

RD51, status and perspectives

6th International Conference on Micro Pattern Gaseous Detectors

5-10th May 2019

M. Chefdeville, LAPP, Annecy



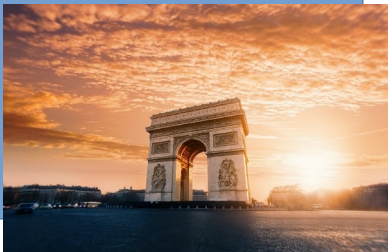
Introduction & overview

- I of course regretted to have accepted this talk
 - How to put together such wealth of results?
 - Previous reviews were both exhaustive and inspiring (M. Titov, E. Oliveri)!
- In 2010, I was given the chance to talk on the collaboration behalf
 - Looking back
- As a physicist working at LHCb
 - Imminent Run III of LHC
- Highlights of recent developments
 - Resistive detectors, timing

Looking back

- 5th symposium on TPC for Low Energy Rare Event detection, 2010
- RD51, a world-wide collaboration for the development of Micro Pattern Gas Detectors

2010



2012



2014



2016



2018



Large area in 2010

- At that time, a selection:

Commissioning of T2K std-uM TPC
 Big readout board for MAMMA
 Trapezoidal shaped GEM for CMS
 Upgrade of TOTEM GEMs
 M2 uM prototype for ILC calorimetry
 ILC TPC: LP, octopuce...

- Today: data taking completed
 or ready for data taking
 or ready for future experiments

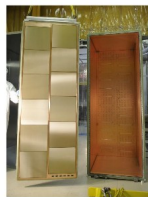
arXiv:1111.4426 All three TPCs were [...] operational during the first T2K physics run [...] and the second one.



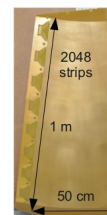
Large area Micromegas and GEM

TPC for T2K near detector

3 TPC with total readout area of 9 m²
 1 endplate (0.7x2 m²) made of 12 modules of 34x36 cm²
 Each module has 48 rows of 36 pads (1726 pads)

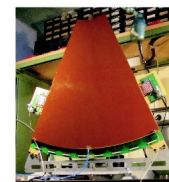


Upgrade of ATLAS forward muon spectrometer



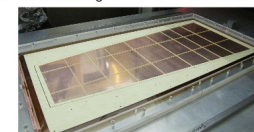
Possible upgrade of TOTEM T1 tracker

Triple GEM prototype of 1/5 m², based on 66x66 cm² foils
 New manufacturing techniques
 → 2 mm dead regions between foils
 → Very fast gain stabilization (no rim, tens of seconds)



Extension of CMS muon detection system

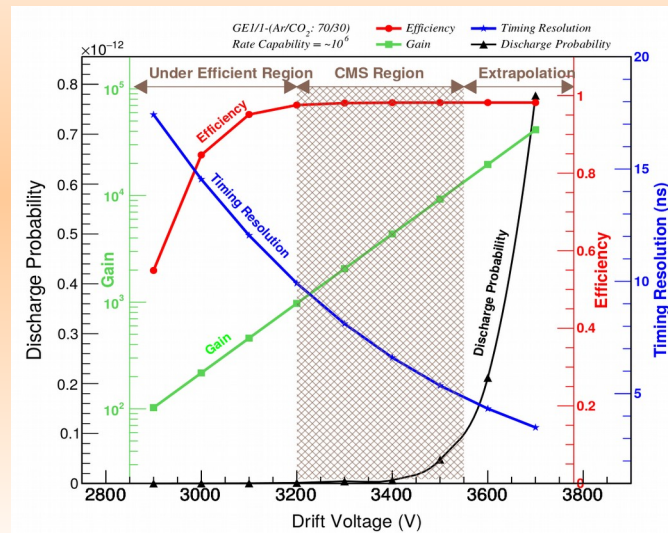
First prototype of trapezoidal shape with triple GEM
 Total area of 99 x 45-22 cm² ~ 1/3 m²
 Divided into 4 eta regions readout with radial strips



Gas chambers for a sampling HCAL for ILC

Construction of a 1 m³ physics HCAL prototype with 40 layers
 1 m² chamber made of 6 modules of 32x48 cm² (1/6 m²)
 Each module has 1536 square pads of 1 cm²
 Dead area < 2% inside gas volume, chamber thickness of 12 mm

arXiv:1903.02186 The design of these chambers is finalized, and the installation is foreseen during the LS2 starting at the beginning of 2019.



mpgd Structures in 2010

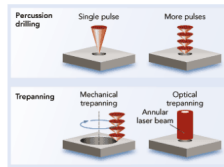
Ultrafast drilling with laser beams

Laser ablation
Remove material from a solid surface with a pulsed laser
Precision depends on pulse duration and material

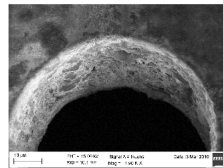
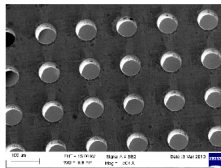


Application for making GEM holes
Make it possible to drill more perfect holes in quantities
Kapton and copper have very different thermal and physical properties
Need to tune the laser parameters (duration, wavelength, fluence, drilling strategy)
Complete control of the geometry (diameter, pattern)

Promising results
High repeatability but
Cu deposition inside hole (Electrical isolation not always guaranteed)
→ post-process etching or drilling assisted by inert gas flow



Laser parameters:
• wavelength: 1064 nm
• pulse duration: 100 ps
• repetition rate: 100 kHz
• average power: 0.7 W
• spot size: 30 μm
• trepanning radius: 20 μm



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- Bulk μm & double-mask GEM

- At that time:

Single-mask GEMs

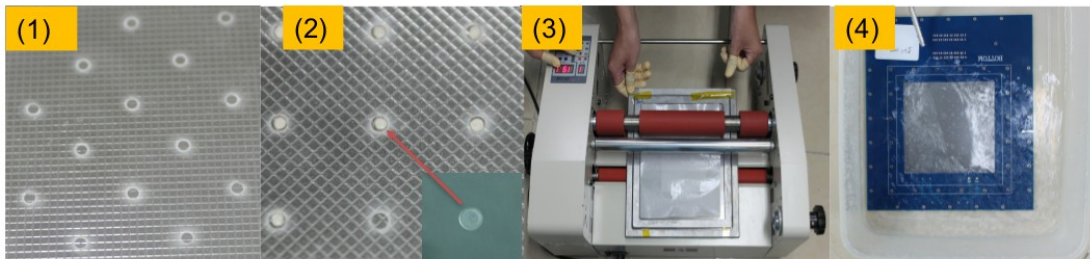
THGEM, RTHGEM, uBulk

Laser-drilled foils

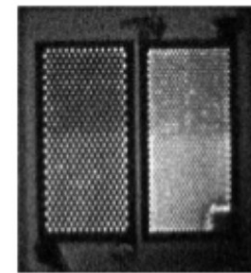
- The rise of resistive (cf. later)
- Still new ideas

Thermal bonding (J. Liui et al., USTC, 2018)

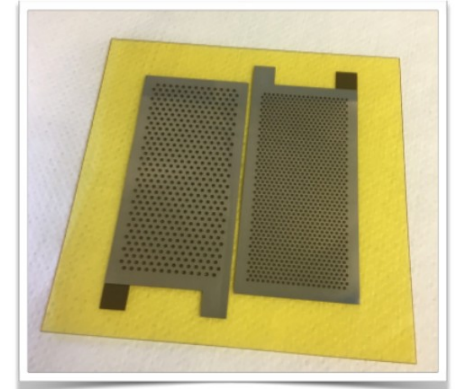
→ We have developed a new spacer setting technique using water-soluble film to optimize the thermal-bonding process.



3D inkjet printing of functional detector structures (F. Brunbauer, CERN, 2018)



950 V
 ΔV_{THGEM}



Production in 2010

Production of MPGD

Objective
Development of cost effective technologies and industrialization

Today, CERN workshop is the unique MPGD production facility
Generic R&D, production of detector components, quality control

Future upgrade of the workshop has been approved by CERN management
New equipment to fabricate larger area detectors
Requests for SLHC experiments

In parallel, steps toward technological transfer to industrial partners for mass production are taken
GEM : New Flex (Korea), Tech-ETCH (USA), Scienergy (Japan)
Micromegas : CIRE (France), SOMACIS (Italy), Triangle labs (USA)

Detector technology	Currently produced cm * cm	Future requirements cm * cm
GEM	40 * 40	50 * 50
GEM, single mask	70 * 40	200 * 50
THGEM	70 * 50	200 * 100
RTHGEM, serial graphics	20 * 10	100 * 50
Micromegas, bulk	150 * 50	200 * 100
Micromegas, microbulk	10 * 10	30 * 30
MHSP (Micro-Hole and Strip Plate)	3 * 3	10 * 10



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Building 107: “a safe space for chemicals”
(Feb. 2018 CERN news [link](#))

ALICE, TPC read-out, ~ 500 m² of GEM foils
ATLAS, small wheels, 1200 m² to be instrumented
CMS, GE1/1 forward detectors, 250 m² of GEM foils
COMPASS RICH, 4.5 m² to be instrumented, single photon detection

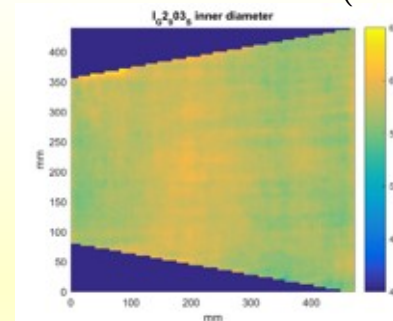
QA of ALICE GEMs: Uniformity, spark detection system
(M. Ball et al., HISKP, 2017)

- Was mostly CERN-centered
- New workshop → new capabilities

2x1m² Bulk uM & 2x0.5m² GEM

- Transfer to industry happened (had to)

Strong interplay with CERN
→ importance of QA tests

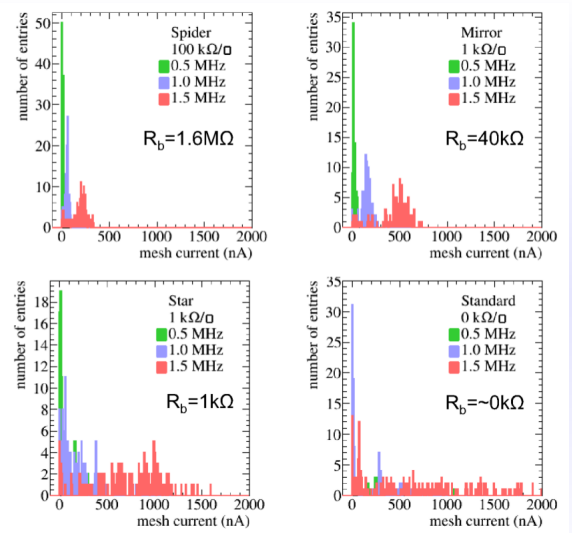
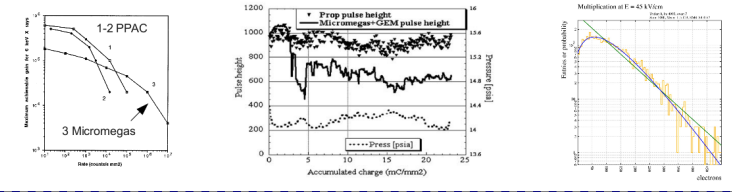


Physics phenomena

- Focused on:
 - Sparks – Aging – Charge-up – Fluctuations
- No change really but much progress
 - Several studies @ GIF of techno for LHC upgrades
 - Spark: region of stability known (still largely empirical)
 - Growing interest for timing (cf later)

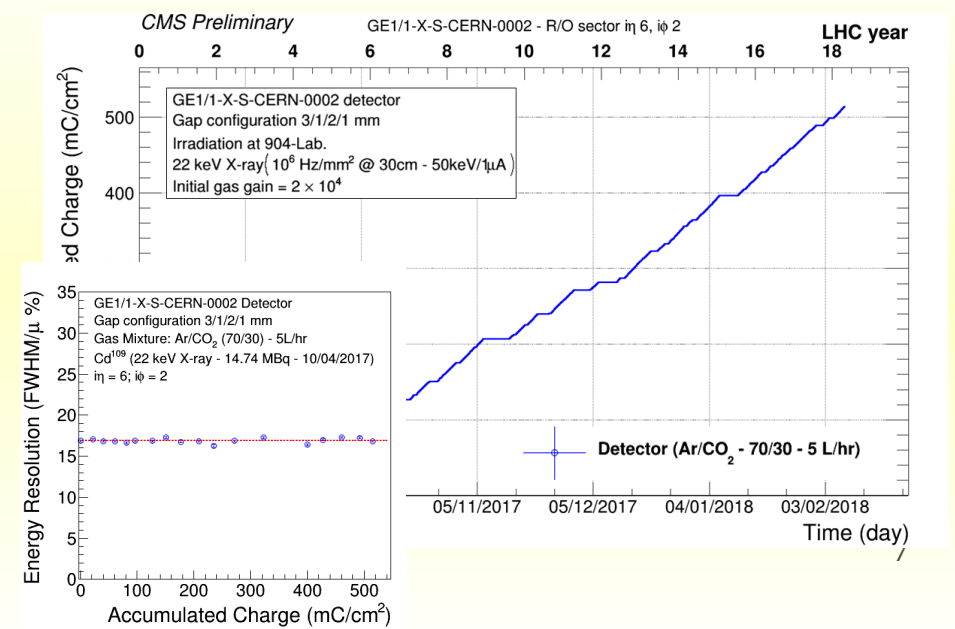
Study of phenomena related to MPGD operation

Gas discharges	Aging	Charging-up	Gain fluctuations
Micro-defects Rather limit Max. gain VS radiation	Material outgassing Radiation hardness Database of bad/good materials	Dielectric charging-up Diffusion of avalanche charge	Single electron response Polya VS exponential
Feedback phenomena Ion impact in noble gas Photo-effect in avalanche	Gas flow/mixture ppm Impurities	Geometry Influence of dielectric Shielding against avalanche charge	Photon feedback Second Townsend coef.
High rate mechanisms Avalanche overlap Ion space charge at the cathode	Rate effects Polymer deposits Matter effects Photo-cathode QE loss	Gain stability Time constants Discharges	Penning transfers Gain enhancement
			Electric field Low VS High Hole edges



μM SDHCAL Mesh current through embedded-R (Chefdeville et al., 2015)

CMS GEM 18 years of ME0 operation @ HL-LHC (F. Fallavollita et al, 2018)

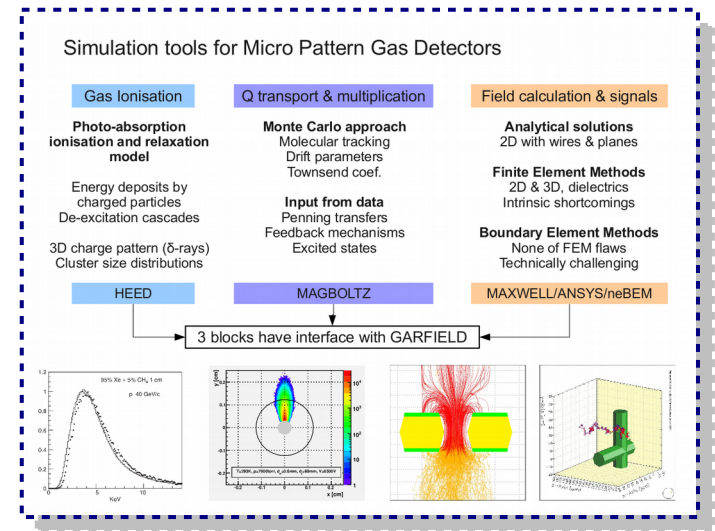


Simulation in 2010

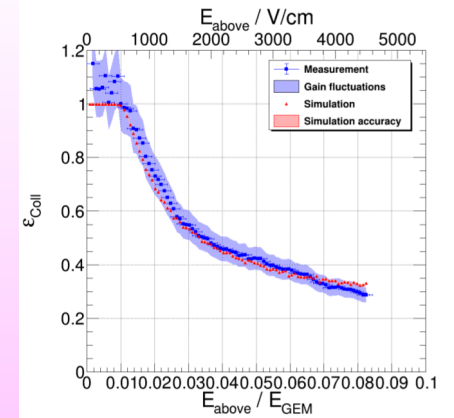
- Focused on:
 - Ionisation – Transport – Field solver & signals
- Maintained & improved tools

Complete set of programs with interfaces (Magboltz-Heed-Garfield-Geant4-Field solvers).
 Long-term use → Garfield C++.

Microscopic tracking, hydrodynamic model
 → Can model transparency, charge-up, streamer dvp^t



MultiGEM (J. Ottvad, 2018)



Precursor & streamer (P. Fonte, 2018)

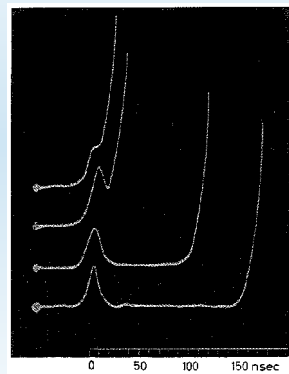
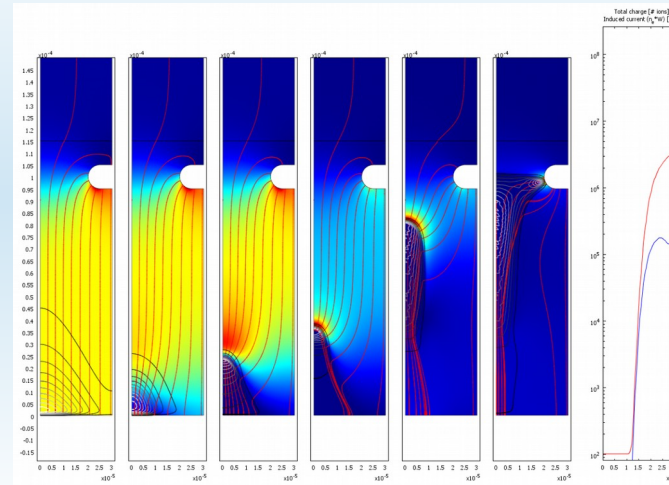
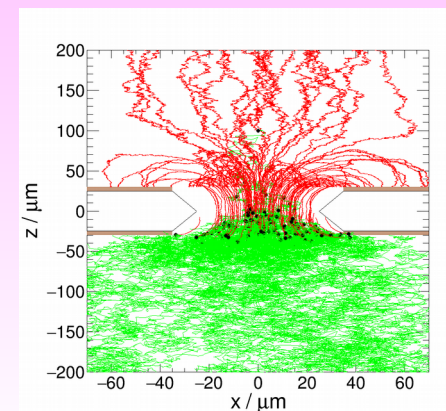
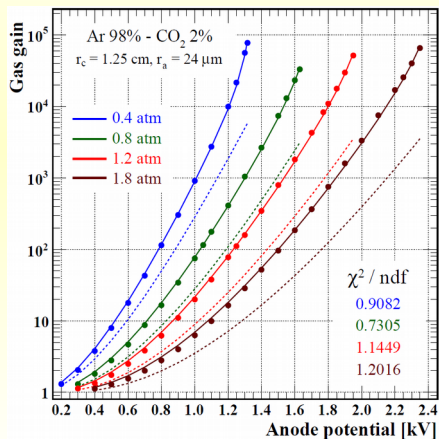


Figure 5.14. Current oscillograms of static breakdown in methylal. Optical method. $E_{lp} = 64.4$, $p d = 250$ Torr cm, $d = 0.8$ cm, $T_e \sim 90$ nsec $RC \sim 5$ nsec²

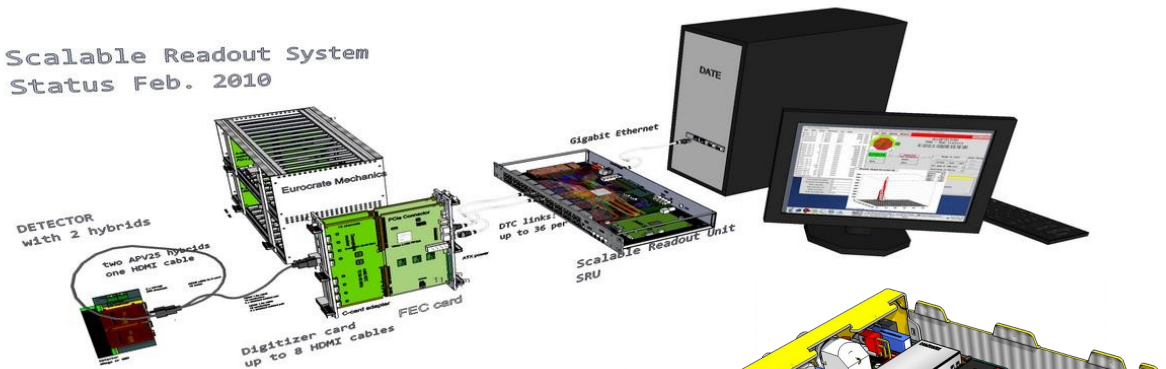
Penning & γ-feedback (O. Sahin, 2018)



SRS in 2010

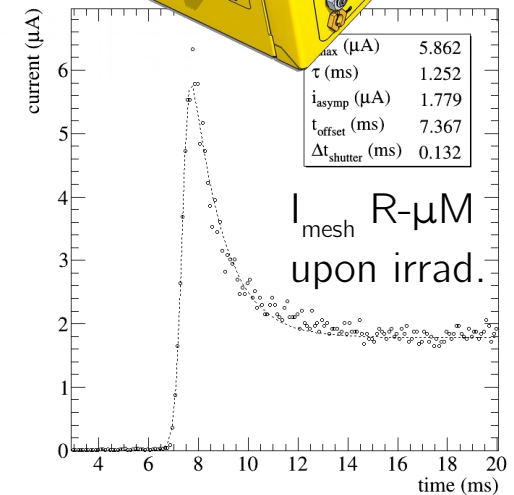
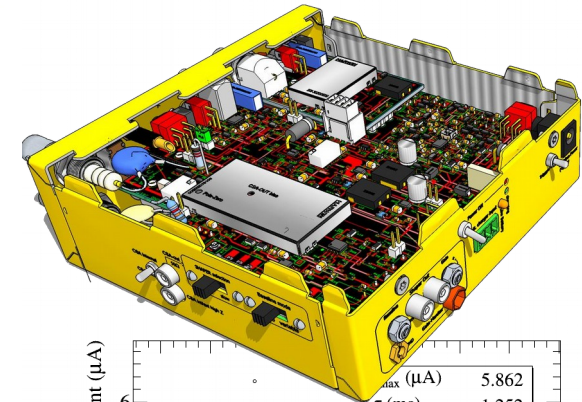
Scalable Readout System (SRS)

Scalable Readout System
Status Feb. 2010



APIC

H. Muller 2018



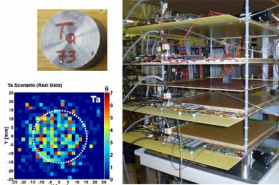
Implementation of the SRS

Muon tomography with GEM

High-Z material \rightarrow significant multiple scattering of muons
Measure scattering angle with tracking stations

Minimal system with prelim. electronics

4 triple GEM stations of 30x30 cm²
Strip readout (X/Y) over 5x5 cm²

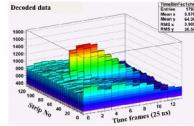
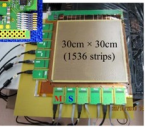


First complete small SRS prototype in fall 2010

12 APV25 chips
master & slave boards
1536 channels

ADC/FEC cards
8 HDMI inputs
12 bit ADC 50 MS/s

PC
with DATE/AMORE
software (ALICE)



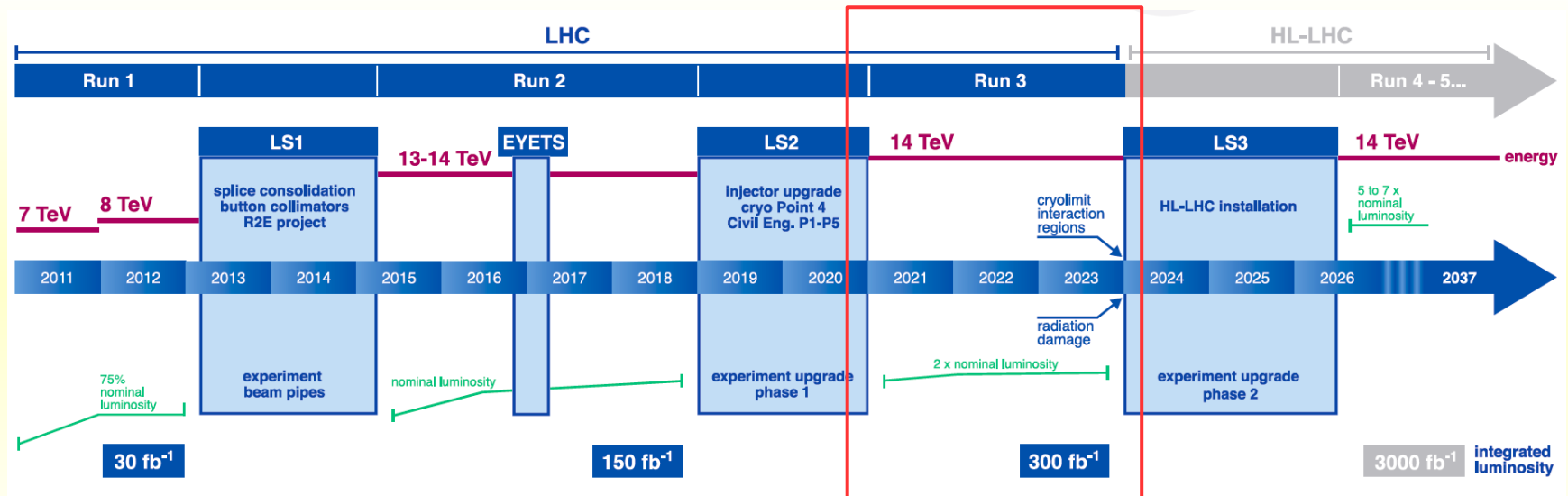
Full chain functional after 1 day
5 stations successfully tested (1 after the other)
Next: equip 10 stations \rightarrow 16 k channels \rightarrow SRU

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- First implementation around 2010
- Since then, quite successful:
>100 small systems (critical for TB) + interface to APV & VMM
In-house prod. stopped \rightarrow direct SPS sales > 2017
- Service electronics in GDD lab: versatile tools
APIC is a pre-amplifier, dual shaper and dual polarity trigger discrim.

FemtoMeter box (I was happy to find it), LED pulser coming soon

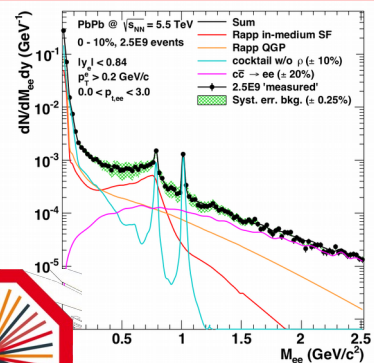
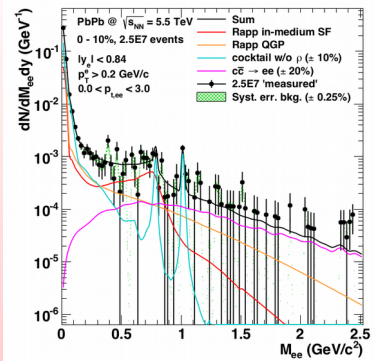
Imminent Run III



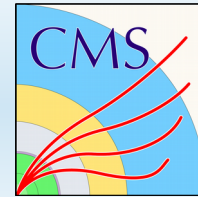
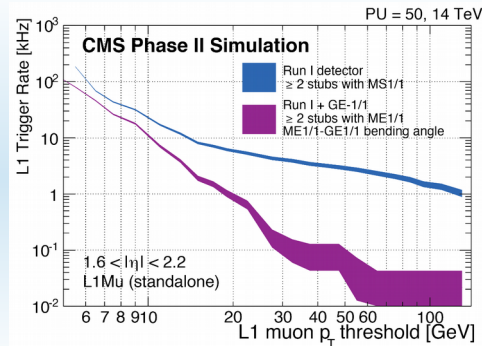
- Now preparing last Run (III, lumix2) before high-luminosity LHC
→ MPGDs moving LHC experiments. This is now!!!
- Major machine upgrade @ LS3 (2024-26) (lumix5-7)
New focus quadrupoles, lumi levelling @ IPs, crab cavities, new collimators, more compact dipoles to free space, renovated accelerator chain (new linac, improved Booster...)
→ introduction of new detector technologies to mitigate pile-up

LHC detector upgrades

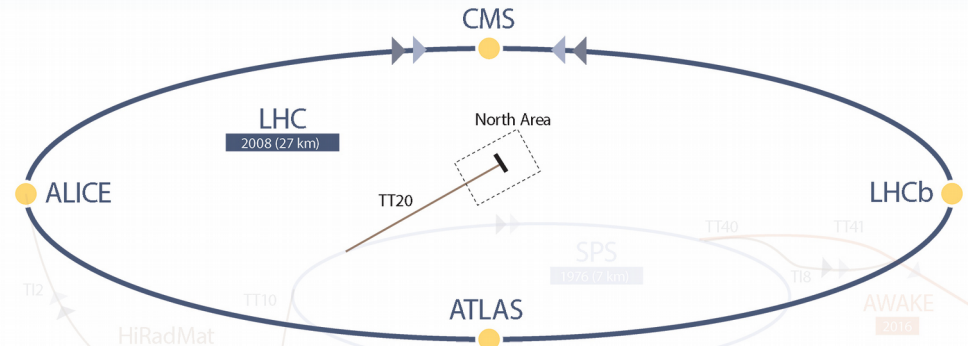
CERN-LHCC-2013-020
ALICE-TDR-016



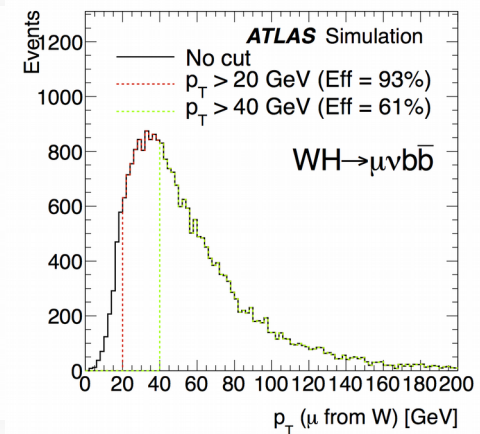
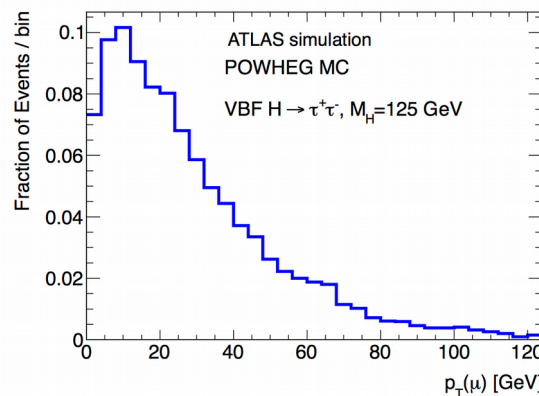
ALICE



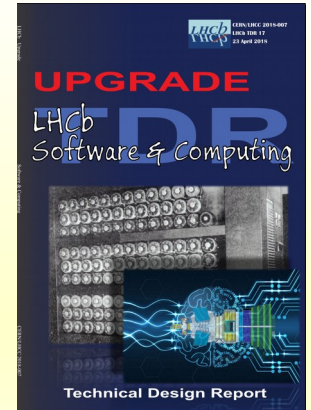
CERN-LHCC-2015-012
CMS-TDR-013



CERN LHCC-2013-006
ATLAS-TDR-20-1013



CERN-LHCC-2018-007
LHCb-TDR-017



ALICE TPC

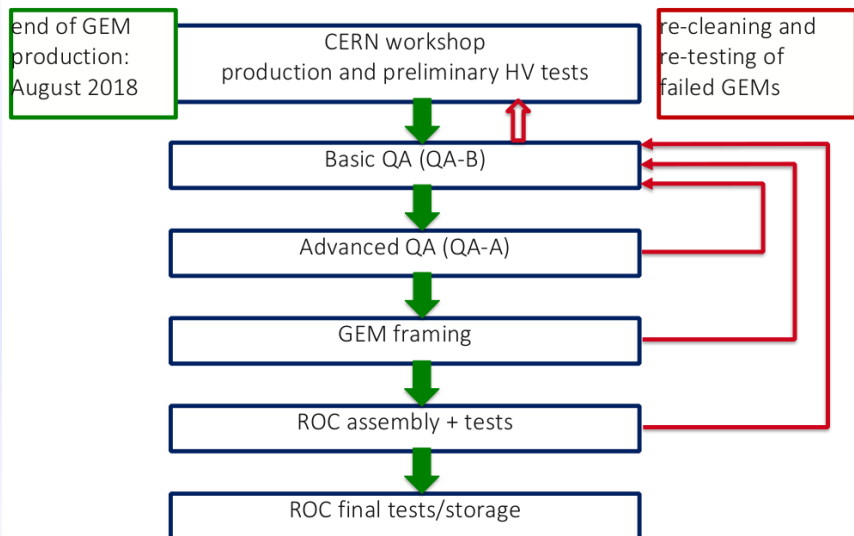
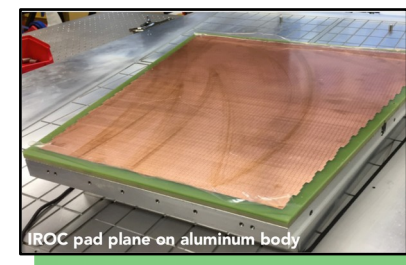
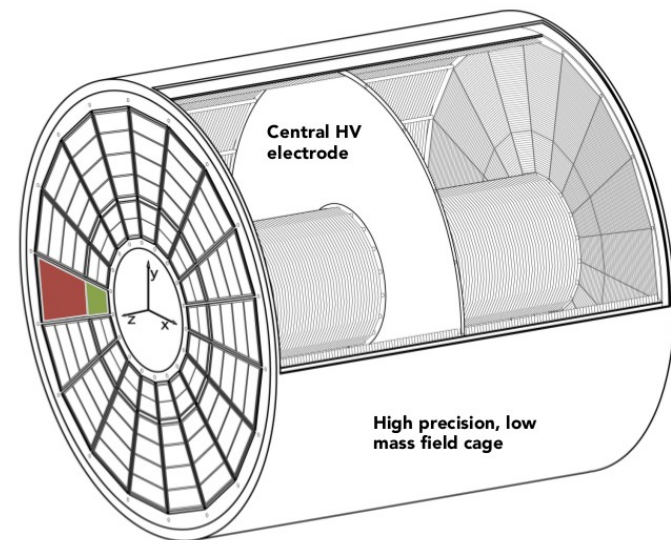
- Continuous readout in Run 3 to maximise physics (Pb-Pb rate $\times 100$)

Overlapping events \rightarrow Replace MWPC & gate by GEMs

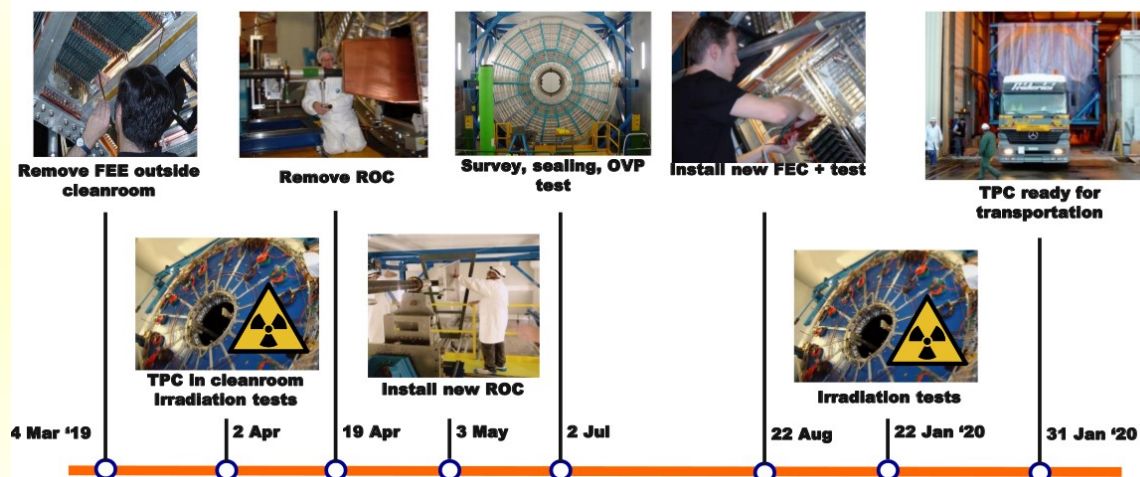
Operate @ low gain ($2 \cdot 10^3$) & low IBF + new FE

Extensive R&D \rightarrow 4 GEMs (mix 2 hole pitches, 90 deg tilt)

- About 700 foils, stringent QA tests, 90% yield
- Foil production @ CERN, ROC assembly in 3 sites



Schedule: installation of new ROC in May!



CMS forward μ -trigger



- Improve triggering capability @ high η
 Add redundancy (CSC) + lower trigger rate @ same threshold
 For Run 3: 2 wheels of GEMs @ 5-6 m from IP (GE1/1)
 HL-LHC: gain knowledge & add more chambers (GE2/1 & ME0)
- 36 staggered triple-GEM chambers / endcap
 → 5 years of design maturation & detailed characterisation (TB, in-situ tests during YETS)
- Production load distributed btw. CMS institutes (2y training program)

Schedule: as of Feb. 2018...

GE1/1 Project development

2010 **2011** **2012** **2013** **2014** **2015**

Generation I
The first 1m-class detector ever built but still with spacer ribs and only 8 sectors total.

Generation II
First large detector with 24 readout sectors (3x8) and 3/1/2/1 gaps but still with spacers and all glued.

Generation III
The first sans-spacer detector, but with the outer frame still glued to the drift

Generation IV
First detector with complete mechanical assembly; no more gluing parts together!

Generation V
Stretching apparatus that is now totally inside gas volume. test beam campaign for final performance measurements.

Generation VI
First superchamber in test beam campaign with V2 electronics, Optohybrid and GEB

2015: Prototyping, DAQ & trigger and QC procedure of detectors. First prototype of VFAT3

YETS 2016: electronics & chamber prototype installation-

2016/17: Slice and trigger commissioning.

2017/18: Production GE1/1 chambers with final electronics

2018/19: Full-production of chambers and electronics started

2018/19: Full installation of GE1/1 with final electronics

TDR Approved: 30.9.2015

	2017												2018												2019				
	June	July	August	September	October	November	December	January	February	March	April	May	June	July	August	September	October	November	December	January	February	March	April	May					
1 st endcap production	Production 1 st endcap												OK																
1 st endcap super-chamber								S-C Assembly and cosmic test (1 st endcap)					OK																
2 nd endcap production													Production 2 nd endcap					OK											
2 nd endcap super-chamber															S-C Assembly and cosmic test (2 nd endcap)					OK									
Production reviews																													

Ready for P5 installation

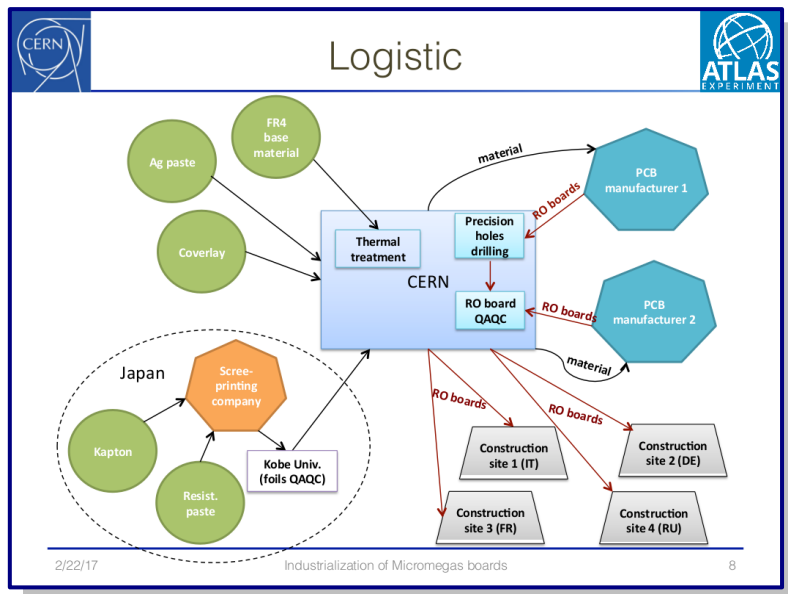
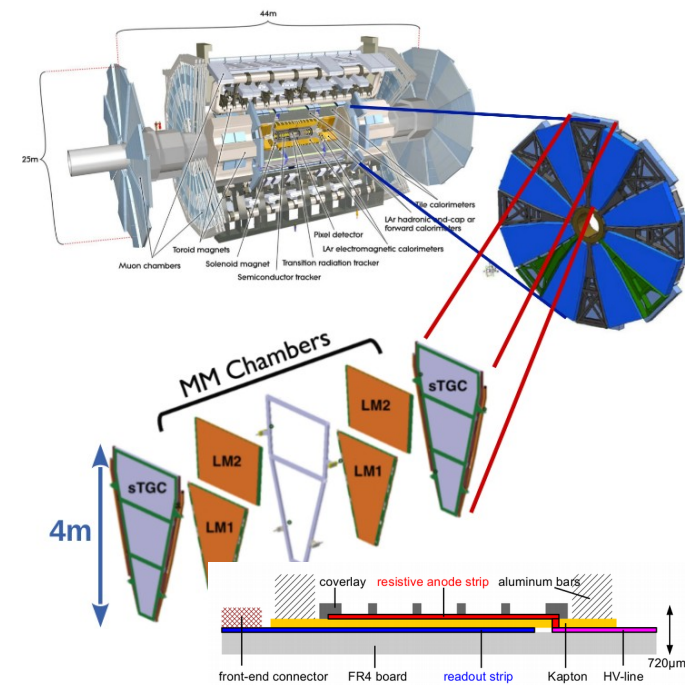
ATLAS μ -Wheel

- Improve triggering capability in endcap

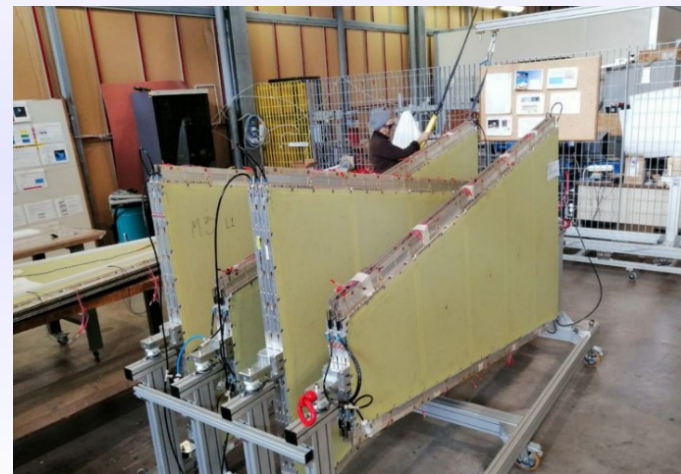
Reduce trigger rate (15 kHz/cm², 90% fake)
 + maintain P_T resolution @ higher lumi (improved tracking)
 → 2 quadruplets Micromegas between 2 quadruplets sTGC

- Most challenging project

10 m diameter wheel (1200 m²), 2176 boards (32 different shapes), Resistive detector!
 Mechanical precision – high Q production of the R-boards – stability against discharges.
 Several issues recently solved.



2019: All sites ramped up production.
 First quads @ integration site at CERN.



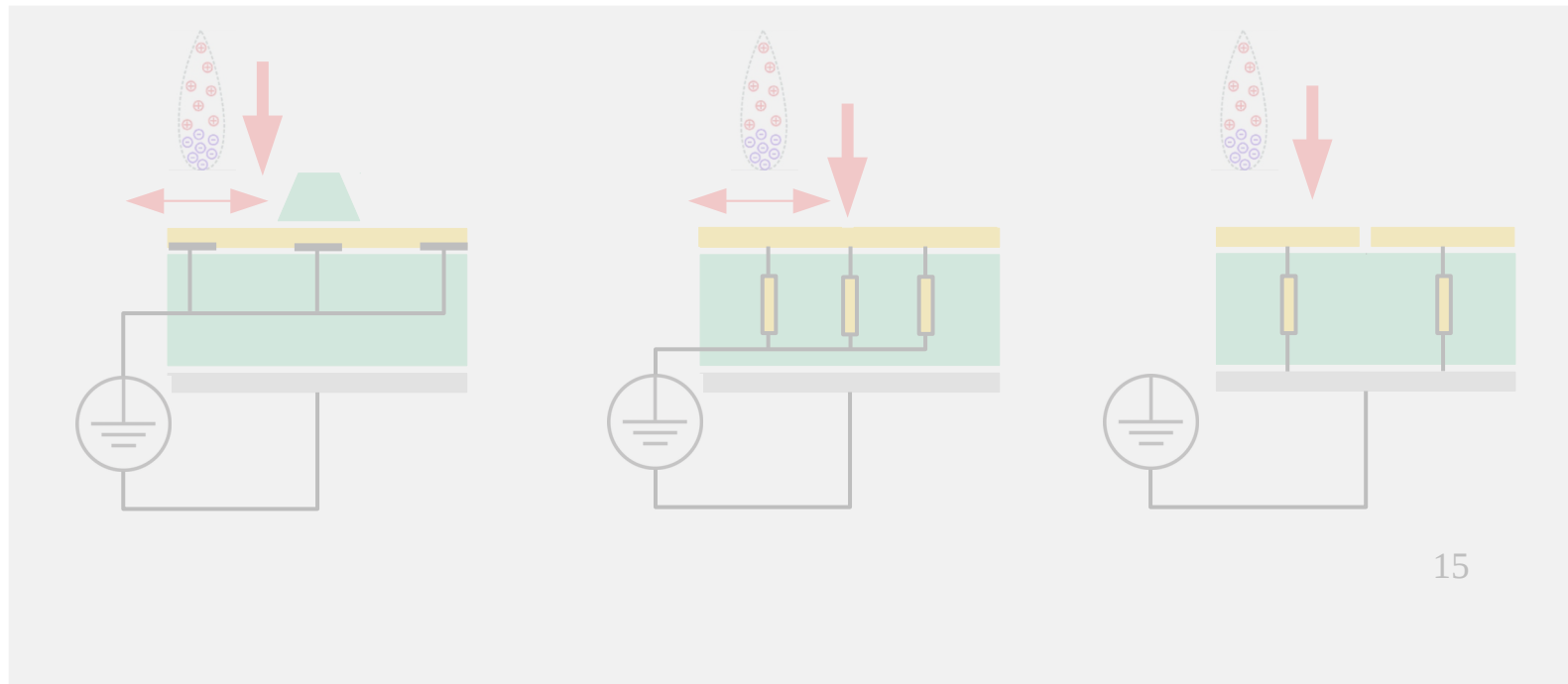
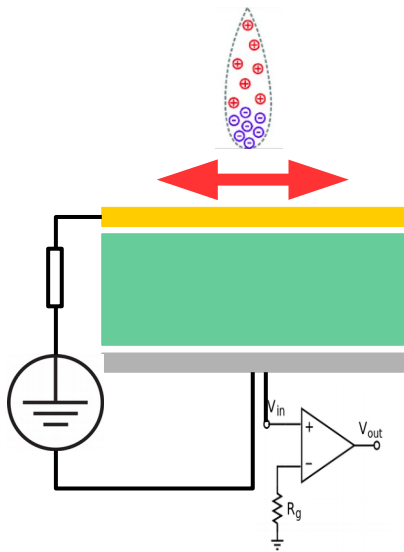
Resistive MPGD

- Resistive electrodes Charge spread (σ_x), local charge-up (no spark but rate effects)
- Simplest (and first) implementation

Continuous layer C-coupled to anode and grounded on edges of active region

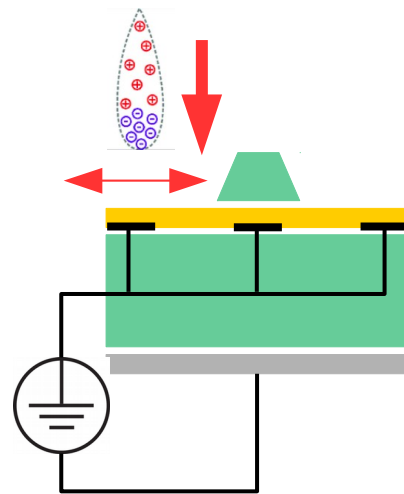
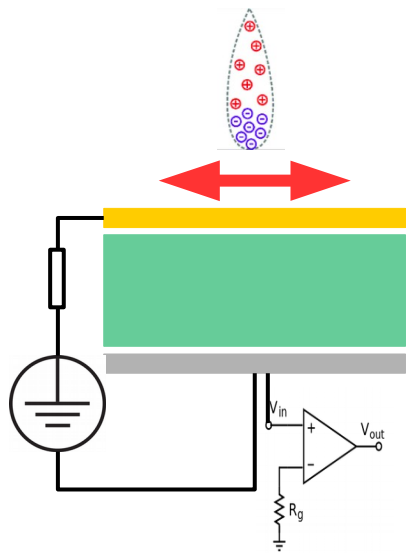
→ fine up to moderate particle rates / unit area. Used for ATLAS, LC-TPC, μ RWELL.

- For higher rates: reduce R by e.g. shortening the path to ground
→ several options (keeping some R btw avalanche spot & ground in case of short with mesh)

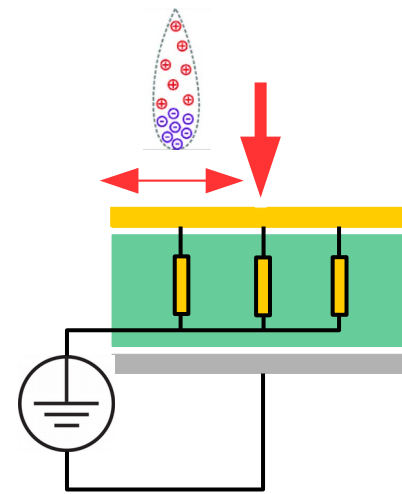


The path to ground

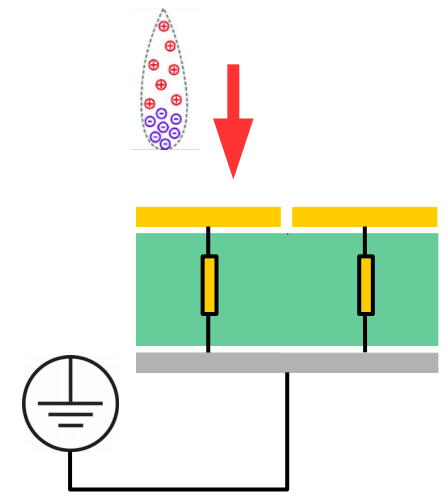
- **Resistive electrodes** Charge spread (σ_x), local charge-up (no spark but rate effects)
- **Simplest (and first) implementation**
 Continuous layer C-coupled to anode and grounded on edges of active region
 → fine up to moderate particle rates / unit area. Used for ATLAS, LC-TPC, μ RWELL.
- **For higher rates: reduce R by e.g. shortening the path to ground**
 → several options (keeping some R btw avalanche spot & ground in case of short with mesh)



Metalic strips. μ RWELL SG
(Hide critical spots)



Embedded R layer or grid
 μ RWELL RG, R- μ M



Segmented pads
No spread → any R!

In practice, the μ RWELL

- Current resistive designs driven by Construction simplicity - Fast Q evacuation - Reliable R-coatings

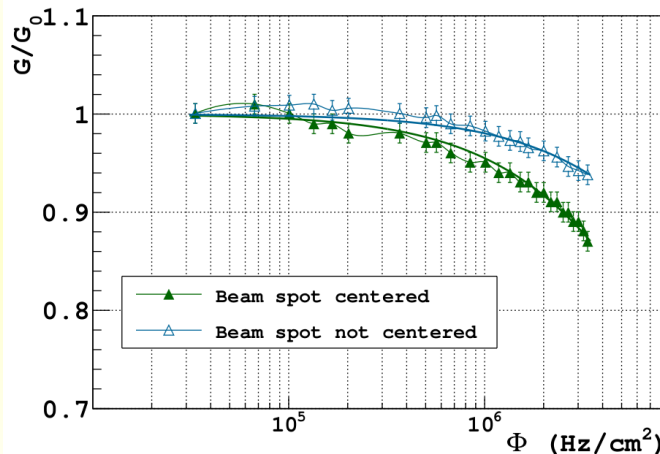
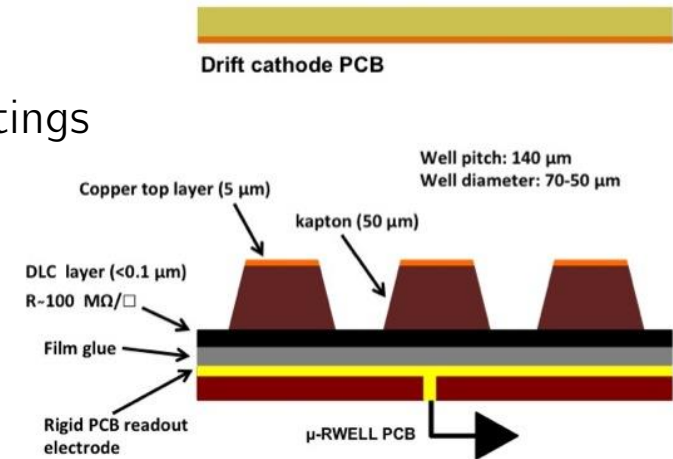
- Smart choice is the μ RWELL

Kapton foil with Cu & DLC coatings + insulator + PCB

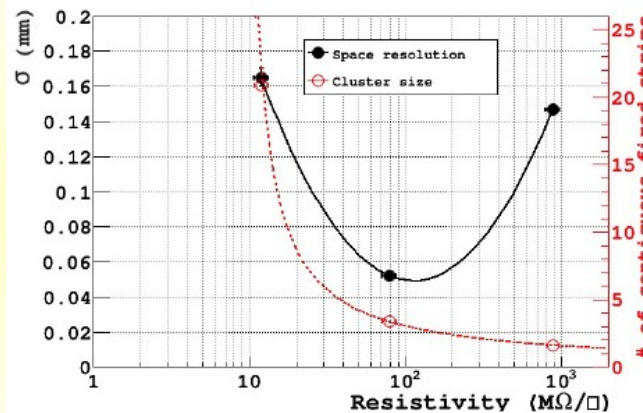
Surface-R of 100 M Ω /sq for best x-resolution (50 μ m)
 Gas gain ($>10^4$) in Ar/CO₂, good $\Delta E/E$ (10% @ 5.9 keV)

Flux limit ~ 100 kHz/cm² @ G=2.10³, position-dependent

Industry-friendly



Bencivenni et al., 2018



1.9x1.2 m²
 (GE2/1) μ -RWELL
 (ELTOS)

Higher rates (planar)

- Rate capability

Measured in the lab on given position with no activity around.

Real life (uniform illumination): should be worse as surface charges pile up $\rightarrow \Delta V(x,y)$

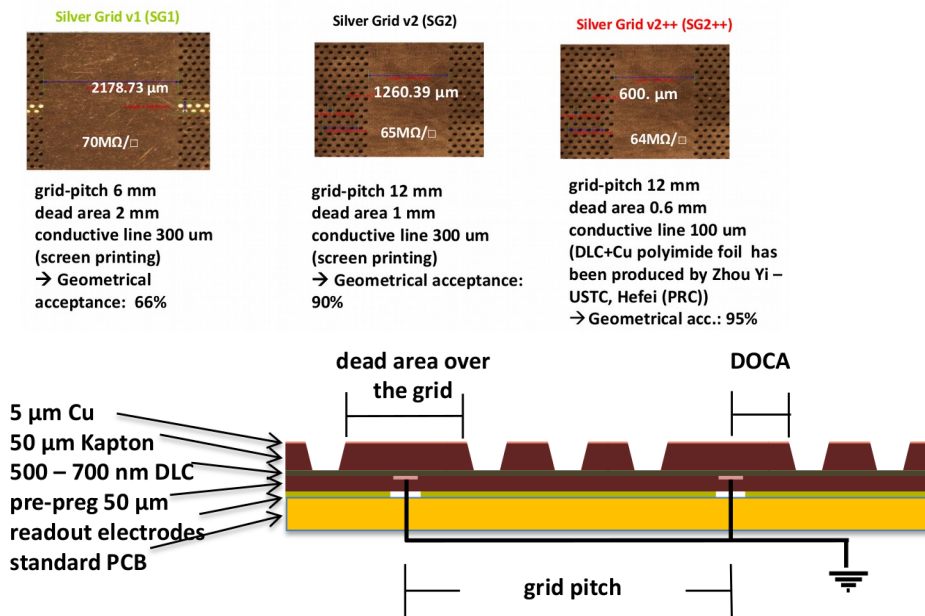
- Planar charge collection with conductive electrodes

Conductive strips printed onto DLC and grounded at the edges of the active area

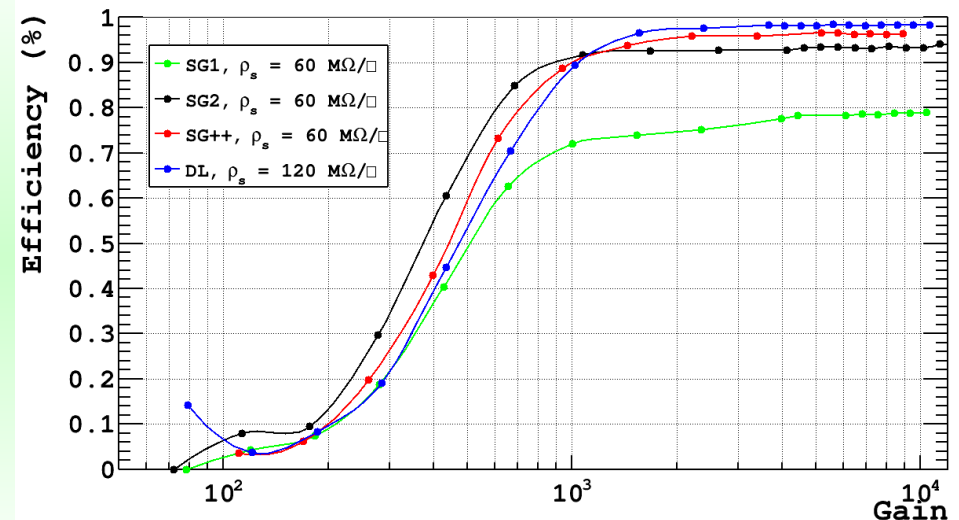
- masked region around strips to avoid instabilities: as small as 5% dead zone achieved!

- lower effective resistance: higher rate capability expected

Next: resistive strips to eliminate dead zones or conductive dashed-strips



Bencivenni et al., 2018



Higher rates (vertical)

- Rate capability

Measured in the lab on given position with no activity around.

Should be worse with uniform illumination as surface charges pile up $\rightarrow \Delta V(x,y)$

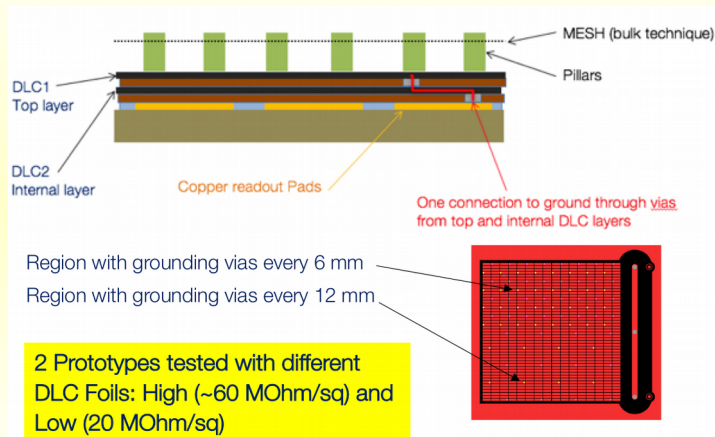
- Vertical charge collection

Sandwich of insulating and resistive layers connected through conductive vias

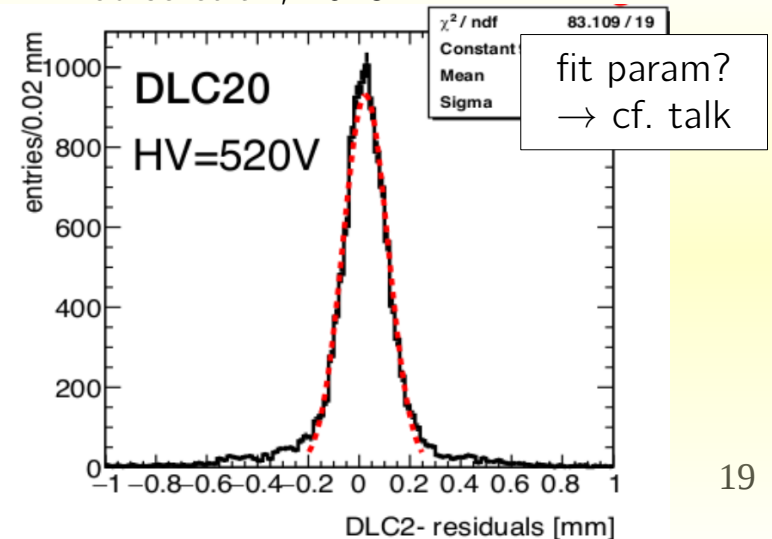
Pioneered by COMPASS group with small mm²-sized pads

2 flavours: continuous top R-surface (R_s tuned for σ_x) with μM or μRWELL (2018 TB)

Or segmented (R_s tuned to spark limit) with μM : MHz/mm² but $p/\sqrt{12}$ spatial resolution



M. Iodice et al., 2018



Higher rates (vertical)

- Rate capability

Measured in the lab on given position with no activity around.

Should be worse with uniform illumination as surface charges pile up $\rightarrow \Delta V(x,y)$

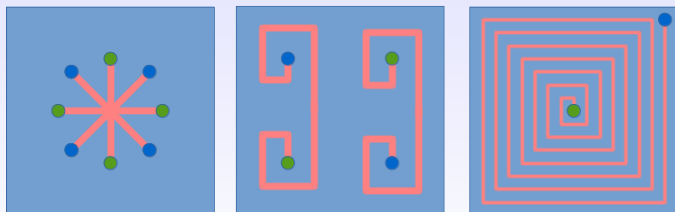
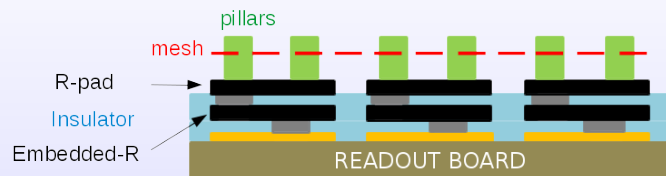
- Vertical charge collection

Sandwich of insulating and resistive layers connected through conductive vias

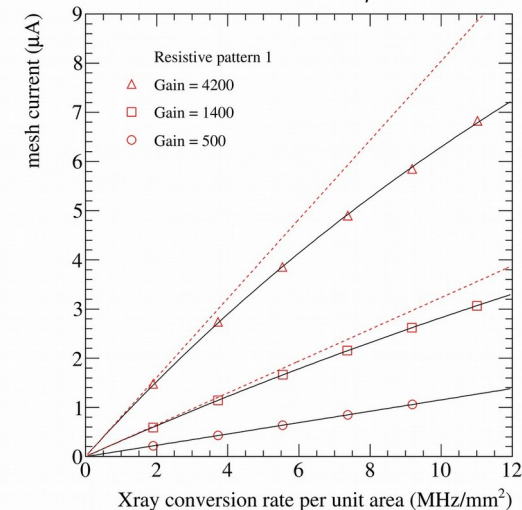
Pioneered by COMPASS group with small mm²-sized pads

2 flavours: continuous top R-surface (R_s tuned for σ_x) with μM or μRWELL (2018 TB)

Or segmented (R_s tuned to spark limit) with μM : MHz/mm² but $p/\sqrt{12}$ spatial resolution



M. Chefdeville et al., 2015



Improved Timing @ HL-LHC

- The challenge of pile-up @ 5-fold increased luminosity

200 pp col. / BX with $\sigma_z = 50$ mm ($\langle d \rangle = 0.6$ mm) and $\sigma_t = 180$ ps

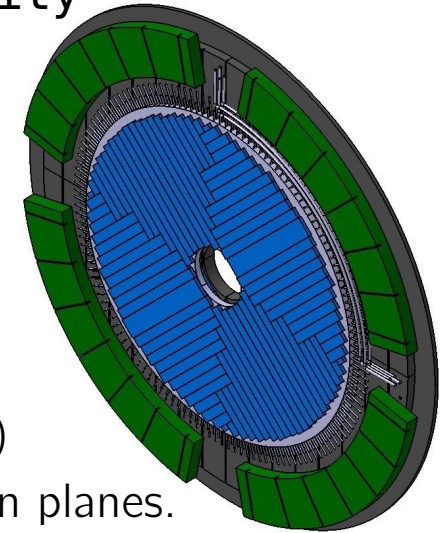
- Mitigated by associating tracks (& calo clusters) to PVs
→ associate time to a PV by time-stamping the track(s)

- ATLAS High Granularity Timing Detector (HGTD)

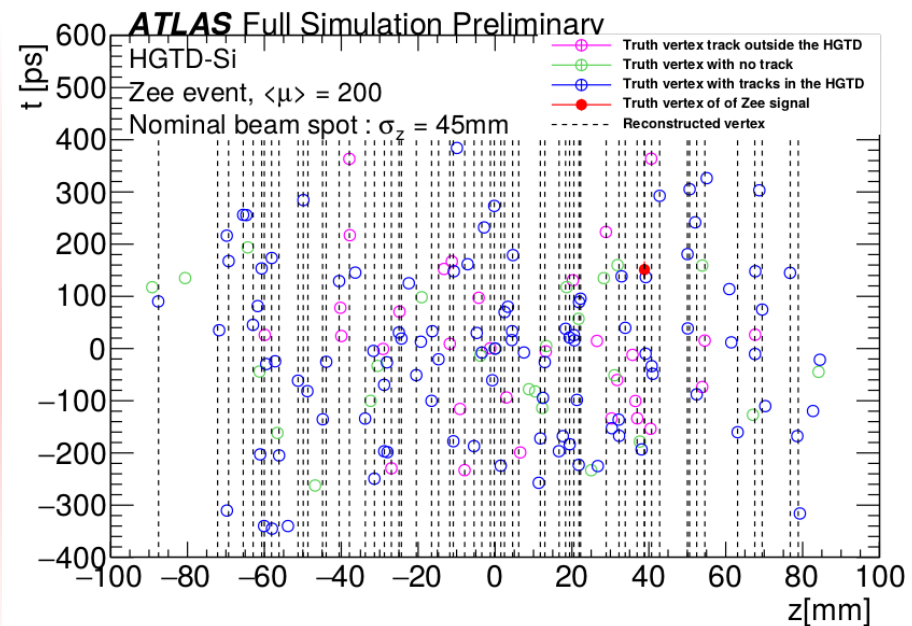
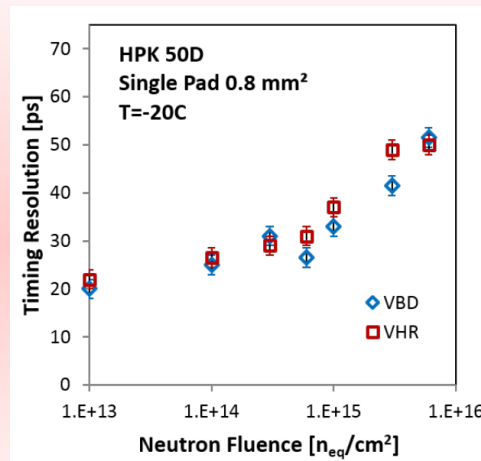
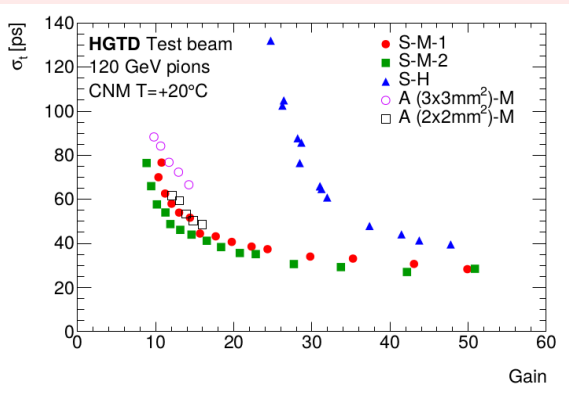
Si Low Gain APD (σ_t of 30 ps) - 1.3×1.3 mm² pixels (<10% occupancy)

Wheel inner/outer radius of 1.2-6.4 m. Covering $|\eta| = 2.4-4$. 3 detection planes.

→ Similar performance in forward & central regions



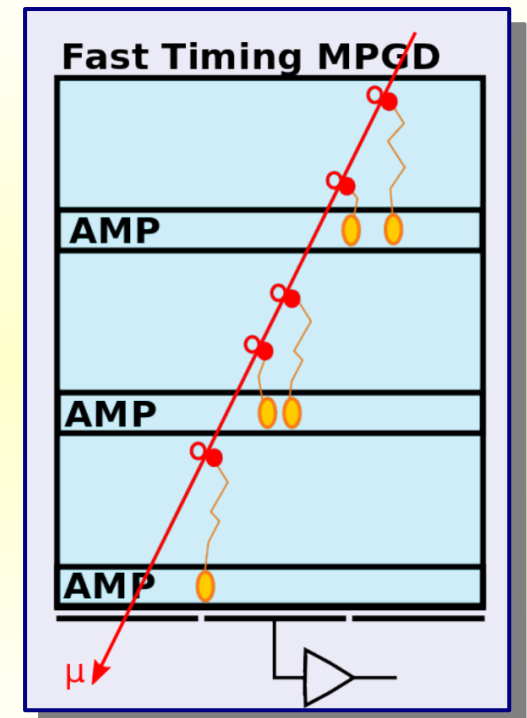
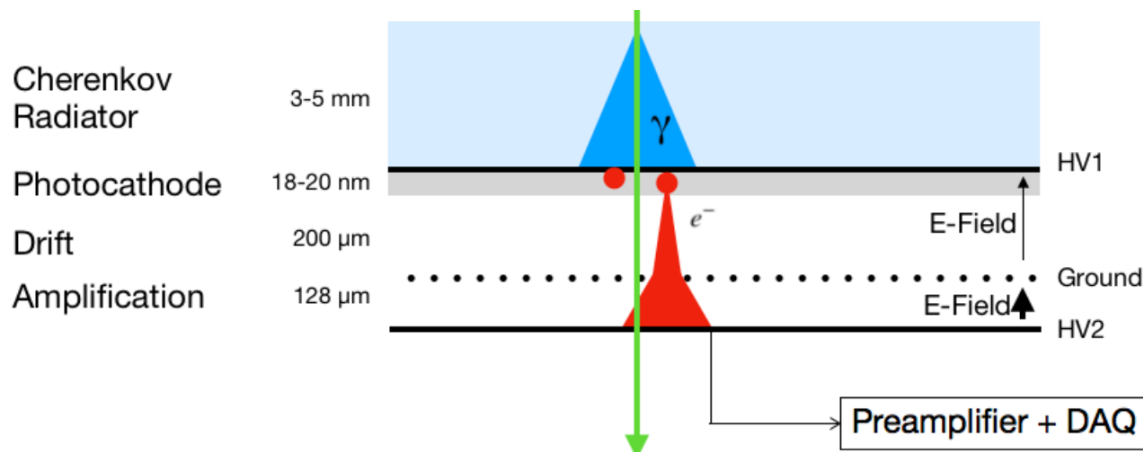
ATL-LARG-PROC-2018-003



Timing with gas

- Standard MPGDs show moderate time resolution for MIPs
Poisson-like statistic of primary ionisation (in gas: ns-range)
- Split drift region in several layers (MRPC-like)
Fast Timing Mpgd. using resistive stages \rightarrow all layers contribute to induced signal $\rightarrow \sigma_t/N$
- Remove primary fluctuations

Have all ionisation at a fixed distance from the anode
 \rightarrow longitudinal diffusion-limited resolution (modulo PE stat)
 Acheived with radiator & photo-cathode: picosec project.



picoSec

- Growing interest since 2014

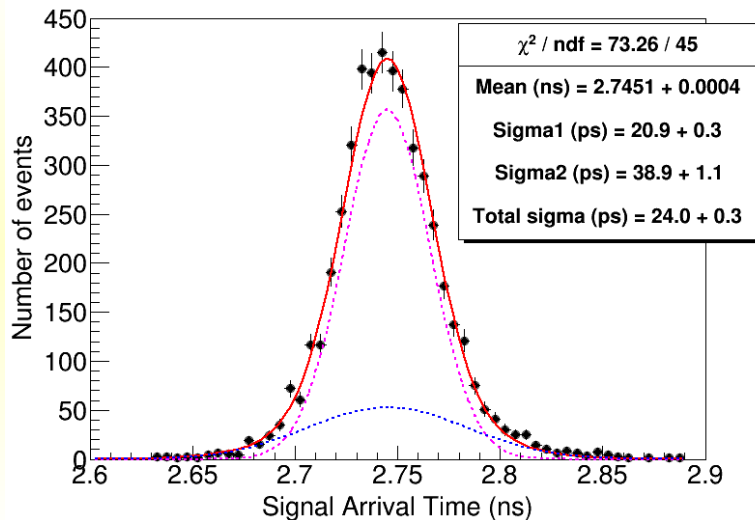
Participation from several institutes
Flagship RD51 project: touches all WG

- Performance & simulation

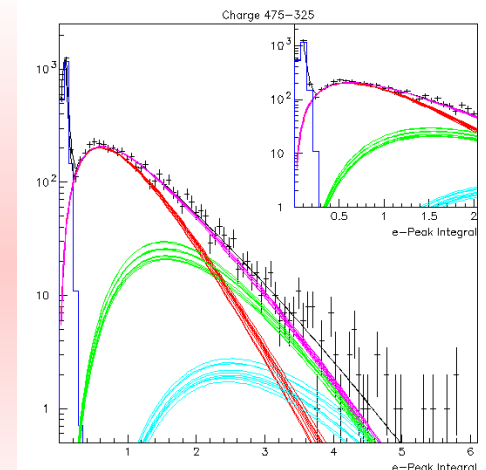
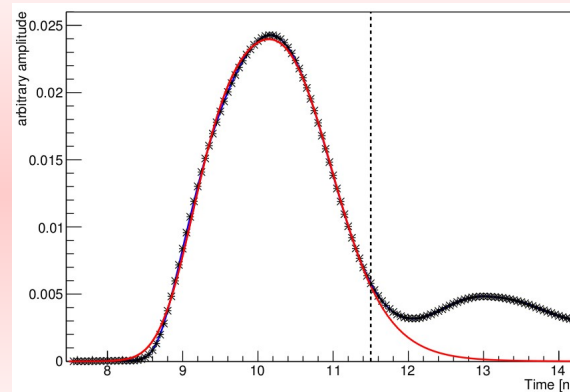
Arrival time & resolution: waveform analysis & (x,t) corrections
Garfield++, understand laser & TB data, validate corrections

- Beam tests & electronics (T_{ref} , amplifier & digitiser)

Single pad with CsI (24 ps with 10 PE/muon)



Inputs to simulation



The PICOSEC Collaboration

F.J. Iguaiz^a, J. Bortfeld^b, F. Brunbauer^c, C. David^d, D. Desforge^e, G. Fanourakis^f, J. Franchi^g, M. Gallinaro^h, F. Garciaⁱ, I. Giomataris^j, D. González-Díaz^k, T. Gustavsson^l, C. Guyot^m, M. Kebbiriⁿ, P. Legou^o, J. Liu^p, M. Lupberger^q, O. Maillard^r, I. Manthos^s, H. Müller^t, V. Niaouris^u, E. Oliver^v, T. Papaevangelou^w, K. Parasciou^x, M. Pomorski^y, B. Qi^z, F. Resnati^{aa}, L. Ropelewski^{ab}, D. Sampsonidis^{ac}, T. Schneider^{ad}, P. Schwenling^{ae}, L. Sohl^{af}, M. van Stenis^{ag}, P. Thüner^{ah}, Y. Tspitoli^{ai}, S.E. Tzamaras^{aj}, R. Veenhof^{ak}, X. Wang^{al}, S. White^{am}, Z. Zhang^{an}, Y. Zhou^{ao}

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^bEuropean Organization for Nuclear Research (CERN), CH-1211 Geneva 23, Switzerland

^cState Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei 230026, China

^dDepartment of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

^eInstitute of Nuclear and Particle Physics, NCSR Demokritos, 15271 Agia Paraskevi, Attika, Greece

^fNational Technical University of Athens, Athens, Greece

^gLaboratório de Instrumentação e Física Experimental de Partículas, Lisbon, Portugal

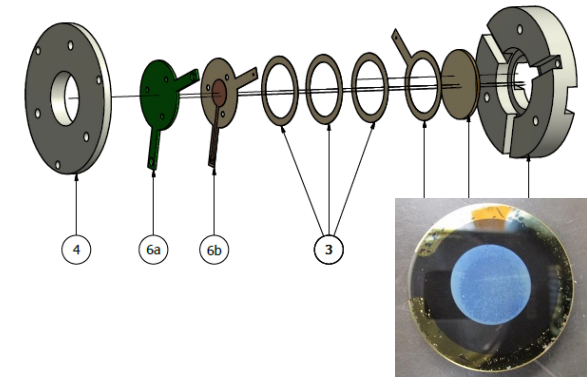
^hRD51 collaboration, European Organization for Nuclear Research (CERN), CH-1211 Geneva 23, Switzerland

ⁱLIDY, CEA, CNRS, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

^jCEA-LIST, Diamond Sensors Laboratory, CEA Saclay, F-91191 Gif-sur-Yvette, France

^kHelsinki Institute of Physics, University of Helsinki, 00014 Helsinki, Finland

^lInstituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Spain



picoSec

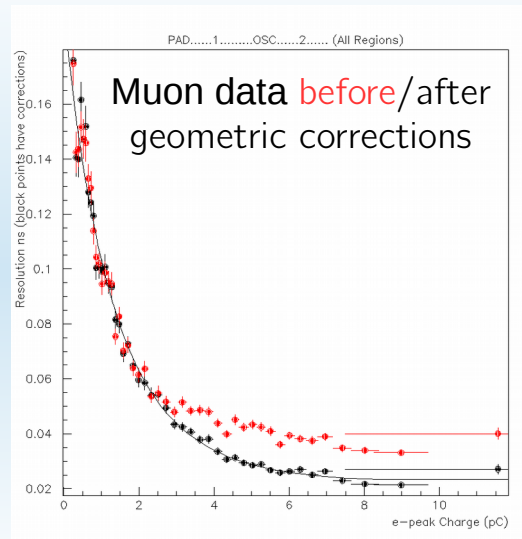
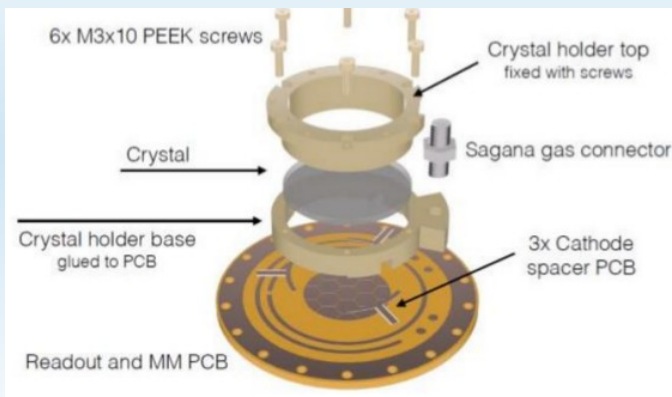
- New materials: (CsI,) metal, DLC
Rad. harder photocathodes with high PE yield?
- New structures tested:

Reduce large ion backflow ('bad' field ratio): double mesh

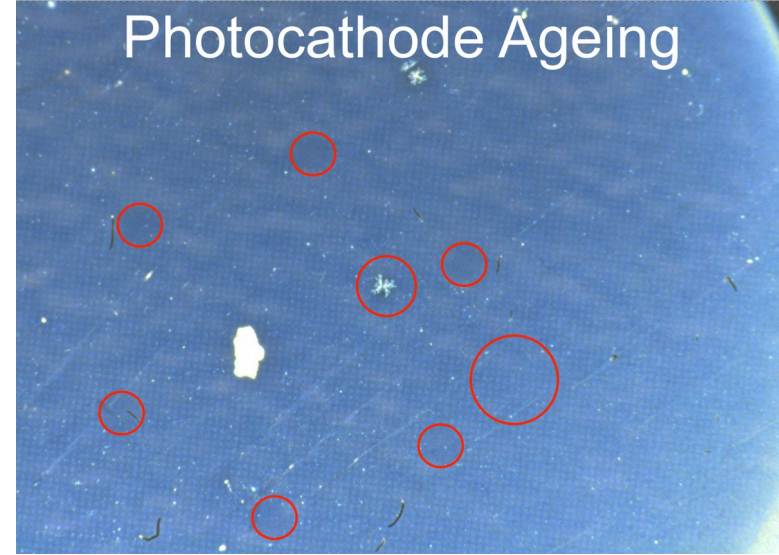
Improved stability: R-bulk, floating strips

Scaling up: Multipad: 36 mm diameter (19 pads).
Cerenkov cone can overlap with more than 1 pad

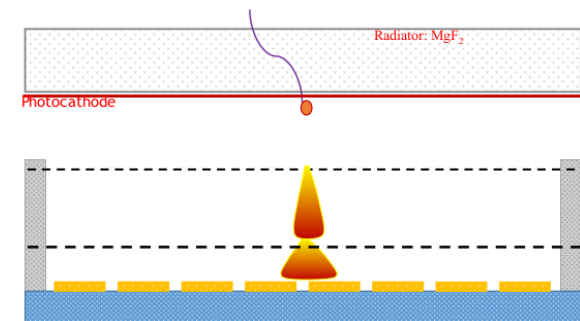
Combine pads + x-corrections
Restore full signal & <25 ps reso



Photocathode Ageing



Thickness of DLC film (nm)	Npe/per muon	Detection efficiency for muons
1	Bad	Bad
2.5	3.7	97%
5	3.4	94%
7.5	2.2	70%
10	1.7	68%
5 nm Cr + 18 nm CsI	7.4	100%



Outlook

- Legacy of the MSGC

Much alive field of research today!

These slides are modestly dedicated to the memory of a pioneer A. Oed.

- Personal choice to emphasize HEP @ LHC

Obviously restricts discussion while phase-space embraced by MPGD is so much larger

Apologies for skipping all over exciting developments (HCAL, RICH, TPC, neutrinos, DM...)

Next speakers will fortunately correct this bias

- I of course regreted to have accepted this talk...

I hope you don't.

Welcome to France



Welcome to La Rochelle



And enjoy the conference!