Low Mass Dimuon Production in Proton-Nucleus Collisions at 400 GeV/c

Antonio Uras
University of Cagliari & INFN
The NA60 experiment

Electromagnetic form factors for the eta and omega mesons

Comparison with the theoretical predictions and the available experimental results

Relative production cross sections

Outlook
Low Mass Dimuon Production in proton-nucleus Collisions at 400 GeV/c
Single Dalitz decays:

- virtual photon (converting into a *lepton pair*) + third body
- lepton pair mass distribution first derived by Kroll and Wada for point-like interactions
- the observed mass distribution deviates from the Kroll-Wada one by the so-called **electromagnetic form factor**

\[
\frac{dN}{dM} = |F(M)|^2 \times \frac{1}{M} \left( 1 + 2 \frac{m_\mu^2}{M^2} \right) \left( 1 - \frac{M^2}{m_\eta^2} \right)^3 \sqrt{1 - \frac{4m_\mu^2}{M^2}}
\]

\[
\frac{dN}{dM} = |F(M)|^2 \times \frac{1}{M} \left( 1 + 2 \frac{m_\mu^2}{M^2} \right) \left[ \left( 1 + \frac{M^2}{m_\omega^2 - m_{\pi^0}^2} \right)^2 - \frac{4m_\omega^2 M^2}{(m_\omega^2 - m_{\pi^0}^2)^2} \right]^{3/2} \sqrt{1 - \frac{4m_\mu^2}{M^2}}
\]
Vector Meson Dominance Model (VDM):

Photon-hadron interactions proceed via a transition to a vector meson

The VMD model provides a description of the electromagnetic form factor

\[
F(M) = \frac{\sum_{V=\rho,\omega,\phi} [g_{ABV} / 2g_{V\gamma}] m_V^2}{\sum_{V=\rho,\omega,\phi} [g_{ABV} / 2g_{V\gamma}] m_V^2 - M^2 - i\Gamma_V m_V}
\]

Which is usually parametrized as:

\[
F(M) \approx \left[ 1 - \frac{M^2}{\Lambda^2} \right]^{-1}
\]
Measurements currently available for the $\Lambda$ parameters:

- **Lepton-G** measurements in pion-nucleus collisions
- **NA60** measurements in peripheral In-In collisions
Data (black triangles) are fitted with the superposition of the expected sources:

- **2-body** and **Dalitz** decays of the neutral mesons $\eta$, $\rho$, $\omega$, $\eta'$, $\phi$
- open charm contribution
Eta Dalitz and Omega Dalitz processes are isolated, together with the 2-body decay of $\rho$.

Normalization for rho decay is not easy to find from the fit of the mass spectrum, so it is not subtracted.
The correction is evaluated:

- for each process, separately
- for the sum of the three processes, according to the normalization extracted from the fit

The correction for **Rho** dominates for mass > 0.6 GeV/c²

The correction for **Eta** dominates for mass < 0.5 GeV/c²
Fitting the Mass Spectrum after Correction

Five free parameters:
- normalization for the three processes
- $\Lambda_{\eta}^{-2}$ and $\Lambda_{\omega}^{-2}$ parameters

Rho 2-body decay: line shape characteristic for hadro-production

Dalitz processes: Kroll-Wada (KW) expression multiplied by the form-factor parametrization:

$$|F(M)|^2 = \left[1 - \frac{M^2}{\Lambda^2}\right]^{-2}$$
Preliminary Results on the E.M. Form Factors (I)

NA60 (p-A) : $\Lambda^{-2} = 1.95 \pm 0.05 \pm 0.04$ [GeV/c^2]^2
NA60 (In-In) : $\Lambda^{-2} = 1.95 \pm 0.17 \pm 0.04$ [GeV/c^2]^2
Lepton-G : $\Lambda^{-2} = 1.9 \pm 0.4$ [GeV/c^2]^2
VDM : $\Lambda^{-2} = 1.8$ [GeV/c^2]^2

NA60 (p-A) : $\Lambda^{-2} = 2.273 \pm 0.015 \pm 0.012$ [GeV/c^2]^2
NA60 (In-In) : $\Lambda^{-2} = 2.24 \pm 0.06 \pm 0.02$ [GeV/c^2]^2
Lepton-G : $\Lambda^{-2} = 2.4 \pm 0.2$ [GeV/c^2]^2
VDM : $\Lambda^{-2} = 1.68$ [GeV/c^2]^2
New (preliminary) results are in **good agreement** with the previous ones:
- Results for the eta **agree** with the VMD predictions
- Results for the omega confirm the **discrepancy** with the VMD predictions
- Errors are **significantly improved**, due to the larger statistics available in p-A
- Further improvements are coming soon, thanks to the **p-A sample at 158 GeV/c**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( \Lambda_\eta^{-2} ) [GeV/c(^2)](^{-2} )</th>
<th>( \Lambda_\omega^{-2} ) [GeV/c(^2)](^{-2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton-G</td>
<td>1.9 ± 0.4</td>
<td>2.4 ± 0.2</td>
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<tr>
<td></td>
<td>600 events</td>
<td>60 events</td>
</tr>
<tr>
<td>NA60 (In-In periph.)</td>
<td>1.95 ± 0.17 ± 0.04</td>
<td>2.24 ± 0.06 ± 0.02</td>
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<tr>
<td></td>
<td>9'000 events</td>
<td>3'000 events</td>
</tr>
<tr>
<td>NA60 (p-A, <strong>PRELIM.</strong>)</td>
<td>1.95 ± 0.05 ± 0.04</td>
<td>2.273 ± 0.015 ± 0.012</td>
</tr>
<tr>
<td></td>
<td>55'000 events</td>
<td>14'000 events</td>
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p-A collisions also allow to study production cross sections in **cold nuclear matter**: this is mandatory in order to be able to identify “anomalous” effects possibly happening in **hot nuclear matter** (e.g. heavy ions collisions)

How to extract the production cross section for a particle, using our data?

- **Fit of the raw mass spectrum**: allows us to evaluate how many reconstructed events we have for a given process. From here we recover the number of generated parent particles

- We study the trend of the cross section **as a function of the mass number A**, normalizing the cross sections to one of the Be targets

- Since the targets were **simultaneously** exposed to the beam, the uncertainties on the luminosity cancel out
We studied several *dimuon-target association criteria*, evaluating their performance by means of MC simulations. Each criterion has a *fraction $\xi$ of lost events* and allows us to have a *correctness equal to $\epsilon$*. Ideal case: $\xi = 0\%$, $\epsilon = 100\%$

Both $\xi$ and $\epsilon$ depend on the *dimuon mass*: at low mass $\xi$ increases and $\epsilon$ decreases. The chosen criterion allows to have $\epsilon > 90\%$ even for low masses. Testing it with MC simulations of $\eta \to \mu^+ \mu^- \gamma$ process we obtain
Fit of the Low Mass Spectrum (target by target)

\[ \chi^2/\text{ndf} = 89/55 \quad \text{p-Be} \]

\[ \chi^2/\text{ndf} = 98/55 \quad \text{p-Cu} \]

\[ \chi^2/\text{ndf} = 162/55 \quad \text{p-In} \]

\[ \chi^2/\text{ndf} = 214/55 \quad \text{p-W} \]

\[ \chi^2/\text{ndf} = 139/55 \quad \text{p-Pb} \]

\[ \chi^2/\text{ndf} = 152/55 \quad \text{p-U} \]
Relative Production Cross Section vs A

The **overall trend** of the points seems to follow a power law as a function of A.

**More investigations and systematic checks** are needed before a fit could be performed.
- $\eta/\omega$ ratio, within large error bars, shows a **decreasing trend** with the size of the nuclear target. NA27 measured $\eta/\omega = 0.77 \pm 0.07$ in $p$-$p$, and HELIOS-1 measured $\eta/(\omega+\rho) = 0.62 \pm 0.07$ in $p$-$Be$. These values significantly deviate from the trend observed in our data.

- $\rho/\omega$ ratio is **independent** on the size of the nuclear target, within the errors. The NA27 measurement in $p$-$p$ falls within two standard deviations from our trend: $\rho/\omega = 0.98 \pm 0.08$.
\( \phi/\omega \) ratio shows a significant increase with the size of the nuclear target: enhancement of strange production as a function of the mass number \( A \). The NA27 measurement in p-p \( \phi/\omega = 0.048 \pm 0.006 \) is compatible with the observed trend.
Preliminary results for the electromagnetic form factors of $\eta$ and $\omega$ mesons: we confirmed currently available results improving their precision by a factor $\sim 10$ (w.r.t. Lepton-G) and $\sim 3$ (w.r.t. NA60 In-In periph.)

VMD predictions confirmed for the $\eta$. Discrepancy between VMD and data is also confirmed for the $\omega$.

Relative production cross sections for $\eta$, $\rho$, $\omega$ and $\phi$ mesons have been studied as a function of $A$. The overall trend of the experimental points seems to follow a power law function.

Clear enhancement is observed for the $\phi/\omega$ ratio as a function of $A$. 
Outlook

- Extend the analysis of the electromagnetic form factors of \( \eta \) and \( \omega \) mesons, including the p-A sample at 158 GeV/c
- Further systematics tests on the stability of the results, including new checks concerning the rho spectral function used for the fit
- Further systematics checks on the relative cross sections as a function of A: could we fit a power law trend?

**BONUS TRACKS:**

- Evaluation of the ratio between the 2-body and Dalitz decays of the \( \eta \) and \( \omega \) mesons, in the dimuon channel
- Study of \( \rho/\omega \) interference effects in the dimuon mass spectrum