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

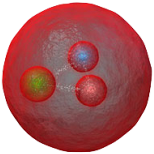
Context

Why study pA and A 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



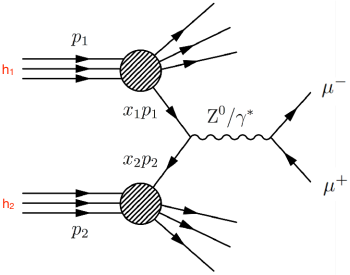
Drell-Yan production in hh collisions

Hadronic cross-section

$$\frac{d\sigma(h_1h_2)}{dx_F\, dM} = \sum_{i,j=q,\bar{q},g} \int_0^1 dx_1 \int_0^1 dx_2 \underbrace{f_i^{h_1}(x_1) f_j^{h_2}(x_2)}_{\text{PDF}} \underbrace{\frac{d\hat{\sigma}_{ij}}{dx_F\, dM}(x_1x_2s)}_{\text{Hard process}}$$

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

- x_1 momentum fraction in h_1
- x_2 momentum fraction in h_2
- $x_F = x_1 - x_2$, $M = \sqrt{x_1x_2s}$

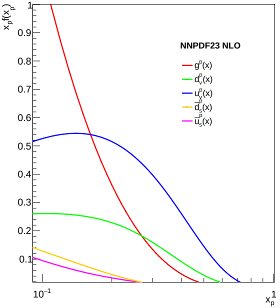


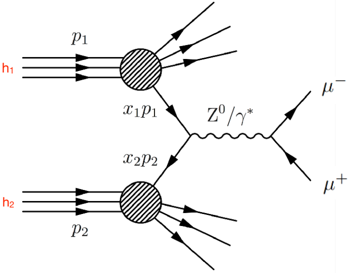
Drell-Yan production in hh collisions

Hadronic cross-section

$$\frac{d\sigma(h_1h_2)}{dx_F\,dM} = \sum_{i,j=q,\bar{q},g} \int_0^1 dx_1 \int_0^1 dx_2\, \underbrace{f_i^{h_1}(x_1) f_j^{h_2}(x_2)}_{\text{PDF}}\, \underbrace{\frac{d\hat{\sigma}_{ij}}{dx_F\,dM}(x_1x_2s)}_{\text{Hard process}}$$

Proton PDF



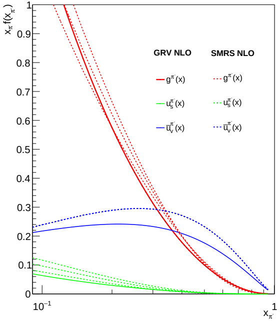


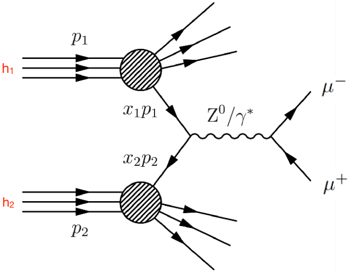
Drell-Yan production in hh collisions

Hadronic cross-section

$$\frac{d\sigma(h_1h_2)}{dx_F\,dM} = \sum_{i,j=q,\bar{q},g}\int_0^1 dx_1 \int_0^1 dx_2\, \underbrace{f_i^{h_1}(x_1)\, f_j^{h_2}(x_2)}_{\text{PDF}}\, \underbrace{\frac{d\hat{\sigma}_{ij}}{dx_F\,dM}(x_1x_2s)}_{\text{Hard process}}$$

PDF





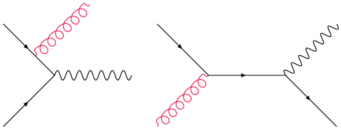
Drell-Yan production in hh collisions

Hadronic cross-section

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

Drell-Yan process

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



Drell-Yan production in hA collisions

Hadronic cross-section

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

Drell-Yan process

- Leading order in $O\ \ {}^2;\ {}^0_s$: $qq \to \ \to l^+ l$
- Next-to-Leading order in $O\ \ {}^2;\ {}_s$: $qg \to q\ ^\star$ and $qq \to g\ ^\star$

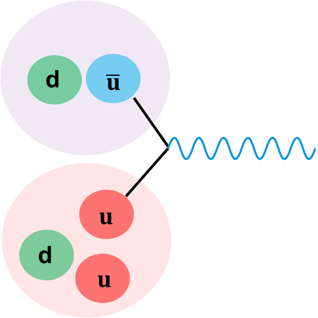
$$f_j^A(x_2;\ {}^2_R) = \frac{Z}{A} f_j^p(x_2) + \frac{A \quad Z}{A} f_j^n(x_2)$$

Drell-Yan process in fixed target

In fixed target hadron-nucleus collisions: $x_F \quad 0$) $x_1 \quad x_2$

) (*hA*) is dominated by contributions from **beam valence quark**

- In A collisions: probing valence quarks distributions in the nuclei

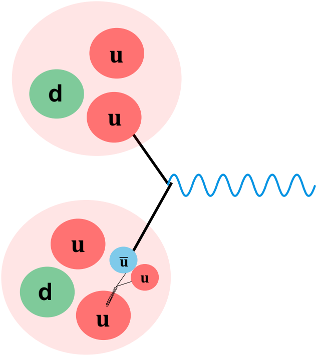


Drell-Yan process in fixed target

In fixed target hadron-nucleus collisions: x_F 0) x_1 x_2

) (*hA*) is dominated by contributions from **beam valence quark**

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

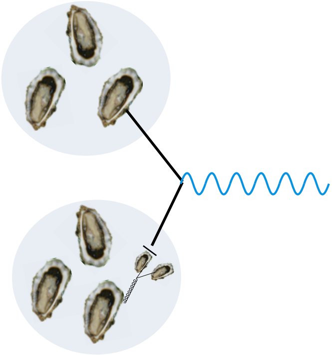


Drell-Yan process in fixed target

In fixed target hadron-nucleus collisions: $x_F \quad 0 \;) \; x_1 \quad x_2$

) (*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: $x_F \quad 0$) $x_1 \quad x_2$

) (hA) is dominated by contributions from **beam valence quark**

Drell-Yan nuclear dependence

$$R_{\mathrm{h}}^{\mathrm{DY}}(\mathrm{A{=}B}; x_{\mathrm{F}}) = \frac{B}{A} \quad \frac{\mathrm{d} \quad (\mathrm{hA})}{\mathrm{d}x_{\mathrm{F}}} \qquad \frac{\mathrm{d} \quad (\mathrm{hB})}{\mathrm{d}x_{\mathrm{F}}}^{\quad 1}$$

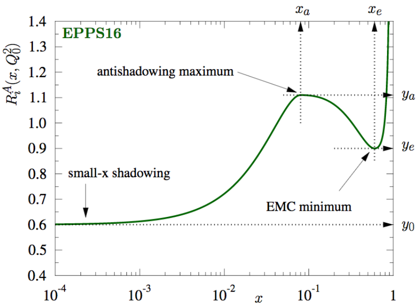
Content

Nuclear PDFs

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

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 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 A	✓	

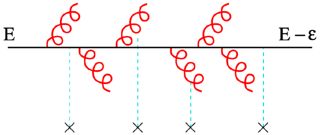
Parton energy loss

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

Energy loss effects

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

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 L))

$$h \; i_{LPM} \quad \int \mathrm{d} \quad P_i(\;) \; / \quad {}_s \hat{q} L^2$$

- hA ! `+` + X (DY)
- eA ! $e + h$ + X (SIDIS)

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

$$h \; i_{coh} \; / \; \sqrt{\hat{q}L}/M \;\; E \qquad h \; i_{LPM}$$

- hA ! $[QQ(g)]_8$ + X (Quarkonium)

Transport coe□cient : the scattering properties of the medium

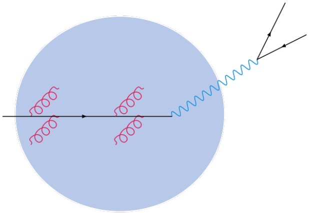
$$\hat{q}(x) = \frac{4 \;\; ^2 \;\; {}_s N_c}{N_c^2 \quad 1} \; xG(x) = \hat{q}_0 \quad \frac{10 \;\; ^2}{x} \;\; ^{0.3} \qquad ! \;\; \hat{q}_0 = [0{:}07 \quad 0{:}09]\mathrm{GeV}^2/\mathrm{fm}$$

Content

1. Hard processes to probe the nuclear medium
   - Drell-Yan production in hA collisions
2. Cold nuclear effects
   - Nuclear PDFs
   - Parton energy loss
3. Drell-Yan phenomenology
   - Data analysis
   - Violation of QCD factorization in Drell-Yan process in pA collisions
   - COMPASS expectations

Goal

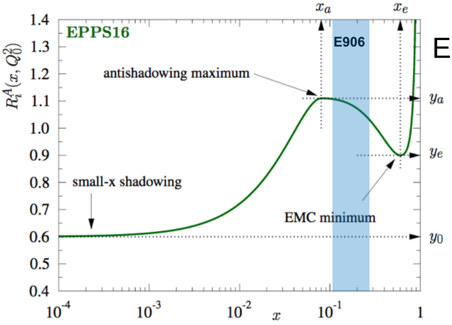
- Explore energy loss phenomenological consequences ;
- Test of universality of nPDF ;
- Extract transport coefficient of cold QCD matter ;
- Observables : Drell-Yan suppression in R_{pA} and $R_{\pi\mathrm{A}}$.



Data analysis of hA collisions at SPS energy

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

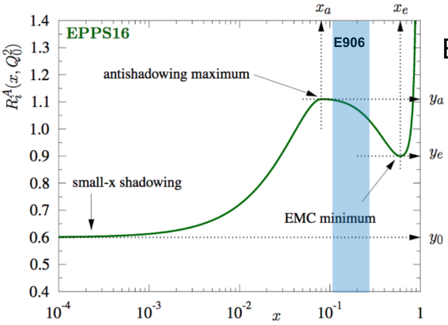
pA collisions



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 *2* [0.1-0.3]

pA collisions



E906/SeaQuest

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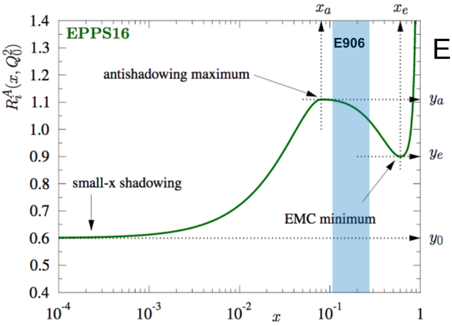
- E_{beam} = 120 GeV : probing of sea quark of nuclei
- x_2 2 [0.1-0.3]

$$R_p^{DY}(W/C; x_F) \;/\; \frac{d\ (pW)}{dx_F} \qquad \frac{d\ (pC)}{dx_F} \quad ^{1}$$

Data analysis - E906/SeaQuest preliminary data

pA collisions



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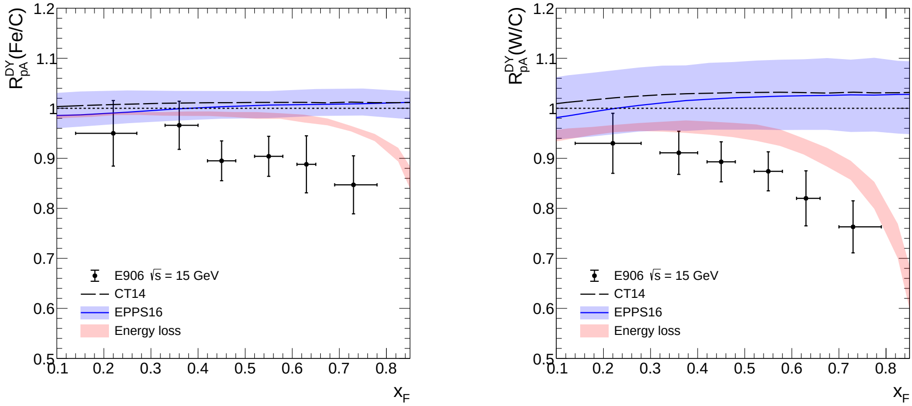
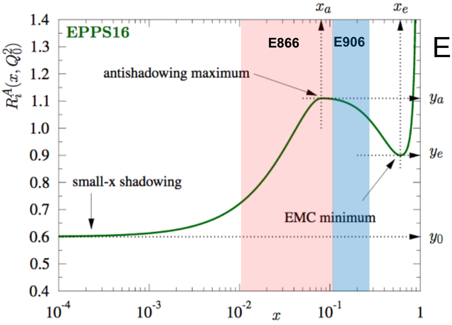
Data analysis - E906/SeaQuest preliminary data



- Comparison between nPDF (blue curve) and energy loss model (red curve) $\hat{q}_0$ 2 [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

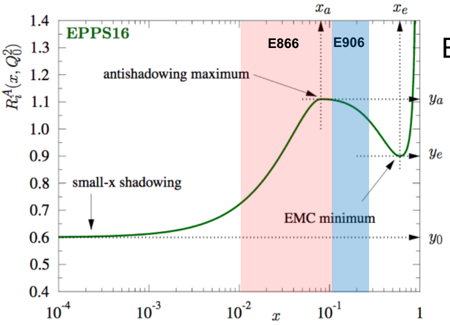


E866

- Drell-Yan data on Be (9), Fe (56) and W (184)
- E_{beam} = 800 GeV : probing of sea quark of nuclei
- x_2 *2* [0.01-0.1]

Data analysis - E866 data

p A collisions

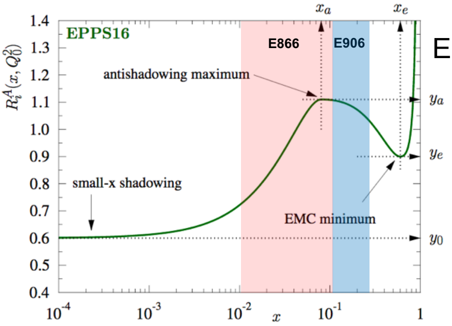


E866

- Drell-Yan data on Be (9), Fe (56) and W (184)
- $E_{beam} = 800$ GeV : probing of sea quark of nuclei
- x_2 *2* [0.01-0.1]

$$R_p^{DY}(W/Be; x_F) \;/\; \frac{d\ (pW)}{dx_F} \qquad \frac{d\ (pBe)}{dx_F}^{\;1}$$

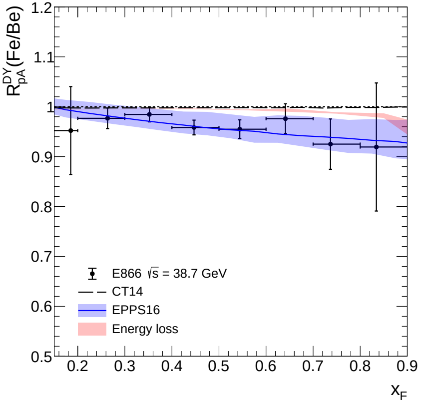
p A collisions

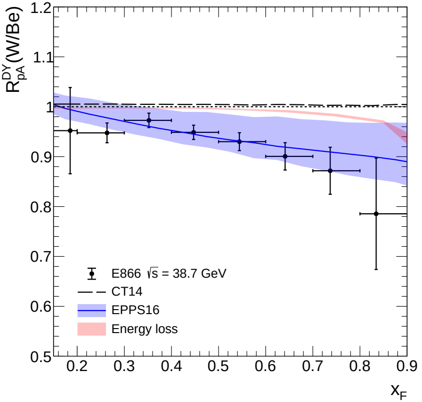


E866

- Drell-Yan data on Be (9), Fe (56) and W (184)
- $E_{beam} = 800$ GeV : probing of sea quark of nuclei
- x_2 2 [0.01-0.1]

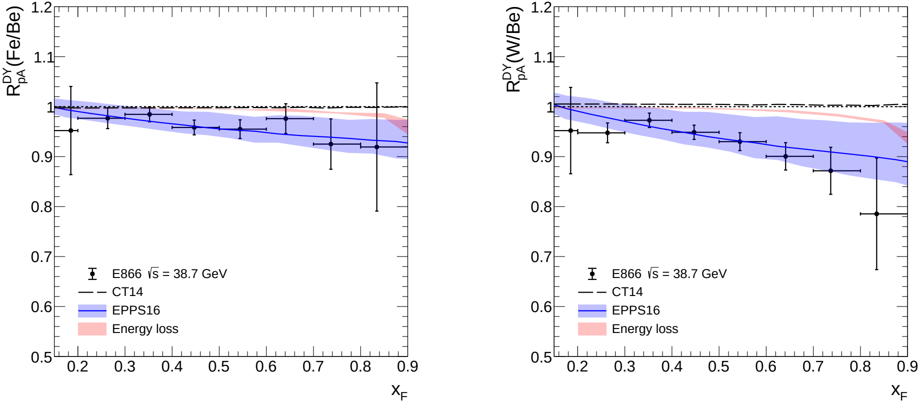
$$R_p^{DY}(Fe/Be; x_F) \;/\; \frac{d\ (pFe)}{dx_F} \qquad \frac{d\ (pBe)}{dx_F} \qquad 1$$





- 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

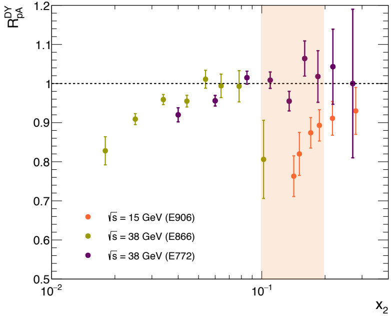
Data analysis - E866 data



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

In forward rapidity :

$$\frac{d\sigma(pA)}{dx_F\, dM} \simeq f_q^p(x_F) \left(\sum_{j=q,\bar{q},g} f_j^A(x_2)\, \frac{d\hat{\sigma}_{qj}}{dx_F\, dM}(M^2) \right)$$



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

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

A collisions

NA10

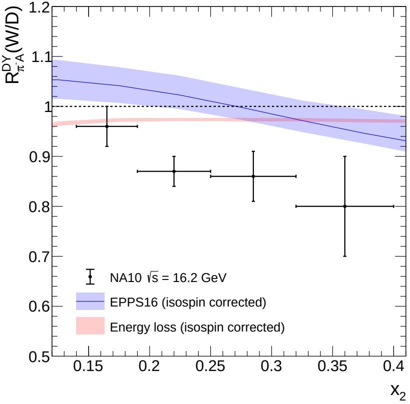
- Drell-Yan data on D (2), Pt (195)
- $E_{beam} = 140$ GeV : probing of valence quark of nuclei
- x_2 *2* [0.15-0.5]

A collisions

NA10

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

$$R_{\pi}^{DY}(Pt/D; x_F) \; / \; \frac{d\;(\quad Pt)}{dx_F} \qquad \frac{d\;(\quad D)}{dx_F}^{\;1}$$



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

NA58/COMPASS expectations

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 *2* [0.15-0.5]

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 *2* [0.15-0.5]

$$R_{\pi}^{DY}(W/NH_3; x_F) \; / \; \frac{d \; (\quad W)}{dx_F} \quad \frac{d \; (\quad NH_3)}{dx_F}^{\;1}$$

NA58/COMPASS expectations

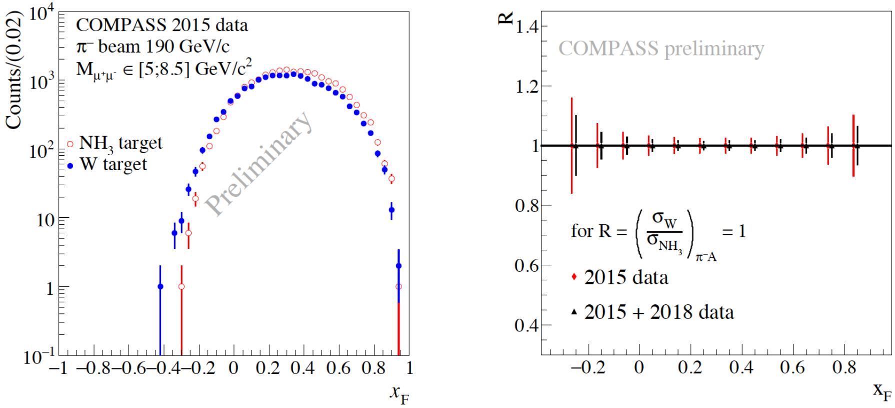
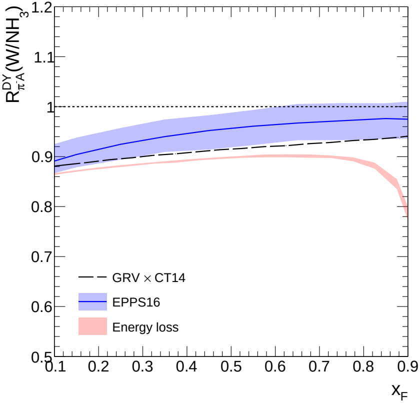


Figure: Projective statistical accuracy of the measurement of the nuclear modification effect in the pion-induced Drell-Yan at COMPASS

NA58/COMPASS expectations



- Comparison between nPDF (blue curve) and energy loss model (red curve) $\hat{q}_0$ *2* [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 *!* 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.