The study of cold nuclear matter effects in charmonia production in π-A collisions with COMPASS

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for the COMPASS Collaboration

Workshop on
Fixed-target experiments at LHC

Fixed-Target@LHC

Centre Paul Langevin, Aussois

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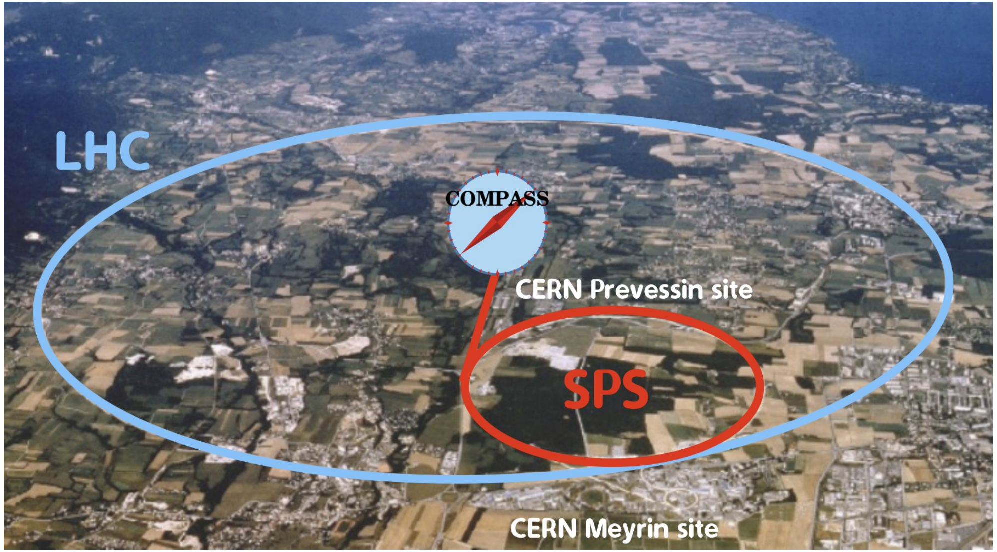
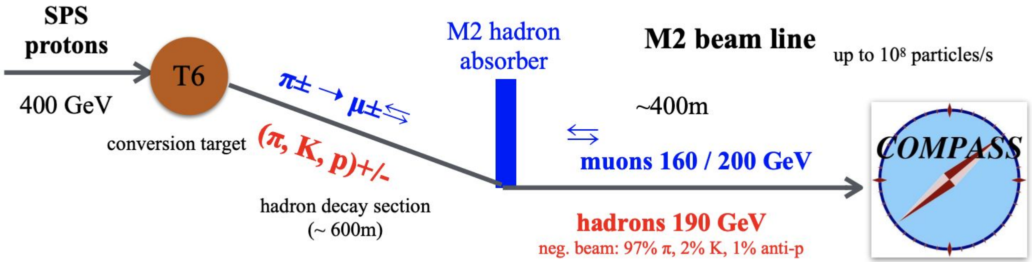
The COMPASS experiment

NA58: fixed target experiment in the north area of CERN

- Secondary beam from SPS at M2 beam line.
- First data taking in 2002 with a muon beam and polarised proton and deuteron targets.
- Data taking complete with muon run 2022.
- Recently COMPASS celebrated its 25th years anniversary since approval with IWHSS-2022 at CERN.
  [https://indico.cern.ch/event/1121975/]





Physics programs

COMPASS-I (2002-2011)

- Polarizable beams and targets.
- 160 GeV/c muon beam and polarised ^{6}LiD and polarized NH_3
- SIDIS experiments provided important results on nucleon spin structure.
- Gluon polarisation [PLB 633 (2006) 25–32]
- Quark spin structure (valence and transverse), and nucleon tomography TMD PDFs. [PLB 612 (2005) 154, PRL 94 (2005) 202002]

COMPASS-II (2012-2022)

- 2012: Primakoff and Deeply Virtual Compton Scattering
- 2016-2017: DVCS + Unpolarized SIDIS
- ***2015-2018: Drell-Yan (present talk)***
- 2021-2022: Transversely polarized SIDIS on ^{6}LiD target.

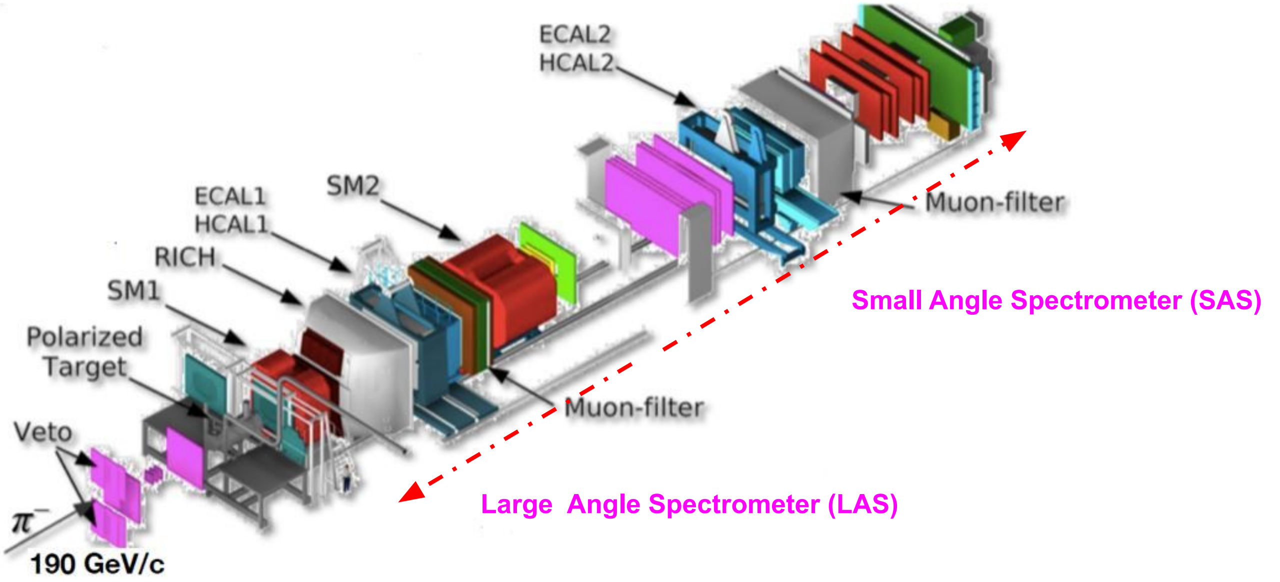
For detail COMPASS program → Overview talk on spin physics by Bakur Parsamyan on 5th.

COMPASS-II DY experimental set up

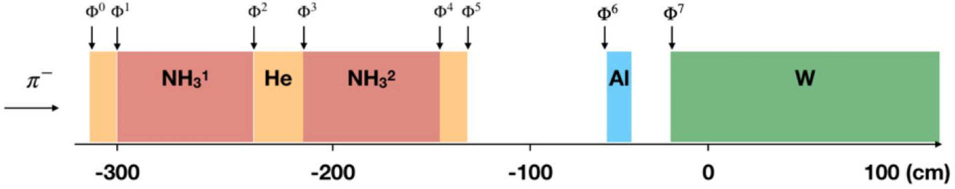
J/ψ = $\mu^+ + \mu^-$ ($2 < M < 4.3$ GeV/c^2)
DY = $\mu^+ + \mu^-$ ($4.3 < M < 8.5$ GeV/c^2)

Beam:
π- beam at 190 GeV
I_{beam} ~10^8 hadrons.s^{-1}

DY trigger (dimuon) setup:
LL: 2 muons in LAS
LO: 1 muon in LAS and 1 muon in SAS (LO)



DY targets:
NH3 - 17 nucleons (3 polarizable)
Al - 27 nucleons
W - 184 nucleons



Physics goal

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

Which CNM effects at COMPASS?

- **Initial state effects:**
  - Nuclear modification of the PDFs
  - Initial state energy loss
  - Cronin effect (nuclear enhancement in low p_T)
- **Final state effects:**
  - Final state energy loss
  - Nuclear absorption
- These effects can be quantified by measuring nuclear modification factor ($R_{\pi A}$) as a function of rapidity and p_T.

Possible CNM effects at COMPASS

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

  $R_{hA} = 1/A(d\sigma_{hA}/dx_F)/(d\sigma_{hp}/dx_F)$

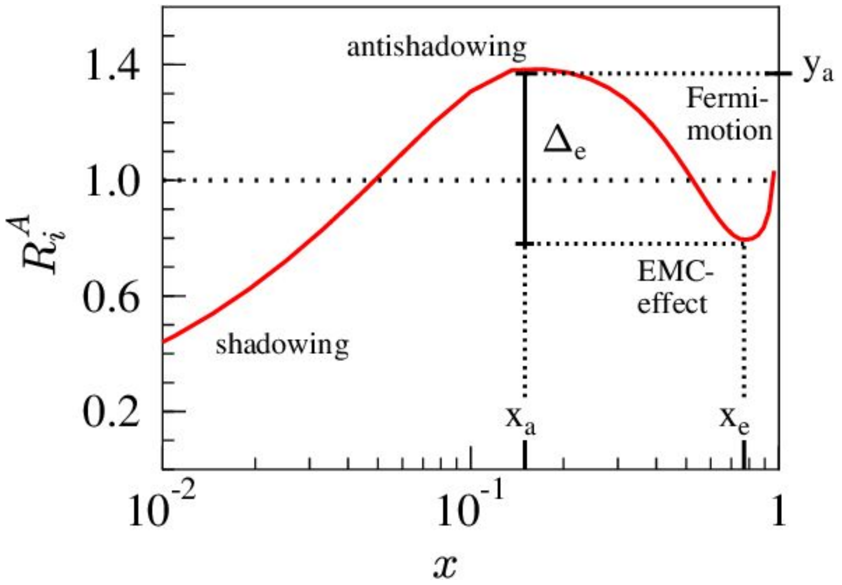
  $\cong$ (1 or no nuclear effects)

- Nuclear modification factor depends on nPDF

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

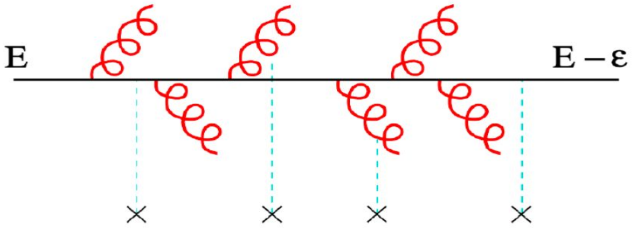
- nPDF depends on bjorken-*x*, distinguishes among Nuclear Shadowing, Anti-Shadowing and EMC effects.
- At COMPASS access to wider positive x-Feynman range covers the anti-shadowing and EMC region.

[JHEP 2008 (2008) 102]



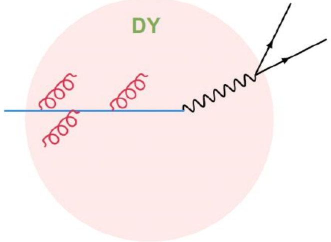
Parton energy loss effects

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



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: $hA \to \ell^+ \ell^- + X$
- 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: $hA \to [Q\hat{Q}(g)]_8 + X$

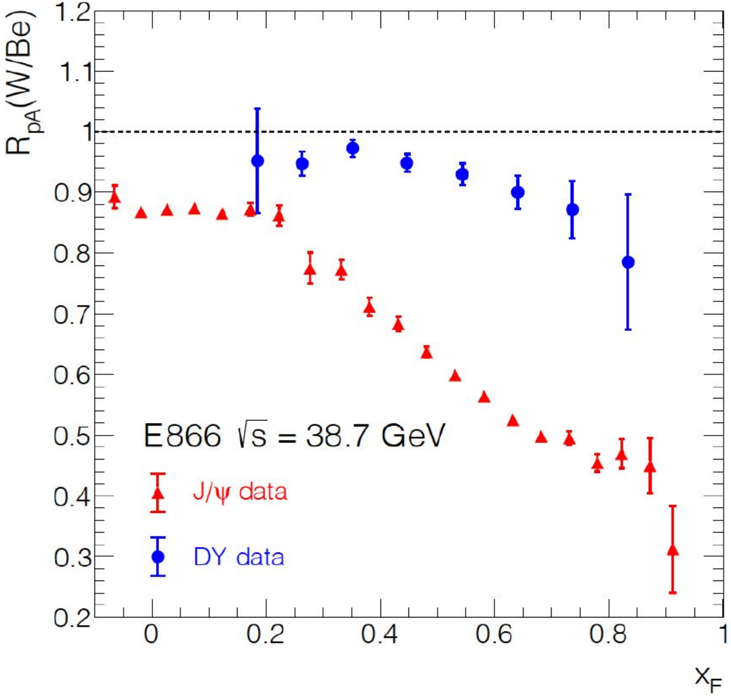
Transport coefficient : The scattering properties of the medium, depends on x_F and $p_\perp$ distribution

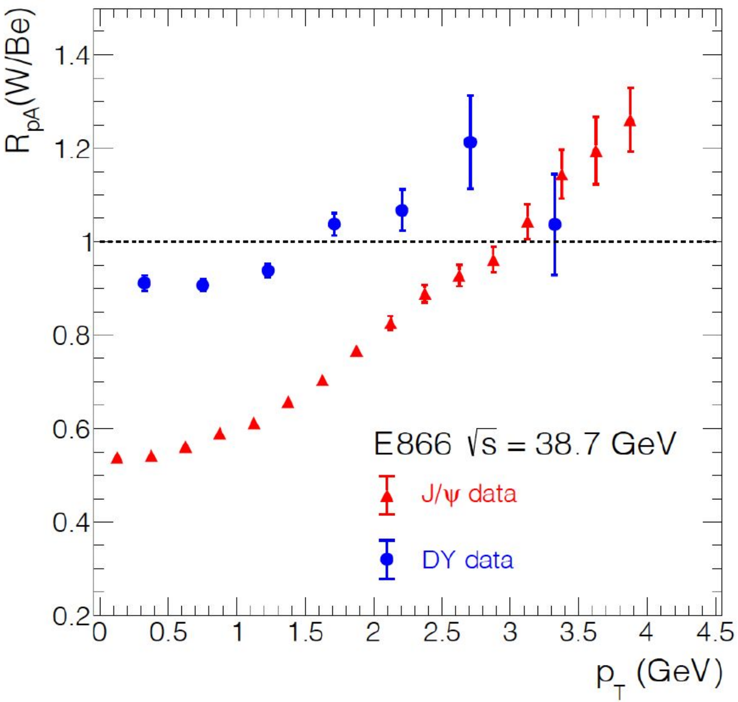
$$\hat{q} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \rho \times xG(x, Q^2), \hat{q} \equiv \frac{\mu^2}{\lambda} = \frac{\mathrm{d}\Delta \mathrm{p}_\perp^2}{\mathrm{dL}}$$

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

Observations from previous fixed target experiments

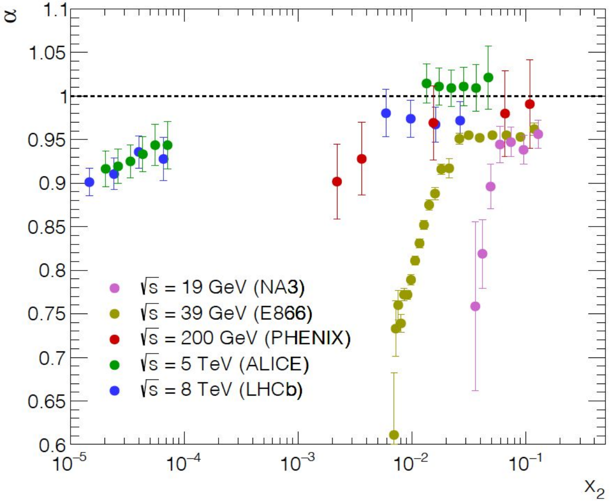
- J/ψ is more suppressed than DY as a function of x_F and p_T
- Different CNM effects for J/ψ and DY [PRL 84 (2000) 3256]

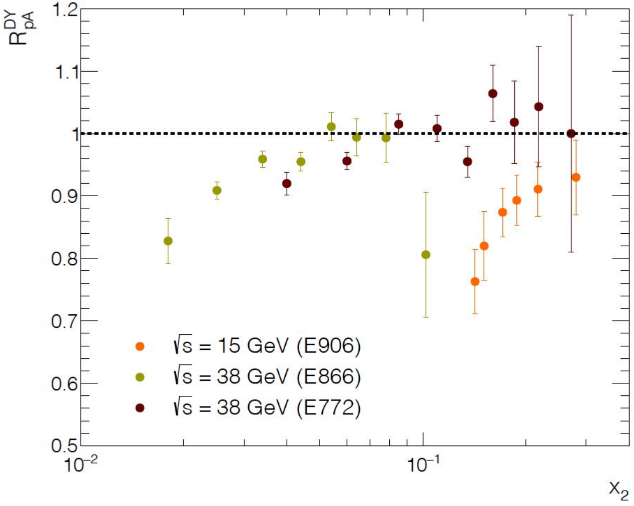




Observations from previous experiments

- J/ψ suppression depends on center of mass energy.
- No scaling as a function of x_2 : R_{pA} = $R_{pA}(x_2,\sqrt{s}) \neq R_{pA}(x_2)$ [Arleo, NaÏm, Platchkov, JHEP01(2019)129]


J/ψ data


DY data

- Coherent energy loss regime explains alone E866 J/ψ data at $\sqrt{s}$=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]
- The final state effects, specially nuclear absorption along with initial state effects describes the data at SPS energies. [A. Capella et al., PLB393 (1997) 431]

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,

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

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

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

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

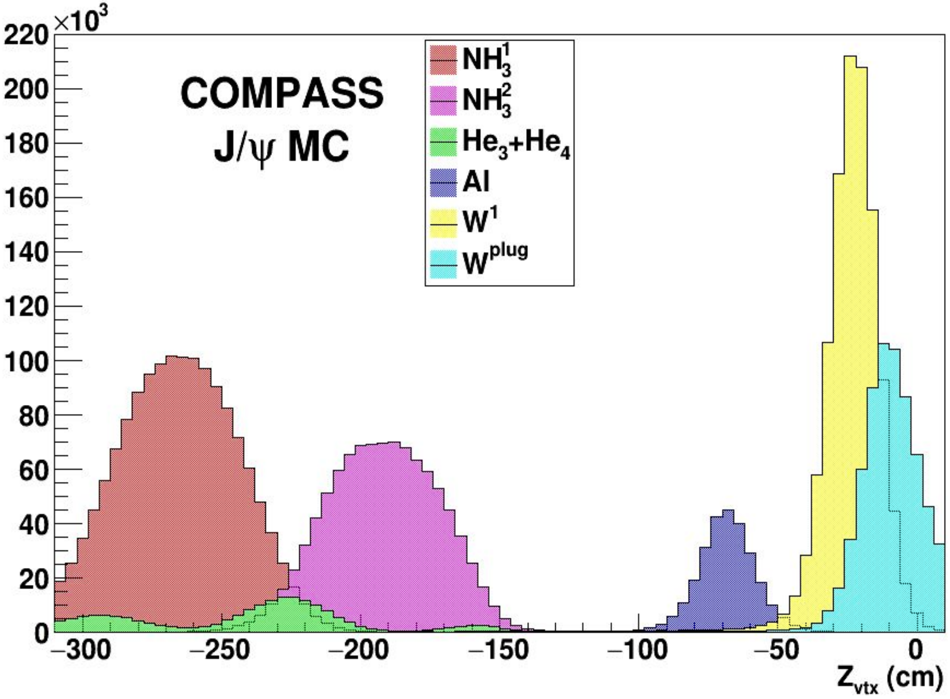
$$R^{J/\psi}_{\pi^- A}(W/Al) = \frac{\mathrm{N}^{\mathrm{J}/\psi}_{\mathrm{W}}(\mathrm{x_F}, \mathrm{p}_\perp)}{\epsilon_W.\alpha^W.L^W_{eff}.\rho^W} \Big/ \frac{\mathrm{N}^{\mathrm{J}/\psi}_{\mathrm{Al}}(\mathrm{x_F}, \mathrm{p}_\perp)}{\epsilon^{Al}.\alpha^{Al}.L^{Al}_{eff}.\rho^{Al}}$$

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 ⟶ Al

- Dimuon events
    - W target = 1.18×10^6
    - Al target = 2.06×10^5

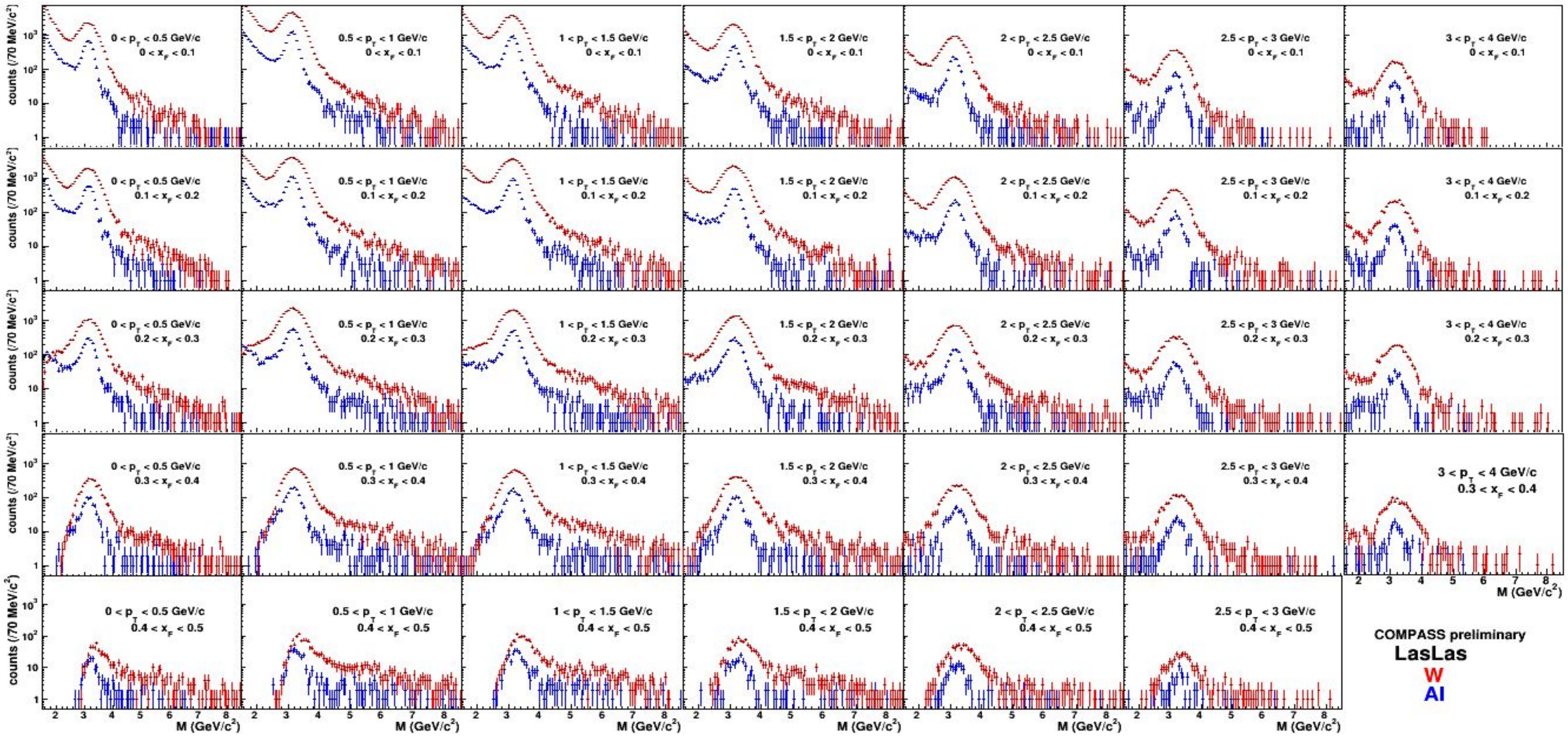


Dimuon invariant mass

p_T →

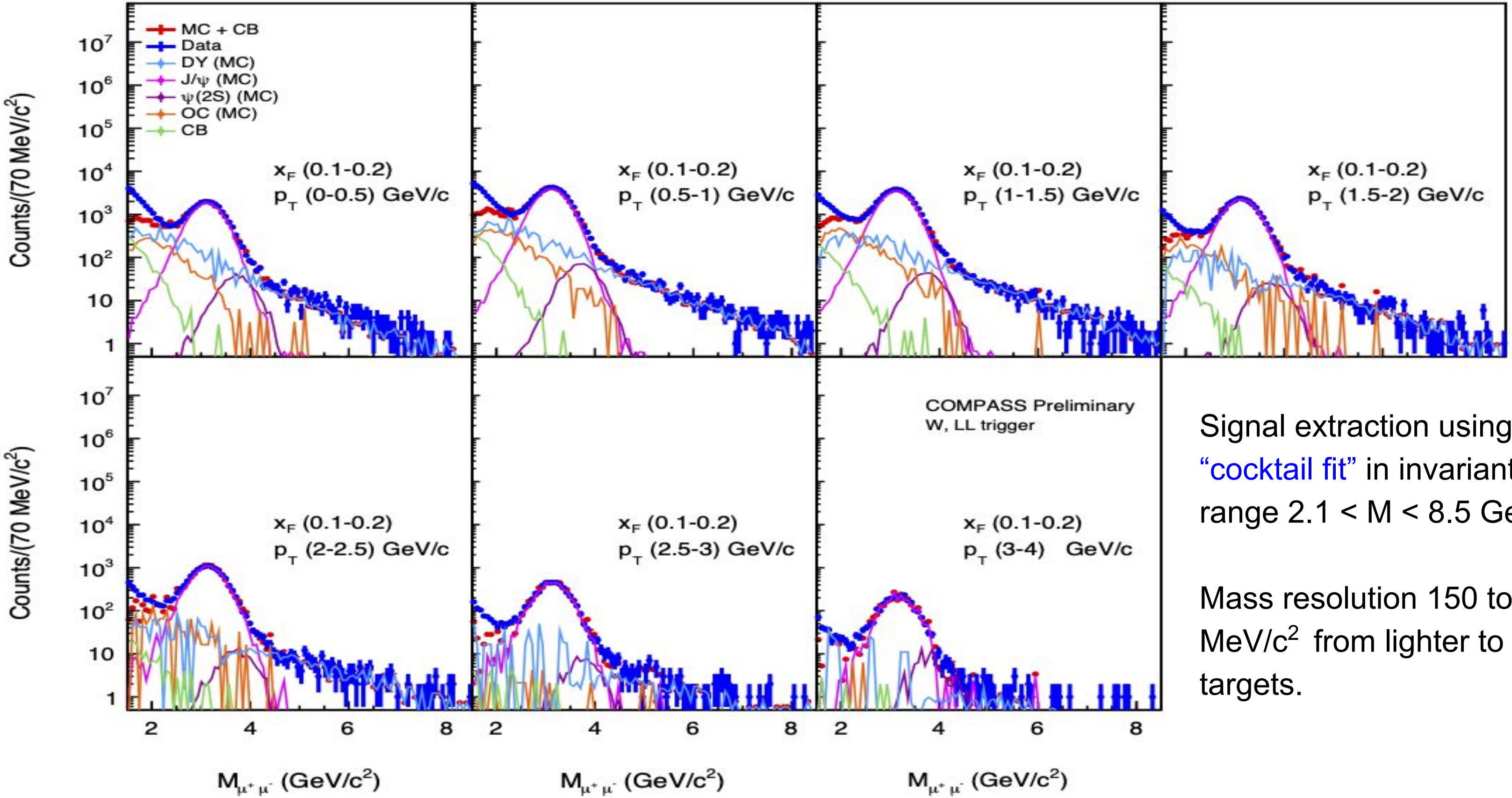
Example shown for W and Al targets, LL triggers

x_F ↓



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

Signal extraction : method 1



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

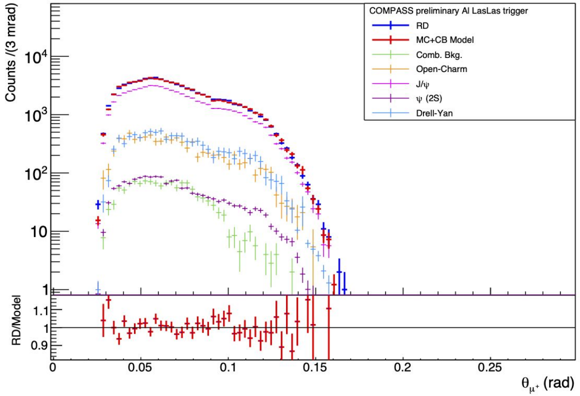
Mass resolution 150 to 300 MeV/c^2 from lighter to heavier targets.

Comparison between Real Data and Monte Carlo

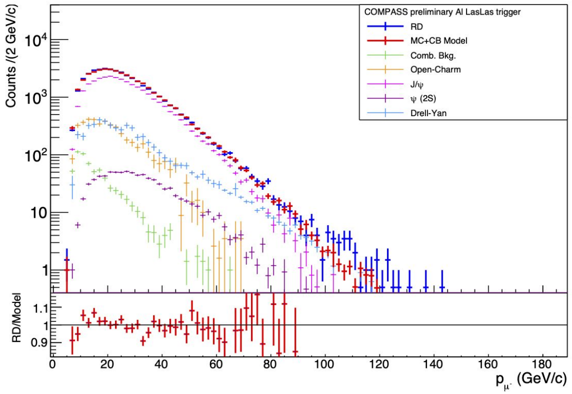
- MC production at COMPASS: (PYTHIA8 + GEANT4)
- Real Data (RD) → J/ψ + ψ(2S) + DY + OC + CB

  “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.

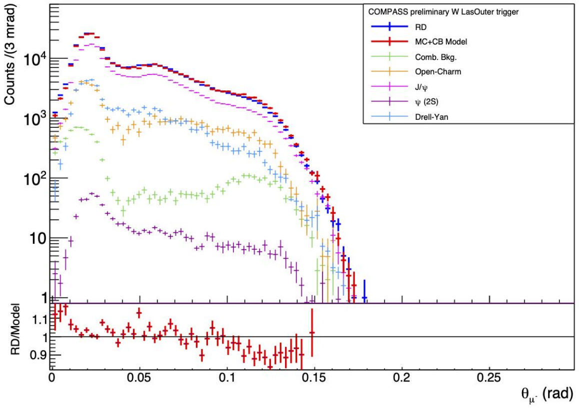
Al, LL trigger, $\theta\mu+$



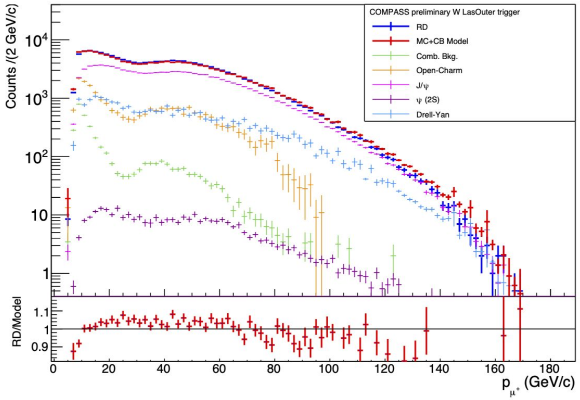
Al, LL trigger, Pμ-



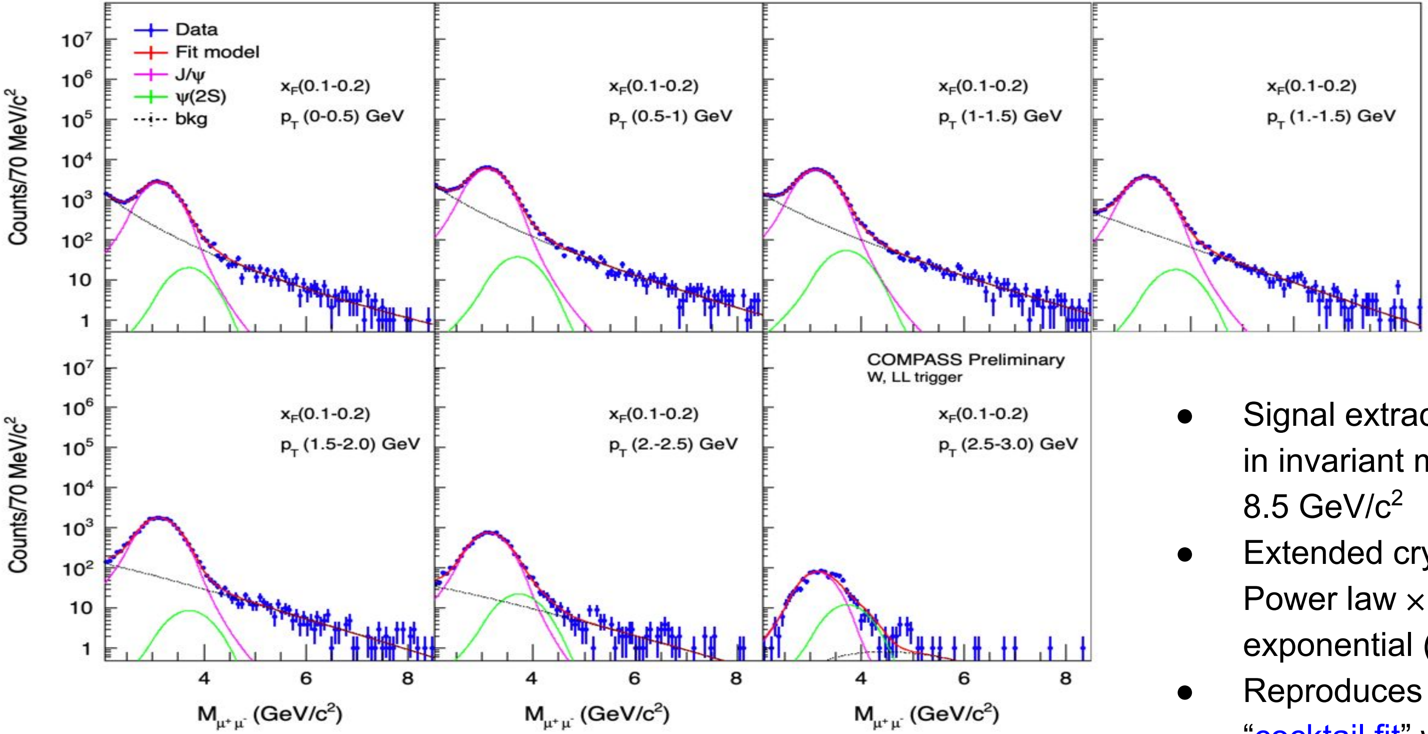
W, LO trigger, $\theta\mu-$



W, LO trigger, Pμ+

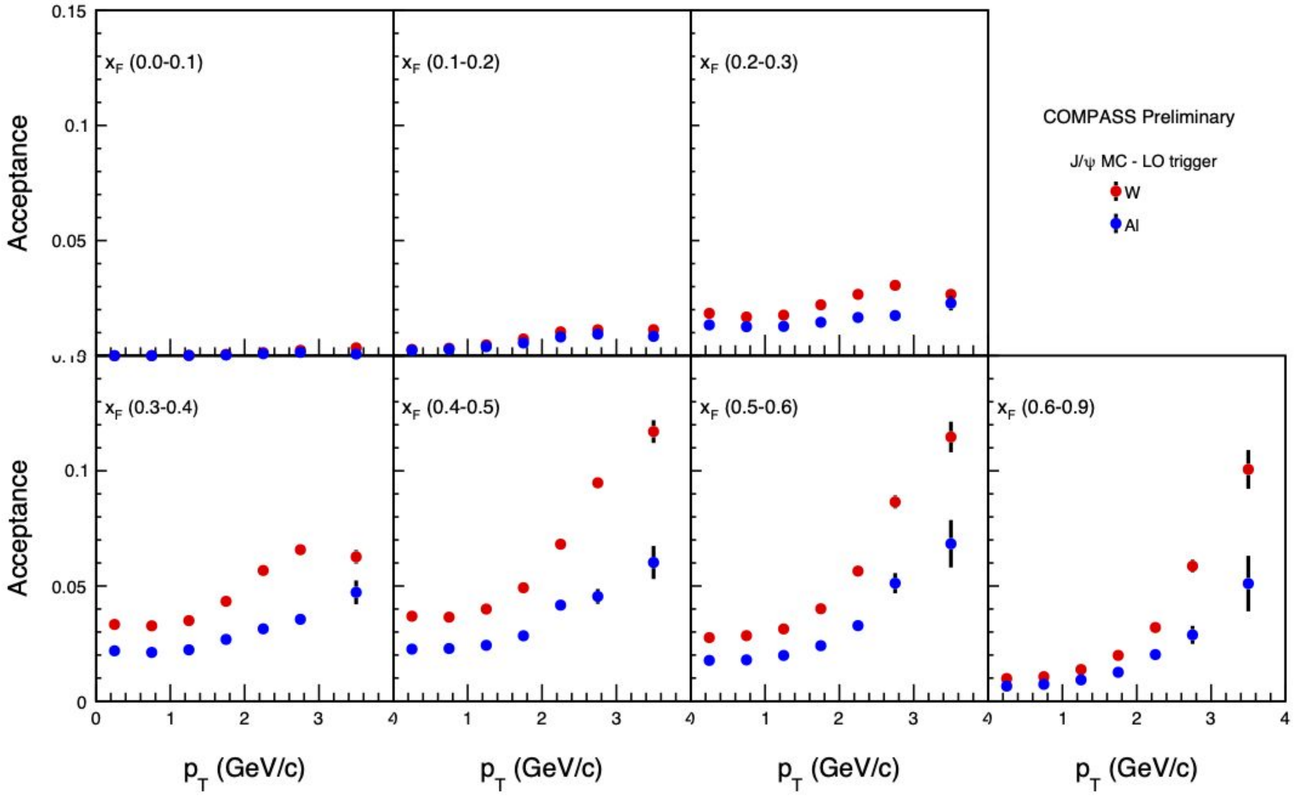


Signal extraction : method 2



- Signal extraction using “fit model” in invariant mass range $2.1 < M < 8.5$ GeV/c^2
- Extended crystal ball (signal) + Power law × polynomial(0) × exponential (background)
- Reproduces signal extracted with “cocktail fit” with ~ 5% systematic uncertainty.

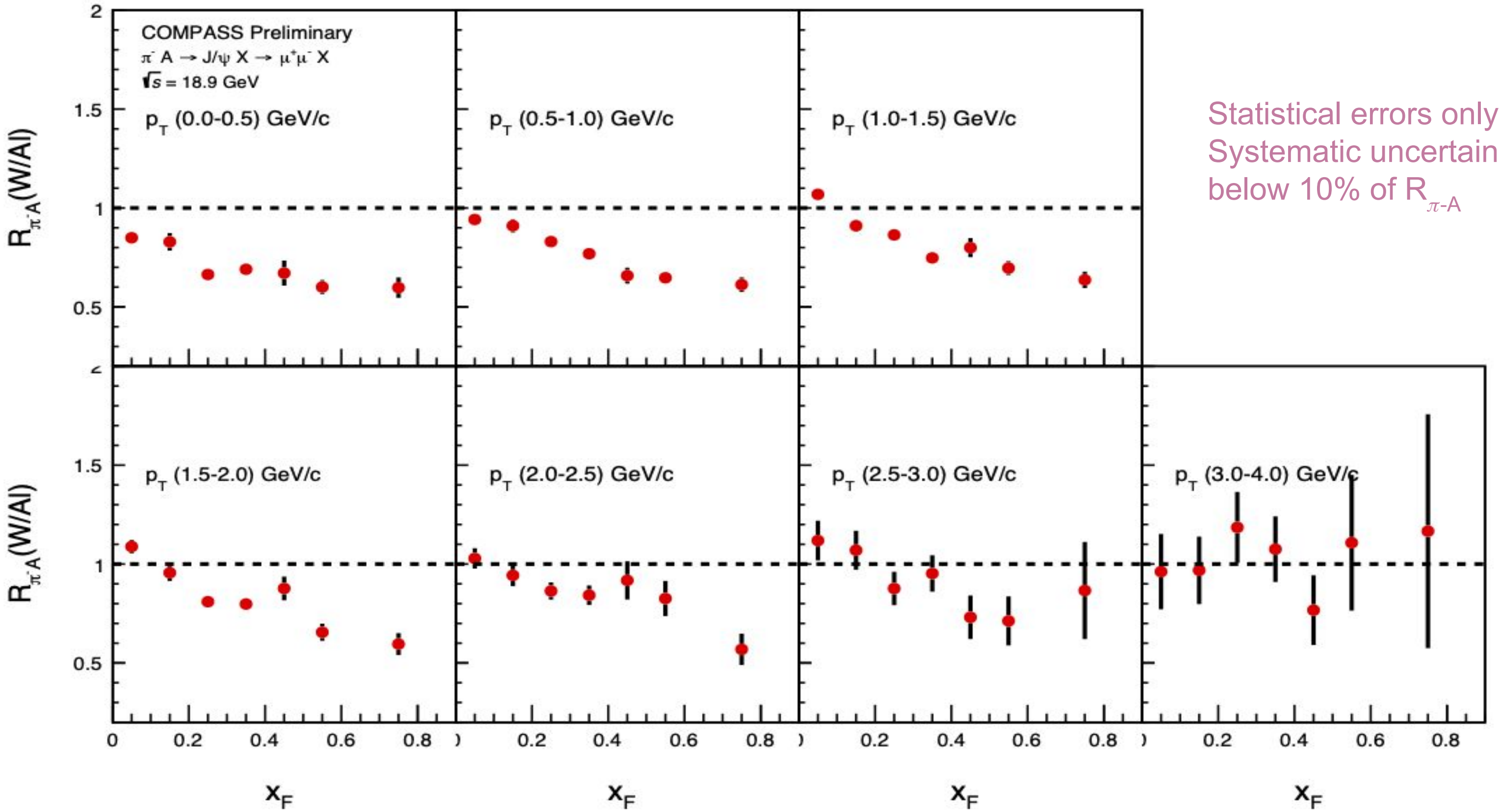
Acceptance



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

J/ψ acceptance shown for W and Al targets in LO trigger.

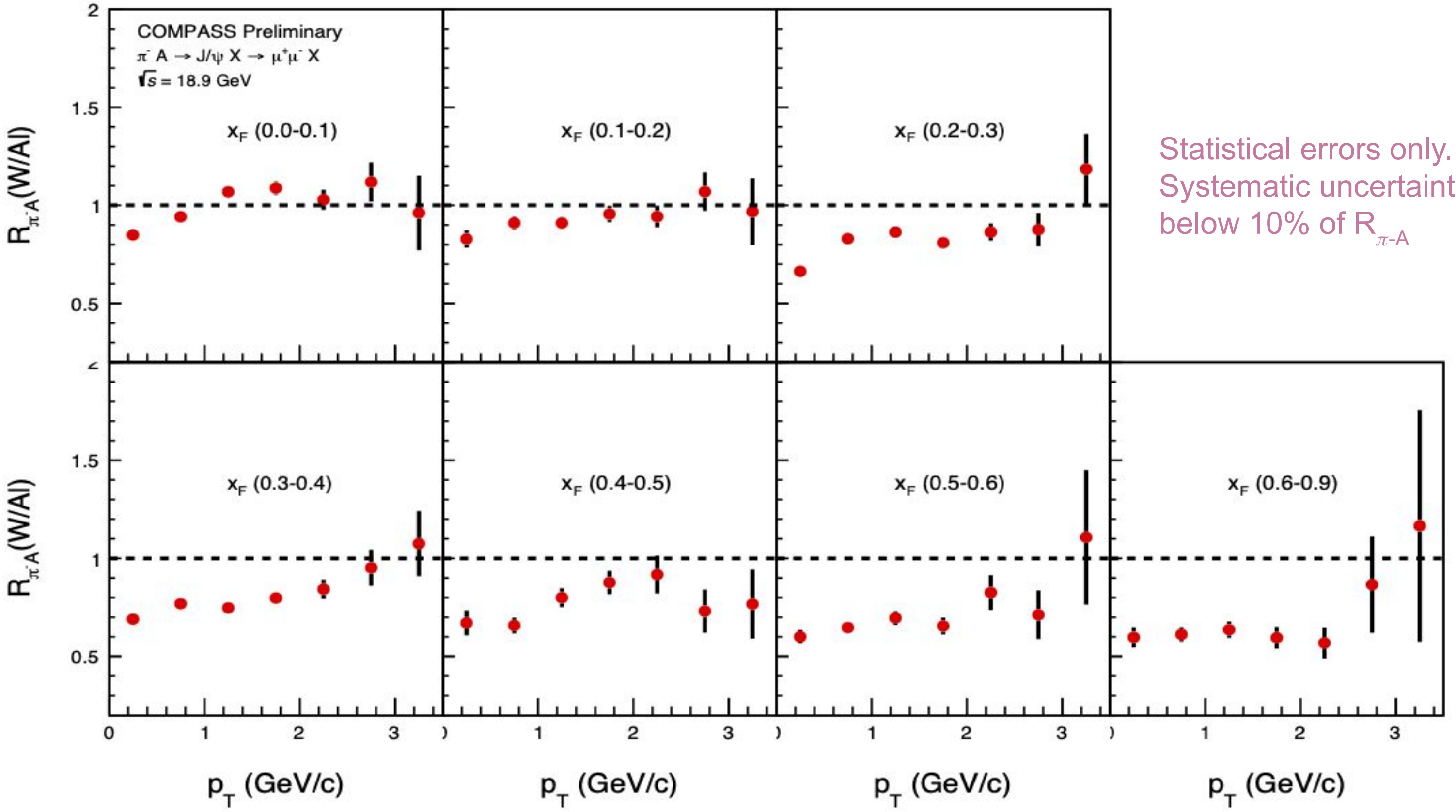
Results: p_T differential $R_{\pi\text{-}A}$ as a function of x_F



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

Suppression towards large x_F, more prominent at low p_T.

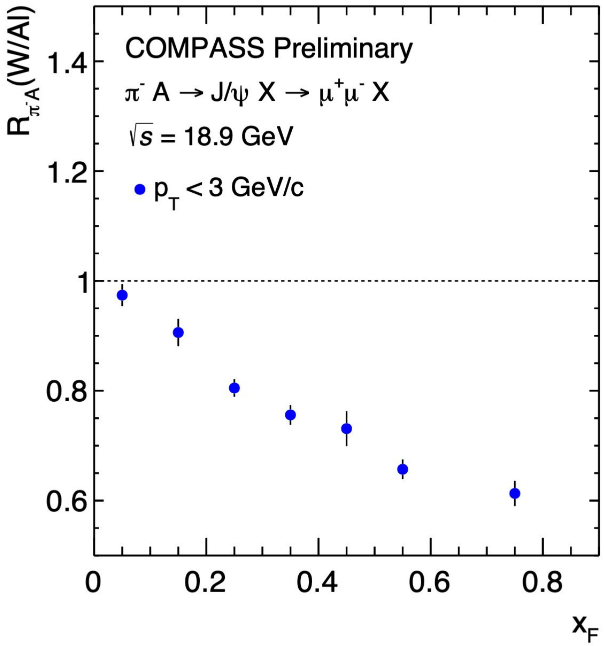
Results: x_F differential $R_{\pi\text{-}A}$ as a function of p_T

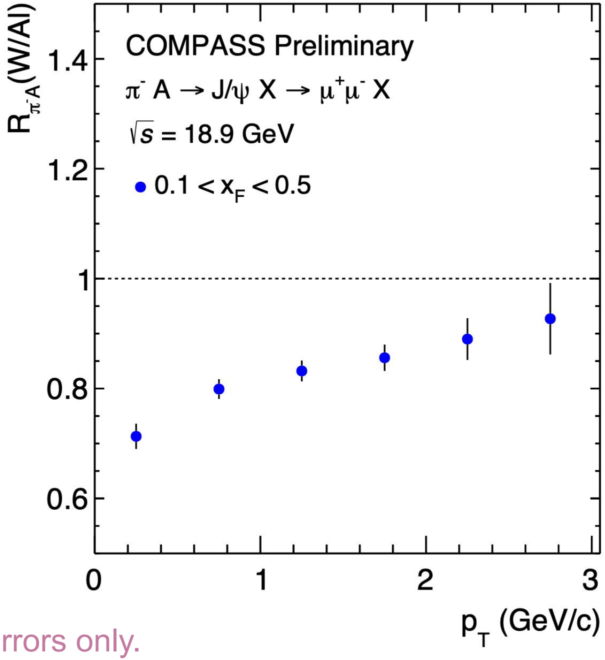


Statistical errors only. Systematic uncertainty below 10% of $R_{\pi\text{-}A}$

Suppression at low p_T, more prominent at large x_F.

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

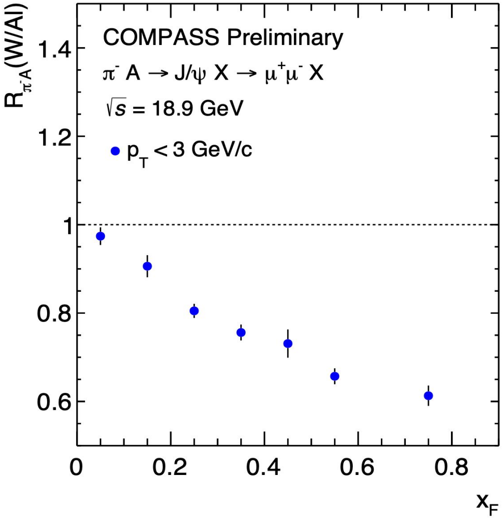


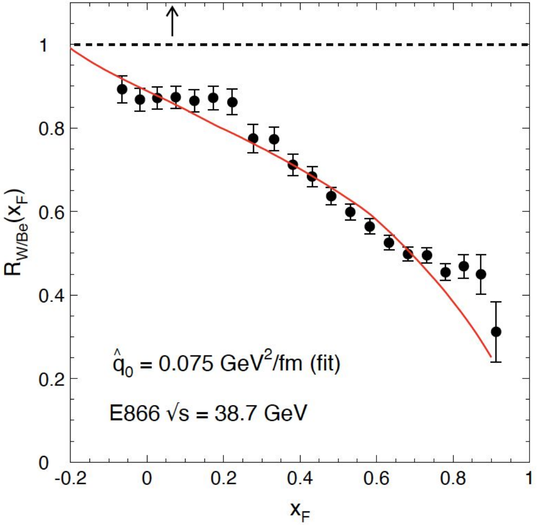


Statistical errors only.
Systematic uncertainty
below 10% of $R_{\pi\text{-}A}$

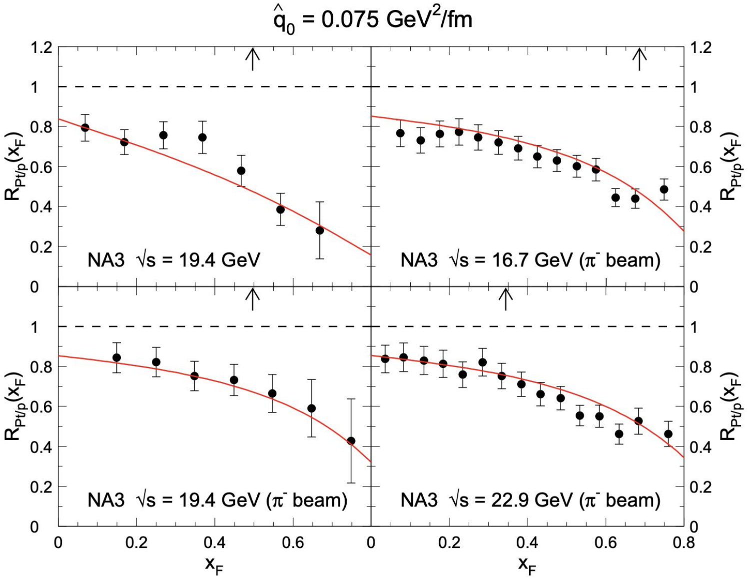
- Combined for two trigger by taking average over common kinematic range.
- Suppression towards high x_F and low p_T observed similar to 2D results.

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 and nuclear absorption.
- AMBER "New QCD facility at the M2 beam line of the CERN SPS".
  [https://amber.web.cern.ch/]

Thank you for your attention!

Extras

Kinematic variable definition

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

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

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

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

$$x_{\mathrm{F}} \simeq 2M_{\perp}/\sqrt{s} \times \sinh(y)$$

Nuclear absorption

Final-state inelastic interactions can dissociate the quarkonia bound state when passing through the nucleus end up in suppression.

Condition for quarkonium formation time inside nuclei

$$t_{had} = \gamma \tau_{had} = \frac{E}{M_Q} \tau_{had} \lesssim L$$


$t_{had} \lesssim L$ $t_{had} \gtrsim L$

[C-J. Naïm, PhD. Thesis (2020)]