Probing cold QCD matter with the COMPASS experiment

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Introduction

Cold QCD matter effects in fixed-target experiments:

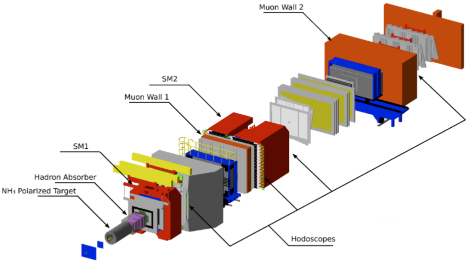
- Access to large values of $x_F \lesssim 0.9$ and low values of $p_\perp \lesssim M$
- Study the A-dependence of nuclear effects
  - Nuclear Parton Distributions Function (nPDF)
  - Energy loss effects

$$\text{Observable: } R_{hA}(x_F) \quad \frac{1}{A}\frac{d\sigma_{hA}}{dx_F} \Big/ \frac{d\sigma_{hp}}{dx_F}$$

Two hard processes to study nuclear medium at COMPASS

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

COMPASS apparatus



Beam

- beam at 190 GeV
- I_{beam} 7 10^7 s ^{1}

Nuclear targets

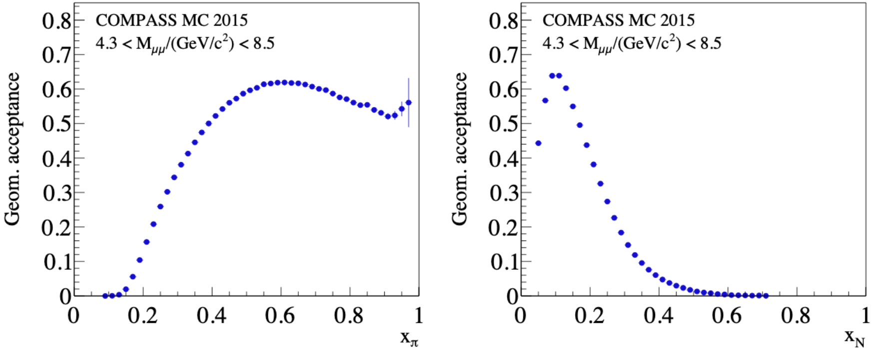
1. Ammonia (NH_3)
2. Aluminium (Al^{27})
3. Tungsten (W^{184})

Physics data taken

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

COMPASS acceptance

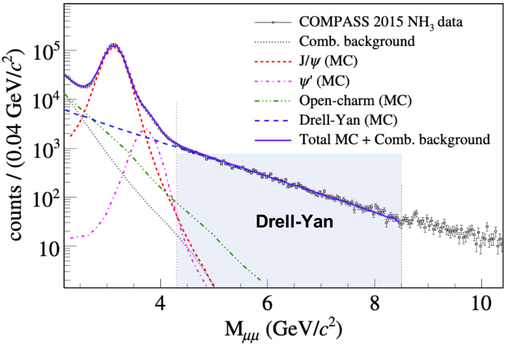
- Large angular acceptance: 8 < (mrad) <160
- Large kinematics acceptance in Drell-Yan region [4.3-8.5] GeV



Access to large values of x_π . 0:9

Invariant mass distribution at COMPASS

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

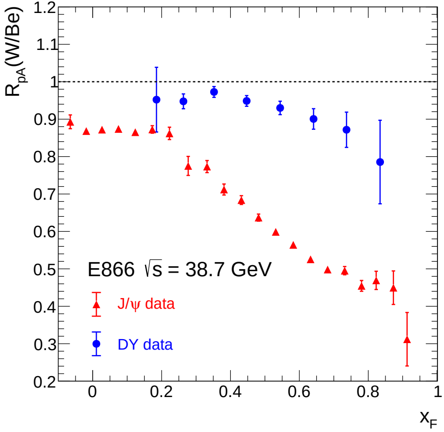


At COMPASS, it is possible to study these two processes

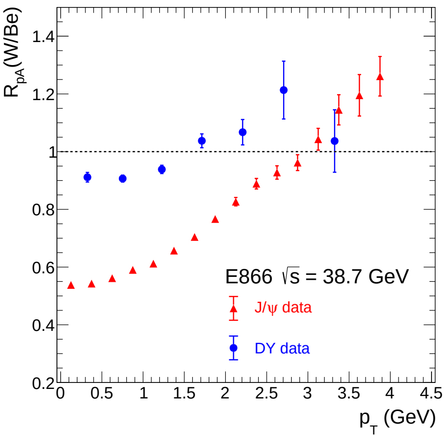
Empirical observations: from previous experiments

- More suppression for *J*= compared to DY for both x_F and *p*? . *M*
- Cold nuclear matter affects differently DY and *J*= data

x_F



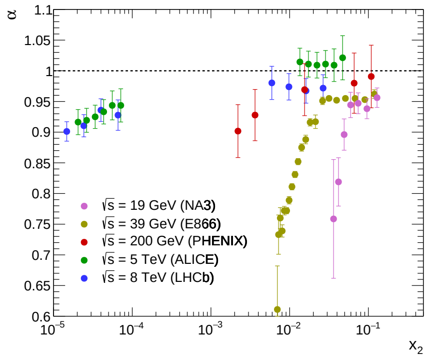
p?



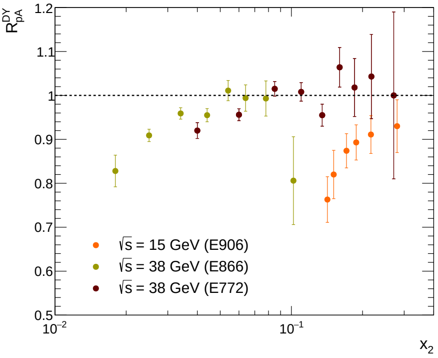
Empirical observations: from previous experiments

- More suppression for $J=$ compared to DY for both x_F and $p_?$. M
- Cold nuclear matter affects differently DY and $J=$ data

$J=$ data



DY 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	A
E906	p	15	DY	C, Fe, W
COMPASS		18.9	DY	NH3[1], Al, W
			J=	NH3, Al, W
NA3	p	19.4	J=	H, Pt
		16:7=19:4=22:9		
	+	19.4		
		16:7=19:4=22:9	DY	H, Pt
NA10		16:2=23:1	DY	D, W
		23:1	J=	D, W
E772	p	38.7	DY	Ca, Fe, W
E866	p	38.7	DY	Be, Fe, W
			J=	Be, Fe, W

! New data for both DY and J= from COMPASS experiment

[1] NH3+He mix

Explanations

Possible explanations :

- nuclear PDF effects (shadowing and EMC)
  ! 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_F
- Probing transverse momentum broadening as a function of $p_?$

Current nuclear PDFs extraction

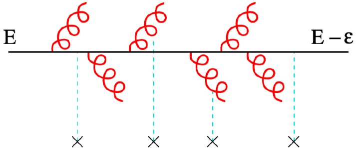
	EPS09	DSSZ	nCTEQ	EPPS16
e-DIS	X	X	X	X
-DIS		X		X
Drell-Yan pA	X	X	X	X
RHIC hadrons	X	X	X	X
LHC data pA				X
Drell-Yan A				X

Flavor decomposition			X	X
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 A

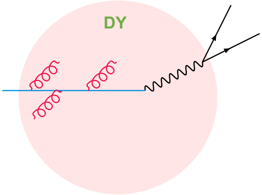
Energy loss effects

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: $hA \to \ell^+\ell^- + X$
   - Initial state radiation
2. Hadron production: $hA \to q/g\,(\to h') + X$
   - Initial state radiation
   - Final state radiation
   - Interferences initial/final state radiation



Energy loss effects

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

$$\langle \Delta E \rangle_{\mathrm{LPM}} \propto \alpha_s \hat{q} L^2$$

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

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

$$\langle \Delta E \rangle_{\mathrm{coherent}} \propto \sqrt{\hat{q}L}/M \; E \gg \langle \Delta E \rangle_{\mathrm{LPM}}$$

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

3. $p_\perp$ broadening effect

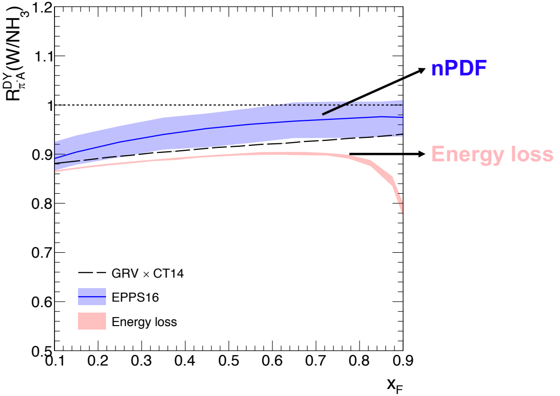
$$\Delta p_\perp^2 = \langle p_\perp^2 \rangle_{hA} - \langle p_\perp^2 \rangle_{hp} = \hat{q}L$$

Transport coefficient : the scattering properties of the medium

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

Probing nPDF and radiative energy loss in DY and $J=$ data at COMPASS

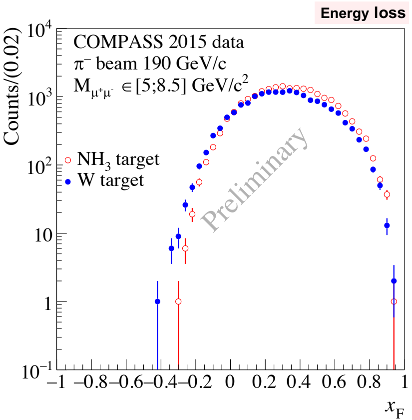
Energy loss prediction for Drell-Yan data - [CJ-Naïm et al (2019)]

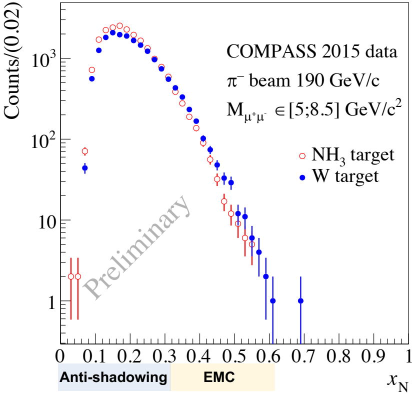


- Energy loss plays a key role in Drell-Yan data at all x_{F}
- Important suppression at x_{F} 0:7 due to energy loss

What can COMPASS Drell-Yan data bring?

Drell-Yan kinematics distributions at COMPASS

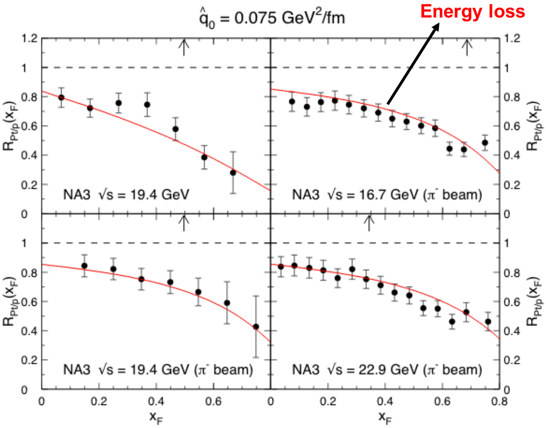




- Probing anti-shadowing and EMC effect with good statistics
- Access large x_F 0:7 where energy loss effects dominate
- New information about nuclear matter effects at large x

Suppression observed in $J=$ data

Energy loss dominant e□ect in the $J=$ data - [Arleo et al (2012)]



- Important suppression at large x_F explained by energy loss e□ect
- Different suppression for p and beam at the same energy

COMPASS, new precise measurements from $J=$ data

COMPASS can

- access large values of x_F . 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		200	H (3000)	Pt (131000)
COMPASS		190	NH_3 (10^6)	W (10^6)

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

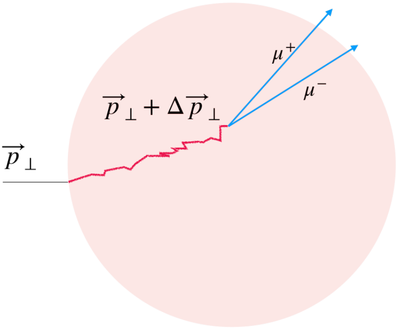
Ongoing analysis ...

Probing transverse momentum broadening with DY and $J=$ data

$p_?$ 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 $p_?$ broadening



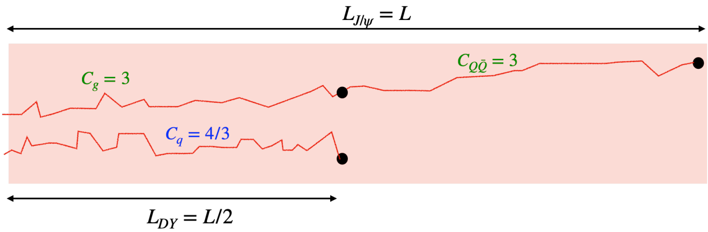
$p_?$ broadening effect

$$p_?^2 = \langle p_?^2 \rangle_{\text{hA}} \quad \langle p_?^2 \rangle_{\text{hp}} = \hat{q}L \; / \; xG(x)$$

Colorimetry

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

$$p^2_? = \frac{C_R + C_{R^0}}{2N_c}(\hat{q}_A L_A \quad \hat{q}_p L_p)$$



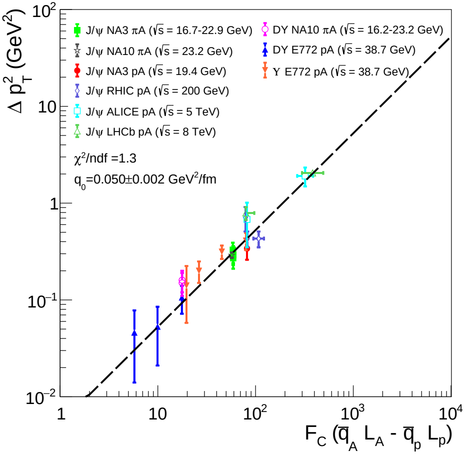
- Drell-Yan - $C_q = 4/3$
- Quarkonia in pA - $C = C_g + C_{QQ} = 3 + 3$
- Quarkonia in A - $C = C_q + C_{QQ} = 4/3 + 3$

$p_?$ brodadening scaling

- Simple model used

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

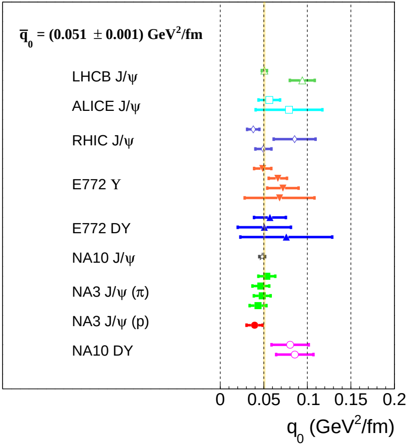
- $xG(x;\hat{q}L) \;/\; x^{\;0.25}$ at $x \quad 10^{\;5}$
- Extraction of q_0
  $q_0 = 0.050 \quad 0.02\ \text{GeV}^2/\text{fm}$



! Remarkable scaling from low to high energies

Extraction of transport coefficient for each experiment

- General agreement between experiments
- Universality of transport coefficient q_0
- Compatibility with radiative energy loss extraction



COMPASS can give an additional important constrain from DY and $J=$

Conclusion

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

- radiative energy loss reproduces J/ψ data in nuclear collisions
- 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, Al and W)
- access large $x_F \gtrsim 0.9$ and low $p_\perp \lesssim M$
- good place to study nPDF and medium transport properties
- 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 ...

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

$$\frac{\mathrm{d}\,{}^{\mathrm{nPDF}}_{\mathrm{hA}}}{\mathrm{d}p_\perp} = \underbrace{R_i^{\mathrm{A}}\left(x_2\left(p_\perp\right); Q^2\right)}_{\text{if only normalisation : cancellation in } p_\perp^2} \frac{\mathrm{d}\,{}_{\mathrm{hp}}}{\mathrm{d}p_\perp}$$

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