From Fixed Targets to LHC Beam Energies: Insights into the (Cold) QCD Medium

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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** non perturbative.

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

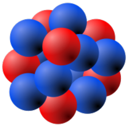
Proton-nucleus collisions

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**.

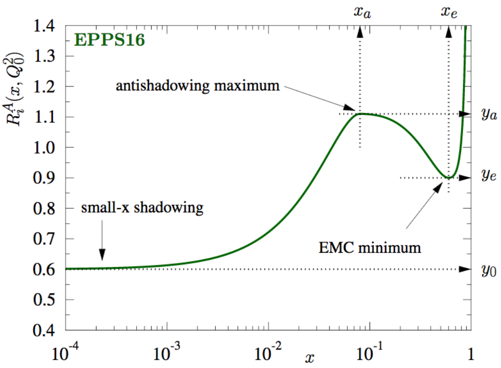
Effects of cold nuclear matter:

- 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)

- nPDF ratio $R_j^A = f_j^{p/A}/f_j^p$ 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)					✓

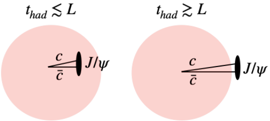
Data from proton-nuclei collisions are used for the global fit.
Can there be other nuclear effects in these collisions ?

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

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



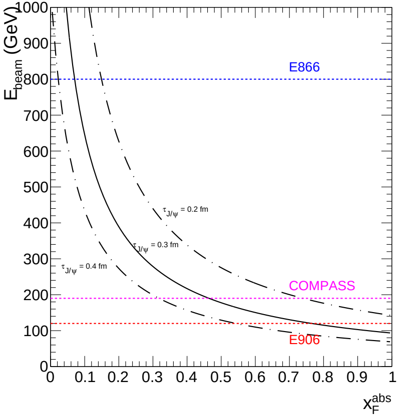
The absorption survival probability by the medium computed as

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

The pA cross section can be written like

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

Data explained by nuclear absorption?

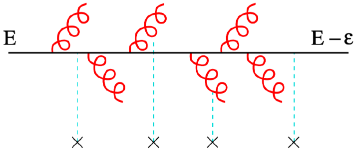


- x_F where $t_{had} \lesssim L$ by assuming $0.2 < \tau_{had}^{J/\psi} < 0.4$ (fm) and W nuclei
- Possible absorption effect **only at low beam energy** (SPS energy)

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



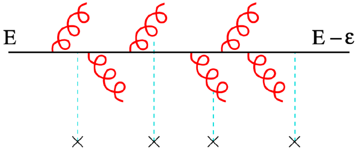
Energy loss effects

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

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

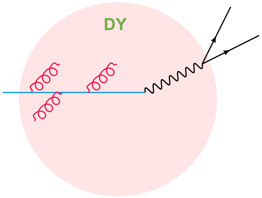
Energy loss effects

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

Energy loss in initial or final state (small formation time $t_f \lesssim L$))

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

- $\mathrm{hA} \to \ell^+ \ell^- + \mathrm{X}$ (DY)
- $\mathrm{eA} \to \mathrm{e} + \mathrm{h} + \mathrm{X}$ (SIDIS)

Energy loss in initial/final state (large formation time $t_f \gg$ 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)

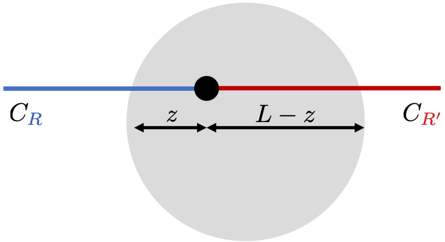
Transport coefficient : scattering property of the medium

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

Broadening effect

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

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

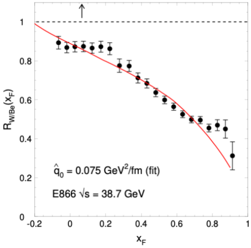


- The $p_\perp$ spectra is modified in pA compared to pp collisions;
- This quantity is also related to $\hat{q}$.

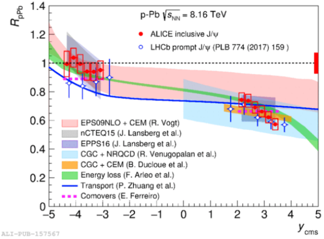
The complete picture is: energy loss and broadening.

Empirical observations:

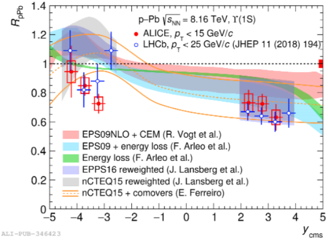
J/ψ



J/ψ



Υ



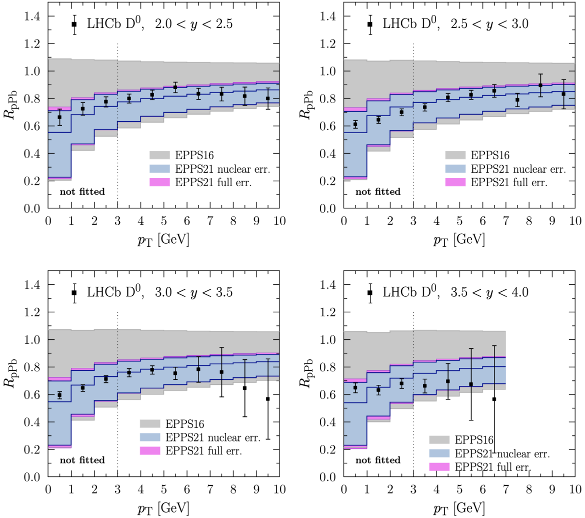
Interpretation:

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

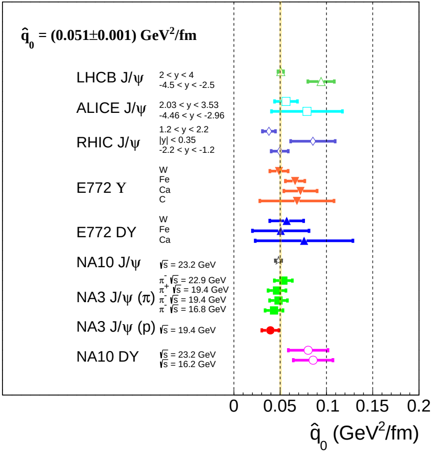
Difficult interpretation due to the models' error bands

[EPPS21]

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



Global broadening analysis:



- Remarkable scaling from low to high energies $\rightarrow$ common effect

What puzzle!

Quarkonium production model

- Quarkonium model production **is not very well known** (CSM, CEM, NRQCD ...);
- Heavy quark pair production **should proceed via gluon fusion**,

$$g^{p} g^{\mathrm{A}} \to Q\bar{Q} \to H + \mathrm{X}$$

A simple approximation:

$$R_{\mathrm{pA}}^{H}(y) \approx R_{\mathrm{g}}^{\mathrm{Pb}}\left(x_2, Q^2 = M_H^2\right)$$

$$x_2 = M_H e^{-y}/\sqrt{s}$$

- x_2 given by LO kinematics,

  $\to$ precise value not crucial as R_{g} is flat at $x \lesssim 10^{-2}$.

The double ratio ...

A new observable

$$\mathcal{R} \equiv R_{\mathrm{pA}}^{J/\psi} / R_{\mathrm{pA}}^{\Upsilon}$$

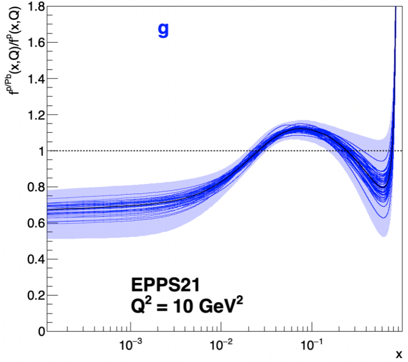
- $x \ll 1$: **gluon channel dominates the cross section**;
- $\mathcal{R} \propto G^A(x, Q^2 = M_{J/\psi}^2) / G^A(x, Q^2 = M_{\Upsilon}^2)$;
- $G^A(x, Q^2 = M_{J/\psi}^2)$ and $G^A(x, Q^2 = M_{\Upsilon}^2)$ **are fully correlated**:

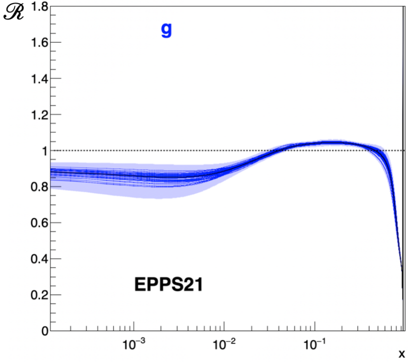
Calculations

- Quarkonia cross sections are calculated using **CEM model** (LO);
- $G^A(x)$ given by global fit (EPSS21), band computed from the spread of $\sim$ 50 uncertainty sets.

Υ vs J/ψ, what we can learn?

Last nPDF extraction ...



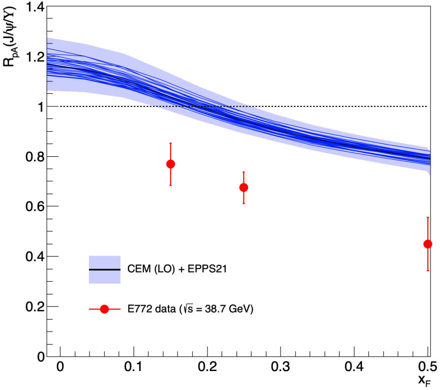


- **Left**, $R_{\rm pA}^{J/\psi}$ for gluon density: **large uncertaities**;
- **Right**, $\mathcal{R}$ for gluon density **sensitive just to Q^2 evolution**.

Uncertainties reduced significantly

Fixed-target experiment

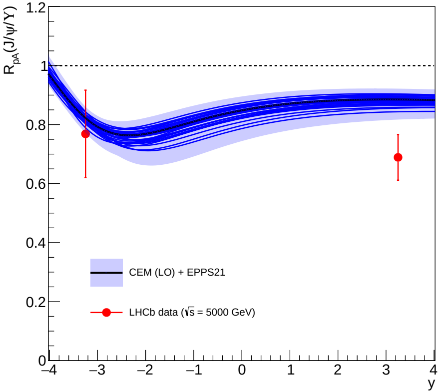
[E772, 38.7 GeV, J/ψ] [E772, 38.7 GeV, Υ]



- At this energy, σ^{H} includes both quarks and gluons channels;
- $t_f \lesssim 10$ fm from $x_{\mathrm{F}} \lesssim 0.1$;
- $R_{\mathrm{pA}}^{J/\psi} < R_{\mathrm{pA}}^{\Upsilon}$: **$\mathbf{J/\psi}$ is more suppressed**.

LHC experiment I

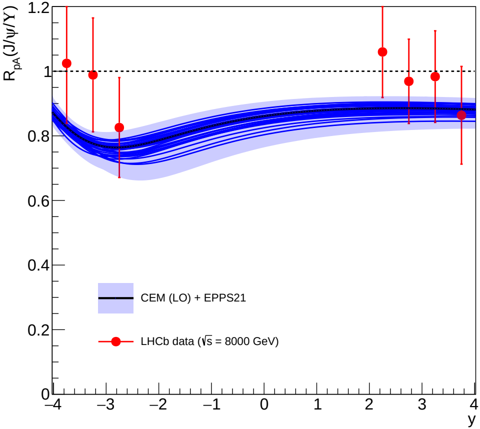
[LHCb, 5 TeV, J/ψ] [LHCb, 5 TeV, Υ]



- At backward $x_2 \sim 0.01$ ($t_f \sim 1$ fm) and at forward $x_2 \sim 10^{-5}$;
- $R_{\mathrm{pA}}^{J/\psi} < R_{\mathrm{pA}}^{\Upsilon}$: $\mathbf{J}/\psi$ **is more suppressed**.

LHC experiment II

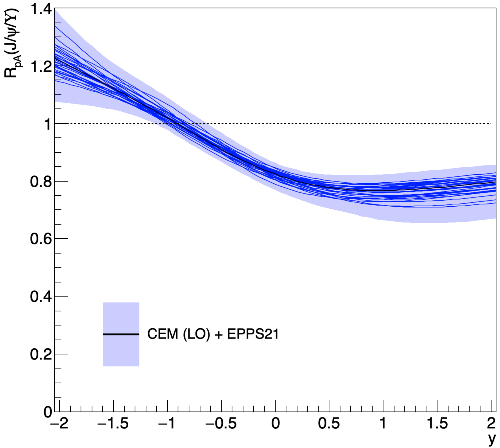
[LHCb, 8 TeV, J/ψ] [LHCb, 8 TeV, Υ]



- $R_{\rm pA}^{J/\psi} \sim R_{\rm pA}^{\Upsilon}$: **same suppression**.

RHIC experiment

Beam energy: $\sqrt{s} = 200$ GeV



- **Small error band at mid rapidity.**

Parton energy loss regimes

[Arleo, Peigné, JHEP03(2013)122]

Energy loss in initial/final state (large formation time $t_f \gg$ L)

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

- $\mathrm{hA} \rightarrow [Q\bar{Q}]_8 + \mathrm{X}$

$$M_{J/\psi} > M_{\Upsilon} \rightarrow R_{\mathrm{pA}}^{J/\psi}(\mathrm{Eloss}) < R_{\mathrm{pA}}^{\Upsilon}(\mathrm{Eloss})$$

Observations:

- **We observe that from fixed-targets to LHC (5 TeV) energies ...**;
- **But not at 8 TeV**;
- Hot QCD medium at 8 TeV: comovers effects?.

Preliminary conclusion

The double ratio:

1. is model production **independent**;
2. allows for a significant reduction in the nPDF error band.

Observation:

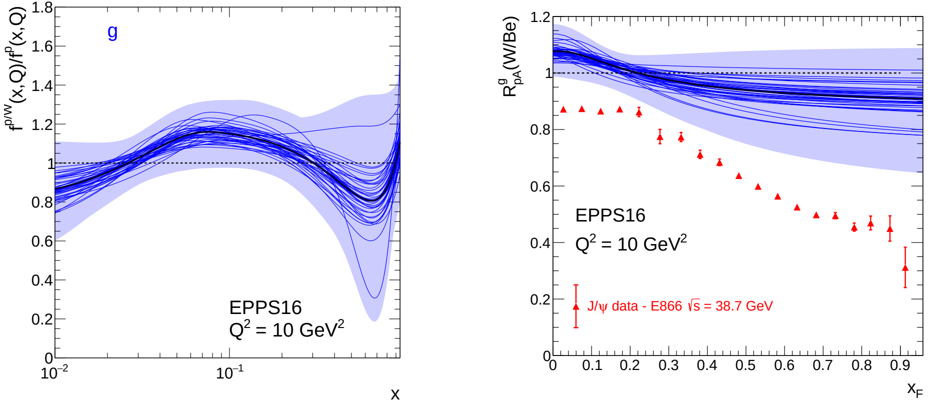
1. The latest EPPS16 extraction does not describe any data;
2. Other QCD (hot and cold) effects should explains these data:
   - $R_{\mathrm{pA}}^{J/\psi} \lesssim R_{\mathrm{pA}}^{\Upsilon}$ up to 5 TeV,
   - $R_{\mathrm{pA}}^{J/\psi} \sim R_{\mathrm{pA}}^{\Upsilon}$ at 8 TeV.
3. RHIC data at $y \sim 0$ might clearly highlight the limitation of nPDFs.

Next step:

1. Include energy loss effects;
2. Other QCD effects should explains these data;
3. $R_{\mathrm{pA}}^{J/\psi} \sim R_{\mathrm{pA}}^{\Upsilon}$ at 8 TeV.

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

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

- **1st method : Kaplan fit**

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

- **2nd 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

$\rightarrow$ **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 $R_{\mathrm{pA}}(\mathsf{p_T})$
   - 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

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

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