TRACKING DETECTORS

Lecture 1

Basics: propagation of particles in media and measurements

Lecture 2

Main tracking detector concepts and examples of their use

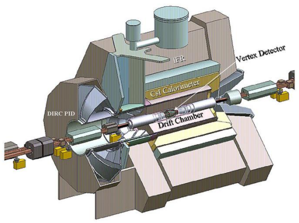
Lecture 3

Overview of muons systems at collider experiments

Recent colliders

Type	~sqrt(s)	Colliders
ee	few-10 GeV	a whole bunch, including B-factories
	100 GeV	LEP
	1000 GeV	future ILC
pp	0.5 TeV	SppS
	2 TeV	Tevatron
	10 TeV	LHC
ep	300 GeV	HERA

20+ collider detectors…



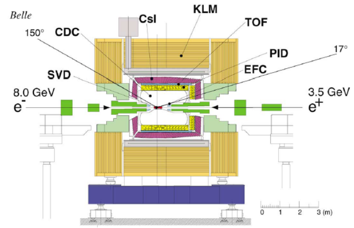
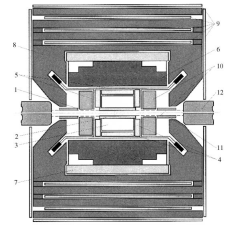
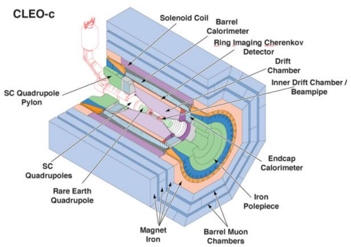
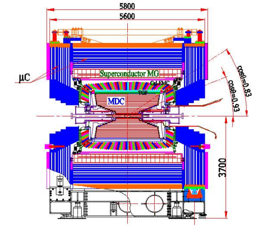
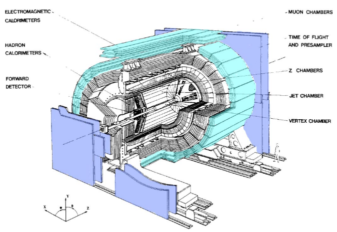


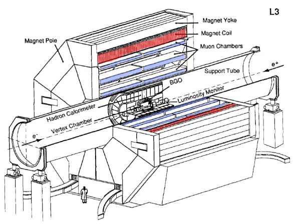
Fig. 1. Side view of the Belle detector.

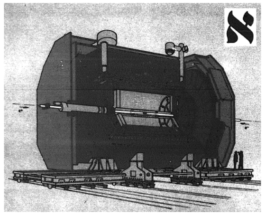


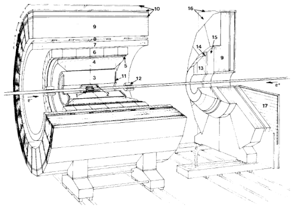


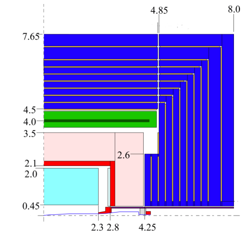


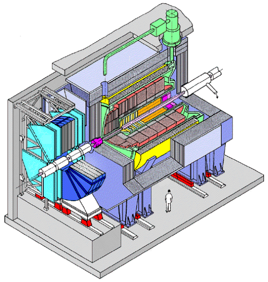


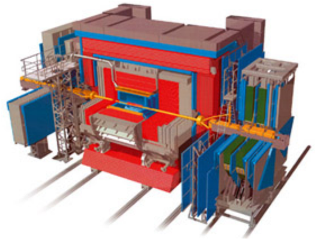


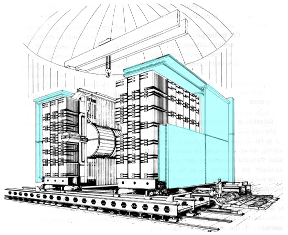


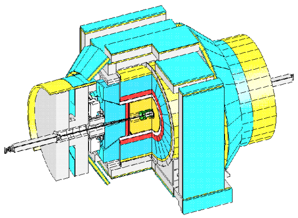


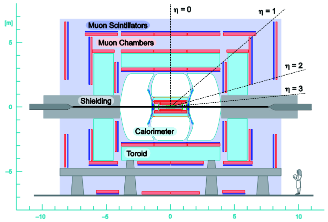


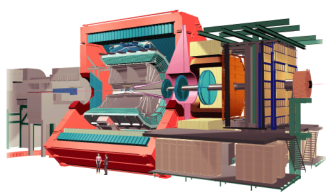


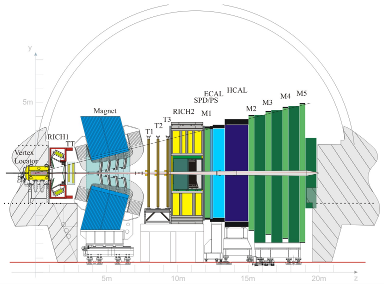


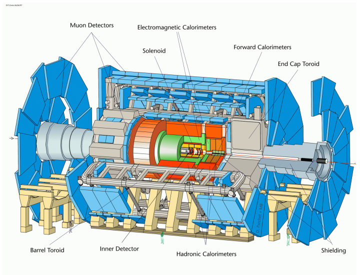


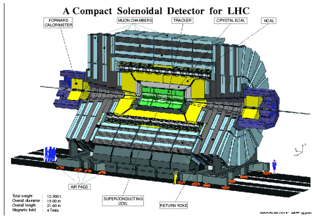




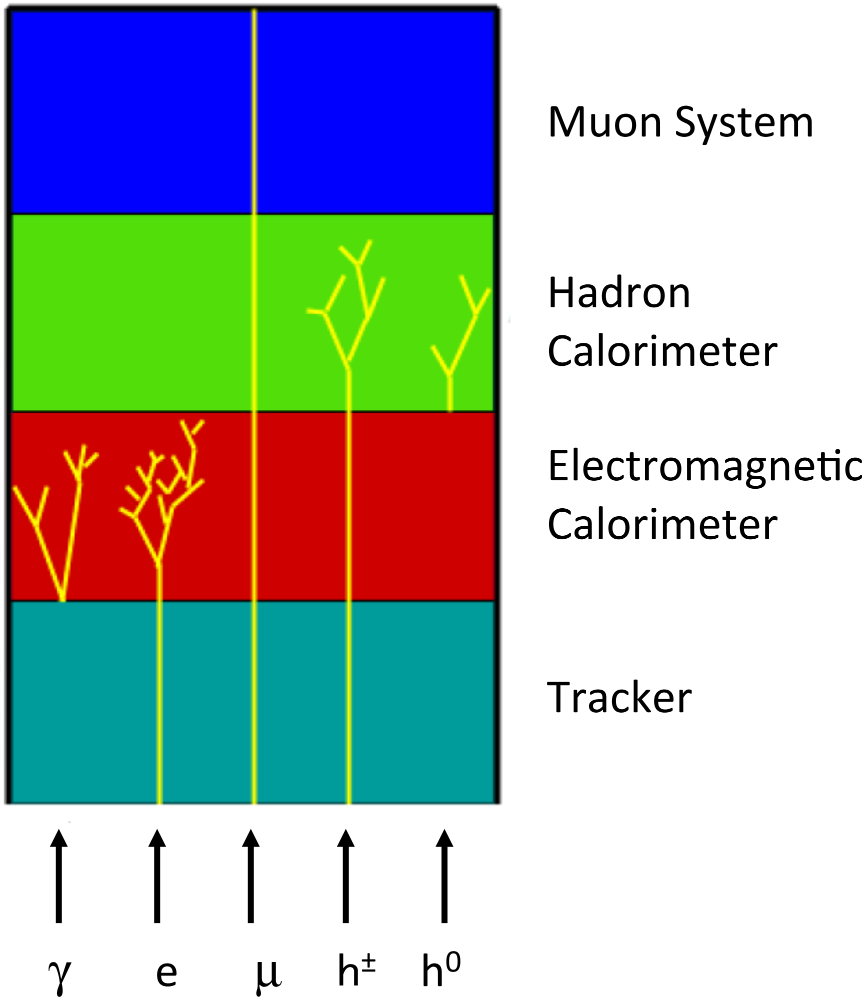


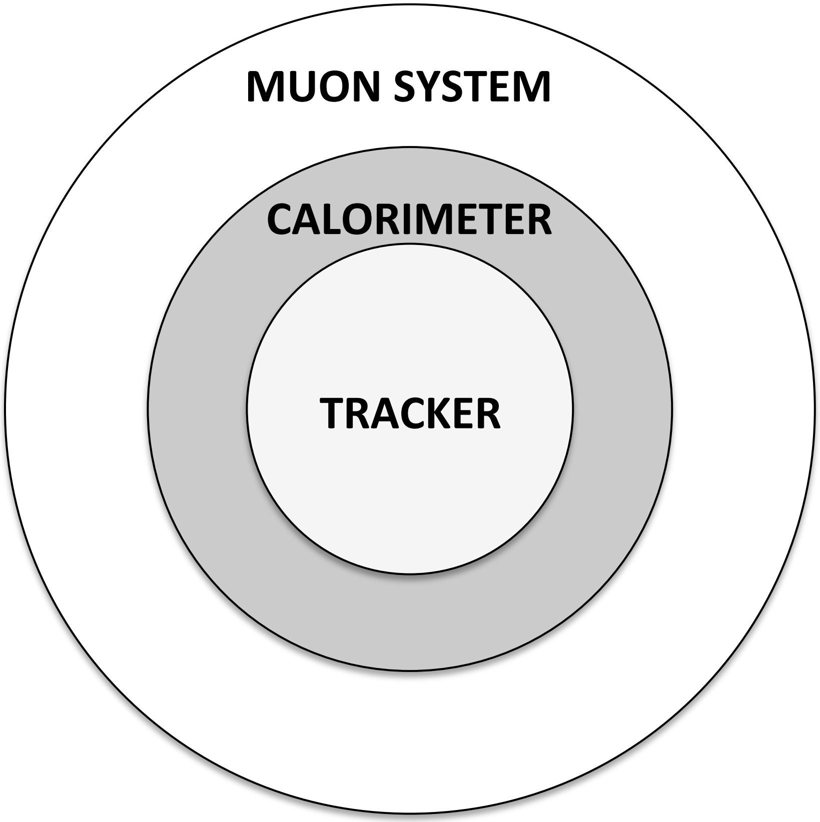




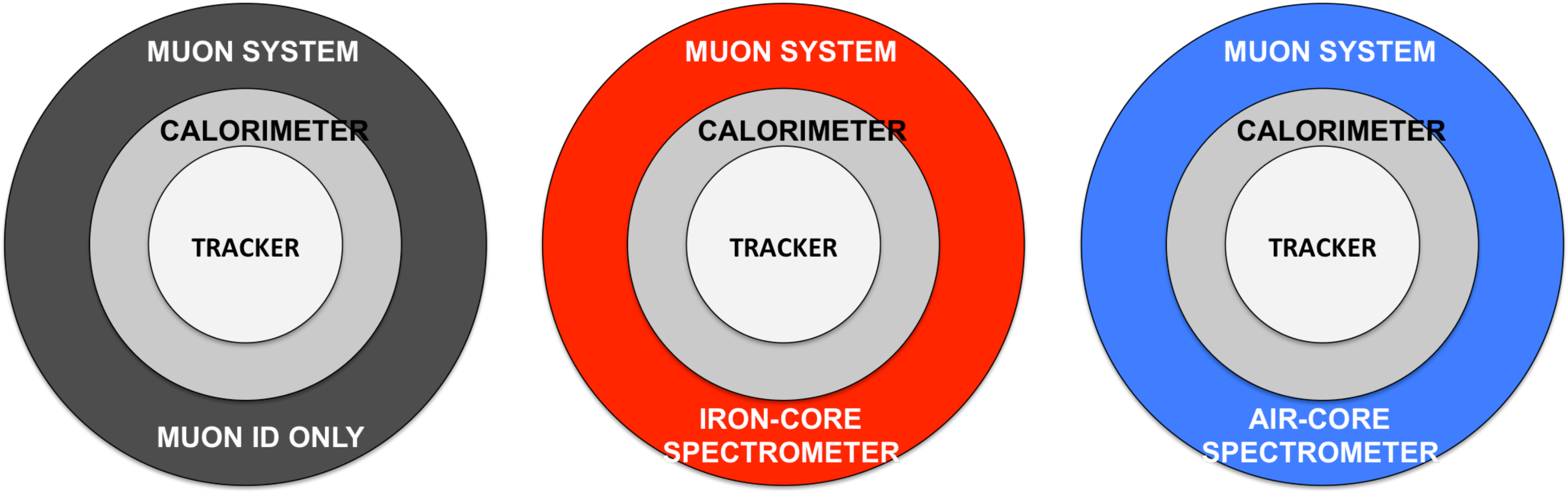


Generic collider detector layout

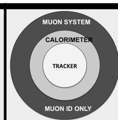
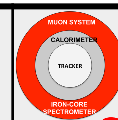
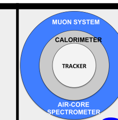




20+ collider experiments…
but only 3 distinct muon system concepts



Muon Systems at Colliders

		 Muon ID only	 Iron-core spectrometer	 Air-core spectrometer
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	100 GeV (LEP)	ALEPH, DELPHI, OPAL		L3
	1000 GeV (ILC)	LDC, GLD, SiD		4th
pp	0.5 TeV (SppS)	UA1		
	2 TeV (Tevatron)	CDF	D0	
	10 TeV (LHC)	LHCb	CMS	ATLAS
ep	300 GeV (HERA)		H1, ZEUS	

Requirements and basic parameters

- Large area (cost)
  - from 1000 m^2 to above 10,000 m^2 (hectares)
- Low rates, relatively low that is…
  - from cosmic rates (0.01 Hz/cm^2) to 1 kHz/cm^2
- Precision requirements
  - from ~1 cm to <100 μm
- Number of readout channels
  - from 1K to 1M
- Trigger
  - from NO to YES with a few ns accuracy and <0.5 μs latency

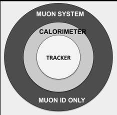
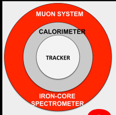
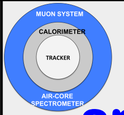
Detector technologies

Tubes	RPC
MWPC	Scint

DETECTORS	READOUT
Tubes	yes/no drift time wire charge division induced cathode charge
MWPC	yes/no drift time induced cathode charge
RPC	yes/no
Scintillators	yes/no

Muon Systems at Colliders

Tubes	RPC
MWPC	Scint

		 **Muon ID only**	 **Iron-core spectrometer**	 **Air-core spectrometer**
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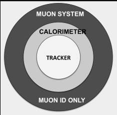
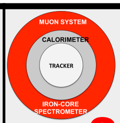
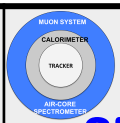
Muon Systems at Colliders

Tubes	RPC
MWPC	Scint

		 **Muon ID only**	 **Iron-core spectrometer**	 **Air-core spectrometer**
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Muon Systems at Colliders

Tubes	RPC
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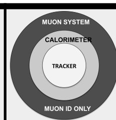
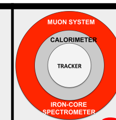
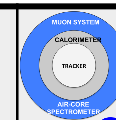
		 Muon ID only	 Iron-core spectrometer	 Air-core spectrometer
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Muon Systems at Colliders

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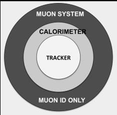
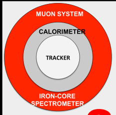
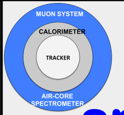
		 Muon ID only	 Iron-core spectrometer	 Air-core spectrometer
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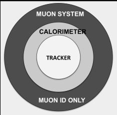
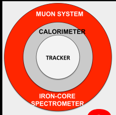
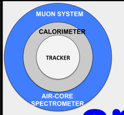
Muon Systems at Colliders

Tubes	RPC
MWPC	Scint

		 Muon ID only	 Iron-core spectrometer	 Air-core spectrometer
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Muon Systems at Colliders

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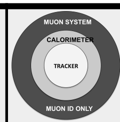
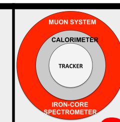
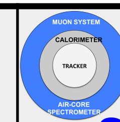
		 Muon ID only	 Iron-core spectrometer	 Air-core spectrometer
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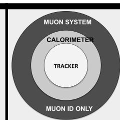
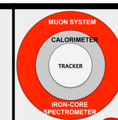
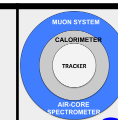
Muon Systems at e^+e^- colliders

Tubes	RPC
MWPC	Scint

		 Muon ID only	 Iron-core spectrometer	 Air-core spectrometer
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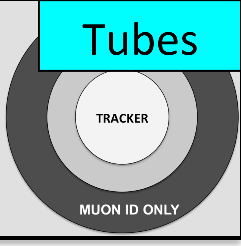
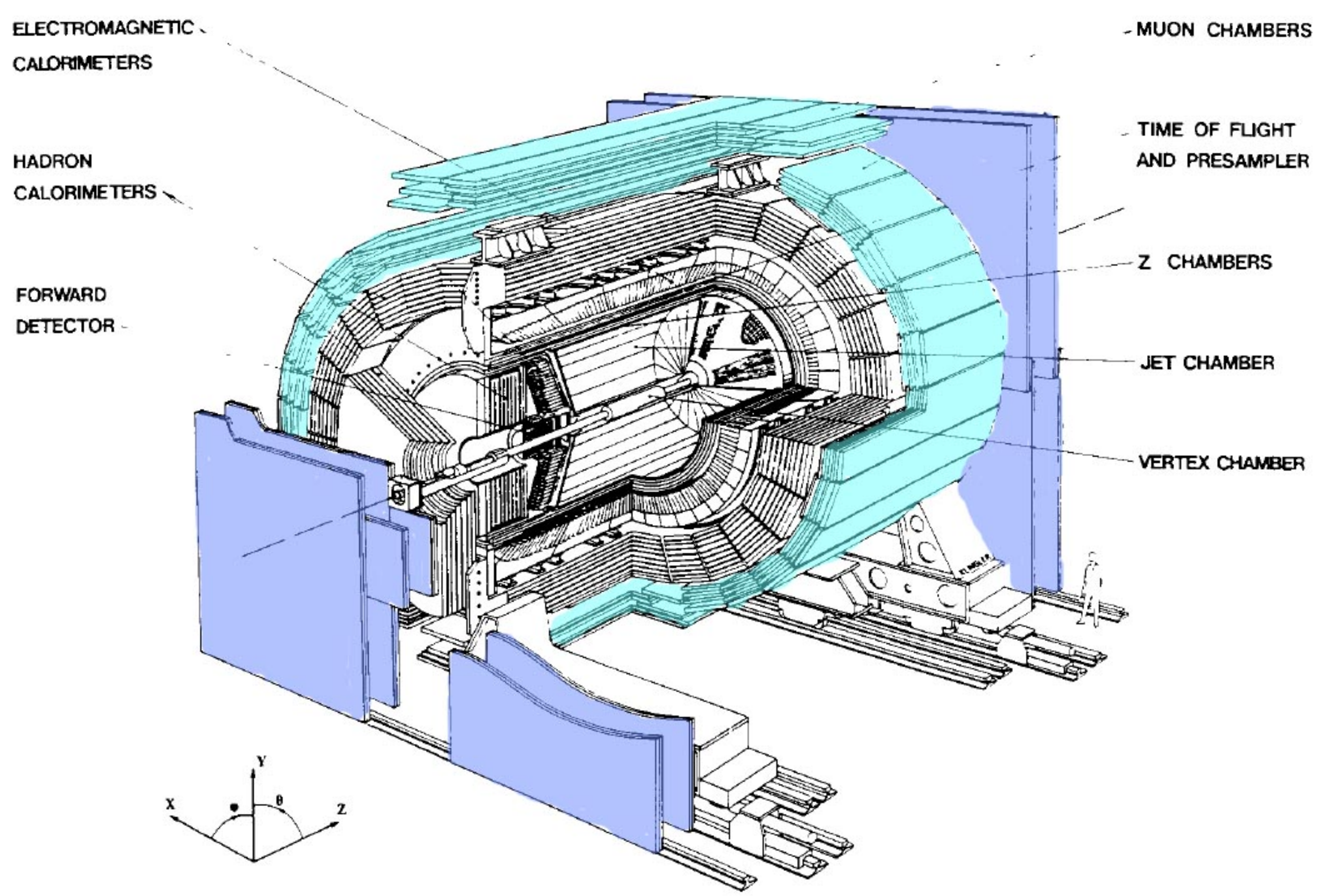
OPAL

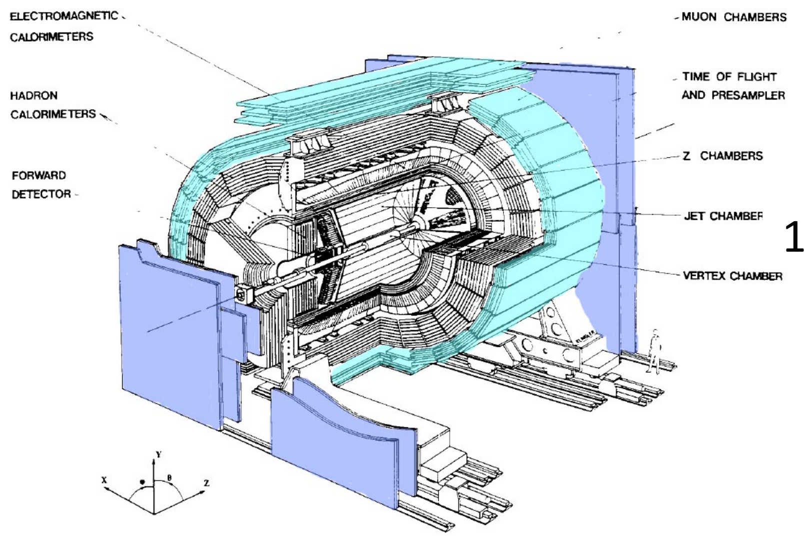




Barrel:
30 cm Drift Tubes

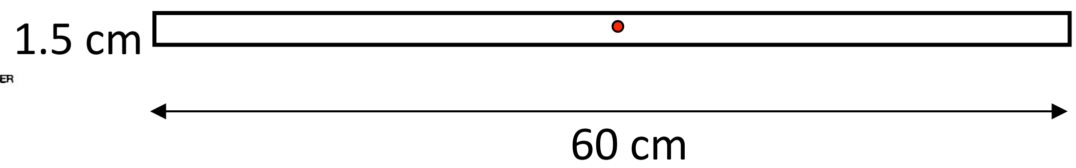
Endcaps:
Iarocci Tubes

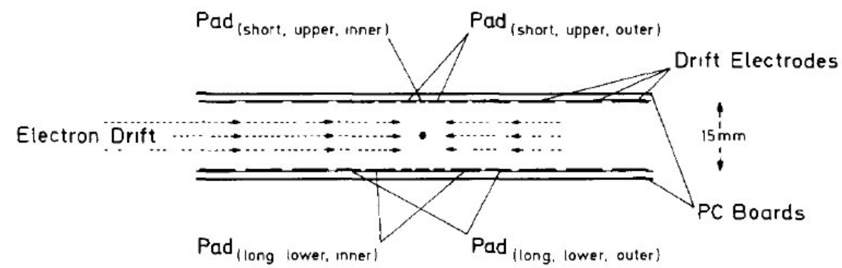
OPAL: barrel muon chambers



30 cm Drift Tubes

(inspired by design of chambers for JADE)





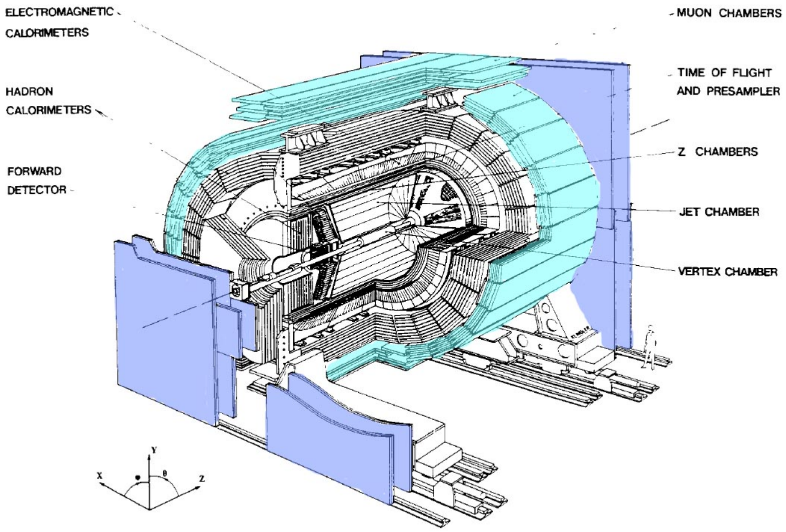
- 60 x 1.5 cm^2 cells, 30 cm drift
- field-shaping electrodes (25% of insulator is exposed—takes a few hrs to charge up)
- only ~1K readout channels
- resolution

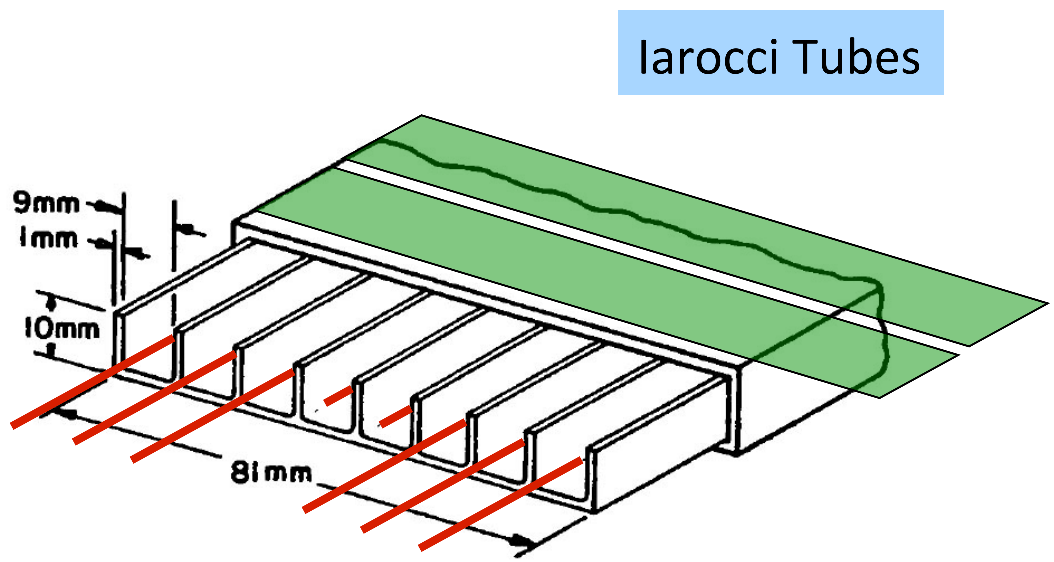
  ~1 mm coordinate resolution from drift time

  ~2 mm along wires (charge division, vernier pads)

DELPHI used conceptually similar design (10 cm drift) for its entire muon system

OPAL: endcap muon chambers



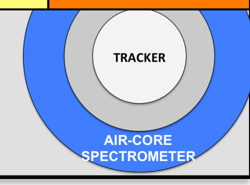


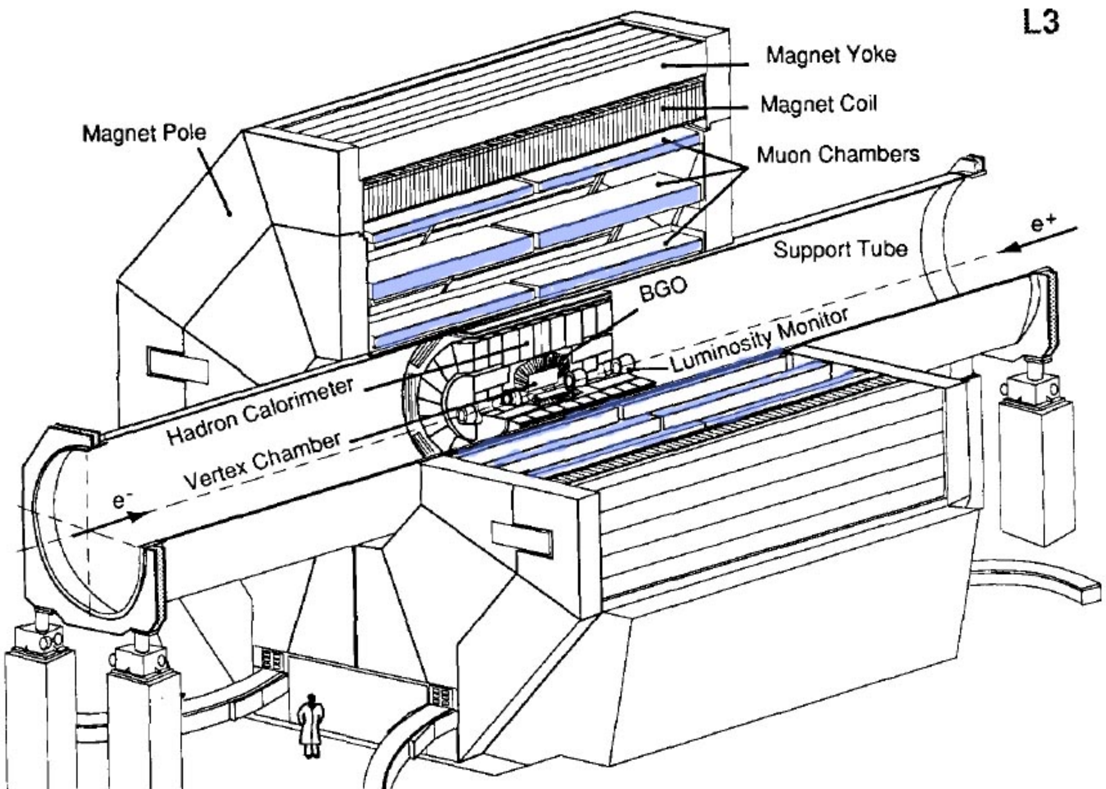
- 1 x 1 cm^2 cells
- 1 cm wide strips on both sides (across and along wires)
- 42K readout channels
- resolution:
  - ~1 mm coordinate resolution along wires (induced charge on 1 cm strips)
  - ~3 mm across wires (yes/no from 1 cm strips)

ALEPH, CLEO used Iarocci tubes throughout their whole muon systems
ZEUS, H1 used Iarocci tubes for most of their muon systems

L3 Detector

Tubes | MWPC | RPC





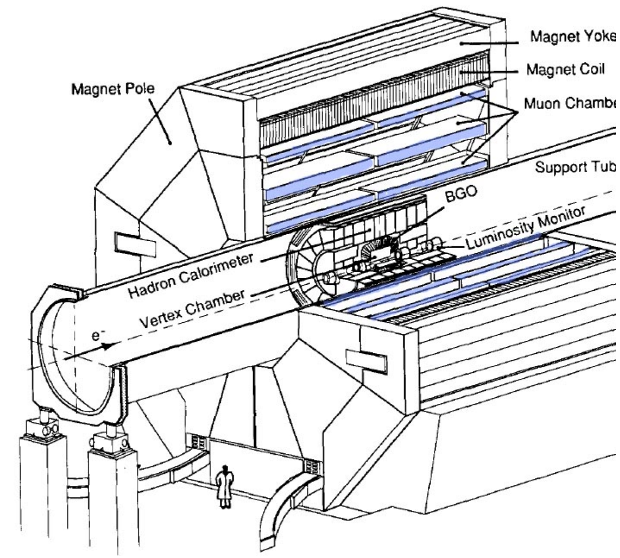
<u>Barrel</u>

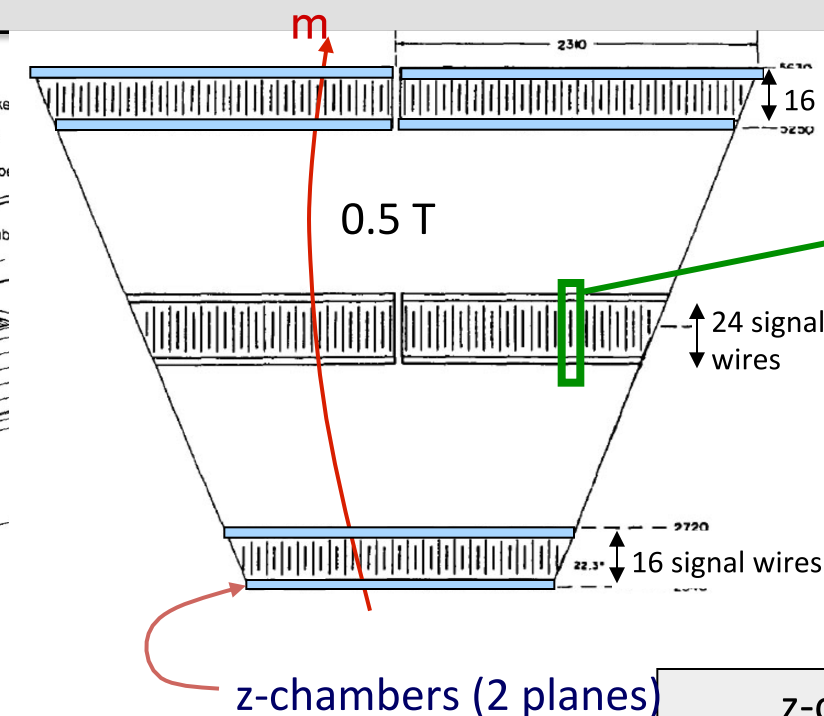
- Air-core spectrometer
- Multi Wire Drift Chambers
- Drift Tubes

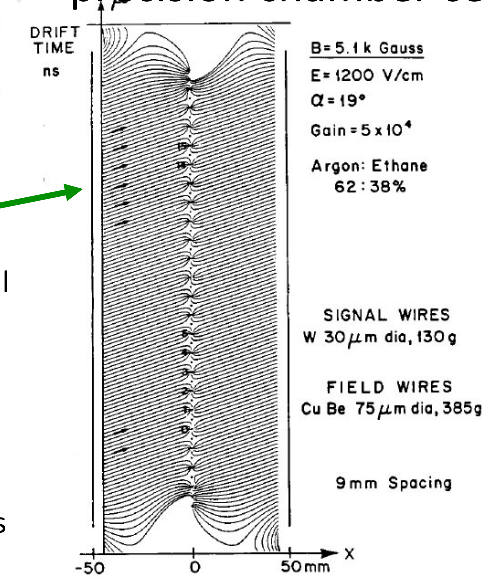
<u>Endcap upgrade for LEP-2 (not shown)</u>

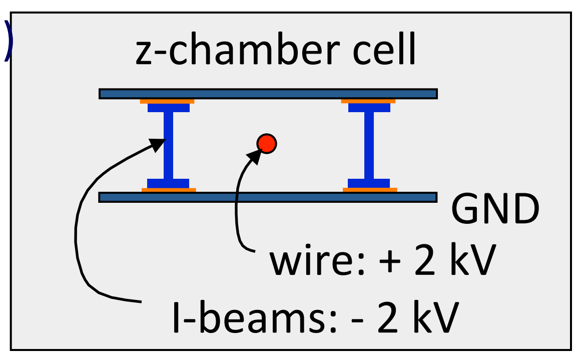
- Iron-core spectrometer
- Multi Wire Cell Chambers
- RPCs

L3: barrel muon chambers



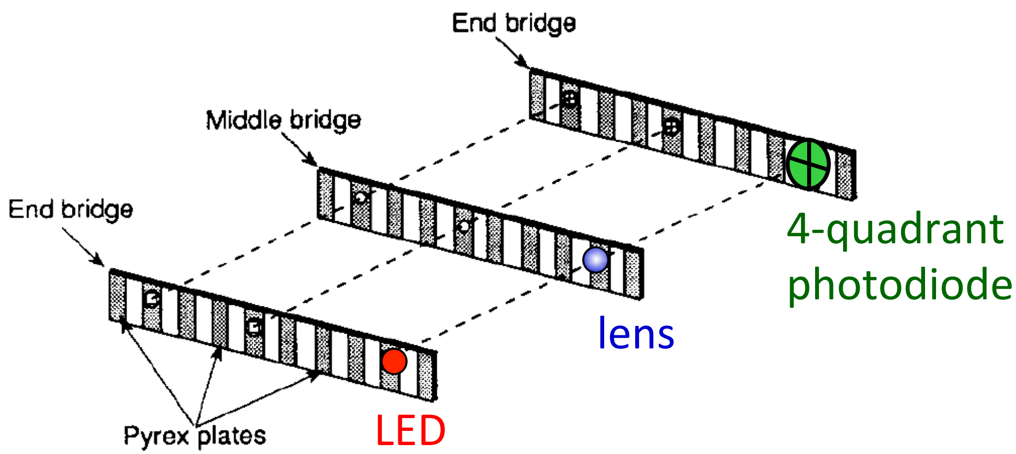


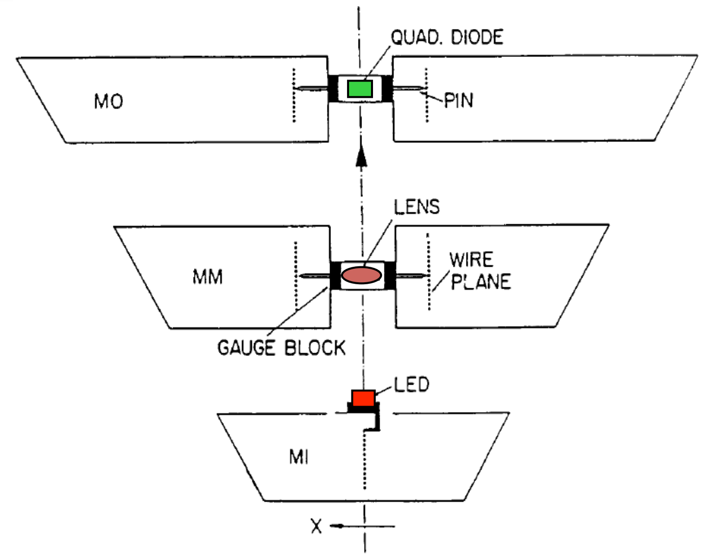


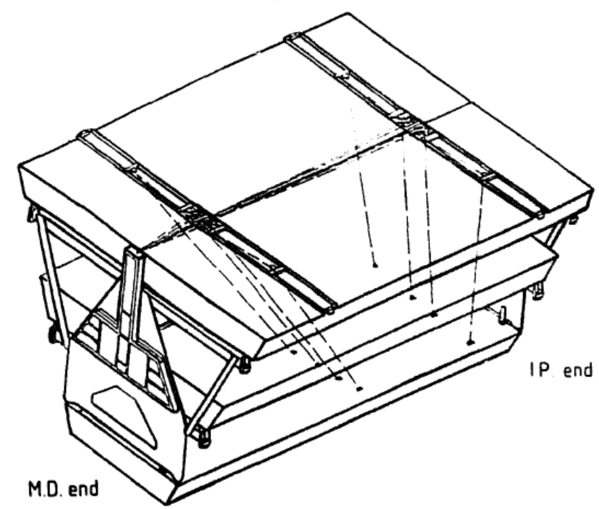


- precision chambers: Multi Wire Drift Chambers
- z-chambers: Drift Tubes
- 250K wires
- 24K readout channels
- resolution:
  - ~200 μm rφ-resolution per wire (drift time) → ~30 μm alignment is needed
  - ~500 μm z-resolution per wire (drift time)

L3: 30-mm alignment of chambers



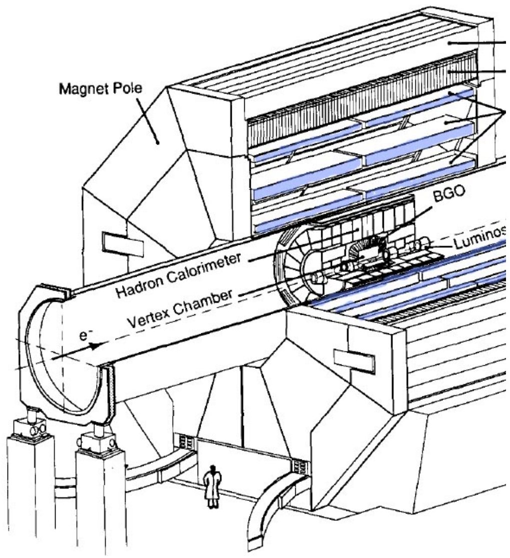




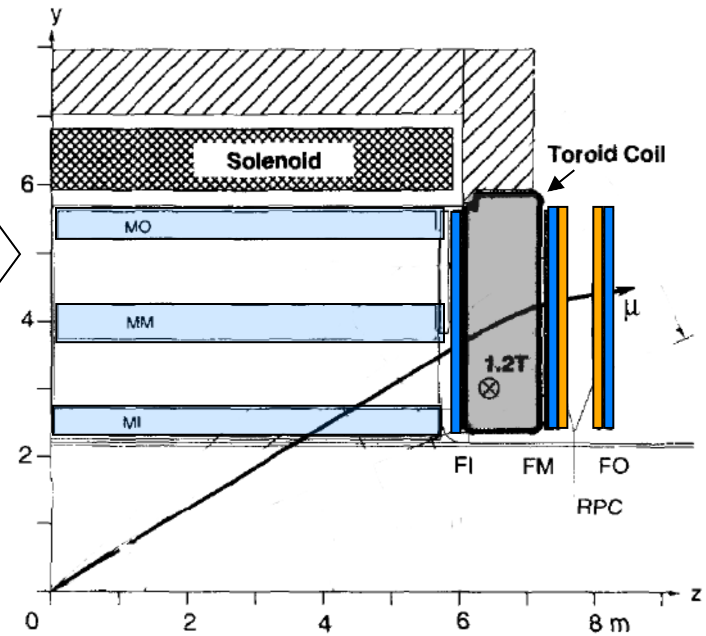
The UV laser system.

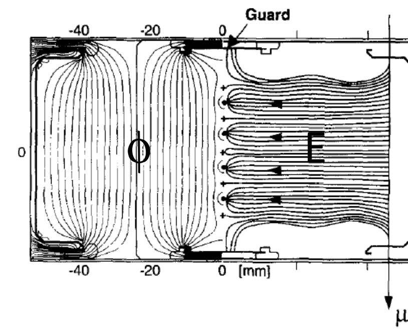
- passive alignment:
  5-µm accurate bridges for wires
- active alignment:
  wire straightness monitor within a chamber
  rφ-alignment of three chambers
  laser beacon to monitor torsion
- validation:
  radial laser beam (equivalent of a straight track)
  cosmic ray muons (B=0)

L3: forward muon chambers



upgrade



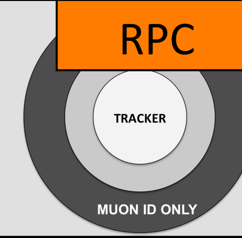


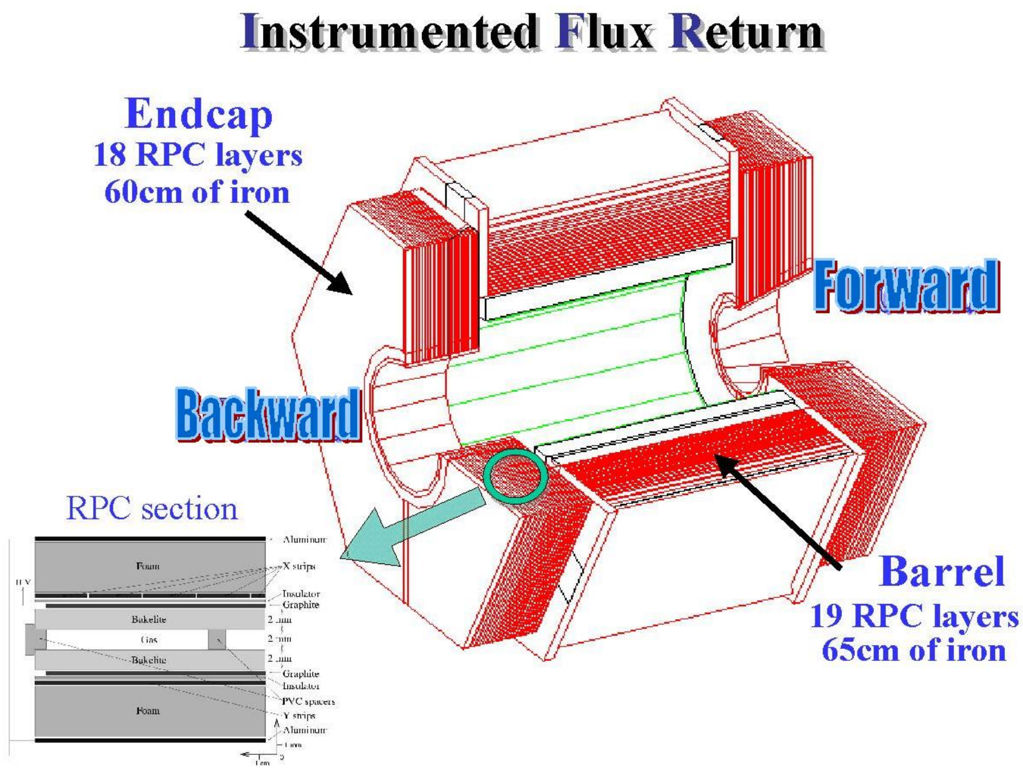
- endcaps of magnet yoke are magnetized

- 3 layer of precision chambers: Multi Wire Cell Chambers (3 layers each)
- resolution: ~250 μm resolution per wire (drift time)

- 2 layers of RPCs for trigger (first use of RPCs in collider experiments)

BaBar





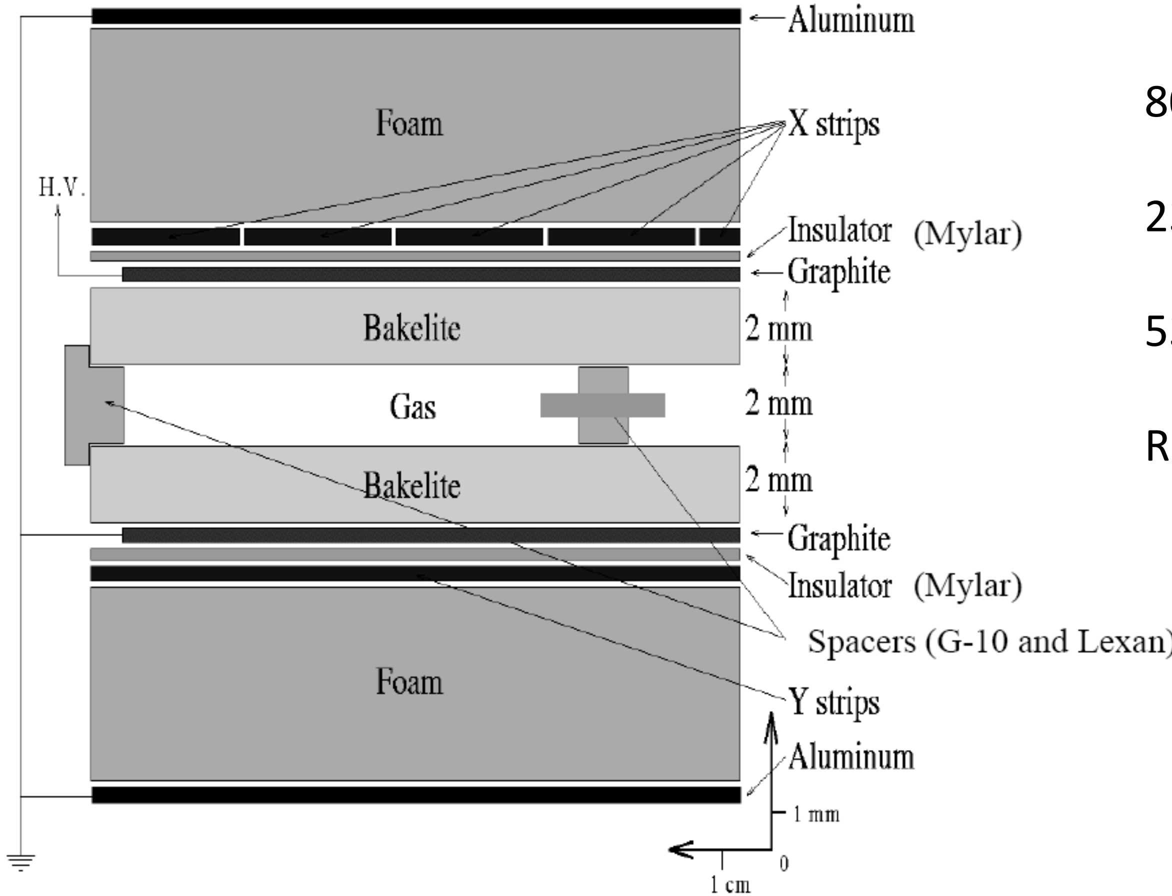
Classical muon ID-only

- RPCs in iron muon filter (although there is B, no momentum measurement is intended and strips are made very wide)

- Momentum is from central tracker

$$\frac{\delta p}{p} = 1.3 \cdot 10^{-3}\ p\ \oplus\ 0.0045$$

BaBar: RPCs



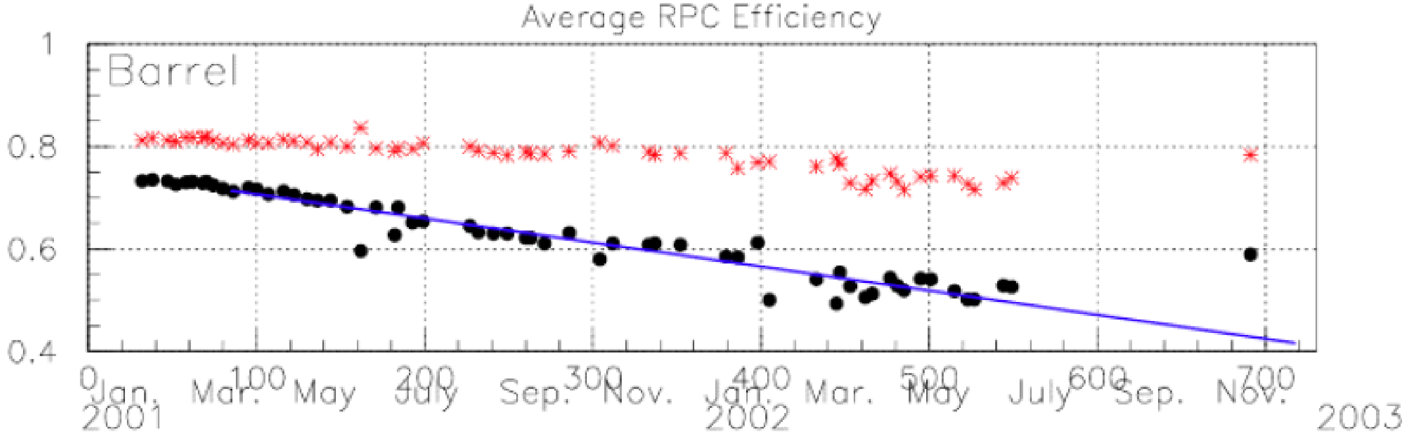
800 single-gap chambers

2300 m^2 area

53K channels

Readout from both sides (x,y)

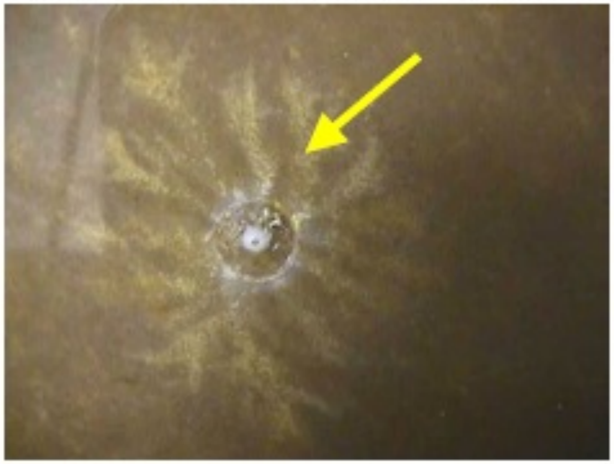
BaBar: RPC (Lesson 1)

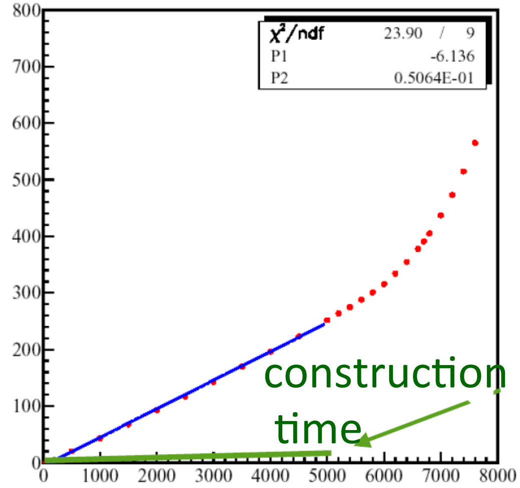


Replacement of 2000:
1/3 linseed oil, problem remains

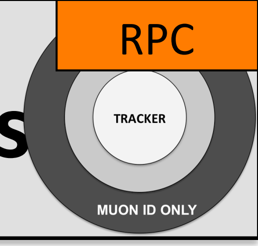
What does "too much of oil" means ?

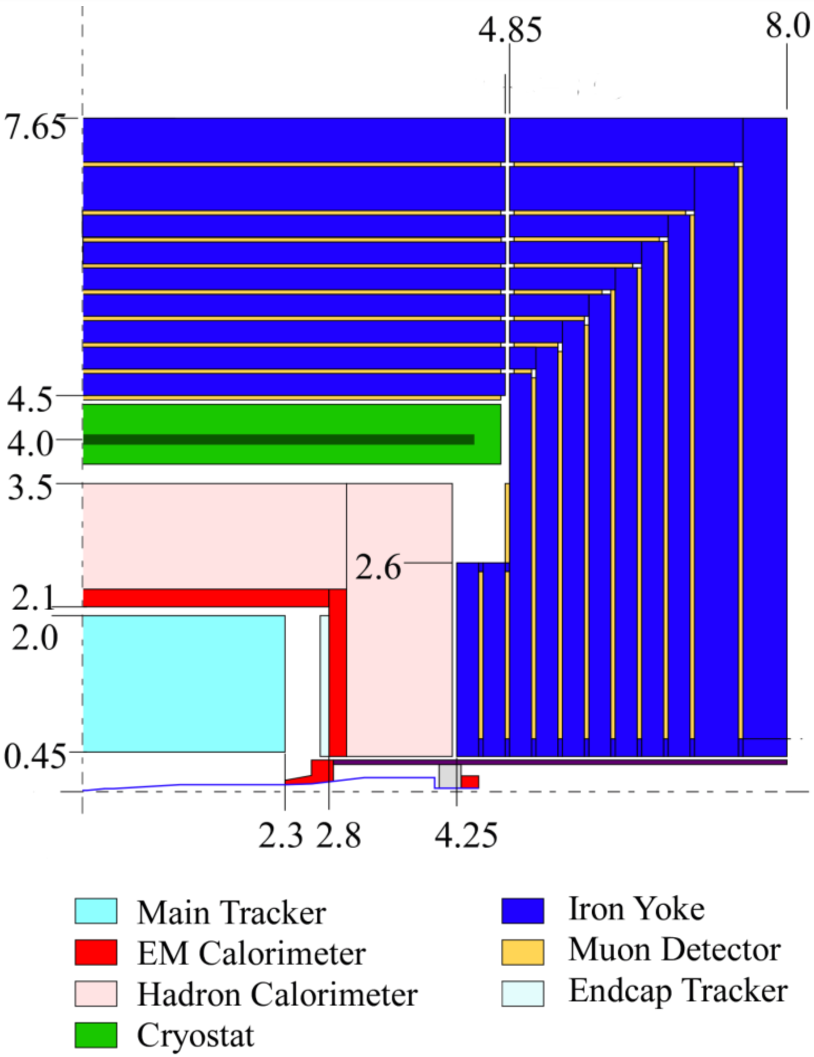
A "beam tree" around the button on the anode





Three of 4 ILC Detector Concepts





LDC, GLD, SiD

Muon ID only:

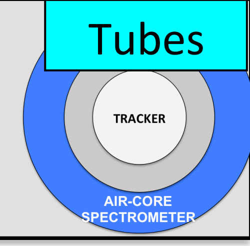
RPC is a favorite choice

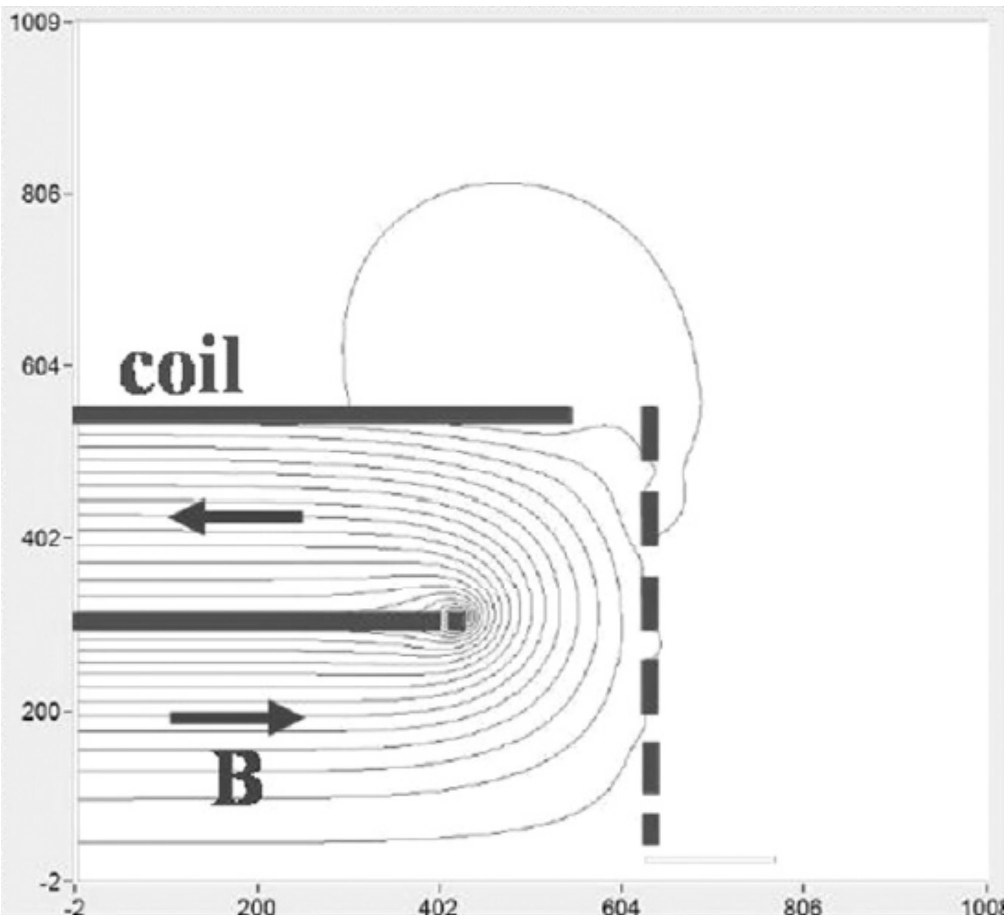
- ~1 cm resolution (3 cm strips)
- ~4,000 m^2 area
- ~100K readout channels

Momentum measurement from a main tracker (TPC or Si):

$$\frac{\delta p}{p} = 2 \cdot 10^{-5}\ p$$

The 4th ILC Detector Concept





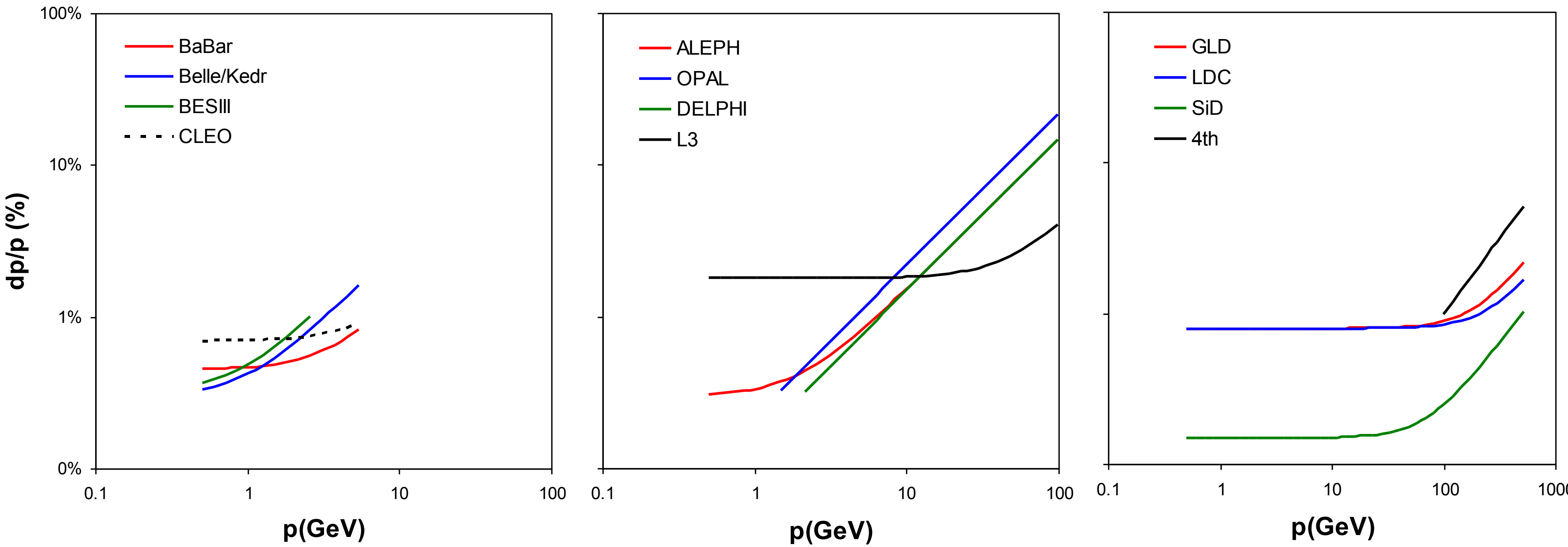
Muon air-core spectrometer:

- Dual solenoid and end coils form "two co-axial fields"
- Muon system resides in the outer annulus field
- Precision cylindrical drift tubes (ATLAS design): ~80 μm resolution

Momentum measurement:

$$\frac{\delta p}{p} = 10^{-4}\ p$$

Momentum Resolution comparison

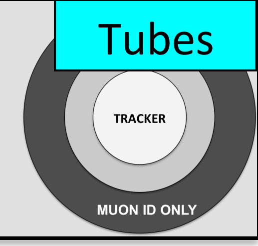


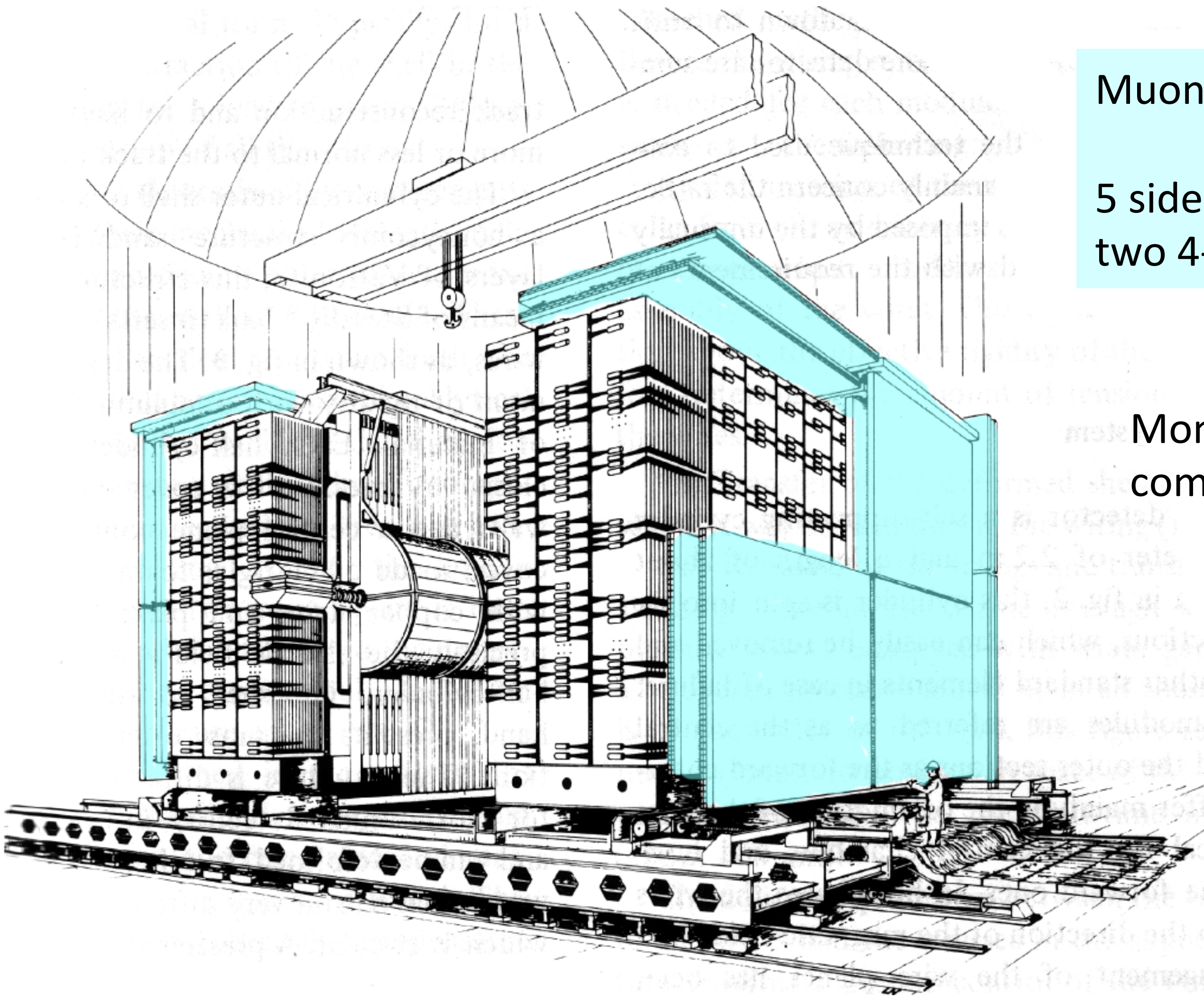
Muon Systems at pp colliders

Tubes	RPC
MWPC	Scint

		Muon ID only	Iron-core spectrometer	Air-core spectrometer
ee	few-10 GeV	BaBar, Belle, CLEO, BES, KEDR		
	100 GeV (LEP)	ALEPH, DELPHI, OPAL		L3
	1000 GeV (ILC)	LDC, GLD, SiD		4th
pp	0.5 TeV (SppS)	UA1		
	2 TeV (Tevatron)	CDF	D0	
	10 TeV (LHC)	LHCb	CMS	ATLAS
ep	300 GeV (HERA)		H1, ZEUS	

UA1 at Sp$\bar{p}$S





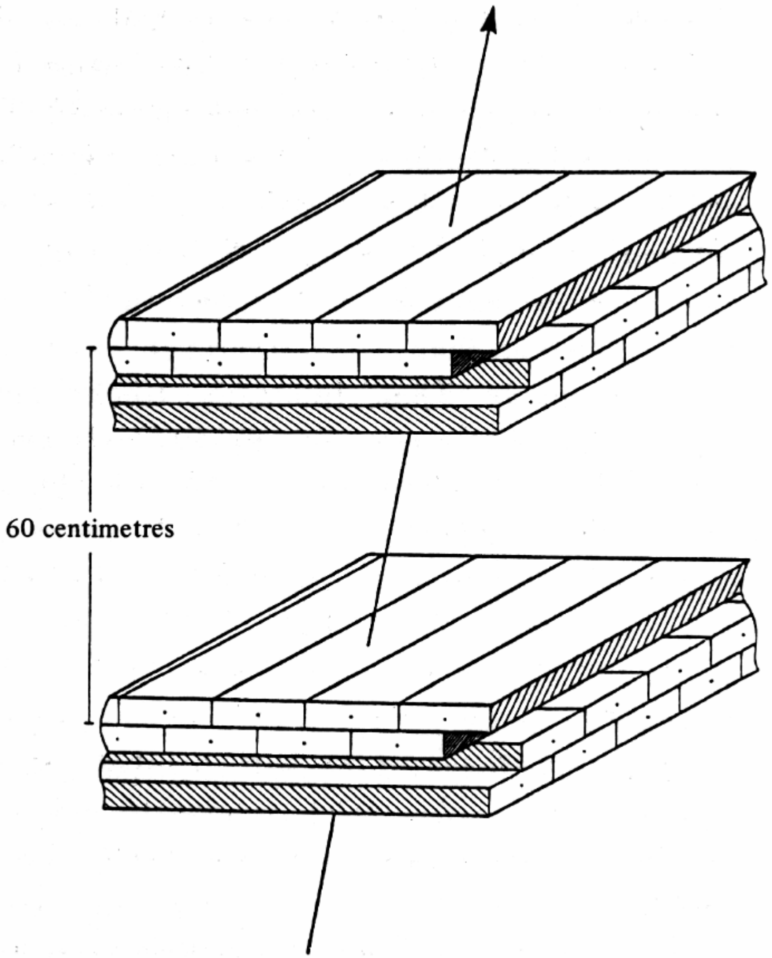
Muon System: ID only

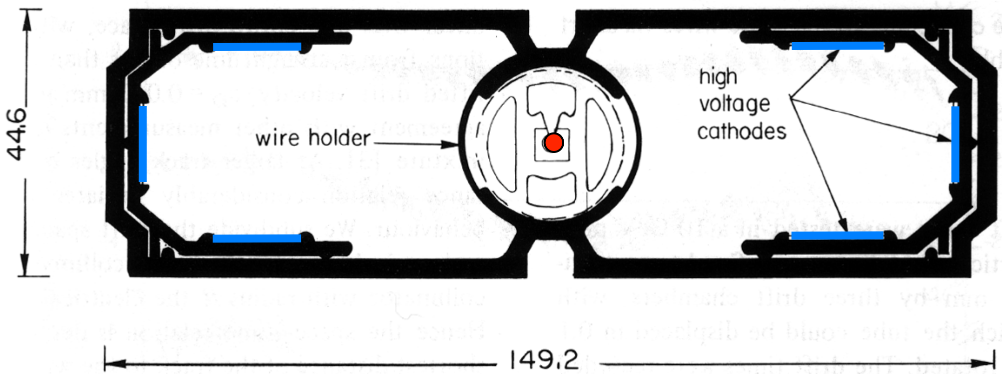
5 sides of 6 are covered with two 4-layer Drift Tubes

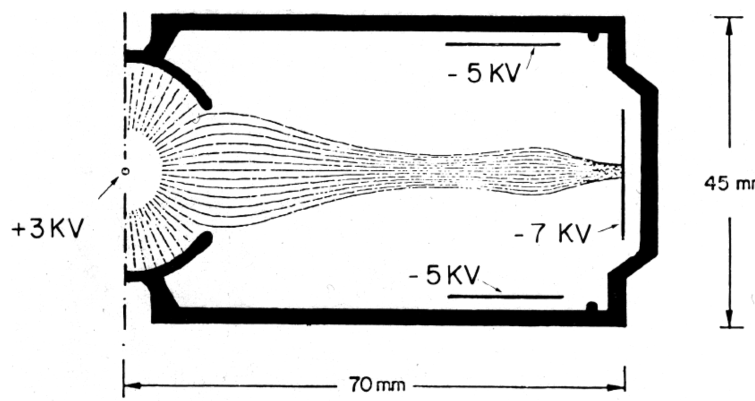
Momentum measurement comes from the tracker:

$$\frac{\delta p}{p} = 5 \cdot 10^{-3}\ p$$

UA1 Muon Chambers

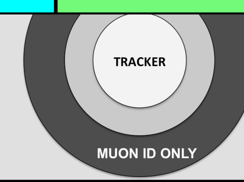


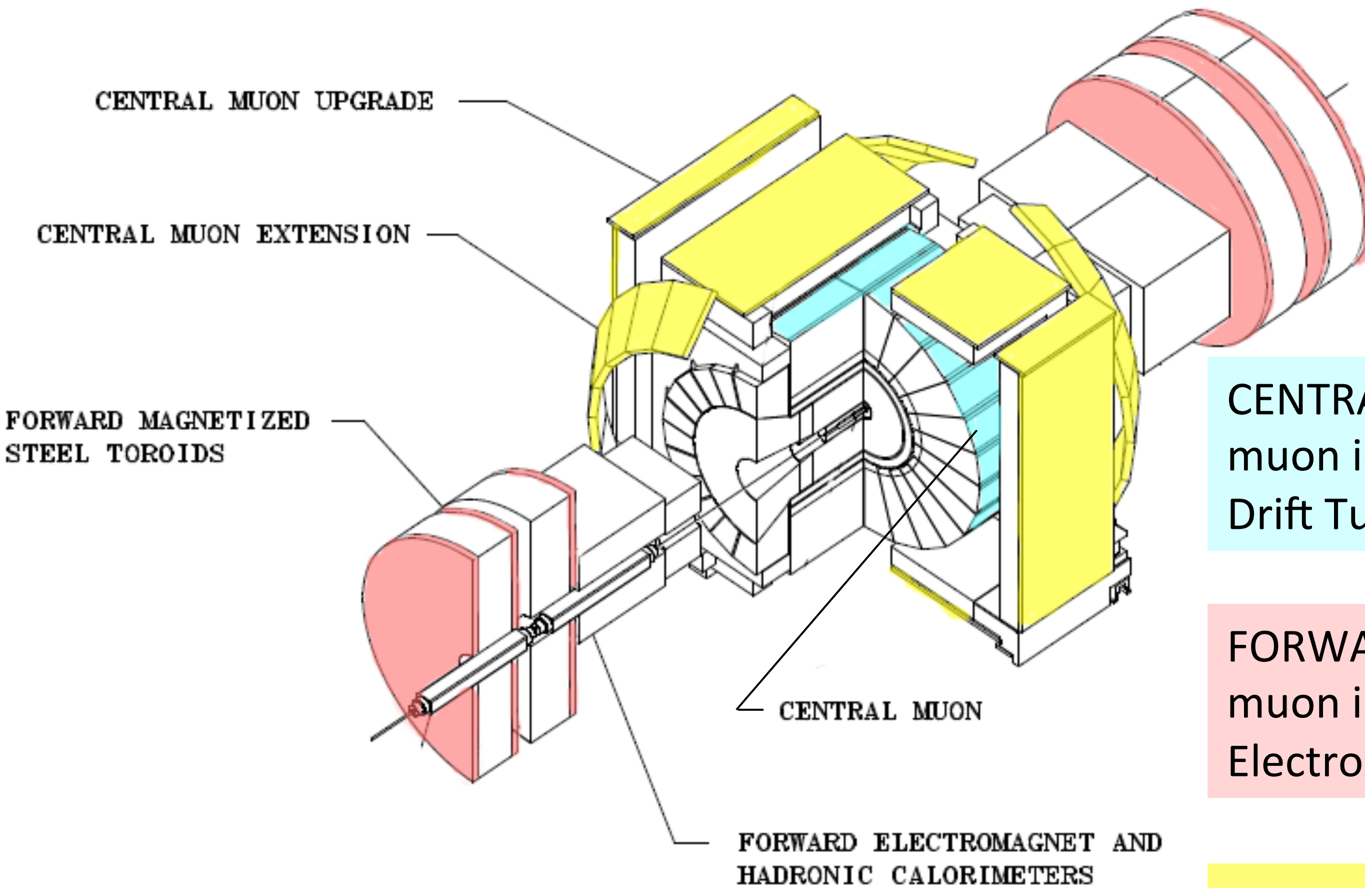




CDF-I at Tevatron Run 1

Tubes | Scint



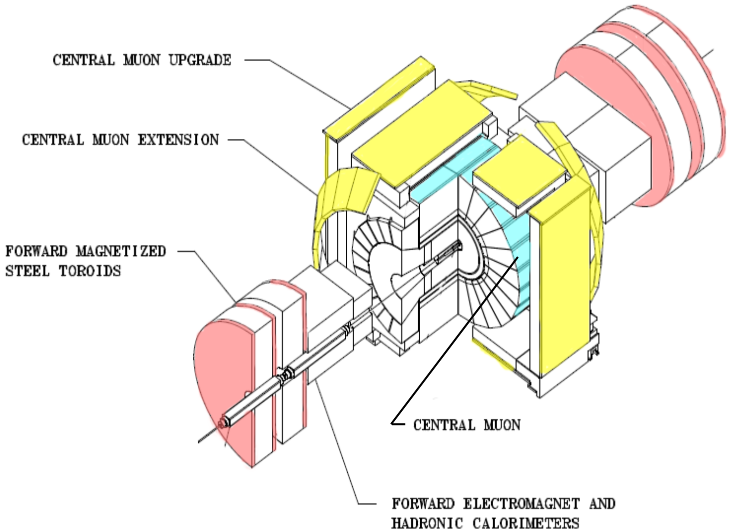


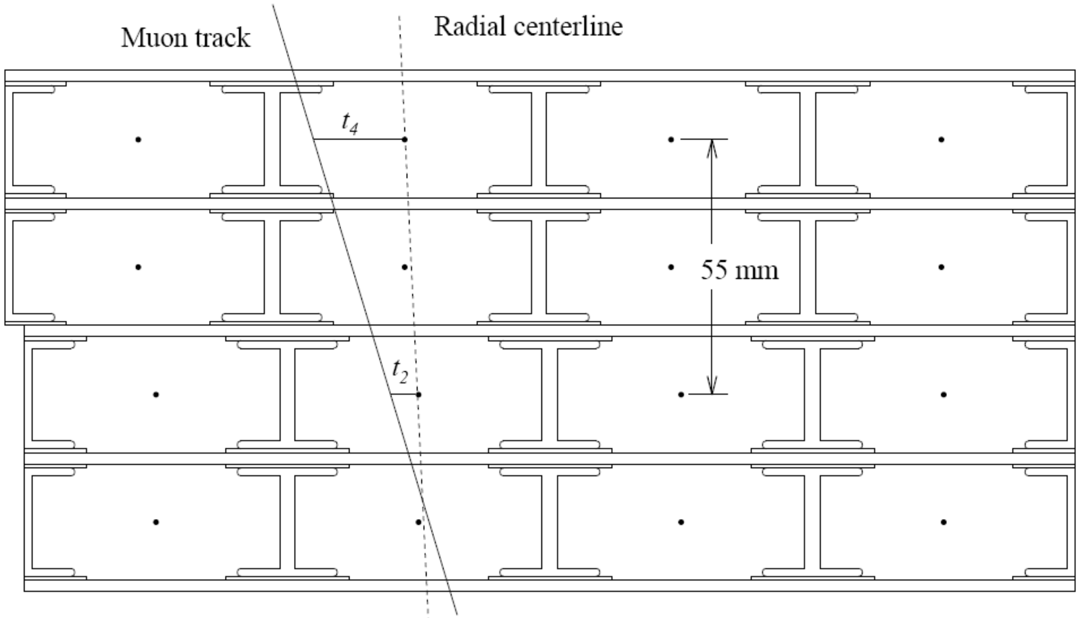
CENTRAL MUON
muon id only
Drift Tubes

FORWARD MUON
muon iron-core spectrometer
Electrodeless Drift Tubes

CENTRAL UPGRADE+EXTENSION
muon id only
Drift Tubes

CDF-I: Central Muon System



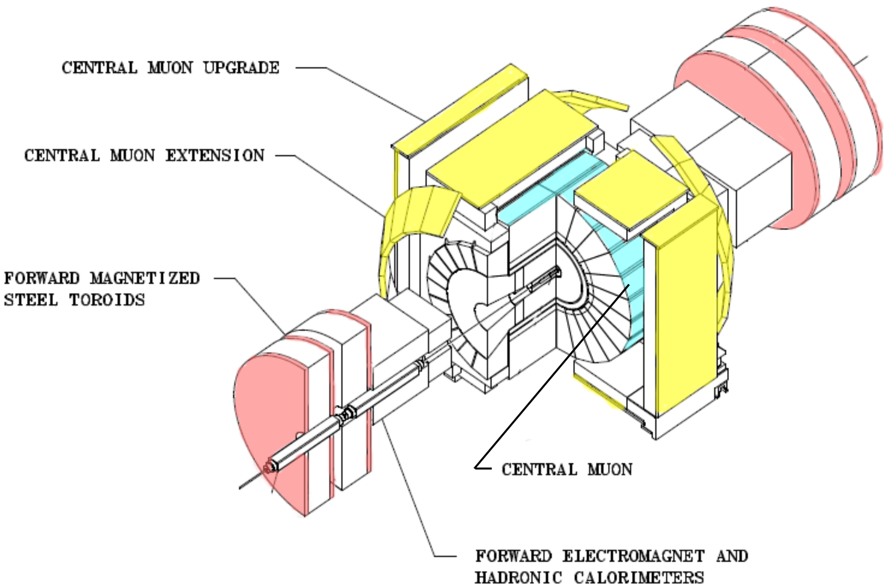


CENTRAL MUON
(right after calorimeters, only 5.4λ)

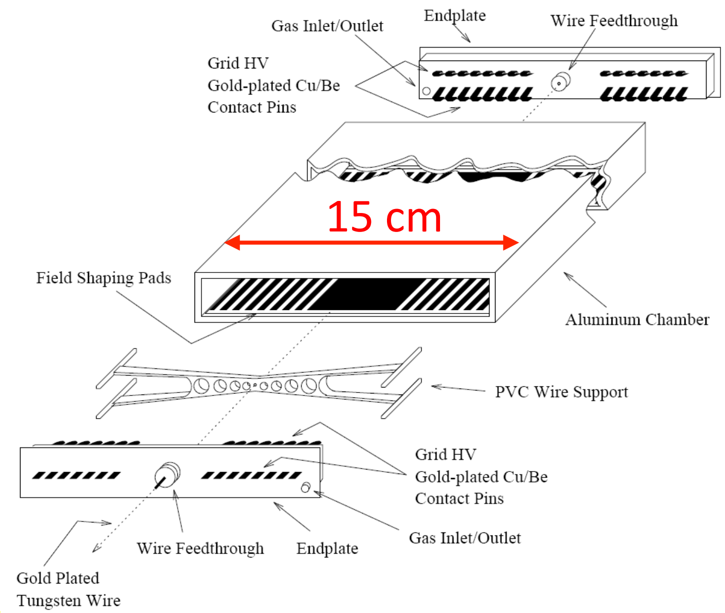
- Single Wire Cell Chambers
- dx ~ 250 μm (from drift time)
- dz ~ 1.2 mm (from charge division)

Momentum resolution from the tracker: $$\frac{\delta p}{p} = 2 \cdot 10^{-3}\ p$$

CDF-I: Central Muon Upgrade (Lesson 2)



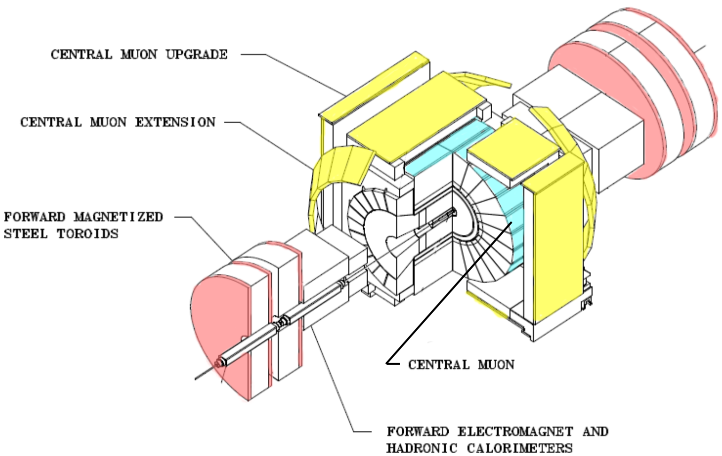
CENTRAL MUON UPGRADE
- after magnet return yoke (60 cm, +3.5λ)
- direct π punchthrough probability ~10^{-4}
- 4 layers of Drift Tubes



CENTRAL MUON
- right after calorimeters, only 5.4λ
- direct π punchthrough probability ~0.5%

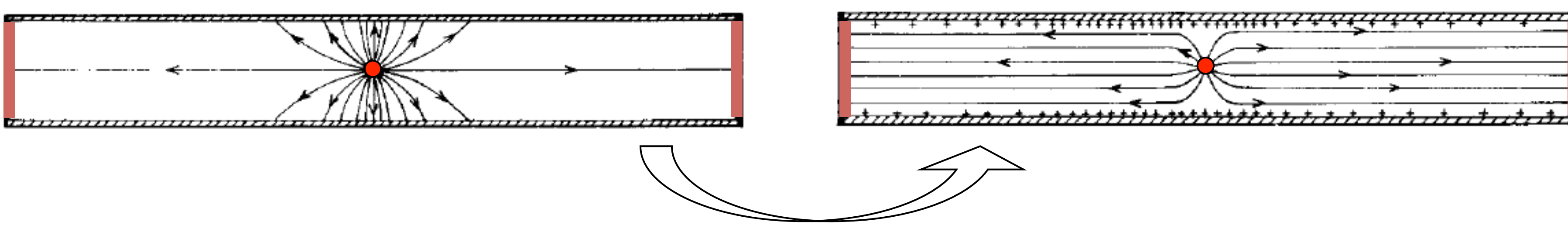
CENTRAL MUON EXTENSION
- extends η-coverage
- same detector technology
- sandwiched between scintillator counters

CDF-I: Forward Muon System (Lesson 3)



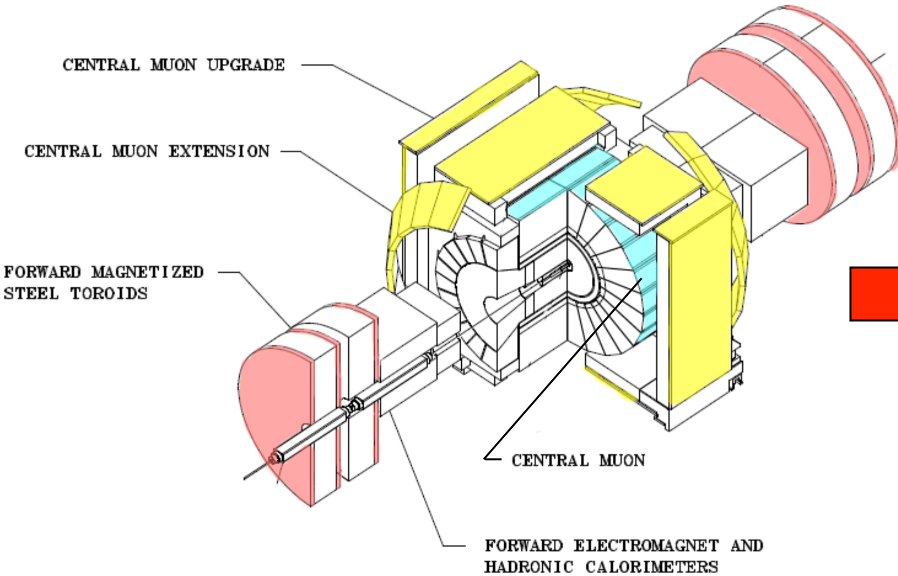
FORWARD MUON

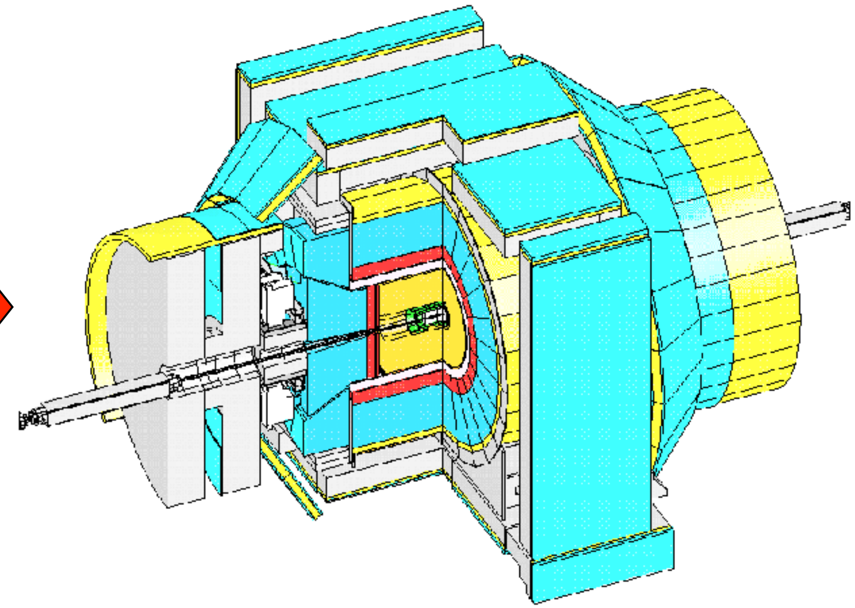
- use magnetized iron toroids to measure muon p
- rely on field shaping made by charged up large area of an insulator (recent idea of electrodeless drift chambers from Manchester: NIM 201 (1982) 341)
- used by JADE/OPAL in a limited extent



- Proved to be unreliable in environment of <u>high</u> and <u>variable</u> rates (difficult to maintain gas gain and efficiency equilibrium across the system and in time)
- Discarded for Run II

CDF-II at Tevatron Run II



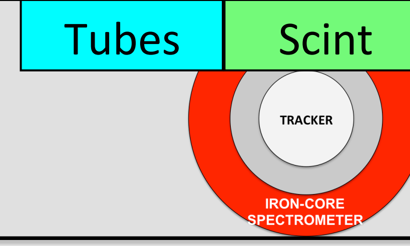


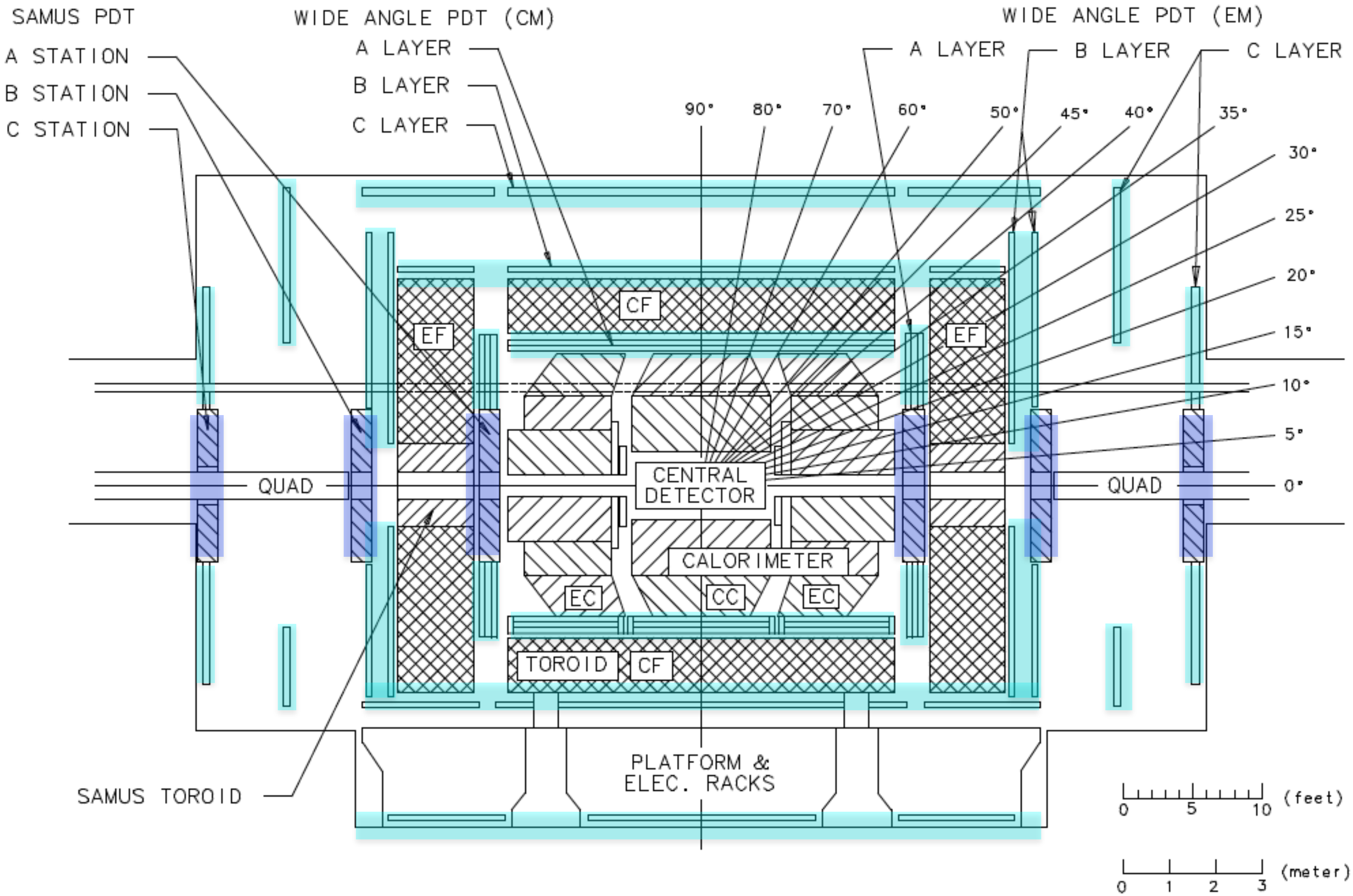
Discard Forward Muon System

Double η-coverage of the central region

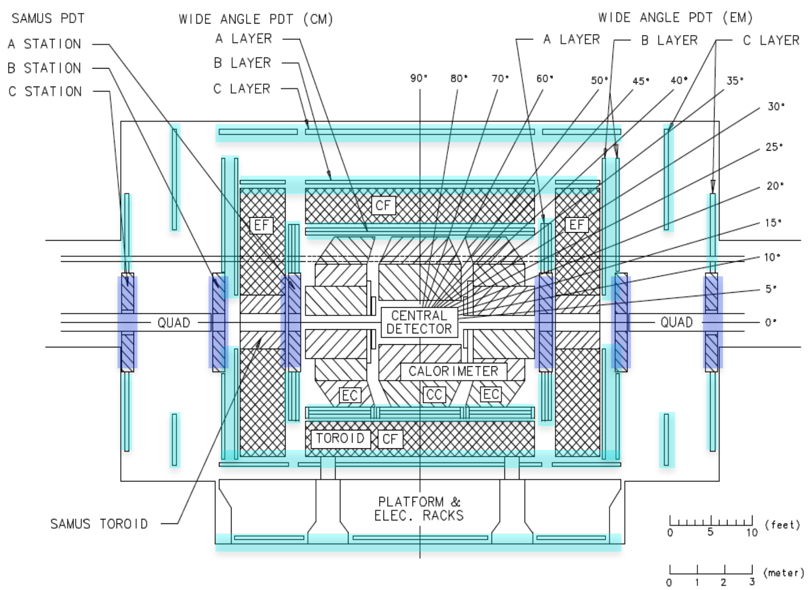
Same technology as already used in CDF-I:
- Drift Tubes
- Scintillators

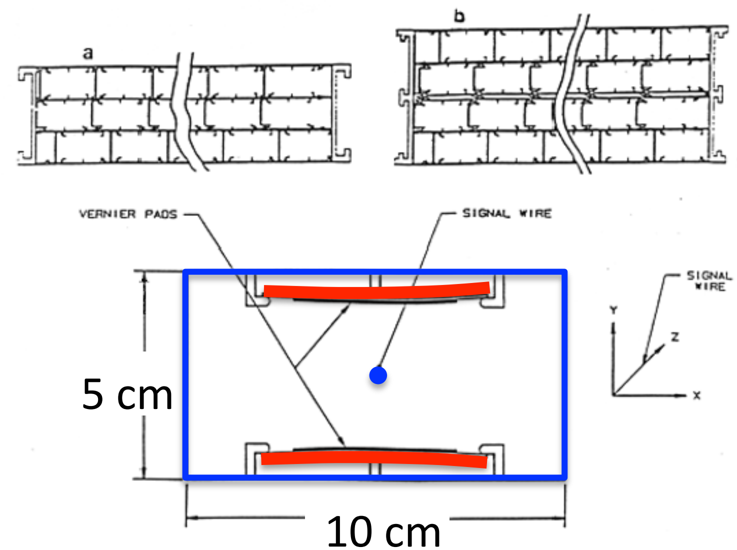
D0-I at Tevatron Run I





D0-I: Proportional Drift Tubes

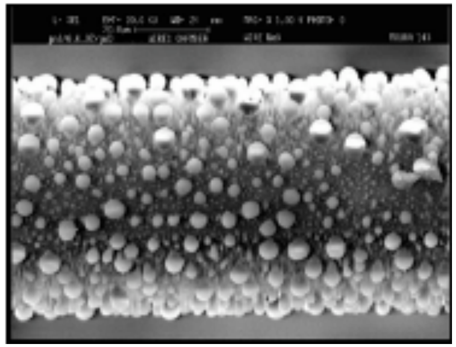




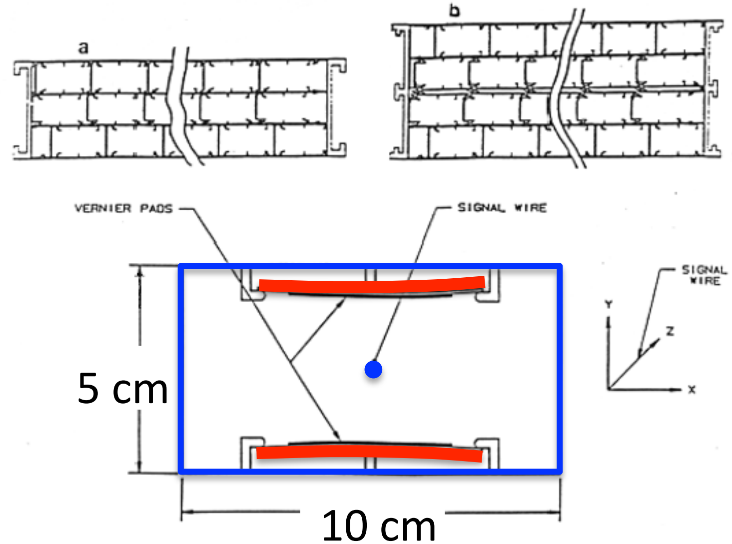
IRON-CORE SPECTROMETER

- WIDE ANGLE PDTs - proportional drift tubes of rectangular shape
  - precise coordinate from drift time
  - induced charge from Vernier pads on Glasteel substrate for hit coordinate along the wire
- SMALL ANGLE PDTs – classical round proportional drift tubes

D0-I: Proportional Drift Tubes (Lesson 4)



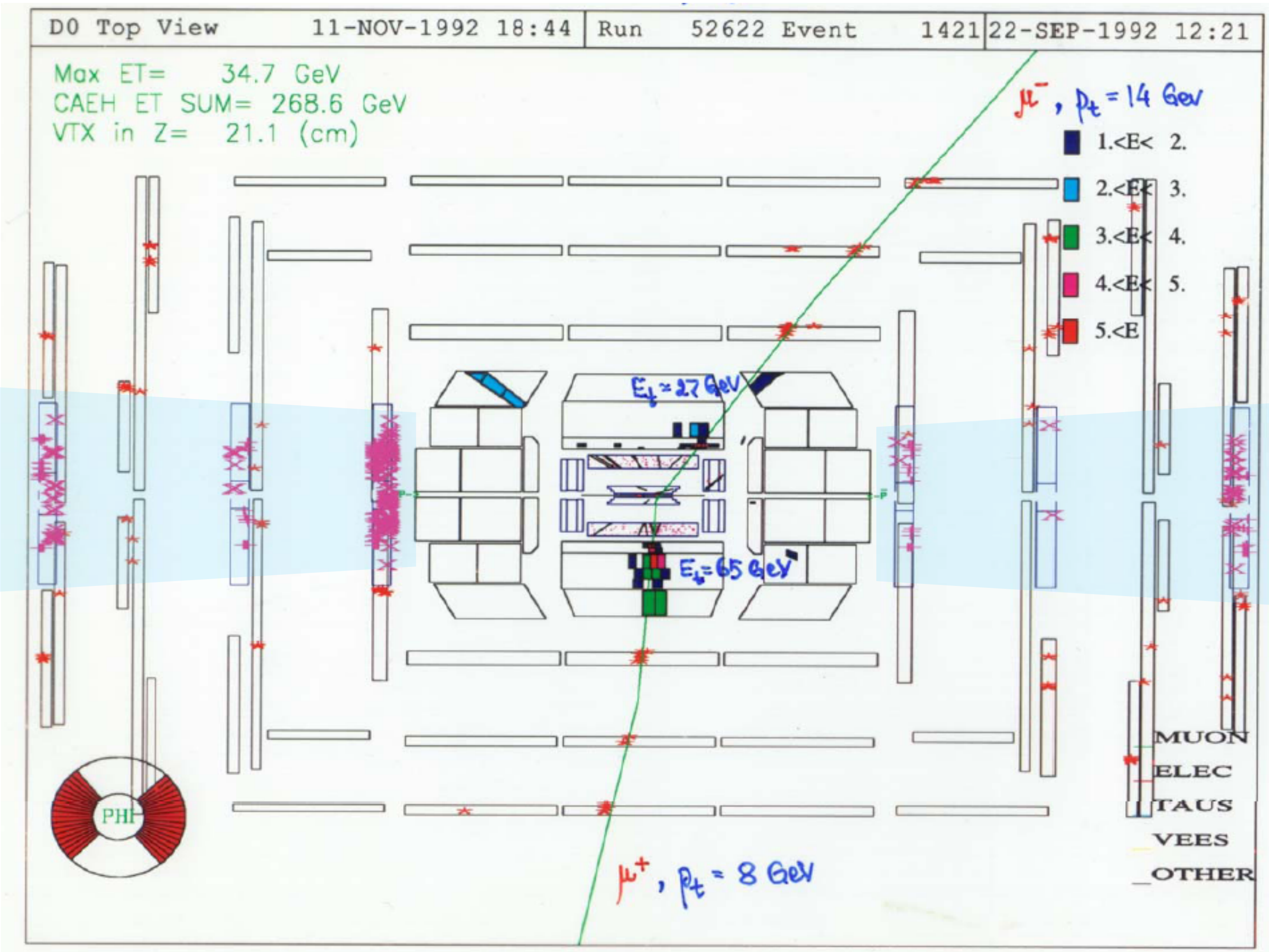
(these aged wire images are for illustration purposes only, they are not from D0)



Fast aging observed:

- crud formed on wires (traced to outgassing from Glasteel)
- zapping wires with “just right” discharge allowed to save barrel chambers
  - too low charge would solidify the crud on wires
  - too high charge would melt gold on wires
  - “just right” discharge would evaporate the crude

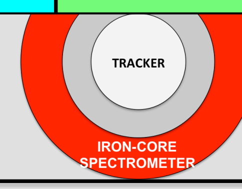
D0-I: Forward Drift Tubes (Lesson 5)

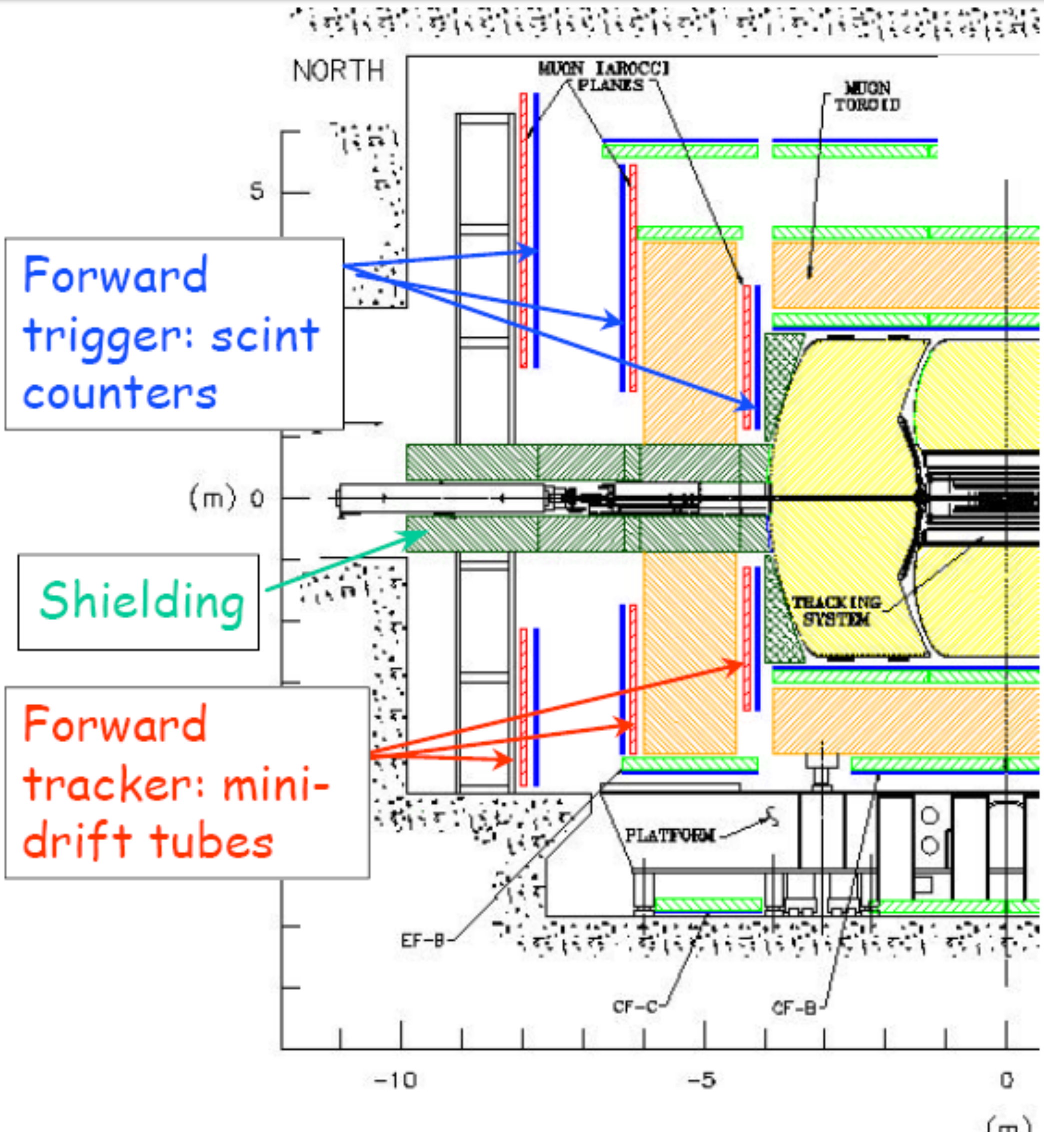


Backgrounds at small polar angles are very high

D0-II at Tevatron Run II

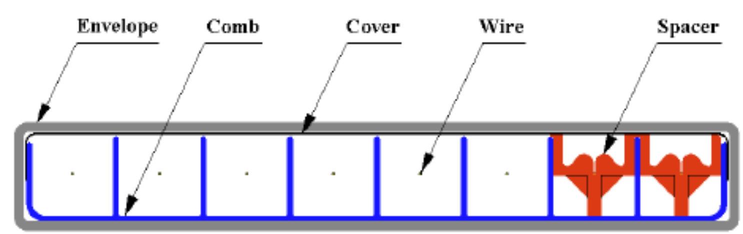
Tubes | Scint



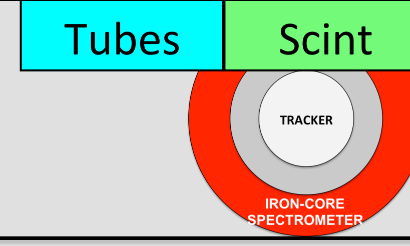


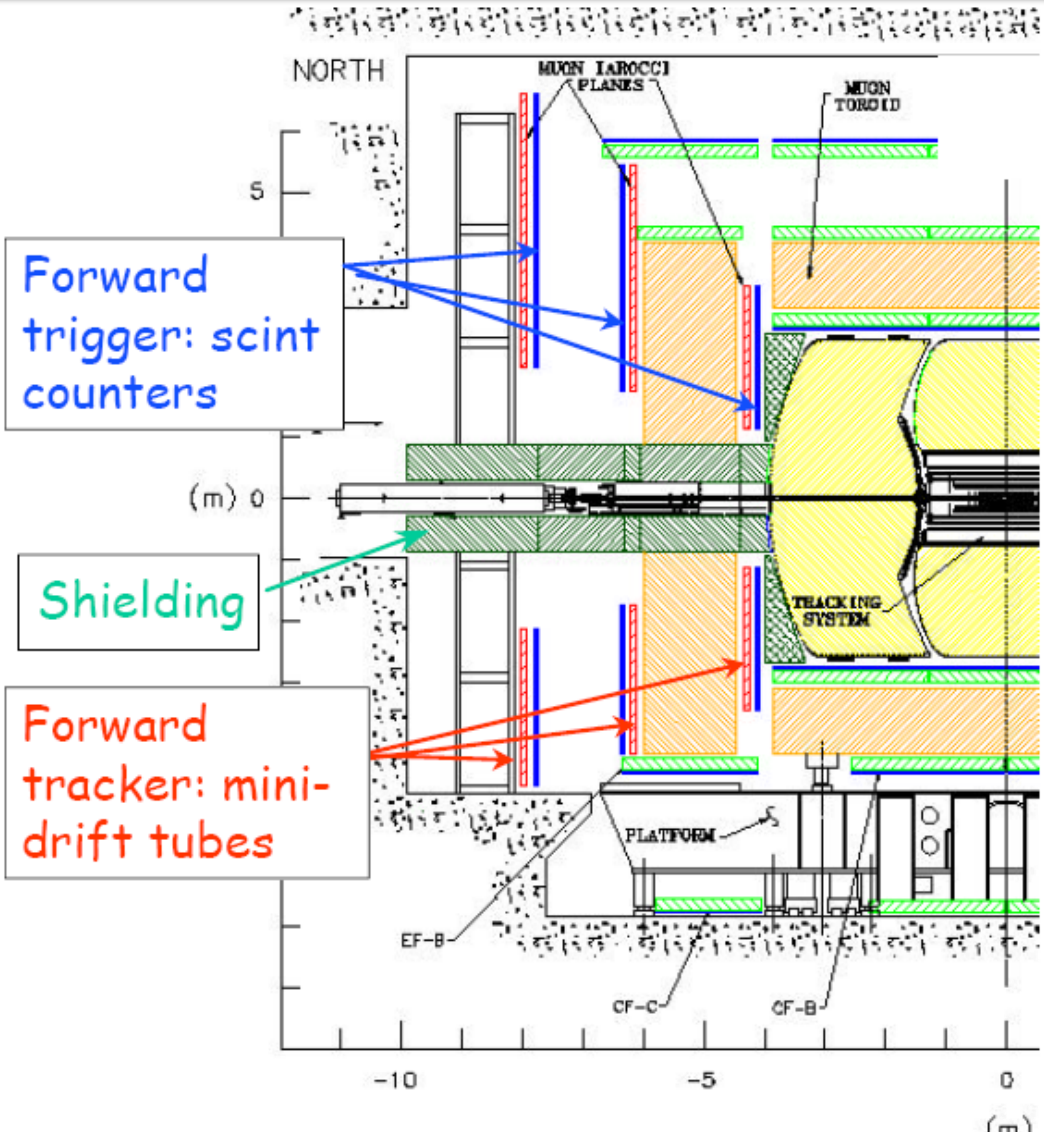
- Small angle muon system is replaced with shielding

- Forward muon chambers are replaced with Aluminum Iarrocci Drift Tubes (mini-drift tubes)

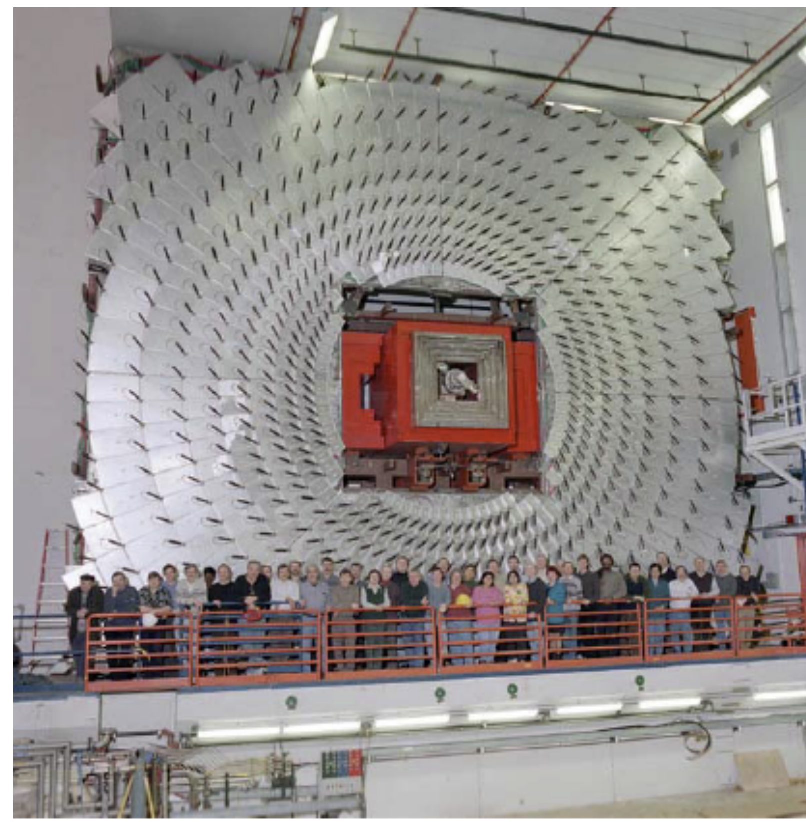


D0-II at Tevatron Run II



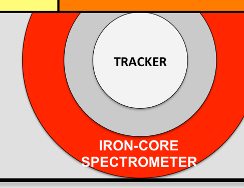


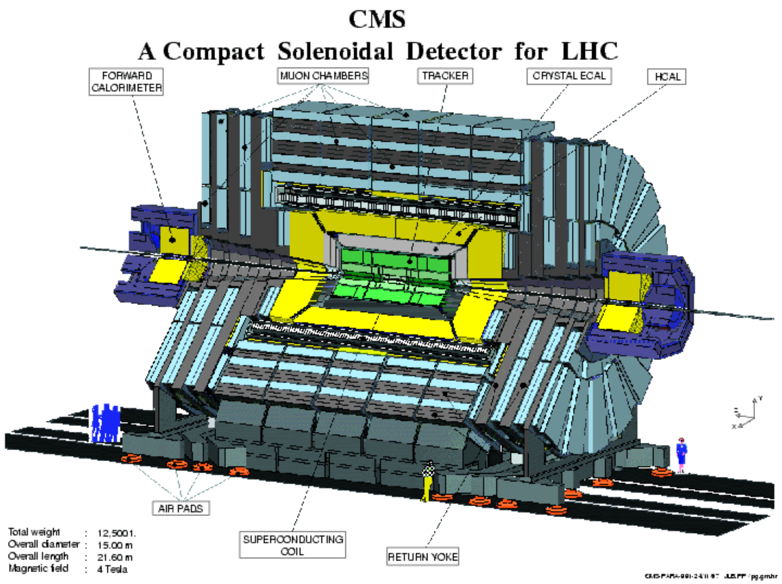
Scintillator counters

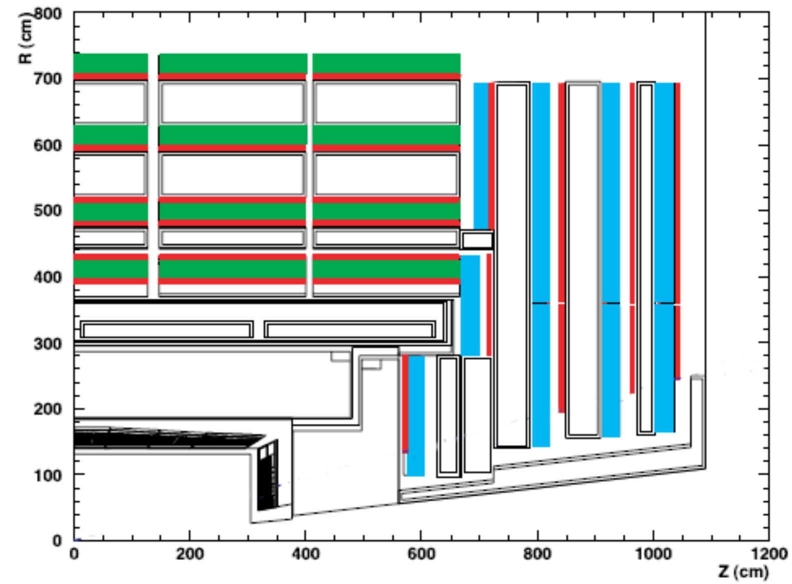


CMS

Tubes	MWPC	RPC





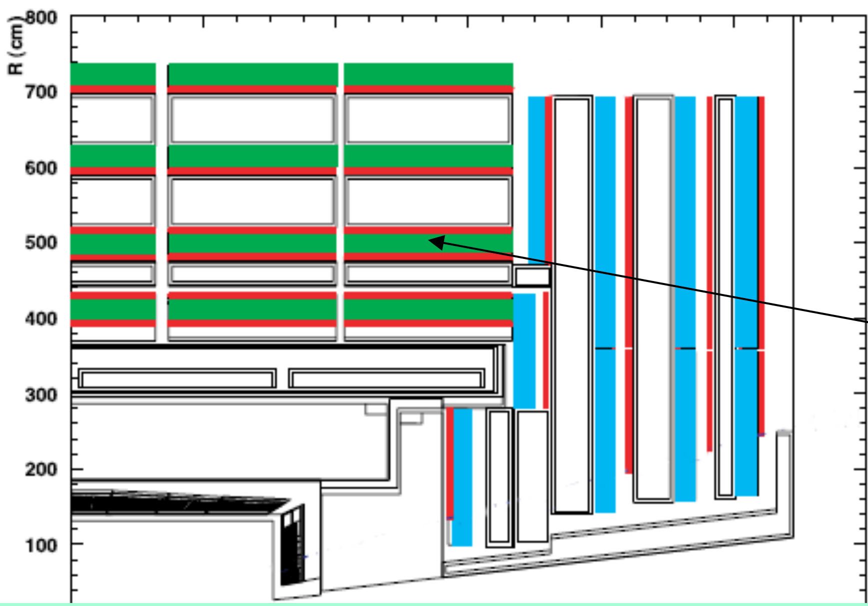


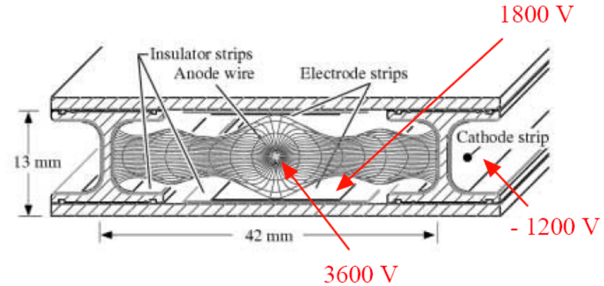
Muon System: iron-core spectrometer

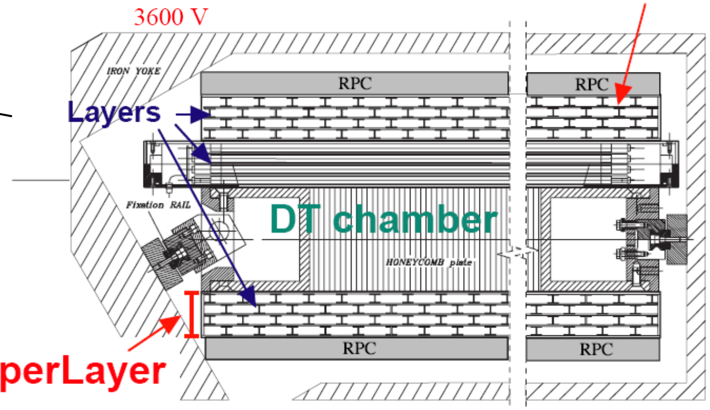
Barrel: Drift Tubes
+ RPCs

Endcap: Cathode Strip Chambers
+ RPCs

CMS: Drift Tubes (barrel)





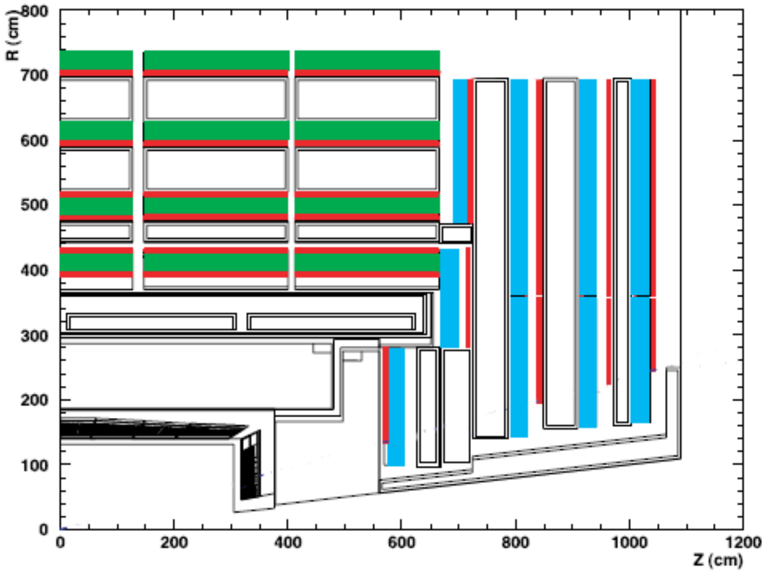


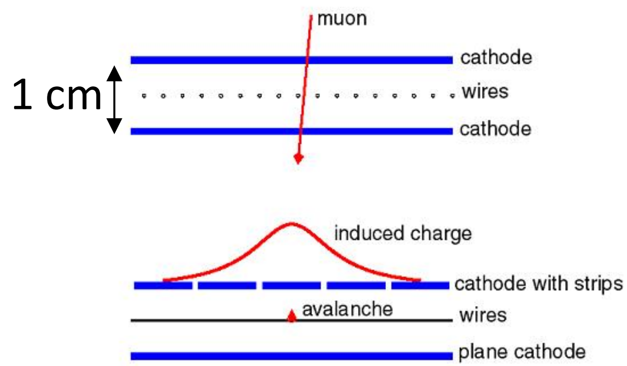
Iron-core spectrometer

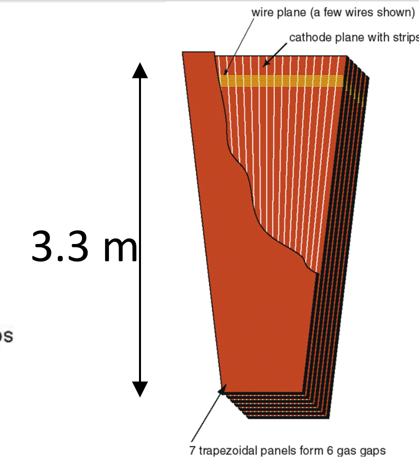
- 250 chambers, 12 layers each
- 200K channels
- 250 μm resolution (drift time)
- self-triggering using mean-timers (high p_T)

RPCs help trigger at lower p_T and add redundancy

CMS: Cathode Strip Chambers (endcaps)



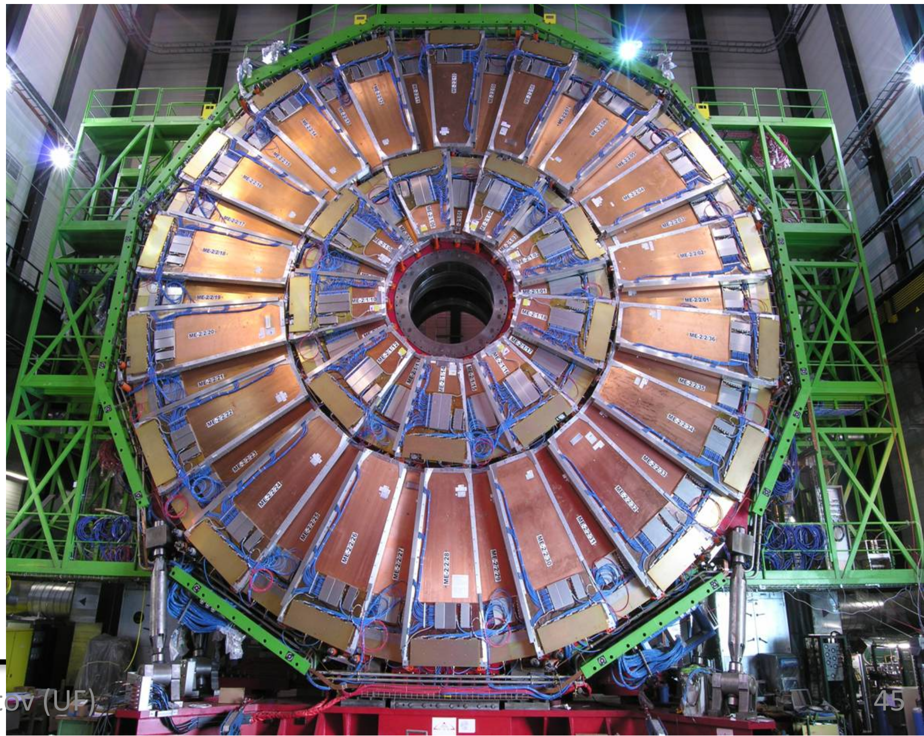




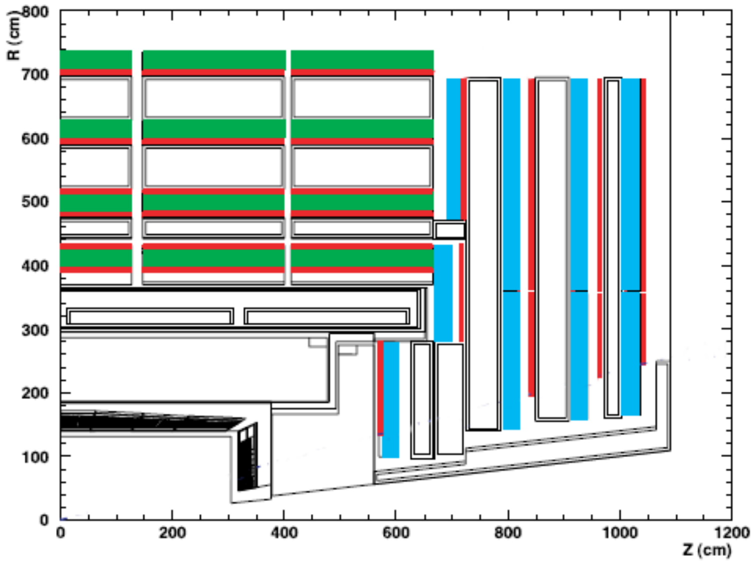
Iron-core spectrometer

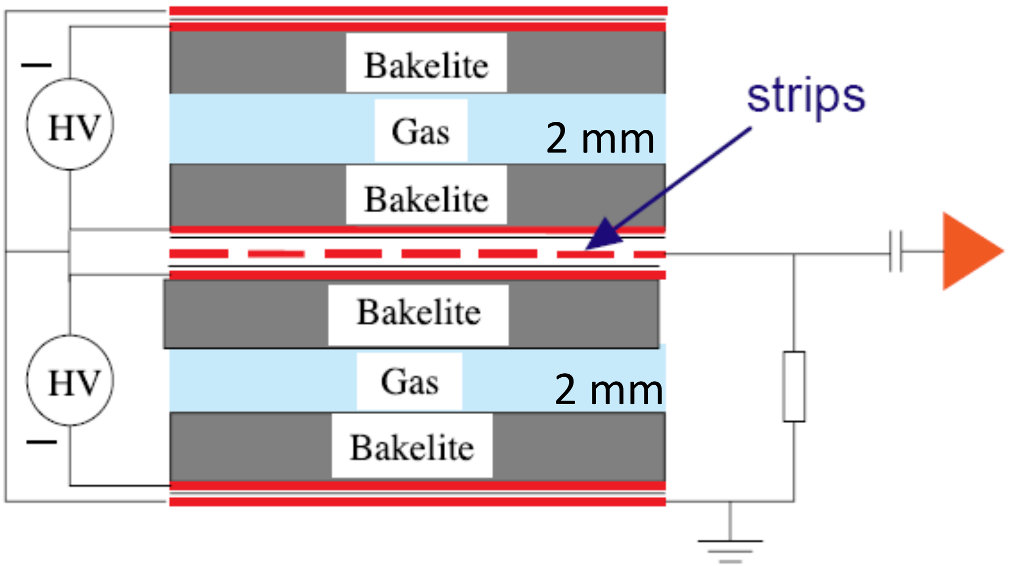
- CSCs – first time at this scale
- 540 chambers, 6 layers each
- 500K channels
- 6,000 m^2 sensitive area
- ~300 μm resolution (induced charge)
- self-triggering

RPCs add redundancy



CMS: RPCs (barrel and endcap)



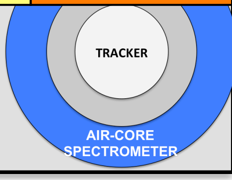


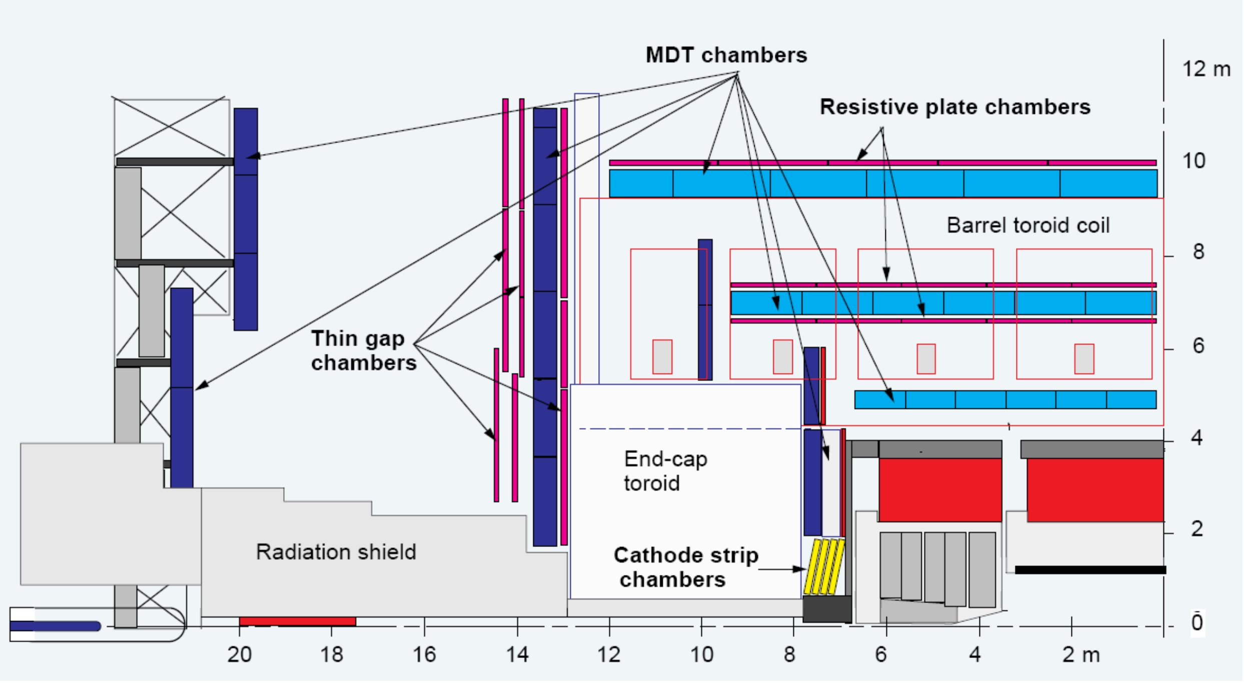
RPCs
- a la BaBar design, but: <u>double gap</u> and operate in <u>prop mode</u>
- extensive aging studies show no aging
- 1000 chambers
- 150K readout channels

Used mostly for redundancy: trigger and pattern recognition

ATLAS

Tubes	MWPC	RPC





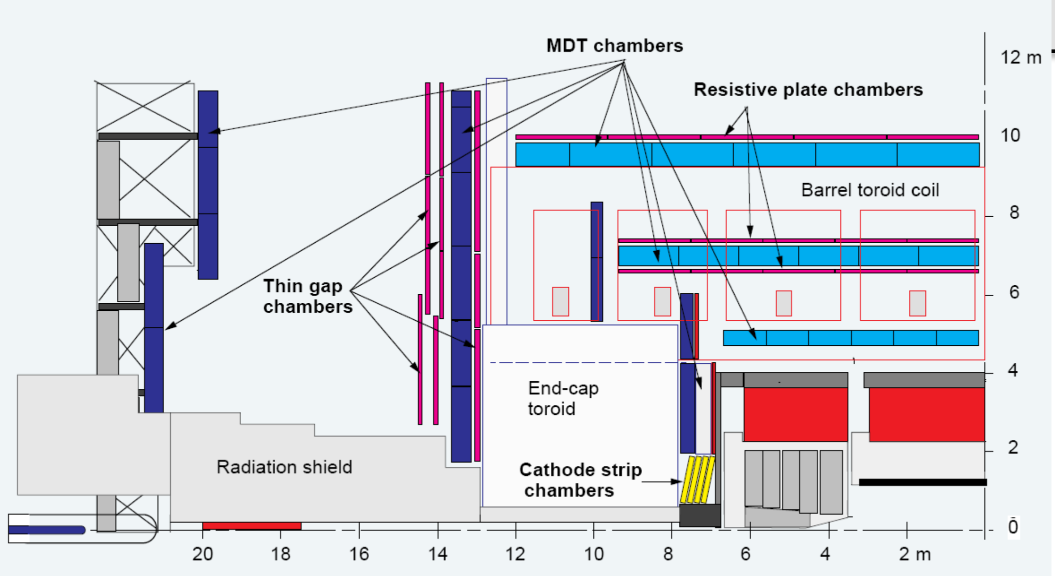
Muon System:
- air-core spectrometer

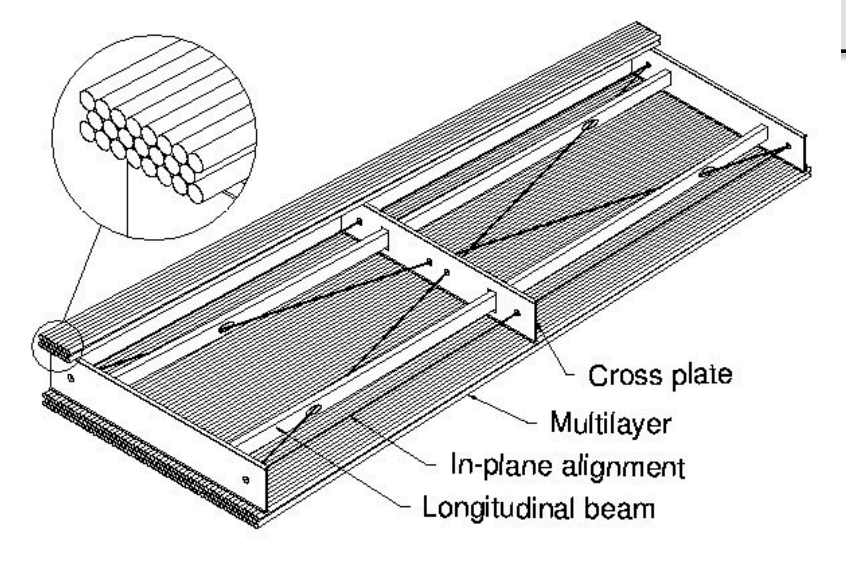
Barrel:
- Monitored Drift Tubes
- RPCs

Endcap:
- Monitored Drift Tubes
- MWPC (Thin Gap Chambers)

Very Forward:
- Cathode Strip Chambers

ATLAS: Monitored Drift Tubes

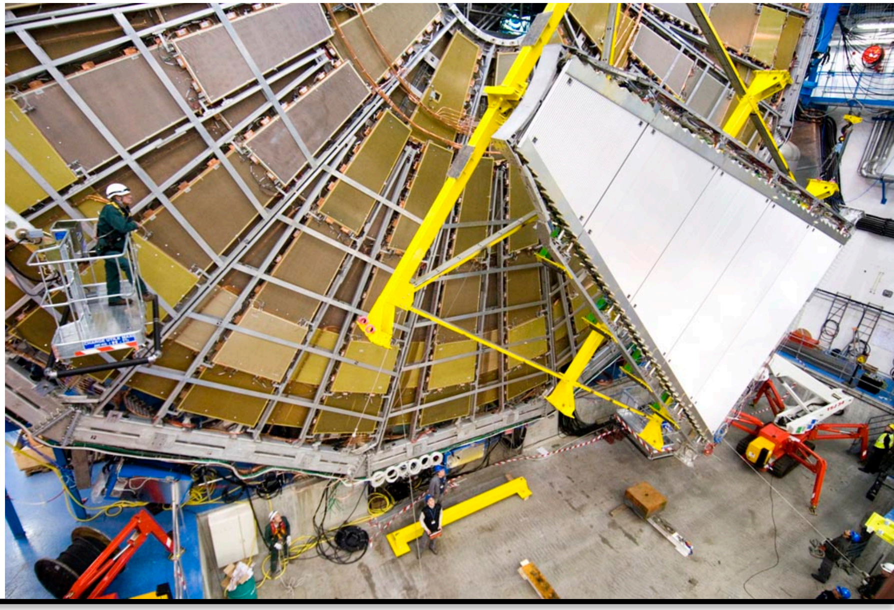




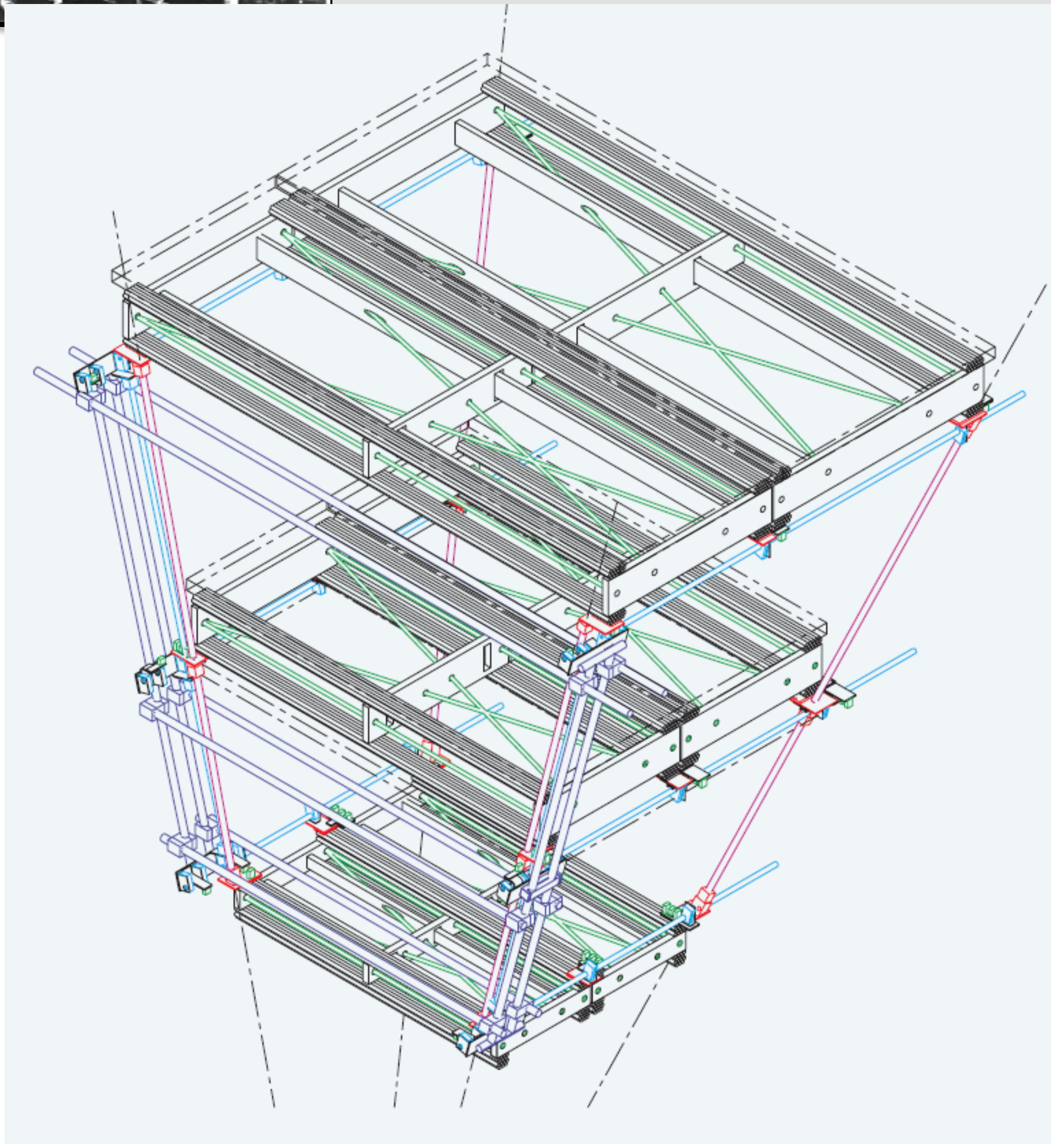
Air-core spectrometer

- 3 cm pressurized tubes– basic element
- 80 μm resolution per tube

- 1200 chambers, 6 layers each
- 400K 3-cm tubes
- 5,500 m^2 active area



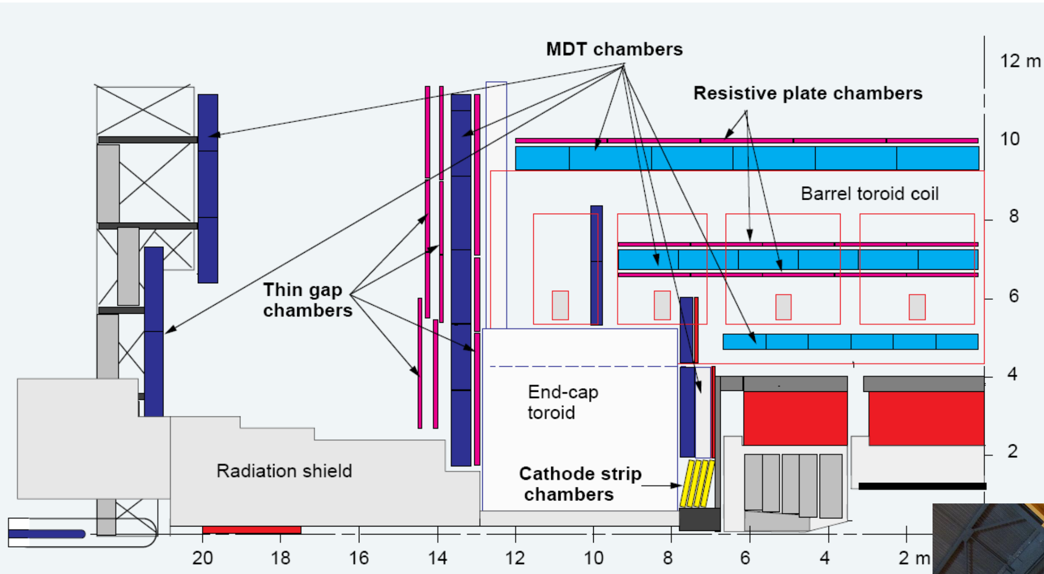
ATLAS: 20-mm MDT alignment

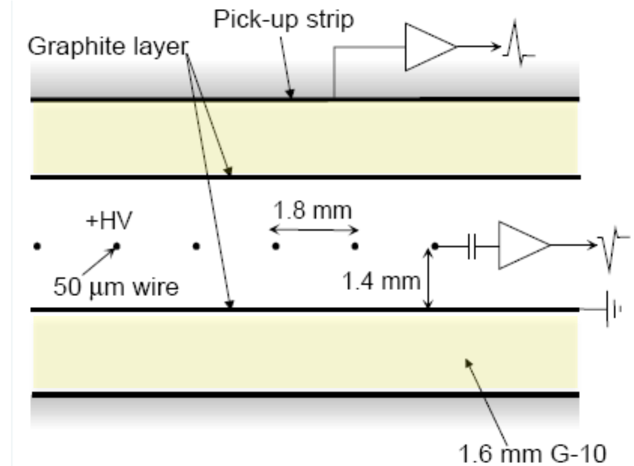


- In-plane alignment for chamber deformations (calibrated)
- <u>Projective alignment</u> for relative positions of ‘triplets’ (20 μm)
- Axial alignment to limit number of projective rays (20 μm)

\+ Proximity sensors to couple between adjacent structures

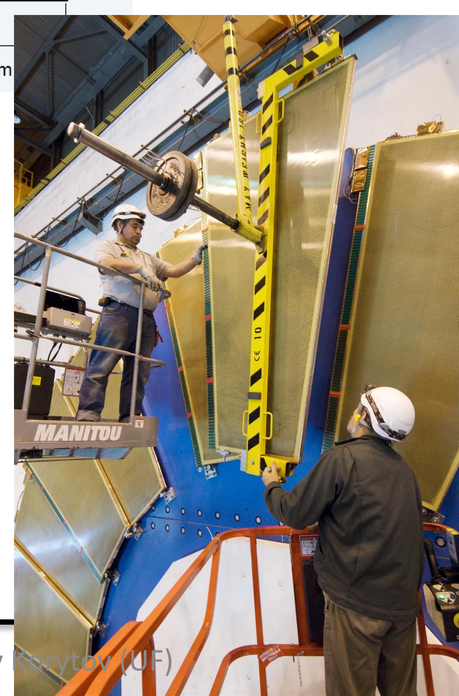
ATLAS: Thin Gap Chambers



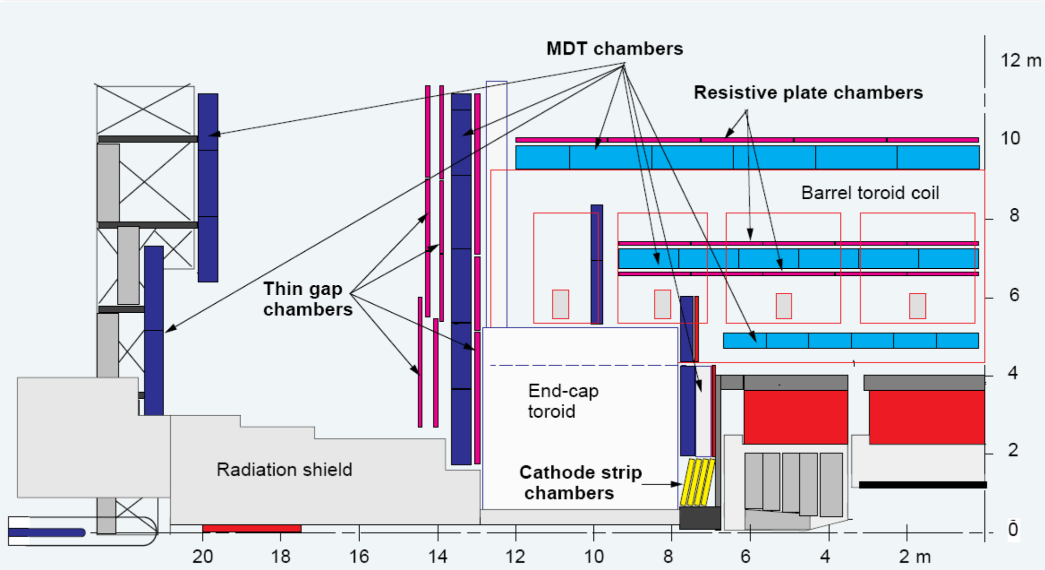


Trigger Detector

- 6,600 m² of single plane area (two planes per chamber)
- 440K readout channels
- 5 mm granularity

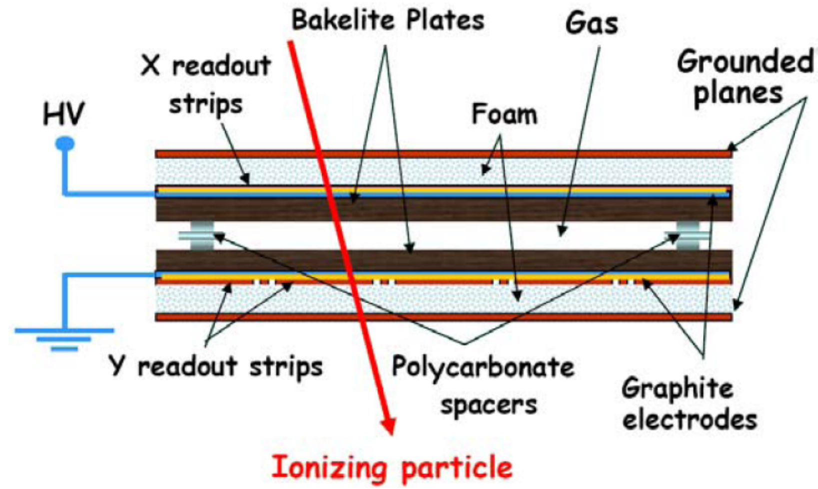


ATLAS: RPCs



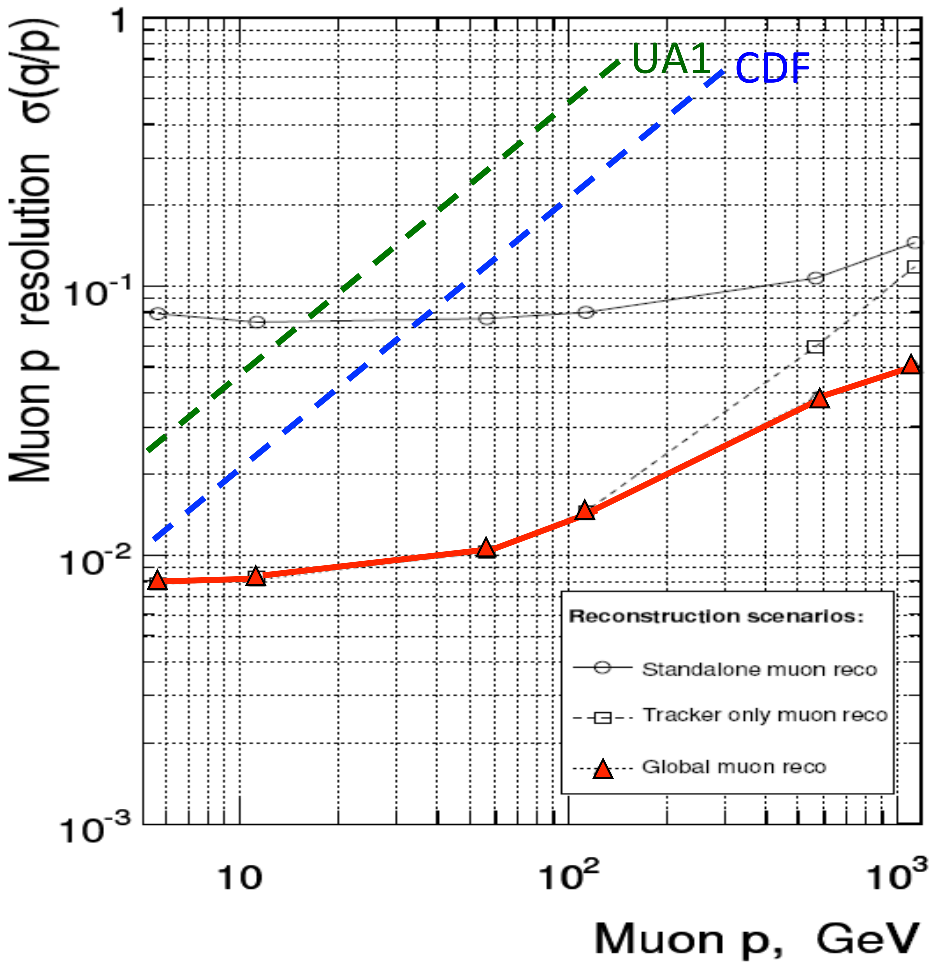
Trigger Detector

- a la BaBar design, but in proportional mode
- 7,200 m^2 of single plane area
  (two planes with two-side readout per chamber)
- 355K readout channels (3 cm strips)

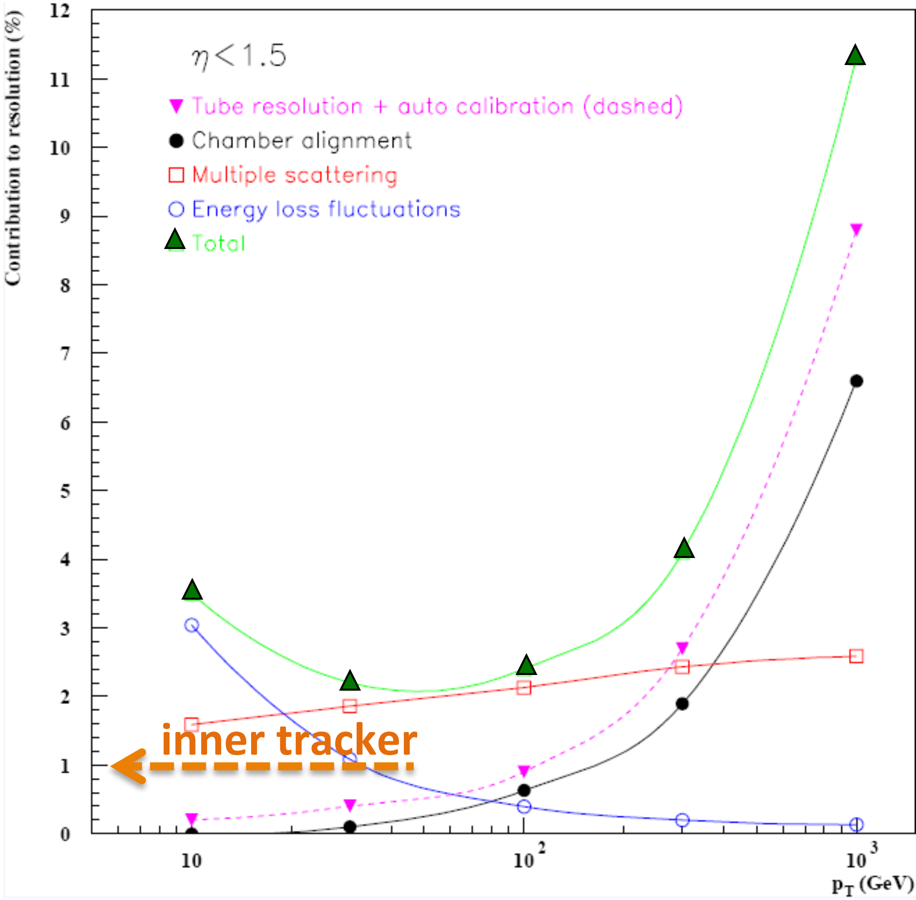


Momentum Resolution comparison

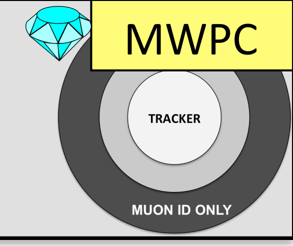
CMS



ATLAS

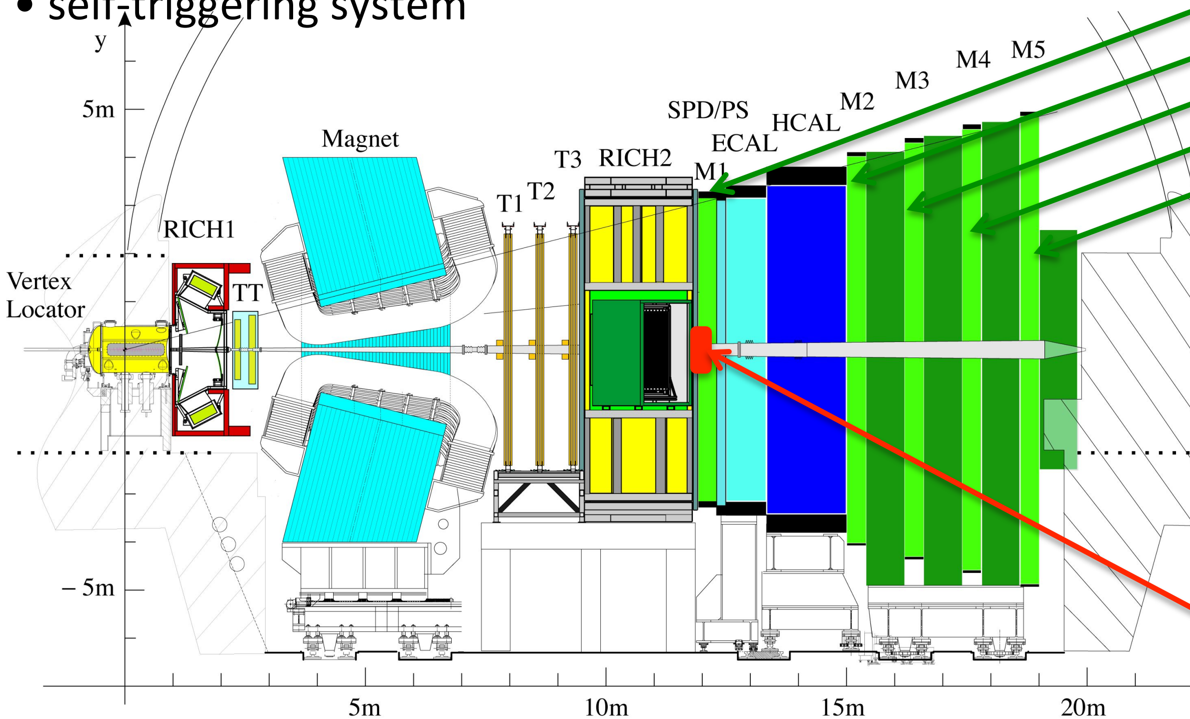


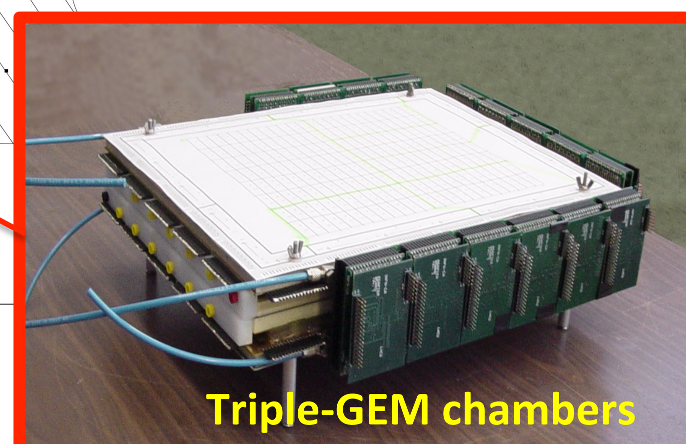
LHCb



MUON-ID ONLY

- **1,368 MWPCs** (total sensitive area 435 m^2), 80 kHz/cm^2
- **24 Triple-GEM detectors** (each 24x20 cm^2), 500 kH/cm^2
- 120K readout channels
- self-triggering system





Muon Systems at Colliders

Tubes	RPC
MWPC	Scint

		Muon ID only	Iron-core spectrometer	Air-core spectrometer
ee	few-10 GeV	BaBar Belle CLEO BES KEDR		
	100 GeV (LEP)	ALEPH DELPHI OPAL		L3
	1000 GeV (ILC)	LDC GLD SiD		4th
pp	0.5 TeV (SppS)	UA1		
	2 TeV (Tevatron)	CDF	D0	
	10 TeV (LHC)	LHCb	CMS	ATLAS
ep	300 GeV (HERA)		H1 ZEUS	

Summary

Muon systems allow for

- sensitive area: 10,000 m^2
- muon identification: a must
- measuring its parameters: none, crude, precise
- Triggering: yes or no

Most popular recent technological choices

- drift tubes (in various reincarnations)
- multi-wire proportional chambers (with strip readout)
- RPCs

A few lessons learned hard way…