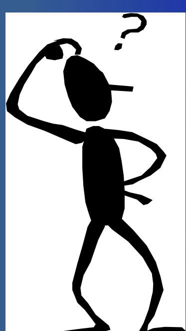
Next Frontiers in Particle Physics Detectors: Conference Summary and Perspectives

Maxim Titov, CEA Saclay, Irfu, France

International Conference « Instrumentation for Colliding Beam Physics (INSTR – 2020), Budker Institute of Nuclear Physics, Novosibirsk, Russia, February 24 – 28, 2020

NOVOSIBIRSK CONFERENCE HAS A LONG-STANDING TRADITION (SINCE 1977)

AND HAS TO BE CONTINUED !!!



Will it look like in Feb. 2050 @ Budker / Novosibirsk ???

INSTR2020 in Budker INP / Novosibirsk: Highlights

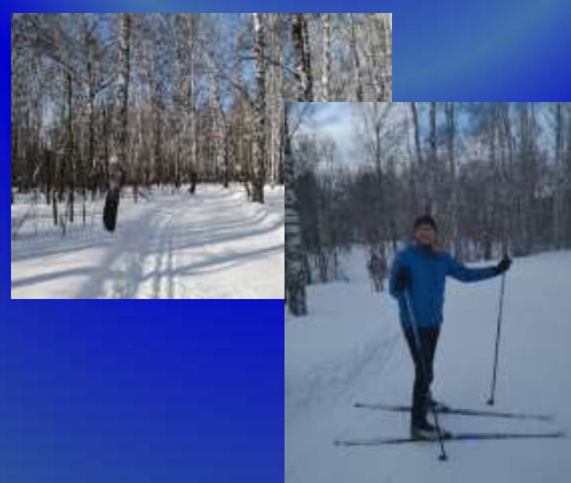
Welcome address by A. Vasil’ev (Minister of Science & Innovation Policy of Novosibirsk region) and P. Logachev (Director of BINP)

91 (non-RU) / 108 (RU) participants;
~ 85 talks and ~ 95 posters

Visit to BINP Facilities:

Music Concert (Filarmonica-Quartet):

“LUNCH OR SKI”:



Conference Dinner:

Science is getting more and more global …

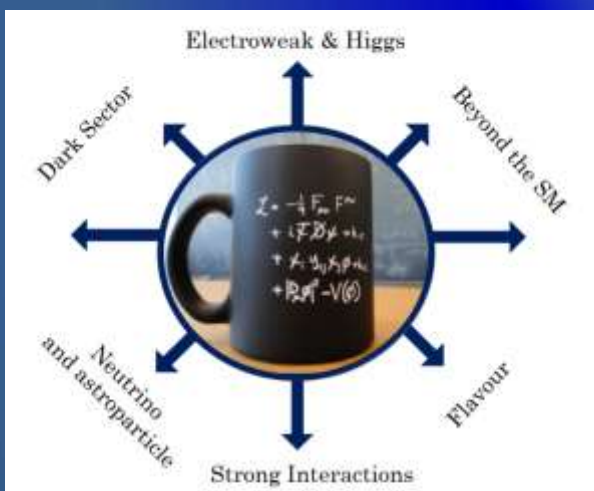
Towards 2020 Update of European Strategy for Particle Physics

→ Need to present and discuss new large scale projects in an international context before making choices

→ Need to present physics case(s) always taking into account latest results at existing facilities

→ Need to present (additional) benefits to society from the very beginning of the project

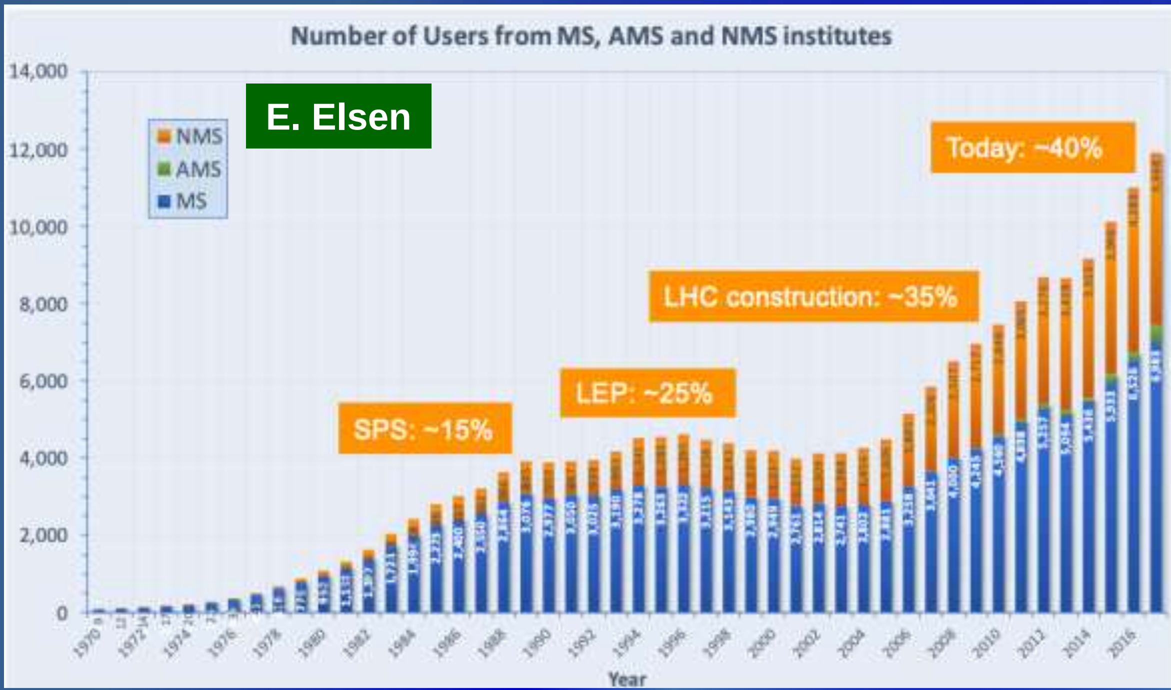
→ Need to have excellent communication and outreach accompanying all projects



- LHC and HL-LHC Exploitation
- Next Step at the Energy Frontier (FCC / ILC / CLIC) and R&D beyond
- Accelerator-based Neutrino Programme (US & Japan) via Neutrino Platform
- Rich Diversity Physics Programme Beyond Colliders

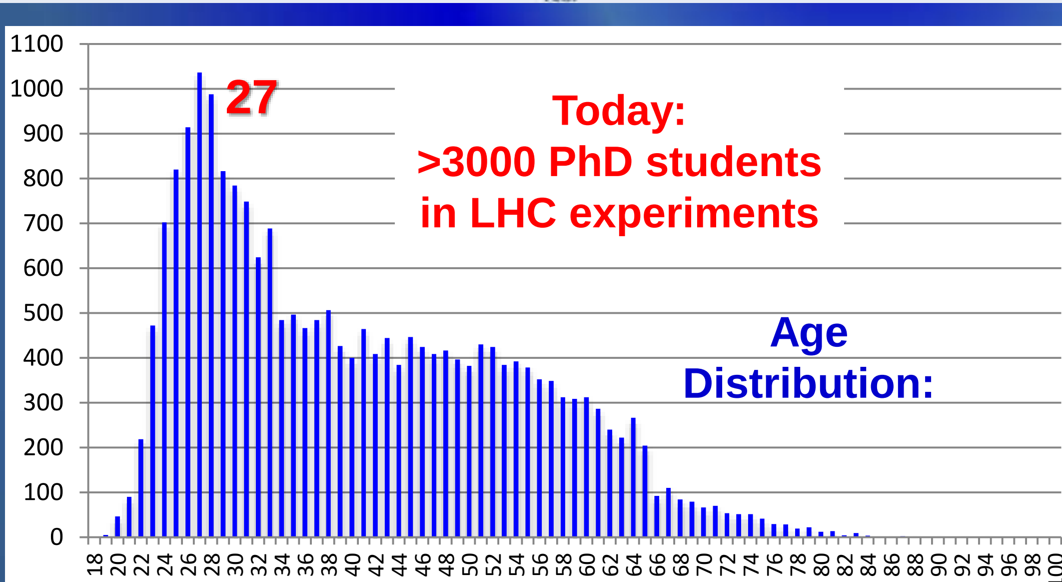
EPPSU becomes public in Budapest (May 2020) at the Special Session of the CERN Council

CERN: Promote Knowledge Transfer Through People

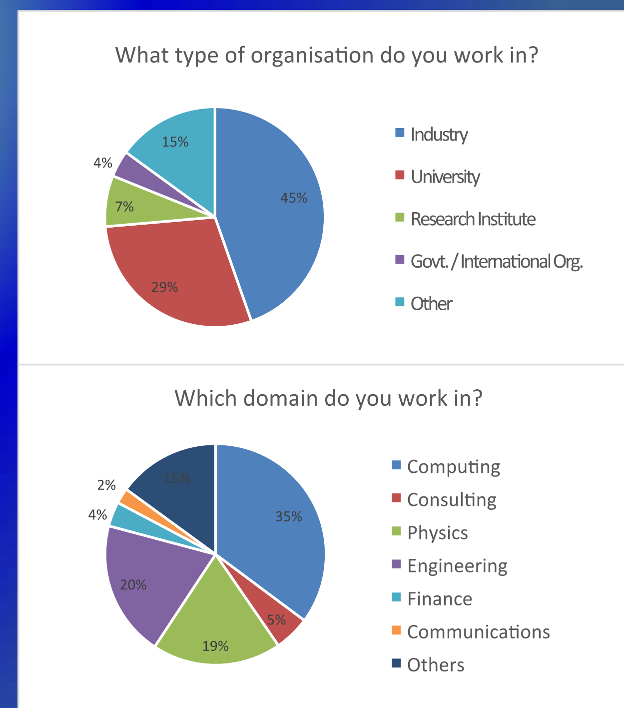


« The Largest PhD Factory in the world »

→ ~ 1000 PhD students per year, working @ CERN receives PhD degree from their home universities

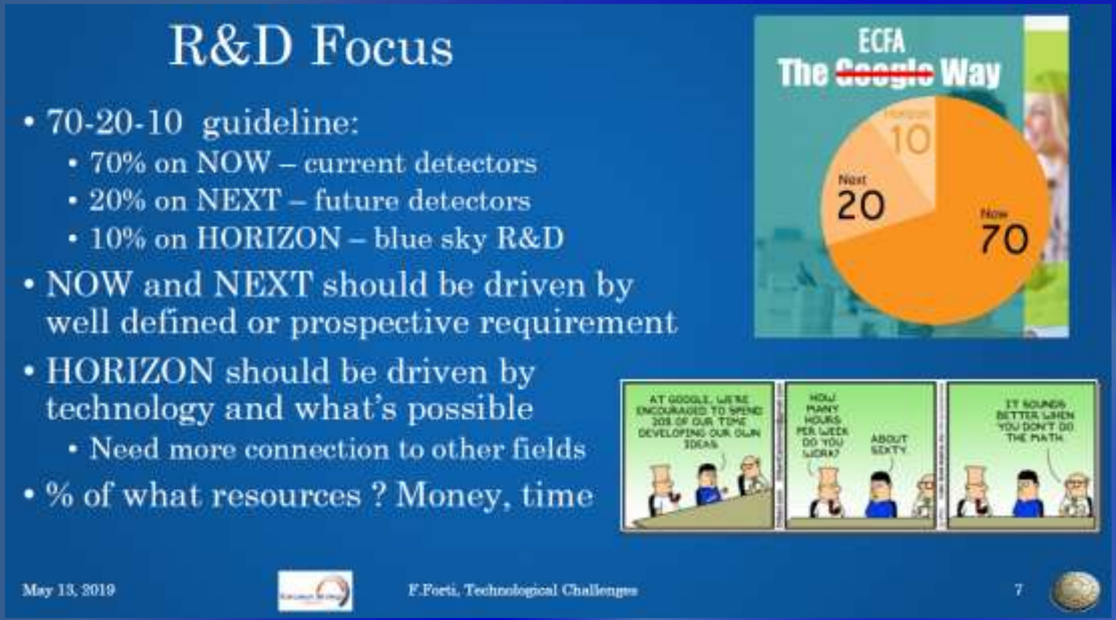


Where do they go?



European Strategy Discussion on (Future) Instrumentation R&D

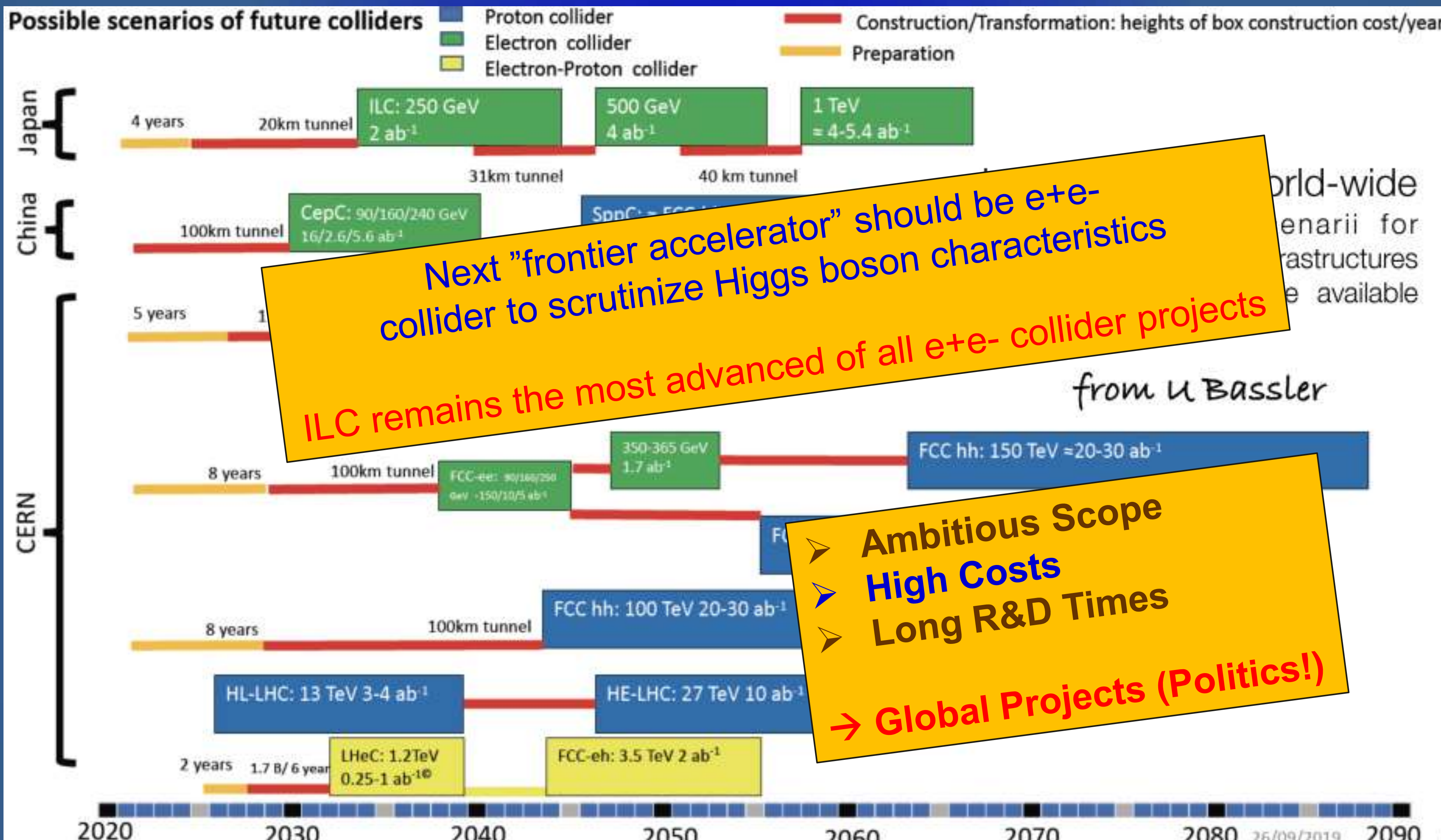
ESPP Symposium: https://indico.cern.ch/event/808335/timetable/#all.detailed



Community messages:

- Importance (at appropriate level) – **"blue sky" R&D**
- Recognition of **excellence in instrumentation** → Career opportunities for detector physicists in universities/research institutes must be greatly strengthened and kept open in a systematic way

Shaping the Future of Particle Physics: Long-Term Options



- Global vision for our field going beyond regional boundaries
- CERN is playing a major role in this global endeavour

The Role of Big Laboratories

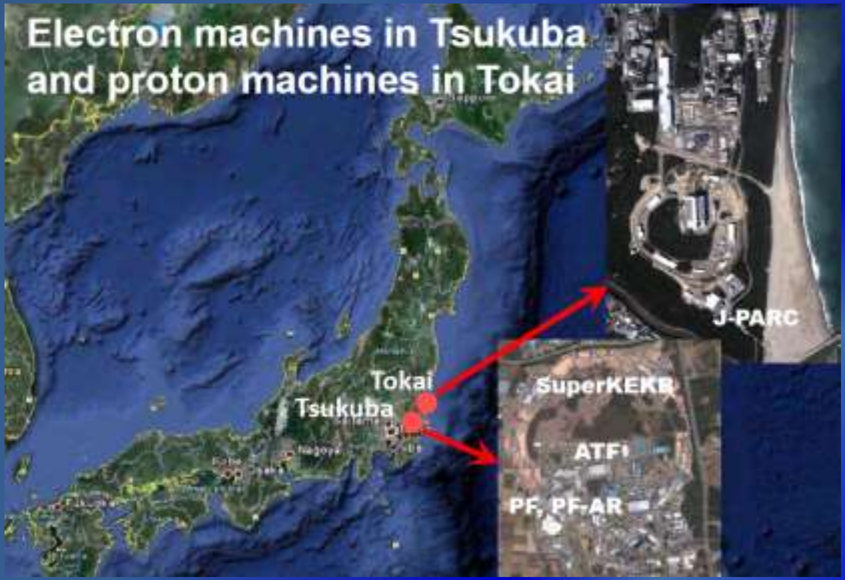
BIG LABORATORY = RESEARCH INFRASTRUCTURE

→ KNOWELEDGE FRONTIER / INNOVATION / EDUCATION / OUTREACH

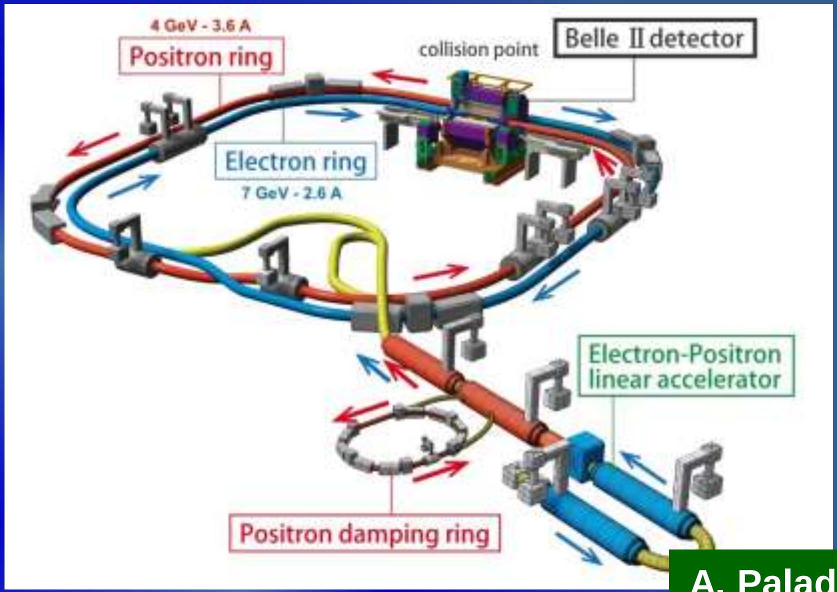
To advance future accelerators it is important:

- maintain accelerator expertise in all regions;
- ensure long term stability in all three regions;
- engage all countries with particle physics communities
  → international cooperation is vital (“sociology“);

KEK Status: SuperKEKB / Belle II and JPARC

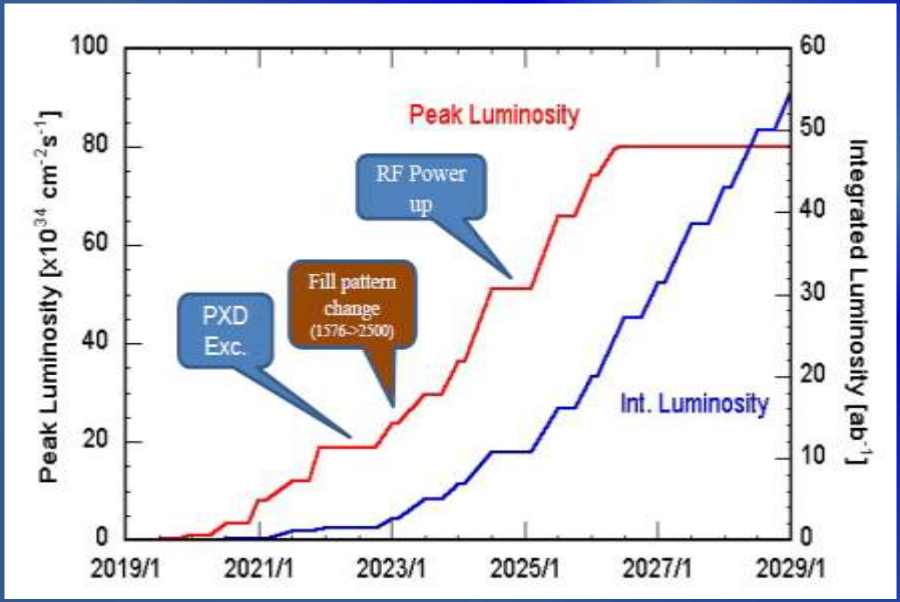


SuperKEKB and Belle-II: 8 x 10^{35} (40 x luminosity)



A. Paladino

BELLE II luminosity projection: S. Uno



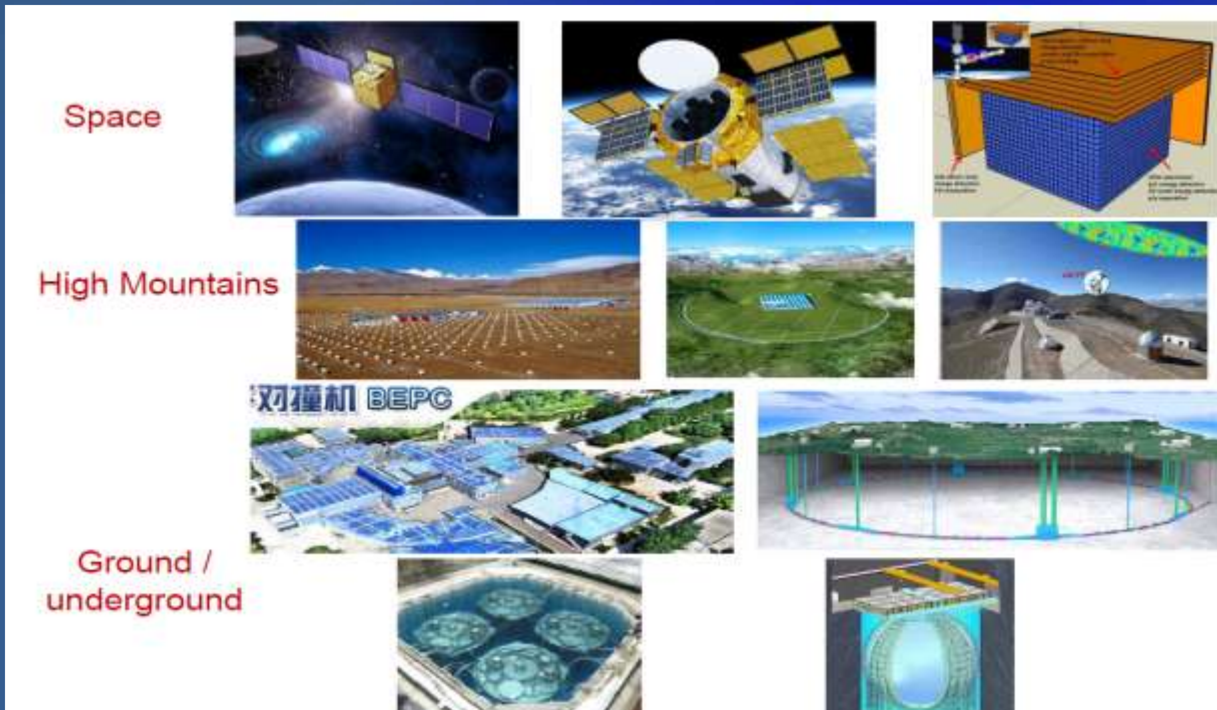
- ✓ **Verification of nano-beam collision scheme (L ~1.1 x 10^{34} – similar to KEKB)**
- ✓ **Beam backgrounf is still high compared with KEKB/Belle (due to the lack of vacuum scrabbing time)**
- ✓ **First physics papers submitted (Z')**

JPARC:

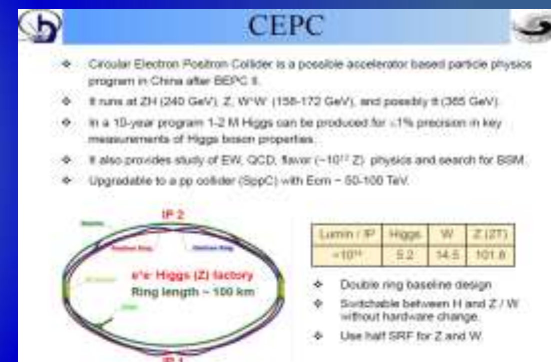
✓ **HyperKamiokande projet approved last month: construction 2020, operation in 2027**

Experimental Program at IHEP CAS

J. Wang



Collider Experiments:



General Experimental Platforms:

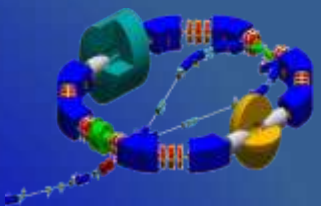
Budker Institute of Nuclear Physics: From VEPP to Tau-Charm Factory

VEP-1

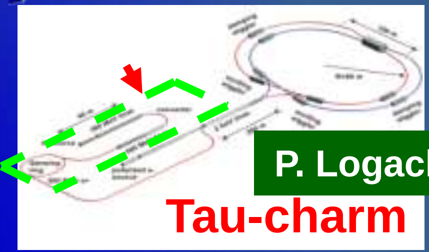
VEPP-2

VEPP-3

VEPP-4M



VEPP-2000



P. Logachev

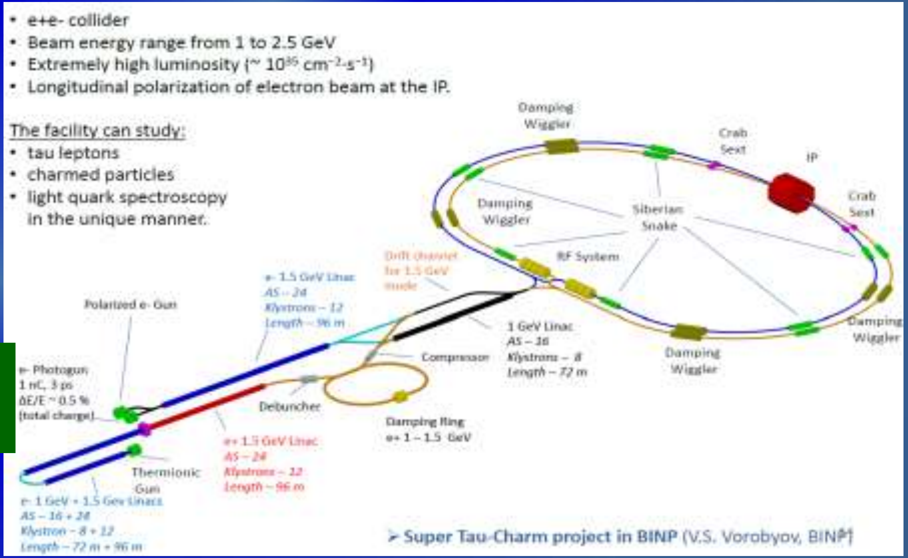
Collider	2E, Gev	Detectors	Operation
VEP-1 (e⁻e⁻)	0.32	2 detectors	1965-67
VEPP-2	1.4	3 detectors	1967-72
VEPP-3 (booster and Nucl. Phys)	2.0	2 detectors	1972-
VEPP-4	11.0	OLYA, MD-1	1980-85
VEPP-2M	1.4	OLYA, ND, CMD SND, CMD-2	1974-2000
VEPP-4M	11.0	KEDR	2004-
VEPP-2000	2.0	SND, CMD-3	2009-
Tau-Charm Factory			

L. Shekhtman
N. Muchnoi

VEPP-4M / VEPP-2000 with 3 detectors are in operation (~ 15 years of future physics):

- → high precision measurements of particle masses (e.g. J/ψ, D, τ-lepton)
- → study of e+e- → 2(3,4) h cross sections

Towards Super-Charm Tau Factory:

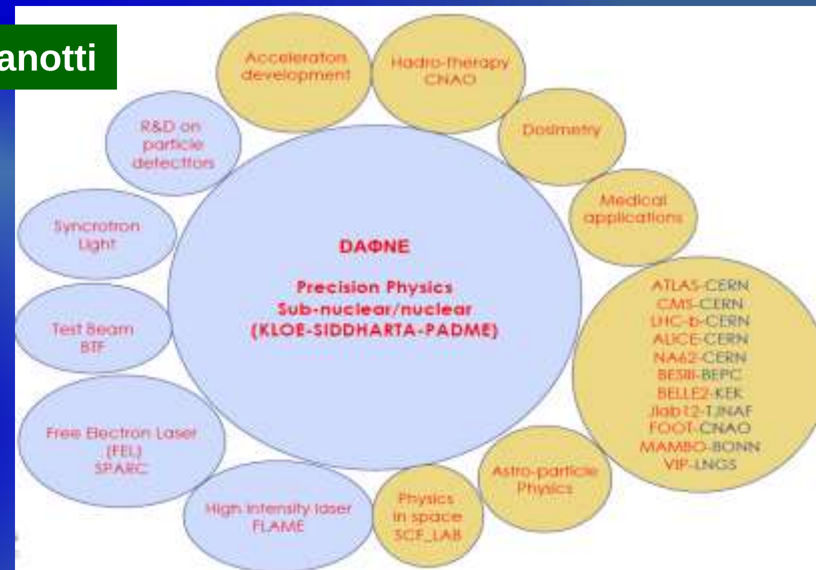


4th generation low-emittance synchrotron facility @ 3 GeV – construction start next year

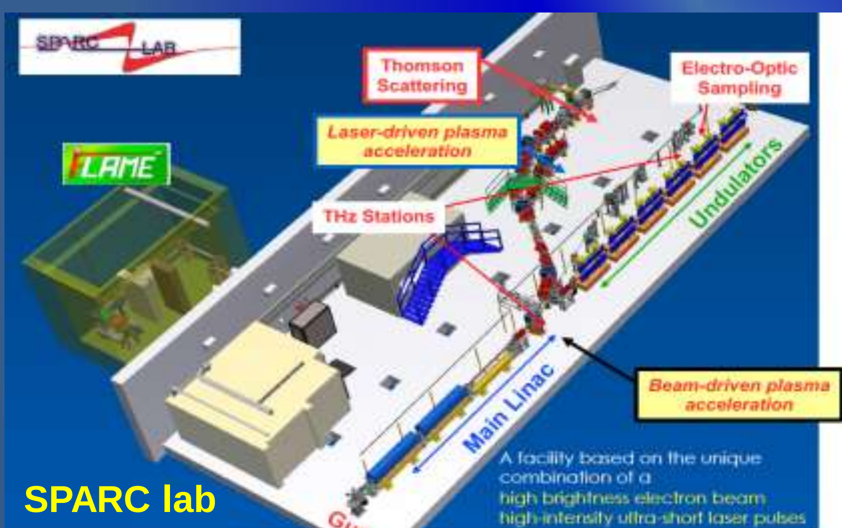
LNF Frascati Laboratory Research Activities

Tradition: Hadron Physics (2001 – today DAΦNE e^+e^- collider: c.m. energy 1.120 GeV) → Implemented Crab-Waist collision scheme

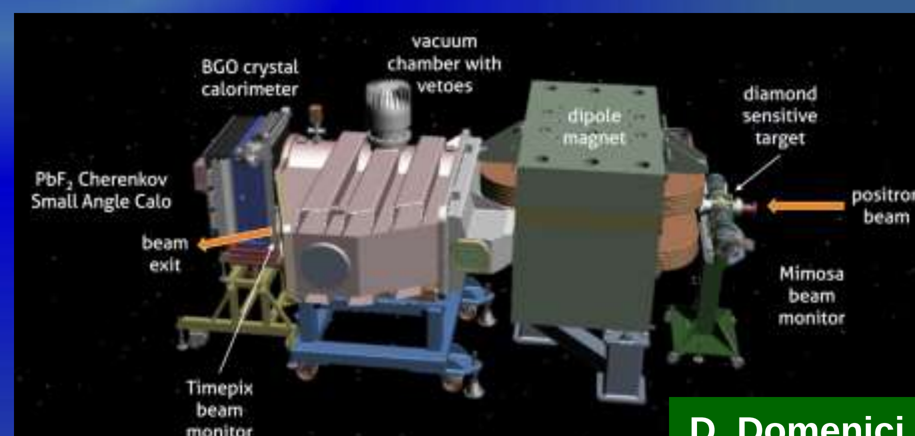
P. Gianotti



Large involvement in accelerator & detector activities: today, LNF is exploiting new possibillities (e.g. use of plasmas in RF acc. fac.)

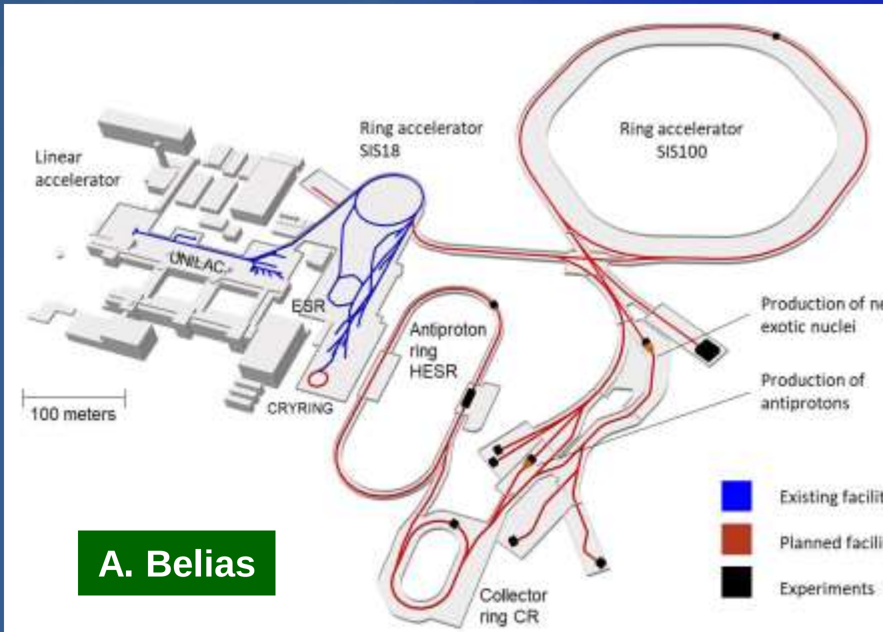


PADME Experiment: searches for Dark Photon

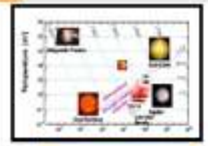


D. Domenici

FAIR: Facility for Antiproton and Ion Research

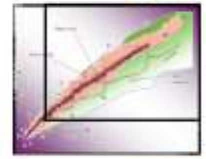


The FAIR science: four pillars

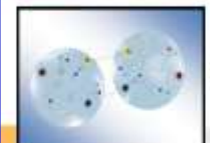


atomic physics, biophysics, plasma physics, material research, other applications — **APPA**

nuclear- and quark-matter — **CBM**



nuclear structure and nuclear astrophysics — **NuSTAR**



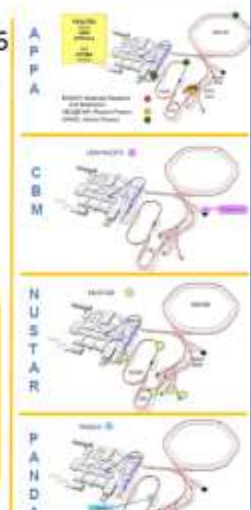
hadron structure and dynamics — **PANDA**

Status of FAIR Project: Civil Construction

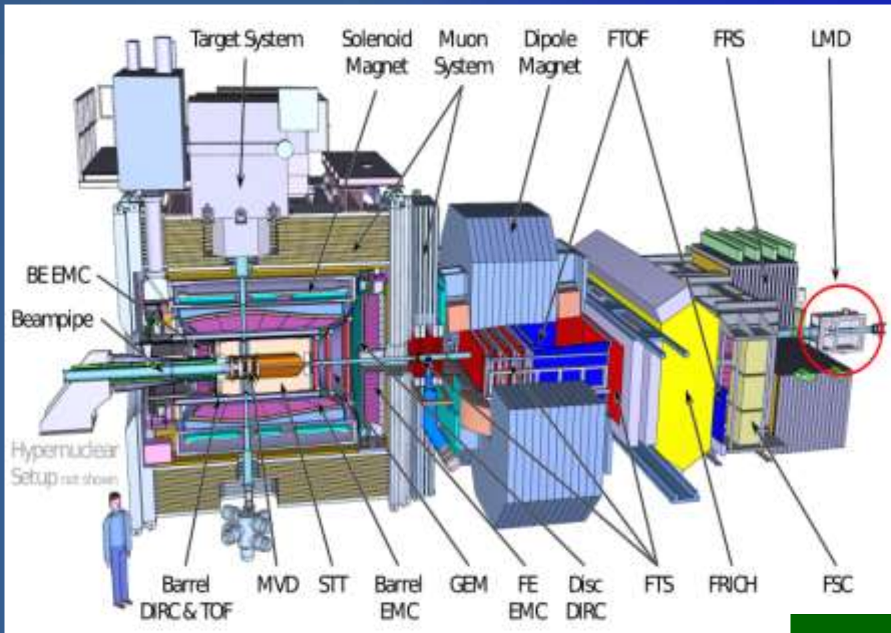
Progress since ground breaking event 4-July-2017

Schedule for FAIR Science

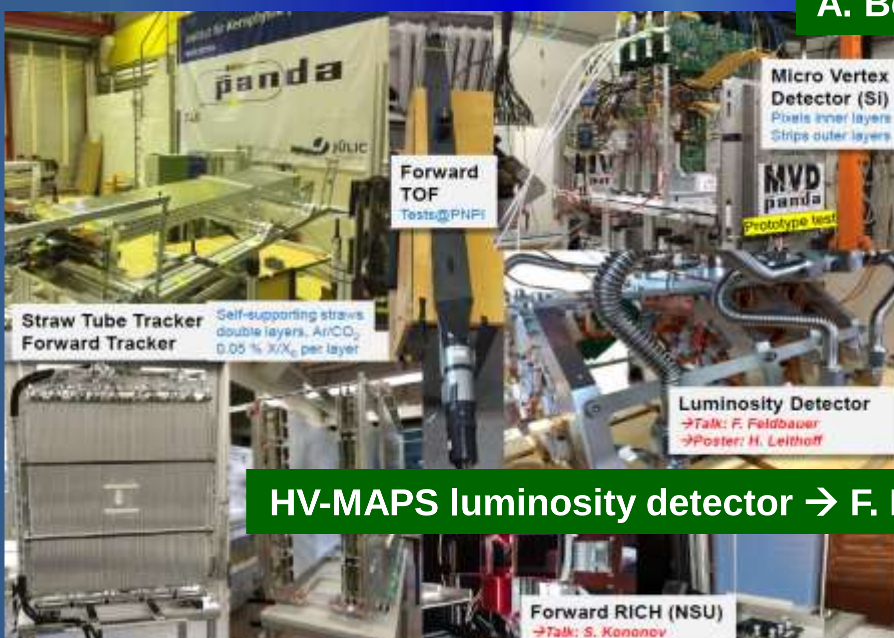
- Working towards the completion of FAIR by 2025/26
- Major thrust is on construction of FAIR accelerators and experiments.
- At the same time *staged approach to FAIR science and progressive commissioning of accelerators and detectors*:
  - *FAIR phase 0 : start in 2018/2019*
  - FAIR day 1 configurations/ phase 1 experiments with FAIR accelerators progressively approaching design parameters → 2024/25 ...
  - Full FAIR operation 2025/26+



Antiproton Facility PANDA @FAIR: Detector Challenges



A. Belias

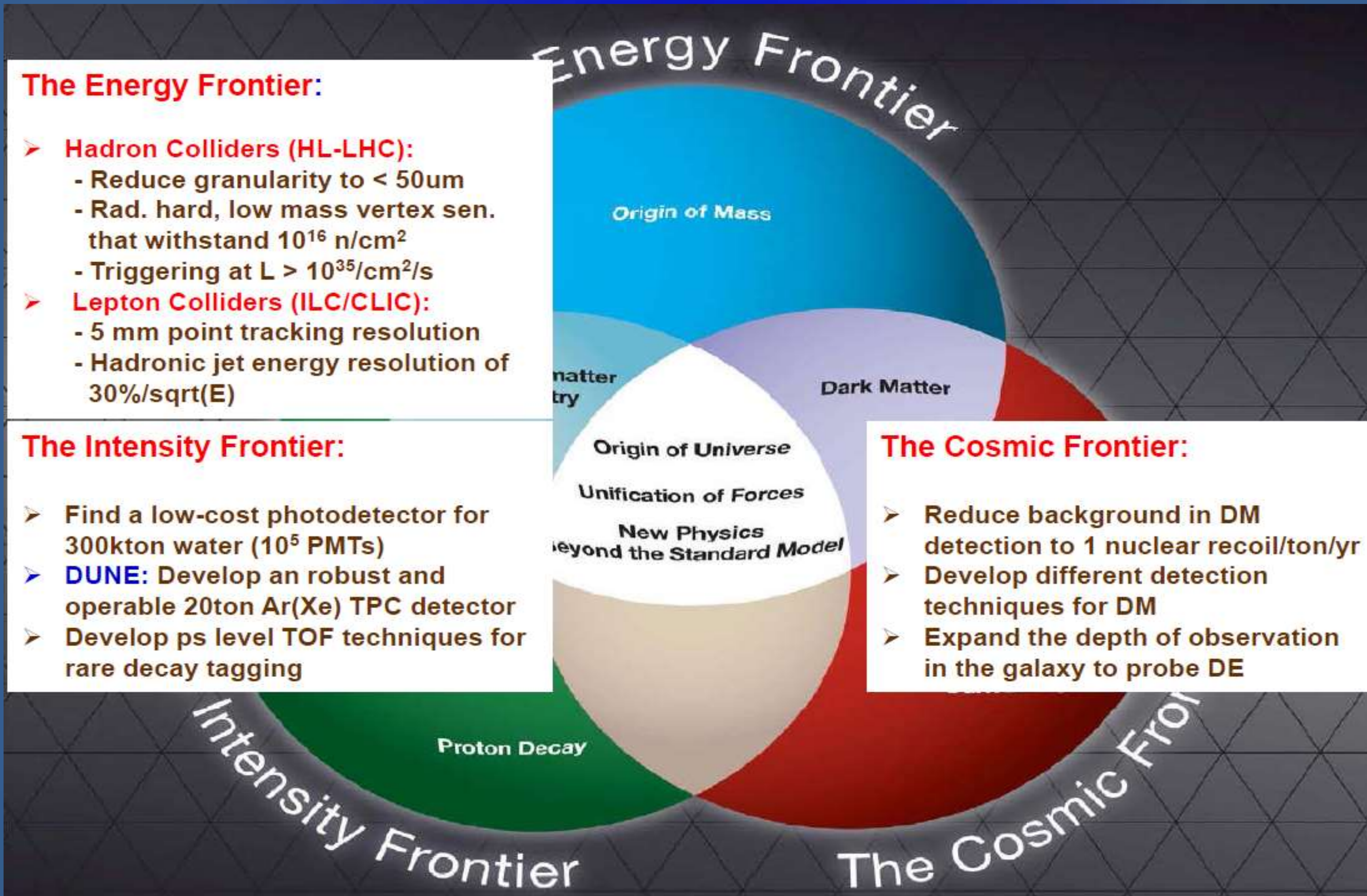


HV-MAPS luminosity detector → F. Feldbauer

E. Pyata

Cutting Edge Science Relies on Cutting Edge Instrumentation

Detectors / Instrumentation for Energy Frontier are (often) driving the progress



The Energy Frontier:

- Hadron Colliders (HL-LHC):
  - Reduce granularity to < 50um
  - Rad. hard, low mass vertex sen. that withstand 10^{16} n/cm^2
  - Triggering at L > 10^{35}/cm^2/s
- Lepton Colliders (ILC/CLIC):
  - 5 mm point tracking resolution
  - Hadronic jet energy resolution of 30%/sqrt(E)

The Intensity Frontier:

- Find a low-cost photodetector for 300kton water (10^5 PMTs)
- DUNE: Develop an robust and operable 20ton Ar(Xe) TPC detector
- Develop ps level TOF techniques for rare decay tagging

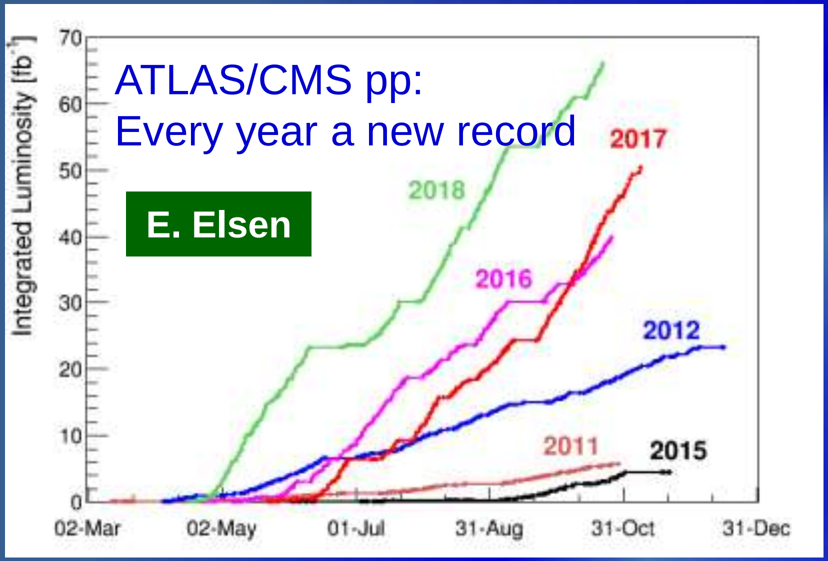
The Cosmic Frontier:

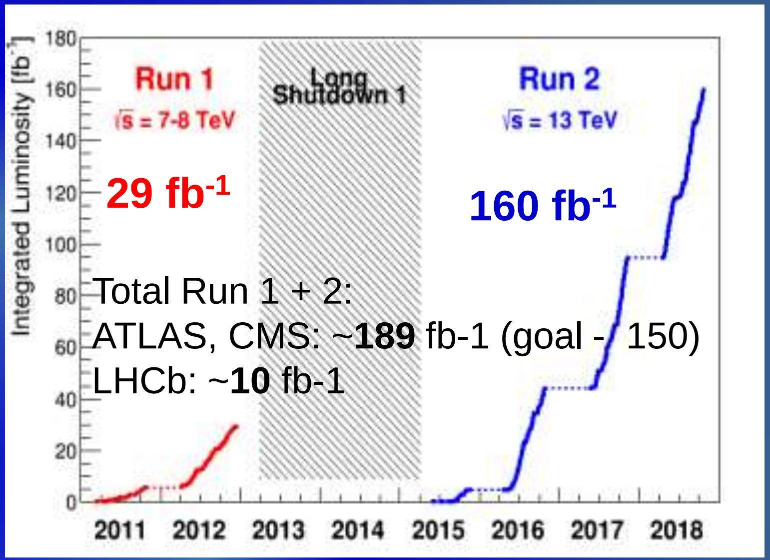
- Reduce background in DM detection to 1 nuclear recoil/ton/yr
- Develop different detection techniques for DM
- Expand the depth of observation in the galaxy to probe DE

What will be the role of quantum sensors in Particle Physics?

LHC Accelerator Complex: Glorious Run 2

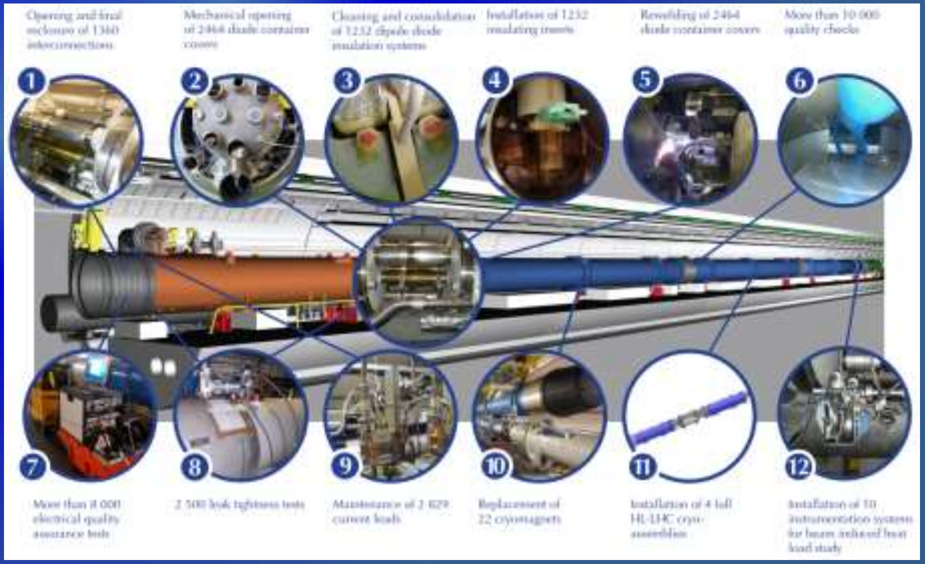
Experiments enjoying a large data sample of Runs 1 and 2:





- **LHC peak luminosity: ~2 x 10^{34} cm^{-2} s^{-1} (2 x nominal): thanks mainly to brightness of beams from injectors and β* ≤ 30 cm**
- **Fraction of time in physics: ~ 50%**
- **Integrated luminosity in 2018:**
  ~ 66 fb^{-1} ATLAS, CMS (goal was 60 fb-1)
  ~ 2.5 fb^{-1} LHCb (goal was 2 fb-1)
  ~ 27 pb^{-1} ALICE

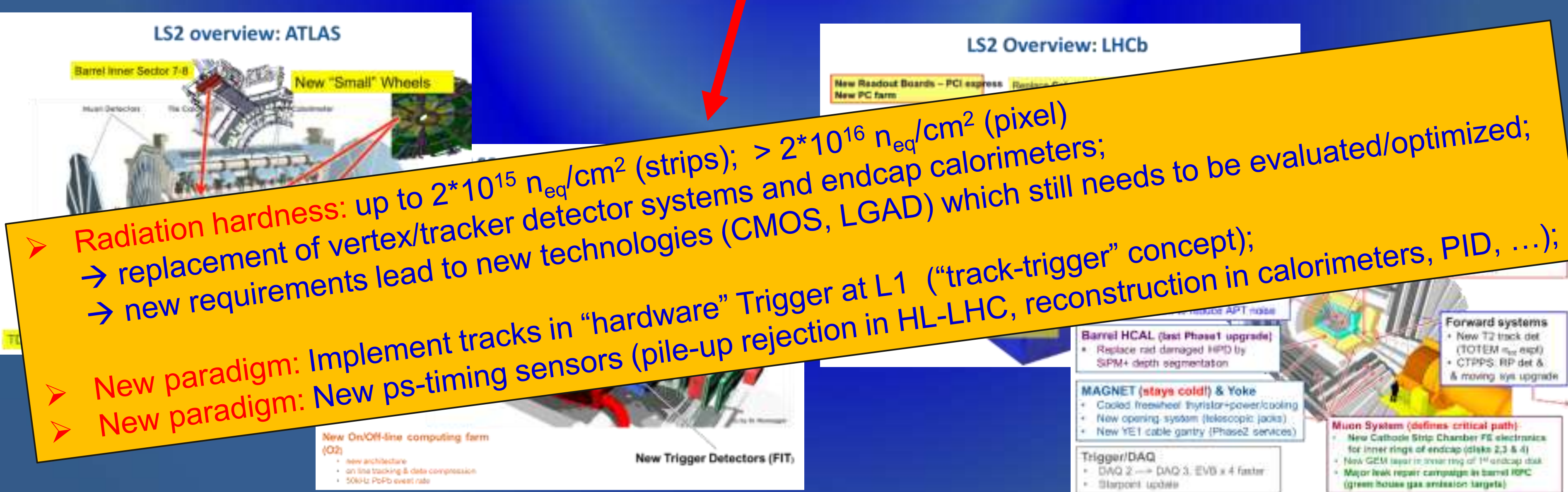
LHC Long Shutdown 2 activities:



LHC Run 2 is over, … welcome to LS 2
Revised Schedule for Run 3 and HL-LHC

- LS2 extended by 2 months (injectors and fixed target start in 2020)
- Run 3 extended by 1 year → LS3 begin in 2025

E. Elsen



- Radiation hardness: up to $2 \cdot 10^{15}$ n_{eq}/cm^2 (strips); > $2 \cdot 10^{16}$ n_{eq}/cm^2 (pixel)
  → replacement of vertex/tracker detector systems and endcap calorimeters;
  → new requirements lead to new technologies (CMOS, LGAD) which still needs to be evaluated/optimized;
- New paradigm: Implement tracks in "hardware" Trigger at L1 ("track-trigger" concept);
- New paradigm: New ps-timing sensors (pile-up rejection in HL-LHC, reconstruction in calorimeters, PID, …);

Worldwide LHC Computing Grid (WLCG) Collaboration

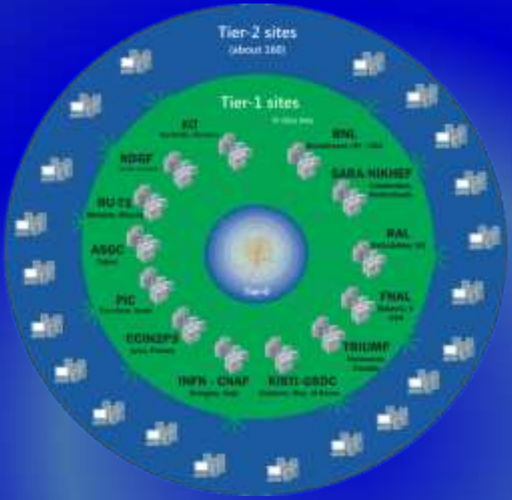
Initiated in 2002, an International collaboration was launched to distribute/analyse LHC data

~170 sites, 42 countries **> 2 million jobs/day** **10-100 Gb links**

Tier-0: data recording, reconstruction/ distribution

Tier-1: permanent storage, re-processing, analysis

Tier-2: Simulation, end-user analysis



Computing power in 2020

- ✓ **CPUs: 6.500.000 of today's fastest cores (6.5 million)**
- ✓ **Storage: Disk: 575 PB**
- ✓ **Tape: 800 PB**

Challenges on HL-LHC computing:

- ✓ **HEP computing much more capacity is needed**
- ✓ **New computing models and more efficient software have to be developed**

- Additional resources are needed – Cloud Computing, High-Performance Computing
  - Cloud resources are much more competitive in terms of cost than in the past
  - Increasing usage of HPC resources in the mid to long term future; usage of best technologies available
  - An important resource as supplement to the existing resources

HELIX NEBULA THESCIENCECLOUD

- Modern tools and methods are used - Big-Data, Machine Learning - Deep Learning
  - Used in many ranges of application in HEP (monitoring, analysis optimization, particles classification)

N. Krammer

LHC Computing - Towards a Change of Paradigm …

Machine Learning in HEP has a long history:

1992:


SÉMINAIRES TECHNIQUES DU DAPNIA

Le Mardi 19 Mai 1992 à 11 heures

RÉSEAUX DE NEURONES
EN PHYSIQUE
DES HAUTES ÉNERGIES

par Jean-Louis FAURE

du

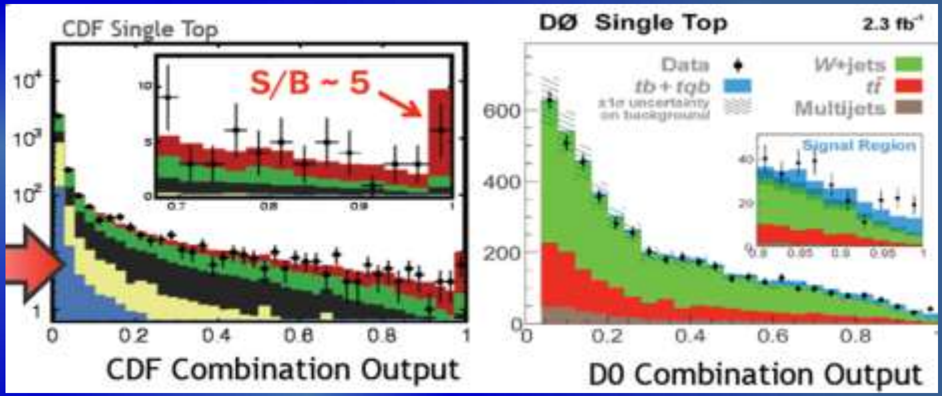
Service de Physique des Particules

DSM - DAPNIA - Saclay

Courtesy of J.-L. Faure

Discovery of single top quark at FNAL (all before the LHC)

2009:



Computing infrastructure so far has been largely based exclusively on X86 architecture using CPUs. GPUs are gaining a lot of popularity as co-processors due to the success of Machine Learning and „Artificial Intelligence“.

- ✓ ALICE will employ a GPU based Online/Offline system (O2)
- ✓ CMS is porting part of their trigger software to run on GPU processors
- ✓ LHCb is exploring GPUs for their online data reduction
- ✓ ATLAS is developing algorithms to run on GPUs

E. Elsen

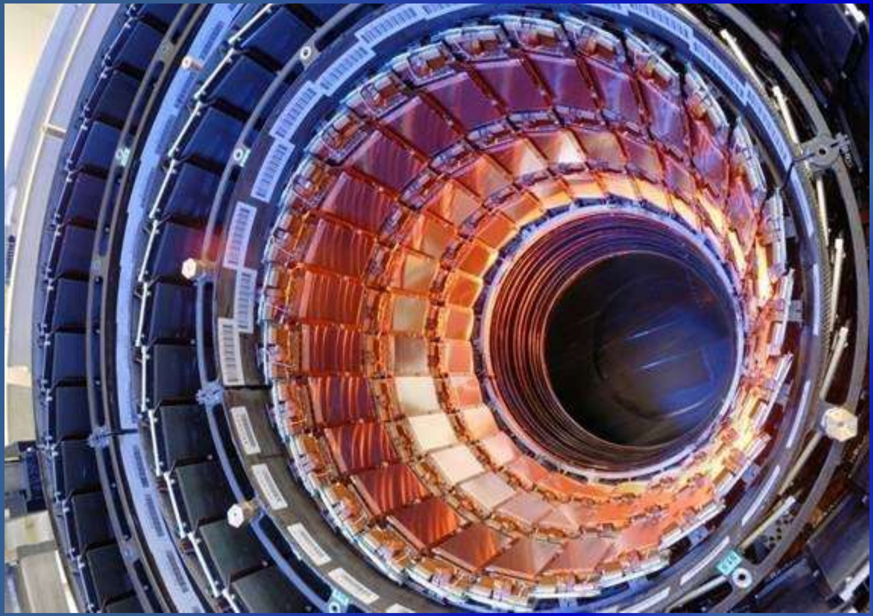
High Performance Computing often employ GPU architectures to achieve record breaking results (towards exa-scale)

→ this will requite a fundamental re-write/optimization of the LHC software

State-of-the-Art in Tracking and Vertex Detectors

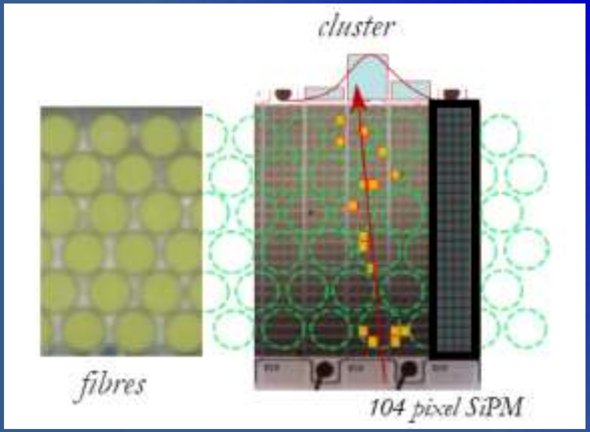
3 major technologies of Tracking Detectors:

Silicon Microstrip/Pixel Detectors:



Gaseous (MWPC, TPC, RPC, MPGDs):

Fiber Trackers: e.g. LHCb Upgrade: 6 layers of scintillating fibers 250µm readout by SiPM array



12 layers covering a sensitive area of 6 x 4.8 m2 result to the largest high-precision scintillating fiber tracker

A. Massafferri

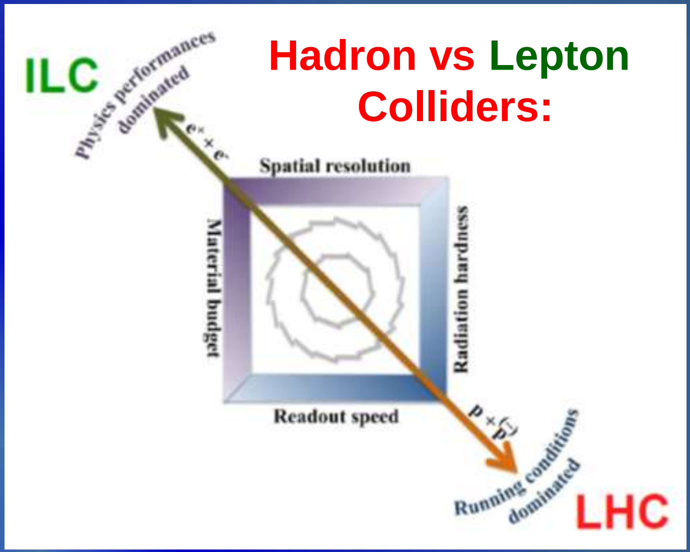
Si-Vertex and Tracking Detectors in HEP: State-of-the-Art

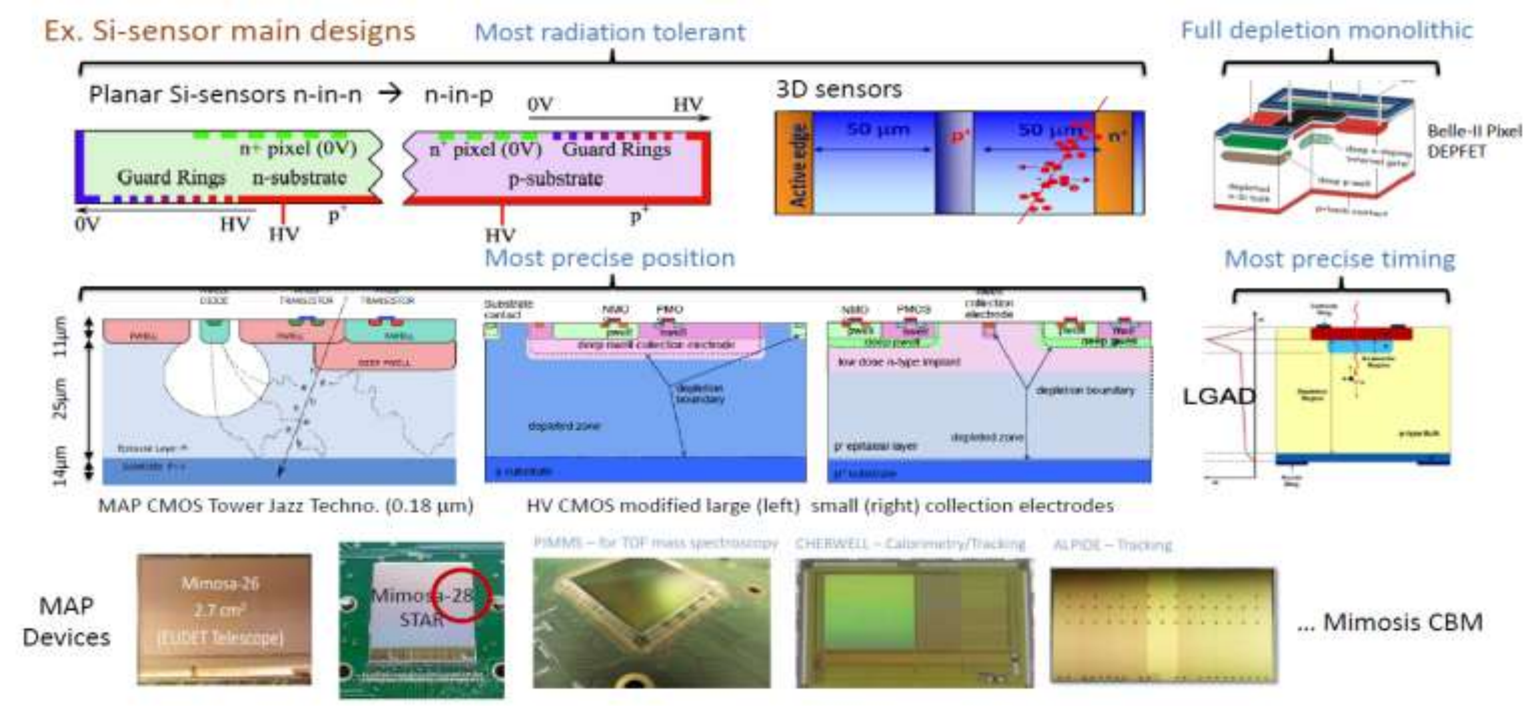
Low mass, pixelated, radiation hard vertex detectors are needed for the LHC ILC, CLIC, FCC, B-factories, ….:

Major challenges:
granularity, speed, material budget, radiation resistance

Sensor-type options (can be thinned to become flexible):

- ✓ Hybrid pixel detectors (planar and 3D-sensors – most rad-hard technology to-date)
- ✓ CMOS technologies (MAPS, HV/HR-CMOS)



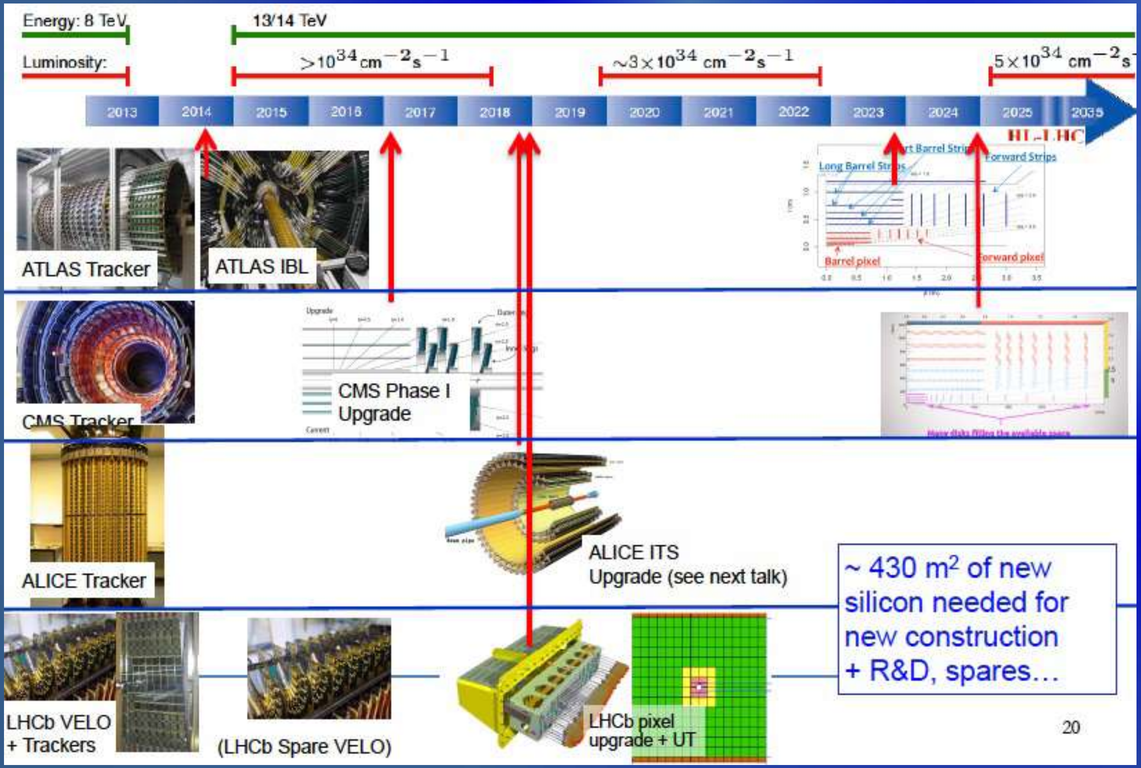


Si-Vertex and Tracking Detectors @ LHC (Hadron Colliders)

All LHC experiments are based on hybrid pixels → admirable achievement in complex engineering / integration

Ongoing R&D effort for HL-LHC (Phase II): Fast readout / Radiation hardness needed

- ✓ Readout in 65 nm technology (RD53 – ATLAS and CMS FEE ASICs)
- ✓ Small pixel sizes 50 μm x 50 μm
- ✓ Output bandwidth 8 Gbit/s

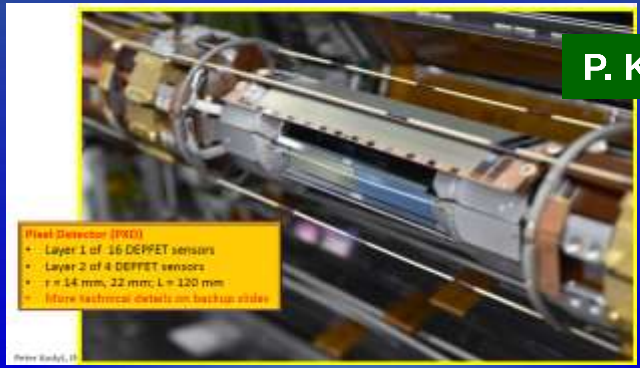


What's Next in HEP (some observations):

- ✓ Going to smaller node sizes does not necessarily guarantee radiation hardness improvement (e.g. RD53)
- ✓ The impact of "digital" is still very small in HEP, replace "quantity" of data with "quality" of data
- ✓ More exotic technologies (TSVs, wafer stacking, adv. packaging...) may become available also for low-volume, but history teaches one should bet on mainstream opportunities

Pixel and Si-Strip Detectors @ INSTR2020

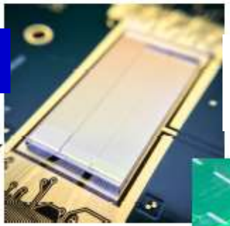
Belle II Pixel (PXD-DEPFET) and Silicon Strip Detector (SVD)



P. Kodys

Silicon Pixel Detector R&D for CLIC:

- **monolithic CMOS**
  - ATLASpix_simple
    180nm HV CMOS process
    with a large collection electrode
  - CLICTD
    180nm CMOS imaging process
    with small collection electrode



HV-MAPS (designed for ATLAS-ITK)

HR-CMOS

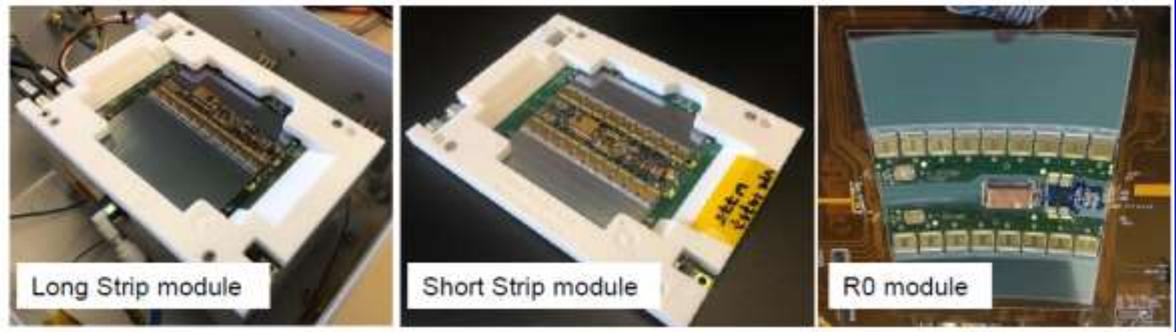
J. Kroeger

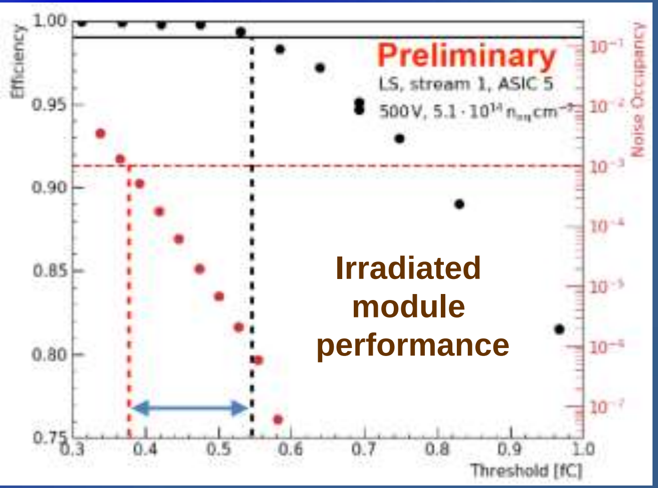
Requirements (CLIC Tracking Detector)	ATLASpix	CLICTD
• spatial resolution		
→ in y: < 7 µm (RMS)	~11.3 µm	~6 µm
→ in x: 1-10 mm (pixel size)	130 µm	37.5 µm
• timing resolution ~5 ns	6.8 ns at ~480e thres	~6.3 ns (not yet fully optimiz
• material budget < 200 µm	62-100 µm (50 µm possible)	300 µm (40 µm to be tested)
• efficiency > 99.7-99.9%	> 99.7%	> 99.8%

ATLAS Strip Detector System for HL-LHC:

A. Rodriguez

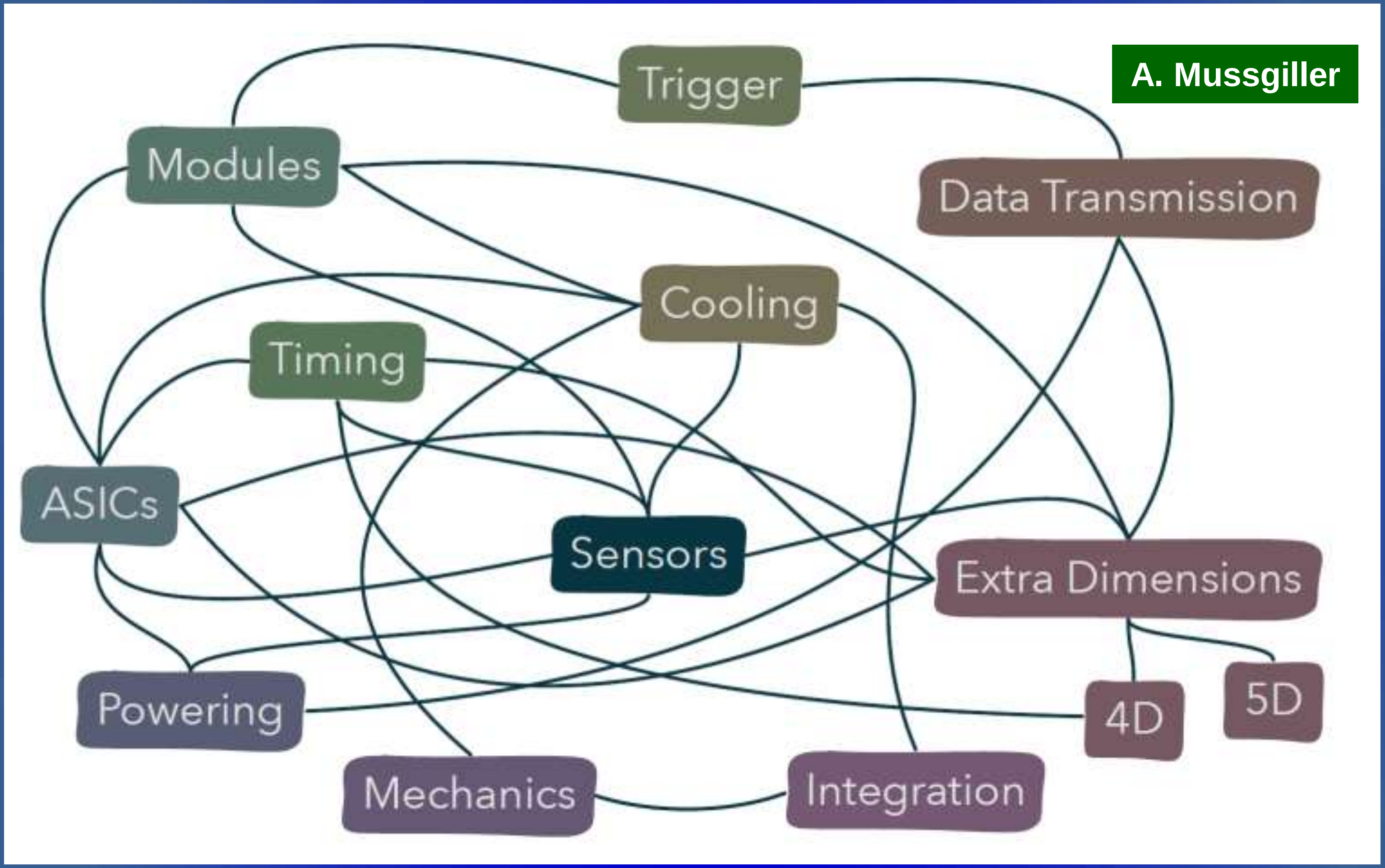
17,888 strip modules required (barrel + end-cap)





Irradiated module performance

More than ASICS and sensors, we have to take of all aspects – mechanics, Integration and cooling, etc …

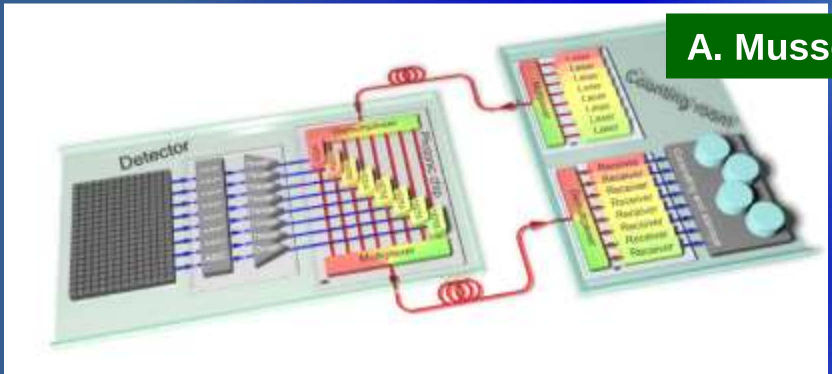


Keeping the radiation budget under control needs efforts in all areas below:

- **Advanced powering schemes**
- **Advanced materials and integration**
- **Heat management (cooling) integrated in the detector design**

Optical Links, Powering Schemes, Mechanics and Cooling

- ✓ Current link implementation based on vertical cavity surface emitting lasers (VCSEL)
- ✓ Higher bandwidth requirements could be addressed by silicon photonics and Wavelength Division Multiplexing (WDM)

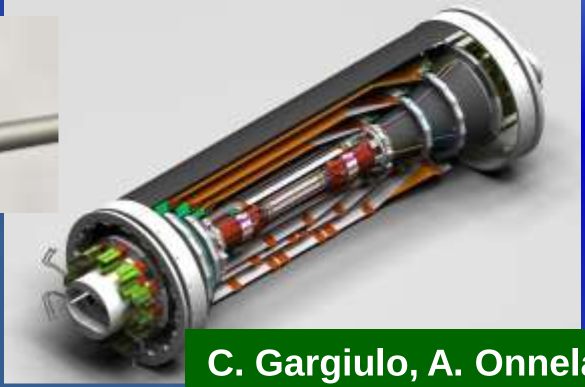


A. Mussgiller

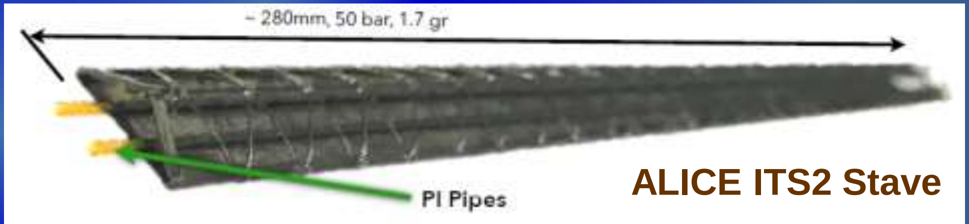
- ➢ DC-DC powering widely accepted in HEP
- ➢ Serial powering will be used in Phase-2 pixel detectors

Experiment	Sub-detector	What	How	Where
CMS	Outer Tracker	Strip modules, LpGBT, VTRx+	DC-DC	Front-end
	Phase-1 pixel	Pixel modules	DC-DC	Patch panel
	Phase-2 pixel	LpGBT, VTRx+	DC-DC	Patch panel
		Pixel modules	Serial	
	Endcap calorimeter	Silicon modules, LpGBT, VTRx+	DC-DC	Patch panel or front-end
	Barrel calorimeter	Crystal ADC	DC-DC	Front-end
	Muon system (GEM)	Chambers	DC-DC	Front-end
	Timing detector	Readout, LpGBt, VTRx+	DC-DC	Front-end
ATLAS	Strips	Strip modules, LpGBT, VTRx	DC-DC	Front-end
	Phase-2 pixel	LpGBT, VTRx+	DC-DC	Patch panel
		Pixel modules	Serial	
	Tile calorimeter	Electronics	DC-DC	Patch panel
	Liquid argon calorimeter	Electronics	DC-DC	Front-end
	Muon micromegas	GBTx, VTRx	DC-DC	Front-end
LHCb	Velo	Pixel modules, GBTx	DC-DC	Patch panel
	Fiber tracker	Fiber modules, GBTx, FPGA	DC-DC	Front-end
ALICE	Pixels	Pixel modules	DC-DC	Front-end
Belle 2	SVD	Silicon modules	DC-DC	Patch panel

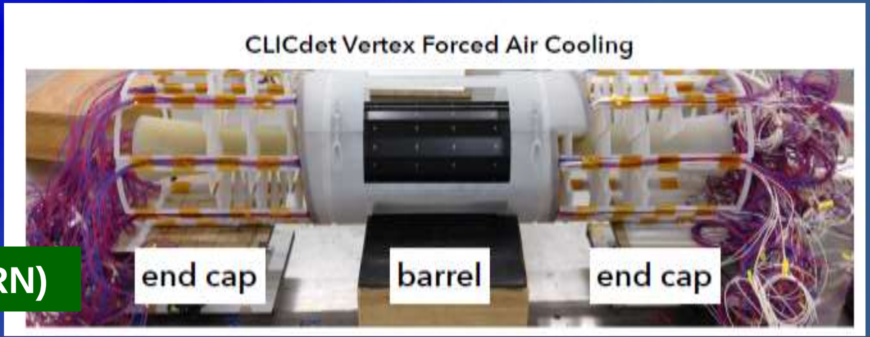
Belle II PXD Support and Cooling Block (SCB) printed in stainless steel potential of additive manufacturing has to be exploited also inside trackers



C. Gargiulo, A. Onnela (CERN)



ALICE ITS2 Stave



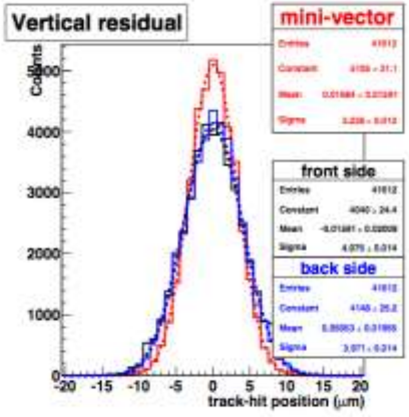
Are We on the Verge of the CMOS Revolution in HEP ?

- CMOS image pixel sensor invented in the early ‘90
- CMOS MAPS for charged particle tracking was initiated for ILC in 1998 (many deployed by nuclear physics community these days)

- MAPS Radiation tolerance: ~10^{13} neq/cm2
- Partial depletion extends the operability of MAPS to ~10^{15} neq/cm2

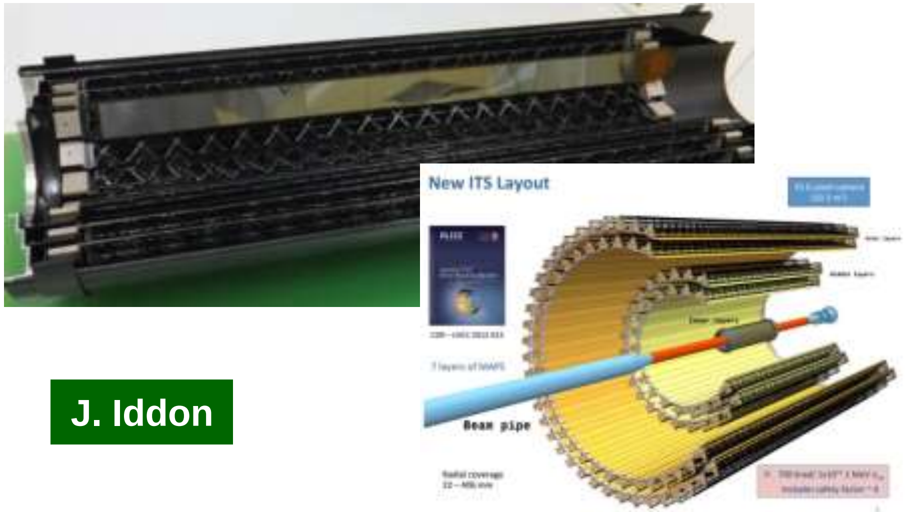
MIMOSA sensors equipping EUDET BT :

~ 3μm track resolution achieved:



ALICE ITS Upgrade @ LHC

Ultra light system to improve IP resolution by ≃ 3
- Installation in LS2 2019-2020
- 7 layers of MAPS ≃ 10 m^2 with 12.5 Gpix
- e.g. 28x28 μm2 & 0.3% X0/layer from 20-40 mm



J. Iddon

Also proposed for CBM MVD @ FAIR

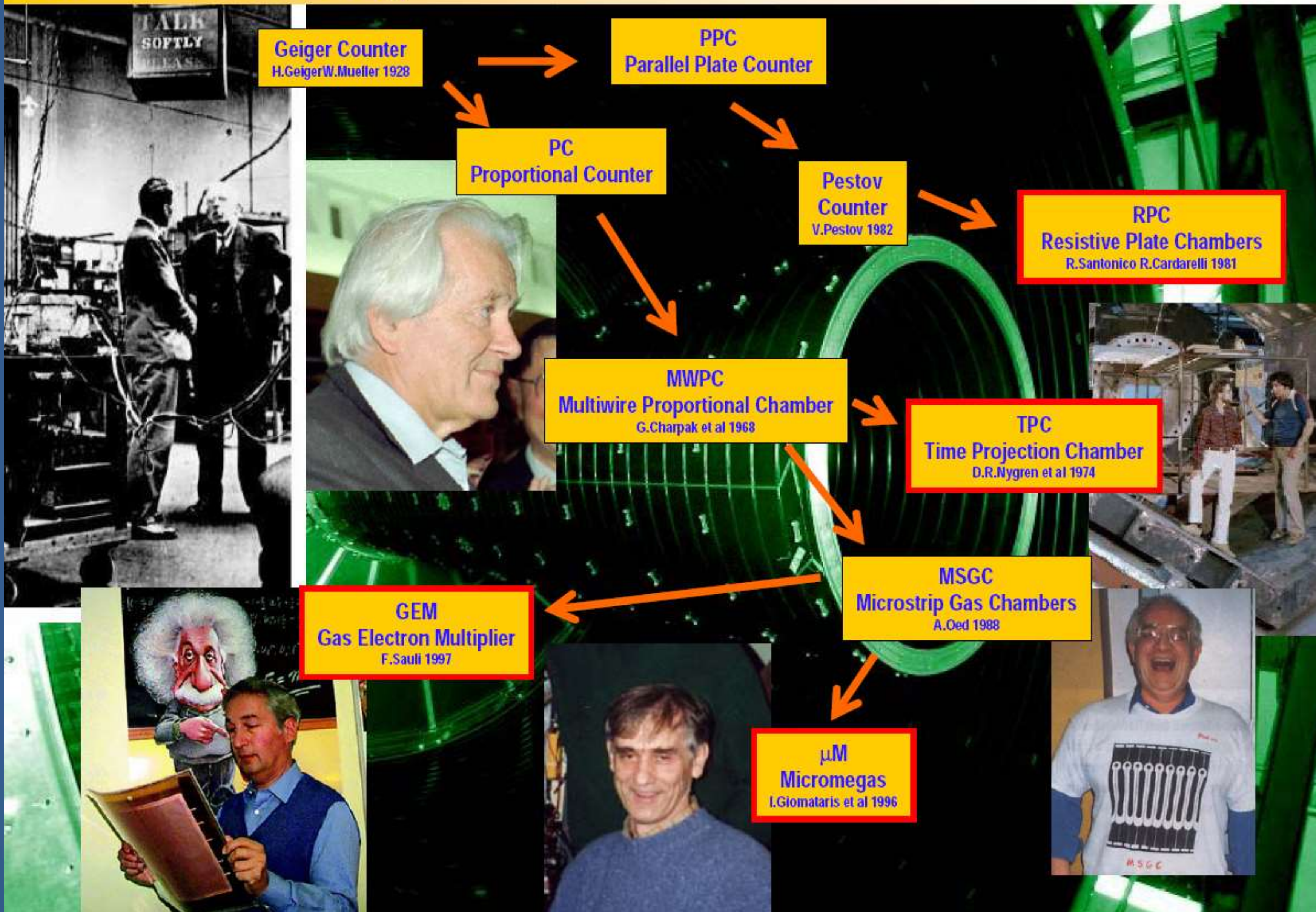
STAR HEAVY Flavour Tracker @ RHIC(2014):

Ladder with 10 MAPS sensors (~2x2 cm each) mounted on carbon fiber sectors: 356M pixels on ~0.16 m^2(Si);
50 um thin sensors;
20 to 90 kRad/year

Recent advances:

- Moving towards smaller feature size (180 nm, Tower Jazz)
- Higher-resistivity substrates (few kOhm cm) → HR-CMOS
- Promising timing performance (double-sided CMOS ladders → mini-vector concept)

Gas Detector History



The Evolution of Drift Chambers at e+e- Colliders

past

Collider	Experiment	Tracker
SPEAR	MARK2	Drift Chamber
	MARK3	Drift Chamber
DORIS	PLUTO	MWPC
	ARGUS	Drift Chamber
CESR	CLEO1,2,3	Drift Chamber
VEPP2/4M	CMD-2	Drift Chamber
	KEDR	Drift Chamber
	NSD	Drift Chamber
PETRA	CELLO	MWPC + Drift Ch.
	JADE	Drift Chamber
	PLUTO	MWPC
	MARK-J	TEC + Drift Ch.
	TASSO	MWPC + Drift Ch.
TRISTAN	AMY	Drift Chamber
	VENUS	Drift Chamber
	TOPAZ	TPC

Collider	Experiment	Tracker
PEP	MARK2	Drift Chamber
	PEP-4	TPC
	MAC	Drift Chamber
	HRS	Drift Chamber
	DELCO	MWPC
BEPC	BES1,2	Drift Chamber
LEP	ALEPH	TPC
	DELPHI	TPC
	L3	Si + TEC
	OPAL	Drift Chamber
SLC	MARK2	Drift Chamber
	SLD	Drift Chamber
DAPHNE	KLOE	Drift Chamber
PEP2	BaBar	Drift Chamber
KEKB	Belle	Drift Chamber

present

Collider	Experiment	Tracker
VEPP2000	CMD-3	Drift Chamber
VEPP4	KEDR	Drift Chamber
BEPC2	BES3	Drift Chamber
S.KEKB	Belle2	Drift Chamber

future

Collider	Experiment	Tracker	
ILC	ILD	TPC	
	SiD	Si	
CLIC	CLIC	Si	
FCC-ee	CLD	Si	
	IDEA	Drift Chamber	
CEPC	Baseline	TPC	Si
	IDEA	Drift Chamber	
SCTF	BINP	Drift Chamber	
STCF	HIEPA	Drift Chamber	

Lesson #1 - from "open" to "closed" cell

- closed cells limit the very long tails in the drift time distribution
- closed cells make the time to distance relations less dependent from the trac
- square
- small dr

... but

- portions envelop
- small ra use of t contribu
- some p

Lesson #3 – small cells and He gas

- He radiation length 50× longer than Ar
- slower drift velocity implies smaller Lorenz angle for a given B-field
- He has a smaller cross section for low energy photons than Ar
- small size cells limit the electron diffusion contribution to spatial resolution
- small size cells provide high granularity (improving occupancy) and allow for a larger number of hits per track, improving spatial resolution

... but

- portions of active volume not sampled between the cylindrical envelope of axial wires and the hyperboloid envelope of stereo wires
- accumulation of trapped electrons and ions in a region of very low field
- longitudinal gain variation at boundaries between axial and stereo layers
- spatial resolution dominated by ionization statistics fo
- adding more quencher to compensate, mitigates the

Lesson #4 – full stereo configuration

- no gaps between axial and stereo layers which may trap ions and electrons in regions of very low electric field
- con
- larg
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- two

... but

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- con

Lesson #5 – summary

- the configuration offering the best performance in terms of **momentum resolution** is one with small, single sense wire closed cells, arranged in contiguous layers of opposite sign stereo angles, obtained with constant stereo angle transverse projection
- the gas mixture is based on helium with a small amount of quencher (90% He / 10% iC_4H_{10}, KLOE gas) which, besides low multiple scattering contribution, allows for the exploitation of the cluster timing technique, for improved spatial resolution, and of the cluster counting technique, for excellent particle identification
- suggested wire material is Ag coated Al, but lighter materials are under scrutiny (like metal coated carbon monofilaments)

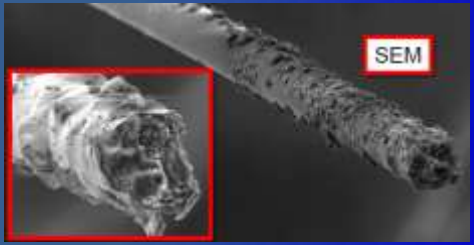
F. Grancagnolo

Drift / Multi-Wire Chambers @ INSTR2020

Drift Chamber of the MEGII Experiment:

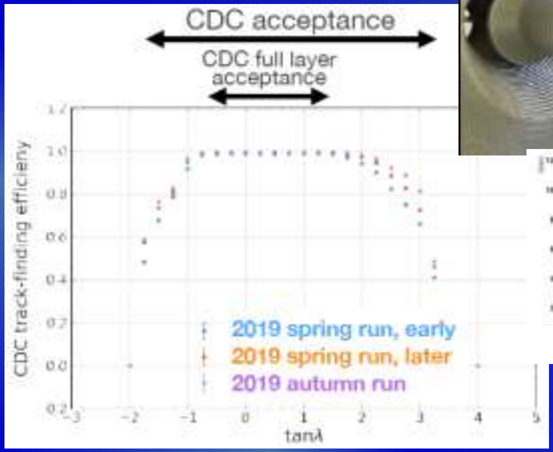
G. Tassielli

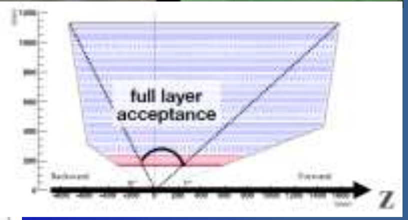
60 out of 1200 wire broken (corrosion issue)



Install chamber in 2020 for final commissioning / data taking

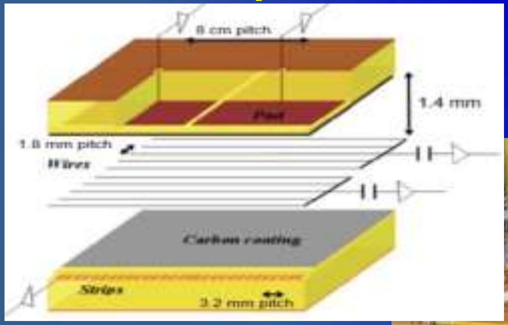
Belle II Central Drift Chamber:



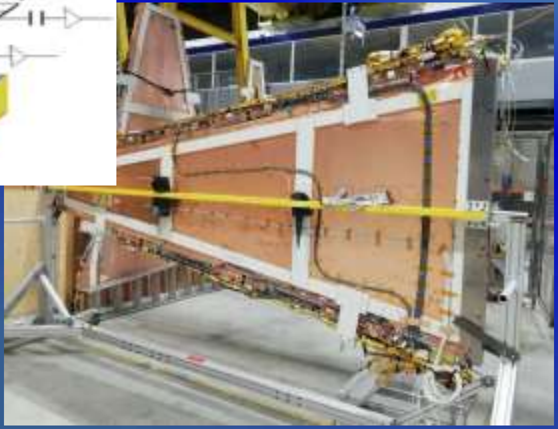


K. Nakagiri

Small-Strip Thin Gap Chambers for ATLAS Muon Spectrometer (NSW) Upgrade



D. Pudzha



Installation of a first NSW in ATLAS in autumn 2020

Novel Focal Plane Detector Concepts for the NSCL/FRIB S800 Spectrometer

M. Cortesi

Goal: development of new readout concept based on a Hybrid MPGD-stricture (MM +THGEM) to replace cathode-readout drift chamber

Some Detectors in Particle and Ion Physics using TPC

PEP4 (SLAC)

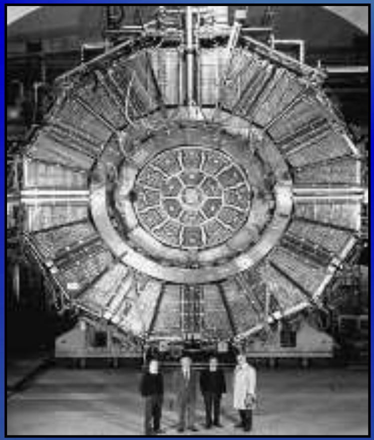
- ✓ Invented by David Nygren (Berkeley) in 1974
- ✓ Proposed as a central tracking device for the PEP-4 detector @SLAC 1976
- ➢ More (and even larger) were built, based on MPWC readout
- ➢ New generation of TPCs use MPGDs: e.g. T2K, ILD (ILC), ALICE TPC upgrade

PARAMETER / EXPERIMENT	PEP4	TRIUMF	TOPAZ	ALEPH	DELPHI	STAR	ALICE [1]
1. OPERATION	1982 / 1984	1982 / 1983	1987	1989	1989	2000	2009
INNER / OUTER RADIUS [m]	0.2 / 1.0	~0.15 / 0.50	0.38 / 1.1	0.35 / 1.8	0.35 / 1.4	0.5 / 2.0	0.85 / 2.5
MAX. DRIFTLENGTH (L/2) [m]	1	0.34	1.1	2.2	1.34	2.1	2.5
MAGNETIC FIELD [T]	0.4 / 1.325	0.9	1	1.5	1.23	0.25 / 0.5	0.5
GAS :	Ar / CH4	Ar / CH4	Ar / CH4	Ar / CH4	Ar / CH4	Ar / CH4	Ne /CO2/ N2
Mixture	80 / 20	80 / 20	90 / 10	91 / 9	80 / 20	90 / 10	90/ 10/ 5
Pressure [atm]	8.5	1	3.5	1	1	1	1
DRIFT FIELD [KV / cm / atm]	0.088	0.25	0.1	0.11	0.15	0.14	0.4
ELECTRON DRIFT VELOCITY [cm/μsec]	5	7	5.3	5	6.69	5.45	2.7
ωτ (see 2.2.1.3)	0.2 / 0.7	2	1.5	7	5	1.15 / 2.3	< 1
PADS: Size w•L [mm•mm]	7.5x7.5	(5.3-6.4)x19	(9-11)x12	6.2x30	~7x7	2.85x11.5	4x7.5
						6.2x19.5	6x10/15
Max. no. 3-D points	15 - straight	12	10 - linear	9+12 - circular	16 - circular	13+32 - straight	63+64+32
dE/dx: Max. no. samples/track	183	12	175	148+196	192	13+32	63+64+32
Sample size [mm mm]; w or p	4•8.5; wires	6.35; wires	4x3.5; wires	4 ; wires	4 ; wires	11.5 + 19.5pads	7.5+10+15; pads
GAS AMPLIFICATION	1000	50 000		3000-5000	5000	3000/1100	20 000
GAP a-p; a-c; c-gate [2]	4; 4; 8	6	4; 4; 8	4; 4; 6	4; 4; 6	2; 2; 6 / 4; 4 ; 6	2; 2; 3 / 3; 3; 3
PITCH a-a; cathode; gate	4; 1; 1		4; 1; 1	4; 1; 2	4; 1; 1	4; 1; 1/ 4; 1; 1	2.5; 2.5; 1.5
PULSE SAMPLING [MHz/ no. samples]	10/455, CCD	only 1 digitiz., ADC	10/ 455, CCD	11/ 512, FADC	14/ 300, FADC	9.6 / 400	5-10/500-1000, ADC
GATING [3]	≥1984 o.on tr.	≥1983 o.on tr.	o. on tr.	synchr. cl.w.o.tr	static	o.on tr.	o.on tr.
PADS, total number	15 000	7800	8200	41 000	20 000	137 000	560 000
PERFORMANCE :							
Δx_T [μm]-best / typ.	130-200	200/	185/230	170/200-450	180/190-280	300-600	spec 800-1100
Δx_L [μm]-best / typ.	160-260	3000	335/900	500-1700	900	500-1200	spec 1100-1250
2-TRACK SEPARATION [mm]: T / L	20		25	15	15	8 - 13 / 30	
$\delta p/p^2$ [GeV/c]$^{-1}$: TPC alone, high p	0.0065		0.015	0.0012	0.005	0.006	spec 0.005
dE/dx [%] SINGLE TRACKS/ IN JETS	2.7 / 4.0		4.4 /	4.8 /	5.7 / 7.4	7.4 / 7.6	spec 4.9 / 6.8
COMMENTS		ωτ in single PCs	chevron pads	circular pad rows	circular pad rows	No field wires	No field wires
		strong ExB effect				> 3000 tracks	≤ 20 000 tracks

1) Expected performance
2) a = anode, p = pads, c = cathode grid
3) o. on tr.: gate opens on trigger; cl.wo tr. : opens before collision and closes without trigger; static : closed for ions only (see text).

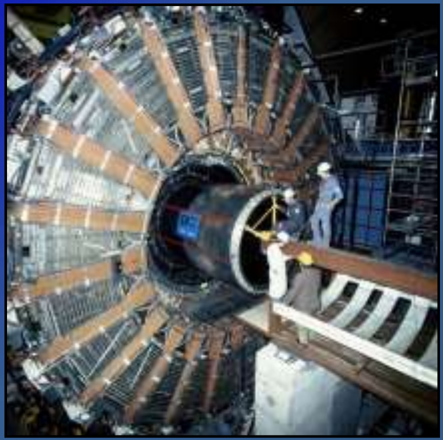
TOPAZ (KEK)

ALEPH (CERN)



STAR (LBL)

DELPHI (CERN)



Time Projection Chambers @ INSTR2020

CYGNUS-TPC project multi-ton gas target for DM as various TPC detectors distributed in underground labs. Combine:

- MPGD (GEM) + Optical readout
- Negative Ion TPC technique

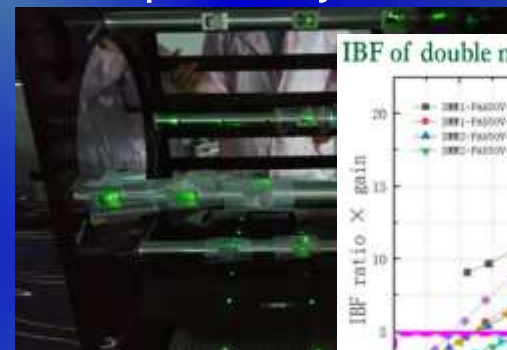
G. D'Imperio

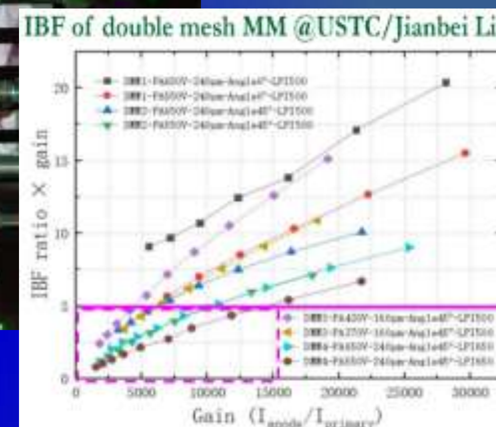
TPC with MPGD readout for CepC Collider:

Operate TPC at higher luminosity
→ No Gating options

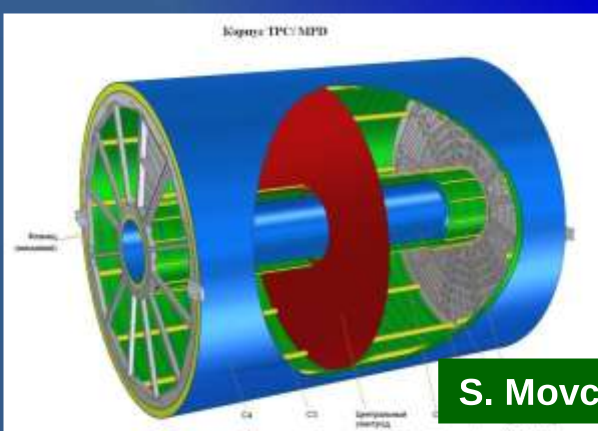
H. Qi

Option 1: Pad TPC based on GEM or MM
Option 2: Pixel TPC / GridPix
→ Complementarity with ILC TPC developments

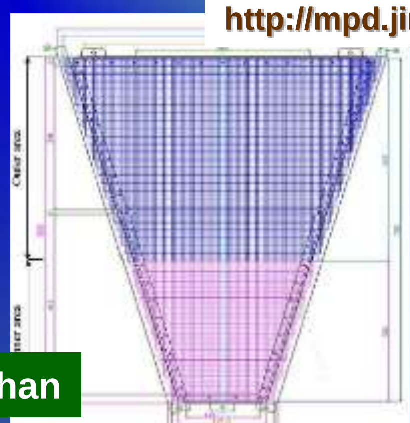




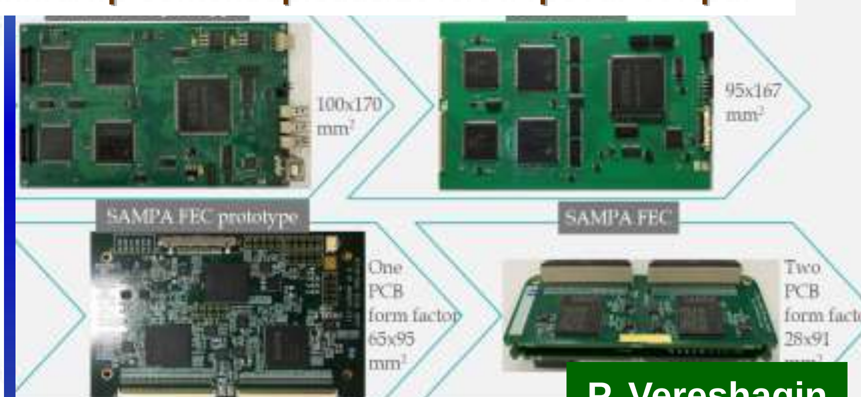
TPC with MWPC readout for the MPD @ NICA Project:



S. Movchan



http://mpd.jinr.ru/wp-content/uploads/2019/01/TpcTdr-v07.pdf



P. Vereshagin

Technology-oriented R&D COLLABORATIONS

- Originally: ”Cell” approach, oriented to select the different LHC experiment detector technologies - CERN DRDC program (90’s)
  → http://committees.web.cern.ch/Committees/obsolete/DRDC/Projects.html

- Today: Successful approach to streamline effort/resources, handle new techniques and common components to on-going detector engineering developments or production:

✓ RD42 – Diamond detectors
✓ RD50 – Silicon radiation hard devices
✓ RD51 – Micropattern gas detectors
✓ RD53 – Pixel readout chip for ATLAS and CMS

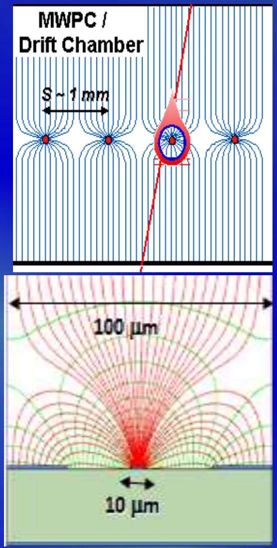
→ In general, large collaborations of interacting institutes
→ Good model, allows to consolidate resources – especially peope
→ CERN is central, but support needed from other labs and agencies

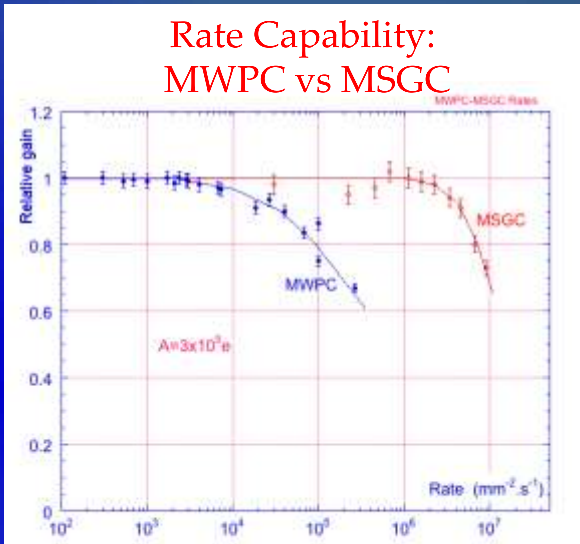
- Other R&D Programs - ILC and CLIC
  → CALICE high granularity electromagnetic and hadronic calorimeters (since 2001 for ILC)
  → Developments of Monolithic Active Pixels (MAPs) (since 1998 for ILC)

Complementary/commonalities of technical options in different program can be exploited
→ CALICE enabled high granularity calorimetry choice for CMS HL-LHC upgrade
→ MAPs enabled application in EUDET telescope, STAR (RICH), ALICE ITS, CBM vertex

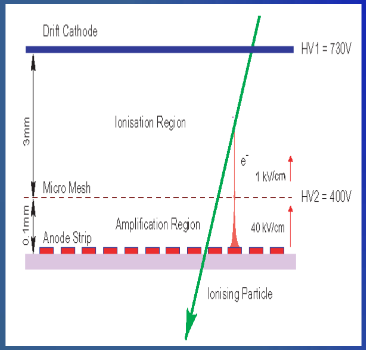
Micro-Pattern Gaseous Detector Technologies (MPGD)

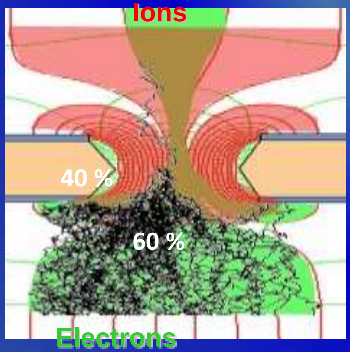
- Micromegas
- GEM
- Thick-GEM, Hole-Type and RETGEM
- MPDG with CMOS pixel ASICs ("InGrid")
- Micro-Pixel Chamber (mPIC)

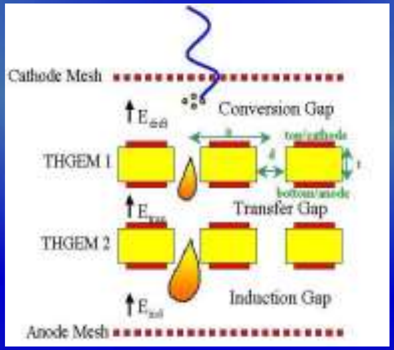


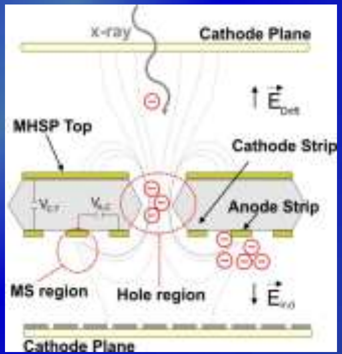


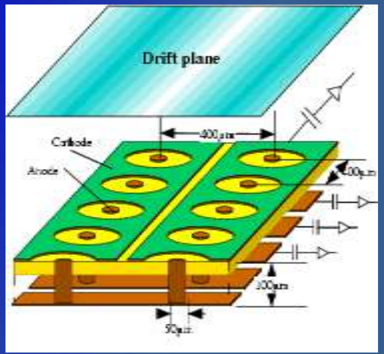
Micromegas　GEM　THGEM　MHSP　µPIC

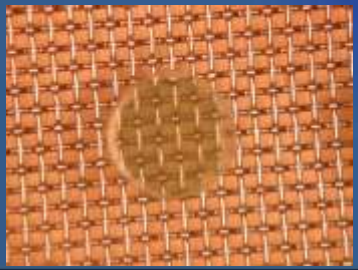


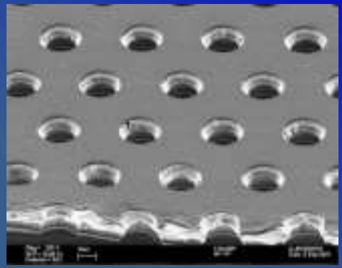


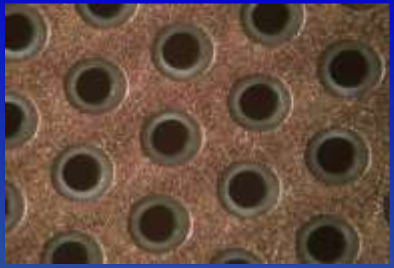


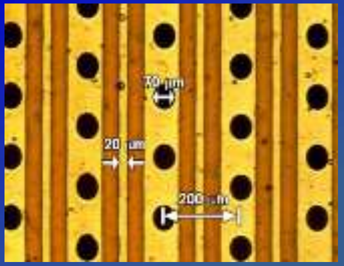


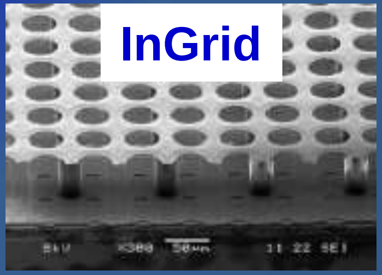












World-Wide RD51 Collaboration

Started in 2008: approved by the CERN RB for the third 5-years term (2018-2023)

Coordination through RD51 ("RD51 Model"): combination of generic and focused R&D with bottom-top decision processes, full sharing of "know-how", information, common infrastructures → can be exported to other detector domains

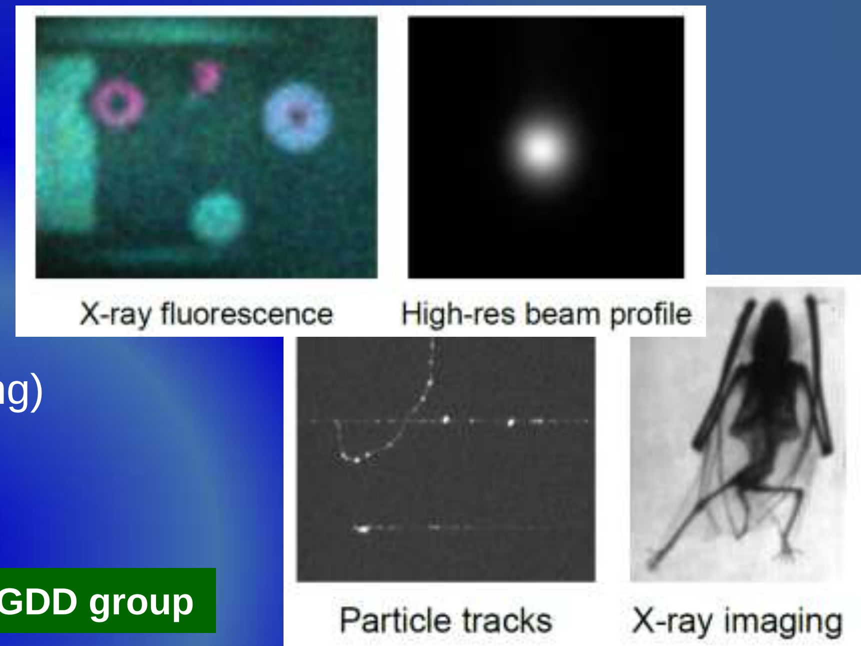
K. Gnanvo

RD51 proposal for extension beyond 2018: arXiv: 1806.09955

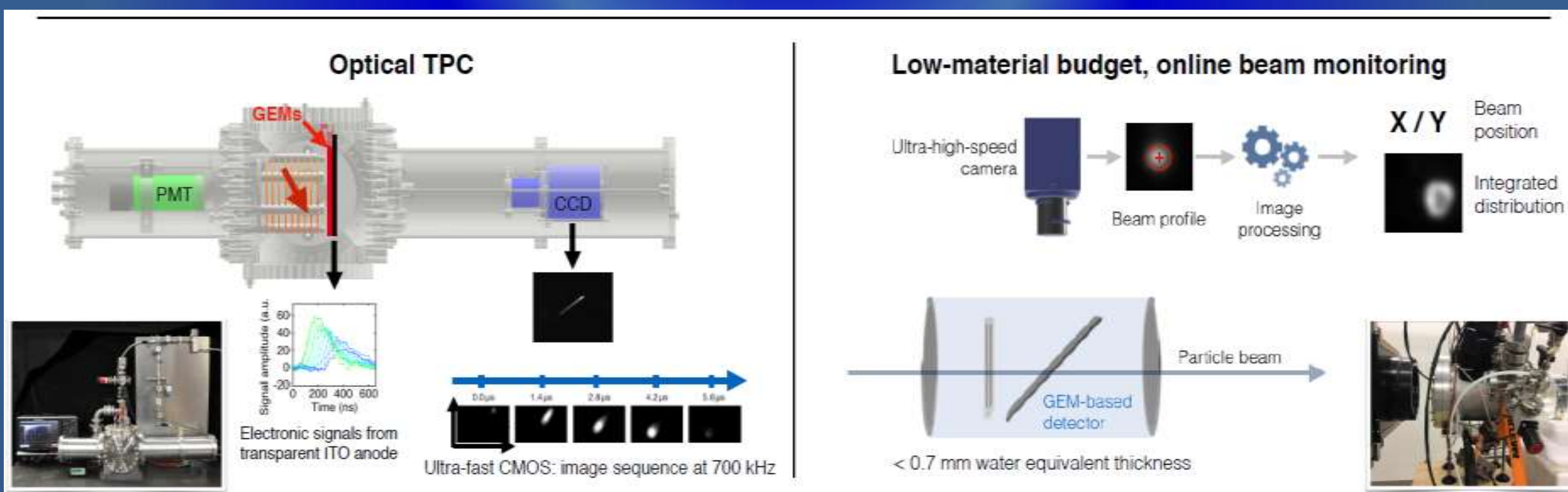
Optical Readout of MPGD’s @ CERN GDD Lab

Developments of scintillation light readout of MicroPattern Gaseous Detectors (MPGDs): GEMs, Micromegas, …

- ✓ Optical TPC (Combined electronic + optical readout)
- ✓ Ultra-fast optical readout (TPCs, beam monitoring)
- ✓ Low-material budget, online beam monitoring
- ✓ Detector physics studies
- ✓ among other applications…



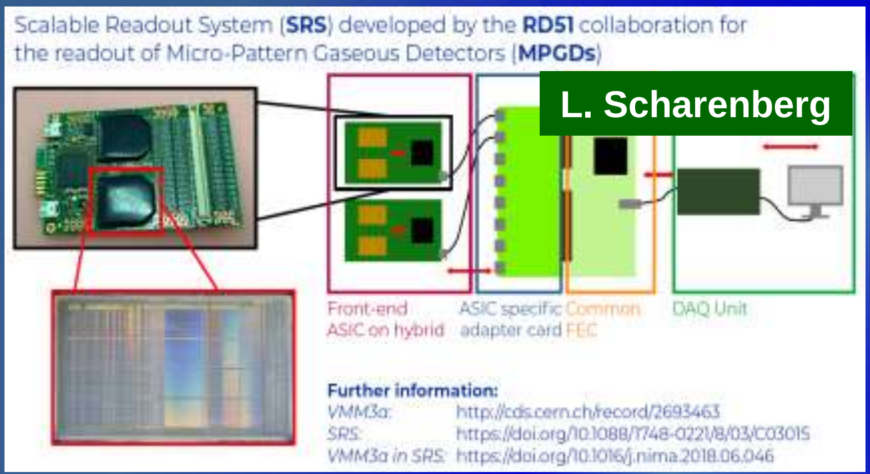
Courtesy CERN GDD group



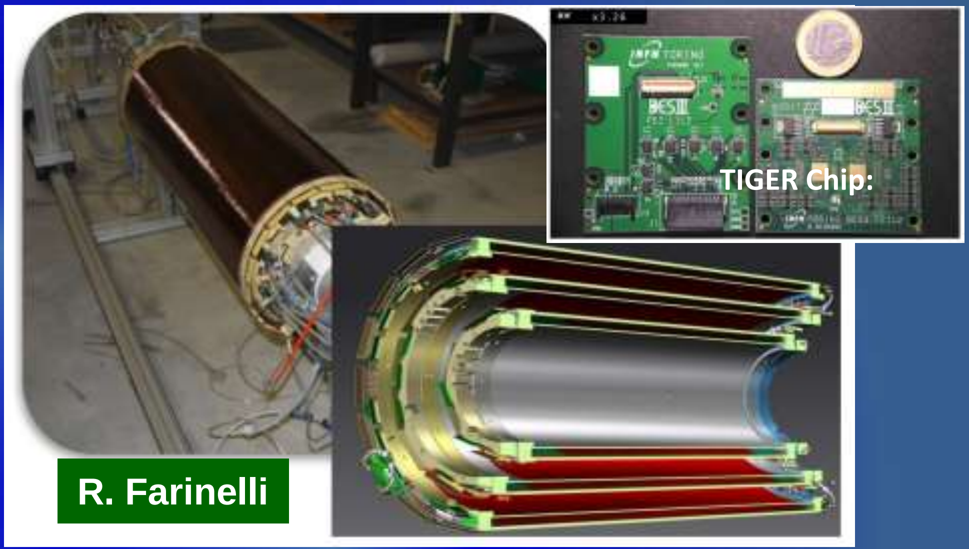
MPGD Applications @ INSTR2020

MPGD with VMM3 ASIC and SRS:

X-Ray Imaging / Fluoriscence



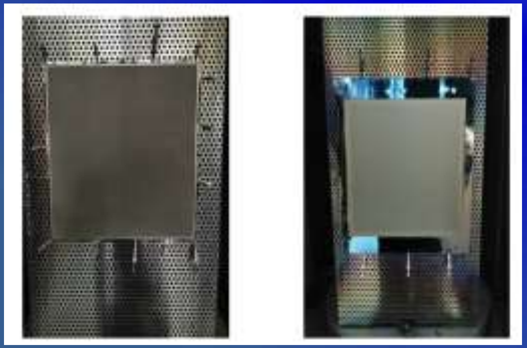
Cylindrical GEMs for BES-III Experiment:



MPGDs for CePC Digital calorimetry:

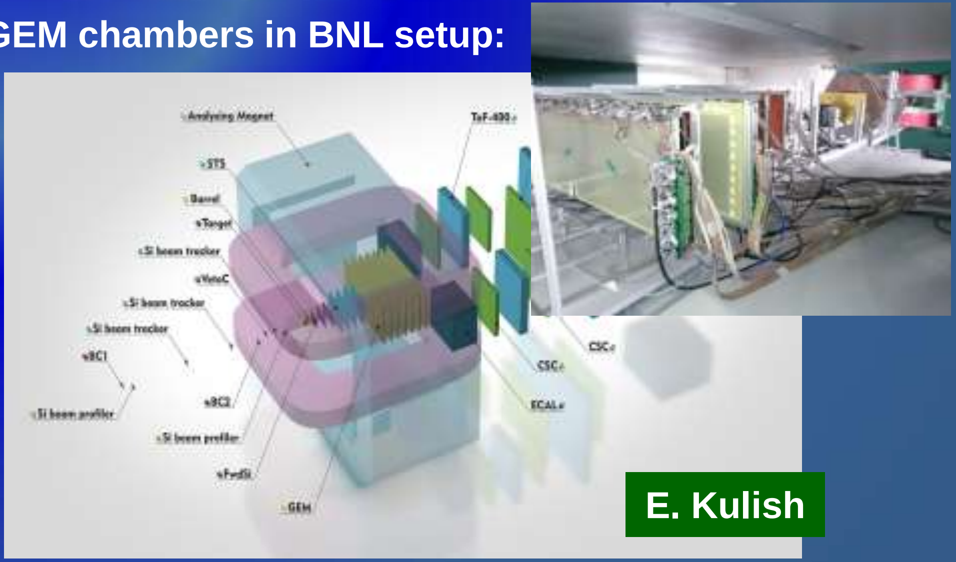
- **GEM** (dead area using self-strechning technique is hard to reduce);
- **RWELL with resistive layer** DLC (diamond-
- Like carbon) is promising

D. Hong



GEM Tracking System of the BM@N Exp.

GEM chambers in BNL setup:



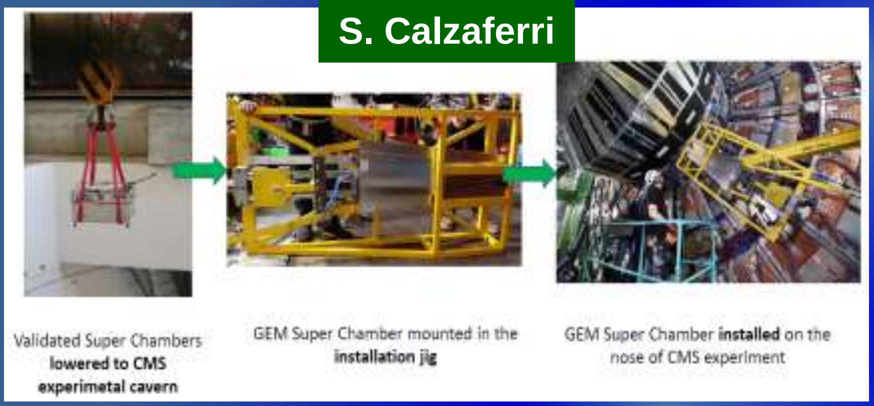
Development of Large-Area MPGDs for Colliders

GEMs for CMS Muon System Upgrade:

- ✓ Single-mask GEM t(instead of double-mask)
- ✓ Assembly optimization: self-stretching technique:

Time to assemble chamber: 1 day

S. Calzaferri

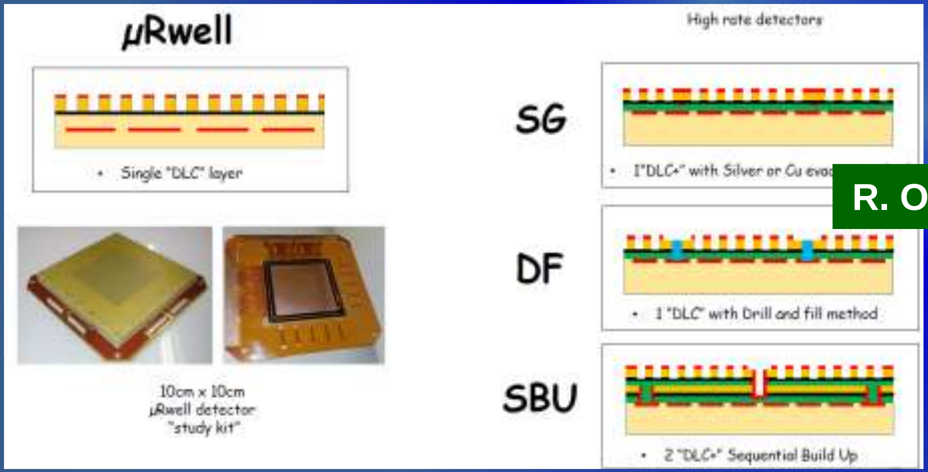


Resistive MM for ATLAS NSW Muon Upgrade:

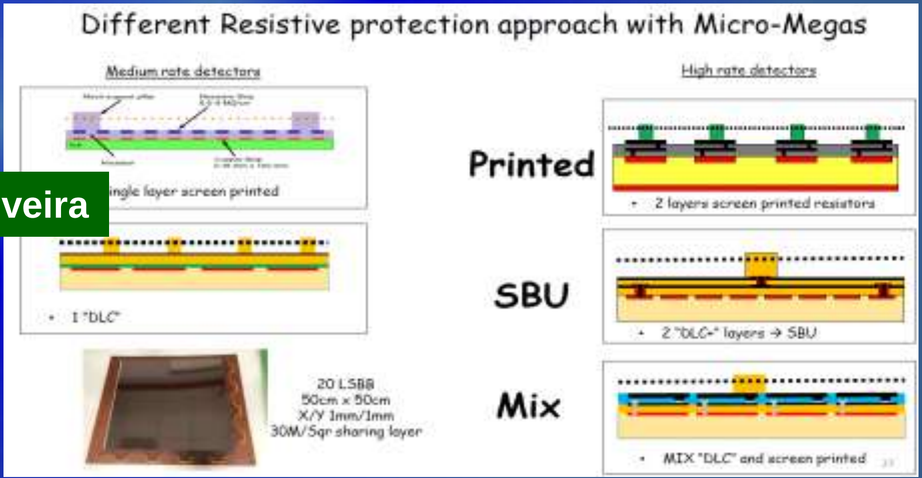
Main issue encountered: HV unstability
==> found to be correlated to low resistance of resistive strip anode
==> applied solutions + passivation in order to deactivate the region where R<0.8 MΩ

I. Gnezi

DLC-based electodes for future resistive MPGDs:



R. Oliveira

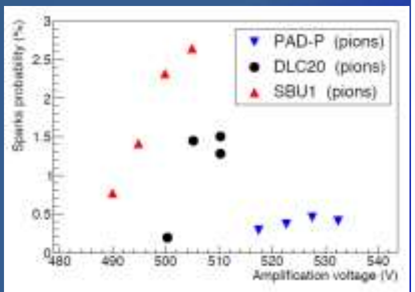


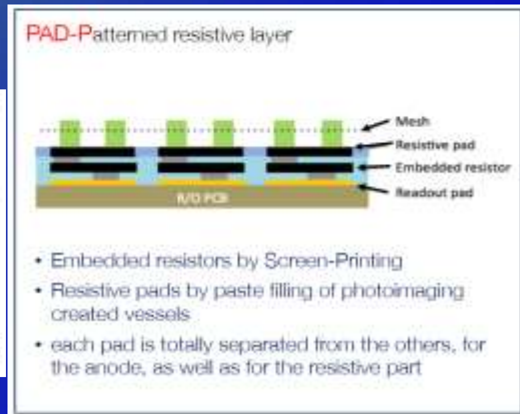
Simple DLC material ready for large-size detectors; need to improve « DLC+ » material (Cu adhesion)

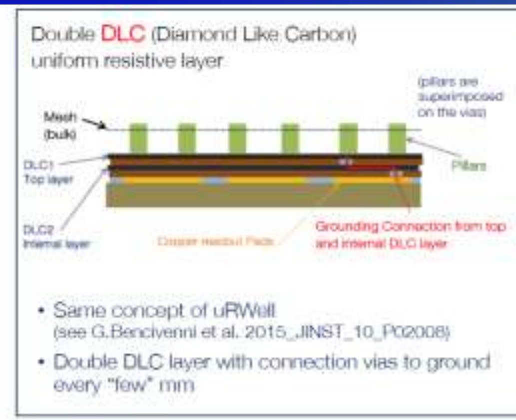
R&D on Resistive MM and μWELL for High-Rate Applications

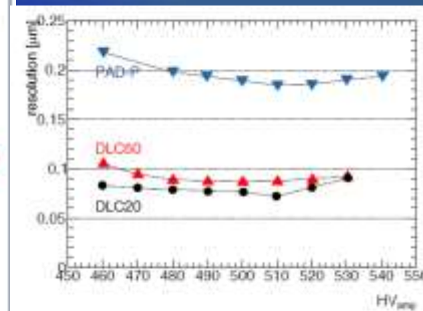
Pixelated Restitive MM Studies for high rates (~10's MHz/cm^2):

M. Iodice



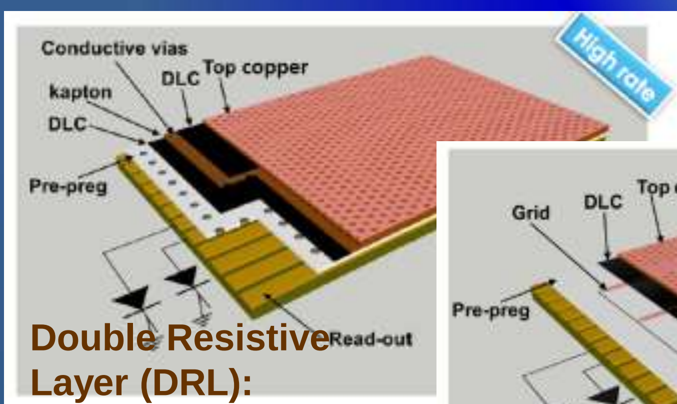




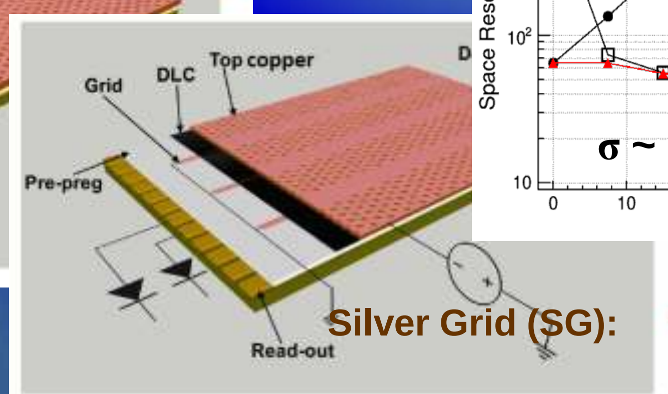


- **Quite significant charging-up that nevertheless saturate at $\mathcal{O}$(1MHz/cm2)**
- **Degraded performance on energy and spatial resolution compared to DLC**
- Best performance with the "low resistivity" DLC (~20 MW/□) and with fine network of grounding vias(~6 mm)
- Robustness not yet at the level of PAD-P à the DLC-SBU technique promising but not yet conclusive

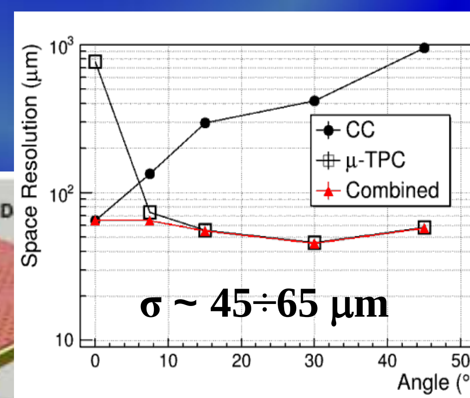
μWELL Studies for high rates (~10's MHz/cm2):



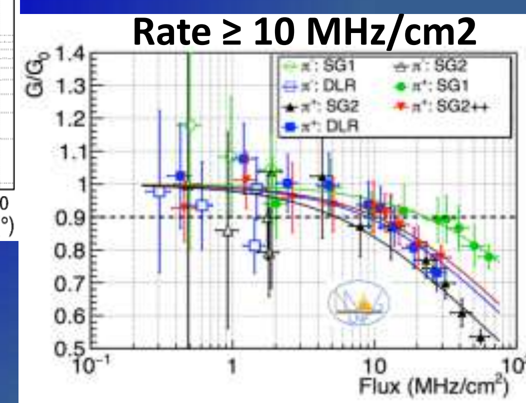
Double Resistive Layer (DRL):



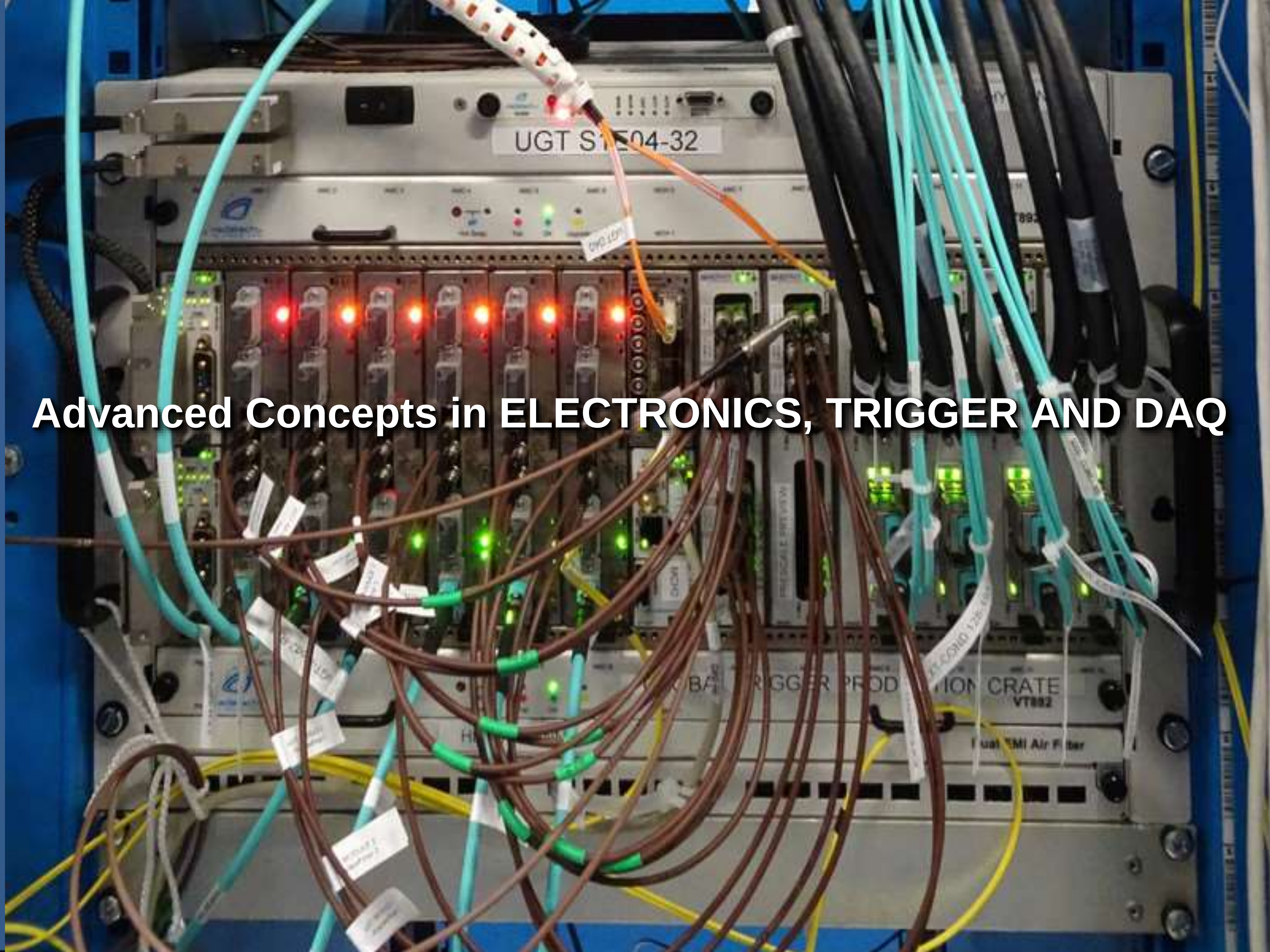
Silver Grid (SG):



M. Giovanetti

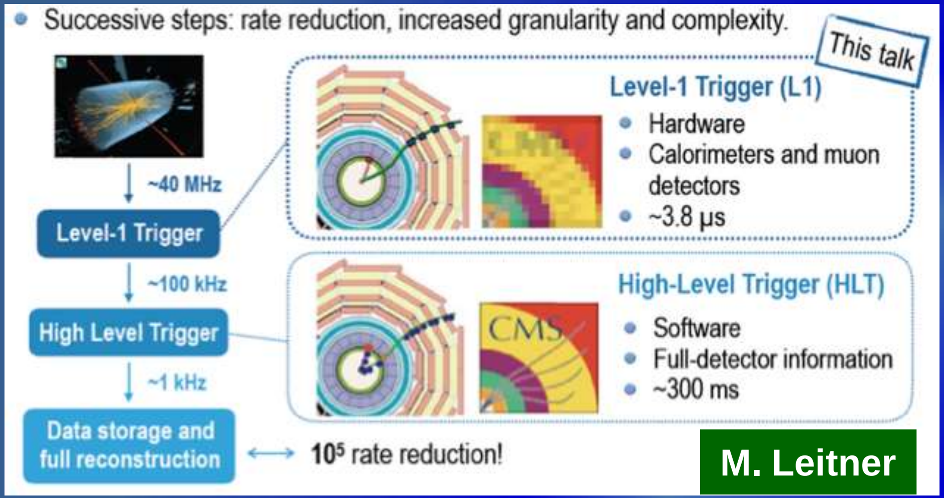


Advanced Concepts in ELECTRONICS, TRIGGER AND DAQ



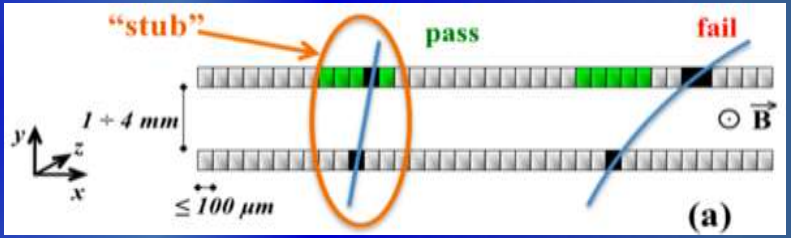
"Intelligent Trackers": Frontier Application for HEP?

CMS Level-1 Trigger System:



Trigger has to become ‚smarter' → use tracker information in an earlyL1 trigger stage

- ✓ Cannot send all hits to trigger at 40 MHz → local "intelligence" needed to reduce rate (only tracks with pT > 2 GeV are sent to tracker trigger)
- ✓ "Particle Flow" approach now possible at L1 trigger – use information from all detectors (e.g. trigger on secondary vertices using NN or "anomaly detection" by machine learning)



"Mini-vectors" concept for ILC Vertex Detector:

- ILC will run without trigger

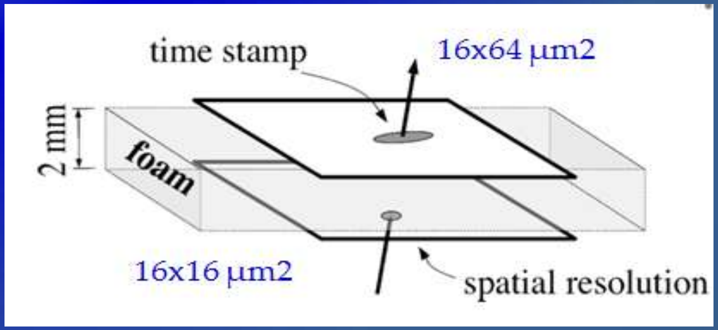
- Develop concept of 2-sided ladders using 50 μm thin CPS → "mini-vectors" providing high spatial resolution & time stamping

- Realization of double-sided ultra-light ladders (PLUME) equipped with two complementary types of CPS

- Introduce NN in CPS to mitigate data flow from beam-related background

DOUBLE-SIDED CMOS LADDERS for ILC:

Issues: high precision alignment & power cycling in high magnetic field (ILC)



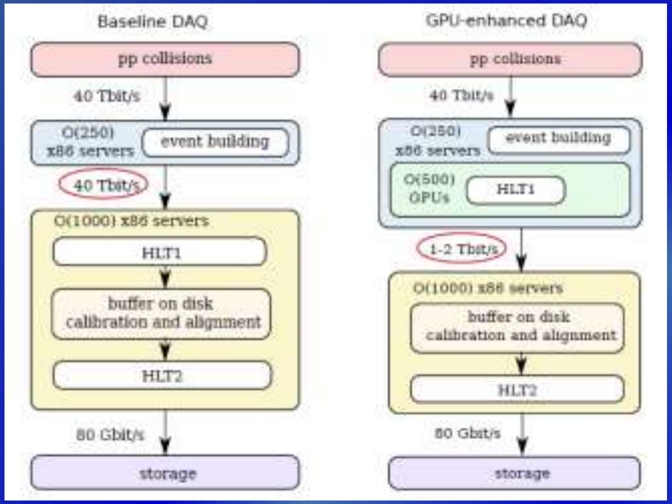
Advanced Concepts in TRIGGER @ INSTR2020

LHCb High Level Trigger System:

From CPU to GPU-accelerated trigger

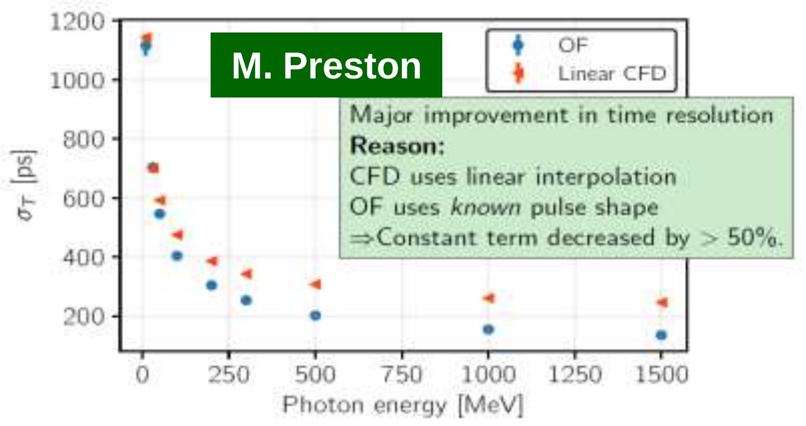
Under investigation: in a few months (Allen project)

A. Poluektov



FPGD-based algorithm for PANDA CALO:

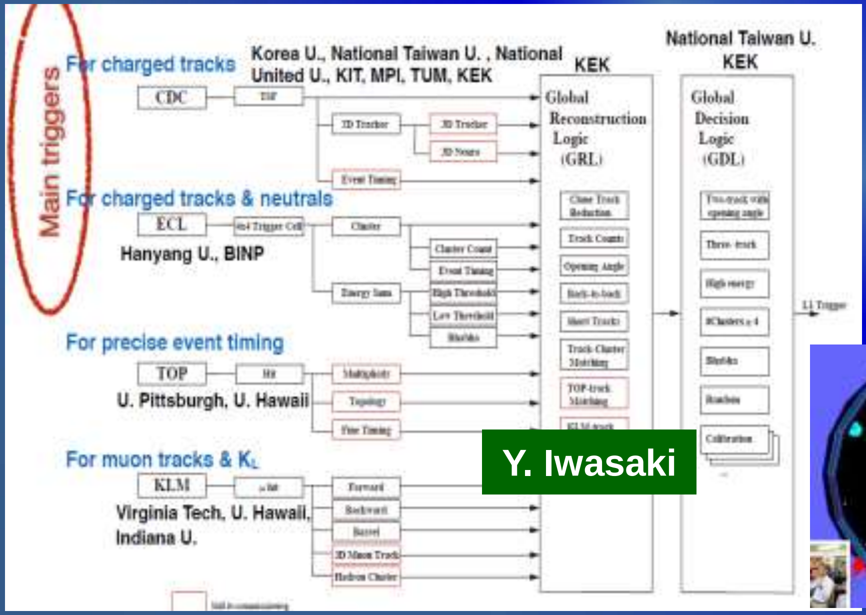
M. Preston



Method allows to reconstruct pile-up events

Belle-II Level-1 Trigger System:

Main triggers (CDC and ECL) worked as expected

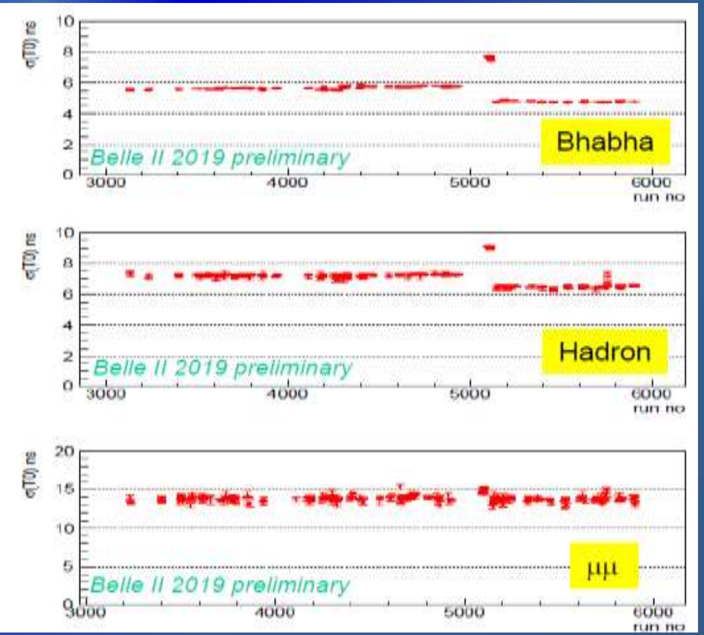


Y. Iwasaki

B. Cheon

ECL timing; a main Trigger Timing source

Belle-II Calorimeter Trigger:

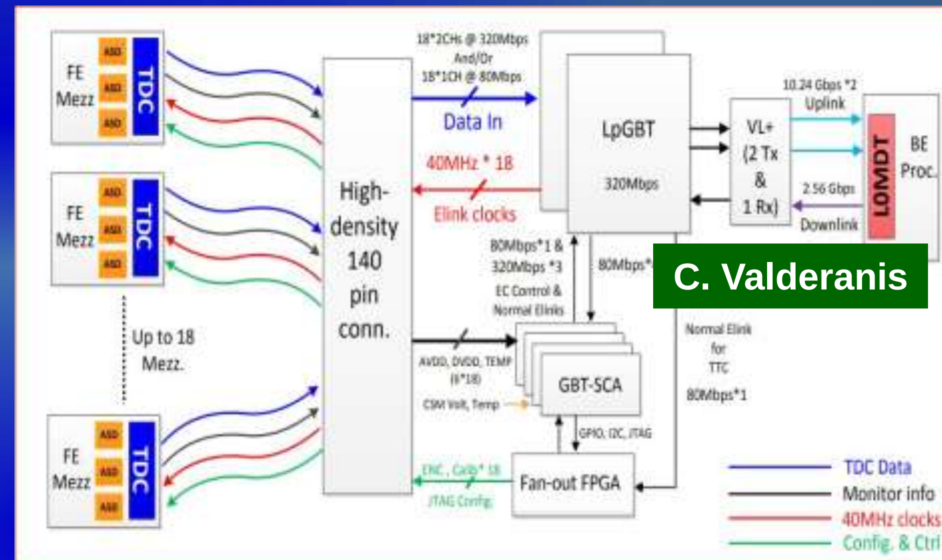


ATLAS TRIGGER / ELECTRONICS @ INSTR2020

ATLAS NSW MM Electronics for HL-LHC:

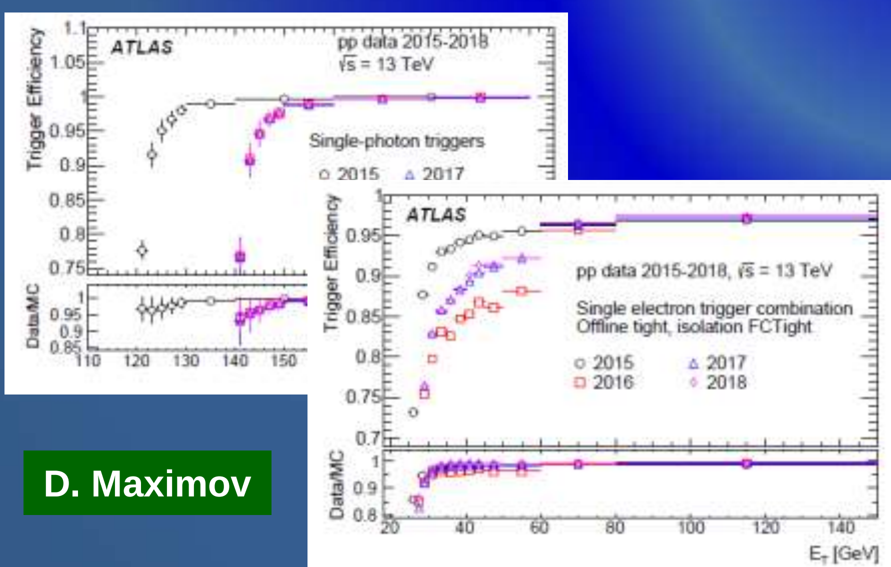
P. Tzanis

ATLAS MDT Electronics Upgrade for Phase-II:



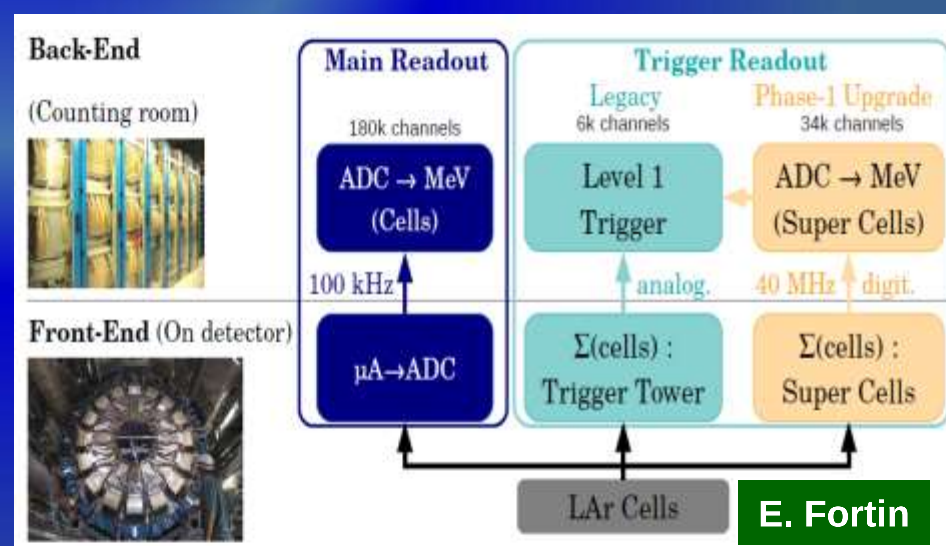
C. Valderanis

ATLAS e/γ Trigger Performance:



D. Maximov

ATLAS LAr Phase-I Trigger Electronics:



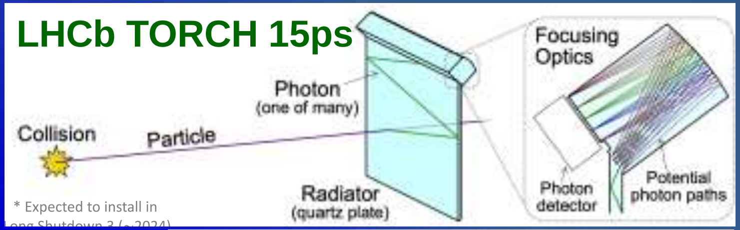
E. Fortin

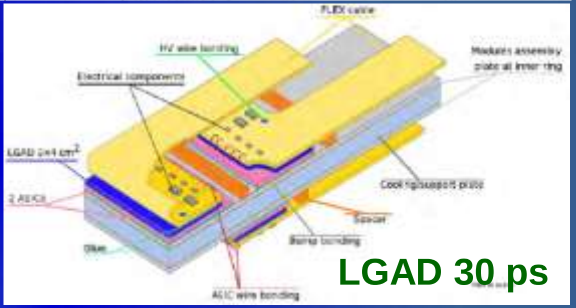
TIMING Detectors with a few 10’s of picosecond resolution

- **Fast development of precise timing sensors**
  - Pileup rejection in HL-LHC → 4D tracking for ATLAS/CMS ~ 10’s of ps & 10’s of μm per MIP/pixel
  - Reconstruction in calorimeter → CMS HGCAL
  - Time of flight and time of propagation (PID) → new RICH DIRC applications ~ 10’s of ps & 10’s of μm per MIP/pixel)
  - General push for higher luminosity at LHC, Belle-II, Panda, Electron-Ion Collider

- **Challenges:**
  - Radiation hardness
  - Large background environment
  - Very large detectors applications → System aspects of timing (e.g. precision clock distribution systems)

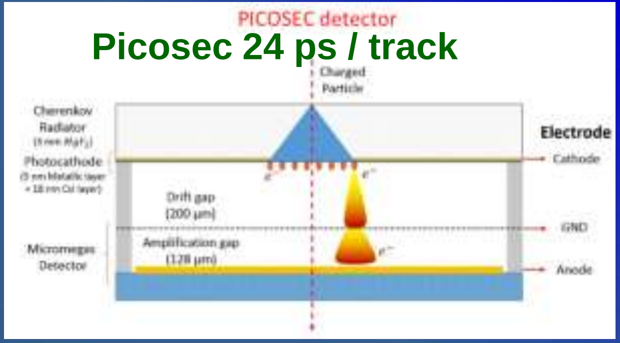
LHCb TORCH 15ps





Bellell TOP 35 ps *Example of Cherenkov-photon paths for 2 GeV/c $\pi^{\pm}$ and $K^{\pm}$.*

Picosec 24 ps / track



Maximum rate and charge dose capability

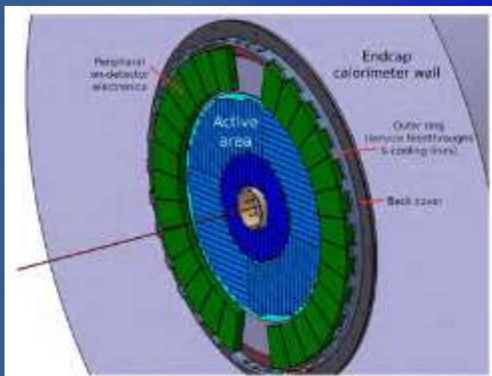
Detector	Experiment or beam test	Maximum rate	Maximum anode charge dose	Timing resolution	Ref.
MRPC presently	ALICE	~500 Hz/cm^2 *** (tracks)	-	~60 ps/track (present) ***	[4]
MRPC after upgrade	ALICE	Plan: ~50 kHz/cm^2 ** (tracks)	-	Plan: ~20 ps/track	[4]
MCP-PMT	Beam test	-	-	< 10 ps/track *	[7,8,9]
MCP-PMT	Laser test	-	-	~27 ps/photon *	[14]
MCP-PMT	PANDA Barrel test	10 MHz/cm^2 * (laser)	~20 C/cm^2 *	-	[11]
MCP-PMT	Panda Endcap	~1 MHz/cm^2 ** (photons)	-	-	[28]
MCP-PMT	TORCH test	-	3-4 C/cm^2 *	~90 ps/photon *	[27]
MCP-PMT	TORCH	10-40 MHz/cm^2 ** (photons)	5 C/cm^2 **	~70 ps/photon **	[24-27]
MCP-PMT	Belle-II	< 4MHz/MCP *** (photons)	-	80-120 ps/photon ***	[23]
Low gain AD	ATLAS test	~40 MHz/cm^2 ** (tracks)	-	~ 34 ps/track/single sensor *	[34,35]
Medium gain AD	Beam test	-		< 18 ps/track *	[39]
Si PIN diode (no gain)	Beam test (electrons)	-		~23 ps/32 GeV e$^-$	[8]
SiPMT (high gain)	Beam test – quartz rad.	-	< 10^{10} neutrons/cm^2	~ 13 ps/track *	[8]
SiPMT (high gain)	Beam test - scint. tiles	-	< 10^{10} neutrons/cm^2	< 75 ps/track *	[41]
Diamond (no gain)	TOTEM	~3 MHz/cm^2 * (tracks)	-	~ 90 ps/track/single sensor *	[36]
Micromegas	Beam test	~100 Hz/cm^2 * (tracks)	-	~24 ps/track *	[31,32,40]
Micromegas	Laser test	~50 kHz/cm^2 * (laser test)		~76 ps/photon *	[31,32,40]

* Measured in a test
** Expect in the final experiment
*** Status of the present experiment

J. Va’vra

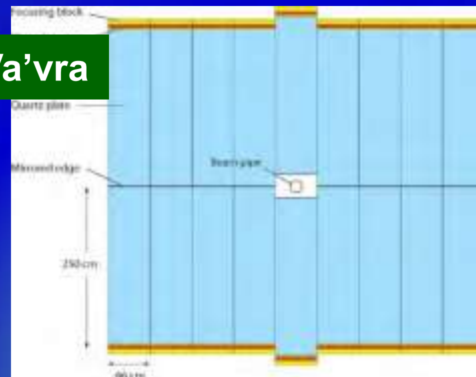
Examples of High resolution Timing Detectors at a level of ~30 ps for MIPs, and ~100ps for single photons

ATLAS High-Granularity Timing Detector (HGTD) with Low Gain Avalanche Diodes (LGAD):

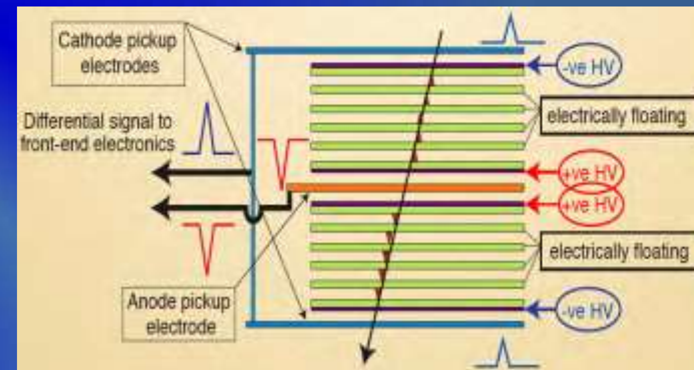


TORCH DIRC at LHCb:

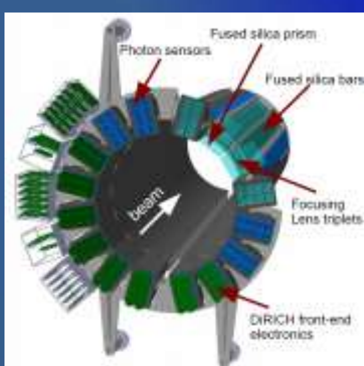
J. Va'vra



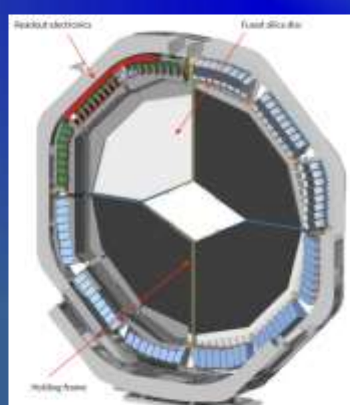
ALICE-like MRPC TOF counters:



Panda Barrel DIRC:

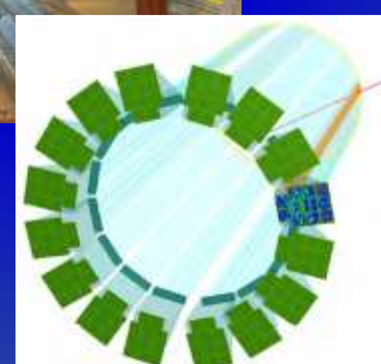


Panda Endcap DIRC:

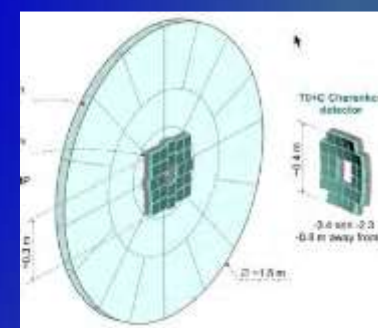


Belle-II TOP DIRC:

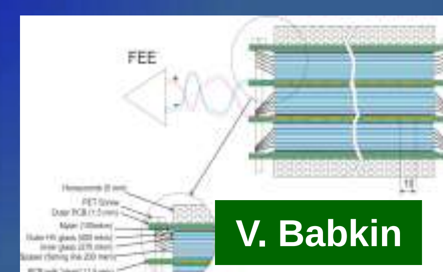
EIC DIRC in USA:



FIT at ALICE:



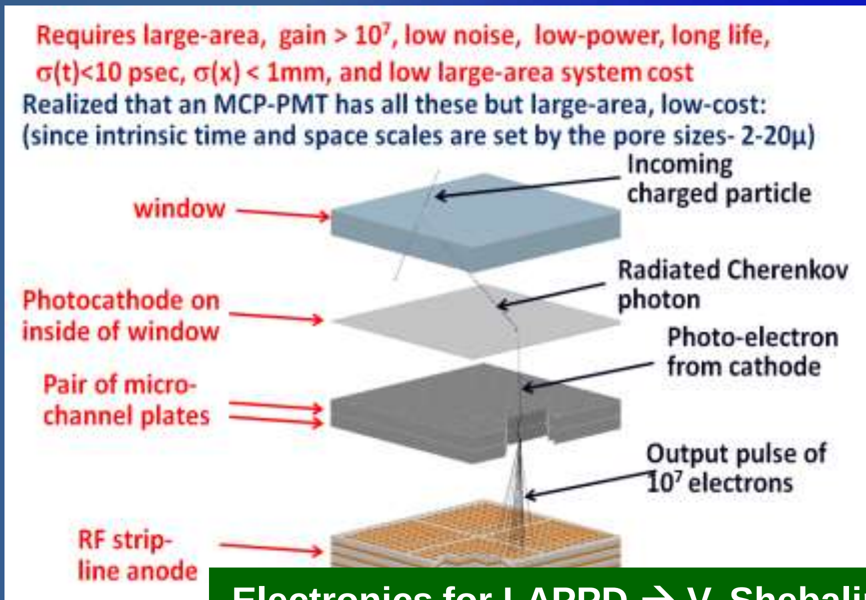
TOF-MPD @ NICA



V. Babkin

Towards Large Area in Fast TIMING DETECTORS

Large Area Picosecond PhotoDetectors (LAPPD):



Electronics for LAPPD → V. Shebalin talk

Generation-I detectors: Strip line readout is now commercially available from Incom, Inc.

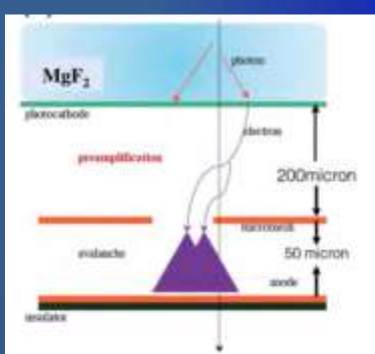
https://psec.uchicago.edu/

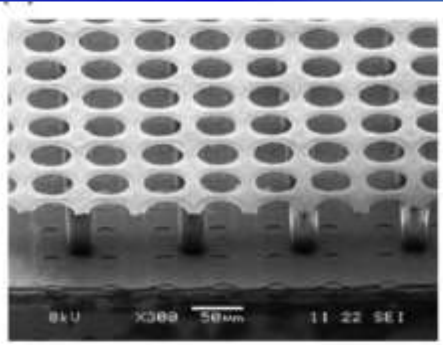
US provisional Patent (62928598) submitted for a batch production using 'air-transfer', capable of 100's of modules /week

Gaseous Detectors: Micromegas with Timing

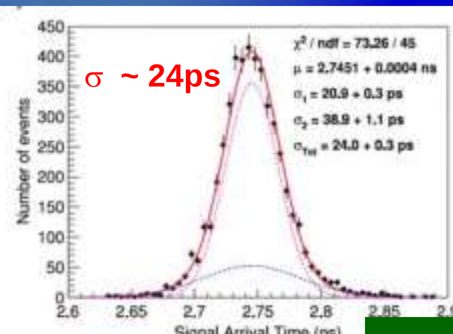
RD51 PICOSEC-Micromegas Collaboration

Cherenkov radiator + Photocathode + MM

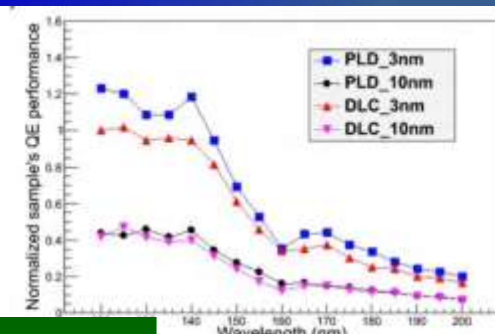




Timing (MIP test-beam):



CsI / DLC PC:



F. Brunbauer

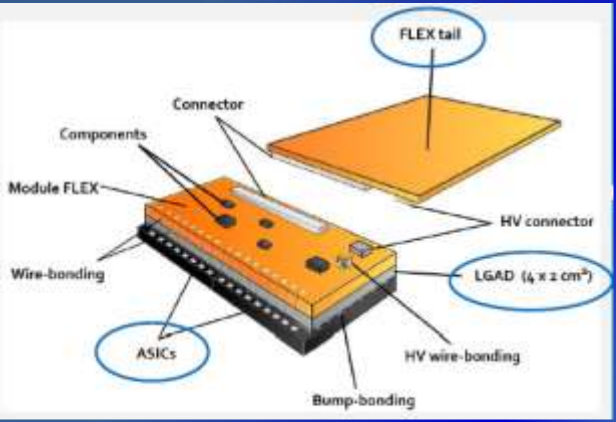
Towards large-area: stability (res. MM), PC robustness, large-area (from single to multi-pad)

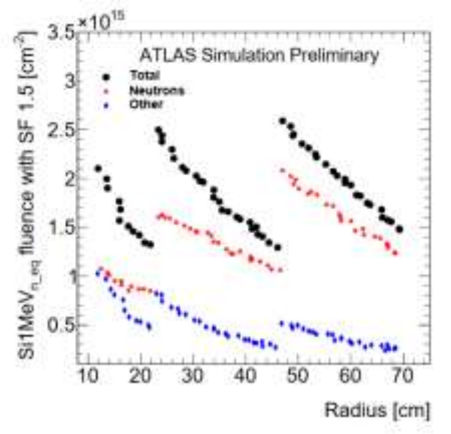
TIMING DETECTORS for ATLAS / CMS Phase-II Upgrade

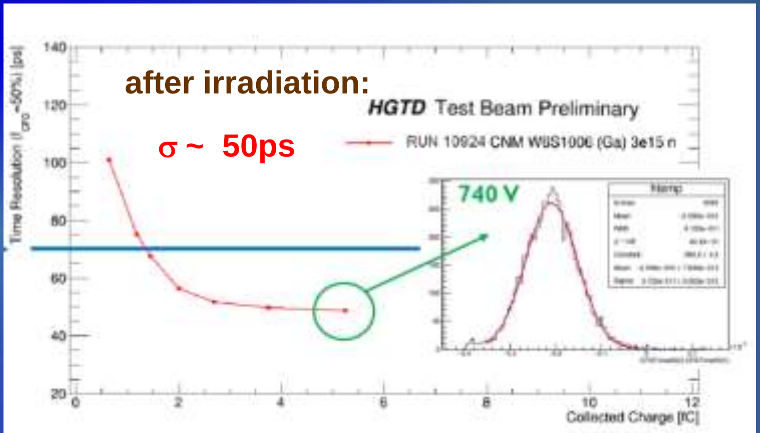
High-Granularity Timing Detector (HGTD) for ATLAS Phase-II Calorimeter System:

Low Gain Avalanche Detectors (LGADs) readout by FEE ASICs (ALTIROC):

L. Garcia

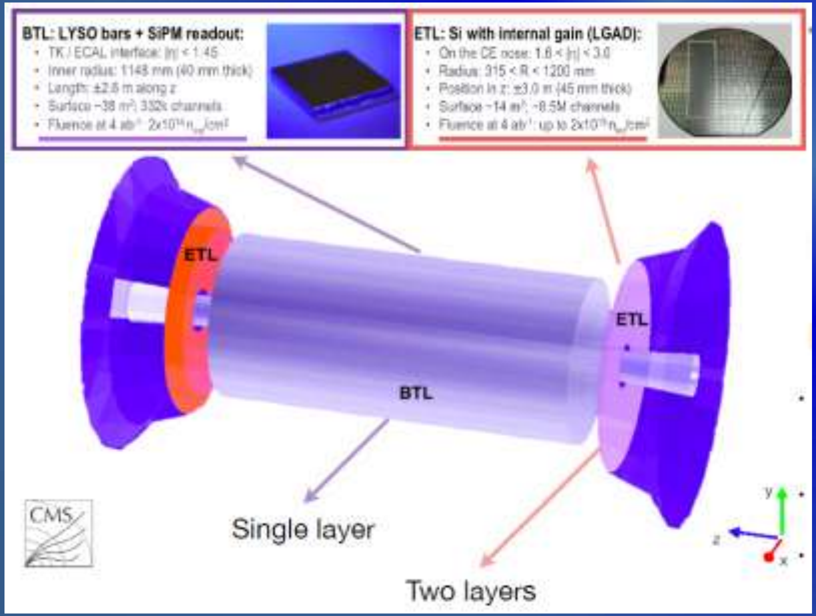




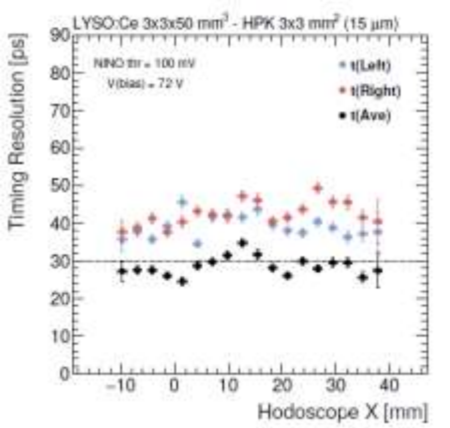


MIP Timing Detectors (ETL & BTL) for the CMS Phase-II Upgrade:

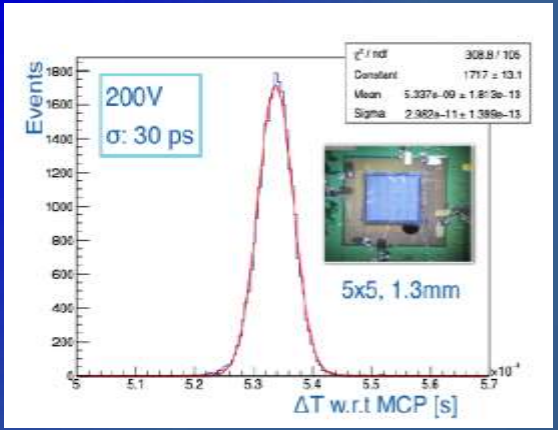
O. Sahin



LYSO + SiPM + TOFHIR ASIC:



LGAD + ETROC ASIC:



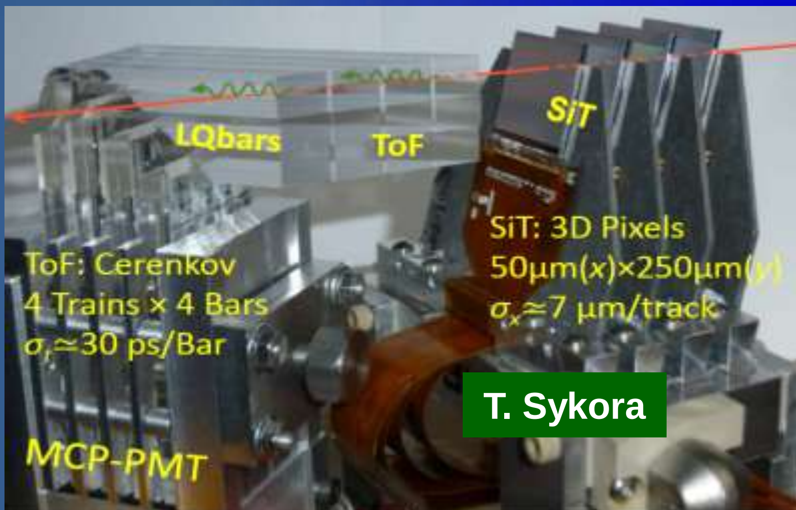
LGAD sensors are common ATLAS/CMS development

Detector / Materials R&D for Fast TIMING Applications

ATLAS AFP-TOF Detector in LHC Run 2:

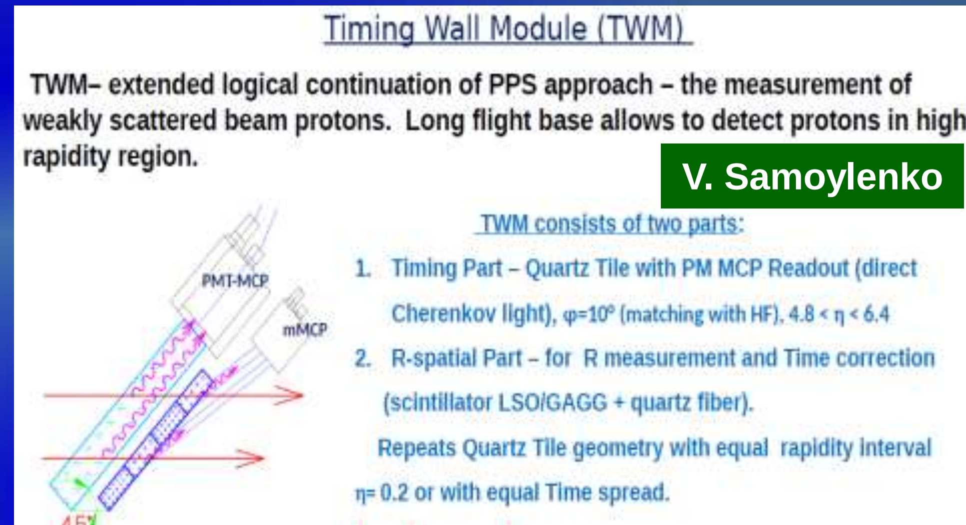
pileup suppression; possibility for a dedicated trigger

Operated in 2017; will be re-installed for the LHC Run3



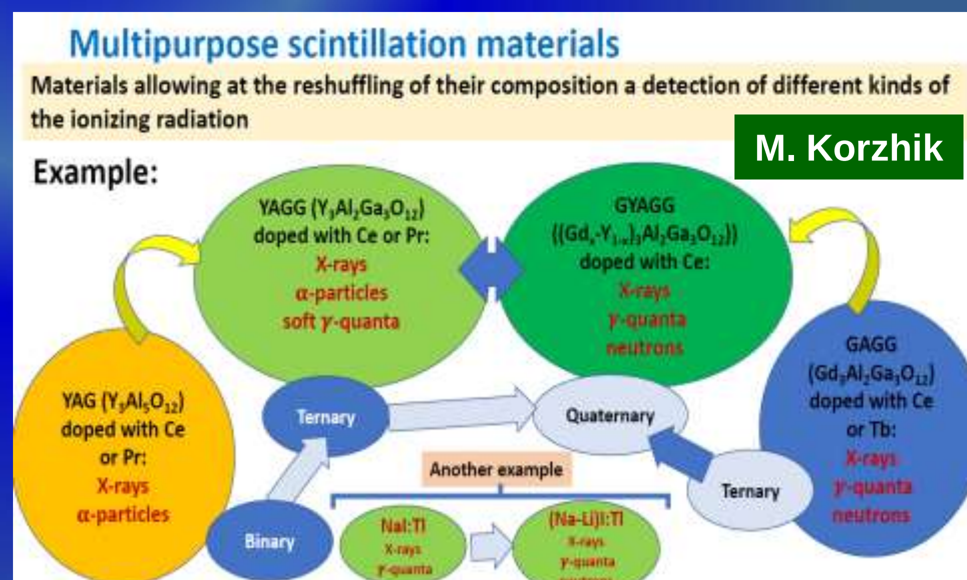
T. Sykora

Timing Wall Detector for HF CMS ($3 < \eta < 5$):



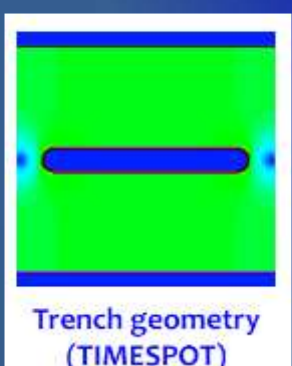
V. Samoylenko

R&D on Multipurpose Scintillation Materials:

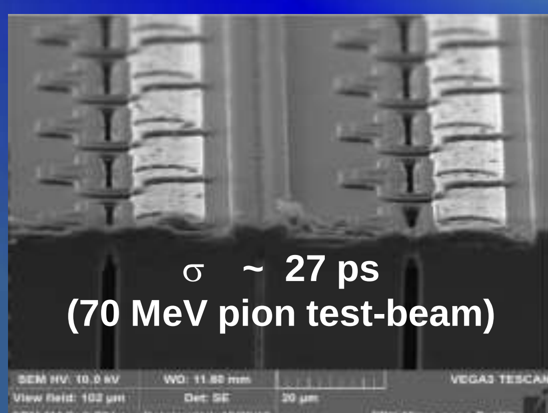


M. Korzhik

3D-Trench Silicon Sensors R&D for LHCb :



Frist 3D-trench batch Delivered in June 2019



σ ~ 27 ps
(70 MeV pion test-beam)

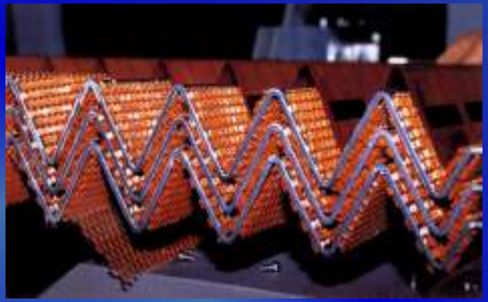
A. Lai

Advanced Concepts in CALORIMETRY

Main techniques, depending on applications:

✓ Crystals (ultimate resolution)
✓ Scintillator (sampling)
✓ Liquid Noble Gas (intrinsic rad. hard)
✓ Particle flow calorimetry (SiW-based, 5D)
✓ DREAM (Dual readout)

2 concepts: homogeneous crystals & sampling



Particle Flow calorimetry is a Linear Collider (ILC, CLIC) driven effort:

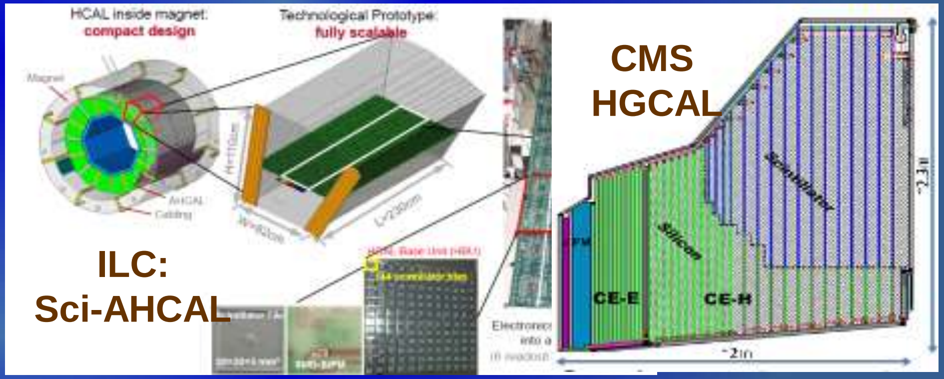
Silicon sensors expand from trackers to calorimeters (if budget allows):

✓ **Approved: CMS HGCAL phase II** → ECAL + HCAL endcaps

✓ **Proposed: ATLAS High Granularity Timing Detector** → preshower→ 4 forward Si-layers (low gain) for precision timing

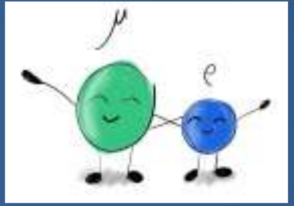
✓ **Proposed:** few Si-layers for **timing detector** (in shower maximum) **for LHCb Phase-II**

✓ **Possible:** applications in near detector systems In **neutrino beams**
✓ **Possible: CEPC, FCC**



Combined beam-test of CMS HGCAL +CALICE AHCAL:

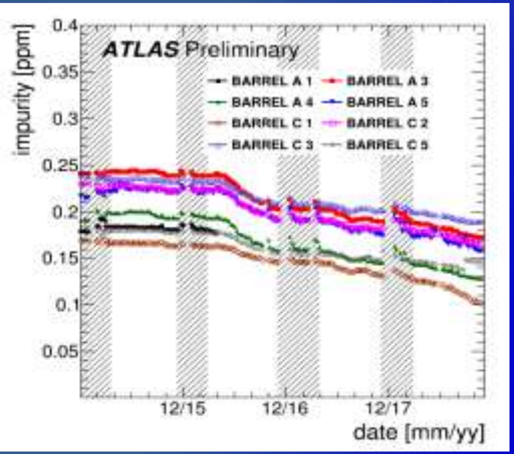
ATLAS Calorimeter & Upgrades @ INSTR2020

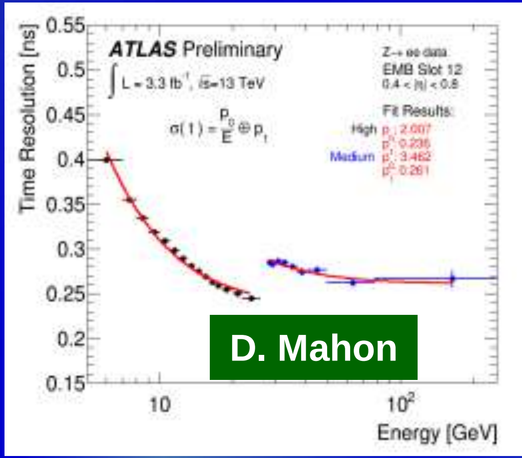


ATLAS LAr Performance / Upgrade for Phase-I:

LAr impurities remained stable during Run 2

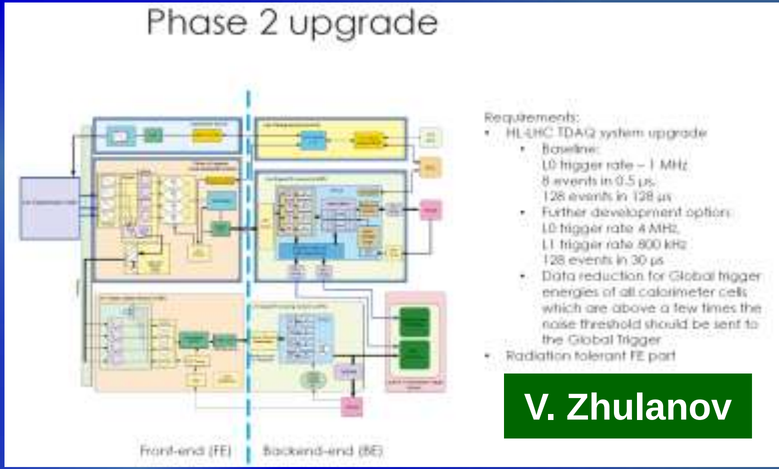
LAr provides the most precise timing in ATLAS





D. Mahon

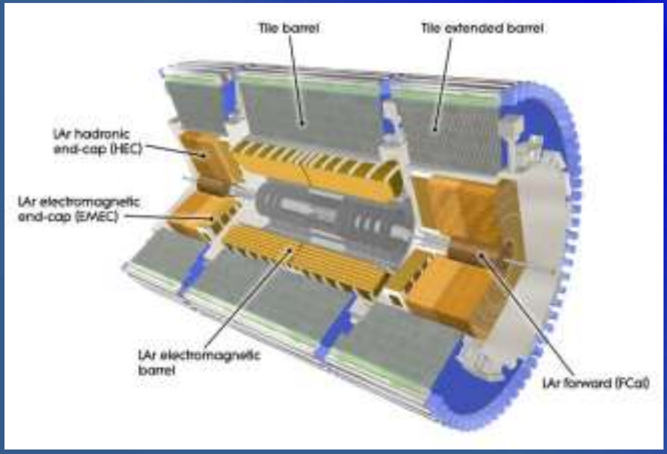
LAr Calo Electronics Upgrade for HL-LHC:



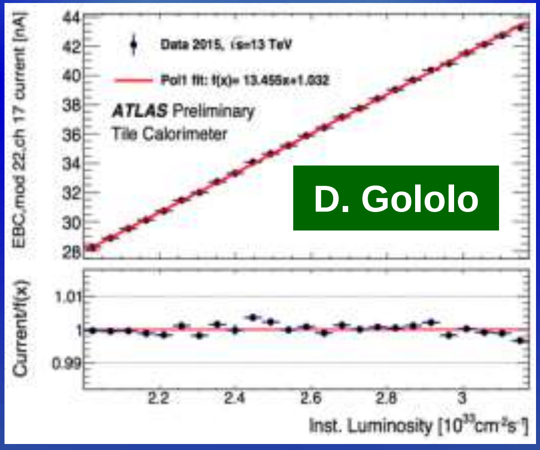
V. Zhulanov

ATLAS Tile Calorimeter Performance:

Hadronic scintillator-steel sampling calo (measure 4-vectors of jets, MET, L1 trigger)

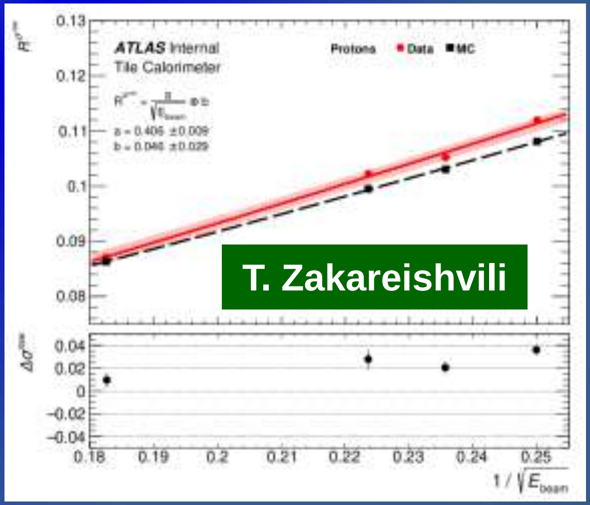


Instantaneous lumi measurement:



D. Gololo

Test-beam with new readout electronics



T. Zakareishvili

LHCb and CMS Calorimeter Upgrade @ INSTR2020

LHCb Calorimetry Upgrade:

Phase I:

- PS/SPD removed: no need for particle ID in L0
- No change in the present ECAL and HCAL

Phase II:

- Central area: radiation doses of up to ~ 1 MGy and neutron fluences of up to $6 \cdot 10^{15}$ 1MeV neq/cm ^{2} (scintillating garnet crystals)



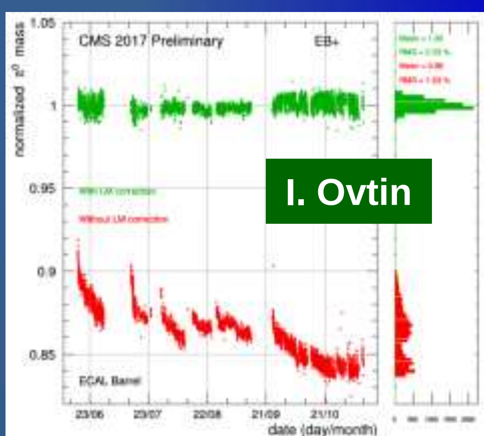
Y. Guz

- Outer area: Shashlik is a viable option
- Middle area: not defined yet (e.g., PWO?)

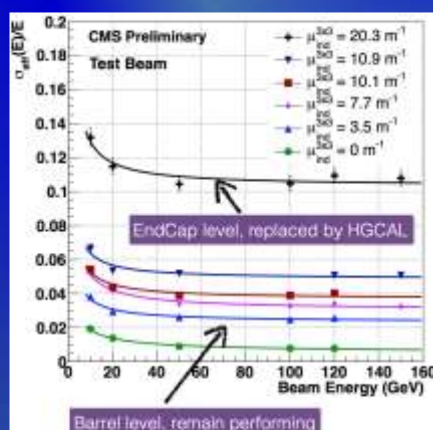
Radiation Hard Scintillating crystals:

	$Y_3Al_5O_{12}$:Ce (YAG)*	$Lu_3Al_5O_{12}$: Ce (LuAG)*	$Gd_3Al_2Ga_3O_{12}$: Ce (GAGG)**	Lu_2SiO_5:Ce (LSO)
density (g/cm^3)	4.57	6.73	6.63	7.4
X_0 (cm)	3.5 cm	1.3	1.59	1.1
Refraction index	1.83	1.84	1.85	1.82
Λ_{max} (nm)	550	535	520	420
LY @ RT (ph/MeV)	35000	25000	50000	30000
decay time (ns)	70 + slow component	70 + slow component	60 + slow component	40
rise time (ps)	1590-137	923-230	497-92	59

CMS ECAL Laser Monitoring for HL-LHC:

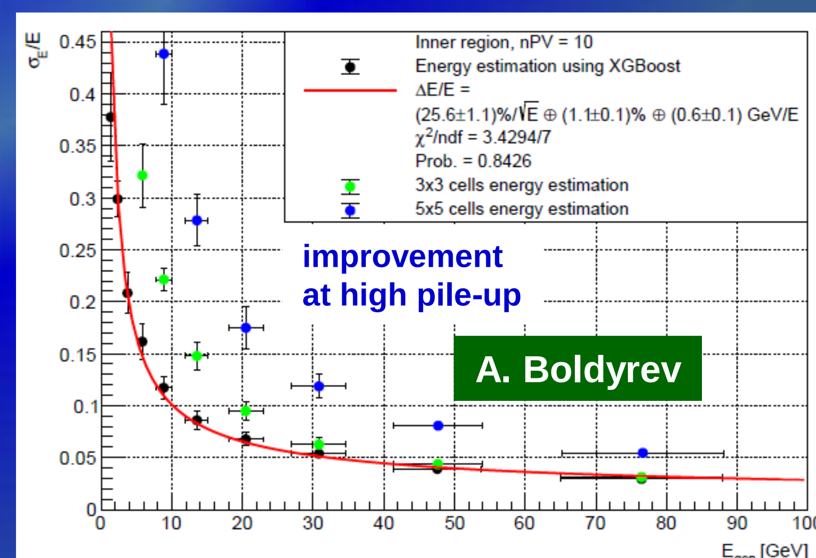


I. Ovtin



Phase-II Upgrade: EB upgrade (pin-diodes, fibers) + EE complete replacement (Si-based)

LHCb EMCAL R&D: ML Approach (XGBoost)

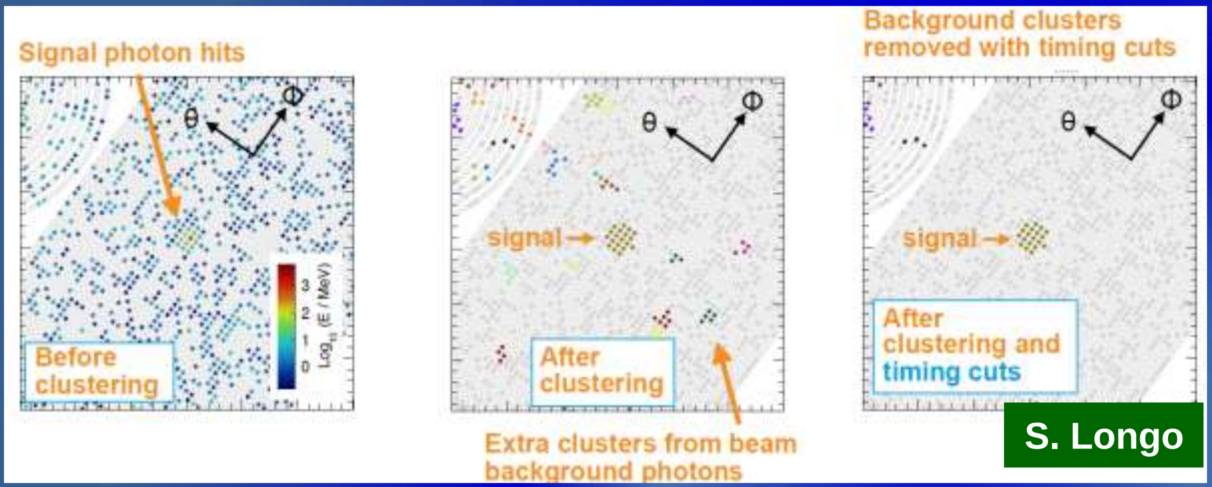


A. Boldyrev

Crystal Calorimeters @ INSTR2020

Belle II EMCAL Performance:

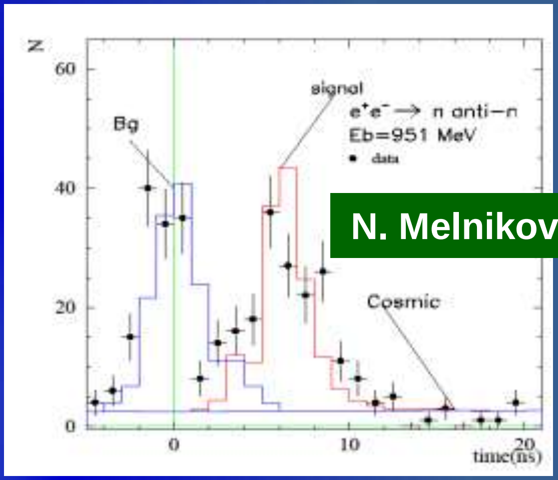
Use CsI(Tl) Pulse Shape Discrimination to improve particle ID (hadron component of scintillation emission is present)



S. Longo

SND EMCAL @ VEPP2000:

NaI(TL) crystals: use timing info to separate bkg. events near threshold

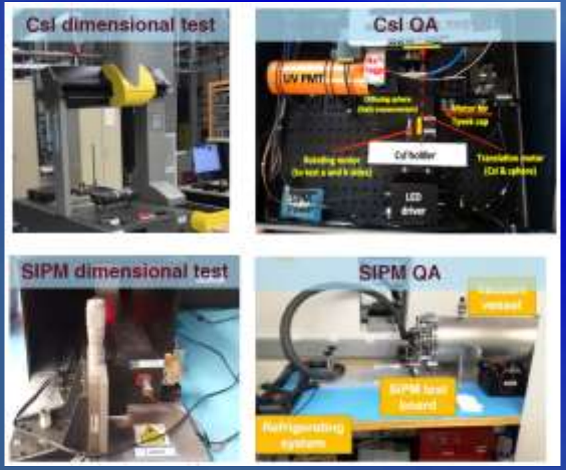


N. Melnikova

Mu2e EMCAL crystal calorimeter:

Use of 674 CsI crystals, each readout by 2 SiPMs (CsI, SiPM after irradiation to Mu2e eq. dose is OK)

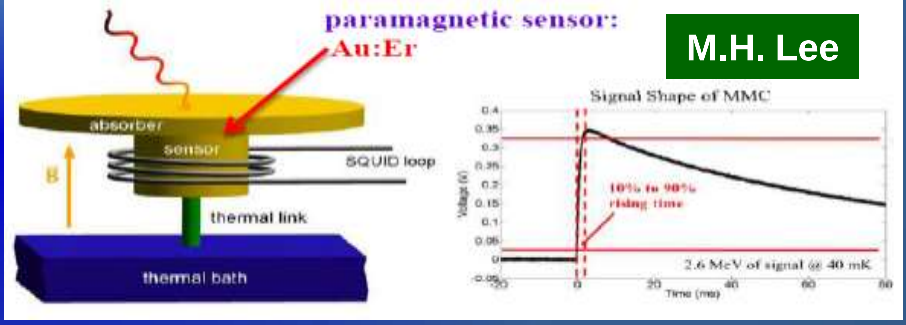
EMCAL Installation in MU2E exp.hall is planned in 2021



R. Donghia

AMORE Experiment: Neutrino $0\nu\beta\beta$ Decay

Use of Metalic Magnetic Calorimeter using crystals $^{40}Ca^{100}MoO_4$(CMO) at 10-30 mK temperature



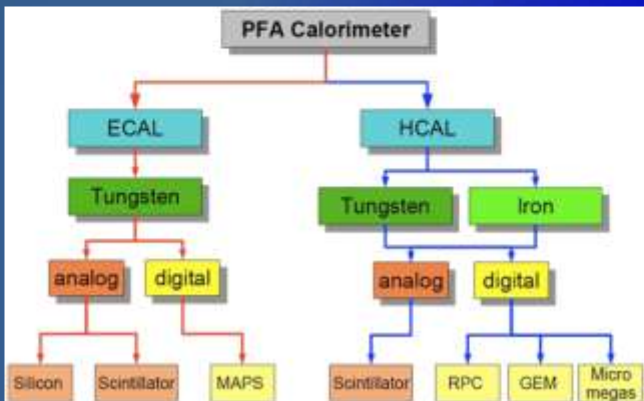
M.H. Lee

R&D ongoing on various low bkg. Molybdate crystals (FOMOS Materials, Russia)

Advanced Concepts in CALORIMETRY for ILC

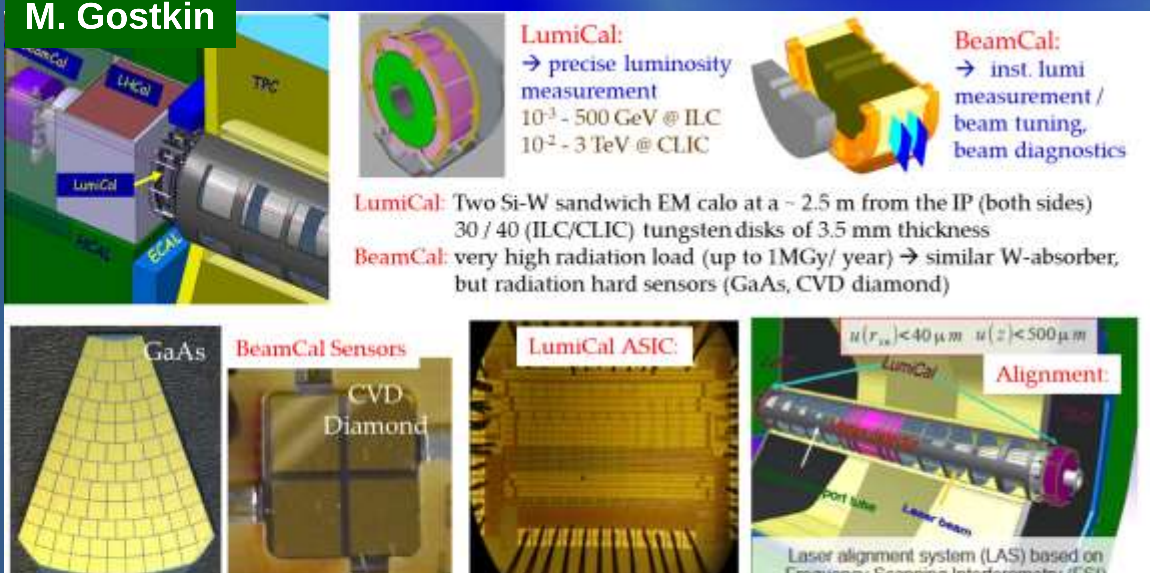
CALICE Highly Granular Calorimeter:

Development and study of finely segmented/imaging calorimeters:



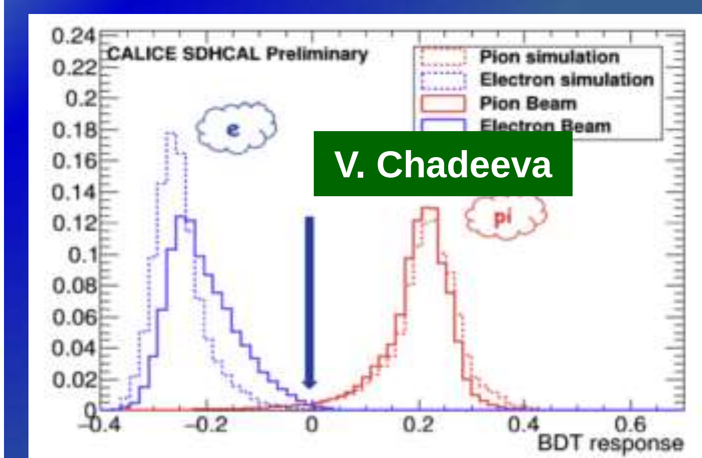
FCAL Collaboration: LumiCal Prototype

M. Gostkin



Particle identification in the SDHCAL using BDT (CALICE-CAN-2019-01)

V. Chadeeva



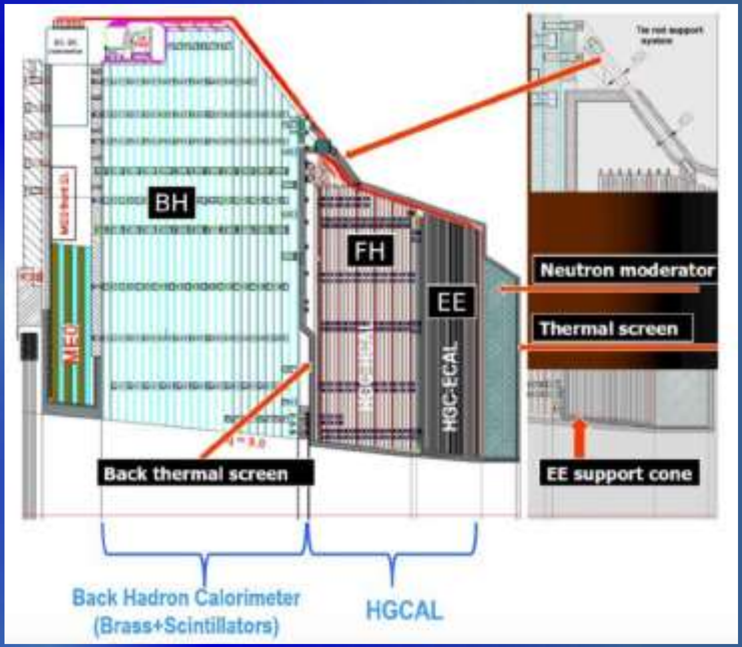
Highly Granular Calorimeter for CMS PhaseII Endcap Upgrade

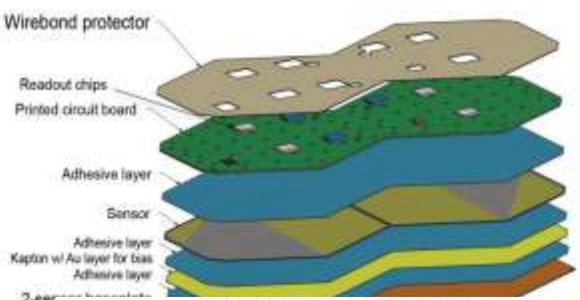
Similar trend as developments within the CALICE collaboration → aggressive time scale, reality check for LC driven ideas

Key parameters:

- **HGCAL covers 1.5 < η < 3**
- **Full system maintained at -30°C**
- **~ 600 m2 of silicon**
- **~ 500 m2 of scintillators**
- **~ 6M silicon channels, ~0.5 and ~1 cm2 cell-size**
- **Power at end of life ~120 kW of which ~20% is sensor leakage current**

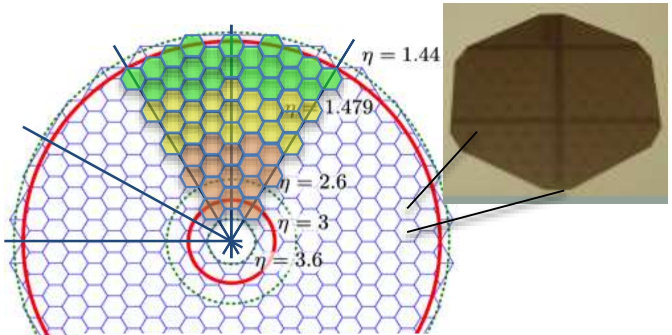
ILD/SiD ECAL: 2500 (1200) m^2



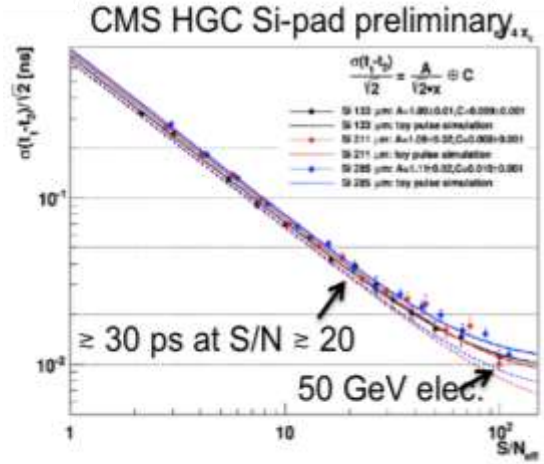


Parameters of the EE and FH.

	EE	FH	Total
Area of silicon (m^2)	380	209	589
Channels	4.3M	1.8M	6.1M
Detector modules	13.9k	7.6k	21.5k
Weight (one endcap) (tonnes)	16.2	36.5	52.7
Number of Si planes	28	12	40



Si-Sensor technology as for tracker targeting 8″ wafers



ASICs: Evolution of Technologies

✓ More and more functions are integrated inside chips (ASICs)

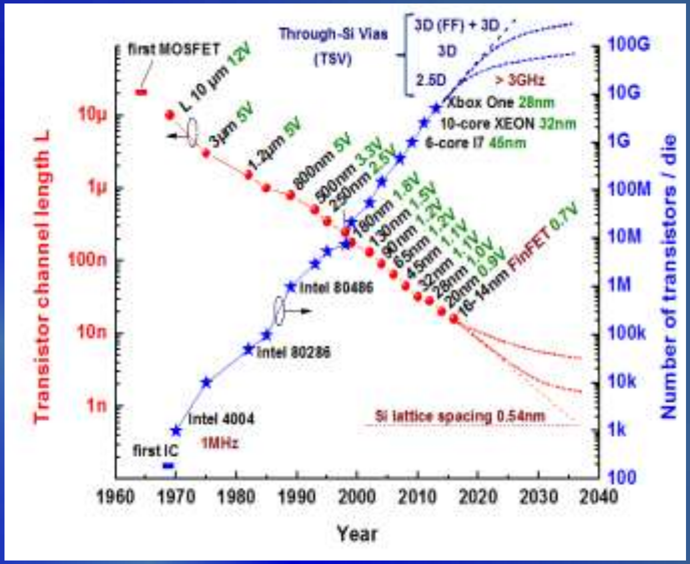
Evolution of technologies make them more and more performant but more and more complex

- ➢ **Cost increases… (MPW costs):**
- ➢ – 350 nm : 1 k€/mm²
- ➢ – 130 nm : 2 k€/mm²
- ➢ – 65 nm : 6 k€/mm²

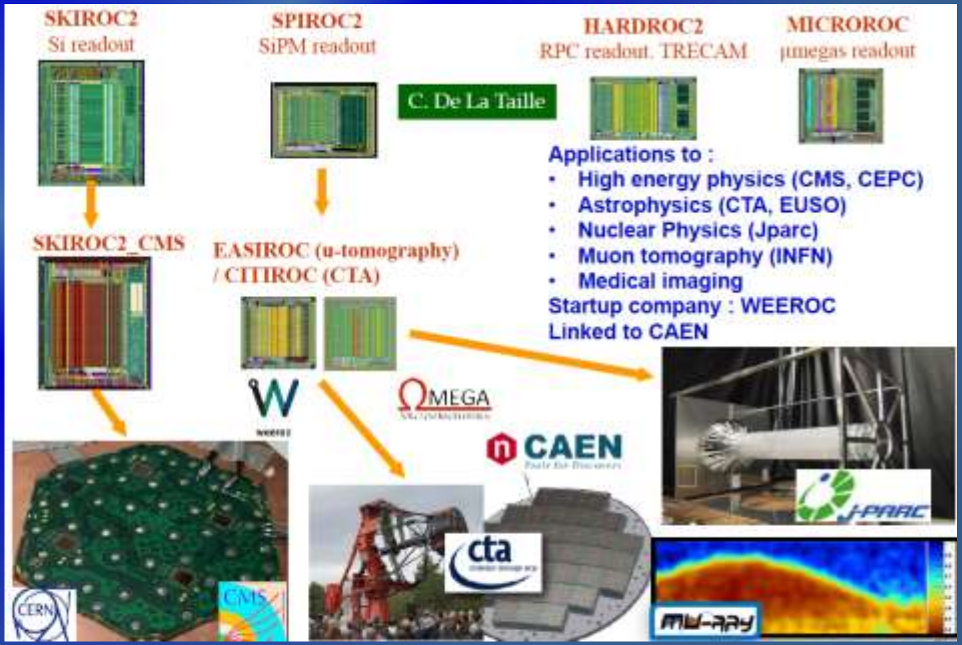
Chip size also…
→ CERN targets - 65/130 nm

❖ **Imaging calorimeters:**

– Require highly integrated R/O electronics: System On Chip
– Low power, low noise, high speed, large dynamic range
– Timing capability down to a few tens ps
– Lots of system issues



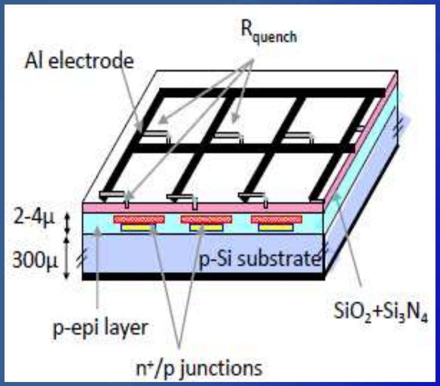
Impact of Electronics (e.g. OMEGA Chips) beyond ILC:

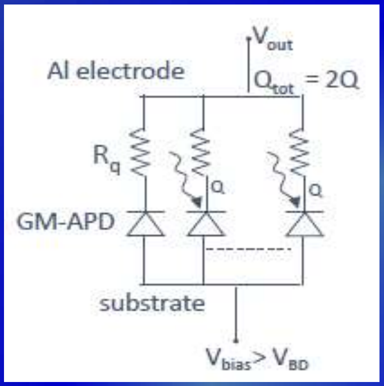


State-of-the-Art in Silicon Photomultipliers

Most recent, and arguably most popular, solid state photon detector is the SiPM

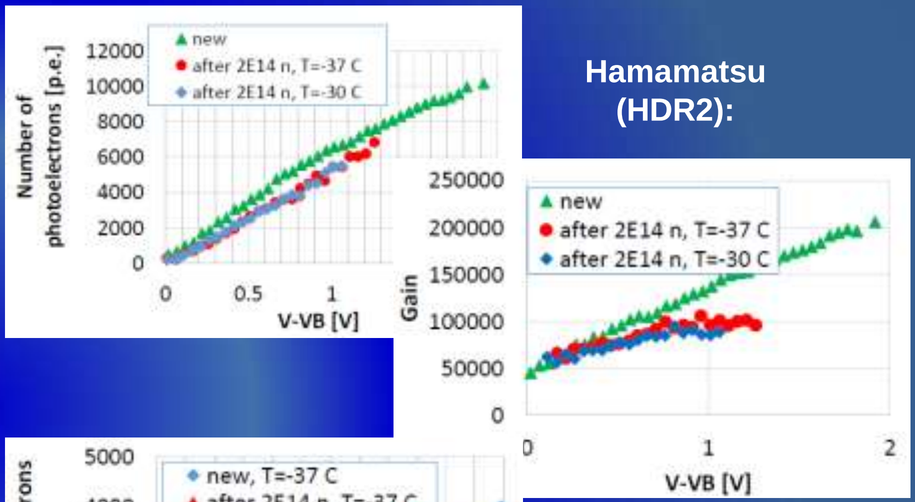
A. Gasanov, V. Golovin, Z. Sadygov, N. Yusipov (1989)

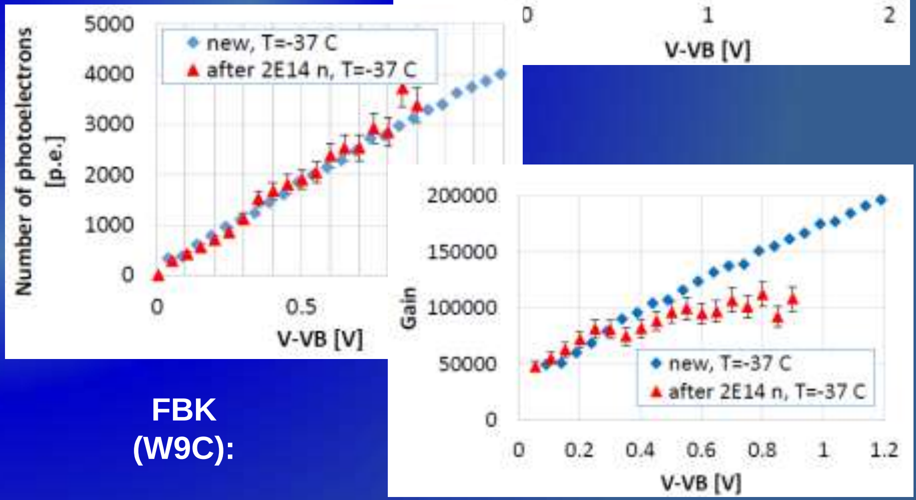




Change of SiPM parameters after very high neutron irradiation:

Hamamatsu (HDR2):





FBK (W9C):

Significant progress in understanding of SiPM physics was achieved during last 5 years:

Breakthrough in SiPM production:

- ✓ **Reduced correlated noise**
  → cross-talk, afterpulsing
- ✓ **Improved PDE (50-65 %, blue-green light)**
- ✓ **Reduced dark noise**

- ✓ **Encouraging results with 15 μm cells (FBK, HPK) and operation at -30C indicate ability to operate up to ≃ 2x10^{14} neq/cm^2**

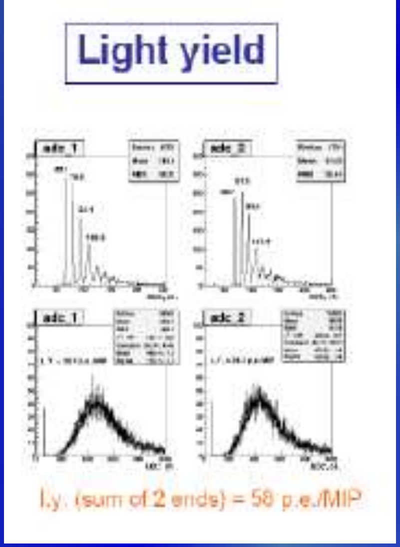
Y. Musienko

The HPK and FBK SiPM are still operational after ≃ 2x10^{14} neq/cm^2 → main limitation is due to high power dissipation, caused by dark current increase, limiting to operation at ΔV ~< 1V

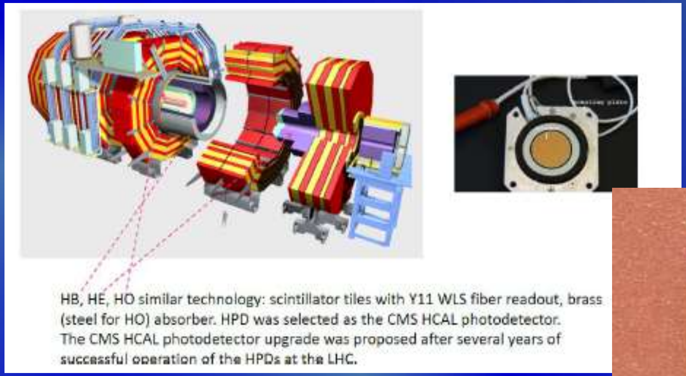
Some Examples of SiPM Applications in Experiments

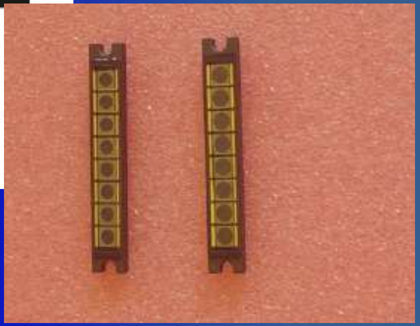
T2K Near Detector: Large scale (~60 000) use of SiPMs: Sci-detector with WLS fibers

Hamamatsu MPPC:
Active area:
1.3 x 1.3 mm2



CMS HCAL Phase I Upgrade: replacement of HPDs with 20 000 SiPMs – higher QE, better immunity to magnetic fields, depth segmentation, timing (kill bkg)

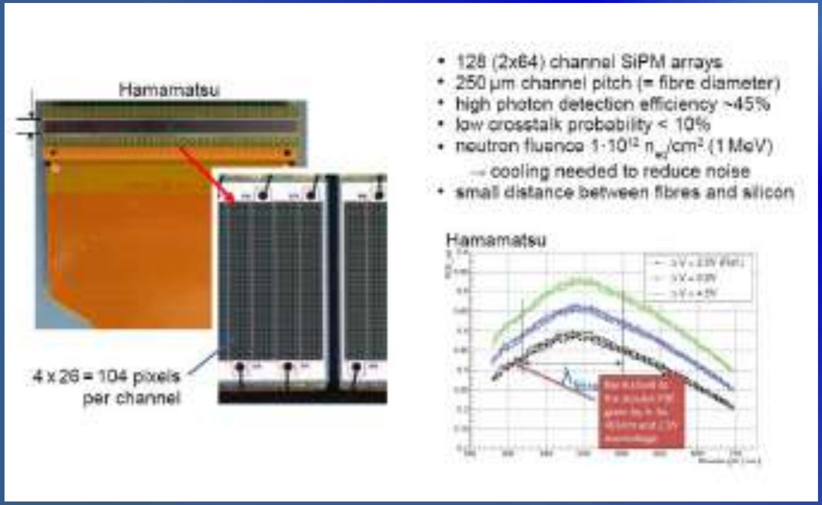




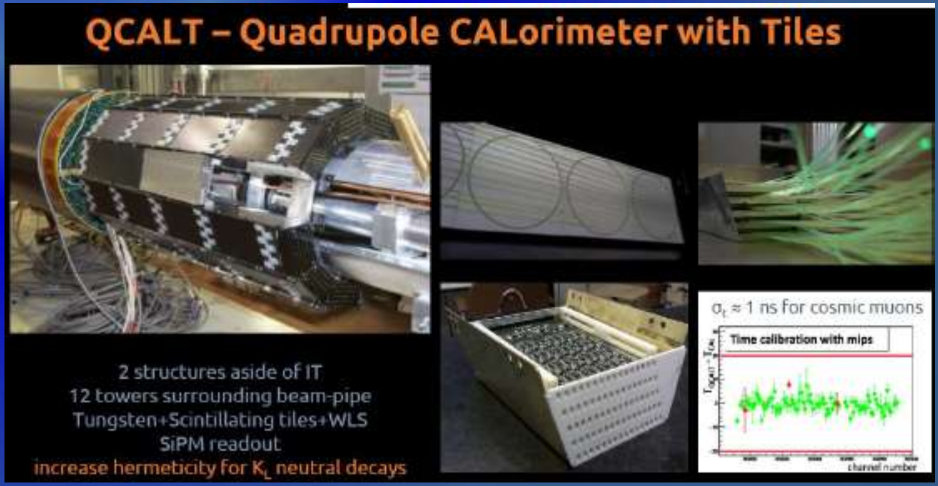
SiPM:
2.8-3.3 mm diameter

Y. Musienko

SciFi Tracker @LHCb: 6 layers of 2.5 m long Sci-fibers readout by 128 SiPM array



KLOE2 Calorimeter: SiPM will be used to read-out LYSO crystals and W/Sci tiles with WLS fibers



Advanced Concepts in PARTICLE IDENTIFICATION

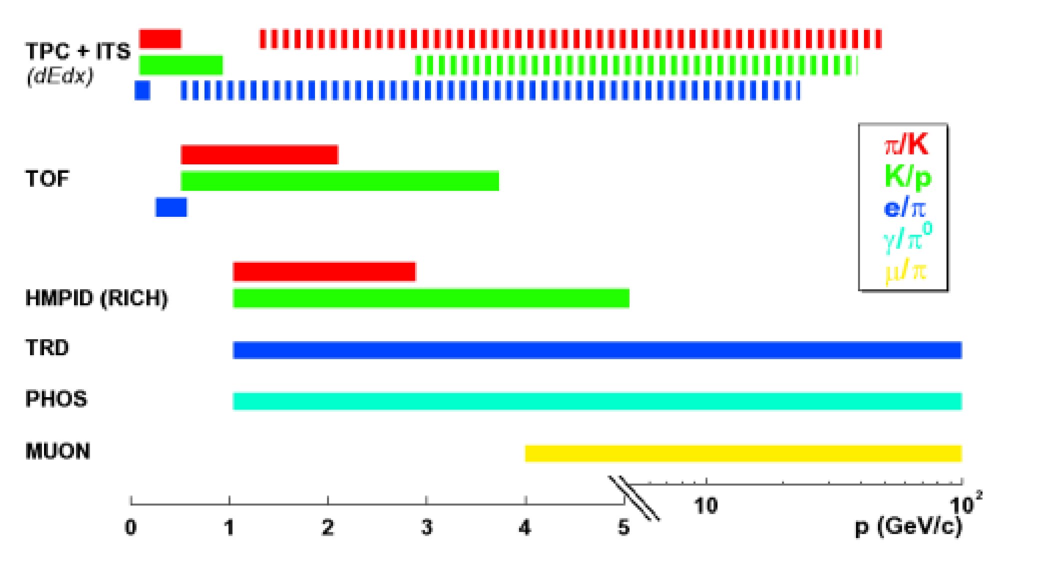
Essential to identify decays when heavy flavour are present: everywhere

Three legs: dE/dx, Time-of-Flight, Cherenkov radiation

Admirable workmanship in radiators and light transport:

- ✓ **Vacuum Photon Detectors**
  - **– Photo Multiplier Tubes**
  - **– MCP-PMT**
  - **– Hybrid Tubes**
- ✓ **Solid State Photon Detectors**
  - **– Silicon-based (MPPC, CCD)**
- ✓ **Gas-based Photon Detectors**
  - **- Photosensitive (TMAE/TEA) in gas**
  - **- MWPC/MPGD + CsI**
- ✓ **Superconducting Photon Detectors**
  - **– Transition Edge Detectors**
  - **– Kinetic Inductance detectors**

Excellent PID capabilities by combining different techniques over a large momentum range



- ➢ Threshold Cherenkov Counters (Aerogel + PMT)
- ➢ RICH Detectors (measurement of Cherenkov angle / particle velocity or yield) :

- TOP principle: 1-time of propagation + Cherenkov angle (instead of 2D imaging)
- RICH+TOF: Measure timing of Cherenkov light
- ALICE MRPC: Gaseous timing
- TRD: Cluster Counting method (dN/dx)

More → P. Krizan review talk

Photon Detection in RICH Counters

Photon Detector is the most crucial element of a RICH counter

LHCb RICH I and II Upgrade for Run-III:

- New photon detectors for RICH1 and RICH2: MaPMTs
- New electronics @ 40 MHz
- New optics layout for RICH 1

Cherenkov angle resolution: **A. Papanestis**

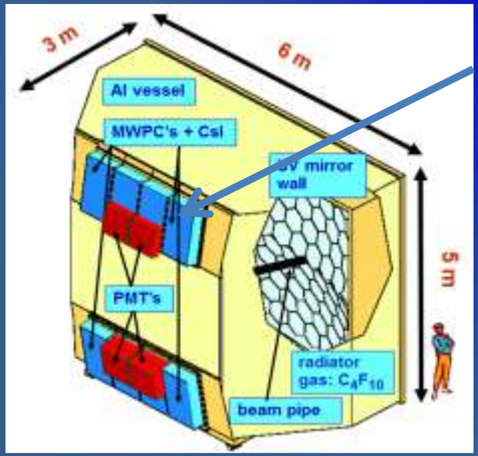
Contributions to resolution (in mrad)	RICH1-2015 HPD	RICH1-Upgrade MaPMT	RICH2-2015 HPD	RICH2-Upgrade MaPMT
Chromatic	0.84	0.58	0.48	0.31
Pixel	0.60, PSF=0.86	0.44	0.19, PSF=0.29	0.19 0.41 (large)
Emission Point	0.76	0.37	0.27	0.27
Overall	**1.60** →	**0.78**	**0.65** →	**0.45**

NA62 RICH:

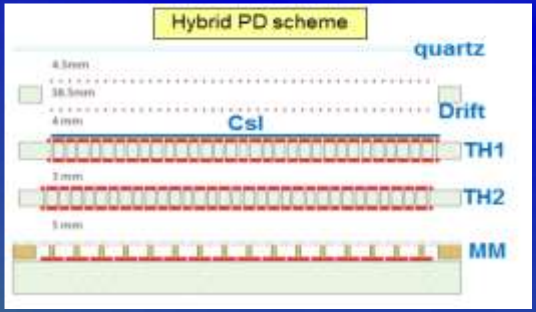
- ✓ 17m long, 200m3 vacuum tank with Ne radiator
- ✓ Photon detectors: 2000 PMTs
- ✓ **Good test for GPU-based online selection (RICH participates in the trigger)**

N. Tursini

COMPASS RICH Upgrade:

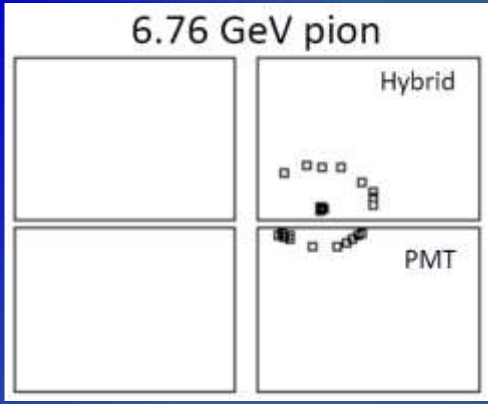


Replace 8 MWPC's/CsI with hybrid (THGEM /Micromgas) with CsI



S. Dasgupta

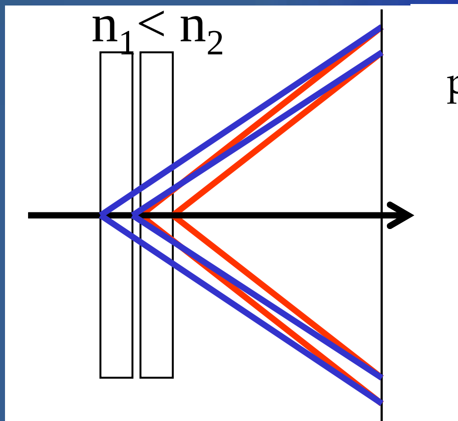
COMPASS
event display



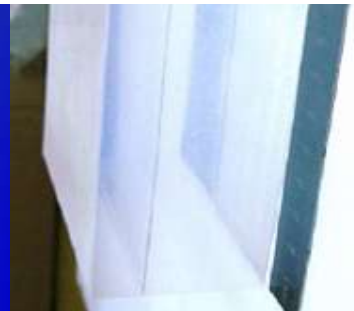
- Exploring a possibility to use more robust PC: hydrogenated nano-diamond crystals
- R&D towards compact RICH for the future EIC

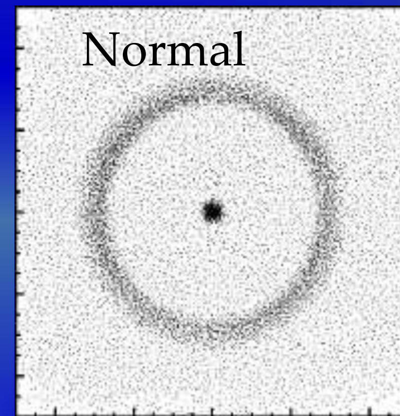
Trends in Aerogel Radiator RICH devices

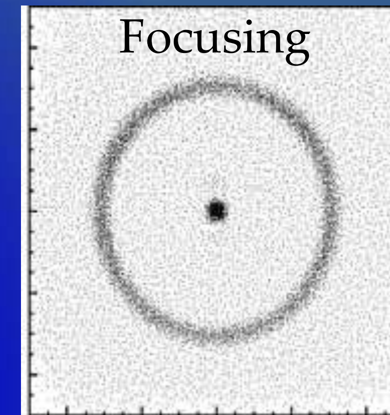
Use of focusing configuration: ARICH (Belle), FARICH (PANDA, ALICE, Super c-τ)



Thicker aerogel → parallax error increase

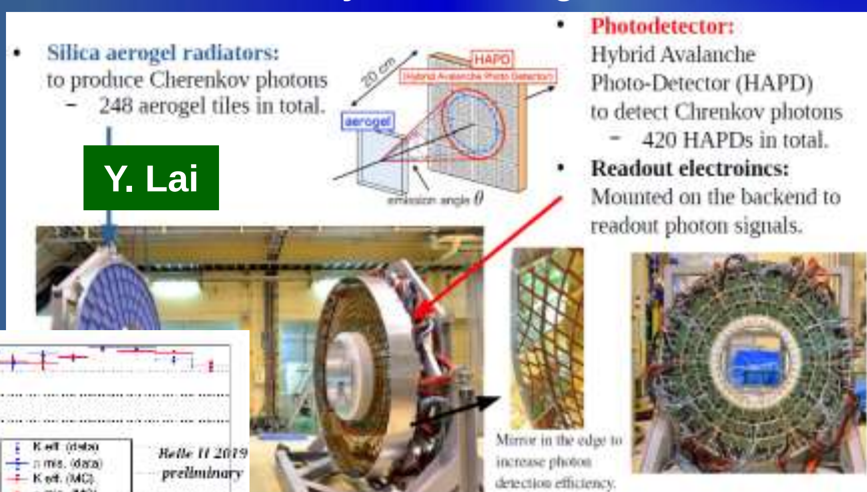




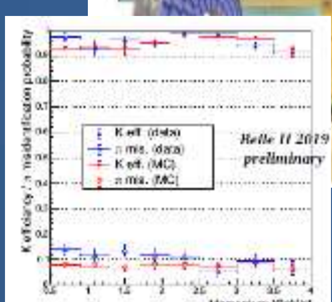


BELLE-II ARICH:

Two 2 cm thick layers of aerogel radiator:



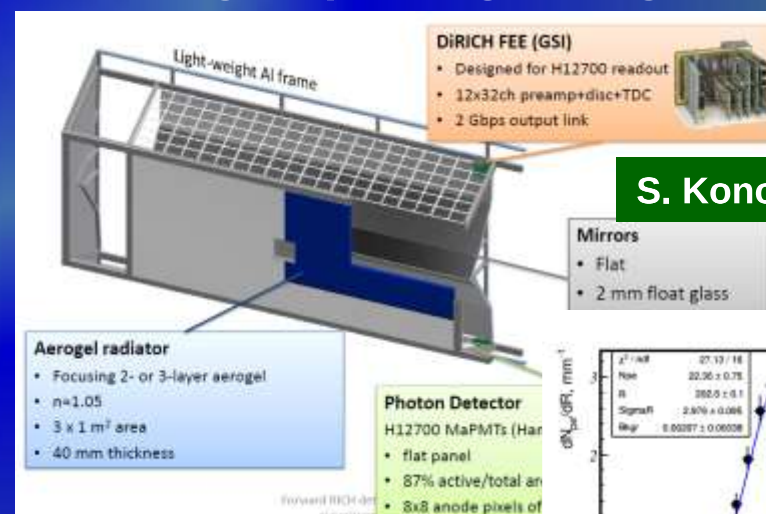
Y. Lai



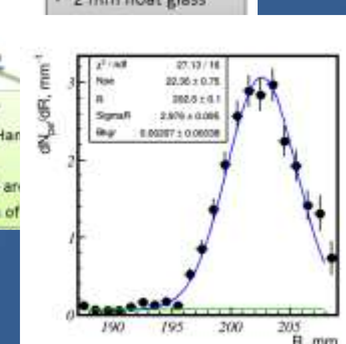
Good agreement between DATA and MC

Forward RICH for PANDA:

Focusing 2-layer aerogel configuration



S. Kononov



Test-beam results in good agreement with MC

Many Clever Techniques for Ultra-Fast TOF and TOP

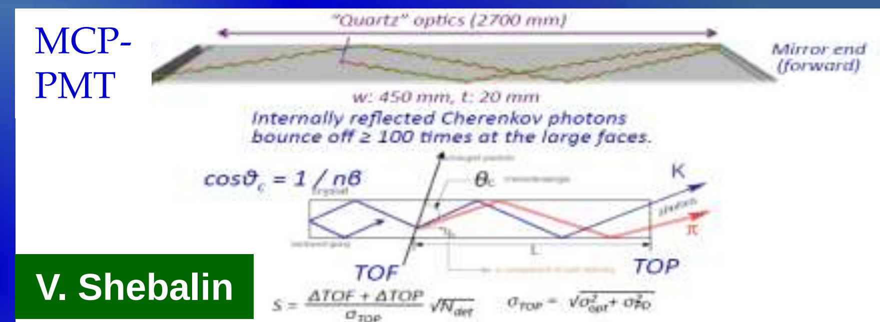
Fast progress in new DIRC (Detector of internally reflected Cherenkov light)
- RICH/TOF counters with excellent timing (MCP-PMTs)

GLueX DIRC @JLAB:

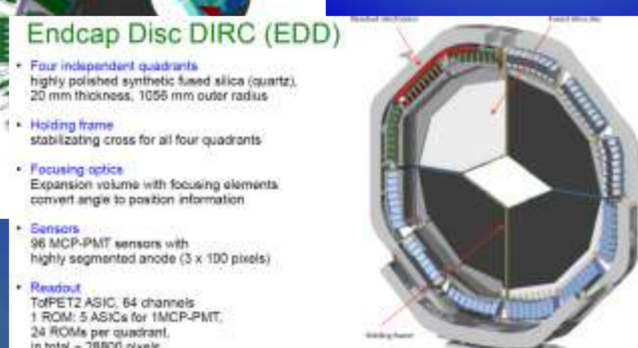
Four BaBar DIRC bar boxes transported safely from SLAC to JLab, combined with new

Belle-II TOP Detector:

Based on a DIRC concept: instead of 2D-imaging,
→ Cherenkov ring imaging with precise timing

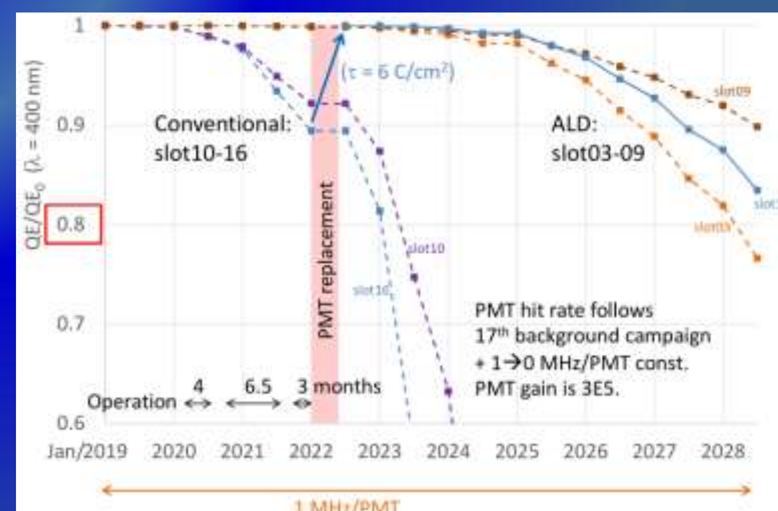


Barrel and Endcap DIRC @PANDA:



C. Schwarz

Replace conventional PMT with ALD-PMT

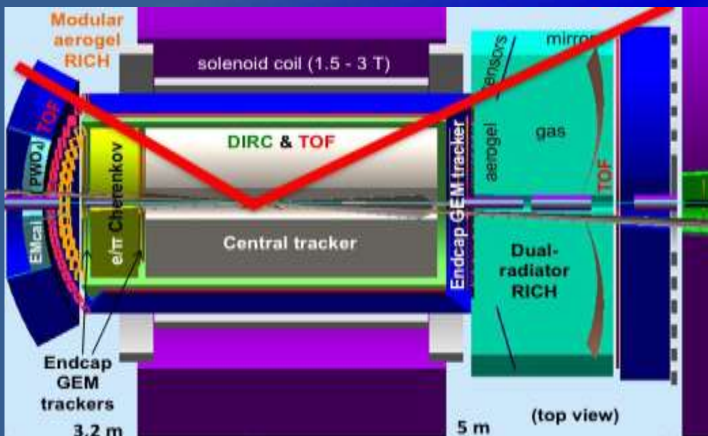


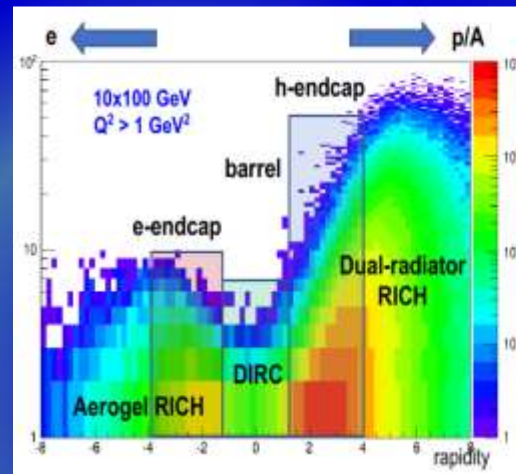
Particle Identification (PID) for Electron-Ion Collider

RICH Detectors for Particle Identification @EiC

- ✓ dRICH: dual-radiator (aerogel & C2F6) RICH
- ✓ mRICH: lens-focusing modular aerogel RICH
- ✓ hpDIRC: compact fast focusing DIRC

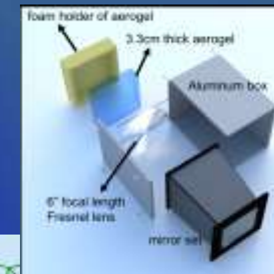
TOF (and/or dE/dx in TPC): can cover lower momenta



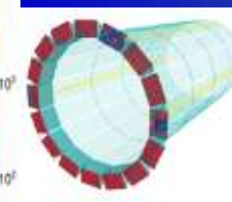


J. Schwiening

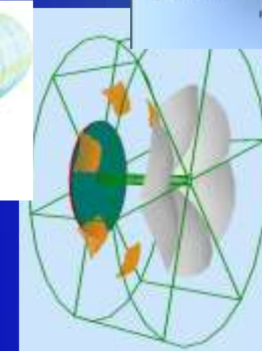
mRICH:



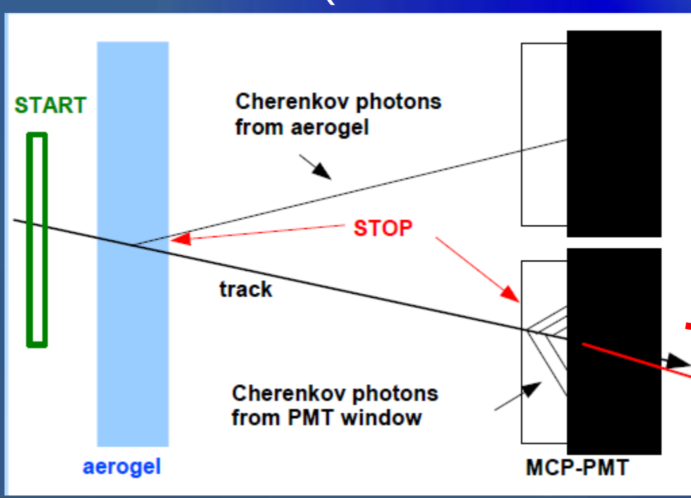
hpDIRC:

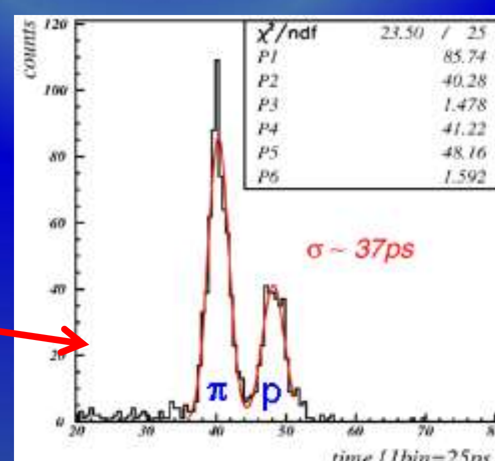


dRICH:



Generic R&D: combination of proximity focusing RICH + TOF with fast new photo-sensors (MCP-PMT or SiPM) using Cherenkov photons from PMT window

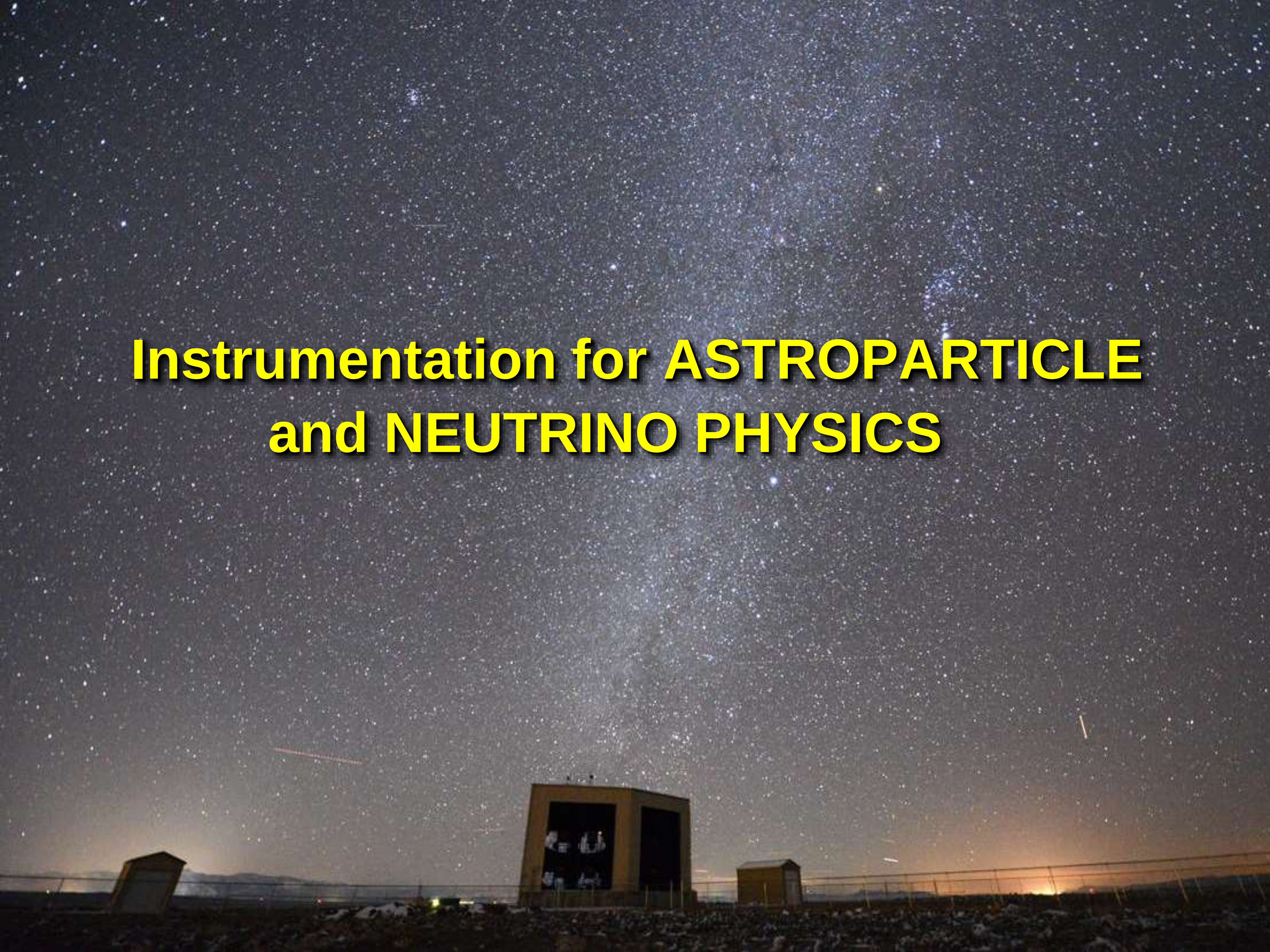




Cherenkov photons from PMT window can be used to positively identify particles below threshold in aerogel

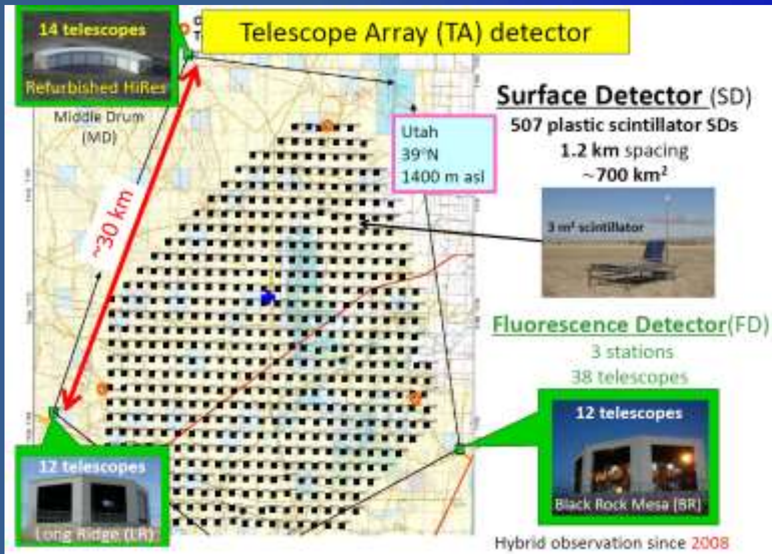
P. Krizan

Instrumentation for ASTROPARTICLE and NEUTRINO PHYSICS



Ultra-High Energy Cosmic Rays: Present and Future

Telescope Array Collaboration:



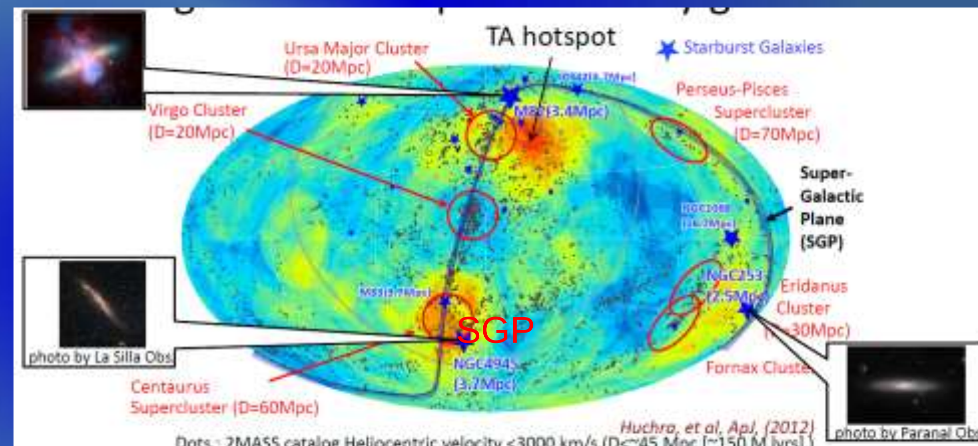
The TAIGA experiment - a hybrid array for very high energy γ-ray astronomy (> 30 TeV) & cosmic ray physics in the Tunka valley

V. Budnev

Taiga – Muon installation → A. Vaidyanathan

Arrival directions of highest energy cosmic rays: Large Scale Anisotropy and Hotspot

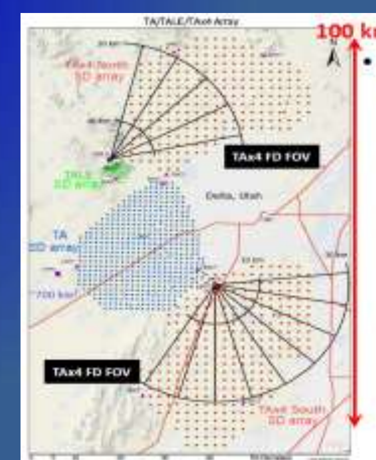
An anisotropy is seen for cosmic rays above cutoff energy (E > 57 EeV, 168 events) by TA in 11 years. Post-trial significance to see this level of flux enhancement anywhere in TA's field of view is 0.2% (2.9 σ).



Significance of excess (red/yellow) is close to Super Galactic Plane!

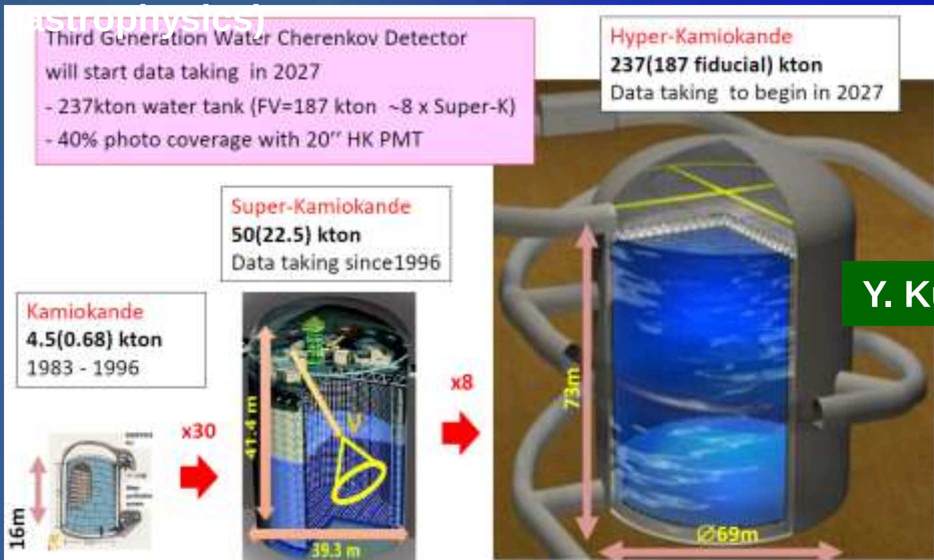
TAx4 has partially started:
TA SD → TAx2.5 now

H. Sagawa



Advanced Detector Concepts for HypeK Experiment

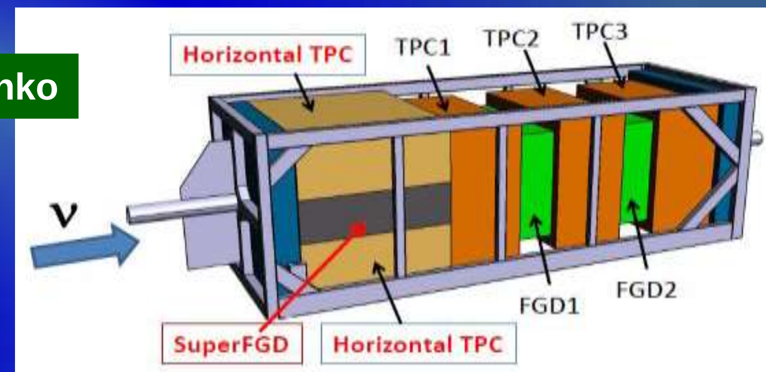
HyperKamiokande goals: search for CP violation @ 5σ, proton decay, neutrino astrphysics
astrophysics)



Y. Kudenko

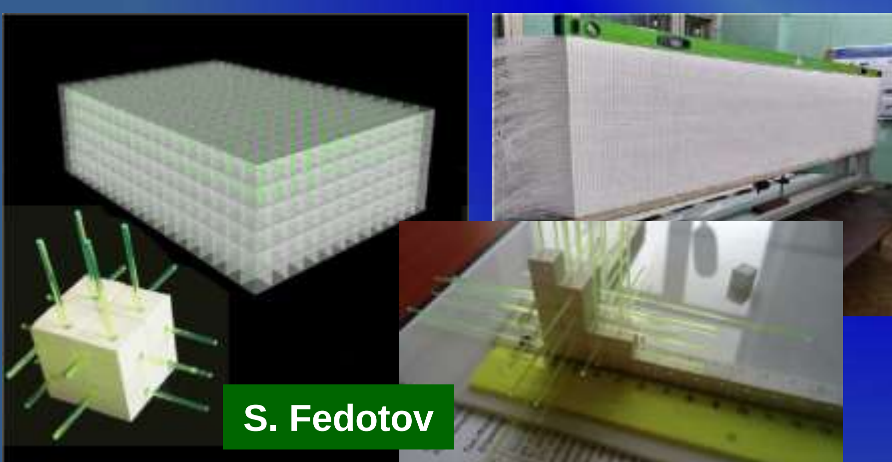
New upstream tracker (ND280) to reduce syst.:

- 2 high-angle Horizontal TPC
- 3D fine-grained scintillator target SuperFGD
- TOF system around new tracker



ND280 scintillator detectors (FGD) for T2K

SuperFGD concept with 3D fiber readout and MPPC

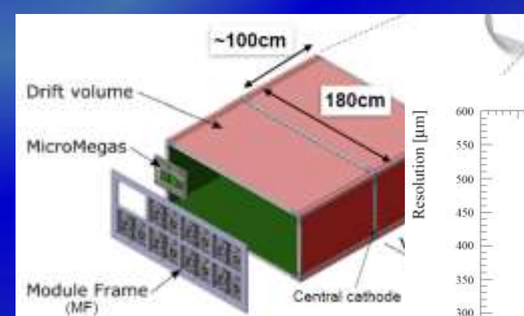


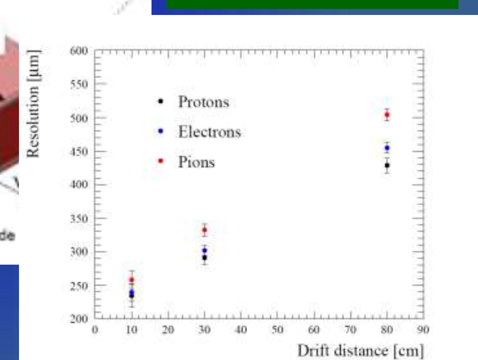
S. Fedotov

ND280 TPC with Resistive MM for T2K

Resistive MM tested @ CERN & DESY:

C. Jesus-Valls





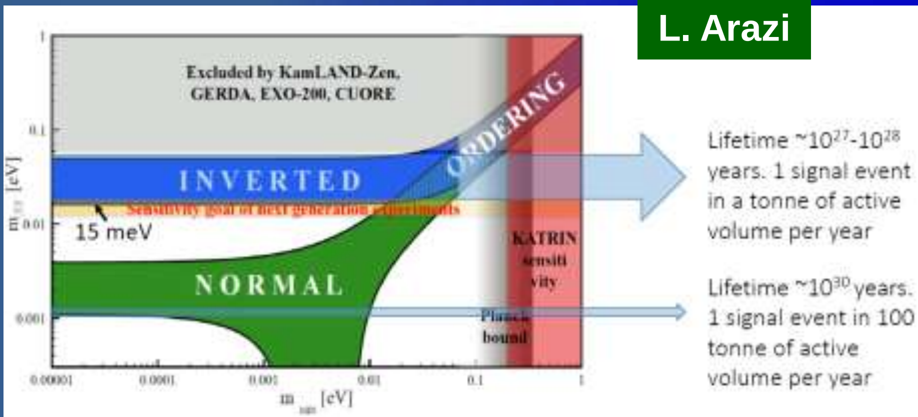
Installation is scheduled for fall 2021

Advanced Detector Concepts for Neutrino Physics

Next generation of 0νββ experiments:

probe the inverted hierarchy region

L. Arazi



Use different technologies/approaches:

- Germanium detectors
- Bolometers
- Loaded liquid scintillators
- Liquid Xe- TPCs
- High-pressure gaseous Xe-TPCs
- (Others)

A coherent elastic neutrino-nucleus scattering (CEvNS): n + *A* → n '+*A*':

COHERENT Collaboration (LAr detector):

- ➢ First measurement (3σ level) at the SNS (Oak Ridge) in agreement with SM (within 1σ)
- ✓ Background for future Dark Matter searches

Multitarget experiment

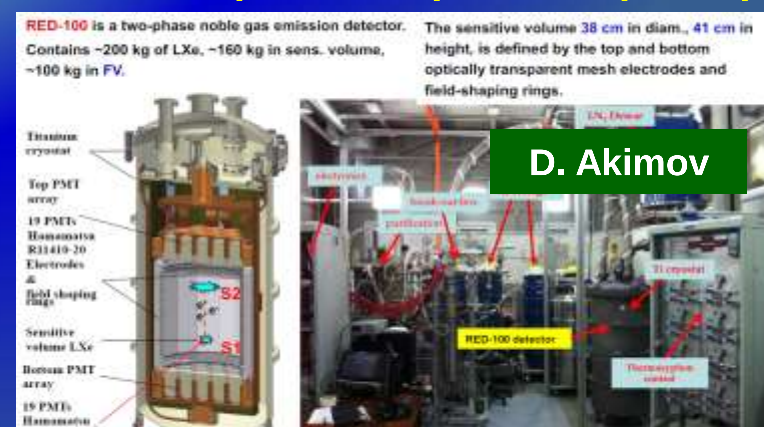
A. Kumpan

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	(keVnr)
CsI[Na]	Scintillating crystal	14.6	19.3	6.5
LAr	Single-phase	24	27.5	20
NaI[Tl]	Scintillating crystal	185 → 3338	28	13
Ge	HPGe PPC	16	20	2-2.5

Will be deployed

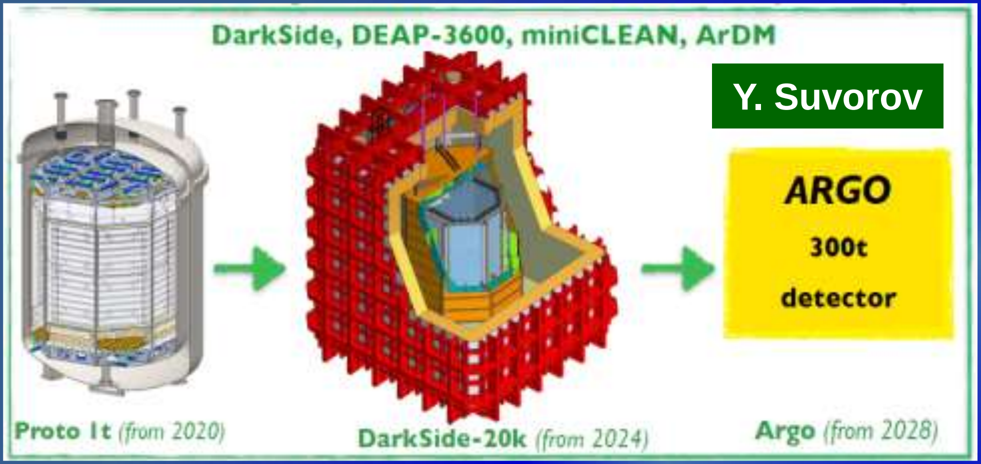
RED-100 Experiment (LXe two-phase):

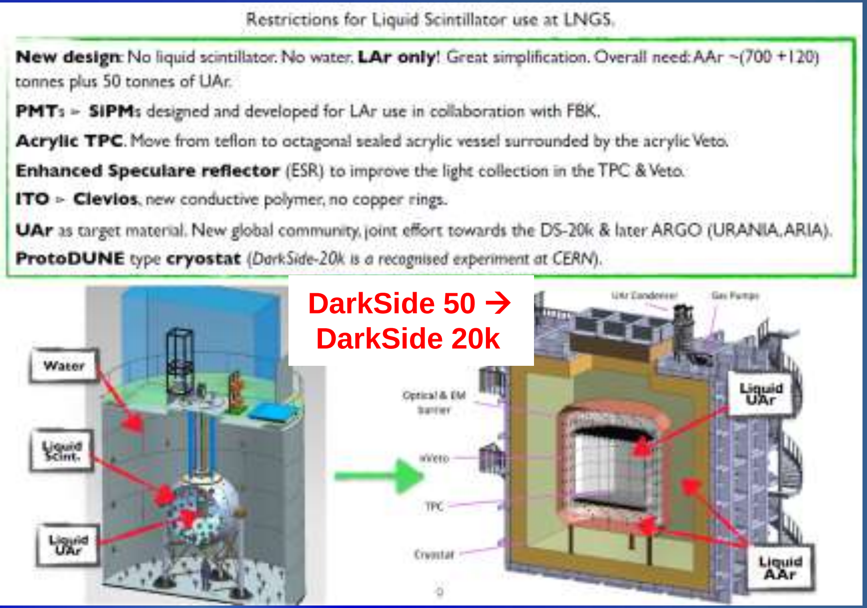
D. Akimov



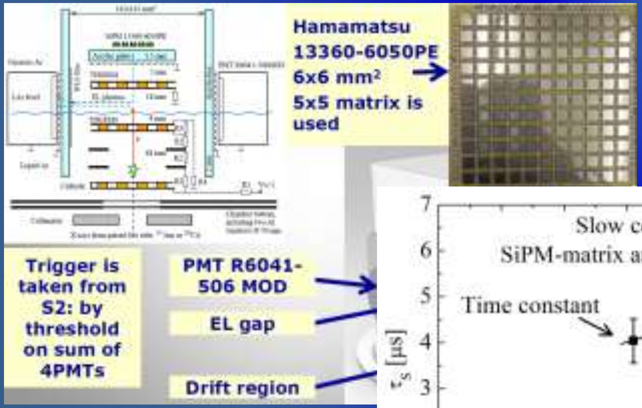
Ar-based Detectors for Dark Matter Searches

2017 - Global Argon Dark Matter Collaboration

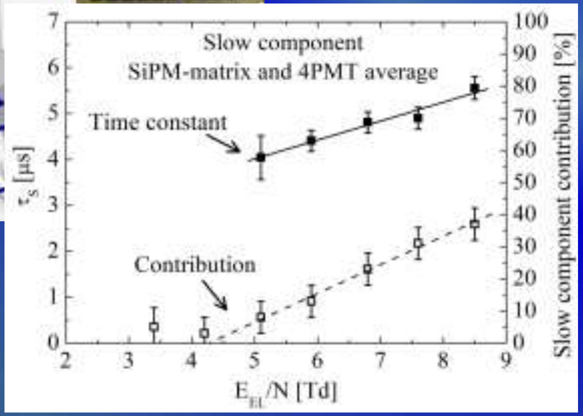




2-phase Ar detector for Dark Matter Experiments:



E. Frolov



Unusual slow component has been observed in electroluminescence signal (S2) of two-phase Ar

Ar-Scintillation and –Electroluminescence for WIMP Dark Matter Searches

Construction of LAr high field / high light yield det.

It was an exciting week with a lot of presentations and discussions !

TIME TO RELAX and HAVE a SAFE TRIP HOME !

THANKS A LOT TO THE LOCAL ORGANIZING COMMITTEE

FOR THE EXCELLENT CONFERENCE !!!


BACK-UP SLIDES