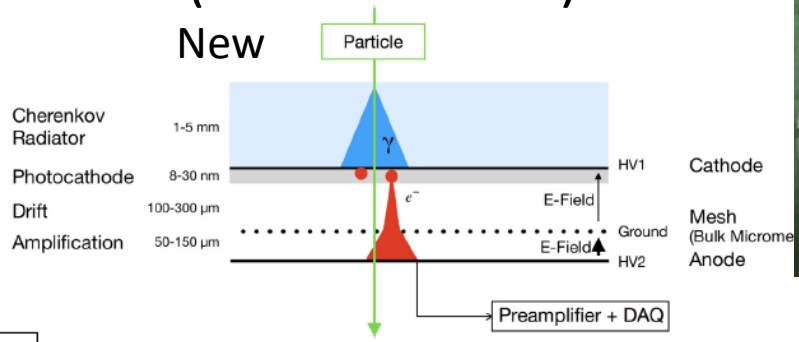
Time Measurement

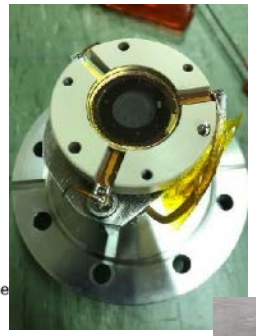
PICOsecond Collaboration (RD51 - MPGD)

Classic MicroMegas

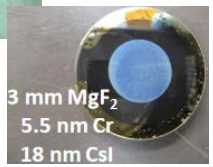


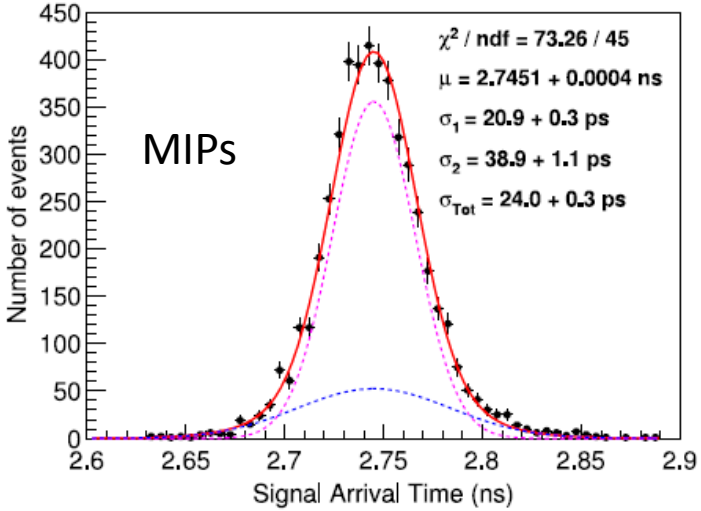
New





Single channel prototype

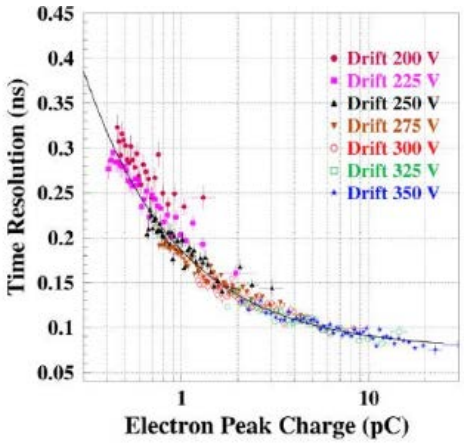




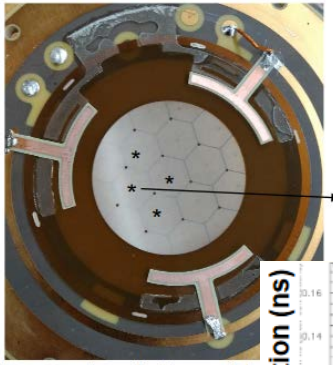
Best time resolution: 24ps 24.0±0.3 ps

J. Bortfeldt et. al. (RD51-PICOSEC collaboration), Nuclear. Inst. & Methods A 903 (2018) 317-325

Synchronous p.e. enter the 2nd stage

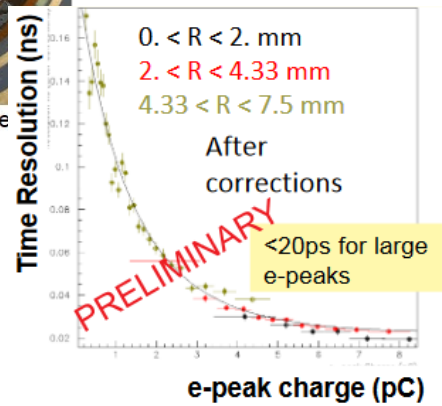


Time Resolution depends mostly on e-peak charge



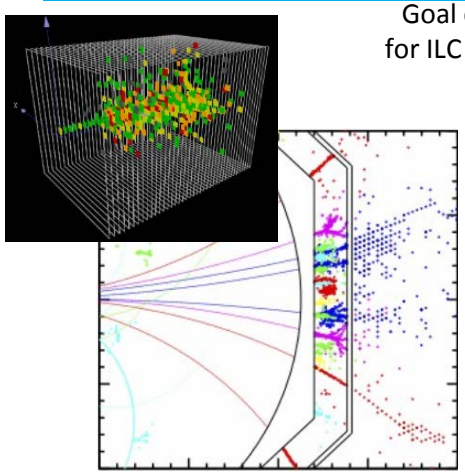
Hexagonal pads 5mm side

Multi-pad prototype

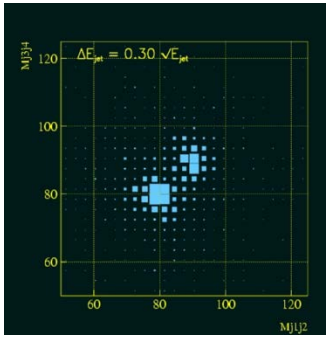


Ioannis Manthos talk at MPGD2019

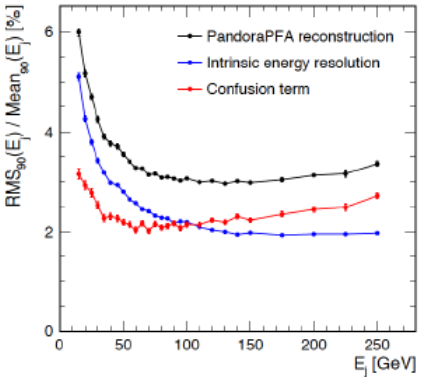
Energy Measurement



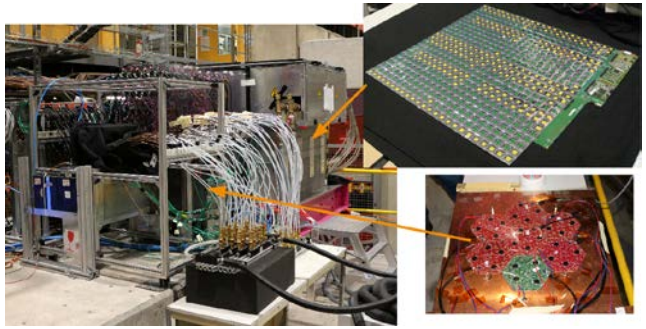
Goal of ~3% jet energy resolution for ILC experiments, W/Z separation, high precision studies.
(H. Videau, J-C Brient)



High Granularity Calorimetry

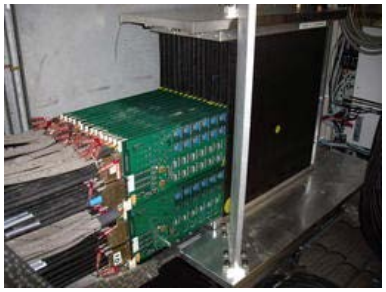


CMS HGCAL + CALICE AHCAL

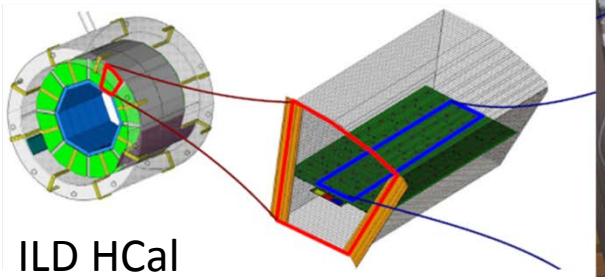


CALICE combined physics prototype

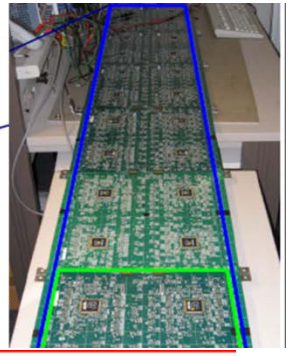
CALICE SiW ECal



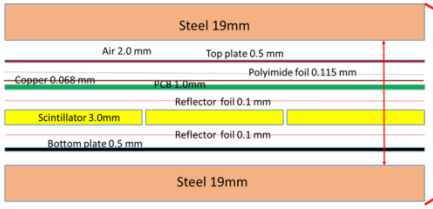
Towards an engineering design



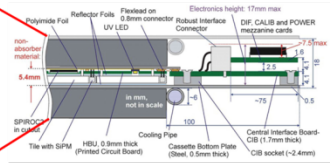
ILD HCal

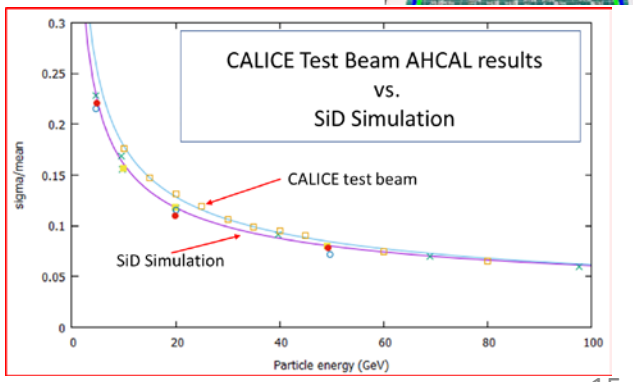


SiD



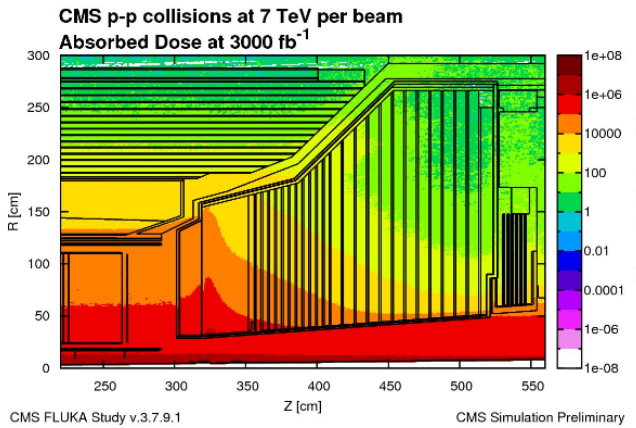
CALICE design

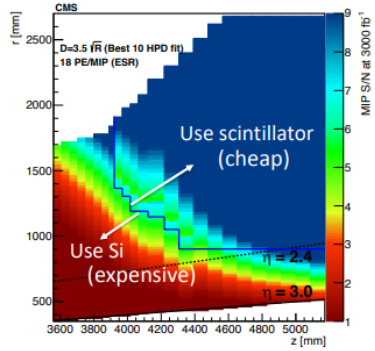




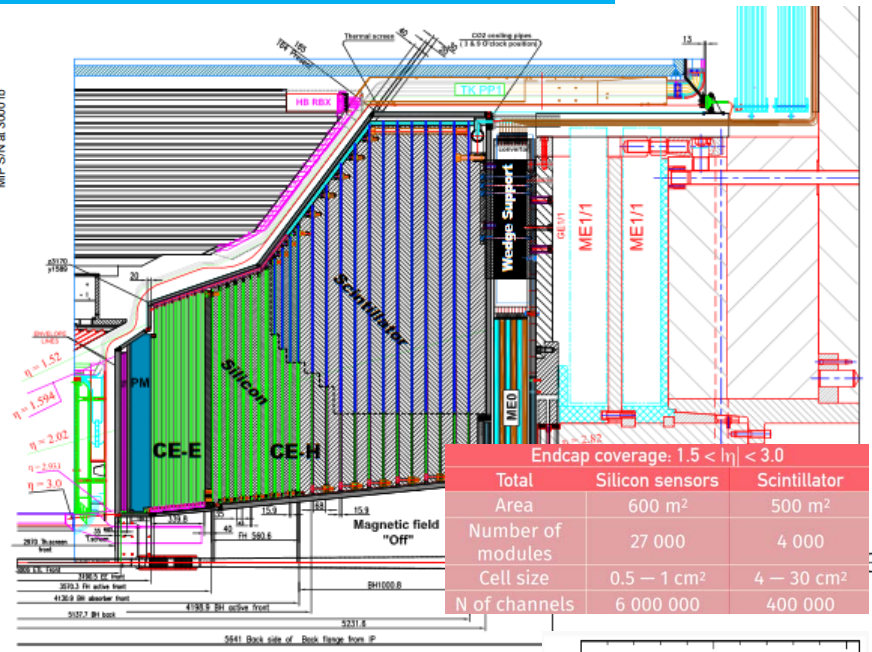
Energy Measurement

CMS Endcap Calorimeter Replacement

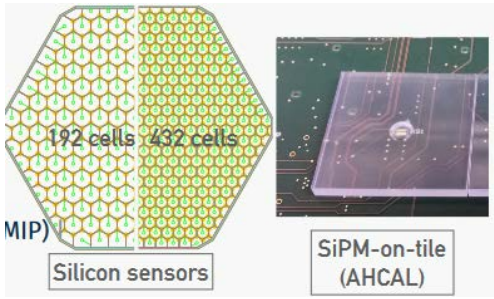


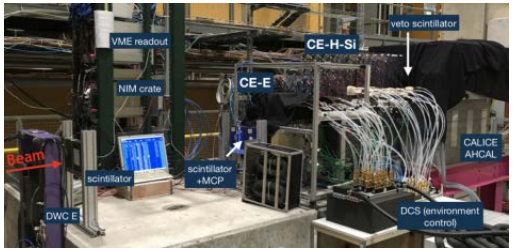


R. Yohay
VCI 2019

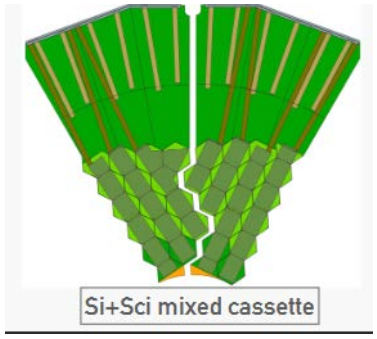


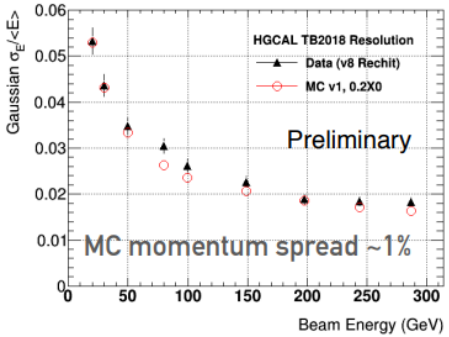
Endcap coverage: 1.5 < |η| < 3.0		
Total	Silicon sensors	Scintillator
Area	600 m²	500 m²
Number of modules	27 000	4 000
Cell size	0.5 – 1 cm²	4 – 30 cm²
N of channels	6 000 000	400 000

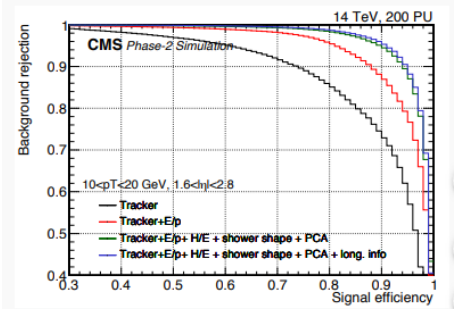




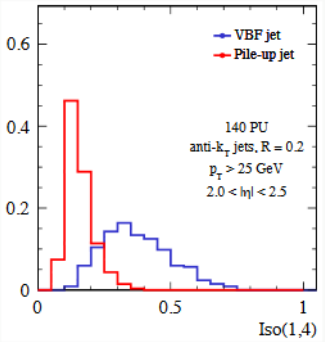
Test Beam 2018





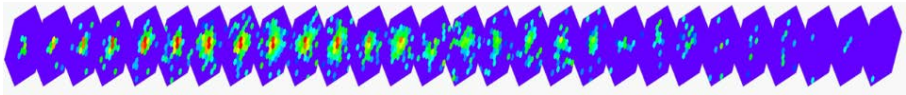


Electron ID for p_T in 10-20 GeV



VBF vs PU jet isolation

Great detail – 80 GeV electron!

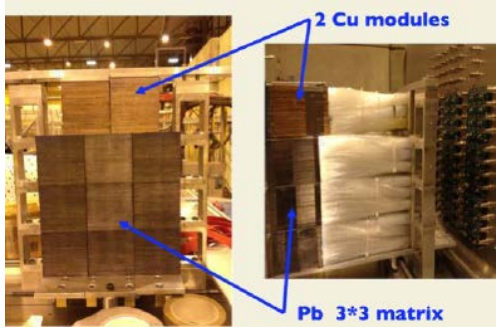


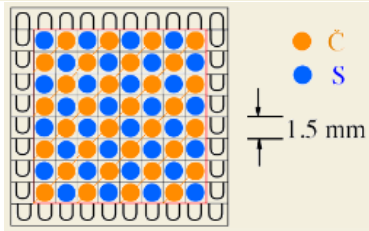
A. Lobanov ICHEP2018

Energy Measurement

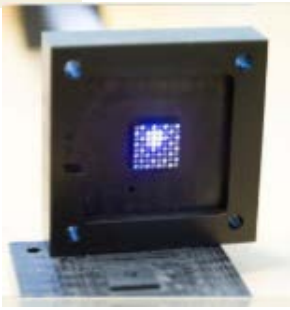
Tests of a dual-readout fiber calorimeter with SiPM light sensors

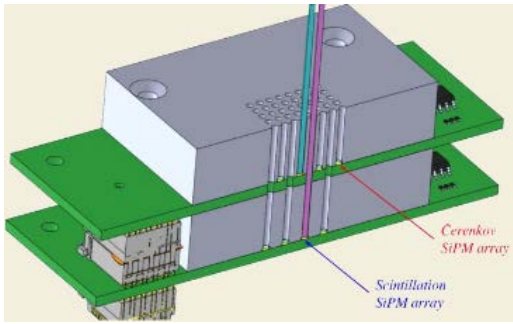
Evolution from DREAM-RD52





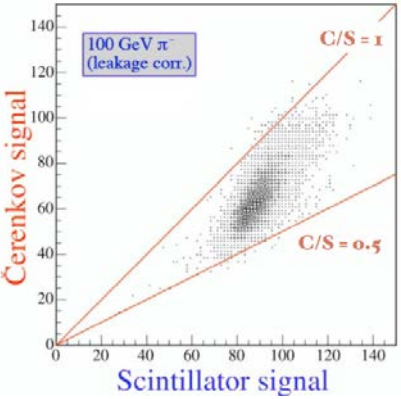
112 cm long, 15 x 15 mm2 wide

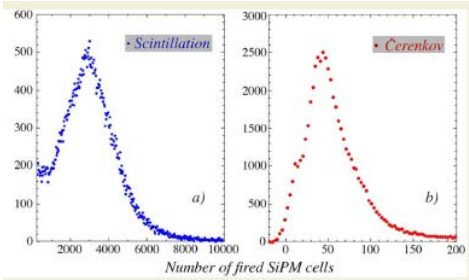




C ↔ S crosstalk measured ~0.3-0.4%

Using beam muons

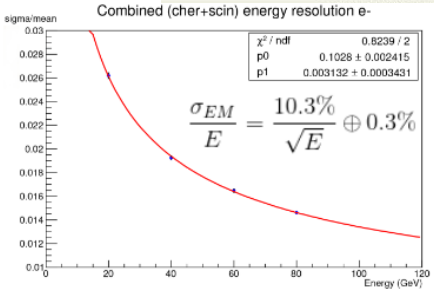


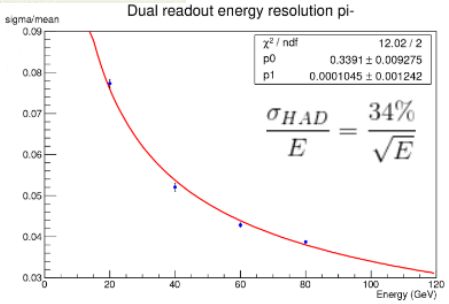


$$C = E\left[f_{em} + \frac{1}{(e/h)_C}(1-f_{em})\right]$$

$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1-f_{em})\right]$$

$$E = \frac{S-\chi C}{1-\chi}$$

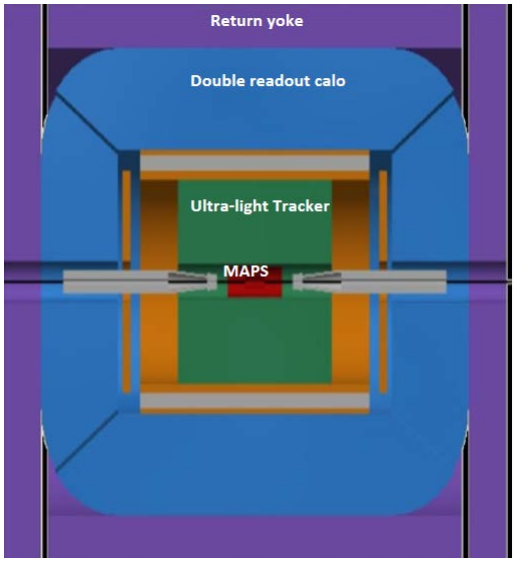




Massimiliano Antonello - FCC week 2018

Lorenzo Pezzotti - CALOR 2018

IDEA Detector for FCCee Dual Readout Calorimeter

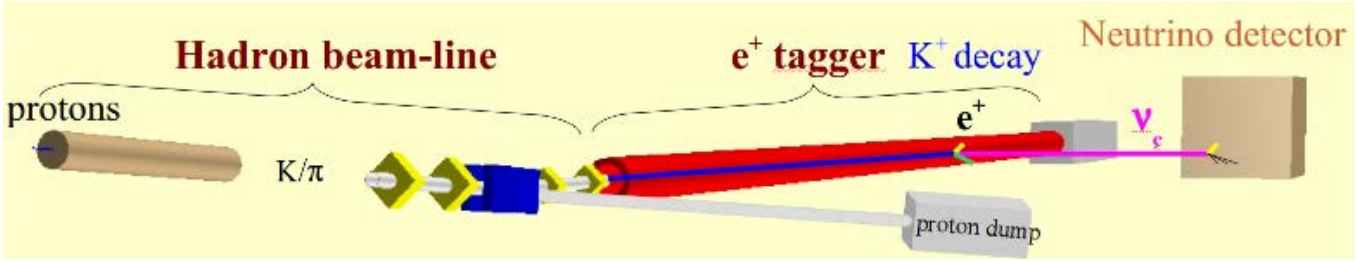


Energy Measurement

Neutrino experiments – need good measurement of initial flux (low systematics ~1%) to preserve CPV discovery potential and physics understanding

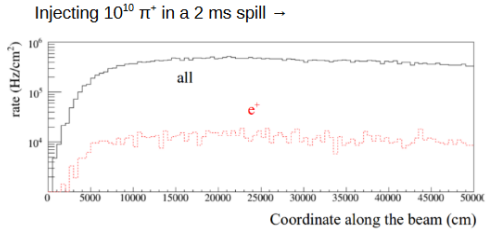
The ENUBET project

Monitored
- Fully instrumented decay region
- $K^+ \rightarrow e^+ \nu_e \pi^0$ (K_{e3})
- large angle e^+ (~90 mrad)
- ν_e flux prediction = e^+ counting

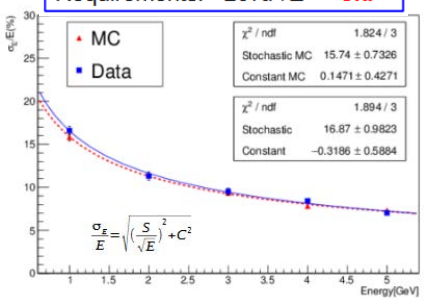


Longhin, L. Ludovici, F. Terranova, Eur. Phys. J. C75 (2015) 155

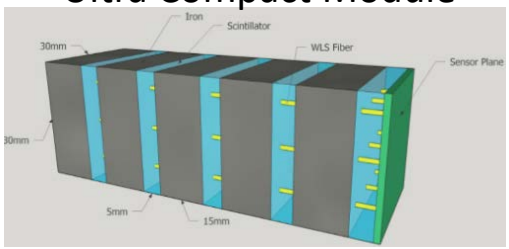
e+ tagging: challenging task



Stochastic term ~17%/√E
Requirements: <20%/√E → ok!

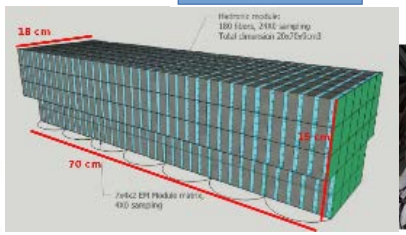


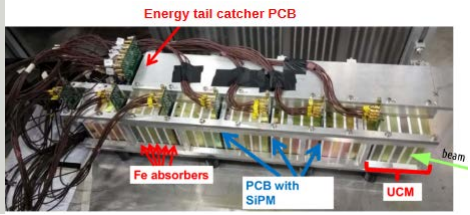
Shashlik "UCM"
Ultra Compact Module



WLS fibers;
FBK SiPMs

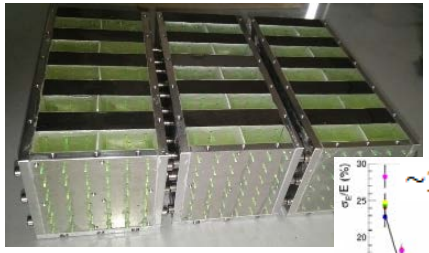
$e^+/\pi^+/\mu^+$ separation → Longitudinally segmented calorimeter

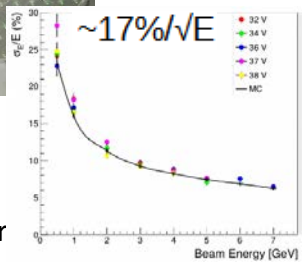




G. Ballerini et al, JINST 13 (2018) P01028

Polysiloxane calorimeter

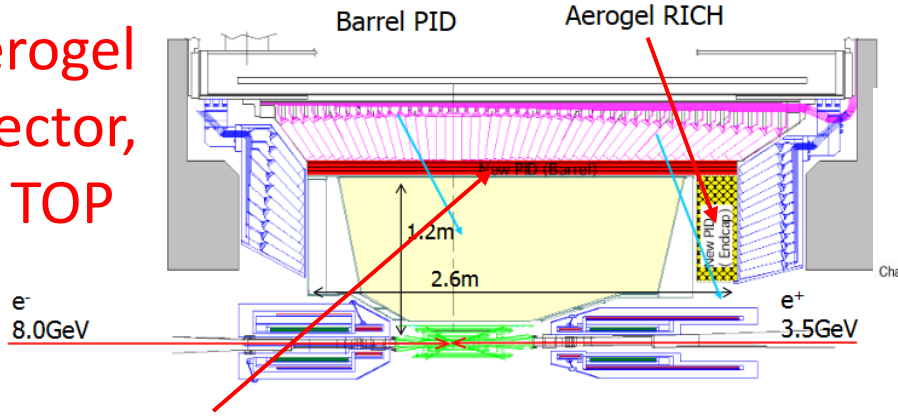




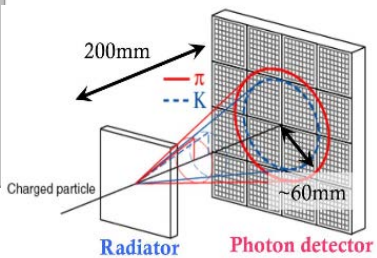
No drilling of scintillator
- pour over fibers
Soft solid at room temp.
X10 rad. Hardness
~30% light yield
Best optical contact w/fibers

Particle ID

Belle II aerogel RICH detector, Imaging TOP

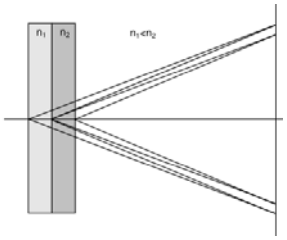


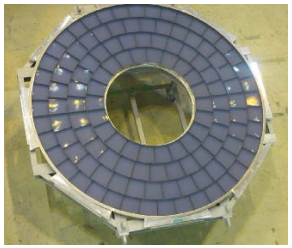
Target performance : K/pi separation at > 4σ C.L. @ 0.5 < p < 4 GeV/c



Rare B-decays (NP sensitive) require good K/π separation up to 4 GeV/c

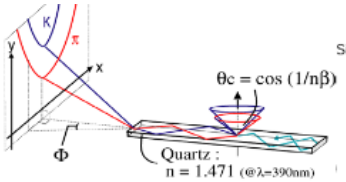
Silica aerogel dual focusing radiator

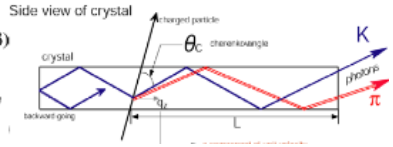


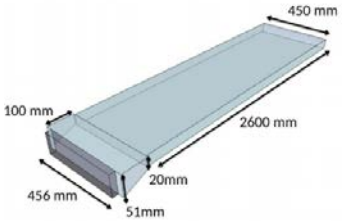


Imaging TOP (Time Of Propagation)

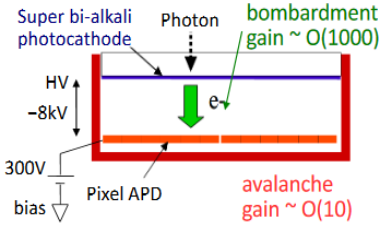
Very limited space (2cm!)

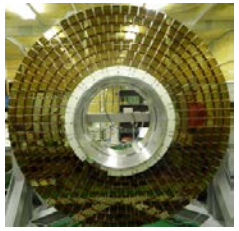




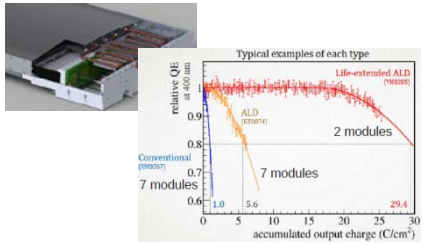


Hybrid Avalanche Photon Detector (HAPD)





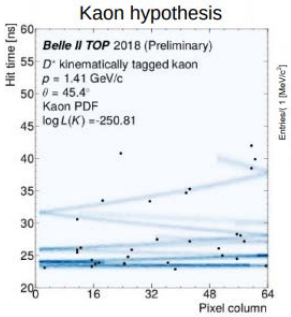
Micro-channel plate (MCP)photon sensors



Single photon timing σ ~100 ps

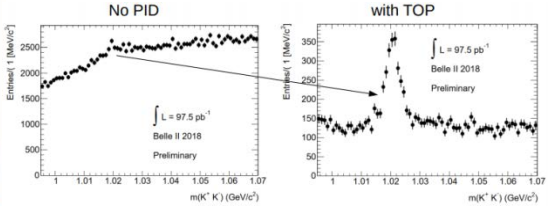
Channel:

$D^{*+} \rightarrow D^0 \pi_s^+$ with $D^0 \rightarrow K^- \pi^+$

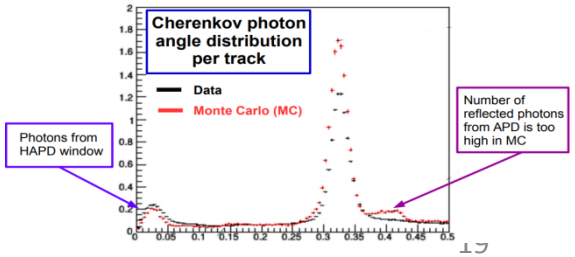


ϕ decaying to kaons

TOP particle identification only



Data vs Monte Carlo (without any tuning)



NIM A907 (2018) 46-59

Martin Bessner VCI 2019

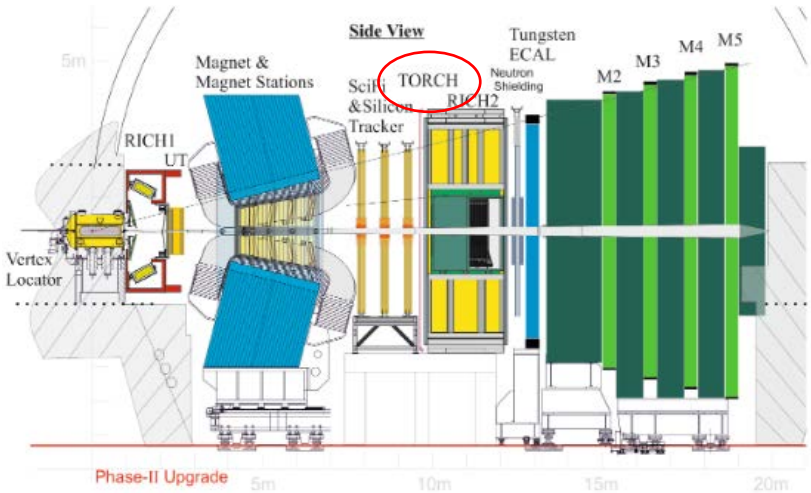
Leonid Burmistrov VCI2019

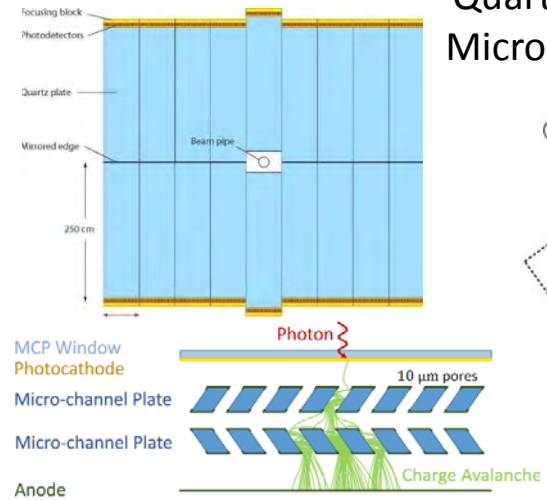
Particle ID

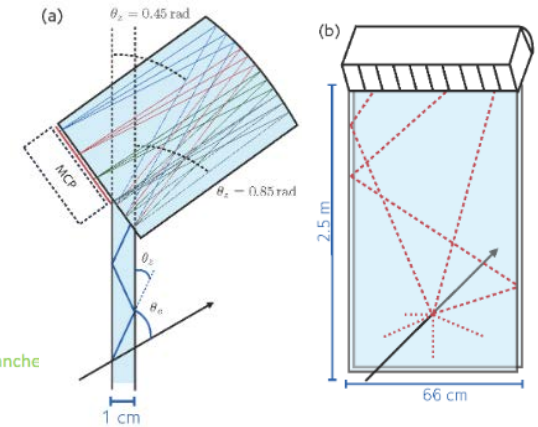
LHCb – TORCH

Time Of internally Reflected Cerenkov light

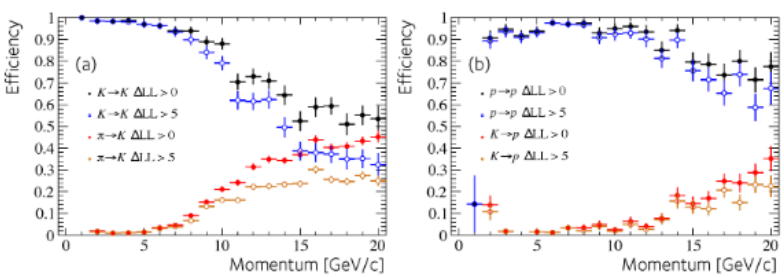
10m path ~35ps → Need σ_t ~10-15ps
(70ps/photon, 30 photons/charged track)
Quartz (1cm) – fast signal
Micro-Channel Plate PMTs







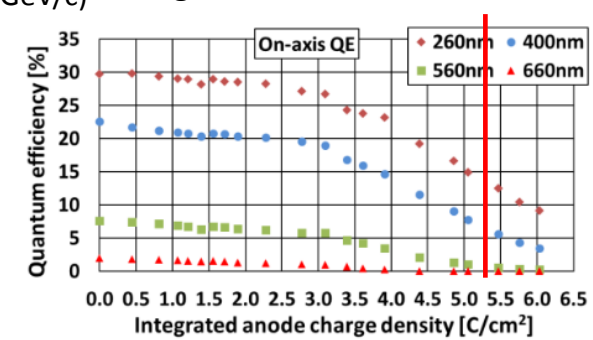
Goal: distinguish π/K/p 2-10 GeV
(Currently no positive kaon or proton identification below 10 GeV/c)



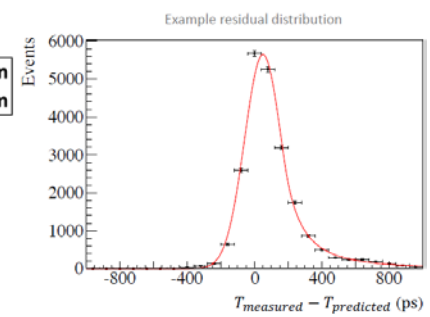
Simulation – heavy flavor production

arXiv:1812.09773v1

Long-term test of MCP-PMT



Phase 3 (Photek) tubes
being tested

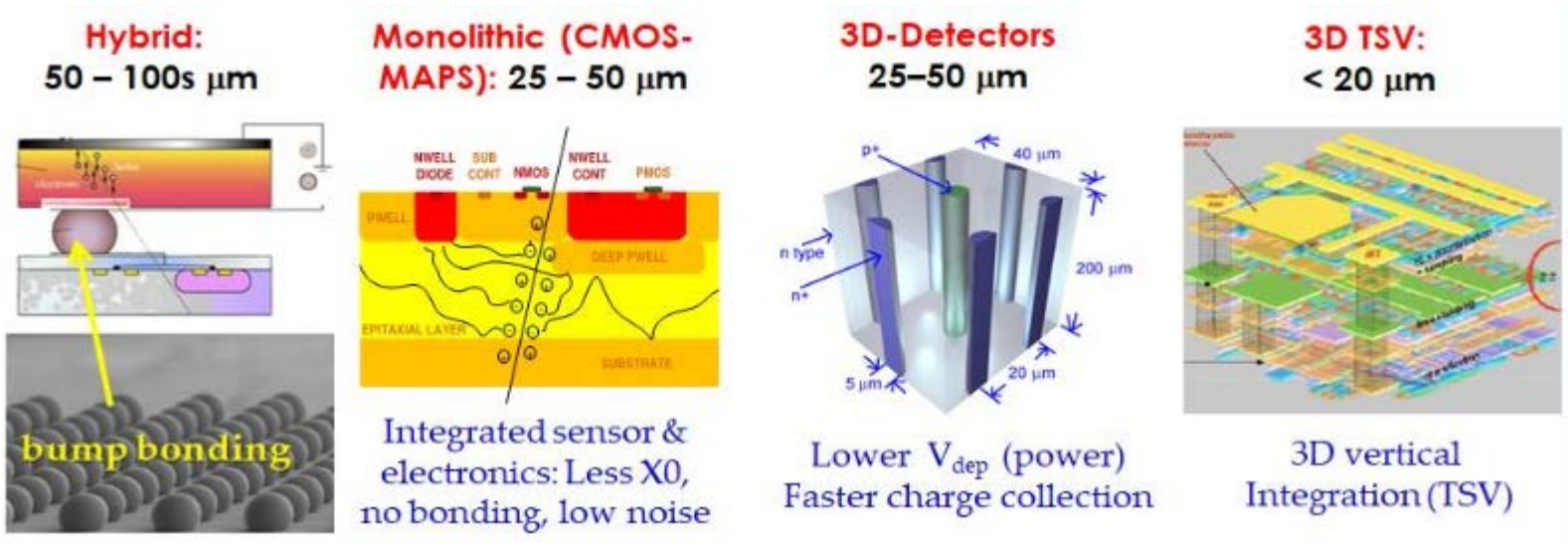


5 GeV/c pion beam

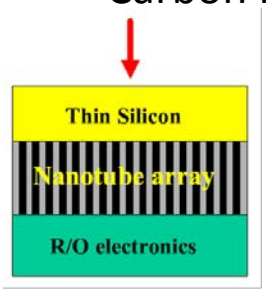
Best achieved is 88.8 ± 1.3 ps

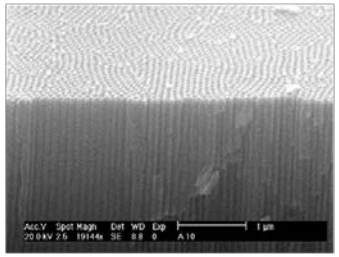
Thomas H. Hancock – VCI2019

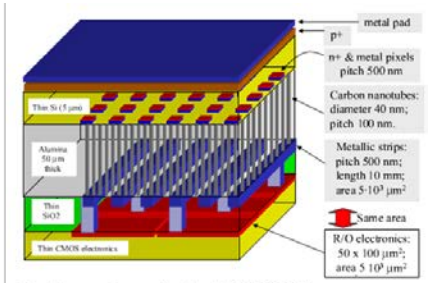
Innovation



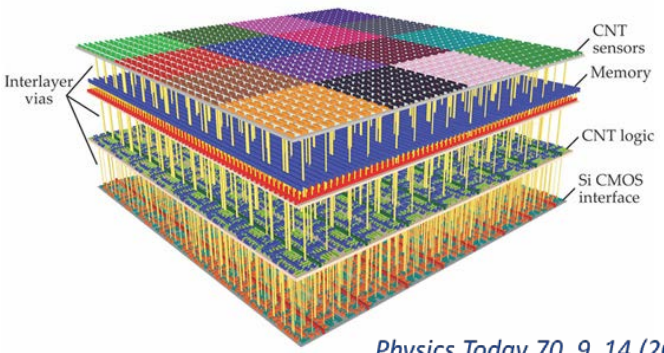
Carbon nanotubes for HEP?







R. Angelucci et al (2002)



Physics Today 70, 9, 14 (2017)

HEP goal ~1μm?
CNT pixels…how small?

~1M CNT FETs
Initial use – gas molecule detection
-> X-ray imaging
?-> HEP particles?

0νββ - Barium Tagging

Innovation

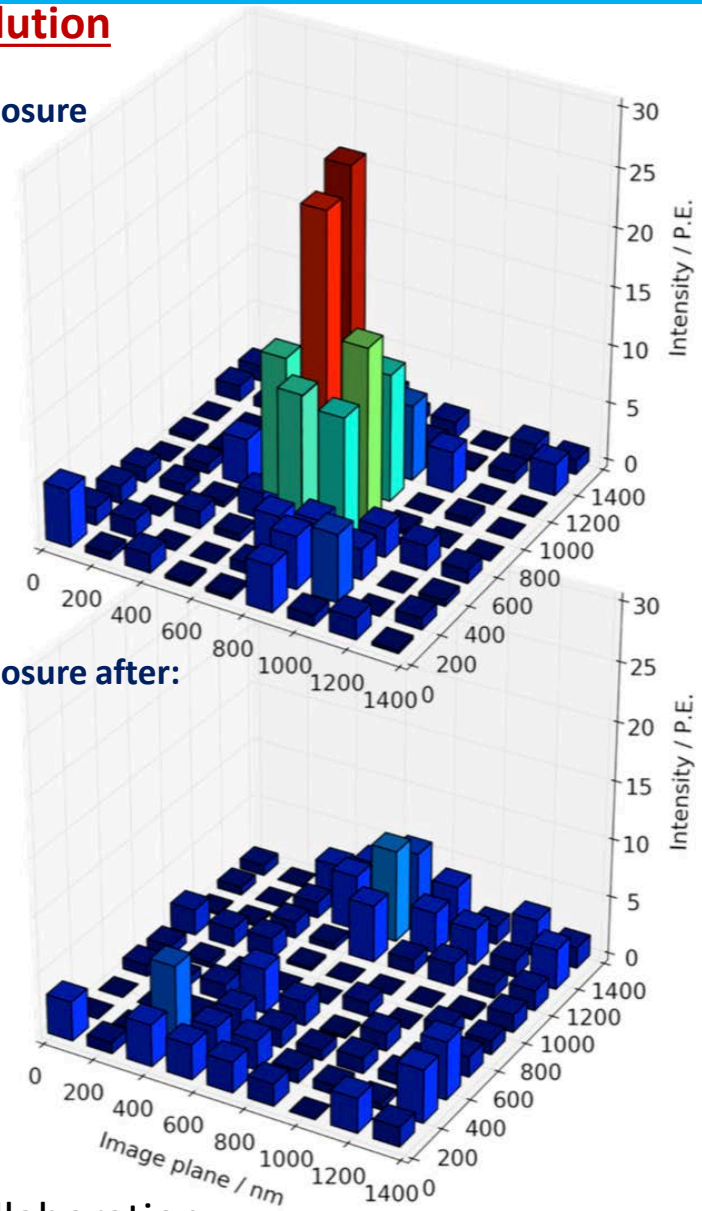
(N. Byrnes – talk at this meeting)

- Detection of neutrinoless double beta decay with background <0.1 counts per ton per year in the ROI is a formidable experimental challenge.
- Energy resolution better than 1% FWHM coupled with detection of a single barium ion in Xe has long been recognized as a background-free method.
- Recent important progress in "barium tagging" has yielded single ion sensitivity.

Single ion resolution

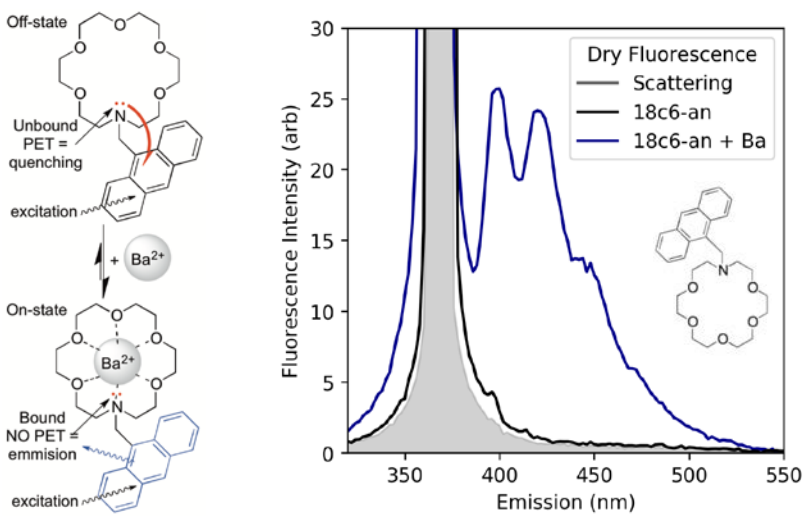
0.5s exposure before:

0.5s exposure after:



NEXT Collaboration

Novel dry chemosensor development



https://arxiv.org/pdf/1904.05901.pdf

Phys.Rev.Lett. 120 (2018) no.13, 132504

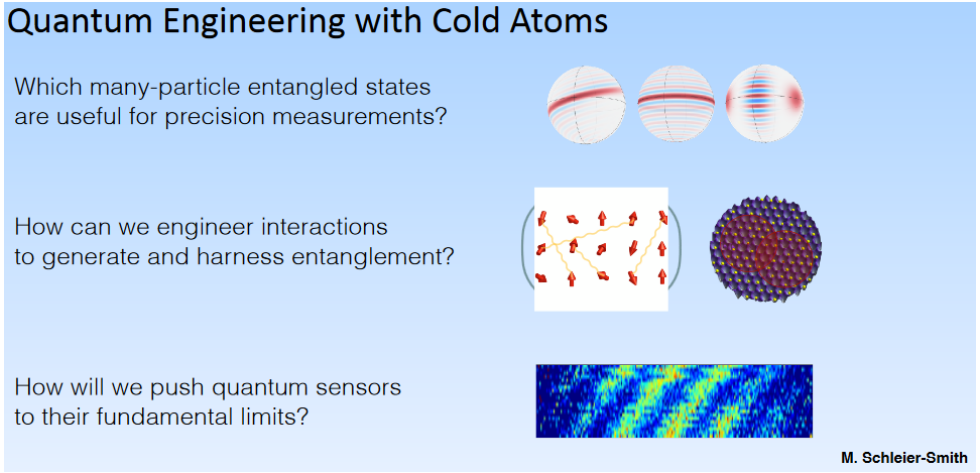
Innovation - QIS

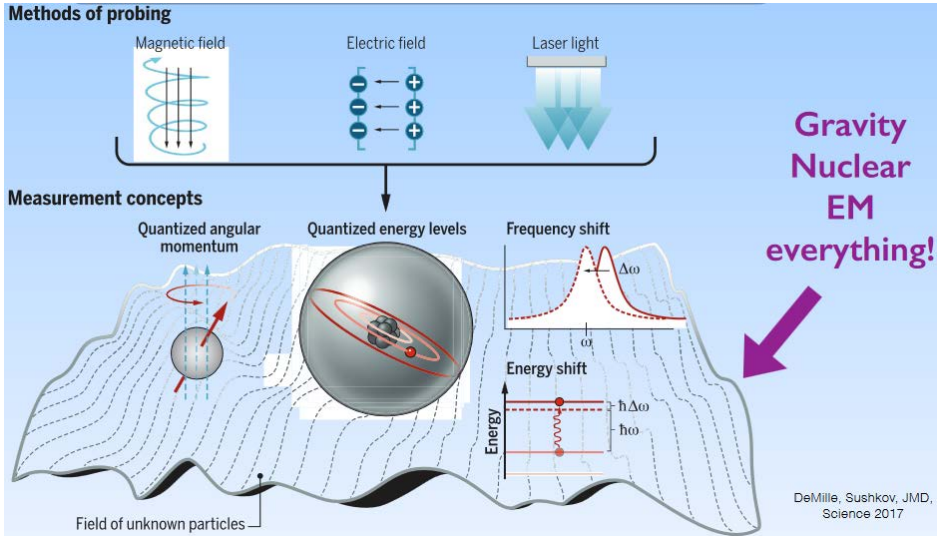
Exploiting small quantum level changes for new particle/field detection?

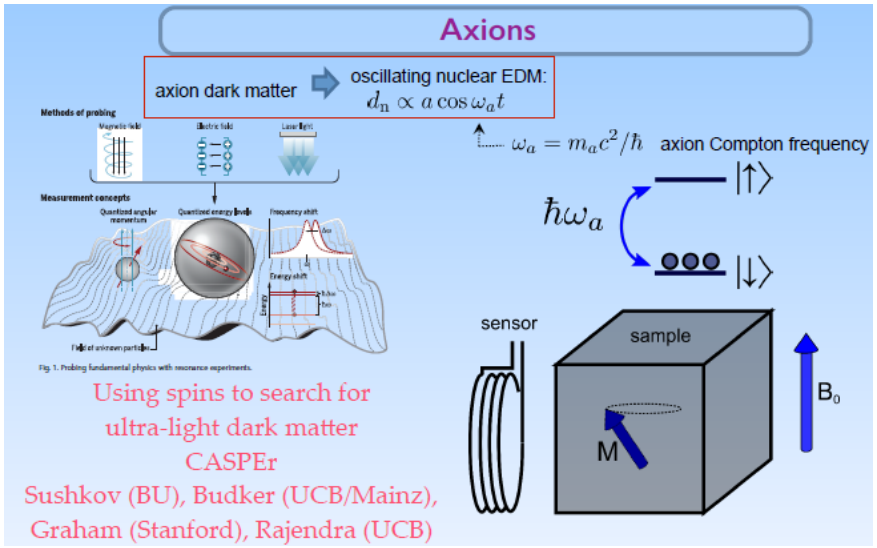
How to improve precision measurements using spin state “squeezing”?

How to use entanglement to couple across arrays of quantum systems?

How to leverage use of QIS for HEP?







Perspectives on the Development and Applications of New Technologies

Technology has taken us to a new level of detector functionality for high energy physics (high precision tracking, track triggering, precise timing, imaging calorimetry,…)

1) Need driven solutions
   - e.g. LHC environment – radiation and pile-up
     Enabling new physics studies at heavy ion colliders

2) Availability of new device(s)
   - e.g. use of SiPM's to enable practical designs for HG and DR calorimetry
     Wide use of CMOS technology – moves into monolithic CMOS

3) Solutions for new physics
   - e.g. detectors for high precision Higgs studies (ILC, CLIC,…)

4) Extension(s) of existing technologies
   - e.g. adding a Cerenkov component to MicroMegas for fast timing

5) Import technology(s) from other fields
   - e.g. Chemical barium-tagging
     WLS nano-particles, carbon-nanotube pixels?

Perspectives on the Development and Applications of New Technologies

6) Going further – once we have a new technological solution for a HEP application we should always ask what else could be enabled by this technology.

7) Keep monitoring developments – delay technology choices

8) "Blue sky"
- always need this component
- imagine solutions even if technology does not (yet) exist
- what could we achieve by further extension of existing technologies
  (e.g. what would be enabled by sub-picosecond timing, sub-micron pixels?)

9) What collaborative/administrative structures best support detector R&D?

Detector R&D - Issues

U.S.

HIGH ENERGY PHYSICS DIVISION

Coordinating Panel for Advanced Detectors

CPAD

CPAD: to promote, coordinate and assist in the research and development of instrumentation for High Energy Physics nationally, and to develop a detector R&D program to support the mission of High Energy Physics for the next decades.

The creation of an APS DPF Award for Excellence in Instrumentation Research and Development
Graham Smith, Gabriella Sciolla

Input to the yearly SBIR/STTR proposal calls
Clarence Chang, Maurice Garcia-Sciveres, Wesley Smith, Rick van Berg

Creation of a National Instrumentation Fellowship program for both post docs and graduate students
Matt Wetstein, Gabriella Sciolla, Maurice Garcia-Sciveres, Ulrich Heintz, Juan Estrada

Establish an improved model of an equipment pool that could be used for instrumentation development at U.S. universities and labs
Erik Ramberg, Maurice Garcia-Sciveres

Coordination of instrumentation resources at National Labs for the HEP community
Graham Smith, David McFarlane, Erik Ramberg

A program to further develop instrumentation schools and education
Bob Wagner, Rick van Berg, Marina Artuso, Erik Ramberg, Juan Estrada

Develop a plan to establish and maintain a repository of examples of migration of technologies and instrumentation into high-energy physics and new developments that might benefit HEP
Ron Lipton, Clarence Chang

Continuation and organization of an, at least, annual national instrumentation workshop for HEP & enhancement of interdisciplinary aspects of instrumentation
Ulrich Heintz, Ron Lipton, Bob Wagner, Matt Wetstein, Rick van Berg

CERN

CERN – future detector R&D
Organize into 8 Work Packages
Target specific R&D challenges

- RD50 radiation tolerant n-in-p Si-sensors (ATLAS/CMS/LHCb), LGADs (Timing ATLAS/CMS)
- RD51 MPGD GEMs, Micromegas (ATLAS/CMS/LHCb/ALICE)
- RD18 Crystals (Barrel Timing Layer CMS)
- Electronics common components: 130 & 65 nm radiation tolerant technologies for ASICs, LpGBT, Optical Links, DCDC & serial powering
- RD53 Pixel detector ASIC first version with all features fully functional (ATLAS/CMS)
- Mechanics: new light material structure for trackers, CO_2 cooling with modularity toward detector needs
- Qualification: GIF++ Irradiation and rate facility

Can we benefit from more specific collaboration/coordination?
Some parallelism/competition is good, but resources are limited.

Basic Research Needs (BRN) Study

- Assess the present status of the HEP technology landscape
- Identify key enabling capabilities and associated performance requirements in pursuit of the P5 Science Drivers
- Identify strategic technology areas
- Formulate a small set of high-impact instrumentation "Key Challenges"
- Set up study Working Groups:

- Physics-focused WGs
  - Higgs: Jim Hirschauer (FNAL), Gabriella Sciolla (Brandeis)
  - Neutrinos: Ornella Palamara (FNAL), Kate Scholberg (Duke)
  - Dark Matter: Jodi Cooley (SMU), Dan McKinsey (Berkeley)
  - Dark Energy and Inflation: NN, NN
  - Explore the Unknown: Monica Pepe Altarelli (CERN), Sarah Demers (Yale)
- Technology-focused WGs
  - Quantum Sensors: Andy Geraci (Northwestern), Kent Irwin (SLAC)
  - Noble Liquids: Roxanne Guenette (Harvard), Jocelyn Monroe (RHUL)
  - Photodetectors: Peter Krizan (IJS), Lindley Winslow (MIT)
  - Solid State and Tracking: Marina Artuso (Syracuse), Carl Haber (LBNL)
  - Calorimetry: Francesco Lanni (BNL), Roger Rusack (Minnesota)
  - T/DAQ: Darin Acosta (UFlorida), Tulika Bose (Wisonsin)
  - Readout and ASICs: Gabriella Carini (BNL), Mitch Newcomer (UPenn)

- "Technology Perspectives Factual Document"
  Workshop in the DC area December 11-14, 2019

Conclusions

Detector technology has enabled a new generation of detectors and detector upgrades for HEP.

BSM physics is proving hard to find – requires refined, precise, and innovative technology solutions!

There are great opportunities waiting for the application of new technologies to HEP!

Fostering the development of new detector technologies deserves major attention, and support, and it pays off!

Thank you!