

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

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IS2016, Lisbon, May 24.

Reference: H.Paukkunen, Phys.Lett.B745 (2015) 73–78

# Introduction - Motivation

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

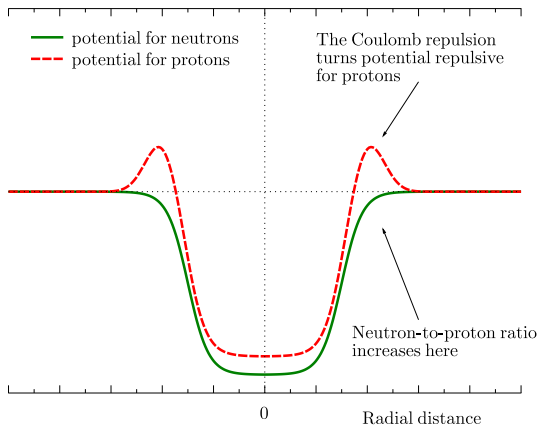
- In Pb-Pb e.g. the appearance of angular anisotropies supports this.
- In p-Pb this has led to very counterintuitive results — similar issues found in d-Au at RHIC.

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.

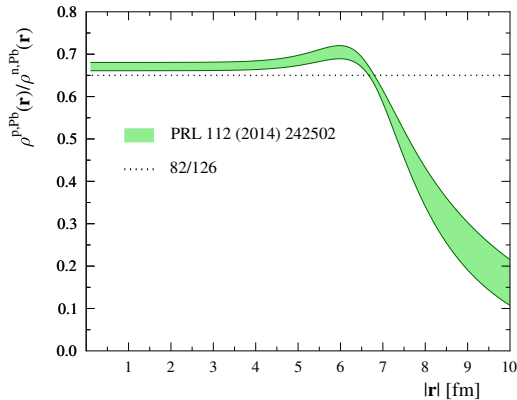
# Origin of the neutron skin

Spherical, neutron-rich nucleus as a 1-D potential well:



# Measurement suggests a halo-like neutron skin for $^{208}\text{Pb}$

Ratio of proton and neutron densities,  $\rho^{p,A}(|\mathbf{r}|)/\rho^{n,A}(|\mathbf{r}|)$ :



# Framework in A-A

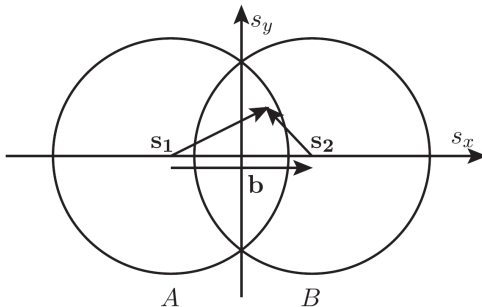
In A-A, the hard-process cross sections are computed as

$$d\sigma_{AA}^{\text{hard}}(C_k) = \underbrace{2\pi \int_{b_k}^{b_{k+1}} db b \int_{-\infty}^{\infty} d^2\mathbf{s} \sum_{i,j} T_A^i(\mathbf{s}_1) T_A^j(\mathbf{s}_2)}_{\text{"nucleon-nucleon luminosity''}} \underbrace{d\sigma_{ij}^{\text{hard}}(A, \mathbf{s}_1, \mathbf{s}_2)}_{\text{nucleon-nucleon xsec}}$$

where

$$T_A^i(\mathbf{r}) \equiv \int_{-\infty}^{\infty} dz \rho^{i,A}(\mathbf{r}, z), \quad \mathbf{s}_{1,2} \equiv \mathbf{s} \pm \mathbf{b}/2.$$

Fig. from JHEP 1207 (2012) 073



Define effective number of protons  $Z_{\text{eff}}(\mathcal{C}_k)$  and neutrons  $N_{\text{eff}}(\mathcal{C}_k)$ :

$$Z_{\text{eff}}(\mathcal{C}_k) \equiv \left[ 2\pi \int_{b_k}^{b_{k+1}} db b \int_{-\infty}^{\infty} d^2\mathbf{s} T_A^p(\mathbf{s}_1) T_A^p(\mathbf{s}_2) \right]^{1/2} \xrightarrow{\text{min.bias}} Z(=82)$$

$$N_{\text{eff}}(\mathcal{C}_k) \equiv \left[ 2\pi \int_{b_k}^{b_{k+1}} db b \int_{-\infty}^{\infty} d^2\mathbf{s} T_A^n(\mathbf{s}_1) T_A^n(\mathbf{s}_2) \right]^{1/2} \xrightarrow{\text{min.bias}} N(=126)$$

$\Rightarrow$

$$\begin{aligned} d\sigma_{AA}^{\text{hard}}(\mathcal{C}_k) &\approx Z_{\text{eff}}^2(\mathcal{C}_k) \times d\sigma_{pp}^{\text{hard}}(A, \mathcal{C}_k) + N_{\text{eff}}^2(\mathcal{C}_k) \times d\sigma_{nn}^{\text{hard}}(A, \mathcal{C}_k) \\ &\quad + 2Z_{\text{eff}}(\mathcal{C}_k)N_{\text{eff}}(\mathcal{C}_k) \times d\sigma_{pn}^{\text{hard}}(A, \mathcal{C}_k) \end{aligned}$$

“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

$$d\sigma_{pA}^{\text{hard}}(\mathcal{C}_k) = \underbrace{2\pi \int_{b_k}^{b_{k+1}} db b \sum_j T_A^j(b)}_{\text{amount of nucleons}} \underbrace{d\sigma_{pj}^{\text{hard}}(A, b)}_{\text{proton-nucleon xsec}}$$

Define effective number of protons  $Z_{\text{eff}}(\mathcal{C}_k)$  and neutrons  $N_{\text{eff}}(\mathcal{C}_k)$ :

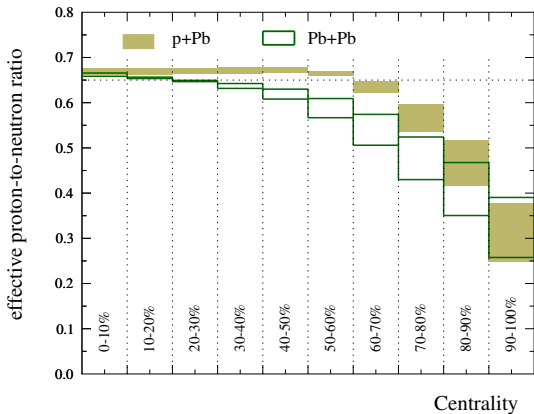
$$Z_{\text{eff}}(\mathcal{C}_k) \equiv 2\pi \int_{b_k}^{b_{k+1}} db b T_A^p(b) \xrightarrow{\text{min.bias}} Z(= 82)$$

$$N_{\text{eff}}(\mathcal{C}_k) \equiv 2\pi \int_{b_k}^{b_{k+1}} db b T_A^n(b) \xrightarrow{\text{min.bias}} N(= 126)$$

“The proton sees a nucleus of  $Z_{\text{eff}}$  protons and  $N_{\text{eff}}$  neutrons”

# The ratio $Z_{\text{eff}}(C_k)/N_{\text{eff}}(C_k)$

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

# Application to $W^\pm$ production

If the nuclear effects (shadowing etc.) are not important, we can account for the centrality dependence by defining the PDFs by

$$f_i^{\text{Pb}, \mathcal{C}_k}(x, Q^2) \equiv Z_{\text{eff}}(\mathcal{C}_k) f_i^{\text{p}}(x, Q^2) + N_{\text{eff}}(\mathcal{C}_k) f_i^{\text{n}}(x, Q^2),$$

where  $f_i^{\text{p}}$  and  $f_i^{\text{n}}$  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

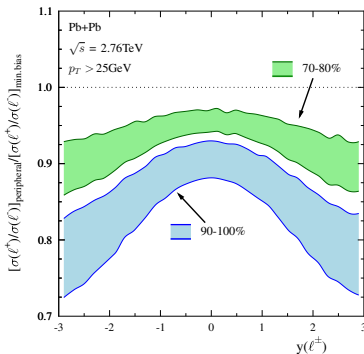
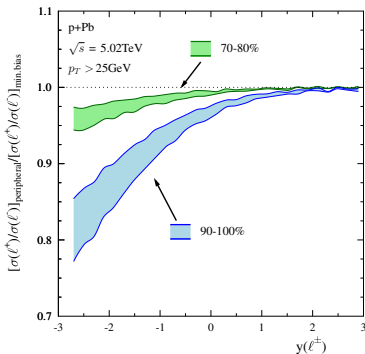
$$d\sigma(\ell^+)/d\sigma(\ell^-)$$

which we compute by MCFM at NLO accuracy.

# Predictions for p-Pb and Pb-Pb

## Results for the ratios

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



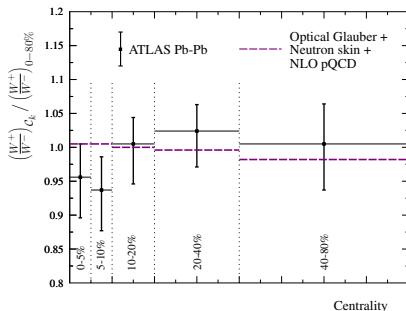
At small  $x$ ,  $f_i^p \approx f_i^n$ , but at high  $x$ ,  $f_i^p \neq f_i^n$

⇒ Largest effects when valence quarks are important

# Comparison to ATLAS Pb-Pb data

Measurement by ATLAS [Eur.Phys.J. C75 (2015) no.1, 23]

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



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

⇒ 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.  
 $\Rightarrow$  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).  
 $\Rightarrow$  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.