Design Considerations for a FCC Muon System at $\sqrt{s} = 100$ TeV

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MIT
August 27, 2014

Next steps in the Energy Frontier – Hadron Colliders

ATLAS
$M_{4\mu} = 123$ GeV
Muons – Window to Physics

CMS

ATLAS

8/25/2014

Muons - 100 TeV Workshop F. E. Taylor
Parts of a Muon System

- Central Tracker with Vertex Determination
- EM/Hadron Calorimeter & Muon Filter
- Magnetic Field(s)
- Trigger and Tracking Chamber System
- DAQ & Environmental Monitoring
Approach to Design

- Design of muon system concomitant with full detector integration
  - The muon system design requirements influence most parts of detector design
    - Magnet System: Configuration (Solenoid or Toroid), Size and Cost
    - Calorimeter/muon filter thickness required
    - Shielding to control backgrounds
- Develop scaling rules using LHC & SSC detectors as benchmarks
  - Design requirements for $\eta$ and $p_T$ range
  - Performance requirements for muon triggering and tracking technologies
  - Alignment requirements
  - Cost of muon system
  - R&D program for muon chamber technology choice
CMS Muon System

W = 2.3 GJ

CMS DETECTOR
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 5.8 T

STEEL RETURN YOKE
- 12,500 tonnes

SILICON TRACKERS
- Pixel (100x150 μm) ~16 cm² ~66M channels
- Microstrips (80x180 μm) ~200 cm² ~9M channels

SUPERCONDUCTING SOLENOID
- Niobium titanium coil carrying ~18,000 A

MUON CHAMBERS
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
- Silicon strips ~16 cm³ ~137,000 channels

FORWARD CALORIMETER
- Steel + Quartz fibres ~2,000 channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~76,000 scintillating PWO, crystals

HADRON CALORIMETER (HCAL)
- Brass + Plastic scintillator ~7,000 channels
ATLAS Muon System

$\Delta pT/pT < 10\%$ up to 1 TeV

- Thin-gap chambers (TGC)
- Cathode strip chambers (CSC)
- Resistive-plate chambers (RPC)
- Monitored drift tubes (MDT)
- Barrel toroid
- End-cap toroid

- 1,200 MDT chambers for tracking
- 32 CSC for high $|\eta|$ region
- 600 RPC and 3,600 TGC trigger

2-6 Tm $|\eta| < 1.3$
4-8 Tm $1.6 < |\eta| < 2.7$

Diameter 24 m
Length 45 m
$W(B) = 1.0$ GJ

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GEM-SSC Inspired Design – Option 1A

- GEM @ SSC $v_s = 40$ TeV $B = 0.8$ T, $W = 2.5$ GJ

Assume performance adequate @ SSC then $BL^2$ is scaled 2.5 by increasing $L$ by $(2.5)^{1/2} = 1.58$. $W = 2.5 \times (1.58)^3 = 9.9$ GJ

Forward Fe B-field shaper for more bending at high $|\eta|$
Designer’s Tool Kit - Resolution

• Resolution for momentum $p$
  – Momentum dispersion in B-field
    • Field Strength $B$
    • Length of measured track $L$
  – Chamber spatial resolution
    • Constant $a$
    • Resolution of chamber $\sigma(X_{ch})$
  – Multiple scattering in system
    • Constant $\alpha$
    • Thickness of middle layer $X_m$
  – Energy loss fluctuations
    • Constant $b = 15\%$
    • $dE/dx \approx 1.6E^{0.0572} + 0.0034E^{1.0897}$
    • Thickness of dead mat’l $X$

\[
\delta s_{ch} \sim a \frac{\sigma(X_{ch}) \, p}{B \, L^2} \\
\delta s_{ms} \sim \alpha \sqrt{\frac{X_m}{X_0}} \\
\delta s_{\Delta E} \sim \frac{\delta p_{\Delta E}}{s} \sim \frac{b\Delta E(p, X)}{p}
\]
ATLAS Design vs. Toy Model ($\eta \sim 0$)

- MS in middle station
- Chamber alignment + resolution
- Energy loss compensation

<table>
<thead>
<tr>
<th>Standard ATLAS</th>
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<tbody>
<tr>
<td>B (T)</td>
<td>L (m)</td>
<td>BL$^2$ (Tm$^2$)</td>
<td>BL (Tm)</td>
</tr>
<tr>
<td>0.50</td>
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<table>
<thead>
<tr>
<th>$X_{\text{Middle}/X0}$</th>
<th>Station Resol'n ($\mu$m)</th>
<th>Alignment ($\mu$m)</th>
<th>SR $\sqrt{1.5}$ ($\mu$m)</th>
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</thead>
<tbody>
<tr>
<td>34.0%</td>
<td>50.00</td>
<td>20.00</td>
<td>65.95</td>
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</table>

Calorimeter ($n\lambda$)

<table>
<thead>
<tr>
<th>$\lambda$ (g/cm$^2$)</th>
<th>$\delta(\Delta E)/\Delta E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.50</td>
<td>15.0%</td>
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</tbody>
</table>

$s \sim 675 \, \mu$m @ $p_T = 1$ TeV/c

**Muon System Resolution**

- $ds/s$ (MS)
- $ds/s$ (dE/dx)
- $ds/s$ (Chamber Resol’n)
- $ds/s$ (Total)
Design Criterion

• LHC @ $\sqrt{s} = 14$ TeV
  – $|\eta|$ range < 2.7
  – Momentum Resolution $\sigma(p_T)/p_T \sim 10\% @ p_T = 1$ TeV
  – Beam Cross Tagging $\tau << 25$ ns
  – Trigger 1 MU $p_T > 20$ GeV/c, 2 MU $p_T > 10$ GeV/c, 3 MU $p_T > 6$ GeV/c
  – Highest detector hit rate $\sim 15$ kHz/cm²

• Scaling factors
  – $\sqrt{s}$ ratio $\sim 7$
  – $|y_{\text{max}}|$ ratio $\sim \ln[(\sqrt{s}=100)/M_p]/[(\sqrt{s}=14)/M_p] \sim 11.5/9.5 \sim 1.2$

• FCC @ $\sqrt{s} = 100$ TeV
  – $|\eta|$ range $< 2.7 \times y_{\text{max}}(100)/y_{\text{max}}(14) \sim 3.2$
  – Momentum resolution $\sigma(p_T)/p_T \sim 10\% @ p_T = 7$ TeV/c
  – Beam Cross Tagging $\tau << 25$ ns
  – Trigger 1 MU $p_T > 20$ GeV/c, 2 MU $p_T > 10$ GeV/c, 3 MU etc.
    • With $BL^2 \sim 7X$ could raise threshold to higher value but threshold will be
determined by bkg. suppression, trigger bandwidth & physics
  – Highest detector hit rate $\sim 30$ kHz/cm²
Calorimeter & Muon Filter

ATLAS

Calorimeter thickness for 100 TeV detector

Compare E = 50 TeV vs. E = 7 TeV

Womersley et. al
\( \lambda (99\%) \sim 0.64 + 1.063 \ln(E(\text{GeV})) \)

Ratio of thickness for same shower containment (99%):
\( \frac{\lambda(50 \text{ TeV})}{\lambda(7 \text{ TeV})} \sim 1.2 \)

LHC 11 to 14 \( \lambda \) -> FCC 13 to 17 \( \lambda \)

Highly segmented calorimeter useful for isolation cuts around muon in
\[ \Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} \]
**dE/dx correction & Co-traveling BKG**

Muon radiation before Tracking station → air gap and B-field needed as well as good double track capability.
Achieving Goal Performance ($\eta \sim 0$)

<table>
<thead>
<tr>
<th>Option 3</th>
<th>B (T)</th>
<th>L (m)</th>
<th>$BL^2$ (Tm$^2$)</th>
<th>BL (Tm)</th>
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<tr>
<td>1.70</td>
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<td>128.67</td>
<td>14.79</td>
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<table>
<thead>
<tr>
<th>$X_{Middle}/X_0$</th>
<th>Station Resol'n ((\mu m))</th>
<th>Alignment ((\mu m))</th>
<th>SR $\sqrt{1.5}$ ((\mu m))</th>
</tr>
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<tbody>
<tr>
<td>34.0%</td>
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</table>

<table>
<thead>
<tr>
<th>Calorimeter ($n_\lambda$)</th>
<th>$\lambda$ (g/cm$^2$)</th>
<th>g/cm$^2$</th>
<th>$\delta(\Delta E)/\Delta E$</th>
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<tbody>
<tr>
<td>15.00</td>
<td>132.00</td>
<td>1980.00</td>
<td>15.0%</td>
</tr>
</tbody>
</table>

- Increase $BL^2$ by 7/LHC
- Increase calorimeter thickness by 1.2 to have same containment

In order to meet design criterion must measure this to 10%
B-Field Configuration*

• Option 1: Single 6T Solenoid Design – CMS Inspired
  – Add 2 endcap dipoles and Fe return Yoke

• Option 1A: Single Solenoid Design – GEM Inspired
  – Add 2 Fe field shaper cones in endcap

• Option 2: Twin Solenoid – MRI Inspired
  – 6 T inner solenoid, 3T shielding coil, 2 endcap 2T dipoles

• Option 3: Central 3.5 T solenoid and External Toroid – ATLAS Inspired
  – Add 2 internal 2T dipoles

*Follow Herman ten Kate and Jeroen van Nugteren, CERN, 14 February 2014
  Following discussions with D. Fournier, F. Gianotti, A. Henriques, L. Pontecorvo
  https://indico.cern.ch/event/282344/session/13/contribution/87/material/slides/0.pdf
Option 1: Solenoid-Yoke + Dipoles (CMS inspired)

- 5-6 T Solenoid
  - 12 m diameter
  - 23 meters long

- 10 Tm Dipole

- Stored magnetic energy 54 GJ
- Dipole or radial field in high rapidity region for enhanced bending power
- Iron Flux return makes design massive
  - mass ≈120 k tons (>200 M€ raw material) in comparison to CMS 12.5 k tons
  - Large mechanical engineering challenge – design impractical
Option2: Double Solenoid Design – MRI Inspired

- Resultant Fields – vector sum of inner & outer coils (inner has 8.3 T windings)
  - 6 T central solenoid – inner tracker
  - -3 T outer solenoid – muon system
  - Magnetic circuit $\Phi_{\text{outer}} = -\Phi_{\text{inner}}$
- Low mass construction
- Stored energy $W = 65 \text{ GJ}$

$P > 12 \text{ GeV/c}$ to get out of inner solenoid
Option 3: Solenoid + Toroids + Dipoles – ATLAS Inspired

- Air core Barrel Toroid with 7 x muon bending power $BL^2$.
- 2 End Cap Toroids to cover medium angle forward direction.
- 2 Dipoles to cover low-angle forward direction.
- Overall dimensions: 30 m diameter x 51 m length (36,000 m$^3$).

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Cost of Magnet System

- M. A. Green & B. P. Strauss
  - IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 18, NO. 2, JUNE 2008

Cost 2007 US$

\begin{align*}
C(M\$) &= 0.58 [E(MJ)]^{0.69}, \\
C(M\$) &= 0.55 [\Omega(T\cdot m^3)]^{0.65} \\
C(M\$) &= 0.75 [M(tons)]^{0.80}
\end{align*}

Cost(W(60 GJ)) \sim 1,150 M$

(no cryogenics)

\sim 10X CMS

Cost(W(9.9 GJ)) \sim 331 M$

\begin{align*}
\frac{B L^2}{\left( B^2 L^3 \right)^{2/3}} &\sim B^{-1/3}
\end{align*}

Cost considerations favor lower B-field and larger size
Appraisal of Designs

• GEM-SSC Design: Single solenoid with field shaper, $W = 9.9$ GJ
  – Least stored energy but may fall short in high $|\eta|$ performance limited by iron saturation
  – Muon system and calorimeter all within solenoid
  – Laissez-faire Flux return

• Option 1: Single solenoid with Fe Yoke + EC, $W = 54$ GJ
  – Expensive and heavy construction $\approx$ disfavored

• Option 2: Double Solenoid + EC, $W = 65$ GJ
  – Elegant and lighter design
  – Worry about getting enough bending at high $|\eta|$ 

• Option 3: Central solenoid and toroids + EC, $W = 55$ GJ
  – Complicated magnet designs but good performance at high $|\eta|$ and large $BL^2$

(Bending power/Cost) favors smaller B
R&D Program – Time Frame

New LHC / HL-LHC Plan

- Mandate is to fully exploit LHC < 2035
- FCC TDR around 2030 -> 16 years of R&D for chamber technology development
- Phase I and Phase II LHC Upgrades will provide important R&D lessons
Chamber Technologies

• Choice should be ‘conservative’ with test experience in a hadron collider environment
  – Will be a result of a long period of development
  – Drift-based technologies relatively inexpensive way of covering large areas with precision – hence may be suitable for barrel region
  – Technology with highly-segmented readout would be more suitable for endcap where bkg. expected to be higher
  – Should strive for at least 100 μm single layer resolution and expect station resolution to improve by $\sim 1/\sqrt{N_{\text{layers}}}$
  – Integrated design to provide both the 1st & 2nd coordinates

• R&D advantage to use the same technology for both triggering and tracking in both barrel & endcap
  – However technology choice tends to become highly political and ‘Balkan’ with individual factions offering their technology for a specific region backed up by their funding agency
  – But may not be optimal in terms of performance
Backgrounds of neutrons & $\gamma$s

- Most of backgrounds originate from energy deposited in detector by p-p collisions $\sim \frac{1}{2}$ comes from beam line small $\theta$
  - Preliminary ATLAS shielding study predicts a 20% increase from $\sqrt{s} = 8$ TeV to $\sqrt{s} = 14$ TeV per p-p collision
  - Assuming scaling by $\sqrt{s}$ would predict $\sim 10X$ bkg. of 14 TeV at 100 TeV

Likely an issue and has to be considered carefully when integrated detector, beam pipe and shielding become realistic.
Background Sensitivity

• Important that tracking/triggering technologies have low sensitivity to background neutrons and gammas
  – Requires Low Z and minimum material (ATLAS BKG Study)
Likely Design Principles

- Technology will be light weight, low Z and non-hydrogenous material and be inexpensive/m²
  - Based on gas amplifier with gain ~ 10⁴
- Large areas will have to be covered
  - ATLAS 5,800 m² Tracking, 9,300 m² Triggering
  - FCC 100 TeV would be larger by √7
- Precision chamber alignment system required ~ 20 μm
- Station Resolution ~ 100/√4 = 50 μm position
- Local vector determination δθ ~ 0.5 mrad
- Front-end ASICS will have more functionality
  - Multiple inputs, ASD, ADC, data flow through fiber optic links
  - High density 3D/2.5 D interconnects
- Have 16 years for R&D

Gianluigi De Geronimo, TIPP 2014
Consideration I

- **Lorentz angle**
  - Deployment in large B-field will result in a large L-angle depending on gas and E-operating point
    - Drift vector $\mathbf{V}_D$ rotates away from E
  - Naive configuration is to make the wires $||$ to B but serious consideration of effect needed for any gas technology in the large B-field options

$$\omega = \frac{eB}{m} = 17.6\text{MHz} / G$$

$$\tan \alpha = \omega \tau$$

$$V_D = \left(\frac{e\tau}{m}\right)E \frac{1}{\sqrt{1 + \omega^2 \tau^2}}$$

Example of compensation by using back-to-back HV planes in a Micromega
Consideration-II

• dE/dx
  – Larger dynamic range needs to be accommodated as muon ionizes gas in chamber
  – Roughly a factor of 25 \( N_T = 94 \times 25 \) = 2,350 ion pairs/cm
  – Frontend electronics has to have a larger dynamic range
  – Chamber HV system has to be ‘stiff’ enough not to saturate
  – Perhaps operate at \( \sim 10^3 \) gain

• Effect needs a more definitive calculation with realistic gas mixtures and chamber design

\[ dE/dx \text{ in gaseous Argon estimated by scaling critical energy to 565 GeV} \]
Drift Based Technologies

• Such as CMS barrel deployment
  – Inexpensive way to cover large area with smaller channel count – watch L-angle

12 layers per chamber: 4 z, 8 (r,θ)
Gas: Ar(85%) CO₂(15%), max
t_{drift}=380ns

Cell resolution (r_φ) <250\,\mu m, chamber (r_φ) ~100\,\mu m
BX assignment efficiency >99%

Cell layers staggered by ½ cell to resolve left/right asymmetry

Honeycomb layer position for minicrate
(front-end, trigger electronics)

2 x 4 layers “bending”
θ Superlayer (SL θ)

4 layers “non-bending”
θ Superlayer (SL θ)

Drift cell
Charge Interpolation Technologies

- Charge Measurement: 8-bit resolution
- Negative Input
- Micro-TPC mode for inclined tracks 2 ns time resolution
- Large strip capacitance ~ 200 pF
- Trigger primitive: Mmegas Address of first arrival above threshold in a given IC and Bunch crossing
- Shaping time: 50-100 ns

- Charge Interpolation: 8-bit resolution
- Positive Input
- Trigger prompt (at BC clock) 6-bit amplitude from each strip
- Large strip capacitance ~ 200 pF
- Shaping time: 25 ns

Triggering

• Large B fields will make a natural filter blocking low p from muon system
  – For double solenoid design (Option 2) p > 13 GeV/c to get out of inner solenoid
  – Level 1 Threshold value determined by trigger bandwidth
• Design the trigger to measure the actual 3-station track-sagitta
  – In ATLAS, due to cost control, the first layer of barrel was not instrumented with RPC trigger planes
    • Improvements to the barrel trigger using the MDTs are being studied for Phase II
  – And the first layer of the endcap was only minimally instrumented
    • The endcap trigger is being upgraded in Phase I with New Small Wheel
• Ideal would be to have a dual function technology that does both triggering and tracking
  – Fast enough to label beam crossing $\tau \sim$ few ns
  – Develop FE ASIC to generate trigger signal as well as precision hit signal for tracking
  – Fiber optics, fast communications, multiplexing will make more complicated Level 1 triggering feasible
  – Build sufficient trigger latency to form first Level trigger easily
    • Latency 10 to 20 $\mu$s (ATLAS presently has 2.5 $\mu$s but will be extended to $\sim$ 6 $\mu$s in Phase II)
# Table of Muon Technologies

<table>
<thead>
<tr>
<th>Muon Chamber Technology</th>
<th>Deployment</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift Tubes with field shaper electrodes</td>
<td>Barrel Tracking &amp; Triggering Cell resol'n ( (r\phi) &lt; 250 \mu m )</td>
<td>CMS</td>
</tr>
<tr>
<td>MDT (Monitored Drift Tubes) 3 cm dia.</td>
<td>Barrel Tracking Tube resol'n ( (r\theta) \sim 150 \mu m ) resolution</td>
<td>ATLAS</td>
</tr>
<tr>
<td>Small Diameter MDT 1.5 cm dia.</td>
<td>Tracking in some special regions of barrel</td>
<td>ATLAS</td>
</tr>
<tr>
<td>Cathode Strip Chambers (CSC)</td>
<td>Endcaps Tracking &amp; CMS Triggering ATLAS: ( \eta ) strip pitch 5.5 mm, ( \phi ) strip pitch 13 - 21 mm</td>
<td>CMS and ATLAS ( 2&lt;</td>
</tr>
<tr>
<td>Micromegas</td>
<td>Endcaps Tracking &amp; Triggering Readout pitch ~ 0.4 mm</td>
<td>ATLAS Phase I Upgrade New Small Wheel</td>
</tr>
<tr>
<td>Thin Gap Chambers (TGC)</td>
<td>Endcaps Triggering &amp; Tracking 2nd coordinate</td>
<td>ATLAS 1st and 2nd stations Endcap</td>
</tr>
<tr>
<td>Small-strip Thin Gap Chambers (sTGC)</td>
<td>Endcaps Triggering &amp; Tracking Fast enough for BC tagging 95% ( \tau &lt; 25 ) ns; 3 mm strip-pitch</td>
<td>ATLAS Phase I Upgrade New Small Wheel</td>
</tr>
<tr>
<td>Resistive Plate Chambers (RPC)</td>
<td>Barrel and Endcaps Triggering Fast ( \tau \sim 3ns ) ATLAS: ( \eta ) strip pitch ~ 30 mm, ( \phi ) strip pitch ~ 30 mm</td>
<td>ATLAS and CMS</td>
</tr>
<tr>
<td>Low Resistivity RPC</td>
<td>Higher rate capability ( 10^{10} \Omega ) cm</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>Multi-gap Resistive Plate Chamber</td>
<td>Very fast ( \tau \sim 50 ) ps</td>
<td>ALICE and R&amp;D</td>
</tr>
<tr>
<td>GEMs (3 layer)</td>
<td>Endcaps Rate ~ ( 10^9 ) Hz/cm(^2) \ ; Fast ( \tau \sim 4-5 ) ns</td>
<td>CMS Phase I Test &amp; Phase II</td>
</tr>
</tbody>
</table>

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John Sealy Townsend
Circa 1900
Discussion & Summary

- Cost of B-field is likely quite high – but of order of $\nu s$ ratio 7
  - Follow SMES development in power industry
    - SMES = Superconducting Magnetic Energy Storage and note that large SMES favor toroidal geometry
    - Lower B-field options favored (Bending Power/Cost) $\sim \frac{BL^2}{(B^2L^3)^{2/3}} \sim B^{-1/3}$
  - Neutron and $\gamma$ background may be troublesome
    - Crude scaling from 14 TeV to 100 TeV is factor of 10
      - Should be done much more carefully
- Co-traveling EM bkg. around muon track following muon calorimeter/filter may be problematic
  - Design an air gap with B-field sweeping and deploy fine-grained multiple layers for 1st muon station
- Tracking and Triggering chamber technologies will develop over the next $\sim 20$ years – especially the readout and DAQ electronics
  - Gas amplifiers likely to provide the foundation operating principle
  - How will they work when $dE/dx \sim 50$ MeV/(g/cm$^2$) for high $p$ muons?
  - How will they work in large B-field?
References

• 1st CFHEP Symposium on circular collider physics 23-25 February 2014
  – http://indico.ihep.ac.cn/conferenceDisplay.py?confId=4068
• BSM physics opportunities at 100 TeV, 10-11 February 2014
  – http://indico.cern.ch/event/284800/other-view?view=standard
• Workshop on Physics at a 100 TeV Collider, 23-25 April 2014
  – https://indico.fnal.gov/conferenceDisplay.py?confId=7633
• Large Hadron Collider Physics (LHCP) Conference, 2-7 June 2014
  – https://indico.cern.ch/event/279518/
• Future Circular Collider Study Kickoff Meeting, 12-15 February 2014
  – https://indico.cern.ch/event/282344/
• International Conference on Technology and Instrumentation in Particle Physics
  – http://www.tipp2014.nl/
• XII workshop on Resistive Plate Chamber and Related Detectors
  – http://166.111.32.59/indico/conferenceProgram.py?confld=1
• HADRON SHOWERS IN A LOW-DENSITY FINE-GRAINED FLASH CHAMBER CALORIMETER, W.J. Womersley et al. NIM A267 (1988) 49-68
Additional Slides
General Considerations

- Design Driver is momentum dispersion $BL^2 \mid_{100 \text{ TeV}} \sim 7 \mid_{14 \text{ TeV}}$
  - Obviously increasing $B$ increases mechanical stresses through magnetic pressure $\sim B^2/2\mu_0$ and by a factor of 7 is untenable
  - More practicable is to increase $L$ with modest increase in $B$

- Solenoidal Configuration
  - First coordinate (bending) $\phi$, second $\theta$
    - Advantage of good vertex determination

- Toroidal Configuration
  - First coordinate (bending) $\theta$, second $\phi$
    - Advantage of higher bending power at larger $|\eta|$

- Muon Chamber system must determine both first and second coordinate
  - High precision required for first coordinate
  - Second coordinate needed for vector $p$ as well as a pattern recognition invariant
3.5 T in Solenoid, 2 T - 10 Tm in dipoles and ≈ 1.7 T in toroid
55 GJ stored energy (for 16 Tm; 130 Tm²)
Complicated and non-uniform B-field
  Will require high instrumentation
  Lorentz angle corrections if drift chamber technology used
Search for Massive Gauge Bosons

- Search for massive objects will be a major focus with a 100 TeV Collider
  - Assume $\mathcal{L} \sim 1 \text{ ab}^{-1}$ by Rizzo* $\mathcal{L}\sigma_{	ext{B}}$

<table>
<thead>
<tr>
<th>Model</th>
<th>10 TeV</th>
<th>15 TeV</th>
<th>20 TeV</th>
<th>Disc.</th>
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<tbody>
<tr>
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<td>24.62</td>
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<td>$\psi$</td>
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<td>65.93</td>
<td>10.37</td>
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<td>22.7</td>
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<td>71.82</td>
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<td>20.3</td>
<td>23.8</td>
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<td>$I$</td>
<td>1241.</td>
<td>144.4</td>
<td>22.94</td>
<td>22.4</td>
<td>25.7</td>
</tr>
</tbody>
</table>

- Di-electron mass resolution is better but di-muons may be cleaner
- **A challenge is to design a muon system with sufficient resolution**
  - If $\delta p/p \sim 10\%$ for $p \sim 10$ TeV then $\delta m \sim 2$ TeV for $m \sim 20$ TeV

Dealing with $\Delta E_\mu$

- The $\Delta E_\mu$ correction is unimportant in CMS-like detector (central tracker)
- In muon system stand-alone operation the $\Delta E_\mu$ correction is important

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Figure 8: The momentum distribution of 1 TeV/c muons after traversing 3 m of iron, as obtained with the MARS14 Monte Carlo code [59]. The comparative rarity of very low final momenta follows from the approach of the cross sections to zero as $\nu \rightarrow 0$.

$$\frac{\delta s_{\Delta E}}{s} \sim \frac{\delta p_{\Delta E}}{p} \sim \frac{b\Delta E(p, X)}{p}$$

Reality check of $b = 15\%$

$\Delta E = 23$ GeV, FWHM = 9 GeV

$\sigma = 3.8$ GeV

$\sigma/\Delta E = 3.8/23 = 16.5\%$
Drift Technologies – Barrel Deployment

- ATLAS – Monitored Drift Tubes

A drift-based technology is an efficient way to cover large areas without high channel counts. Resolution degrades in high backgrounds.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube material</td>
<td>Al</td>
</tr>
<tr>
<td>Outer tube diameter</td>
<td>29.970 mm</td>
</tr>
<tr>
<td>Tube wall thickness</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>Wire material</td>
<td>gold-plated W/Re (97/3)</td>
</tr>
<tr>
<td>Wire diameter</td>
<td>50 μm</td>
</tr>
<tr>
<td>Gas mixture</td>
<td>Ar:CO₂/H₂O (93/7/≤ 1000 ppm)</td>
</tr>
<tr>
<td>Gas pressure</td>
<td>3 bar (absolute)</td>
</tr>
<tr>
<td>Gas gain</td>
<td>2 \times 10^{4}</td>
</tr>
<tr>
<td>Wire potential</td>
<td>3080 V</td>
</tr>
<tr>
<td>Maximum drift time</td>
<td>~ 700 ns</td>
</tr>
<tr>
<td>Average resolution per tube</td>
<td>~ 80 μm</td>
</tr>
</tbody>
</table>
High Rate Micromega

Floating Strip Micromegas

challenge: discharges

- charge density \( \geq 2 \times 10^6 \text{ e}/0.01 \text{ mm}^2 \)
- conductive connection \( \rightarrow \) potentials equalize
- non-destructive, but dead time \( \rightarrow \) efficiency drop

idea: minimize the affected region

- “floating” copper strips:
  - strip can “float” in a discharge
  - individually connected to HV via 22M\( \Omega \)
  - capacitively coupled to readout electronics via \( \text{pF} \) HV capacitor
  - only two or three strips need to be recharged

\( \rightarrow \) dedicated measurements & detailed simulation
CMS Gas Electron Multipliers

- **Phase II Upgrade – Forward Trigger**

  - **Rate capability:** $10^5 \text{Hz/cm}^2$
  - **Spatial/Time resolution:** $\sim 100 \text{ m\/cm} / \sim 4-5 \text{ ns}$
  - **Efficiency:** $> 98\%$
  - **Gas Mixture:** Ar/CO$_2$/CF$_4$ (45/15/40), non flammable
  - **Typical Gas gain:** $>10^4$
  - **Radiation hardened**

  - **GEM foils developed using PCB manufacturing techniques**
  - **Large areas:** $\sim 1\text{m} \times 2\text{m}$ with industrial processes (cost eff.)
  - Each foil (perforated with holes) is $50\mu\text{m}$ kapton sheet with copper coated sides ($5\mu\text{m}$)
  - **Typical hole dimensions:** Diameter = $70\mu\text{m}$, Pitch = $140\mu\text{m}$

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Cesare Calabria – ICHEP2014 - "Large-size triple GEM detectors for the CMS forward muon upgrade"
Outline

• Examples of muon systems/physics discovery
  – J/Psi
  – Upsilon
  – W/Z
  – Higgs

• Measurement problem – emulate the present LHC detector performance
  – Size of point-like cross section vs. sqrt s
  – Luminosity needed and backgrounds
  – Designer’s toolkit
    • Bending
    • MS
    • Rad loss
    • Filtering/punch-through
    • Chamber resolution

• Basic configuration
  – Toroid vs. Solenoid – strong central tracker vs. strong stand-alone muon system
    • Comparison of ATLAS vs. CMS
    • How will these configurations scale?

• Triggering & Tracking
  – Gas amplification
  – Strip & pad vs. Pixels (pixel possible?)
  – Costs & channel count
  – Combined function the best – example micromega and the ATLAS New Small Wheel project