NTD ANALYSIS FOR SCHWINGER MONOPOLES

(RUN–2 HEAVY ION RUN)

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FOLLOW-UP ANALYSIS TO THE SCHWINGER MMT STUDY

- NTDs were exposed to the Pb–Pb Run–2 in 2018.
- Integrated luminosity at IP8 during the Run → 0.235 nb⁻¹.
- $\sqrt{s_{NN}} = 5.02$ TeV.

- Monopoles were simulated through the MoEDAL Run–2 geometry in Gauss using the Schwinger FPA kinematics.
- Magnetic charges up to 3 $g_D$ are currently simulated and the results presented today.
- The simulations for higher charges to 4 and 5 $g_D$ are currently ongoing. They would increase the reach of MoEDAL’s search to charges beyond the MMTs.
SCHWINGER MONOPOLES HITTING THE NTDs
(5 MILLION EVENTS)

HCC (at z = 2270mm) comprises of the majority of the hits.

Mass = 100 GeV
Charge = 1gD
5e6 events simulated
This plot shows the number of monopoles hitting at least one layer of the NTDs.

Raw NTD hits on at least one foil = 25823

The steep drop in NTD hits after foil 2 is because the HCC (which has 2 foils) comprises of significant number of hits.

MMT efficiency (default) = $721/5e6 = 1.45e^{-4}$

<table>
<thead>
<tr>
<th>$M$ (GeV/c$^2$)</th>
<th>$\epsilon \times 10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>$1.19^{+1.46}_{-0.64}$</td>
</tr>
<tr>
<td>75</td>
<td>$1.34^{+1.61}_{-0.72}$</td>
</tr>
<tr>
<td>80</td>
<td>$1.41^{+1.66}_{-0.76}$</td>
</tr>
<tr>
<td>85</td>
<td>$1.45^{+1.68}_{-0.78}$</td>
</tr>
<tr>
<td>100</td>
<td>$1.52^{+1.57}_{-0.83}$</td>
</tr>
<tr>
<td>105</td>
<td>$1.57^{+1.68}_{-0.82}$</td>
</tr>
</tbody>
</table>
On why is the efficiency of NTDs is much greater than MMTs?

- Any monopoles within a particular $\beta (= v/c)$ and incident angle ($\alpha$) set by calibration passing though the NTDs would register, creating a hit.
- The NTDs occupy a much larger area than the MMTs facing the interaction point.
- High charge catcher (HCC) is placed in a region where the amount of material is very low, whereas in other parts the efficiency is reduced due to most particles ranging out before reaching the detectors.

- For MMTs, the incoming monopoles need to be trapped (based on a condition on $\beta$ or energy). Thus, the higher energy monopoles can punch through without being trapped.
NTD EFFICIENCY CALCULATION
MONOPOLE REL FOR MAGNETIC CHARGES UP TO 5G_D IN MAKROFOL

- Interpolated in the region $0.01 < \beta < 0.05$

- For a monopole to be detected, its REL must be greater than the detection threshold of Makrofol ($\text{REL}_{MM} > 2700 \text{ MeV cm}^2/\text{g}$)

Energy losses of magnetic monopoles and dyons in scintillators, streamer tubes and nuclear track detectors

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ADITYA UPRETI - MOEDAL ANALYSIS
The detection threshold depends on the incident angle of the monopole on the NTDs

\( \delta = G4_{\text{NTD\_ALPHA}} \)

- The calculation of \( \alpha \), the incident angle of the incoming particle on the NTDs needed to be updated due to a bug in the values of the surface normal (which was hardcoded).

- In the updated code, it is directly calculated by Geant4 classes.

- The connection between the threshold and the maximum angle of incidence (\( \delta_{\text{Max}} \)) to the normal to the NTD that the monopole can make and still be detected

\[ p = \frac{1}{\cos(\delta_{\text{Max}})} \]
After applying the calibration threshold, we calculate the NTD efficiency for monopoles produced via Schwinger Mechanism.

NTD EFFICIENCY OF 1G\textsubscript{D} SCHWINGER MONOPOLES

(about 2 orders of magnitude greater than MMT acceptance)

* 3 geometry versions due to uncertainty in material budget.
Expected Rate ($R_{\text{exp}}$)

Calculated using two cross section approximations for the Schwinger Mechanism in Heavy Ions.

1. The FPA (photon–monopole coupling treated perturbatively, spacetime dependence of external EM field is full integrated).

2. The LCFA (spacetime dependence of EM fields treated perturbatively, photon–monopole coupling is full integrated).

Both cross sections are conservative lower limits to the overall Schwinger cross section.

\[ R_{\text{exp}} = \sigma_{\text{FPA}} \times L_{\text{IP8}} \times \varepsilon_{\text{NTD}} \]

- No Monopoles were detected by the MoEDAL detectors in the Pb–Pb Run–2 in 2018.

- Masses excluded at 95% C.L. up to 125 GeV based on Schwinger FPA kinematics and FPA cross section for $I_g^{\text{D}}$ Monopoles for the NTD Run–2 analysis.

- The grey region corresponds to the systematic error, dominated by the material budget.
• Monopole Masses excluded up to 76 GeV for 1gD, based on the LCFA limits and conservative limits.
2G\textsubscript{D} SIMULATIONS – 500 MILLION EVENTS.

- Masses simulated – 70, 80, 85, 90, 100 GeV
- NTD efficiency for 2G\textsubscript{D} about two orders of magnitude greater than MMT 2gD.
EXCLUSION LIMITS 95% C.L. USING $\sigma_{\text{FPA}} 2G_D$

- Monopole Masses excluded up to 90 GeV for $2g_D$, based on the FPA limits and conservative limits.
EXCLUSION LIMITS 95% C.L. USING $\sigma_{LCFA}$ $2G_D$

- Monopole Masses excluded up to 211 GeV for $2g_D$, based on the LCFA limits.
**3G\textsubscript{D} SIMULATIONS – 5 BILLION EVENTS.**

- Monopole Masses excluded up to 85 GeV for 3gD, based on the FPA limits and conservative limits.
EXCLUSION LIMITS 95% C.L. USING $\sigma_{LCFA} \ 3G_D$

- Monopole Masses excluded up to 388 GeV for 2gD, based on the LCFA limits. (same as the LCFA 3gD mass limit for MMT, due to huge mass dependence on the LCFA cross section)
OVERALL, 95 % CL MASS LIMITS FOR NTD ANALYSIS

<table>
<thead>
<tr>
<th>Schwinger cross section approximation</th>
<th>1g_D</th>
<th>2g_D</th>
<th>3g_D</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPA</td>
<td>125 GeV</td>
<td>90 GeV</td>
<td>85 GeV</td>
</tr>
<tr>
<td>LCFA</td>
<td>76 GeV</td>
<td>211 GeV</td>
<td>388 GeV</td>
</tr>
<tr>
<td>Conservative</td>
<td>76 GeV</td>
<td>90 GeV</td>
<td>85 GeV</td>
</tr>
</tbody>
</table>

..comparing with the MMT limits from our Nature article.

Table 1 | 95% confidence level mass limits (in GeV/c²) on MM pair production in LHC Pb–Pb collisions

<table>
<thead>
<tr>
<th>2x cross-section approximation</th>
<th>Magnetic charge (g_D)</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPA</td>
<td></td>
<td>90</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>LCFA</td>
<td></td>
<td>75</td>
<td>210</td>
<td>388</td>
</tr>
<tr>
<td>Conservative limit</td>
<td></td>
<td>75</td>
<td>70</td>
<td>70</td>
</tr>
</tbody>
</table>

* Analysis for higher charges 4 and 5 g_D are ongoing and expected to be included in the Run-2 NTD analysis for Schwinger monopoles.
• Mass bounds for Pb–Pb Run2 search for Schwinger monopoles with the NTDs.

• (preliminary – still to be updated with higher charges > 3g_D)
• MoEDAL’s monopole mass limit projections from Schwinger Mechanism for future Pb–Pb collisions at LHC Run 3, 4.

• Five Pb-Pb runs in total up to the end of Run-4 would allow to collect 11–14 nb$^{-1}$ at ALICE, ATLAS and CMS, and up to 2.5 nb$^{-1}$ at LHCb. (https://doi.org/10.1140/epjp/s13360-021-01685-5)

• Beam energy expected to increase to a of 7 Z TeV, up from 6.37 Z TeV, or a centre-of-mass energy per nucleon of 5.52 TeV from 5.02 TeV. (https://cds.cern.ch/record/2722753)
EXPECTED MASS LIMITS FOR FULL DETECTOR – RUN 3, 4

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<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPA limits (GeV)</td>
<td>160</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>LCFA limits (GeV)</td>
<td>81</td>
<td>220</td>
<td>407</td>
</tr>
<tr>
<td>Conservative limits</td>
<td>81</td>
<td>120</td>
<td>120</td>
</tr>
</tbody>
</table>
• Questions and comments?

• Thanks.