Investigating cold nuclear matter effects in charmonia at the fixed-target COMPASS experiment

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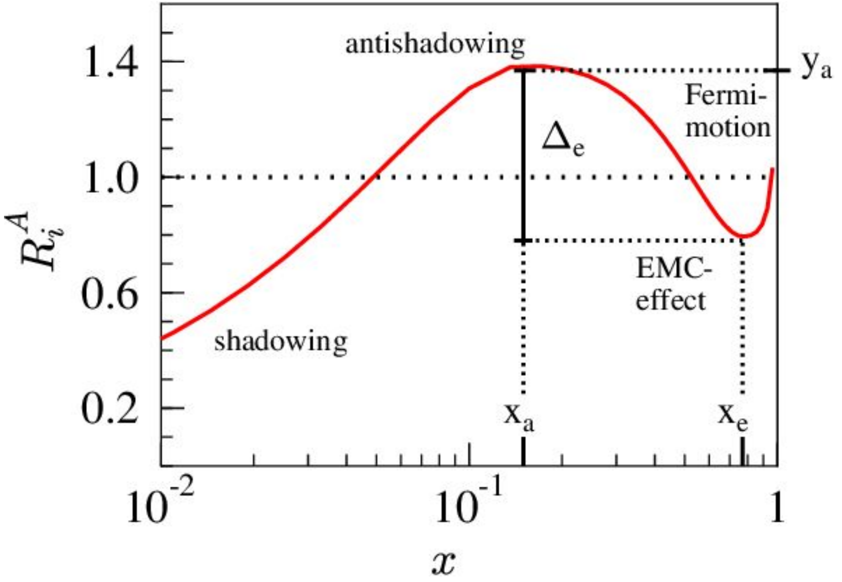
Introduction

- Heavy quarkonia suppression is one of the most distinctive signatures of QGP in heavy-ion collisions.
- Suppression in hh and hA collisions ⟶ Cold Nuclear Matter (CNM) effects.
- Disentangle the CNM effects from QGP to interpret AA collisions.
- Quarkonia and Drell-Yan cross-sections ⟶ crucial tool to study CNM effects.

CNM effects ?

- **Initial state effects:**
  - Nuclear modification of the PDFs Anti-shadowing, EMC effects are dominant at SPS energies. ⟶
  - Initial state energy loss.
- **Final state effects:**
  - Final state energy loss.

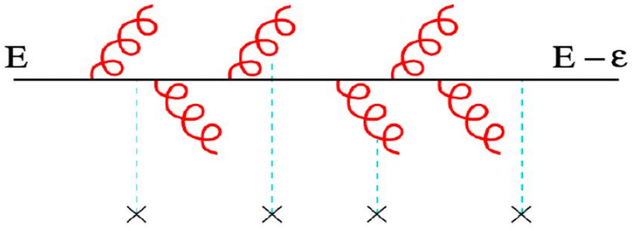
- These effects can be quantified by measuring nuclear modification factor ($R_{\pi A}$).



[JHEP 2008 (2008) 102]

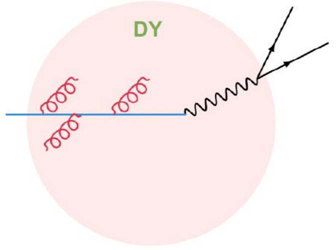
Parton energy loss effects

A high energy parton travelling in a medium can radiate gluons induced by the elastic scatterings with the constituents of the medium



Parton energy loss effects in different hard processes:

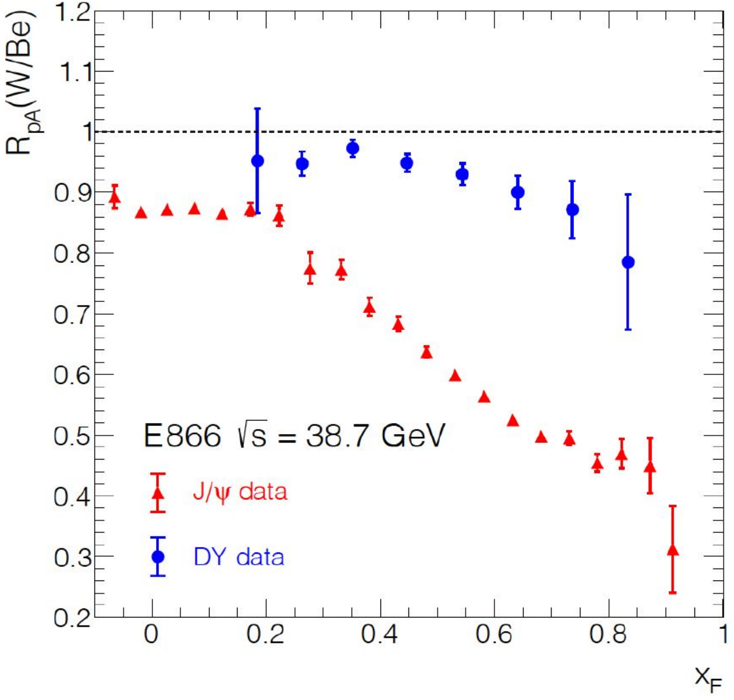
- Drell-Yan process: $hA \rightarrow \ell^+\ell^- + X$
  - Initial state radiation
- Hadron production: $hA \rightarrow q/g(\rightarrow h') + X$
  - Initial state radiation
  - Final state radiation
  - Interference of both

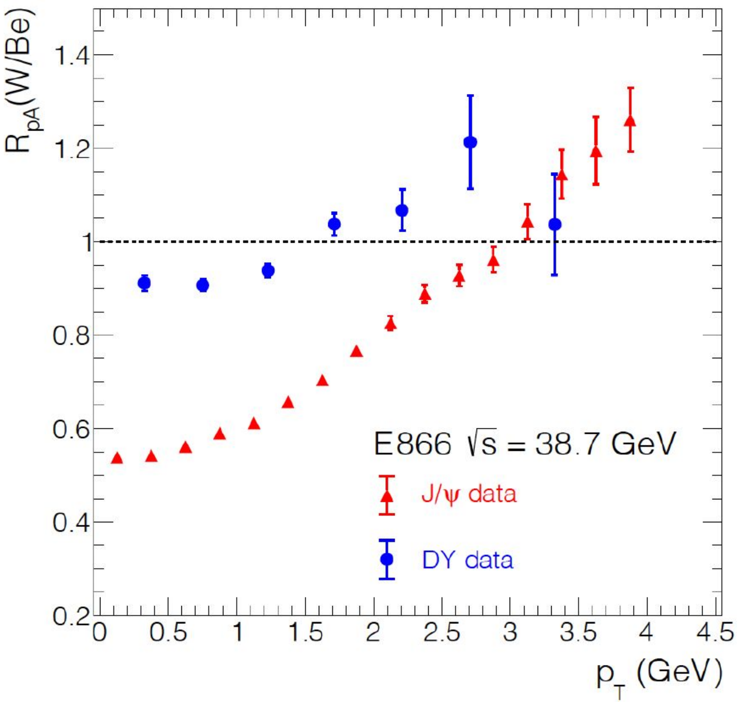


CNM effects are studied at COMPASS via J/ψ production at √s=18.9 GeV.

Observations from previous fixed target experiments

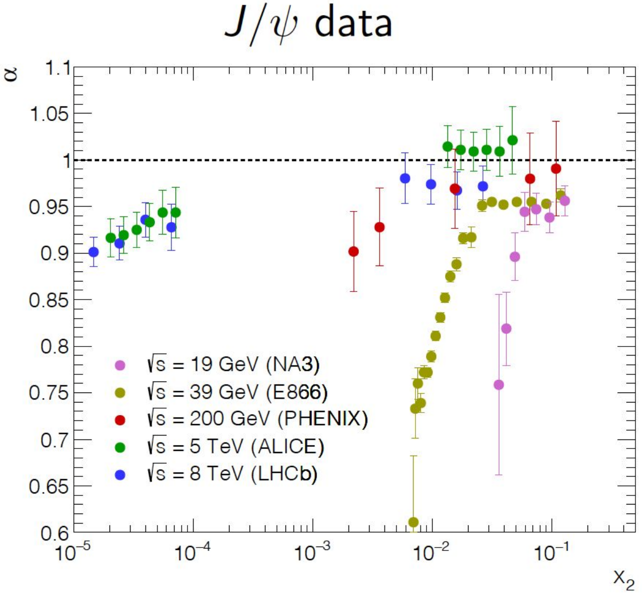
- J/ψ is more suppressed than DY as a function of x_F and p_T
- Different CNM effects for J/ψ and DY [PRL 84 (2000) 3256]

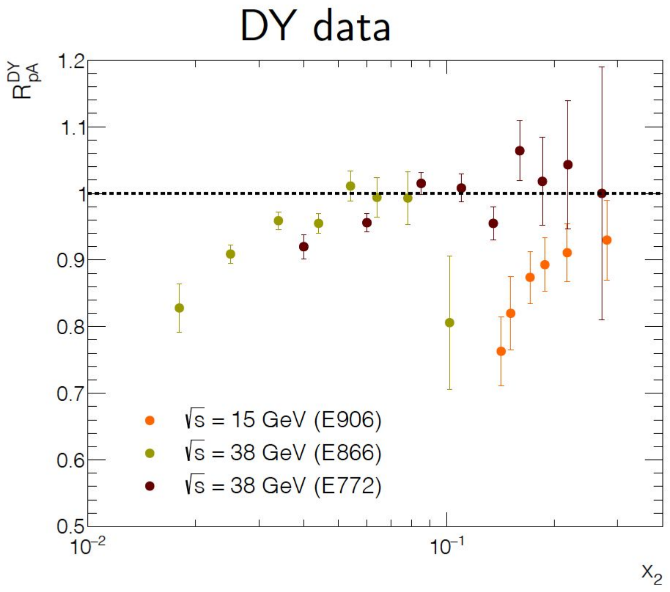




Observations from previous experiments

- No scaling as a function of x_2. [Arleo, NaÏm, Platchkov, JHEP01(2019)129]
- J/ψ suppression depends on center of mass energy.


J/ψ data


DY data

- Coherent energy loss regime explains alone E866 J/ψ data at √s=38.7 GeV. [Arleo, Peigne, JHEP03(2013)122]
- Energy loss model explains the strong suppression at large x_F for DY. [Arleo, NaÏm, Platchkov, JHEP01(2019)129]

COMPASS experimental set up

J/ψ = $\mu^+ + \mu^-$ ($2 < M < 4.3$ GeV/c^2)

DY = $\mu^+ + \mu^-$ ($4.3 < M < 8.5$ GeV/c^2)

Beam:

π- beam at 190 GeV

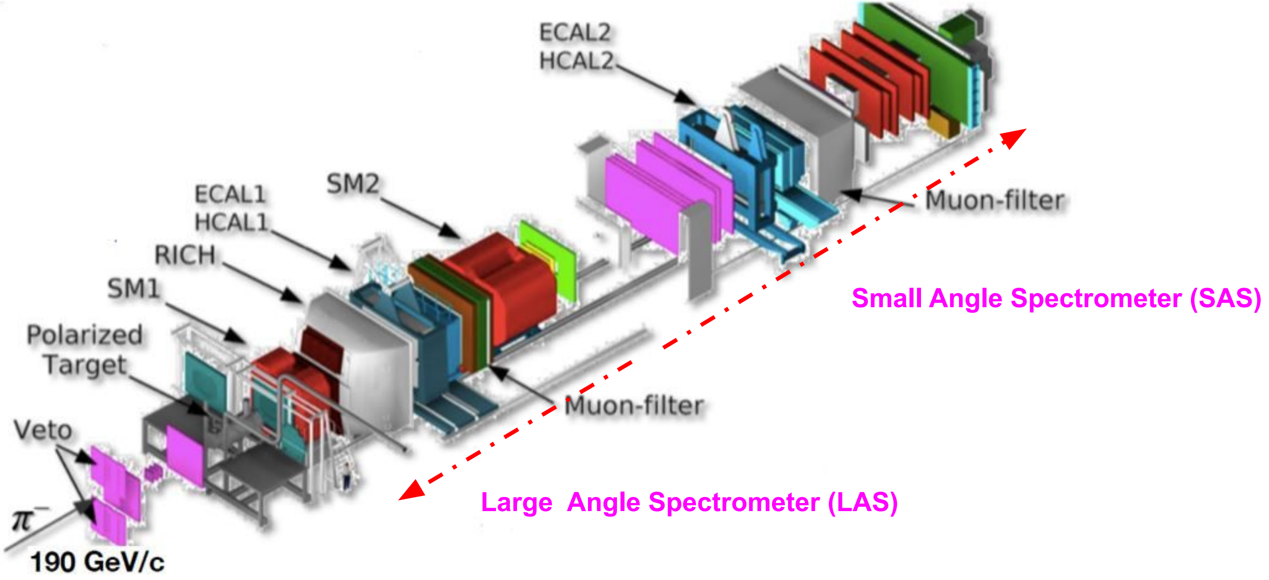
$I_{beam} = 7 \times 10^7$ hadrons.s^{-1}

DY trigger(dimuon) setup:

Middle (SAS) and LAS

Outer (SAS) and LAS

LAS and LAS

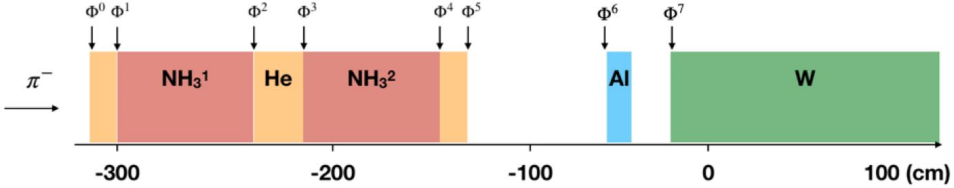


DY targets:

NH3 - 17 nucleons (3 polarizable)

Al - 27 nucleons

W - 184 nucleons



Main Observable

The double differential cross-section

$$\frac{\mathrm{d}^2\sigma^{\pi^- \mathrm{A}}}{\mathrm{d}\mathrm{x_F}\mathrm{d}\mathrm{p}_\perp} J/\psi = \frac{\mathrm{N}^{\mathrm{J}/\psi}_{\mathrm{events}}(\mathrm{x_F},\mathrm{p}_\perp)}{\epsilon^A.\mathrm{BR}.\Delta\mathrm{x_F}.\Delta\mathrm{p}_\perp.\mathcal{L}}$$

With integrated luminosity,

$$\mathcal{L} = \alpha^i \Phi^0 \times L^i_{\mathrm{eff}} \times \rho^i \times \frac{\mathcal{N}_A}{M^i}$$

With effective length, taking into account the beam attenuation inside the target

$$L^i_{\mathrm{eff}} = \frac{\lambda_{\mathrm{int}}}{\rho}\left[1 - \exp\left(\frac{-\rho\, L}{\lambda_{\mathrm{int}}}\right)\right]$$

All the targets have the the same initial beam flux measured by beam telescopes and the Avogadro’s number is constant, therefore

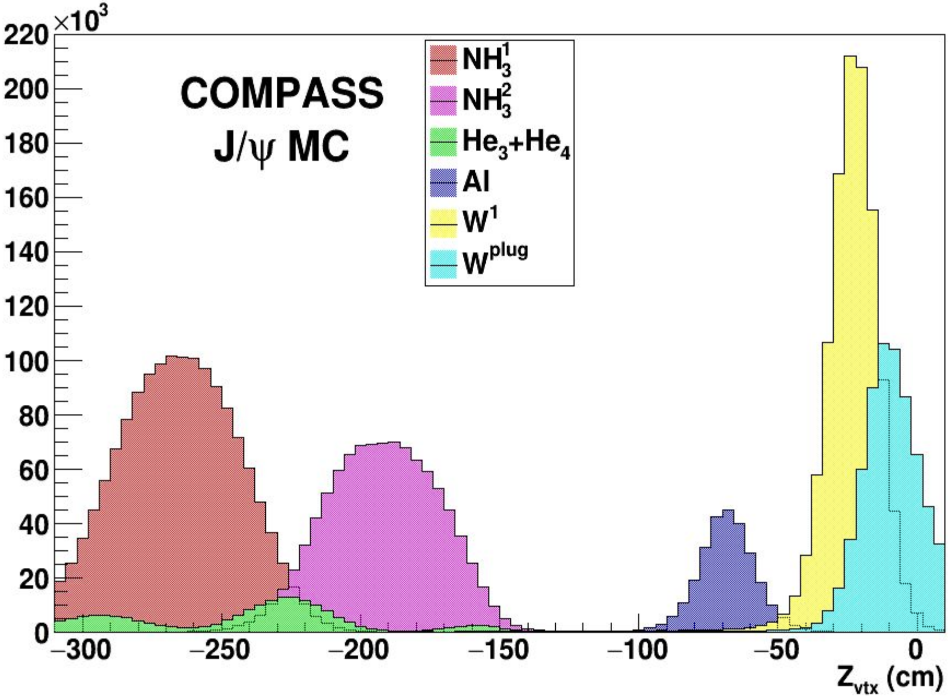
The double ratio cross-section

$$R^{J/\psi}_{\pi^- A}(W/Al) = \frac{\mathrm{N}^{\mathrm{J}/\psi}_{\mathrm{W}}(\mathrm{x_F},\mathrm{p}_\perp)}{\epsilon_W.\alpha^W.L^W_{eff}.\rho^W} \Big/ \frac{\mathrm{N}^{\mathrm{J}/\psi}_{\mathrm{Al}}(\mathrm{x_F},\mathrm{p}_\perp)}{\epsilon^{Al}.\alpha^{Al}.L^{Al}_{eff}.\rho^{Al}}$$

Analysis Ingredients

- Kinematic variables: Exact definition (see back-up slide)
- Targets range:
  - W : $-30 < Z_{vtx} < -20$ (cm)
  - Al : $-73.5 < Z_{vtx} < -66.5$ (cm)

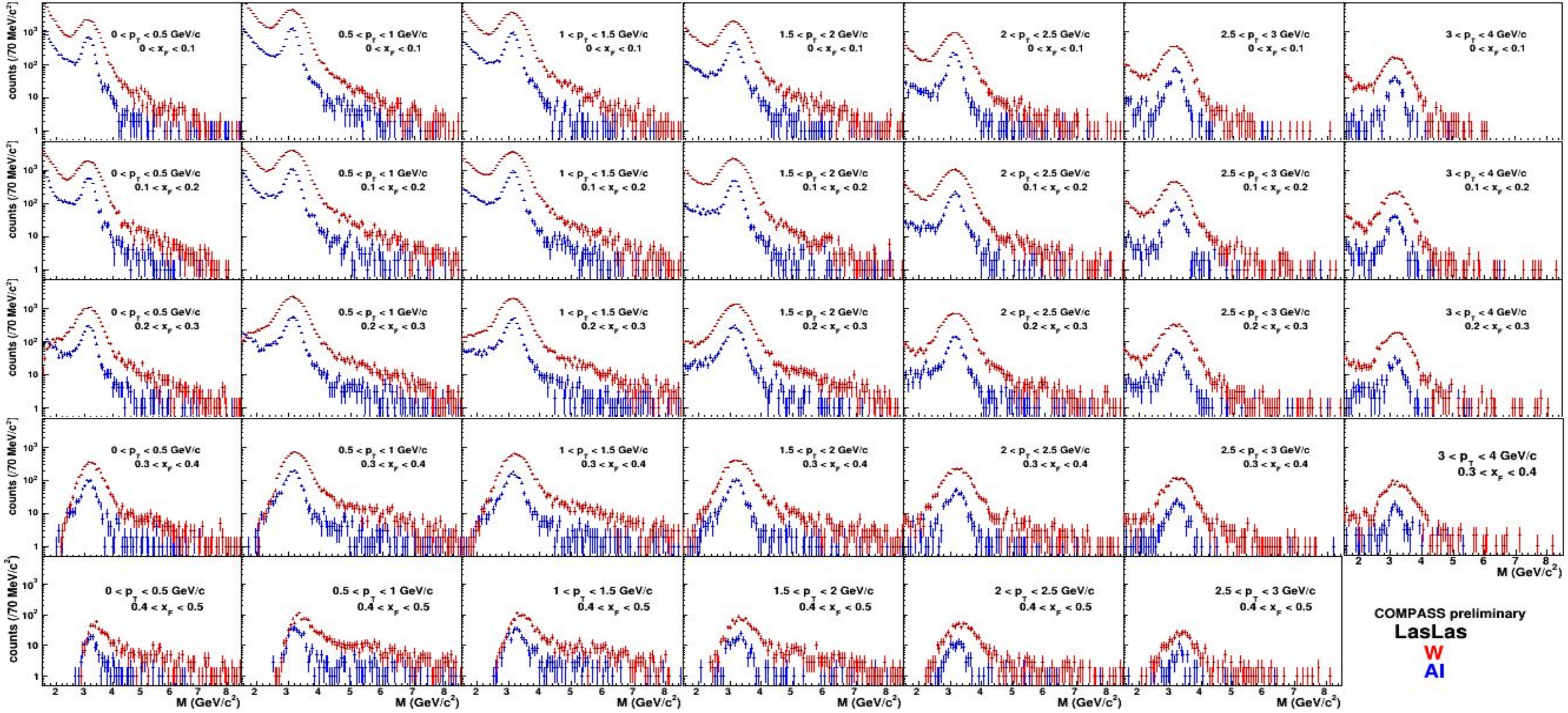
- $0 < xF < 0.9$
- $0 < pT < 4$ GeV/c
- Migration correction:
  W $\longrightarrow$ Al



Dimuon invariant mass

p_T →

x_F ↓



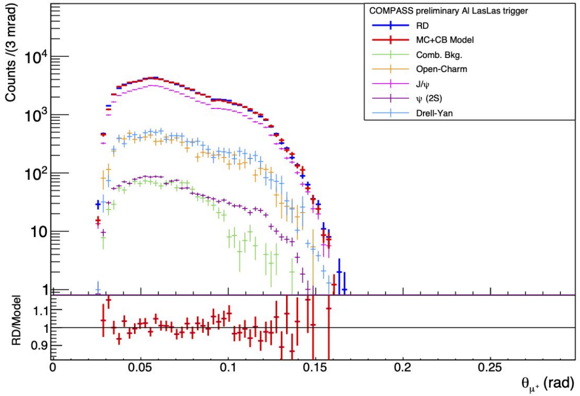
Double differential analysis using data taken in 2018 per trigger basis.

Comparison between Real Data and Monte Carlo

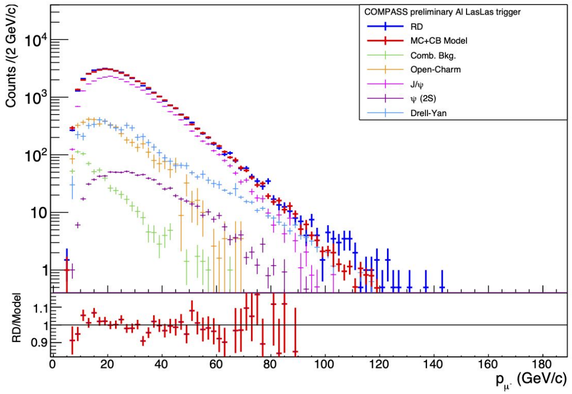
- MC production at COMPASS: (PYTHIA8 + GEANT4)
- Real Data (RD) →
  J/ψ + ψ(2S) + DY + OC + CB

  “Cocktail Fit”
- CB: correlated muon pairs from RD.
- MC-RD comparison: The momenta and angle of single muon after adding all the components from MC and CB.
- Good agreement between MC-RD after including all the components.

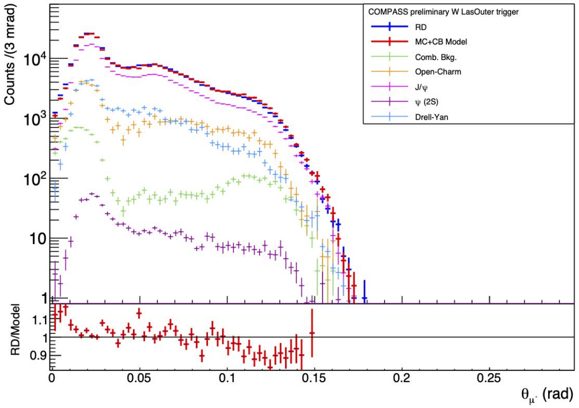
Al, LL trigger, θμ+



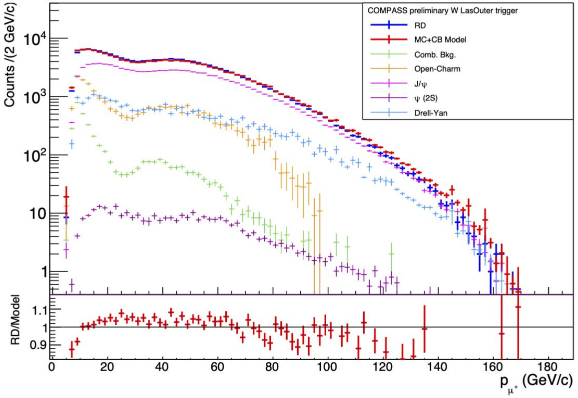
Al, LL trigger, Pμ-



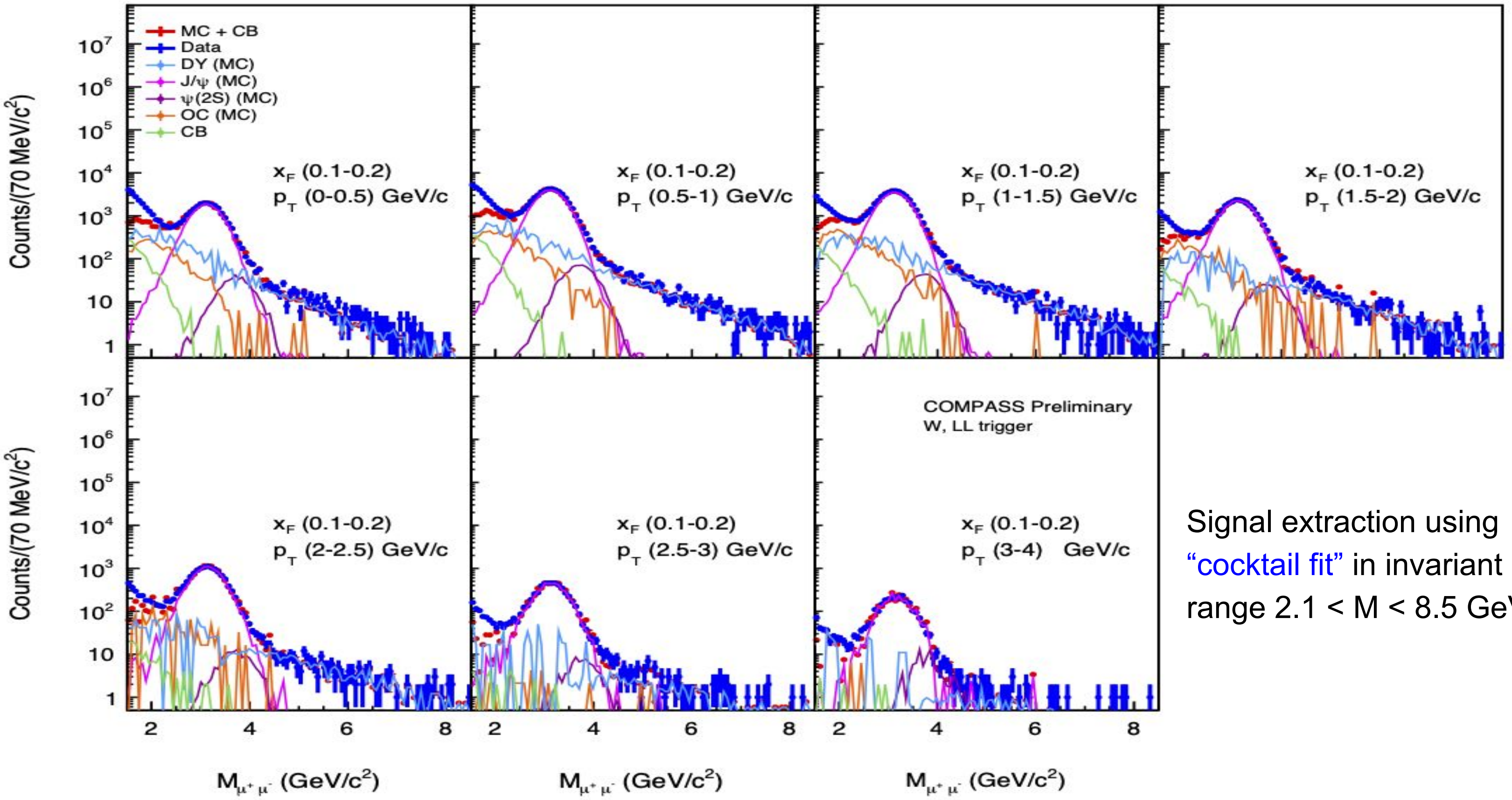
W, LO trigger, θμ-



W, LO trigger, Pμ+

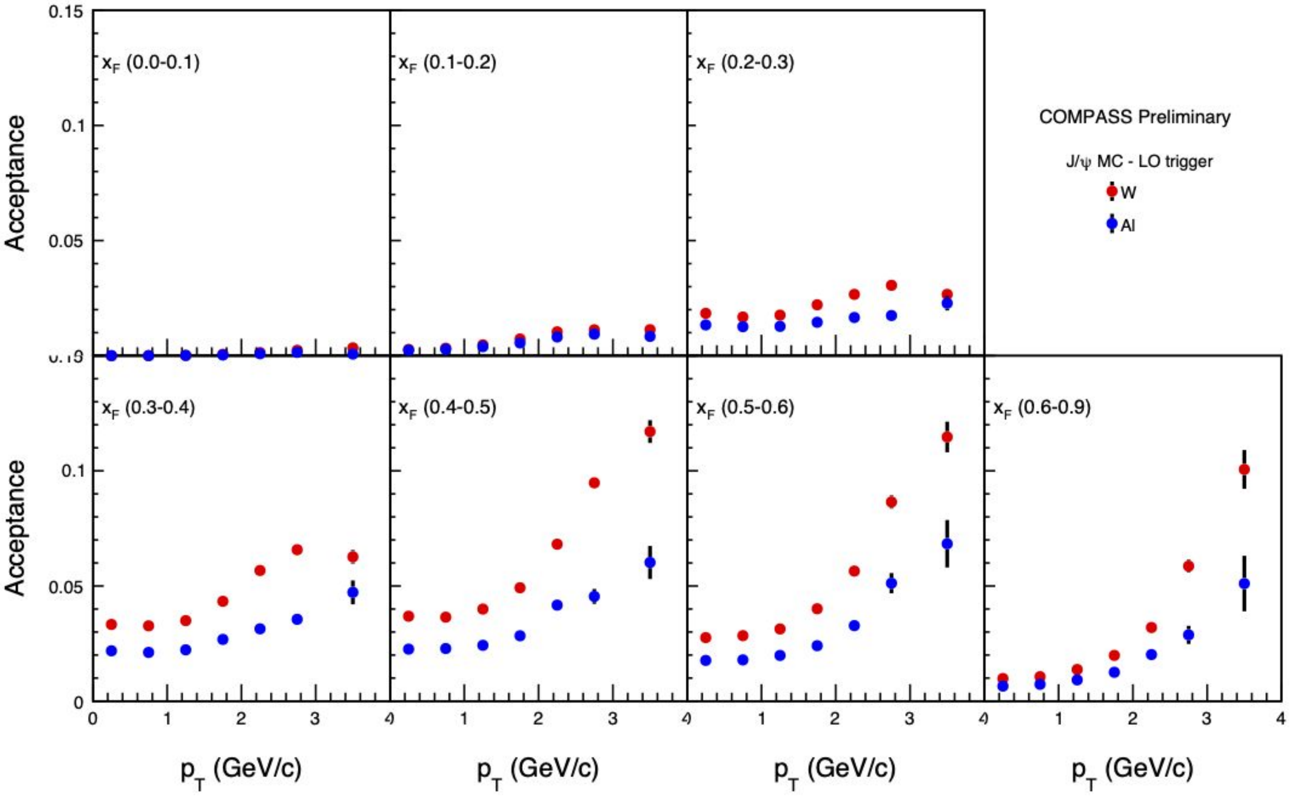


Signal extraction



Signal extraction using "cocktail fit" in invariant mass range $2.1 < M < 8.5$ GeV/c^2

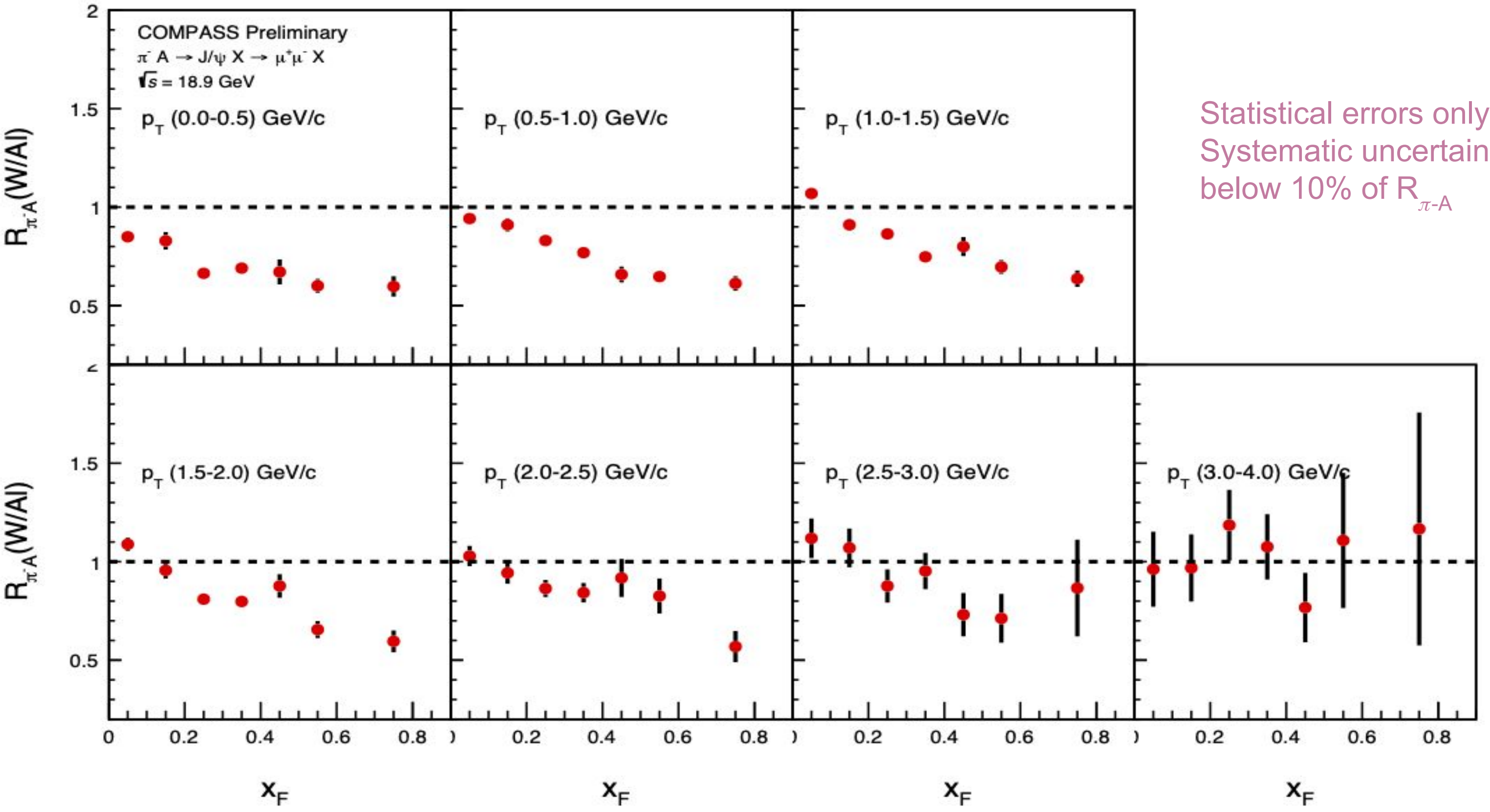
Acceptance



The total acceptance -> Geometrical acceptance + detector & trigger efficiency.

No contamination correction applied for Aluminium.
Acceptance goes up to 12% .

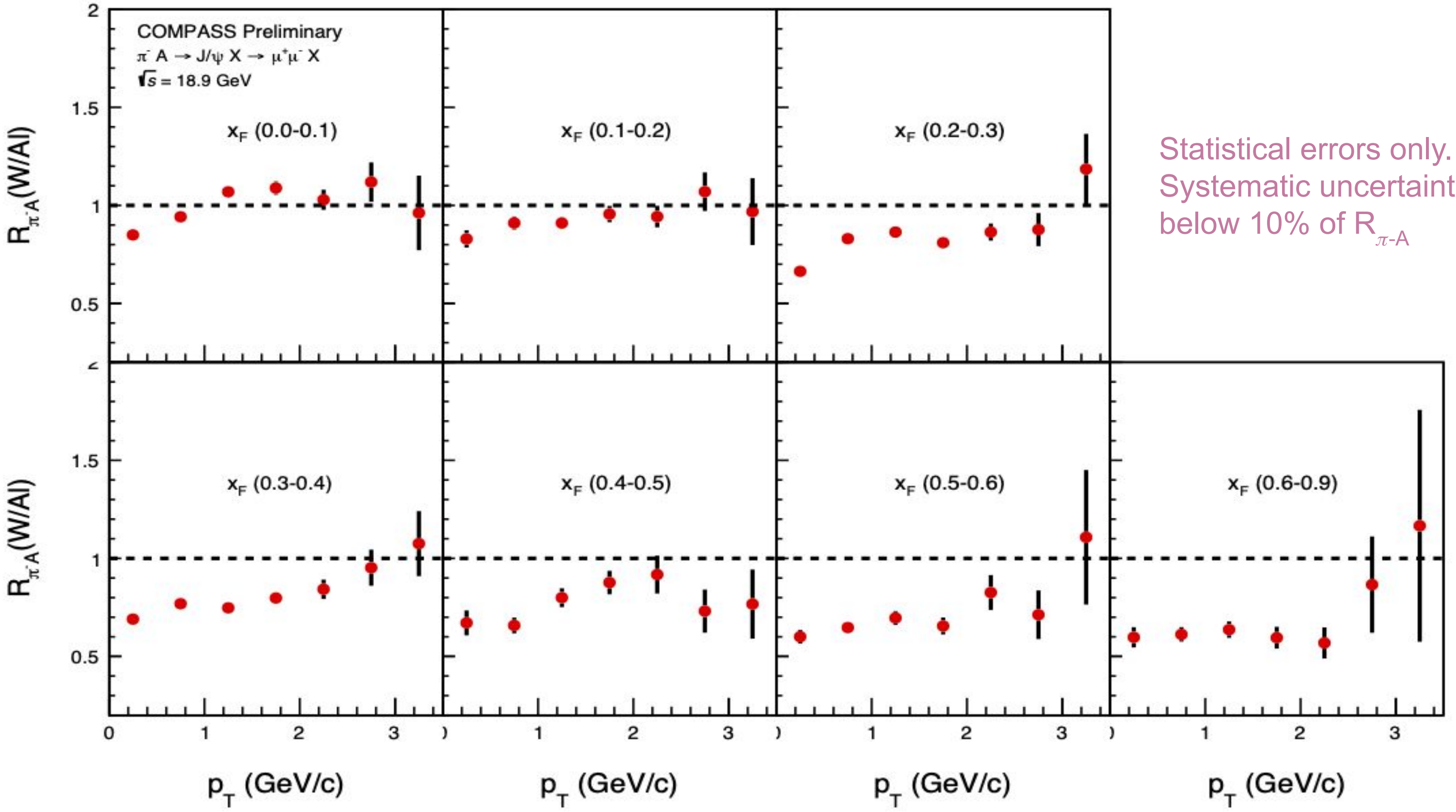
Results: p_T differential $R_{\pi\text{-}A}$ as a function of x_F



Statistical errors only.
Systematic uncertainty below 10% of $R_{\pi\text{-}A}$

Suppression towards large x_F, more prominent at low p_T.

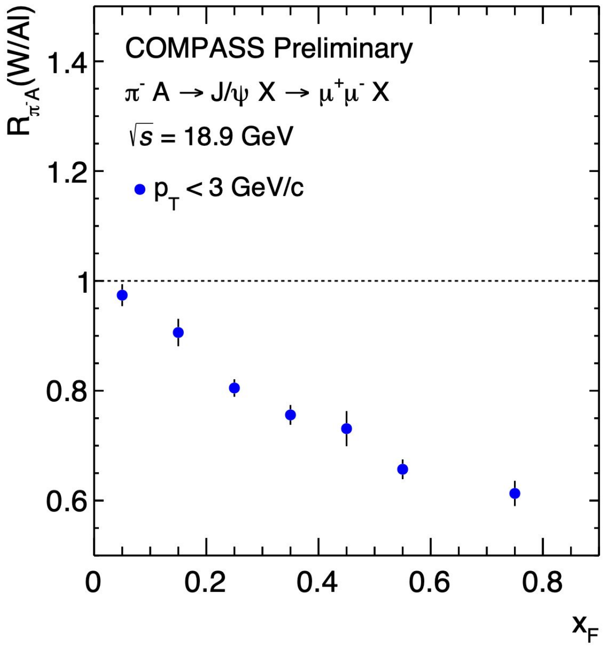
Results: x_F differential $R_{\pi\text{-}A}$ as a function of p_T

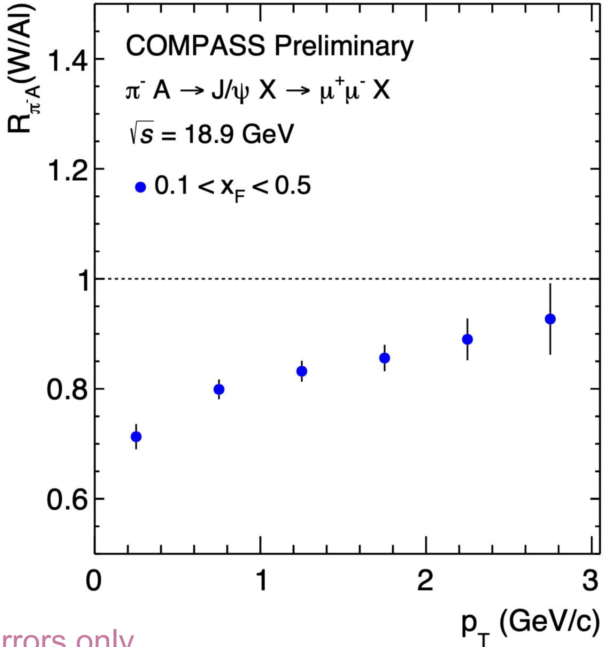


Statistical errors only. Systematic uncertainty below 10% of $R_{\pi\text{-}A}$

Suppression at low p_T, more prominent at large x_F.

Results: $R_{\pi\text{-}A}$ integrated over x_F and p_T

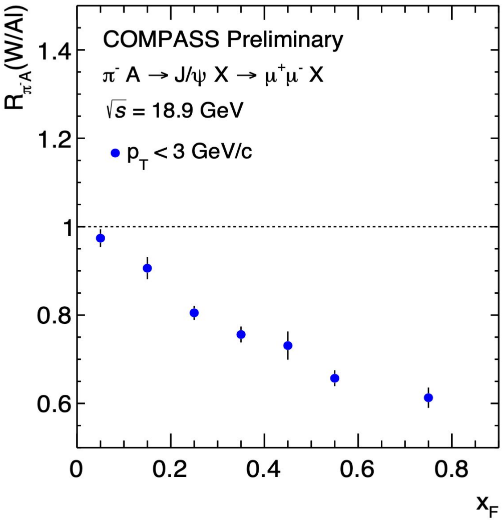


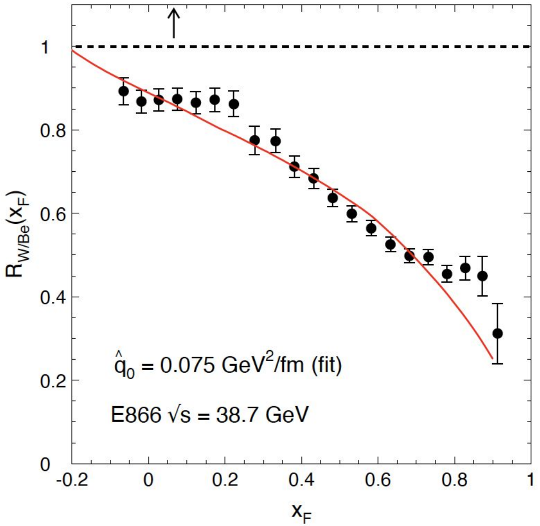


Statistical errors only.
Systematic uncertainty
below 10% of $R_{\pi\text{-}A}$

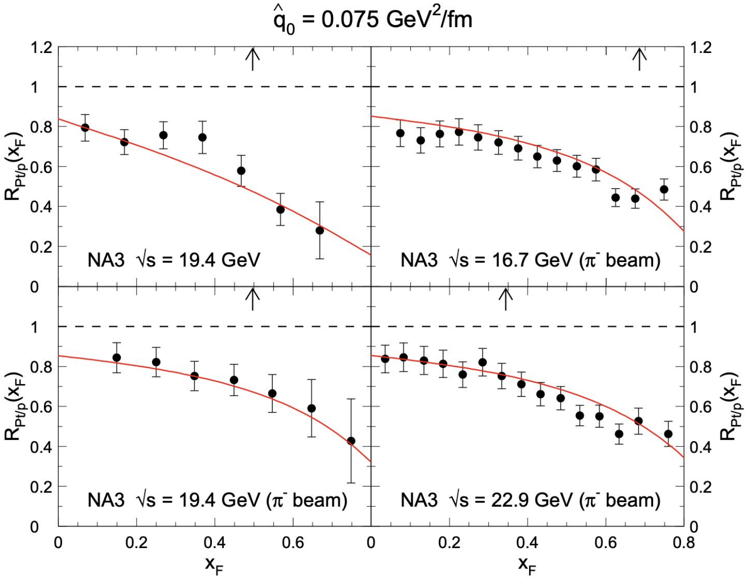
- Combined for two trigger by taking average over common kinematic range.
- Suppression towards high x_F and low p_T observed similar to 2D results.

Comparison with other fixed-target experiments





[PRL 84 (2000) 3256]



[Z. Phys. C20 (1983) 101]

- Qualitative comparison with previous fixed target experiments E866, NA3 results.
- Data from E866, NA3, E537,NA60 are well described by the energy loss model [Arleo, Peigne, JHEP03(2013)122].
- Hint of energy loss effect for COMPASS data.

Summary and Outlook

- Preliminary results of nuclear dependence of J/ψ data have been presented.
- Suppression towards large x_F and low p_T.
- Maximum suppression at the highest x_F and the lowest p_T interval ~40%
- Qualitative comparison with previous fixed target experiments shows similar trend.
- Suppression towards large x_F, indicating possible energy loss effect.

Thank you for your attention!

Extras

Kinematic variable definition

x-Feynman definition used by previous fixed target experiments NA3 [Z. Phys. C20 (1983) 101]

$$x_F = \frac{p_z}{p_z^{max}} = \frac{p_z}{\sqrt{s}/2}$$

$$x_1 = 0.5 \times (\sqrt{x_F^2 + 4Q^2/s} + x_F)$$

$$x_2 = 0.5 \times (\sqrt{x_F^2 + 4Q^2/s} - x_F)$$

Physics motivation

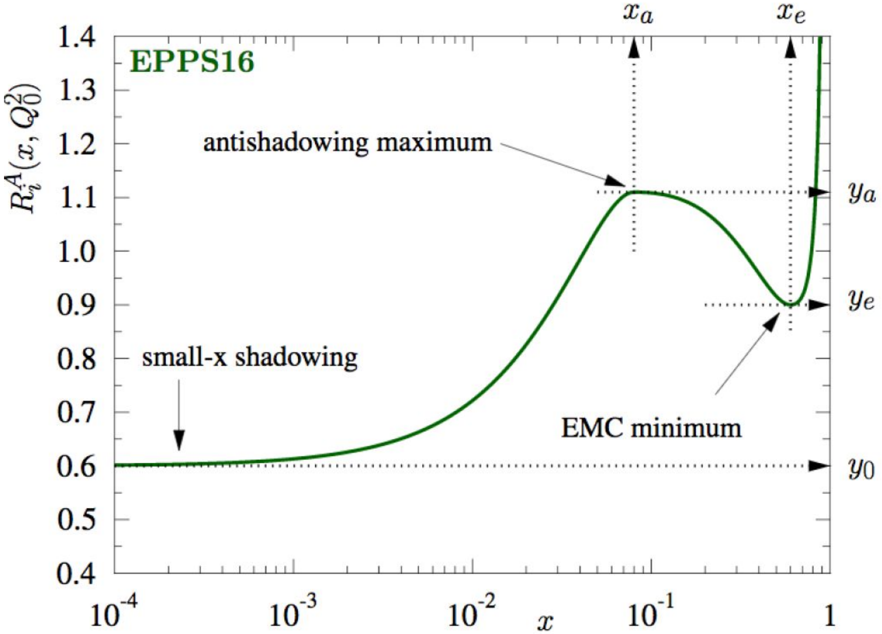
- The cold nuclear effects in hA collisions characterized by nuclear modification factor:

  $R_{hA} = 1/A(d\sigma_{hA}/dx_F)/(d\sigma_{hp}/dx_F)$
  $= (1$ or no nuclear effects)

- Nuclear modification factor depends on nPDF

  $f_j^{p/A} \neq f_j^{p}$

- nPDF depends on bjorken-*x,* distinguishes among Nuclear Shadowing, Anti-Shadowing, EMC effects.
- At COMPASS access to wider positive x-Feynman range, possible to study nPDF.
- The anti-shadowing (**$0.01 \lesssim x \lesssim 0.3$**) and EMC region (**$0.3 \lesssim x \lesssim 0.7$**) are covered by COMPASS.



Parton energy loss regimes

- Landau Pomeranchuk Migdal or the LPM effect (small formation time $t_f \leq L$)

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

  - Drell-Yan process: $hA \rightarrow \ell^+ \ell^- + X$
- Full coherent parton energy loss effect (large formation time $t_f \gg L$)

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

  - Quarkonium production: $hA \rightarrow [Q\hat{Q}(g)]_8 + X$

Transport coefficient : The scattering properties of the medium, depends on x_F and $p_\perp$ distribution

$$\hat{q} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \rho \times xG(x, Q^2), \hat{q} \equiv \frac{\mu^2}{\lambda} = \frac{\mathrm{d}\Delta \mathrm{p}_\perp^2}{\mathrm{dL}}$$

Single $\hat{q}$ to study both energy loss effects and $p_\perp$ broadening.
These nuclear effects are worth investigating with COMPASS DY data.