Neutron skin at the LHC - the case of $W^\pm$ production

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The centrality categorization at the LHC is typically based on energy deposit at $|\eta| \gg 0$

- In Pb-Pb e.g. the appearance of angular anisotropies supports this.
- In p-Pb this has led to very counterintuitive results — similar issues found in d-Au at RHIC.

Model-independent ways to verify/benchmark the methods used for centrality determination would be welcome.

⇒ An idea: Make use of the mutually different spatial distribution of protons and neutrons inside the nuclei - the neutron skin effect.
Spherical, neutron-rich nucleus as a 1-D potential well:

- Green line: potential for neutrons
- Red dashed line: potential for protons

The Coulomb repulsion turns potential repulsive for protons.

Neutron-to-proton ratio increases here.
Measurement suggests a halo-like neutron skin for $^{208}\text{Pb}$

Ratio of proton and neutron densities, $\rho_{p,A}(|r|)/\rho_{n,A}(|r|)$:
In A-A, the hard-process cross sections are computed as

\[ d\sigma_{AA}^{\text{hard}}(C_k) = 2\pi \int_{b_k}^{b_{k+1}} dbb \int_{-\infty}^{\infty} d^2s \sum_{i,j} T_A^i(s_1) T_A^j(s_2) \ d\sigma_{ij}^{\text{hard}}(A, s_1, s_2) \]

where

\[ T_A^i(r) \equiv \int_{-\infty}^{\infty} dz \rho_{i,A}^i(r, z), \quad s_1, 2 \equiv s \pm b/2. \]
Define effective number of protons $Z_{\text{eff}}(C_k)$ and neutrons $N_{\text{eff}}(C_k)$:

$Z_{\text{eff}}(C_k) \equiv \left[ 2\pi \int_{b_k}^{b_{k+1}} dbb \int_{-\infty}^{\infty} d^2s \; T_p^p(s_1) T_p^p(s_2) \right]^{1/2} \xrightarrow{\text{min. bias}} Z(=82)$

$N_{\text{eff}}(C_k) \equiv \left[ 2\pi \int_{b_k}^{b_{k+1}} dbb \int_{-\infty}^{\infty} d^2s \; T_n^n(s_1) T_n^n(s_2) \right]^{1/2} \xrightarrow{\text{min. bias}} N(=126)$

\[
\begin{align*}
\frac{d\sigma_{AA}^\text{hard}}{d\sigma_{PP}^\text{hard}}(A, C_k) &\approx Z_{\text{eff}}^2(C_k) \times d\sigma_{pp}^\text{hard}(A, C_k) + N_{\text{eff}}^2(C_k) \times d\sigma_{nn}^\text{hard}(A, C_k) \\
&\quad + 2Z_{\text{eff}}(C_k) N_{\text{eff}}(C_k) \times d\sigma_{pn}^\text{hard}(A, C_k)
\end{align*}
\]

“Collisions of nuclei consisting of $Z_{\text{eff}}$ protons and $N_{\text{eff}}$ neutrons”
In p-A, the hard-process cross sections are computed as

\[ d\sigma_{pA}^{\text{hard}}(C_k) = 2\pi \int_{b_k}^{b_{k+1}}dbb \sum_j T_j^A(b) \]

Define effective number of protons \( Z_{\text{eff}}(C_k) \) and neutrons \( N_{\text{eff}}(C_k) \):

\[ Z_{\text{eff}}(C_k) \equiv 2\pi \int_{b_k}^{b_{k+1}}dbb T_A^P(b) \xrightarrow{\text{min.bias}} 82 \]

\[ N_{\text{eff}}(C_k) \equiv 2\pi \int_{b_k}^{b_{k+1}}dbb T_A^n(b) \xrightarrow{\text{min.bias}} 126 \]

"The proton sees a nucleus of \( Z_{\text{eff}} \) protons and \( N_{\text{eff}} \) neutrons"
The ratio $Z_{\text{eff}}(C_k)/N_{\text{eff}}(C_k)$ as a function of centrality

Need rather peripheral events to see the effect
If the nuclear effects (shadowing etc.) are not important, we can account for the centrality dependence by defining the PDFs by

\[ f_{i}^{Pb,C_k}(x, Q^2) \equiv Z_{\text{eff}}(C_k) f_{i}^{p}(x, Q^2) + N_{\text{eff}}(C_k) f_{i}^{n}(x, Q^2), \]

where \( f_{i}^{p} \) and \( f_{i}^{n} \) are proton and neutron PDFs.

We consider the inclusive \( W^{\pm} \) production

\[ H_1 + H_2 \rightarrow W^- + X \rightarrow \ell^- + \bar{\nu} + X, \]
\[ H_1 + H_2 \rightarrow W^+ + X \rightarrow \ell^+ + \nu + X, \]

To minimize uncertainties (theory & experiment), we take ratios

\[ \frac{d\sigma(\ell^+)}{d\sigma(\ell^-)} \]

which we compute by MCFM at NLO accuracy.
Predictions for p-Pb and Pb-Pb

Results for the ratios

\[
\left[ \frac{d\sigma(\ell^+)/d\sigma(\ell^-)}{d\sigma(\ell^+)/d\sigma(\ell^-)} \right]_{\text{peripheral}} / \left[ \frac{d\sigma(\ell^+)/d\sigma(\ell^-)}{d\sigma(\ell^+)/d\sigma(\ell^-)} \right]_{\text{min.bias}}
\]

At small \( x \), \( f_i^p \approx f_i^n \), but at high \( x \), \( f_i^p \neq f_i^n \)

\( \Rightarrow \) Largest effects when valence quarks are important

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Comparison to ATLAS Pb-Pb data


\[
\left[ \frac{d\sigma(\ell^+) / d\sigma(\ell^-)}{d\sigma(\ell^+) / d\sigma(\ell^-)} \right]_{C_k} / \left[ \frac{d\sigma(\ell^+) / d\sigma(\ell^-)}{d\sigma(\ell^+) / d\sigma(\ell^-)} \right]_{0-80}\%
\]

The most peripheral class still “too central” to see the effects

\[\text{Need a tighter binning in centrality}\]
Proton and neutron densities are mutually different in nuclei.

The relative amount of produced $W^+$ and $W^-$ bosons should correlate with the centrality of p-Pb and Pb-Pb collisions.

Could verify/benchmark the centrality measures.

The effects most pronounced in forward/backward directions (need to pick a valence quark from a nucleus).

Other sensitive observables at hadron colliders are isolated photons and $h^+/h^-$ ratio (I. Helenius in DIS2016).

These could also be measured at RHIC.

At an electron-ion collider e.g. neutral- and charged-current xsecs should have a mutually different centrality dependence.