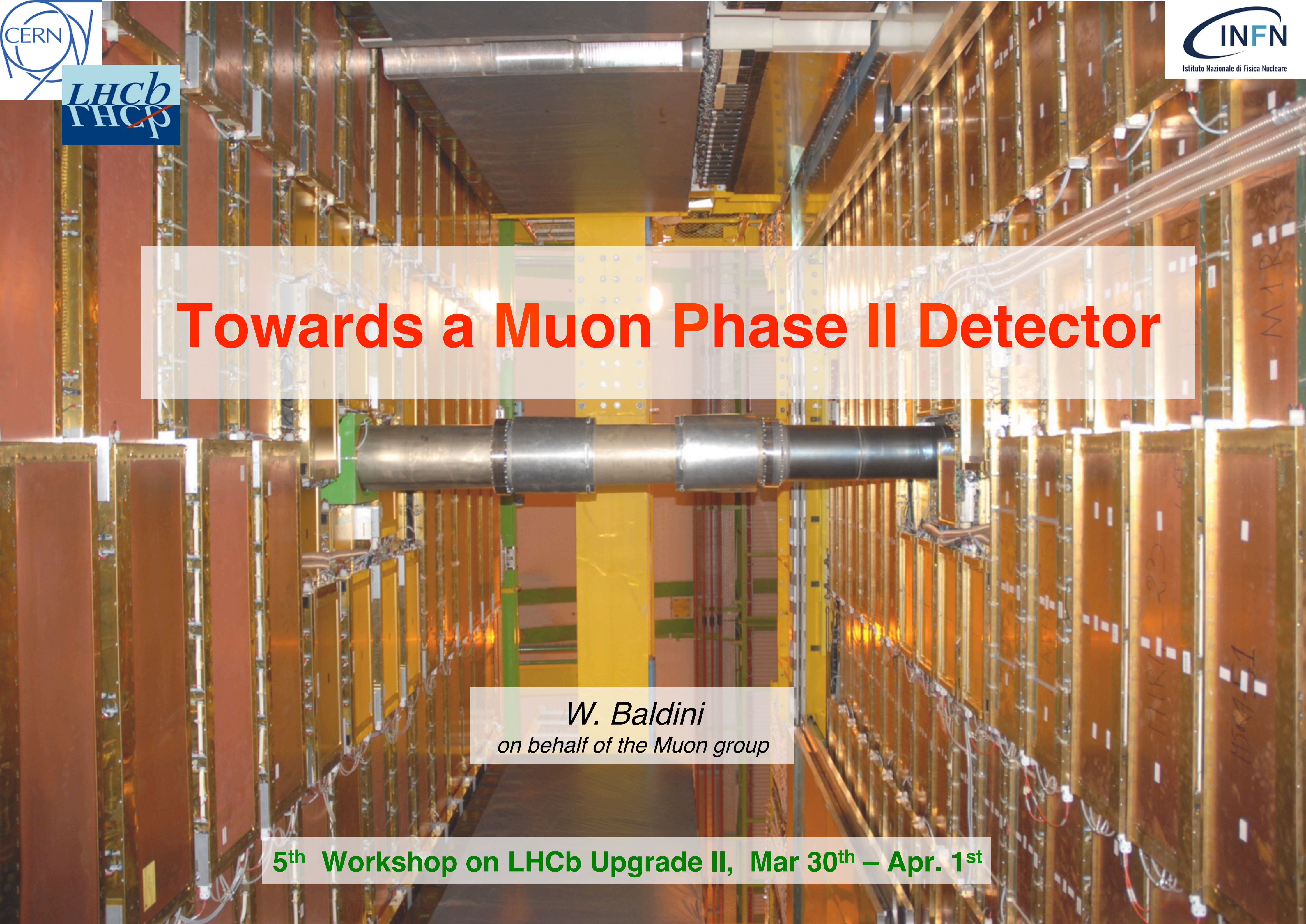

CERN LHCb

INFN Istituto Nazionale di Fisica Nucleare

Towards a Muon Phase II Detector

W. Baldini
on behalf of the Muon group

5th Workshop on LHCb Upgrade II, Mar 30th – Apr. 1st

Overview

- Present and future Muon Detector
- Iron wall shielding project and expected rates
- u-RWELL for R1and R2 regions
- Options for R3 and R4 Regions
  - MWPCs
  - RPCs
  - Scintillating-Tiles
- Conclusions & Final remarks

Discussion on Readout Electronics in the next Talk (Giulietto)

Muon Upgrade II Note

The ongoing discussion on the Muon Upgrade II Detector has been summarized in the internal note **LHCb-INT-2020-007:** https://cds.cern.ch/record/2714057/files/LHCb-INT-2020-007.pdf

Warm thanks to all the people who contributed to the note and to this presentation!

LHCb-INT-2020-007
March 27, 2020

Considerations on Muon detector upgrade II

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Abstract

In this document we present a preliminary discussion about the muon upgrade II, which includes options on detector technology, electronics and readout, and very first cost estimates.

The MU2 Detector: a Challenge for the Future

this is fixed *to be discussed*

With almost 400 m^2 of sensitive area and ~1650 m^2 of chambers the LHCb Muon Detector is one of the largest and most irradiated detectors in the world

Prehistory: 1995 – 1996
LOI

The newborn LHC-B collaboration in 1995 faced a formidable task: to design a very large detector for muon triggering and identification with

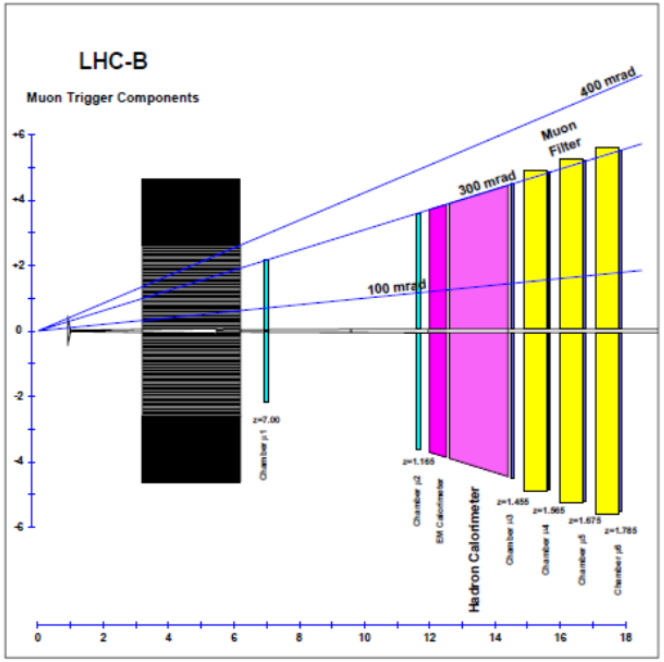
- ~~good p_T resolution~~ *abandoned at Run 3*
- high efficiency (>95%) in a 25 ns window, requiring better than 99% in a single station
- flux changing almost by 4 orders of magnitude across the sensitive area

key ingredient for success in Run1/2

flux at Run 5= Run3 x10 !

At **LOW** cost!

even more important now…



Six (!) Muon Stations
Full Wire Chamber technology
Projective geometry,
pad readout

Slide from G. Carboni (LHCb week Dec. 2018)

Rates extrapolated at $2x10^{34}$

From the upgrade 1 PID TDR estimates, and taking into account the measured fractions of correlated/uncorrelated hits, it is possible to extract the single-gap rate expected on MWPCs, which is assumed as the starting point for the expected rate on a generic detector

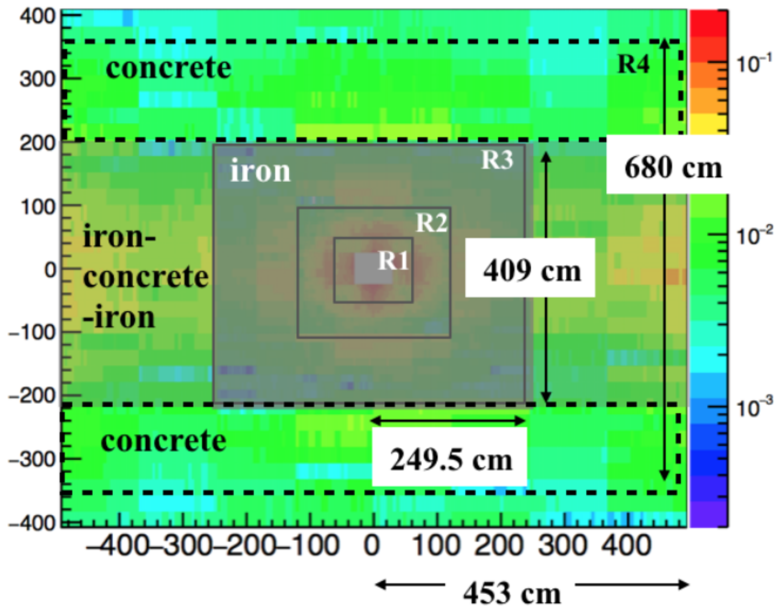
max values		kHz/cm^2		kHz/cm^2		kHz/cm^2		kHz/cm^2
single gap	M2R1	998	M3R1	575	M4R1	211	M5R1	179
	M2R2	98	M3R2	72	M4R2	30	M5R2	20
	M2R3	13	M3R3	8	M4R3	5	M5R3	4
	M2R4	10	M3R4	3	M4R4	2	M5R4	2

- average ~1/2 of max values
- nominal phase 2 lumi is $1.5x10^{34}$, we're considering here $2x10^{34}$ as additional margin, also in view of the large uncertainties related to this extrapol.

In the above numbers, we're considering to replace HCAL (1.7 m thick) with a mixture of Iron and concrete;
from simulation results (LHCb-INT-2019-008) a possible design consists of an Iron core 1.7m covering regions R1-R3 and a mixed structure covering R4, composed by concrete top/bottom and Iron/concrete sandwich on the middle plane.

Estimated rate reduction factors on M2 are:

M2R1	x0.58
M2R2	x0.31
M2R3	x0.36



simulation work by A. Sarti, P. Griffith

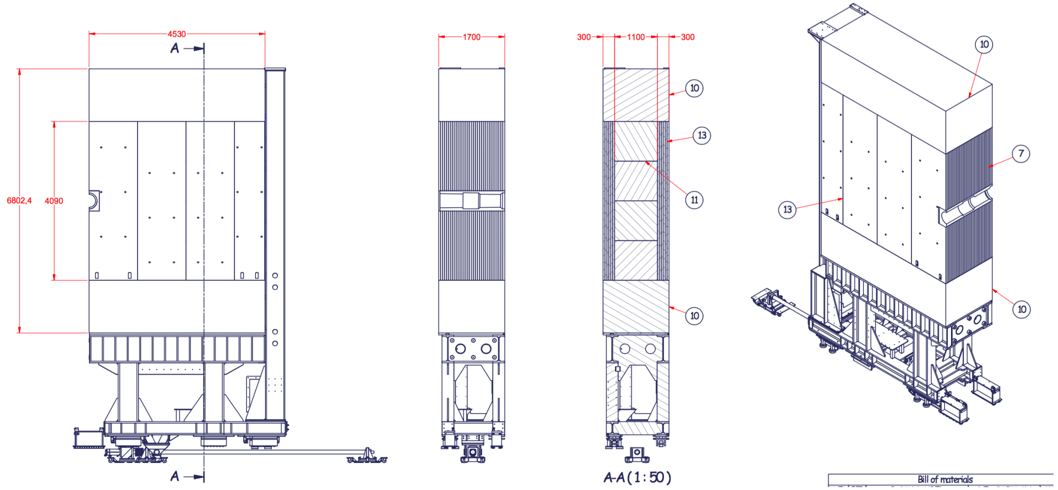
Studies to be refined, useful suggestions from a recent U2PG review

Status of the shielding project

A.Cardini, M.Palutan, A.Saputi, A.Sarti

Preparatory drawings ready (A. Cardini, A. Saputi, EDMS 2068799), based on available iron slabs from the Opera magnet, with a reinforced HCAL support

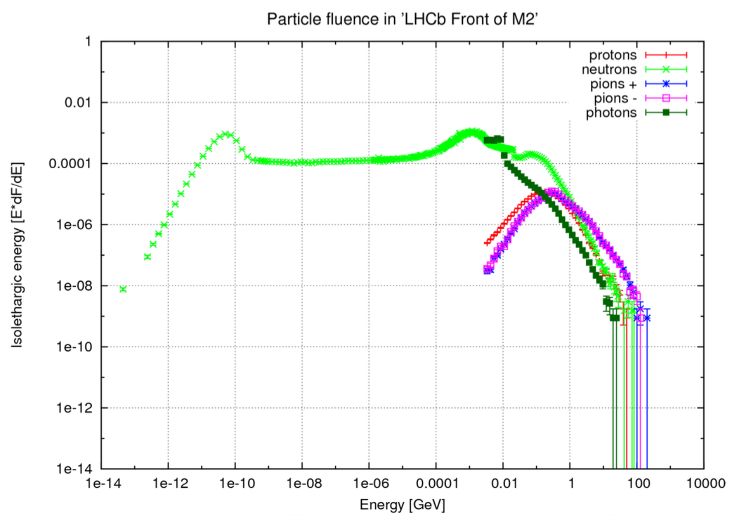
The needed iron slabs from Opera (92 on a total of 336 available) will be stored in LNF



Following the U2PG suggestions (LHCb-INT-2019-011), **we're now scoring the different contributions to the rate** on the muon stations close to the beam pipe in order to possibly **optimise the shielding composition**

The same effort on simulation is also fundamental to analyse the different options for the detector technology

Volume for fluence scoring: Air volume around beam pipe upstream of the second Muon chamber (M2).



M. Karacson

Scenario's for an upgraded detector

1) R1 and R2 all stations, rates ~ few MHz: 144 chambers, 23 m^2

➜ **μ-RWELL** — MPGD detector of new generation

intense R&D ongoing

2) R3+R4 all stations, rates ~10 kHz: 960 chambers, 364 m^2

➜ **MWPC** — explore the possibility to reuse large fraction of the present chambers: ageing studies required, need new FEE electronics

more than 20 years of experience in our group

➜ **RPC** — RPC developed for ATLAS BI project (and further developments) may be a viable option for a fraction of the interested area

➜ **Scintillating tiles** — compact and relatively easy to build (synergy with other LHCb subdetectors?)

discussion just started in the muon group, but solid experience outside

(Separation btw inner/outer regions not sharp: some of the proposed solutions may have a broader range of applicability, decision will depend on performance vs cost)

The μ-RWELL technology
for High Rate Regions

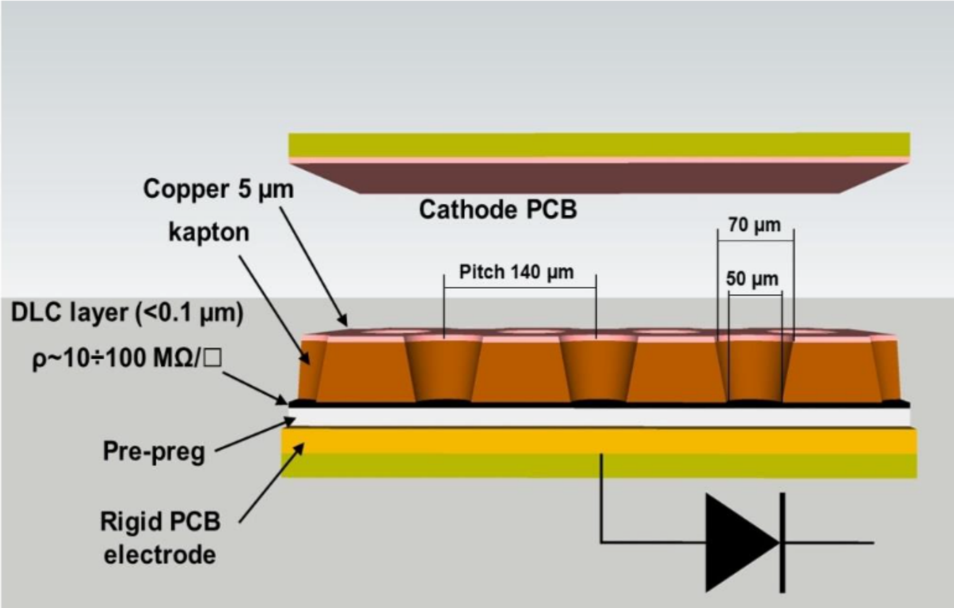
G. Bencivenni, P. Ciambrone, G. Felici, , M.Poli Lener, G. Morello

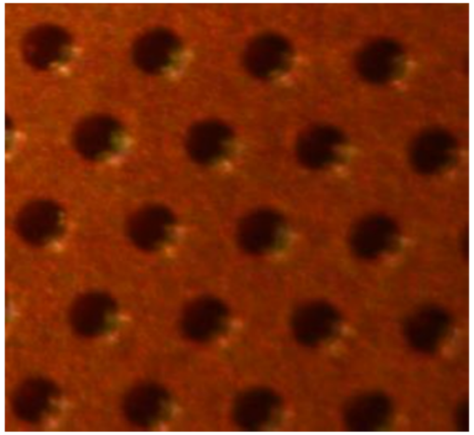
The μ-RWELL architecture

The μ-RWELL is composed of only two elements: the μ-RWELL_PCB and the cathode defining the gas gap.

The μ-RWELL_PCB, the core of the detector, is realized by coupling:

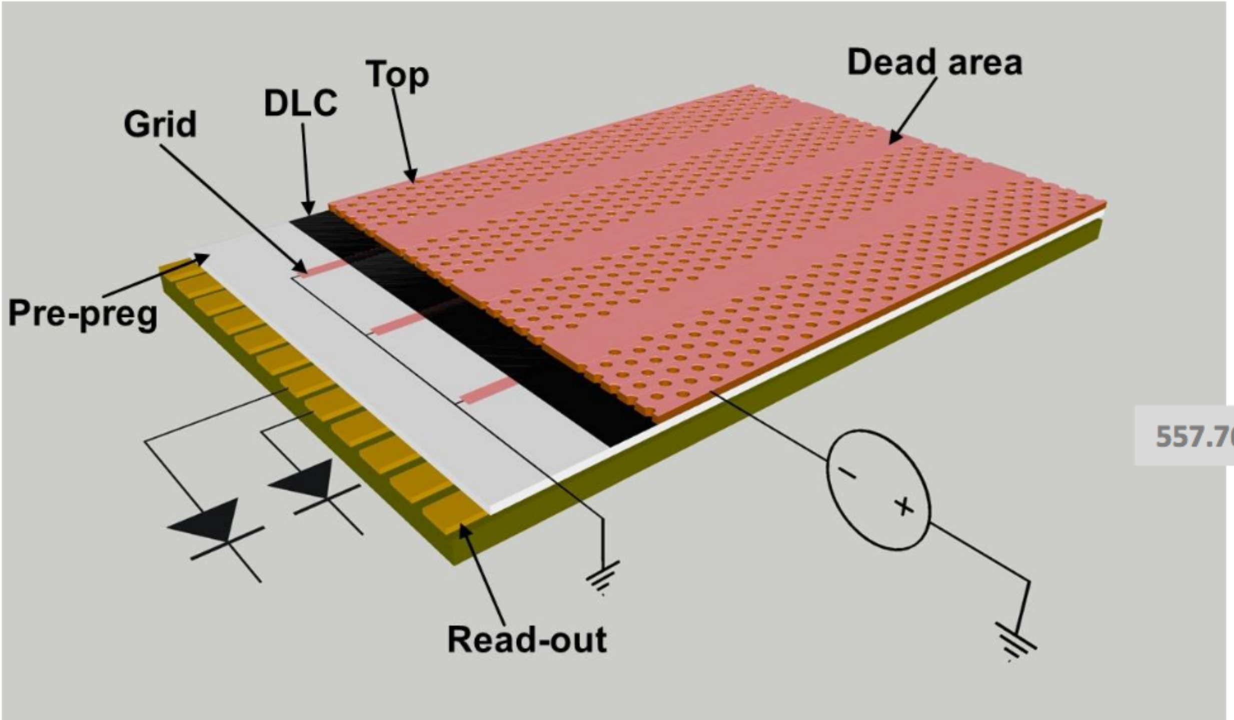
1. a WELL patterned Apical® foil acting as amplification stage
2. a resistive layer for discharge suppression w/surface resistivity ~ 10÷100 MΩ/☐ - different current evacuation schemes can be implemented
   i. LR << 1 MHz/cm² - SHiP, STCF, EIC, HIEPA
   ii. HR >>1 MHz/cm² - LHCb-Muon phase 2-upgrade & future colliders - CepC, Fcc-ee/hh
3. a standard readout PCB

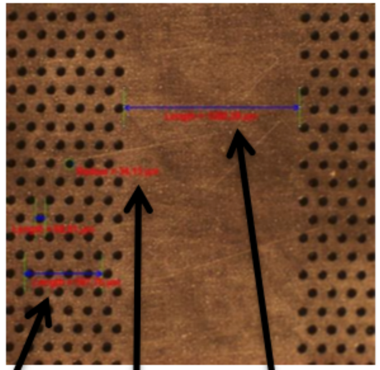




The μ-RWELL amplification stage

HR layouts: the Silver grid





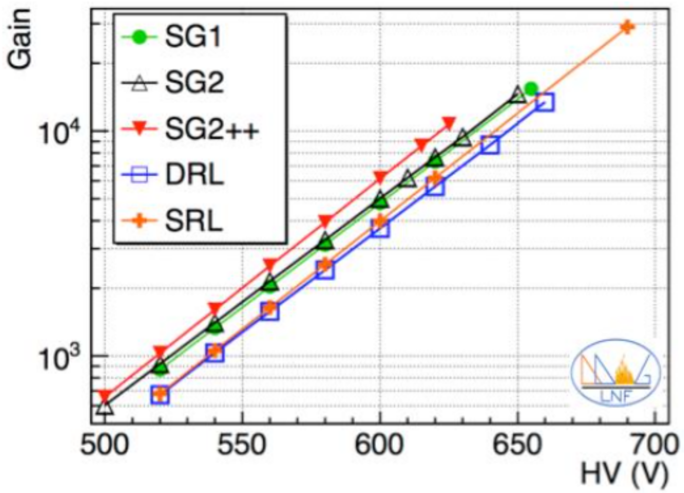
The **SG** is a **simplified HR scheme** based on a **Single Resistive layer** with a **2-D grounding** by means a **conductive strip lines grid** realized on the DLC layer.
The **conductive grid lines** can be screen-printed or **etched** by photo-lithography (*using the DLC+Cu deposition technology developed at USTC – Hefei*).

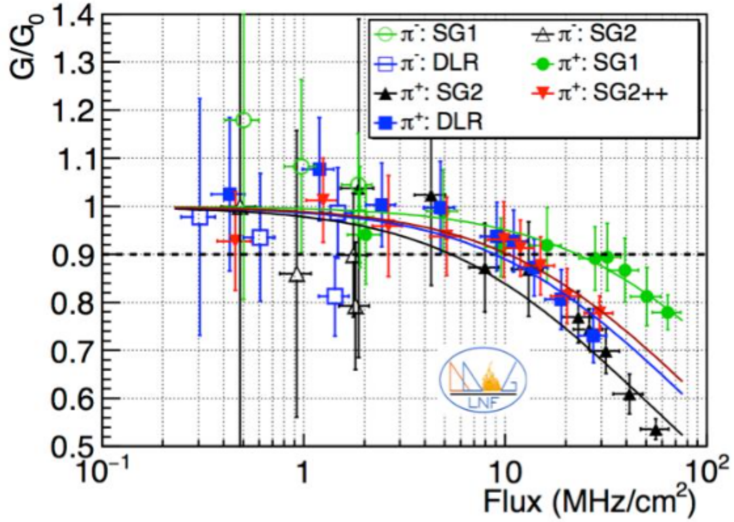
The **conductive grid** can **induce instabilities due to discharges over the DLC surface**, thus requiring for the **introduction of a small dead zone** on the amplification stage.

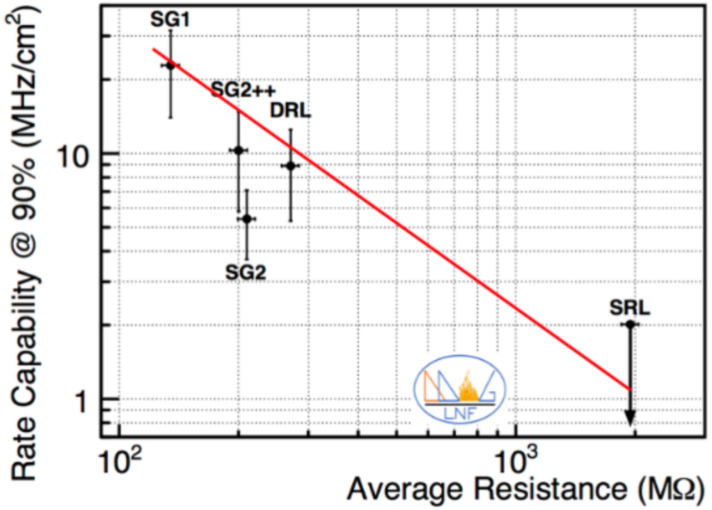
Detector performance

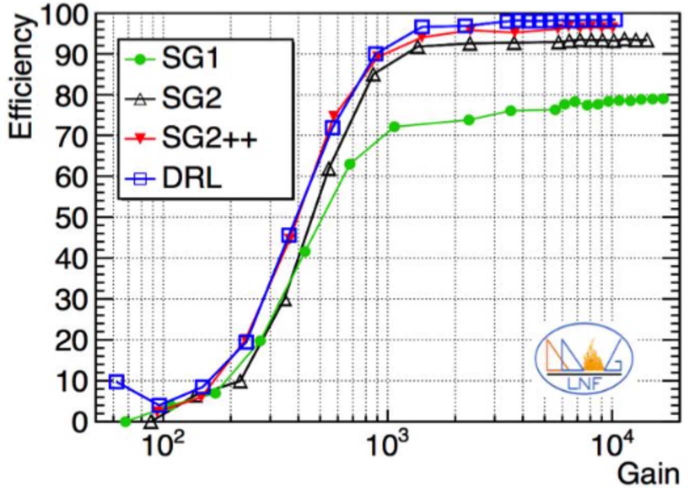
G ~ 10^4

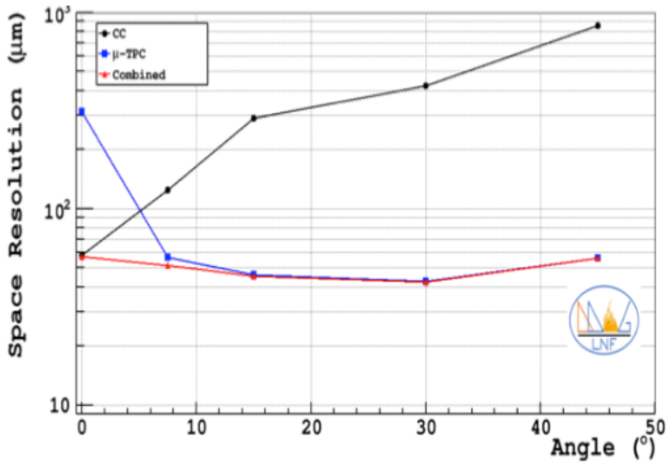
Rate capability ~ 10 MHz/cm^2











σ$_t$ (ns)

Present time resolution prelim. meas., 5-6 ns, was saturated by the FEE used, to be repeated (same reso as GEM is expected)

Efficiency ~ 98%

σ_x ~ 40 – 60 μm

σ_t ~ 5- 6 ns

Work plan for RWELL

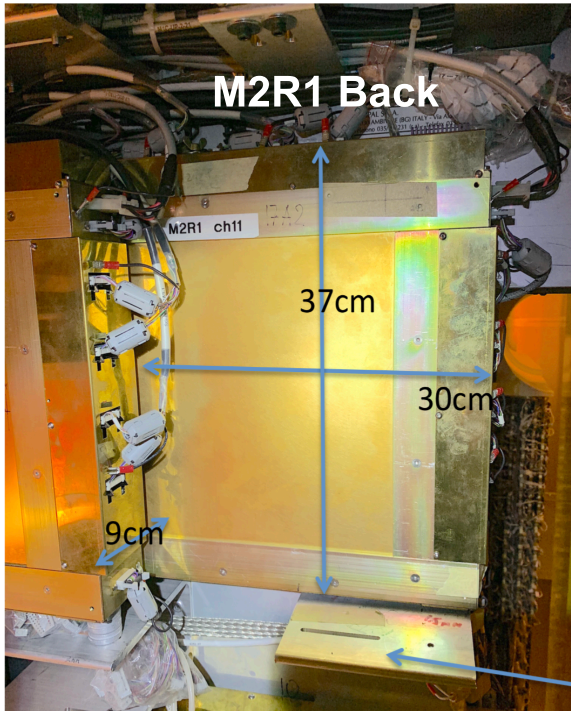
1) Ongoing R&D on resistive layer (DLC): RD51 project (USTC - Hefei, Kobe Univ., CERN, LNF-INFN)

2) Performance and spark probability measured at PSI, first ageing tests done at various facilities, showing no performance degradation

source	spot (cm^2)	rate (kHz/cm^2)	q_{int} (mC/cm^2)	t_{LHCb} (years)
GIF++	100	200	175	1.1
PSI	9	1E+4	125	0.8
X-ray	50	700	90	0.6

3) Tests on stability of DLC ongoing

4) Ageing studies: a **long-term slice test in LHCb** would be extremely important to assess the detector behaviour in a realistic environment. One/two gaps could be installed on the M2 wall to monitor the currents under heavy irradiation.



5) This year production of first prototypes for high rate with dimensions ~M2R1/R2, integration test with the VFAT3 FEE chip

Matching with the readout electronics of paramount importance → see Giulietto's Talk

MWPCs For R3 and R4 Regions

O. Maev, N. Bondar

Considerations about MWPC aging

Estimated average deposited charge (C/cm of wire) after 50/fb, in the most irradiated chamber of each station/region.

	R1	R2	R3	R4
M2	0.67	0.42	0.10	0.02
M3	0.17	0.08	0.02	0.01
M4	0.22	0.06	0.01	0.004
M5	0.15	0.03	0.01	0.003

LHCb-TDR-014

The most irradiated chambers in M1R2 already reached 0.7 C/cm, w/o visible effect; in addition, the fraction of gaps affected by Malter is stable at the moment **[JINST 14, P11031]**

If we consider regions in the red squares (~95% of the area) **0.7 C/cm will be reached only in M2R3 after 400 fb^{-1} all other regions will be well below** → This gives the opportunity to propose a **massive reuse of the present MWPCs** and of the existing detector infrastructure

A **direct inspection of a couple of M1R2 chambers** will be fundamental to check for possible ageing effects (on wires or cathodes) → preparation (was) ongoing in Lab 3, (in collabortation with T. Schneider and B. Schmidt)

Given the above, targeting 500/fb seems possible for R3 and R4 of all stations, provided the projections above are confirmed by the first years of operation in Run 3

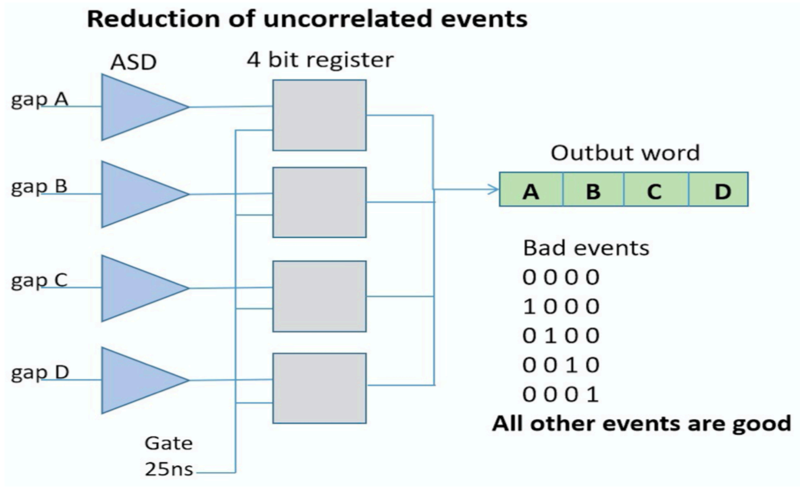
M2 @ Upgrade Conditions

A critical point is the maximum rate to the R/O, this can be reduced:

→ Single PAD readout, instead of present large area X-Y strips

→ Separate the 4 GAPs where is possible (everywhere apart R4 regions in M2-M4): we expect a **~ 30-40% reduction** of background hits (now OR-ed in bi-gaps)

→Logical combination of the gaps **rejecting combinations with one hit only**: could reduce the rate **~ factor 3**



Maximum expected rates at RUN5 conditions **extrapolated from RUN2 measurements**:

- considering the effect of additional shielding
- background hits suppression from above R/O scheme
- reduced pad dimensions where rate >1MHz per R/O channel

	R4		R3	
16	389864	187680	160121	
15	242682	171184	127905	
14	305293	150321	103220	
13	179937	116459	68511	
12	411322	450906	99167	122345
11	253417	350004	52328	71316
10	310948	286492	48719	90661
9	287754	210973	31240	50598
8	147263	182499	470646	429083
7	180003	136223	281437	424047
6	179765	112926	249034	320772
5	116654	85489	166407	204181
4	678158	58138	138715	165998
3	450413	66191	98443	112448
2	419367	70018	100360	119324
1	214900	84401	90257	113213
	D	C	B	A

MWPC same size R3 but x2 granularity, 40 to be produced

MWPC present R3, 24 to be produced

MWPC present R4 0 to be produced

Maximum expected rates per R/O channel in M2 station

Same exercise done for all stations

Summary on MWPC

Reuse present MWPCs where possible and produce new MWPCs only where needed

This plan would reduces significantly the resources needed for new detectors

In a maximal configuration a total of **128 NEW MWPCs** should be built, and **880 re-used**

sta/reg	# cha reuse	# cha new	# FEE ch
M2R3	24	24	58368
M2R4	152	40	6144
M3R3	48	0	24576
M3R4	176	16	8448
M4R2	0	24	18432
M4R3	48	0	9216
M4R4	192	0	9216
M5R2	0	24	18432
M5R3	48	0	9216
M5R4	192	0	18432
Total	880	128	180480

Next steps:

- **feasibility study of the new FEE**
- **a irradiation campaign at GIF++ (or other facilities) must be carried out**

RPC For R4 Regions

M. De Serio, S. Simone

https://cds.cern.ch/record/2285580/files/ATLAS-TDR-026.pdf

RPCs: status of the art

Thanks to low cost per unit area, high space and time resolution as well as ease of construction, RPCs have been widely used in many HEP experiments.

Current developments, aimed at increasing the rate capability as well as improving the time resolution, make them still an interesting option to be investigated for future projects where large sensitive areas exposed to *high* particle rates are required.

$$\langle V_{\text{gas}} \rangle = V - 2\rho d \langle Q \rangle \Phi_{\text{eff}}$$

Voltage drop: to be minimized in order to reduce efficiency loss with increasing flux

- Reduce electrode resistivity
- Reduce electrode thickness
- Reduce average charge per event

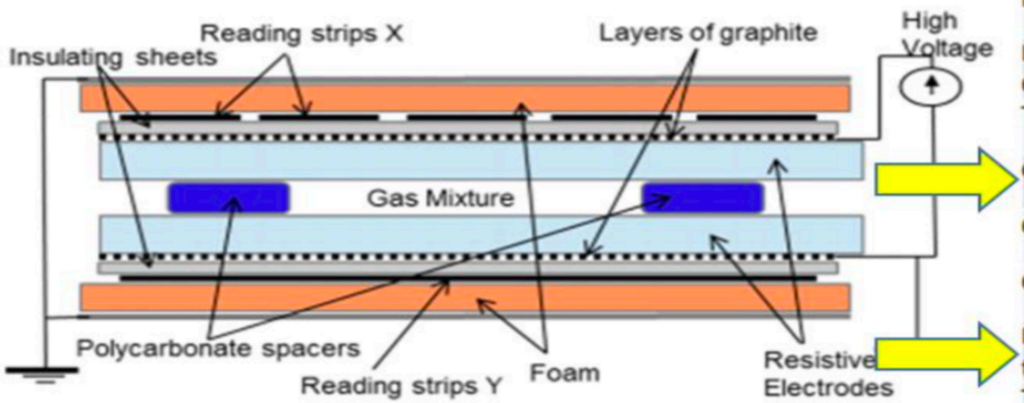
RPCs: status of the art

New Generation RPCs for the BIS78 Upgrade

- Thinner gas gap → improved time resolution
- Thinner electrodes → higher induced signal
- Reduced thickness and weight → easier installation
- Almost one half the current operating voltage
- Same avalanche saturation with less developed charge → improved ageing
- New Front-End electronics → Smaller detectable signals

Rate capability up to 10 kHz/cm²

Pilot project for the Phase II BI upgrade of the ATLAS Muon Spectrometer



	Standard RPC	BIS78 RPC
Effective threshold	1 mV	0.3 mV
Power Consumption	30 mW	6 mW
Technology	GaAs	BJT Si + SiGe
Gap Width	2 mm	1 mm
Operating Voltage	9600 V	5800 V
Charge x hit	30 pC	5-7 down to 3 pC
Electrode thickness	1.8 mm	1.2 mm
Time resolution	1 ns	0.4 ns
Gaps per chamber	2	3

ATLAS Coll., RPC2018

Time resolution ~ 0.4 ns (RPC2020)
single gap, with triplets it will further improve!

A time resolution of ~ 0.4 ns or better (using 3 gaps) would be very useful to reject combinatorial background

Main developments

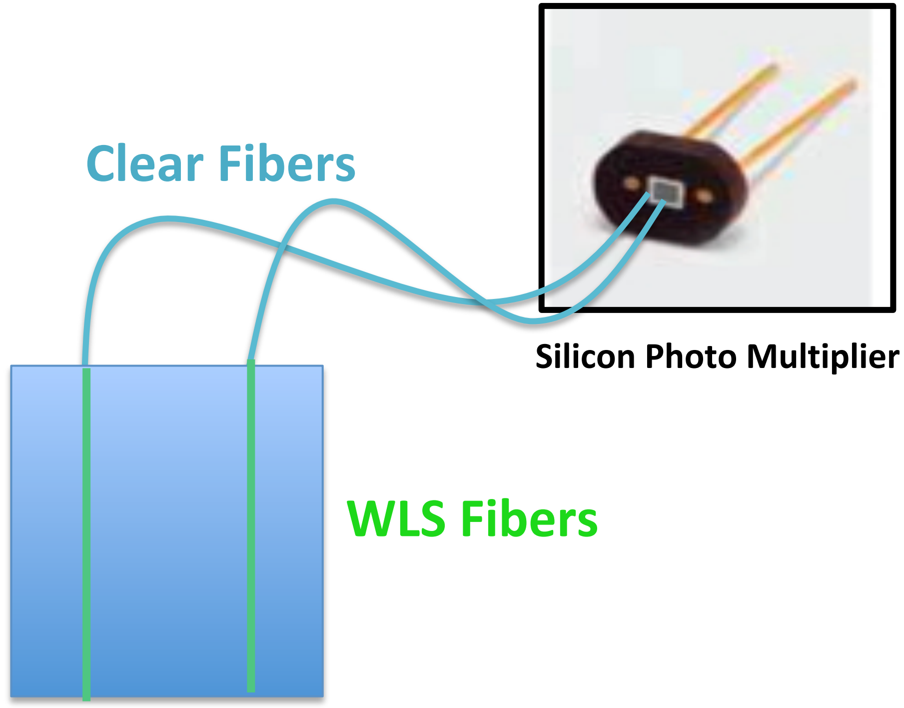
- Finalize studies on eco-friendly gas mixtures (e.g. HFO-based)
- Test new-generation (*thin)* RPCs with standard / eco-friendly gas mixtures at GIF++ to assess high rate capability and study ageing effects
- Development of low-noise high-amplification front-end electronics

Scintillating Tiles for R4 Regions

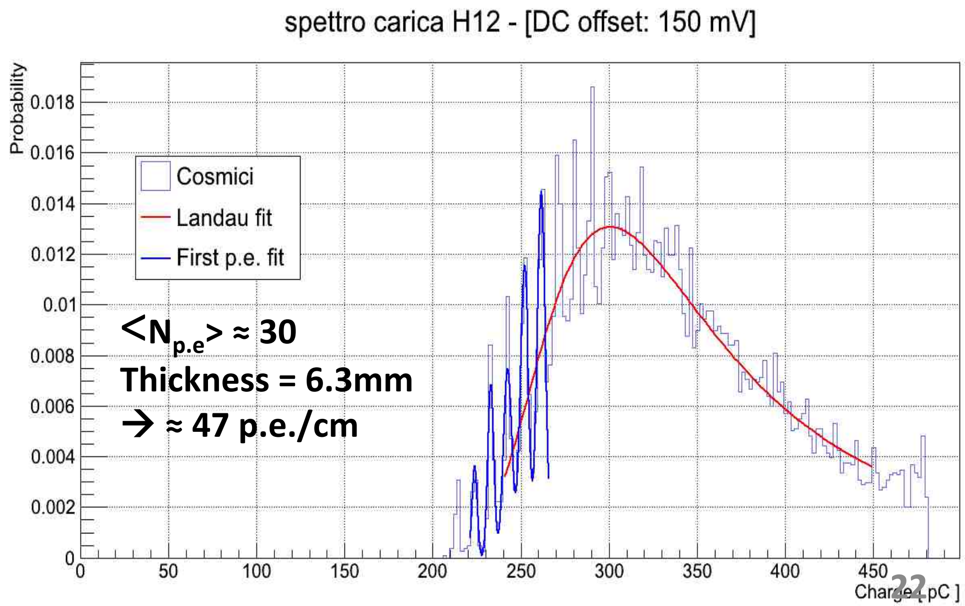
W. Baldini

The Idea

- **Scintillating tiles** read out through WLS/Clear fibers and SiPMs
- each scintillator tile can be 1-2 cm thick, in order to have a high light yield → high detection efficiency
- scintillator+fiber+SiPM yield is usually **40-50 p.e./cm** → high thresholds → lower Dark Count Rate (DCR)
- Scint. light collected by short **WLS fibers** (~25cm) and guided to SiPMs via **clear fibers**



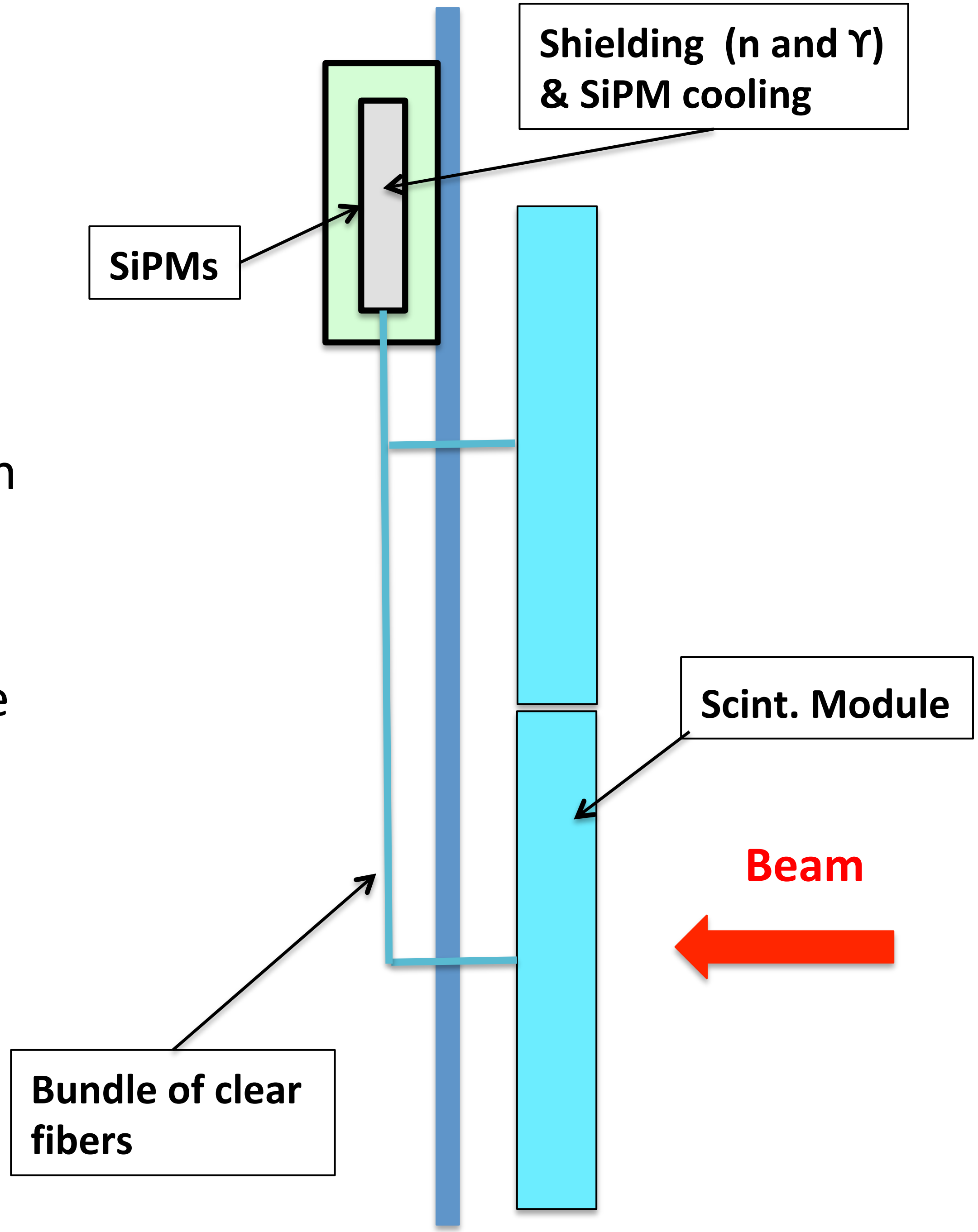
Surface grooves or embedded holes in extruded scintillators



- **Critical point is the SiPMs damage with radiation, especially Neutrons**

The Idea

- The scintillator can be put on the front of the support wall
- SiPMs and FE electronics can be located on the back
- Location of SiPMs should be chosen where the integrated neutron flux is lower, but keeping fibers as short as possible to maximize light transmission
- In this way we could keep SiPMs 4π shielded from radiation (polyethylene + boron for neutrons) and cooled



Detection Options: Single tile and TDC Readout

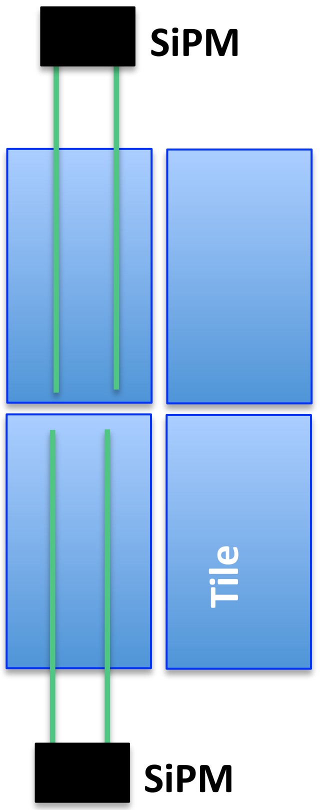
Assuming tiles 10 x 25cm^2 in M2

→ ~40 tiles/m^2 in M2

→ All R4 regions ~ 290 m^2

→ ~**9200 tiles** in total (M2-M5 only R4)

Single Tile Readout



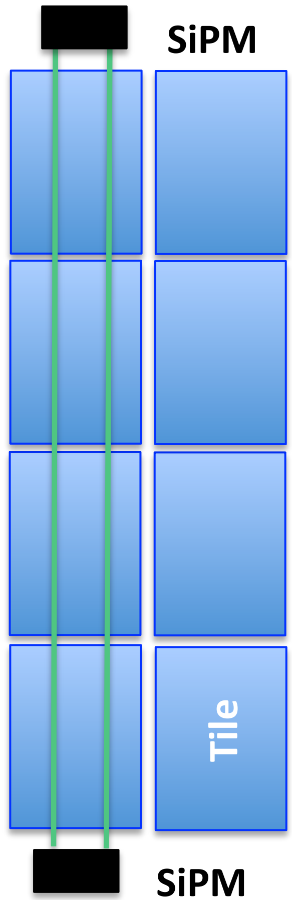
PRO:

- More robust against performance degradation

CONS:

- construction more complex
- more fibers and SiPMs
- more electronic channels (but cheaper: no "High-Res" TDC)

TDC Readout



PRO

- Simpler construction
- 2 Independent time measurements → Dark noise rejection
- ~ 1ns time resolution → ~ 20 cm space resolution in Y (c ≅ 17cm/ns)
- less SiPMs
- less fibers

CONS

- Electronics more expensive
- performance degradation with time
- rates and occupancies vs dose to be carefully evaluated

Conclusions

Ongoing discussions for a possible Muon Phase II Detector have been reported

- Additional iron/concrete shielding in place of HCAL is being evaluated, the **possible benefit of keeping HCAL at Run 4 needs to be investigated by the collaboration** before giving green light.

- To better define detector parameters (granularity, rate capability, time resolution) more detailed simulations are needed

- Strong expertise in the present Muon group for all the proposed technologies: μ-RWell, MWPCs, RPCs, Scintillating Tiles

- Clearly, additional studies are needed: aging, rate capability, time resolution

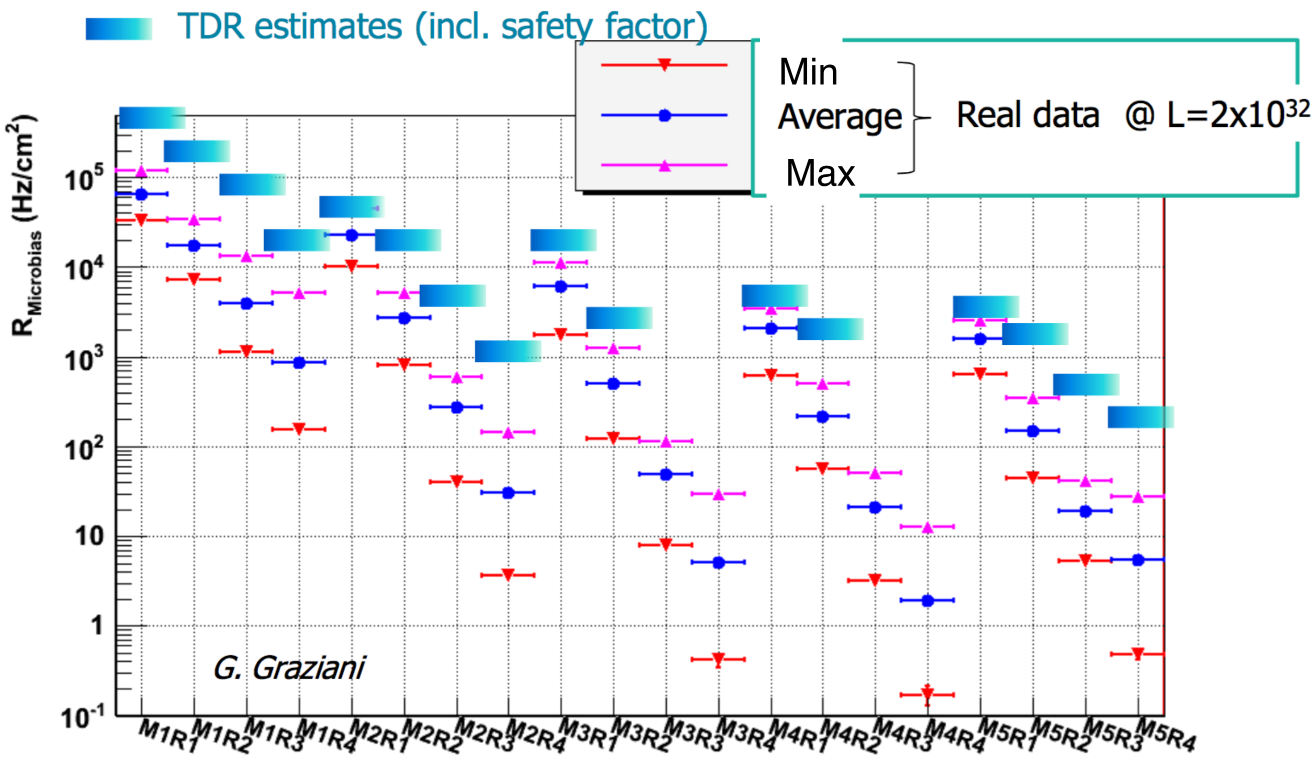
Final Remarks

- At present we're open to all possible solutions, the choice will be driven by **physics performance, cost and also by person-power availability**.

An ambitious project like building a new MUON detector from scratch can only be afforded if new groups/communities join the effort!

SPARES

Being conservative pays!



We worked at $4x10^{32}$ starting from 2011, a factor of 2 above the design value, with efficiency >99% in every station/region!

Several ingredients for the success: excellent design and construction quality, 4 gaps (redundancy), excellent maintenance and operation, HV training, time response stability **[JINST 14, P11031]**

Expected Rates at RUN5

M3

	D (R4)	C	B (R3)	A
16	357554	265666	281013	
15	430567	230063	265158	
14	318171	177132	175583	
13	353465	127393	117398	
12	232073	288481	80279	284003
11	273781	207220	51624	136927
10	194764	161683	35502	77161
9	219198	114371	23534	42858
8	150992	93827	212336	275905
7	169612	71307	136671	171158
6	107440	58672	113454	121013
5	126139	44490	77361	78757
4	83425	39005	65274	58841
3	98893	30707	46105	45427
2	63149	27286	41438	40949
1	70849	26100	34138	35185

MWPC present R3, 16 to be produced

MWPC present R4 0 to be produced

M4

	D (R4)	C	B (R3)	A (R2)
16	37688	148466	271617	151843
15	58375	123521	243838	116641
14	34320	91376	131467	75124 134816
13	51463	66927	100656	30245 62782
12	26770	45642	67827	179719
11	44310	33642	45342	135224
10	23639	25783	32621	61790
9	37509	19241	17820	34926
8	20183	16087	36968	42328
7	31345	12229	22614	26254
6	17578	10158	19722	18009
5	26082	7679	12656	11656
4	15483	6443	11100	9135
3	20998	5246	7378	6684
2	11836	4707	7031	5744
1	16428	3827	5134	4722

MWPC same size R2 but x4 granularity, 24 to be produced

MWPC present R3, 0 to be produced

MWPC present R4 0 to be produced

M5

	D (R4)	C	B (R3)	A (R2)
16	16750	18099	200366	108537
15	13306	7782	196464	79754
14	16052	12336	115349	51545 136406
13	11705	9345	88844	36441 56162
12	12333	7910	60135	221875
11	10244	7598	49713	125260
10	4175	9976	57556	72150
9	8934	15863	113152	100756
8	8905	21887	40590	42251
7	11346	33817	66685	44623
6	13265	26070	35788	23339
5	6162	19236	22832	17951
4	6675	17078	16018	12755
3	5247	11158	13286	13711
2	4923	6137	7353	5930
1	4015	4705	6610	5740

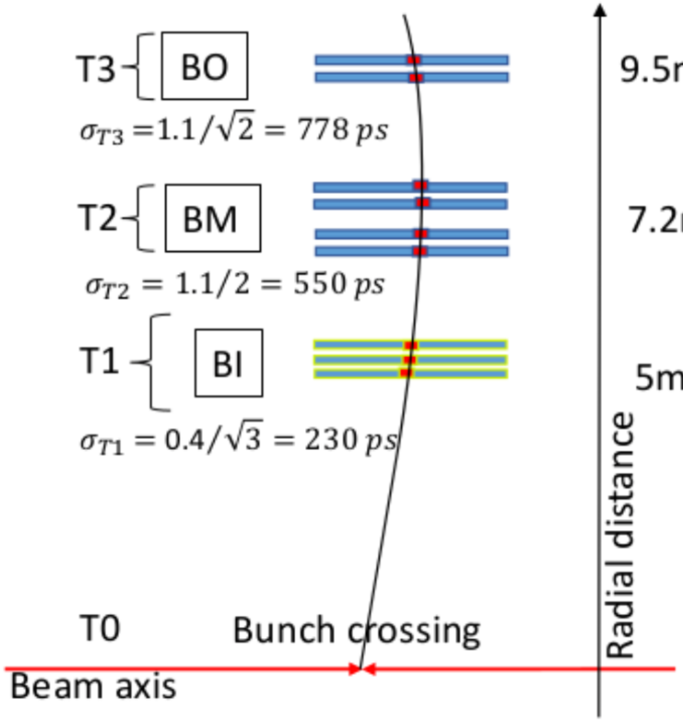
MWPC same size R2 but x4 granularity, 24 to be produced

MWPC present R3, 0 to be produced

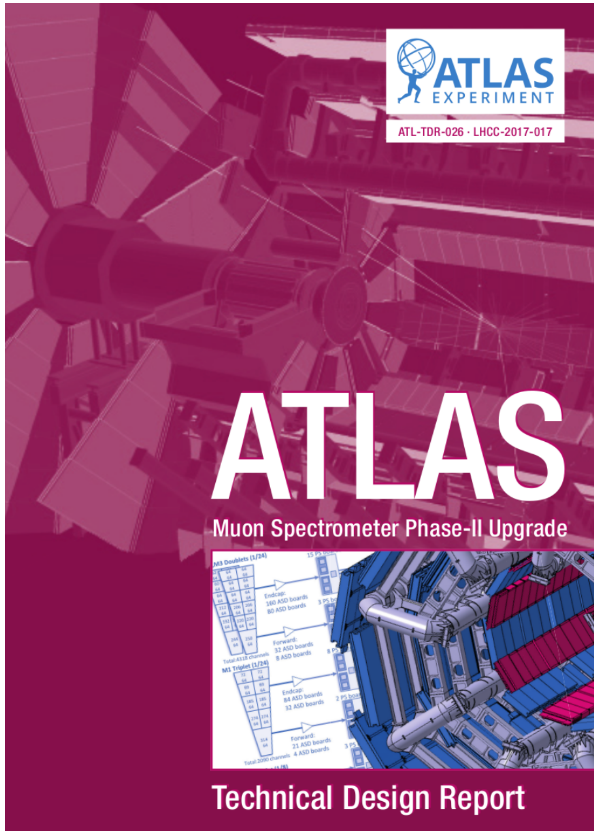
MWPC present R4 0 to be produced

The BI RPC project for the ATLAS muon phase 2

A major re-design of the RPC technology started around the year 2010, mainly aiming at a better rate capability and ageing behaviour. The new design is based on a reduced thickness of the gas gaps (from 2 mm to 1 mm) and of the resistive electrodes (from 1.8 mm to 1 mm), and on the use of a new generation of low-noise high-sensitivity amplifiers. Using these amplifiers, full efficiency can be achieved for a lower voltage across the gas gap, thus transferring part of the amplification from the gas avalanche to the electronics. In this way, the RPCs can be operated at a reduced charge per avalanche, reducing the detector current and thus improving rate capability and ageing.



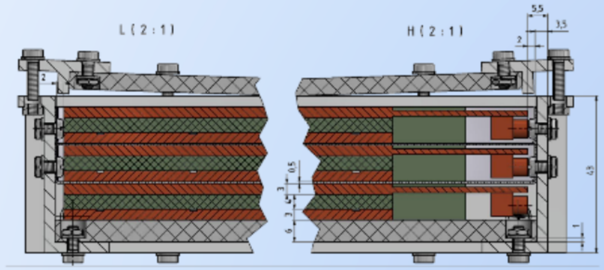
https://cds.cern.ch/record/2285580/files/ATLAS-TDR-026.pdf



The BI RPC system covers an area of 470 m^2, corresponding to a total active surface of 1410 m^2 (1/5 of the present RPC system). It comprises 272 triplet RPC chambers, equipped with 13500 FEBs.

The BI RPC project for the ATLAS muon phase 2

New RPCs for Phase-II Upgrade



1 mm thick gas gaps

Thinner gas gap (2 mm → 1 mm)
Thinner electrodes (1.8 mm → 1.2 mm)

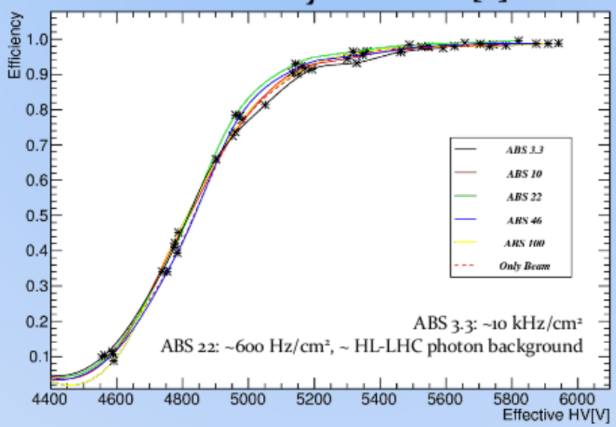
- Lower detector weight
- Thinner supports allowed
- More efficient signal collection
- Improved charge distribution
- Double time resolution (0.4 ns)
- Full efficiency reached at an HV of 5.4 kV, as tested at CERN GIF++ using a muon beam and a ^{137}Cs photon source with different absorption factors [1].

Front-End Electronics in SiGe BiCMOS technology

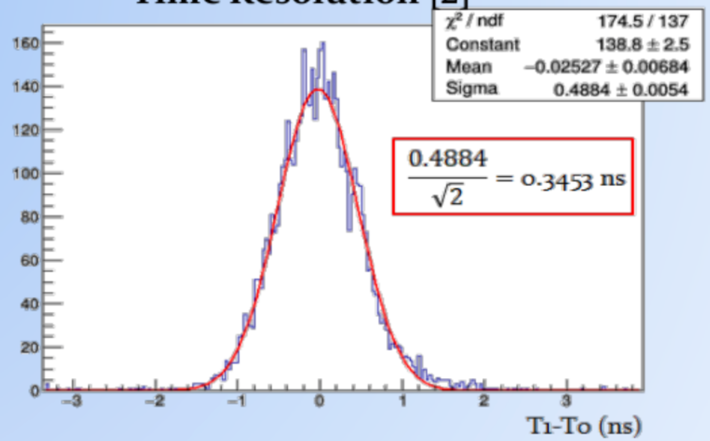
There will be a low-cost, high-performance and low-power Front-End board, allowing higher rate capability, more radiation hardness and better space-time resolution with respect to the performances of the present RPCs.
The new ASIC will have function of amplifier, discriminator, TDC and serializer, improving the time resolution and allowing Time-Over-Threshold measurements.

- The new preamplifier and discriminator prototypes have been tested on 1 mm RPCs, reaching a time resolution of 0.35 ns measured with an high rate muon beam[2]
- The new TDC with serializer, with a time resolution of 100 ps, has been prototyped, measuring an intrinsic jitter of 10.77 ps [3]

Efficiency Plateau [1]



Time Resolution [2]



Bibliography

TDR: *CERN-LHCC-2017-017 / ATLAS-TDR-026*

[1] *https://indico.cern.ch/event/644205/contributions/2862274*

[2] *https://indico.cern.ch/event/644205/contributions/2862251*

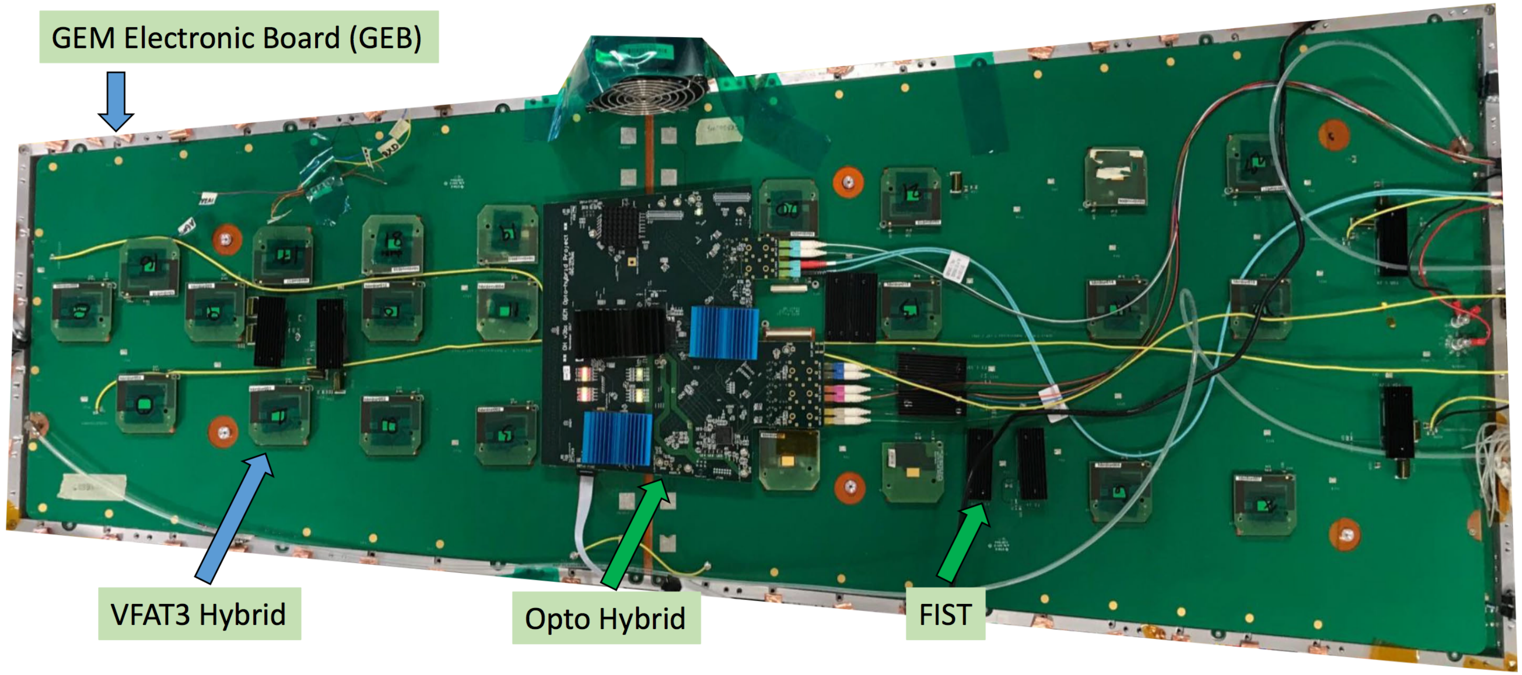
[3] *https://indico.cern.ch/event/644205/contributions/2862314*

Rate capability ~10 kHz/cm^2, time resolution ~ 0.5 ns per gap

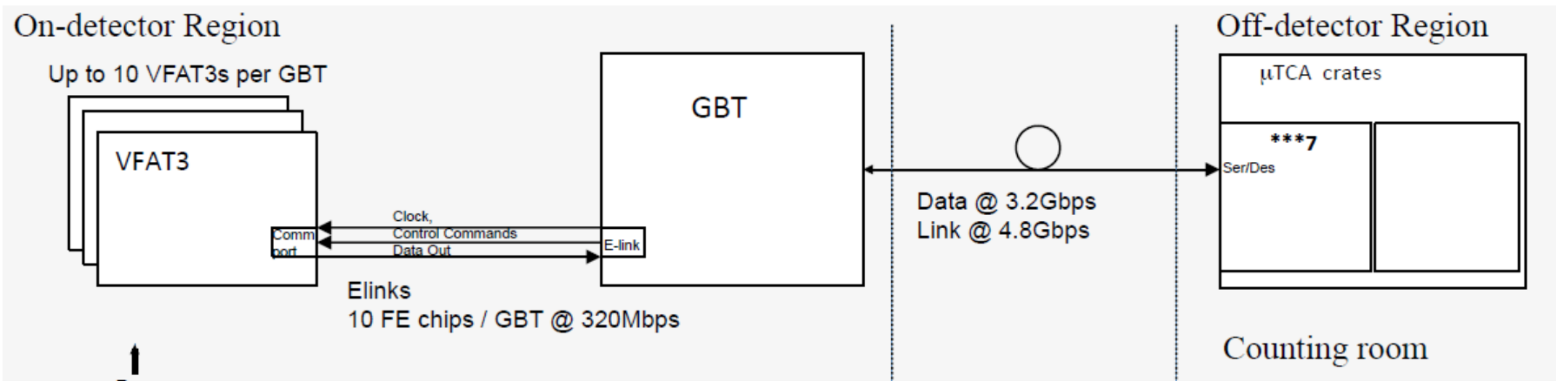
Front-end electronics

G. De Robertis
(INFN Bari)

CMS GE1/1 Chamber

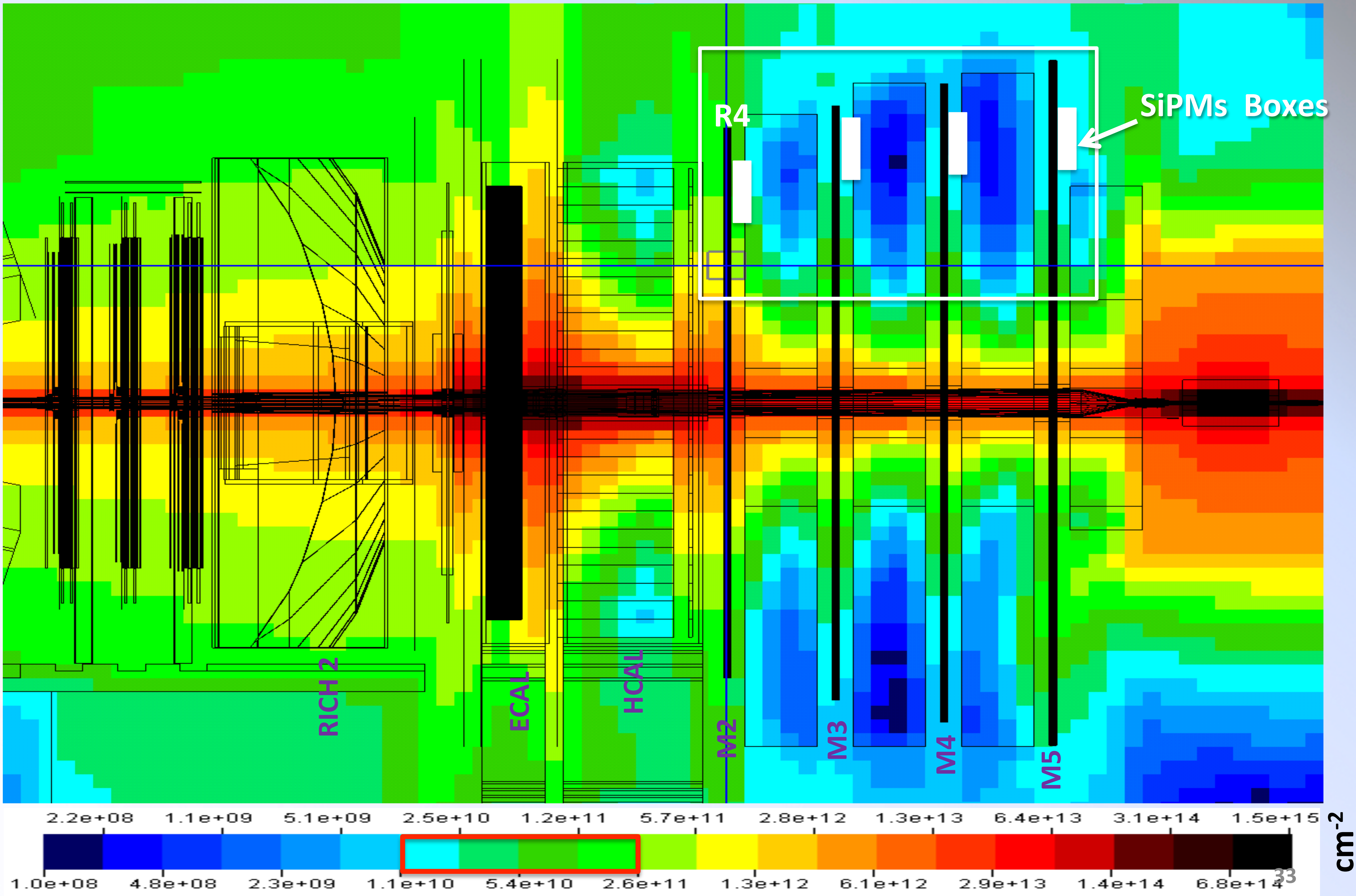


For CMS up to 10 FEBs interfaced with 1 GBT, not possible for LHCb



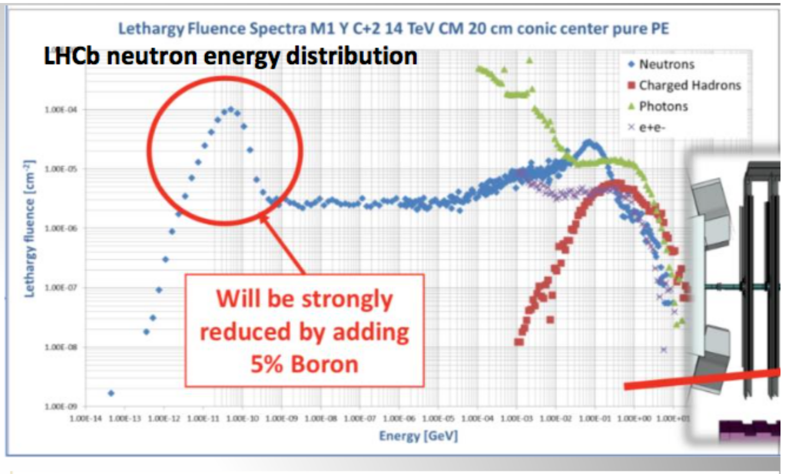
Expected Neutron Flux @ U2 Conditions (50 fb^{-1})

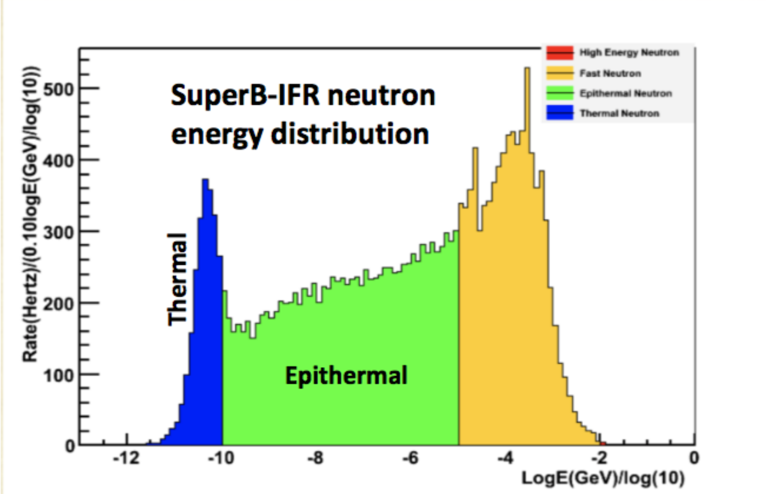
M. Karachson

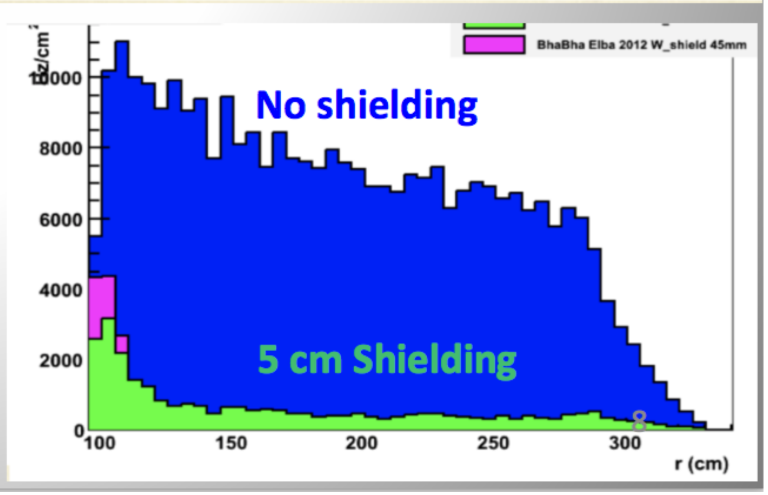


Neutrons Shielding

- Poliethylene + 5% Boron as a neutron shielding, to absorb slow/thermal neutrons
- As a very rough number:
  → ≈ factor 10 reduction of the fluence for a 5 cm layer
- neutrons generate lots of ϒ
  → few mm Pb shielding?







High Energy Neutrons have energy >100 MeV
Fast Neutron have energy 10 KeV -100 MeV
Epithermal Neutron are Neutrons with energy 10 KeV and 0.1 ev
Thermal Neutron have energy <0.1 eV