Initial-state energy loss in cold QCD matter and the Drell-Yan process

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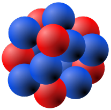
Context

Why study pA and πA collisions ? (A = nuclei)

- **Lots of measurements** from fixed-target to collider experiments
- **Study confined nuclear matter**
  - **Static matter** and **known nuclear density**
  - Important for LHC data interpretation !
- In the future, precise measurements from COMPASS

Study nuclear medium via

- Drell-Yan production
- Hadron production (mostly charmonium)

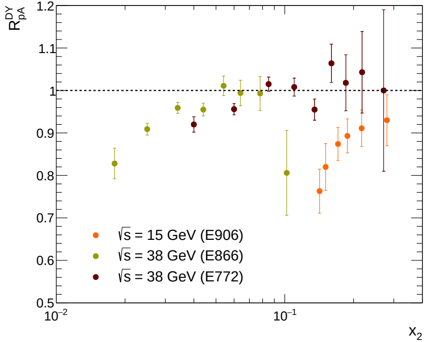


based on **F. Arleo, C-J. Naïm and S. Platchkov**
"Initial-state energy loss in cold QCD matter and the Drell-Yan process"
arXiv:1810.05120

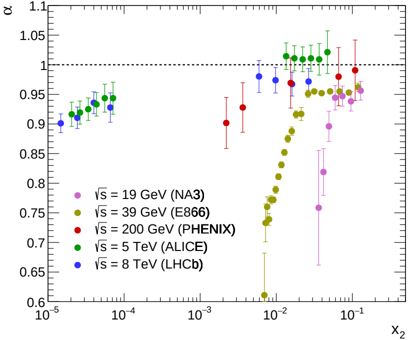
Experimental obervation

Observable : $R(\mathrm{A}/\mathrm{B}, x_2) = \frac{B}{A}\left(\frac{\mathrm{d}\sigma(\mathrm{hA})}{\mathrm{d}x_2}\right) \times \left(\frac{\mathrm{d}\sigma(\mathrm{hB})}{\mathrm{d}x_2}\right)^{-1}$

Drell-Yan production



J/ψ production

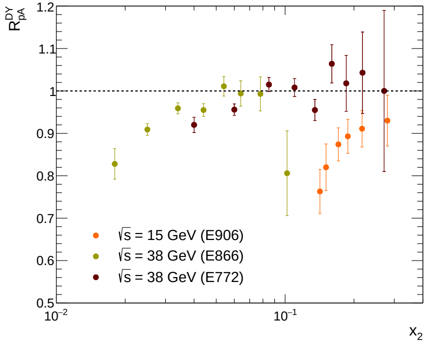


1. Strong **suppression** in J/ψ data at all $\sqrt{s}$ from SPS to LHC energies
$\sigma(\mathrm{pA} \to J/\psi + \mathrm{X}) \equiv \sigma(\mathrm{pp} \to J/\psi + \mathrm{X}) \times A^{\alpha}$

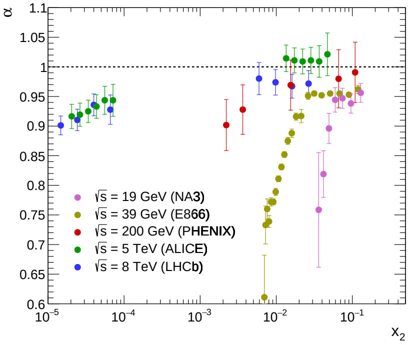
Experimental obervation

Observable : $R(\textcolor{red}{A/B}, x_2) = \frac{B}{A}\left(\frac{d\sigma(hA)}{dx_2}\right) \times \left(\frac{d\sigma(hB)}{dx_2}\right)^{-1}$

Drell-Yan production



J/ψ production

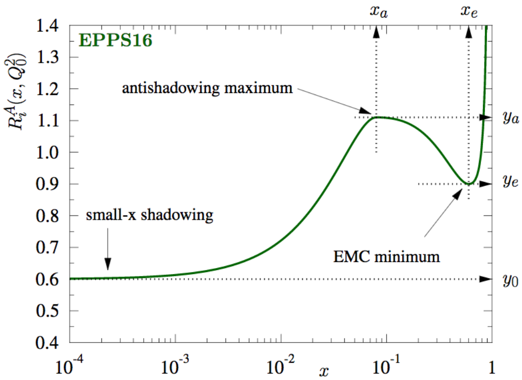


1. Strong **suppression** in J/ψ data at all $\sqrt{s}$ from SPS to LHC energies
2. **Suppression** in Drell-Yan data **lower** compared to J/ψ data
3. **No scaling** as a function of the x_2 momentum fraction

Nuclear effects

Nuclear Parton Distribution Functions (nPDF)

1. EMC effect discovered in 1983 in DIS on nuclear targets
2. **PDF is modified in nuclei** : $f_j^{p/A} \neq f_j^p$
3. Extraction of nPDF ratio $R_j^A = f_j^{p/A} / f_j^p$ with a **global fit**



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	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 π A	✓	

Nuclear effects

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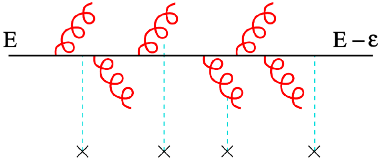
- **No scaling** as a function of x_2 in Drell-Yan and J/ψ data
  → **nPDF alone cannot explain** the data !
  ⚠**Drell-Yan data used in the nPDF global fits**

Other nuclear effects in hadron-nuclei collision ?

Parton energy loss

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

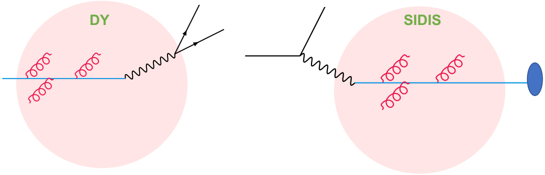


Energy loss effects

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

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

Parton energy loss in hard processes



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

- Initial state radiation

Hadron production in SIDIS : $e\mathrm{A} \to \mathrm{e} + \mathrm{h} + \mathrm{X}$

- Final state radiation

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

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

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

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

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

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

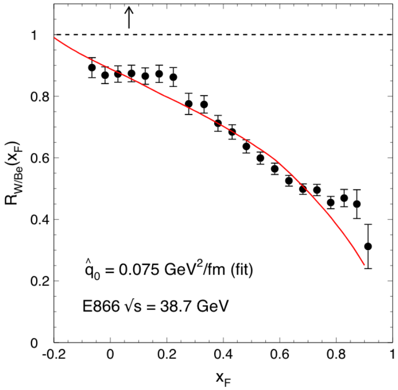
$$\langle \epsilon \rangle_{coh} \propto \sqrt{\hat{q}L}/M \cdot E \gg \langle \epsilon \rangle_{LPM}$$

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

Transport coefficient : the scattering properties of the medium

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

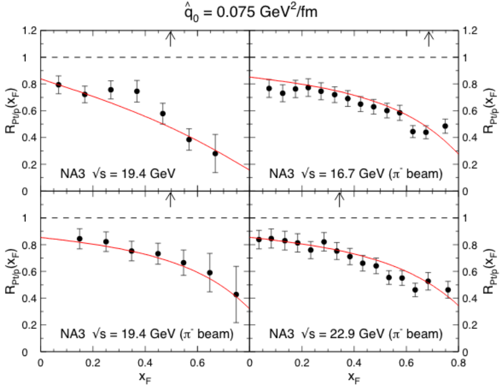
E866 - $R_{W/Be}(x_F)$



Extraction of $\hat{q}_0$ with J/ψ data:
$\hat{q}_0 = [0.07 - 0.09]$ GeV^2/fm

Fit of J/ψ data (F. Arleo and S. Peigné 1212.0434)

NA10 - $R_{Pt/D}(x_F)$

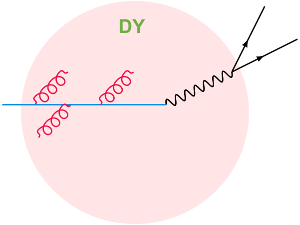


Test universality of the transport coefficient via in Drell-Yan production !

Drell-Yan phenomenology

Goal

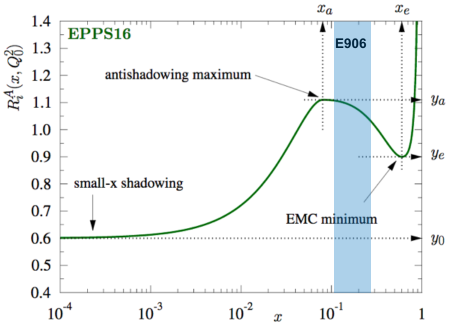
- Explore energy loss effects
- Extract transport coefficient of cold QCD matter
- Observables : Drell-Yan suppression in pA and πA collisions



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)

pA collisions

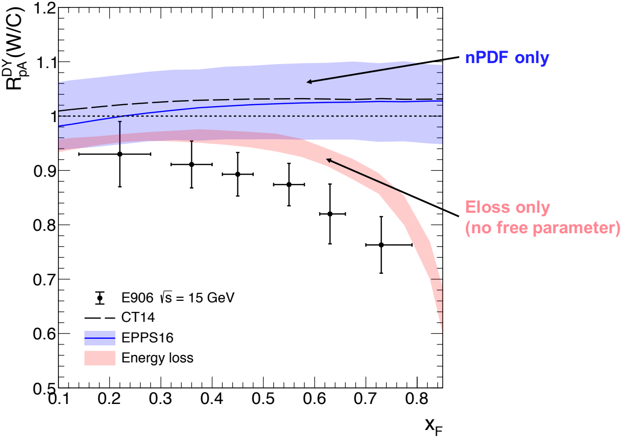


E906

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

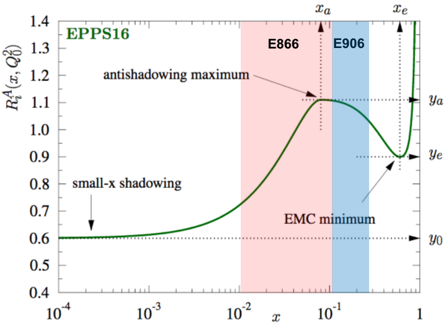
$$R_{pA}^{DY}(W/C, x_F)$$

Data analysis - E906 preliminary data



- **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

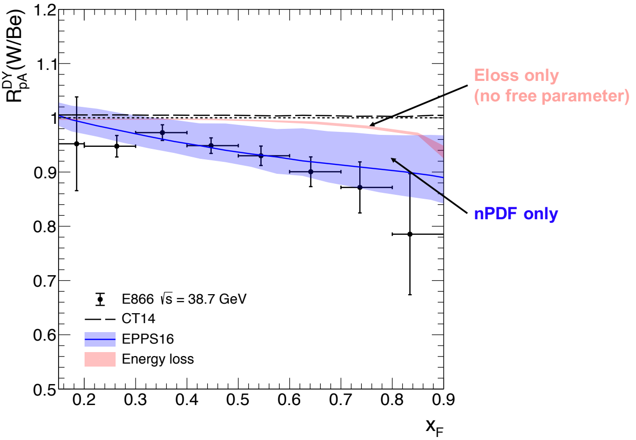


E866

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

$$R_{\mathrm{pA}}^{\mathrm{DY}}(\mathrm{W/Be}, x_F)$$

Data analysis - E866 data



- **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)

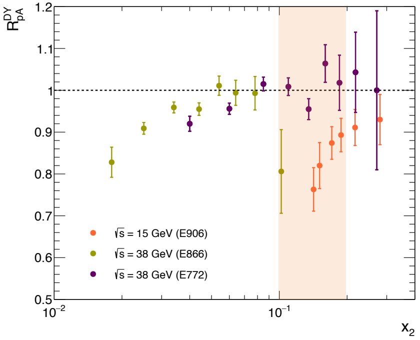
Universality of nPDF verified in Drell-Yan process ?

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

Scaling as a function of the x_2 :

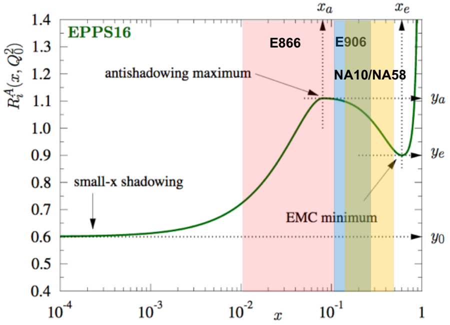
- Yes in E866/E772 data (same $\sqrt{s}$!)
- No in E906 data

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



Data analysis - NA10 data

$\pi^- A$ collisions

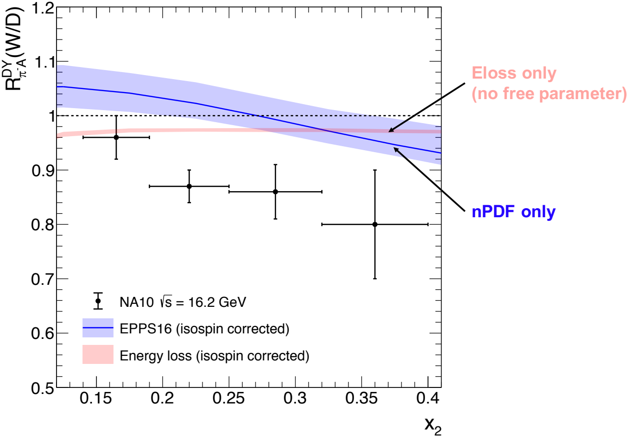


NA10

- Drell-Yan data on D (2), Pt (195)
- **Pion beam** at $E_{\text{beam}} = 140$ GeV
- $x_2 \in [0.15\text{-}0.5]$

$$R^{\text{DY}}_{\pi^- \text{A}}(\text{Pt}/\text{D}, x_\text{F})$$

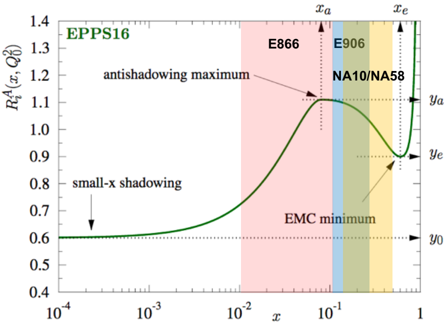
Data analysis - NA10 data



- Clear disagreement with the nPDF expectations and energy loss !
- **If both effects are taken into account, more compatible with the data** (6-7% normalization uncertainty of NA10 data)

NA58/COMPASS expectations

$\pi^- A$ collisions

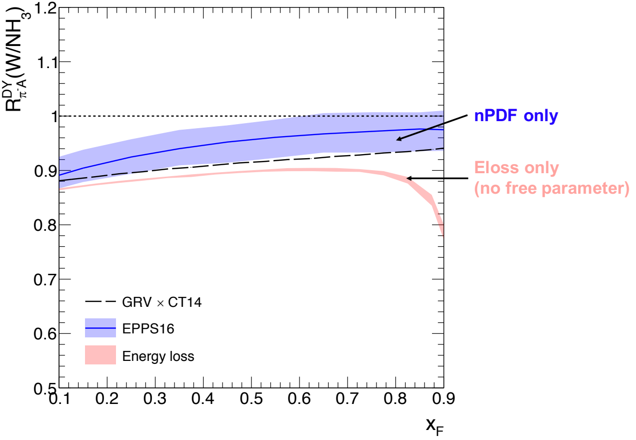


NA58/COMPASS

- 2 Drell-Yan data taking (2015 and 2018) on NH_3 (17), W (184)
- **Pion beam** at $E_{beam} = 190$ GeV
- $x_2 \in [0.15\text{-}0.5]$

$$R^{\mathrm{DY}}_{\pi^- \mathrm{A}}(\mathrm{W}/\mathrm{NH}_3, x_\mathrm{F})$$

NA58/COMPASS expectations



- **Isospin effect important** with pion beam (target valence quark distribution)
- **Energy loss shows a suppression at large x_F → future measurement will constrain $\hat{q}$** !

Conclusion

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 largex_F
E866	800 GeV	Dominant except at large x_F	