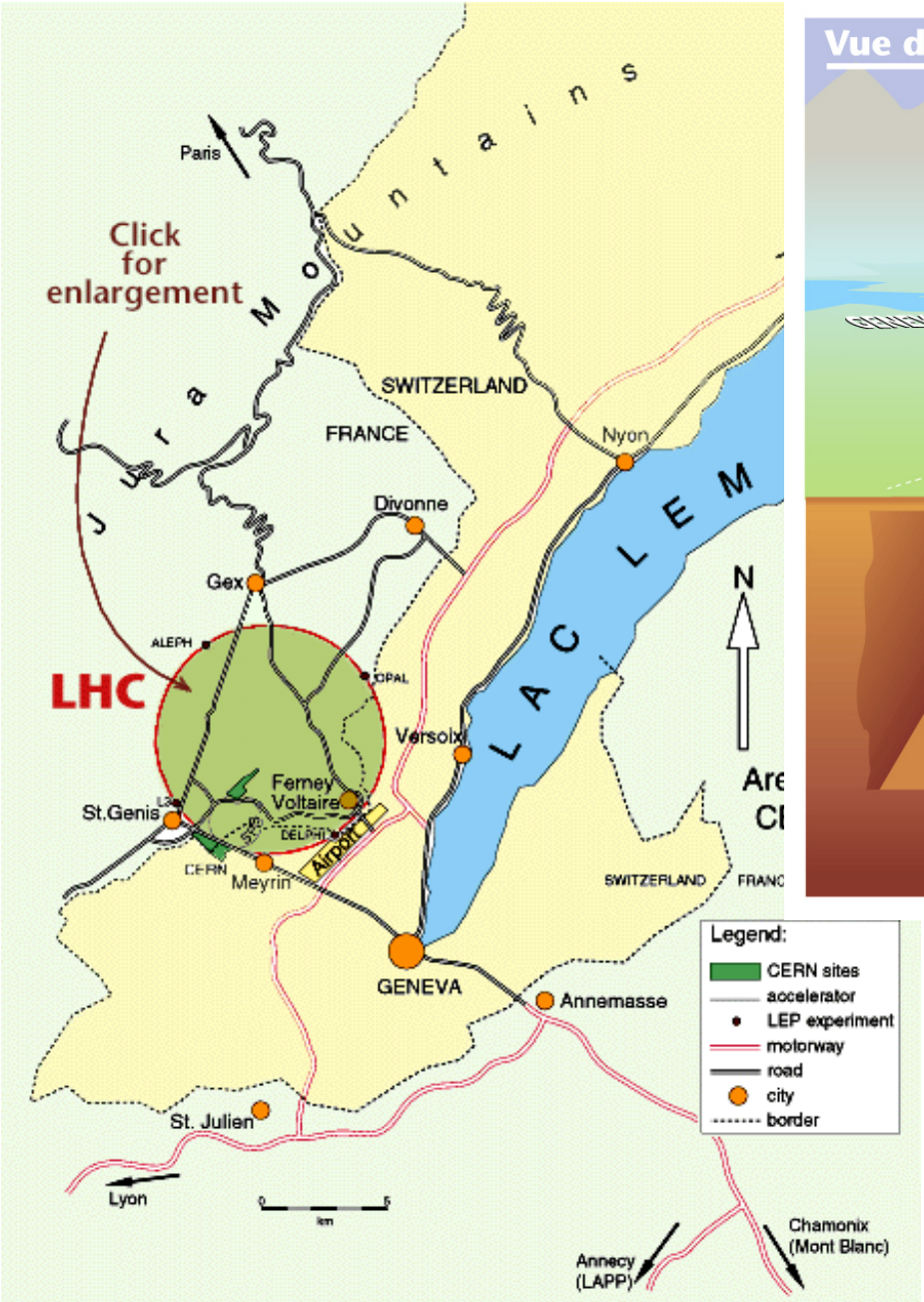
Development of Micromegas Detectors for the ATLAS Muon System Upgrade

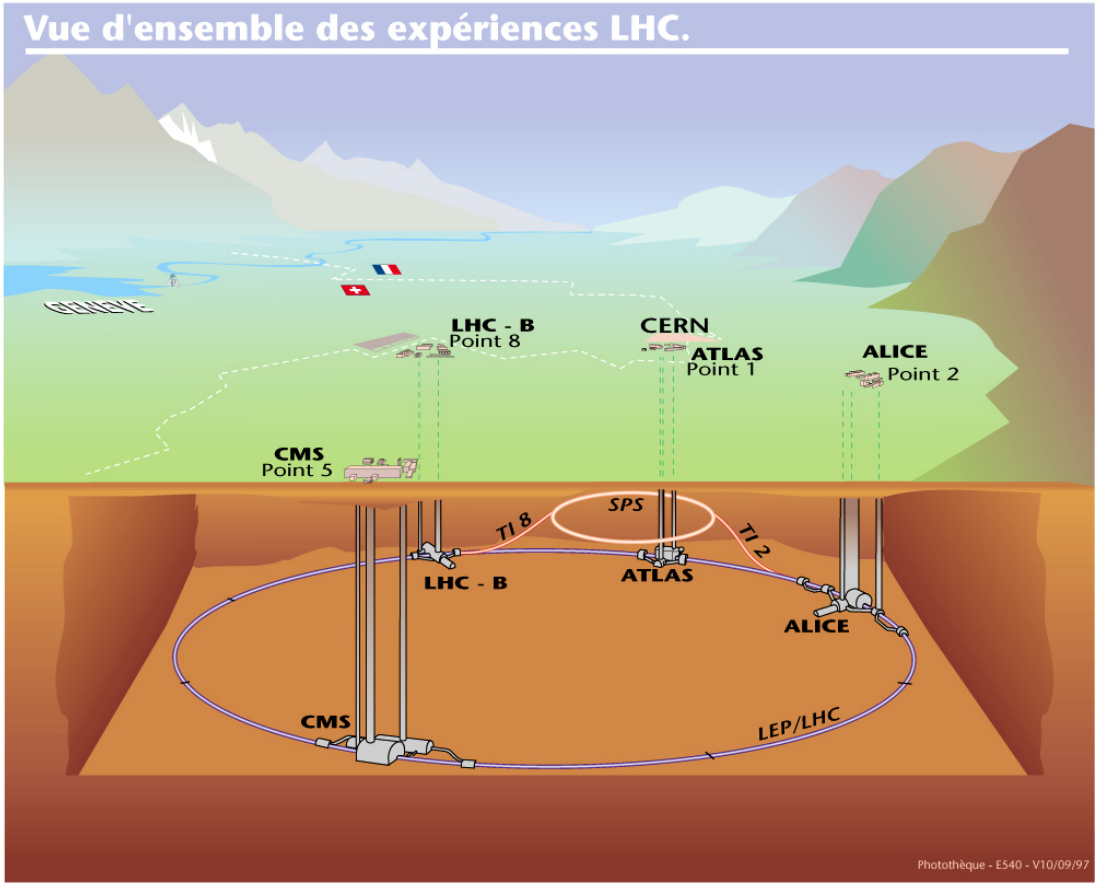
V. Polychronakos, Physics

Many thanks to my collaborators
Especially Valeri Cherniatin,
Joerg Wotschack
Rui de Oliveira

Overview

- The Large Hadron Collider – A Brief Overview
- The ATLAS Experiment
- Muon System
  - Limitations of the Endcap Detectors,
  - Need for Upgrade
  - Requirements and technologies under consideration
- The Micromegas Option
- Development of Spark-resistant detectors
- Towards Large Area Micromegas panels
- Electronics and Trigger





Ring inclined 1.23 deg towards
The lake in order to reduce depth
At the Jura side

LHC Design Parameters

LHC General Parameters		
Energy at collision	7	TeV
Energy at injection	450	GeV
Dipole field at 7 TeV	8.33	T
Coil inner diameter	56	mm
Distance between aperture axes (1.9 K)	194	mm
Luminosity	1	E34 $cm^{-2}s^{-1}$
Beam beam parameter	3.6	E-3
DC beam current	0.56	A
Bunch spacing	7.48	m
Bunch separation	24.95	ns
Number of particles per bunch	1.1	E11
Normalized transverse emittance (r.m.s.)	3.75	µm
Total crossing angle	300	µrad
Luminosity lifetime	10	h
Energy loss per turn	7	keV
Critical photon energy	44.1	eV
Total radiated power per beam	3.8	kW
Stored energy per beam	350	MJ
Filling time per ring	4.3	min

3.5

0.125

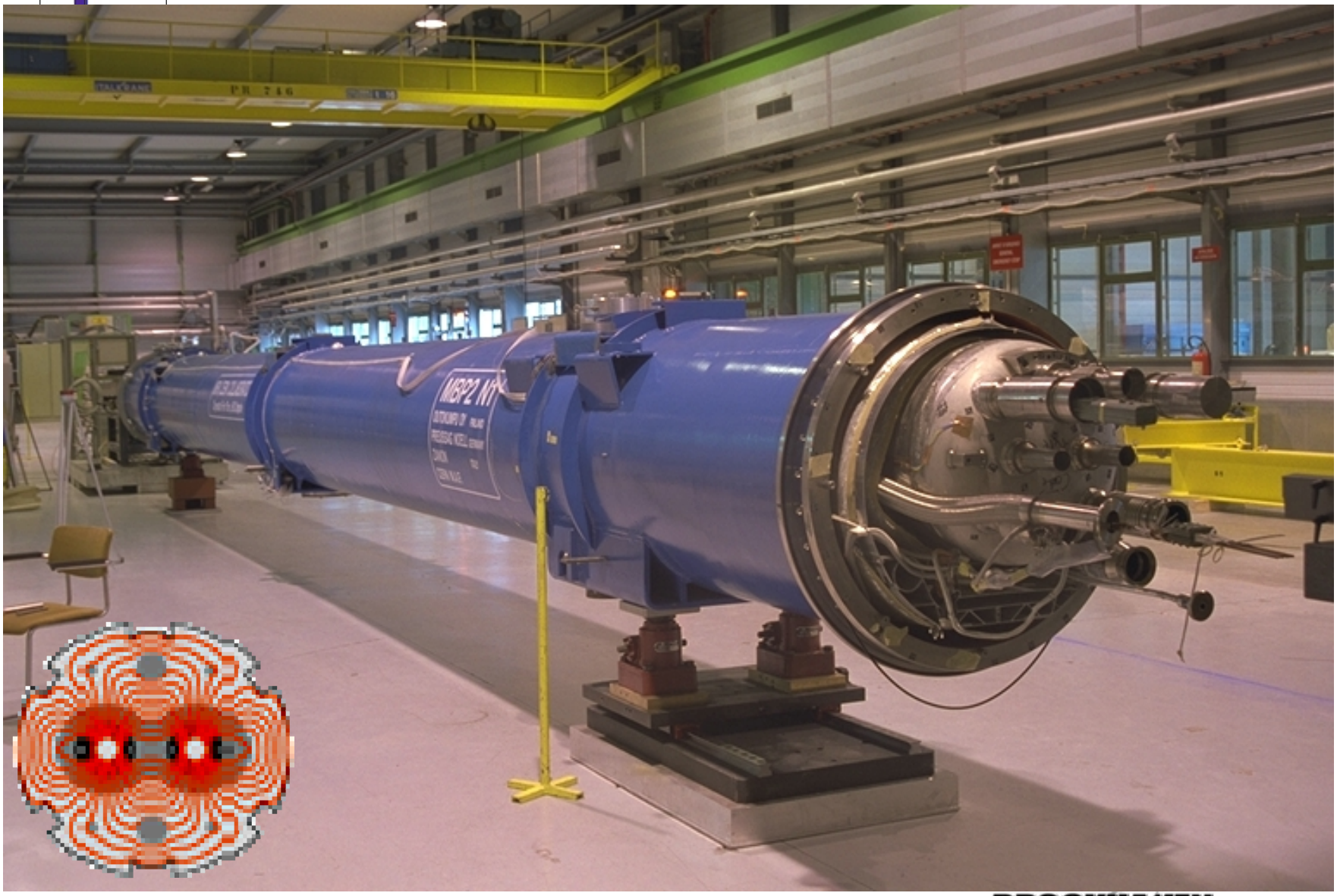
1.7

What would 1e9 Joules of Stored Energy compare to?

Approximate energy in joules associated with various events and phenomena

Description	Energy
Big Bang	10^{68}
Radio energy emitted by the Galaxy during its lifetime	10^{55}
Rotational energy of the Milky Way	10^{52}
Energy released in a supernova explosion	10^{44}
Oceans' hydrogen in fusion	10^{34}
Rotational energy of the earth	10^{29}
Annual solar energy incident on the earth	5×10^{24}
Annual wind energy dissipated near earth's surface	10^{22}
Annual global energy usage by humans	3×10^{20}
Annual energy dissipated by the tides	10^{20}
Annual U.S. energy usage	8×10^{19}
Energy release during Krakatoan eruption of 1883	10^{18}
Energy release of 15-megaton fusion bomb	10^{17}
Annual electrical output of large generating plant	10^{16}
Thunderstorm	10^{15}
Energy released in burning 1000 kg of coal	3×10^{10}
Kinetic energy of a large jet aircraft	10^{9}
Energy released in burning 1 litre of gasoline	3×10^{7}
Daily food intake of a human adult	10^{7}
Kinetic energy of a home run in baseball	10^{3}
Work done by a human heart per beat	0.5
Turning this page	10^{-3}
Flea hop	10^{-7}
Discharge of a single neuron	10^{-10}
Typical energy of a proton in a nucleus	10^{-13}
Typical energy of an electron in an atom	10^{-18}
Energy to break one bond in DNA	10^{-20}

Superconducting (2 in 1) Dipoles



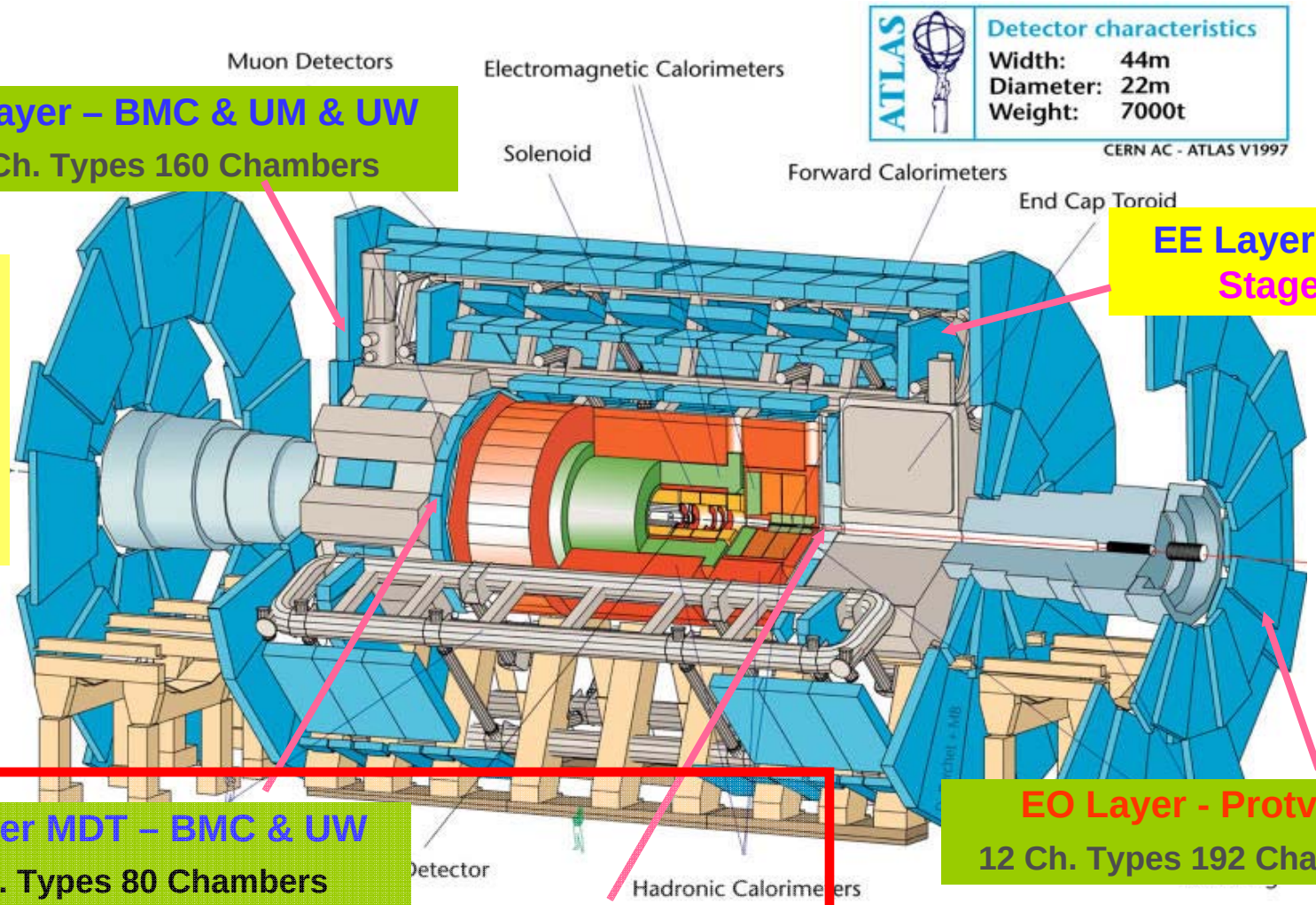
Experiments at the LHC

- Four Experiments being constructed:
- "General Purpose" ATLAS and CMS
  - 4-pi Geometry
  - Electroweak Symmetry Breaking (Higgs Boson)
  - Supersymmetry
  - Compositness
  - New Vector Bosons?
  - Extra Dimensions?
  - ……
- ALICE – Heavy Ion Experiement (akin to PHENIX)
- LHCb – Dedicated "b-physics" Experiement (CP violation in the b sector

The importance of leptons (e,**m**) for the Higgs search

- Mass of the Higgs Boson not a priori constrained by theory (but < ~700 Gev/c^2)
- LEP experiments → M_H > 114 GeV /c^2, most likely value 170>M_H > 120
- H likes to decay into the heaviest possible particles, hence H→Z^0Z^0 Z^0 --> $\mu+\mu-$
- Of course H decays into electrons at about the same rate (measured by the EM Calorimeter – most important BNL contribution to ATLAS)
- P_T of **m**(e) 5-50 GeV/c, easy to trigger

ATLAS Muon Endcap System



EM Layer – BMC & UM & UW
10 Ch. Types 160 Chambers

EE Layer – US
Staged

BMC
Boston
Brandeis
Harvard
MIT
Tufts

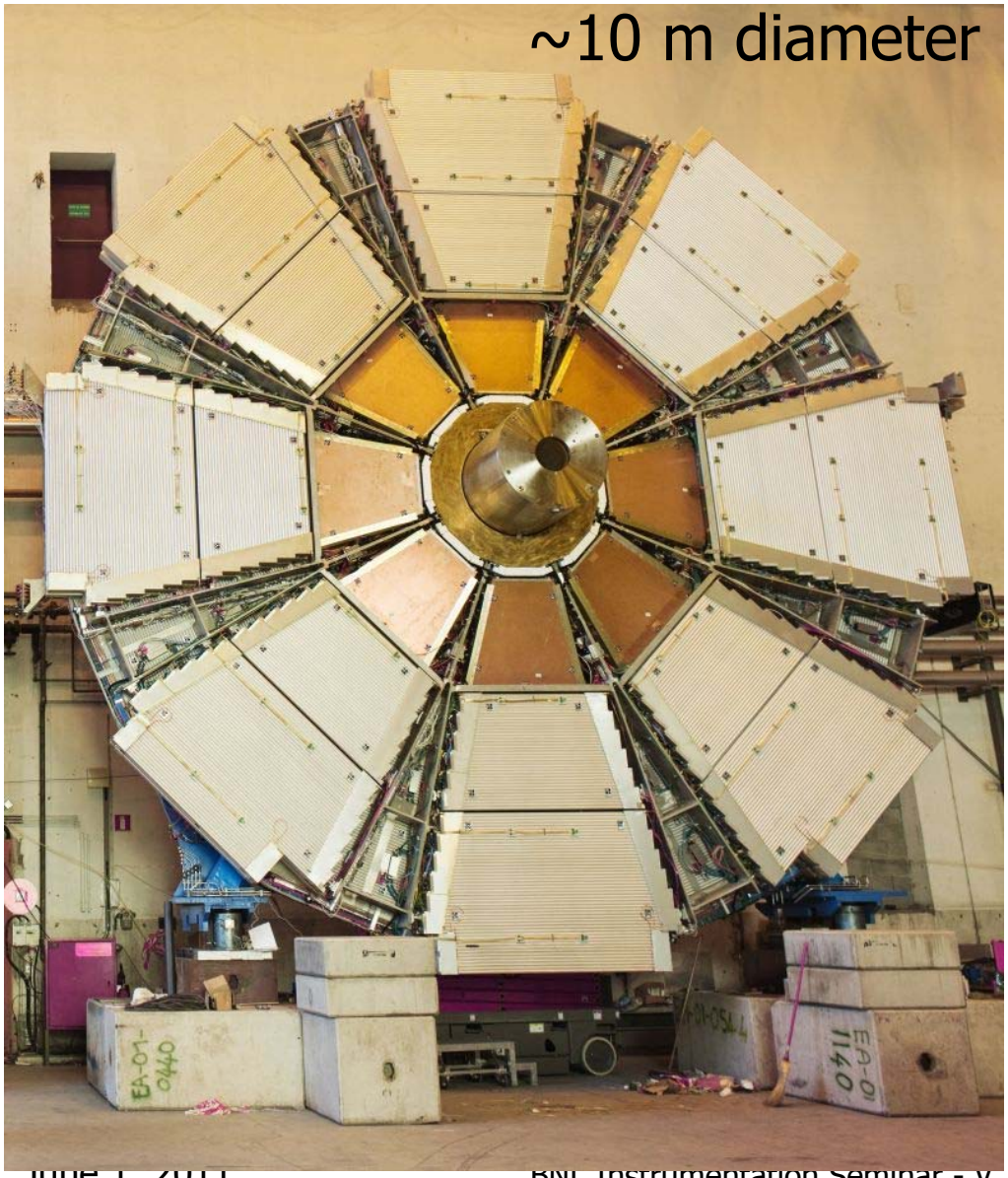
EO Layer - Protvino
12 Ch. Types 192 Chambers

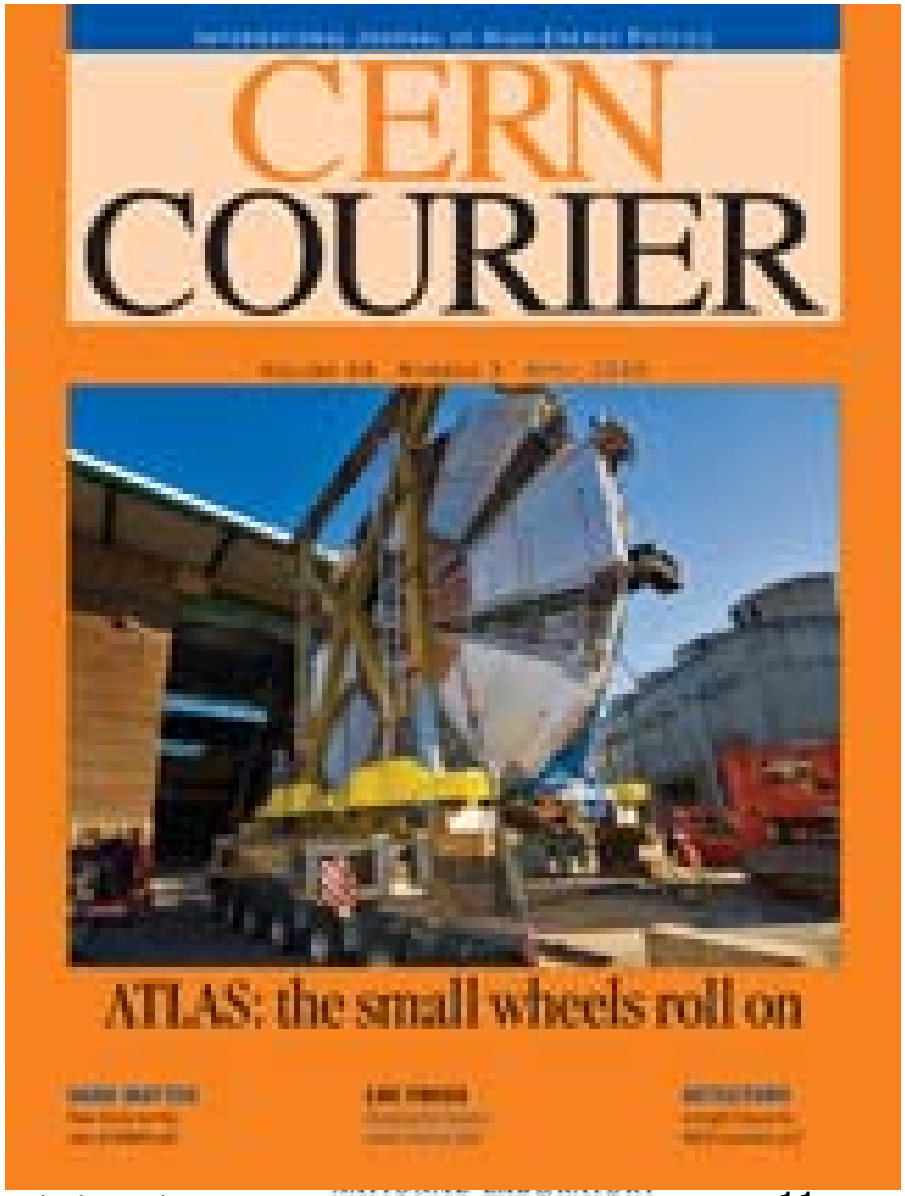
EI Layer MDT – BMC & UW
5 Ch. Types 80 Chambers

EI Layer CSC – BNL & UCI
2 Ch. Types 32 Chambers

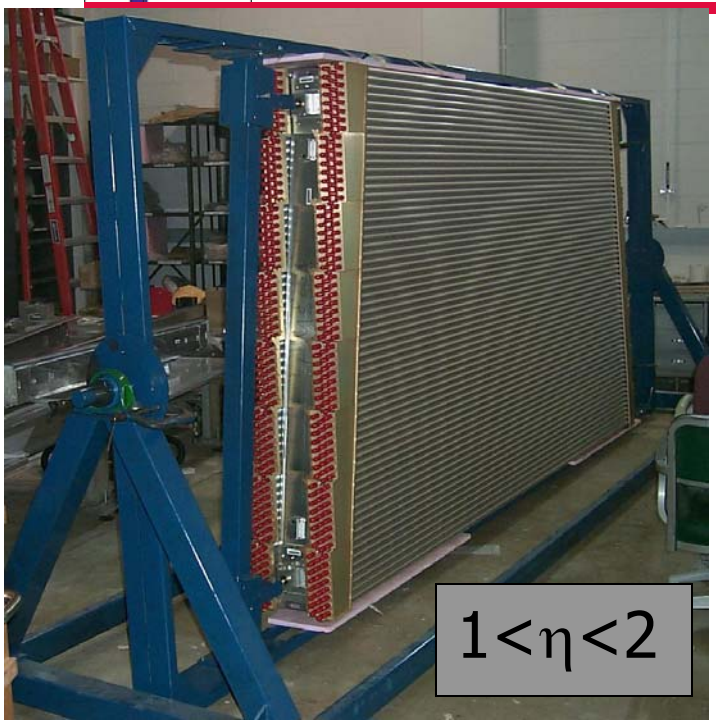
Small Wheels

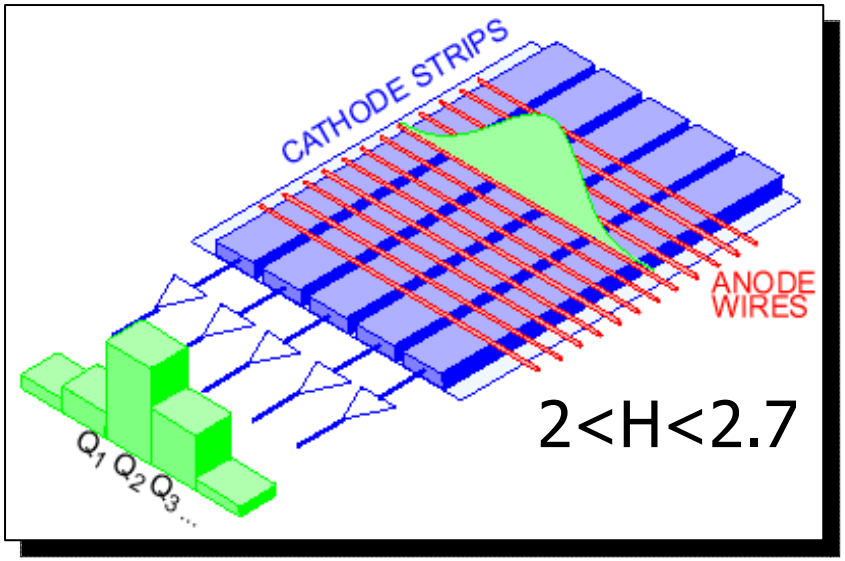
The "Small Wheels"





Present Detectors (MDT and CSC)

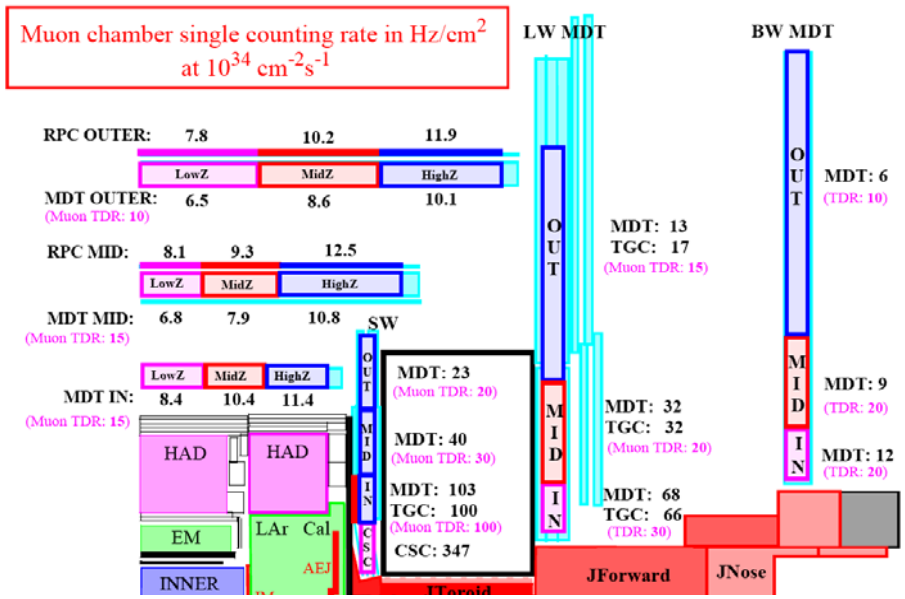




80 Monitored Drift Tube Chambers
32 Cathode Strip Chambers
Total area ~300 m2

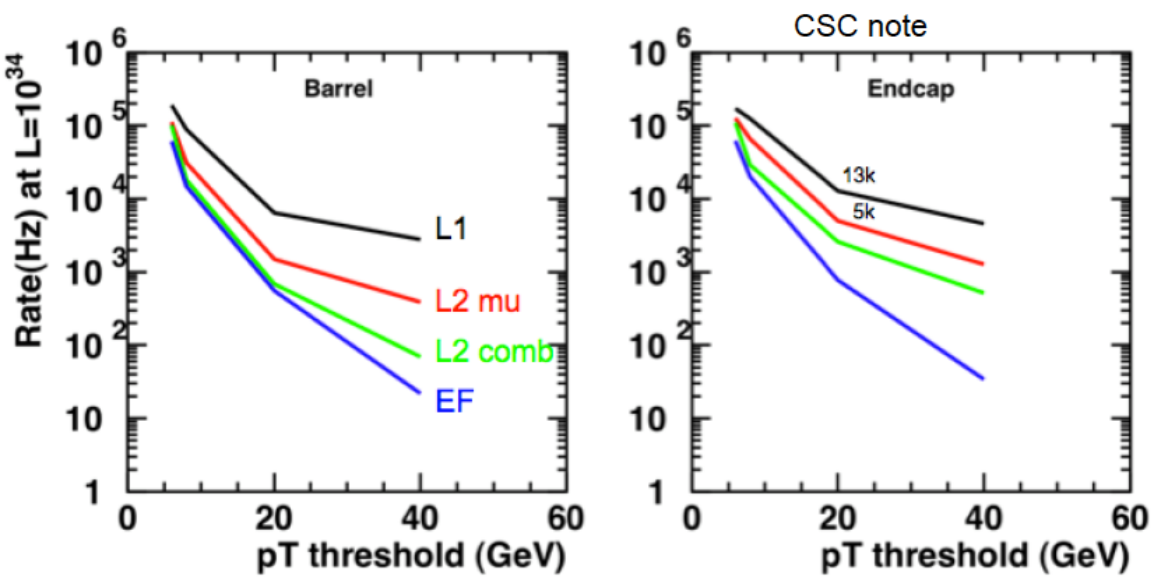
Design derives from
E814 Pad Chambers
Graham Smith
Bo Yu

3 Challenges for the Muon System at Higher Luminosity



#1

- Forward precision chambers will be at their rate limit at nominal luminosity
- CSC system (U.S. responsibility) has only 4 layers (as opposed to 8-MDT)
- Chamber Technology NOT YET decided (micromegas, Thin Gap Chambers the most likely technologies



2

Need to improve pT resolution

Goal is to improve L1 to ~Level 2 or so

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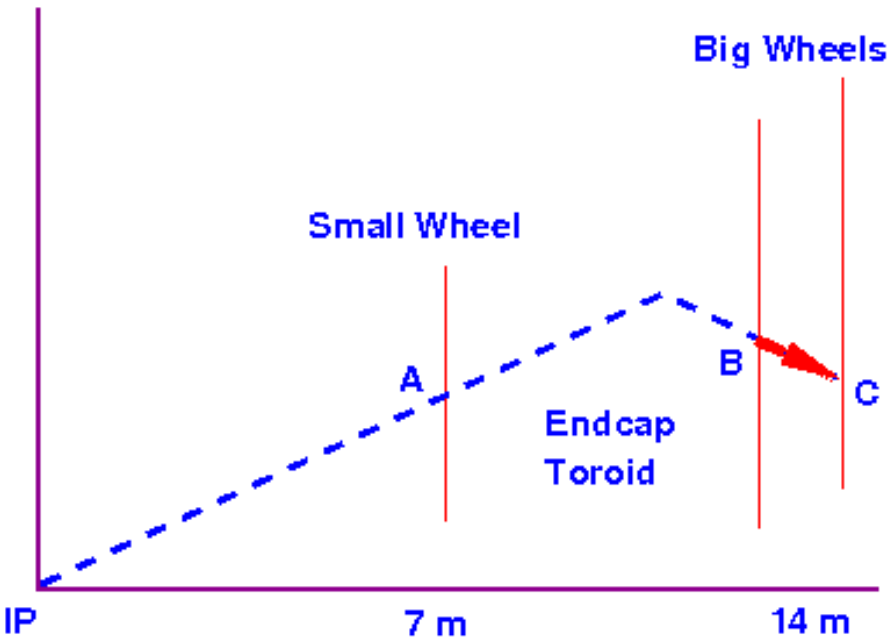
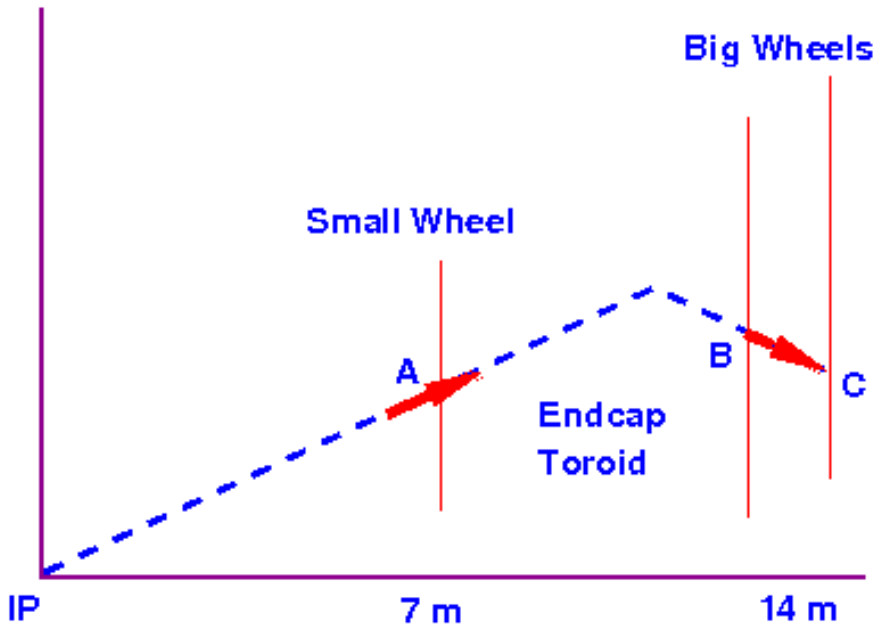
#3 Fake High pT Triggers





Current Endcap Trigger

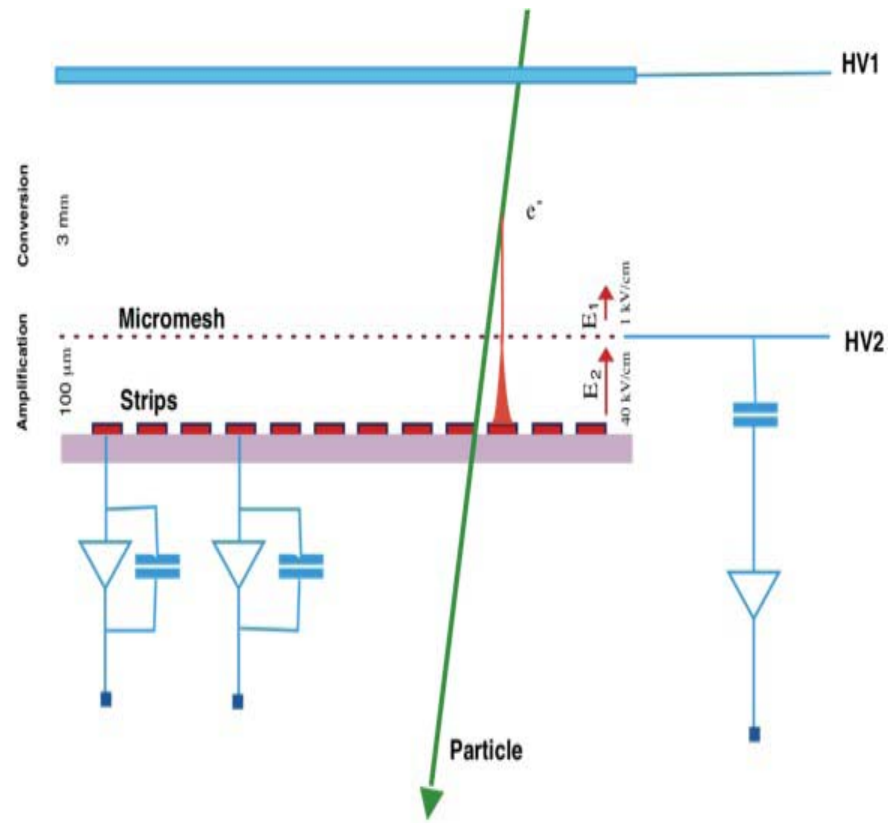
- Only a vector BC at the Big Wheels is measured
- Momentum defined by implicit assumption that track originated at IP
- Random background tracks can easily fake this

ProposedTrigger

- Provide vector A at Small Wheel
- Powerful constraint for real tracks
- With pointing resolution of ~1 mrad it will also improve pT resolution
- Currently 96% of High pT triggers have no track associated with them

MicroMegas Principles of Operation

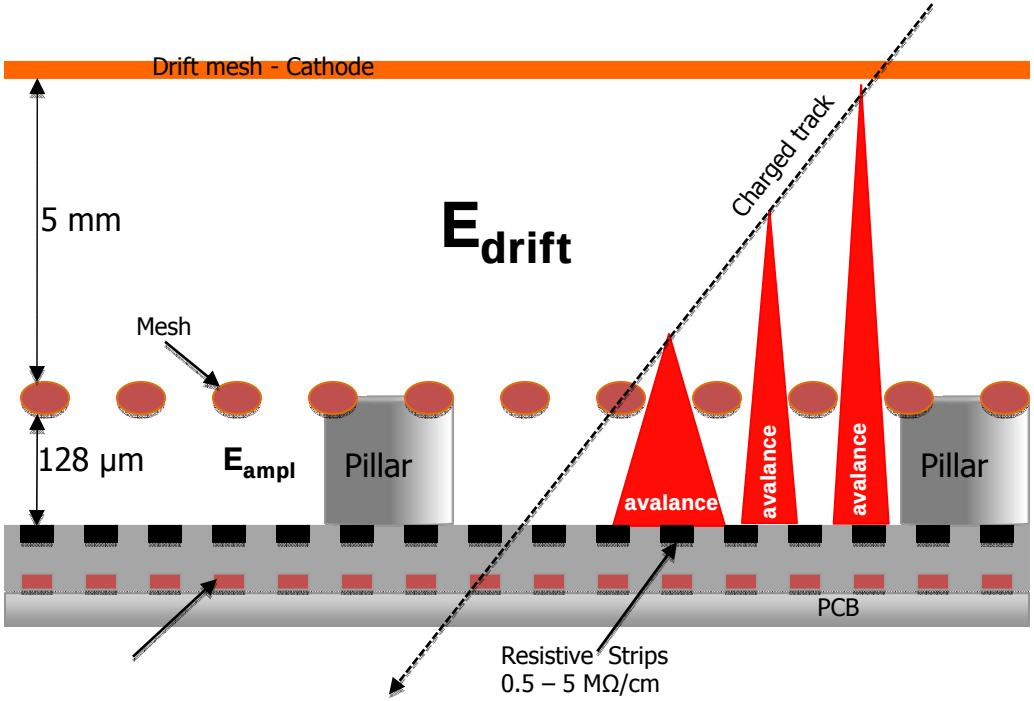
- Many good characteristics
  - Able to operate in high rate environment
  - Detector efficiency ~ 99%
  - Spatial resolution 80 mm
  - Time resolution 5 ns
  - Level-1 trigger capability
- Technology challenges
  - Fabricate large size chambers (~ 1x2 m^2)
  - Frontend electronics 2M channels
  - Discharges due to heavily ionizing events



Micro-TPC mode of operation to improve resolution of inclined tracks

Will address progress/status in all three challenges

Why not Cathode Strip Chambers?



Problem with Inclined Tracks

- Resolution degrades with tan(theta)
- Fine for tracks at small angles (detectors can be inclined to mitigate the effect)
- Impractical for larger coverage

Furthermore

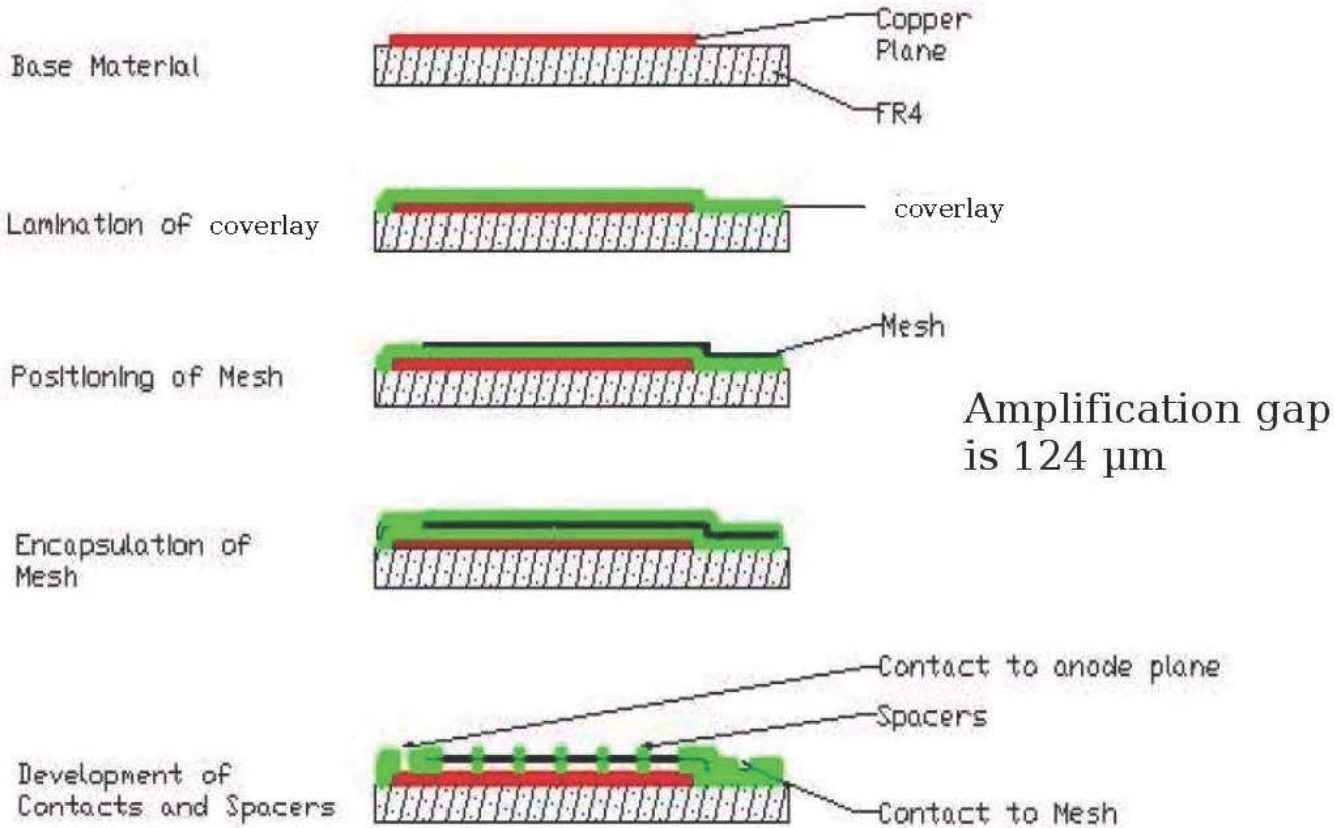
- Induced charge footprint rather large, need better double track resolution
- Construction of large area chambers is labor intensive

Micromegas can be operated in a micro-TPC mode

Use time of arrival of ionization to reconstruct track

Need both amplitude and time measurement

Mini-review of Bulk Micromegas (Rui de Oliveira, CERN)

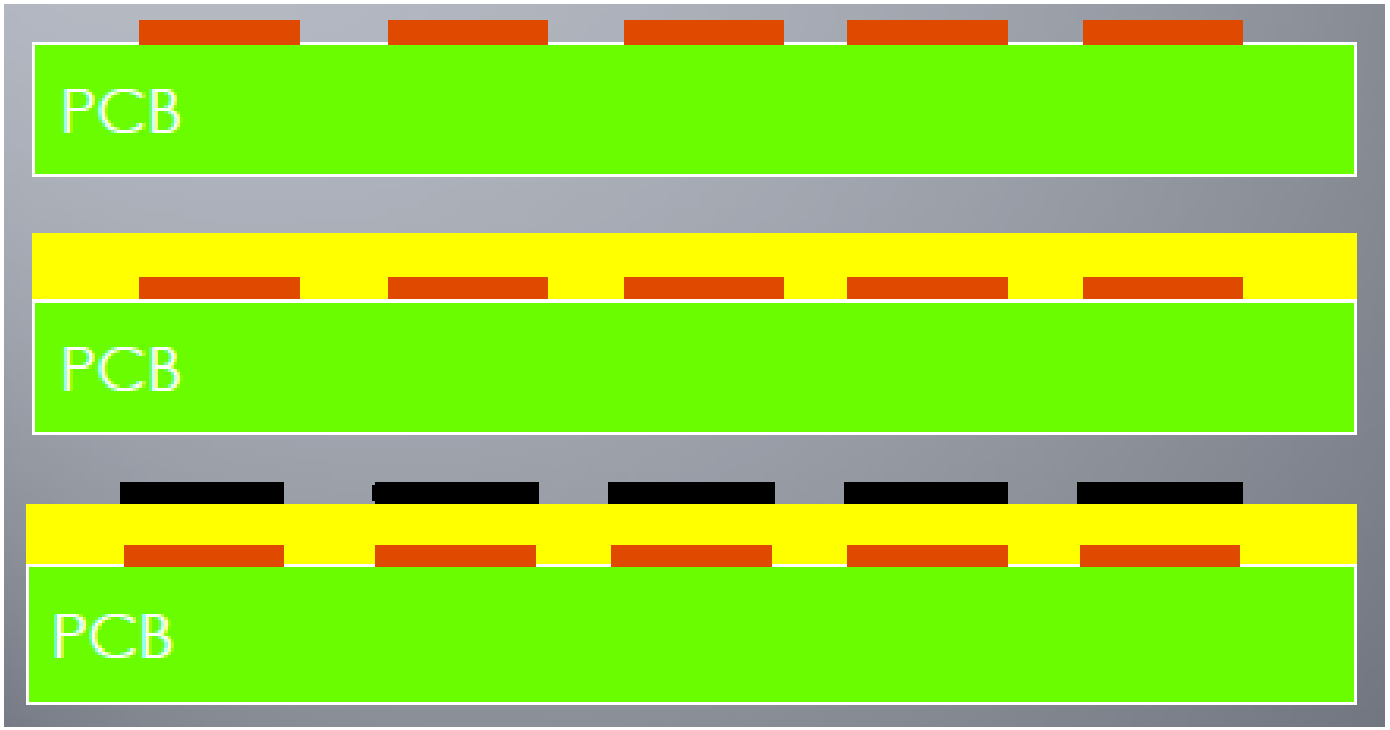


PRODUCTION SEQUENCE OF A BULK MICROMEGAS

F.Pierre IPRD'06 Siena, october 2, 2006 9

Resistive Micromegas

PC board before mesh lamination

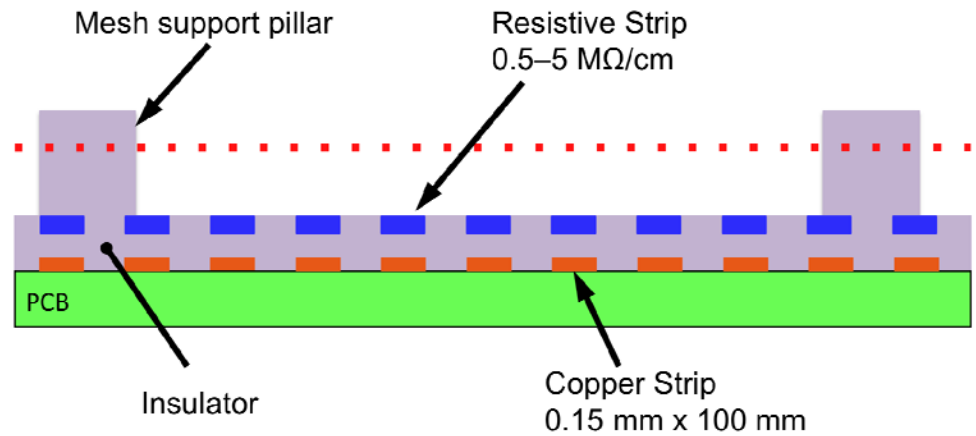


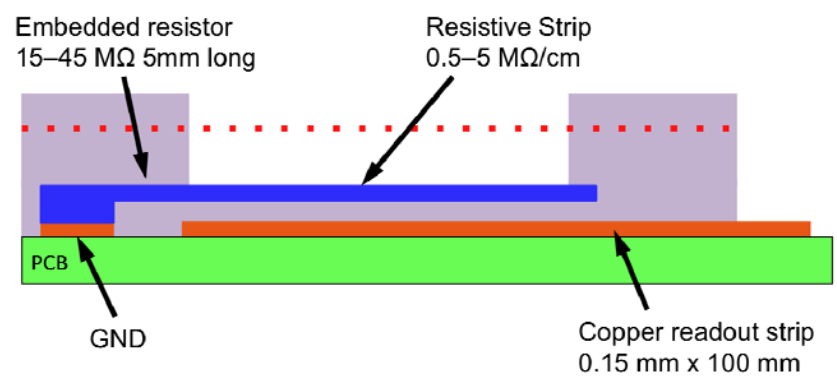
Resistive Micromegas (cont.)

- Small 100 x 100 mm^2 chamber with 100 mm long strips and 250 µm strip pitch, 360 strips in total

Characteristics:

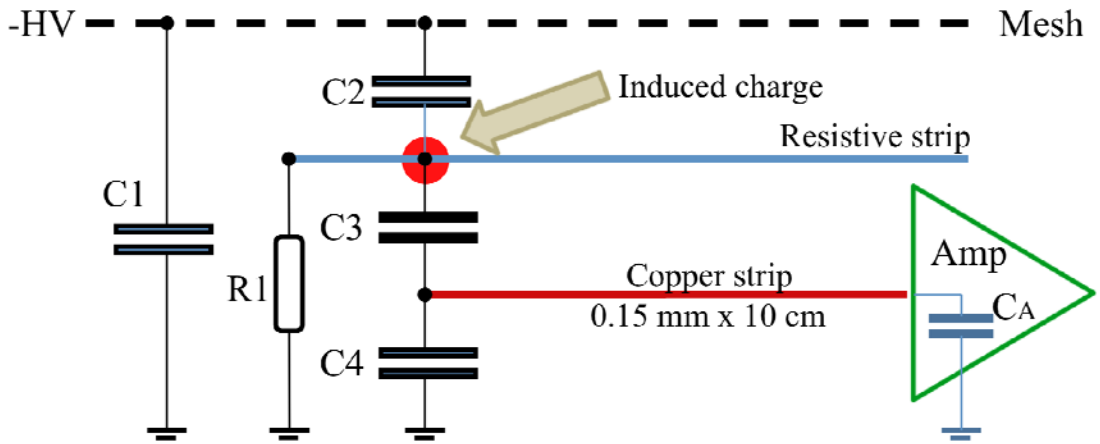
- Resistive strips connected to the ground
- Thin insulating layer between of the resistive and readout strips
- AC coupling of signals
- Sparks are neutralized through the resistive strips to the ground



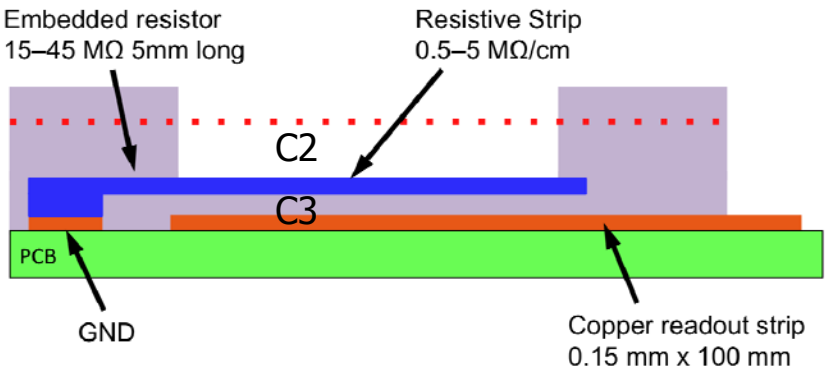


CHAMBER	R11	R12	R13
Resistance to Ground (MΩ)	15	45	20
Resistance along strip (MΩ/cm)	2	5	0.5

Equivalent Circuit

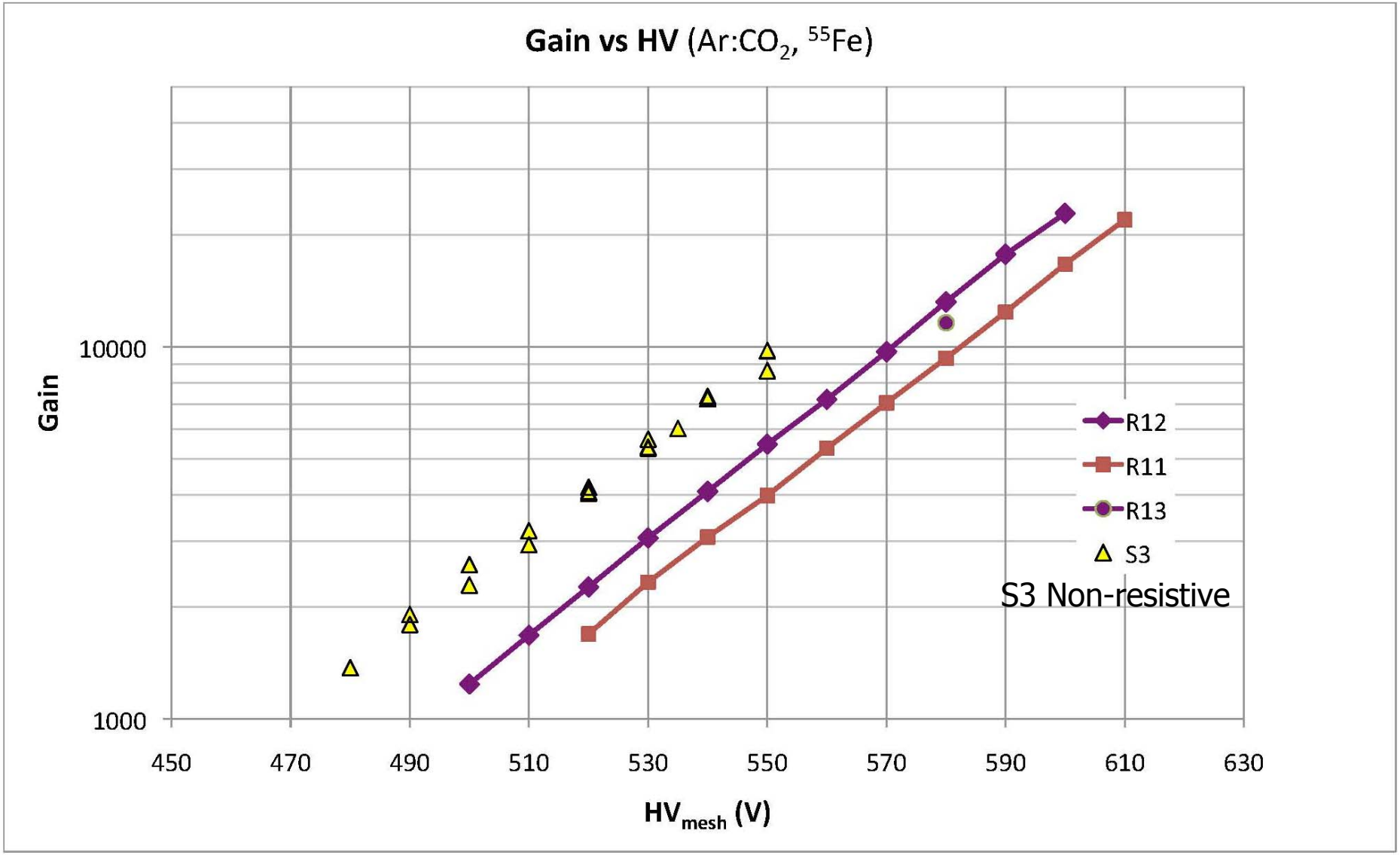


C1 – capacitance Mesh to ground
C2 – capacitance R-strip to ground
C3 – capacitance R-strip to readout strip
C4 – capacitance readout strip to ground
CA – input capacitance of preamplifier

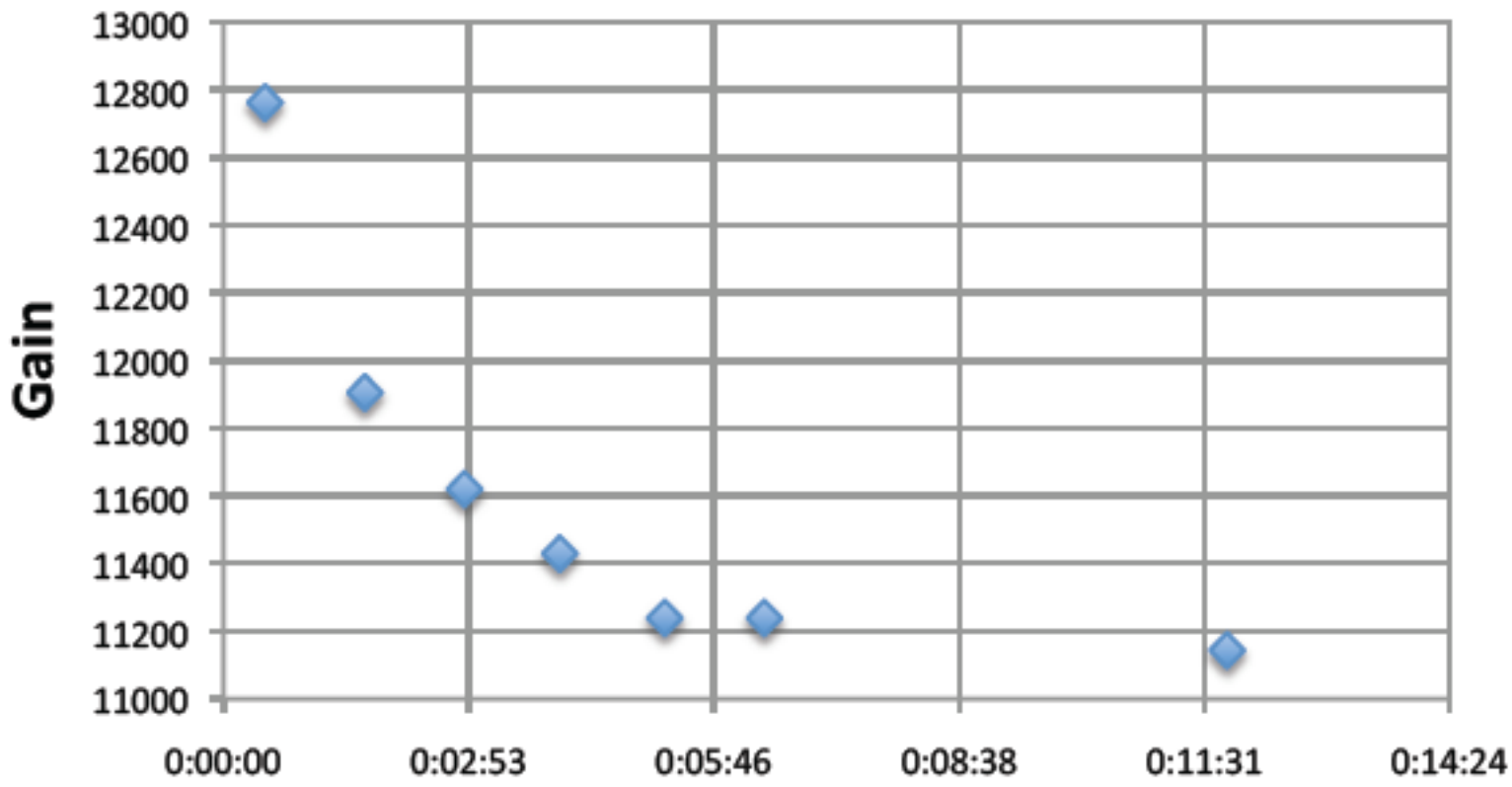


C3/C2 ~ 8

Gas Gain as a function of HV comparison with "Standard Micromegas"



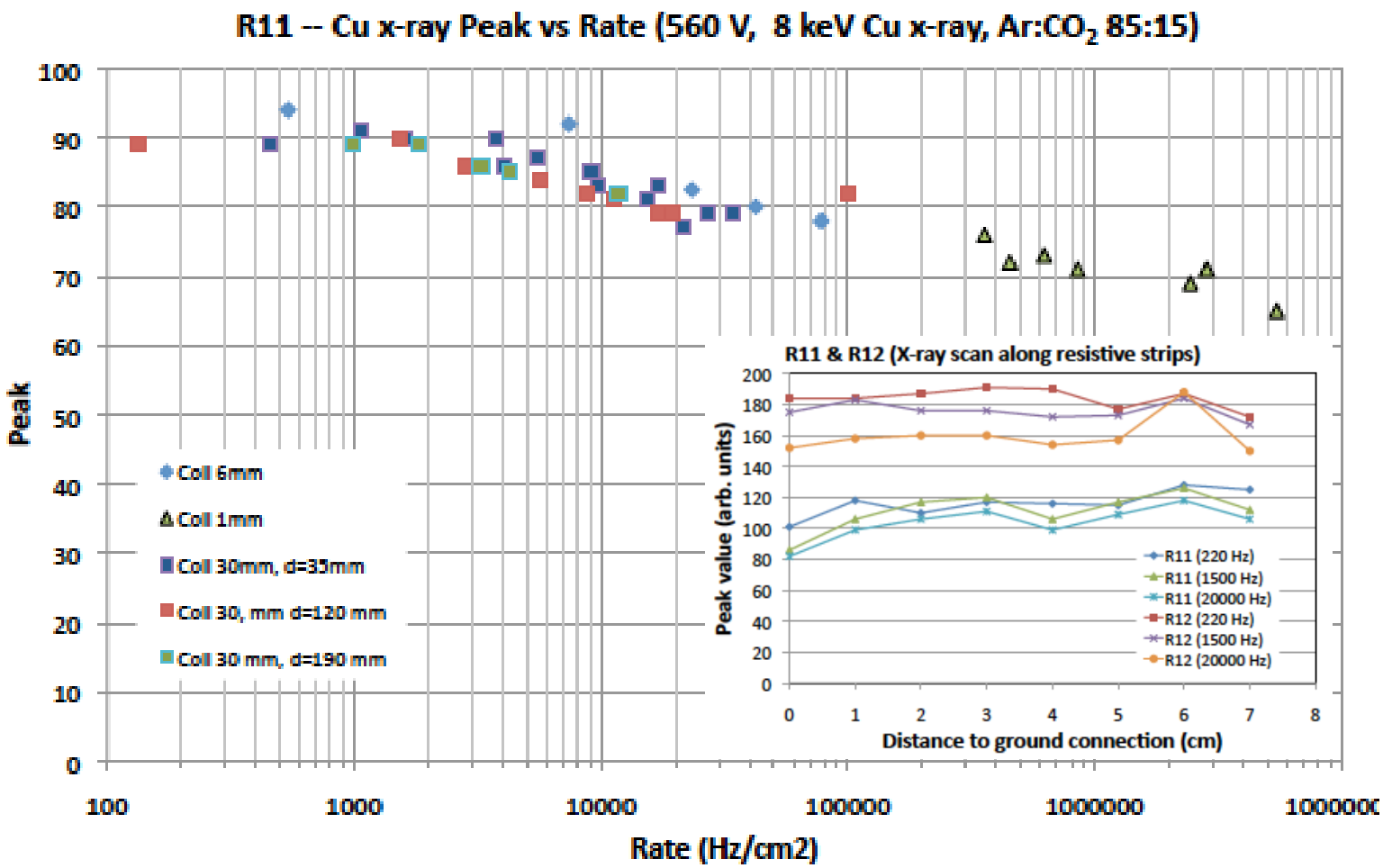
Gain as a function of time from HV turn-on



Time to stable gain depends on rate

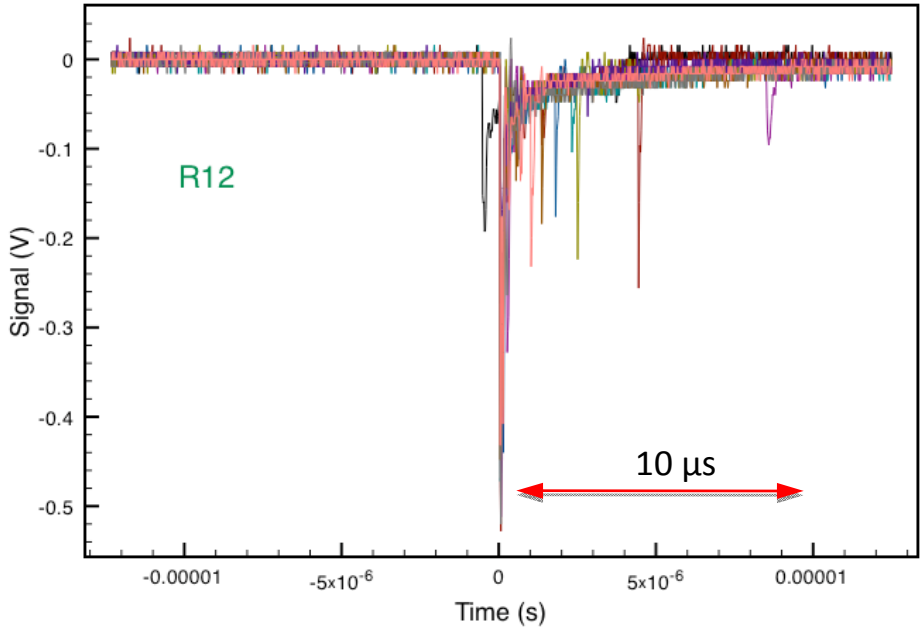
U.S. ATLAS

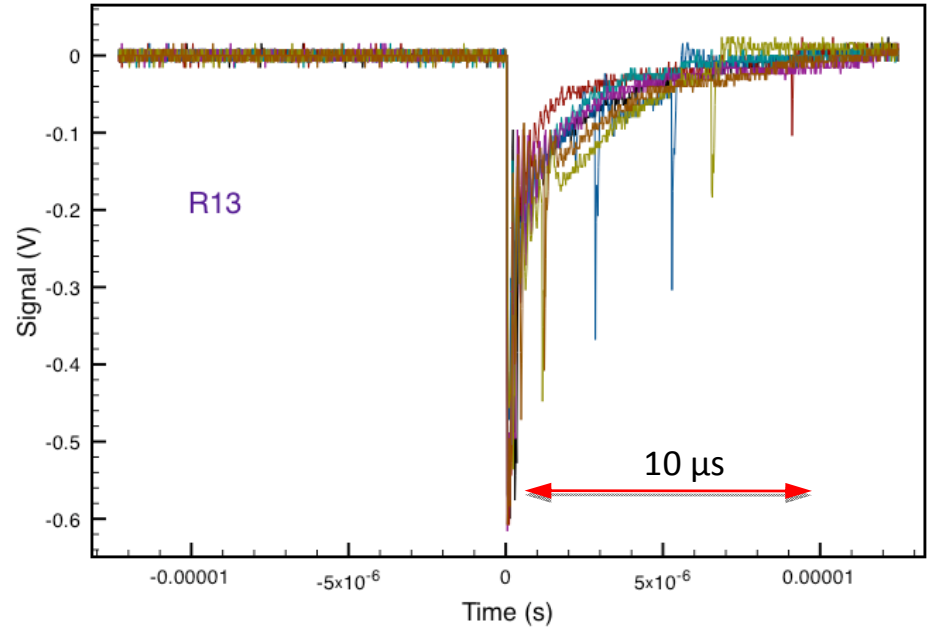
Response of R11 to 8 keV Cu X-ray signal as function of rate/cm^2.



SPARKS

Spark shape & characteristics – R12 & R13



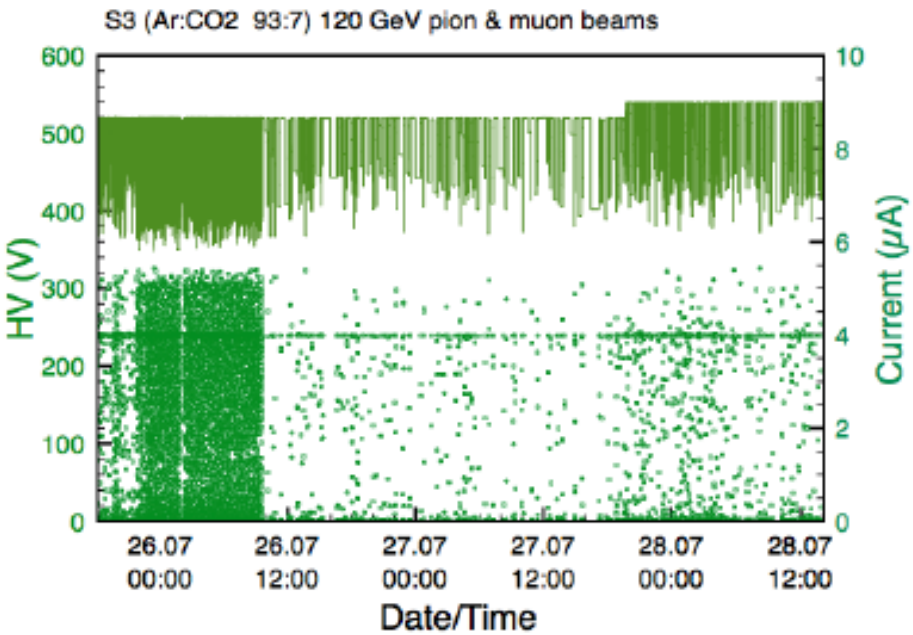


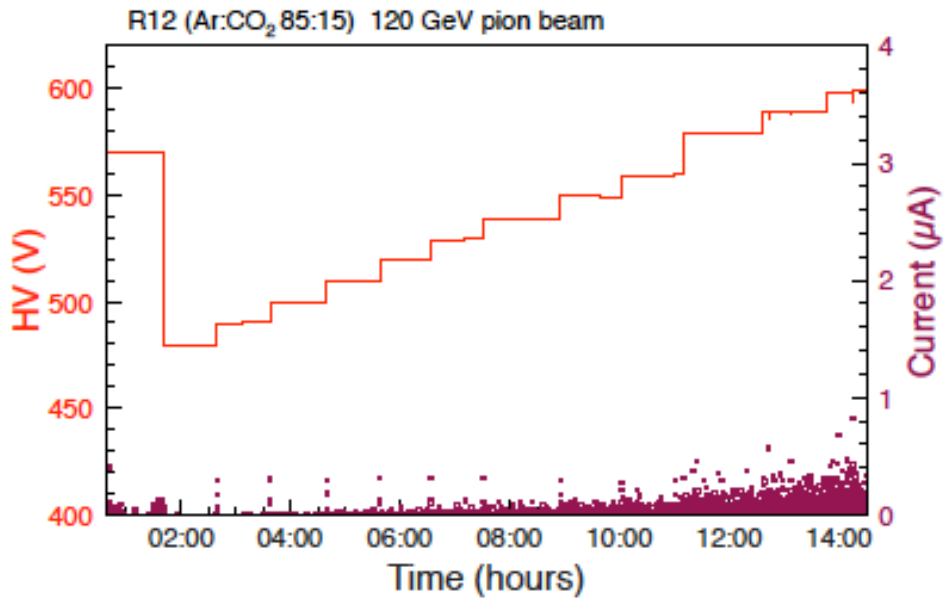
- Low spark rate
- Spark current is the order of 10-20 nA, almost 1000 times less than for S3 chamber (non-resistive)
- No HV breakdown, no dead time

CHAMBER	R11	R12	R13
Resistance to Ground (MΩ)	15	45	20
Resistance along strip (MΩ/cm)	2	5	0.5

- Short signal ≤ 100 ns
- Maximum 0.5–1 V (direct measurement (50 Ω), w/o amplifier)
- Frequently several short pulses up to 10 µs total duration
- Max current for spark is 10–20 nA (1000 times smaller than for non-resistive chambers)
- No breakdown of HV

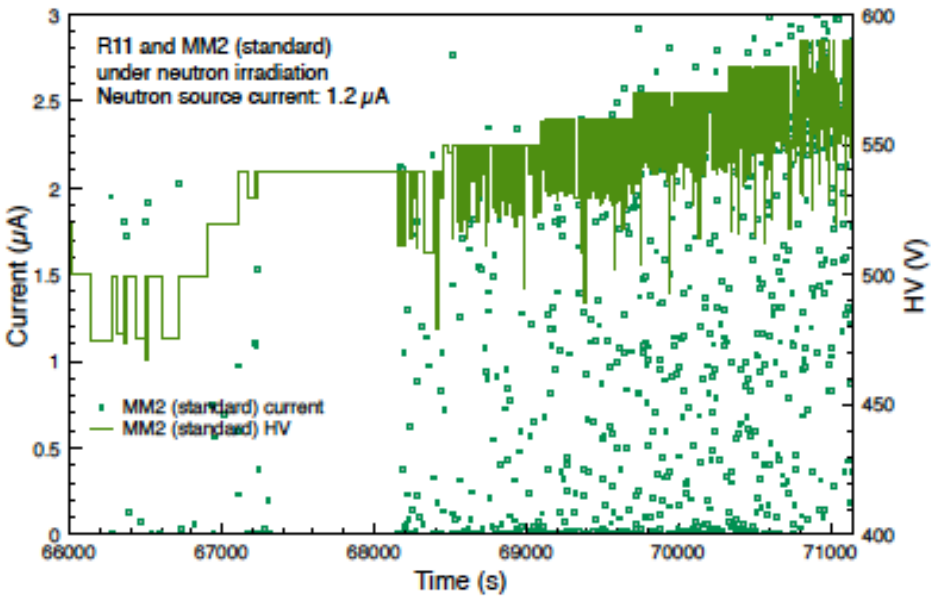
Response to 120 GeV Pion Beam

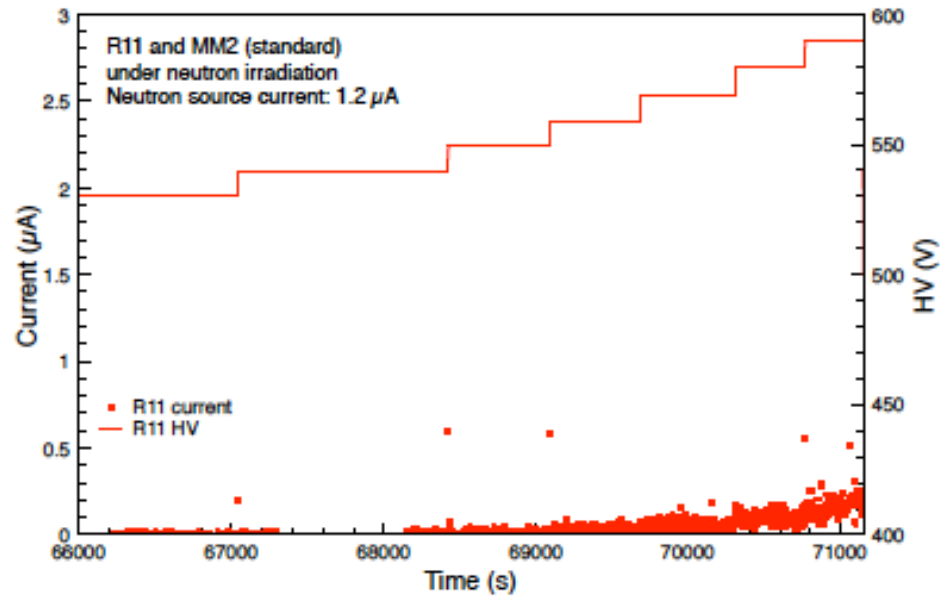




- HV and current History for a standard Micromrgas (Left)
- and a resistive one (R12) of identical otherwise geometry
- Observed currents are more than two orders of magnitude lower
- No HV dips

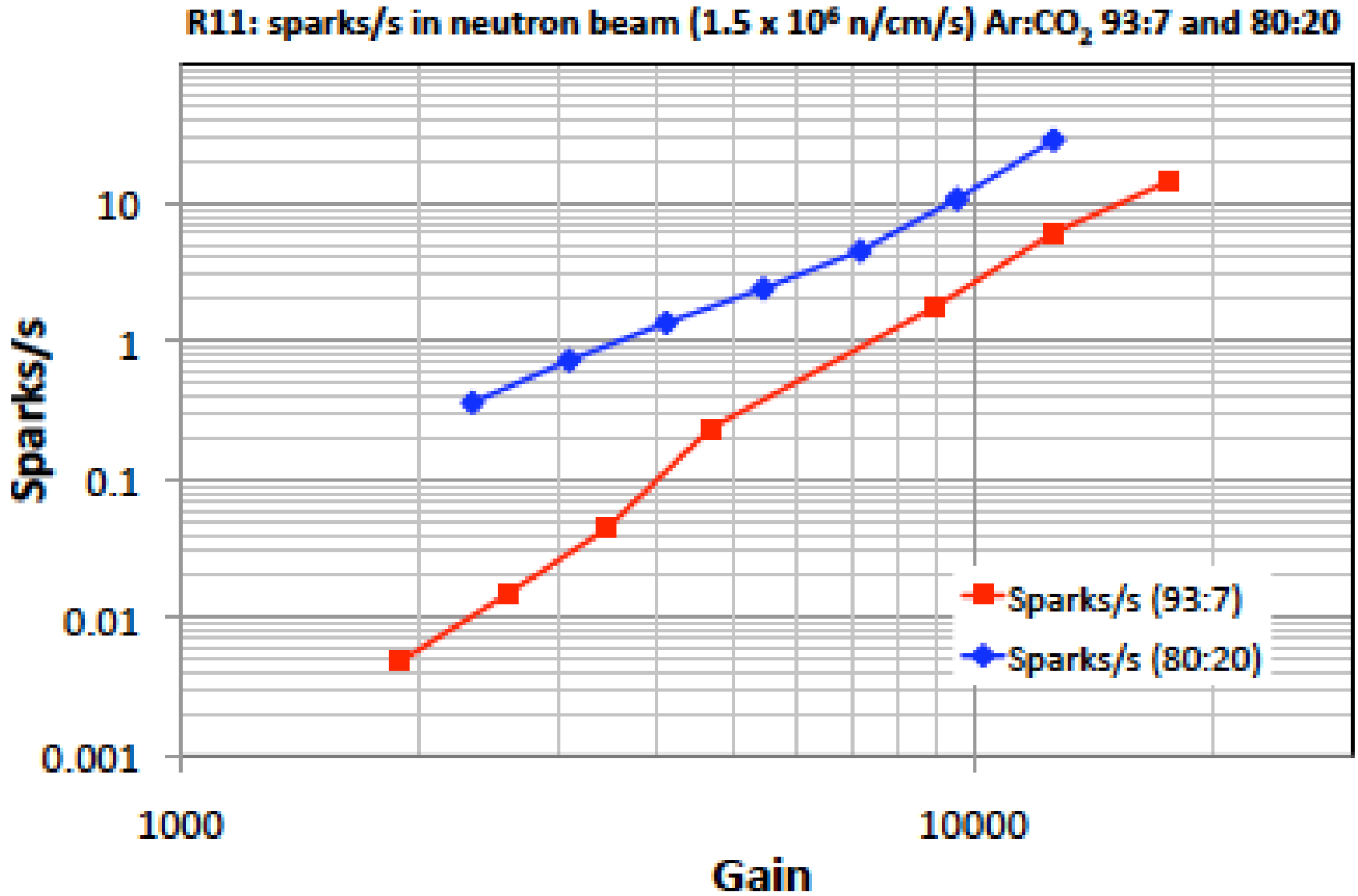
Response to 5.5 MeV neutrons



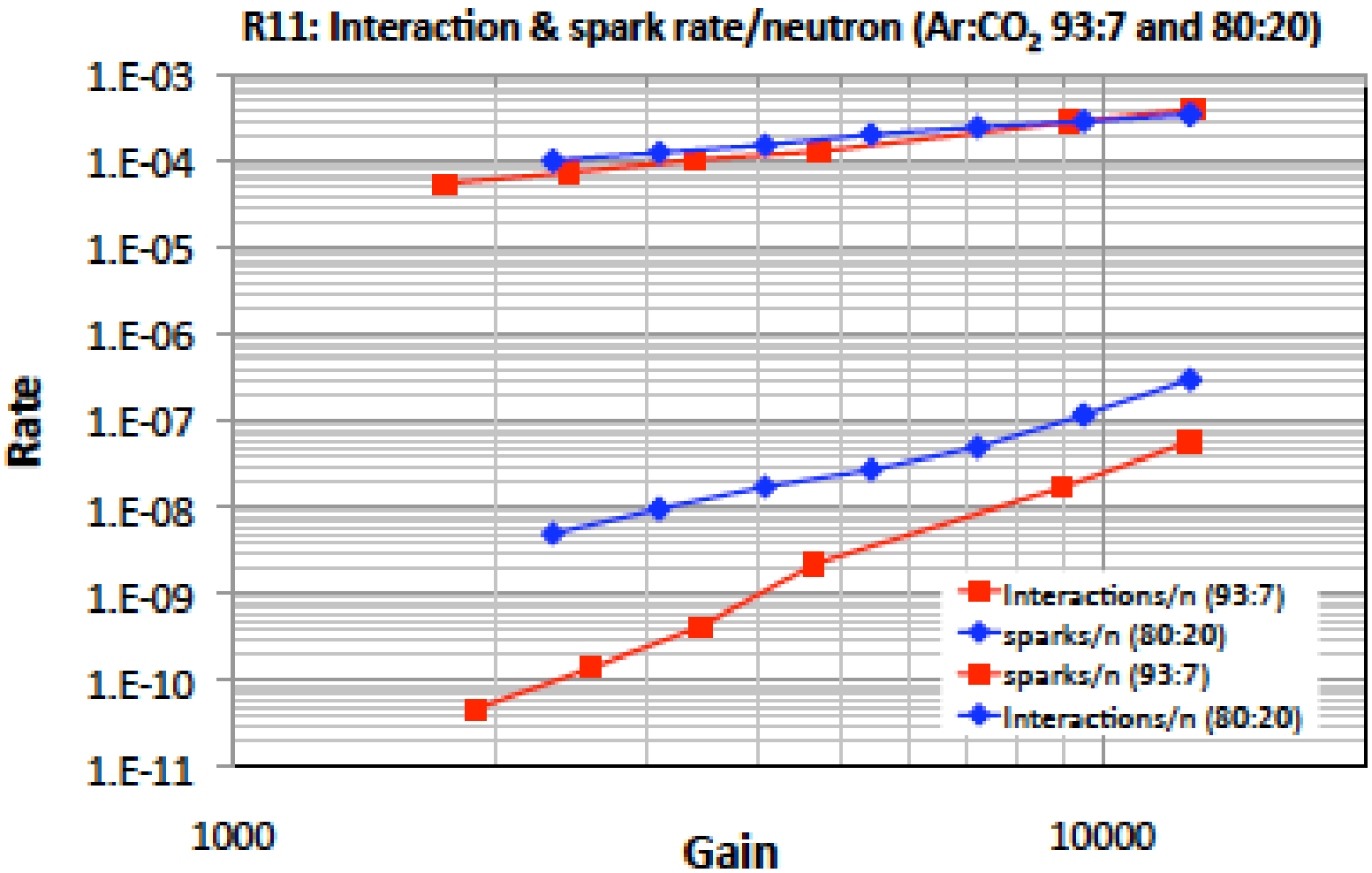


5.5 MeV neutrons (Demokritus Nuclear Research Center, Athens)
~1e6 neutrons/cm^2

Spark Rate as a function of Gas Gain

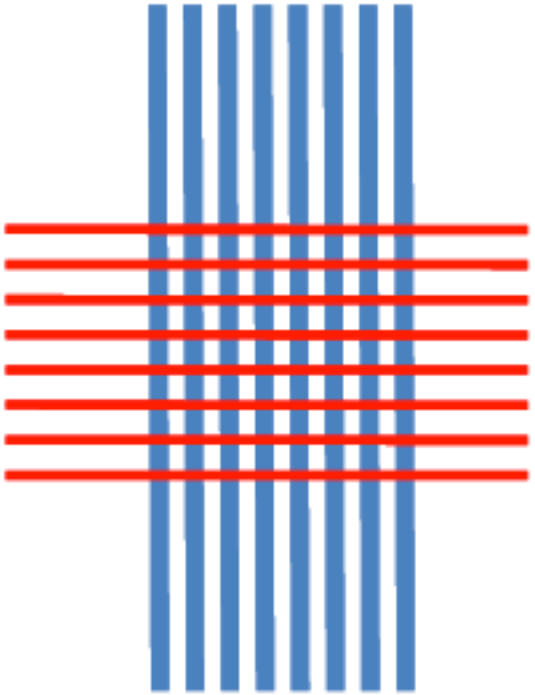


Neutron sensitivity and Spark rate per Neutron



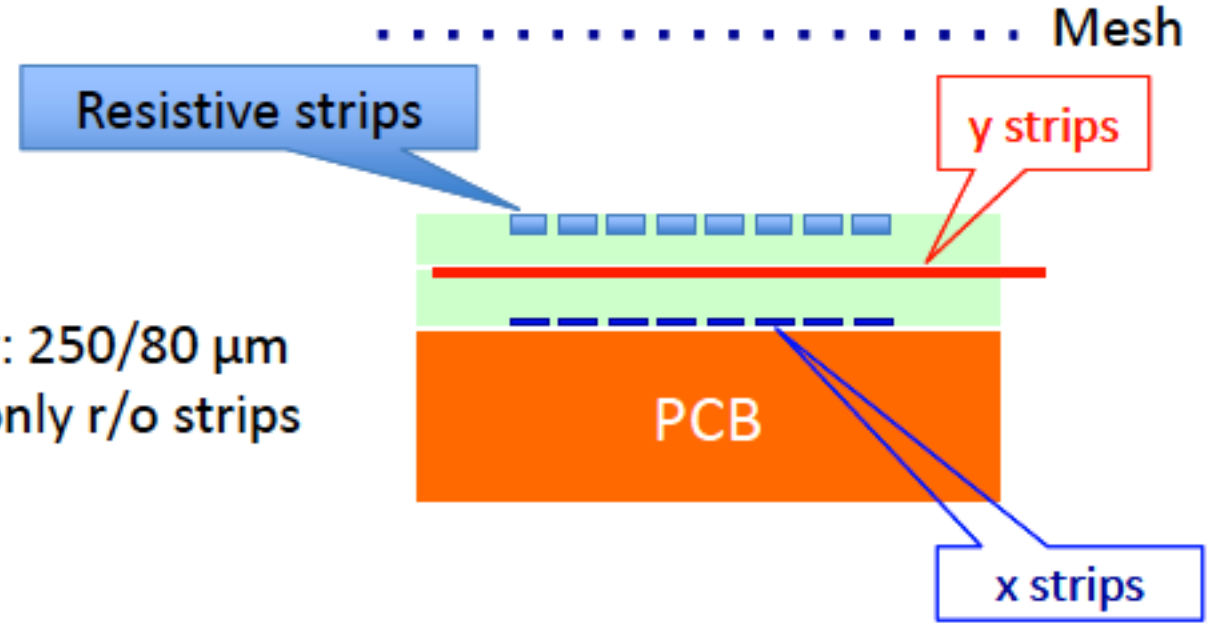
Paper accepted for publication NIMA, DOI: 10.1016/j.nima.2011.03.025

Resistive Micromegas with two-dimensional Readout



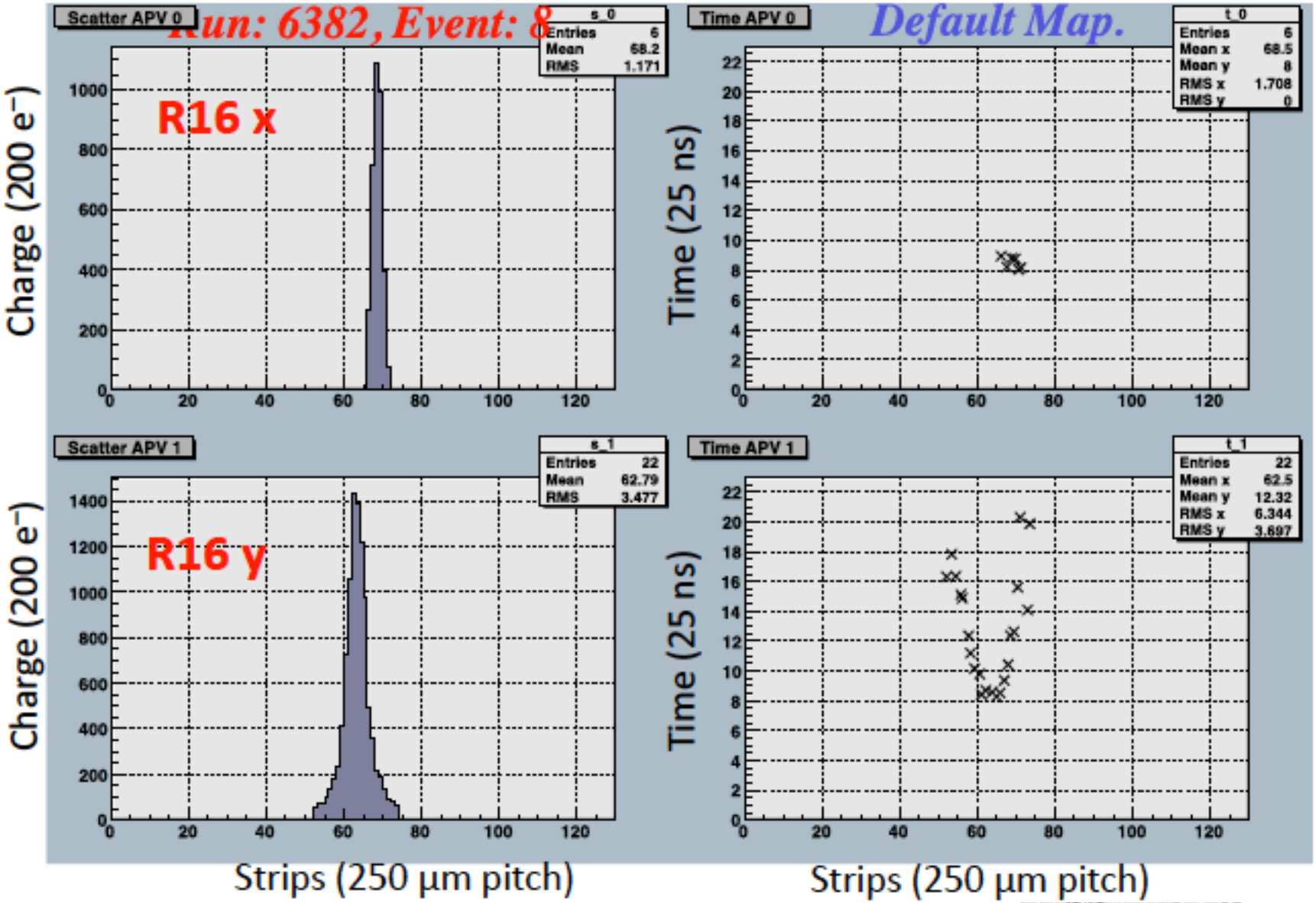
x strips: 250/150 µm
r/o and resistive strips

y: 250/80 µm
only r/o strips



Resistivity values
$R_G \approx 55\ M\Omega$
$R_{strip} \approx 35\ M\Omega/cm$

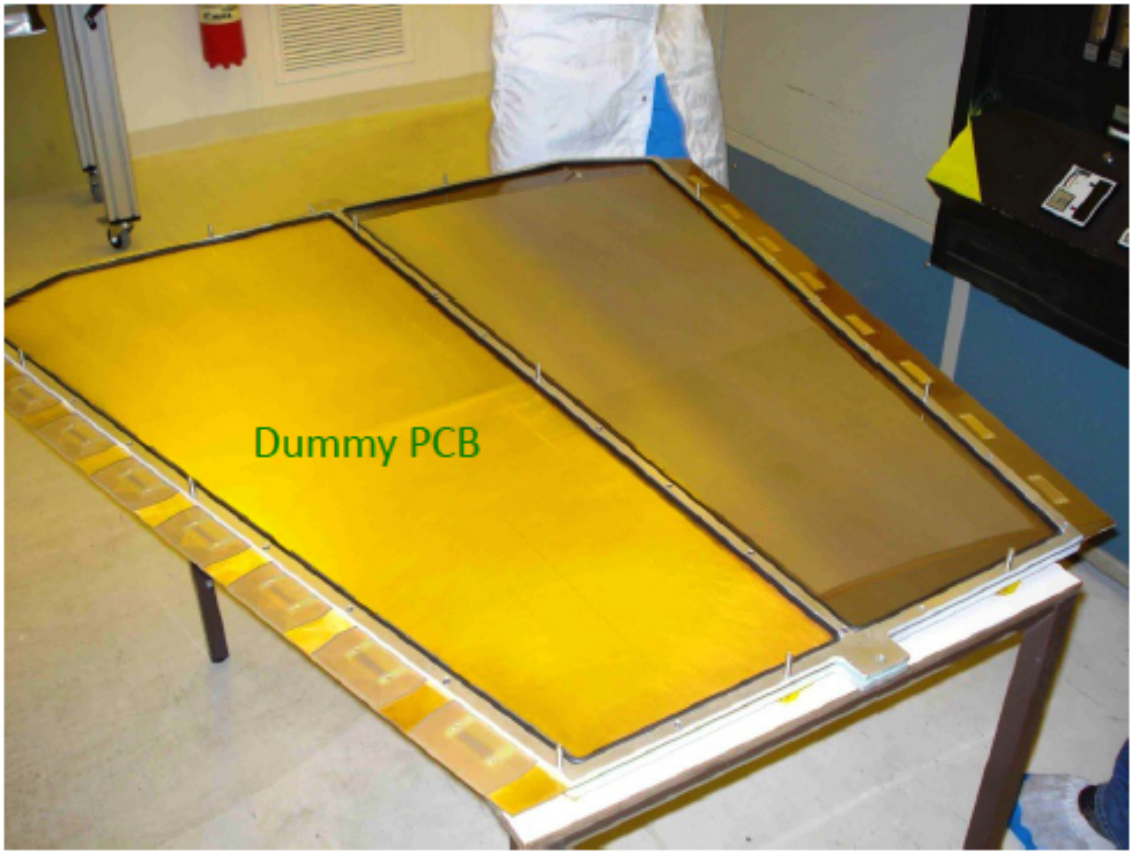
X-Y Event Display (^{55}Fe)



Large Area Detectors (brief update)

Standard MM 1.2 x 0.6 m^2 (Nov 2010)

Rui De Oliveira Shop



- 2048 circular strips
- Strip pitch: 0.5 mm
- 8 connectors with 256 contacts each
- Mesh: 400 lines/inch
- 5 mm high frame defines drift space
- O-ring for gas seal
- Closed by a 10 mm foam sandwich panel serving at the same time as drift electrode

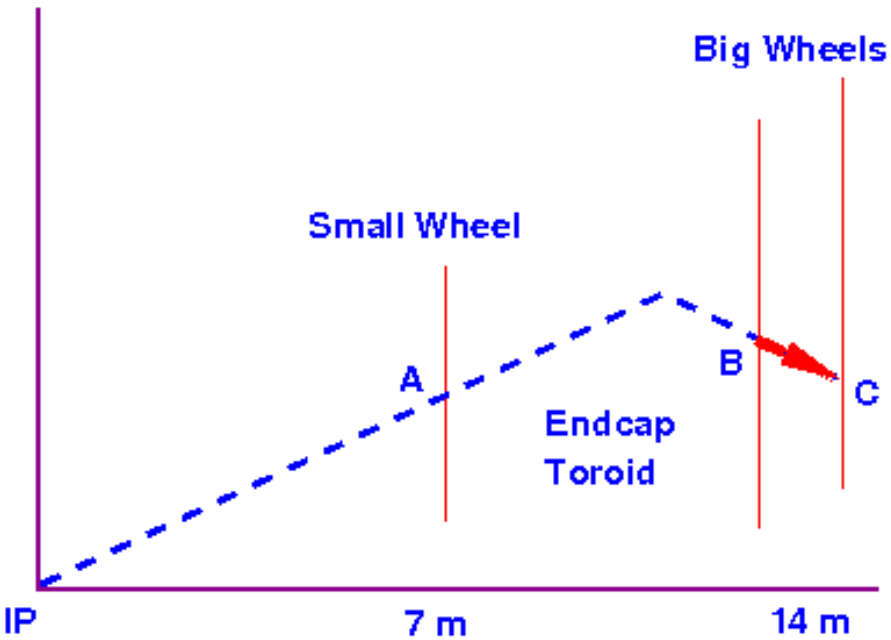
PC Boards fabricated in U.S. Industry

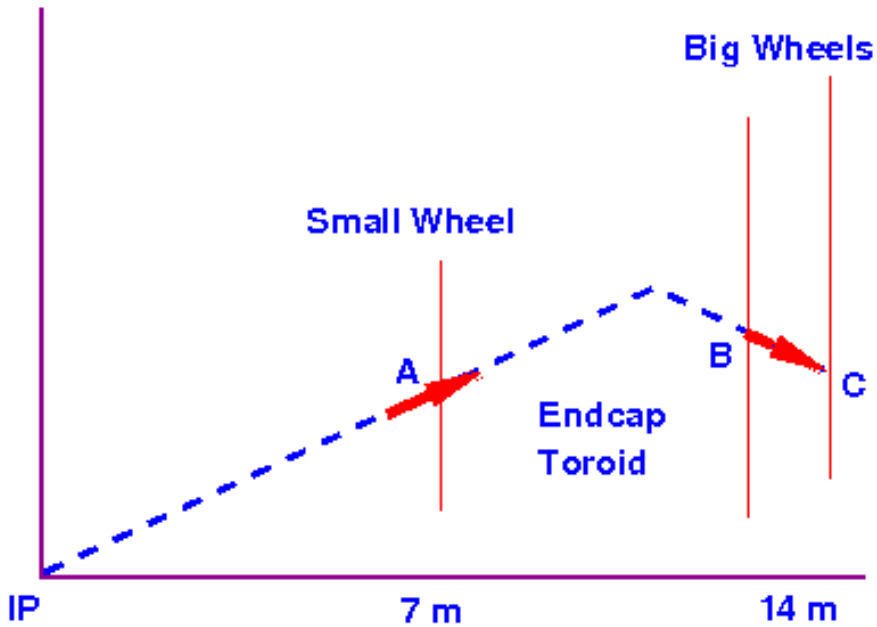
Large Area Chambers (cont.)

- Work just starting
- CERN Shop to be upgraded to handle 4 ft wide boards
- Wish to engage Industry
- U.S. vendor interested in these developments
- Need to develop efficient technique for resistive strips

A similar size resistive detector is currently under construction (Also made of two halves)

Recall The Problem with High pT Triggers





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- Only a vector BC at the Big Wheels is measured
- Momentum defined by implicit assumption that track originated at IP
- Random background tracks can easily fake this

ProposedTrigger

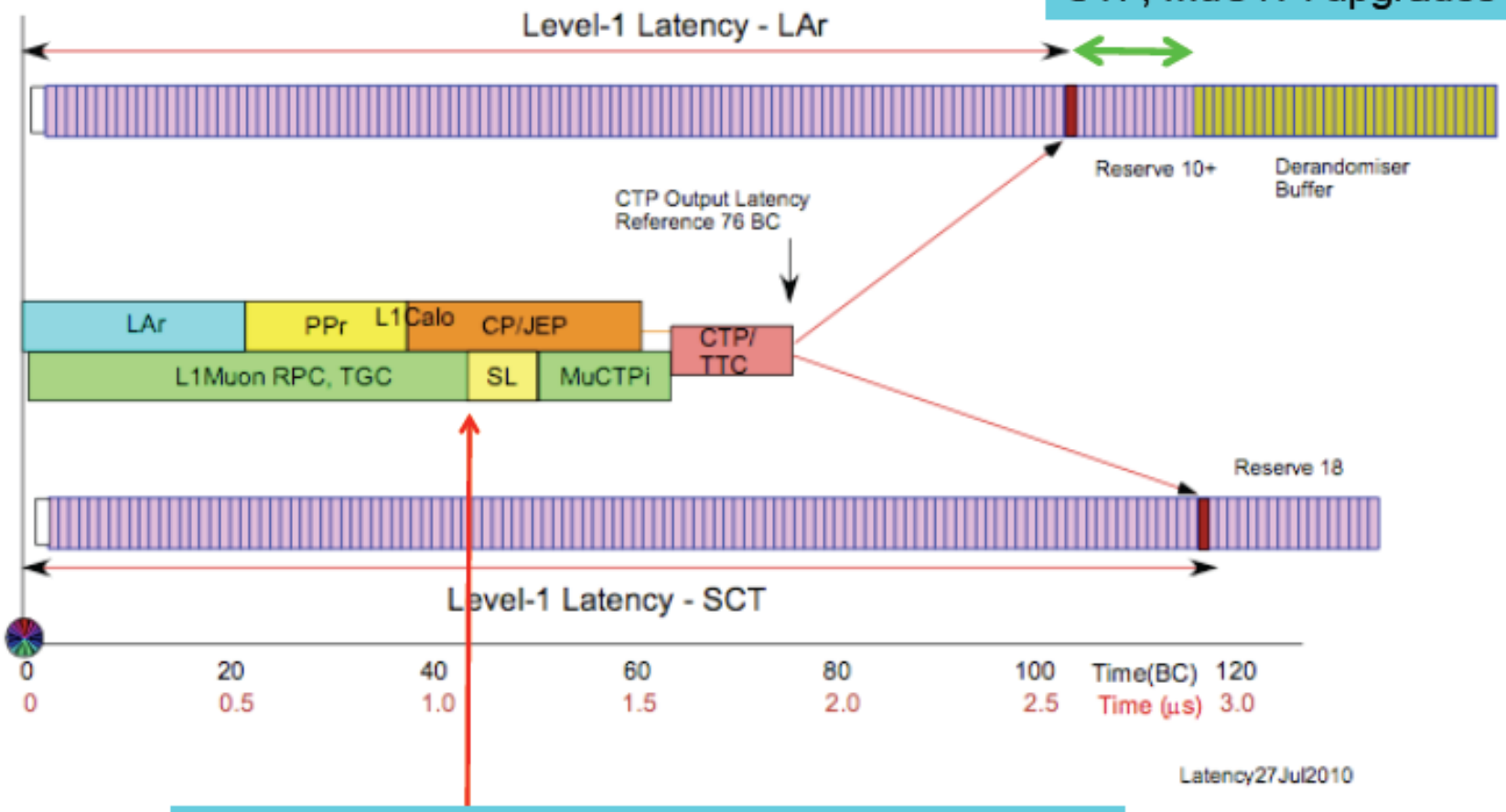
- Provide vector A at Small Wheel
- Powerful constraint for real tracks
- With pointing resolution of 1 mrad it will also improve pT resolution
- Currently 96% of High pT triggers have no track associated with them

U.S. ATLAS

L1 latency

Current L1 Latency

This margin is shared by muon upgrade, topo trig, CTP, MuCTPi upgrades



BW TGC data arrives at SL 1088ns after collision.

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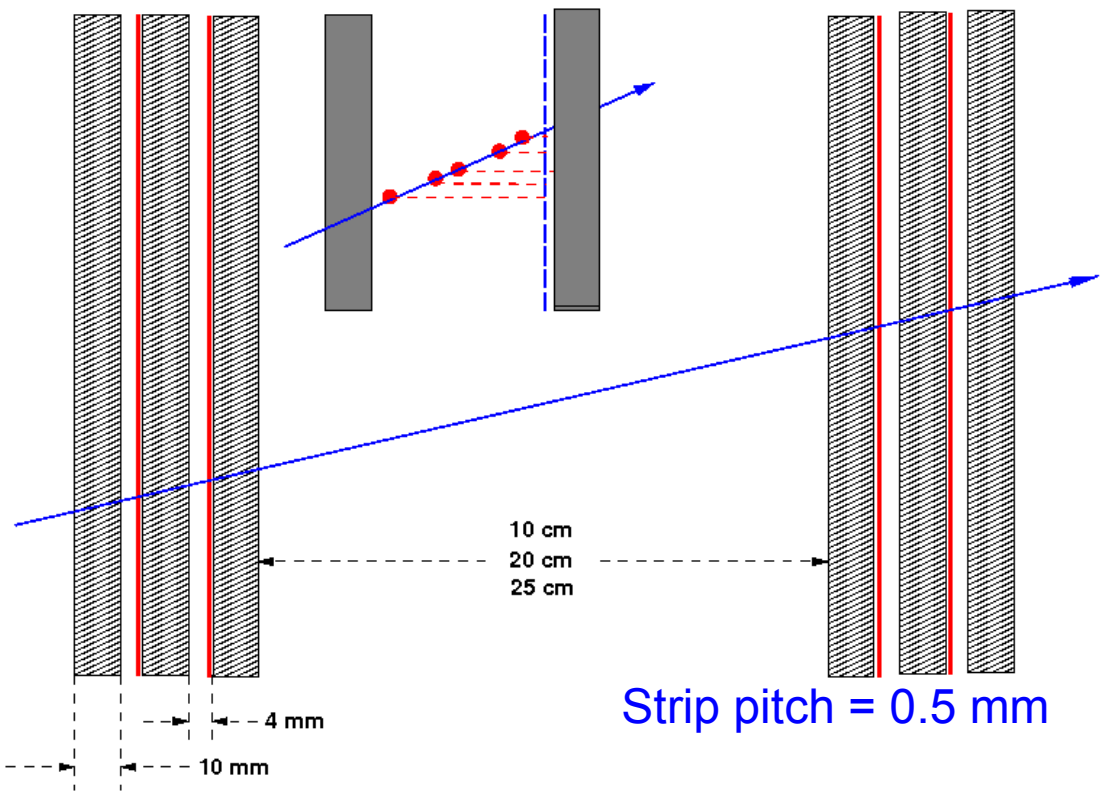
Trigger Concept/Toy Monte Carlo

Challenge: How to do this with a system if 2 Million Channels

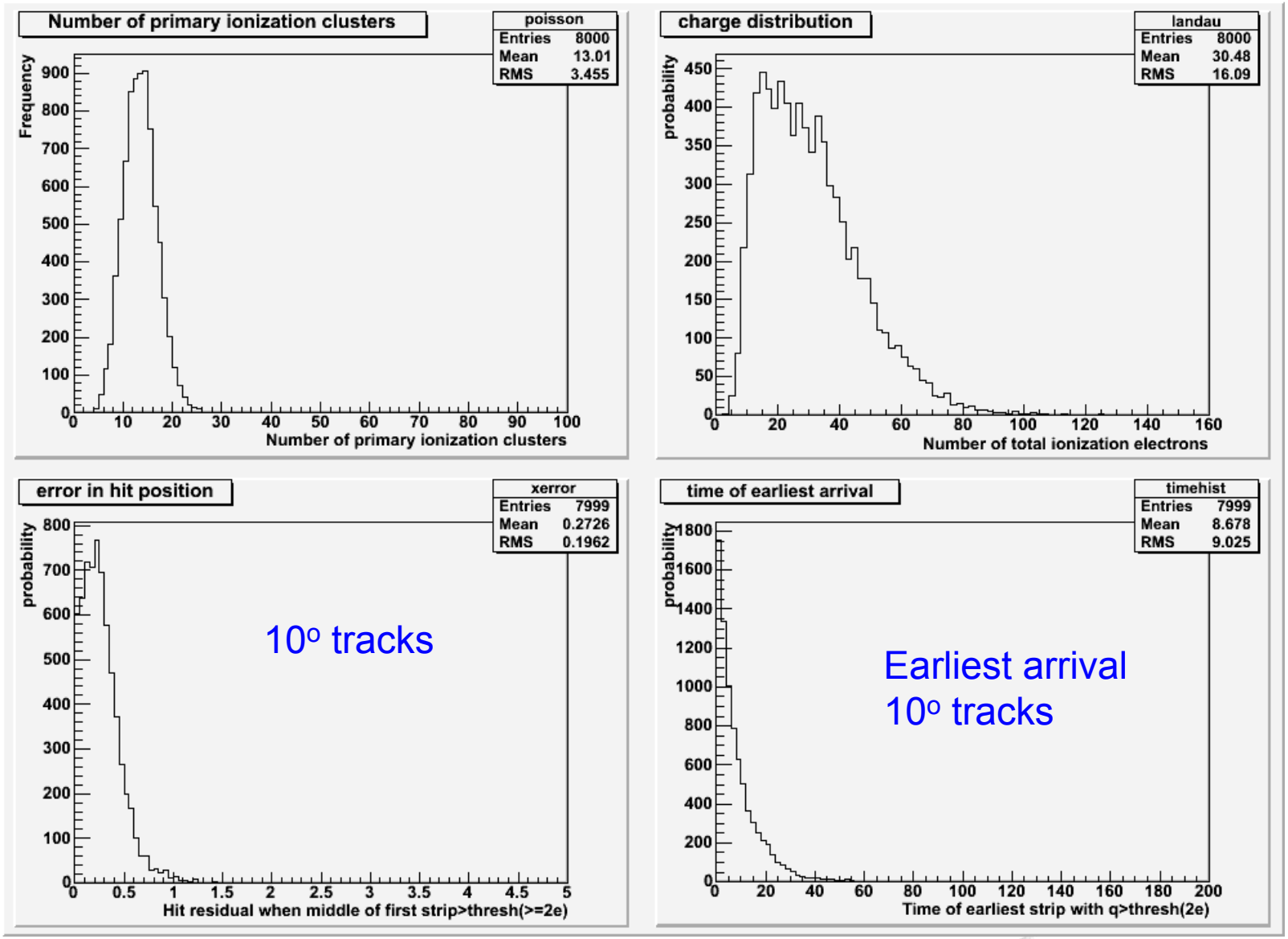


Strip pitch = 0.5 mm

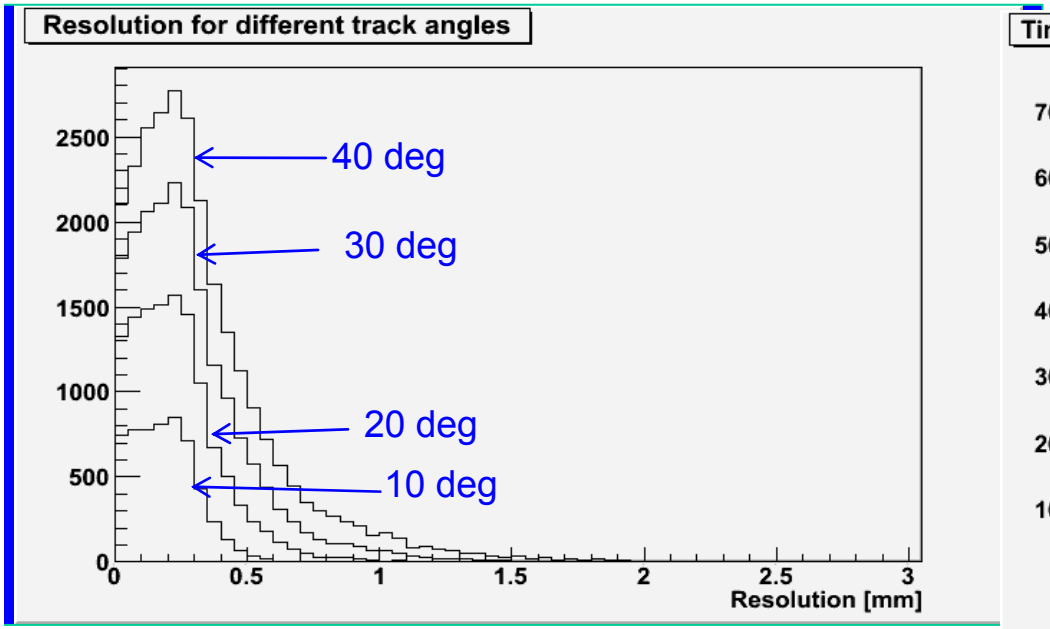
- Generate track at a given angle
- Track crosses a strip at a random position
- Generate primary ionization clusters Poisson distributed
- Generate number of electrons for each cluster
- Take strip with earliest time and charge over a certain threshold as the track's coordinate

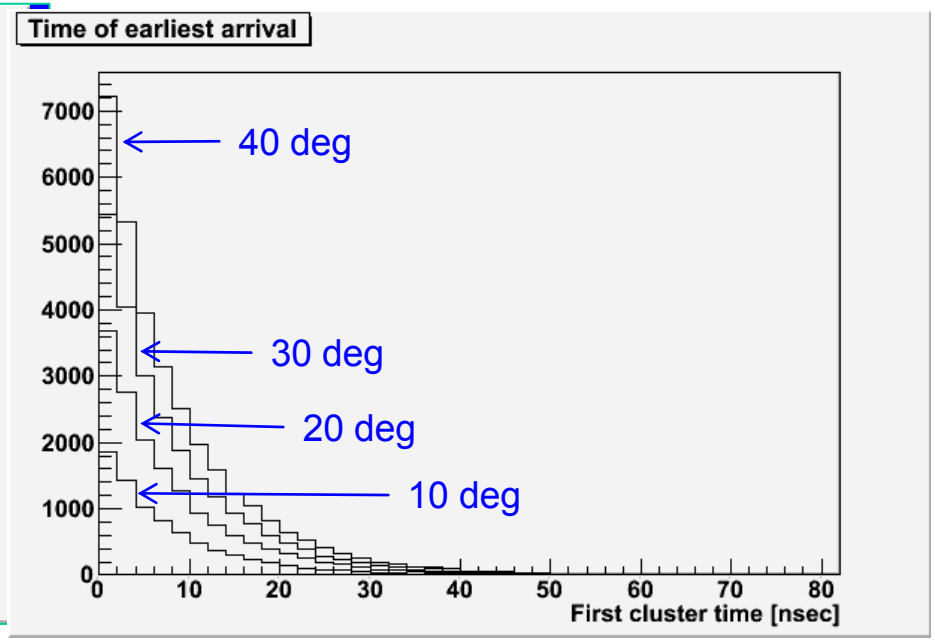
Reconstruct track and compare slope with the generated one
No transverse diffusion considered but effect is negligible for the first arriving cluster

Sanity Check
Distributions of MC generated Events



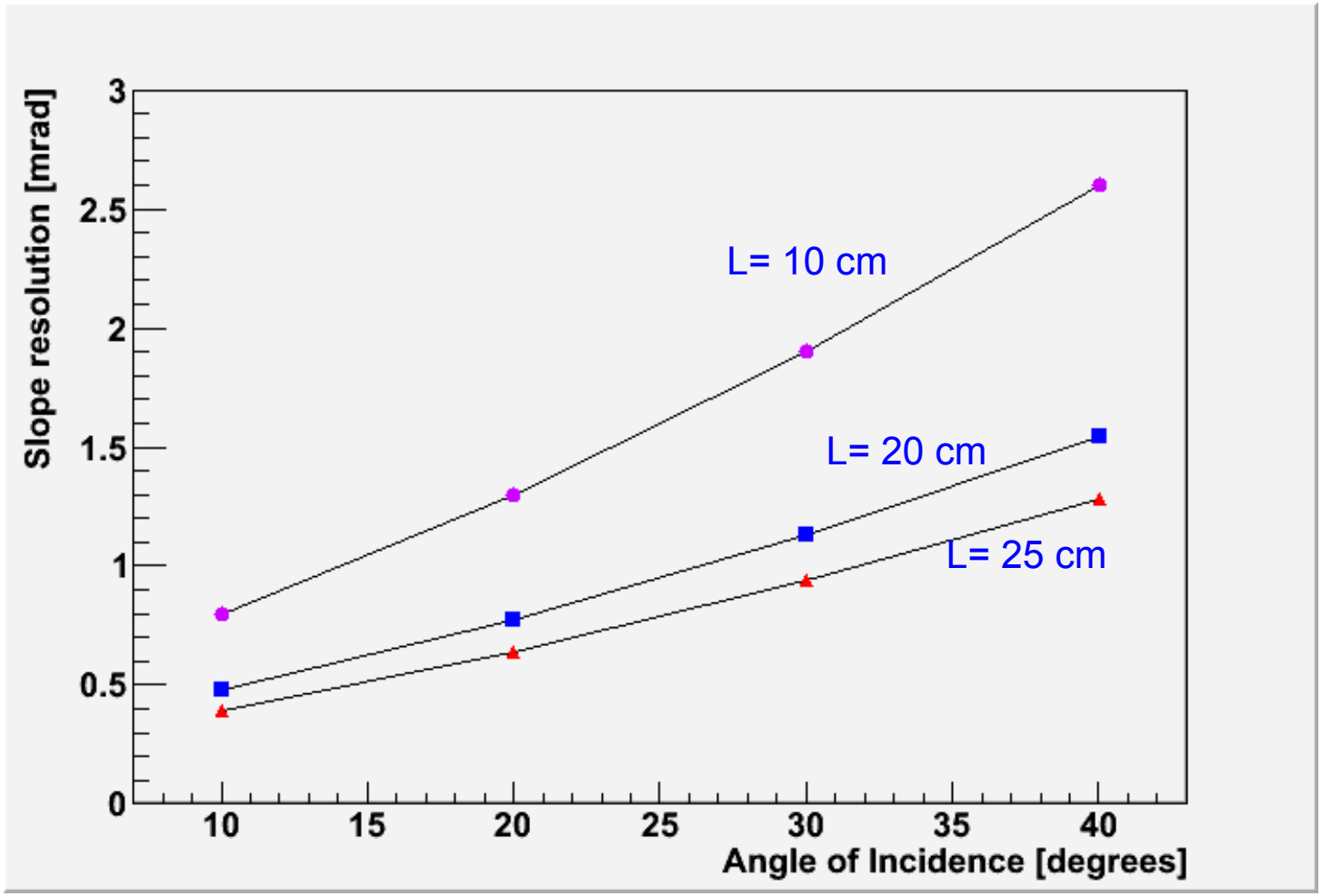
Position and Timing Resolution as a function of incidence angle



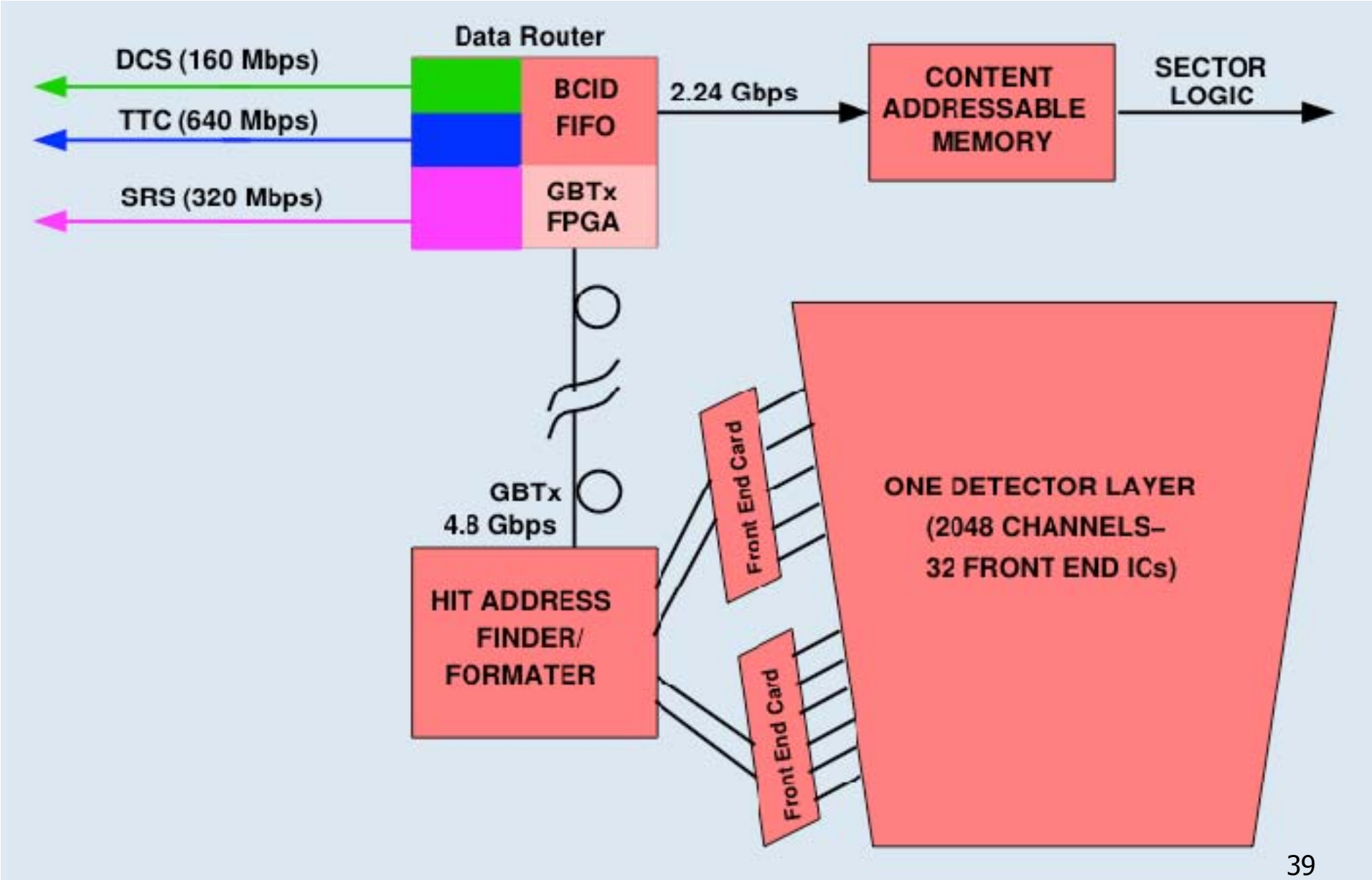


- ❑Average spatial resolution below 0.5 mm for all angles in Small Wheel acceptance
- ❑Time of first cluster above threshold mostly below 25 nsec
- ❑Requiring, e.g, 3 out of 4 detectors to be within a BC should result in ~100% efficiency
- ❑Address of strips can be directly used in a lookup table (e.g. Content addressable memories similar to FTK

Slope Resolution



Trigger/DAQ Block Diagram



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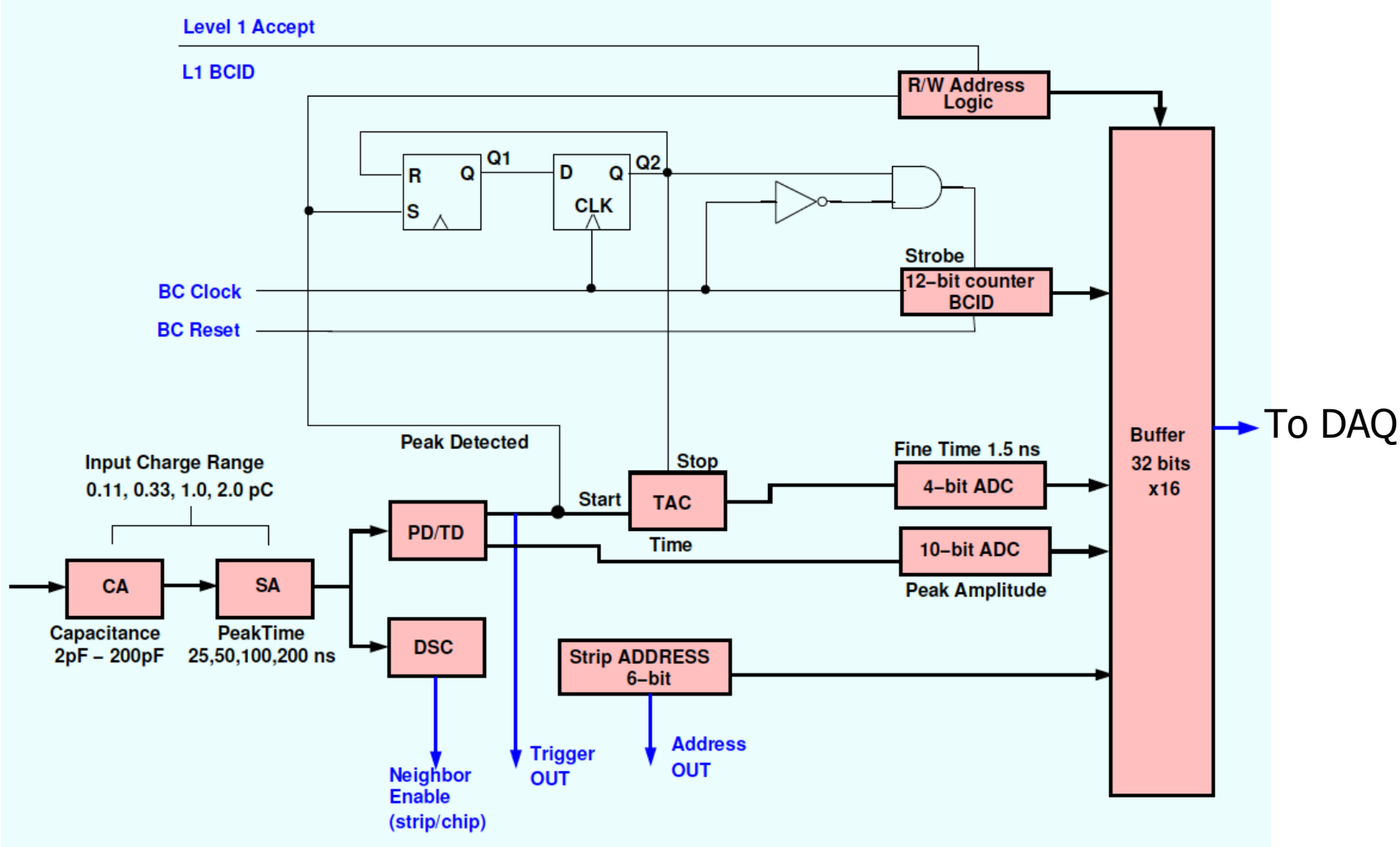
Block Diagram of the IC being designed (Gianluigi De Geronimo)



For TGC there will be fewer (16 or 32) channels with LVDS outputs of individual discriminators
All other features remain the same

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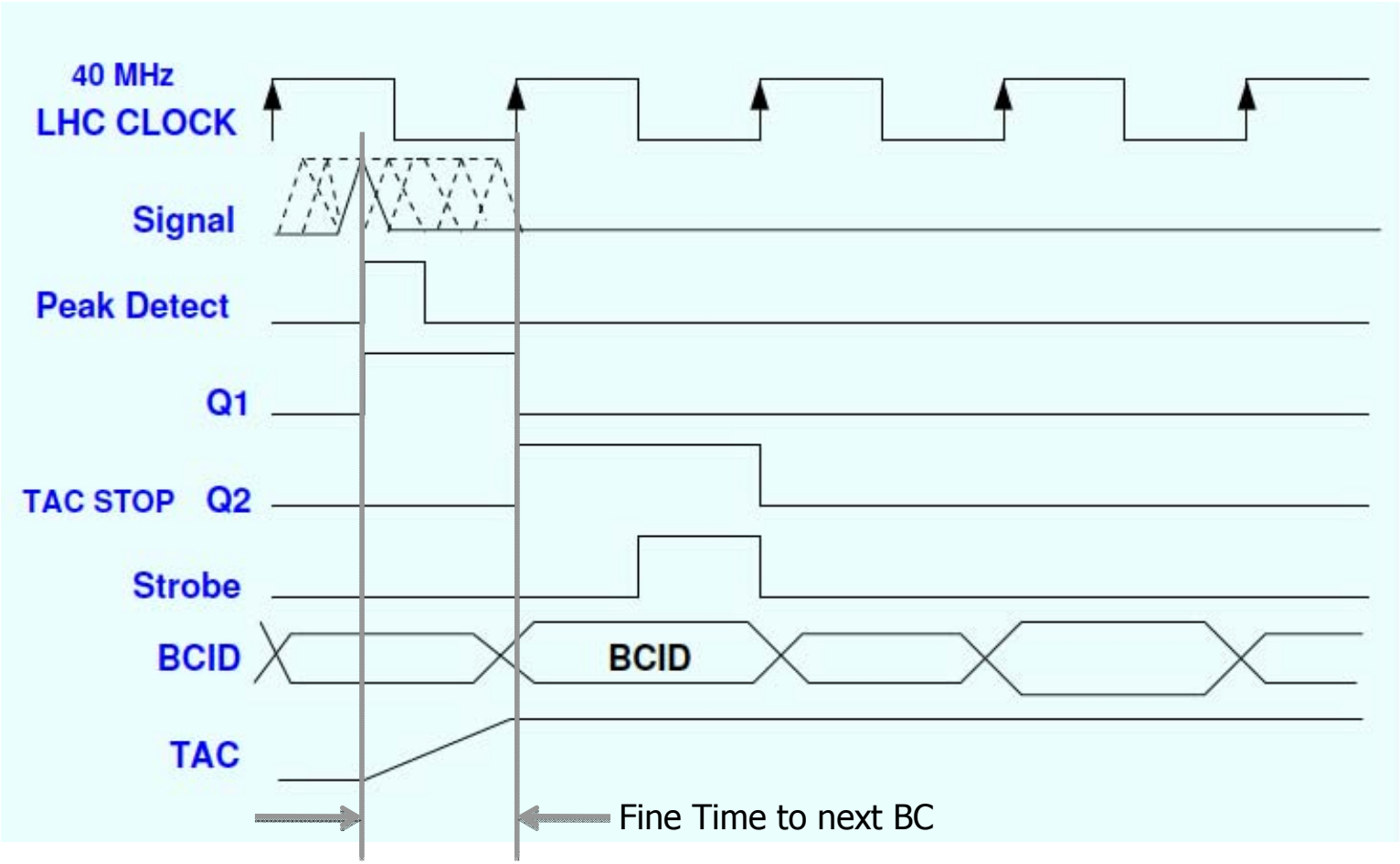
Some Features of the New IC

- 64 channels
- adj. polarity, gain (0.11 to 2 pC), and peaking time (25-200 ns)
- derandomizing peak detection (10-bit) and time detection (1.5 ns), built-in ADC
- real-time event peak trigger and address
- integrated threshold with trimming, sub-threshold neighbor acquisition
- integrated pulse generator and calibration circuits
- analog monitor, channel mask, temperature sensor
- continuous measurement and readout, derandomizing FIFO
- few mW per channel, chip-to-chip (neighbor) communication, LVDS interface
- Redundant logic to mitigate Single Event Upsets (SEU)

Timing Diagram

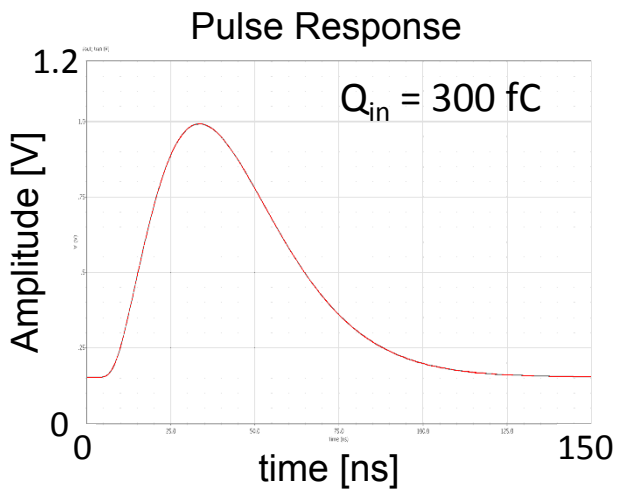


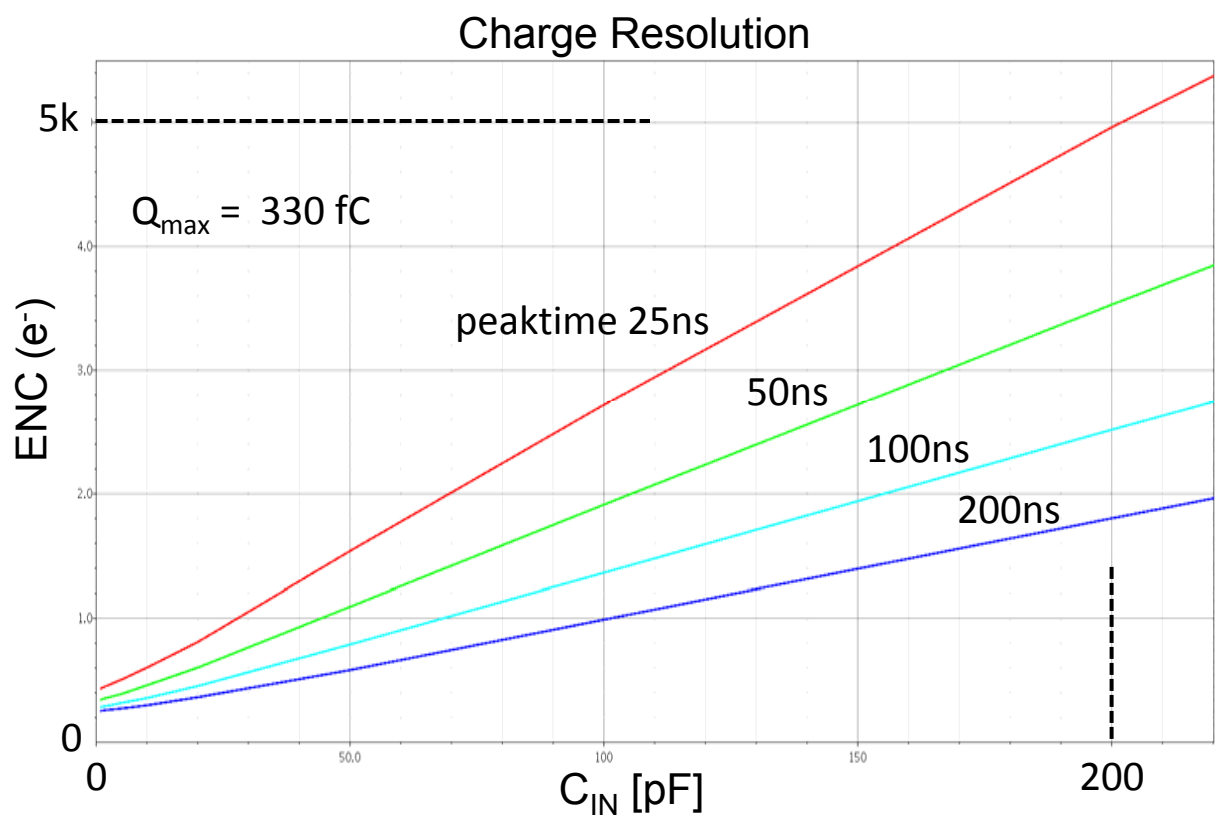
40 MHz BC clock convenient for LHC but any clock can be used to relate hit with trigger accept

Expected Front End Performance

130 nm, 1.2V

Analog section:
transistor-level simulations
power ≈ 4 mW





Effect of considering only one hit per IC

Taking ONLY the first arriving hit per 64-Channel IC reduces the number of Channels used for Trigger from 2M → ~30,000, while maintaining spatial resolution <0.5 mm with an effective granularity of 3.2 cm (64x0.5 mm)

But are we paying a price for this? i.e. efficiency loss?

Consider worst case at η= 2.4:
Rate r = 10 kHz/cm^2, strip length l = 50 cm, strip width w = 0.5 mm

Occupancy/BC = rlwt = 6.25×10^{-4}

	Probability per Front End IC [%]		
# Hits	Probability per Chip per Bunch Crossing	Probability per Chip per 3 Bunch Crossings	Probability per Chip per 5 Bunch Crossings
0	96.1	88.7	81.9
1	3.8	10.6	16.5
>=2	0.1	0.6	1.6

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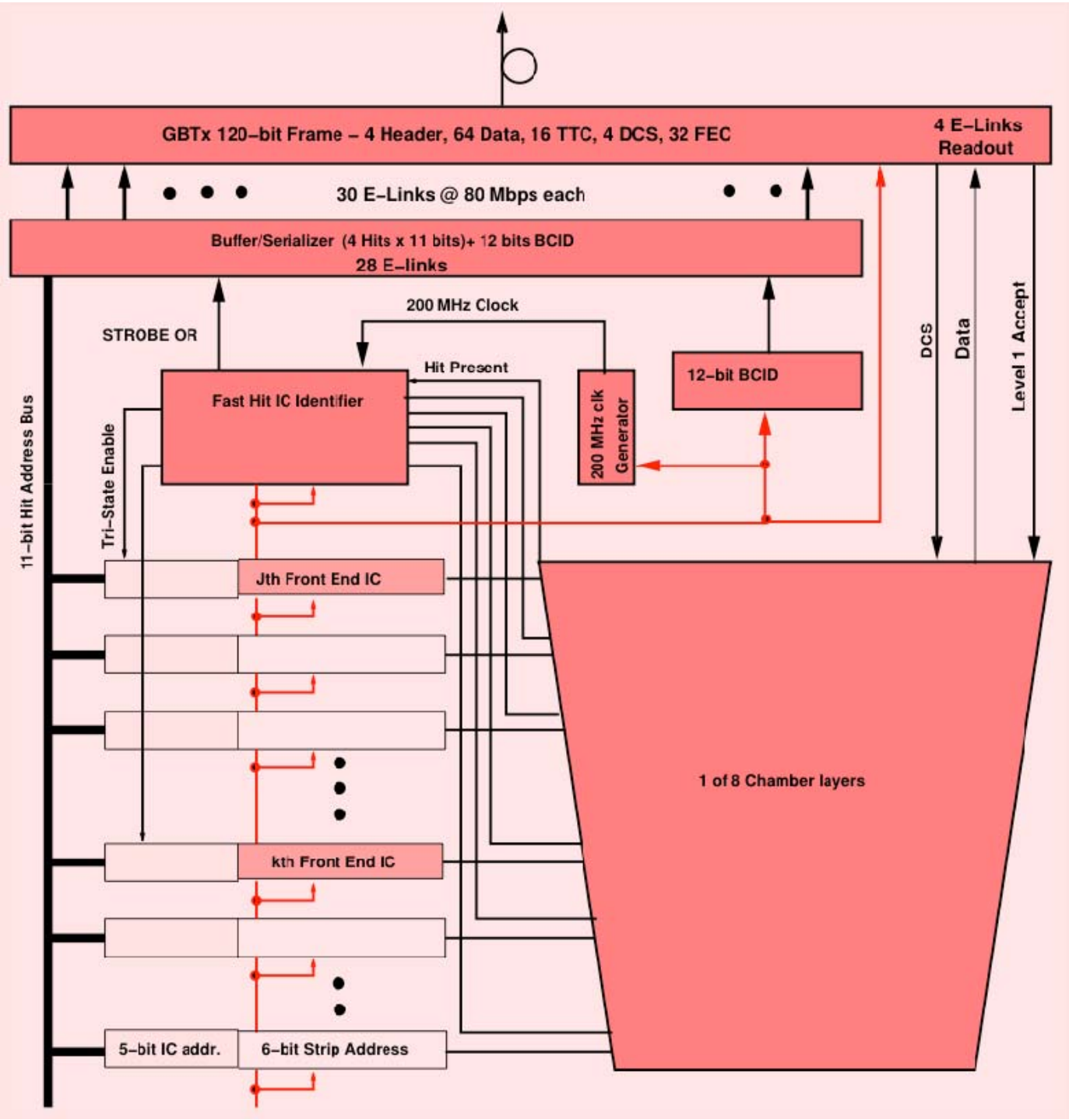
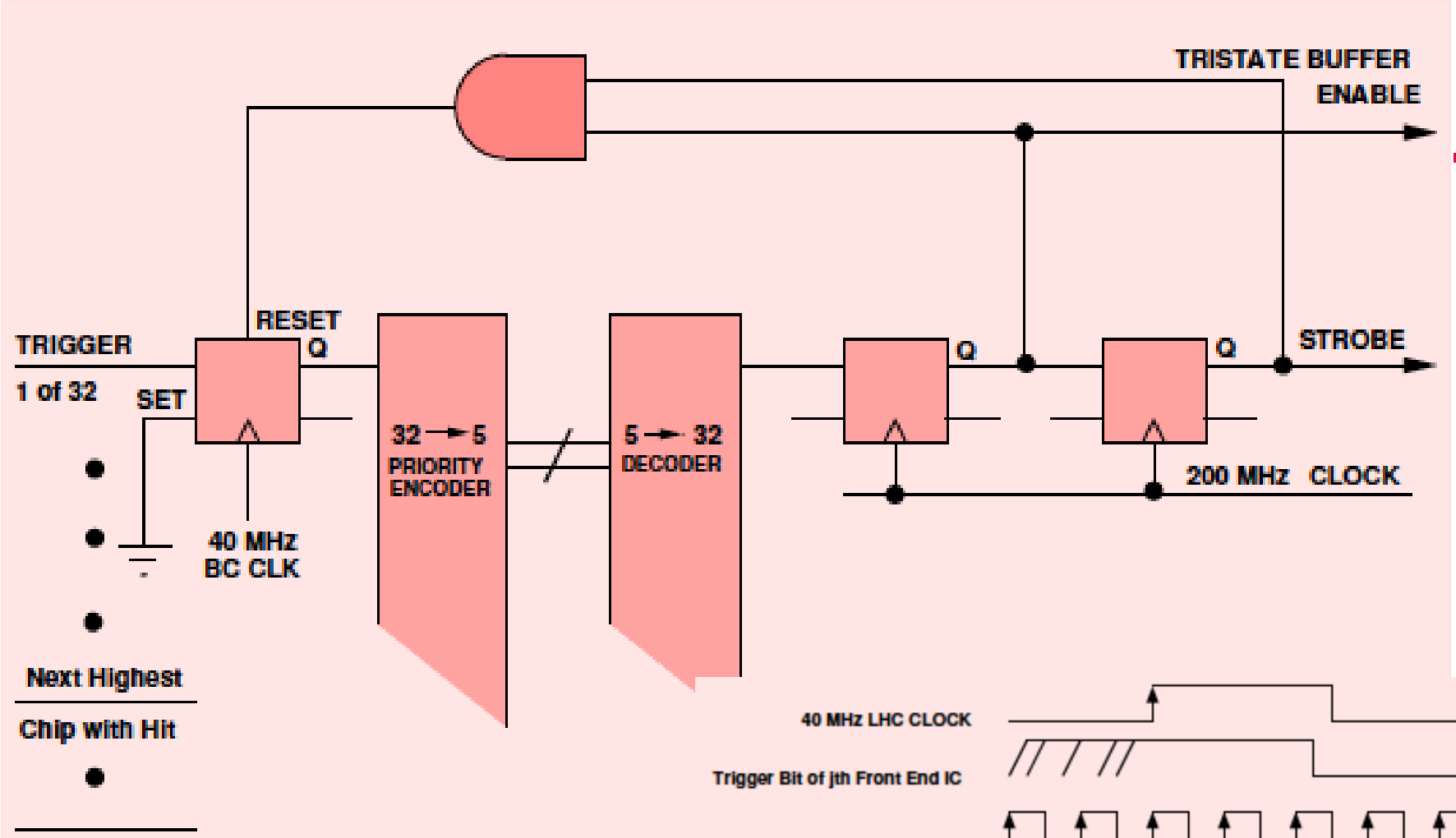
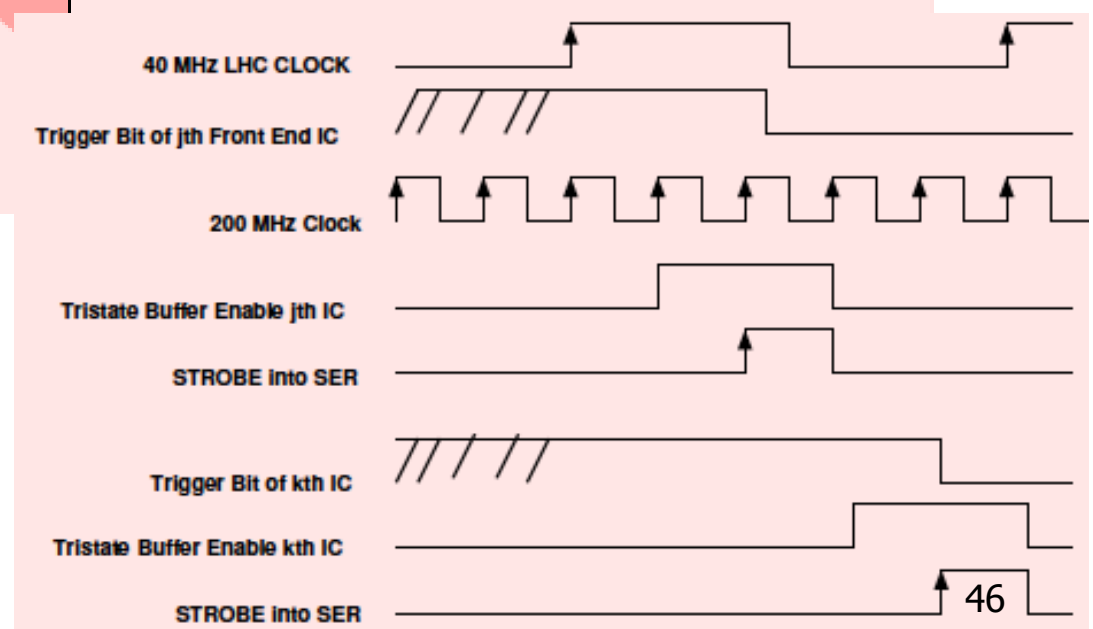

GBTx 120–bit Frame – 4 Header, 64 Data, 16 TTC, 4 DCS, 32 FEC
4 E–Links Readout
30 E–Links @ 80 Mbps each
Buffer/Serializer (4 Hits x 11 bits)+ 12 bits BCID
28 E–links
200 MHz Clock
STROBE OR
Hit Present
Fast Hit IC Identifier
200 MHz clk Generator
12–bit BCID
DCS
Data
Level 1 Accept
11–bit Hit Address Bus
Tri–State Enable
Jth Front End IC
kth Front End IC
1 of 8 Chamber layers
5–bit IC addr.
6–bit Strip Address

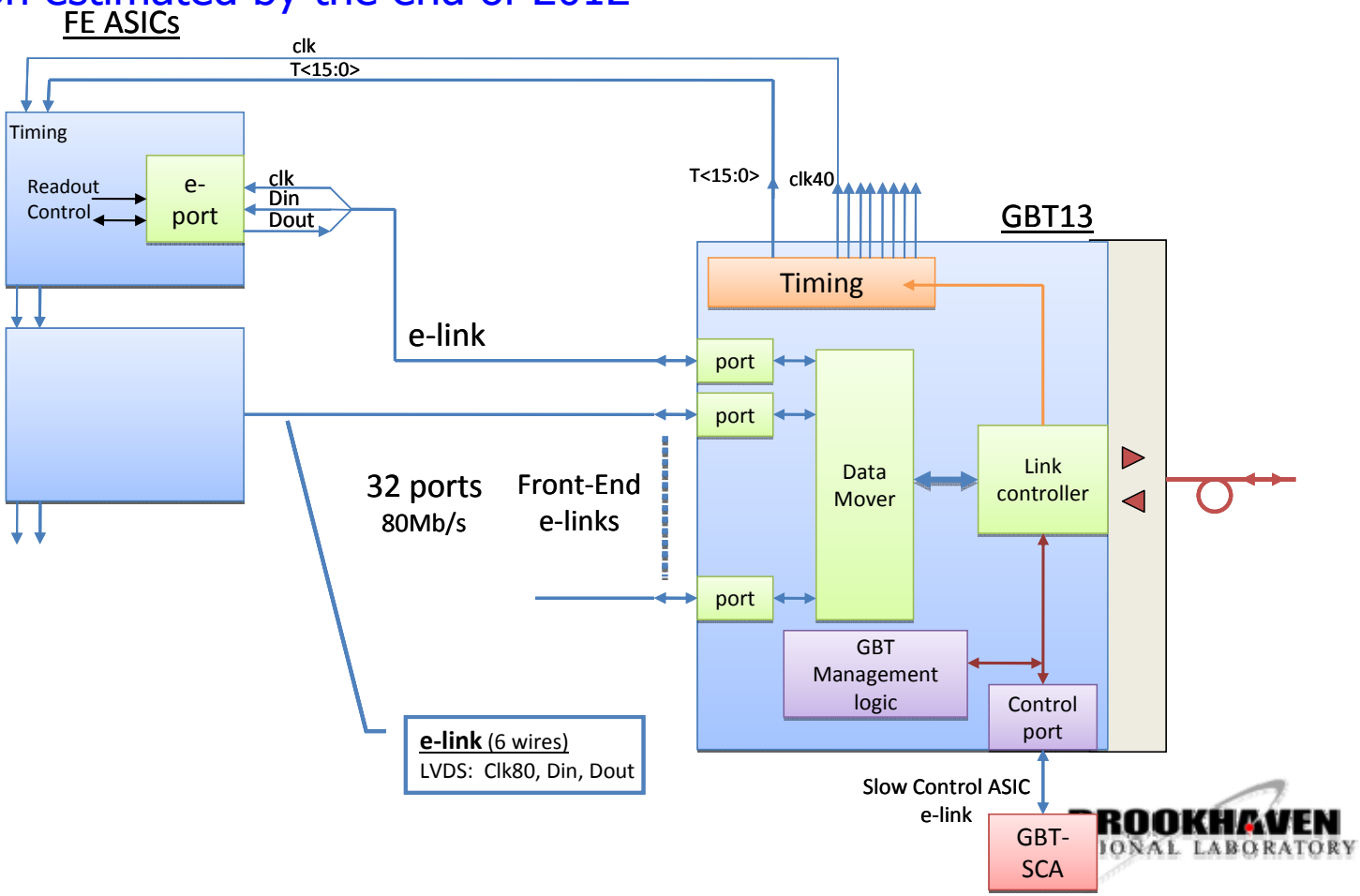


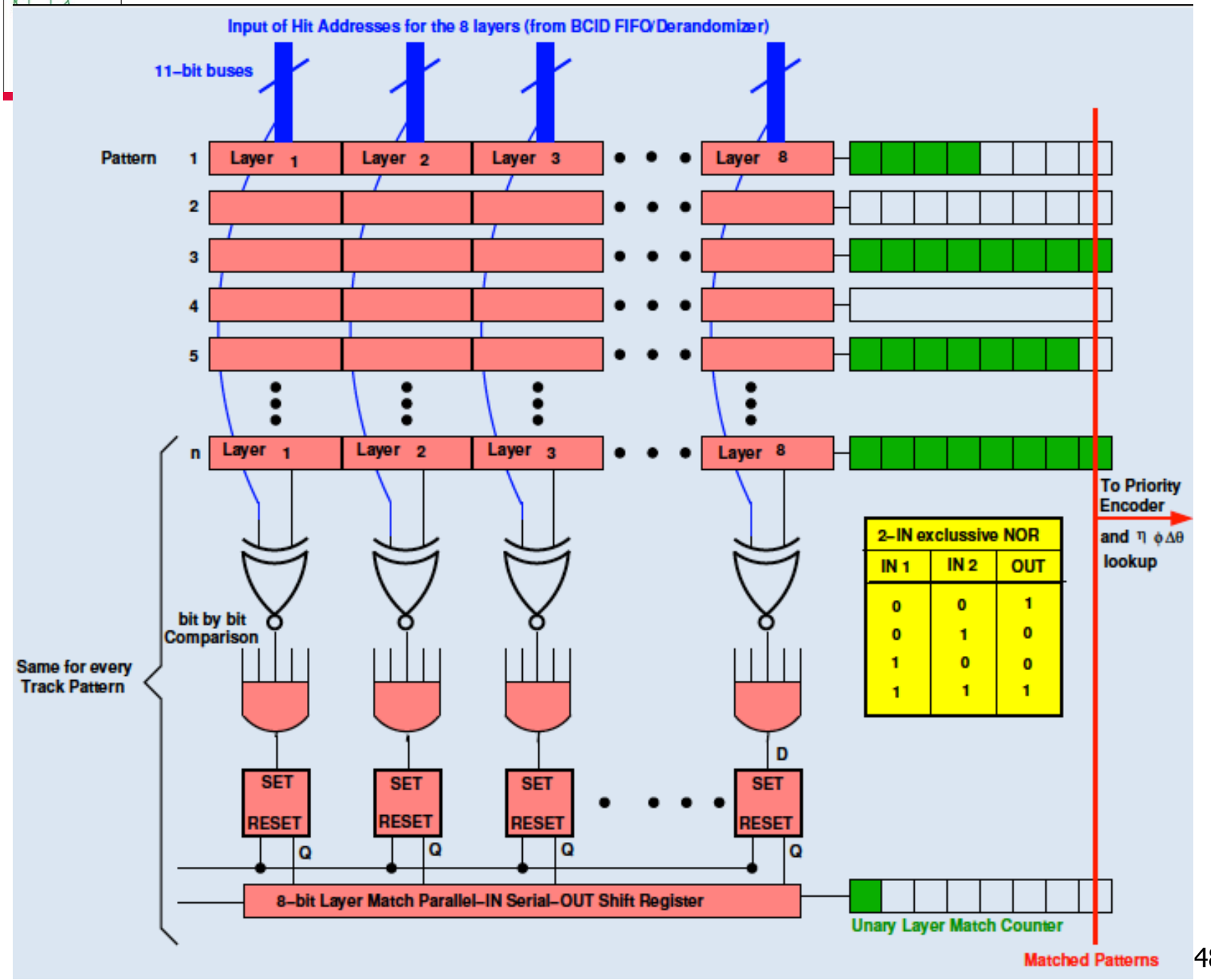


- Can transfer 2 addresses in 1 BC
- If 2 parallel paths each handling 16 chips then 4 hits can be moved in 1 BC
- Is 200 MHz clock too aggressive? (long ~0.5 m connections)
- Develop custom digital ASIC?

GBTx (Gigabit tranceiver) Chipset, being developed at CERN

- Will combine bidirectional data transfer, TTC, and DCS
- 4.8 Gbps (2.56 Gbps data, 160 Mbps DCS, 640 MBps TTC), + (1.28 Gbps FEC, 160 Mbps Header)
- First generation prototypes exist, a clock driver error resulted in reduced bandwidth
- Production estimated by the end of 2012




Input of Hit Addresses for the 8 layers (from BCID FIFO/Derandomizer)
11-bit buses
Pattern
1
2
3
4
5
n
Layer 1
Layer 2
Layer 3
Layer 8
To Priority Encoder
and η φΔθ lookup
2-IN exclussive NOR
IN 1 IN 2 OUT
0 0 1
0 1 0
1 0 0
1 1 1
bit by bit Comparison
Same for every Track Pattern
D
SET
RESET
Q
8-bit Layer Match Parallel-IN Serial-OUT Shift Register
Unary Layer Match Counter
Matched Patterns

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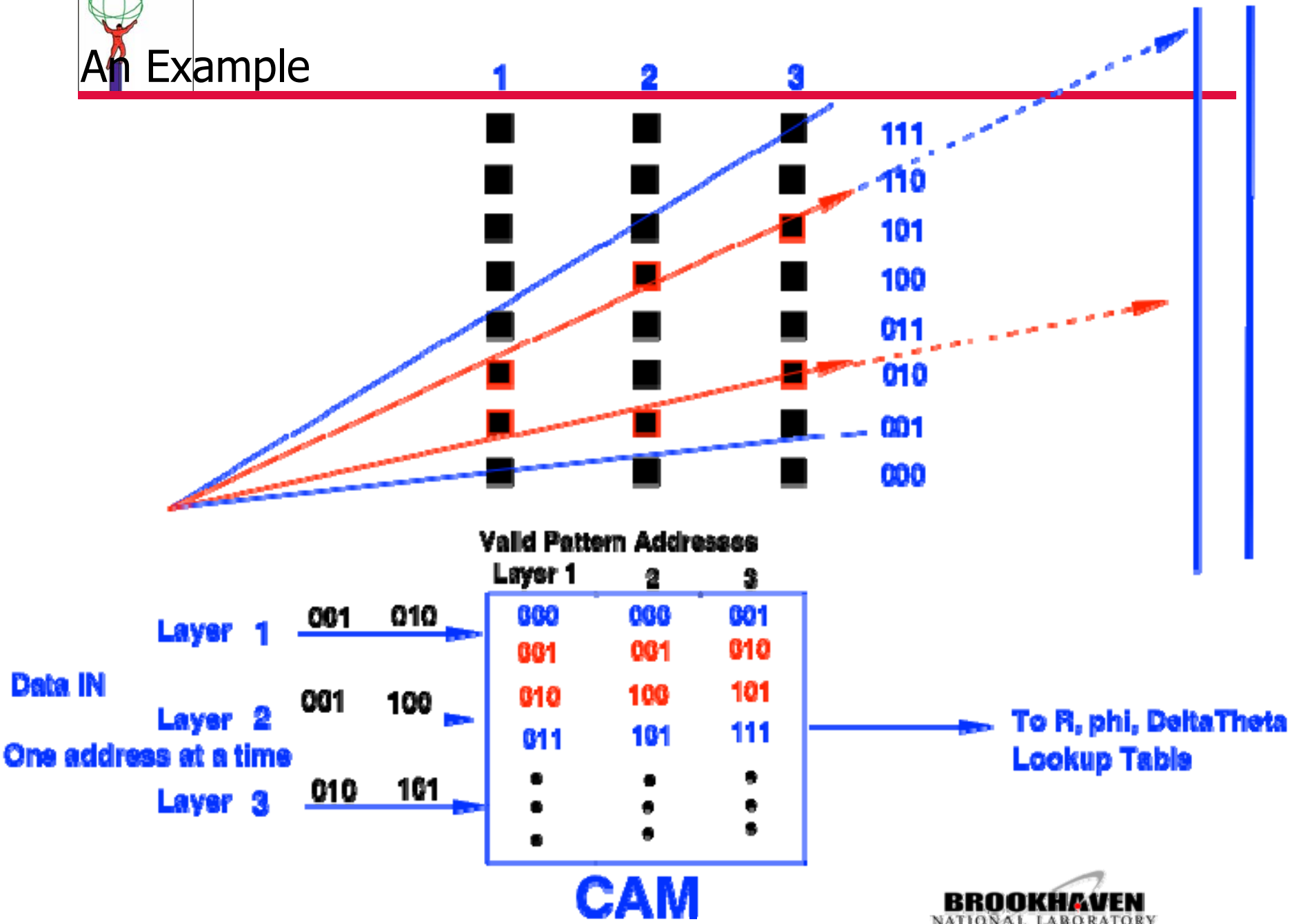
An Example



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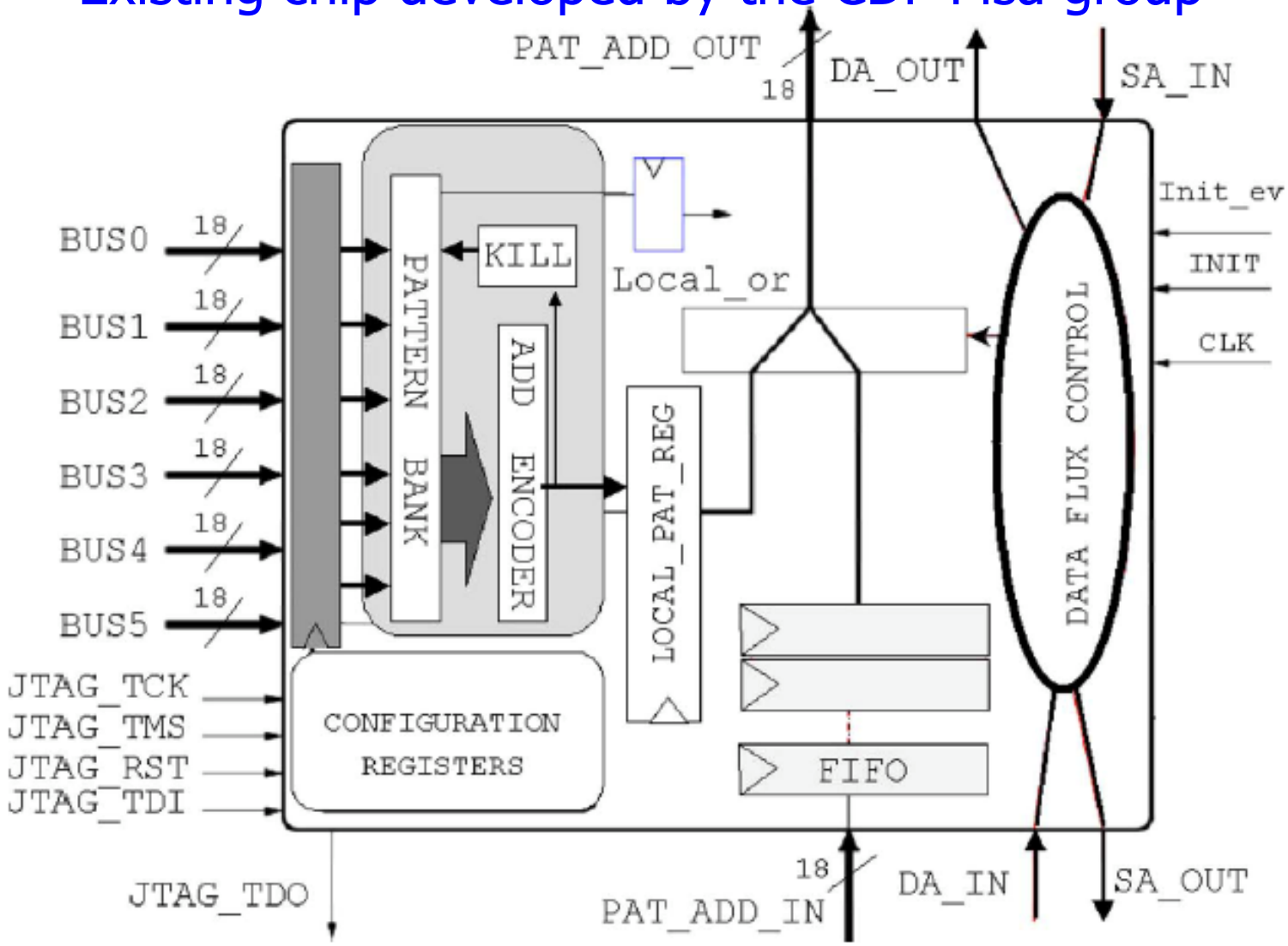
Existing chip developed by the CDF Pisa group



Time Required (25 ns BC)

Muon TOF	1
Detector Response (drift time)	1
Front End Response (peaking time)	2 -- 3
Front End to GBTx	2
To USA15 (80 m fiber)	15
GBTx FPGA to CAM (up to 5 addresses per BCID)	1 – 2
CAM Read (160 MHz clock)	2 – 3
To Sector Logic	1 – 5*
Total	25 – 32

* Assumes that existing sector logic clocked @ 40 MHz

Summary

- ATLAS Muon Upgrade of Small Wheels a challenging project requiring high precision and fast trigger
- Micromegas based detectors a promising technology
- Resistive strips provide spark resistance without compromising performance
- Progress towards Large Area Detectors
- Readout and Trigger concept that seems feasible
- MOST of the electronics processing is for the trigger
- Concept reduces the 2M channels to ~30,000 – eliminates argument that Mmegas will be much more expensive because of channel cnt.
- One optical fiber per layer (GBTx assumed)
- Custom Front End IC under development at BNL Instr. Div.
- Need to develop one or two custom digital ICs