Cold nuclear matter transport coefficient in Drell-Yan and quarkonium production

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Why hard processes in hadron-nuclei collisions?

Hadron-nuclei collisions pA/πA

- Lot of measurements from SPS to LHC energies ($\sqrt{s} \approx 20$ GeV - 8 TeV)
- Study confined nuclear matter
  - Static matter and known nuclear density
  - Important for LHC data interpretation !
- In the future, precise measurements from COMPASS

Hard processes to study nuclear medium

- Drell-Yan production
  - hA $\to \ell^+\ell^-$ + X
  - **Colorless final state**
  - Very well understood in QCD
- Hadron production (mostly charmonium)
  - hA $\to q/g\,(\to h') + X$
  - **Color in initial and final state**
  - Hadron production mechanism not really known

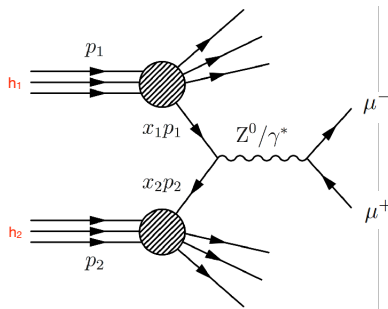# Collinear factorization

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

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

Collinear factorization

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

Collinear factorization

Proton-nucleus (pA) collisions

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

- Probing of PDF of a nuclei (without nuclear effects)

$$f_i^A = Z f_i^p + (A - Z) f_i^n$$

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

- 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 hA ...
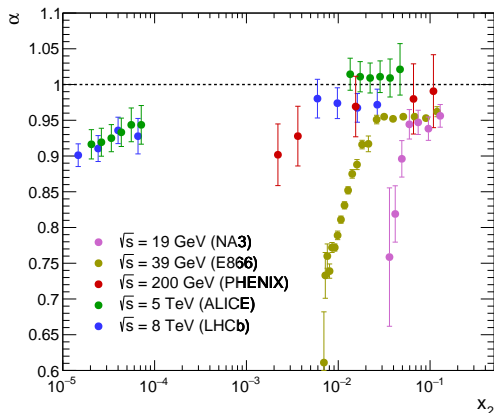
Observable : $\quad \sigma(\mathrm{pA} \to J/\psi + \mathrm{X}) \equiv \sigma(\mathrm{pp} \to J/\psi + \mathrm{X}) \times A^{\alpha}$

① Strong **suppression** in J/ψ data at all $\sqrt{s}$ from SPS to LHC energies

Observable : $\sigma(\text{pA} \rightarrow J/\psi + \text{X}) \equiv \sigma(\text{pp} \rightarrow J/\psi + \text{X}) \times A^{\alpha}$
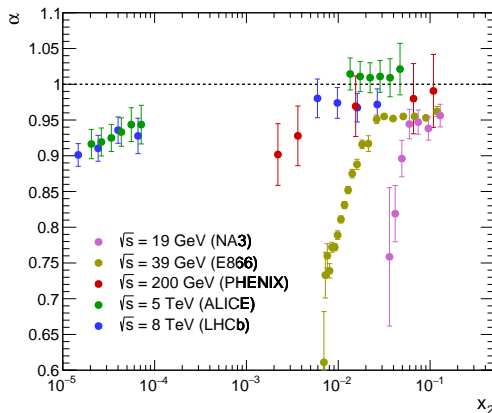
1. Strong **suppression** in J/ψ data at all $\sqrt{s}$ from SPS to LHC energies
2. **No scaling** as a function of the x_2 momentum fraction
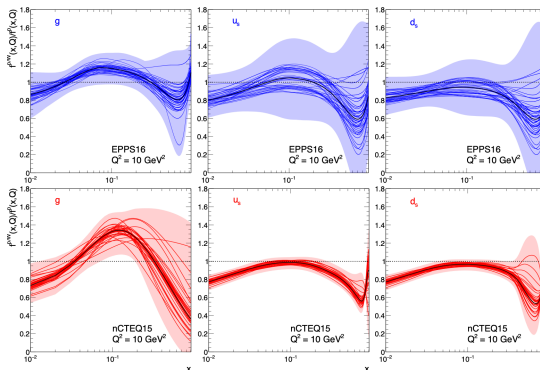
Nuclear PDF effects

Nuclear Parton Distribution Functions (nPDF)

- EMC effect discovered in 1983 in DIS on nuclear targets
- PDF is modified in nuclei : $f_j^{p/A} \neq f_j^p$
- nPDF ratio $R_j^A = f_j^{p/A}/f_j^p$ via a **global fit** assumed to be **universal**
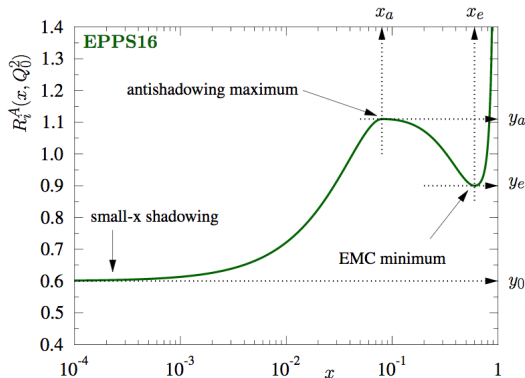
Nuclear PDF effects

	EPPS16	nCTEQ15
Neutral current DIS l+A/p+d	✓	✓
Drell-Yan dilepton p+A/p+d	✓	✓
RHIC pions d+Au/p+p	✓	✓
Neutrinos-nucleus DIS	✓	
LHC p+Pb jet data	✓	
LHC p+Pb W and Z bosons data	✓	
Drell-Yan dilepton πA	✓	

Empirical observations in J/ψ data

- **Amplitude of the suppression** depends on the beam energy
- **No scaling** as a function of x_2

Nuclear PDF effects

- Nuclear PDF from global fit **cannot explain alone** these observations in hadron-nuclei collisions
- **Other physics effects are present**

⚠️Drell-Yan data used in the nPDF global fits

Quid of other hard processes in hadron-nuclei collisions ?

Parton energy loss

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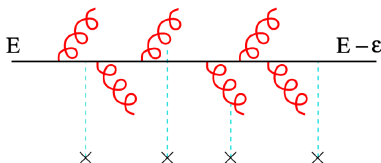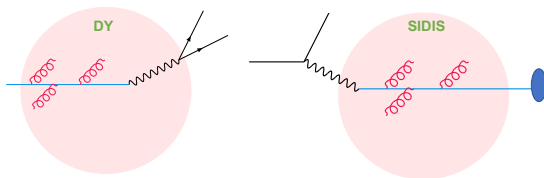

Energy loss effects

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

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

Parton energy loss in hard processes

Drell-Yan process : $hA \to \ell^+\ell^- + X$

- Initial state radiation

Hadron production in SIDIS : $eA \to e + h + X$

- Final state radiation

Hadron production in hA : $hA \to q/g(\to h') + X$

- Initial state radiation
- Final state radiation
- Interferences initial/final state radiation

Parton energy loss in BDMPS formalism

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

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

- $hA \rightarrow \ell^+\ell^- + X$ (DY)
- $eA \rightarrow e + h + X$ (SIDIS)

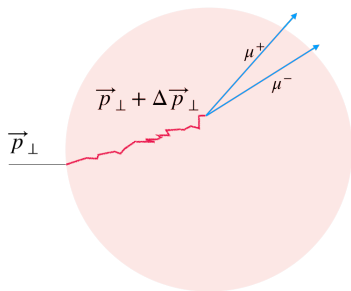## Energy loss in initial/final state (large formation time $t_f \gg L$)

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

- $hA \rightarrow [Q\bar{Q}(g)]_8 + X$ (Quarkonium)

Transport coefficient : the scattering properties of the medium

$$\hat{q}_g(x) = \frac{4\pi^2 \alpha_s(\hat{q}L)N_c}{N_c^2 - 1} \rho x G(x, \hat{q}L)$$

p_T broadening as a probe for transport coefficient

$$\Delta p_\perp^2 = \langle p_\perp^2 \rangle_{\mathrm{hA}} - \langle p_\perp^2 \rangle_{\mathrm{hp}} = \hat{q}(x)L$$

$$\langle p_\perp^2 \rangle_{\mathrm{hA}} = \frac{\int \mathrm{d}p_\perp\, p_\perp^2 \frac{\mathrm{d}\sigma_{\mathrm{hA}}}{\mathrm{d}p_\perp}}{\int \mathrm{d}p_\perp \frac{\mathrm{d}\sigma_{\mathrm{hA}}}{\mathrm{d}p_\perp}}$$

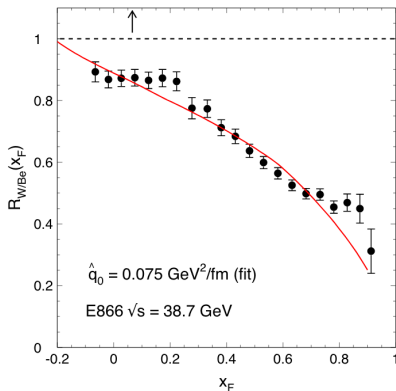- if $\hat{q}L \lesssim 1\,\mathrm{GeV}^2$, we can neglect Q^2 and α_s evolution

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

where $x = \min(x_0, x_2)$ and $x_0 \equiv \frac{1}{2m_\mathrm{p}L}$

Fit of J/ψ data

Energy loss model only explains the J/ψ suppression [1]

E866 - $R_{W/Be}(x_F)$

- $\hat{q}_0$ extraction with J/ψ data: $\hat{q}_0 = [0.07 - 0.09]$ GeV^2/fm
- no nPDF calculation can explain these data

Goal

- **Explore energy loss effects**
- **Test universality of transport coefficient** extracted with J/ψ data
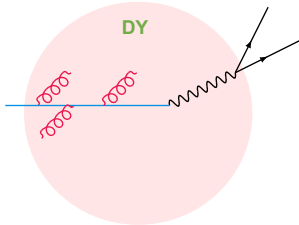
Data analysis of hA collisions at SPS energy

- pA : E906 ($\sqrt{s} = 15$ GeV) and E866 ($\sqrt{s} = 38.9$ GeV)
- πA : NA10 ($\sqrt{s} = 16.2$ GeV) and NA58/COMPASS ($\sqrt{s} = 18.9$ GeV)

Model of initial-state energy loss

Energy shift

$$\frac{\mathrm{d}\sigma(hA)}{\mathrm{d}x_{\mathrm{F}}\mathrm{d}M} = \sum_{i,j=q,\bar{q},g} \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2 \int_0^{(1-x_1)E_{\mathrm{b}}} \mathrm{d}\epsilon\, \mathcal{P}_i(\epsilon) f_i^h \left(x_1 + \frac{\epsilon}{E_{\mathrm{b}}} \right) f_j^A(x_2)$$

$$\times \frac{\mathrm{d}\widehat{\sigma}_{ij}}{\mathrm{d}x_{\mathrm{F}}\mathrm{d}M} (x_1 x_2 s)$$
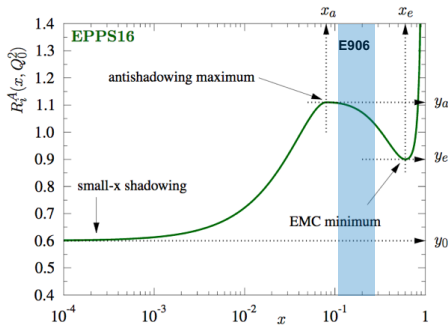
Calculation

- Drell-Yan partonic cross section at Next-to-Leading order (NLO)
- $\mathcal{P}(\epsilon)$: quenching weight related to the induced gluon spectrum
- Nuclei length L given by Glauber model
- $\hat{q}_0 = [0.07 - 0.09]\mathrm{GeV}^2/\mathrm{fm}$ fixed $\rightarrow$ no free parameter in the model !

Observable

$$R\left(\mathrm{A/B}, x_{\mathrm{F}}\right) = \frac{B}{A} \left(\frac{\mathrm{d}\sigma(\mathrm{hA})}{\mathrm{d}x_{\mathrm{F}}} \right) \times \left(\frac{\mathrm{d}\sigma(\mathrm{hB})}{\mathrm{d}x_{\mathrm{F}}} \right)^{-1}$$

pA collisions

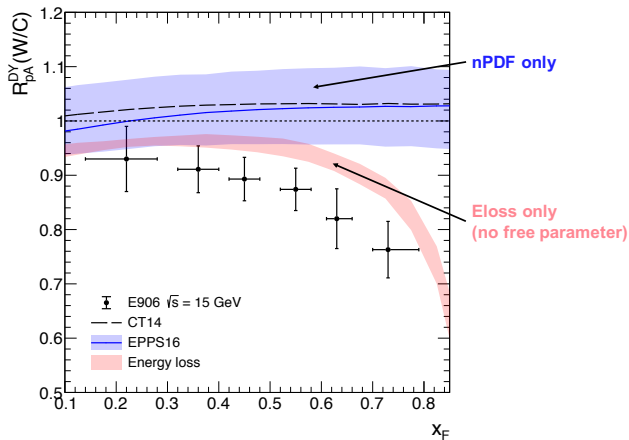**E906**

- Drell-Yan data on Carbon (12), Fe (56) and W (184)
- **Proton beam** at $E_{beam} = 120$ GeV
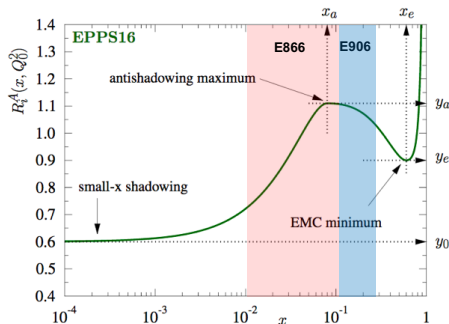- $x_2 \in [0.1\text{-}0.3]$

$$R_{pA}^{DY}(W/C, x_F)$$

- **Clear disagreement with the nPDF expectations !**
- **Qualitative agreement of energy loss shape and E906**
- **Strong indication in favour of energy loss in DY data**
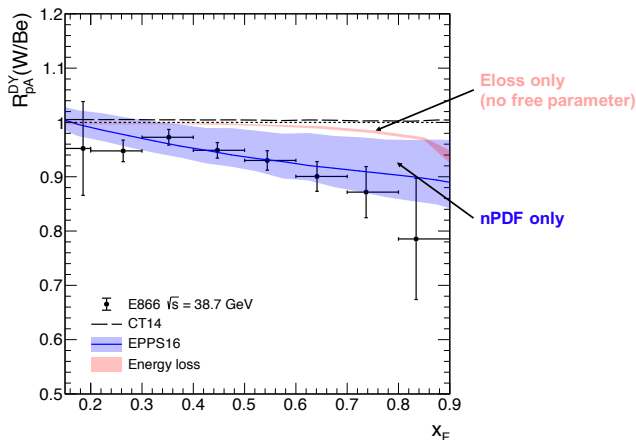
pA collisions

E866

- Drell-Yan data on Be (9), Fe (56) and W (184)
- **Proton beam** at $E_{beam} = 800$ GeV
- $x_2 \in [0.01\text{-}0.1]$

$$R^{\mathrm{DY}}_{\mathrm{pA}}(\mathrm{W/Be}, x_{\mathrm{F}})$$

- **Good agreement with the nPDF expectations (used for the global fit)**
- **Energy loss effect more important at large x_F**
- **Good data to extract nPDF** but need to **take into account energy loss effect** (few percent at large x_F)
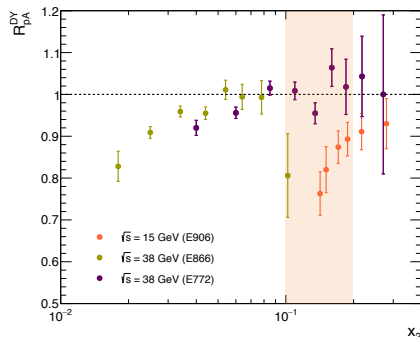
Violation of QCD factorization in DY process in pA collisions

Universality of nPDF verified in Drell-Yan process ?

$R_{pA}^{DY} = R_{pA}^{DY}(x_2)$: as a function of x_2 independent of $\sqrt{s}$

Scaling as a function of the x_2 :

- No between E866/E772 and E906 data

Indication in favour of violation of QCD factorization in pA in DY

p_T broadening phenomenology

Goal

- **Explore energy loss effects** with p_T broadening
- **Test universality** of transport coefficient extracted with J/ψ data
- **Probe the** $xG(x, Q^2)$ **dependence** at $Q^2 \sim \hat{q}L$ (**saturation scale**) and at small $x_2 \sim 10^{-5}$ thanks to LHC data

Observable

$$\Delta p_\perp^2 = \langle p_\perp^2 \rangle_{\mathrm{hA}} - \langle p_\perp^2 \rangle_{\mathrm{hp}}$$

Data analysis in hA from SPS to LHC energy (world data):

- Drell-Yan data
- J/ψ data
- Υ data

$\rightarrow$ Different color state but probing the same effect !

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

1. **Energy loss effect**
   - Affects only the normalisation of $R_{\mathrm{pA}}(p_{\mathrm{T}})$
   - 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 $R_i^{\mathrm{A}}\left(x, Q^2\right) > 1$

Data analysed

Exp.	Beam	$\sqrt{s}$ (GeV)	Process	A	Ref.
NA3	p	19.3	J/ψ	Pt	[5]
	π^-	16.7/19.3/22.9			
	π^+	19.3			
NA10	π^-	16.2/23.1	DY	W	[6]
		23.1	J/ψ		
E772	p	38.7	DY	Ca, Fe, W	[7]
			Υ	Ca, Fe, W	
RHIC	d	200	J/ψ	Au	[8]
ALICE	p	5020	J/ψ	Pb	[9]
LHCb	p	8160	J/ψ	Pb	[10]

$\rightarrow$ from SPS to LHC energies : factor 400 !

Colorimetry

Computation of broadening depending on initial and final color state

$$\Delta p_\perp^2 = \left\langle p_\perp^2 \right\rangle_{\mathrm{hA}} - \left\langle p_\perp^2 \right\rangle_{\mathrm{hp}} = \mathcal{C} \left(\hat{q}_A L_A - \hat{q}_p L_p \right)$$

with $\mathcal{C} = \frac{C_R + C_{R'}}{2 N_c}$
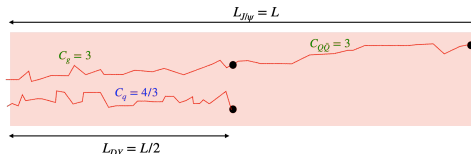
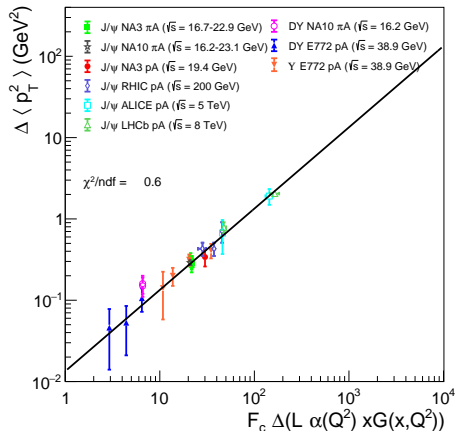| Process	Collision	$C_R + C_{R'}$
Drell-Yan	πA	C_F
Drell-Yan	pA	C_F
Quarkonium	πA	$C_F + N_c$
Quarkonium	pA	$N_c + N_c$

Broadening with simple model
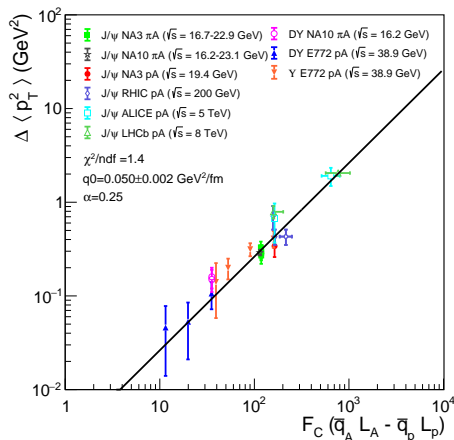
- Simple model used

$$\hat{q}_g(x) = \hat{q}_0 \left[\frac{10^{-2}}{x} \right]^{0.25}$$

- See talk of C. Marquet,
  $xG(x) \sim x^{-0.28}$

- **Very nice scaling !!**

- Extraction of $\hat{q}_0$:

$$\hat{q}_0 = 0.050 \pm 0.002 \text{ GeV}^2/\text{fm}$$
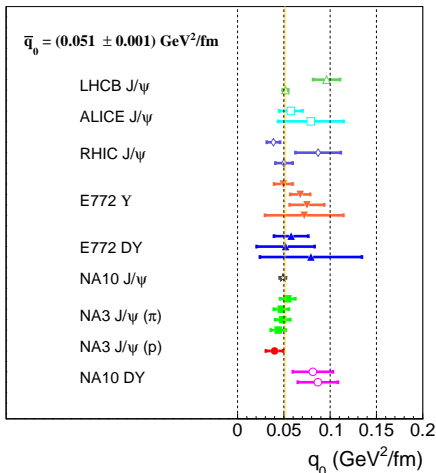
Broadening with xG(x) distribution

$$\hat{q}_g(x) = \frac{4\pi^2 \alpha_s(Q^2) N_c}{N_c^2 - 1} \rho x G(x, Q^2)$$

- Use the $xG(x, Q^2)$
- $Q^2 = \max(N \hat{q} L, Q_0^2)$
- $\alpha_s(Q^2)$ running

PDF nnlo	χ^2/ndf	N
CT14	0.6	4.7

- Extraction of transport coefficient compatible with previous studies
- Good agreement for all data
- A transport coefficient universal at all energies !

Conclusion I

1. **Initial-state energy loss plays an important role on Drell-Yan suppression**
   - E906 data shows a strong indication in favour of energy loss
   - At SPS energies, important effect !

2. **Test of universality of transport coefficient extracted with J/ψ**
   - Two different energy loss regimes but the same transport coefficient
   - Compatibility with all Drell-Yan data

3. **Nuclear PDF effects on Drell-Yan process**
   - Clear disagreement between E906 data and EPPS16 nPDF
   - nPDF effects are not dominant at SPS energies in Drell-Yan
   - Violation of QCD factorization from the comparison of E906 and E866/E772 data

Experiment	Beam energy	nPDF (EPPS16)	Energy loss
E906	120 GeV		Dominant
NA10	140 GeV	Equal	Equal/dominant at large x_F
NA58	190 GeV	Equal	Equal/dominant at large x_F
E866	800 GeV	Dominant except at large x_F	

1. **Extraction of cold nuclear matter transport coefficient**
   - Scaling in $\Delta p_\perp^2$ for different processus $\rightarrow$ common physic effect !
     - Different hard processes, different color state and a factor 400 between low and high energy
   - Extraction of transport coefficient compatible with previous studies
     - Compatible with R_{pA} study in J/ψ and DY data
   - Universality of transport coefficient at all energies !
2. $xG(x)$ dependence of transport coefficient
   - The best χ^2/ndf gives a $xG(x) \sim x^{-\alpha}$ with $\alpha = 0.25$ at $x \sim 10^{-5}$ at $Q^2 \sim \hat{q}L$ GeV^2

[1] F. Arleo, R. Kolevatov, S. Peigné, and M. Rustamova, "Centrality and $p_\perp$ dependence of J/ψ suppression in proton-nucleus collisions from parton energy loss," JHEP, vol. 05, p. 155, 2013.

[2] F. Arleo, C.-J. Naïm, and S. Platchkov, "Initial-state energy loss in cold QCD matter and the Drell-Yan process," JHEP, vol. 01, p. 129, 2019.

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PhD thesis, Colorado U., 2017.

[4] M. A. Vasilev et al., "Parton energy loss limits and shadowing in Drell-Yan dimuon production," Phys. Rev. Lett., vol. 83, p. 2304, 1999.

[5] J. Badier et al., "Experimental J/ψ Hadronic Production from 150 GeV/c to 280 GeV/c," Z. Phys., vol. C20, p. 101, 1983.

[6] P. Bordalo et al., "OBSERVATION OF A NUCLEAR DEPENDENCE OF THE TRANSVERSE MOMENTUM DISTRIBUTION OF

MASSIVE MUON PAIRS PRODUCED IN HADRONIC COLLISIONS," Phys. Lett., vol. B193, p. 373, 1987.

[7] P. L. McGaughey, J. M. Moss, and J. C. Peng, "High-energy hadron induced dilepton production from nucleons and nuclei," Ann. Rev. Nucl. Part. Sci., vol. 49, pp. 217–253, 1999.

[8] A. Adare et al., "Transverse-Momentum Dependence of the J/ψ Nuclear Modification in dAu Collisions at $\sqrt{s_{NN}} = 200$ GeV," Phys. Rev., vol. C87, no. 3, p. 034904, 2013.

[9] J. Adam et al., "Centrality dependence of inclusive J/ψ production in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV," JHEP, vol. 11, p. 127, 2015.

[10] R. Aaij et al., "Prompt and nonprompt J/ψ production and nuclear modification in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV," Phys. Lett., vol. B774, pp. 159–178, 2017.