Long term Upgrade of the RPCs

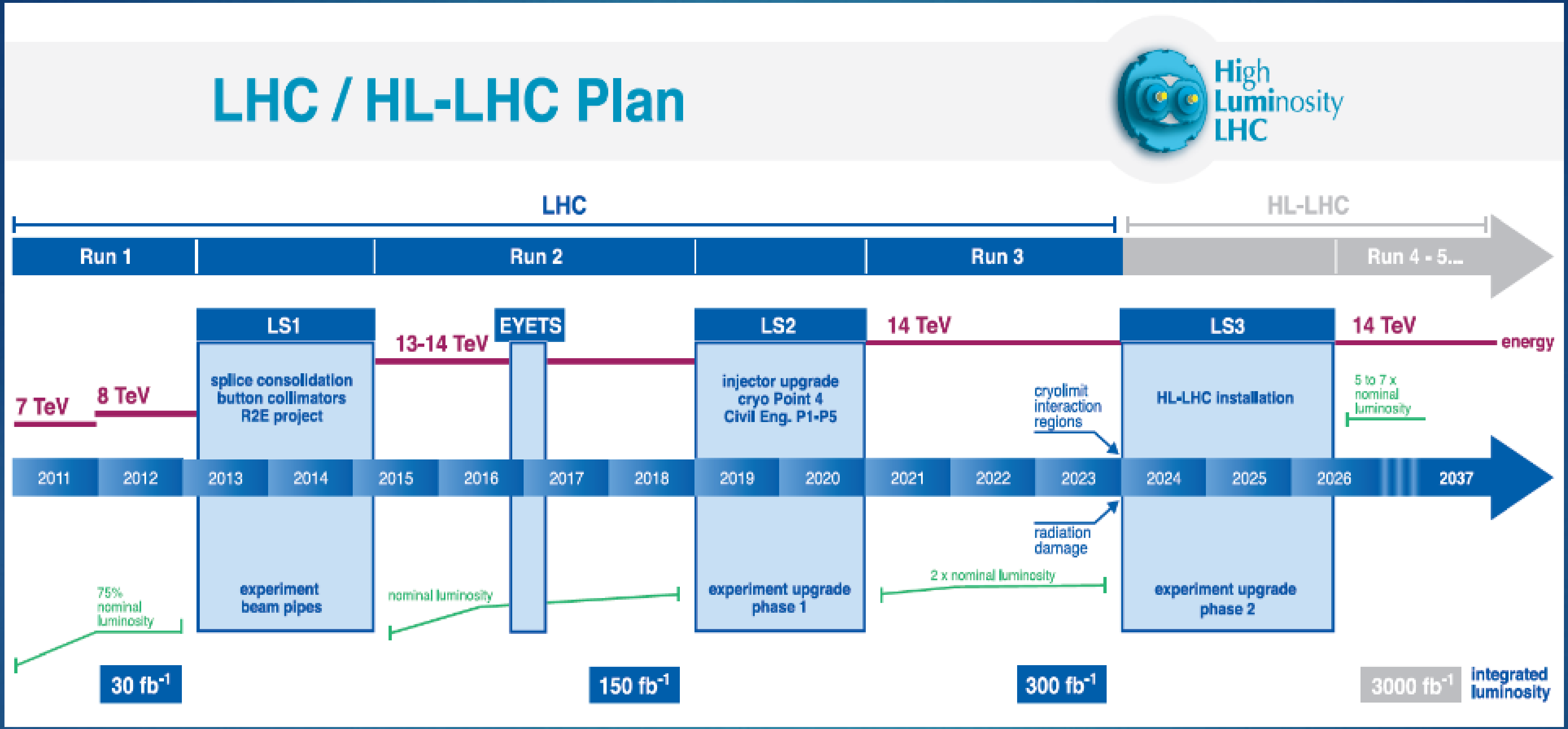
When the going gets tough
THE
TOUGH
GET GOING

Withstanding the ultimate HL-LHC performance
with aged, rugged and fearless RPCs
And one eye on future colliders
…keep calm and upgrade…

G. Aielli

U. Ibero Americana
February, 16 2018
Mexico City

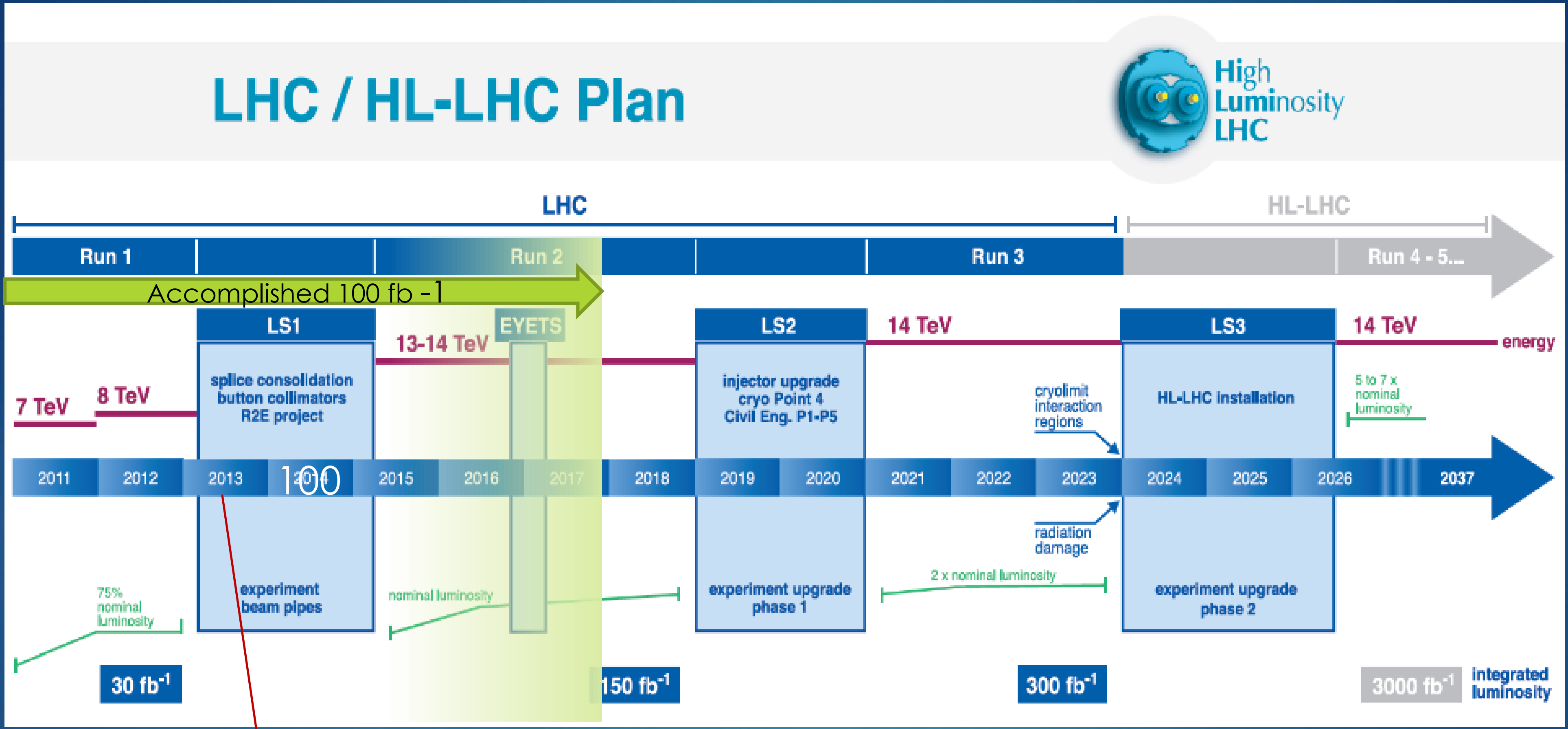
Overview of the challenge

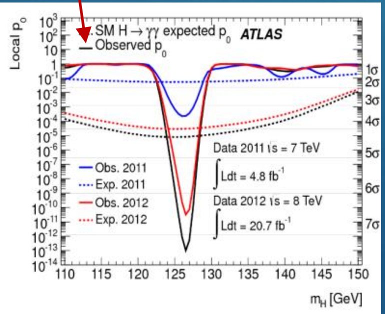


European Strategy for Particle Physics

*"Europe's **top priority** should be the **exploitation** of the **full potential of the LHC**, including the high luminosity upgrade of the machine and the detectors with a view to collecting 10 times more data than in the initial design, by around 2030"*

Time overview of the challenge





We accumulated just about 2% of the extended HL-LHC programmed luminosity
Most of the discovery potential still to be used:

- ~7 x better sensitivity

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17/02/2018

IT'S ALL A MATTER

OF

SIGNAL

NOISE

From 1981 to nowadays

- Space resolution from 1 cm to 0.01cm
- Rate capability from 10 Hz/cm^2 to 30000 Hz/cm^2
- Time resolution from 0.7 ns a 0.03 ns

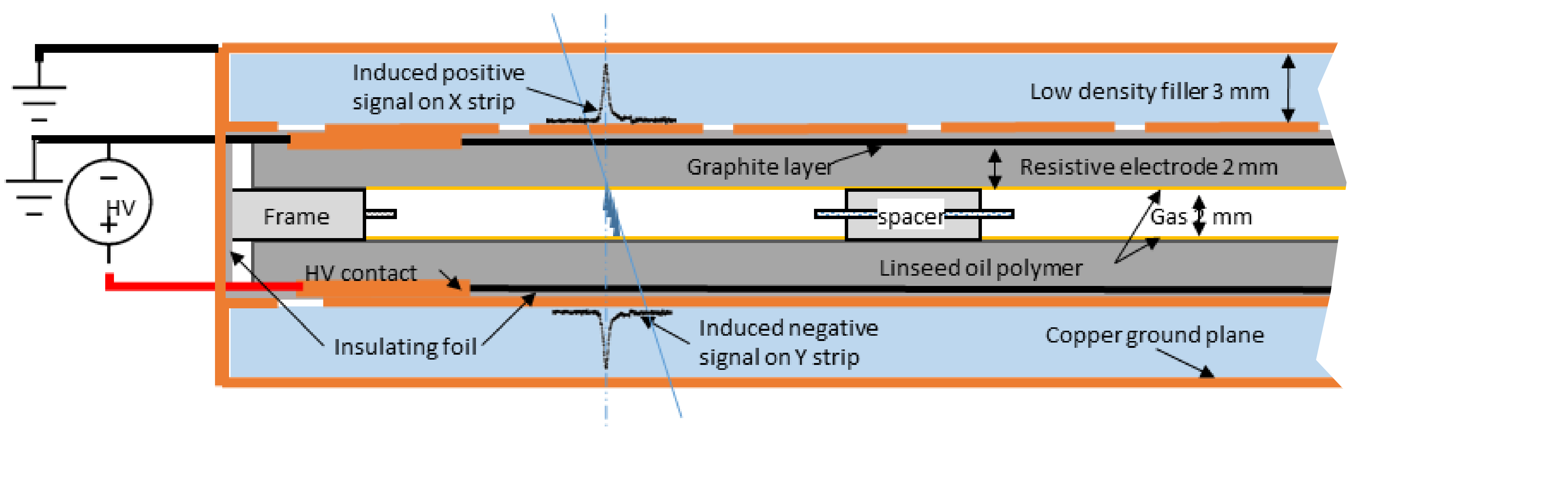
But pure performance is not all: the increase is obtained while keeping the same simple structure which always allowed to scale the detector to large surfaces

The Secret?

- Simple physics laws and right choice of materials do most of the job
- The physical event is very local in space-time
- A discharge (local) can never evolve in spark (global)
- Better electronics → better performance → widely span over the avalanche dynamical range

NEW generation RPC R&D framework

- In the late '90 the INFN groups defined common RPC standards becoming a world reference
  - "classic" optimized for large surfaces for muon and CR systems (ALICE, Argo, ATLAS, BaBar, CMS, Opera, INO)
  - "timing" optimized For TOF applications ALICE TOF as example in LHC
- The standard was founded on :
  - common construction site and procedures , (e.g. General Tecnica)
  - common qualification site (GIF)
- Success → RPC in all LHC perform very well.
- After about 15 years we started again a common effort to face the challenge of HL-LHC and other next coming experiments.
- What's next…?



Further insight in RPC physics

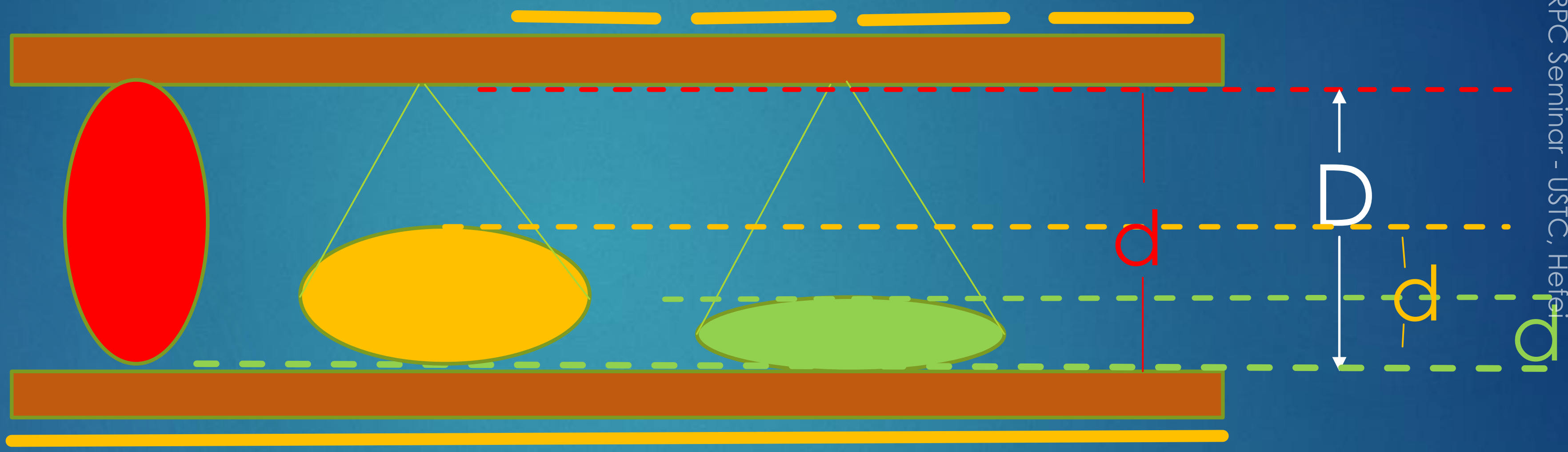
Parameters for optimization of the RPC

- To optimize the RPC performance four elements are considered

1. The working mode: Q_{el} and charge distribution (gap S/N)
2. The Gap: for the saturation and timing, T_{el} (Time resolution and gap S/N)
3. The pick-up geometry: d/D (maximize Q_{el}/Q_{tot}) (gap S/N, space-time performance)
4. The Front-End performance: A_{FE} and Bandwidth (compensation all above)

- In a given design these criteria must compensate each other to obtain a sufficient S/N and performance
- In the present ATLAS and CMS we needed an highly saturated avalanche due to the FE limits and a total delivered charge of about 20 pC

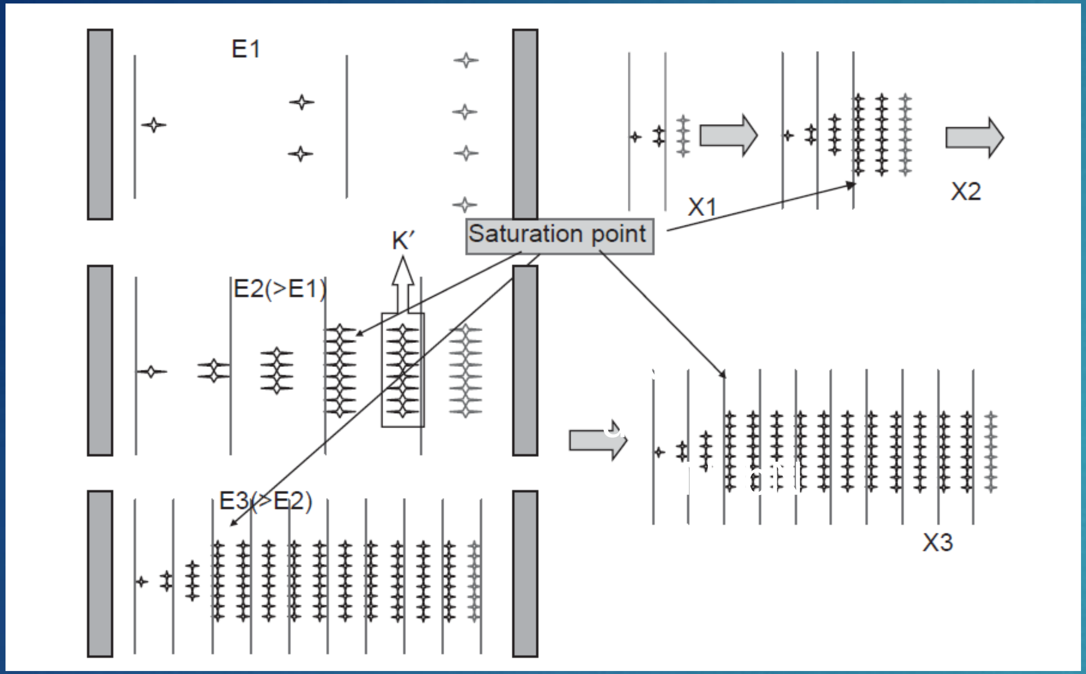
Electronic charge (Q_{el}) to ionic charge (Q_{ion}) ratio

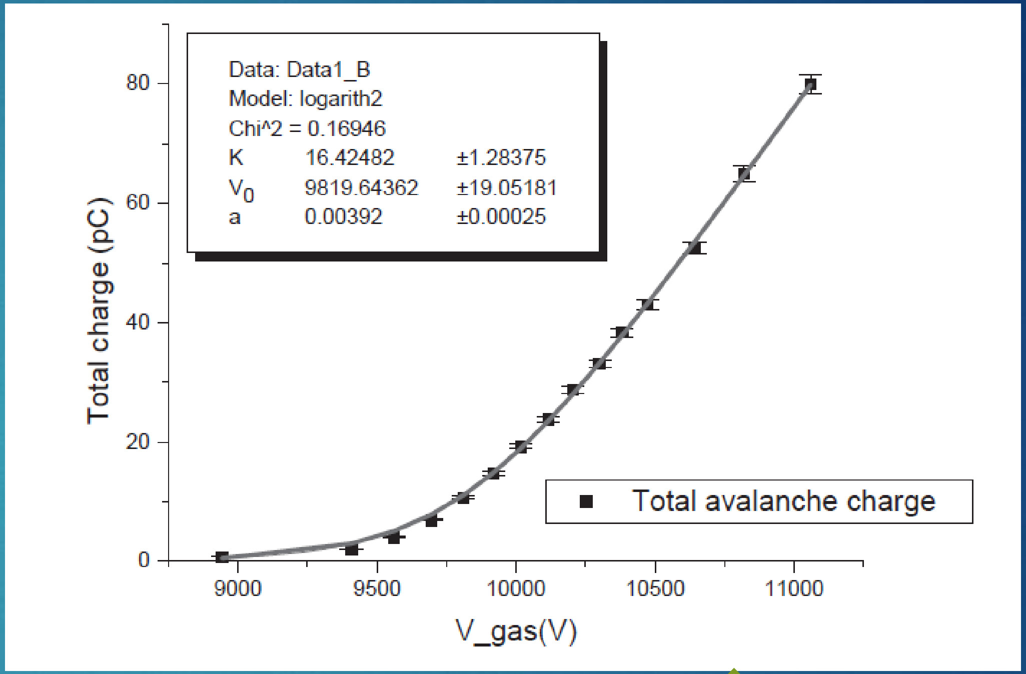


Working mode of RPC:	**Streamer**	**Highly saturate avalanche**	**Low saturate avalanche**
Total charge:	1-0.1 nC	40-20 pC	5-1 pC
Q_{el}/Q_{ion}:	1-0.3	0.1	0.05

$$Q_{el}/Q_{ion} = d/D$$

Avalanche saturation (logistic model)

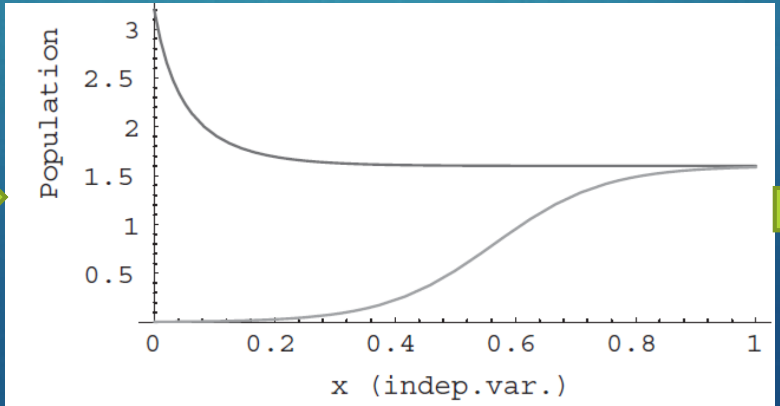




$$\frac{dN}{dx} = \alpha N - \beta N^2$$

$$\frac{dN}{dx} = \alpha N\left(1 - \frac{N}{K}\right)$$

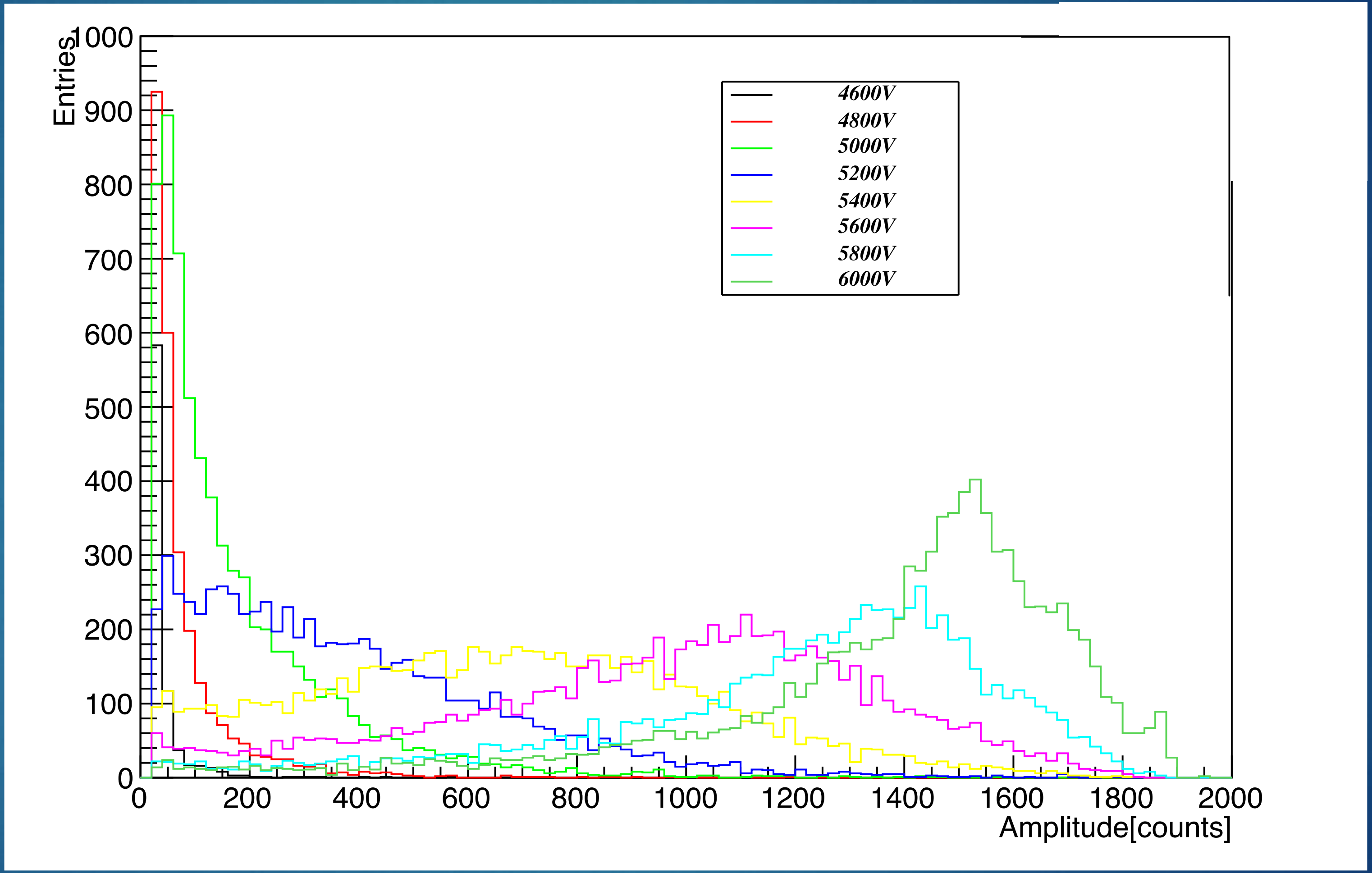
$$K = \frac{\alpha}{\beta}$$



Integral of the active Population in time or E field

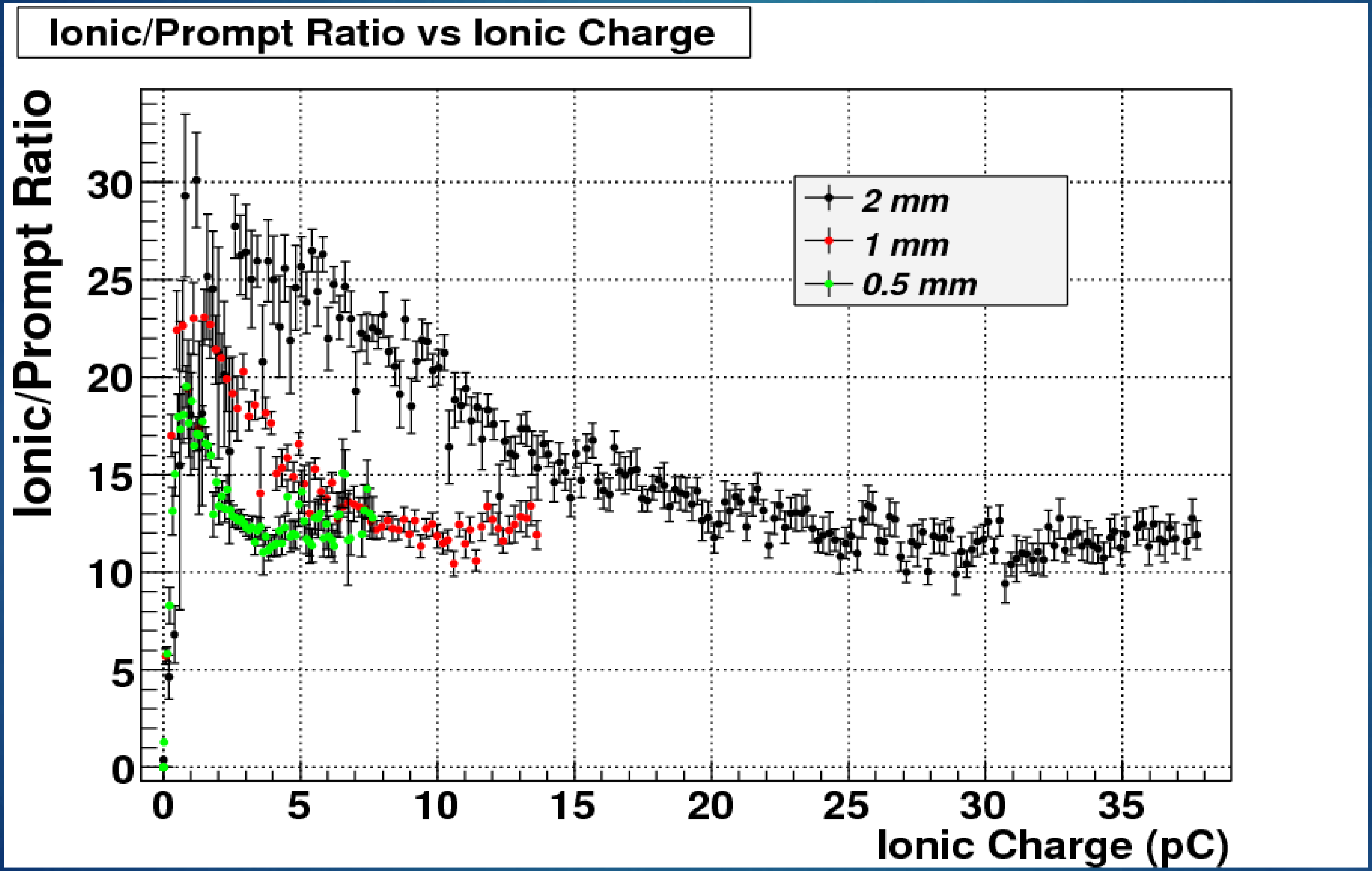
Saturation and charge distribution

- An exponential avalanche accumulates the charge distribution close to the 0
- Very difficult to discriminate the signals from the pedestal
- A very saturated avalanche produces a peaked distribution



How smaller the threshold with respect to the average value for >95% efficiency?

Q_{ion}/Q_{el} ratio for RPCs vs. gap width



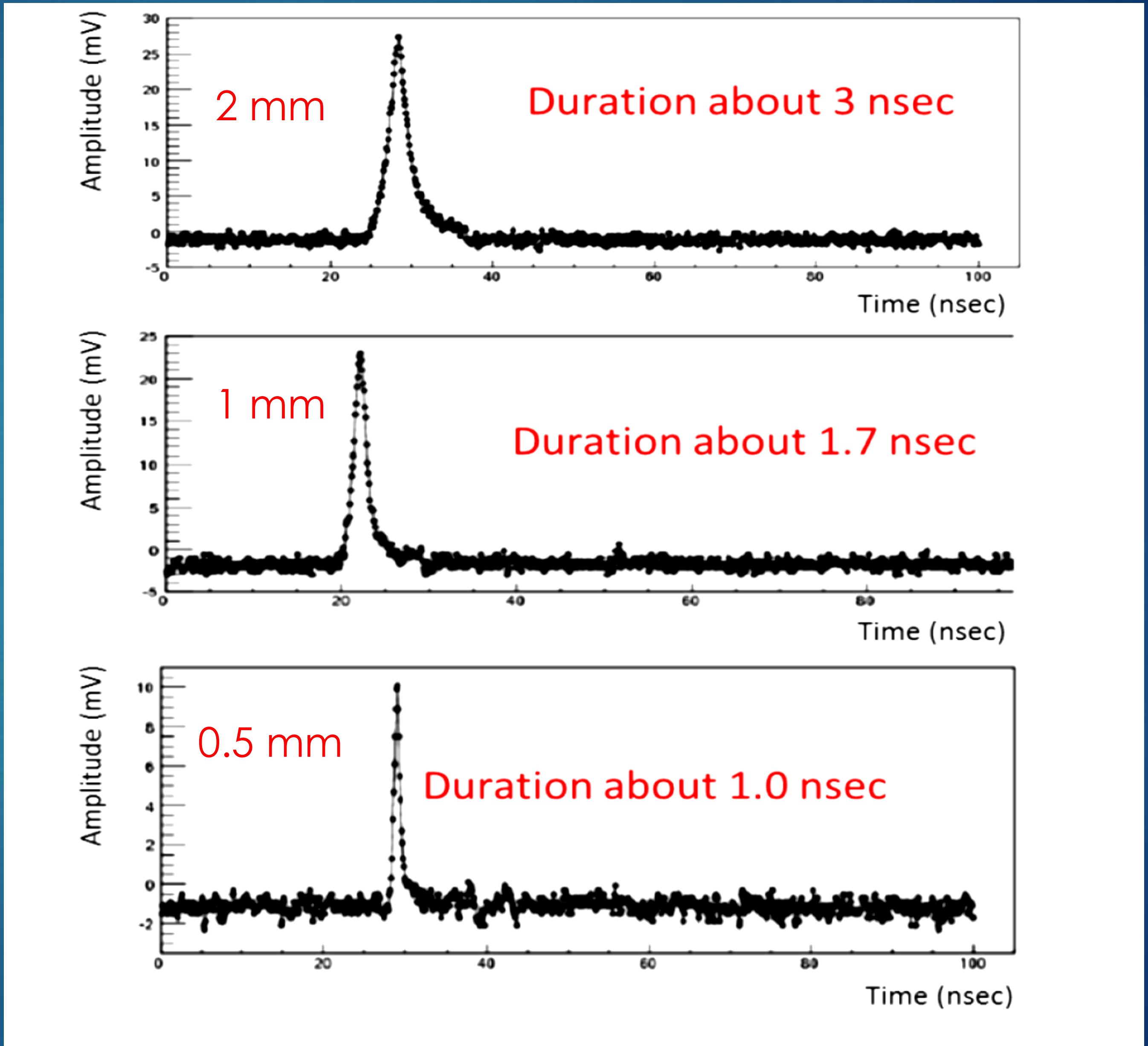
Thinning the gas gap less charge is needed to reach the same level of saturation

More prompt signal available → more amplification

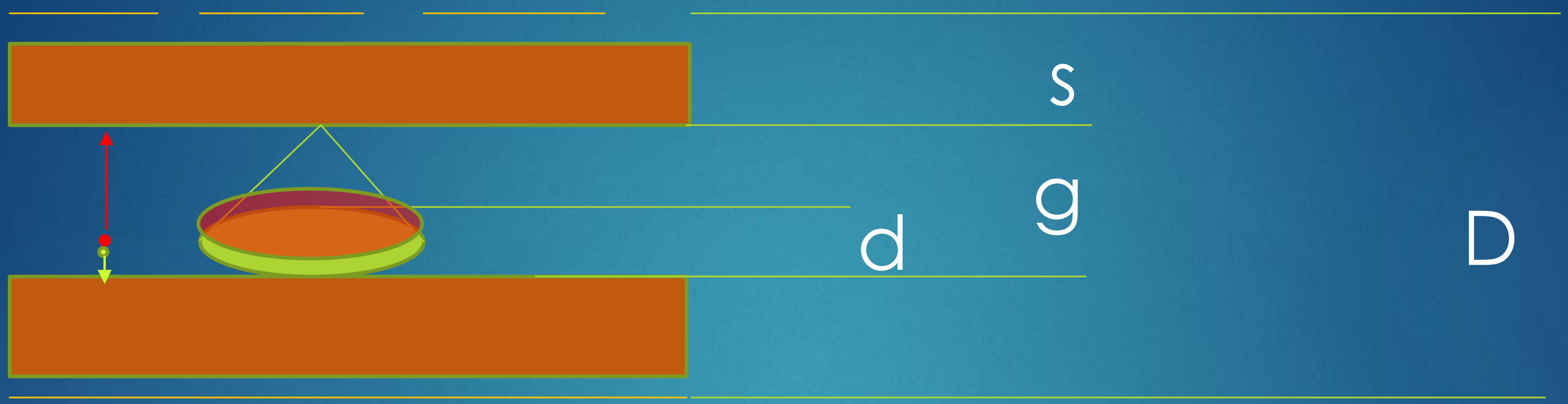
Timing vs. gap width

For having the same signal in less space and with less primary ionization
→

- Higher Townsend coefficient
- Faster growth
- Shorter duration
- Higher saturation
- Higher Q_{prompt}/Q_{tot}



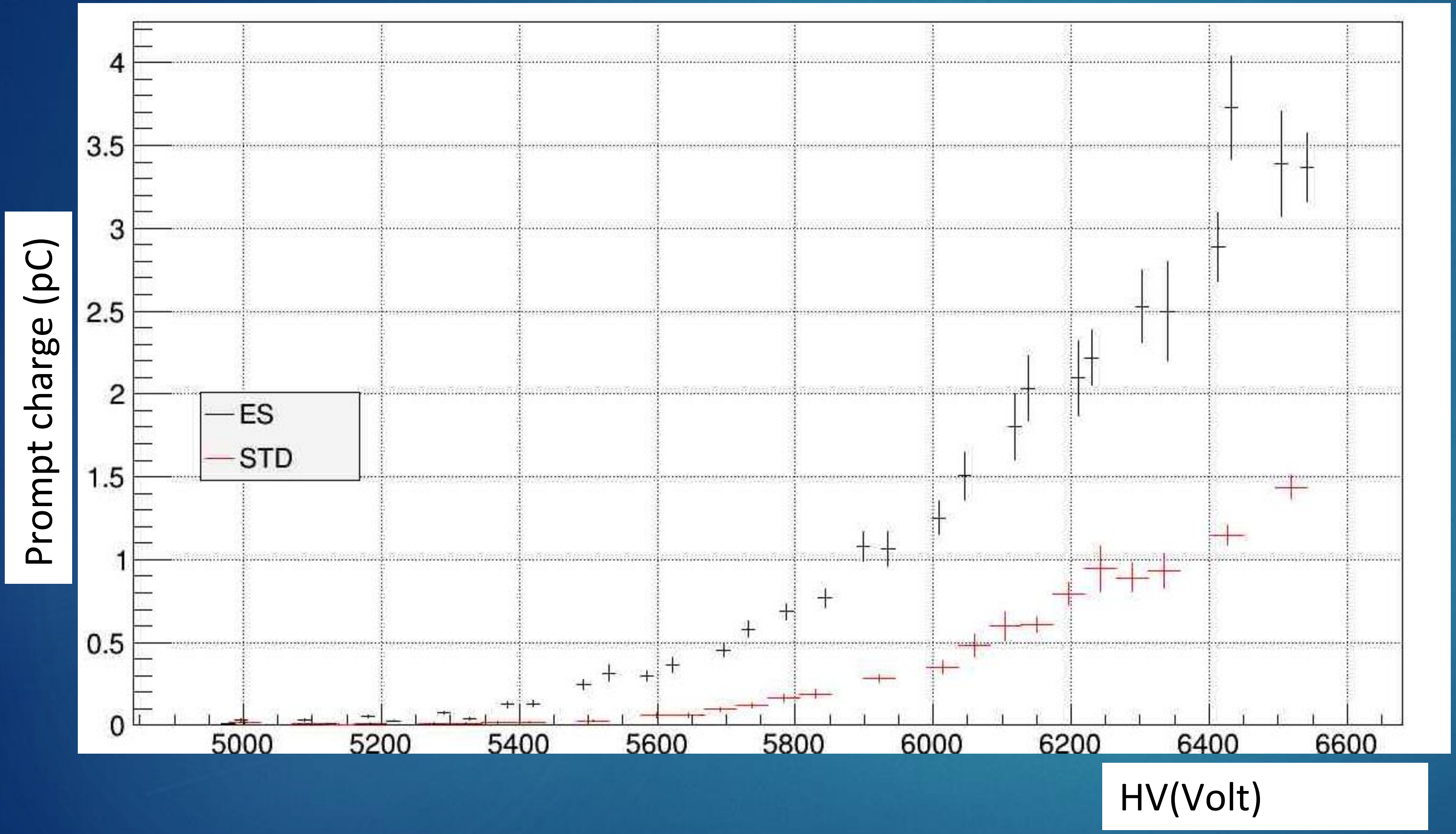
The role of the electrodes thickness



$$Qtot = Qion + Qel \qquad Qind/Qel = 1 / (1+(2s/\varepsilon_r)/g$$

The transfer efficiency is influenced by the geometrical parameters of the gap as well as the geometrical parameters of the avalanche

0.8 mm vs. 2 mm comparison



- More than a factor of 2 of collected signal
- Effect beyond expectations to be fully understood…
- this works as a net increase of S/N

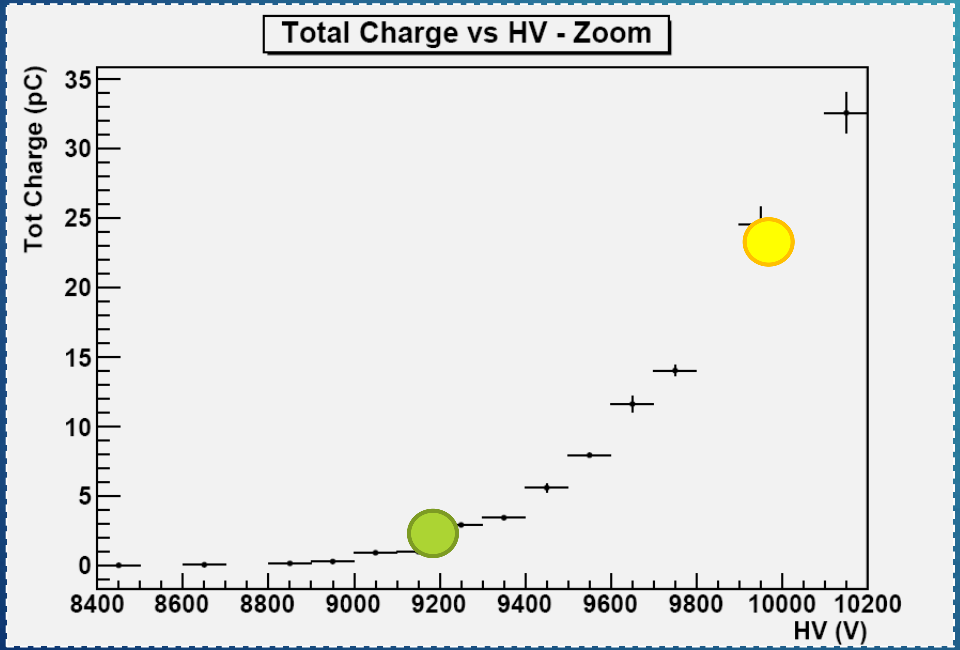
Moving the amplification?

Gas amplification

- A_{gas} streamer ≅ $6 \cdot 10^7$ to $6 \cdot 10^8$
- A_{gas} high sat. ≅ $1.2 \cdot 10^7$ to $2.5 \cdot 10^7$
- A_{gas} low sat. ≅ $6 \cdot 10^5$ to $3 \cdot 10^6$

Electronic Charge= d/D x Q_{tot}

- Q_{el} streamer ≅ 0.1 to 1 nC
- Q_{el} high sat. ≅ 2 to 4 pC
- Q_{el} low sat. ≅ 50 to 250 fC



Lowering the total charge keeping the same gas gap and electrodes will transfer a large fraction of the amplification from the gas to the FE electronics!

Moving the amplification from the gas to the Front End electronics

A_{FE} (Amplification of the Front End electronics)

$A_{FE} \times A_{gas} = k$ where k is the discriminator threshold

A_{FE} streamer – We assume it is 1 for streamers

A_{FE} high saturation = Q_{el} streamer / Q_{el} high saturation ≅ 100

A_{FE} low saturation = Q_{el} Stramer / Q_{el} low saturation ≅ 1000

Signal/Noise requirements

- threshold $\cong 0.1\cdot\langle Q_{el}\rangle$ and V_{th} at 5σ over the front-end noise
- The 0.1 factor accounts for the charge distribution

Noise of the front end $< 0.1\cdot\langle Q_{el}\rangle\cdot 0.2 \rightarrow$ factor 50 less

For streamer $N \cong 10^{-10} \cdot 0.1 \cdot 0.2 = 2 \cdot 10^{-13} = 5 \cdot 10^{6}$ e^{-} rms

For high saturation $N \cong 2 \cdot 10^{-12} \cdot 0.1 \cdot 0.2 = 2 \cdot 10^{4}$ e^{-} rms

For low saturation $N \cong 2 \cdot 10^{-13} \cdot 0.1 \cdot 0.2 = 2 \cdot 10^{3}$ e^{-} rms

KEEP CALM
AND
SMALLER
AVALNCHES

The ATLAS and CMS RPC case

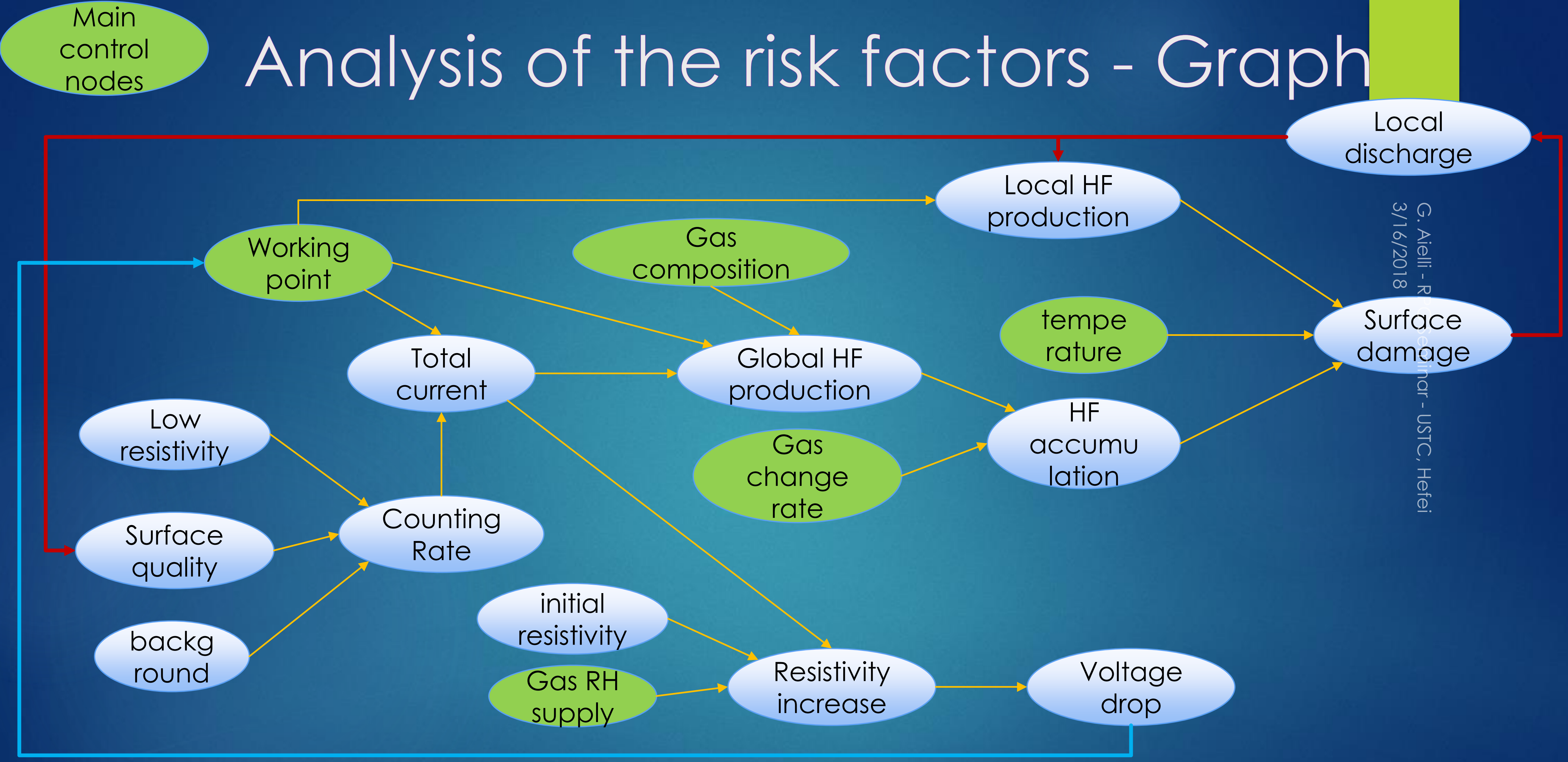
The ATLAS RPCs is the result of an intensive R&D finished 15 years ago

- New FE electronics
- New gas mixture
- New working mode (saturated avalanche)

The detector parameters fixed the total charge per count (30 pC) for efficiency >96% requested

The ATLAS cavern background fixed the certification boundaries for the ageing studies

Analysis of the risk factors - Graph



- Resistivity increase can be controlled through the RH and has a negative feedback
- Noise induced by HF can be controlled by lowering the current. It has a positive feedback

Observed Ageing effects on RPCs

Detector lifetime from the electric point of view (from ageing tests)

- stability of the electrode conduction properties and surface integrity
- Two potential problems have been pointed out:
  - Increase of the electrode resistivity due to the loss of ionic carriers. This would harm the rate capability by means of a non negligible voltage drop across the electrode plates
  - **Damaging of the inner surface by means of HF deposit from the discharge. This increases the dark current and the noise rate and if left without control my seriously harm the detector**
- Risk factors are influenced by
  - Total charge per count → integrated charge and the local discharge probability
  - Local counting rate → integrated charge and HF production rate
  - Local gas change rate and composition → HF production and removal rate
  - Gas and environment humidification → electrode resistivity control
  - Temperature → electrode resistivity, increase of the noise, acceleration of the HF damage
  - Gap features (plate resistivity oiling type…) endurance in harsh conditions

HL-LHC long term operation problem

The challenge for muon trigger in brief:

- It has to run at 8 x the original design intensity and pileup
- It has to run for 30 years instead of 10
- Higher performance is requested to the trigger system

A critical review of the system generates the following questions:

- What performance the experiment physics goals assume on RPC system?
- Can the existing detector support the future performance request?
  - Counting Rate and longevity, trigger selectivity and efficiency, space-time precision and pile-up tolerance
- Can exploit better the RPCs to extend the discovery potential of the experiment?
- what is needed for keeping compatibility with the future the experiment?

Background maps

Sector	RPC unit Id. along Z direction																				Avera ge
Φ Id.	-6.2	-6.1	-5.0	-4.0	-3.2	-3.1	-2.2	-2.1	-1.2	-1.1	1.1	1.2	2.1	2.2	3.1	3.2	4.0	5.0	6.1	6.2	
01.01	342	280	301	225	145	114	128	101		61	61	71	113	122	127	136	214	276	269	285	180
01.02	293	281	303	218	159	133	129	143		76	71	75	127	143	140	148	215	295	278	297	188
2	168	204	188	138	109	90	77	63	55	56	45	48	61	79	94	104	140	207	196	152	115
03.01	297	296	281	198	148	128	119	119	68	67	65	71	131	125	114	125	207	329	268	290	177
03.02	300	243	277	210	151	129	155	122	85	75	75	70	122	127	152	132	207	315	243	299	179
4	112	166	158	151	101	83	65	77	41	53	46	41	73	68	92	108	160	196	175	112	101
05.01	171	173	263	138	105	102	140	127	68	60	60	69	124	177	102	137	185	290	173	171	149
05.02	227	198	237	158	109	105	136	143	77	61	63	71	111	136	108	141	200	267	255	282	159
6	175	186	208	163	105	95	90	95	77	59	52	59	84	81	106	124	189	200	227	167	131
07.01	305	263	288	191	154	129	131	114		76	78		122	139	124	148	185	261	268	305	183
07.02	327	258	216	203	141	112	129	108		74	77		105	114	112	152	184	278	276	279	175
8	146	196	195	161	103	85	80	70	50	57	54	54	67	74	85	108	168	196	194	156	118
09.01	319	246	301	206	155	117	149	119		46	64		106	134	124	135	197	283	262	297	181
09.02	347	258	287	205	143	95	107	103		58	67		99	112	95	137	188	285	265	292	174
10	174	201	207	147	99	86	68	71	46	43	41	50	64	69	80	103	148	193	201	170	115
11.01	308	244	237	157	97	84	81	87		40	43		83	94	92	94	148	227	215	278	132
11.02	196	193	157	105	78	66	55	57		33	31		50	62	58	71	98	151	160	185	98
12						80	81	66	51	36	36	51	75	87	80						64
13.01	291	278	253		140	102	96	84	43	41	47	50	87	95	99	123		249	263	319	149
13.02	299	264	262		104	97	105	86	49	48	50	56	93	103	97	110		252	227	294	146
14						142	68	64	52	41	40	49	63	68	136						76
15.01	196	221	148	113	76	71	67	49		38	36		50	59	86	87	104	156	173	196	104
15.02	183	159	246	164	116	98	103	75		44	43		75	106	112	107	158	248	159	183	133
16	173	214	216	173	108	89	54	75	56	59	50	50	77	54	87	103	177	209	208	154	124
Average	229	223	234	167	118	101	96	88	56	52	51	56	86	97	103	118	171	240	221	221	137

- Hz/cm^2 measured at $L=6*10^{33}$ cm^{-2} s^{-1} and extrapolated at 7.5 10^{34} cm^{-2} s^{-1} and 13 TeV
- Values spread = 7
- Max rate 350 Hz cm^{-2}

Ageing test:

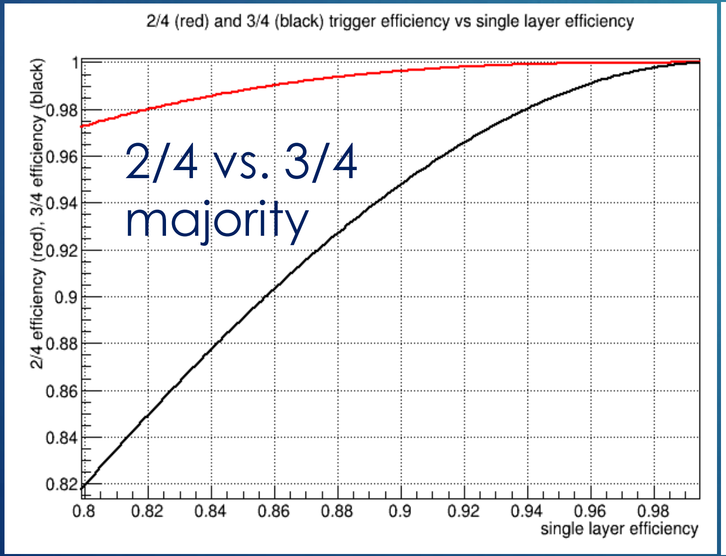
- 0.3 C/cm^2 → 300 fB^{-1}
- 100 Hz/cm^2 x 10 LHC years

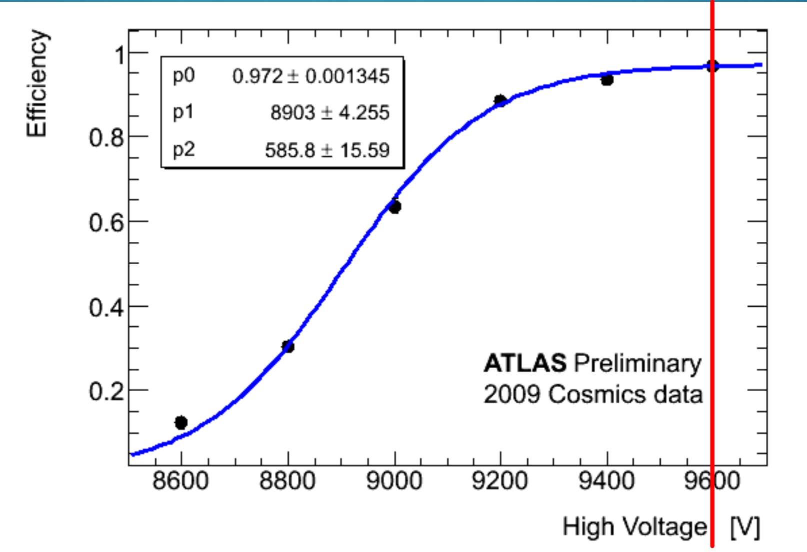
Extrapolating…

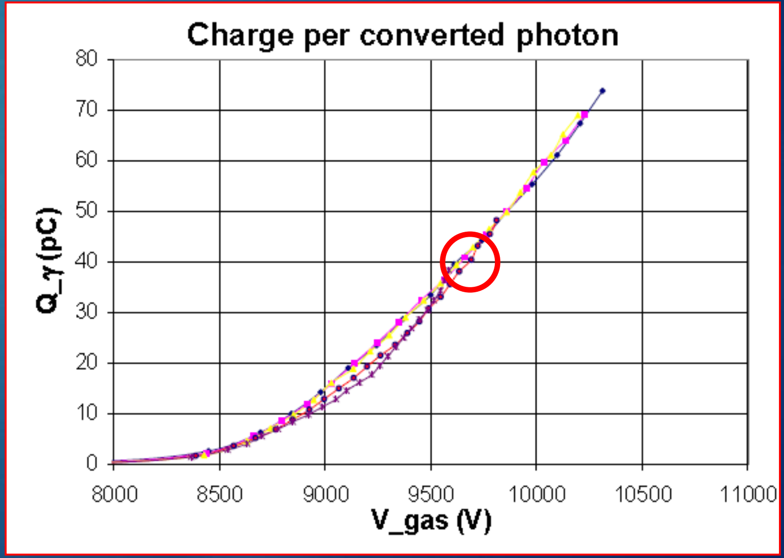
- 5 C/cm2 → 5000 fB^{-1}

Mitigation strategy: an example

- If we apply on the BM station **a 2/4** majority **instead** of the **3/4**, **it** allows a consistent reduction of gap efficiency **without affecting** the **trigger** efficiency
- it is possible to recuperate a **LARGE SAFETY FACTOR →** working at constant current above the known limits
- **To operate this majority an increase of redundancy is needed**
- **It can be generalized to make a real tracking trigger**



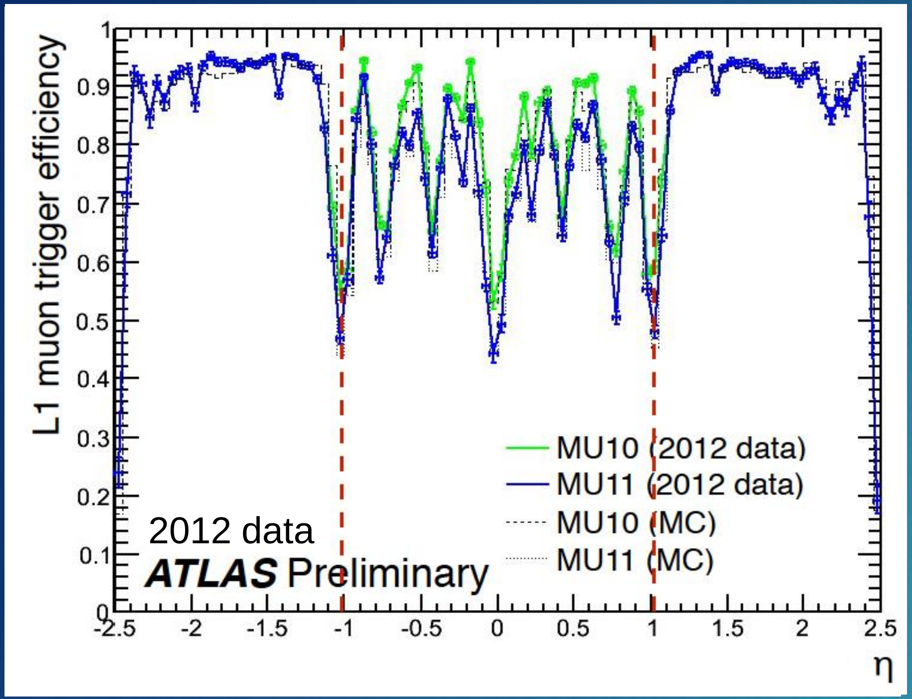


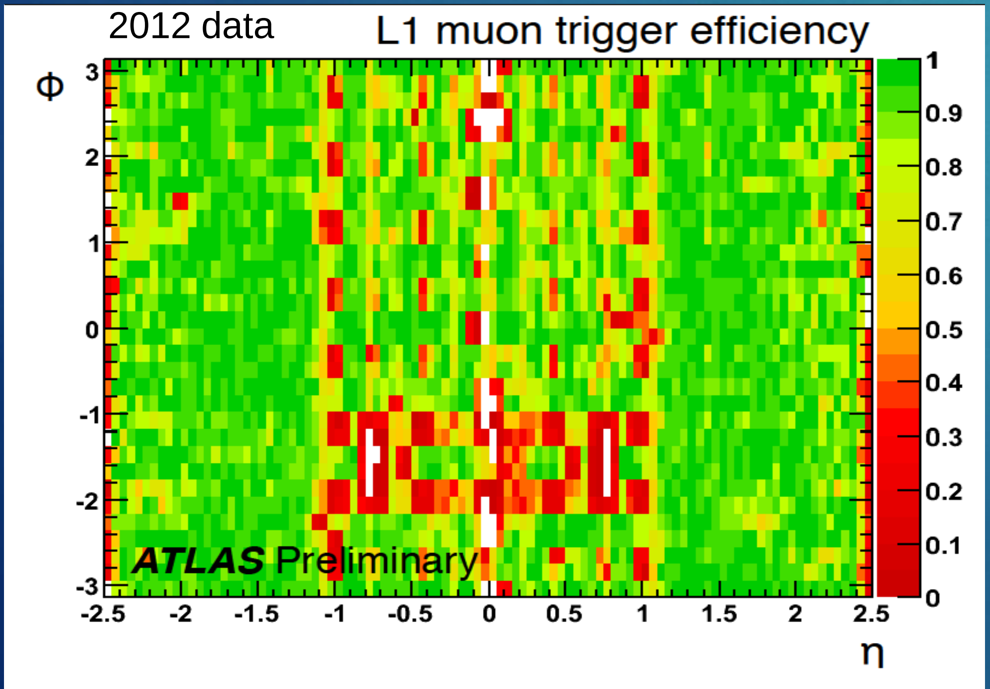


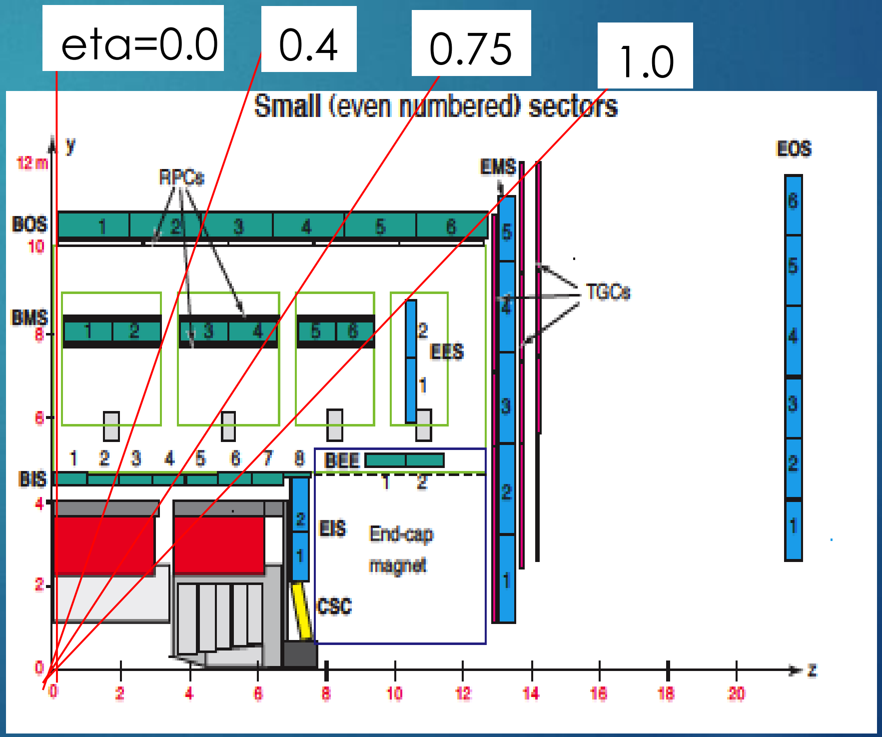
barrel acceptance limits

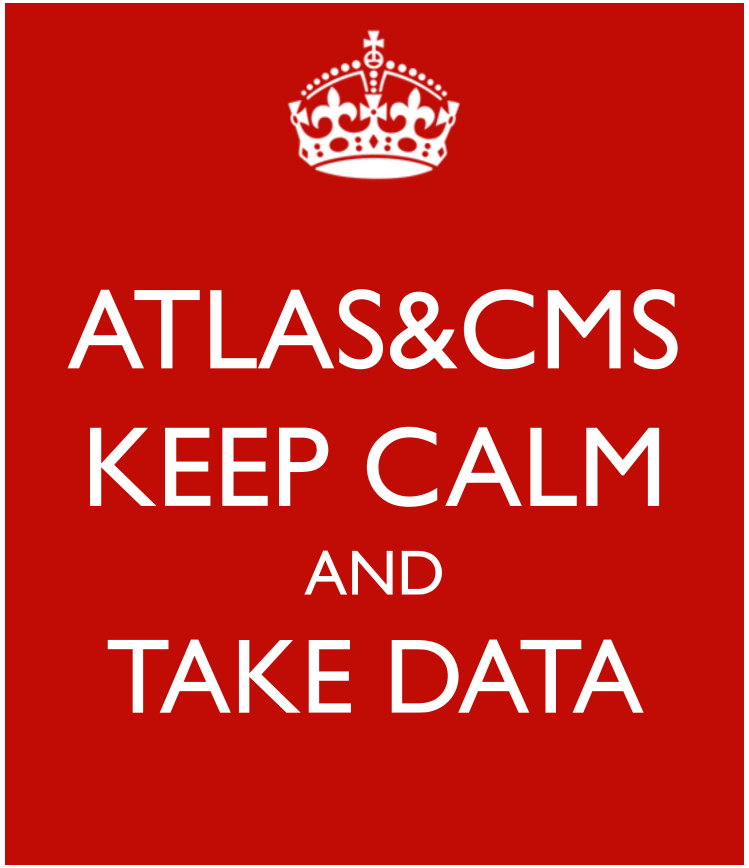
Acceptance holes of L1 barrel trigger 22 %

- Holes due to toroid ribs (small sectors) and Z=0 crack (Large sectors
- The 3.8 % (feet region) out of the 78% covered region has limited redundancy (3/4 only)








ATLAS&CMS
KEEP CALM
AND
TAKE DATA

The ATLAS RPC upgrade project

THE SCOPE

- Ensure long term operation to the muon trigger in the barrel
- Maximize the system performance in coverage and selectivity
- Exploit RPC full potential…

THE PLAN

- Replace the RO electronics on the old chambers in compliance with the new T/DAQ schema. And exploit this opportunity for a better readout….
- Operate legacy RPCs at lower gap efficiency to extend the lifetime
- **Increase redundancy and acceptance with a new Inner Barrel RPCs**
- Refurbish the most critical and exposed legacy RPCs

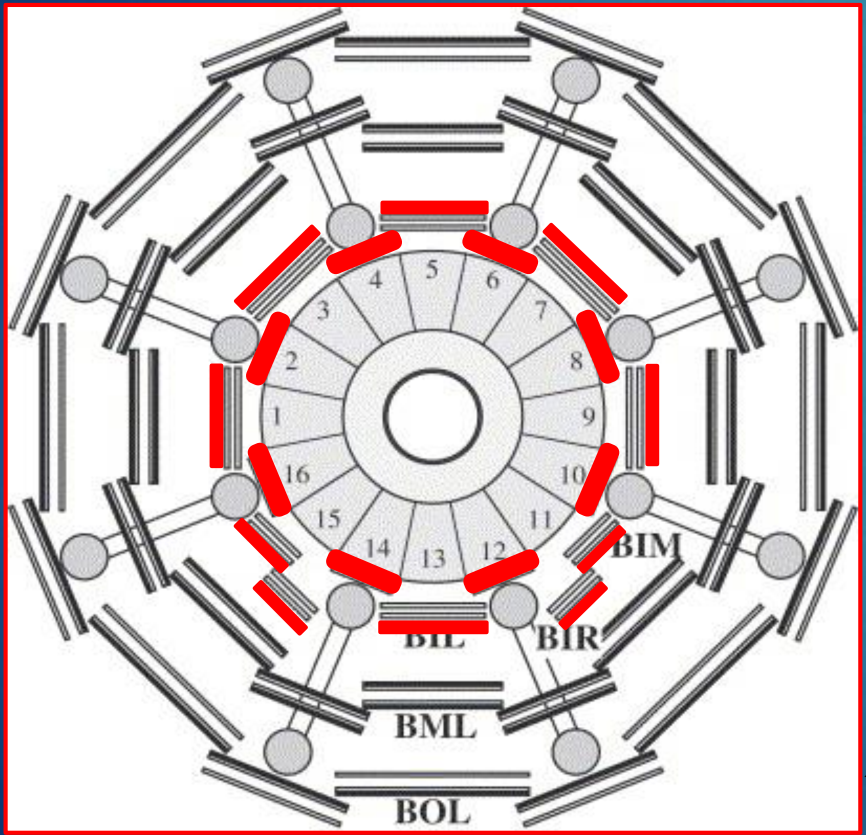
THE STRATEGY

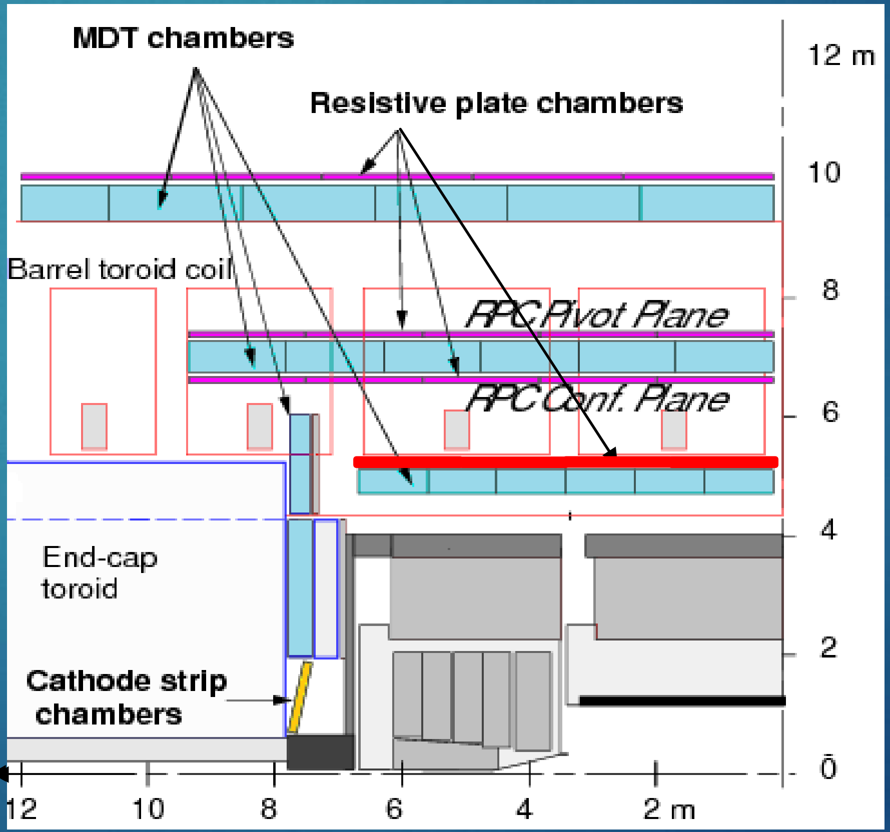
- Introduce a new generation of high performance RPCs
- Use Phase 1 project as an extended test bed for the new RPC technology

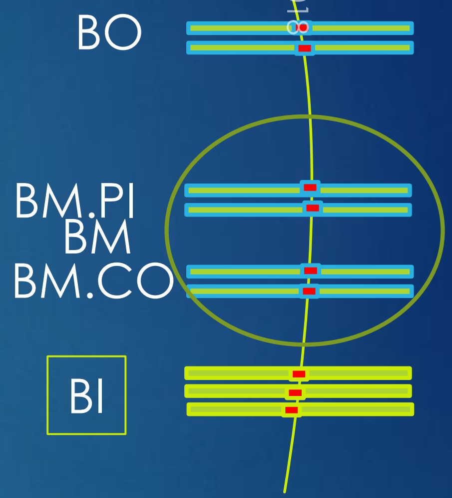
A new layer of RPCs: BI

increase the redundancy by adding the RPC inner layer

This idea was already considered in the original project of the barrel trigger detector, but at that time the need for the 3rd station was not stringent and it was canceled when a substantial downgrade was required to Atlas





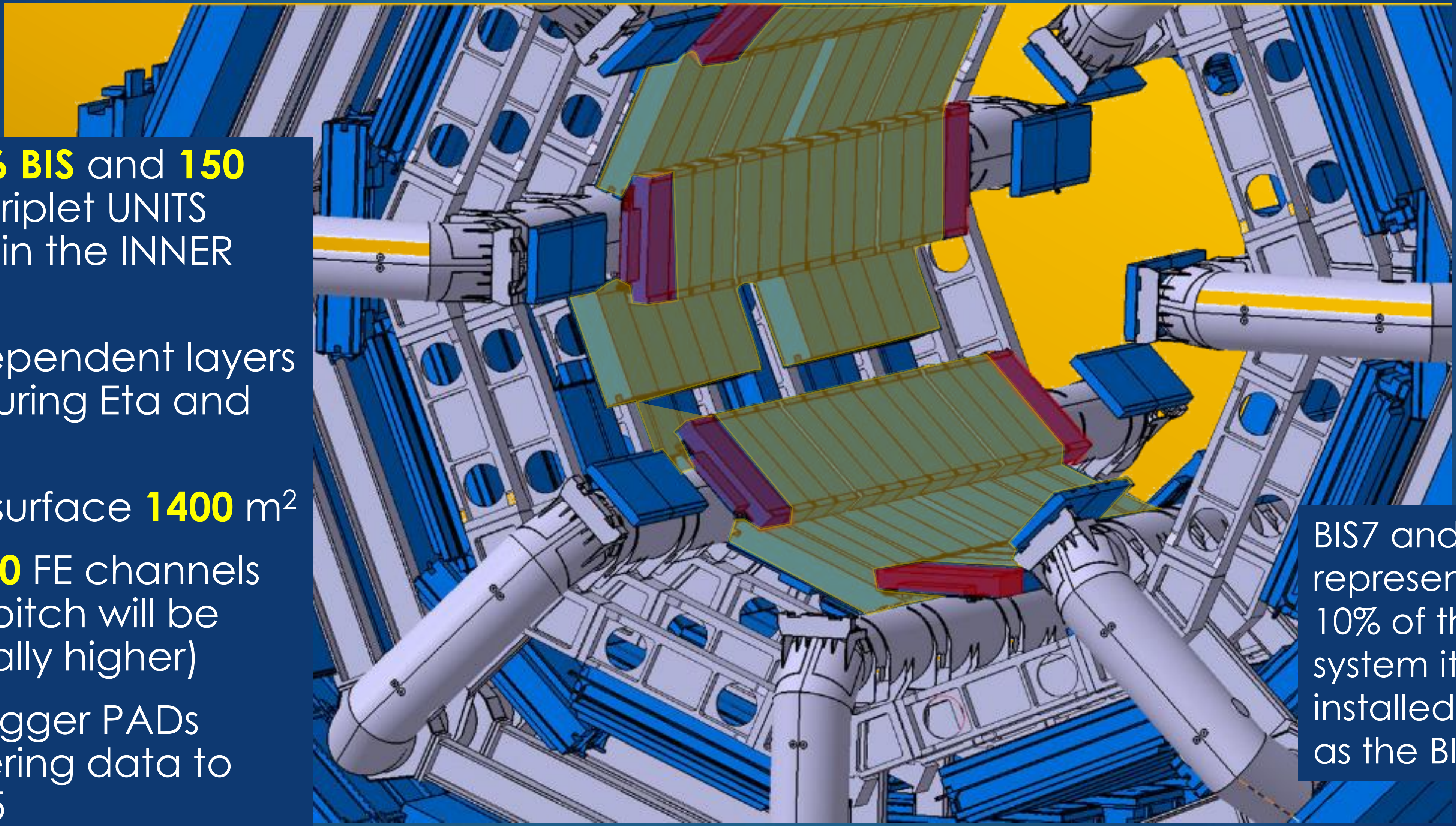


- 9 layers instead of 6
- 4 chambers instead of 3

The new RPCs: BIS78 + BI

About **96 BIS** and **150 BIL** RPC triplet UNITS installed in the INNER LAYER

- 3 independent layers measuring Eta and Phi
- Total surface **1400** m^2
- **115000** FE channels (strip pitch will be naturally higher)
- **200** trigger PADs delivering data to USA15

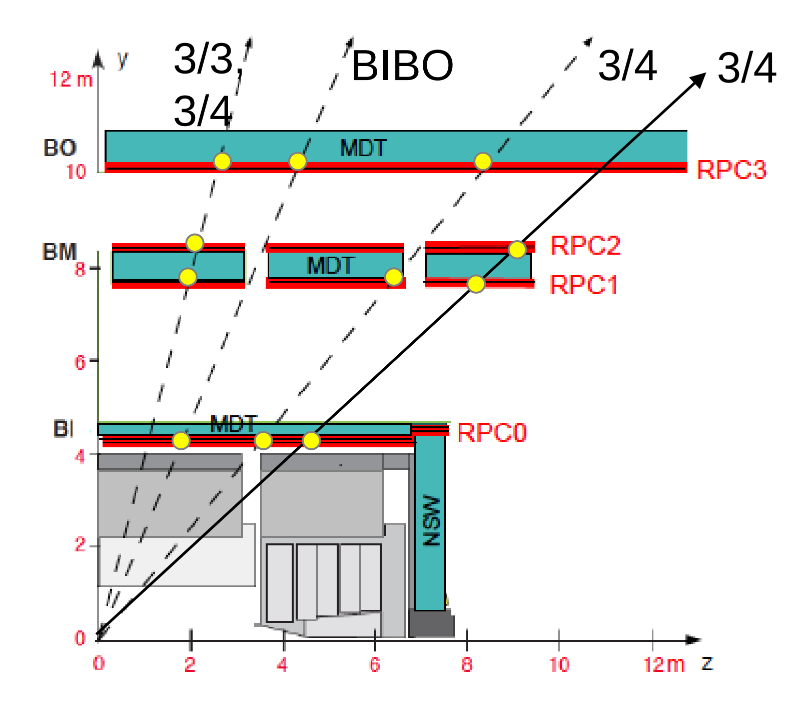


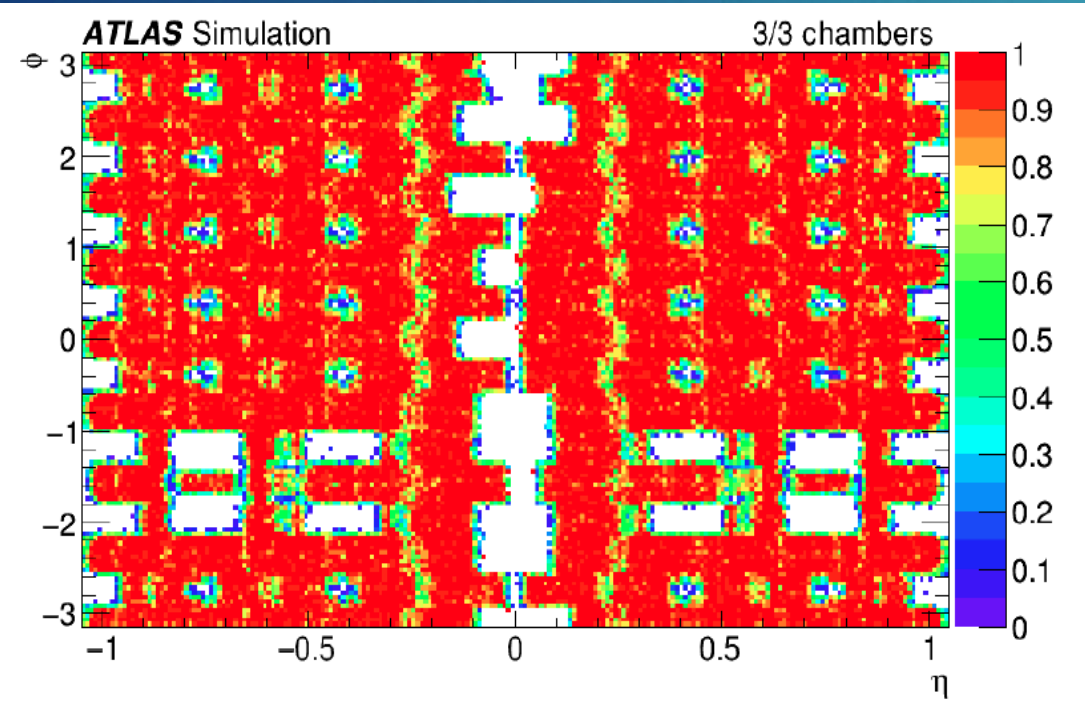
BIS7 and 8 represent about 10% of the full BI system it will be installed in 2019 as the BI pilot

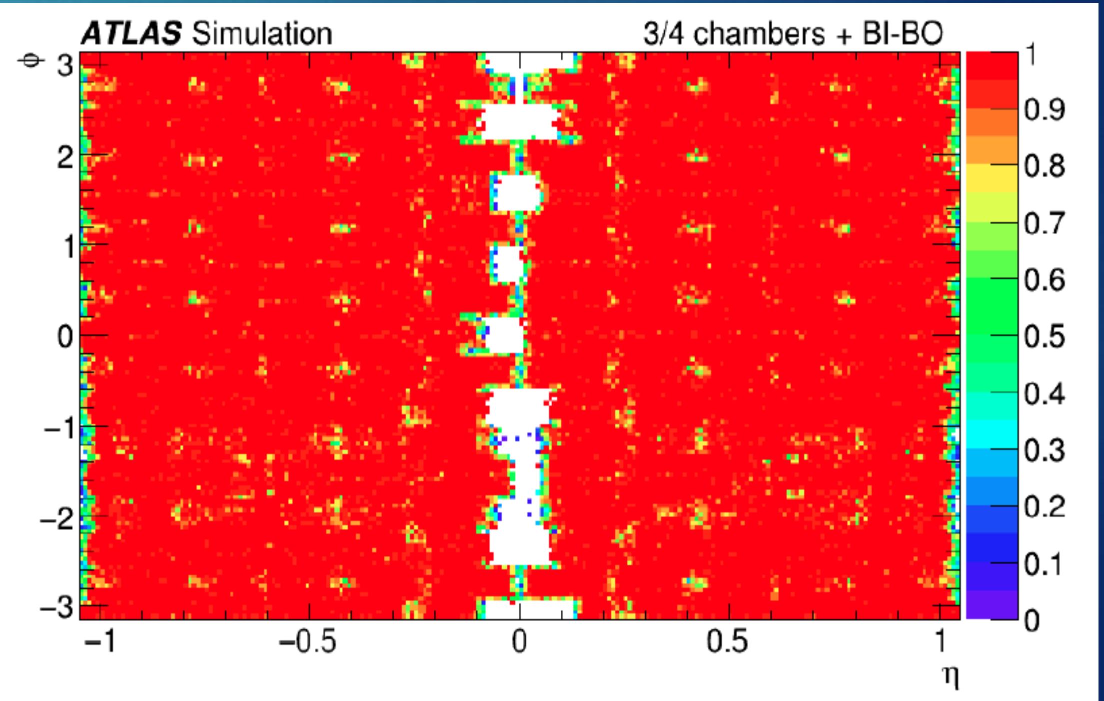
Improving trigger acceptance

The acceptance limitation is recovered introducing the BI RPC layer and a new flexible trigger logic:

- Replace "3-out-of-3 chambers" requirement with "3-out-of-4 chambers"
  - Acceptance 78% → 92%
- Adding BI-BO two-chambers coincidences
  - Acceptance → 96%







Efficiency × acceptance

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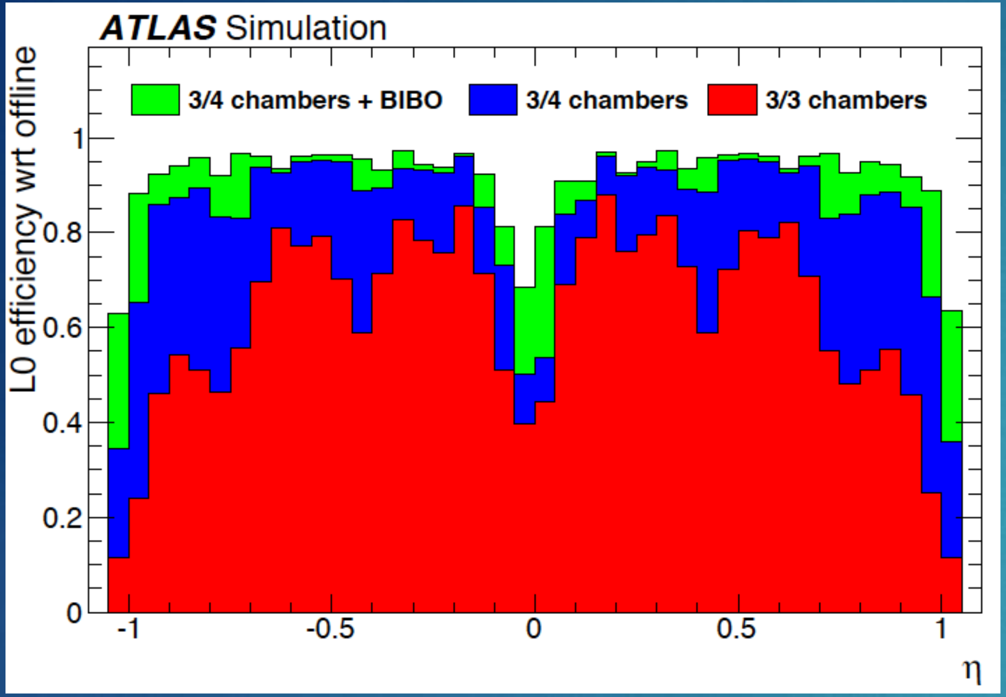
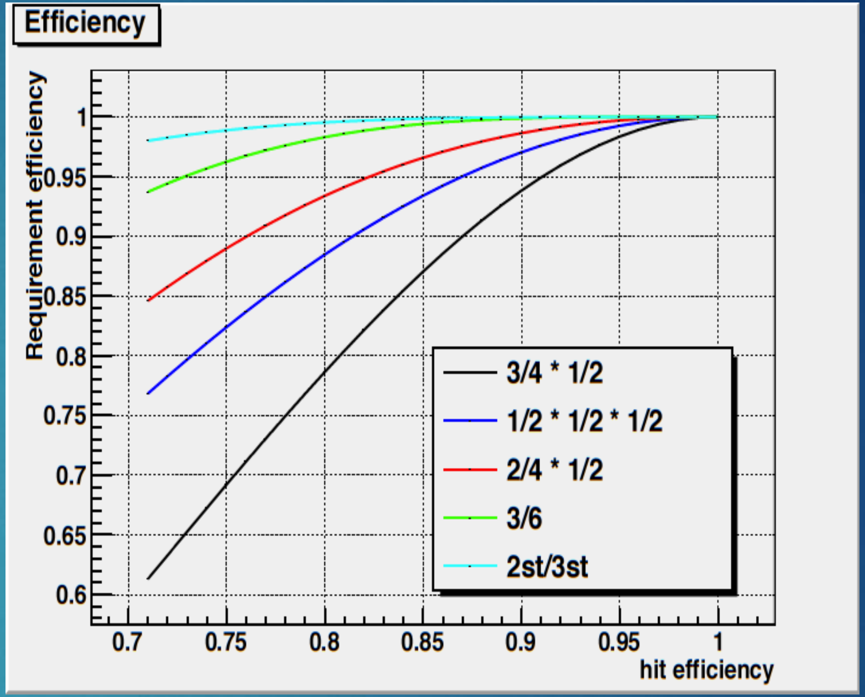


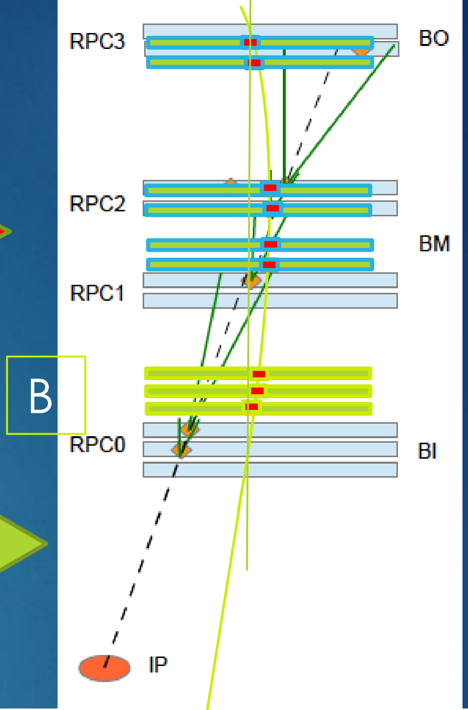


- New trigger is robust against large variation of RPC gap efficiency
- Worst case scenario:
  - 90% → eta=0
  - 55% → eta=1
- $\varepsilon \times A > 92\%$

BM and BO efficiency (%)	Trigger efficiency × acceptance (%) 3/3 chambers	3/4 chambers	3/4 chambers + BI-BO
100	78	91	96
90	73	90	95
80	62	87	93
Worst case	63	85	92

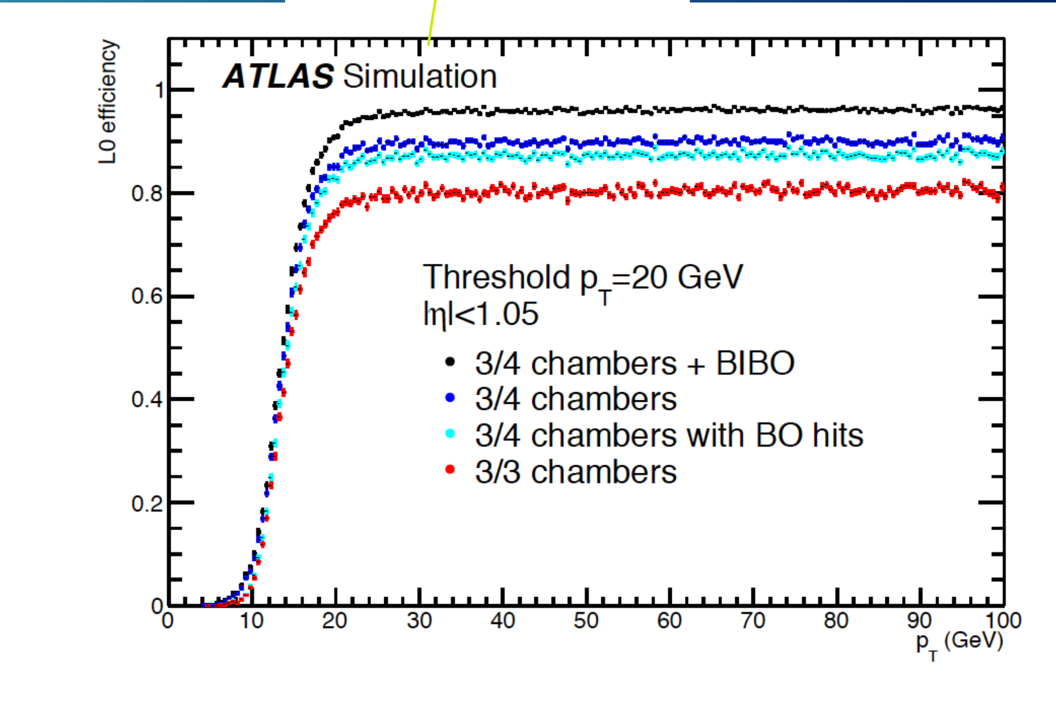
Trigger performance

- Momentum selection based on pre-computed coincidence windows
- Similar sharpness of the turn-on curve as present trigger
- Maximum rate expected 50 kHz on single muon > 20 GeV/c
- Assumin IP position → IP spread is the main limiting factor



- 9 independent measurements
- 2D position a few mm resolution
- From 0.4 to 1 ns resolution per gap
- 10 m lever arm
- Charge information
- FPGA based fast local processing

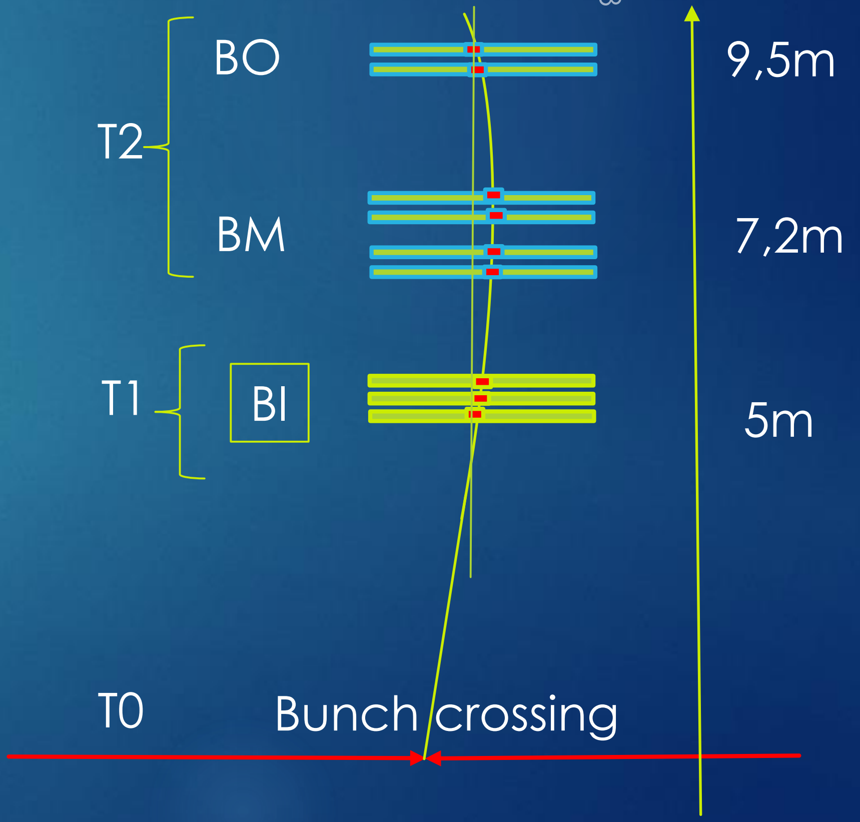
- Possible a fast sagitta measurement using available points → independent on IP
- Charge information → better resolution
- Can implement new special trigger entries in the trigger menu → new physics
- lower pT thresholds should be also considered for multi-object triggers



Further impact on physics

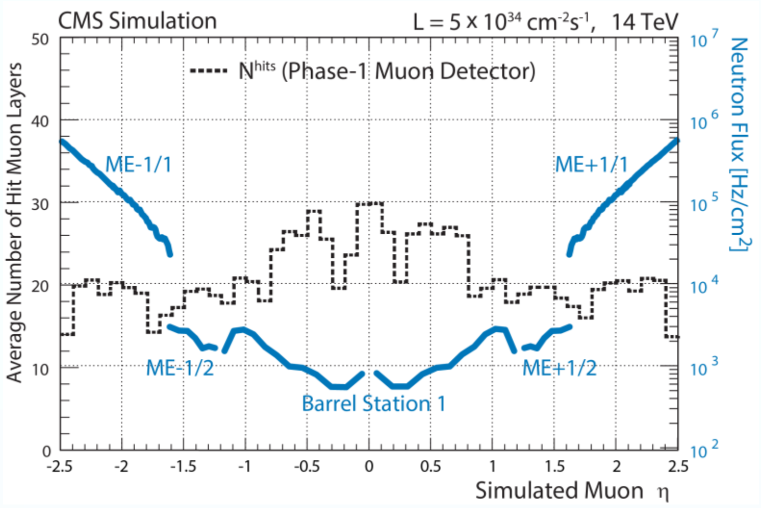
- **Benefits of the extended coverage in the barrel.**
  - E.g. Channels with a single muon (for example W')
  - pT distribution is more peaked in the barrel.
  - Spatial correlation effect for two muon decays (also holes are very correlated in space).

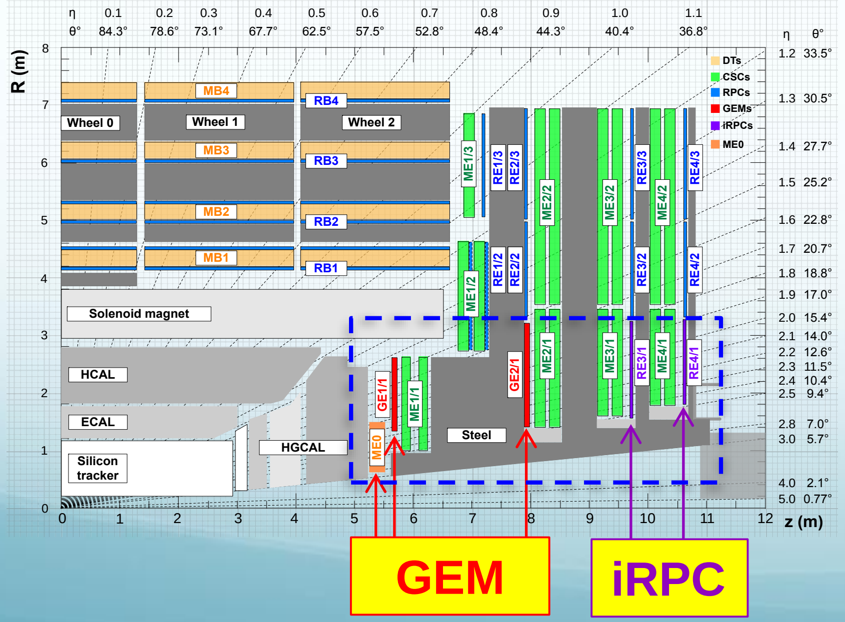
- **TOF AND POSSIBLE TOF TRIGGER**
  - BI RPCS BOOST THE TOF PERFORMANCE:
    - ALMOST DOUBLED LEVER ARM OF THE ACTIVE VOLUME
    - NEW GAS GAPS WITH 0.5 NS RESOLUTION EACH → ~200PS FOR A QUADRUPLET → 1% OF SENSITIVITY ON β
  - A NEW POSSIBILITY IS TO IMPLEMENT A TRIGGER BASED ON β TO SELECT SLOW PARTICLES



G. Pugliese

System enhancement in the forward region





VERY CHALLENGING REGION, both for trigger and offline reconstruction

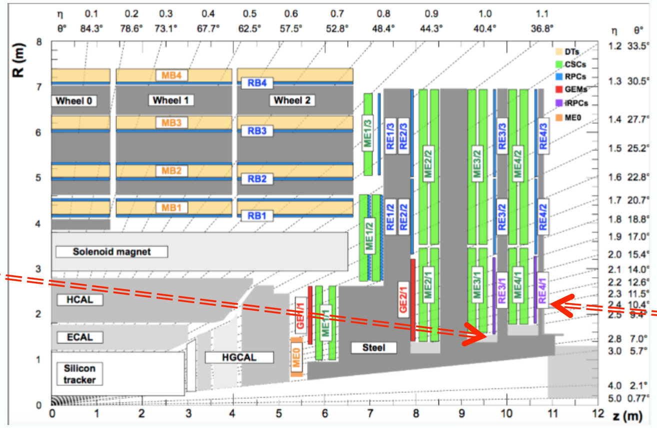
- **high rates due to n/γ-induced background, punchthrough and muons**
- **Expected 600 Hz/cm^2**
- **small bending of muons by magnetic field**
- **small number of measurements per muon in forward direction (present system); smaller than in the barrel**

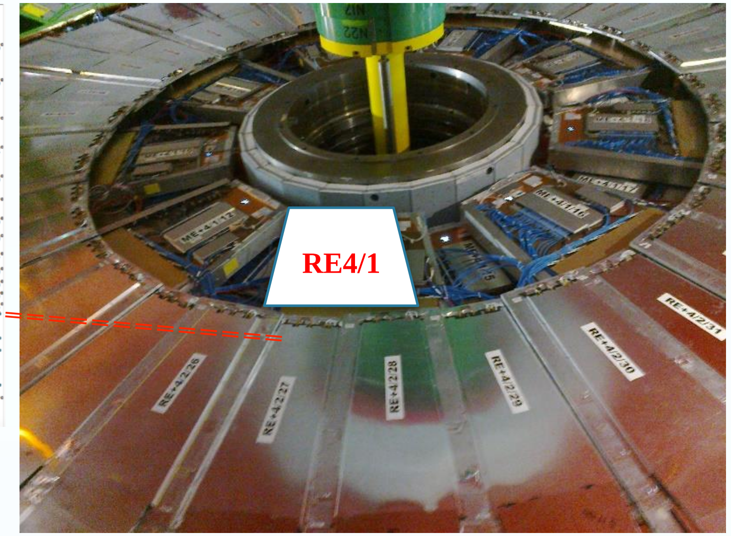
UPGRADE: augment the system by adding new detectors in the forward direction:

- **GEM: ME0, GE1/1 and GE2/1**
- **iRPC: RE3/1 and RE4/1**

G. Pugliese

Improved RPC in RE3/1 and RE4/1





The 3th and 4th stations will be equipped with a new generation of RPC with improved performance **(iRPC)**: each chamber spans 20° in φ for a total of 72 chambers (18 ch/disk)

Performance iRPC:

- Handle up to 2 kHz/cm^2 (3 x HL-LHC)
- **Spatial resolution:**

in φ ~ 5 mm

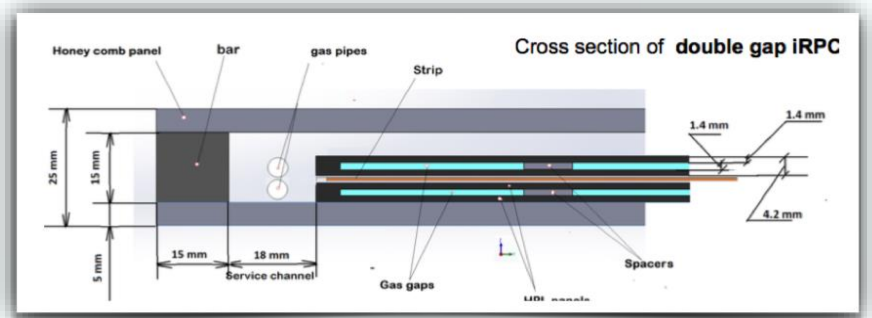
in **η** ~ 2 cm (from ~17 cm) by reading both sides of strips (2D readout)

G. Pugliese

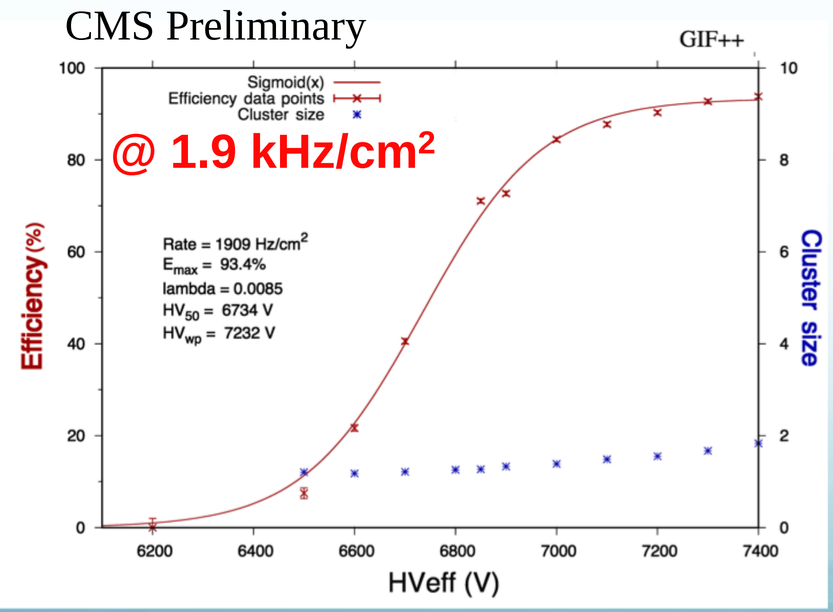
Improved RPC design

Design of iRPC:

- Reduced gas gap from 2 mm to 1.4 mm
- Reduced electrode resistivity: about 10^{10} Ωcm
- New generation of Front-End Board electronics to reduce the charge threshold from 150 fC to 50 fC



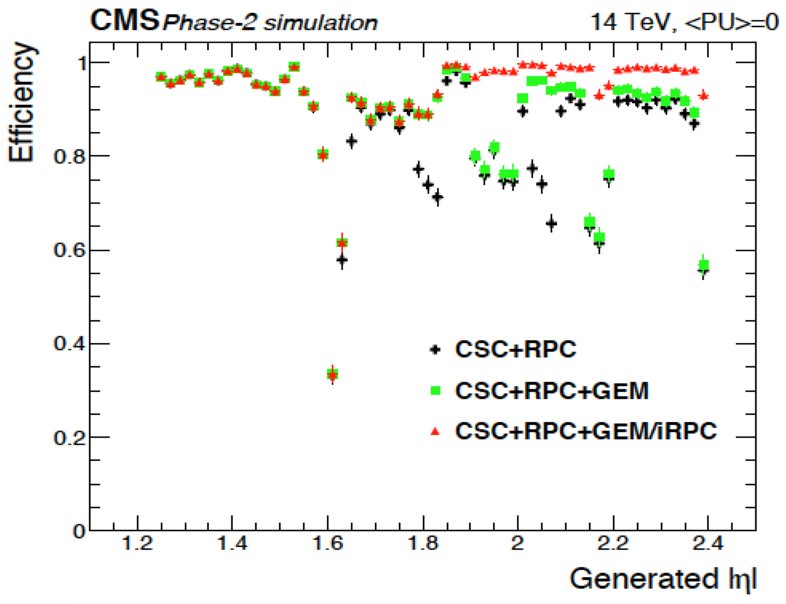
HL-LHC conditions has been satisfied

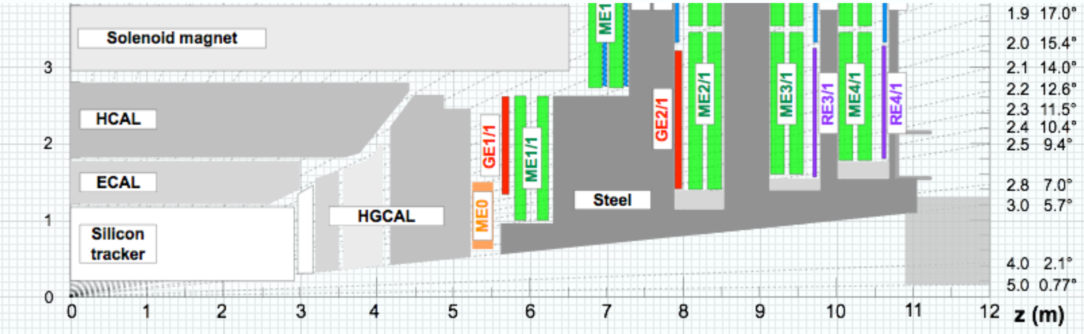


- New readout schema reading both end of strip
- New FEB will include a TDC (50 -100 ps resolution) to define the muon position along the strip with a spatial resolution of 2 cm

G. Pugliese

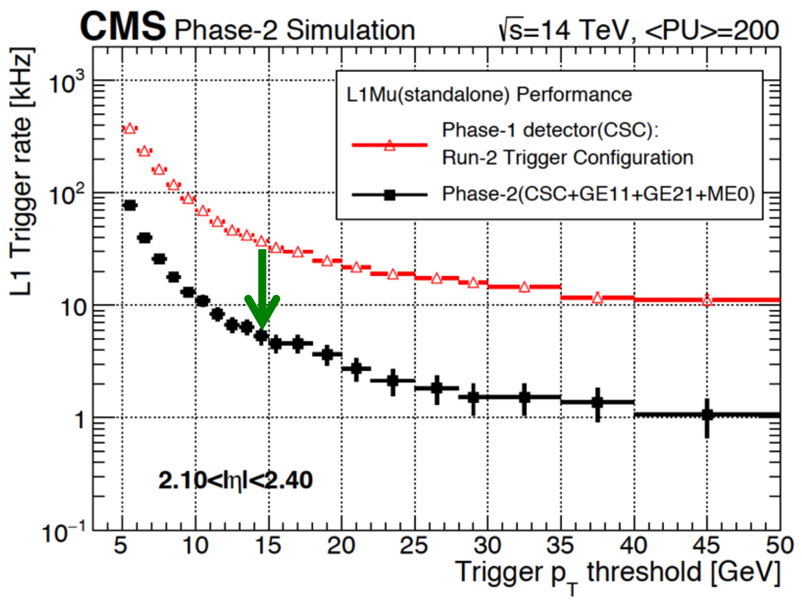
L1 muon trigger performance





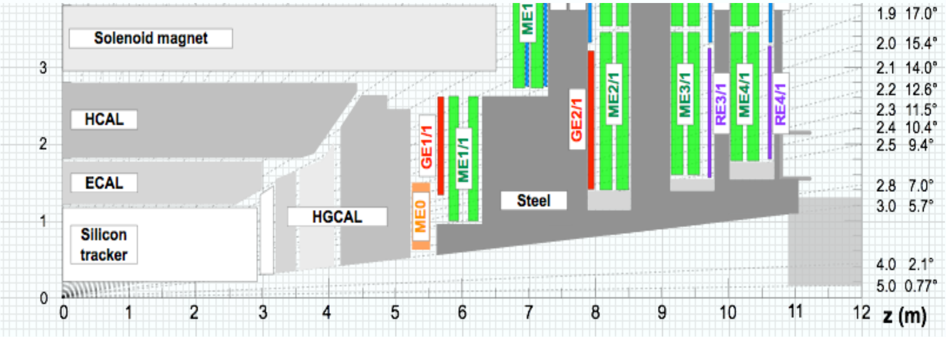
L1 muon trigger **efficiency** benefits from the addition of GEM and iRPC in the high η region.

Combine information from GEM-CSC in stations 1 and 2 will give much more accurate measurement of p_T and, hence, the L1 muon trigger **rate** drops (gain is as large as a factor of 10)



Muon reconstruction

G. Pugliese

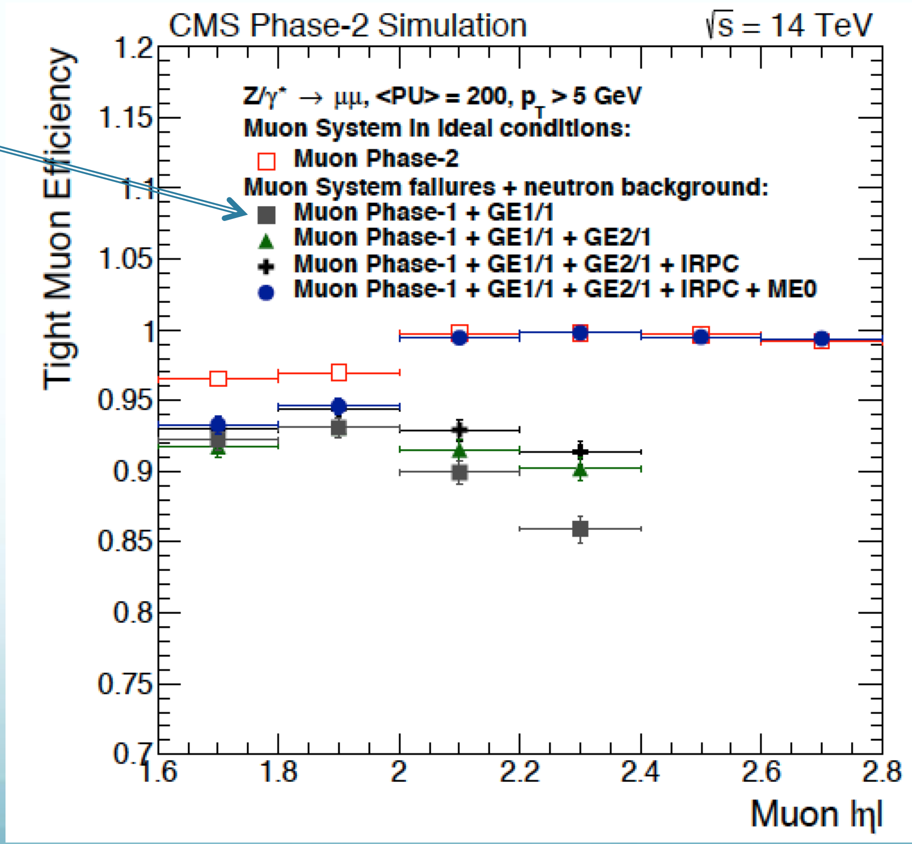


- The high pileup conditions expected at HL-LHC will reduce the muon reconstruction efficiency

Adding iRPC, GE2/1, and ME0 stations:

- **substantially increases efficiency** of muon reconstruction in the range 1.6 < η < 2.4

- makes possible to reconstruct muons in the extended range 2.4 < η < 2.8

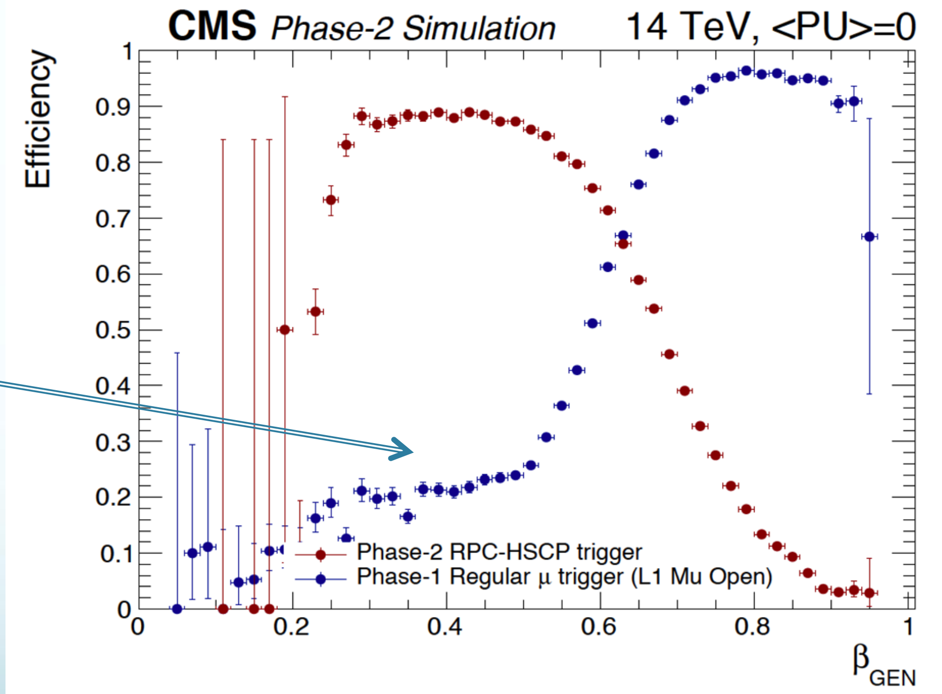


New Physics opportunities

The upgrade of the RPC Link System will allow us to explore the RPC intrinsic time resolution ≈ 1.5 ns (from the present 25 ns readout window).

- A new **RPC trigger (RPC-HSCP)** will be devoted to identify very slow "Heavy Stable Charged Particle (HSCP)"
- It will be based on TOF technic to identify the slow particle and to measure the β
- The efficiency of the present muon trigger drops for particle with β < 0.6
- The RPC HSCP trigger capabilities will be extended up to β ~ 0.2.

Factor of 4-5 improvement



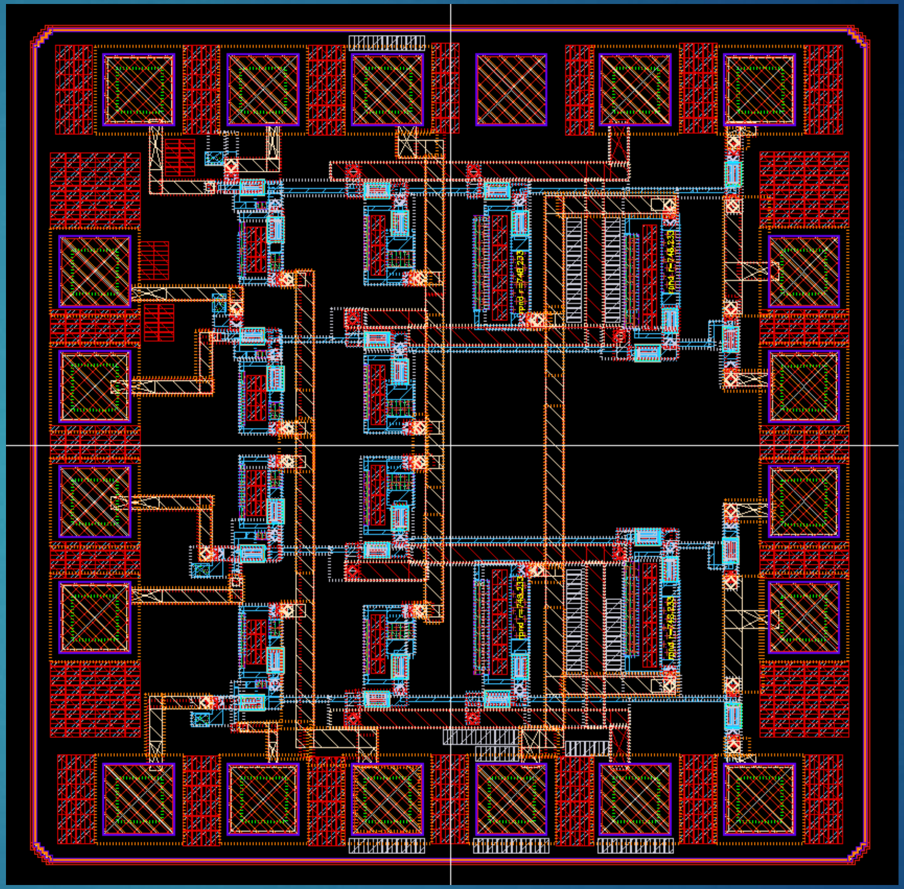
L1 Trigger efficiency as a function of an HSCP velocity β for the 'regular' muon trigger (in blue) and a dedicated HSCP trigger (red points)

DESIGN
PROTOTYPE
AND
TEST BEAM

RPC generations comparison

	Standard RPC	BIS78 RPC (expected FDR)	BI RPC (TDR baseline/options)
FE Electronics			
Effective threshold	1 mV	0.3 mV	0.1
Power Consumption	30 mW	6 mW	10 mW
Technology	GaAs	BJT Si	Bi-CMOS SiGe
Discriminator	Embedded GaAs	Separated SiGe	Embedded SiGe
TDC embedded	No	No	Yes
Channels/IC	8	4	8
TDC Resolution	3.125 ns→0.5 in phase2	0.3 ns	0.1 ns
Detector			
Gap Width	2 mm	1 mm	1 mm
Operating voltage	9600 V	5800 V	5200 V
Electrode thickness	1.8 mm	1.2 mm	1.2/0.8 mm
Electrode Material	Phenolic laminate	HPL	HPL/Phenolic glass
Time resolution per gap	1 ns	0.4 ns	0.4 ns
Space resolution	6 mm (3-4 mm in phase2)	1 mm	< 1 mm (under study)
Gaps per chamber	2	3	3
Efficiency with eco-gas	~80%	FULL	FULL
Readout	2D orthogonal	2D orthogonal	2D/1D meantimer

The new FE electronics



BJT Si v.s. SiGe

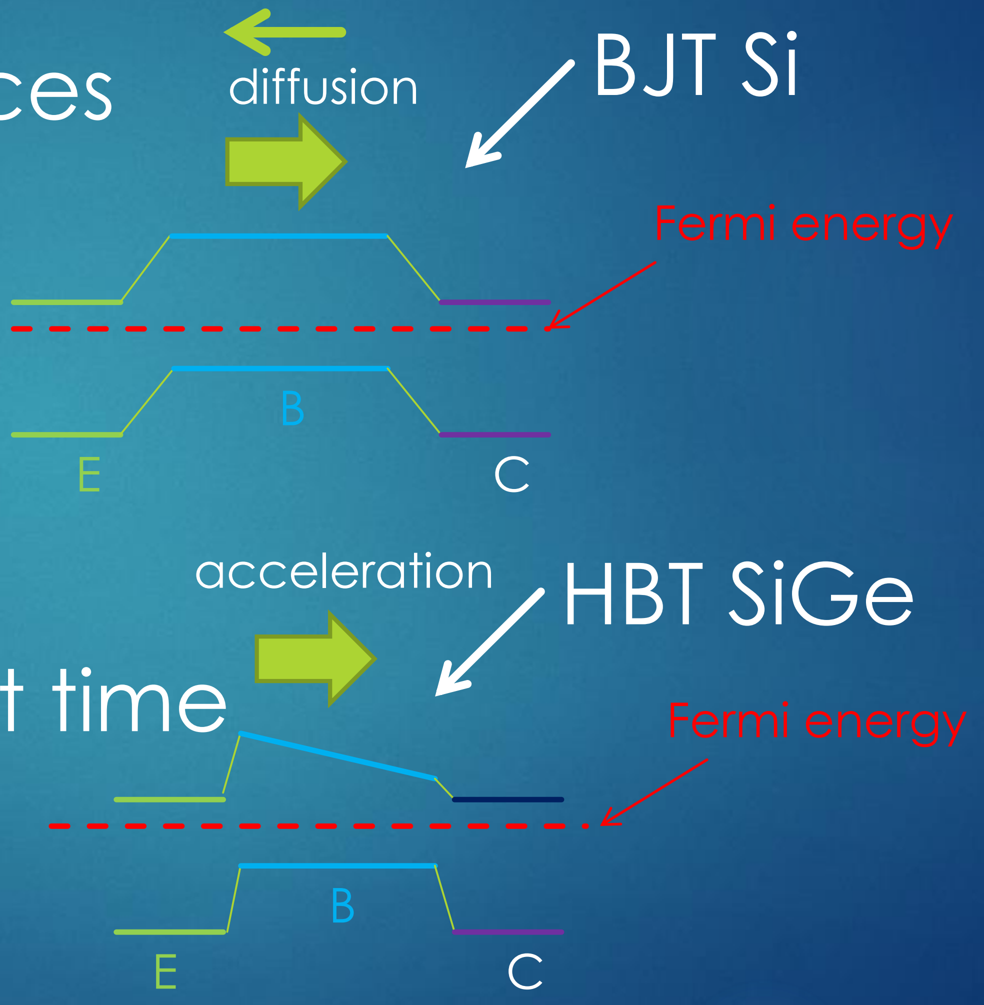
B JT performances

- $\beta = \tau_c / \tau_t$
- $f_t = 1/\tau_t$
- $N = K^* \tau_t$

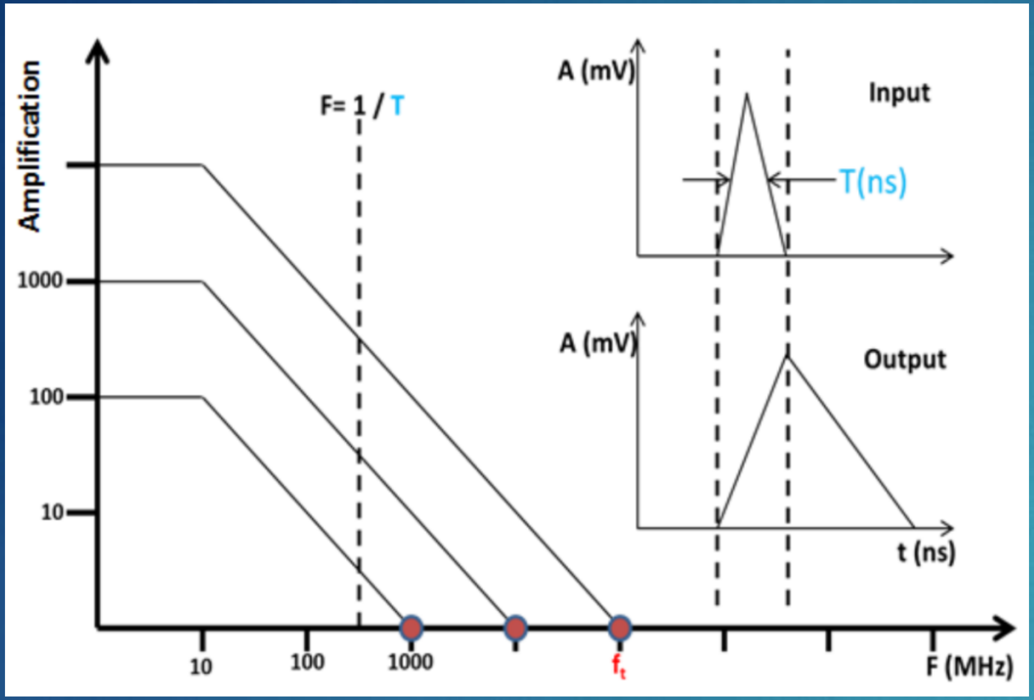
τ_c = base life time

τ_t = base transient time

τ_t (Si) >> τ_t (SiGe)

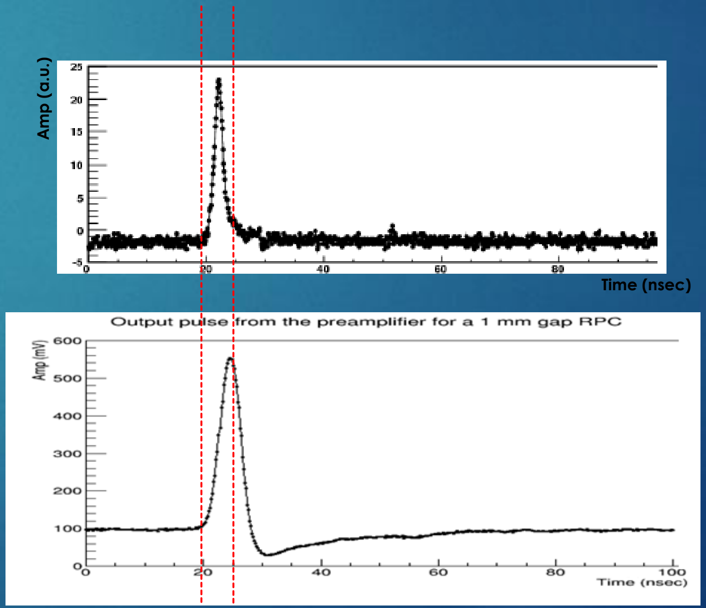


Strategy for the new front-end (SiGe)



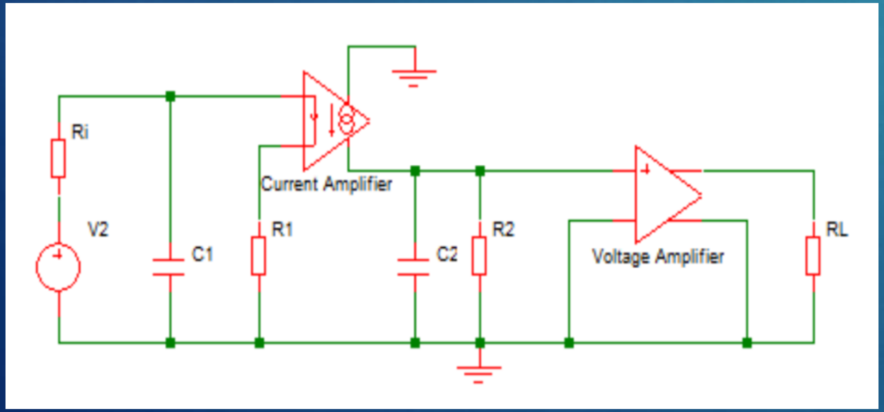
Working strategy

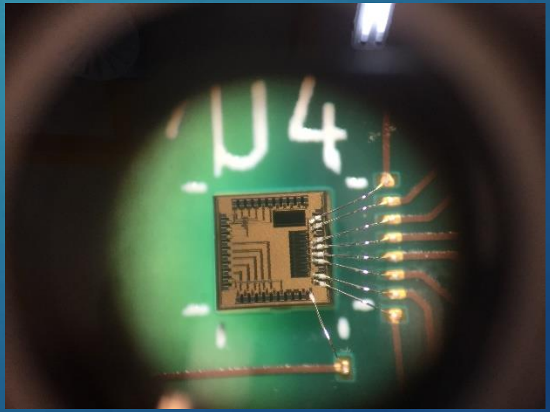
Actual result for the RPC signal



The new Amplifier

Feature	BJT Si (BIS78)	Bi-CMOS SiGe
Voltage supply	3-5 Volt	3-5 Volt
Sensitivity	2-4 mV/fC	3.5 - 6 mV/fC
Noise (up to 20 pF input capacitance)	1500 e^- RMS	500 e^- RMS
Input impedance	100-50 Ohm	100-200 Ohm
B.W.	10-100 MHz	100-200 MHz
Power consumption	10 mW/ch	10 mW/ch
Rise time $\delta(t)$ input	300 – 600 ps	200 – 400 ps
Radiation hardness	1 Mrad, 10^{13} n cm^{-2}	50 Mrad, 10^{15} neq cm^{-2}



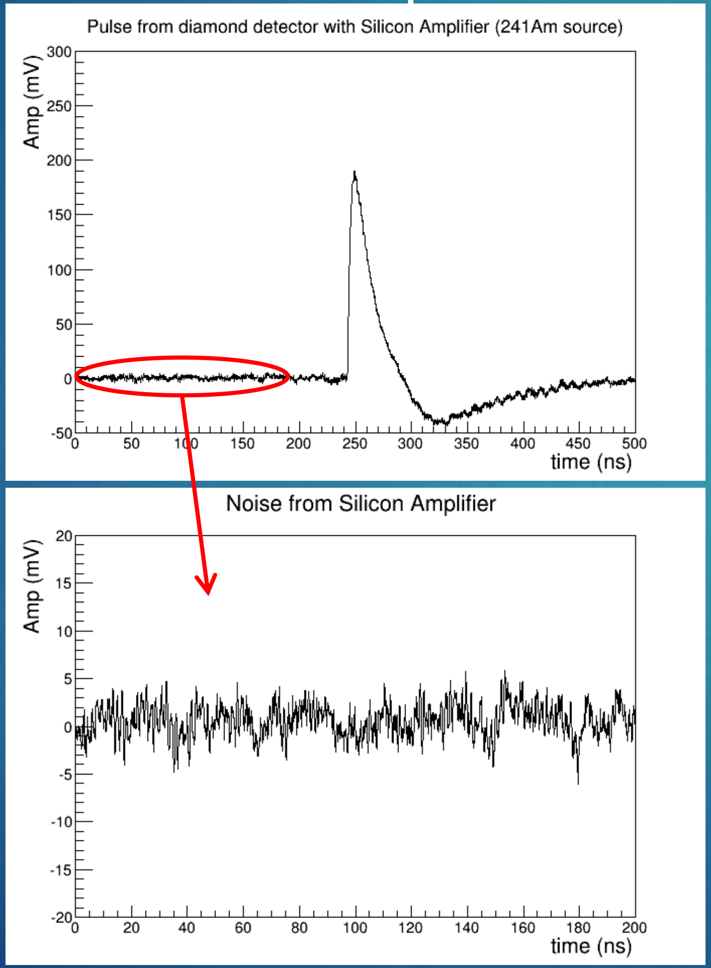


Test IC produced and tested on Diamond and Silicon

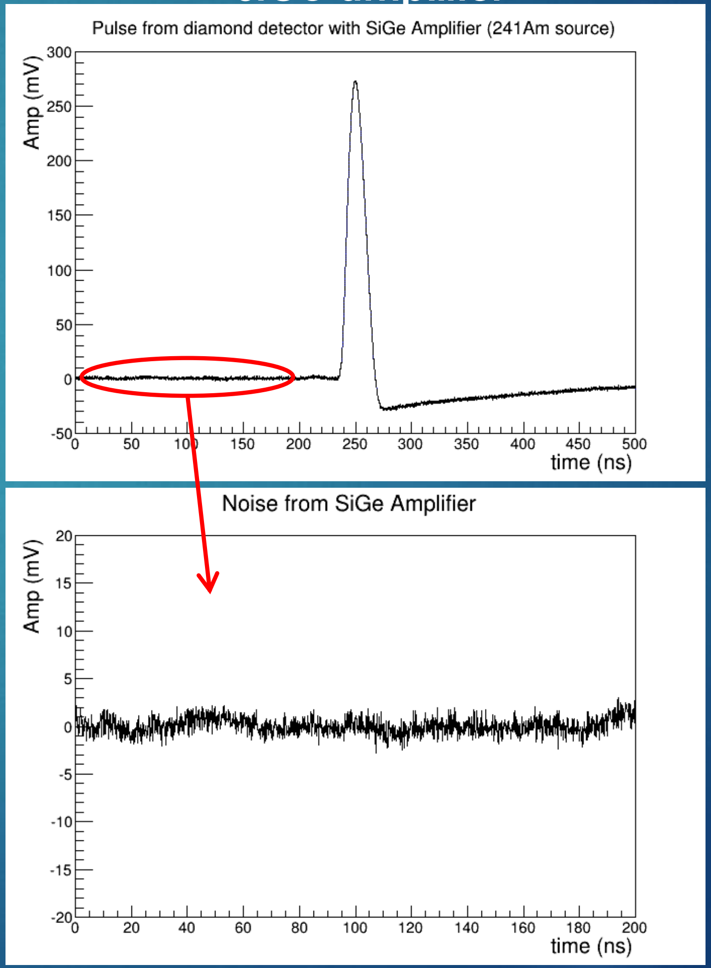
Signal and noise from SiGe Amplifier and Silicon Amplifier

Pulses recorded from a 500 micron diamond sensor irradiated by ^{241}Am source.

Silicon amplifier

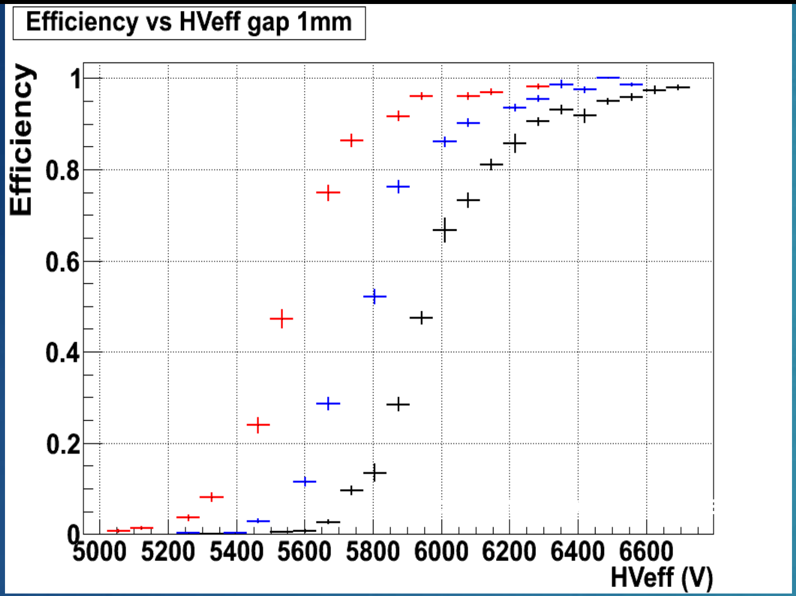


SiGe amplifier



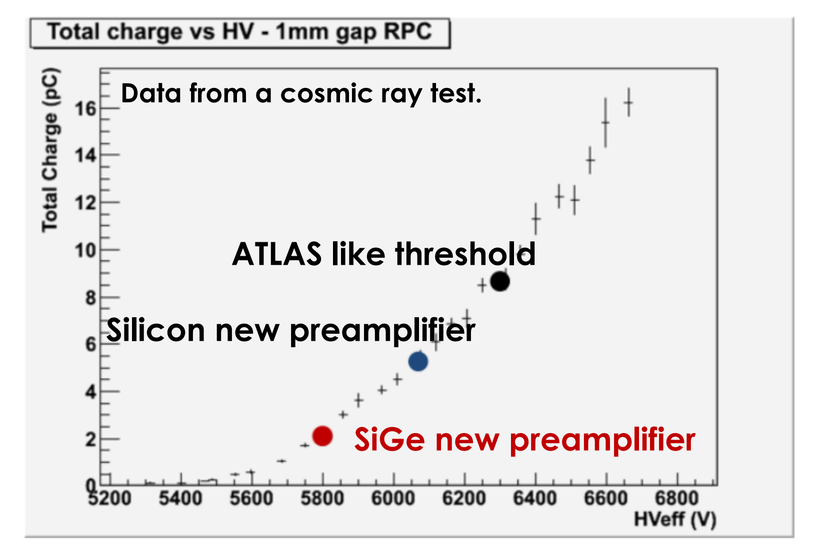
SiGe amplifier application on Resistive Plate Chamber detector

A 1 mm gap RPC detector read out with a ATLAS like threshold (black), the new preamplifier in silicon technology (blue) and in SiGe technology (red)



Using a more sensitive front end allows to operate the detector at a lower gain.

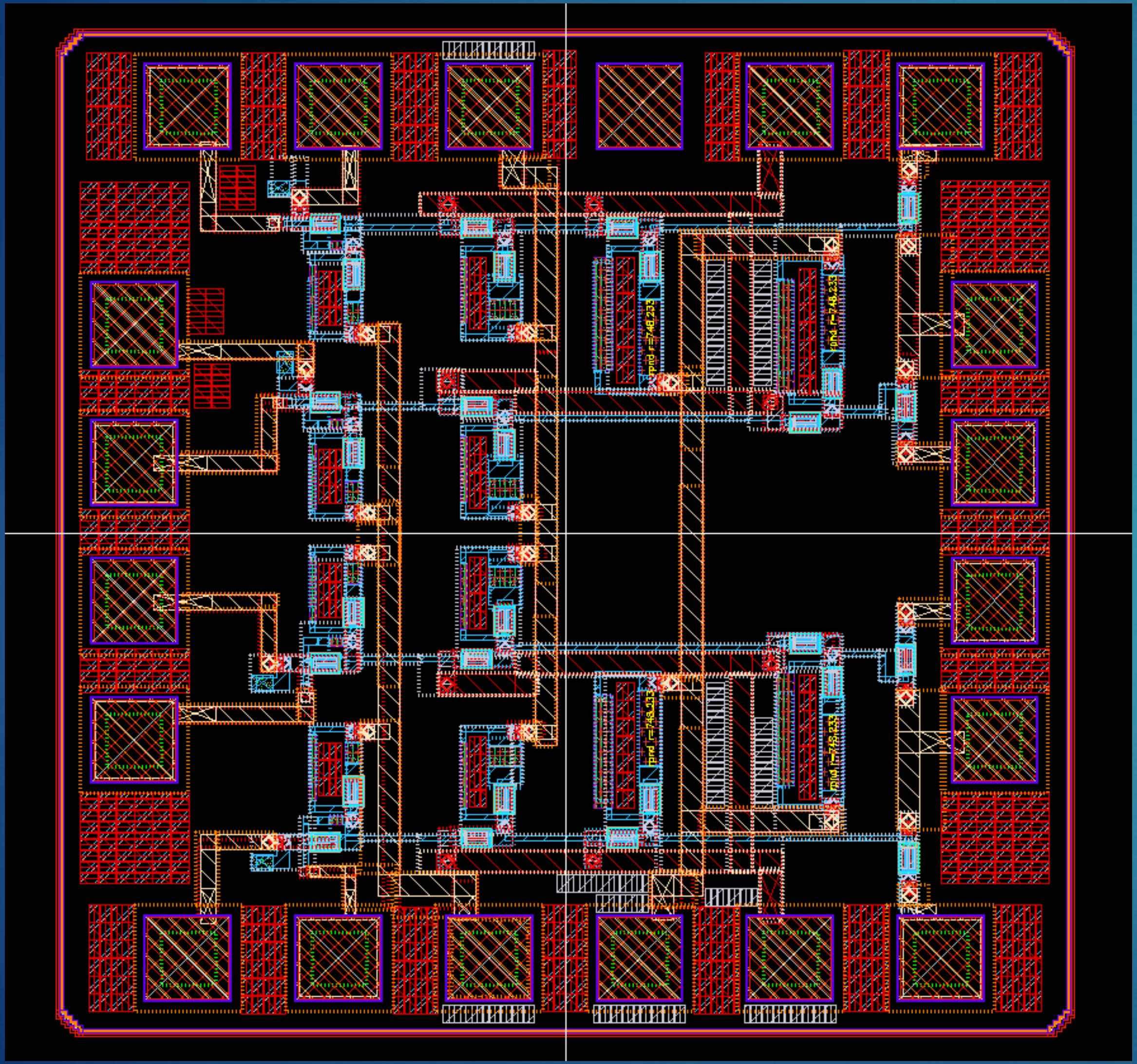
Total delivered charge per count in the detector. The working point with different front



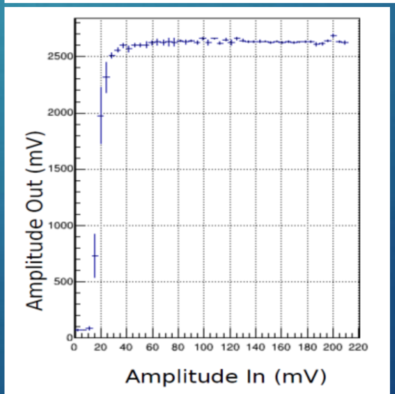
Lower gain means lower charge per count.

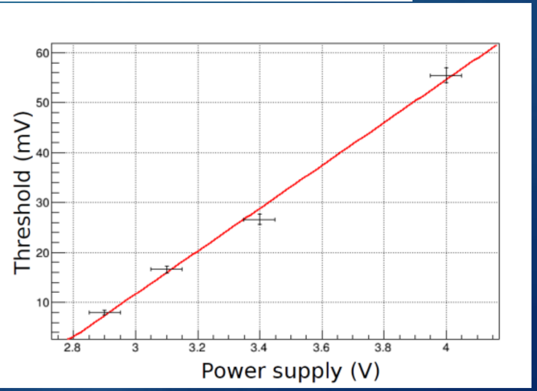
NOTE: the total charge reported is not the prompt charge collected in the front end.

4 ch. Discriminator final layout



Feature	value
Technology	BiCMOS IHP SiGe
Voltage supply	2-3 V
Threshold	3-200 mV
Input impedance	100 Ohm
B.W.	500 MHz
Power consumption	10 mW/ch
Rise time output	300 ps
Radiation hardness	1 Mrad, 10^{13} n cm^{-2}
Discriminator type	Updating
Min. duration input pulse	0.5 ns
Double pulse separation	1 ns
Channels per chip	4

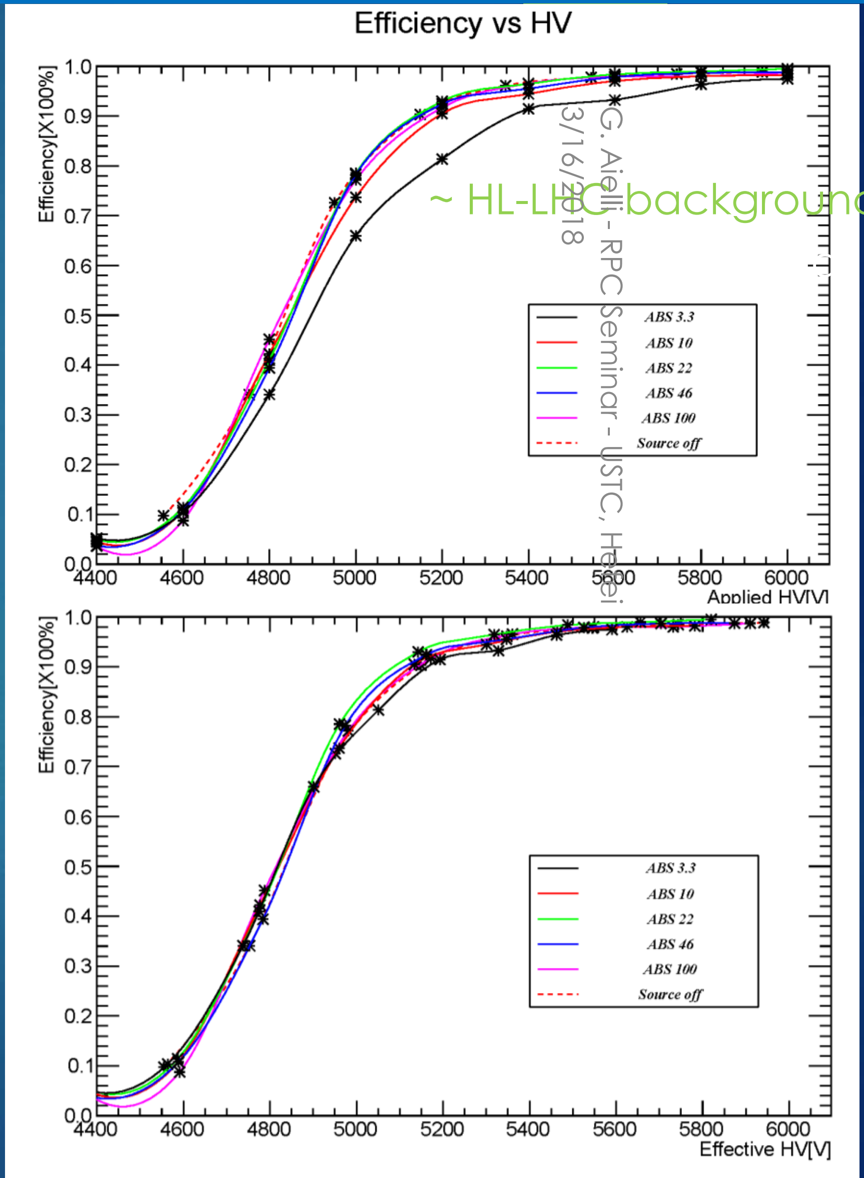




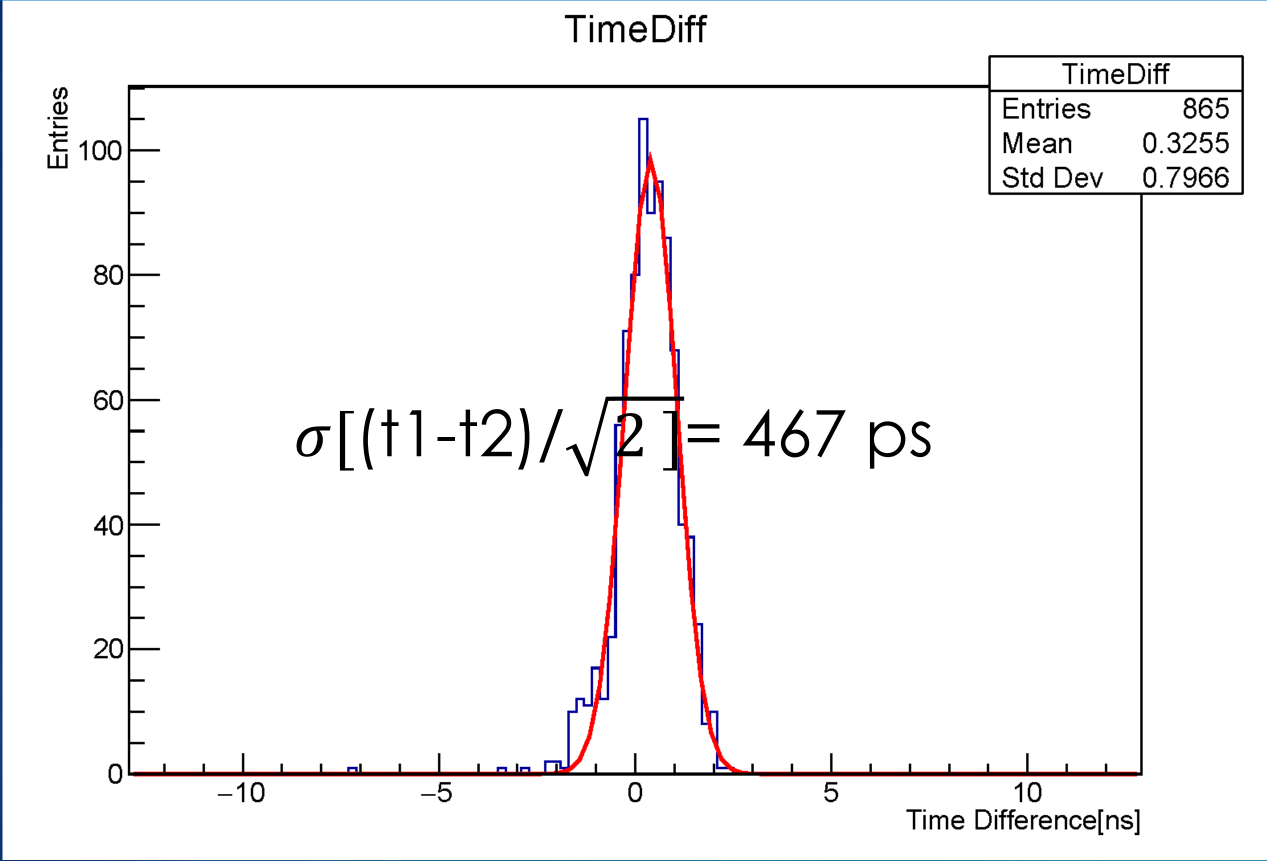
Efficiency

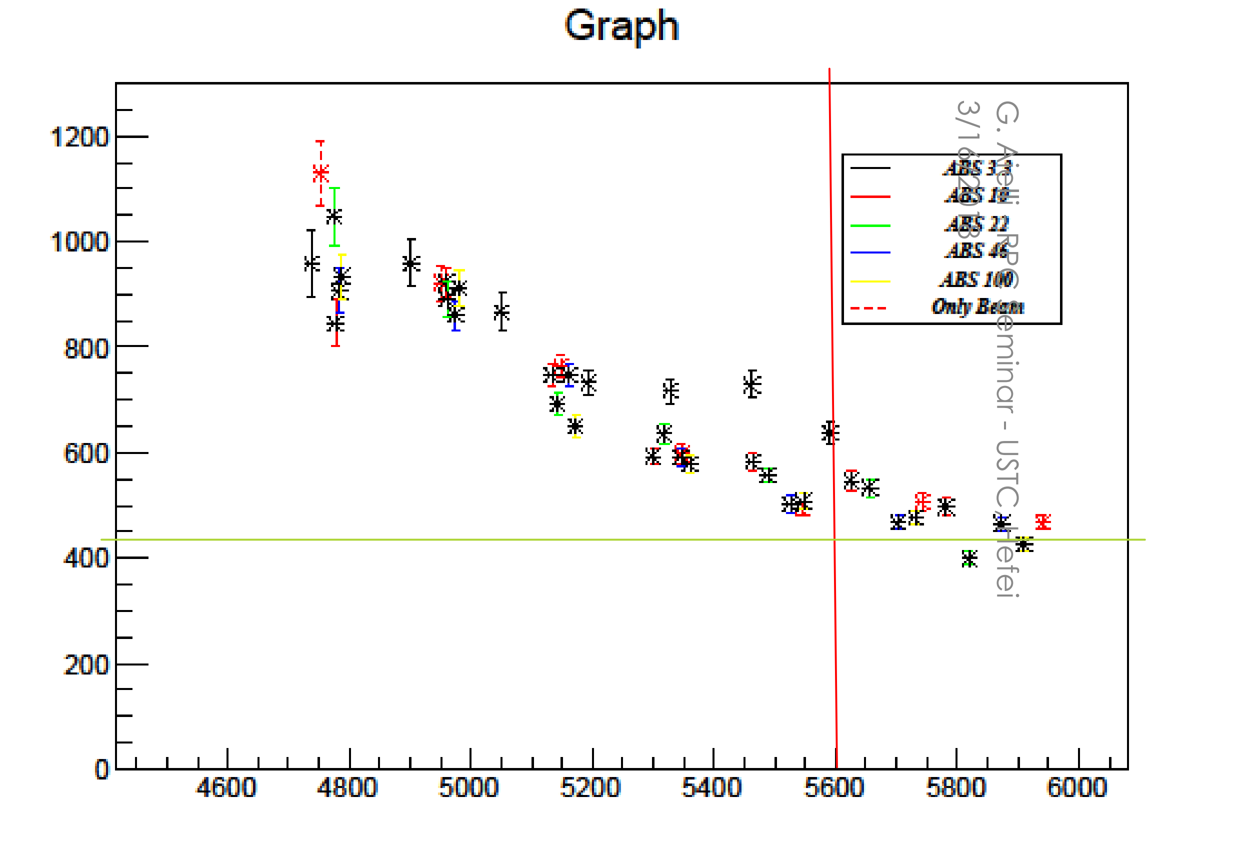
- Trigger from 2 scintillators 12x12 cm^2
- Use 1 chamber as monitor and calculate the efficiency of the other chamber.
- An efficient hit must be correlated in time (20 ns) and space (+- 1 strip) with the monitor hit on both x-y views

5400V is an excellent working point for 1 mm gap (95% eff.)



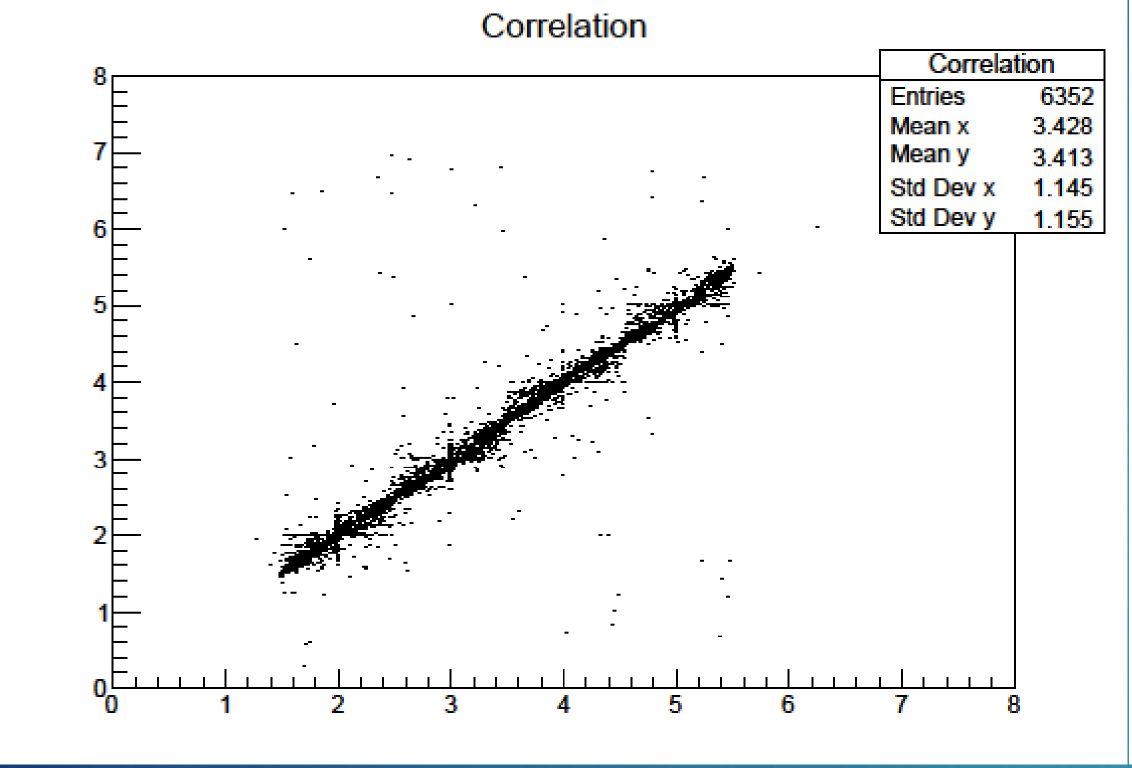
Time resolution

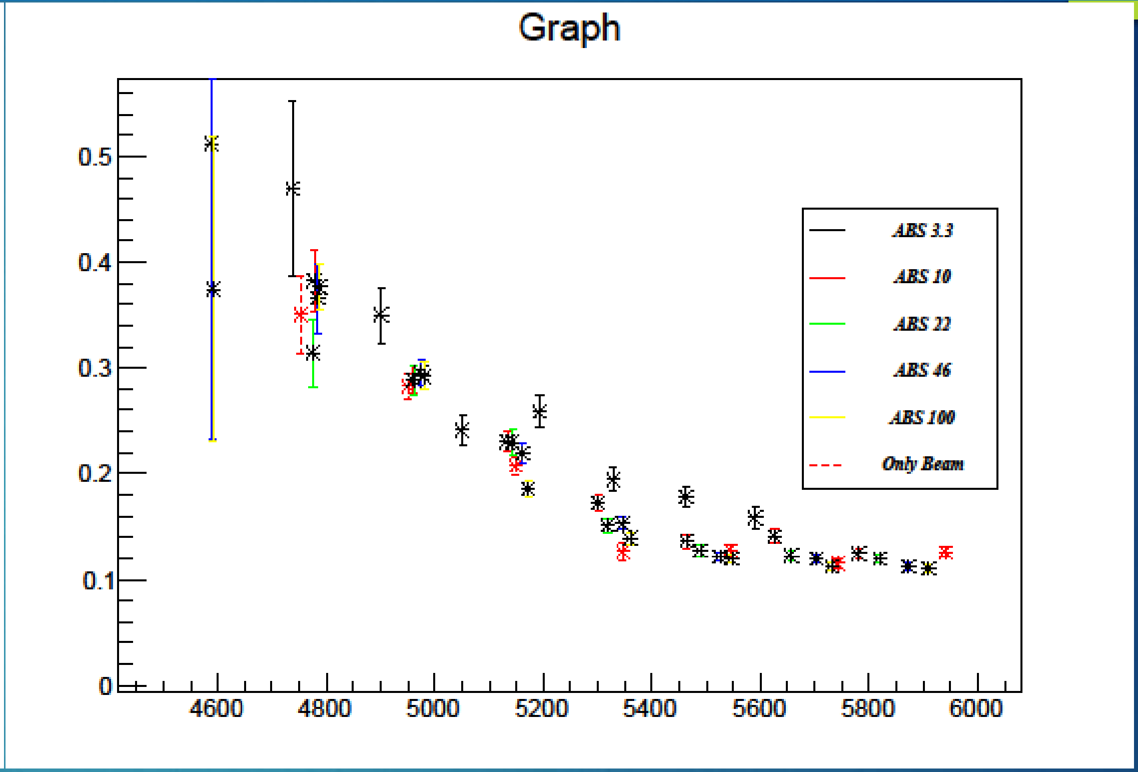


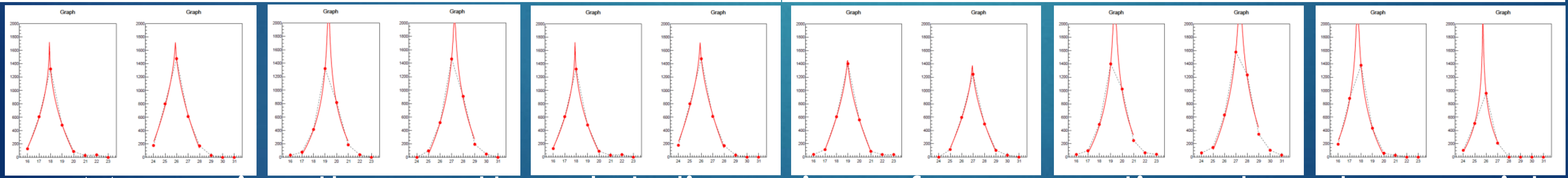


- The hv in time resolution is corrected by temperature and humidity.
- Time diff is at 6000 V without source.
- No skew correction and no channel calibration applied

Space resolution

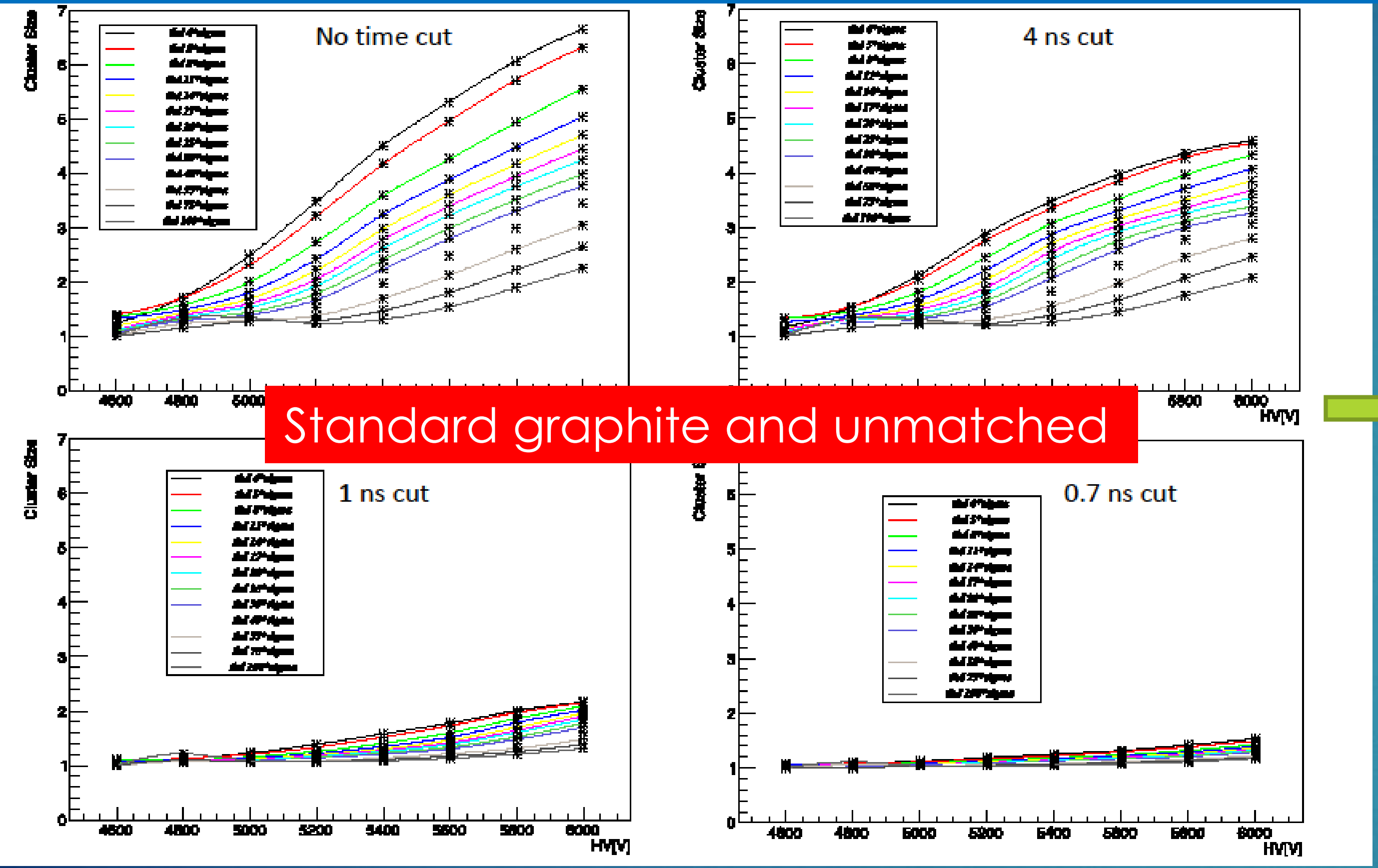




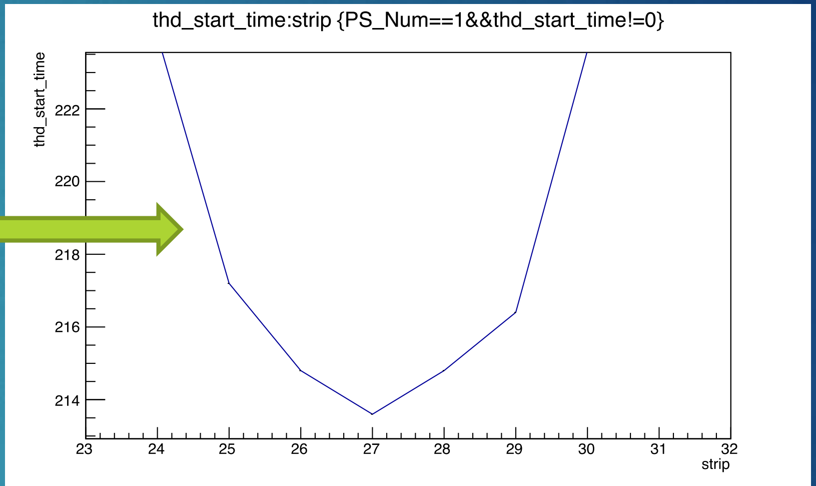


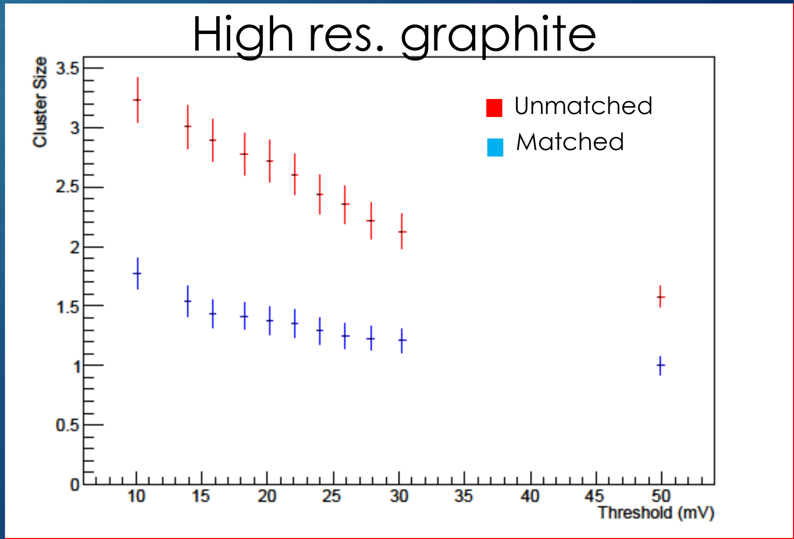
- Measuring the scatter plot dispersion of consecutive chambers residuals
- 1 mm resolution with 25 mm pitch strips!

Cluster Size



Time delay





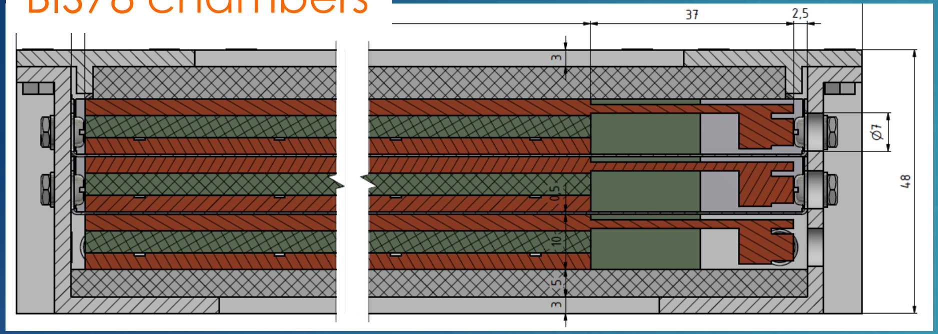
- Cluster size depends on the spurious coupling and FE sensitivity
- Lateral hits are delayed w.r.t. the primary one.
- Graphite resistivity has found to be a crucial element
- Strip matching and isolation is also crucial

G. Aielli - RPC2018
17/02/2018

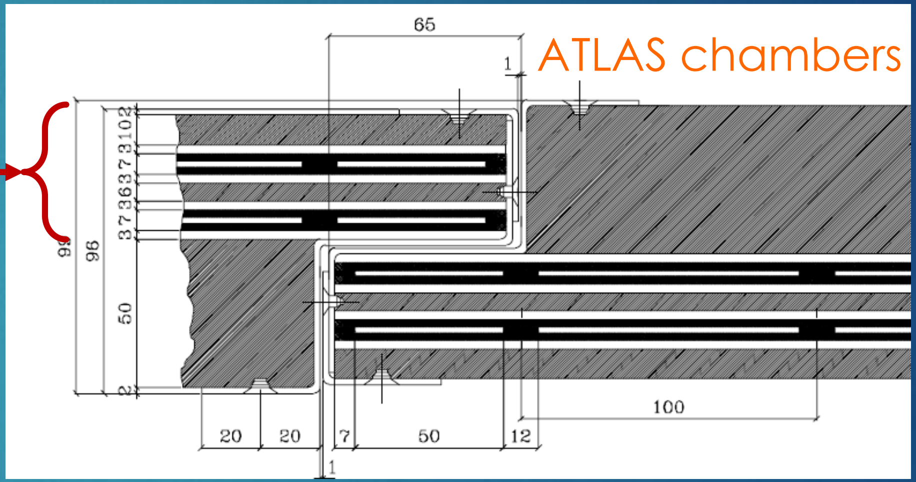
The BI RPC specific design

- BIS78 are just on the edge of the Inner barrel
- Critical accessibility for BI → enhanced reliability
- No overlap possible on siding chambers → maximum sensitive area

BIS78 chambers



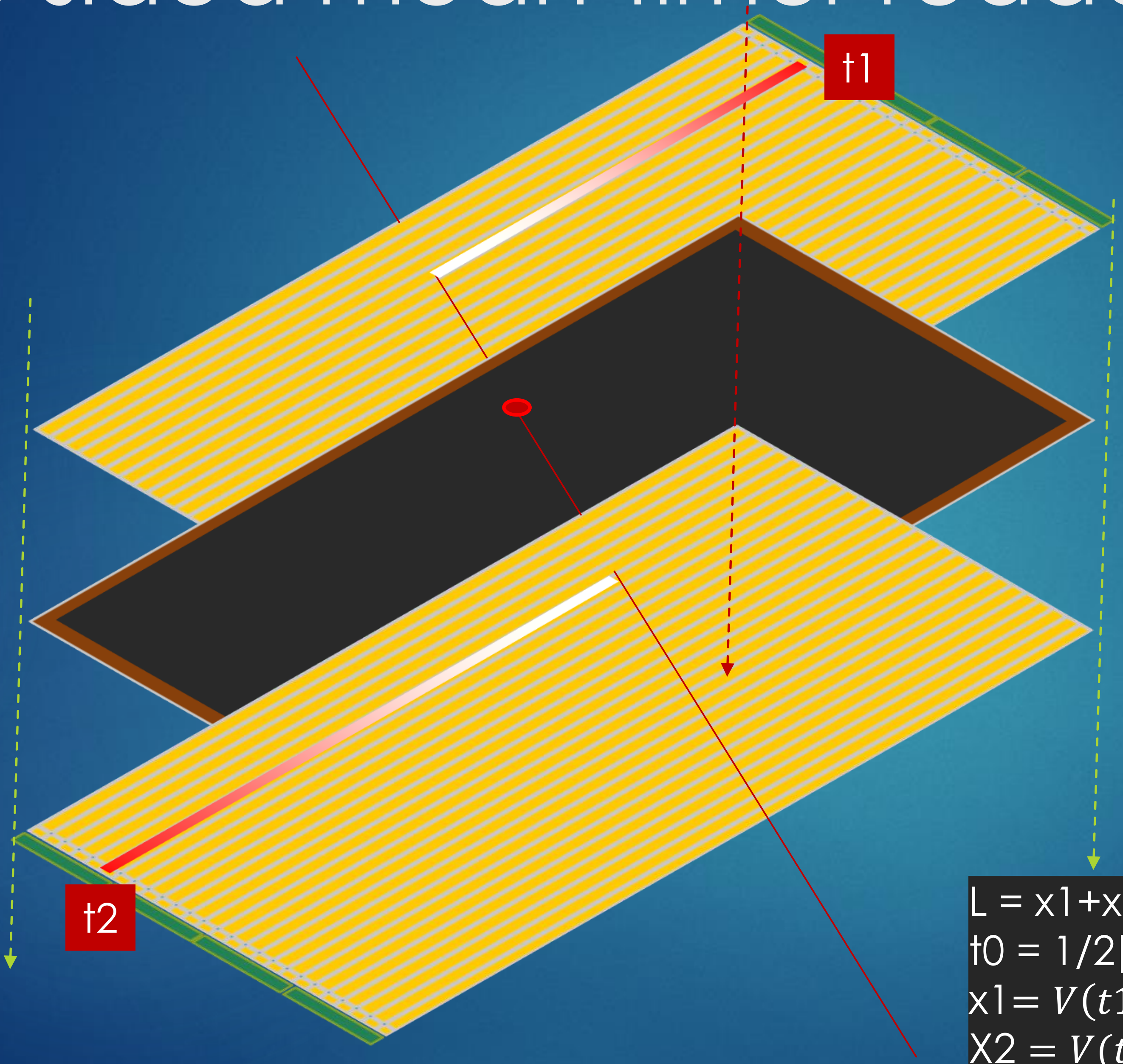
Dead space for the FE
(in legacy RPCs overlapped to the gap)



Main differences in order of priority and likelihood (under development)

- FE and RO electronics (TDC embedded in the FE)
- New readout pattern to maximize the sensitive area
- Better materials (smoother, thinner, harder)
- Gap layout (thinner electrodes, bi-gap design)

Two sided mean-timer readout



- The advantage is to eliminate the FE on the long side and maximize the active surface
- FE on separated panels → no interference
- Resolution limited by TDC speed and signal dispersion
- Target 1 cm with 100 ps TDC

L = x1+x2 = V(t1+t2-2t0)

t0 = 1/2[(t1+t2)-L/v]

x1= $V(t1 - t0)$

X2 = $V(t2 - t0)$

What's next?

A simple and successful idea

- The RPC technology is constantly evolving since almost 40 years
- The third generation is coming, aimed to the Phase-2 upgrades
- New reaches on materials and electronics may push the RPCs toward new fields of application:
  - High rate for forward detectors
  - High space-time granularity for calorimetry
- The classic RPC can be industrialized for applications requesting huge coverage

RPC MUON TOMOGRAPHY

G. AIELLI

ACADEMIA MEETS INDUSTRY

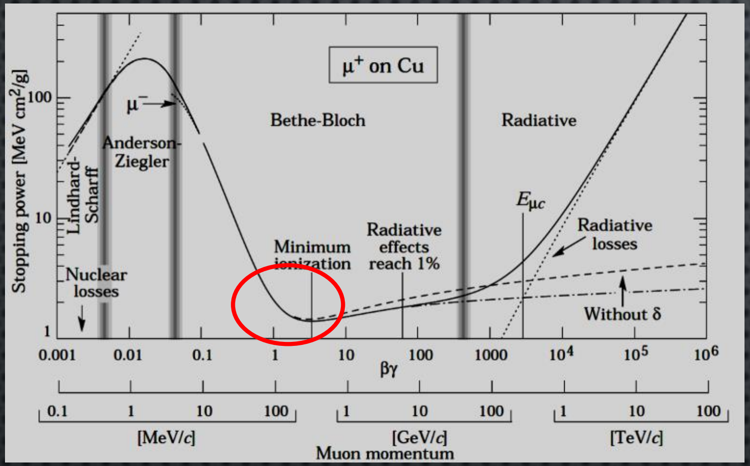
25/03/2014 VIENNA

INTRODUCTION

- RPC 2014 Conference in Beijing (23-28 February 2014)
- Muon tomography has been declared the "hot topic" of the conference
- 6 Oral presentation given from different institutes shown that in the last years the technology stepped up bringing this application to a pre-industrialization stage
- I Acknowledge all the speakers from which I reported some material
- In random order…
- Mr. Li SHI, Prof. Yi WANG, Ms. Baihui YU, Mr. Ziran ZHAO, Mr. Dufan WU, Mr. Sidong CHEN, Dr. Qite LI, Mr. Xiaoguang YUE, Dr. Paolo BAESSO, Dr. David CUSSANS, Dr. Jaap VELTHUIS, Mr. Christian THOMAY

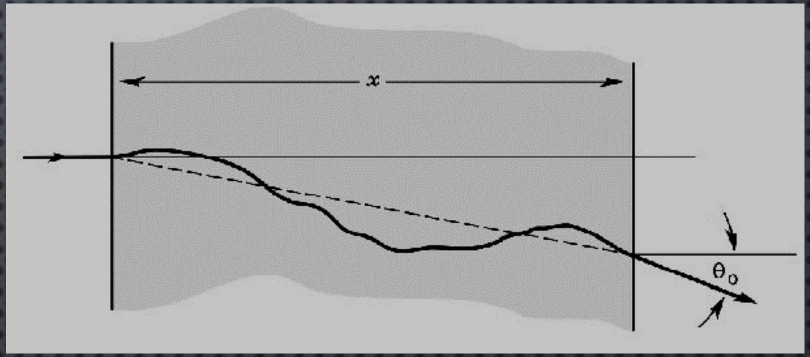
THE MUON RADIOGRAPHY CONCEPT

- Muons slowly loose energy by ionization passing through matter → high penetration power



- MIPs loose ~1-1.5 MeV cm^2/g
- Iron ρ=7.87→ 11.4 MeV/cm
- To stop a 3 GeV muon
  - → 263 cm of iron
  - → 146 cm of Uranium…

- Muon undergo multiple scattering on nuclea while passing through matter



- The mean exit angle is given by

$$\theta_0 = \frac{13.6\text{ MeV}}{\beta c p} z \sqrt{x/X_0}\left[1 + 0.038 \ln(x/X_0)\right]$$

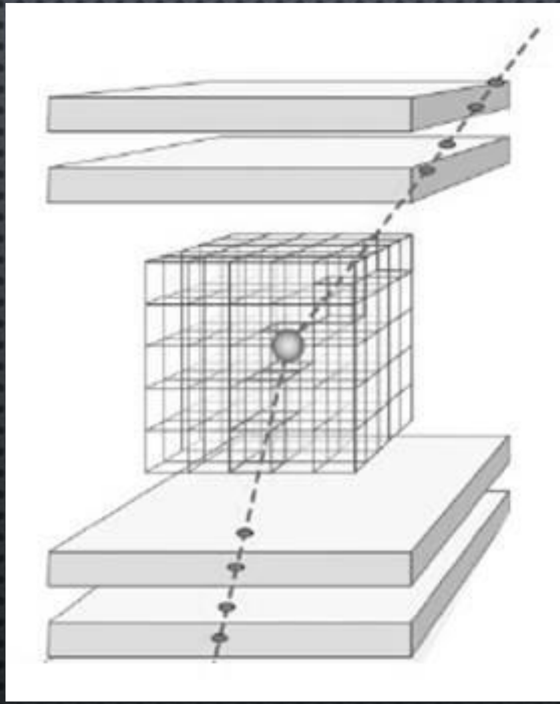
- It depends explicitly by the atomic number **Z** and the muon momentum **P**
- By measuring $\boldsymbol{\theta_0}$ and **P** it is possible to have information on the Z of the material
- The higher **Z** the higher the sensitivity!

COSMIC MUONS VS. GAMMA RAY SCANNERS

COSMIC RAY MUONS

DIFFUSION BASED RADIOGRAPHY

- ALWAYS AVAILABLE, WITH FLUX OF ~100 HZ/M^2 .FOR FREE
- WIDE ANGLE RANGE AVAILABLE→ TOMOGRAPHY
- VIRTUALLY IMPOSSIBLE TO SCREEN AGAINST.
- CHARGED; HIGH DETECTION EFFICIENCY.
- NO RADIATION HAZARD → WIDE APPLICATION FIELD
- NO DAMAGE OF THE MATERIALS



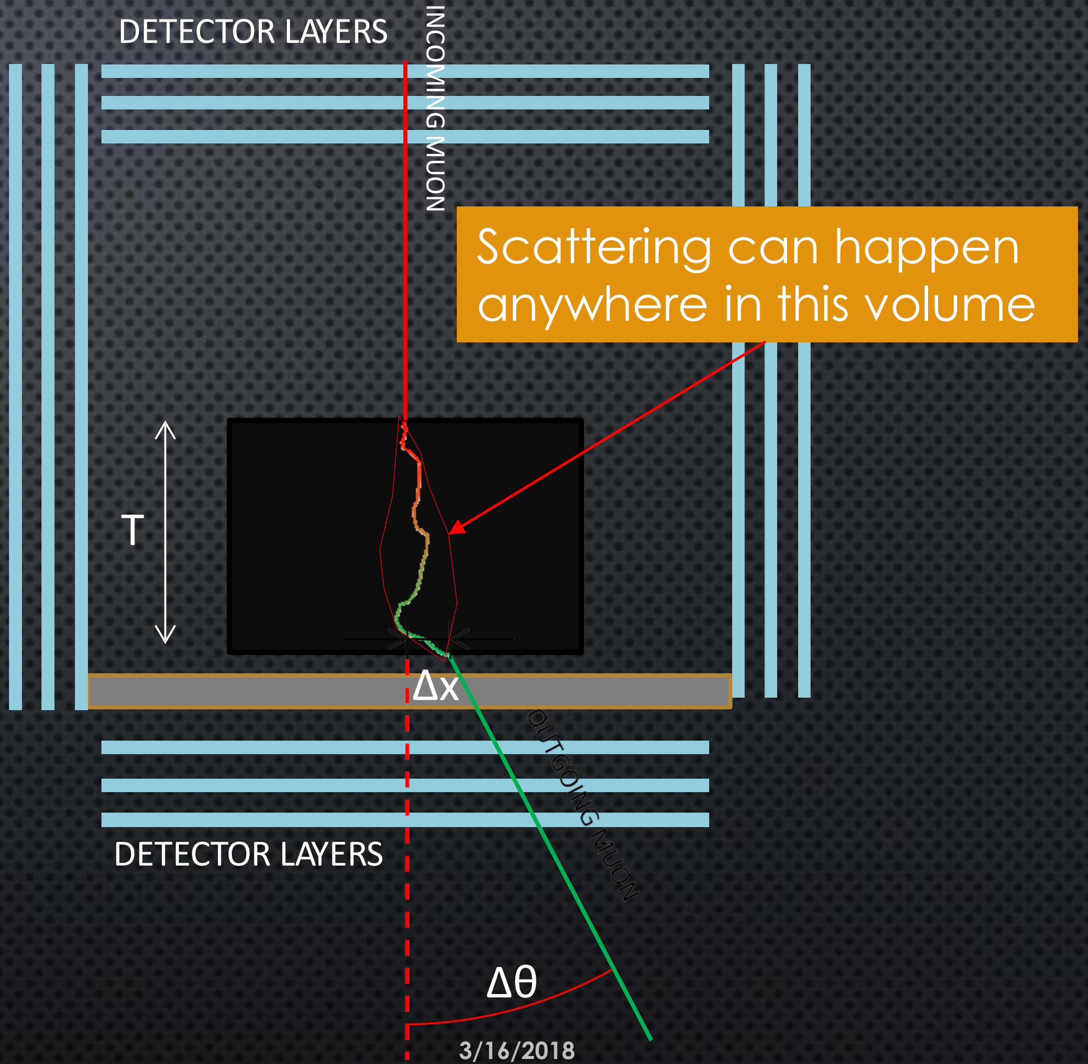
X/GAMMA RAY SCANNERS

ABSORPTION BASED RADIOGRAPHY

- MAINSTREAM SOLUTION IN HOME LAND SECURITY APPLICATIONS
- OPTIMAL FOR LIGHT MATERIALS OR LIGHT CONTAINERS (SUITCASES)
- FOR HIGH Z MATERIAL NEED HIGH INTENSITIES AND ENERGY
  - RADIATION HAZARD
  - HIGH OPERATION COST
  - NOT SUITABLE FOR VEHICLES AND BUILDINGS
- HIGH SENSITIVITY GAMMA DETECTOR → HEAVY AND EXPENSIVE
- MULTIPLE SOURCES TOMOGRAPHY

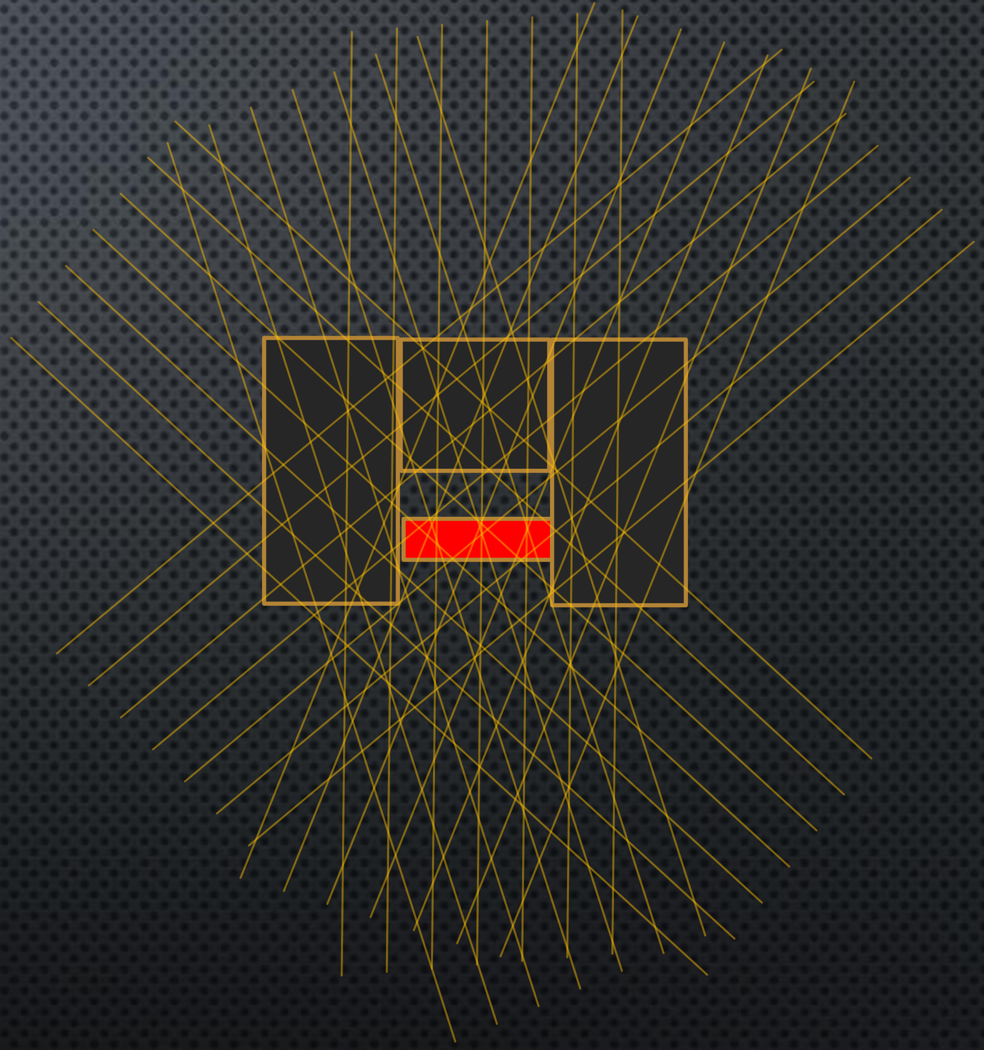
MUON TOMOGRAPHY SYSTEM DESIGN GUIDELINES

- MEASUREMENT OF θ_1, θ_2 → MEASURE TRACK ANGLE WITH A PRECISION GIVEN BY THE LOWEST SCATTERING TO BE DETECTED:
  - 1 CM OF IRON → 10 MRAD → 3 MRAD RESOLUTION → 0.3 MM @ 10 CM LEVER ARM
  - 1 GEV MUON → β=0,995 → 100PS (3 CM ΔX) RESOLUTION WITH 6 M LEVER ARM → 6M CEILING
  - DOWN TO 2π SOLID ANGLE COVERAGE → FULL COVERAGE → FOR A CONTAINER IDEALLY 750 M^2 KEEPING 6 M ALL AROUND
  - AT LEAST 3 DETECTOR LAYERS



MUON TOMOGRAPHY SYSTEM DESIGN GUIDELINES

- From radiography to tomography
  - Radiography → projection on a plane defined by a given direction
    - Typical for single source Xray
  - Tomography → reconstruct the 3D distribution of the sample by "cutting" it by planes with different angle → need multi directional source
- Different directions → the same point is correlated by tracks with different sets of points
- Sophisticated software (adaptive networks) can improve the reconstruction as data are collected



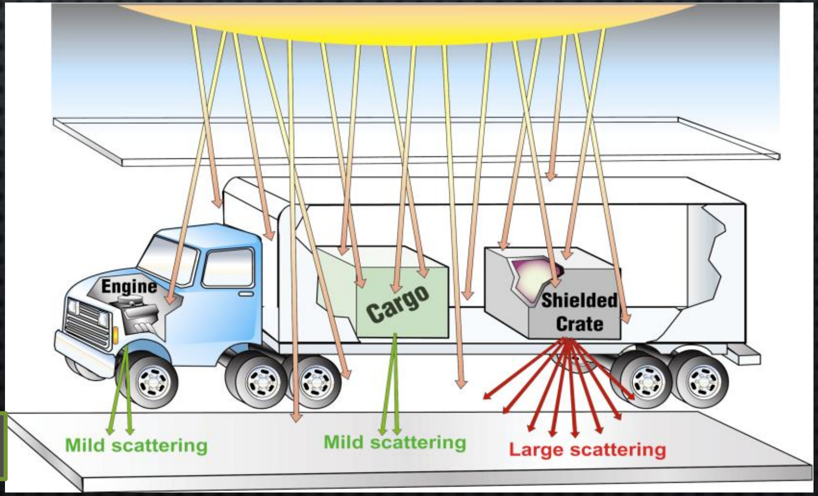
Some Application Scenarios

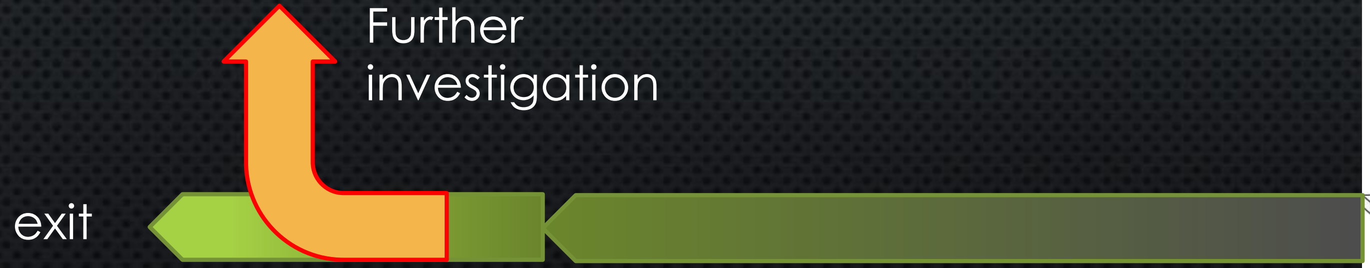
Homeland security use cases

FLAWLESS VEHICLES CONTROL – THE MUON TUNNEL -

- Tunnel long enough to allow a continuous flow of vehicles:
  - 60 s @ 20 Km/h → ~ 300 m using the present simulated performance
- A good margin of improvement can be obtained by:
  - further extending the acceptance → 2 π
  - Intelligent, pattern recognition based, inference → recognize the vehicle apply the "expected" model of material distribution to the data → **Bayesian information criterion**
  - Use the trigger level concept providing that a the first level there are not too many false positives

Los Alamos test setup

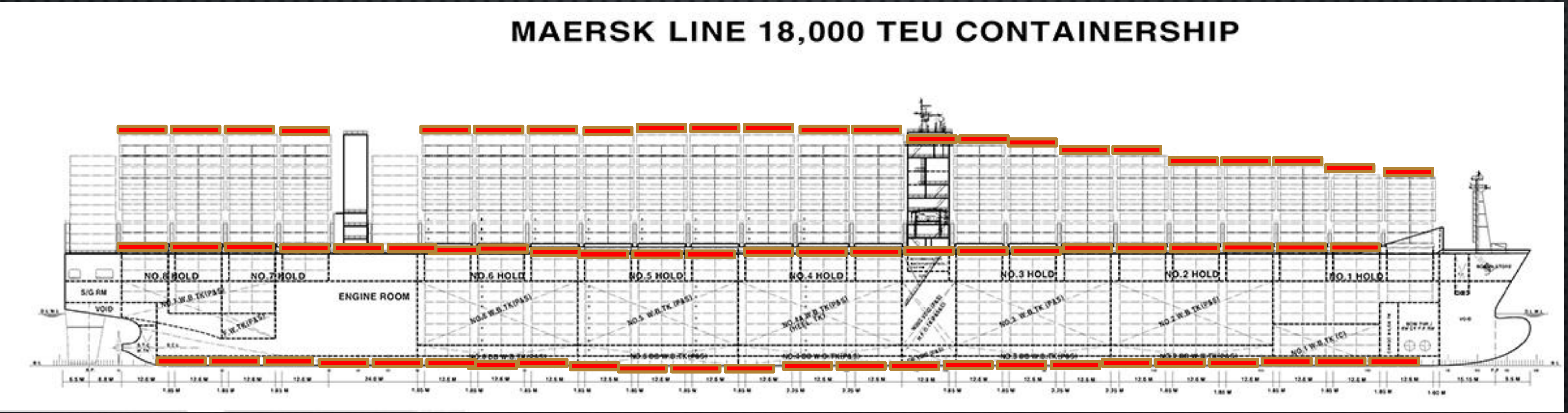




EMBEDDED MONITORING OF VEHICLES AND BUILDINGS

A VERY DIFFERENT CASE:

- NO STRICT TIME LIMITS
- STRUCTURAL MONITORING
- DETECTORS AS PART OF ARCHITECTURAL MODULES
- DAQ/DCS CHALLENGE



LOGISTIC STOCKING AREAS GATEWAYS

- USEFUL TO REPLACE THE GAMMA RAY SCANNER FOR ENTRANCE AND EXIT VALIDATION
- DIFFERENT CASE: HIGH PERFORMANCE LOCALIZED STATION
- TUNNEL LIKE. THE MAX SPEED SETS THE TUNNEL LENGTH
- CONTAINERS DRAGGED BY A TAPE AT THE NECESSARY SPEED
- CONTAINERS IN PARALLEL
- AUTOMATIC ASSIGN THE IN AND OUT SCANNING TO THE CONTAINER ID