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

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based on **F. Arleo, C-J. Naïm and S. Platchkov** arXiv:1810.05120

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Contents

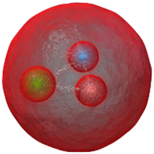
Context

Why study pA and πA collisions ?

- Lots of measurement from fixed targets ($\sqrt{s}$ = 20 GeV to 40 GeV)
- Study cold QCD matter (confined nuclear matter):
  - nuclear Parton Distribution Function (nPDF)
  - QCD radiative energy loss

Good probes to study nuclear medium

- Drell-Yan process
- Charmonium production



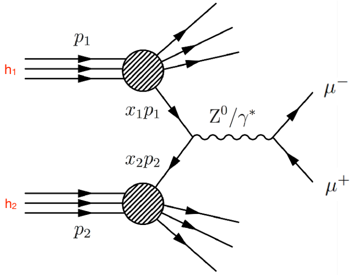
Drell-Yan production in hh collisions

Hadronic cross-section

$$\frac{d\sigma(h_1 h_2)}{dx_F\, dM} = \sum_{i,j=q,\bar{q},g} \int_0^1 dx_1 \int_0^1 dx_2 \underbrace{f_i^{h_1}(x_1) f_j^{h_2}(x_2)}_{\text{PDF}} \underbrace{\frac{d\hat{\sigma}_{ij}}{dx_F\, dM}(x_1 x_2 s)}_{\text{Hard process}}$$

Parton Distribution Function (PDF) depends on x-Bjorken:

- x_1 momentum fraction in h_1
- x_2 momentum fraction in h_2
- $x_F = x_1 - x_2,\ M = \sqrt{x_1 x_2 s}$

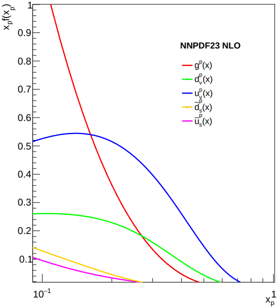


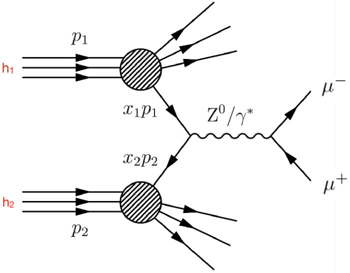
Drell-Yan production in hh collisions

Hadronic cross-section

$$\frac{\mathrm{d}\sigma(\mathrm{h_1 h_2})}{\mathrm{d}x_{\mathrm{F}}\,\mathrm{d}M} = \sum_{i,j=q,\bar{q},g} \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2 \underbrace{f_i^{\mathrm{h_1}}(x_1) f_j^{\mathrm{h_2}}(x_2)}_{\text{PDF}} \underbrace{\frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}x_{\mathrm{F}}\,\mathrm{d}M}(x_1 x_2 s)}_{\text{Hard process}}$$

Proton PDF



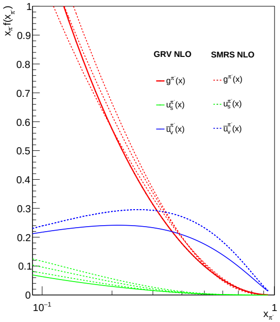


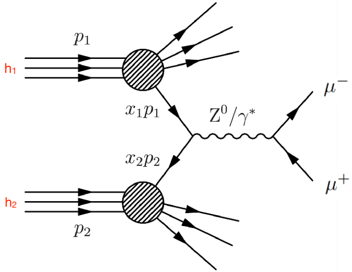
Drell-Yan production in hh collisions

Hadronic cross-section

$$\frac{d\sigma(h_1h_2)}{dx_F\, dM} = \sum_{i,j=q,\bar{q},g} \int_0^1 dx_1 \int_0^1 dx_2 \underbrace{f_i^{h_1}(x_1) f_j^{h_2}(x_2)}_{\text{PDF}} \underbrace{\frac{d\hat{\sigma}_{ij}}{dx_F\, dM}(x_1 x_2 s)}_{\text{Hard process}}$$

π^- **PDF**





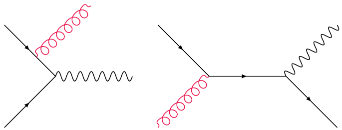
Drell-Yan production in hh collisions

Hadronic cross-section

$$\frac{\mathrm{d}\sigma(\mathrm{h_1 h_2})}{\mathrm{d}x_\mathrm{F}\,\mathrm{d}M} = \sum_{i,j=q,\bar{q},g} \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2 \underbrace{f_i^{\mathrm{h_1}}(x_1) f_j^{\mathrm{h_2}}(x_2)}_{\text{PDF}} \underbrace{\frac{\mathrm{d}\widehat{\sigma}_{ij}}{\mathrm{d}x_\mathrm{F}\,\mathrm{d}M}(x_1 x_2 s)}_{\text{Hard process}}$$

Drell-Yan process

- Leading order in $\mathcal{O}\left(\alpha^2, \alpha_s^0\right)$: $q\bar{q} \to \gamma \to l^+ l^-$
- Next-to-Leading order in $\mathcal{O}\left(\alpha^2, \alpha_s\right)$: $qg \to q\gamma^\star$ and $q\bar{q} \to g\gamma^\star$



Drell-Yan production in hA collisions

Hadronic cross-section

$$\frac{\mathrm{d}\sigma(hA)}{\mathrm{d}x_{\mathrm{F}}\,\mathrm{d}M} = \sum_{i,j=q,\bar{q},g} \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2 \underbrace{f_i^h(x_1) f_j^A(x_2)}_{\text{PDF}} \underbrace{\frac{\mathrm{d}\hat{\sigma}_{ij}}{\mathrm{d}x_{\mathrm{F}}\,\mathrm{d}M}(x_1 x_2 s)}_{\text{Hard process}}$$

Drell-Yan process

- Leading order in $\mathcal{O}\left(\alpha^2, \alpha_s^0\right)$: $q\bar{q} \to \gamma \to l^+ l^-$
- Next-to-Leading order in $\mathcal{O}\left(\alpha^2, \alpha_s\right)$: $qg \to q\gamma^\star$ and $q\bar{q} \to g\gamma^\star$

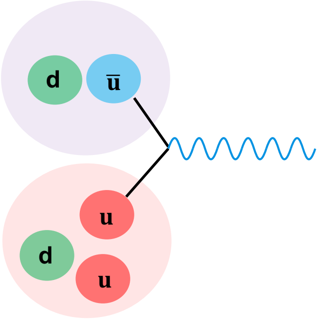
$$f_j^A(x_2, \mu_R^2) = \frac{Z}{A} f_j^p(x_2) + \frac{A-Z}{A} f_j^n(x_2)$$

Drell-Yan process in fixed target

In fixed target hadron-nucleus collisions: $x_F \geq 0 \Rightarrow x_1 \geq x_2$

$\Rightarrow \sigma(hA)$ is dominated by contributions from **beam valence quark**

- In πA collisions: probing **valence quarks** distributions in the nuclei

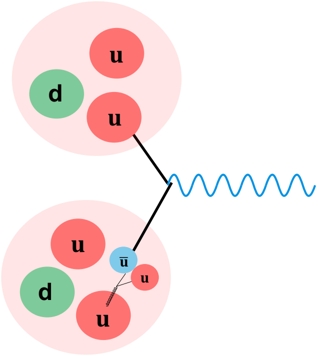


Drell-Yan process in fixed target

In fixed target hadron-nucleus collisions: $x_F \geq 0 \Rightarrow x_1 \geq x_2$

$\Rightarrow \sigma(hA)$ is dominated by contributions from **beam valence quark**

- In pA collisions: probing **sea quarks** distributions in the nuclei

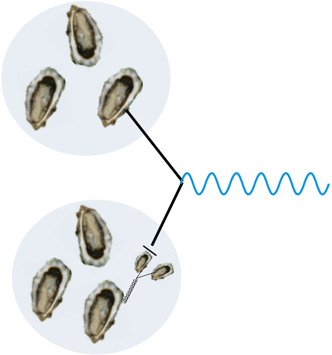


Drell-Yan process in fixed target

In fixed target hadron-nucleus collisions: $x_F \geq 0 \Rightarrow x_1 \geq x_2$

$\Rightarrow \sigma(hA)$ is dominated by contributions from **beam valence quark**

- In *Oyster-Oyster* collisions (BSM): probing **"Atlantique" sea Oyster** distributions in the Oyster



Drell-Yan process in fixed target

In fixed target hadron-nucleus collisions: $x_F \geq 0 \Rightarrow x_1 \geq x_2$

$\Rightarrow \sigma(hA)$ is dominated by contributions from **beam valence quark**

Drell-Yan nuclear dependence

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

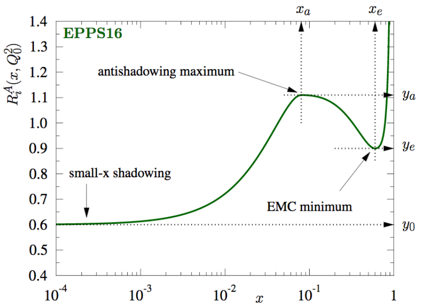
Content

Nuclear PDFs

$$f_j^A(x_2) = \frac{Z}{A} f_j^{p/A}(x_2) + \frac{A-Z}{A} f_j^{n/A}(x_2)$$

with,

$$f_j^{p/A}(x_2) = \underbrace{R_j^A(x_2)}_{\text{nuclear modif.}} \underbrace{f_j^p(x_2)}_{\text{free PDF}}$$



	EPPS16	nCTEQ15
Order in α_s	NLO	NLO
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	✓	

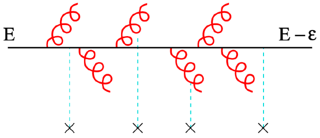
Parton energy loss

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

Energy loss effects

$$\frac{dN^{out}(E)}{dE} = \int D(\epsilon, E) \frac{dN^{in}(E+\epsilon)}{dE} \, \mathrm{d}\epsilon$$

with $D(E, \epsilon)$: probability distribution in the energy loss (quenching weight)



- DY: affects only initial state !
  1. Shift of incident parton energy
  2. $f_i^h(x_1) \rightarrow f_i^h(x_1 + \Delta x_1)$

Parton energy loss

Energy loss in initial state (small formation time $t_f \leq$ L))

$$\langle \epsilon \rangle_{LPM} \equiv \int \mathrm{d}\epsilon \, \epsilon \, \mathcal{P}_i(\epsilon) \propto \alpha_s \hat{q} \, L^2$$

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

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

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

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

Transport coefficient : the scattering properties of the medium

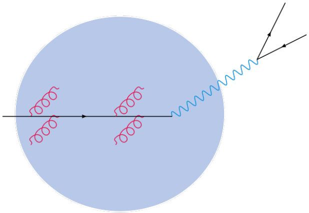
$$\hat{q}(x) = \frac{4\pi^2 \alpha_s N_c}{N_c^2 - 1} \rho x G(x) = \hat{q}_0 \left[\frac{10^{-2}}{x}\right]^{0.3} \to \hat{q}_0 = [0.07 - 0.09]\mathrm{GeV}^2/\mathrm{fm}$$

Content

Drell-Yan phenomenology

Goal

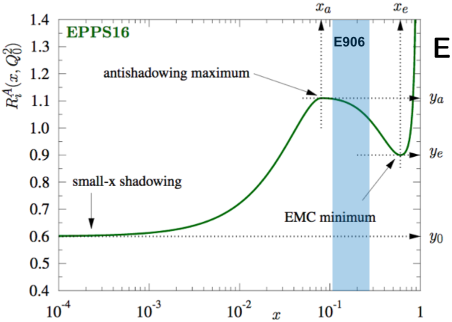
- Explore energy loss phenomenological consequences ;
- Test of universality of nPDF ;
- Extract transport coefficient of cold QCD matter ;
- <u>Observables</u> : Drell-Yan suppression in R_{pA} and $R_{\pi\mathrm{A}}$.



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

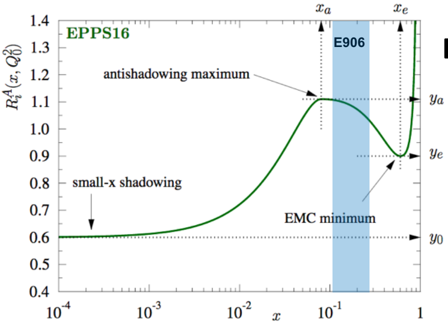


E906/SeaQuest

- Drell-Yan data on Carbon (12), Fe (56) and W (184)
- $E_{beam} = 120$ GeV : probing of sea quark of nuclei
- $x_2 \in [0.1\text{-}0.3]$

Data analysis - E906/SeaQuest preliminary data

pA collisions



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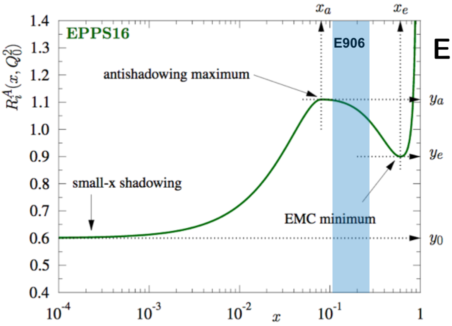
$$R_{\mathrm{p}}^{\mathrm{DY}}(\mathrm{W/C}, x_{\mathrm{F}}) \propto \left(\frac{\mathrm{d}\sigma(\mathrm{pW})}{\mathrm{d}x_{\mathrm{F}}}\right) \times \left(\frac{\mathrm{d}\sigma(\mathrm{pC})}{\mathrm{d}x_{\mathrm{F}}}\right)^{-1}$$

pA collisions



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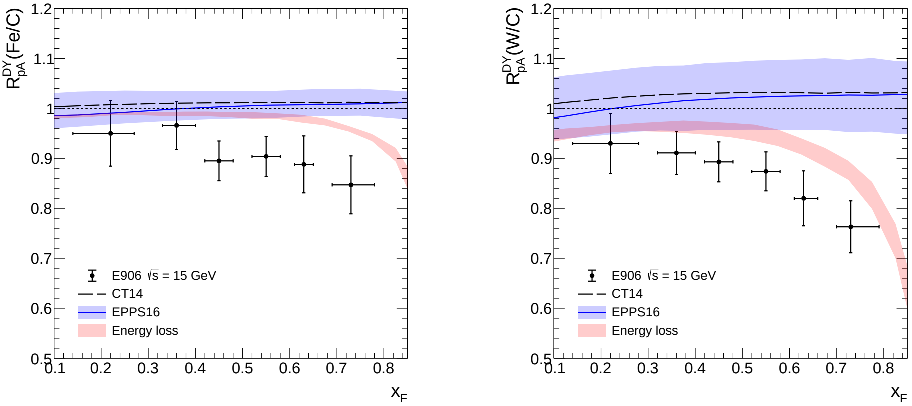
- $E_{\text{beam}} = 120$ GeV : probing of sea quark of nuclei
- $x_2 \in [0.1\text{-}0.3]$

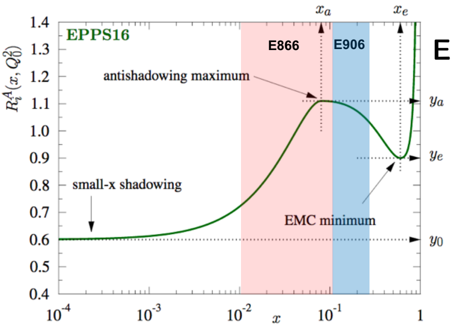
$$R_{\text{p}}^{\text{DY}}(\text{Fe/C}, x_{\text{F}}) \propto \left(\frac{\text{d}\sigma(\text{pFe})}{\text{d}x_{\text{F}}}\right) \times \left(\frac{\text{d}\sigma(\text{pC})}{\text{d}x_{\text{F}}}\right)^{-1}$$

Data analysis - E906/SeaQuest preliminary data



- Comparison between nPDF (blue curve) and energy loss model (red curve) $\hat{q}_0 \in [0.07, 0.09]$ GeV^2/fm **(no free parameter)**
- Clear disagreement with the nPDF expectations !
- Qualitative agreement of energy loss shape and E906 : **first evidence of energy loss in DY data**

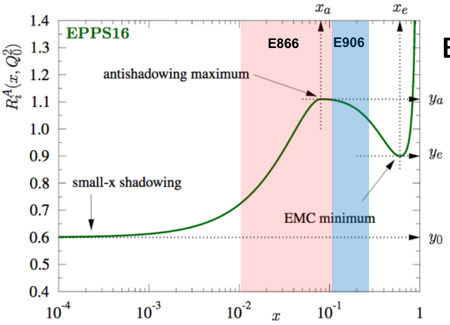
p A collisions



E866

- Drell-Yan data on Be (9), Fe (56) and W (184)
- $E_{beam} = 800$ GeV : probing of sea quark of nuclei
- $x_2 \in [0.01\text{-}0.1]$

p A collisions



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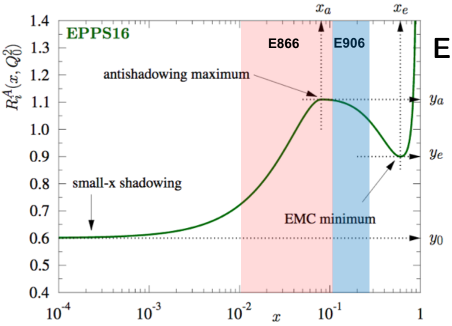
- Drell-Yan data on Be (9), Fe (56) and W (184)
- $E_{beam} = 800$ GeV : probing of sea quark of nuclei
- $x_2 \in [0.01\text{-}0.1]$

$$R_p^{DY}(W/Be, x_F) \propto \left(\frac{d\sigma(pW)}{dx_F}\right) \times \left(\frac{d\sigma(pBe)}{dx_F}\right)^{-1}$$

p A collisions

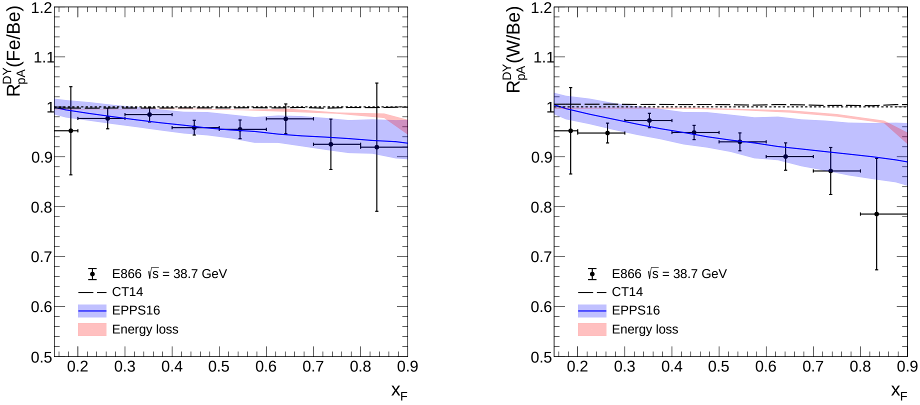


E866

- Drell-Yan data on Be (9), Fe (56) and W (184)
- $E_{beam} = 800$ GeV : probing of sea quark of nuclei
- $x_2 \in [0.01\text{-}0.1]$

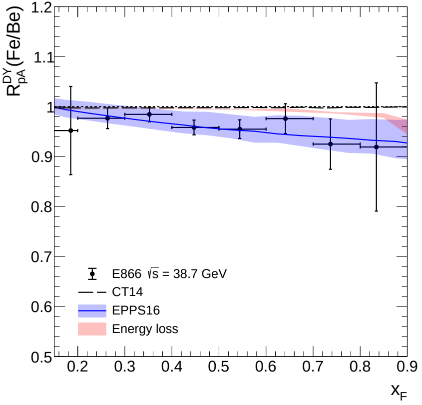
$$R_{p}^{DY}(\mathrm{Fe/Be}, x_F) \propto \left(\frac{d\sigma(p\mathrm{Fe})}{dx_F}\right) \times \left(\frac{d\sigma(p\mathrm{Be})}{dx_F}\right)^{-1}$$

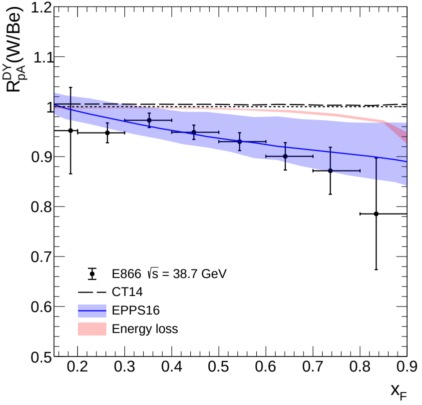
Data analysis - E866 data



- Comparison between nPDF (blue curve) and energy loss model (red curve) $\hat{q}_0 \in [0.07, 0.09]$ GeV^2/fm **(no free parameter)**
- Good agreement with the nPDF expectations but data used for the global fit
- Energy loss effect more important at large x_F in particular for W

Data analysis - E866 data

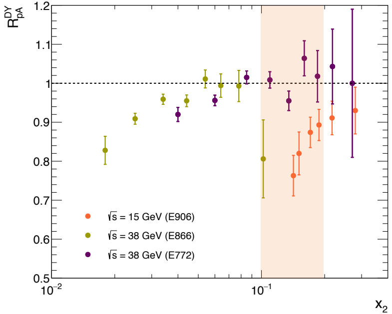




- Good agreement with the nPDF expectations but data used for the global fit
- Energy loss effect more important at large x_F in particular for W
- **Good data to extract nPDF** but need to **take into account energy loss effect** (few percent at large x_F)

In forward rapidity :

$$\frac{\mathrm{d}\sigma(\mathrm{pA})}{\mathrm{d}x_\mathrm{F}\,\mathrm{d}M} \simeq f_q^p(x_\mathrm{F}) \times \left(\sum_{j=q,\bar{q},g} f_j^\mathrm{A}(x_2)\, \frac{\mathrm{d}\widehat{\sigma}_{qj}}{\mathrm{d}x_\mathrm{F}\,\mathrm{d}M}(M^2) \right)$$

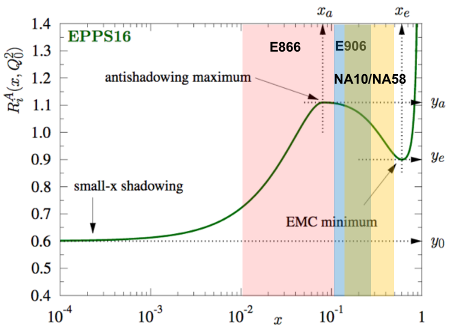


$R_{pA} = R_{pA}(f(x_2))$: function of x_2 independante of $\sqrt{s}$

E906 data shows for the first time a violation of QCD factorization in pA in DY

Data analysis - NA10 data

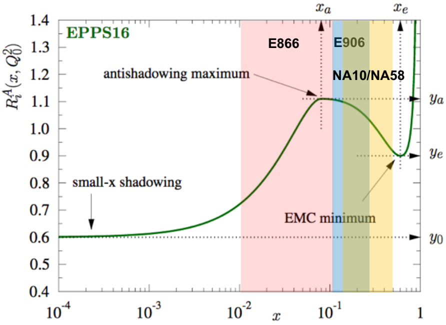
$\pi^- A$ **collisions**



NA10

- Drell-Yan data on D (2), Pt (195)
- $E_{beam} = 140$ GeV : probing of valence quark of nuclei
- $x_2 \in [0.15\text{-}0.5]$

$\pi^- A$ collisions

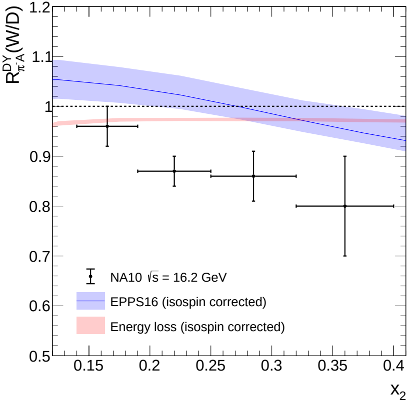


NA10

- Drell-Yan data on D (2), Pt (195)
- $E_{beam} = 140$ GeV : probing of valence quark of nuclei
- $x_2 \in [0.15\text{-}0.5]$

$$R^{\mathrm{DY}}_{\pi^-}(\mathrm{Pt/D}, x_\mathrm{F}) \propto \left(\frac{\mathrm{d}\sigma(\pi^-\mathrm{Pt})}{\mathrm{d}x_\mathrm{F}}\right) \times \left(\frac{\mathrm{d}\sigma(\pi^-\mathrm{D})}{\mathrm{d}x_\mathrm{F}}\right)^{-1}$$

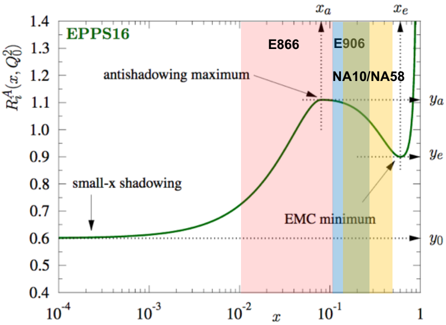
Data analysis - NA10 data



- Comparison between nPDF (blue curve) and energy loss model (red curve) $\hat{q}_0 \in [0.07, 0.09]$ GeV^2/fm **(no free parameter)**
- Clear disagreement with the nPDF expectations and energy loss !

NA58/COMPASS expectations

$\pi^- A$ collisions

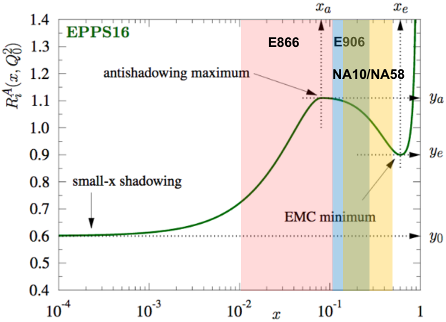


NA58/COMPASS

- 2 Drell-Yan data taking (2015 and 2018) on NH_3 (17), W (184)
- $E_{beam} = 190$ GeV : probing of valence quark of nuclei
- $x_2 \in [0.15\text{-}0.5]$

NA58/COMPASS expectations

$\pi^- A$ collisions



NA58/COMPASS

- 2 Drell-Yan data taking (2015 and 2018) on NH_3 (17), W (184)
- $E_{beam} = 190$ GeV : probing of valence quark of nuclei
- $x_2 \in [0.15\text{-}0.5]$

$$R^{DY}_{\pi^-}(W/NH_3, x_F) \propto \left(\frac{d\sigma(\pi^- W)}{dx_F}\right) \times \left(\frac{d\sigma(\pi^- NH_3)}{dx_F}\right)^{-1}$$

NA58/COMPASS expectations

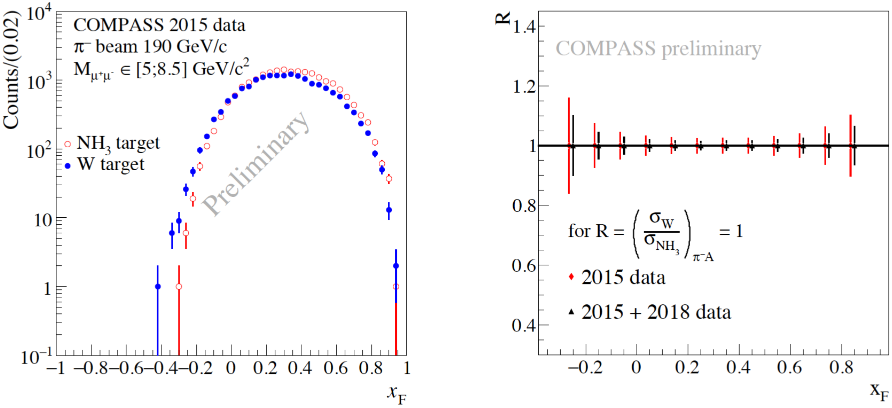
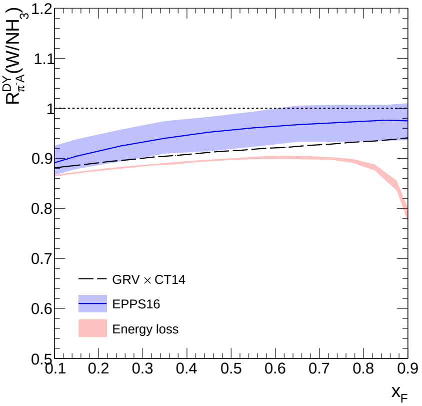


Figure: Projective statistical accuracy of the measurement of the nuclear modification effect in the pion-induced Drell-Yan at COMPASS

NA58/COMPASS expectations



- Comparison between nPDF (blue curve) and energy loss model (red curve) $\hat{q}_0 \in [0.07, 0.09]$ GeV^2/fm **(no free parameter)**
- Isospin effect important with pion beam (target valance quark distribution)
- Energy loss shows a important suppression at large x_F $\rightarrow$ **future measurement will constrain $\hat{q}$!**

Conclusion

- **Initial state energy loss**:
  1. First evidence without ambiguity of energy loss effect in E906/SeaQuest data ;
  2. Important effect at SPS energy (from $\sqrt{s} = 20$ GeV to $\sqrt{s} = 40$ GeV) ;
  3. Test of universality coefficient transport between energy loss regimes ;
  4. E906/SeaQuest preliminary data show for the first time a violation of QCD factorization in Drell-Yan process in pA collisions.

- **Nuclear PDF extraction (nPDF):**
  1. ⚠At SPS energy, energy loss is the dominant effect/equivalent effect in DY data in hA.