Probing cold QCD matter with the COMPASS experiment

C-J. Naïm
on behalf of the COMPASS Collaboration

CEA/Saclay - LLR/Ecole Polytechnique

Second LHCb Heavy Ion Workshop

September, 5th 2019 - Chia Laguna

Introduction

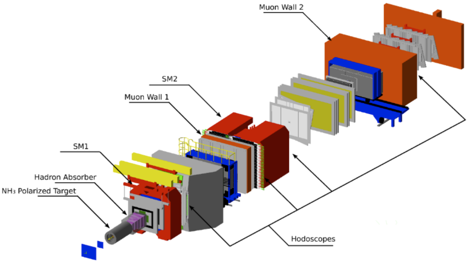
Why fixed-target experiments?

- Possible access to **large values** of $x_{\mathrm{F}} \lesssim 0.9$
- Study the A-dependence of nuclear effects
  - Nuclear Parton Distributions Function (nPDF)
  - Energy loss effects

Hard processes to study nuclear medium at COMPASS

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

COMPASS apparatus



Beam

- π^- beam at 190 GeV
- $I_{beam} \approx 7 \times 10^7\ s^{-1}$

Nuclear targets

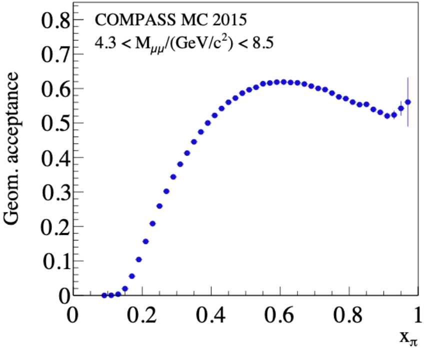
1. Ammonia (NH_3)
2. Aluminium (Al^{27})
3. Tungsten (W^{184})

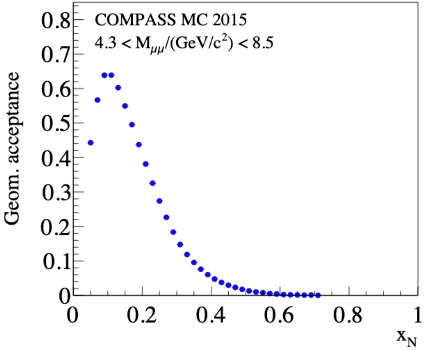
Physics data taken

- $\sim$ 4 months in 2015: high statistics for Drell-Yan ($\sim$ 30 000 events) and J/ψ ($\sim 10^6$ events) in W target
- $\sim$ 5 months in 2018: ongoing analysis

COMPASS acceptance

- **Large angular acceptance**: $8 < \theta$ (mrad) <160
- **Large kinematics acceptance** in Drell-Yan region [4.3-8.5] GeV

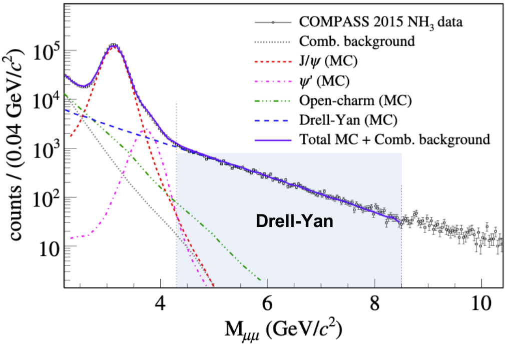




Access to large values of $x_\pi \lesssim 0.9$

Invariant mass distribution at COMPASS

- Drell-Yan in [4.3-8.5] GeV: **low signal** but **less than 4% of background**
- J/ψ peak with a **good signal/background ratio**



At COMPASS, it is possible to study these two processes

A-dependence study in fixed-target experiments

An overview (non-exhaustive !) of nuclear dependence studies

Exp.	**Beam**	$\sqrt{s}$ **(GeV)**	**Process**	**A**
E906	p	15	DY	C, Fe, W
COMPASS	π^-	18.9	DY	NH3, Al, W
			J/ψ	NH3, Al, W
NA3	p	19.4	J/ψ	H, Pt
	π^-	16.7/19.4/22.9		
	π^+	19.4		
	π^-	16.7/19.4/22.9	DY	H, Pt
NA10	π^-	16.2/23.1	DY	D, W
		23.1	J/ψ	D, W
E772	p	38.7	DY	Ca, Fe, W
E866	p	38.7	DY	Be, Fe, W
			J/ψ	Be, Fe, W

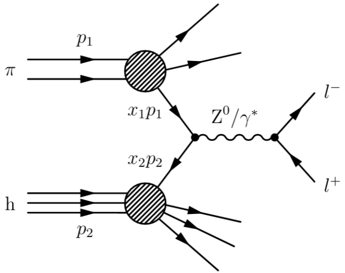
Why study A-dependence with a pion beam?

Pion-nucleus collisions

Pion-nucleus (πA) collisions

$$\frac{\mathrm{d}\sigma_{\pi \mathrm{A}}}{\mathrm{d}x_{\mathrm{F}}\mathrm{d}Q} \approx \sum_{i,j} \int \mathrm{d}x_1 f_i^{\pi}\left(x_1, Q^2\right) \int \mathrm{d}x_2 f_j^{A}\left(x_2, Q^2\right) \frac{\mathrm{d}\hat{\sigma}_{ij}\left(x_1, x_2, Q^2\right)}{\mathrm{d}x_{\mathrm{F}}\mathrm{d}Q}$$

- $\hat{\sigma}_{ij}$ 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



A-dependence of Drell-Yan procerss

Pion-nucleus (πA) collisions

$$\frac{\mathrm{d}\sigma_{\pi \mathrm{A}}}{\mathrm{d}x_{\mathrm{F}}\mathrm{d}Q} \approx \sum_{i,j} \int \mathrm{d}x_1 f_i^{\pi}\left(x_1, Q^2\right) \int \mathrm{d}x_2 f_j^{A}\left(x_2, Q^2\right) \frac{\mathrm{d}\hat{\sigma}_{ij}\left(x_1, x_2, Q^2\right)}{\mathrm{d}x_{\mathrm{F}}\mathrm{d}Q}$$

- Probing PDF in nuclei (assuming no nuclear effects)

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

$$\mathrm{d}\sigma_{\pi \mathrm{A}} = Z \mathrm{d}\sigma_{\pi \mathrm{p}} + (A - Z)\mathrm{d}\sigma_{\pi \mathrm{n}}$$

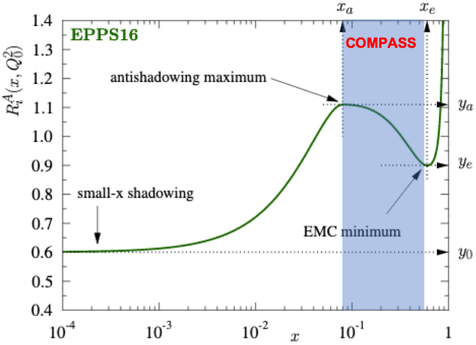
- At large $x_{\mathrm{F}} \sim x_1$, we investigate nuclear effects via

$$R_{\pi^- \mathrm{A}} \equiv \frac{1}{A} \frac{\mathrm{d}\sigma_{\pi^- \mathrm{A}}}{\mathrm{d}\sigma_{\pi^- \mathrm{p}}} \simeq \frac{4u^A\left(x_2\right) + \bar{d}^A\left(x_2\right)}{4u^p\left(x_2\right) + \bar{d}^p\left(x_2\right)}$$

Probing of valence u quark distribution from nuclear target

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. nPDF ratio $R_j^A = f_j^{p/A}/f_j^p$ via a **global fit** assumed to be **universal**



COMPASS data probe anti-shadowing and EMC regions

Nuclear Parton Distribution Functions (nPDF)

- $R_j^A = f_j^{p/A} / f_j^p$ parameterization depends on data used
- **EPSS16 nPDF supersedes the previous EPS09 analysis** including neutrino and LHC data

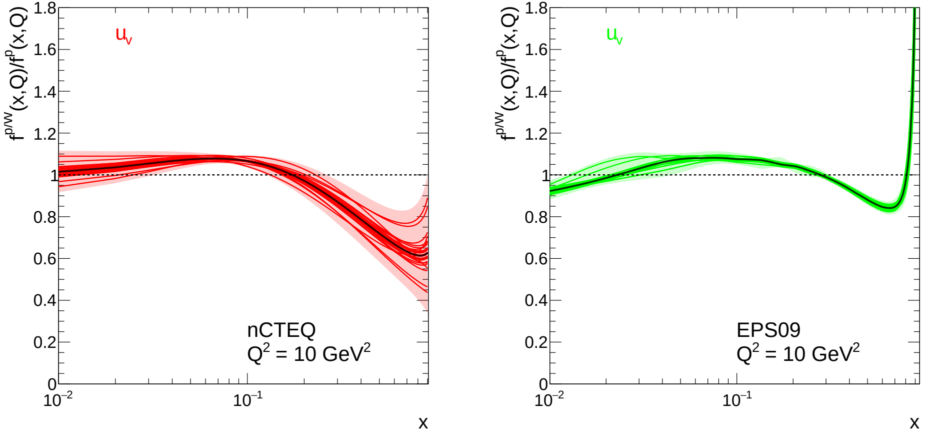
	EPS09	DSSZ	nCTEQ	EPPS16
e-DIS	✓	✓	✓	✓
ν-DIS		✓		✓
Drell-Yan pA	✓	✓	✓	✓
RHIC hadrons	✓	✓	✓	✓
LHC data				✓
Drell-Yan πA				✓

Flavor decomposition			✓	✓
Proton PDF	CTEQ6.1	MSTW2008		CT14

What can the new measurements from COMPASS bring?

Valence nPDF from nCTEQ and EPS09

W nuclei (A=184) from nCTEQ and EPS09 groups



- nCTEQ: global fit of $f^{p/A}$ predicts EMC effect $R^{W}_{u_v} \lesssim 0.8$
- EPS09: global fit of $R^A_j = f^{p/A}/f^p$ predicts **smaller EMC effect**

Valence nPDF from EPPS16

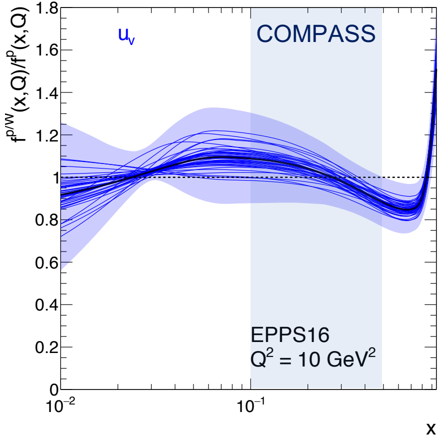
W nuclei (A=184) from EPPS16 group

- $R_j^A = f^{p/A}/f^p$ from global fit
- $Z^0/W^{+/-}$ data from LHC
  1. $u\bar{d} \to W^+$
  2. $d\bar{u} \to W^-$

  constrain $10^{-3} \lesssim x \lesssim 10^{-1}$

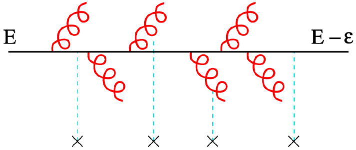
$\to$ To take into account **flavor dependence** from LHC, 5 more free parameters compared to EPS09

$\to$ **Larger error band** compared to previous analysis from EPS09



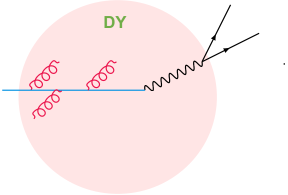
COMPASS Drell-Yan data will further constrain anti-shadowing and EMC regions for u_v quark

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. Hadron production: $\mathrm{hA} \to q/g(\to h') + \mathrm{X}$
   - Initial state radiation
   - Final state radiation
   - Interferences initial/final state radiation



Energy loss effects

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

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

$\mathrm{hA} \to \ell^+\ell^- + \mathrm{X}$ (Drell-Yan)

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

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

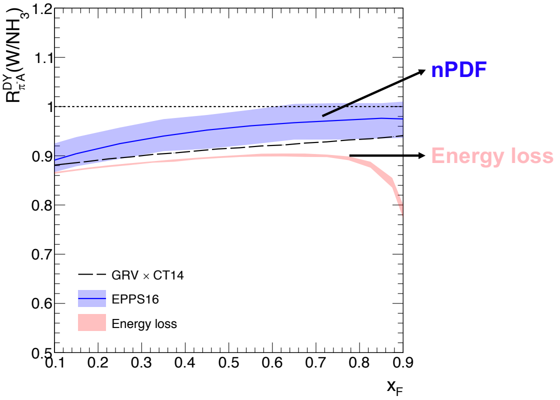
$\mathrm{hA} \to [Q\bar{Q}(g)]_8 + \mathrm{X}$ (Quarkonium)

Transport coefficient : the scattering properties of the medium

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

2 different energy loss dynamics but the same transport coefficient

Energy loss prediction for Drell-Yan data - Arleo et al (2019)

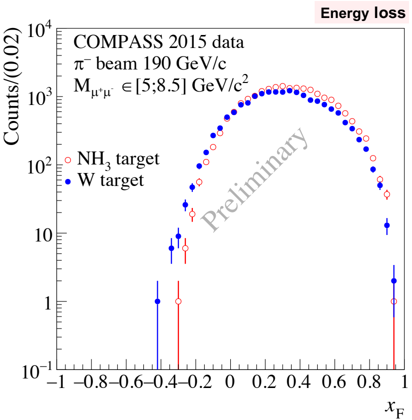


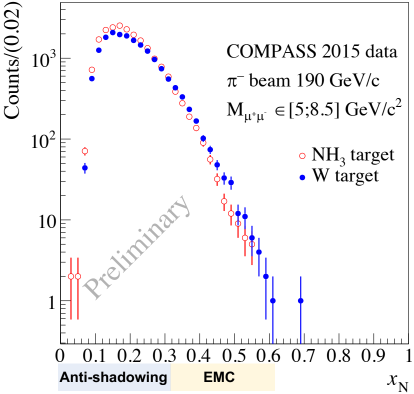
- Energy loss **plays a key role in Drell-Yan data** at all x_F
- **Important suppression** at $x_F \sim 0.7$ due to energy loss

COMPASS can constrain energy loss effect

What can COMPASS Drell-Yan data bring?

Drell-Yan kinematics distributions at COMPASS

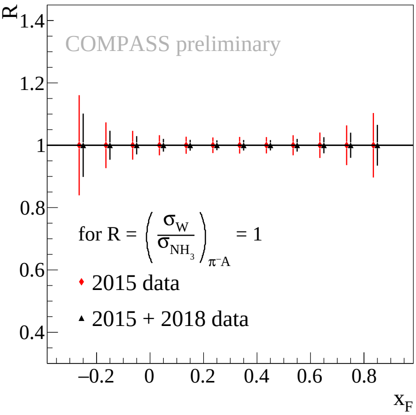


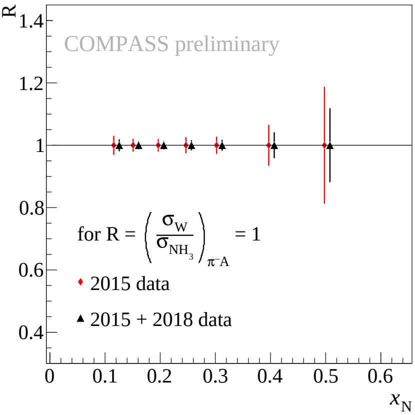


- **Large acceptance** up to $x_F \lesssim 0.9$
- Probing anti-shadowing and EMC effect with good statistics
- **Access large $x_F \sim 0.7$** where energy loss effects dominate

What can COMPASS Drell-Yan data bring?

Uncertainties projection of Drell-Yan cross section ratios





- In red, uncertainties projection only for 2015 data
- In black, uncertainties projection for 2015 and 2018 data

A-dependence of J/ψ in pion collisions

J/ψ production in πA collisions more delicate due to:

1. ignorance about production model
   $\rightarrow$ but nuclear dependence depends negligibly on the production model
2. color charge in initial and final states
   $\rightarrow$ sensitive to coherent energy loss
3. two possible channels $q\bar{q}$ and gg at leading order:

At large $x_F \sim x_1$, J/ψ cross section is dominated by valence quark from π^-

$$R^{J/\psi}_{\pi^-\mathrm{A}} \equiv \frac{1}{A}\frac{\mathrm{d}\sigma_{\pi^-\mathrm{A}}}{\mathrm{d}\sigma_{\pi^-\mathrm{p}}} \simeq \frac{u^A(x_2) + \bar{d}^A(x_2)}{u^p(x_2) + \bar{d}^p(x_2)}$$

Probing of quark distributions from nuclear target

J/ψ production in pion collisions

But at $0 \lesssim x_F \ll 1$, the situation is more complex:

- the **sub-processes** $q\bar{q}$ and gg **depend on the pion PDF**

$$\sigma^{J/\psi} = \sigma_{gg} + \sigma_{\overline{q}q}$$

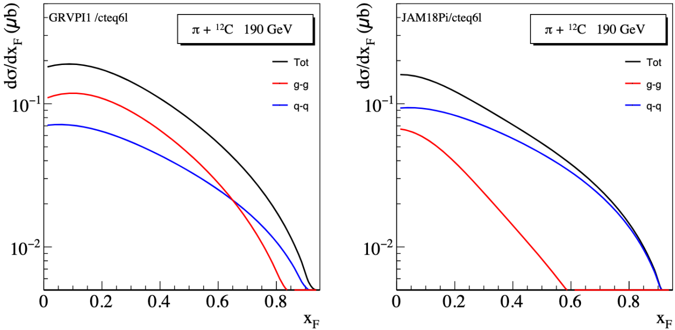
- the **last pion PDF from JAM is more constraint** at small $x_\pi \sim 10^{-3}$ thanks to leading neutron electroproduction from HERA
- the **gluon distribution changes significantly between GRV and JAM**

π^- PDF	$\langle x_\pi \rangle_g$	$\langle x_\pi \rangle_v$	$\langle x_\pi \rangle_s$
GRV	0.45	0.36	0.19
JAM	0.37	0.45	0.18

What is the impact on the J/ψ absolute cross section calculation ?

J/ψ production in pion collisions

Color Evaporation Model (CEM) calculation at leading order



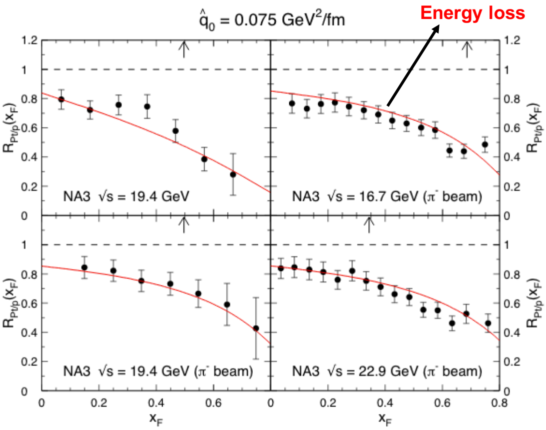
- GRV gives gg dominant at $0 \lesssim x_F \lesssim 0.8$
- JAM gives $q\bar{q}$ dominant at all x_F

$\Big\}$ Unknown initial state

Need to study absolute cross sections to constrain nPDF

Suppression observed in J/ψ data

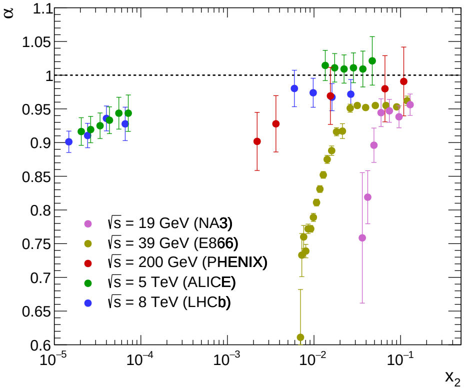
Energy loss dominant effect in the J/ψ data - Arleo et al (2012)



- Important suppression at large x_F **explained by energy loss effect**
- Different suppression for p and π beam at the same energy

Energy loss effects on J/ψ production

Factorisation breaking observed in J/ψ data - Arleo et al (2019)



- No scaling as a function of the x_2 momentum fraction
- **Energy loss effect more important** than nPDF effect

Contradict results to expectations from nPDF

COMPASS, new precise measurements from J/ψ data

COMPASS can

- access large values of $x_F \lesssim 0.9$
- extract the A-dependence using 2 nuclear targets (Al and W)
- have more statistics compared to NA3 (limited because of statistics on proton target)

Exp.	Proj.	Beam (GeV)	A	B
NA3	π^-	200	H (3000)	Pt (131000)
COMPASS	π^-	190	NH_3 ($\sim 10^6$)	W ($\sim 10^6$)

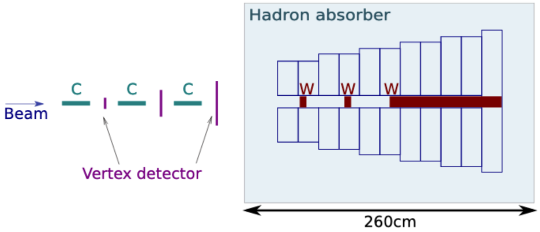
- further **constrain the transport properties** with statistics never reached at this beam energy with pions

Ongoing analysis ...

The story of fixed target experiment at CERN is not finished (hopefully!)

2022-2024: COMPASS++/AMBER proposal - Adams et al (2019)

- Use π^+ and π^- beams of W and C nuclear targets at 190 GeV
- Good opportunity to study nuclear matter



Drell-Yan opportunity

- access to the valence d quarks of nuclei with π^+ beam

J/ψ opportunity

- J/ψ on C target can shed light on the production model

Conclusion

A-dependence study at COMPASS experiment

- High statistics of J/ψ and DY events on 3 nuclear targets
- Access large values of $x_{\mathrm{F}} \lesssim 0.9$
- Good place to study cold nuclear effects to constrain nPDF and medium transport properties

Drell-Yan data can give a constraint

- on valence u quark nPDF in anti-shadowing and EMC regions
- on energy loss effect at large $x_F \sim 0.7$

J/ψ data

- can shed light on the production model and the initial partonic state
- extract the transport properties of nuclear matter and compare them with those of DY