Recent results on nPDFs

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Quarkonia as Tools 2024

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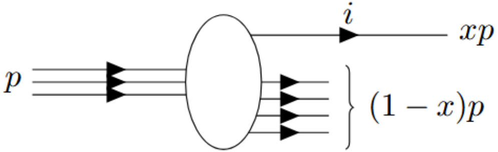
PDFs

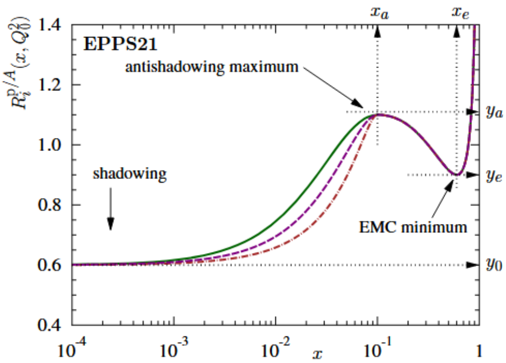
- Probability densities to find a parton with a momentum fraction *x* inside of a hadron of momentum *p*



- Enter calculations involving hadrons in the initial state
- Non-perturbative, Universal objects
- Fitted on experimental data

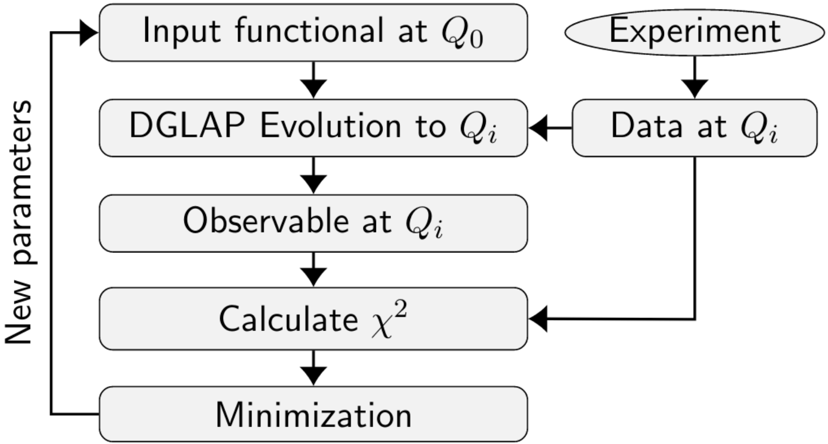
Nuclear PDFs

- PDFs are modified when nuclei are involved
- The nuclear PDF is not just Z times the proton PDF + N times the neutron PDF



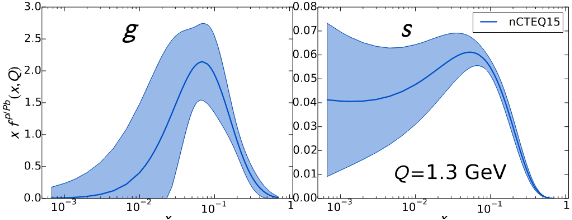
- $f_i^A(x, Q^2) = \frac{Z}{A} f_i^{p/A}(x, Q^2) + \frac{A-Z}{A} f_i^{n/A}(x, Q^2)$
- $f_i^{p/A}(x, Q^2) = R_i^A(x, Q^2) f_i^p(x, Q^2)$
- Isospin symmetry to obtain $f_i^{n/A}(x, Q^2)$

"Standard" fitting procedure



Current status of nPDFs

- More precise (n)PDFs $\rightarrow$ more precise predictions for observables measured at colliders (notably the future EIC)

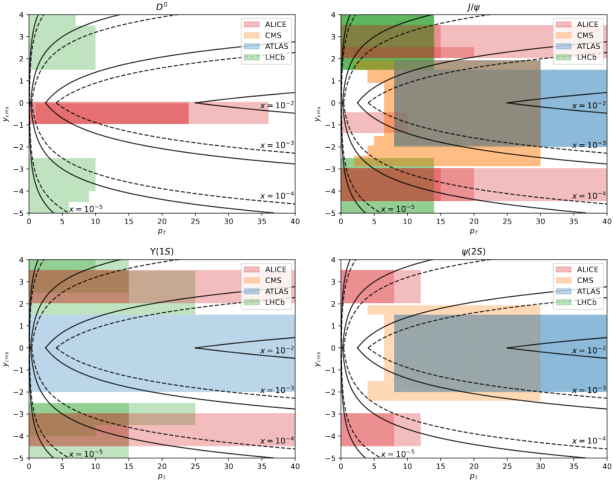


- Very large gluon uncertainties, especially at low x
  $\rightarrow$ large uncertainties on other flavors via DGLAP evolution

Won't be an exhaustive overview, only focus on nPDFs using heavy flavor data

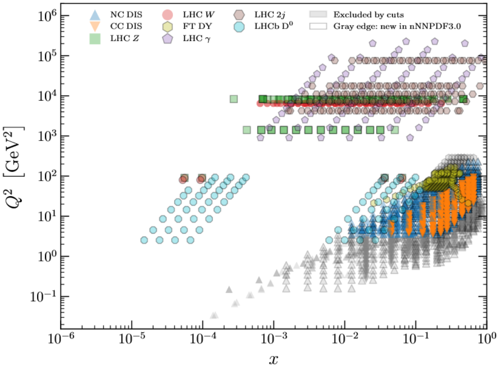
Why quarkonia? (And open heavy flavors)

- Large data sets from LHC experiments
- Sensitivity to gluon nPDFs down to very low x ($\approx 10^{-4.5}$)



nNNPDF3.0 (2201.12363)

- Parametrization of the bound proton PDFs $f_i^{p/A}$ using neural networks at scale $Q_0 = 1$ GeV
- 256 parameters
- 2188 data points (1467 old, 721 new)
- Processes:
  - (ν)DIS (411 new points)
  - DY (146 new points)
  - WZ
  - γ prompt production from ATLAS 8 TeV
  - Dijet (New data from CMS 5 TeV)
  - D meson data from LHCb 5 TeV
    Included via Bayesian reweighting (not fitted)



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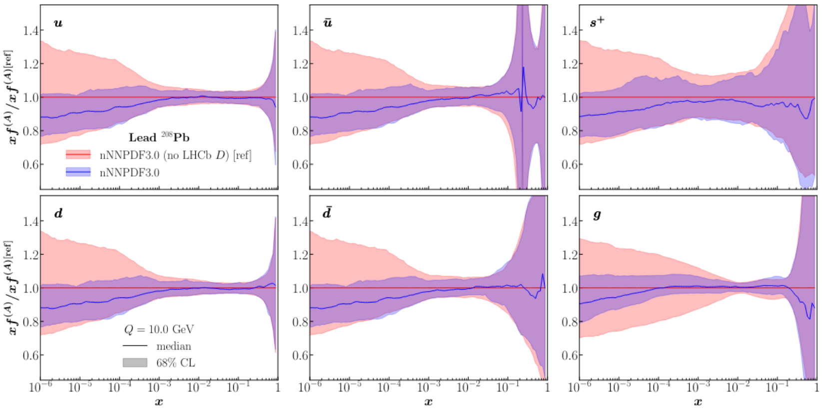
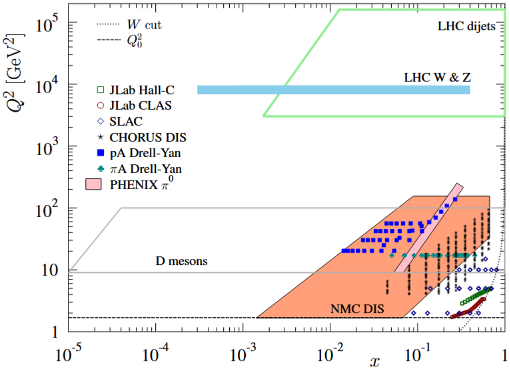


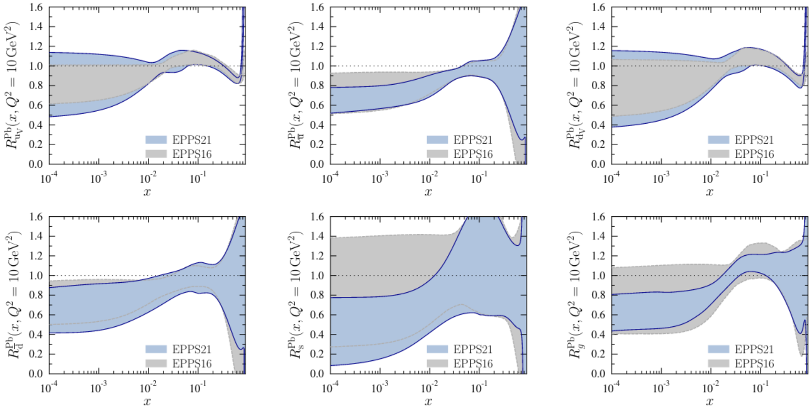
- Large reduction of gluon uncertainties thanks to LHCb D meson data.

EPPS21 (Eur. Phys. J. C 82, 413 (2022))

- Parametrization of the nuclear modification factor $R_i^{p/A}$ at $Q_0 = 1.3$ GeV
- 24 free parameters (from 20 in EPPS16)
- 2077 data points (1742 old, 335 new)
- Processes:
  - (ν)DIS (New data from JLAB)
  - DY
  - SIH
  - WZ (New $W^{\pm}$ data from CMS 8 TeV)
  - Dijet (New data from CMS 5 TeV)
  - D meson data from LHCb 5 TeV



EPPS21 (Eur. Phys. J. C 82, 413 (2022))



- Important reduction of gluon and strange quark uncertainties. Due to D meson data for the gluon and due to W data and gluon uncertainty reduction for the strange quark

nCTEQ15HQ (Phys. Rev. D 105, 114043)

- Data-driven approach to include D/quarkonium data (implemented from Phys. Rev. Lett. 121, 052004, Phys. Rev. D 104, 014010)
- Parametrization of the nPDFs at $Q_0 = 1.3$ GeV
- 19 parameters
- 1484 data points (936 old, 548 new)
- Processes:
  - DIS
  - DY
  - WZ
  - SIH
  - D_0 data from LHCb
  - J/Ψ, $\Psi(2S)$ and $\Upsilon(1S)$ data from LHC

$$xf_i^{p/A}(x, Q_0) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5}$$

$$c_k \Rightarrow c_k(A) \equiv p_k + a_k(1 - A^{-b_k})$$

Heavy flavor fitting procedure

- Cross-section parametrized as:

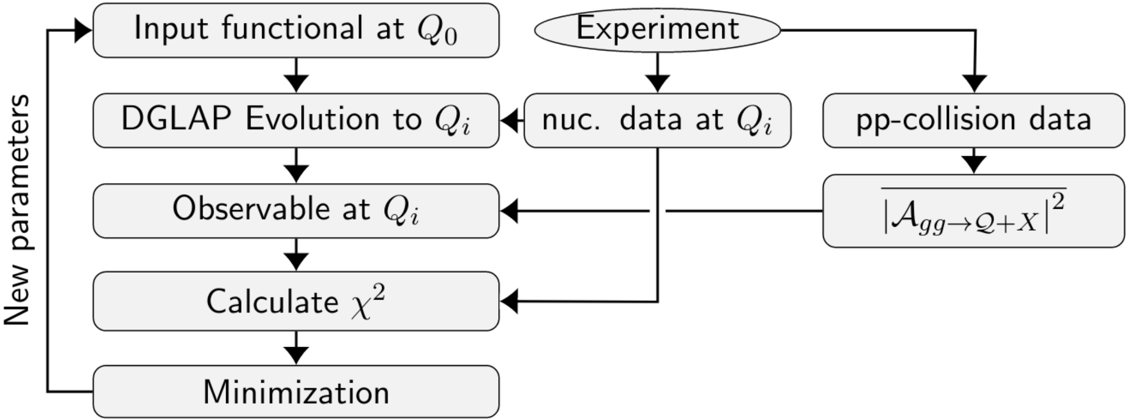
$$\sigma(AB \to \Phi + X) = \int dx_1 dx_2 f_{1,g}(x_1,\mu) f_{2,g}(x_2,\mu) \frac{1}{2\hat{s}} \overline{|\mathcal{A}(gg \to \Phi + X)|^2} dPS$$

$$\overline{|\mathcal{A}(gg \to \Phi + X)|^2} = \frac{\lambda^2 \kappa \hat{s}}{M_Q^2} e^{a|y|} \times \begin{cases} e^{-\kappa \frac{p_T^2}{M_Q^2}} & p_T \leq \langle p_T \rangle \\ e^{-\kappa \frac{p_T^2}{M_Q^2}} \left(1 + \frac{\kappa}{n} \frac{p_T^2 - \langle p_T \rangle^2}{M_q^2}\right)^{-n} & p_T > \langle p_T \rangle \end{cases}$$

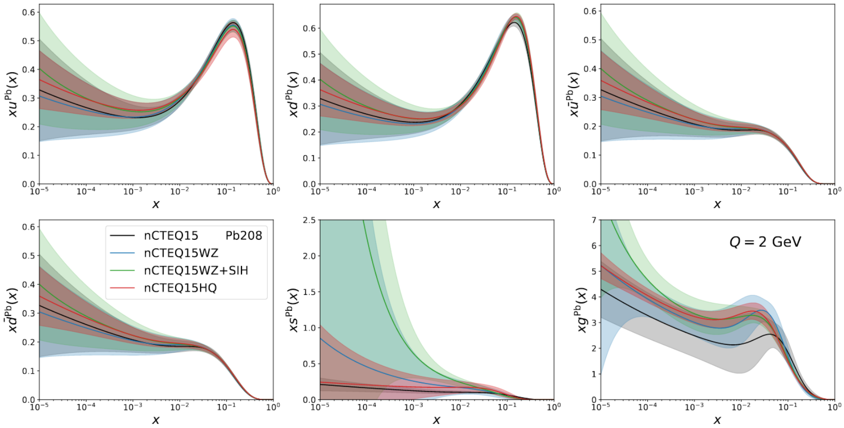
- 2 assumptions:
  - gg-channel dominant
  - Only consider 2→2 kinematics

- 5 additionnal parameters
- a parameter added to include rapidity dependence

Heavy flavor fitting procedure

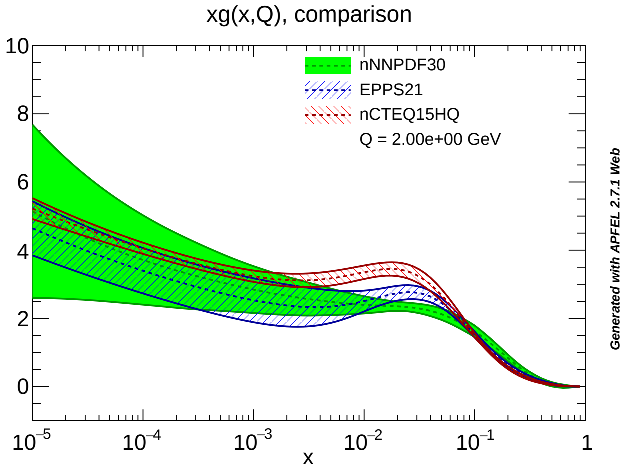


nCTEQ15HQ



- Gluon uncertainties greatly reduced, especially at very low x

Comparison



- Gluon nPDFs in Pb at 2 GeV
- Same distribution shapes, but different uncertainties at very low x
- nCTEQ15HQ has the lowest uncertainties
  $\Rightarrow$ effect of quarkonia data?

Spatial dependence of nPDFs

- Traditionnal nPDFs are fitted on minimum bias data
  $\Rightarrow$ spatially averaged
- Essential to understand the spatial dependence to interpret data in different centrality classes
- So far only one attempt to study impact parameter dependent nPDFs: EPS09s/EKS98s
- Valuable to have a second independent study, with a different methodology

EPS09s (J. High Energ. Phys. 2012, 73 (2012))

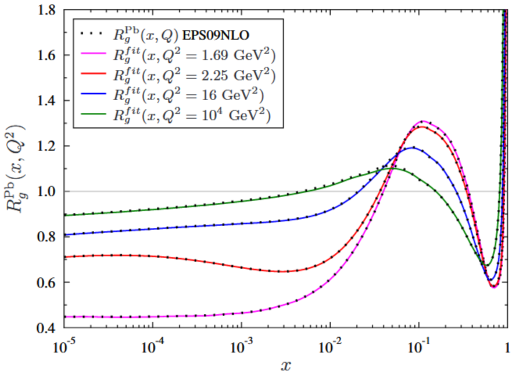
- Parametrization of the spatially dependent nuclear modification by the 2D local nucleon number density (thickness function)

$$R_i^A(x,Q^2) = \frac{1}{A}\int d^2\mathbf{s}\, T_A(\mathbf{s}) r_i^A(x,Q^2,\mathbf{s}) \;\; ; \;\; r_i^A(x,Q^2,\mathbf{s}) = 1 + \sum_{j=1}^{4} c_i^j(x,Q^2)\,[T_A(\mathbf{s})]^j$$

$$\int d^2\mathbf{s}\, T_A(\mathbf{s}) = A$$

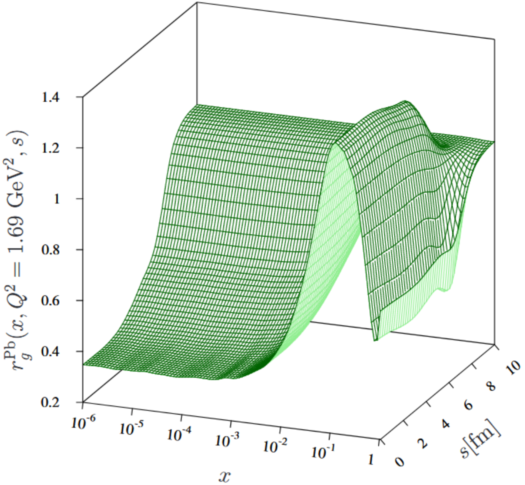
- c_i^j coefficients to be fitted on the nuclear modification factors
- Fit on a wide range of nuclei: A = 16, 20, 27, 40, 56, 64, 84, 108, 115, 117, 131, 184, 195, 197, 208, 238 $\Rightarrow$ Very different nucleon densities

EPS09s (J. High Energ. Phys. 2012, 73 (2012))



- $\chi^2(x,Q^2) \equiv \sum_A \left[\frac{R_i^A(x,Q^2) - \frac{1}{A}\int d^2\mathbf{s}\, T_A(\mathbf{s}) r_i^A(x,Q^2,\mathbf{s})}{W_i^A(x,Q^2)}\right]^2$
- $A \geq 16$ and $W_i^A(x,Q^2) = 1$
- Nuclear modification well reproduced from the spatially dependent ones, at very different scales

EPS09s (J. High Energ. Phys. 2012, 73 (2012))



- Away from the nucleus edge, x-distribution similar to the input distribution
- Nuclear modification dies out when $|\mathbf{s}| > R_A$ as expected

Different ansatz

- Assumption that the spatially dependent nuclear modification can be determined by the thickness function

$$R^A(\mathbf{b}, x, \mu_F) - 1 = (R^A(x, \mu_F) - 1)G\left(\frac{T_A(\mathbf{b})}{T_A(0)}\right),$$

with

$$\int T_A(\mathbf{b})G\left(\frac{T_A(\mathbf{b})}{T_A(0)}\right) d^2\mathbf{b} = A.$$

We take (simplest test example):

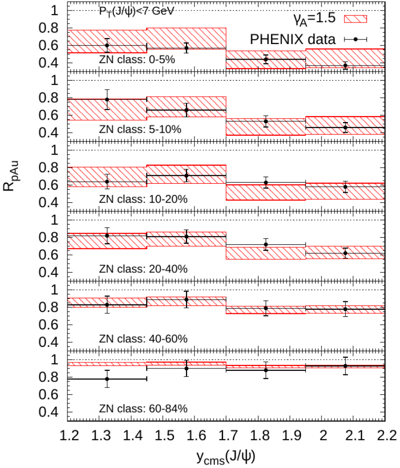
$$G\left(\frac{T_A(\mathbf{b})}{T_A(0)}\right) \propto \left(\frac{T_A(\mathbf{b})}{T_A(0)}\right)^{\gamma_A},$$

with γ_A to be determined ($\gamma_A = 0$ means no spatial dependence)

Observables used

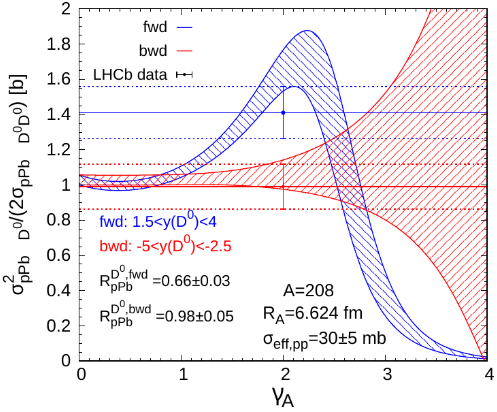
- Direct fit on experimental data
- 2 types of data are used:
  - Centrality dependent R_{pA} for single inclusive particle production (in our case pAu $\rightarrow$ J/Ψ forward data from PHENIX (RHIC) at $\sqrt{s_{NN}} = 200$ GeV)
    - forward: tension between nPDFs and backwards data
    - J/Ψ: Comover effect may be important for excited states like Ψ(2S)
    - RHIC: Large event-by-event fluctuations for LHC data.
  - Double Parton Scattering (DPS) in minimum bias pA collisions.
    - Choice of pPb $\rightarrow D^0 D^0$ LHCb data
    - pPb $\rightarrow J/\Psi D^0$ data also available but suffer from large SPS contamination.

Centrality dependent R_{pA}



- With the Glauber model and assuming the only nuclear effect comes from the nPDFs: $R_{pAu}(b_{min} < b < b_{max}) = 1 - r + rR_{pAu}$
- $$r = \frac{\int_{b_{min}}^{b_{max}} T_A(\mathbf{b}) G\left(\frac{T_A(\mathbf{b})}{T_A(0)}\right) d^2\mathbf{b}}{\int_{b_{min}}^{b_{max}} T_A(\mathbf{b}) d^2\mathbf{b}}$$
- R_{pAu} obtained from experiment (0-100% centrality)
- Best fit gives $\gamma_A = 1.50 \pm 0.10$ with χ^2/ndf = 0.64. (24 data points vs $y_{cms}(J/\Psi)$ and 96 vs $p_T(J/\Psi)$)
- Caveat: "Naive" correspondence between **b** and the centrality classes

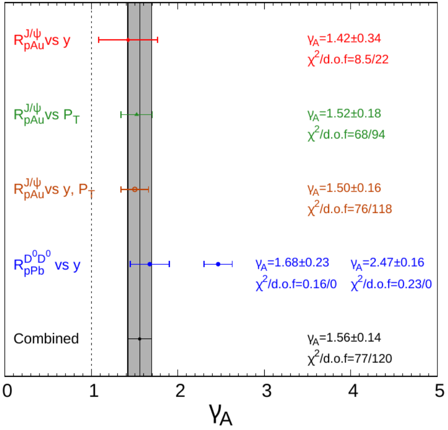
Minimum bias DPS



H.S. Shao, Phys. Rev. D 101 (2020) 5, 054036

- $R^{DPS}_{pPb\to D_0 D_0} = \frac{\sigma^{DPS}_{pPb\to D_0 D_0}}{A\sigma^{DPS}_{pp\to D_0 D_0}}$ $=\Sigma^2_{i,j=1}\left(\hat{T}_{A,ij} + (A-1)\sigma_{eff,pp}\hat{T}^{(2)}_{A,ij}\right)\times \left(R^{D_0}_{pPb}\right)^{2-i}\left(R^{D_0}_{pPb}\right)^{2-j}$
- $\sigma_{eff,pp}$: effective pp cross-section without initial parton-parton correlations, measured from DPS in pp collisions
- $R^{D_0}_{pPb}$: Nuclear modification of single inclusive D_0 production (measured)
- 2 χ^2 minima: $\gamma_A = 1.68 \pm 0.23$ and $\gamma_A = 2.47 \pm 0.16$

Combined results



- 2 very different observables but compatible results
- Atomic numbers of lead and gold are close $\Rightarrow$ combination of fits
- Global fit gives $\gamma_A = 1.56 \pm 0.14$ (less than 10% relative uncertainty) $\Rightarrow$ Highly disfavors $\gamma_A = 0$
- Preliminary study, work still under way

Conclusions

- Global effort towards the determination of more precise (n)PDFs
- Heavy flavor data help constrain the gluon nPDFs at very low x

- Spatial dependence shouldn't be neglected
- Parametrization of the nuclear modification with the thickness function
- Preliminary study with fitting on experimental data

- Correct the impact parameter/centrality correspondance
- Fit on more data?