Probing cold QCD matter with the COMPASS experiment

C-J. Naïm

CEA/Saclay - LLR/Ecole Polytechnique

GDR QCD

November, 25th 2019 - Orsay





Cold QCD matter effects in fixed-target experiments:

- \bullet Access to large values of $x_{\rm F} \lesssim 0.9$ and low values of $p_\perp \lesssim {\sf M}$
- Study the A-dependence of nuclear effects
 - Nuclear Parton Distributions Function (nPDF)
 - Energy loss effects

Observable:
$$R_{hA}(x_{F}) \equiv \frac{1}{A} \frac{d\sigma_{hA}}{dx_{F}} / \frac{d\sigma_{hp}}{dx_{F}}$$

Two hard processes to study nuclear medium at COMPASS

- Drell-Yan production
 - $hA \rightarrow \ell^+ \ell^- + X$
 - colorless final state
- Hadron production (mostly charmonium)
 - $hA \rightarrow q/g (\rightarrow h') + X$
 - color in initial and final state

COMPASS apparatus



Beam

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

Nuclear targets

- Ammonia (NH₃)
- Aluminium (Al²⁷)
- 3 Tungsten (W¹⁸⁴)

Physics data taken

- ~ 4 months in 2015: high statistics for Drell-Yan (~ 30 000 events) and J/ψ (~ 10⁶ events) in W target
- ullet ~ 5 months in 2018: ongoing analysis

COMPASS acceptance

- Large angular acceptance: $8 < \theta \pmod{160}$
- 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

Empirical observations: from previous experiments

- More suppression for J/ψ compared to DY for both $x_{\sf F}$ and $p_{\perp} \lesssim M$
- $\bullet\,$ Cold nuclear matter affects differently DY and J/ψ data



Empirical observations: from previous experiments

- ullet More suppression for J/ψ compared to DY for both $x_{\sf F}$ and $p_\perp \lesssim M$
- $\bullet\,$ Cold nuclear matter affects differently DY and J/ψ data



• No scaling as a function of the x_2 momentum fraction from target

An effect at work to be understood

A-dependence study in fixed-target experiments

Exp.	Beam	\sqrt{s} (GeV)	Process	Α
E906	р	15	DY	C, Fe, W
COMPASS	π^{-}	18.9	DY	NH3 ¹ , Al, W
			J/ψ	NH3, Al, W
NA3	р	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	р	38.7	DY	Ca, Fe, W
E866	р	38.7	DY	Be, Fe, W
			J/ψ	Be, Fe, W

ightarrow New data for both DY and J/ψ from COMPASS experiment

¹NH3+He mix

Possible explanations :

- nuclear PDF effects (shadowing and EMC)
 - \rightarrow but no scaling as a function of x_2
- Energy loss effects
- Both effects ?

What COMPASS can bring with DY and quarkonia processes ?

- Probing nPDF and energy loss effects as a function of $x_{\rm F}$
- Probing transverse momentum broadening as a function of p_{\perp}

	EPS09	DSSZ	nCTEQ	EPPS16
e-DIS	√	\checkmark	\checkmark	\checkmark
u-DIS		\checkmark		\checkmark
Drell-Yan pA	√	\checkmark	\checkmark	\checkmark
RHIC hadrons	√	\checkmark	\checkmark	\checkmark
LHC data pA				\checkmark
Drell-Yan π A				\checkmark

Flavor decomposition			\checkmark	\checkmark
Proton PDF	CTEQ6.1	MSTW2008		CT14

- The parameterization of the nuclear modification factor depends on data used for the global fit
- New nPDF set from EPPS16 constrained by DY data in πA

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



Can affect differently hard processes:

- $\textcircled{ I Drell-Yan process: } hA \rightarrow \ell^+\ell^- + X$
 - Initial state radiation
- 2 Hadron production: $hA \rightarrow q/g(\rightarrow h') + X$
 - Initial state radiation
 - Final state radiation
 - Interferences initial/final state radiation



Energy loss effects

- Energy loss in initial or final state (small formation time $t_f \lesssim L$) $\langle \epsilon \rangle_{\text{LPM}} \propto \alpha_s \hat{q} L^2$ hA $\rightarrow \ell^+ \ell^- + X$ (Drell-Yan)
- Energy loss in initial/final state (large formation time $t_f \gg L$) $\langle \epsilon \rangle_{coherent} \propto \sqrt{\hat{q}L}/M \cdot E \gg \langle \epsilon \rangle_{LPM}$ $hA \rightarrow [Q\bar{Q}(g)]_8 + X$ (Quarkonium)
- 3 p_{\perp} broadening effect

$$\Delta p_{\perp}^2 = \left< p_{\perp}^2 \right>_{\rm hA} - \left< p_{\perp}^2 \right>_{\rm hp} = \hat{q}L$$

Transport coefficient : the scattering properties of the medium

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

Probing nPDF and radiative energy loss in DY and J/ψ data at COMPASS



Drell-Yan expectations at COMPASS

Energy loss prediction for Drell-Yan data - [CJ-Naïm et al (2019)]



- Energy loss plays a key role in Drell-Yan data at all x_F
- Important suppression at $x_{\rm F} \sim 0.7$ due to energy loss

What can COMPASS Drell-Yan data bring?

Drell-Yan kinematics distributions at COMPASS



- Probing anti-shadowing and EMC effect with good statistics
- Access large $x_{\rm F} \sim 0.7$ where energy loss effects dominate
- New information about nuclear matter effects at large x

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

COMPASS can

- $\bullet\,$ access large values of $x_{\rm F} \lesssim 0.9$
- 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	В
NA3	π^{-}	200	H (3000)	Pt (131000)
COMPASS	π^{-}	190	$\rm NH_{3}~(\sim 10^{6})$	W ($\sim 10^6$)

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

Ongoing analysis ...

Probing transverse momentum broadening with DY and J/ψ data



p_{\perp} broadening

[CJ-Naïm et al, in preparation]

- New observable to extract the transport coefficient
- Probe the dependence of the gluon distribution and saturation scale
- Check the universality of the radiative energy loss and p_{\perp} broadening



p_{\perp} broadening effect

$$\Delta p_{\perp}^2 = \left< p_{\perp}^2 \right>_{\rm hA} - \left< p_{\perp}^2 \right>_{\rm hp} = \hat{q}L \propto x G(x)$$

Colorimetry

Broadening depends on initial and final Casimir (C) color factors

$$\Delta p_{\perp}^2 = rac{C_R + C_{R'}}{2N_c} \left(\hat{q}_{\mathrm{A}} L_{\mathrm{A}} - \hat{q}_p L_p
ight)$$

 $L_{J/\psi} = L$ $C_g = 3$ $C_g = 4/3$ $L_{DY} = L/2$

• Drell-Yan -
$$C_q = 4/3$$

- Quarkonia in pA $\mathcal{C}=\mathcal{C}_g+\mathcal{C}_{Q\bar{Q}}=3+3$
- Quarkonia in πA $C = C_{\bar{q}} + C_{Q\bar{Q}} = 4/3 + 3$

• Simple model used

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

- $xG(x,\hat{q}L) \propto x^{-0.25}$ at $x \sim 10^{-5}$
- Extraction of q_0 $q_0 = 0.050 \pm 0.02 \text{ GeV}^2/\text{fm}$



 \rightarrow Remarkable scaling from low to high energies



- Universality of transport coefficient *q*₀
- Compatibility with radiative energy loss extraction



COMPASS can give an additional important constrain from DY and J/ψ

DY and J/ψ complementary probes to study the nuclear matter:

- $\bullet\,$ radiative energy loss reproduces J/ψ data in nuclear collisions
- $\bullet\,$ scaling observed from low to high energy in p_{\perp} broadening in world data

A-dependence study at COMPASS experiment:

- high statistics of J/ψ and DY events on 3 nuclear targets (NH3, AI and W)
- access large $x_{
 m F} \lesssim$ 0.9 and low $p_{\perp} \lesssim M$
- good place to study nPDF and medium transport properties
- \bullet extract the transport coefficient in both J/ψ and DY via
 - radiative energy loss
 - transverse momentum broadening

Other nuclear effects in the broadening calculation

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

- Energy loss effect
 - Affects only the normalisation of $R_{pA}(p_T)$
 - Cancellation in Δp_{\perp}^2
- InPDF effect
 - $0 < p_{\perp} \lesssim M$: fixed target experiment, cancellation in Δp_{\perp}^2
 - $p_{\perp}\gtrsim M$: LHC case, very large error bar in gluon sector but

$$\frac{\mathrm{d}\sigma_{\mathrm{hA}}^{\mathrm{nPDF}}}{\mathrm{d}\rho_{\perp}} = \underbrace{R_{i}^{\mathrm{A}}\left(x_{2}\left(\rho_{\perp}\right),Q^{2}\right)}_{\mathrm{R}_{i}} \times \frac{\mathrm{d}\sigma_{\mathrm{hp}}}{\mathrm{d}\rho_{\perp}}$$

if only normalisation : cancellation in Δp_{\perp}^2

• at $x \lesssim 10^{-4}$: shadowing region $R_i^A(x, Q^2) < 1$ • at $0.05 \lesssim x_2 \lesssim 0.2$: antisadowing region $R_i^A(x, Q^2) > 1$