Hard processes in p-A collisions with MC generator
HARDPING 3.0

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- Introduction: Monte Carlo event generator HARDPING (HARD Probe INteraction Generator)

- HARDPING: soft interactions of hadrons produced in hard lepton-nucleus scattering and formation length of this hadrons

- HARDPING: soft interactions of hadrons before hard interaction in hard proton-nucleus scattering (Drell-Yan reaction), energy losses and soft re-scatterings

- HARDPING: high-pT hadron production in hadron-nucleus interactions at Tevatron and LHC energies

- Conclusion
Monte Carlo event generator HARDPING

HARDPING 1.0: lepton pair production in the hard proton-nucleus interactions (Drell-Yan reaction).
- multiple re-scatterings and energy losses are implemented for projectile hadrons
- parameters: the mean value of transverse momentum of nucleon inside the nucleus, the mean value of transverse momentum of quark inside intranuclear nucleon, the value of quark nucleon cross section were fitted from DY pA data at 800 GeV (Fermilab)

HARDPING 2.0: hadron production in the hard lepton-nucleus interactions
- multiple re-scatterings and energy losses are implemented for produced hadrons
- formation length of produced hadrons
- the mean value of transverse momentum of nucleon inside the nucleus, the mean value of transverse momentum of quark inside intranuclear nucleon, the value of quark nucleon cross section were fitted from HERMES data (DESY).

HARDPING 3.0: hadron production in hard proton-nucleus interactions (Cronin effect). The all parameters had been fixed in the previous versions.
Interaction of produced hadrons after hard collision: lepton-nucleus scattering

Two step hadron formation process [Kopeliovich, Nemchik et al., & Pirner H.J. at el.]:
- Formation of colorless pre-hadron state
- Formation of final hadron from pre-hadron state

\[
f_f(k_{fi}) = \frac{B_f}{\pi} e^{-B_f k_{fi}^2}
\]

\[
f_p(p_{ti}) = \frac{B_p^2}{2\pi} e^{-B_p p_{ti}}
\]

\[
f_{pf}(k_{ti}) = f_p \otimes f_f = \int f_p(p_{ti}) f_f(k_{fi}) \delta^2(k_{ti} - p_{ti} - k_{fi}) d^2p_{ti} d^2k_{fi}
\]
Interaction of produced hadrons after hard collision: lepton-nucleus scattering

Two step hadron formation process [Kopeliovich, Nemchik et al., & Pirner H.J. at el.]:
- Formation of colorless pre-hadron state
- Formation of final hadron from pre-hadron state

$$f_f(k_{fi}) = \frac{B_f}{\pi} e^{-B_f k_{fi}^2}$$

$$f_p(p_{ti}) = \frac{B^2}{2\pi} e^{-B p_{ti}}$$

$$f_{pf}(k_{ti}) = f_p \otimes f_f = \int f_p(p_{ti}) f_f(k_{fi}) \delta^2(k_{ti} - p_{ti} - k_{fi}) d^2 p_{ti} d^2 k_{fi}$$
HARDPING vs HERMES data (2003): hadrons yields ratios for nuclei $N^{14}$ and $D^2$

$$R^h(z, \nu, p_t^2, Q^2) = \frac{N_h(z, \nu, p_t^2, Q^2)}{N_e(\nu, Q^2)}$$

$e^+(27.6 \text{ GeV}) + A \rightarrow e^+ \nu + hh + X$

- HERMES
- HARDPING

$\sigma^{qN} = 7 \text{ mb}$

$k_s = 1.7 \text{ GeV/Fm}$

$$z = \frac{pP}{qP} = \frac{E_h}{\nu}$$

$$\nu = \frac{qP}{\sqrt{P^2}} = E' - E$$

HARDPING vs HERMES data (2003): hadrons yields ratios for nuclei $^{14}$Kr and $^2$D

- HERMES
- HARDPING

$\sigma^{qN} = 7 \text{ mb}$

$k_s = 1.7 \text{ GeV/Fm}$

HARDPING vs HERMES data (2003): $\pi^+$ mesons yields ratios for Kr, N and D nuclei

$\sigma_{qN} = 7 \text{ mb}$

$k_s = 1.7 \text{ GeV/Fm}$

HARDPING vs EMC Coll. data (1991)

ratios of cross sections of hadron production for nuclei Cu & D as a function of virtual photon energy

\[ \mu^-(280 \text{ GeV}) + A \rightarrow \mu'^- + hh \]

a - 5 mb и 1.5 GeV/Fm, b - 5 mb и 3.0 GeV/Fm, 
c - 20 mb и 1.5 GeV/Fm, d - 20 mb и 3.0 GeV/Fm
HARDPING: soft hadron-nucleus interaction before hard collision in proton-nucleus scatterings (Drell-Yan reaction)

- Multiple soft re-scatterings of quark of projectile hadron give the main contribution to the observable A-dependency of produced lepton pairs
- Such effects as soft re-scatterings, energy losses and screening if structure function of intranuclear nucleons are implemented into HARDPING

\[
\begin{align*}
    p_1 &= E_{\text{beam}}(x_1, 0, 0, x_1) \\
    p_2 &= E_{\text{beam}}(x_2, 0, 0, -x_2) \\
    \tau &= x_1 x_2 = M_{ll}^2 / S \\
    x_F &= x_1 - x_2
\end{align*}
\]
HARDPING: energy losses of initial quark

\[ \Delta E = - k_s L \]
\[ \Delta E = - k_s \left( L + \frac{1}{2} \sigma qN \rho_A L^2 \right) \]

\( k_s \) [GeV/Fm] — the mean of string tension inside the nuclear medium

\( L \) — path length of quark inside the nucleus

HARDPING vs E866 data: $pA \rightarrow l^+l^- X \quad 800$ GeV

Ratios of production cross sections of muon pairs on the heavy nuclei to the light nuclei as a function of pair's transverse momentum

- E866
- HARDPING

$4 \text{ GeV/c}^2 < M_{ll} < 8.4 \text{ GeV/c}^2$

\[ \sigma^{qN} = 7 \text{ mb} \quad k_s = 1.7 \text{ GeV/Fm} \]
Comparison of HARDPING data with data obtained in E866 experiment: \( pA \rightarrow l^+l^- X \ 800 \text{ GeV} \)

Ratios of production cross sections of muon pairs on the heavy nuclei to the light nuclei as a function of pair's \( x_1 \)

- E866
- HARDPING

\[ 4 \text{ GeV/c}^2 < M_{ll} < 8.4 \text{ GeV/c}^2 \]

\[ \sigma^{qN} = 7 \text{ mb} \quad k_s = 1.7 \text{ GeV/Fm} \]
HARDPING 3.0: hadron production in proton-nucleus interactions $pA \rightarrow \pi^+ X$ 400 GeV

$$I_i(p_T^a, A) = I_i(p_T^a, 1) \cdot A^{\alpha_i(p_T^a)}$$

The measurements were made at a laboratory angle of 77 mrad. power $\alpha_i$ as a function of transverse momentum of produced $\pi^+$-mesons

$$\sigma^{qN} = 7 \text{ mb}$$

$k_s = 1.7 \text{ GeV/Fm}$
HARDPING predictions for NuSea (Fermilab)

\[ pA \rightarrow l^+l^- X \quad 120 \text{ GeV (targets: D and p)} \]

\[
\frac{\sigma^{pd}}{2\sigma^{pp}} \bigg|_{x_1 \gg x_2} \approx \frac{1}{2} \left(1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right)
\]
HARDPING predictions for NuSea (Fermilab)

\[ pA \rightarrow l^+ l^- X \text{ at 120 GeV (nuclear quark sea precision study)} \]

string tension parameter:
- **blue**: \( k = 1.0 \text{ GeV/Fm} \)
- **red**: \( k = 1.7 \text{ GeV/Fm} \)
- **green**: \( k = 3.0 \text{ GeV/Fm} \)
HARDPING predictions for LHC energy
\[ pA \rightarrow l^+l^- X \] and \[ pA \rightarrow h X \] \( \sqrt{S} = 5.02 \text{ TeV} \)

\[ pA \rightarrow l^+l^- X \]

\[ pA \rightarrow h X \]
Conclusions

- MC generator HARDPING 3.0 has been developed. It provides simulation of hadron production in lepton-nucleus and hadron-nucleus interactions. It takes into account formation length of produced hadron, soft multiple re-scatterings and energy losses in the nuclear medium.

- HARDPING 3.0 with parameters of soft interaction of hadrons with nuclear medium for projectile and produced hadrons, which were fixed in lepton-nucleus interactions and Drell-Yan reactions, provides a reasonably good description of hadron production in proton-nucleus collisions at 400 GeV (Cronin effect)

HARDPING plans:
- more detail comparison with pA collisions data: Protvino, Tevatron, LHC and predictions for various observables
- nuclear density fluctuation (multiquark fluctons)
- hard nucleus-nucleus collisions