



Muons: Lecture #1

Darien Wood
Northeastern University

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Lecture Organization

- Lecture #1
 - Why muons?
 - Sources of muons
 - Muon detection and reconstruction
 - With examples of muon detectors
- Lecture #2
 - Muon identification
 - A little on triggering
 - Alignment
 - Commissioning
- Acknowledgement: Large portions of these slides were taken from lectures from the 2003 New England Particle Physics Student Retreat (NEPPSR) prepared collaboratively with John Butler of Boston University

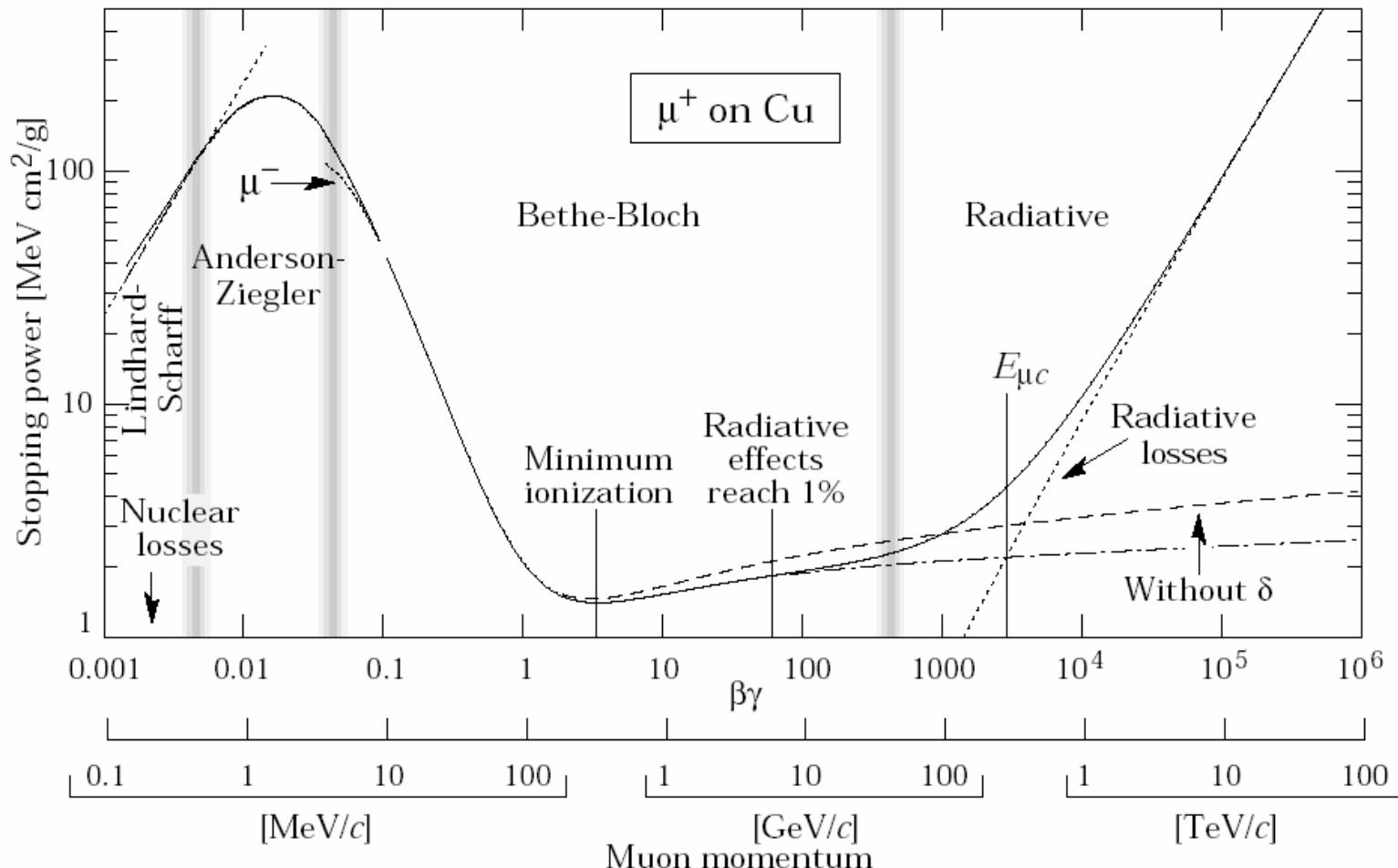
Why Muons?

- “Who ordered that?”
 - Isidor I. Rabi
- Rarity:
 - At hadron colliders, most particles produced are hadrons, so leptons tend to indicate something interesting/unusual
- History
 - The J/ψ , τ , Y , W , Z , and top quark discoveries all relied on muons
- Physics topics at the Tevatron and LHC that use muons
 - Heavy flavors (b , c)
 - Top quark physics
 - Electroweak
 - Searches for new phenomena: Higgs, SUSY...
- b -tagging via $b \rightarrow \mu \nu c$
- Lamp post argument:
 - due to their distinctive interaction with material, muon detection is relatively easy
 - but...requires a very large detector system

Muon Properties

- From the Particle Data Group
 - Mass = $105.7 \text{ MeV}/c^2$
 - Proper lifetime = $2.2 \mu\text{s}$
- However, in hadron collider experiments
 - Muons are stable particles
 - $v \approx c$
- Penetrating
 - Deposit only minimum ionizing energy in detector material (up to the critical energy, more later)
 - Only particles to escape a hadron collider detector are muons and neutrinos

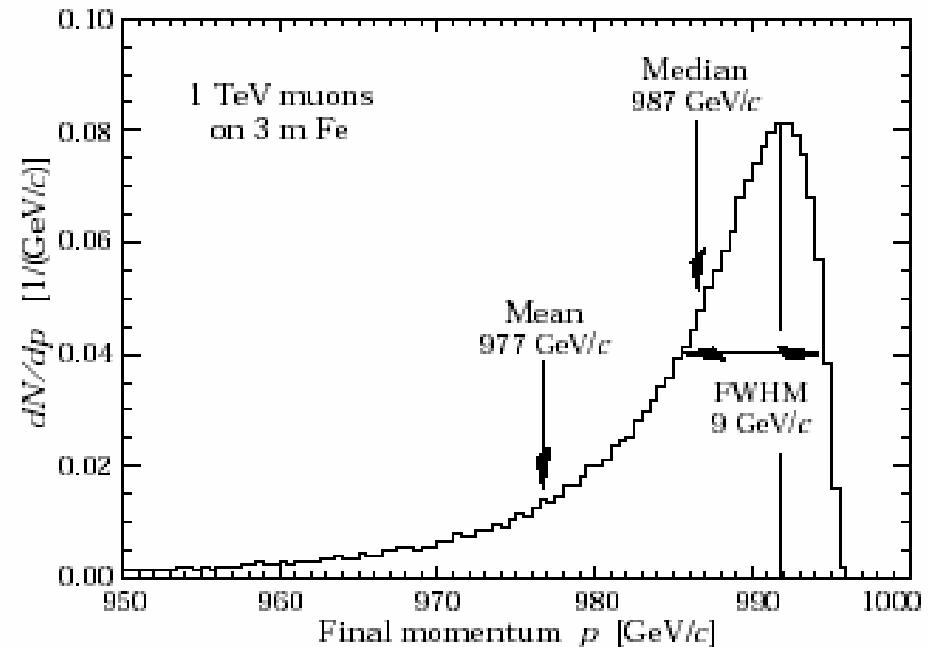
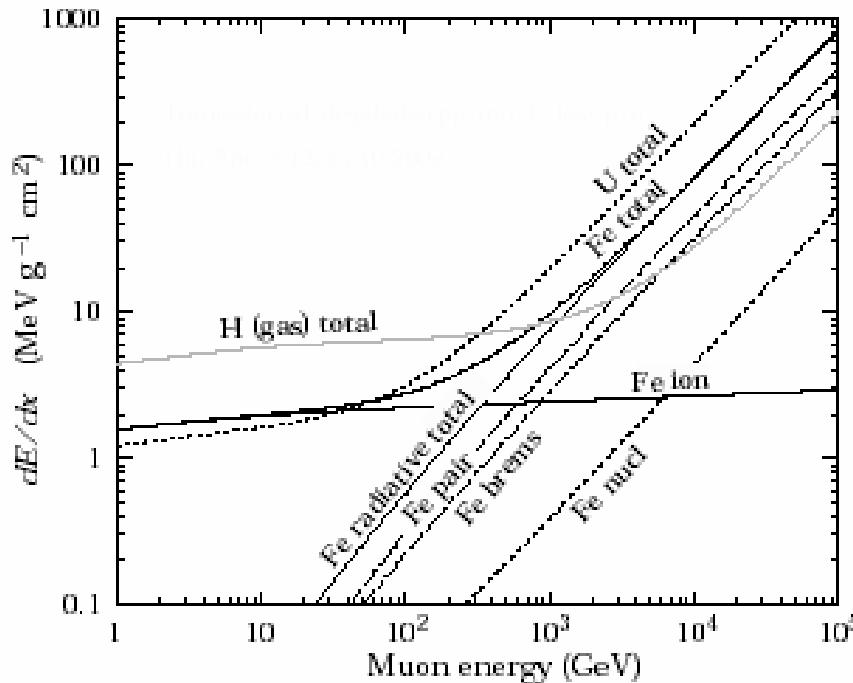
Energy Loss of Muons in Matter



Muons are typically “mips” in the momentum range of interest

Energy Loss of Muons in Matter

PDG



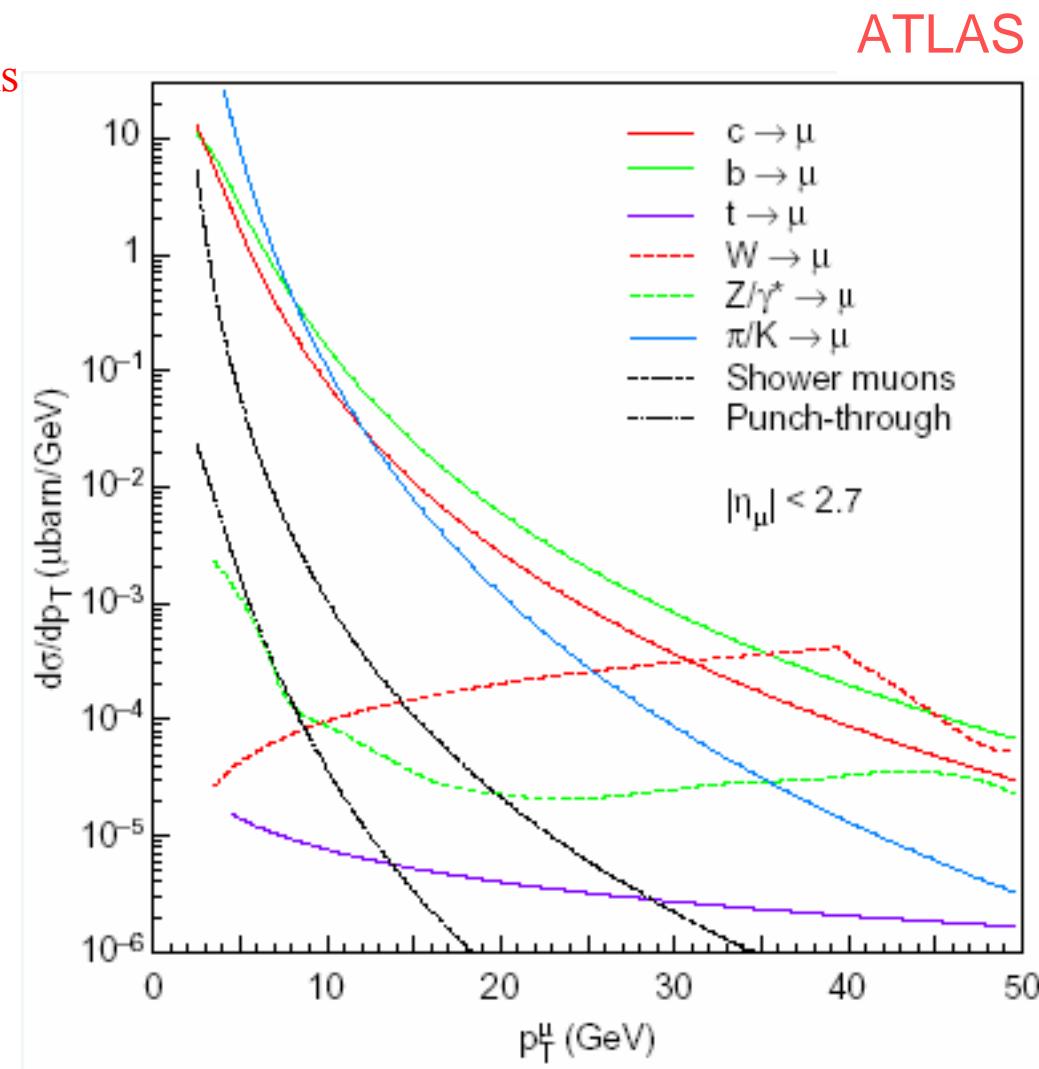
Very high energy muons shower like electrons

Radiative losses dominate above the critical energy $E_{\mu c}$

$E_{\mu c} \sim 350$ GeV for muons in Fe

Sources of Signals in Muon Systems

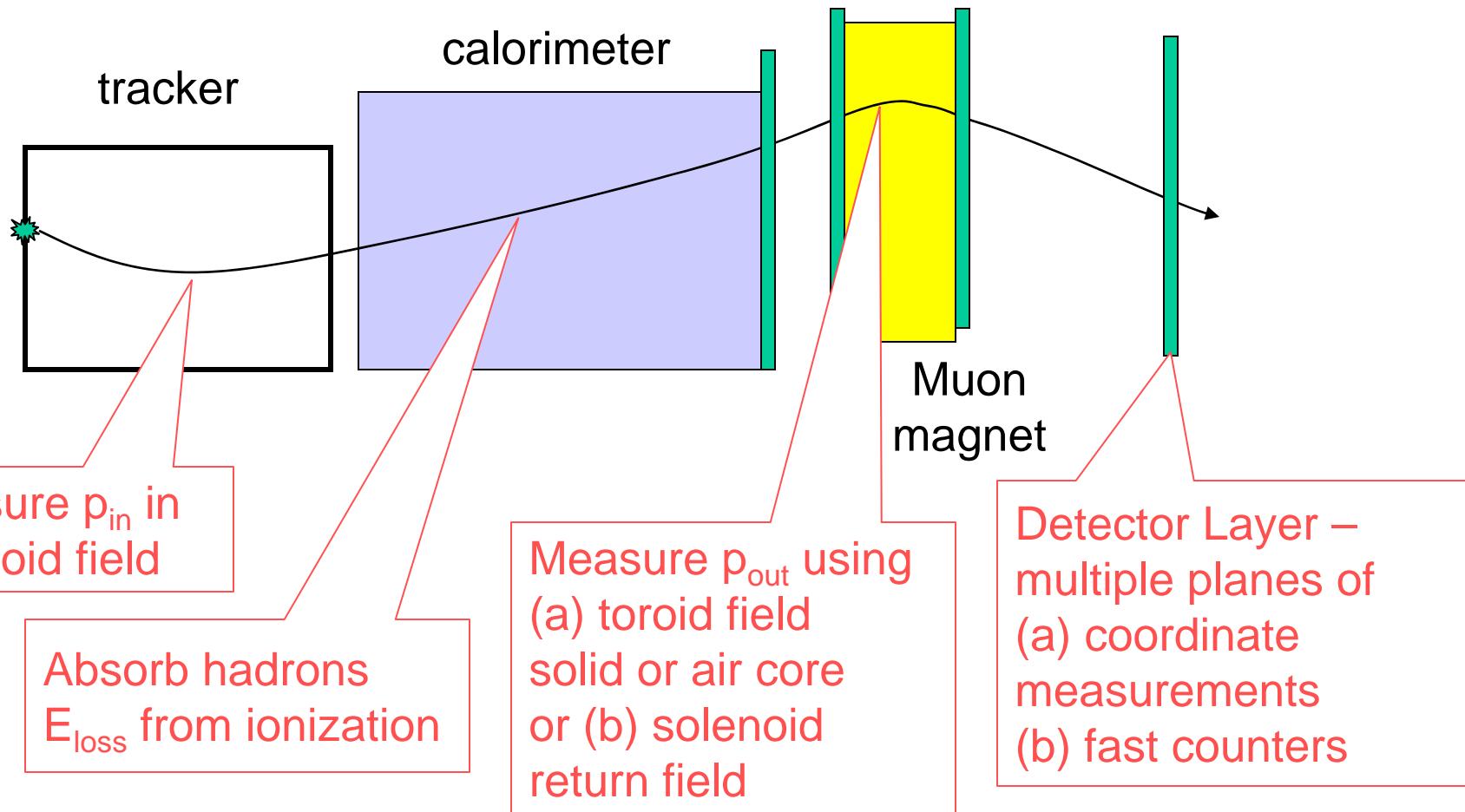
- Physics Processes, Prompt Muons
 - Heavy flavors: c and b quarks
 - W, Z decays
 - Top quarks
 - Higgs, new phenomena
- Backgrounds
 - pion/kaon decays in flight
 - Hadron punch-through
 - Beam Halo
 - Backscatter
 - Cosmic Rays
 - $\langle E \rangle \sim 4$ GeV at sea level
 - Flux $\sim 1/\text{cm}^2/\text{min}$ for horizontal detector
 - Random coincidences



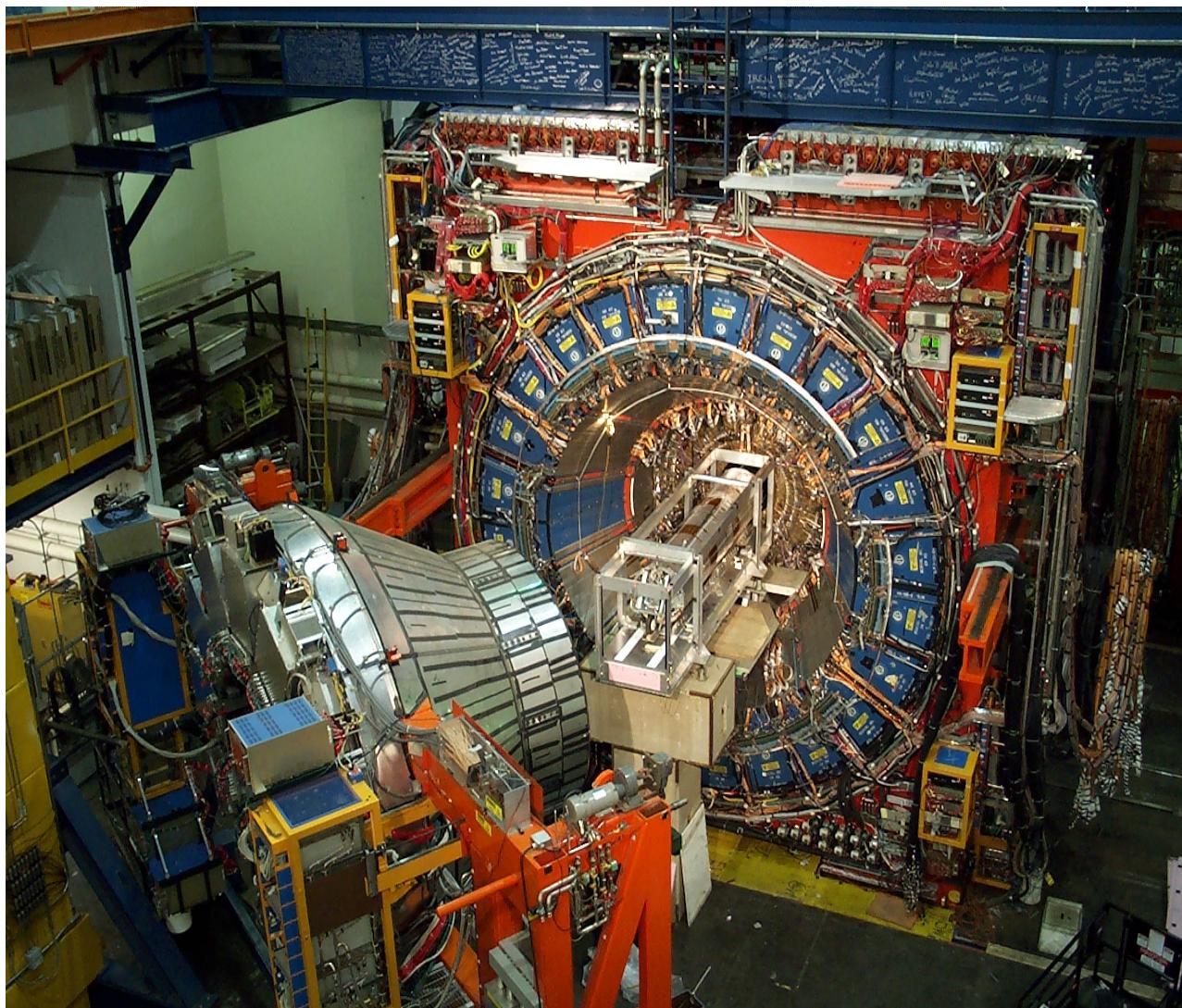
Purposes of Muon Detector Systems

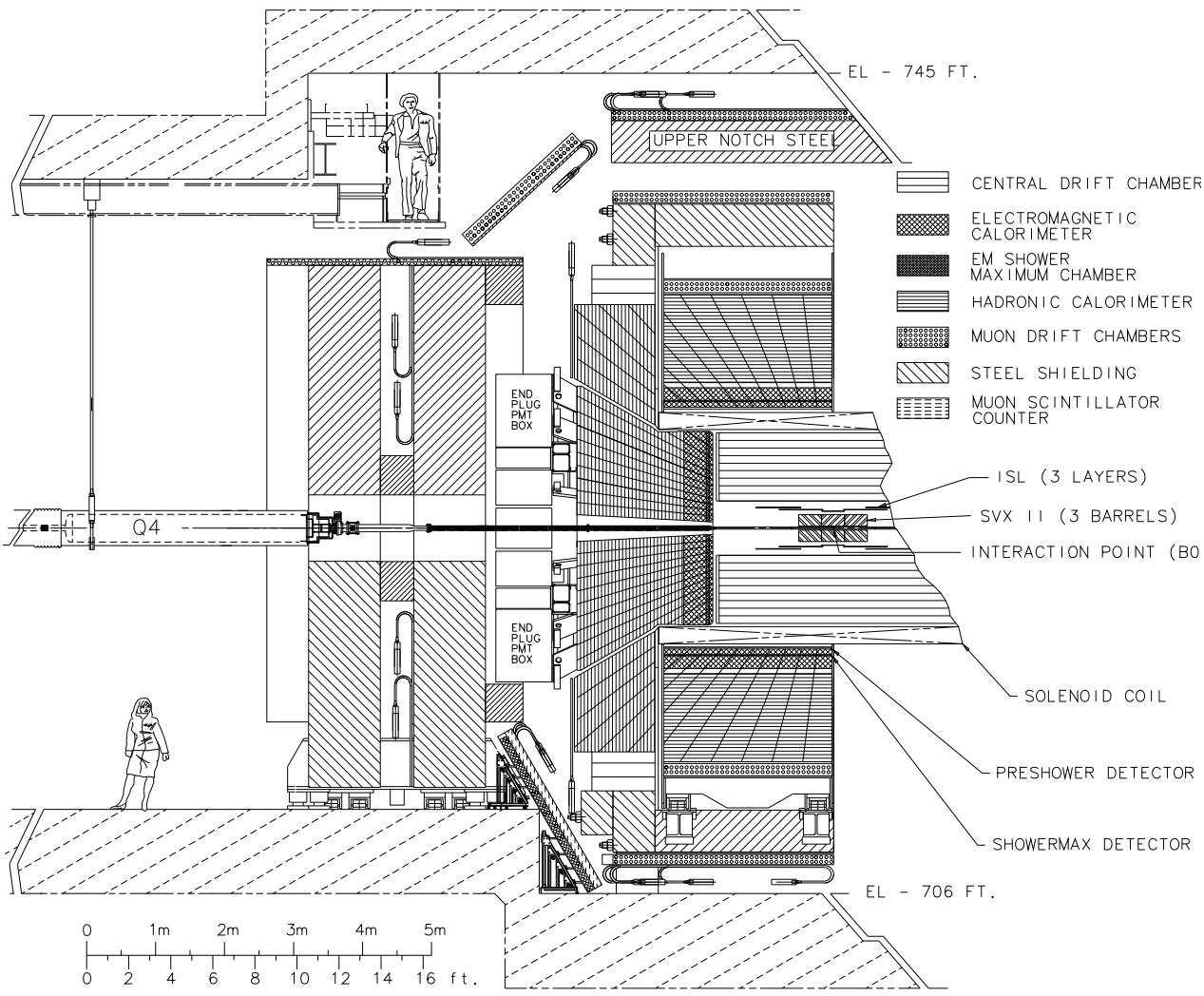
- Identify muons – at the trigger level and offline
- Optionally – measure the muon’s momentum
- Optionally – act as a “tail catcher” for measuring the energy that leaks out of the calorimeter from very high energy jets

Elements of Muon Detection



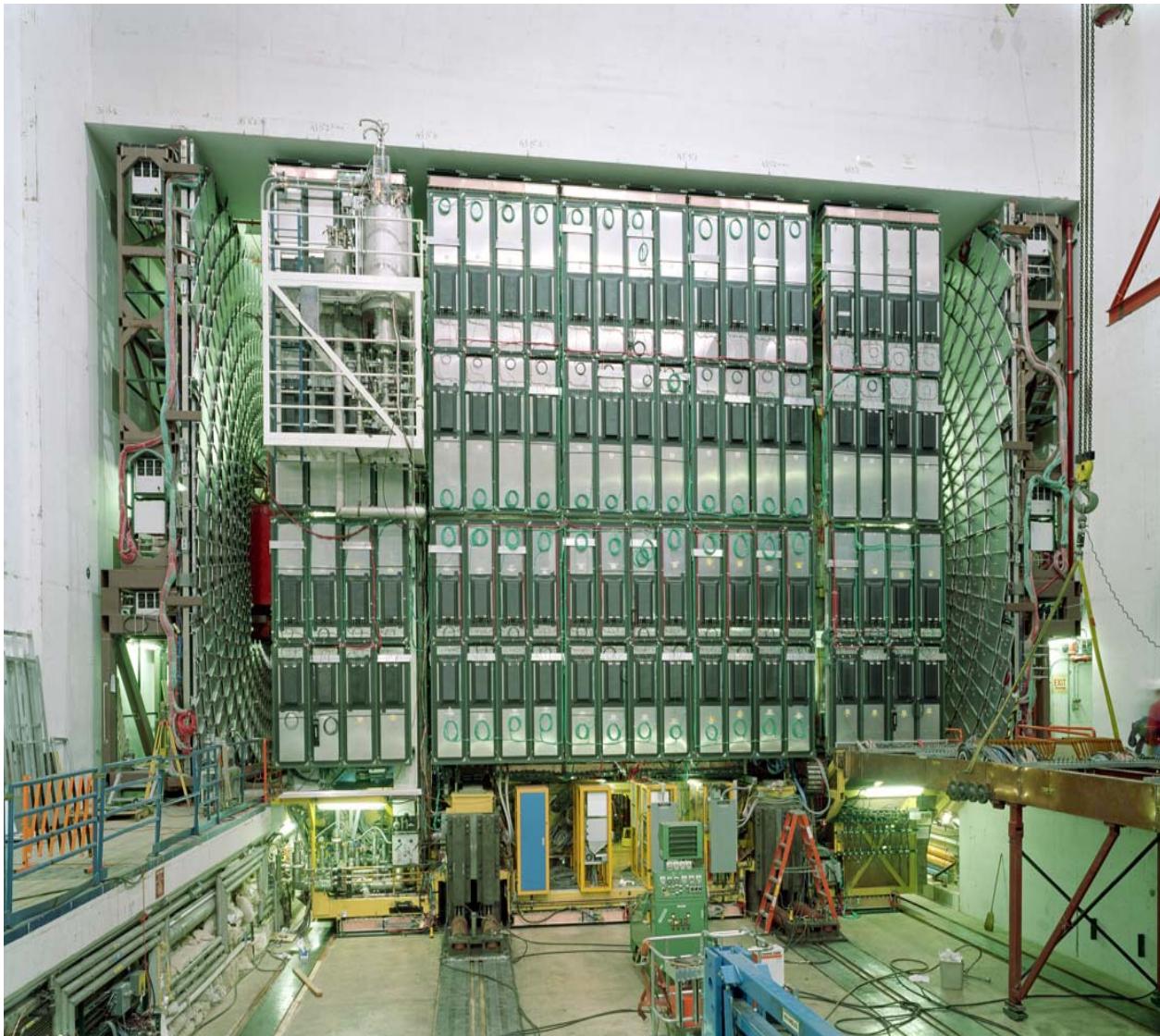
Real Muon Systems: CDF

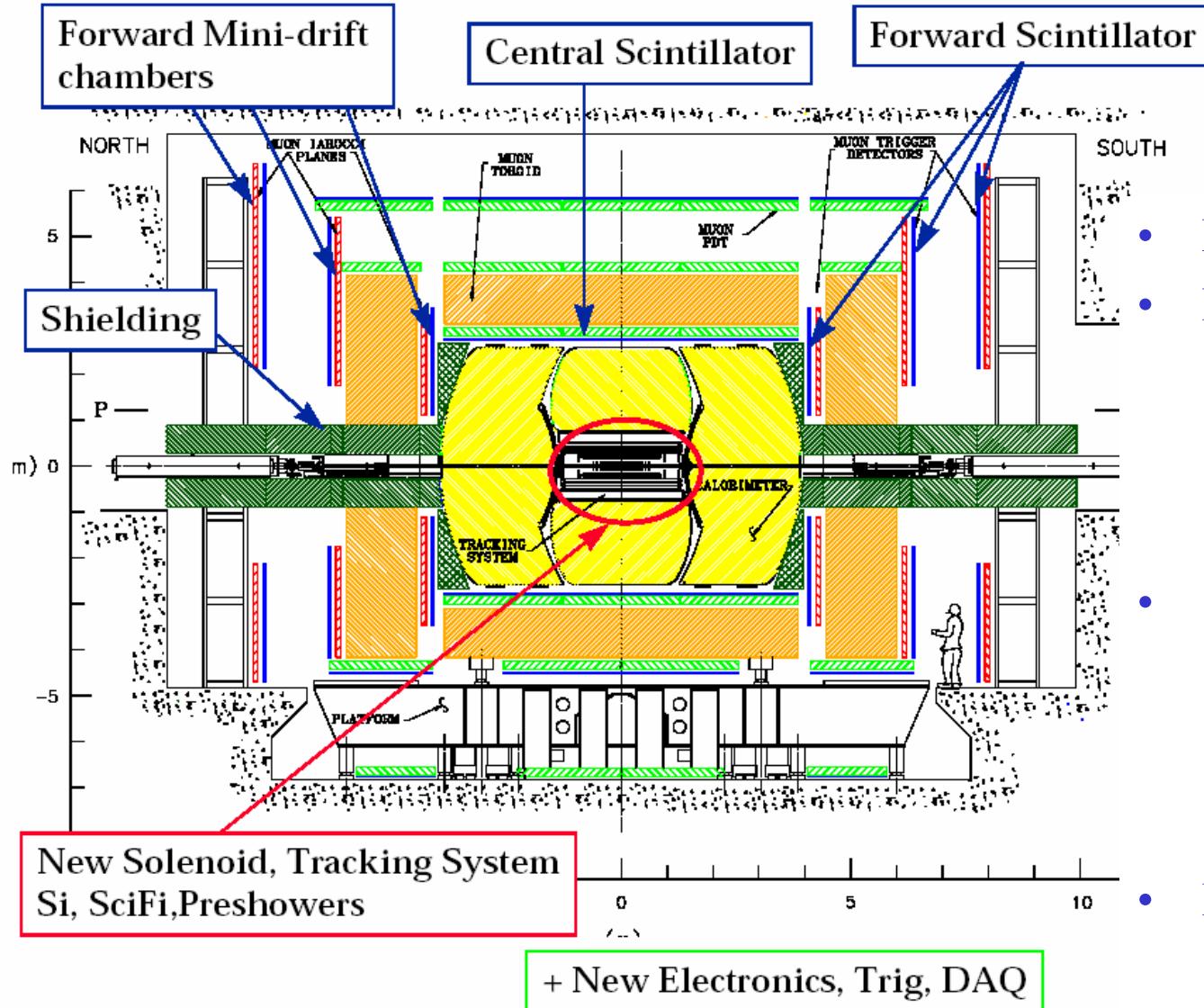




- No p_{out} measurement
- Drift chambers
 - Central: 2-layers (8 planes), 3.4k ch
 - Extension: 1-layer (4 planes), 2.2k ch
 - Intermediate: 1-layer (4 planes), 1.7k ch
- Scintillator
 - Central: 1-layer, 270 ch
 - Extension: 2-layer, 320 ch
 - Intermediate: 1-layer, 860 ch

Real Muon Systems: DØ

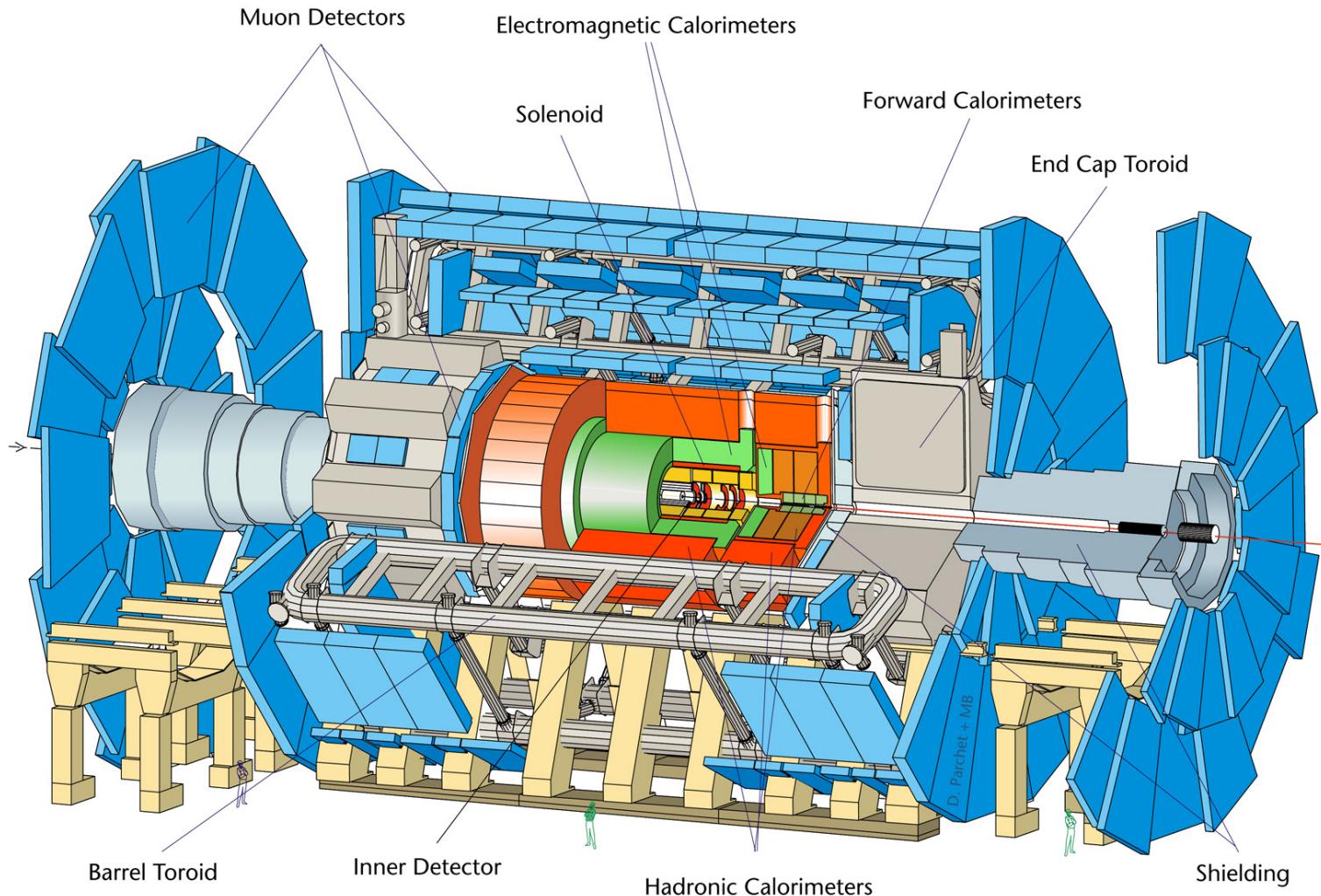


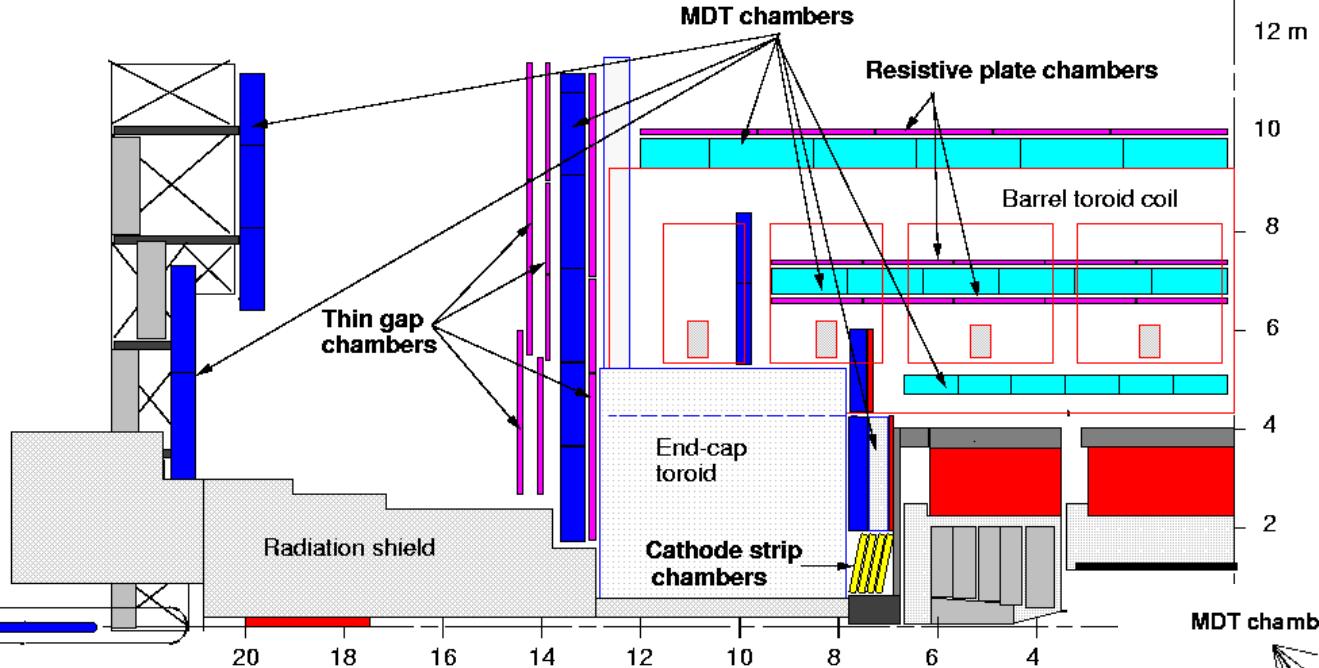


- Fe Toroid – 2 T
- Drift Chambers
 - Central: 3-layers (10 planes), 6.8k ch
 - Forward: 3-layers (10 planes), 50k ch
- Scintillator
 - Central: 2-layers, 990 ch
 - Forward: 3-layers, 4.8k ch
- Extensive shielding

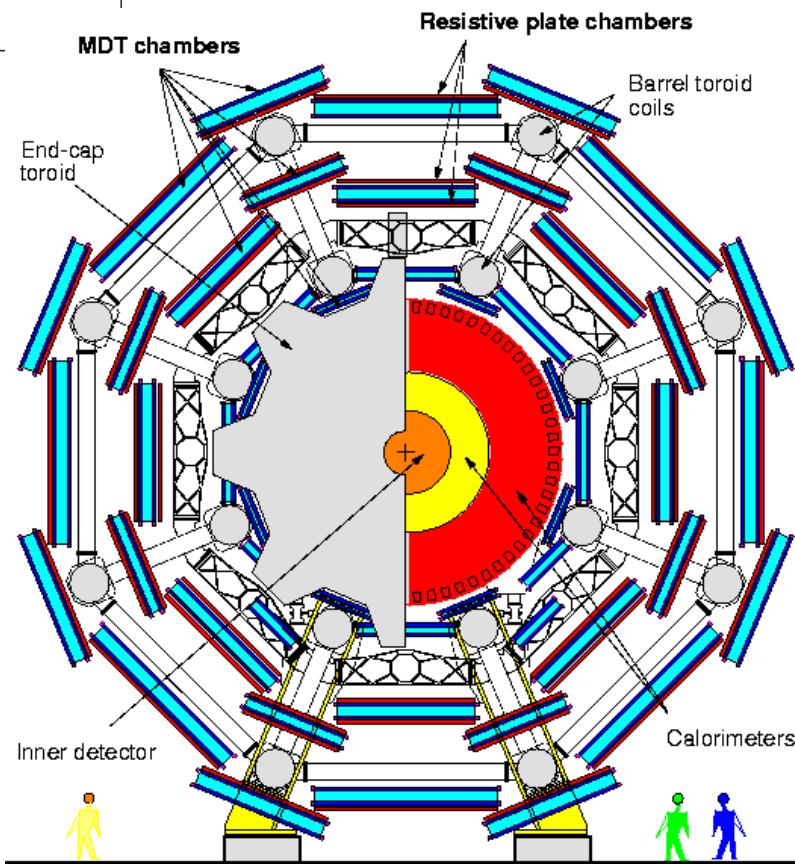
Real Muon Systems: ATLAS

D712/mu-26/06/97

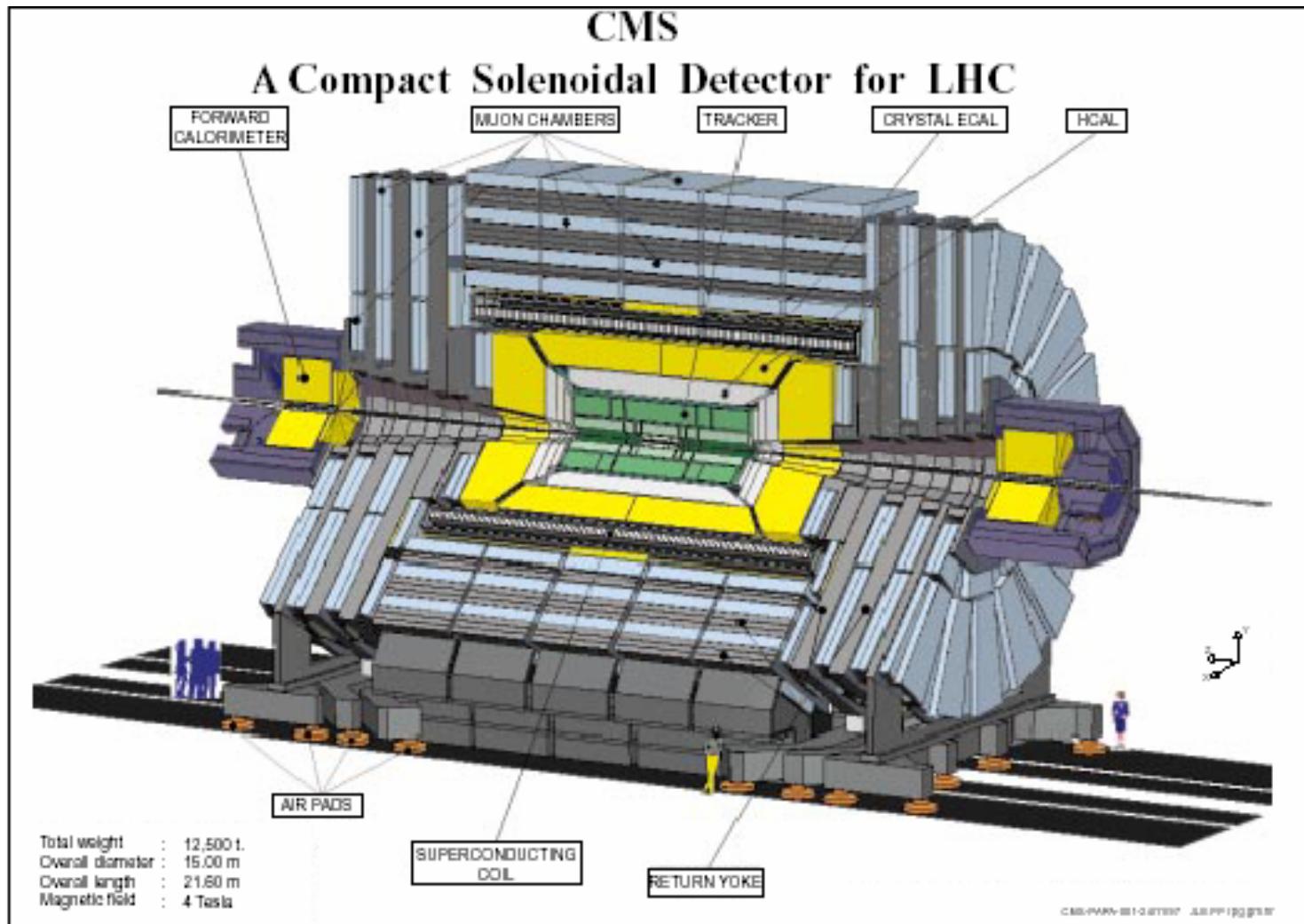




- Air-core Toroids
- Drift Chambers
 - 3-layers (6/8 planes/layer),
370k ch
 - 30 μm relative chamber alignment
- Central RPCs: 3-layers
- Thin Gap Chambers



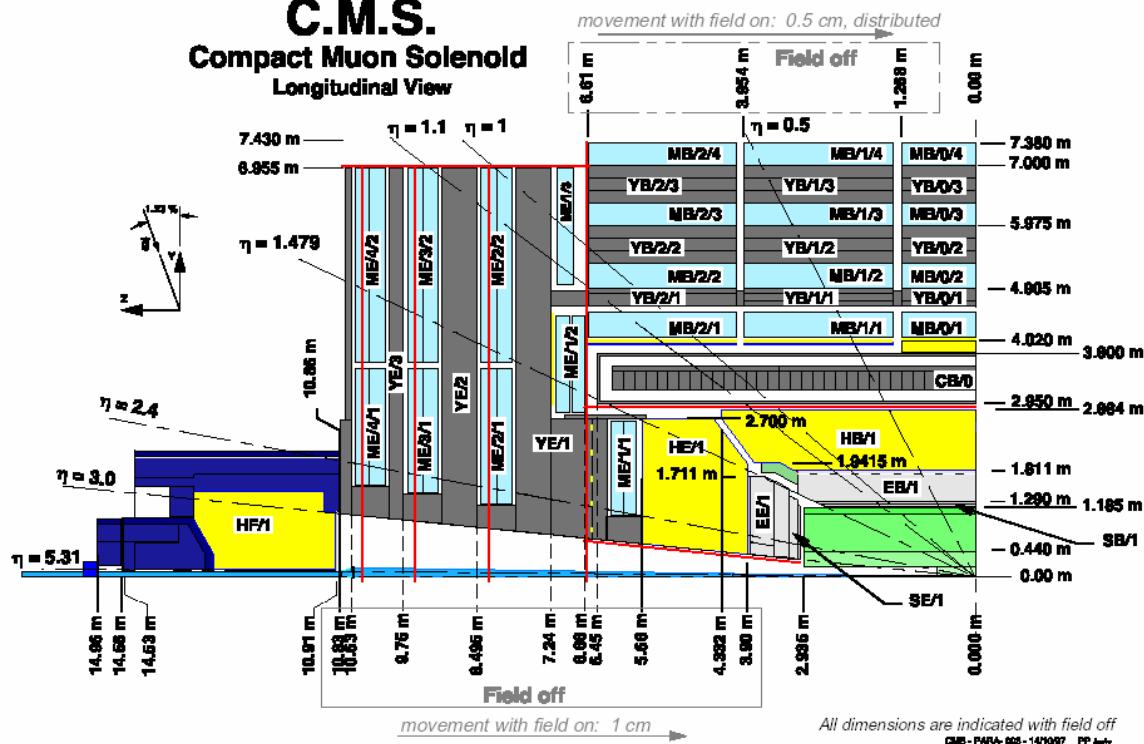
Real Muon Systems: CMS



C.M.S.

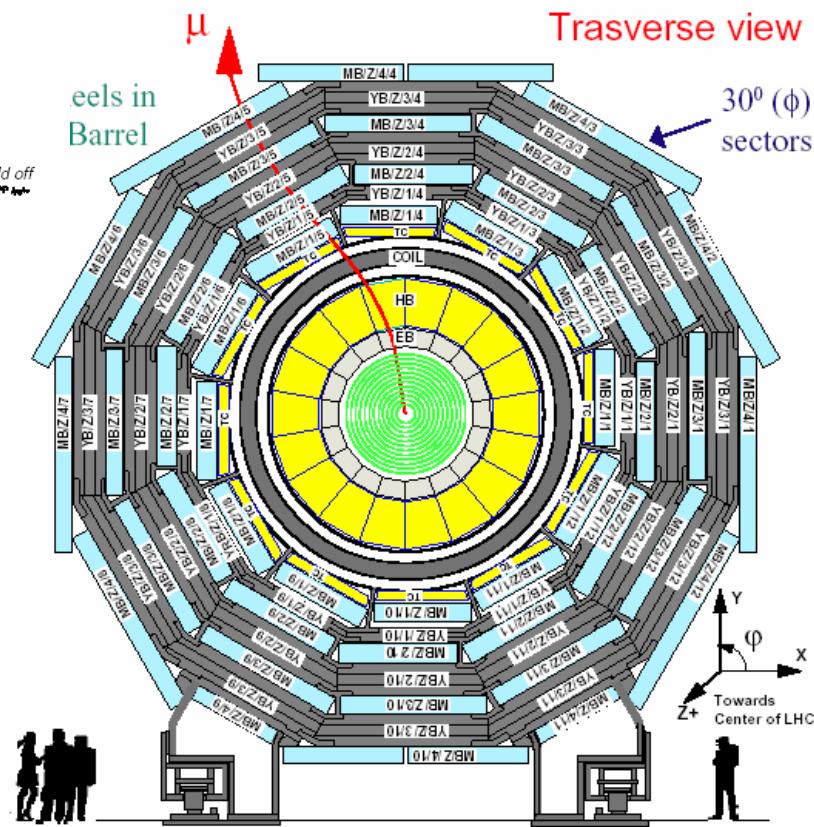
Compact Muon Solenoid

Longitudinal View



All dimensions are indicated with field off
CMS-PARA-005-147087 PP $\mu\mu$

- Return field from solenoid – 2 T
- Central: Drift Chambers
 - 4-layers (32+12 planes), 200k ch
- Forward: Cathode Strip Chambers
 - 4-layers (24 planes), 400k ch
- RPCs: 4-layers (6 planes), 155k ch



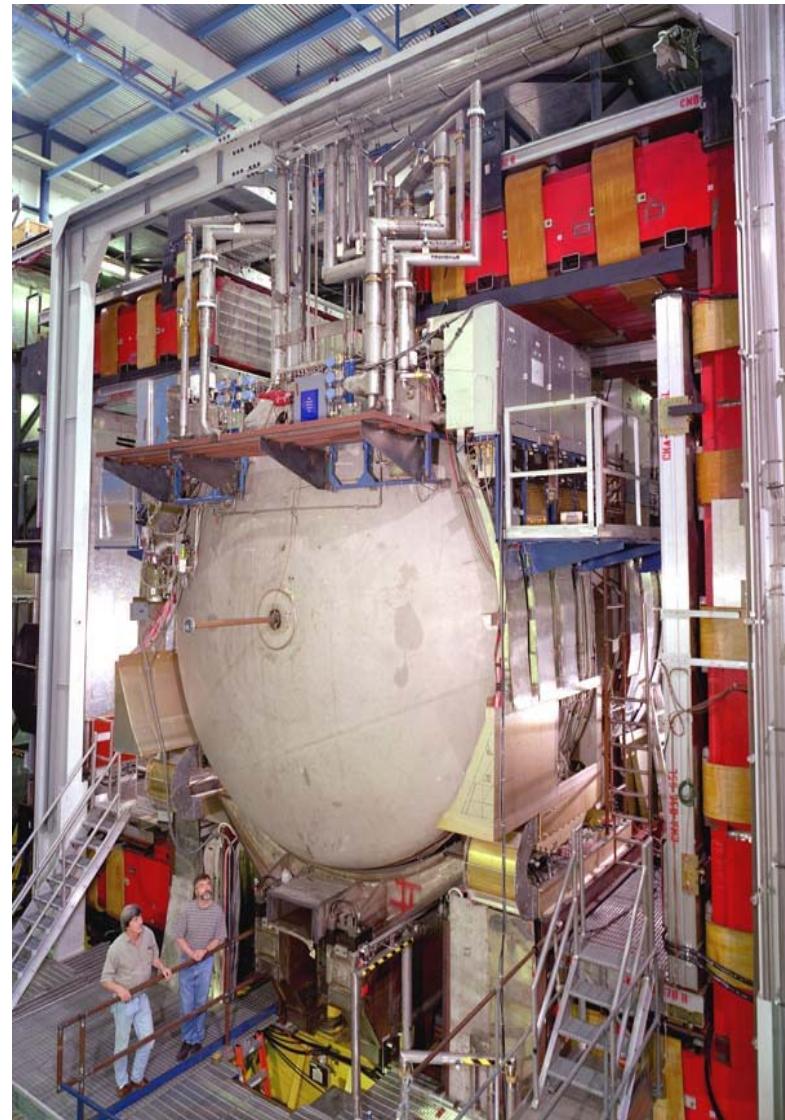
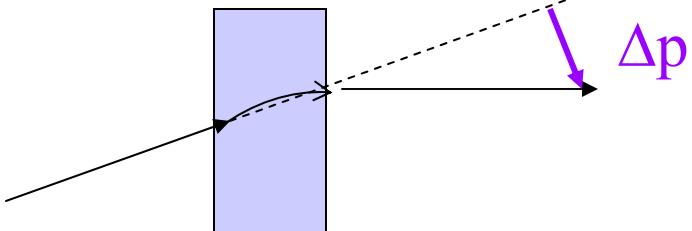
Magnets

- DØ: Solid Core Toroid
 - Iron
 - $B \sim 2$ T
 - Further filters hadrons
 - Multiple scattering in Fe will limit p_{out} resolution
- Bending power is given by

$$\int B d\ell$$

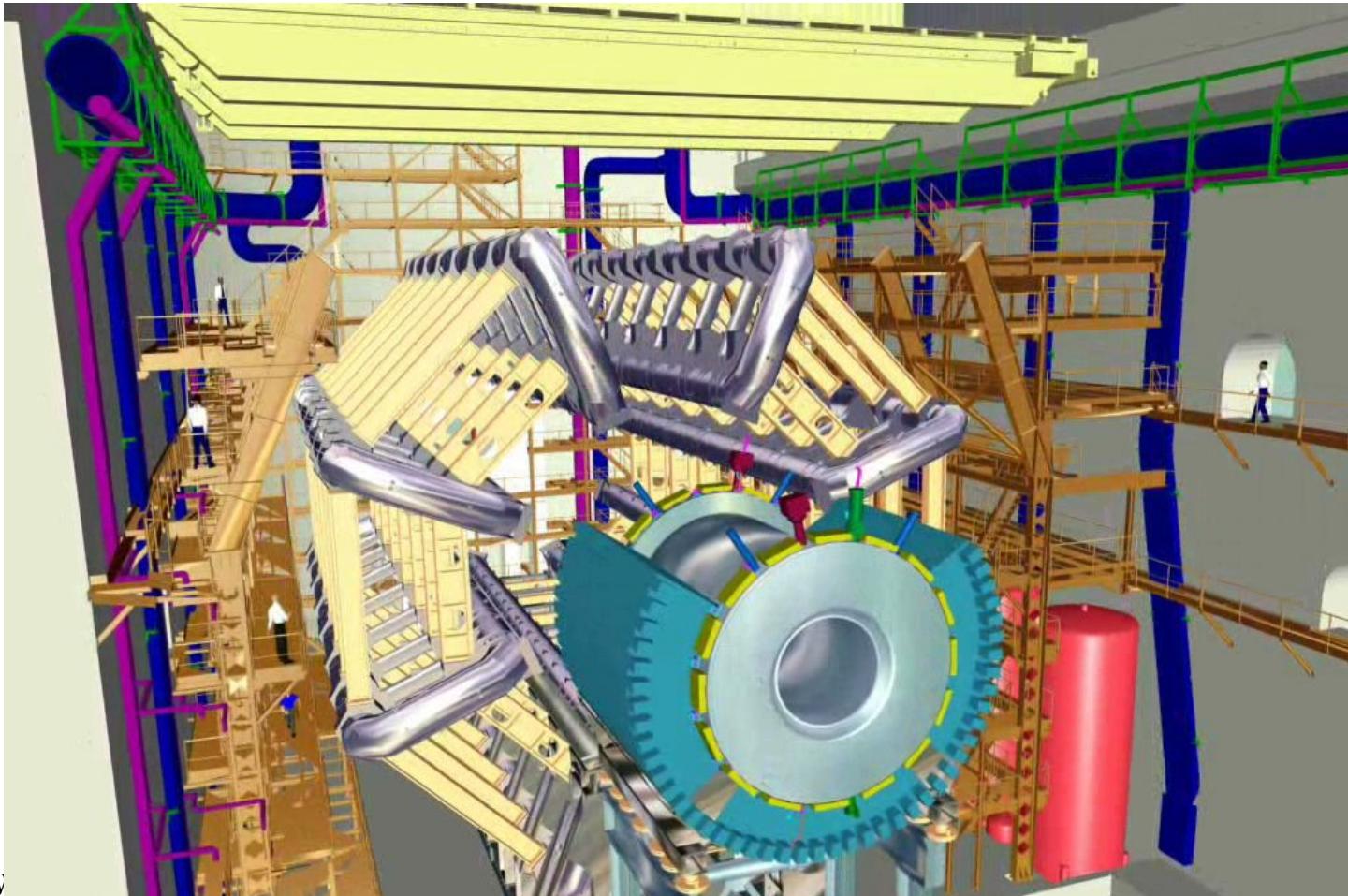
- This can be thought of as the transverse “kick” given to the muon momentum:

- $1 \text{ Tm} \leftrightarrow 0.3 \text{ GeV/c}$



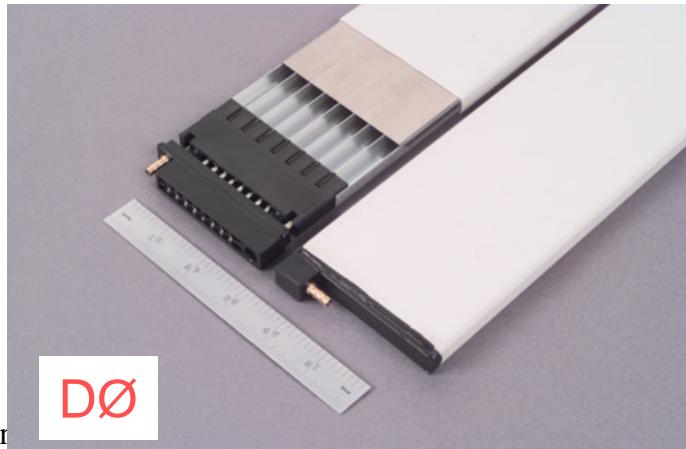
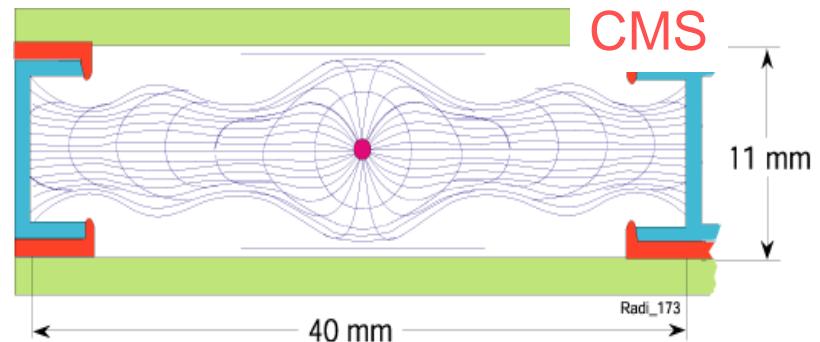
Magnets

- Air Core Toroid
 - $B \sim 0.3\text{-}1 \text{ T}$, $\int B dl \sim 3\text{-}9 \text{ Tm}$ in ATLAS
 - Allows precision measurement of p_{out}



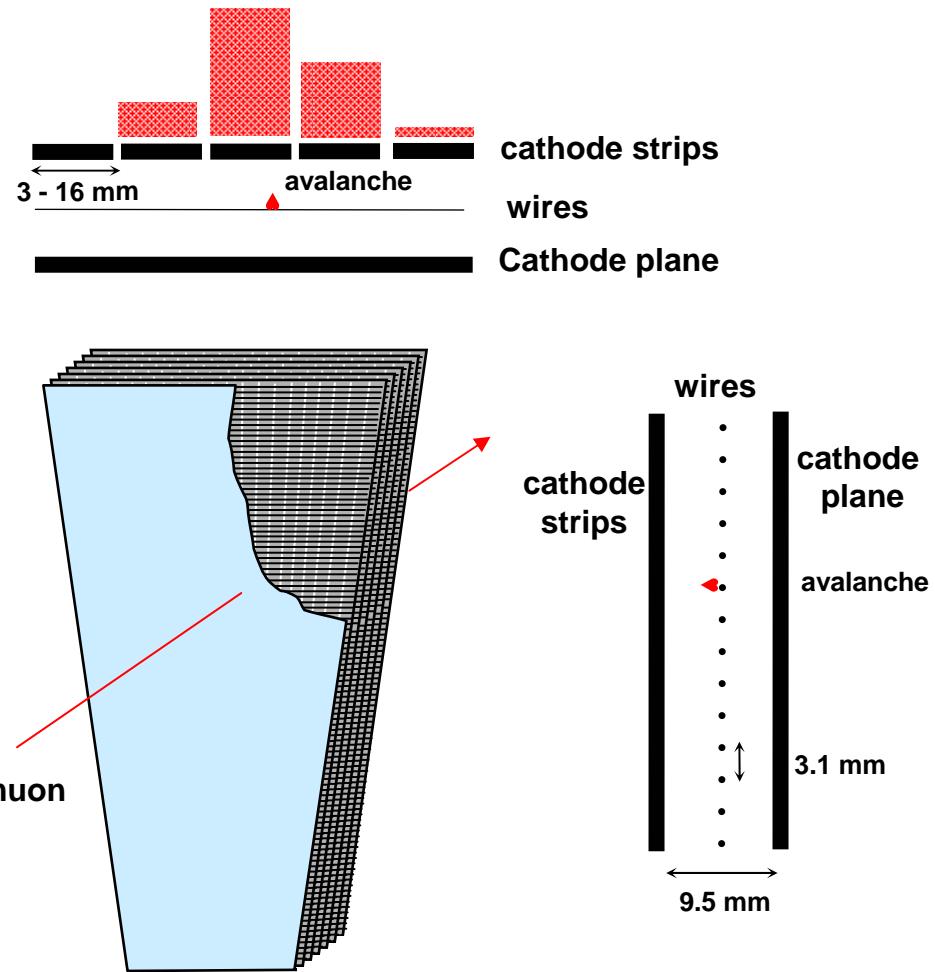
Detector Layer – Drift Tubes

- Coordinate Measurement
 - Drift Chambers, cathode strip chambers
 - Wire pitch \sim 1-10 cm perp. to μ trajectory
 - Resolutions range from 80-700 μm , one limit on momentum resolution
 - Integrate \sim few beam crossings



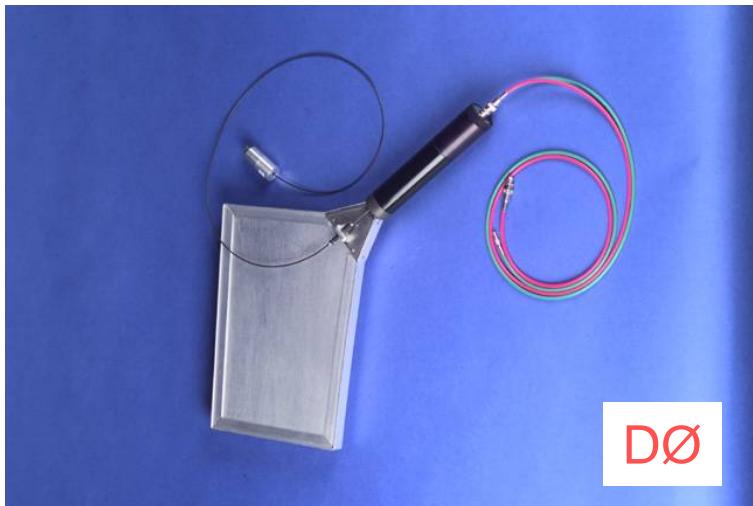
CMS forward/backward: Cathode Strip Chambers

- 6-layer chambers
- Radial, trapezoidal cathode strips
- Azimuthal anode wires
- Induced charges on strips - precise f coordinate
- Closely spaced wires - fast timing
- Wires ganged in groups of 5 -16 for r coordinate

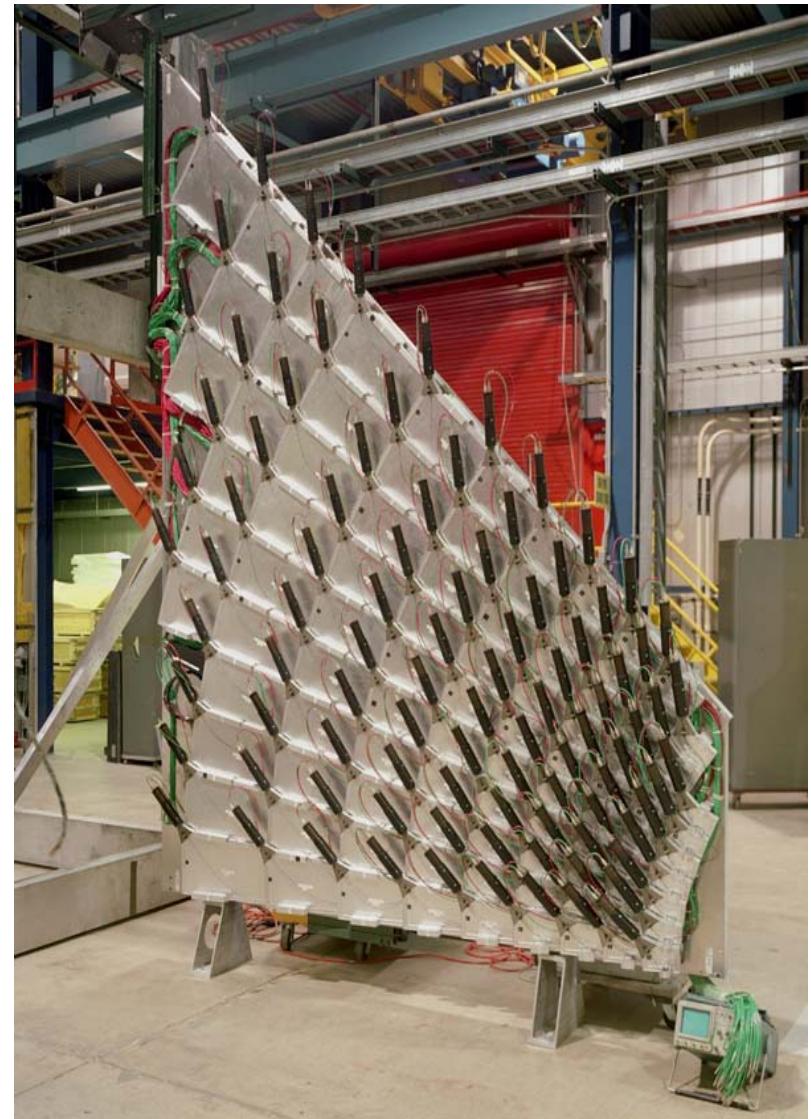


Detector Layer

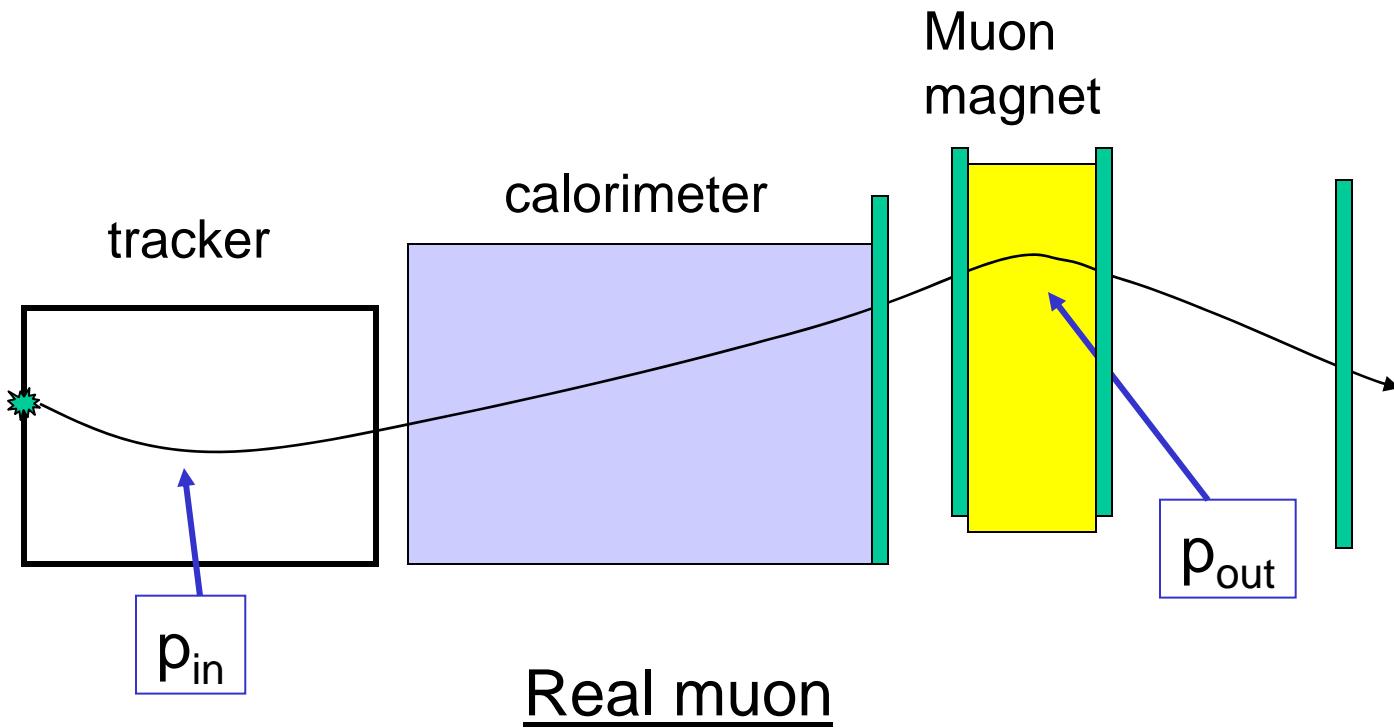
- Fast Trigger Counters
 - Scintillator + PMTs, Resistive Plate Chambers (RPCs)
 - Resolution \sim 1-2 ns
 - Tag beam crossing in trigger
 - Reduce backgrounds



Daniel Wood, HEPSS 2008

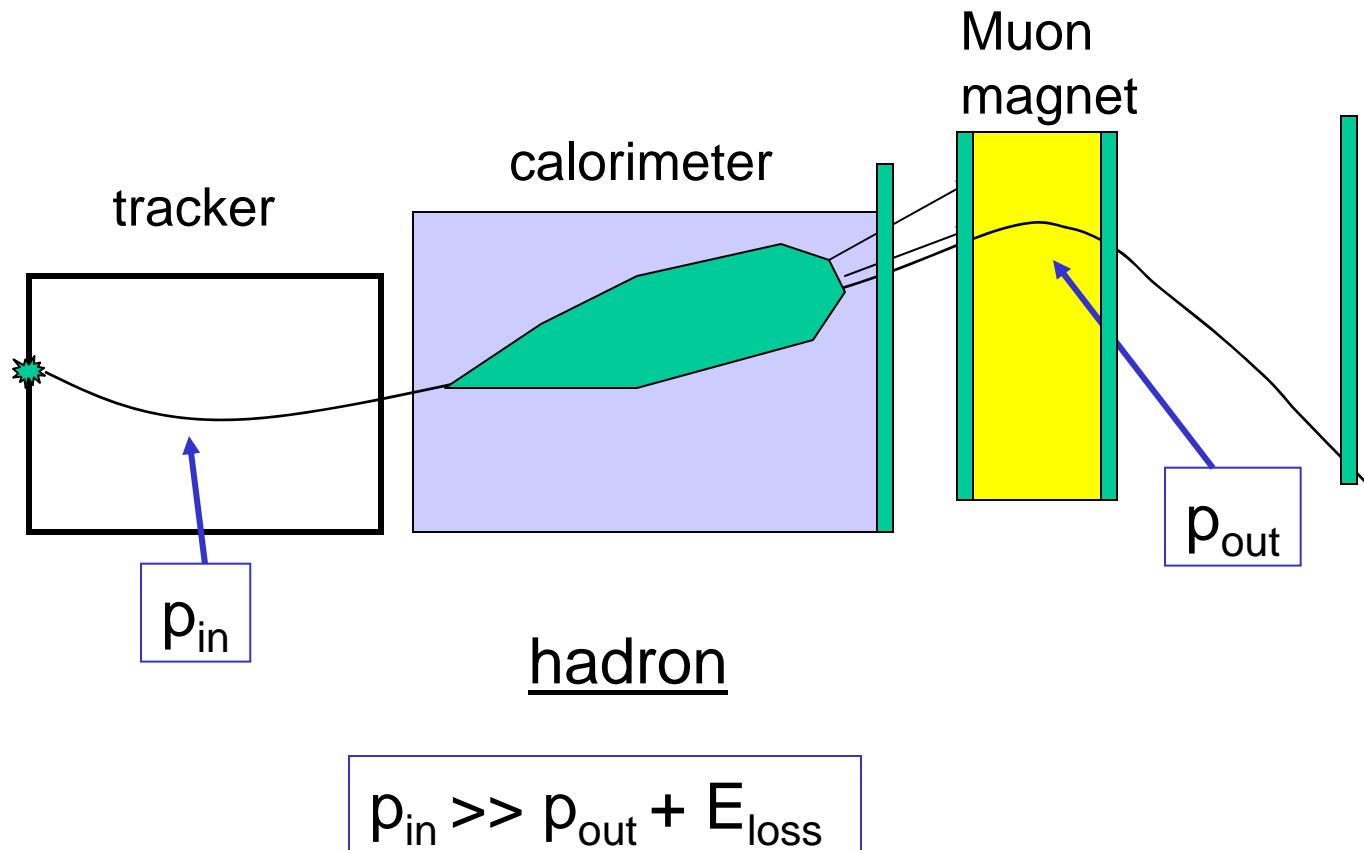


Prompt Muon Signature



$$p_{in} \approx p_{out} + E_{loss}$$

Background – Punch-through and Decay-in-Flight



Outer punch-through/decay track points back to parent hadron, but momenta do not match.

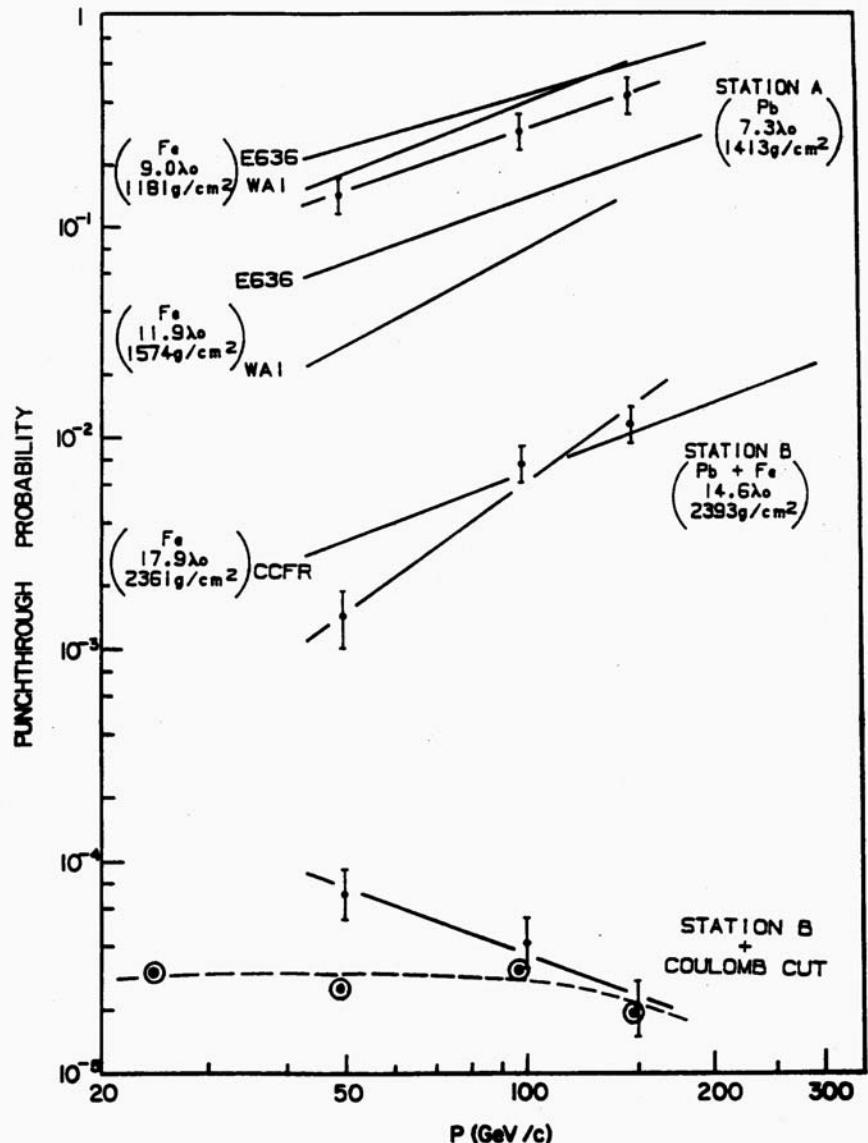
Background: Hadron Punch-through

- Define “punch-through” as particles from late-developing hadron showers that get into the μ system
- “Sneak-through” – probability for a hadron to not interact after penetrating a distance x , typically very small

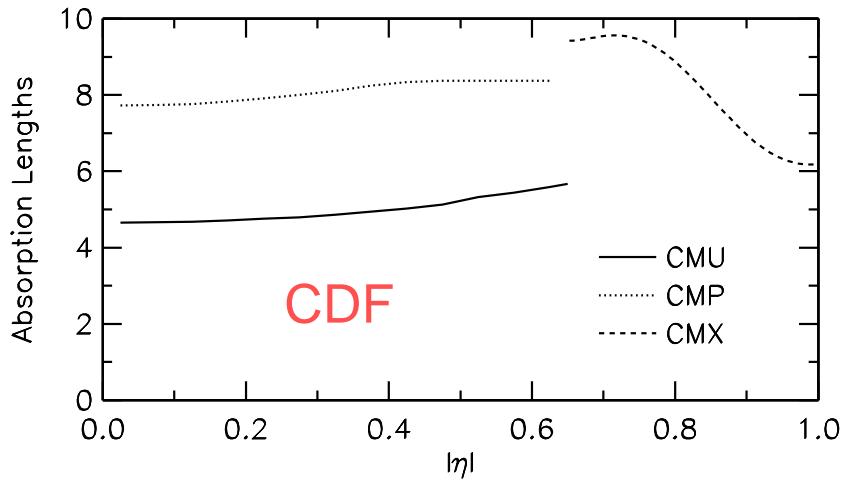
$$P(x) = e^{-x/\lambda_I}$$

- Minimize punch-through by
 - Material as measured in nuclear interaction lengths λ_I
 - “Best μ ID tool is a meter of steel”
 - Good track matches consistent with m_s uncertainty
- Prob $\sim 10^{-3} - 10^{-4}$ in DØ

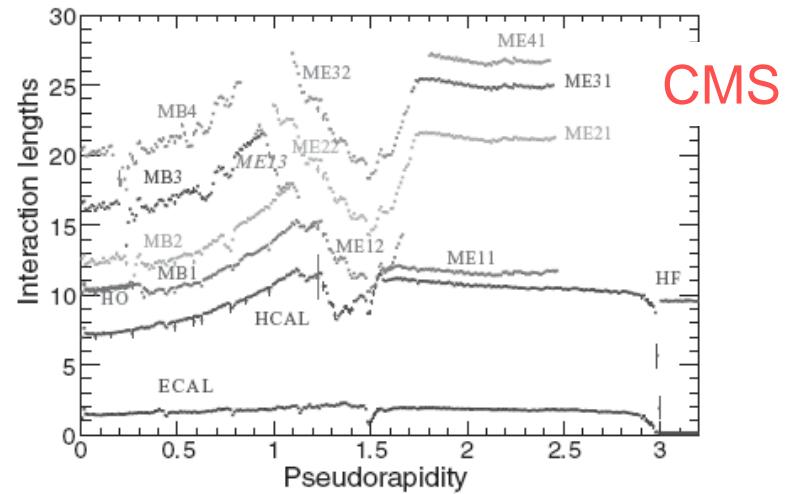
NIM A244, 356 (1986)



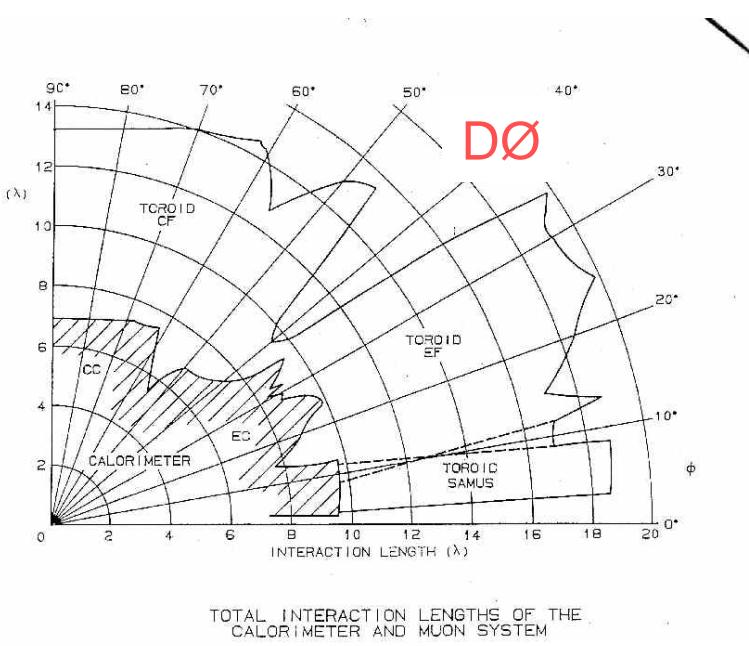
Background: Hadron Punch-through



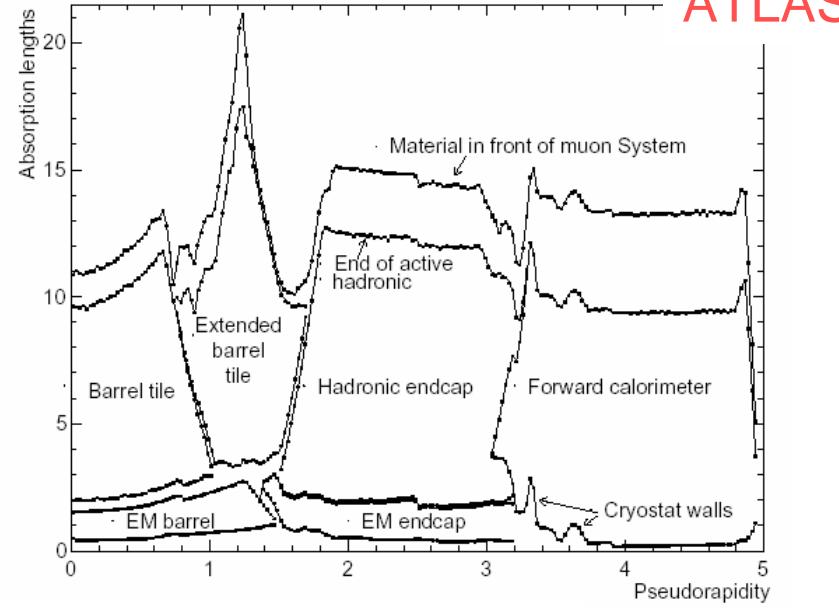
CDF



CMS

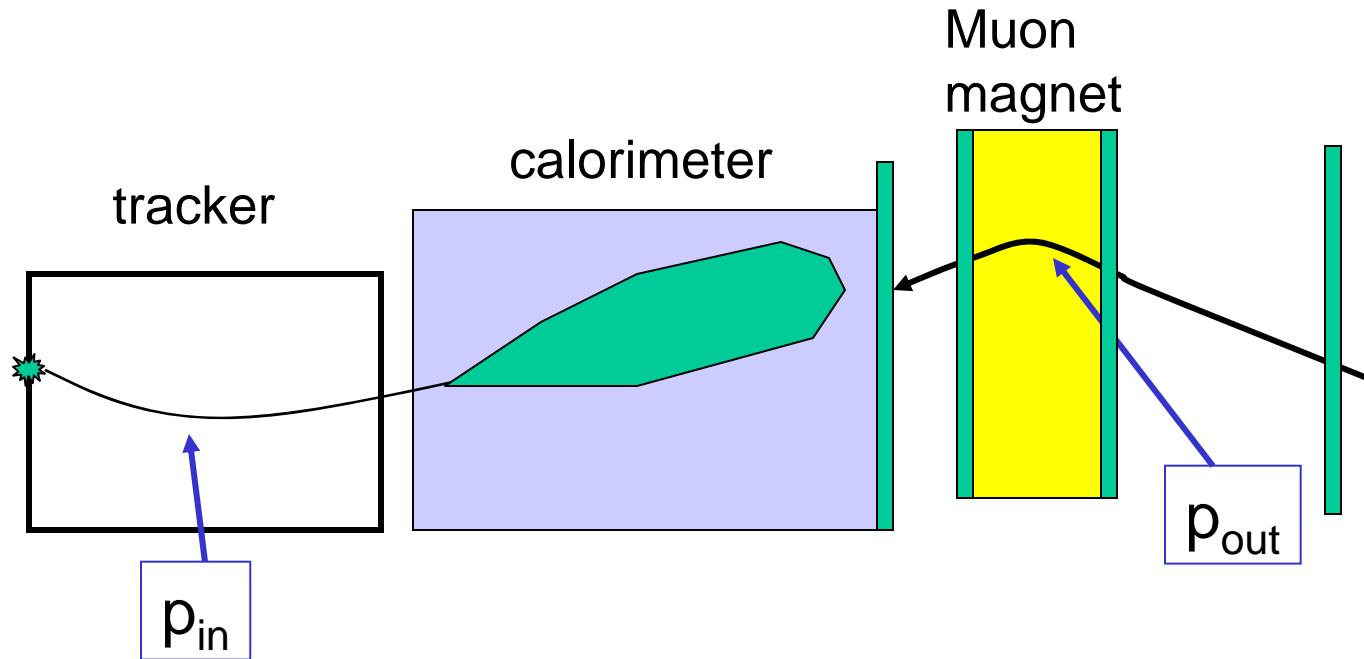


DØ



ATLAS

Background: Beam Halo



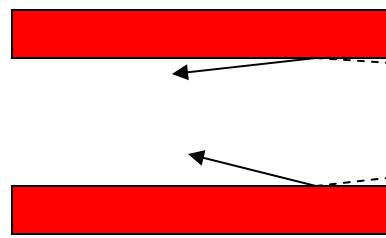
$$p_{in} \neq p_{out} + E_{loss}$$

Good timing (scintillator, RPC) and tunnel shielding can get rid of most of these

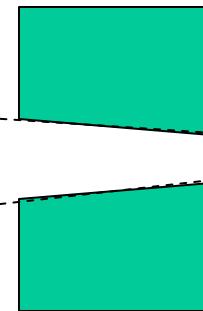
Backscatter Background

- Reduce source: conical beam pipe/calorimeter:

Low β quad/shielding

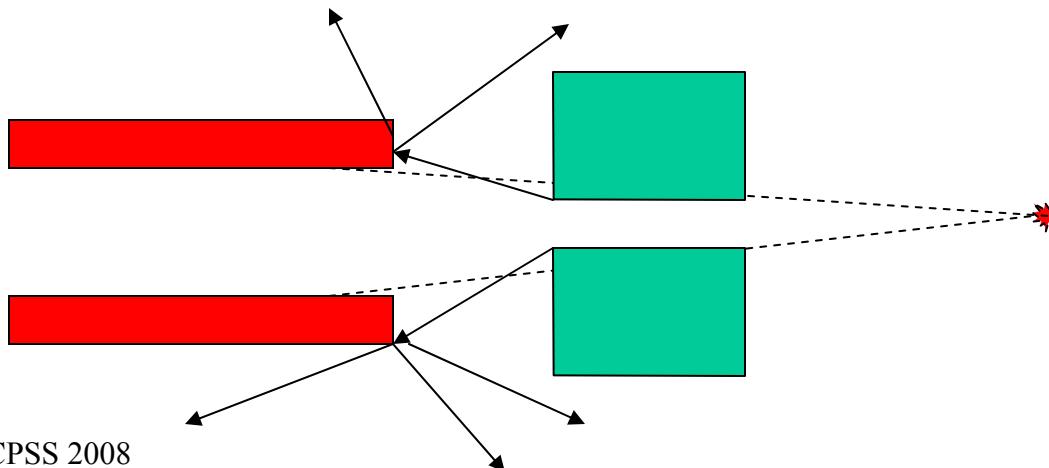


Forward calorimeter
collisions



Or else...

- Shield around quads
- Reject remaining backscatter with timing



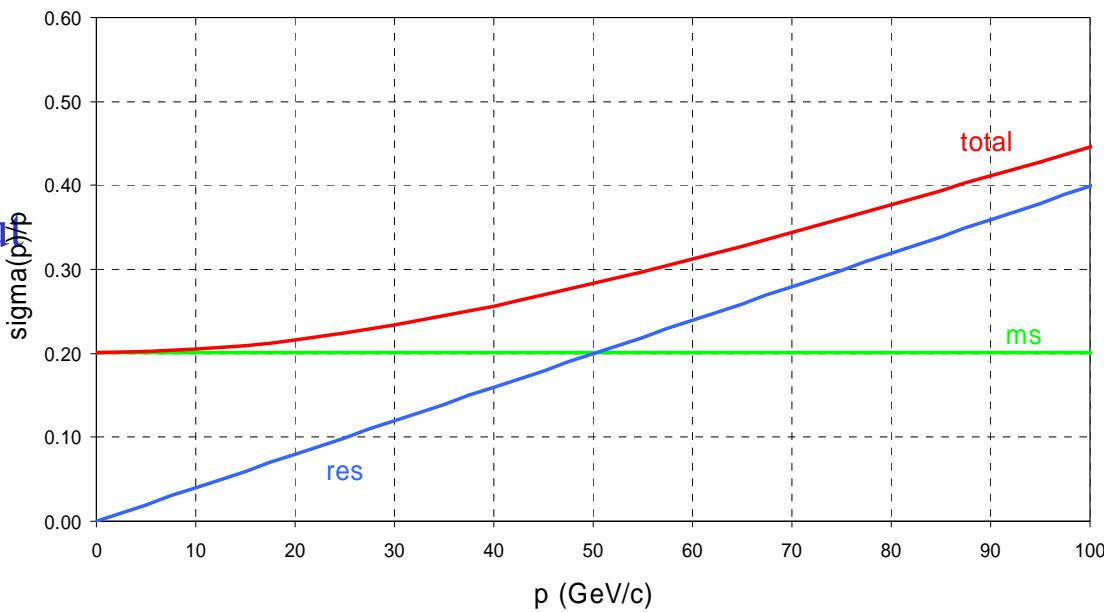
Momentum Resolution

- Two distinct contributions to momentum resolution
 - Multiple Coulomb Scattering in detector material (ms)
 - Finite position measurement resolution (res)
 - Assume θ well measured, so $\delta\theta$ is negligible
 - Survey is another important contribution
- Conventional to quote $\delta p/p$ but measurement is Gaussian in $1/p$, not p

$$\frac{\delta p}{p} = \sqrt{\alpha^2 + (\beta p)^2}$$

where $\alpha = \left(\frac{\delta p}{p}\right)_{ms}$ and $\beta p = \left(\frac{\delta p}{p}\right)_{res}$

α and β depend on the design of your detector



Multiple Coulomb Scattering

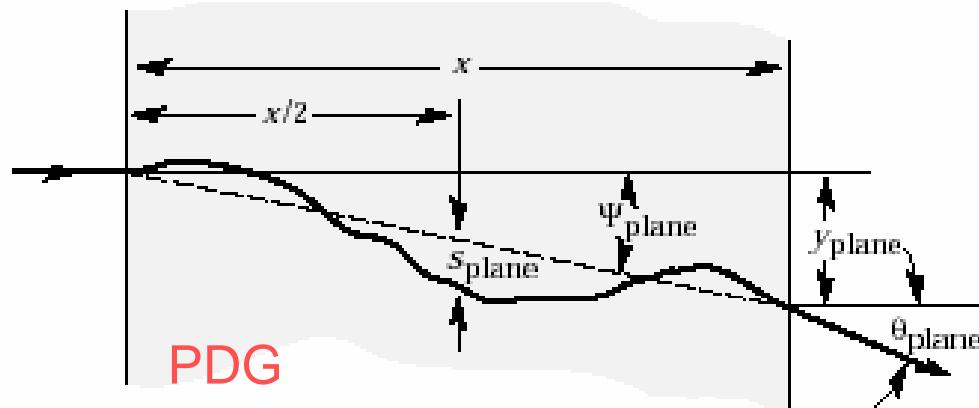
- Muons traversing material are deflected from their original trajectory by multiple small-angle Coulomb scatters off nuclei
- y_{plane} and θ_{plane} are \sim Gaussian distributed

$$\theta_{\text{plane}}^{\text{rms}} = \theta_0$$

$$y_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{3}}x\theta_0 \text{ where}$$

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

The multiple scattering contribution to the momentum resolution is proportional to $y_{\text{plane}}^{\text{rms}}$



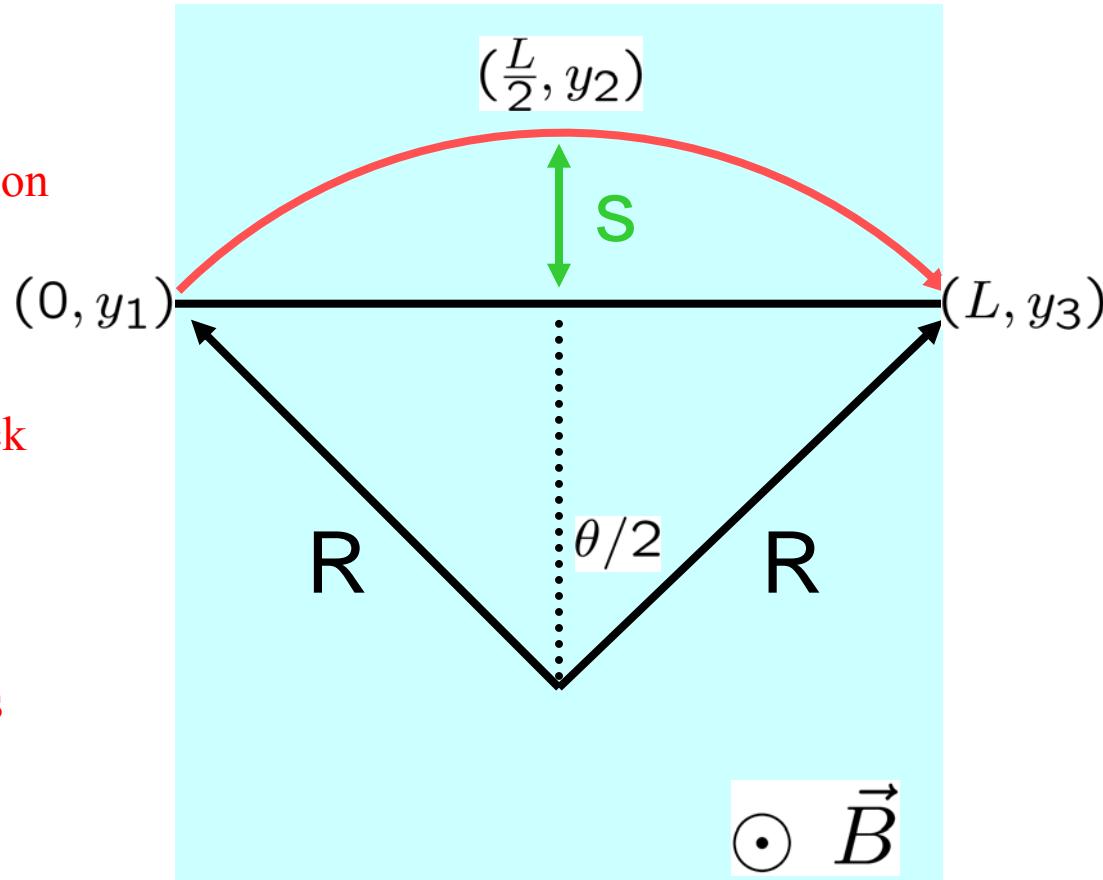
Momentum Resolution

- Multiple Scattering contribution depends on
 - Material through the “radiation length” X_0
 - $X_0 = 1.76 \text{ cm}$ for Fe
 - Path length L' in material
 - B field
 - Units are GeV/c , Tesla, meter
- For example, in DØ iron toroids, $L' = 1\text{m}$ @ normal incidence $B = 2\text{T}$
so the ms error is $\sim 20\%$

$$\left(\frac{\delta p_T}{p_T} \right)_{ms} = \frac{0.016 \text{GeV}/c \sqrt{\frac{L'}{X_0}}}{e \int B_z dl}$$
$$\approx \frac{0.053}{B \sqrt{L' X_0}}$$

Momentum Resolution

- Start with a simple case
- Assume
 - Uniform B field in z-direction
 - small θ
 - L is projected length of track onto bending plane
- To measure p_T , measure the sagitta s
 - 3 equidistant measurements



Momentum Resolution

$$s = R - R \cos \frac{\theta}{2} \approx \frac{R\theta^2}{8}$$

$$\theta \approx \frac{L}{R} = \frac{0.3BL}{p_T}$$

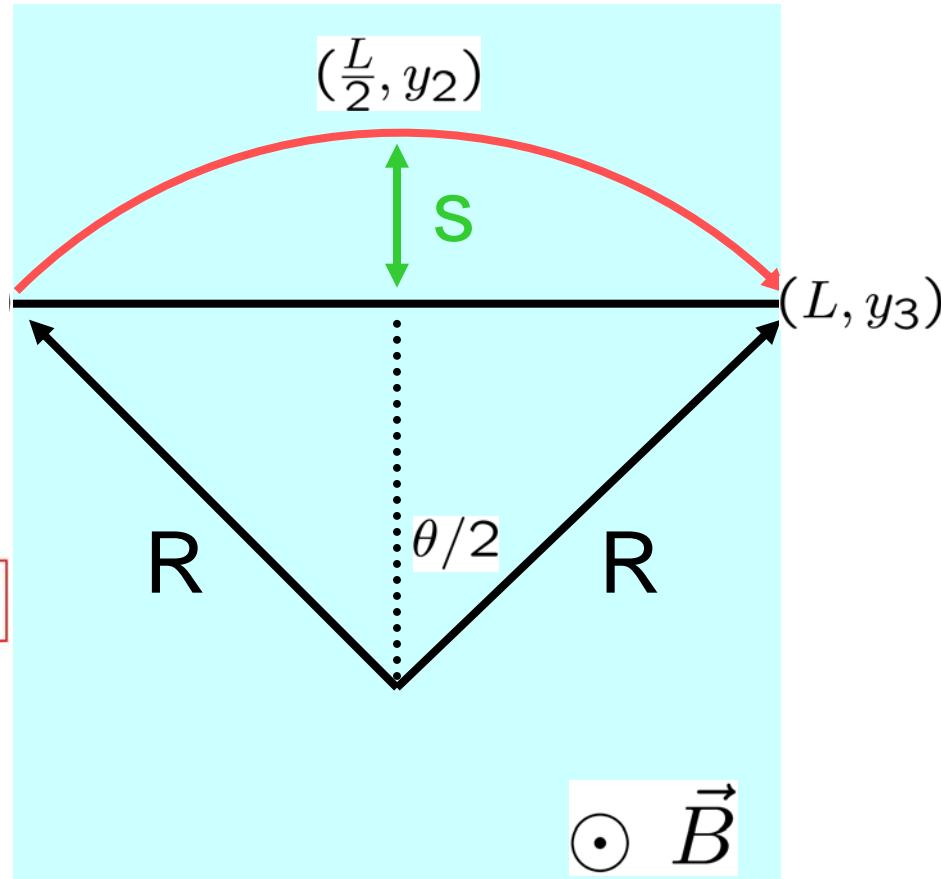
$$s = \frac{0.3BL^2}{8p_T}$$

$$s = y_2 - \frac{1}{2}(y_1 + y_3)$$

$$(\delta s)^2 = (\delta y_2)^2 + \frac{1}{4} [(\delta y_1)^2 + (\delta y_3)^2]$$

Assume $\delta y_1 = \delta y_2 = \delta y_3 \equiv \delta y$

$$\text{then } \delta s = \sqrt{\frac{3}{2}} \delta y$$



Momentum Resolution

Since $s \propto \frac{1}{p_T}$ then

$$\frac{\delta s}{s} = \left(\frac{\delta p_T}{p_T} \right)_{res} \text{ so}$$

$$\left(\frac{\delta p_T}{p_T} \right)_{res} = \frac{8\sqrt{\frac{3}{2}}\delta y}{0.3BL^2} \cdot p_T$$

- Make more measurements
Gluckstern, NIM 24, 381 (1963)
 - N equidistant measurements
 - $N \gg 3$
 - Same δy for each
 - Uniform B field

- To improve resolution with 3-measurement system
 - Increase L
 - Increase B
 - Decrease δy

$$\left(\frac{\delta p_T}{p_T} \right)_{res} = \frac{\delta y}{0.3BL^2} \frac{p_T}{\sqrt{\frac{720}{N+4}}}$$

Momentum Resolution

- Can win further on resolution by
 - Arranging N measurements like the 3-measurement case
 - Clustering measurements also necessary for trigger
 - Primary vertex constraint reduces resolution by factor of $\sim\sqrt{2}$ to 2
- Also by reducing δy but...
 - #channels $\sim 1/y_{cell} \sim \$\$/\epsilon$

$$\delta y = \frac{y_{cell}}{\sqrt{12}} \text{ where } y_{cell} \text{ is cell size}$$

Geometric Coverage

- Important design choice driven by physics and cost
- In hadron colliders, the natural coordinates are not r, ϕ, θ but \mathbf{r}, ϕ, η
- Why pseudo-rapidity η ? Light particles are produced such that

$\frac{d\sigma}{dy} \approx \text{constant ("rapidity plateau")}$

for $|y| < y_{max} = \ln\left(\frac{\sqrt{s}}{m}\right)$

where the rapidity $y = \frac{1}{2} \ln\left(\frac{E+p_z}{E-p_z}\right)$.

For $p \gg m$, $y \approx -\ln \tan(\theta/2) \equiv \eta$

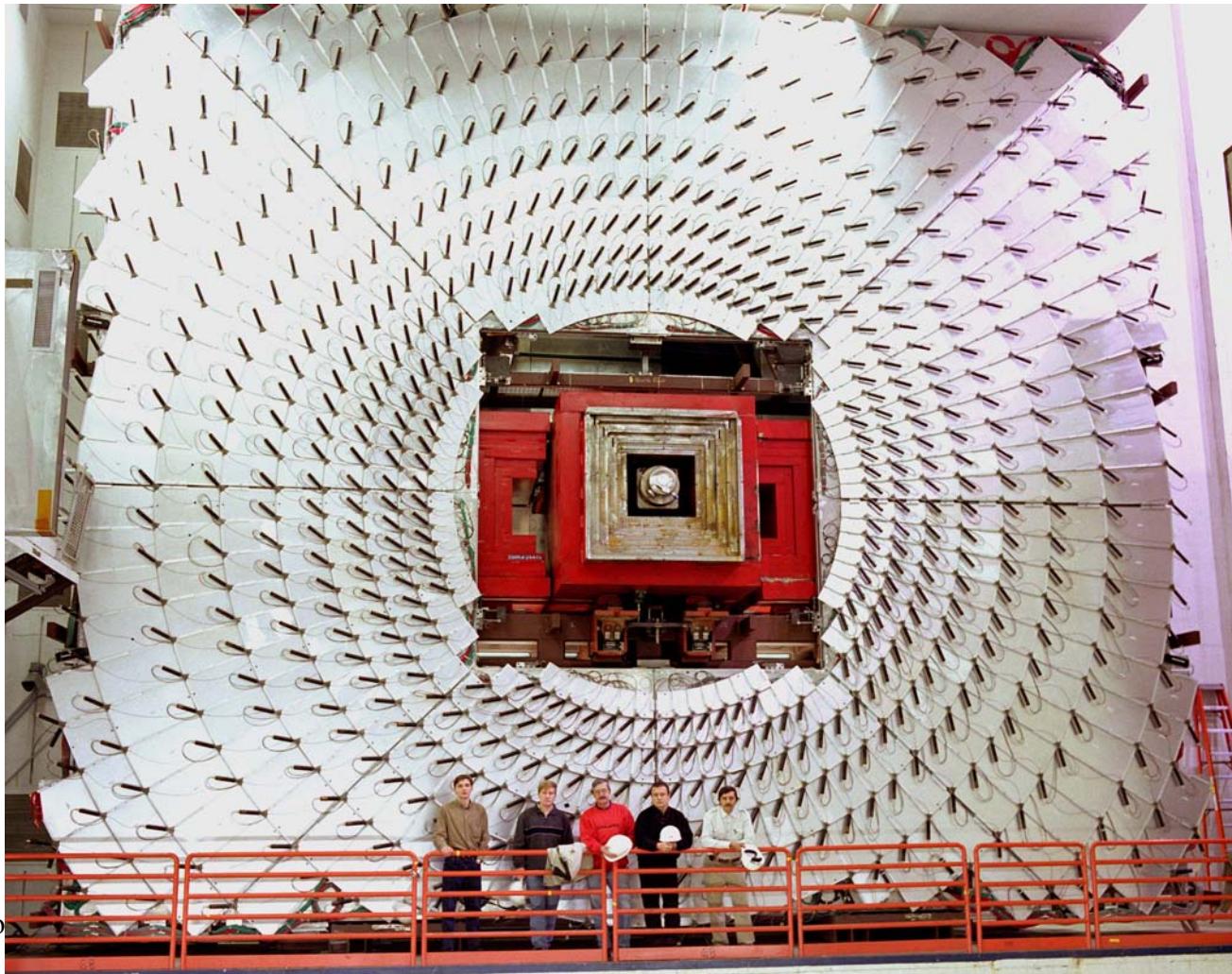
$\Rightarrow \frac{d\sigma}{d\eta} \approx \text{constant}$

$\sqrt{s} = 2 \text{ TeV} @ \text{Tevatron}$
 $\sqrt{s} = 14 \text{ TeV} @ \text{LHC}$

η	θ
0	90°
1	40°
2	15°
3	6°

Geometric Coverage

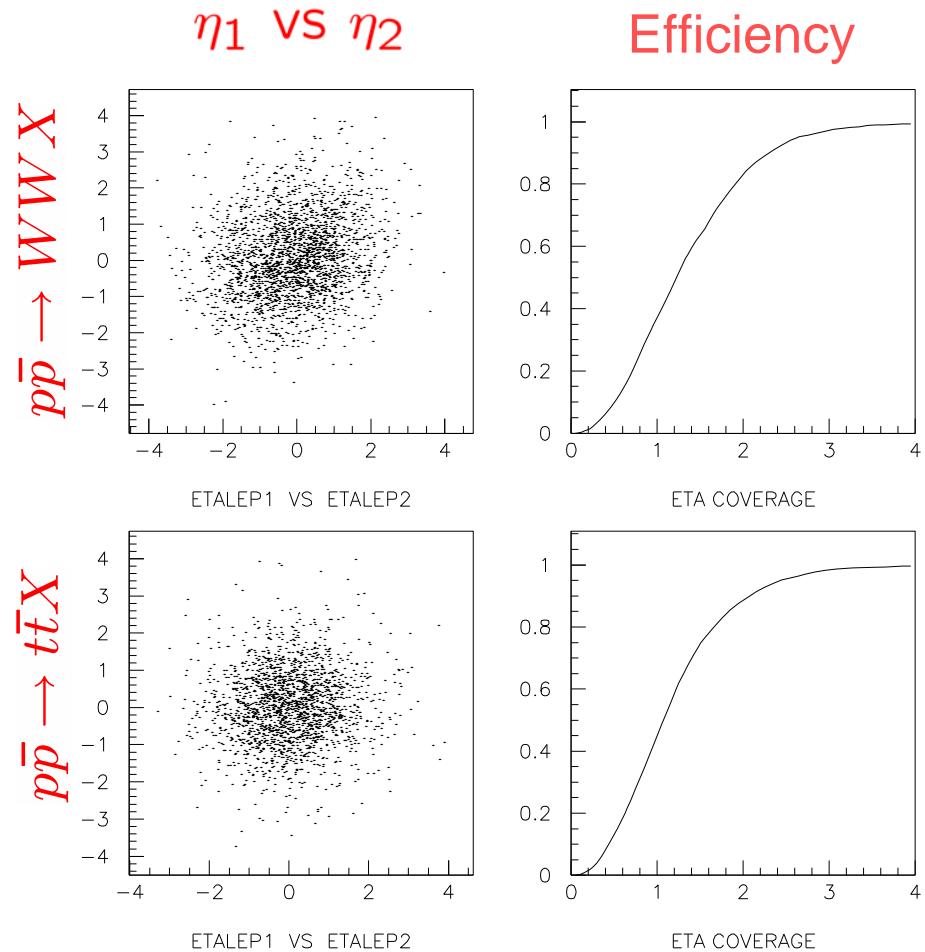
- To achieve \sim constant rate in each detector element, constant $\Delta\eta \times \Delta\phi$ segmentation is preferred. For example, DØ pixel counters have segmentation of $0.1 \times 4.5^\circ$



Geometric Coverage

- In practice, the maximum η is selected to have good acceptance for μ 's from “heavy” particles
- For example, at the Tevatron $\eta_{\max} \sim 2$ is sufficient for top

Experiment	η_{\max}
CDF	1.5
DØ	2.0
ATLAS	2.7
CMS	2.4



Comparing ATLAS and CMS Characteristics

Froidevaux & Sphicas – Annu. Rev. Nucl. Part. Sci. 2006, 56:375-440

Parameter	ATLAS	CMS
Dimensions (cm):		
-radius of outermost measurement	101-107	107-110
-radius of innermost measurement	5.0	4.4
-total active length	560	540
Magnetic field B (T)	2	4
BR^2 ($T \cdot m^2$)	2.0 to 2.3	4.6 to 4.8
Total power on detector (kW)	70	60
Total weight in tracker volume (kg)	≈ 4500	≈ 3700
Total material (X/X_0):		
-at $\eta \approx 0$ (minimum material)	0.3	0.4
-at $\eta \approx 1.7$ (maximum material)	1.2	1.5
-at $\eta \approx 2.5$ (edge of acceptance)	0.5	0.8
Total material (λ/λ_0 at max)	0.35	0.42
Silicon micro-strip detectors:		
-number of hits per track	8	14
-radius of innermost meas. (cm)	30	20
-total active area of silicon (m^2)	60	200
-wafer thickness (microns)	280	320/500
-total number of channels	$6.2 \cdot 10^6$	$9.6 \cdot 10^6$
-cell size (μm in $R\phi \times cm$ in z/R)	80×12	$80/120 \times 10$
-cell size (μm in $R\phi \times cm$ in z/R)		and $120/180 \times 25$
Straw drift-tubes (ATLAS only):		
-number of hits per track ($ \eta < 1.8$)	35	
-total number of channels	250,000	
-cell size (mm in $R\phi \times cm$ in z)	4×70 (barrel) 4×40 (end-caps)	

	ATLAS	CMS
Reconstruction efficiency for muons with $p_T = 1$ GeV	96.8%	97.0%
Reconstruction efficiency for pions with $p_T = 1$ GeV	84.0%	80.0%
Reconstruction efficiency for electrons with $p_T = 5$ GeV	90.0%	85.0%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 0$	1.3%	0.7%
Momentum resolution at $p_T = 1$ GeV and $\eta \approx 2.5$	2.0%	2.0%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 0$	3.8%	1.5%
Momentum resolution at $p_T = 100$ GeV and $\eta \approx 2.5$	11%	7%
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (μm)	75	90
Transverse i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (μm)	200	220
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 0$ (μm)	11	9
Transverse i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 2.5$ (μm)	11	11
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 0$ (μm)	150	125
Longitudinal i.p. resolution at $p_T = 1$ GeV and $\eta \approx 2.5$ (μm)	900	1060
Longitudinal i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 0$ (μm)	90	22-42
Longitudinal i.p. resolution at $p_T = 1000$ GeV and $\eta \approx 2.5$ (μm)	190	70

Comparison of the ATLAS and CMS Muon Systems

Froidevaux and Sphicas

Parameter	ATLAS	CMS
Pseudorapidity coverage:		
- Muon measurement	$ \eta < 2.7$	$ \eta < 2.4$
- Triggering	$ \eta < 2.4$	$ \eta < 2.1$
Dimensions (m):		
- Innermost (outermost) radius	5.0 (10.0)	3.9 (7.0)
- Innermost (outermost) disk (z-point)	7.0 (21-23)	6.0-7.0 (9-10)
Segments/super-points per track for barrel (end-caps)	3 (4)	4 (3-4)
Magnetic field B (T)	0.5	2
- Bending power (BL, in T-m) at $ \eta \approx 0$	3	16
- Bending power (BL, in T-m) at $ \eta \approx 2.5$	8	6
Combined (stand-alone)		
momentum resolution at:		
- $p = 10$ GeV and $\eta \approx 0$	1.4% (3.9%)	0.8% (8%)
- $p = 10$ GeV and $\eta \approx 2$	2.4% (6.4%)	2.0% (11%)
- $p = 100$ GeV and $\eta \approx 0$	2.6% (3.1%)	1.2% (9%)
- $p = 100$ GeV and $\eta \approx 2$	2.1% (3.1%)	1.7% (18%)
- $p = 1000$ GeV and $\eta \approx 0$	10.4% (10.5%)	4.5% (13%)
- $p = 1000$ GeV and $\eta \approx 2$	4.4% (4.6%)	7.0% (35%)

- At high rapidity, toroidal field provides better resolution.
- At central rapidity, high solenoidal field provides better resolution.

Next Lecture

- Muon ID
 - Using muon system features and other subdetectors to
 - Further discriminate muons from backgrounds
 - Identify different sources of muons
 - Efficiency measurement
- Triggering
 - Particular considerations for muons
- Commissioning
- Alignment