Challenges to operate the muon system @ 2×10^{34} $cm^{-2}s^{-1}$

P. de Simone on behalf of the LHCb Muon group

Beyond the LHCb Phase1Upgrade – April 6-7, 2016

outline

1) Muon detector @ 2×10^{33}cm^{-2}s^{-1}

detector layout
studies to improve the MuonID procedure

2) Muon detector @ 2×10^{34}cm^{-2}s^{-1}

expected rates
inefficiency induced by the dead time
MuonID-efficiency
π-MisID

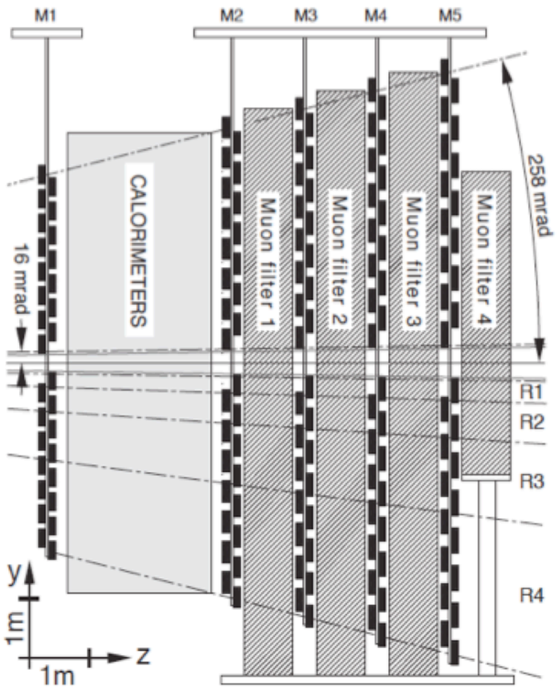
3) the μ-RWELL option for the Muon detector @ 2×10^{34}cm^{-2}s^{-1}

description of the μ-RWELL detector and its performance

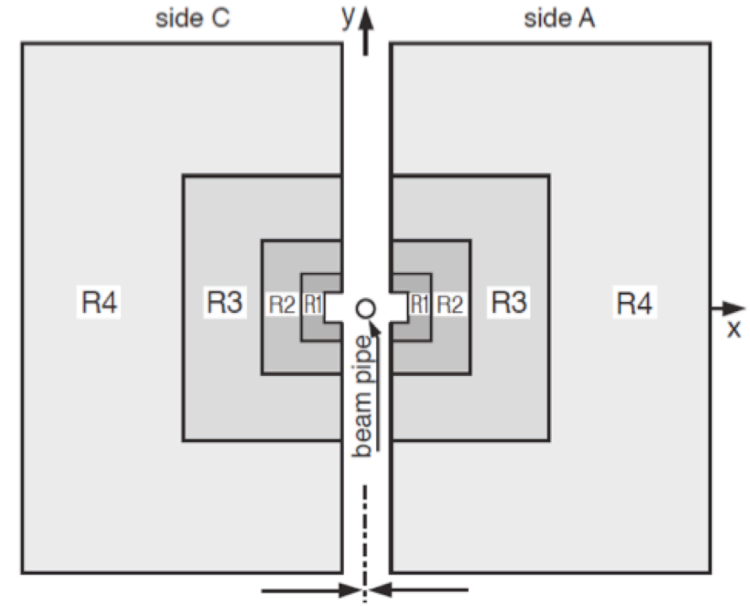
4) conclusion

detector layout @ 2×10^{33} cm^{-2}s^{-1}(I)

muon detector side view



station layout with the 4 regions indicated



MWPCs X-Y strip readout OR-ed by the FE, apart M4R1 and M5R1 pad readout

- **M1 station will be removed**
- new M2 and HCAL plugs together with additional shielding (30 cm tungsten) in front of M2
- additional shielding (Fe) **already installed** behind M5 to reduce back-scattered particles from LHC magnets

detector layout @ 2×10^{33} $cm^{-2}s^{-1}$(II)

at $2\times10^{33}cm^{-2}s^{-1}$, a considerable number of **ghost** is expected:
logical pads readout is based on the logical OR (in X and Y) of the physical channels done by the Intermediate Boards (IB), which are then crossed at the trigger/offline level
readout via logical OR used in all regions but R1: removing the IB would allow to achieve a finer granularity in the detector readout

as an example:
the outermost region R4, of the station M5 (large logical channels up to ≈ 0.5 m^2 resulting from the logical OR) will be subject to a high background coming due to back-scattered particles from the LHC magnets that will be reduced by
✓additional shielding
✓increased granularity of the logical channels in M5R4 by eliminating the IB and replacing them by the off-detector electronics (ODE) *(this is an option under study)*

with a toy MC computation(*) using the rates at $2\times10^{33}cm^{-2}s^{-1}$, and a model for the dead time, we have evaluated the pads occupancy with different detector configurations *Giuseppe Martellotti, Muon Meeting, 24/02/2014* ➔

- **IB removal ➔ factor of 2 reduction** of accidental background in M5R4

(*) "Measurement of the front-end dead-time of the LHCb muon detector and evaluation of its contribution to the muon detection inefficiency", arXiv:1602.08699, accepted by JINST

Muon IDentification **is a two-step procedure**

step 1 ➔ IsMuon

on each station hits around the track extrapolation points are collected within the search windows (FOI) that are parameterized depending on μ momentum and crossed detector region

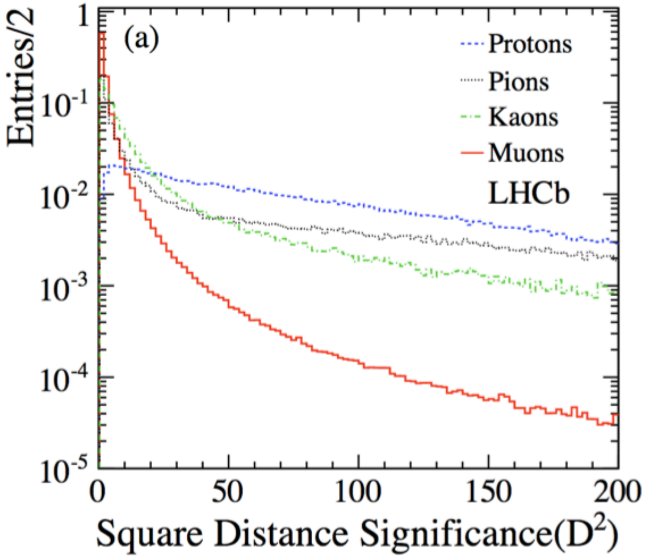
a coincidence of stations is required as a function of momentum ➔

Momentum range	Muon stations
$3\ \mathrm{GeV}/c < p < 6\ \mathrm{GeV}/c$	M2 and M3
$6\ \mathrm{GeV}/c < p < 10\ \mathrm{GeV}/c$	M2 and M3 and (M4 or M5)
$p > 10\ \mathrm{GeV}/c$	M2 and M3 and M4 and M5

step 2 ➔ Muon Likelihood (muDLL)

based on the average squared distance D^2 of the closest μ hit in FOI to the track extrapolation points on each station

$$D^2 = \frac{1}{N}\sum_i \left\{ \left(\frac{x^i_{closest} - x^i_{track}}{pad^i_x} \right)^2 + \left(\frac{y^i_{closest} - y^i_{track}}{pad^i_y} \right)^2 \right\}$$



muDLL is then combined in a likelihood with RICH and CALO (**combDLL**)

improving Muon Identification @ $2\times10^{33}cm^{-2}s^{-1}$

step 1 ➔ IsMuon

IsMuon	collecting all hits in FOI, also from unpaired strips
IsMuonTight	collecting only crossed hits in FOI (crossed hits: both X and Y readout channels fired)

use of isMuonTight implies an effective improvement of the background rejection with a reasonable signal loss: MuonID-ε decreases of ≈ 2 %

step 2 ➔ redefine the muon classifier

exploit the full detector informations to suppress combinatorial background more effectively accounting for correlations

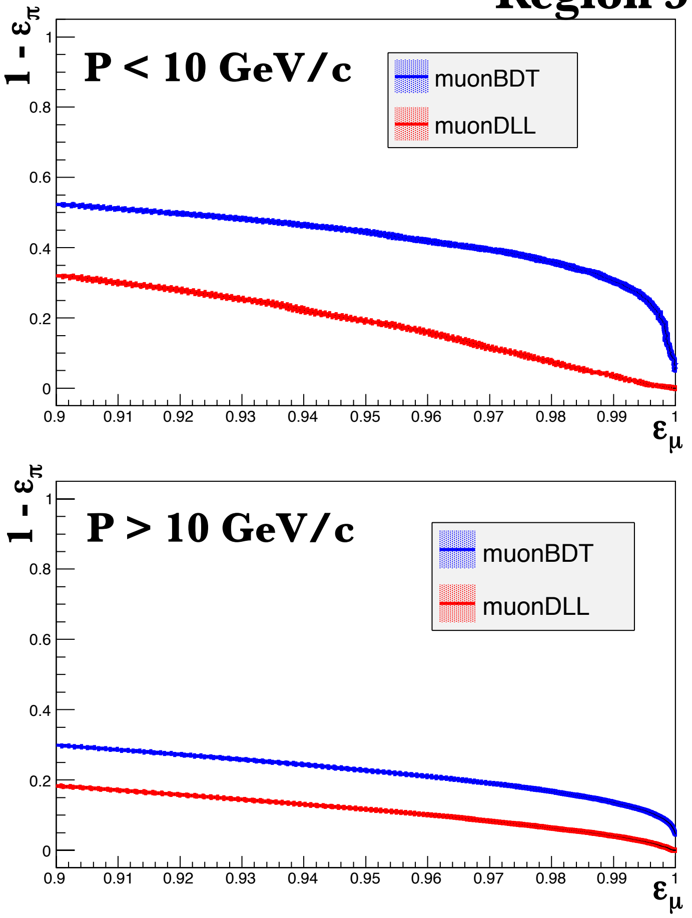
- MVA approach based on Boosted Decision Tree (BDT) combines: space residuals, multiple scattering errors, times, number of shared hits
- new discriminating variable χ^2_{best} accounts for correlations among the hits on different stations induced by multiple scattering

π rejection vs μ efficiency

- ✓ 2012 data control samples of μs from J/ψ →μμ, and πs from $D^0 \rightarrow K\pi$

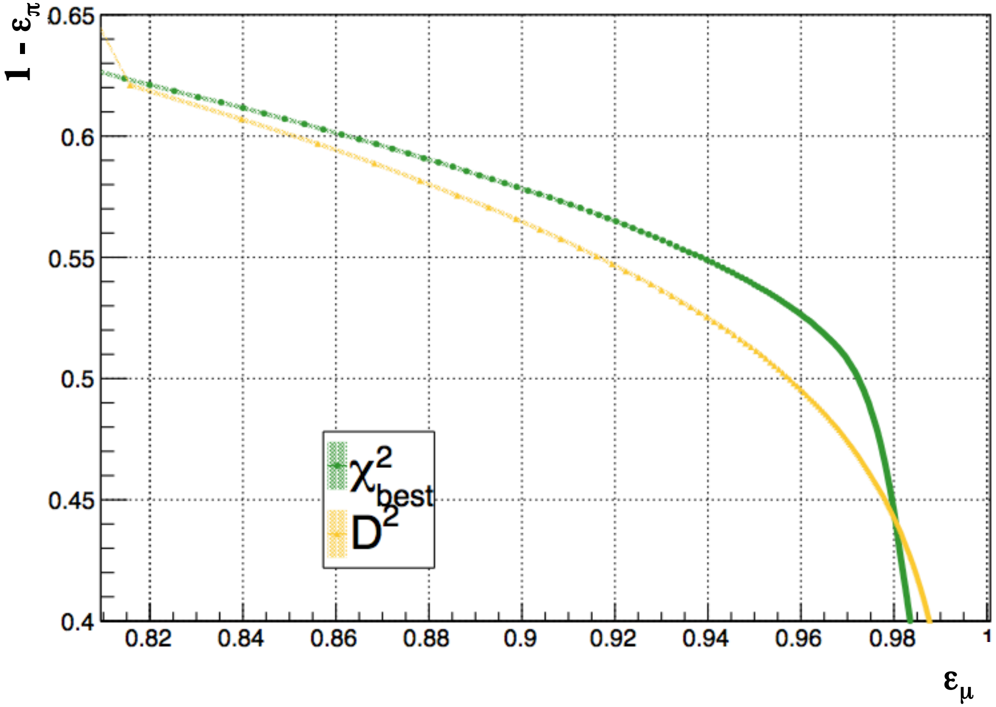
LNF + F. Archilli

Region 3



ROCs curves produced for different regions and momentum ranges, are relative to isMuonTight

Cagliari



ROCs curves relative to isMuonTight

π-MisID performances vs luminosity

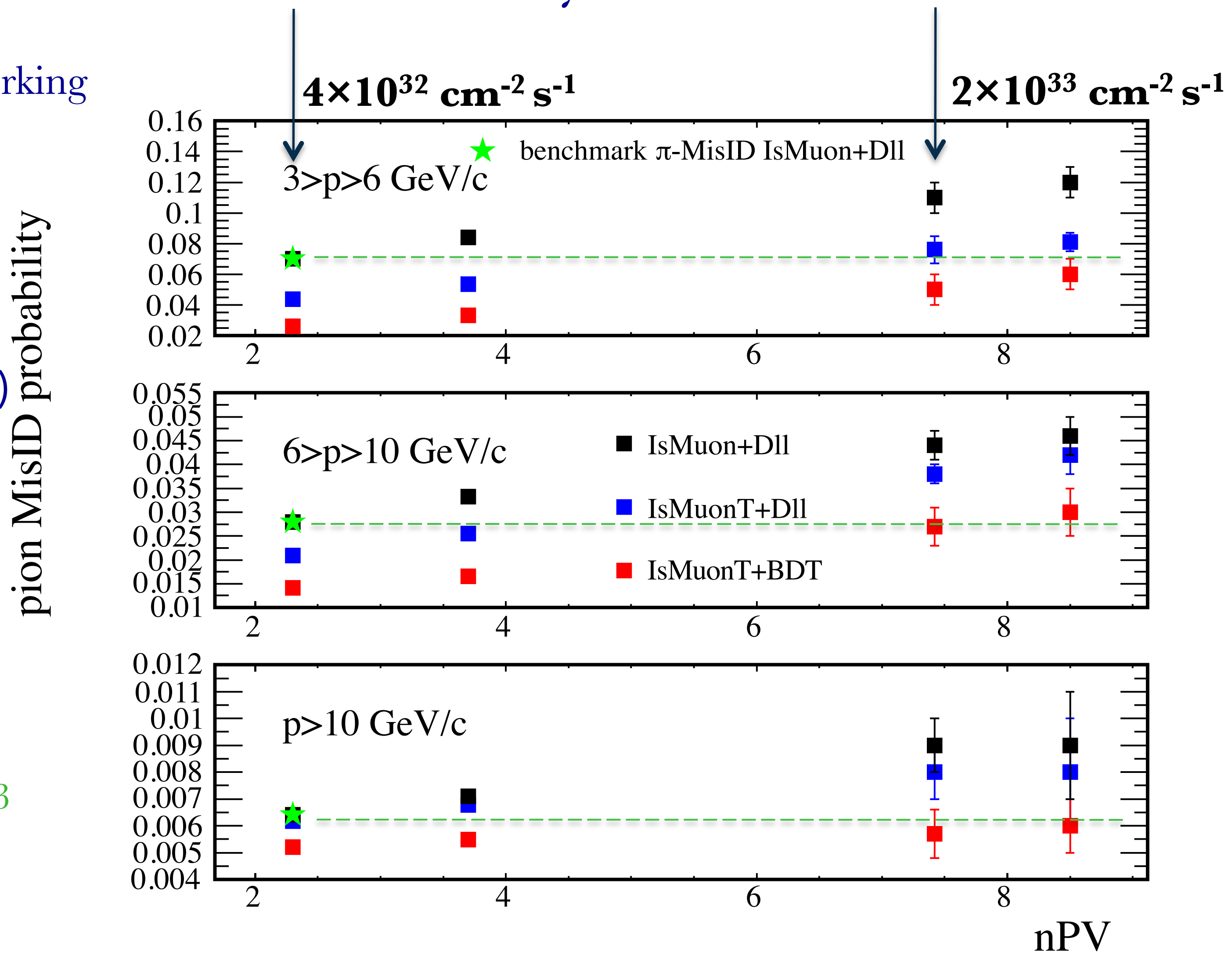
for all scenarios the working point has been chosen in order to give the same MuonID-ε, per region and momentum bin **(IsMuonID-ε ≈ 91%)**

IsMuon+Dll

IsMuonTight+Dll

IsMuonTight+BDT

IsMuon+Dll @ nPV ≈ 2.3
2012 running conditions
➔ benchmark value



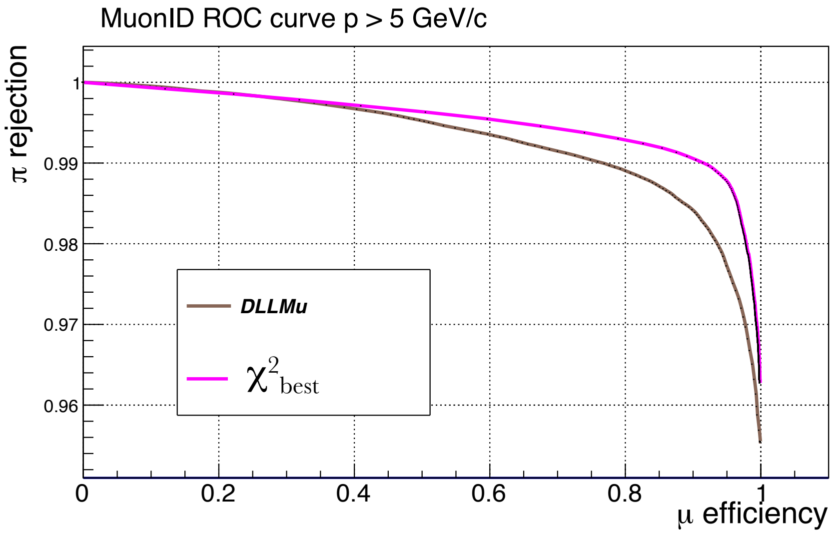
isMuonTight+BDT restores the average π-MisID increase with the pile-up, thus preventing from any sensitivity losses with luminosity increase

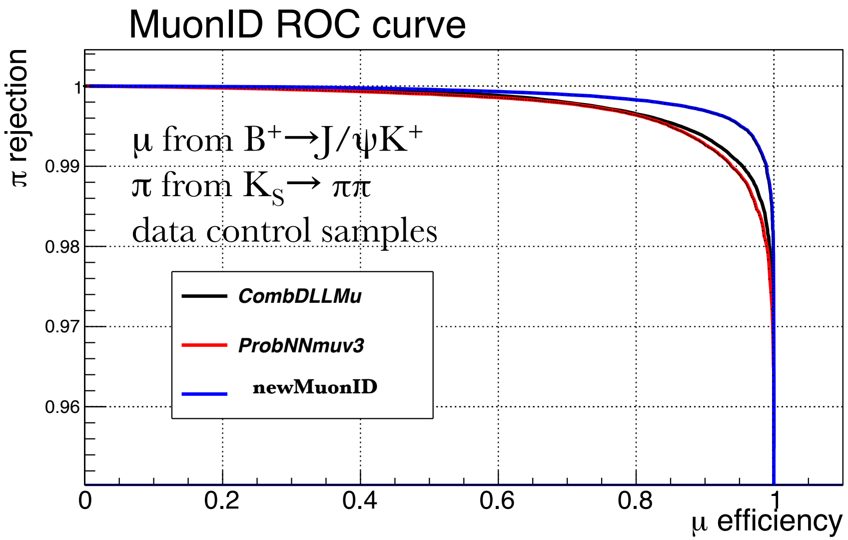
a possible new approach to the MuonID

✓ lower detector efficiencies in upgrade conditions: new MuonID algorithm **more tolerant with station inefficiencies** ➔ *looser coincidence requirements*

✓ the algorithm has been written to improve the background reduction in case of the $K_s \rightarrow \mu^+\mu^-$ analysis by the *Firenze group* **with very encouraging results**

Giacomo Graziani, MuonID Meeting, 21/01/2016





✓ search windows defined in terms of error on muon-hit position and multiple scattering

✓ muon candidate **requires a match in at least two μ-stations**

✓ new discriminating variable χ^2_{best}

✓ following the hits association several variables are defined for each station

✓ combine 17 variables in a BDT, including also combDLL and ProbNN

Muon detector @ 2×10^{34}cm^{-2}s^{-1}

expected rates

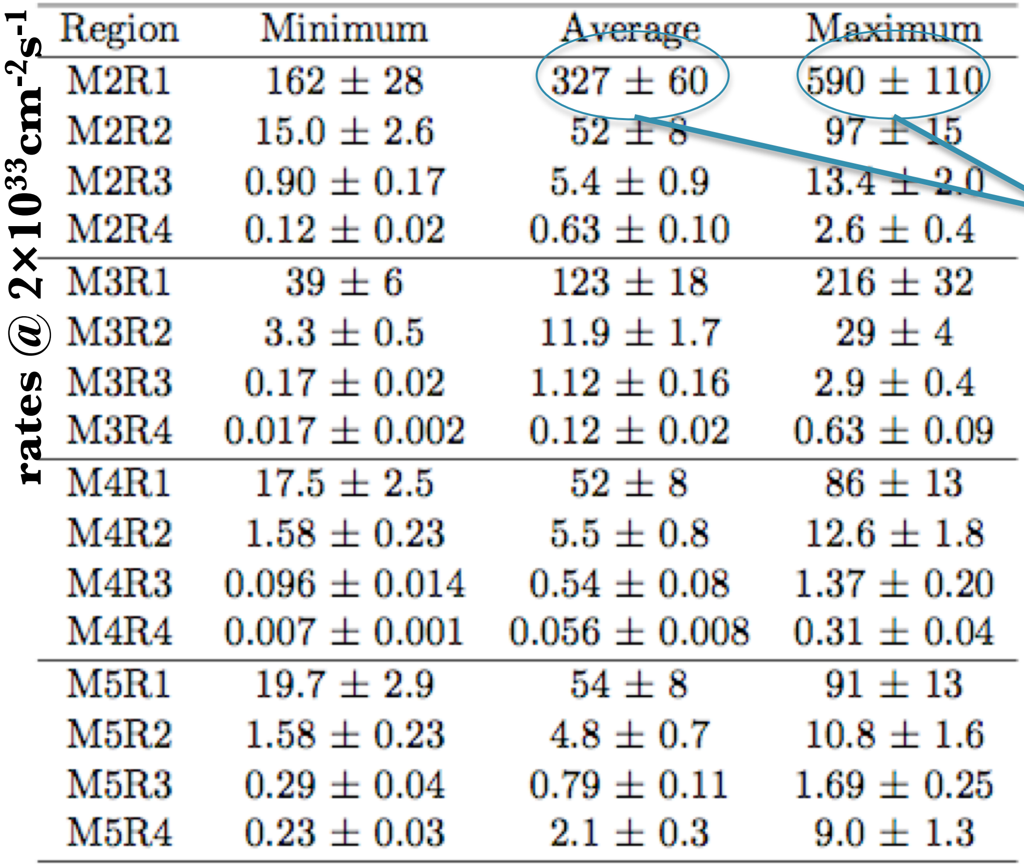
rate extrapolation done for **Phase 1 Upgrade studies**, uses 2012 data and takes into account

✓ the energy increase at 14 TeV

✓ the additional spill-over due to 25ns bunch spacing

✓ the rate reduction in M2R1 by ≈ 26% due to additional shielding

rates @ 2×10^{33}cm^{-2}s^{-1}



Region	Minimum	Average	Maximum
M2R1	162 ± 28	327 ± 60	590 ± 110
M2R2	15.0 ± 2.6	52 ± 8	97 ± 15
M2R3	0.90 ± 0.17	5.4 ± 0.9	13.4 ± 2.0
M2R4	0.12 ± 0.02	0.63 ± 0.10	2.6 ± 0.4
M3R1	39 ± 6	123 ± 18	216 ± 32
M3R2	3.3 ± 0.5	11.9 ± 1.7	29 ± 4
M3R3	0.17 ± 0.02	1.12 ± 0.16	2.9 ± 0.4
M3R4	0.017 ± 0.002	0.12 ± 0.02	0.63 ± 0.09
M4R1	17.5 ± 2.5	52 ± 8	86 ± 13
M4R2	1.58 ± 0.23	5.5 ± 0.8	12.6 ± 1.8
M4R3	0.096 ± 0.014	0.54 ± 0.08	1.37 ± 0.20
M4R4	0.007 ± 0.001	0.056 ± 0.008	0.31 ± 0.04
M5R1	19.7 ± 2.9	54 ± 8	91 ± 13
M5R2	1.58 ± 0.23	4.8 ± 0.7	10.8 ± 1.6
M5R3	0.29 ± 0.04	0.79 ± 0.11	1.69 ± 0.25
M5R4	0.23 ± 0.03	2.1 ± 0.3	9.0 ± 1.3

values are in kHz/cm^2

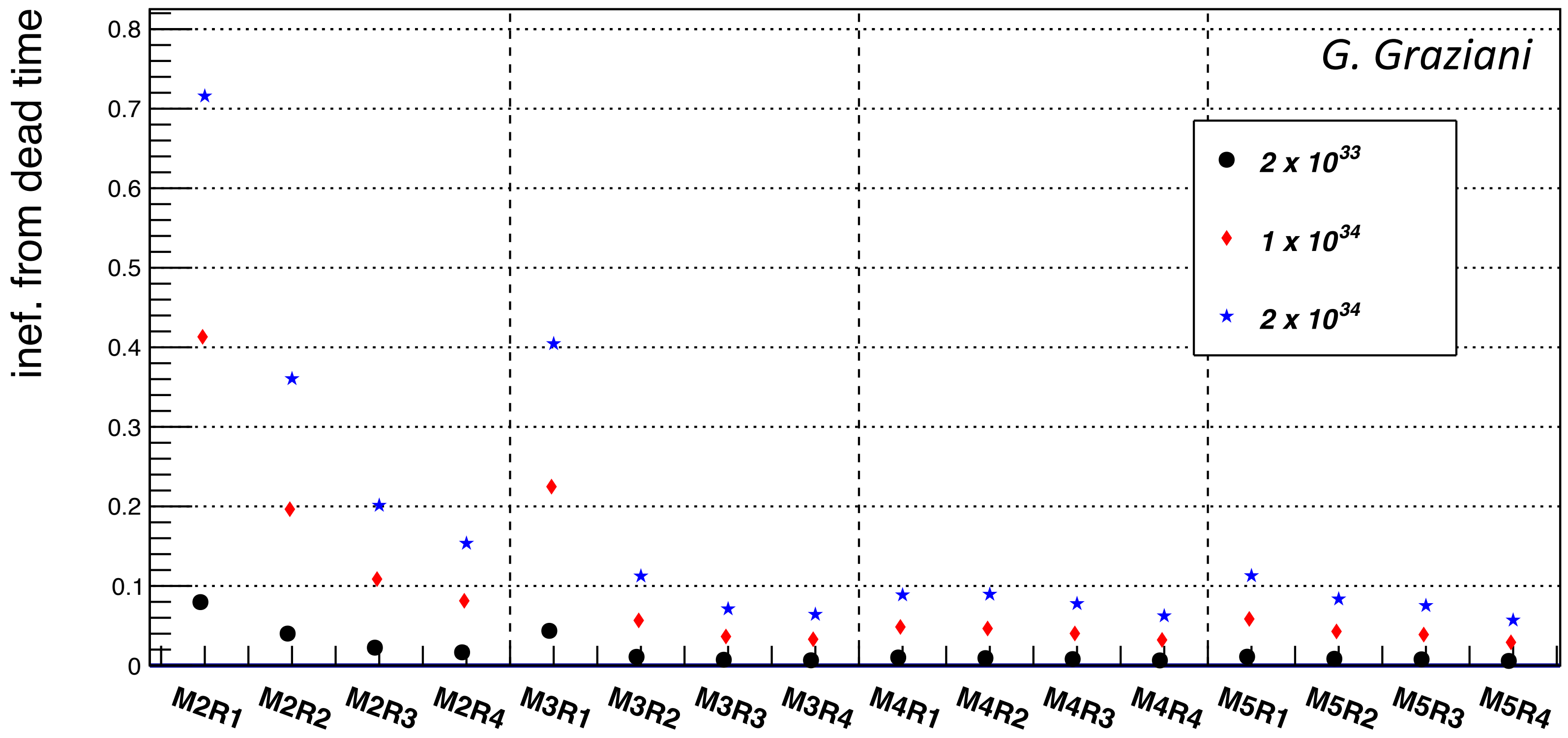
@ 2×10^{34}cm^{-2}s^{-1} values must be multiplied by a factor ≈ 10

➔ in M2R1 expected average rate ≈ 3.3 MHz/cm^2, and maximum rate ≈ 6 MHz/cm^2 !!

✓add an iron (or mixed Fe/W) shielding in front of M2 to reduce the incident rates **by ≈ 50%**

✓ background originates also from high energy particles interacting inside the beam pipe: filter around the beam pipe

dead time induced inefficiency at 2×10^{34} cm^{-2} s^{-1}

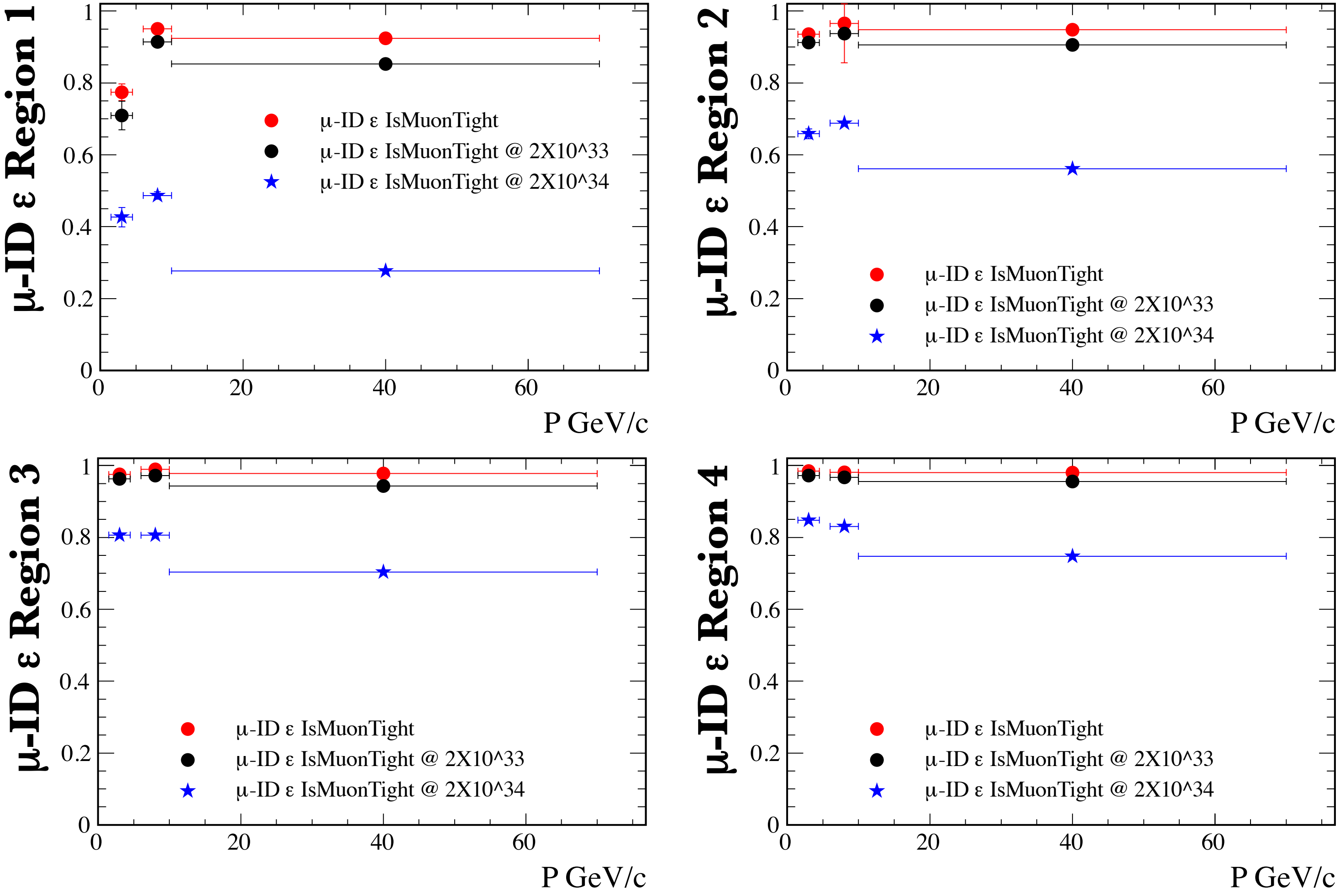


these projections are based on rates measured on detector with 2015 runs and a modelling of dead time vs luminosity (validated on high luminosity special runs)

<u>however the uncertainty on the actual dead time and the extrapolations at very high luminosity bring the uncertainty on the induced inefficiency up to ≈ 50%</u>

dead time effect on ε-MuonID

- ✓ 2012 data control sample of μs from J/ψ →μμ



aside from unavoidable hardware solutions we could attempt the new approach for the MuonID procedure with **looser coincidence** requirements *(slide 10)*

π-MisID at 2 ×10^{34} cm^{-2} s^{-1}

◎ **we will soon deal with detailed Monte Carlo studies**

◎ extrapolation of the π-MisID vs pileup at 2×10^{34}cm^{-2}s^{-1}, nPV≈74, can be used to infer the increase of the π-MisID for tracks **with p > 10 GeV/c**

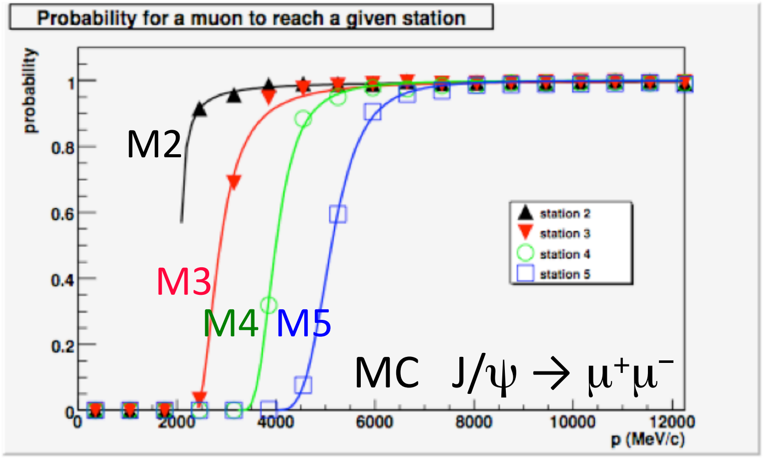
π-MisID	at 2×10^{33}cm^{-2}s^{-1}	**increase at 2×10^{34}cm^{-2}s^{-1}**
Region 1	.007 ± .002	≈ × 22
Region 2	.006 ± .001	≈ × 5
Region 3	.0050 ± .0006	≈ × 3
Region 4	.0009 ± .0002	≈ × 1

Please Note: the above extrapolations, which are based on data, **do not account** for improvements coming from additional shielding

➔ factor of ≈ 2 decrease of uncorrelated background on each station

probability for muon tracks to reach a station as a function of the momentum

a required additional filter shifts the probability by ≈ 1GeV/c towards higher momenta



hardware interventions

muon detector response at 2×10^{34}cm^{-2}s^{-1} is seriously affected by the increased rate

- ◎ new shielding to reduce the rates on M2, **we do expect a rate reduction of ≈ 50%**
- ◎ **new pads detectors in M2R1, M3R1 (and M2R2, M3R2)** pad size X, Y/2 w.r.t. present logical pads
- ◎ **IB removal ➔** this would allow to cancel the ghost pads rate
- ◎ **also** need to define which part of the detector (FE electronics, chambers) must be replaced due to aging

remind from Phase 1 Upgrade studies

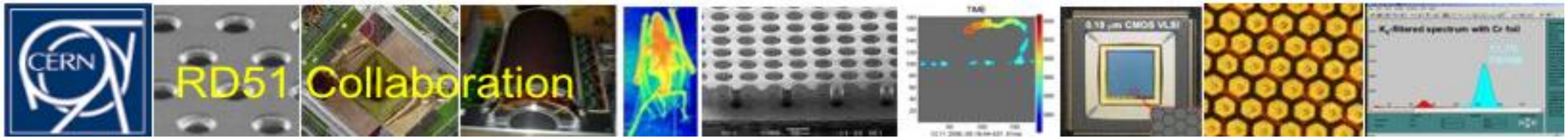
with a toy MC computation using the rates at 2 ×10^{33}cm^{-2}s^{-1}, and a model for the dead time, we have evaluated the pad occupancy with different detector configurations, *Giuseppe Martellotti, Muon Meeting, 24/02/2014* ➔

1) a factor ≈10 less accidental background on the product M2R1×M3R1 with new pad detectors (X, Y/2), and moreover the dead time inefficiency completely solved
2) a factor ≈ 2 reduction in accidental background is obtained removing the IB

detailed MC studies must be done to define the final configuration

the μ-RWELL option for the Muon detector @ $2\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

G. Bencivenni, M. Poli Lener
LNF - INFN



requirements @ $2\times10^{34}cm^{-2}\,s^{-1}$

- ✓ **Rate** up to 3 **MHz/cm²** **with an additional filters in front of M2**
- ✓ **Efficiency** for single gap **> 95%** within a BX (25 ns)
- ✓ **Long stability** up to **6 C/cm²** accumulated charge in **10 y** of operation
- ✓ **Pad cluster size < 1.2**

	Expected max rate MHz/cm² (*)	Active area cm²	Pad Size cm² (*)	Rate/Pad MHz	# pad/gaps	# gaps	#chamber 2 gaps
M2R1	3	30x25	0.63x0.77	1.5	1536	24	12
M2R2	0.5	60x25	1.25x3.15	0.5	384	48	24
M3R1	1	32.4x27	0.67x1.7	1	768	24	12
M3R2	0.15	64.8x27	1.35x3.4	0.15	384	48	24

(*) **average rate is about 50% of maximum rate**

(*) X, Y/4 w.r.t. present logical pads in M2R1; **a factor 2 more in Y, to halve the rate/Pad**
X, Y/2 w.r.t. present logical pads in M2R2, M3R1 and M3R2

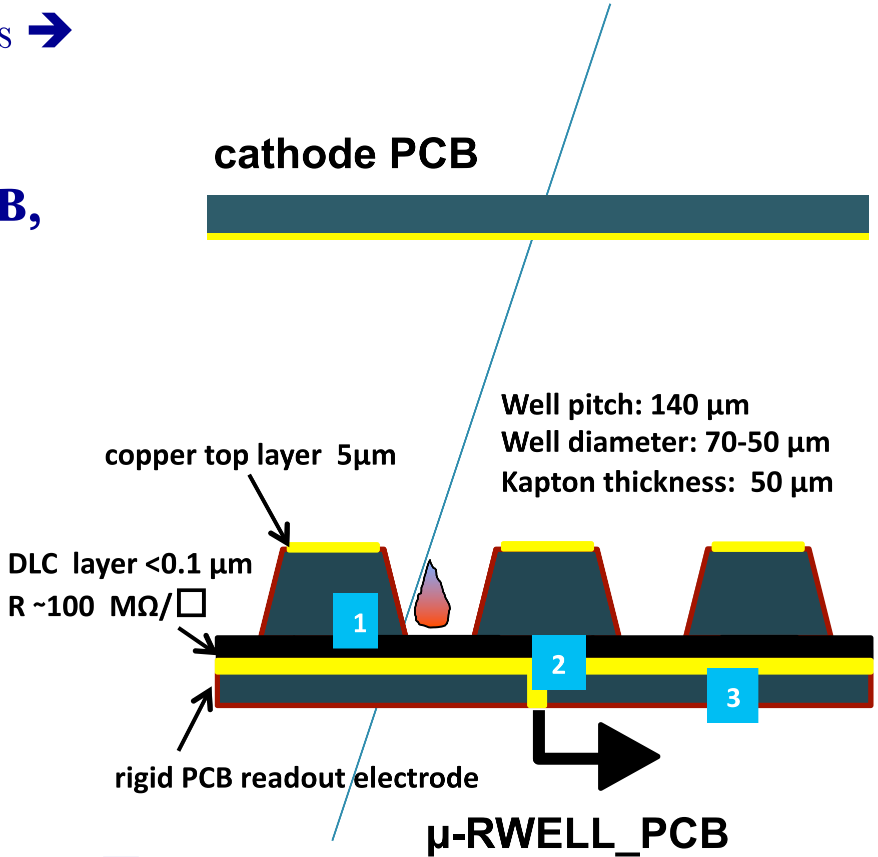
in this framework the **GEM detector** is still **a valid option,**
however we are proposing a new detector ➔ **the μ-RWELL**

the detector architecture

the μ-RWELL detector is composed by two elements ➔
the **cathode** and the **μ-RWELL_PCB**

the main part of the detector is the **μ-RWELL_PCB,** that is realized by assembling

1. a WELL patterned kapton foil that acts as **amplification stage**
2. **resistive stage**, for the discharge suppression and current evacuation
3. a standard readout PCB



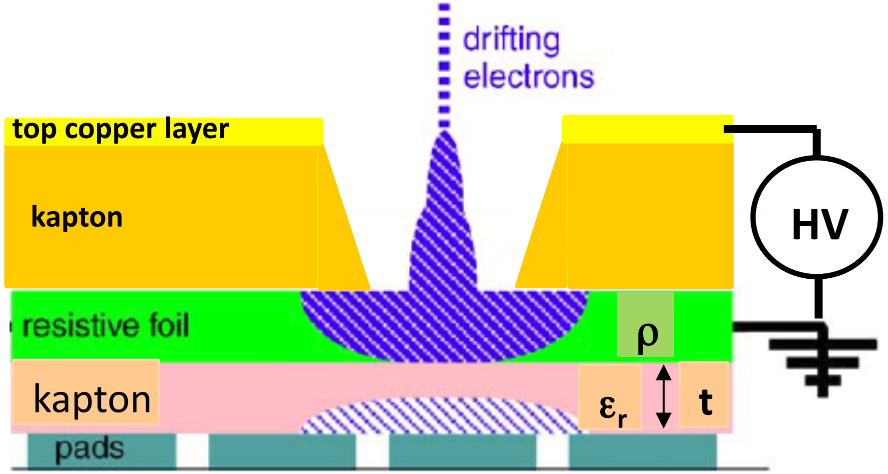
G. Bencivenni et al., 2015_JINST_10_P02008

μ-RWELL **R&D is ongoing** for the CMS Upgrade and for SHIP
the rate requirement is << 100 kHz/cm^2
➔ single resistive layer with surface resistivity ≈100MΩ/☐

LHCb Phase 2 Upgrade rate requirement is >> 100 kHz/cm^2
more sophisticated resistive scheme must be implemented (R&D phase ongoing at LNF funded by INFN)

principle of operation

a voltage 400-500 V between the top copper layer and the grounded resistive foil, generates an an electric field of ~100 kV/cm into the **WELL which acts as multiplication channel**

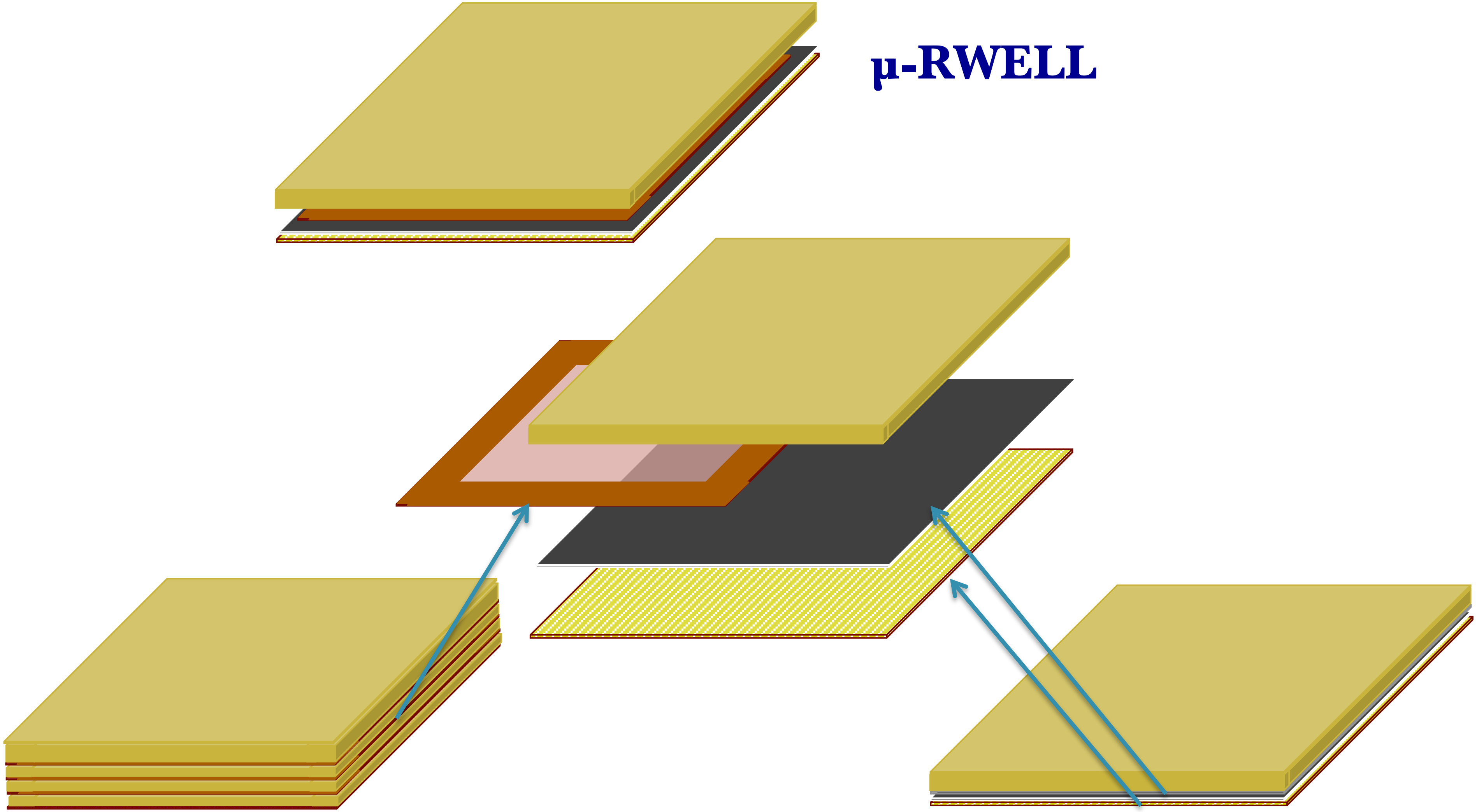


the charge induced on the resistive foil is dispersed with a time constant, RC, determined by

- the surface resistivity, **ρ**
- the capacitance per unit area, which depends on the distance between the resistive foil and the pad readout plane, **t**
- the dielectric constant of the kapton, $\boldsymbol{\varepsilon_r}$ *[M.S. Dixit et al., NIMA 566 (2006) 281]*

the effect of the introduction of the resistive foil is the suppression of the transition from streamer to spark by a local voltage drop around the avalanche location

μ-RWELL ➔ GEM-MicroMegas mixed solution



μ-RWELL

3-GEM detector sketch

MicroMegas detector sketch

main features of the μ-RWELL detector

the **μ-RWELL** is a safe and robust (spark protected) detector, and it has a very simple construction procedure:

- ◎ only two mechanical components → μ-RWELL_PCB + cathode
- ◎ no critical & time consuming assembly steps:
    - ✓ **no gluing**
    - ✓ **no stretching**
    - ✓ **easy handling**
- ◎ no stiff & large frames
- ◎ suitable for large area with PCB splicing technique (more simple than GEM)

cost effective:

- ◎ 1 PCB r/o, 1 μ-RWELL foil, 1 DLC, 1 cathode and low man-power

easy to operate:

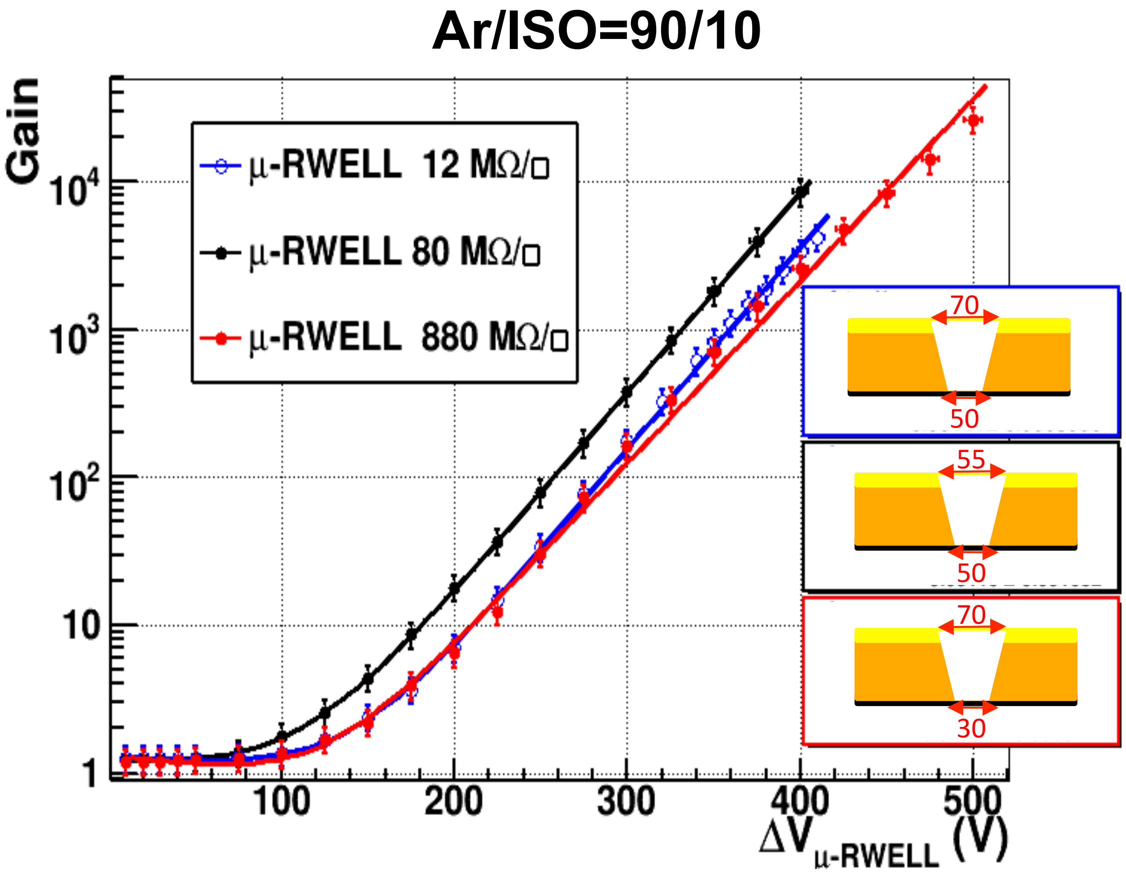
- ◎ very simple HV supply → 2 independent channels or a trivial passive divider (3GEM detector → 7 HV channels)

detector performance

the results presented here came from R&D on μ-RWELL detectors optimized as tracking devices

gas gain

prototypes with different resistivity (12-80-880 MΩ/☐) have been tested with an **X-Ray** gun (5.9 keV), with **Ar/iC_4H_{10}= 90/10** gas mixture, and characterized by measuring the **gas gain** in **current mode**.



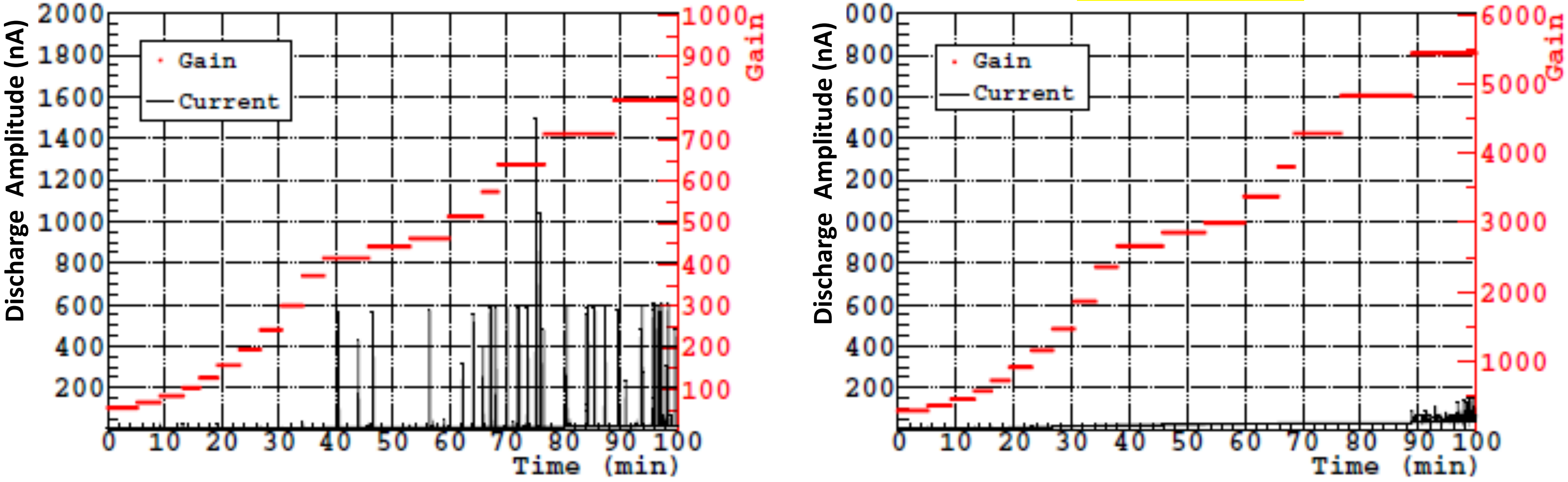
discharges: μ-RWELL vs GEM

test with X-ray

Ar/CO$_2$ = 70/30

single-GEM

μ-RWELL

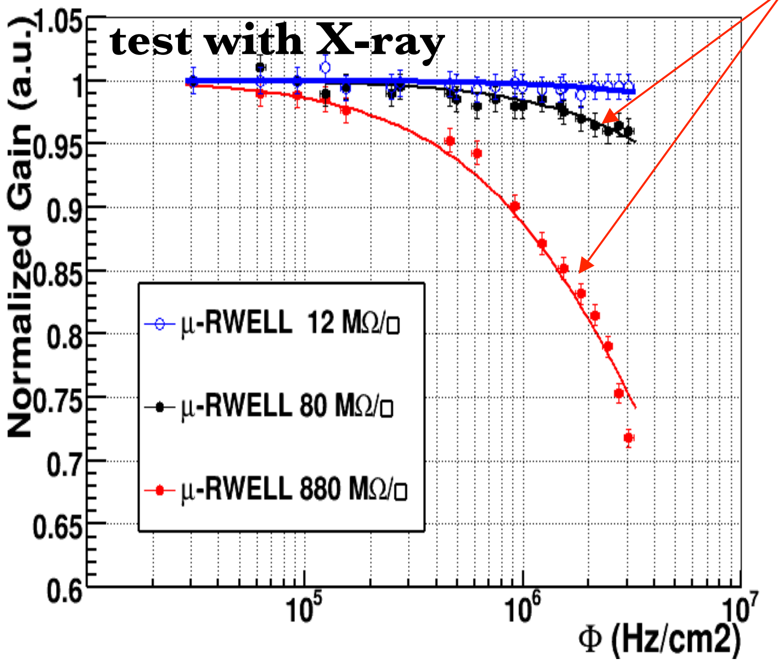


- the **μ-RWELL** detector reaches discharge amplitudes of **few tens of nA, <100 nA @ max gain**

- the **single-GEM** detector reaches discharge amplitudes of **≈ 1μA**
(of course the discharge amplitude is lower for a triple-GEM detector)

rate capability vs layer resistivity

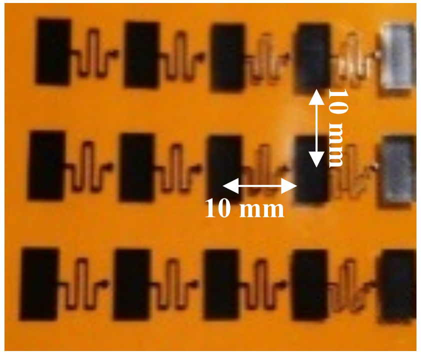
Ar/ISO =90/10, G = 1000



the **gain decrease** is correlated with the voltage drop due to the **resistive layer**

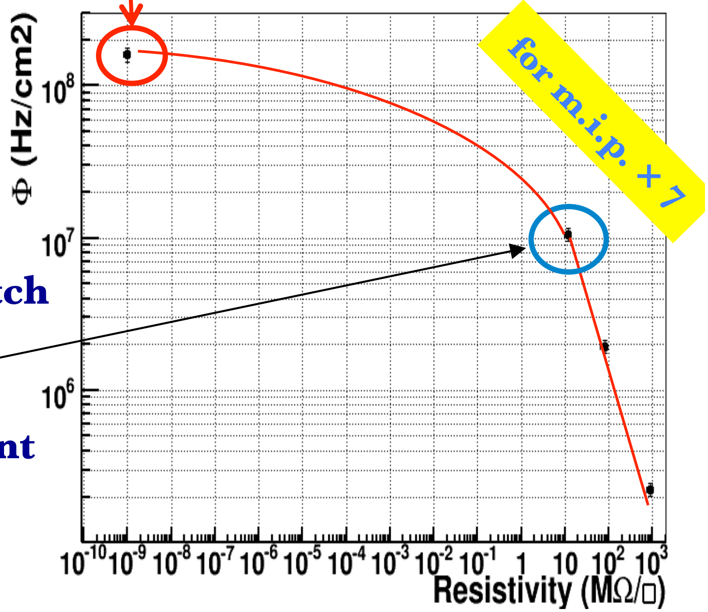
solution: local evacuation of the current through embedded resistors on a kapton layer and connected by vias directly to the pads of the detector

➔ **grounding pitch**



GEM detector rate(*)

rate for a drop ΔG = -3%



a re-scaling with the right gain of 4000 would be required

with a **1×1 cm² µ-RWELL grounding pitch** & a resistivity of ≈**10 MΩ/☐**, a rate capability of ≈**10 MHz/cm²** can be achieved **fulfilling the M2R1 requirement**

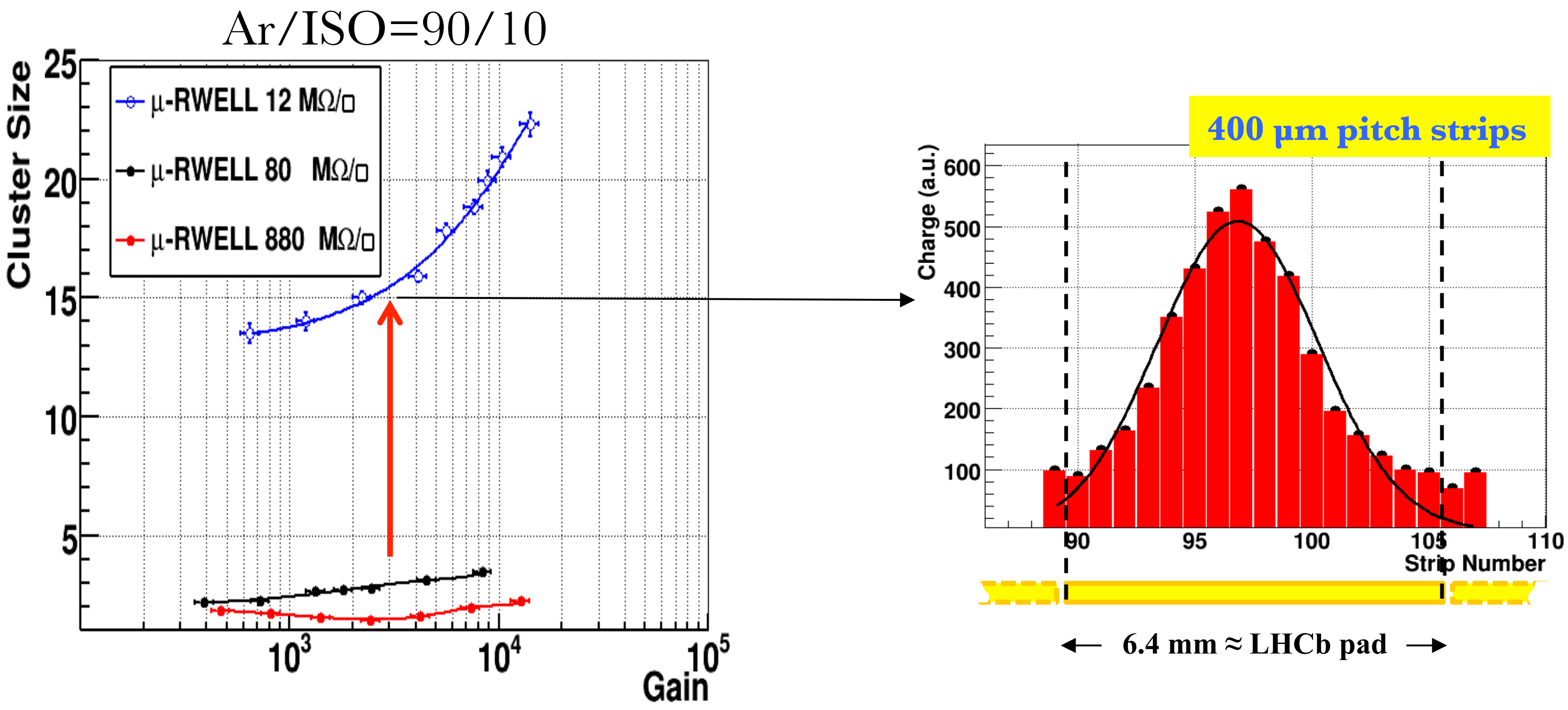
(*) Bellazini et al. NIMA 423 (1999) 125
Sauli et al., NIMA 419 (1998) 410

cluster size vs layer resistivity

G. Bencivenni et al., presented @ 13th Pisa Meeting on Advanced detectors & in press on NIMA

test beam measurements:

H4 Beam Area (RD51), $P_{\mu\text{-beam}}$ = 150 GeV/c, B up to 1.4 T
µ-RWELL prototypes with 12-80-880 MΩ /☐, readout 400 µm pitch strips



use of **low resistivity increases the charge spread (cluster size)** on the readout strips
but ➔ measured charge spread ≈ 16 strips = 6.4 mm ≈ X_{PAD_LHCb}
and the expected cluster size for LHCb is ≈1

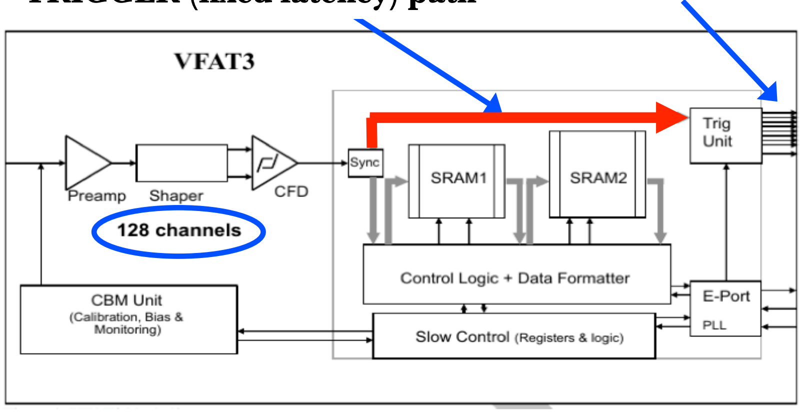
VFAT3 CHIP

VFAT3 front-end chip (128 ch. &130 nm CMOS tech.) is currently under design for the readout of triple-GEM detectors of the CMS phase 1 upgrade ➔
It looks to be an useful starting point on which adjust our needs

VFAT3 features:

TRIGGER (fixed latency) path

9 bits output trigger bus



1. selectable peaking time

Tpeak [ns]	Delay time Td [ns]
25	**15**
50	29
75	43.4
100	57.8

2. **rate capability = 1 MHz @ T_{PEAK} = 25 ns**
3. time resolution ~ 6 ns @ T_{PEAK} = 25 ns
4. noise $e_{RMS} \leq$ 1500e (~ ¼ fC) @ T_{PEAK}= 25 ns, pad capacitance < 20 pF
5. to transfer 128 channels (bits) in 25 ns ➔ 8 bits bus + 640 MHz clock (40 MHz × 16)

G. Felici (LNF), F. Loddo (Bari)

conclusions (I)

✓ muon detector response at 2×10^{34} cm^{-2}s^{-1} is seriously affected by the increased rate

✓ consequence of the increased occupancies ➔ drammatic decrease of the ε-MuonID and large impact on the π-MisID

LHCb phase 2 upgrade

- new shielding in front of M2 to halve the incident rate
- new pad detectors at least in the inner regions
- increase the readout granularity removing the IB
- detailed MC studies to define the configuration of the Muon detector at 2×10^{34}cm^{-2}s^{-1}
- studies on MuonID procedure ongoing and very promising

conclusions (II)

- ✓ muon detector response at 2×10^{34} $cm^{-2}s^{-1}$ is seriously affected by the increased rate
- ✓ consequence of the increased occupancies ➔ drammatic decrease of the ε-MuonID and large impact ond the π-MisID

LHCb phase 2 upgrade: the μ-RWELL option

- **we can profit of a very nice and advanced R&D ongoing at LNF**

DONE

- ◎ gas gain ~10^4
- ◎ rate capability ≈ 10 MHz/cm^2
- ◎ spark protection

TO BE DONE

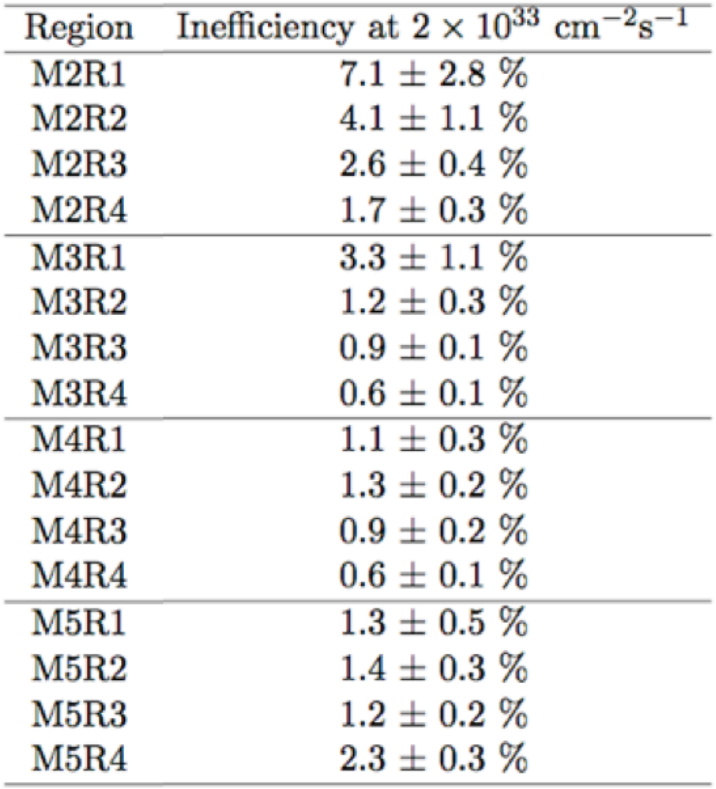
- ◎ detector performance with fast gas mixture and VFAT test (CMS)
- ◎ ageing test
- ◎ M2R1 size with high rate layout

this R&D is in progress in the framework of MPGD_NEXT
(a 3 years project financed by Commissione Nazionale Scientifica 5/INFN)

spares

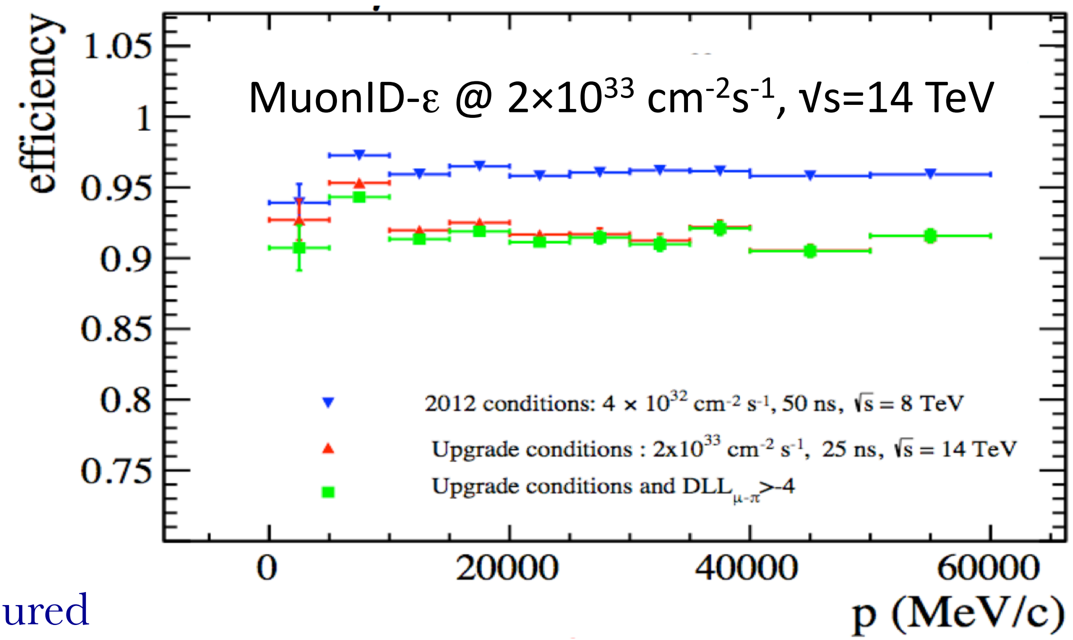
dead time induced inefficiency: TDR

chamber inefficiency at $\mathcal{L} = 2 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}}$



Region	Inefficiency at $2 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}}$
M2R1	7.1 ± 2.8 %
M2R2	4.1 ± 1.1 %
M2R3	2.6 ± 0.4 %
M2R4	1.7 ± 0.3 %
M3R1	3.3 ± 1.1 %
M3R2	1.2 ± 0.3 %
M3R3	0.9 ± 0.1 %
M3R4	0.6 ± 0.1 %
M4R1	1.1 ± 0.3 %
M4R2	1.3 ± 0.2 %
M4R3	0.9 ± 0.2 %
M4R4	0.6 ± 0.1 %
M5R1	1.3 ± 0.5 %
M5R2	1.4 ± 0.3 %
M5R3	1.2 ± 0.2 %
M5R4	2.3 ± 0.3 %

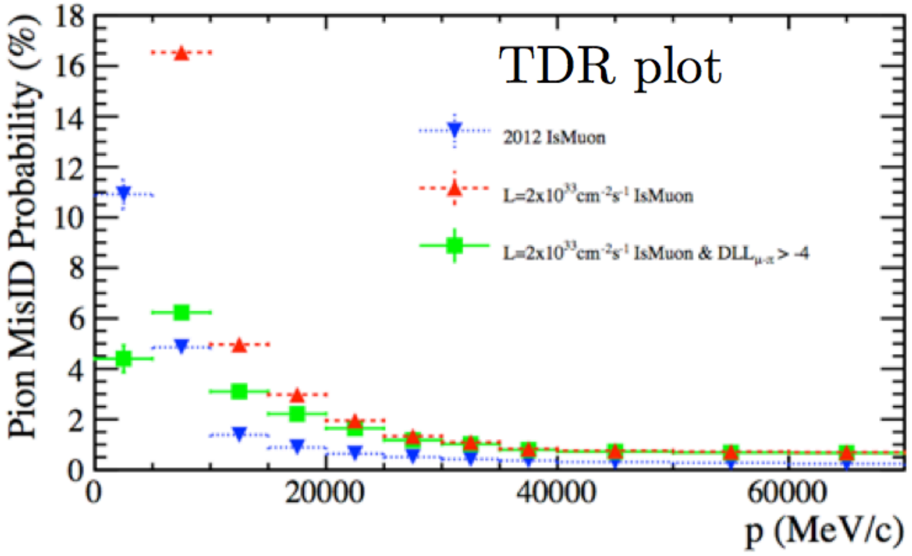
the chamber inefficiency is convoluted with MC ($B_s \to \mu\mu$ events in this case) to get the MuonID algorithm efficiency at $\mathcal{L} = 2 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}}$

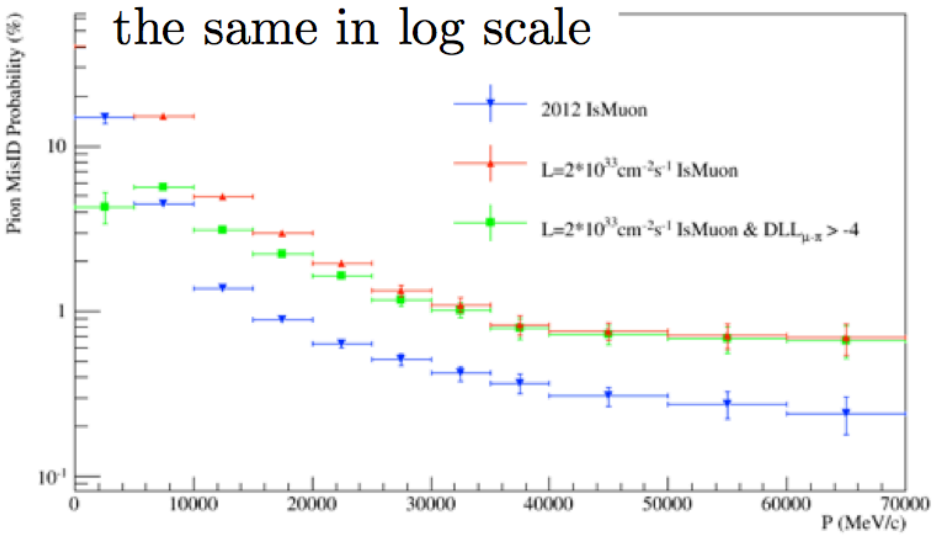


these projections are based on rates measured on detector in 2012 runs + a detailed modelling of dead time vs luminosity (validated on high luminosity special runs)

≃ 5% loss per single μ

pion misidentification: TDR





- π-MisID probability using data control sample of $D^0 \rightarrow K\pi$ extrapolated to pile-up≃7.4 foreseen at $\mathcal{L} = 2 \times 10^{33}$ cm^{-2}s^{-1}
- results with basic MuonID algorithm “IsMuon” is shown as a function of momentum at high luminosity in red compared with the 2012 π-MisID in blue: a factor of 2 background increase is observed
- green points represent what is obtained at $\mathcal{L} = 2 \times 10^{33}$ cm^{-2}s^{-1} using very loose additional cut in the combined DLL variable: it has been shown as an example of what can be done to recover at least the low momentum part ...

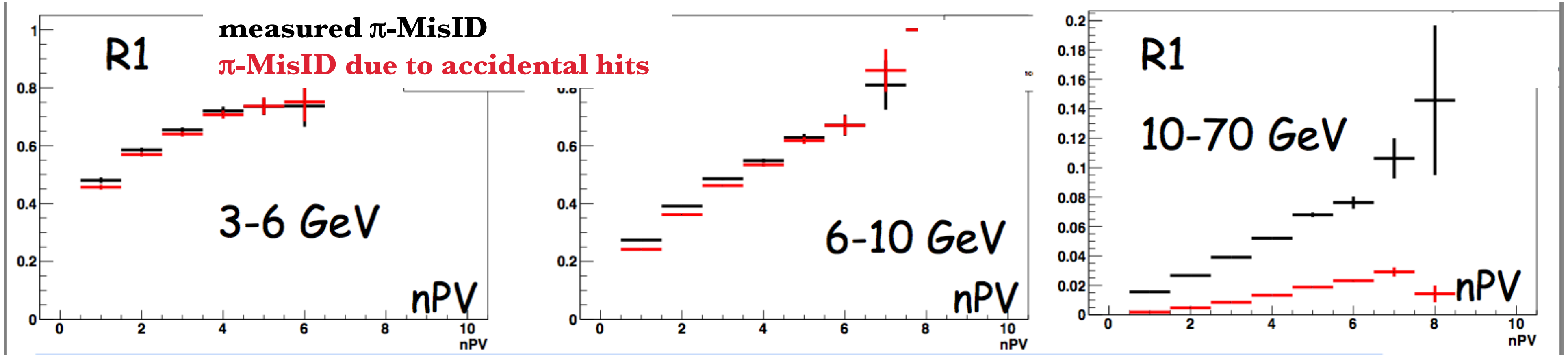
π-MisID vs pile-up in the muon-system inner regions R1

the main sources of background in the muon-system are two:

correlated ➔ muons from decays-in-flight, and punch-through

uncorrelated ➔ accidentals hits

to disentangle the contribution from accidentals, we compute the uncorrelated product of probabilities of having at least one hit in FOI in each station and we compare it to total π-MisID

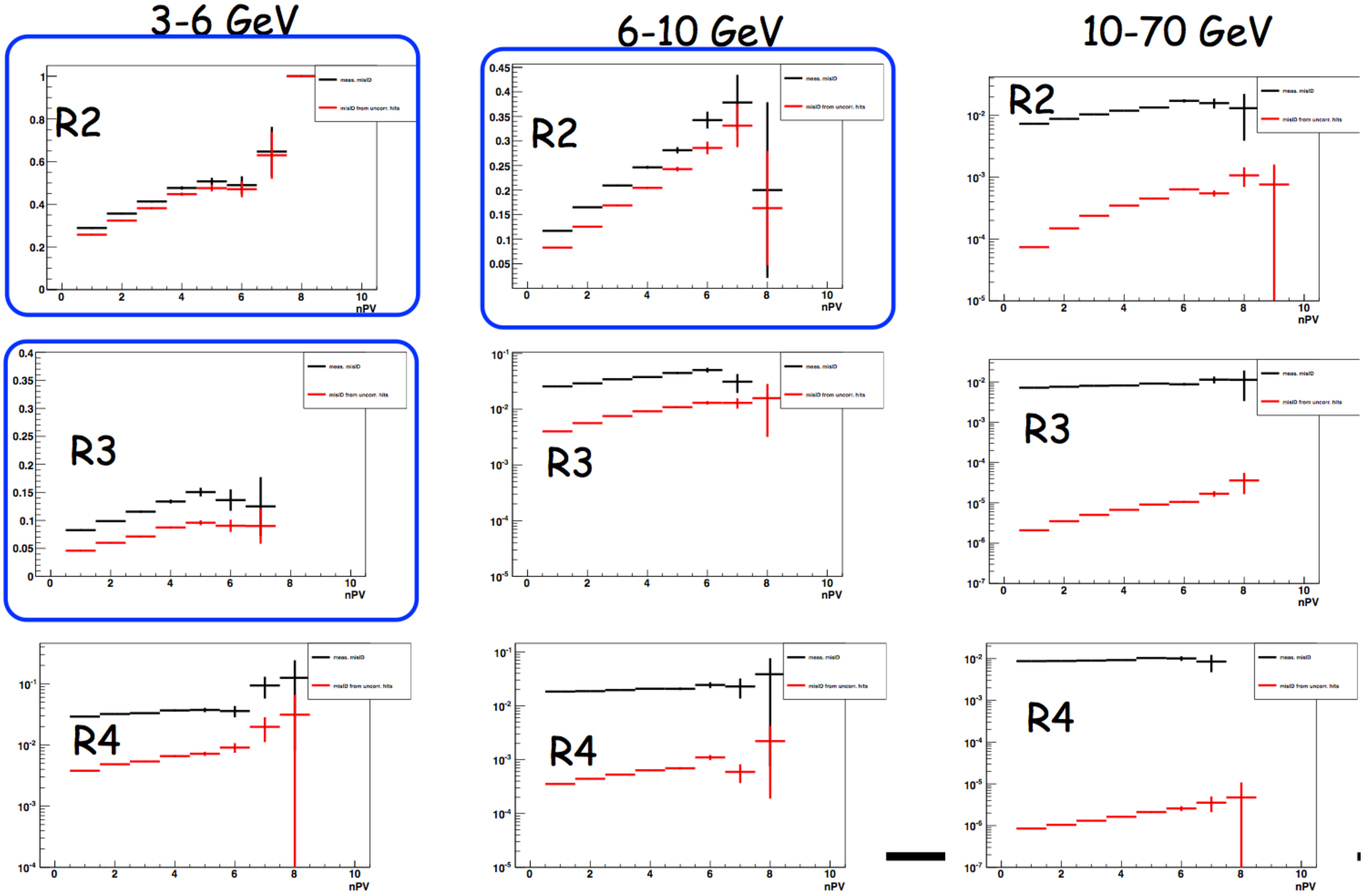


- the 3 momentum bins correspond to a coincidence of 2,3 and 4 stations ➔ IsMuon variable

1) **accidental background is fully dominating the π-MisID below 10 GeV/c**
2) **~1/3 of total above 10 GeV, while the total π-MisID increase with pile-up**

to be noted: results obtained IsMuon variable

π-MisID vs pile-up in the muon-system regions R2, R3, R4

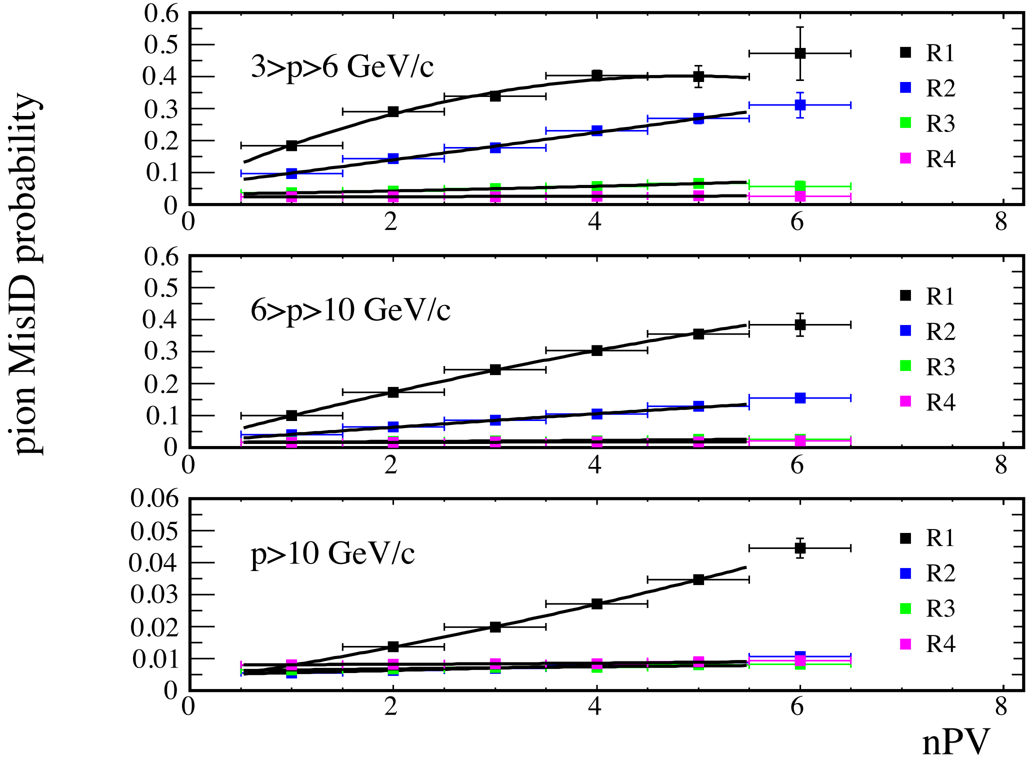


π-MisID extrapolated @ 2 ×10^{33}cm^{-2}s^{-1}

π-MisID as a function of nPV for different regions and momentum ranges, as measured on 2012 calibration data

the observed behaviour is used to extrapolate π-MisID at $\mathcal{L}$ = 2 × 10^{33} cm^{-2}s^{-1} , <nPV> ≃ 7.4

the π-MisID extrapolation @ high nPV is done fitting with a polynomial of the second order in the nPV range 0.5 - 5.5 ➔ systematic is evaluated moving the nPV upper limit



- **the increase of the π-MisID is especially relevant for the inner regions, where it is dominated by accidental hits**

π-MisID at 2×10^{34} cm^{-2} s^{-1}

- **we will soon deal with detailed Montecarlo studies**
- extrapolation of the π-MisID vs pileup at $2{\times}10^{34}$cm^{-2}s^{-1}, nPV≈74, can be used to infer the increase of the π-MisID for tracks **with p > 10 GeV/c**

π-MisID	at $2{\times}10^{33}$cm^{-2}s^{-1}	**increase at $2{\times}10^{34}$cm^{-2}s^{-1}**
Region 1	.007 ± .002	≈ 22
Region 2	.006 ± .001	≈ 5
Region 3	.0050 ± .0006	≈ 3
Region 4	.0009 ± .0002	≈ 1

remind from Phase 1 Upgrade studies

the sources of background in the muon-system are two:

correlated ➔ muons from decays-in-flight, and punch-through
uncorrelated ➔ accidentals hits which include the ghost pads

- **in Regions 1 and 2** the accidental background dominates the π-MisID below 10 GeV/c
- **in Region 1** above 10 GeV/c the accidental background is 1/3 of the total π-MisID
- **in Region 2, 3 and 4** above 10 GeV/c the correlated background is ≈ stable with pile-up

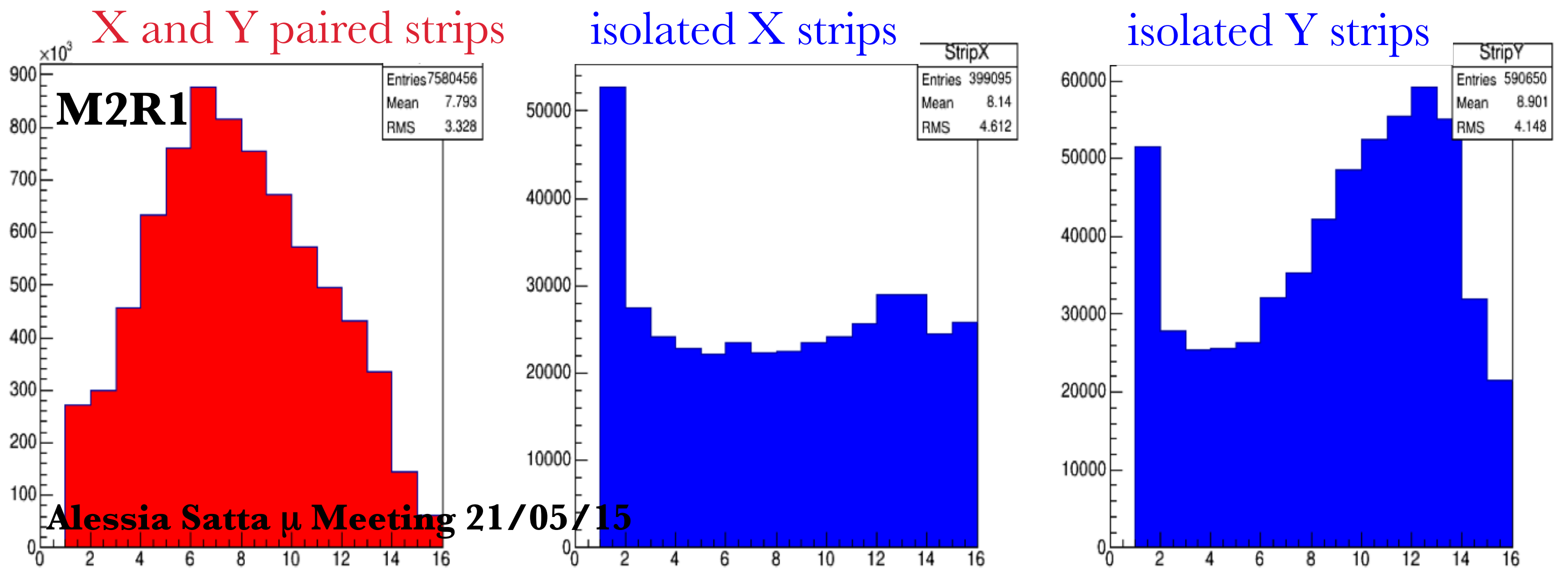
IsMuon and IsMuonTight

IsMuon ➔ collecting all hits in FOI, also from unpaired strips

IsMuonTight ➔ collecting only crossed hits in FOI
(crossed hits: both X and Y readout channels fired)

current MuonId procedures are based on IsMuon variable

time spectra for :



X and Y paired strips isolated X strips isolated Y strips

Alessia Satta μ Meeting 21/05/15

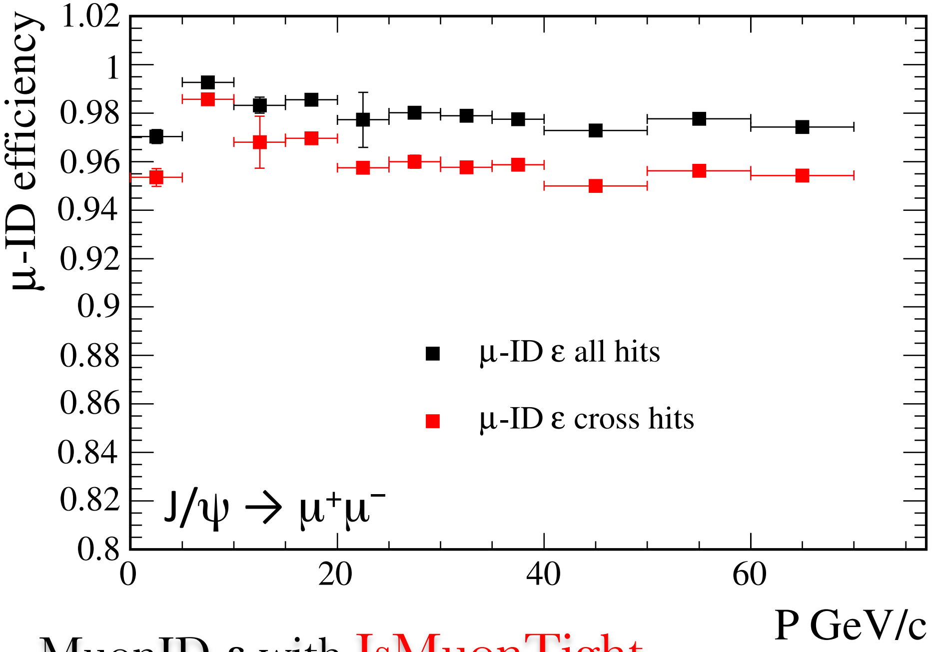
hits from unpaired X or Y strips can be out of time respect to the event bunch crossing

- we (re)studied the performances of the isMuonTight to understand if an improvement of the background rejection is possible at high luminosity with a reasonable signal loss

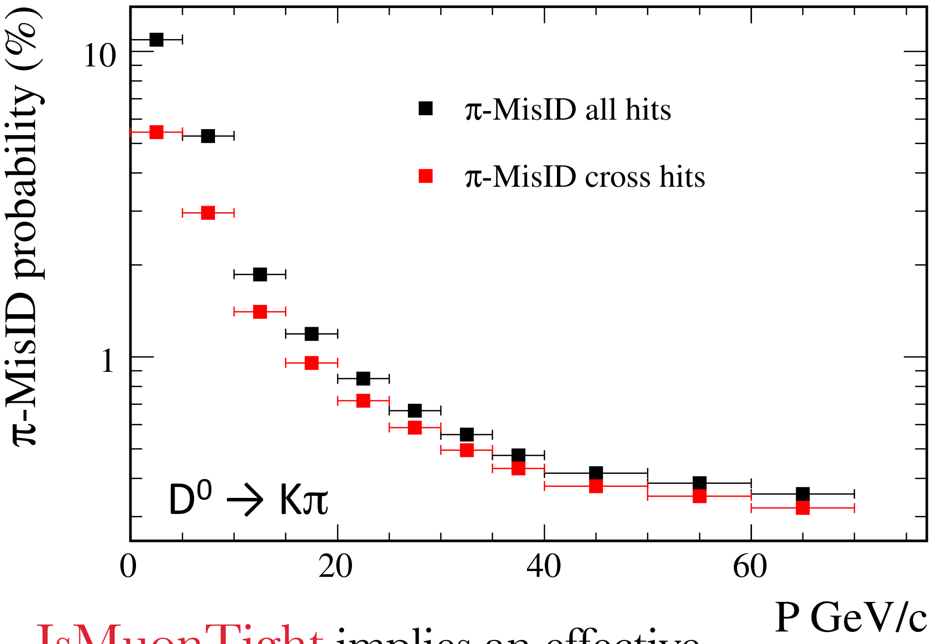
MuonID-ε and π-MisID with IsMuonTight

2012 data samples

✓μs and πs probes are TIS (L0 && HLT1 && HLT2) unbiased



MuonID-ε with IsMuonTight decreases of ≈ 2 % @ p ≳ 30 GeV/c



IsMuonTight implies an effective decrease of the π-MisID

a toy Monte Carlo study

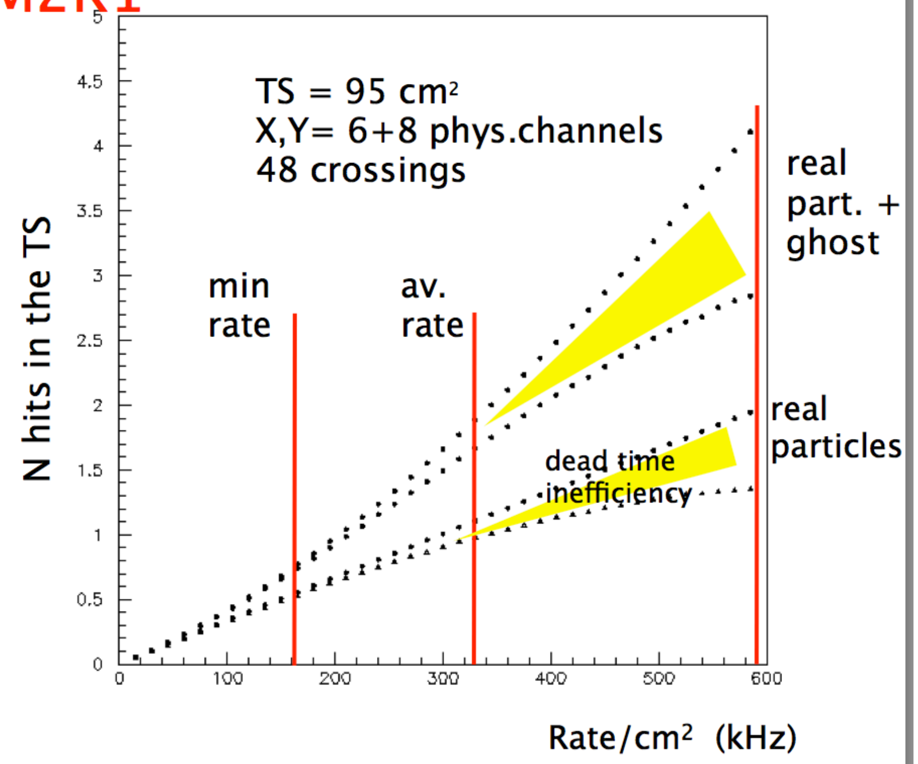
Toy MC computation from rates extrapolated at 2*10^33 and dead time model

Occupancy per trigger sector is ~1 at the upgrade!

Most of the hits are uncorrelated, and come from photon conversions in the high density material before each gap

These low energy particles trigger only one of the 4 gaps in OR: muon detector robustness at low lumi becomes its weakness at high lumi

M2R1



At upgrade lumi, a considerable number of ghost crossings is expected: separate readout of X,Y strips, which are then crossed in the trigger sector at the offline level; this problem is also present in the external regions (pad readout), since we build X and Y strips via OR in the Intermediate Boards before sending the info to the trigger (to spare links)

The µ-RWELL_PCB manufacturing

1

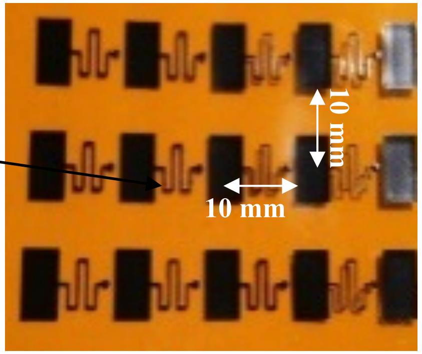
DLC-coated kapton base material: DLC layer < 0.1 µm (5-10 MΩ/)

Kapton layer 50 µm

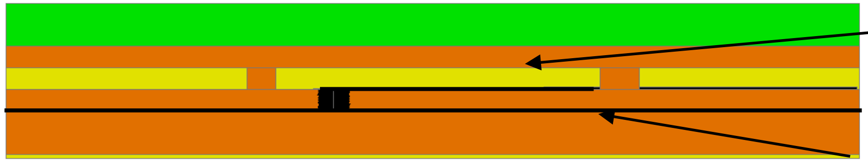
Copper layer 5 µm

2

Kapton layer (~25 µm) with $1/cm^2$ vias density. Screen printed with a “embedded-resistors” pattern (standard PCB technology)



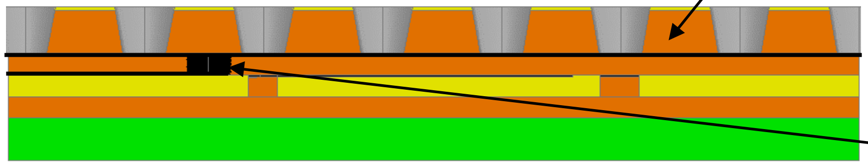
3



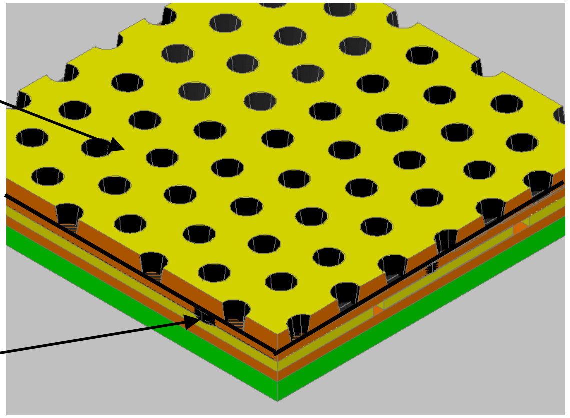
Pad/strips kapton layer (50 µm) + PCB (1 mm)

DLC-coated kapton base material

4

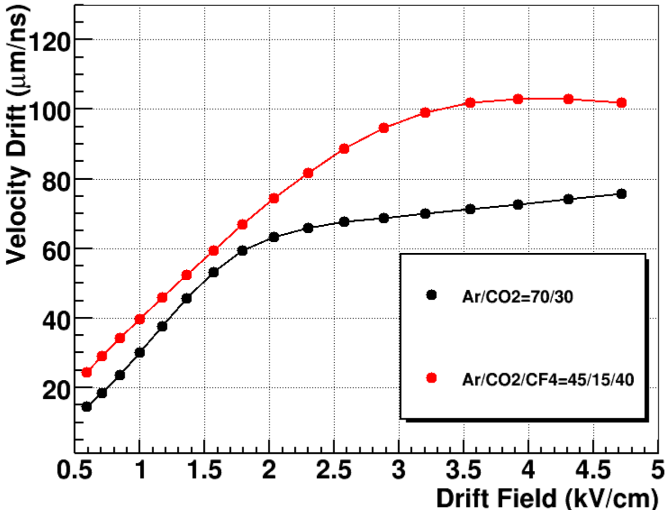


DLC-coated base material after copper and kapton chemical etching (the WELL amplification stage)



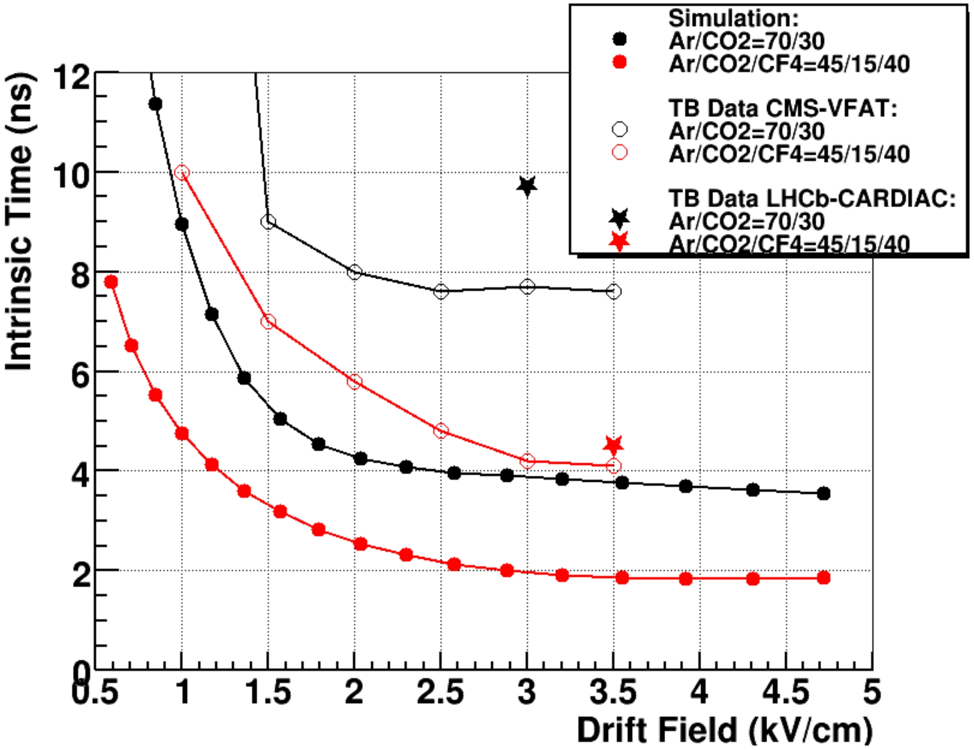
“embedded-resistors”

Gas mixtures properties for triggering detector



$$\sigma_T \sim 1 / n_{clu} * vel_{drift}$$

Gas Mixture	Cluster/cm (μ 10 GeV)	Vd @ 3.5 kV/cm (μm/ns)	Intrinsic time @ 3.5 kV/cm (ns)
Ar/CO_2 = 70/30	37	71	3.8
Ar/CO_2/CF_4 = 45/15/40	53	100	1.9

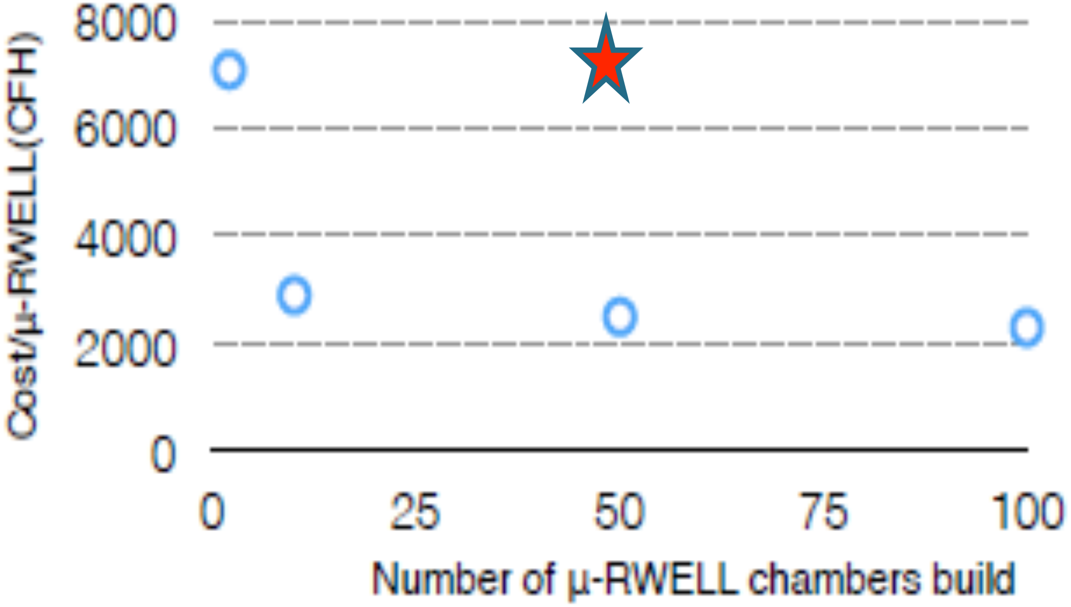


A good detector time performance is expected with the use of a fast gas mixture and a suitable FEE

Cost of μ-RWELL and GEM for large volume production

Open dots: cost estimate (by ELTOS SpA) of a1.2x0.5m² μ-RWELL

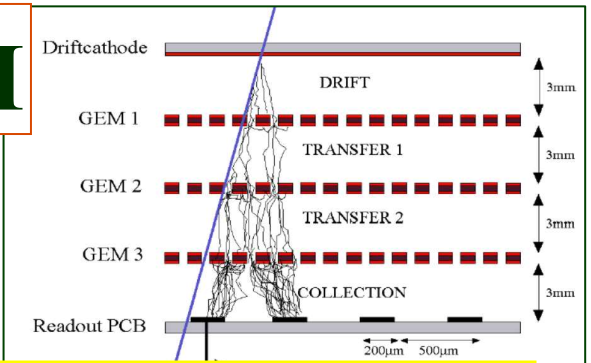
Star: cost (by CERN) of a 1.2x0.5 m² GEM



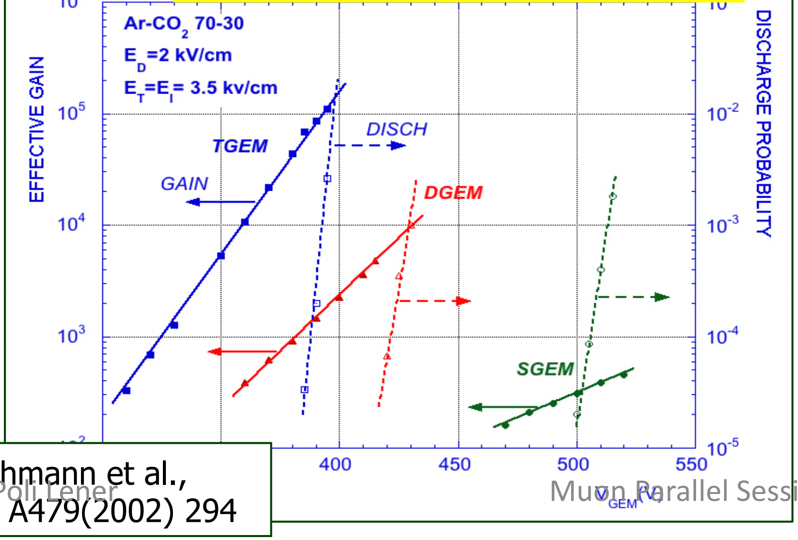
GEMs: stability

The **biggest “enemy”** of MPGDs are the **discharges.**
Due to the **fine structure** and the **typical micrometric distance of their electrodes, GEMs** generally suffer from **spark occurrence** that can eventually **damage the detector and the related FEE.**

GEM



Strongly reduced but not completely suppressed



S. Bachmann et al.,
NIMA A479(2002) 294

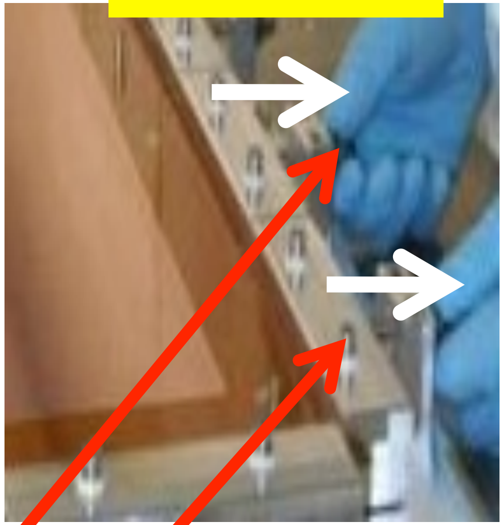
In **M1R1** we have lost **5 sectors for short circuit** in ~ 2 years of running (→ 1% of the whole sectors)

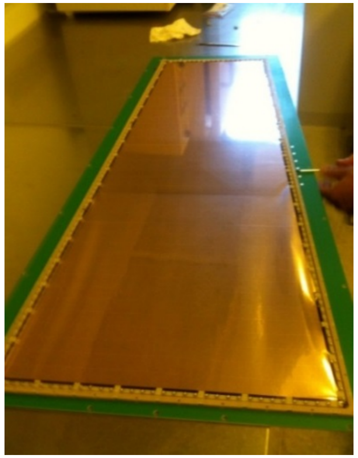
GEMs: the construction challenge

The construction of the **GEM** requires some time-consuming assembly steps such as **the stretching of the 3 GEM foils** (with quite **large mechanical tension** to cope with, **~1 kg/cm**).
An improvement in **the GEM construction process** came from the **NS2 detector assembly scheme** (by Rui): no gluing, no soldering, no spacer in the active area, re-opening of the detector if repairs needed.

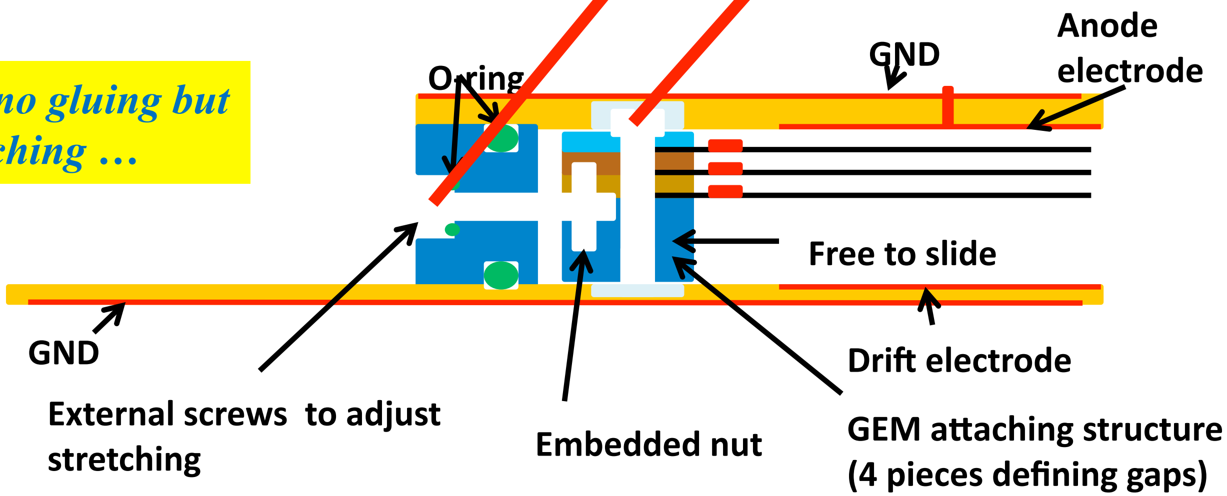
But the GEM construction still remains a demanding & complex operation, requiring delicate stretching with specialized man-power.

LHCb-LNF/Ca



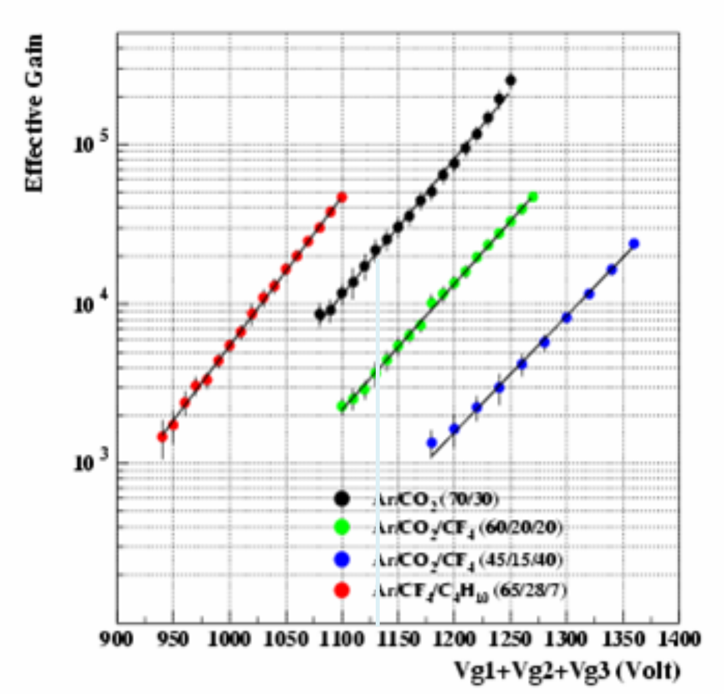


NS2(CERN): no gluing but still stretching …

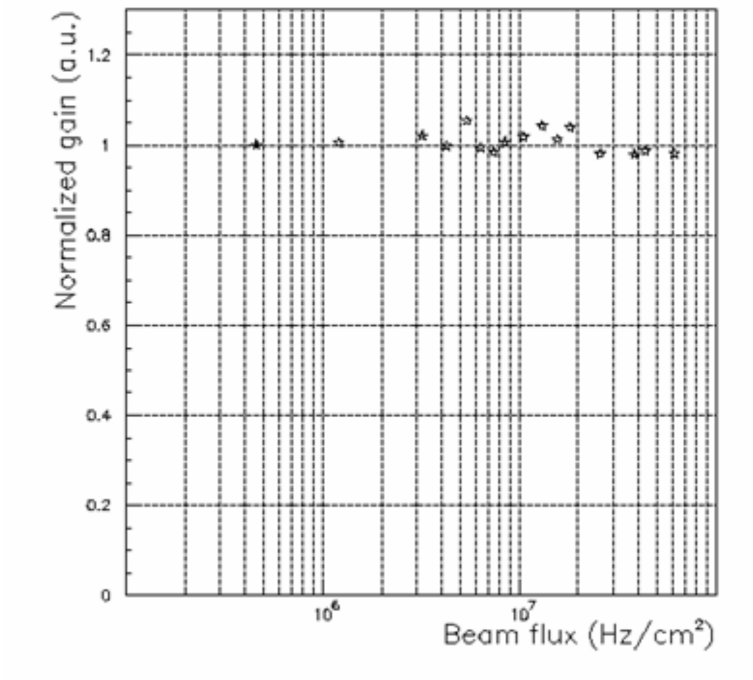


Operation of a GEM detector

Gas Gain



Rate Capability



7^{0}C or 21 mbar → 15V or equivalently ΔG/G~18%

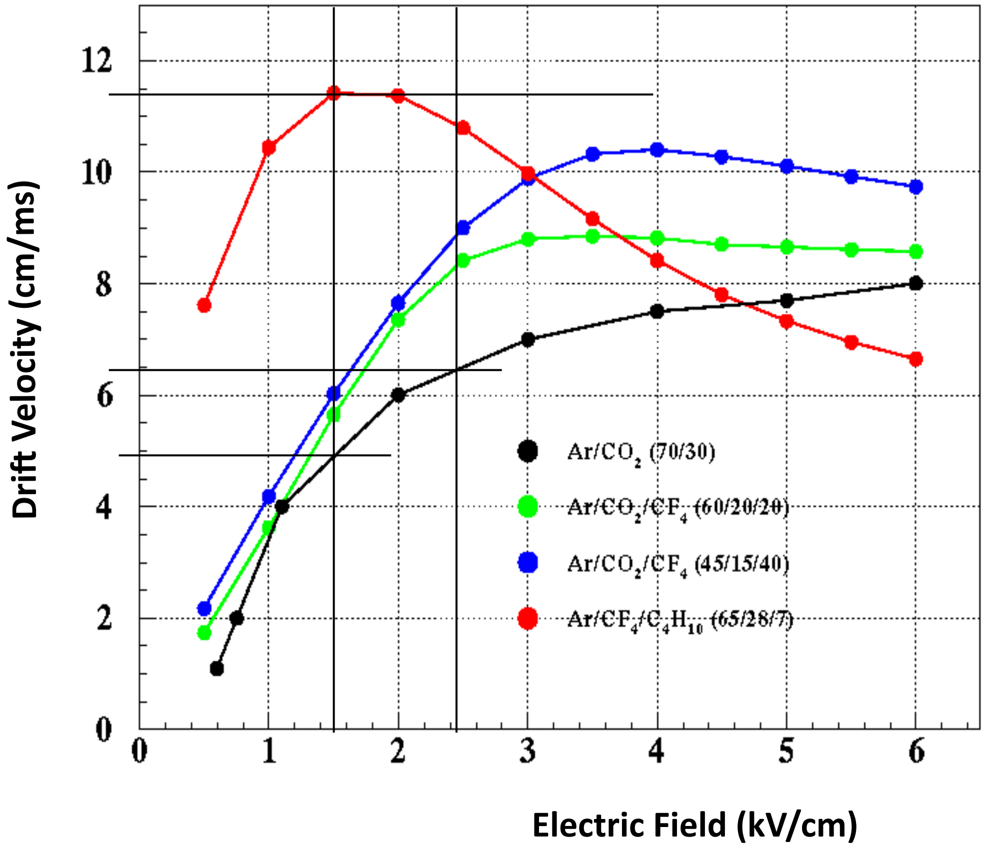
Time Performances: drift velocity & ionization

Ar/CO_2 (70/30):
- 7 cm/µs from @ 3 kV/cm
- 10 clusters in 3 mm

$Ar/CO_2/CF_4$ (60/20/20):
- 9 cm/µs from @ 3 kV/cm
- 15 clusters in 3 mm

$Ar/CO_2/CF_4$ (45/15/40):
- 10.5 cm/µs from @ 3.5 kV/cm
- 16 clusters in 3 mm

$Ar/CF_4/iso\text{-}C_4H_{10}$ (65/28/7):
- 11.5 cm/µs from @ 2 kV/cm
- 17 clusters in 3 mm



High drift velocity at low fields allows fast detector response while keeping high efficiency in electron collection at the first GEM (defocusing effect)