Data-driven low-energy generator for CMD-3

S. Eidelman, A. Korobov

Budker Institute of Nuclear Physics
NSU
ACAT 2019
Outline

- Motivation
- Data
- Structure
- Input and output
- Some applications
- Conclusion
CMD-3 and VEPP-2000

CMD-3

Collider VEPP-2000
$L = 4 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$ at 2.0 GeV
Motivation

- MHG2000-MultiHadronic Generator for VEPP-2000
- pQCD fails at the energy range $\sqrt{s} < 2$ GeV
- One of CMD-3’s goals is the precision measurement of exclusive hadron cross section
- Evaluation of the background for hadronic processes
- It is data-driven generator based on the bulk of measured exclusive cross sections
MHG2000’s features

- An event is sampled with one ISR photon: $d\sigma/d\omega_{\gamma}dE_{\gamma}$ proportional $f(E_{\gamma}, \cos\theta_{\gamma})$
- Currently near 30 different final states
- Matrix elements are added whenever possible, output compared to PHOKHARA for N=3,4
- Use phase volume model otherwise
- We approximate the data by functions for each final state
- Energy dependence of $\sigma_i$, $\sigma_{tot} = \sum_i \sigma_i$, a final state number $i$ is sampled with a weight of $\frac{\sigma_i}{\sigma_{tot}}$
## Data samples

<table>
<thead>
<tr>
<th>Process</th>
<th>Data</th>
<th>Process</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\pi^-$</td>
<td>BaBar</td>
<td>$\pi^+\pi^-\pi^0\pi^0$</td>
<td>DM2, CMD2</td>
</tr>
<tr>
<td>$\pi^0\gamma$</td>
<td>SND</td>
<td>$\pi^+\pi^-\pi^0\eta$</td>
<td>CMD-3</td>
</tr>
<tr>
<td>$\eta\gamma$</td>
<td>SND, CMD2</td>
<td>$K^+K^-\pi^+\pi^-$</td>
<td>CMD-3, BaBar</td>
</tr>
<tr>
<td>$p\bar{p}$</td>
<td>BaBar, CMD-3</td>
<td>$K^0\pi^0\pi^+\pi^0$</td>
<td>BaBar</td>
</tr>
<tr>
<td>$n\bar{n}$</td>
<td>SND</td>
<td>$K^0\pi^+\pi^-$</td>
<td>BaBar</td>
</tr>
<tr>
<td>$K^+K^-$</td>
<td>BaBar CMD2</td>
<td>$K_S^0K_L^0\pi^+\pi-$</td>
<td>BaBar</td>
</tr>
<tr>
<td>$K^+_L^0K^-L^0\pi^0$</td>
<td>BaBar, CMD3, SND</td>
<td>$K_S^0K_S^0\pi^+\pi-$</td>
<td>BaBar</td>
</tr>
<tr>
<td>$\pi^+\pi^-\eta$</td>
<td>SND</td>
<td>$K_L^0K_S^0\pi^0\pi^0$</td>
<td>BaBar</td>
</tr>
<tr>
<td>$K^+K^-\pi^0$</td>
<td>BaBar</td>
<td>$K^+K^0\pi^-\pi^0$</td>
<td>BaBar</td>
</tr>
<tr>
<td>$K^0\pi^-\eta$</td>
<td>BaBar</td>
<td>$2\pi^+2\pi^-\pi^0$</td>
<td>BaBar</td>
</tr>
<tr>
<td>$K^+K^-\eta$</td>
<td>BaBar</td>
<td>$\pi^+\pi^-3\pi^0$</td>
<td>BaBar</td>
</tr>
<tr>
<td>$K^0\pi^+\pi^-$</td>
<td>BaBar</td>
<td>$3\pi^+3\pi^-$</td>
<td>CMD3, BaBar</td>
</tr>
<tr>
<td>$K^0\pi^0\pi^+\pi^-$</td>
<td>BaBar, CMD2, BaBar</td>
<td>$2\pi^+2\pi^-2\pi^0$</td>
<td>BaBar</td>
</tr>
<tr>
<td>$\pi^+\pi^-4\pi^0$</td>
<td>BaBar</td>
<td>$\pi^+\pi^-4\pi^0$</td>
<td>IR</td>
</tr>
</tbody>
</table>

A. Korobov, BINP Switzerland, ACAT 2019
Examples of cross section approximations

Left: $\pi^+\pi^-$

Right: $\pi^+\pi^-\pi^0\pi^0$
MHG2000 structure

modular structure based on C++, HEPMC, ROOT.
ISNR photon

- Convolution of the Born cross section with radiator function
- Choose the final state using corrected cross section
- Generate ISR photon
- Boost to the center-of-mass frame of hadron system and generate hadrons

\[
\frac{d\sigma(s, x)}{dx \, d\cos\theta} = \frac{2\alpha}{\pi x} \cdot \frac{(1 - x + \frac{x^2}{2}) \sin^2 \theta}{(\sin^2 \theta + \frac{m^2}{E^2} \cos^2 \theta)^2} \cdot \sigma_0(s(1 - x)),
\]
Input parameters

- center-of-mass energy in GeV
- isrkey=1 isr is on; isrkey=0 isr is off
- list of required processes
MHG2000 Output

- GenEvent
  - GenVertex
  - Final state id
    - GenParticle:
      - Particle id
      - 4-momentum
Two photon invariant mass: Red for MHG2000 without signal dots for data
CMD-3 preliminary
Application at CMD-3: $\pi^+\pi^-\pi^0\eta$

Two photon invariant mass: Yellow for MHG2000; dots for data

CMD-3 preliminary
Application at CMD-3: $K_L^0 K_S^0 \pi^0$

$K_S^0 \pi^0$ missing mass; Green for MHG2000; Red for data CMD-3 preliminary

A. Korobov, BINP

Switzerland, ACAT 2019
• \( R = \frac{\sigma_{e^+e^- \rightarrow \text{hadrons}}}{\sigma_{e^+e^- \rightarrow \mu^+\mu^-}} \)

• KEDR performed several measurements of \( R \) from 1.84 to 3.72 GeV: V.V. Anashin et al., Phys. Lett. B770 (2017) 174 (13 points, 1.84-3.05 GeV)(last one)

• They use LUARLW and JETSET 7.4 for efficiency calculations, input parameters tuned by comparing 20 parameters with data

• To calculate radiative corrections MHG2000 is used in the region up to 2 GeV
Comparison of three MC generators (charged multiplicity)

Fair agreement of MHG2000 with data at 1.84 and 1.94 GeV
Conclusion and plans

- A data-driven generator of multihadronic final states MHG2000 is based on the measured cross sections at $\sqrt{s} < 2$ GeV
- MHG2000 is used to simulate background in experiments at VEPP-2000
- MHG2000 has been also used in $R$ measurement at KEDR
- Its development is currently in progress: new modes and matrix elements added
- Planning to expand the energy range up to 2.5 GeV using Babar and BESIII data
\[ D(x, s) = \frac{1}{2} \beta (1 - x)^{\beta / 2 - 1} \left( 1 + \frac{3}{8} \beta - \frac{1}{48} \beta^2 \left( \frac{1}{3} L + \pi^2 - \frac{47}{8} \right) \right) - \frac{1}{4} \beta (1 + x) + \frac{1}{32} \beta^2 \left( 4(1 + x) \ln \frac{1}{1-x} + \frac{1+3x^2}{1-x} \ln \frac{1}{x} - 5 - x \right) \] with
\[ \beta = \frac{2\alpha}{\pi} (L - 1); \quad L = \ln \frac{s}{m^2} \]
Exclusive vs Inclusive R measurement

The muon $g - 2$ and $\alpha(M_Z^2)$: a new data-based analysis.
Anomalous magnetic moment of muon

- Magnetic moment of muon: \( \bar{\mu} = g \frac{e\hbar}{2mc} \bar{s} \)
- Gyromagnetic factor \( g \) for
  - Dirac particles (point-like fermions): \( g = 2 \)
  - Higher order contributions (QFT): \( g \neq 2 \)
- Muon anomaly
  - \( a_\mu = (g-2)_\mu / 2 \)

\[ a_\mu^{\text{theory(SM)}} = a_\mu^{\text{QED}} + a_\mu^{\text{weak}} + a_\mu^{\text{had}} \]

<table>
<thead>
<tr>
<th>Source</th>
<th>Value (10^{-10})</th>
<th>Uncertainty (10^{-10})</th>
</tr>
</thead>
<tbody>
<tr>
<td>QED</td>
<td>11 658 471.895</td>
<td>0.008</td>
</tr>
<tr>
<td>Weak</td>
<td>15.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Hadronic + LbL</td>
<td>693.0</td>
<td>4.9</td>
</tr>
<tr>
<td>BNL E821</td>
<td>11 659 208.9</td>
<td>6.4</td>
</tr>
<tr>
<td>BNL - SM Theory</td>
<td>28.7</td>
<td>8.0</td>
</tr>
</tbody>
</table>

\[
a_\mu^{\text{had}} = \frac{\alpha^2}{3 \cdot \pi^2} \int \frac{ds}{s} \frac{K(s)}{4m_e^2} R(s)
\]

\[
R(s) = \frac{\sigma(e^+e^- \to \gamma \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}
\]

\[
a_\mu^{\text{EXP}} - a_\mu^{\text{SM}} = 3.6\sigma \quad \text{(M. Davier et al., EPJC71(2011)1515)}
\]
Energy difference vs total momentum

Left EXP
Right MHG2000 simulation (red-4pi(signal), black-6pi, blue-5pi, yellow-KsKpi)