Monte Carlo Study for COMET

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Outline

• Overview of COMET
• Topics and Motivations
• Status of Each Topic
• Summary
Overview of COMET

• The COMET experiment has a staged plan. The current MC study focuses on COMET Phase-I

• COMET Phase-I consists of a production target surrounded by a capture solenoid, a muon transportation beamline, a stopping target, the Cylindrical Detector (CyDet) which includes the CDC and a trigger hodoscope, and the Strawtube Ecal Detector (StrEcal).
Topics and Motivations

- Monte Carlo study currently include:
  - Beam Study: Beam particles from the production target to the detector section.
    - To get the muon yield to estimate the single event sensitivity
    - To get a beam particle profile for following studies.
  - Room Neutron Study: Neutrons scattering around the experimental hall.
    - Irradiation issue to detector electronics, cryogenics, etc.
    - Noise & background
  - Cosmic Ray Study
    - Background source
    - Design the Cosmic Ray Veto System (CRV)
  - CyDet Hit Rate Study: in the CDC and in the trigger hodoscope
    - Aging of the CDC
    - Event size, trigger rate, single hit rate
    - Noise level, efficiency and resolution
  - CyDet Background Study: Physics goal for COMET Phase-I
    - To evaluate the feasibility of searching for mu-e conversion.
Beam Study

- Comparison between MARS and GEANT:
  - Similar shape
  - QGSP_BERT gives lower yield.
- Comparison between MARS, GEANT and HARP (Exp):
  - At low energy range GEANT_BERT is better. Consistency is good.
- Geant with GEANT_BERT is considered as conservative choice.

* Figures from Andy from UCL
Beam Study

1. Generate $10^7$ protons at production target

2. Take the beam profile at the beginning of 90 degree bending, repeat by 10 times: equivalent to $10^8$ protons

3. Take the beam profile at the end of 90 degree bending, repeat by 10 times: equivalent to $10^9$ protons. At last record particles on the surface of CyDet Box as well as muon/pions stopped in this region.

CyDet are set as black hole for consecutive CyDet studies.
Beam Study

Particles at The beginning of 90 degree

Particles at The end of 90 degree

Particles at CyDet Boundary

Protons from muon capture will further be replaced by AlCap data.
Stopped Muons

- Muons are stopped in target, He gas, and cryostat. The stopping position in target and He gas is recorded for further study (DIO & Muon Capture)
  - Ratio of muon stopping in target and muon stopping in He is 3:1
  - End point energy for DIO in He is ~800 keV smaller than DIO in Al.
- Muons stopped in target is $4.28 \times 10^{-4}$
  - COMET Phase-I can be finished within around 110 days
Stopped Muons in Target

Time window acceptance ratio for signal:

- 500ns: ~45%
- 700ns: ~30%
Beam Study

- According to this beam study, the collimator has been optimized to suppress charge particles with $p_a > 100\,\text{MeV/c}$ while keeping muon yield unchanged (muon with $p_a < 50\,\text{MeV/c}$).

Collimator Plates
Re-sampling For Pion Simulation
(Decay Channel Closed*)

1. Generate $10^9$ protons at production target, take the sample on the surface and repeat by 10 times: equivalent to $10^{10}$ protons

2. Take the beam profile at the end of 90 degree bending, repeat by 10 times: equivalent to $10^{11}$ protons. Pion stopping position is recorded for RPC study.

* Weight is assigned by calculating the decay probability.
Stopped Pions in Target

\[ \pi^- \text{ Stop Time (Before Smear)} \quad \pi^- \text{ Capture Time (After Smear)} \quad \text{Ratio of } \pi^- \text{ Captured in Time Window (After Smear)} \]

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\[ 500\text{ns}: 10^{-11} \quad 700\text{ns}: 10^{-14} \]
Re-sampling For Anti-proton

1. $1.82 \times 10^9$ low energy anti-protons were generated at production target, take the sample on the surface and repeat by 100 times: equivalent to $1.3 \times 10^{19}$ protons

2. Take the beam profile at the end of 90 degree bending, repeat by 10 times: equivalent to $1.3 \times 10^{20}$ protons. Pion stopping position is recorded for further study.

3 Different theoretical models have been considered and the one with largest yield of backward anti-protons is chosen to generate MC sample
Room Neutron Study

• For neutron generation

Spectrum of backward neutrons upon production

• Comparison between PHITS and GEANT
  – Similar shape but different cross section.
  – PHITS is chosen as a conservative estimation
Room Neutron Study

• For neutron interaction
  – compared ENDF (used by Geant) and JENDL (used by PHITS) and the difference is small in low energy region (<20 MeV)
  – For high energy region (>20MeV) we are in lack of knowledge but the yield near detector is much smaller

* Yang Ye from Kyushu is taking care of this study with PHITS
Cosmic Ray Study

- Cosmic ray yield during the whole COMET Phase-I run onto the experimental hall is around $10^{13}$.
- Cosmic ray data taken from CORSIKA calculation but horizontal cosmic rays are somehow difficult to predict.
- Cosmic ray veto system is still under optimization: muon veto ratio VS fake veto signal from neutrons.

Ben from Imperial Colledge is taking care of this study
CyDet Geometry

Particles at CyDet Boundary

CTH

CDC
CyDet Hit Rate Study

• Use the beam profile on CyDet box and stopped muon/pion profile obtained by beam study to simulate the detector response in CyDet
  – Simulation results corresponding to every $8.06 \times 10^6$ protons (one bunch) are composed together to form one “event”
  – Overlapping issue of bunches are carefully considered: long arrival time tail from previous bunches.
  – Hit rate in CDC can be much suppressed if we apply ADC cut
  – Hit rate & trigger rate in & by CTH can be suppressed if shielding layers are adopted.
  – Optimization is still on going

• Result for base line:
  – 12% (8% after ADC cut) CDC occupancy ratio
  – 0.35 mC/cm/day aging effect ($10^5$ gas gain is assumed)
  – CTH instantaneous hit rate (>200ns) is at most 3.7 MHz
  – CTH prompt peak (<200ns) size in CTH is at most 5.5 times as high as the peak by signal tack.
  – CTH average trigger rate (basically from gamma ray) is about 30 kHz (if measure from 700ns)
Event Display: isobutane, CDC window: 700~1520ns

• Red: signal track
• Green: Noise hits (high ADC)
• Blue: Noise hits (low ADC)
• Gray: protons (high ADC)
• Black: protons (low ADC)

#34: Triggered @ 728.181 ns, Ngood = (77,2), Nnoise = (391,277)
Acceptance VS Trigger rate:
- Solid circle stands for acceptance
  - Black: total acceptance
  - Red: acceptance when only counting single-turn tracks
  - Blue: acceptance when only counting multi-turn tracks
- Empty circle stands for trigger rate
  - Magenta: trigger rate if measuring from 500 ns
  - Green: trigger rate if measuring from 700 ns.

Optimization for isobutane
Potential background sources for the search for the $\mu^- N \rightarrow e^- N$ conversion are grouped into four categories: intrinsic physics backgrounds, beam-related prompt backgrounds, beam-related delayed backgrounds, and other backgrounds.
### Intrinsic physics backgrounds

<table>
<thead>
<tr>
<th>Backgrounds</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon decay in orbit (DIO)</td>
<td>$\mu^- + A \rightarrow \nu_\mu + A' + \gamma$ Followed by $\gamma \rightarrow e^- (+e^+)$</td>
</tr>
<tr>
<td>Radiative muon capture (RMC) (external)</td>
<td>$\mu^- + A \rightarrow \nu_\mu + A' + e^- + e^+$</td>
</tr>
<tr>
<td>Radiative muon capture (RMC) (internal)</td>
<td>$\mu^- + A \rightarrow \nu_\mu + A' + e^-$</td>
</tr>
</tbody>
</table>

### Beam Related prompt/delayed Backgrounds

<table>
<thead>
<tr>
<th>Backgrounds</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiative pion capture (RPC)(external)</td>
<td>$\pi^- + A \rightarrow e^- + e^+ + A'$</td>
</tr>
<tr>
<td>Radiative pion capture (RPC) (internal)</td>
<td>$\pi^- + A \rightarrow \gamma + A', \gamma \rightarrow e^- (+e^+)$</td>
</tr>
<tr>
<td>$\bar{p}$ induced backgrounds</td>
<td>$\bar{p}$ hits material to produce $e^-$</td>
</tr>
<tr>
<td>Beam electrons</td>
<td>$e^-$ scattering off a muon stopping target</td>
</tr>
<tr>
<td>Muon decay in flight</td>
<td>$\mu^-$ decays in flight to produce $e^-$</td>
</tr>
<tr>
<td>Pion decay in flight</td>
<td>$\pi^-$ decays in flight to produce $e^-$</td>
</tr>
<tr>
<td>Neutron induced backgrounds</td>
<td>neutrons hit material to produce $e^-$</td>
</tr>
</tbody>
</table>

### Other Backgrounds

<table>
<thead>
<tr>
<th>Backgrounds</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic-ray induced backgrounds</td>
<td>$\mu^-$ etc entering beam line and/or detector</td>
</tr>
<tr>
<td>False tracking</td>
<td>Hit points falsely considered as a $e^-$ track.</td>
</tr>
</tbody>
</table>
CyDet Background Study

For intrinsic backgrounds

• Nuclear physics model is important but unclear:
  – Taking theoretical calculations with conservative estimation

• Estimation for DIO and RMC contribution are 0.01 and 0.005 respectively
CyDet Background Study

For beam related backgrounds

- Computing power is important
  - Resampling method is adopted while further study with more powerful computing resources is needed.
- Delayed backgrounds are not found (except for pion/anti-proton induced) while prompt ones can be suppressed by proton extinction factor ($10^{-11}$)
- Energetic tracks are not entering CyDet within the simulation sample. Only RPC process contributes.
- Background levels from pion and anti-proton are 0.0008 and 0.0012 respectively. From others it’s estimated as smaller than 0.001.

Arrival time of energetic particles in CyDet area
Summary

• Beam Study
  – GEANT_QGSP_BERT_HP is a conservative model. Did simulations for pions, anti-protons, stopped muons/pions and other beam particles separately with re-sampling adopted.
  – Still have to look into background levels in other models.

• Room Neutron Study
  – PHITS and GEANT are equally good for low energy neutron simulation while PHITS is chosen for its higher yield.
  – As for high energy neutrons, further studies are needed.

• Cosmic Ray Study
  – CORSIKA calculation + full simulation of experimental hall is now possible.
  – Further study of CRV is needed.

• CyDet Hit Rate Study
  – CDC occupancy ratio, CDC aging effect, CTH hit rate, CTH prompt peak size, and trigger rate are studied with beam simulation samples.
  – Optimization of CTH is still on going to achieve a better performance.

• CyDet Background Study
  – Some major sources of background have been studied and the level is low enough.
  – Yet more sources (cosmic ray, false tracking, energetic neutron) to be studied.