What is a ‘Hard’ Process?

‘Hard’ processes have a large scale in the calculation that makes perturbative QCD applicable: high momentum transfer, $Q^2$, high invariant mass, $M$, high transverse momentum, $p_T$

Understanding these processes relies on asymptotic freedom to calculate the interactions between two hadrons on the quark/gluon level but the confinement scale determines the probability of finding a particular parton in the proton

This implies factorization between the perturbative hard part and the universal, nonperturbative parton distribution functions

$$\sigma_{AB}(s, m_0^2) = \sum_{i,j=q,g} \int \frac{d\tau}{\tau} \int dx_1 dx_2 \delta(x_1 x_2 - \tau) \times F_i^A(x_1, \mu^2) F_j^B(x_2, \mu^2) \sigma_{ij}(\tau, m_0^2, \mu^2)$$

$F_i^A$ are the parton distributions, either in a proton or a nucleus, determined from fits to data, $x_1$ and $x_2$ are the fractional momentum of the hadron carried by partons $i$ and $j$

$\sigma_{ij}(\tau, m_0^2, \mu^2)$ is partonic cross section calculable in QCD in powers of $\alpha_s^{2+n}$: leading order, $n = 0$; next-to-leading order, $n = 1$...

Studying the Nuclear Gluon Distribution in $pA$

Lepton pairs from heavy quark decays used to compare the $pA/pp$ ratios at the same energy to the input shadowing parameterization

$cc$ and $bb$ pairs produced, hadronized, and decayed, then studied in the PHENIX and ALICE lepton pair acceptances

Both correlated and uncorrelated pairs considered

Figure 8: Scale evolution of the EKS98 ratio $R_0(x,Q^2)$ for $A=208$. The ratios are shown as functions of $x$ at fixed values of $Q^2$ equidistant in $\log Q^2$: $2.25$ GeV$^2$ (solid), $5.39$ GeV$^2$ (dotted), $14.7$ GeV$^2$ (dashed), $39.9$ GeV$^2$ (dotted-dashed), $108$ GeV$^2$ (double-dashed), and $10000$ GeV$^2$ (dashed). The regions between the vertical dashed lines show the dominant values of $x_0$ probed by muon pair production from $DD$ at SPS, RHIC and LHC energies. [K.J. Eskola, V.J. Kolhinen and R.V., Nucl. Phys. A696 (2001) 729.]
Lepton Pair Cross Section

Differential cross section
\[
\frac{d\sigma^{pA\rightarrow ll+X}}{dM_{ll}dy_{ll}} = \int d^6p_T^ll d^6p_T^H d^6p_T^H \delta(M_{ll} - M(p_l,p_l)) \delta(y_{ll} - y(p_l,p_l)) \\
\times \frac{d\Gamma^{H\rightarrow ll+X}(p_T^H)}{d^6p_T^H} \frac{d\Gamma^{H\rightarrow ll+X}(p_T^H)}{d^6p_T^H} \frac{d\sigma^{pA\rightarrow HH+X}}{d^6p_T^H d^6p_T^H} \\
\times \theta(y_{\text{min}} < y_l < y_{\text{max}}) \theta(\phi_{\text{min}} < \phi_l < \phi_{\text{max}})
\]

Decay rate is \(d\Gamma^{H\rightarrow ll+X}(p_T^H)/d^6p_T^H\) for meson \(H\) to decay to lepton

Theta functions define rapidity and \(\phi\) cuts

\(M_{ll}\) and \(y_{ll}\) are the mass and the rapidity of the lepton pair

\[
M(p_l,p_l) = \sqrt{(p_l + p_l)^2}, \\
y(p_l,p_l) = \frac{1}{2} \ln \left( \frac{(E_l + E_l) + (p_{l+} + p_{l-})}{(E_l + E_l) - (p_{l+} + p_{l-})} \right)
\]

Meson pair production cross section
\[
\frac{d\sigma^{pA\rightarrow HH+X}}{d^6p_T^H d^6p_T^H} = \int d^6p_T^E d^6p_T^Q d^6p_T^Q \frac{d\sigma^{pA+QQ+x}}{d^6p_T^H d^6p_T^Q} \int_0^1 dz_1 D_E^E(z_1) \int_0^1 dz_2 D_E^Q(z_2) \\
\times \delta^3(p_T^H - z_1 p_T^Q) \delta^3(p_T^H - z_2 p_T^Q)
\]

Hadronic Heavy Quark Production Cross Section per Nucleon

\[
\frac{1}{A} E_Q E_Q \frac{d\sigma^{A+QQ+X}}{d^6p_T^Q d^6p_T^Q} = \sum_{ij} \int_0^1 dx_1 \int_0^1 dx_2 \int_0^1 dx_3 \int_0^1 dx_4 f_i^A(x_1,Q^2)f_j^A(x_2,Q^2)E_Q E_Q \frac{d\sigma^{ij+QQ}}{d^6p_T^Q d^6p_T^Q}
\]

Parton distribution functions in proton, \(f_i^p\), and nucleus, \(f_i^A = f_i^p R_i^A\), evaluated at \(Q^2 \propto m_t^2\)

Partonic cross sections and convolution of parton distributions with subprocess cross sections

\[
\frac{E_Q E_Q \frac{d\sigma^{ij+QQ}}{d^6p_T^Q d^6p_T^Q}}{2\pi} = \frac{\delta}{dt} \frac{d\sigma^{ij+QQ}}{dt} \delta^{(4)}(p_1 + p_2 - p_Q - p_Q)
\]

\[
\sum_{ij} f_i^A(x_1,Q^2)f_j^A(x_2,Q^2) \int \frac{d\sigma^{ij+QQ}}{dt} dt \delta^{ij}(p_1 + p_2 - p_Q - p_Q)
\]

\[
\int \frac{d\sigma^{ij+QQ}}{dt} dt \delta^{ij}(p_1 + p_2 - p_Q - p_Q)
\]

Differential and total cross sections per nucleon

\[
\frac{d\sigma^{QQ}}{d^3p_T^Q d^3p_T^Q} = \frac{1}{A} \frac{1}{E_Q E_Q} \left[ \frac{1}{A} E_Q E_Q \frac{d\sigma^{A+QQ+X}}{d^3p_T^Q d^3p_T^Q} \right] \\
\]

\[
\frac{\delta^{QQ}}{d^3p_T^Q d^3p_T^Q} = \int d^6p_T^Q d^6p_T^Q d^6p_T^Q d^6p_T^Q \\
\]

\[
= \int d^3p_T^Q d^3p_T^Q d^3p_T^Q d^3p_T^Q \sum_{ij} x_1 f_i^A(x_1,Q^2)x_2 f_j^A(x_2,Q^2) \frac{d\sigma^{ij+QQ}}{dt}
\]
Why Don’t the Results Match the Input Exactly?

Some production is through the $qq \rightarrow QQ$ channel which has different shadowing.

Better agreement at LHC because of reduced $qq$ contribution.

Phase space integration smears the shadowing relative to $R_g^4$ evaluated at the average values of $x_2$ and $Q$.

Curvature of $R_g^4$ with $x$ stronger at large $x$.

Average values of $x_2$ of target is larger for electrons (forward muon coverage allows smaller $x_2$’s to be reached) so the deviations between the output and input are largest in the central coverages of the electron detectors.

Figure 9: The ratios of lepton pairs from correlated $DD$ and $BB$ decays in $pA$ to $pp$ collisions at the same energies (solid curves). Both the $e^+e^-$ and $\mu^+\mu^-$ channels are shown. The results are compared to the input nuclear gluon distribution from EKSS98 at the average $x_2$ and $Q$ (dashed)/$\sqrt{Q}$ (dot-dashed) of each $M$ bin. [K.J. Eskola, V.J. Kolhinen and R.V., Nucl. Phys. A696 (2001) 729.]
Average Values of $x_2$ and $Q$

Correlated and Uncorrelated Decays

Impact parameter integrated cross section

$$
\sigma^{pA+Q\bar{Q}+X} = \int d^2b \left( 1 - e^{-T_A(b)\sqrt{s}} \right) = \int d^2b \sum_{N=1}^{\infty} \frac{N_{Q\bar{Q}}(b)e^{-N_{Q\bar{Q}}(b)}}{N!}
$$

Number of $Q\bar{Q}$ pairs at impact parameter $b$ proportional to thickness function

$$
N_{Q\bar{Q}}(b) = T_A(b)\sigma^{Q\bar{Q}}
$$

$$
T_A(b) = \int ds\rho_A(s,b,z)
$$

Differentiating:

$$
\frac{d\sigma^{pA+Q\bar{Q}+X}}{d^2p_TQd^2\bar{p}_Q} = \int d^2b \sum_{N=1}^{\infty} \frac{N_{Q\bar{Q}}(b)e^{-N_{Q\bar{Q}}(b)}}{N!} \prod_{i=1}^{N} \left( \frac{1}{\sigma^{Q\bar{Q}}} \int d^2p_TQd^2\bar{p}_Q \frac{d\sigma^{Q\bar{Q}}}{d^2p_TQd^2\bar{p}_Q} \right)
$$

$$
\times \left( \sum_{j,k=1}^{N} \delta^{(4)}(\vec{p}_Q - \vec{p}_{Qj})\delta^{(4)}(\vec{p}_{\bar{Q}} - \vec{p}_{\bar{Q}k}) \right)
$$

Correlated pairs: $j = k$

$$
\frac{d\sigma^{corr+Q\bar{Q}+X}}{d^2p_TQd^2\bar{p}_Q} = \int d^2b \sum_{N=1}^{\infty} \frac{N_{Q\bar{Q}}(b)e^{-N_{Q\bar{Q}}(b)}}{N!} \frac{1}{N} \frac{d\sigma^{Q\bar{Q}}}{d^2p_TQd^2\bar{p}_Q}
$$

$$
= \int d^2b T_A(b) \frac{d\sigma^{Q\bar{Q}}}{d^2p_TQd^2\bar{p}_Q} = A^2 \frac{d\sigma^{Q\bar{Q}}}{d^2p_TQd^2\bar{p}_Q}
$$

Uncorrelated pairs: $j \neq k$

$$
\frac{d\sigma^{uncorr+Q\bar{Q}+X}}{d^2p_TQd^2\bar{p}_Q} = \int d^2b \sum_{N=1}^{\infty} \frac{N_{Q\bar{Q}}(b)e^{-N_{Q\bar{Q}}(b)}}{N!} N(N-1) \frac{1}{N} \frac{d\sigma^{Q\bar{Q}}}{d^2p_TQd^2\bar{p}_Q}
$$

$$
= \int d^2b T_A^2(b) \frac{d\sigma^{Q\bar{Q}}}{d^2p_TQd^2\bar{p}_Q} = \pi T_A^2 \frac{d\sigma^{Q\bar{Q}}}{d^2p_TQd^2\bar{p}_Q}
$$

Figure 10: The average values of $x_2$ and $Q$ are given as a function of lepton pair mass for $DD$ decays. The solid lines are for muon pairs while the dashed are for electron pairs. The dotted lines on the average $x_2$ plot indicate the differences between the channels. [K.J. Eskola, V.J. Kolhinen and R.V., Nucl. Phys. A696 (2001) 729.]
Uncorrelated Pairs a Minimal Contribution to Total $DD$ Decays at RHIC

Figure 2: The EKS98 shadowing parameterization evaluated at $Q = m_\pi$. Valence shadowing is shown in (a), sea quark shadowing is shown in (b) for $u = d$ (solid), $s$ (dashed) and $c$ (dot-dashed), and gluon shadowing is shown in (c).

Figure 11: Correlated (solid) and uncorrelated (dashed) $D\bar{D}$ and correlated $B\bar{B}$ (dot-dashed) decays in the $e^+e^-, e^+\mu^\pm$, and $\mu^+\mu^-$ lepton pair channels. If a $K$ factor was included, it would enter linearly for the correlated pairs and quadratically for the uncorrelated pairs. [K.J. Eskola, V.J. Kolhinen and R.V., Nucl. Phys. A696 (2001) 729.]
Shadowing in Gauge Boson Production

Production of a vector particle with mass $m_V$ at scale $Q$ at next-to-leading order

$$\frac{1}{AB} \frac{d^3 \sigma}{d^3 y} = \int \frac{dz_1 dz_2 dx_1 dx_2 dx \delta \left( \frac{m_V^2}{s} - xx_1 x_2 \right) \delta \left( y - \frac{1}{2} \ln \left( \frac{z_1}{x_2} \right) \right)}{x_1 x_2 x_3} \times \left\{ \sum_{i,j \in Q, i} H_{ij}^V C_f^i (q_i, q_j) \Delta q_V(x) F^A_{i,j} (x_1, Q^2) F^B_j (x_2, Q^2) \right. \left. + \sum_{i,j \in Q, i} H_{ij}^V C_f^i (q_i, q_j) \Delta q_V(x) \left[ F^A_{i,j} (x_1, Q^2) F^B_j (x_2, Q^2) + F^A_{i,j} (x_1, Q^2) F^B_j (x_2, Q^2) \right] \right\},$$

$$H_{ij}^V = \frac{8 \pi G_F}{\sqrt{2}} \left( g_i^V \right)^2 = \frac{2 \pi G_F m_W^2}{\sqrt{2}},$$

$$G_F = 1.16639 \times 10^{-5} \text{ GeV}^{-2}$$

Shadowing effects clearest in rapidity distributions

We use MRST HO central gluon and set $Q = m_V$

To study scale dependence, we also take $Q = m_V/2$ and $2m_V$

Universal $\mathcal{O}(\alpha_s \alpha^2)$ Corrections to the LO $\mathcal{O}(\alpha^2)$ Cross Sections

$$\Delta_{qV}(x) = \delta(1 - x) + \frac{\alpha_s}{3 \pi} \left\{ -4(1 + x) \ln \left( \frac{Q^2}{m_W^2} \right) - 8(1 + x) \ln(1 - x) - 4 \ln(1 + x) \ln x \right. \left. + \delta(1 - x) \left[ 6 \ln \left( \frac{Q^2}{m_W^2} \right) + 8 \zeta(2) - 16 \right] + 8 \mathcal{D}_0(x) \ln \left( \frac{Q^2}{m_W^2} \right) + 16 \mathcal{D}_1(x) \right\}. \right.$$
$Z^0$ Production: Convolution of Shadowing Functions with Parton Densities

$qq \to Z^0 X$

$$\sum_{i,j=0QQ} \delta_i^2(A,x_1)S_i(A,x_1)S_j^*(A,x_2)f_W^n_i(x_1,Q^2)f_W^n_j(x_2,Q^2)C^2(q_i,q_j)[(g'_i)^2 + (g'_j)^2]$$

$$= \frac{1}{8}[1-\frac{8}{3}x_W+\frac{8}{9}x_W^2] \{ S_i(A,x_1)S_j^*(A,x_2) \{ ZAF_i^n(x_1,Q^2) + NAF_i^n(x_1,Q^2) \}$$

$$+ \{ ZAF_j^n(x_2,Q^2) + NAF_j^n(x_2,Q^2) \} + 2ABS_i^*(A,x_1)S_j^*(A,x_2)f_W^i(x_1,Q^2)f_W^j(x_2,Q^2) \}$$

$$+ \frac{1}{8}[1-\frac{4}{3}x_W+\frac{8}{9}x_W^2] \{ S_i(A,x_1)S_j^*(B,x_2) \{ ZAF_i^n(x_1,Q^2) + NAF_i^n(x_1,Q^2) \}$$

$$+ \{ ZAF_j^n(x_2,Q^2) + NAF_j^n(x_2,Q^2) \} + 2ABS_i^*(A,x_1)S_j^*(B,x_2)f_W^i(x_1,Q^2)f_W^j(x_2,Q^2) \}$$

$$+ [z_1 \leftrightarrow x_3, A \leftrightarrow B] .$$

$q\bar{q}\to Z^0 X$

$$\sum_{i,j=0QQ} \delta_i^2(A,x_1)S_i^*(A,x_1)S_j^*(B,x_2)f_W^n_i(x_1,Q^2)f_W^n_j(x_2,Q^2)$$

$$+ [z_1 \leftrightarrow x_3, A \leftrightarrow B]C_i^2(q_i,q_j)[(g'_i)^2 + (g'_j)^2]$$

$$= BS_i^1(B,x_2)f_W^n(x_2,Q^2)$$

$$+ \frac{1}{8}[1-\frac{8}{3}x_W+\frac{32}{9}x_W^2] \{ S_i(A,x_1) \{ ZAF_i^n(x_1,Q^2) + NAF_i^n(x_1,Q^2) \}$$

$$+ S_i^2(A,x_1) \{ ZAF_i^n(x_2,Q^2) + NAF_i^n(x_2,Q^2) \} + 2AS_i^*(A,x_1)f_W^i(x_1,Q^2) \}$$

$$+ \frac{1}{8}[1-\frac{4}{3}x_W+\frac{8}{9}x_W^2] \{ S_i(A,x_1) \{ ZAF_i^n(x_1,Q^2) + NAF_i^n(x_1,Q^2) \}$$

$$+ S_i^2(A,x_1) \{ ZAF_i^n(x_2,Q^2) + NAF_i^n(x_2,Q^2) \} + 2AS_i^*(A,x_1)f_W^i(x_1,Q^2) \}$$

$$+ [z_1 \leftrightarrow x_3, A \leftrightarrow B] .$$

Figure 8: The $Z^0$ rapidity distributions in $pp$ collisions at 5.5 (solid) and 14 TeV (dashed), calculated with the MRST HO distributions.
**Z^0 Distributions in Pbp and pPb Collisions at 5.5 TeV**

Small isospin effects on Z^0 production

![Graph showing Z^0 distributions in Pbp and pPb collisions at 5.5 TeV.](image)

**Shadowing Effects on Z^0 Production in Pbp and pPb Collisions at 5.5 TeV**

In Pbp collisions, \( x_1 \) is in nucleus, \( x_1 \) increases with \( y \) into antishadowing and Fermi motion region, ratio increases.

In pPb collisions, \( x_2 \) in nucleus, goes into shadowing region, ratio decreases.

![Graph showing shadowing effects on Z^0 production in Pbp and pPb collisions at 5.5 TeV.](image)
Model Dependence of Shadowing on $Z^0$ Production in Pb$p$ Collisions

Compare EKS98, HPC, and HKM (LO only)

Stronger HKM antishadowing at large $y$ because of increasing $q_S$ with $x_1$ and weaker $q_V$ shadowing

![Graph](image1)

Figure 10: Ratios of shadowed to unshadowed $Z^0$ rapidity distributions in Pb$p$ collisions at 5.5 TeV using the EKS98 (solid), HPC (dashed) and HKM (dot-dashed) shadowing parameterizations.

Model Dependence of Shadowing on $Z^0$ Production in pPb Collisions

HKM shadowing almost independent of $x_2$ due to weaker sea quark shadowing

HPC has stronger shadowing at low $x_2$ because it has no $Q^2$ evolution

![Graph](image2)

Figure 11: Ratios of shadowed to unshadowed $Z^0$ rapidity distributions in pPb collisions at 5.5 TeV using the EKS98 (solid), HPC (dashed) and HKM (dot-dashed) shadowing parameterizations.
Scale Dependence of Shadowing on $Z^0$ Production in Pbp Collisions

Results above $Q = 2m_\gamma$ are unreliable because EKS98 only evolved to 100 GeV

Decreasing scale increases shadowing because evolution reduced

![Graph showing scale dependence of shadowing on Z^0 production in Pbp collisions.]

Figure 12: Ratios of shadowed to unshadowed $Z^0$ rapidity distributions in Pbp collisions at 5.5 TeV using the EKS98 parameterization. The curves show $Q = m_\gamma$ (solid), $m_\gamma/2$ (dashed) and $2m_\gamma$.

Scale Dependence of Shadowing on $Z^0$ Production in pPb Collisions

Evolution of shadowing stronger when Pb is target because shadowing affects sea quarks more strongly at low $x_2$

![Graph showing scale dependence of shadowing on Z^0 production in pPb collisions.]

Figure 13: Ratios of shadowed to unshadowed $Z^0$ rapidity distributions in pPb collisions at 5.5 TeV using the EKS98 parameterization. The curves show $Q = m_\gamma$ (solid), $m_\gamma/2$ (dashed) and $2m_\gamma$. 
$Z^0$ Production Ratios Pb$p/\bar{p}p$ and $pPb/\bar{p}p$ at 5.5 TeV

Ratios without shadowing show isospin effect, small for $Z^0$

Thus ratios with shadowing look like shadowed/unshadowed ratios

$q\bar{q} \rightarrow W^+X$

$$\sum_{i,\alpha \in \{Q, \bar{Q}\}} S^i(A, x_1) S^j(B, x_2) f^i_{\alpha}(x_1, Q^2) f^j_{\alpha}(x_2, Q^2) C^i_{\alpha}(q, \bar{q})$$

$$= \cos^2 \theta_C \left( S^A(A, x_1) S^B(B, x_2) \left\{ Z_A f^A_{\alpha}(x_1, Q^2) + N_A f^A_{\alpha}(x_1, Q^2) \right\} \right.$$  

$$\times \left\{ Z_B f^B_{\alpha}(x_2, Q^2) + N_B f^B_{\alpha}(x_2, Q^2) \right\} + A B S^A(A, x_1) S^B(B, x_2) f^A_{\alpha}(x_1, Q^2) f^B_{\alpha}(x_2, Q^2)$$

$$+ \sin^2 \theta_C \left( S^A(A, x_1) S^B(B, x_2) \left\{ Z_A f^A_{\alpha}(x_1, Q^2) + N_A f^A_{\alpha}(x_1, Q^2) \right\} B f^B_{\alpha}(x_2, Q^2)$$

$$+ S^A(A, x_1) S^B(B, x_2) \left\{ Z_A f^A_{\alpha}(x_1, Q^2) + N_A f^A_{\alpha}(x_1, Q^2) \right\} B f^B_{\alpha}(x_2, Q^2) \right\}$$

$$+ [x_1 \leftrightarrow x_2, A \leftrightarrow B] .$$

$qg \rightarrow W^+X$

$$\sum_{i,\alpha \in \{Q, \bar{Q}\}} S^i(A, x_1) S^j(B, x_2) f^i_{\alpha}(x_1, Q^2) f^j_{\alpha}(x_2, Q^2) + [x_1 \leftrightarrow x_2, A \leftrightarrow B] \right\} C^i_{\beta}(q, g_k)$$

$$= B S^A(B, x_2) f^B_{\alpha}(x_2, Q^2) \left[ S^A(A, x_1) \left\{ Z_A f^A_{\alpha}(x_1, Q^2) + N_A f^A_{\alpha}(x_1, Q^2) \right\} \right.$$  

$$+ S^A(A, x_1) \left\{ Z_B f^B_{\alpha}(x_2, Q^2) + N_B f^B_{\alpha}(x_2, Q^2) \right\} + A \left\{ S^B(B, x_2) f^B_{\alpha}(x_2, Q^2) + S^A(A, x_1) f^B_{\alpha}(x_2, Q^2) \right\} + [x_1 \leftrightarrow x_2, A \leftrightarrow B] .$$

Figure 1.4: The ratio of Pb$p/\bar{p}p$ with (solid) and without (dot-dashed) shadowing and pPb/$\bar{p}p$ with (dashed) and without (dotted) shadowing at 5.5 TeV.
$W^+$ Distributions in $pp$ Collisions at 5.5 and 14 TeV

$pp$ cross sections increase with $y$ due to dominance of $u_p(x_1)d_p(x_2)$ contribution, $u_{Vp}(x_1)$ goes up with $x_1$ while $\bar{d}_p(x_2)$ goes up when $x_2$ decreases, peak at same point as in $u_V$ distribution

![Graph showing $W^+$ distributions in $pp$ collisions at 5.5 and 14 TeV.](image1)

Figure 15: The $W^+$ rapidity distributions in $pp$ collisions at 5.5 (solid) and 14 TeV (dashed), calculated with the MRST HO distributions.

$W^+$ Distributions in Pb$p$ and $p$Pb Collisions at 5.5 TeV

Pb$p$ neutron excess wipes out rise with $y$

$p$Pb, $(N/A)d_p(x_1)d_p(x_2)$ enhances $pA$ because $\bar{d} > u$

![Graph showing $W^+$ distributions in Pb$p$ and $p$Pb collisions at 5.5 TeV.](image2)

Figure 17: The $W^+$ rapidity distributions in Pb$p$ and $p$Pb collisions at 5.5 TeV, calculated with the MRST HO distributions. The solid and dashed curves show the results without and with shadowing respectively with the Pb nucleus coming from the left. The dotted and dashed curves give the results without and with shadowing for the proton coming from the left.
**W⁺ Production Ratios PbP/PP and pPb/PP at 5.5 TeV**

Neutron excess depletes PbP/PP

pPb/PP without shadowing shows a rise due to extra neutrons in Pb (x₂)

\[ \frac{d^2 \sigma}{dy \, dz} \]

**W⁻ Production: Convolution of Shadowing Functions with Parton Densities**

\[ q\bar{q} \rightarrow W⁻X \]

\[ \sum_{i,j=QQ} S_i^i(A, x_1) S_j^j(B, x_2) f_{q_i}^i(x_1, Q^2) f_{\bar{q}_j}^j(x_2, Q^2) C_i^j(q_i, \bar{q}_j) \]

\[ = \cos^2 \theta_C \left( S_i^i(A, x_1) S_j^j(B, x_2) \left[ Z_A f_0^i(x_1, Q^2) + N_A f_1^i(x_1, Q^2) \right] \right) \]

\[ \times \left[ Z_B f_0^j(x_2, Q^2) + N_B f_1^j(x_2, Q^2) \right] + ABS_i^i(A, x_1) S_j^j(B, x_2) f_0^i(x_1, Q^2) f_0^j(x_2, Q^2) \]

\[ + \sin^2 \theta_C \left( S_i^i(A, x_1) S_j^j(B, x_2) \left[ Z_A f_0^i(x_1, Q^2) + N_A f_1^i(x_1, Q^2) \right] B f_0^j(x_2, Q^2) \right) \]

\[ + S_i^i(A, x_1) S_j^j(B, x_2) \left[ Z_A f_0^i(x_1, Q^2) + N_A f_1^i(x_1, Q^2) \right] B f_0^j(x_2, Q^2) \]

\[ + [x_1 \leftrightarrow x_2, A \leftrightarrow B]. \]

\[ g(q)g \rightarrow W⁻X \]

\[ \sum_{i,k=QQ} \left( S_i^i(A, x_1) S_k^k(B, x_2) f_{q_i}^i(x_1, Q^2) f_{g_k}^k(x_2, Q^2) + [x_1 \leftrightarrow x_2, A \leftrightarrow B] \right) C_i^k(q_i, g_k) \]

\[ = BS_i^i(B, x_2) f_0^i(x_2, Q^2) S_k^k(A, x_1) \left[ Z_A f_0^i(x_1, Q^2) + N_A f_1^i(x_1, Q^2) \right] \]

\[ + S_i^i(A, x_1) \left[ Z_B f_0^i(x_2, Q^2) + N_B f_1^i(x_2, Q^2) \right] A \left[ S_k^k(A, x_1) f_0^k(x_1, Q^2) + S_k^k(A, x_1) f_0^k(x_1, Q^2) \right] \]

\[ + [x_1 \leftrightarrow x_2, A \leftrightarrow B]. \]

Figure 19: The ratios of PbP/PP with (solid) and without (dot-dashed) shadowing and pPb/PP with (dashed) and without (dotted) shadowing at 5.5 TeV.
$W^-$ Distributions in $pp$ Collisions at 5.5 and 14 TeV

$W^-$ decreases with $y$ because valence $d$ has smaller $x$

![Graph of $W^-$ distributions in $pp$ collisions at 5.5 and 14 TeV](image)

Figure 20: The $W^-$ rapidity distributions in $pp$ collisions at 5.5 (solid) and 14 TeV (dashed), calculated with the MRST HO distributions.

$W^-$ Distributions in Pb$p$ and $p$Pb Collisions at 5.5 TeV

Neutron excess in Pb enhances Pb$p$ at large $y$ ($(N/A)u_p(x_1)\bar{u}_p(x_2)$)

$p$Pb has smaller isospin effect

![Graph of $W^-$ distributions in Pb$p$ and $p$Pb collisions at 5.5 TeV](image)

Figure 22: The $W^-$ rapidity distributions in Pb$p$ and $p$Pb collisions at 5.5 TeV, calculated with the MRST HO distributions. The solid and dashed curves show the results without and with shadowing respectively with the Pb nucleus coming from the left. The dotted and dashed curves give the results without and with shadowing for the proton coming from the left.
$W^-$ Production Ratios $\text{PbP}/pp$ and $\text{pPb}/pp$ at 5.5 TeV

$\text{PbP}/pp$ enhanced by neutron excess

$\text{pPb}/pp$ shows small depletion with $y$

Figure 24: The ratios of $\text{PbP}/pp$ with (solid) and without (dot-dashed) shadowing and $\text{pPb}/pp$ with (dashed) and without (dotted) shadowing at 5.5 TeV.