Neutron-skin effect and centrality dependence of high-p_T observables in nuclear collisions

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Outline

1. Introduction
   - Neutron-skin effect
2. Framework
   - Centrality classification
   - Spatially dependent nuclear PDFs
3. Results for $\mathrm{Pb}+\mathrm{Pb}$ at the LHC
   - Direct photons
   - Charged hadrons [I.H., H. Paukkunen, K.J. Eskola, *Work in progress*]
   - $W^{\pm}$ production [H. Paukkunen, Phys.Lett. B745 (2015) 73-78]
4. Summary & Conclusions

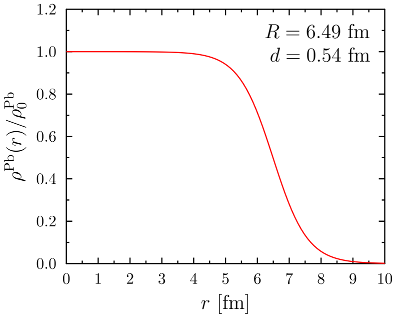
Introduction

Nuclear density

- 2-parameter Woods-Saxon

$$\rho_i^A(r) = \frac{\rho_0^A}{1 + \exp[\frac{r - R_i}{d_i}]}$$

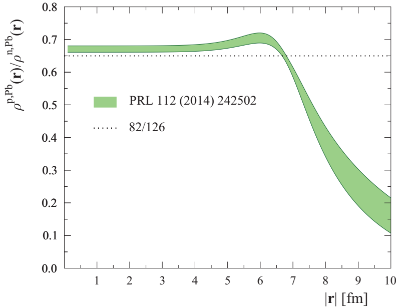
  - R_i = nuclear radius
  - d_i = thickness of the surface



Neutron-skin effect

- Tail of neutrons extends farther
- We use parameters [C.M. Tarbert *et al.*, PRL 112 (2014) 24, 242502]
  - $R_p = 6.680$ fm, $R_n = 6.70 \pm 0.03$ fm
  - $d_p = 0.447$ fm, $d_n = 0.55 \pm 0.03$ fm

$\Rightarrow$ Modification for EM-sensitive observables in peripheral collisions

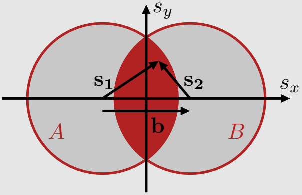


Centrality classification

Optical Glauber model

- Total inelastic cross section in $A{+}B$ collision at given $\sqrt{s}$

$$\sigma_{AB}^{\mathrm{inel}}(s) = \int \mathrm{d}^2\mathbf{b} \left[1 - \mathrm{e}^{-T_{AB}(\mathrm{b})\,\sigma_{NN}^{\mathrm{inel}}(s)}\right]$$



- Where nuclear overlap function

$$T_{AB}(\mathrm{b}) = \int \mathrm{d}^2\mathbf{s}\left[T_p^A(\mathbf{s_1}) + T_n^A(\mathbf{s_1})\right]\left[T_p^B(\mathbf{s_2}) + T_n^B(\mathbf{s_2})\right]$$

with $T_i^A(\mathbf{r}) = \int \mathrm{d}z \rho_i^A(z, \mathbf{r})$

- Centrality classes defined as impact-parameter intervals requiring

$$(c_{k+1} - c_k)\,\% = \frac{1}{\sigma_{AB}^{\mathrm{inel}}} \int_{b_k}^{b_{k+1}} \mathrm{d}b\, 2\pi b \left[1 - \mathrm{e}^{-T_{AB}(\mathrm{b})\,\sigma_{NN}^{\mathrm{inel}}(s)}\right]$$

Hard process cross section

Hard process cross section in given centrality bin $\mathcal{C}_k$

$$\mathrm{d}\sigma_{AB}^{\mathrm{hard}}(\mathcal{C}_k) = 2\pi \int_{b_k}^{b_{k+1}} \mathrm{d}b\, b \int \mathrm{d}^2\mathbf{s} \sum_{i,j} T_A^i(\mathbf{s_1}) T_B^j(\mathbf{s_2}) \mathrm{d}\sigma_{ij}^{\mathrm{hard}}(A, B, \mathbf{s_1}, \mathbf{s_2})$$

where $i, j = \mathrm{p}, \mathrm{n}$

Differential cross section

- Factorize the spatial dependence to nuclear PDFs (nPDFs)
$$\mathrm{d}\sigma_{ij}^{\mathrm{hard}}(A, B, \mathbf{s_1}, \mathbf{s_2}) = \sum_{k,l} f_k^{i/A}(x_1, Q^2, \mathbf{s_1}) \otimes f_l^{j/B}(x_2, Q^2, \mathbf{s_2}) \otimes \mathrm{d}\hat{\sigma}_{ij}^{kl \to X}$$
- The nPDFs can be decomposed as
$$f_k^{i/A}(x, Q^2, \mathbf{s}) = r_k^{i/A}(x, Q^2, \mathbf{s}) f_k^i(x, Q^2)$$
- We use spatially dependent `EPS09s` nuclear modifications satisfying
$$R_k^{i/A}(x, Q^2) = \frac{1}{A} \int \mathrm{d}^2\mathbf{s}\, T_A^i(\mathbf{s}) r_k^{i/A}(x, Q^2, \mathbf{s})$$

Two competing effects

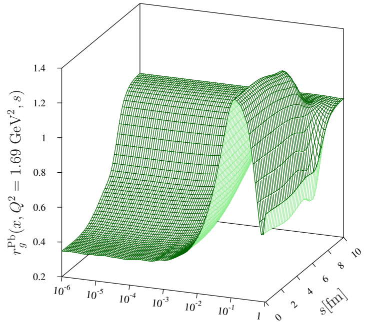
Spatially dependent nPDFs

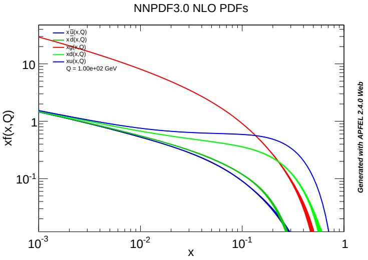
- Smaller nuclear effects in peripheral collisions
- Enhancement or suppression depending on x

Neutron skin (NS)

- More neutrons at large s
  $\Rightarrow\ f_{\mathrm{u}}(x,Q^2)/f_{\mathrm{d}}(x,Q^2)$
  decrease with centrality
- Effect more pronounced at large x

- Goal: Study which observables would be sensitive to NS effect



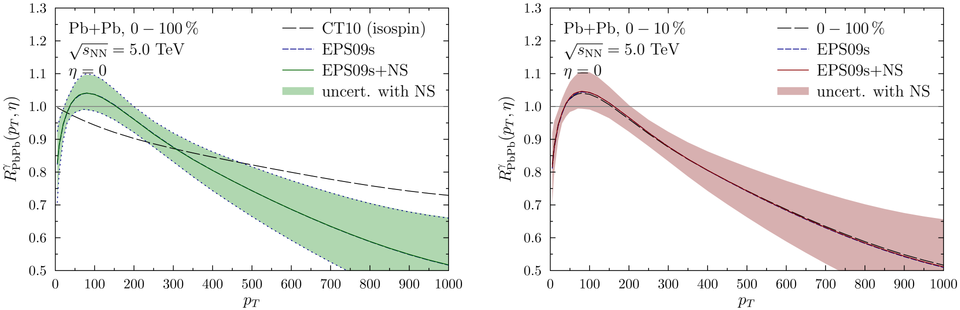


Direct photons

Nuclear modification factor

$$R^{\gamma}_{\mathrm{PbPb}}(\mathcal{C}_k) = \frac{1}{\langle T_{\mathrm{PbPb}}(\mathcal{C}_k)\rangle} \frac{\mathrm{d}\sigma^{\gamma}_{\mathrm{PbPb}}(\mathcal{C}_k)}{\mathrm{d}p_T \mathrm{d}\eta} \Bigg/ \frac{\mathrm{d}\sigma^{\gamma}_{\mathrm{pp}}}{\mathrm{d}p_T \mathrm{d}\eta}$$

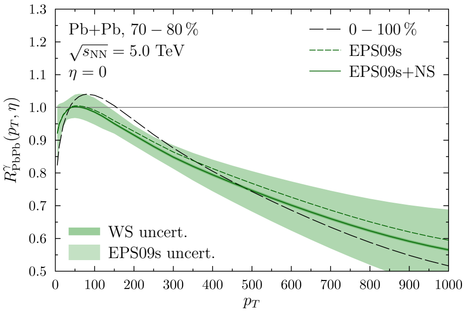
- Cross sections calculated in NLO using `INCNLO` with `BFGII` photon FFs and `CT10` PDFs together with `EPS09s` nuclear modifications

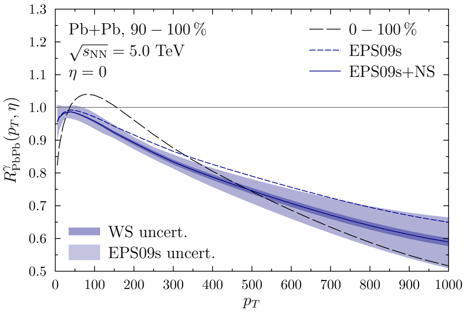


- Neutron-skin (NS) effect does nothing for MB and central events
- Very small difference between central and MB $R^{\gamma}_{\mathrm{PbPb}}$

Direct photons

- Look for more peripheral events: $70-80\,\%$ and $90-100\,\%$





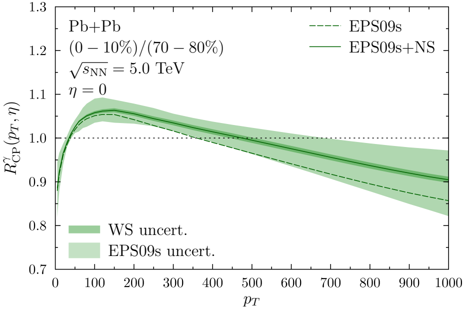
- Need high-p_T ($\gtrsim 300$ GeV/c) (large x) to see the neutron-skin effect
- Need also very peripheral events
- At high-p_T nPDFs and NS have opposite effects vs. centrality
- nPDF uncertainties larger than the uncertainty in WS parametrization

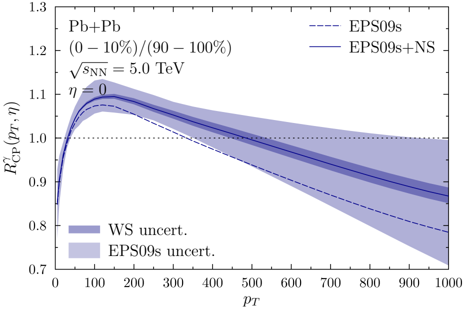
Direct photons

Central-to-peripheral ratio

$$R_{CP} = \frac{\langle T_{\rm PbPb}(P)\rangle}{\langle T_{\rm PbPb}(C)\rangle} \frac{{\rm d}\sigma^{\gamma}_{\rm PbPb}(C)}{{\rm d}p_T{\rm d}\eta} \Bigg/ \frac{{\rm d}\sigma^{\gamma}_{\rm PbPb}(P)}{{\rm d}p_T{\rm d}\eta}$$

- Some uncertainties cancel out





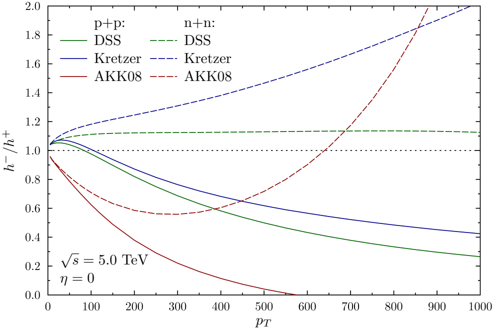
- Still the nPDF-originating uncertainties larger than neutron-skin effect
- Look for observable where the nPDFs cancel out

Charged hadrons

Ratio between negatively and positively charged hadrons

$$\frac{h^-}{h^+}(\mathcal{C}_k) = \frac{\mathrm{d}\sigma^{h^-}_{\mathrm{PbPb}}(\mathcal{C}_k)}{\mathrm{d}p_T\mathrm{d}\eta} \Bigg/ \frac{\mathrm{d}\sigma^{h^+}_{\mathrm{PbPb}}(\mathcal{C}_k)}{\mathrm{d}p_T\mathrm{d}\eta}$$

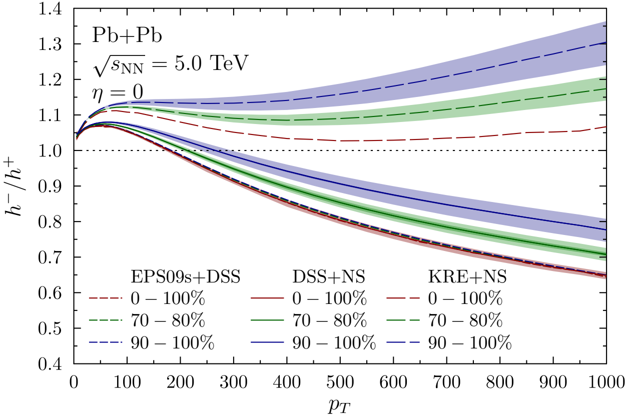
- Hadronization using fragmentation functions (FFs)
- No final state effects for the ratio (flavour independent energy loss)
  Motivated by unmodified K/π and p/π ratios [PRC 93 (2016) 034913]



- Large differences between different FFs
  $\Rightarrow$ Additional uncertainty
- p+p measurement would further constrain FFs
- Negative cross section with `AKK08`, not used here

Charged hadrons

- h^-/h^+ in different centralities at $\mathrm{Pb{+}Pb}$

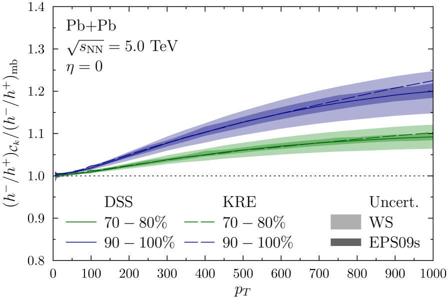


- nPDF effects cancel out
- Dominant uncertainties from WS-parametrization (no normalization with $\langle T_{\mathrm{PbPb}}(\mathcal{C}_k)\rangle$)
- Large differences between different FFs

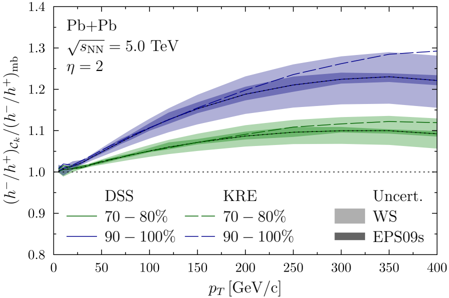
Charged hadrons

- Normalize with minimum bias h^-/h^+ (Ratio unity without NS-effect)

Mid-rapidity



Forward rapidity



- FF-dependence cancels almost completely
  $\Rightarrow$ Observable robust against uncertainties in fragmentation
- nPDF-uncertainties remain small
- With $\eta = 2$ NS-effect enhanced at lower p_T

$W^\pm$ production

Production of $l^\pm$ from $W^\pm \to l^\pm\nu$ decays

- Cross section calculated at NLO in pQCD using `MCFM` code with $Q^2 = M_W^2$ and integrate over $p_T^l > 25\ \mathrm{GeV/c}$
- Observable:

$$\frac{\sigma(l^+)}{\sigma(l^-)}(\mathcal{C}_k) = \frac{\mathrm{d}\sigma^{l^+}(\mathcal{C}_k)}{\mathrm{d}y\mathrm{d}p_T} \Bigg/ \frac{\mathrm{d}\sigma^{l^-}(\mathcal{C}_k)}{\mathrm{d}y\mathrm{d}p_T}$$

- Again, nPDF effects (flavour independet) cancel out

$\mathrm{p+Pb}$ collisions

- Asymmetric collisions (here p with $y > 0$)
- Biases in experimental centrality classification

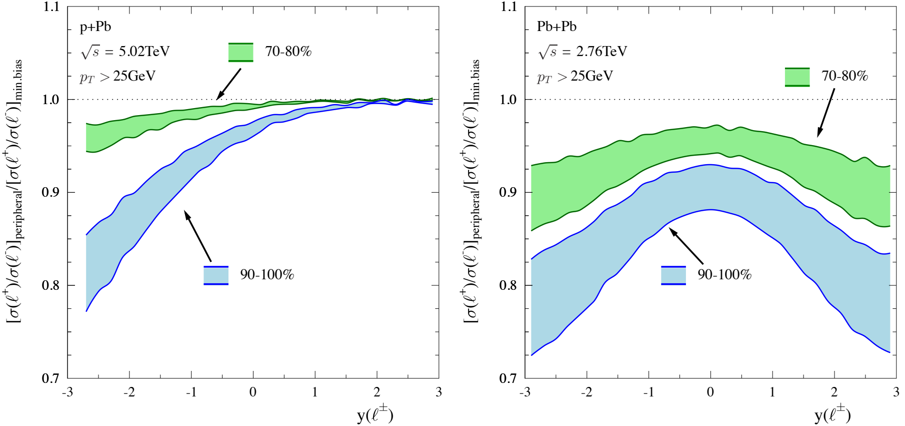
$\mathrm{Pb+Pb}$ collisions

- Symmetric collision
- Centrality classification in better control

$W^{\pm}$ production

- Normalized with $\sigma(l^{+})/\sigma(l^{-})(\mathcal{C}_{\mathrm{MB}})$

[From H. Paukkunen, Phys. Lett. B745 (2015) 73-78]



- Larger effects at large $|y|$ (larger nuclear-x)
- Rather fine centrality binning required
- Use as a benchmark for different centrality definitions at the LHC

Summary

Neutron-skin effect

- Neutron-to-proton ratio grows towards the edge of nucleus
  $\Rightarrow$ Modifications for EM-sensitive observables in peripheral collisions

Direct photon production

- Few percent effects at high-p_T
- Spatially dependent nPDFs complicates the interpretation

Charged hadron production h^-/h^+

- Nuclear PDF effects cancel out
- Some uncertainty due to fragmentation functions – Can be cured by normalizing with MB-result
- Up to 20% effects at the most peripheral bin

Conclusions

$W^{\pm}$ production

- Considered both $\mathrm{p+Pb}$ and $\mathrm{Pb+Pb}$ collisions at the LHC
- Up to 20% effects at large $|y|$

Conclusions

- Neutron-skin effect can produce measurable effects at the LHC
- Could be used to study centrality classification
- Could serve as a handle to study centrality also in DIS
  (Different effects for neutral- and charged-current reactions)

Backup

Model Framework

Nuclear modifications with spatial dependence

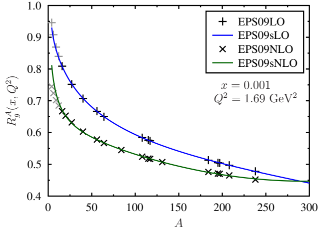
- We replace
$$R_i^A(x,Q^2) \rightarrow r_i^A(x,Q^2,\mathbf{s}),$$
where $\mathbf{s}$ is the transverse position of the nucleon
- Definition
$$R_i^A(x,Q^2) \equiv \frac{1}{A}\int \mathrm{d}^2\mathbf{s}\, T_A(\mathbf{s}) r_i^A(x,Q^2,\mathbf{s}),$$
where $R_i^A(x,Q^2)$ is taken from EKS98 or EPS09 global fits
- Assumption: spatial dependence related to $T_A(\mathbf{s})$ as follows:
$$r_i^A(x,Q^2,\mathbf{s}) = 1 + \sum_{j=1}^{n} c_j^i(x,Q^2)\left[T_A(\mathbf{s})\right]^j$$
- Important: No A-dependence in the fit parameters $c_j(x,Q^2)$

Fitting Procedure

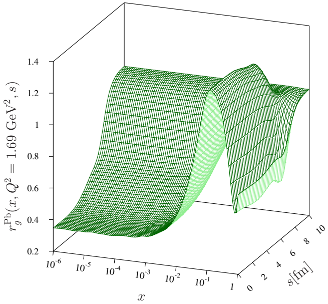
Parameters $c_j(x,Q^2)$ obtained by minimizing the χ^2

$$\chi_i^2(x,Q^2) = \sum_A \left[\frac{R_i^A(x,Q^2) - \frac{1}{A}\int \mathrm{d}^2\mathbf{s}\, T_A(\mathbf{s}) r_i^A(x,Q^2,\mathbf{s})}{W_i^A(x,Q^2)} \right]^2$$

- A-dependence of $R_i^A(x,Q^2)$ well reproduced with $n=4$:

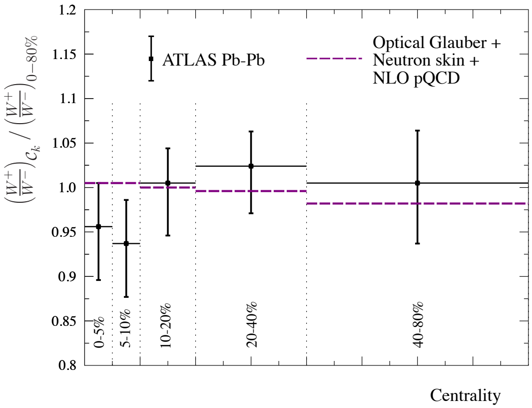


- Fitting is done also for the EPS09 error sets (LO&NLO)



Outcome: Spatially dependent nPDF sets `EPS09s` and `EKS98s`

- Comparison to ATLAS data [Eur. Phys. J. C (2015) 75:23]



[From H. Paukkunen, Phys. Lett. B745 (2015) 73-78]

- Very mild effects with the given centrality binning