Drell-Yan process measurement at COMPASS as inputs to PDFs

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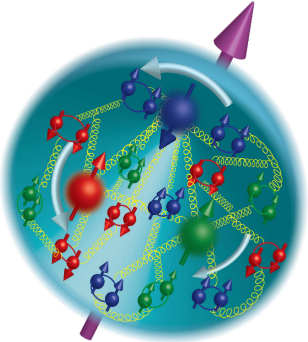
ECT* PDF at crossroad
18^{th}-22^{nd} September 2023
Trento (Italy)

Challenging our understanding of QCD

For decades, the nucleon has been used as test bench to provide observables to test QCD



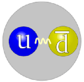
We know it has a complex structure

- Pretty well known unpolarised 1D structure
- Spin distribution better understood
- Entering the era of multidimension/correlations GPDs, TMDs, . . .

but. . .

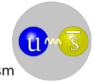
Challenging our understanding of QCD beyond the nucleon

QCD should also encode the differences between hadrons

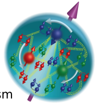


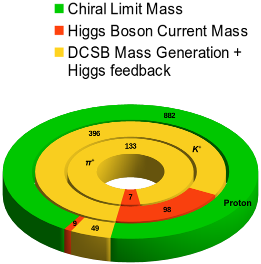
Pion
M∼140 MeV
5% from Higgs mechanism

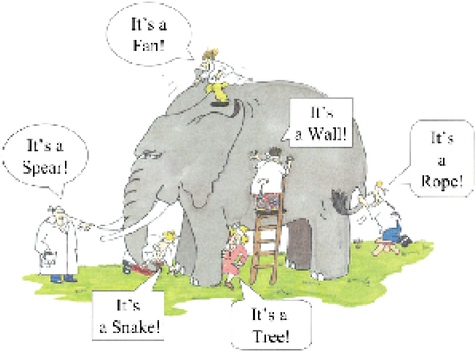
Kaon
M∼494 MeV
20% from Higgs mechanism



Proton
M∼940 MeV
1% from Higgs mechanism



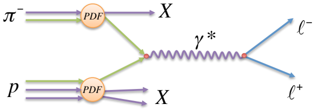




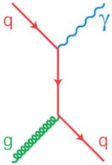
How to provide measurements to confront and constrain theories

How to probe the meson structure?

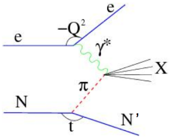
Drell-Yan



Prompt photon



Sullivan process

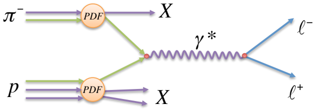


π^--induced Drell-Yan measurements: W.J. Stirling and M.R. Whalley 1993 J. Phys. G: Nucl. Part. Phys. 19 D1

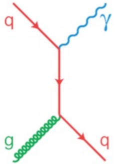
Experiment	Target type	Beam energy (GeV)	DY mass (GeV/c^2)	DY events	Systematics
NA3	30cm H_2	200	4.10 – 8.50	121	12.6%
	6cm Pt	200	4.20 – 8.50	4,961	
NA10	120cm D_2	286	4.2 – 8.5	7,800	6.5%
		140	4.35 – 8.5	3,200	
	12cm W	286	4.2 – 8.5	49,600	
		194	4.07–15.19	155,000 (inc. Υ)	
		140	4.35 – 8.5	29,300	
E615	20cm W	252	4.05 – 8.55	30,000	16%

How to probe the meson structure?

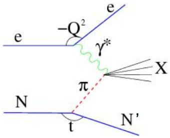
Drell-Yan



Prompt photon

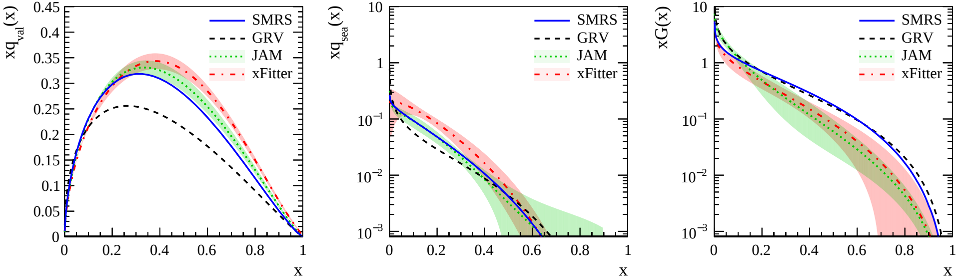


Sullivan process



Status of PDFs extractions from data:

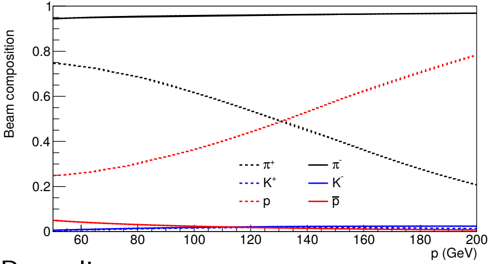
PRD107, 056008 (2023)



Current experimental results are too scarce or not accurate enough to constrain phenomenological approaches

COMPASS Collaboration at CERN

∼ 200 physicists from 25 institutions from 13 countries

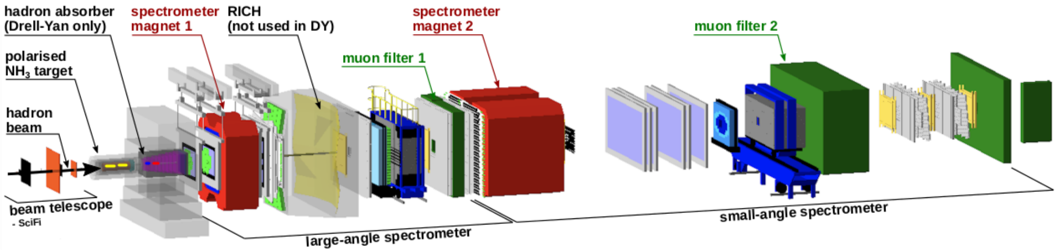


Beam line:

- High intensity hadron beam: ∼70 MHz
- High energy: 190 GeV
- Negative hadron beam composition:
  - **97% pions**
  - 2% kaons
  - 1% anti proton

Apparatus: Two-stage spectrometer

NIMA 577 (2007) 455, NIMA 779 (2015) 69, NIMA 1025 (2022) 166069



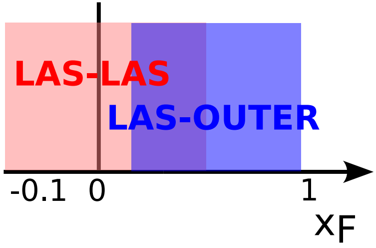
Key elements:

- Versatile target area configuration
- 2 spectrometers in 1 for a wide coverage: 8mrad$<\theta_\mu<$160mrad
- **2 triggering system:**
  - LAS-LAS
  - LAS-OUTER
- 2 Muon filters
- $\sim$ 400 tracking planes

Variable definitions:

$$x_F = \frac{2p_L^*}{\sqrt{s}}$$

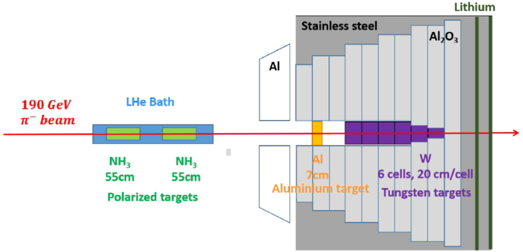
$$x_{\pi/N} = \frac{1}{2}\left(\sqrt{x_F^2 + 4\frac{M^2}{s}} \pm x_F\right)$$



Consideration for the luminosity

Due to high luminosity requirement:

- hadron absorber needed for radio-protection and spectrometer performance
- sequential targets: polarisable target, Al, W



Approximate resolutions:

Target	δx_F	δq_T (MeV/c)	$\delta M/M$
Pol. targ.	0.03	150	3.5%
Al	0.03	245	4.5%
W	0.03	340	6.5%

Analysis performed in multidimensions with:

- 12 bins in x_F
- 3 to 5 (10 for pol. target) bins in Mass from 3D to 1D
- 4 to 5 (10 for pol. target) bins in q_T from 3D to 1D

Zoom on polarisable target material

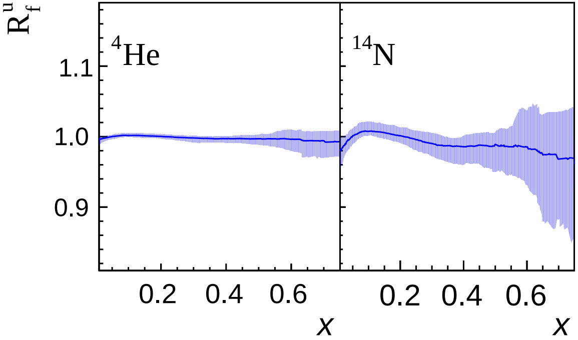
When integrated over the spin states it is mixture of NH_3 and LHe:

molar fraction of nucleons:

H	He	N
15.7%	11.1%	73.2%

Light nuclei with expected small nuclear effects $\sim \pm 2\%$ in the accessible region

Target will be denoted NH_3-He in the following

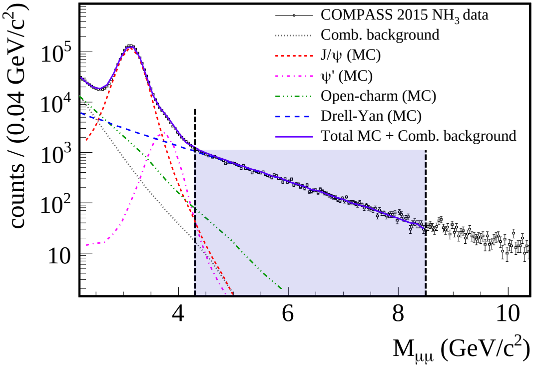


Nuclear modification PDF for u-quark from nNNPDF3.0

Mass spectra and region of interest

Several channels contribute to inclusive dimuon final state production:

- Combinatorial background
- Open-Charm production in low mass
- Resonances: J/ψ and ψ'
- Drell-Yan in high mass



Statistical separation based on the different kinematic dependence with various Monte-Carlo samples and the combinatorial background distribution assessed from like-sign pairs in real data ($2\sqrt{N^{++}N^{--}}$): "Cocktail fit"

Collected pairs in the region of interest 4.3 GeV/c^2 to 8.5 GeV/c^2:
NH_3-He: 36 000   Al: 6 000   W: 43 000

Evaluation of Drell-Yan process purity

Example of extraction method:

"Cocktail fit" from 2.4 (GeV/c^2)
for each kinematic bins of cross-section

Process purity is assessed from the ratio of Drell-Yan component to the total

Purity is above 90% for

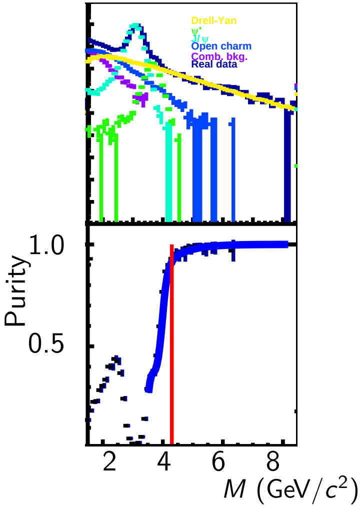
$M > 4.3$ (GeV/c^2) for NH_3-He

$M > 4.7$ (GeV/c^2) for Al

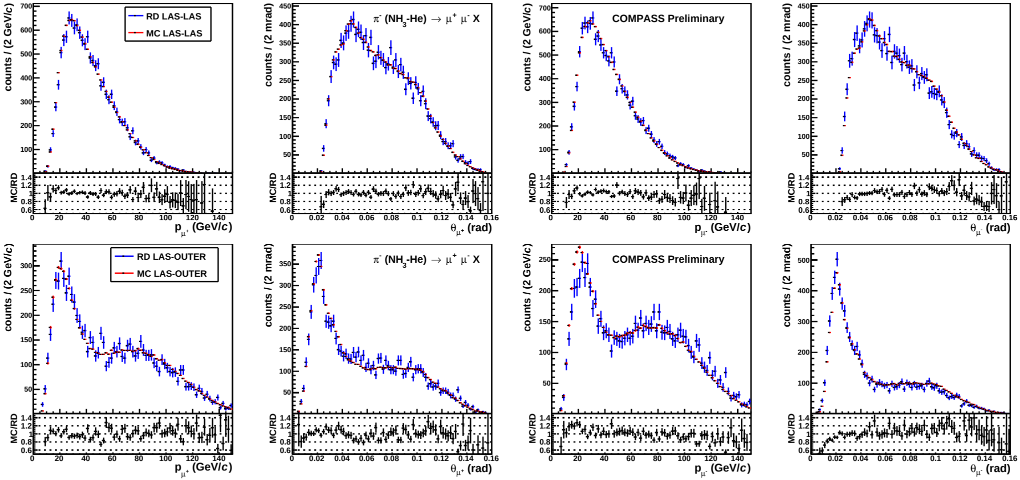
$M > 5.5$ (GeV/c^2) for W

with mild $\nearrow$ with x_F & $\searrow$ with q_T

$0.2 < x_F < 0.3$
$0.7 < q_T/(\text{GeV}/c) < 1.1$



Compare real data with Monte-Carlo for the first cell of NH_3-He target



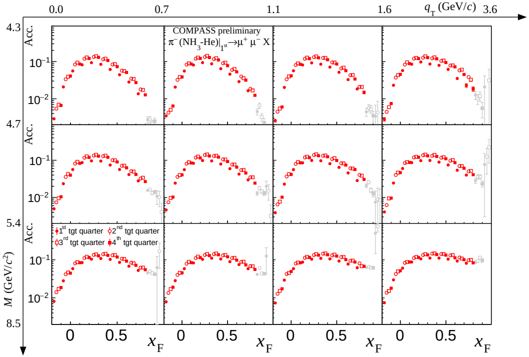
Good description of lab variables with weighted MC sample for $M > 4.3$ (GeV/c^2)

Similar level of agreement for other targets, except for W which shows larger variations

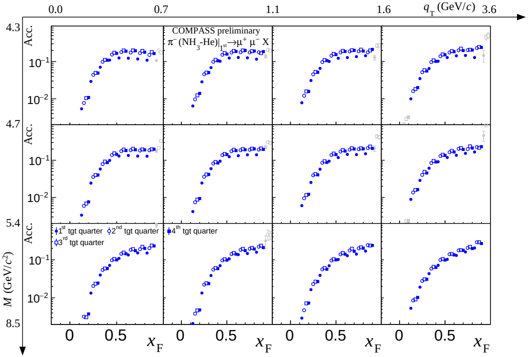
Acceptance example for the first cell of NH_3-He target

Determined from pure Drell-Yan Monte-Carlo sample in 4 dimensions: x_F, M, q_T, Z_{vertex}

LAS-LAS trigger



LAS-OUTER trigger

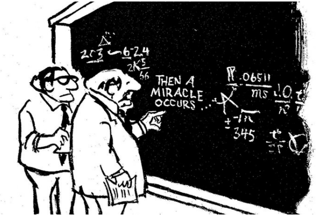


Acceptance restricted to domain where statistical accuracy is better than 10%

it varies between ∼1 to ∼10% with largest dependence on x_F

Contributions to systematic uncertainties

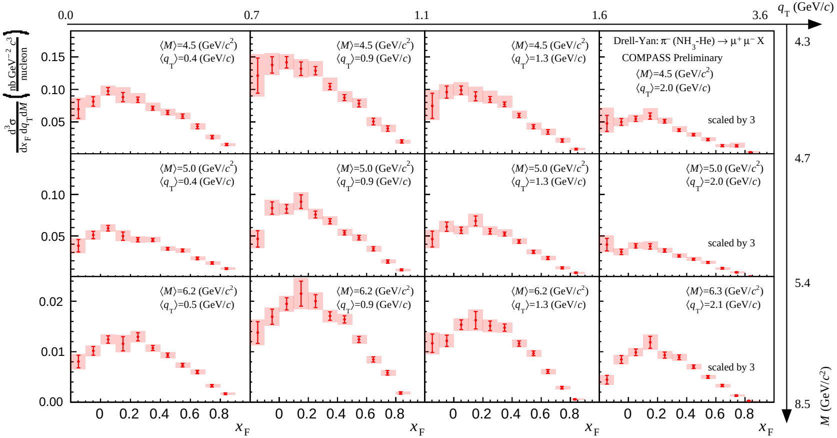
Recorded number of dimuons



Drell-Yan cross section

1. Process purity determination
2. Trigger system normalisation
3. Acceptance
4. Luminosity
5. ...

3 dimensional Drell-Yan cross section on NH_3-He

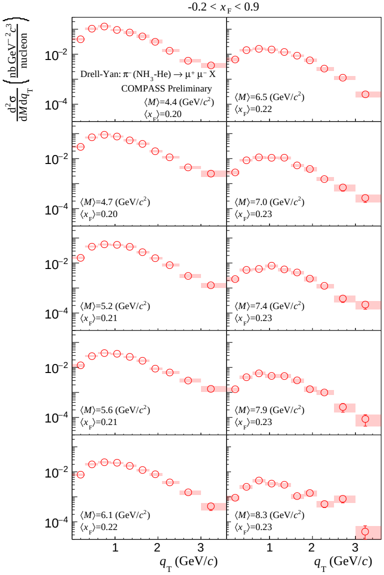


- **First high statistics measurement with light material**
- Red line/shaded area: statistical / total (stat. and syst.) uncertainties
- Dominated by statistical uncertainty

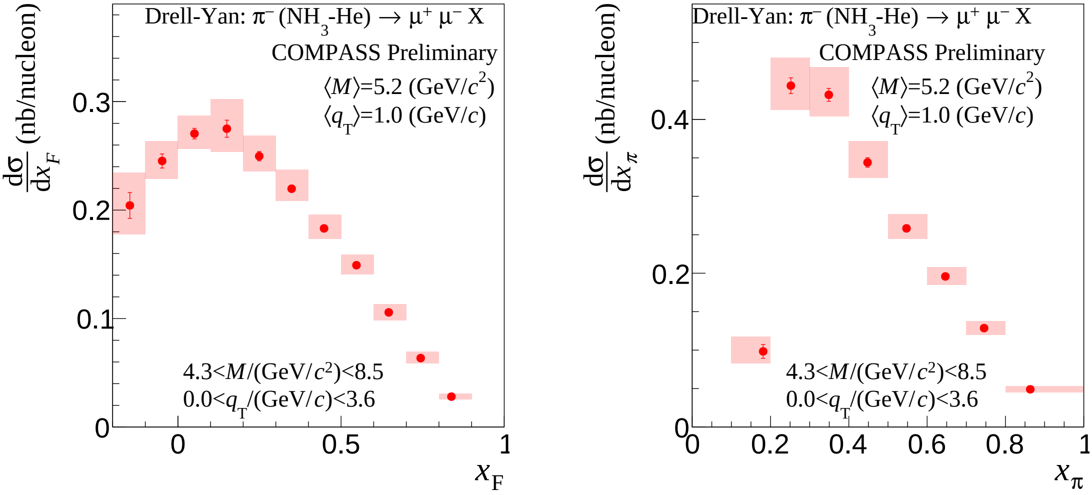
q_T dependence of Drell-Yan cross section on NH_3-He

Unique inputs to extract π TMD with minimum nuclear effects

Systematics uncertainty at the level of statistical precision

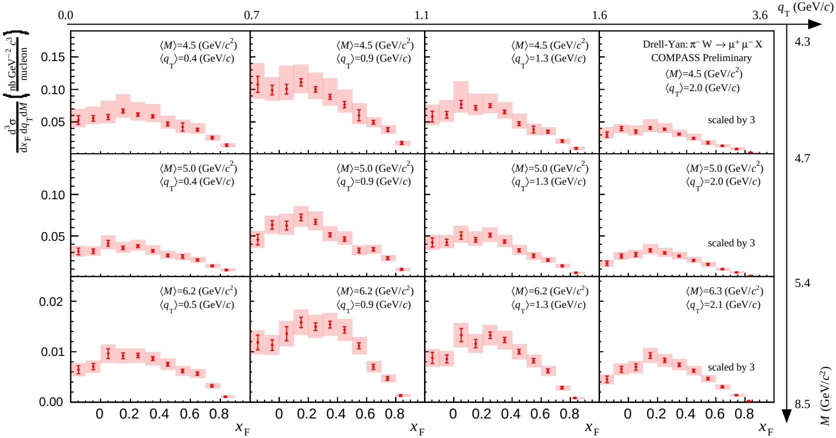


x dependence of Drell-Yan cross section on NH_3-He



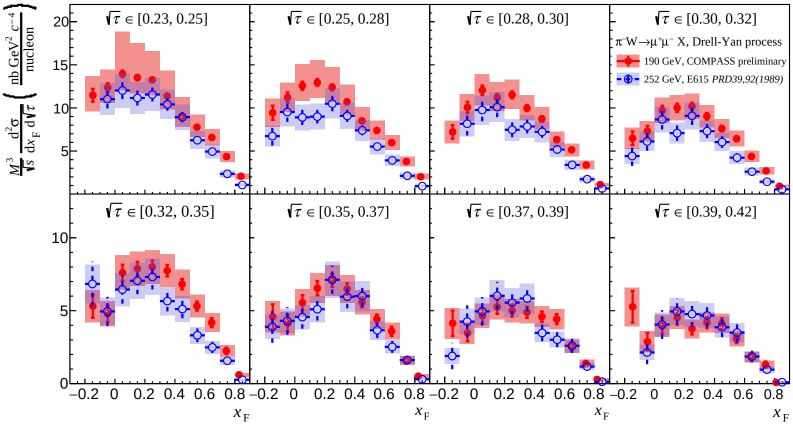
- First high statistics results on light target
- Largest uncertainties come from acceptance and purity corrections

3 dimensional Drell-Yan cross section on W



- Wide kinematic coverage
- Red line/shaded area: statistical / total (stat. and syst.) uncertainties
- Dominated by systematic uncertainty

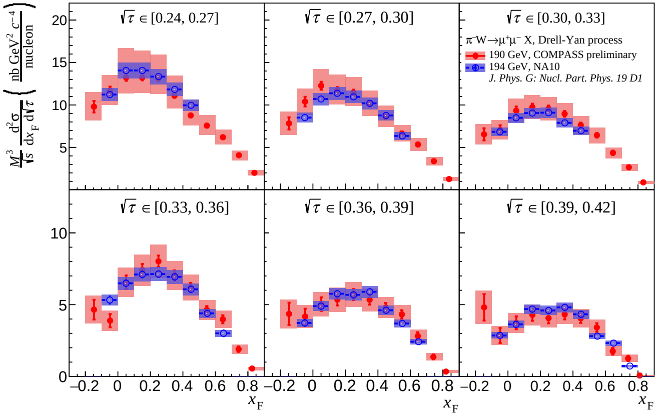
Drell-Yan cross section on W and comparison to E615



$$\sqrt{\tau} = M/\sqrt{s}$$

- **New results since 30 years**
- Similar kinematic coverage as E615
- Better statistics, similar total systematics except for the low mass region

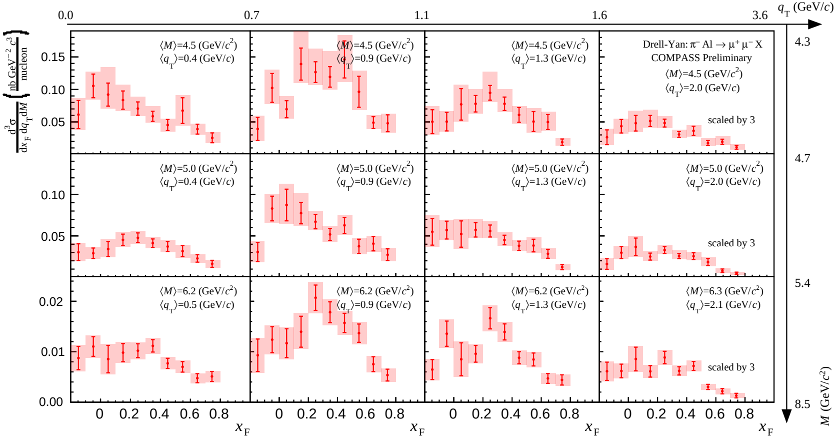
Drell-Yan cross section on W and comparison to NA10



$$\sqrt{\tau} = M/\sqrt{s}$$

- **Wider kinematic coverage**
- Worse accuracy in statistics as well as in systematics

3 dimensional Drell-Yan cross section on Al



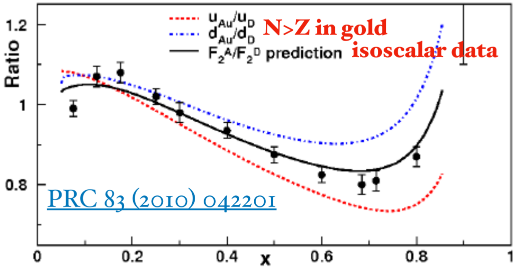
- Measurement with intermediate A number
- Red line/shaded area: statistical / total (stat. and syst.) uncertainties
- Dominated by statistical uncertainty

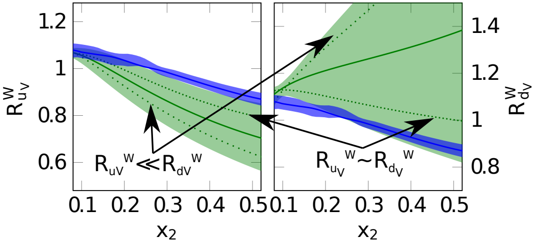
Flavour dependent EMC effect:

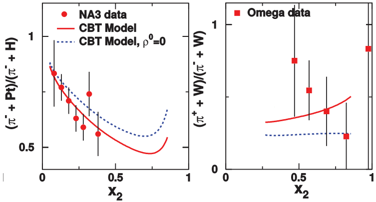
Unlike DIS, π-induced Drell-Yan process tags the quark flavour

nCTEQ15: unconstrained flavour dependence

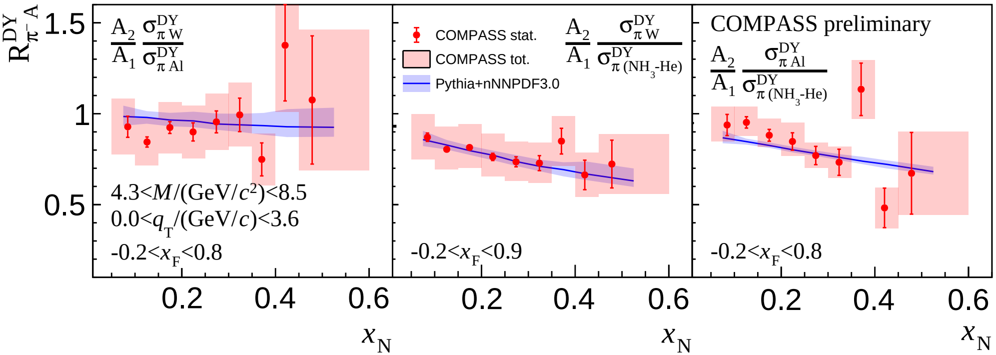
EPS09: no flavour dependence







Flavour dependence of $R^{DY}_{\pi A}(x_N) = (A_2 d\sigma^{DY}_{\pi A_1})/(A_1 d\sigma^{DY}_{\pi A_2})$



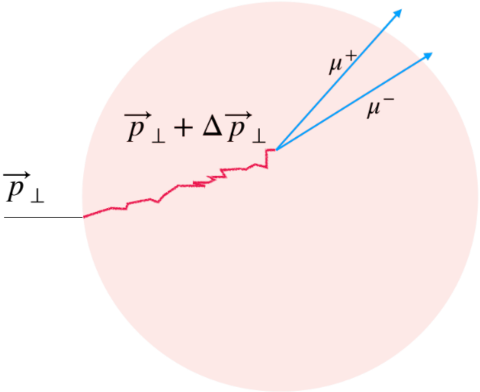
- Ratio of integrated DY cross section per nucleon in all but x_N variable
- Covering the domain between anti-shadowing and EMC
- General trend as expected...
- ... Currently limited by systematics except possibly for Al/(NH_3-He)

Parton energy loss and Cronin effects

Parton crossing nuclear medium, looses energy due to multiple scattering and gluon emission

Signatures:

- Gain of transverse momentum:
  q_T Broadening
- Loss of longitudinal momentum:
  Suppression at large x_F



Broadening of q_T dependence of Drell-Yan cross section

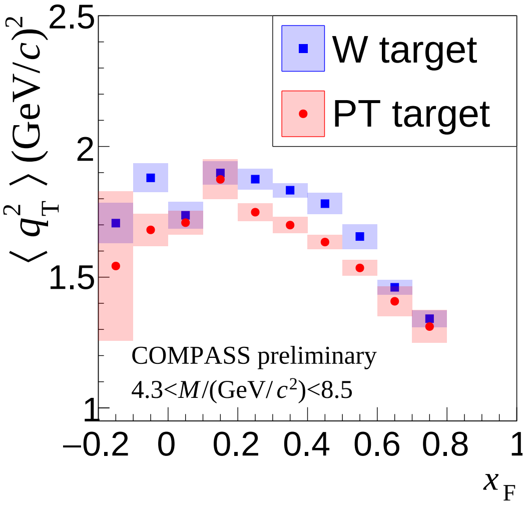
Extracted from a fit to $\frac{d^2\sigma}{dx_F dq_T}$

assuming in each x_F bin an empirical shape:

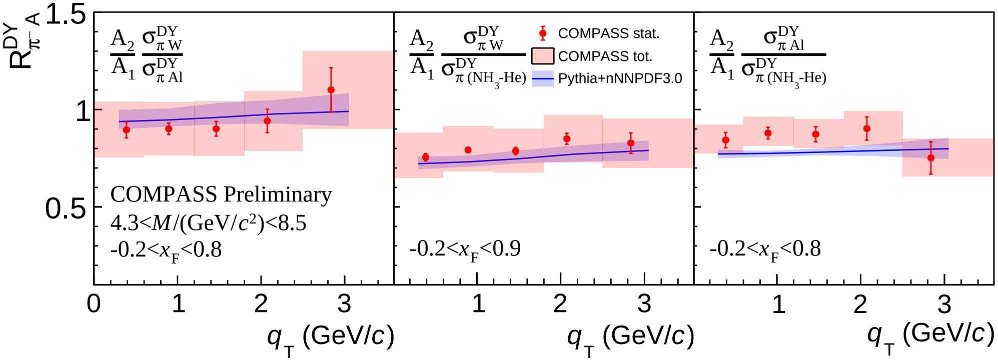
$$2\mathcal{N} q_T (1 + (\frac{q_T}{b})^2)^{-6}$$

Only relevant parameter: $b \to < q_T^2 >$

Evidence for q_T broadening visible

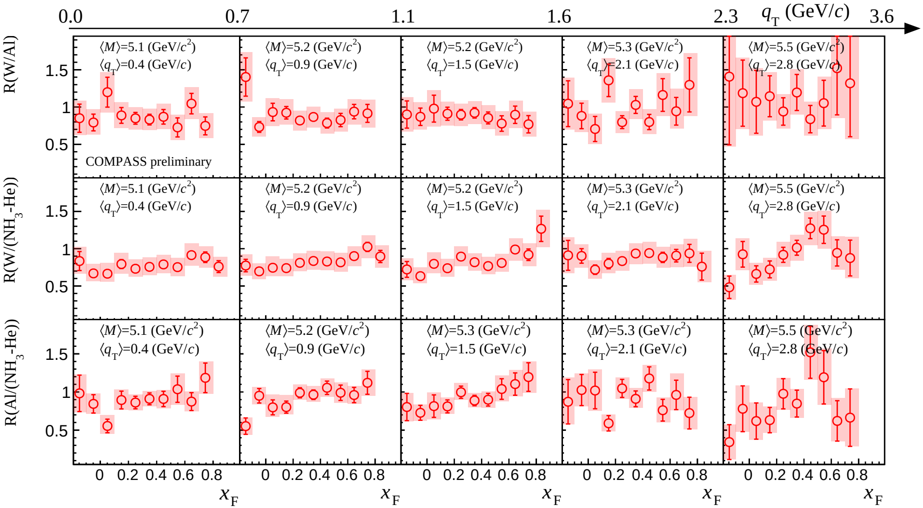


Drell-Yan nuclear modification factor $R^{DY}_{\pi A} = (A_2 d\sigma^{DY}_{\pi A_1})/(A_1 d\sigma^{DY}_{\pi A_2})$ vs q_T



- Ratio of integrated DY cross section per nucleon in all but q_T variable
- Measurements are in agreement with effective effects encoded in nPDF
- Currently limited by systematics except possibly for Al/(NH_3-He)

Drell-Yan nuclear modification factor $R(A_1/A_2)$ in x_F for various q_T bins



Steeper slope in x_F at large q_T mainly in $W/(NH_3\text{-}He)$ and $Al/(NH_3\text{-}He)$

Soon in bins of x_N to disentangle from shadowing and EMC effects

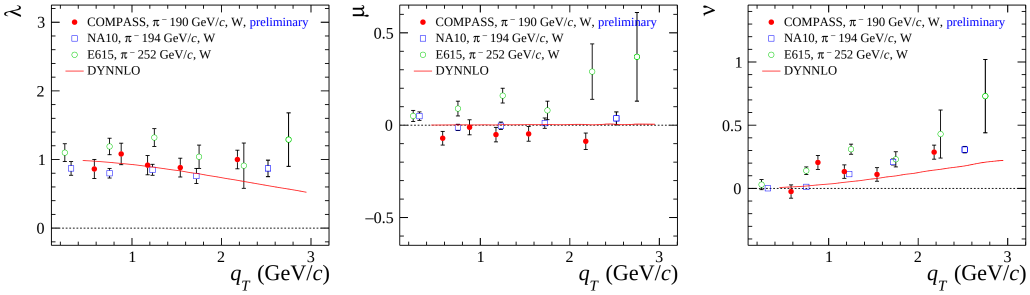
General expression for spin independent cross-section:

$$\frac{dN}{d\Omega} \propto \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1+\lambda\cos^2(\theta_{CS})+\mu\sin(2\theta_{CS})\cos(\phi_{CS})+\frac{\nu}{2}\sin^2(\theta_{CS})\cos(2\phi_{CS})\right)$$

where $\lambda = A_U^1$, $\mu = A_U^{cos(\phi_{CS})}$ and $\nu = 2A_U^{cos(2\phi_{CS})} \propto h_{1,h}^{\perp q} \otimes h_{1,p}^{\perp q}$

In naive Drell-Yan: LO (pure electromagnetic) and no k_T: $\lambda = 1, \mu = \nu = 0$

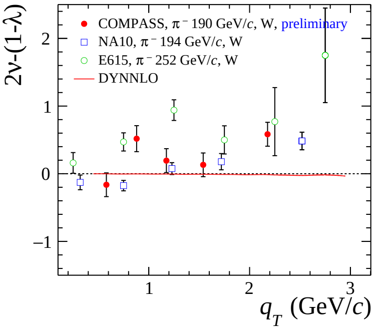
Preliminary 2018 data results, systematic uncertainty (not shown) similar to the statistical ones



- Large effect from higher order corrections
- Hint for non-zero Boer-Mulders effect

Lam-Tung relation

C.S. Lam and W.K. Tung, PRD18 (1978) 2447



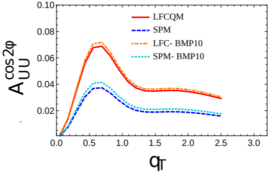
Analog of DIS Callan-Gross relation for Drell-Yan:

$$2\nu = 1 - \lambda$$

- Reflect the spin 1/2 of the quarks
- Less affected by first order QCD corrections

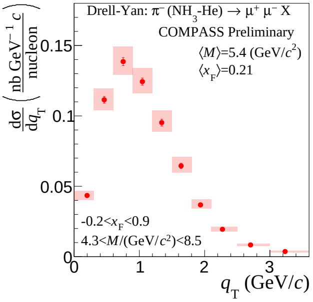
Preliminary systematic uncertainty (not shown) similar to the statistical ones

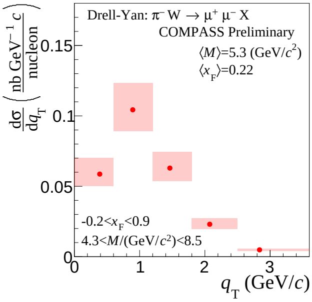
S. Bastami *et al.* JHEP 02 (2021) 166



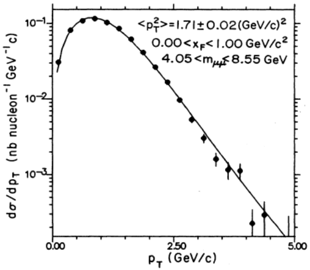
- Consistent with results obtained by past pion-induced Drell-Yan experiments
- Preliminary results indicate a possible violation of Lam-Tung relation
- This leaves some room for Boer-Mulders effects: $2\nu - (1-\lambda) \approx 4A_U^{cos(2\phi_{CS})}$

q_T dependence of Drell-Yan cross section





E615 PRD39 (1989)

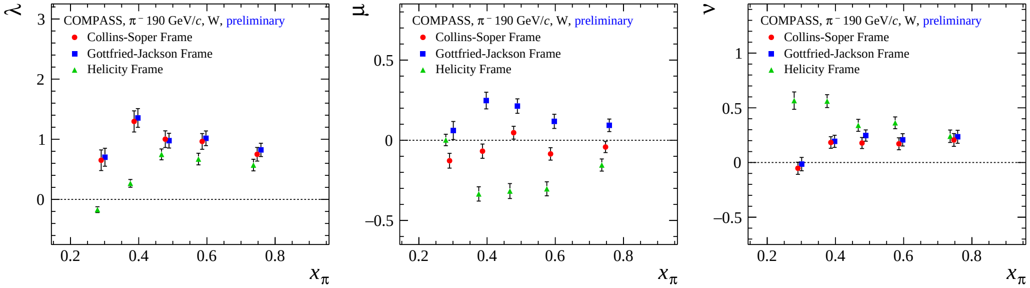


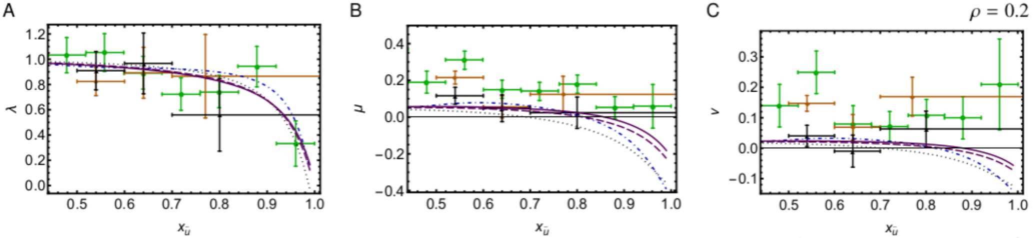
Similar mean value of q_T for COMPASS and E615

$$\Rightarrow \rho = Q_T/M \approx 0.2$$

For comparison with results shown by Hui-Yu Xing on Monday (see next slide)

Drell-Yan angular parameters for several reference frames

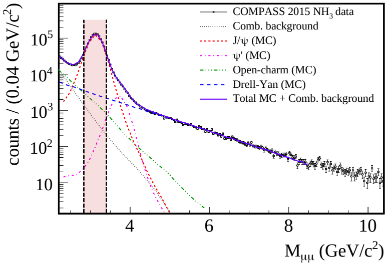




H.-Y. Xing, et al. NJU-INP 077/23

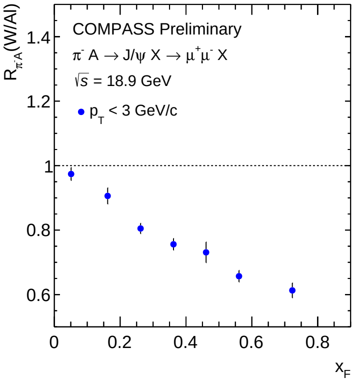
J/ψ region

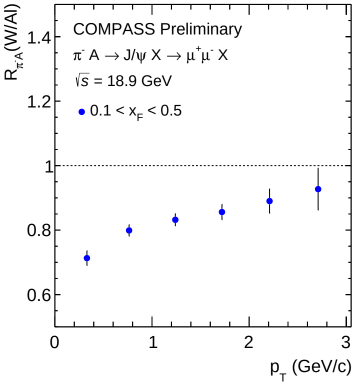
- Larger cross-section $\rightarrow \sim 30\times$ more data compared to high-mass Drell-Yan region
- Probing $\langle x_N \rangle \sim 0.09$: $\approx$valence domain
- J/ψ signal extracted from "cocktail fit"



Results of nuclear modification factor from J/ψ

Ongoing analysis, preliminary systematic uncertainties $\leq 10\%$ (not shown)



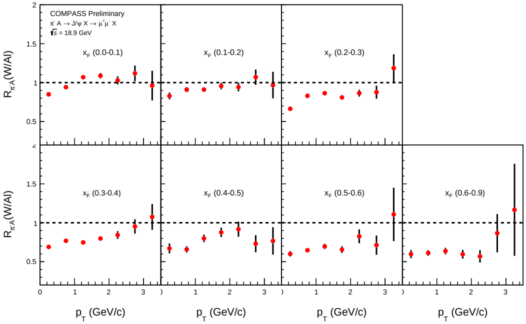


- Similar effects as observed by past experiments, *e.g* NA03 Z.Phys.C20 (1983) 101
- Strong suppression towards large x_F (*i.e* low x_{target} and large x_{beam})
- Increase with q_T due to Cronin effect

Nuclear modification factor in 2 dimensions from J/ψ

To better disentangle the various nuclear effects, the analysis is performed as a function of x_F and p_T

Systematics uncertainty not shown: $\lesssim$10%



Potentially more prominent suppression towards high x_F at low p_T
Additional insights compared to past experiments

Conclusion and Outlook

- $\Rightarrow$ COMPASS has released a wealth of preliminary Drell-Yan cross sections
- $\Rightarrow$ High statistics measurement is available on a light target
- $\Rightarrow$ Systematics uncertainties are at the same order of magnitude as E615
- $\Rightarrow$ Preliminary results of $R_{\pi A}(Al/W)$ for J/ψ production in (x_F, p_T) were shown

Perspective:

Finalisation of Drell-Yan and J/ψ cross-section measurements in the coming months expected

BACKUP

Useful variables

$M^2 = (p_{\mu^+} + p_{\mu^-})^2$
$s = (p_\pi + p_N)^2 \approx 2E_\pi M_{\text{nucleon}}$
q_{L}^*: Photon longitudinal momentum in π-N rest frame
q_{T}: Photon transverse momentum in π-N rest frame
$x_{\text{F}} = 2q_L^*/\sqrt{s}$
$x_{\pi,N} = \frac{1}{2}\left(\sqrt{x_F^2 + 4\frac{M^2}{s}} \pm x_F\right)$
$\tau = M^2/s = x_\pi x_N$

Situation for the other experiments

- NA10: Estimated to be negligeable and no correction
- E615: Evaluation with MC technique and subtraction