Disentangling the Energy Loss Contributions in the Cold QCD Medium

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Cold Nuclear Matter Effects: from the LHC to the EIC

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Proton-proton collisions

At large momentum transfer in pp, scale $Q \gg \Lambda_{\mathrm{QCD}} \approx 200$ MeV

$$\mathrm{pp} \to \gamma^\star/Z^0 \to \ell^+\ell^- + \mathrm{X} \text{ (Drell-Yan)}$$

Factorization of cross section = approximation

$$\frac{\mathrm{d}\sigma_{\mathrm{pp}}}{\mathrm{d}y\mathrm{d}Q} = \sum_{i,j} \int \mathrm{d}x_1 f_i^{\mathrm{p}}(x_1, \mu) \int \mathrm{d}x_2 f_j^{\mathrm{p}}(x_2, \mu) \frac{\mathrm{d}\hat{\sigma}_{ij}(x_1, x_2, \mu')}{\mathrm{d}y\mathrm{d}Q} + \mathcal{O}\left(\frac{\Lambda_{\mathrm{p}}^n}{Q^n}\right)$$

- $\hat{\sigma}_{ij}$: partonic cross section calculable in perturbation theory
- x_1, x_2 : fraction of momentum carried by the parton in proton
- $f_{i,j}$: Parton Distribution Function (PDF), **universal**

Proton-nucleus collisions

Cross section in pA collisions assuming collinear factorization

$$\frac{\mathrm{d}\sigma_{\mathrm{pA}}}{\mathrm{d}y\mathrm{d}Q} = \sum_{i,j} \int \mathrm{d}x_1 f_i^{\mathrm{p}}(x_1, \mu) \int \mathrm{d}x_2 f_j^{\mathrm{A}}(x_2, \mu) \frac{\mathrm{d}\hat{\sigma}_{ij}(x_1, x_2, \mu')}{\mathrm{d}y\mathrm{d}Q} + \mathcal{O}\left(\frac{\Lambda_{\mathrm{A}}^n}{Q^n}\right)$$

- Probing the PDF of a nucleus (without nuclear effects)

$$f_i^{\mathrm{A}} = Z f_i^{\mathrm{p}} + (A - Z) f_i^{\mathrm{n}}$$

$$\sigma_{\mathrm{pA}} = Z\sigma_{\mathrm{pp}} + (A - Z)\sigma_{\mathrm{pn}} \approx \mathrm{A}\sigma_{\mathrm{pp}}$$

- Investigate nuclear effects via

$$R_{\mathrm{pA}} \equiv \frac{1}{A} \frac{\mathrm{d}\sigma_{\mathrm{pA}}}{\mathrm{d}\sigma_{\mathrm{pp}}} \approx 1$$

Let's now study the data in hadron-nucleus collisions

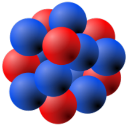
Proton-nucleus collisions

Why study these data:

- a laboratory to study QCD **from SPS to LHC energies**
- to probe the boundaries of **collinear factorization** in the nucleus
- important for **better understanding the formation of QGP**

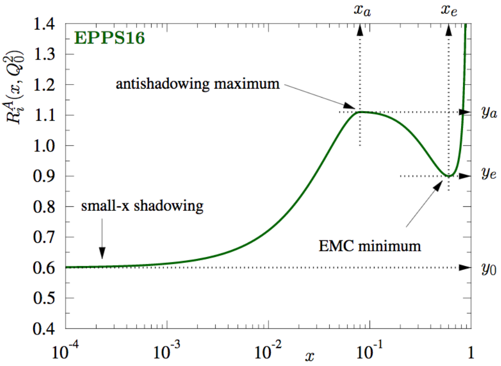
Effects of cold nuclear matter:

- Nuclear PDF (nPDF)
- Radiative energy loss
- Broadening of $p_\perp$
- Nuclear absorption etc



Nuclear parton distribution functions I (initial state)

1. EMC effect discovered in 1983 in DIS on nuclear targets
2. **PDF is modified in nuclei** : $f_j^{p/A} \neq f_j^p$



- The nuclear modification factor depends on x_2
- At $x_2 \lesssim 10^{-3}$: shadowing

Nuclear parton distribution functions II (initial state)

- $R_j^A = f_j^{p/A}/f_j^p$ via a **global fit** assumed to be **universal**
- Factorization leads to x_2 scaling: $R_{\mathrm{pA}} = R_{\mathrm{pA}}(x_2, \sqrt{s}) = R_{\mathrm{pA}}(x_2)$

	EPS09	DSSZ	nCTEQ	EPPS16	EPPS21
e-DIS	✓	✓	✓	✓	✓
ν-DIS		✓		✓	✓
Drell-Yan pA	✓	✓	✓	✓	✓
RHIC hadrons	✓	✓	✓	✓	✓
LHC data pA (QED)				✓	✓
Drell-Yan πA				✓	✓
LHC data pA (D mesons)					✓

Data from proton-nuclei collisions are used for the global fit

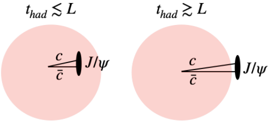
Can there be other nuclear effects in these collisions ?

Nuclear absorption I (final state)

- Multiple scattering of $Q\bar{Q}$ bound state within the nucleons
- Characterised by the nuclear absorption cross section σ_{abs}^{QN}

Condition for quarkonium formation time inside nuclei

$$t_{had} = \gamma\tau_{had} = \frac{E}{M_Q}\tau_{had} \lesssim L$$



The absorption survival probability by the medium computed as

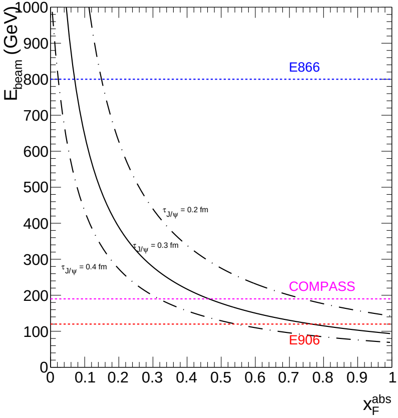
$$S\left(\sigma_{\mathrm{abs}}, L_{\mathrm{A}}\right) = e^{-\rho\sigma_{\mathrm{abs}}\mathrm{L}_{\mathrm{A}}}$$

The pA cross section can be written like

$$\mathrm{d}\sigma^{\mathrm{hA}} = S\left(\sigma_{\mathrm{abs}}, \mathrm{L}_{\mathrm{A}}\right) \times \mathrm{d}\sigma^{\mathrm{hp}} \times \mathrm{A}$$

Nuclear absorption II (final state)

Data explained by nuclear absorption?

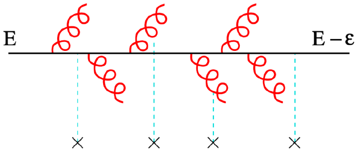


- x_F^{abs}: threshold below which J/ψ is produced in the nucleus
- Possible absorption effect **only at low beam energy**

No nuclear absorption at LHC

Energy loss effects

High-energy partons lose energy via **soft gluon radiation** **due to re-scattering in the nuclear medium**



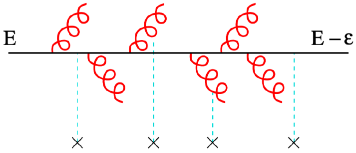
Energy loss effects

$$\frac{dN^{out}(E)}{dE} = \int_{\epsilon} \mathcal{P}(\epsilon, E) \frac{dN^{in}(E+\epsilon)}{dE}$$

$\mathcal{P}(E, \epsilon)$: probability distribution in the energy loss **given by QCD**

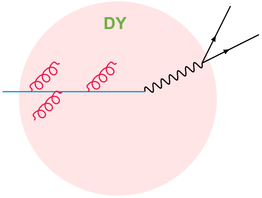
Energy loss effects

High-energy partons lose energy via soft gluon radiation due to re-scattering in the nuclear medium



Can affect differently hard processes:

1. Drell-Yan process: $\mathrm{hA} \to \ell^+\ell^- + \mathrm{X}$
   - Initial state radiation
2. Charmonium production:
   $\mathrm{hA} \to c\bar{c}(\to J/\psi) + \mathrm{X}$
   - Initial state radiation
   - Final state radiation
   - Interferences initial/final state radiation



Parton energy loss regimes

Initial or final state for $t_f \lesssim L$

$$\langle \epsilon \rangle_{\text{LPM}} \propto \alpha_s \hat{q}\, L^2$$

- $\mathrm{hA} \to \ell^+\ell^- + \mathrm{X}$ (DY): Arleo, Naïm, Platchkov, JHEP01(2019)129
- $\mathrm{eA} \to \mathrm{e} + \mathrm{h} + \mathrm{X}$ (SIDIS)

Interference initial and final state for $t_f \gg$ L

$$\langle \epsilon \rangle_{\text{FCEL}} \propto \sqrt{\hat{q} L}/M \cdot E \gg \langle \epsilon \rangle_{LPM}$$

- $\mathrm{hA} \to [Q\bar{Q}]_8 + \mathrm{X}$ (Quarkonium): Arleo, Peigne, PRL.109.122301

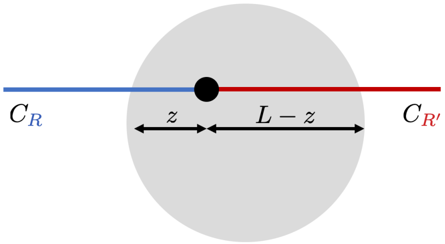
Transport coefficient : scattering property of the medium

$$\hat{q}(x) = \frac{4\pi^2 \alpha_s N_c}{N_c^2 - 1} \rho x G(x) = \hat{q}_0 \left[\frac{10^{-2}}{x}\right]^{0.3}$$

Broadening effect

$p_\perp$ spectra: an other observable to probe transport properties

$$\Delta p_\perp^2 = \left\langle p_\perp^2 \right\rangle_{\mathrm{hA}} - \left\langle p_\perp^2 \right\rangle_{\mathrm{hp}} = \frac{C_R + C_{R'}}{2N_c} \left(\hat{q}_{\mathrm{A}} L_{\mathrm{A}} - \hat{q}_{\mathrm{p}} L_{\mathrm{p}}\right)$$

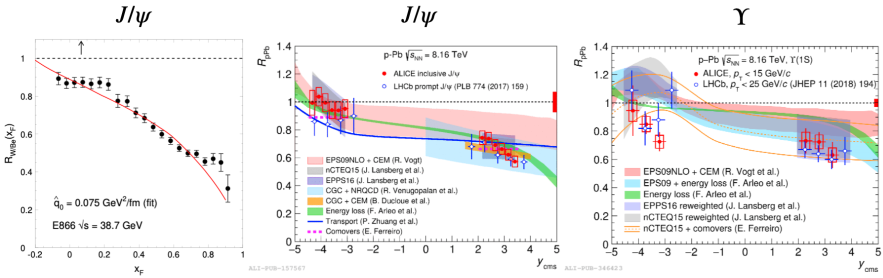


- The $p_\perp$ spectra is modified in pA compared to pp collisions;
- This quantity is also related to $\hat{q}$

The complete picture is: energy loss and broadening

Proton-nucleus collisions: a puzzle!

Empirical observations:



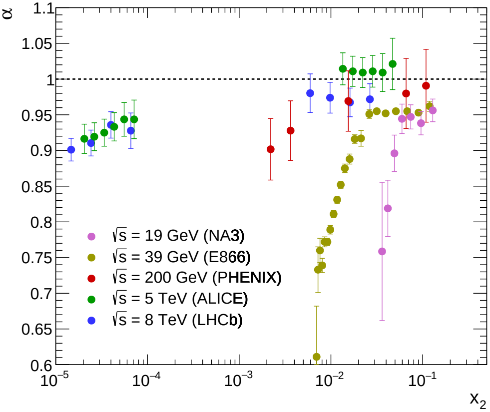
Interpretation:

- The gluon's nPDF shows significant error bands
- Energy loss model describes the suppression of J/ψ

Difficult interpretation due to the models' error bands

Proton-nucleus collisions: quarkonium suppression

J/ψ suppression in world data:

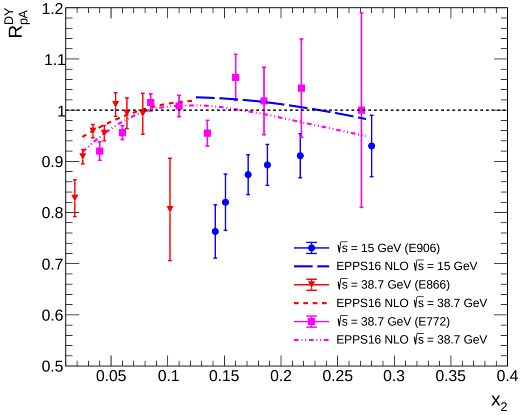


Arleo, Naïm, Platchkov JHEP01(2019)129

- J/ψ suppression depends on the collision energy
- No scaling as a function of x_2 : $R_{\mathrm{pA}} = R_{\mathrm{pA}}\left(x_2, \sqrt{s}\right) \neq R_{\mathrm{pA}}\left(x_2\right)$

Proton-nucleus collisions: DY at fixed-target energies I

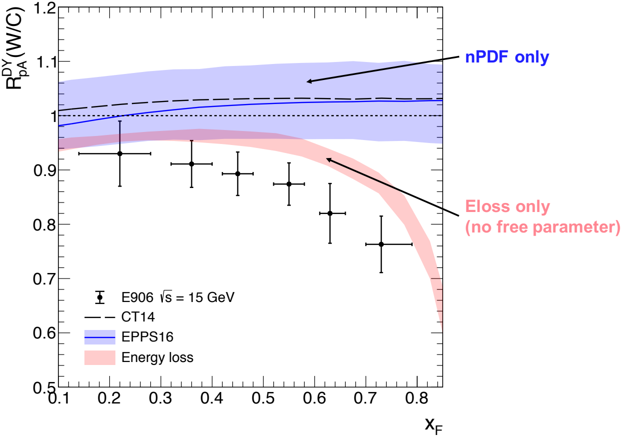
Drell-Yan suppression at fixed-target energies:



Arleo, Naïm, Platchkov JHEP01(2019)129

- **No scaling** as a function of x_2 as for J/ψ production

Proton-nucleus collisions: DY at fixed-target energies II

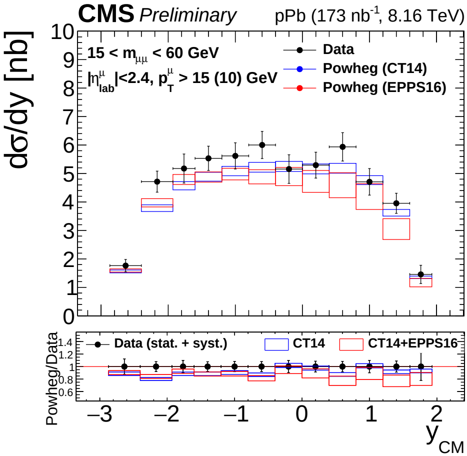


Po-Ju Lin, PhD thesis (2017), Arleo, Naïm, Platchkov JHEP01(2019)129

- **Clear disagreement** between data and nPDF calculation
- Energy loss model exhibits a strong suppression at large x_F

Proton-nucleus collisions: DY at LHC energy

Drell-Yan in pPb at $\sqrt{s} = 8.16$ TeV

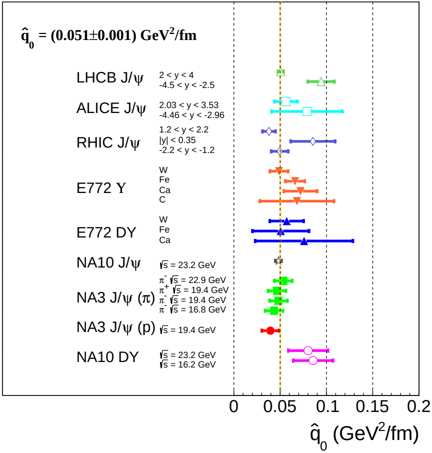


CMS-PAS-HIN-18-003

- No suppression observed
- **Initial-state energy loss is suppresed at high beam energy**

Proton-nucleus collisions: a common effect?

Global broadening analysis:



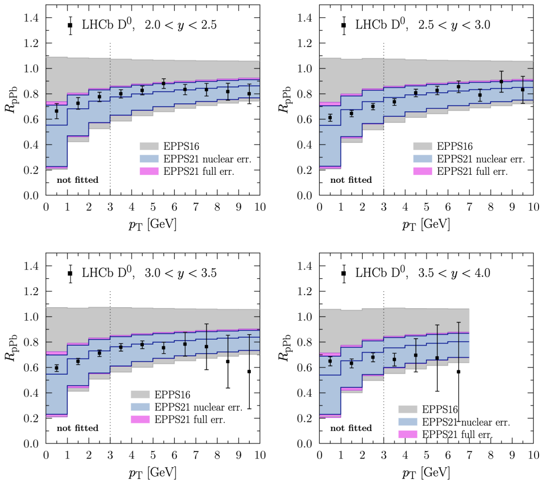
Arleo, Naïm, JHEP07(2020)220

- **Remarkable scaling** from low to high energies → common effect

What puzzle!

Proton-nucleus collisions: pA data for nPDF global fit?

LHCb data: $\mathrm{pA} \to \mathrm{D}^0 + \mathrm{X}$, $10^{-5} \lesssim x \lesssim 10^{-2}$



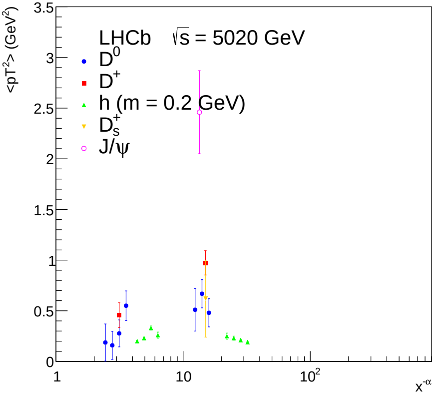
- Large nPDF uncertainties: can one effect hide others?
- Broadening effect on D mesons: $2 \to 2$ kinematic

Laine, Arleo, Naïm, work ongoing

Focus on the broadening effect on D and h data

LHCb data: D^0, D^+, D_s^+, h and J/ψ

$\underline{\alpha = 0.25}$

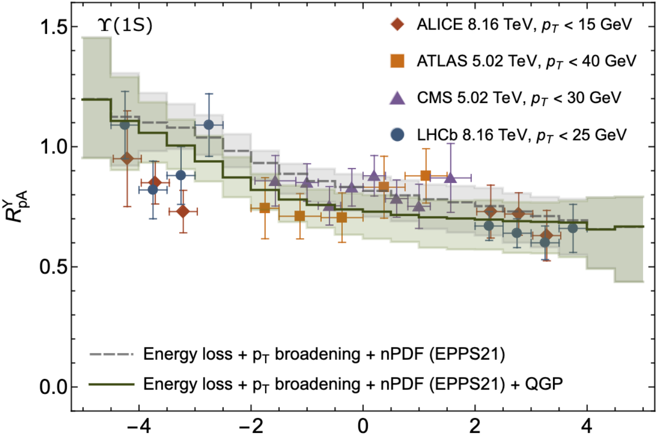


- Common effect observed in D mesons: same color factor?
- Unusual trends in charged hadron data (forward)

Laine, Arleo, Naïm, work ongoing

Include nPDF and energy loss

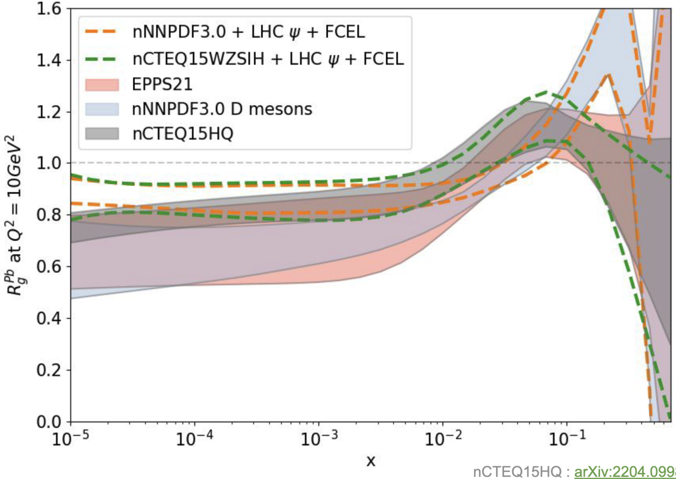
Υ **suppression**: ATLAS, CMS, ALICE and LHCb



Strickland, Thapa, Vogt, PhysRevD.109.096016

- Calculations using **all nuclear effects** reproduce $\Upsilon(1S)$ data
- Weak hot QCD effect on $\Upsilon(1S)$

nPDF including the FCEL effect



nCTEQ15HQ : arXiv:2204.09982

Avez, Arleo, work ongoing

- Energy loss and nPDF fit
- **Significative impact on the shadowing amplitude**

A simple summary?

- **Drell-Yan**
  - nPDF: ✓ ;
  - Initial-State Energy Loss: × (only FT energy);
  - Final-State Energy Loss: × ;
  - $p_\perp$-broadening: ✓ ;
  - Nuclear Absorption: × .
- **Quarkonium**
  - nPDF: ✓ ;
  - FCEL: ✓ (all energies);
  - $p_\perp$-broadening: ✓ ;
  - Nuclear Absorption: × (only FT energy, at small x_F).
- **SIDIS**
  - nPDF: (✓) × ;
  - Initial State Energy Loss: × ;
  - Final-State Energy Loss: × (only FT energy);
  - $p_\perp$-broadening: ✓ ;
  - Nuclear Absorption: × (only FT energy, at large z).

FT=Fixed-Target experiment

What can we do with EIC?

Processes

$$\mathrm{eA} \to \mathsf{e} + \mathsf{h} + \mathrm{X} \ (\mathsf{SIDIS})$$
$$\mathrm{eA} \to \mathsf{e} + \mathrm{X} \ (\mathsf{DIS})$$

CNM effects:

- nPDF: up to $x \sim 10^{-4}$
- $p_\perp$-broadening:
  - $\Delta p_\perp^2 = \hat{q} L \propto G(x, Q_s^2) L_A \propto x^{-\alpha} \quad (\alpha \sim 0.3)$

Interests:

- **Precise** ($\sim$ 10% ?) and **reliable extraction of nPDF** at small x;
- Evidence for **physics beyond nPDF** from the direct comparison of forward hadron production in pA collisions and SIDIS
- Probing **saturation physics** at small x

Conclusion

1. **Energy loss effects can explain data**

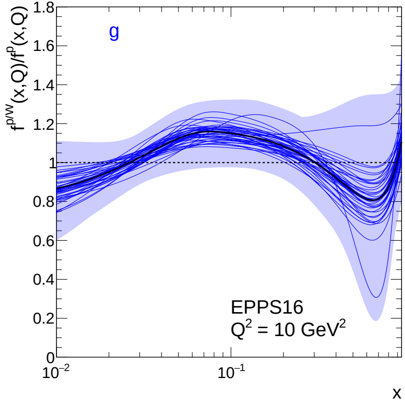
2. **Ignoring FCEL in nPDF global fits leads to wrong nPDF extractions**

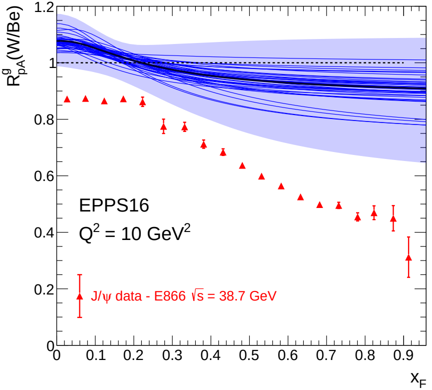
3. **nPDF global fit strategy should either:**
   - exclude measurements of hadron production in pA collisions
   - include FCEL in the theoretical framework

4. **EIC data will be crucial to compare to LHC pA data:**
   - **test the universality of the cold QCD!**

J/ψ suppression from E866/NuSea

Data explained by nPDF ?





nPDF alone cannot explain E866 J/ψ at $\sqrt{s} = 38.7$ GeV

Method to extract the broadening

Definition

$$\langle p_T^2 \rangle \equiv \frac{\int_0^\infty p_T^2 \frac{d\sigma}{dp_T} dp_T}{\int_0^\infty \frac{d\sigma}{dp_T} dp_T} \text{ and } \Delta p_T^2 \equiv \langle p_T^2(A) \rangle - \langle p_T^2(B) \rangle \ (\text{GeV}^2)$$

- **1$^{\text{st}}$ method : Kaplan fit**

$$\frac{d\sigma}{dp_T} = \mathcal{N} \left(\frac{p_0^2}{p_0^2 + p_T^2} \right)^m$$

- **2$^{\text{nd}}$ method : Bin summation**

$$\langle p_T^2 \rangle \approx \frac{\sum_{i=1}^n p_T(i)^2 \frac{d\sigma}{dp_T}(i) dp_T(i)}{\sum_{i=1}^n \frac{d\sigma}{dp_T}(i) dp_T(i)}$$

where "n" is the bin number

→ **Observable independent of normalisation**

Other nuclear effects in the broadening calculation

For this study, we considered only the broadening effect but ...

1. **Energy loss effect**
   - Affects only the normalisation of $R_{\mathrm{pA}}\,(\mathrm{p_T})$
   - Cancellation in $\Delta p_\perp^2$
2. **nPDF effect**
   - $0 < p_\perp \lesssim M$: fixed target experiment, cancellation in $\Delta p_\perp^2$
   - $p_\perp \gtrsim M$: LHC case, very large error bar in gluon sector but

$$\frac{\mathrm{d}\sigma_{\mathrm{hA}}^{\mathrm{nPDF}}}{\mathrm{d}p_\perp} = \underbrace{R_i^{\mathrm{A}}\left(x_2\left(p_\perp\right), Q^2\right)}_{\text{if only normalisation : cancellation in } \Delta p_\perp^2} \times \frac{\mathrm{d}\sigma_{\mathrm{hp}}}{\mathrm{d}p_\perp}$$

- at $x \lesssim 10^{-4}$: shadowing region $R_i^{\mathrm{A}}\left(x, Q^2\right)$ ¡ 1
- at $0.05 \lesssim x_2 \lesssim 0.2$: antisadowing region $R_i^{\mathrm{A}}\left(x, Q^2\right)$ ¿ 1

Quarkonium production model

CEM model formalism

$$\sigma(pp \to \mathcal{Q} + X) = \sum_{i,j,n} \int \int dx_1 dx_2 f_{i/p} f_{j/p} \times \hat{\sigma}[ij \to c\bar{c}X]$$
$$\approx \int dx_1 dx_2 g_p g_p \times \hat{\sigma}[gg \to c\bar{c}X]$$

NRQCD model formalism

$$\sigma(pp \to \mathcal{Q} + X) = \sum_{i,j,n} \int dx_1 dx_2 f_{i/p} f_{j/p} \times \hat{\sigma}\left[ij \to (Q\bar{Q})_n + x\right] \left\langle 0 \middle| \mathcal{O}_n^{\mathcal{Q}} \middle| 0 \right\rangle$$
$$\approx \int dx_1 dx_2 g_p g_p \times \hat{\sigma}\left[gg \to (Q\bar{Q})_n + x\right] \left\langle 0 \middle| \mathcal{O}_n^{\mathcal{Q}} \middle| 0 \right\rangle$$

$$R_{\mathrm{pA}} \equiv \frac{1}{A} \frac{\mathrm{d}\sigma_{\mathrm{pA}}}{\mathrm{d}\sigma_{\mathrm{pp}}} \approx \frac{G^A}{g^p}$$