Recent results on pion-induced Drell-Yan

Catarina Quintans,
on behalf of the COMPASS Collaboration

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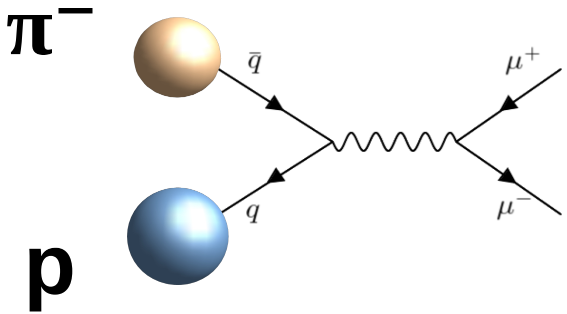


LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

Fundação para a Ciência e a Tecnologia

REPÚBLICA PORTUGUESA

OE, FCT-Portugal, CERN/FIS-PAR/0016/2021

Goals of the COMPASS Drell-Yan measurement

Drell-Yan cross section: $$\sigma_{\pi p} = \sum_{a,b} \int_0^1 dx_\pi \, dx_N \, f_a(x_N, \mu_F^2) \, f_b(x_\pi, \mu_f^2) \, \hat{\sigma}_{ab}$$

The sum is over all parton interactions a,b (q, $\bar{q}$, g)

$\hat{\sigma}_{ab}$ are the partonic cross sections, calculable

$f_{a,b}$ are the parton distribution functions from beam and target.

The cross section can be interpreted in terms of:

$f_{a,b}$ $(x_{N,\pi}, k_T, \mu_f^2)$ → **TMD PDFs**

$f_{a,b}$ $(x_{N,\pi}, \mu_f^2)$ → **PDFs**

- Measure the transverse spin asymmetries from the Drell-Yan process
  - Access TMD PDFs of the proton and the pion
  - Check the sign change of time-reversal odd TMD PDFs when in DY as compared to SIDIS
- Measure the differential Drell-Yan cross sections
  - Access the unpolarized TMD PDF/PDF of the pion
  - Study nuclear effects

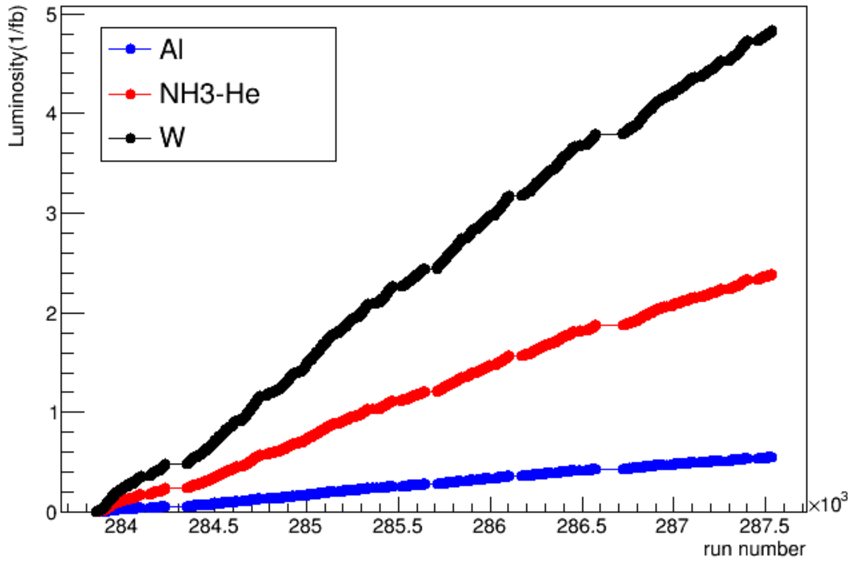
COMPASS beam for Drell-Yan

At the M2 beamline @ CERN

Negative hadron beam, 190 GeV/c: 96.8% π^-, 2.4% K^-, < 1% $\bar{p}$

No beam PID. All beam is considered as pions, beam contamination accounted for in the systematics for π-induced Drell-Yan cross section.

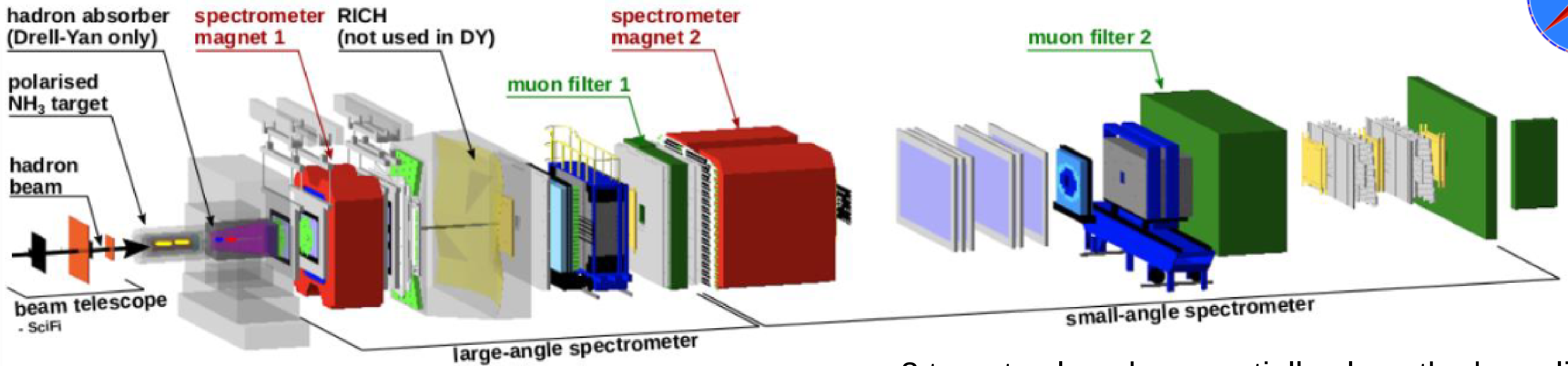
Beam average intensity 70 MHz, with a beam duty cycle of ~30%

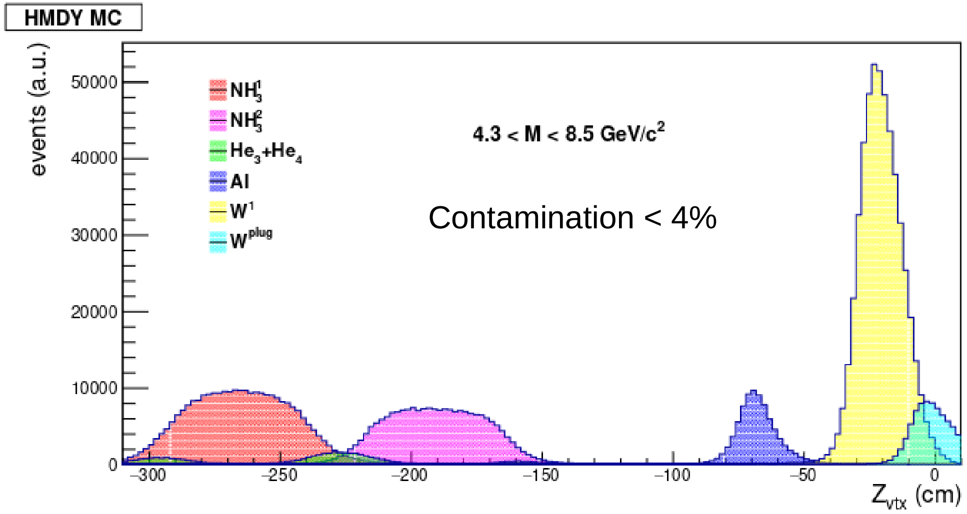


2018 integrated luminosity, per target

An average beam intensity of 55 MHz enters the cross-section analysis, due to time cuts and target volume cuts.

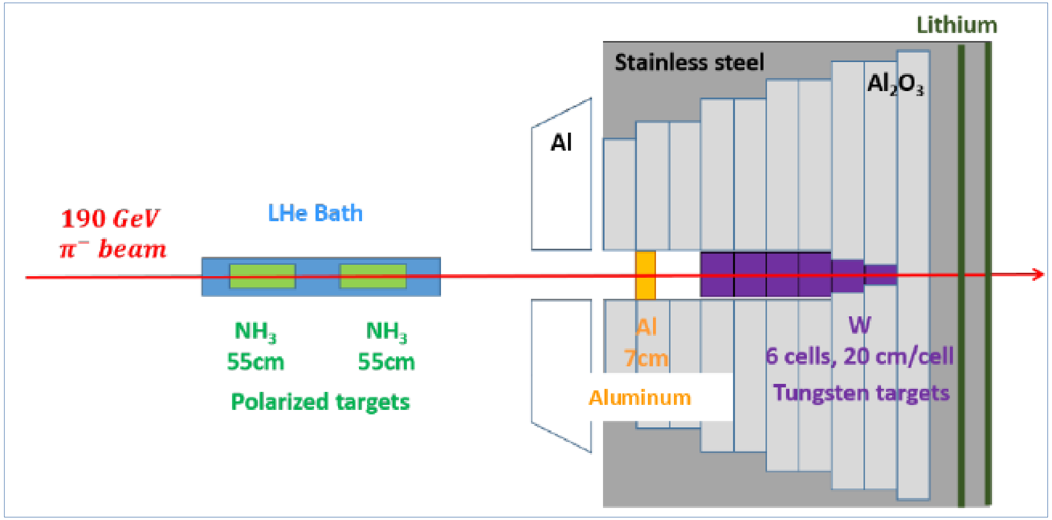
COMPASS Spectrometer





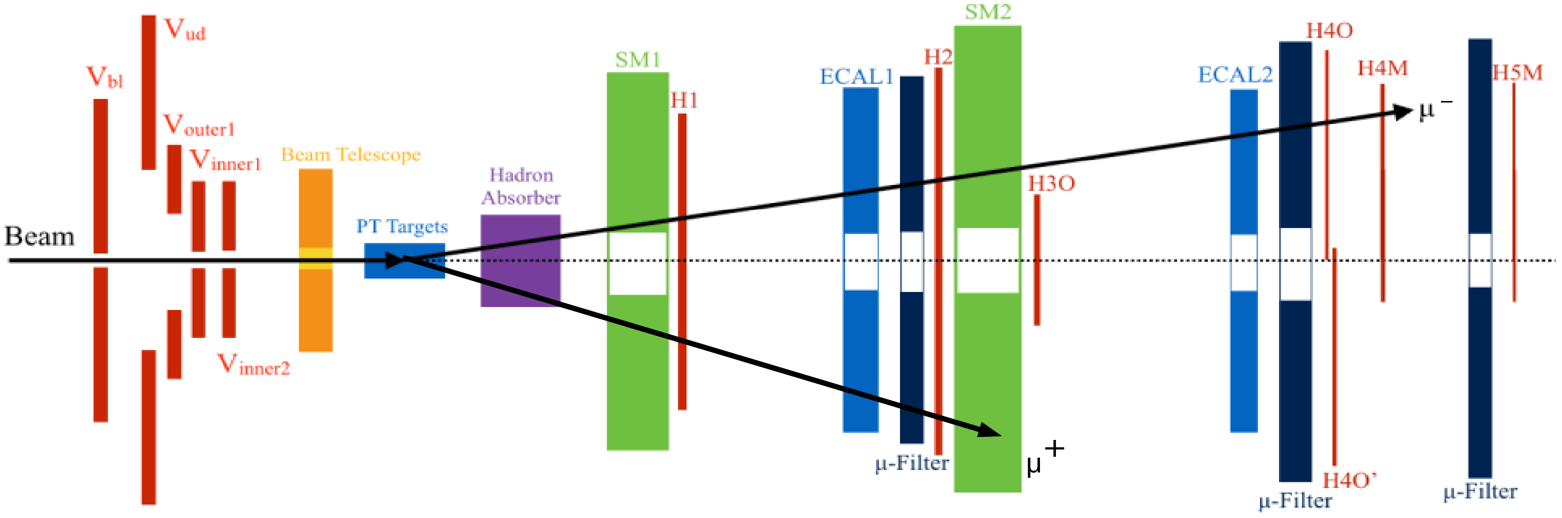
- 3 targets placed sequentially along the beamline:
  - 2 cells of (NH_3-He), transversely polarized;
  - 1 Al cell;
  - 1 W cell (first 20 cm of beam plug).
- Hadron absorber between targets and spectrometer
- 2-staged spectrometer: large angular and momentum coverage
- Dimuon trigger system
- The contamination from other materials into the considered volumes for each target is <4%

COMPASS targets



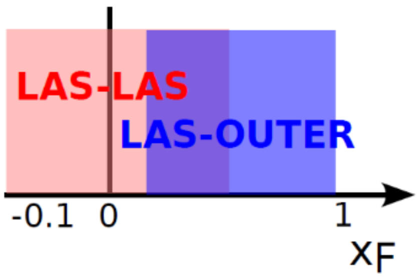
- The transversely polarized target is a mixture: NH_3 beads immersed in a cryogenic He bath.
- The 2 ammonia target cells are oppositely polarized. The spins configuration is reversed every 2 weeks.
- Spin asymmetries are sensitive to the polarizable part only: roughly, the 3 protons in the hydrogen from NH_3
- The sum of events from both ammonia mix cells over the entire year is effectively unpolarized.
- In absolute cross section measurement, all nucleons contribute: for the ammonia mix, consider the molar fractions: 15.7 % H, 11.1 % ^{4}He, 73.2 % ^{14}N

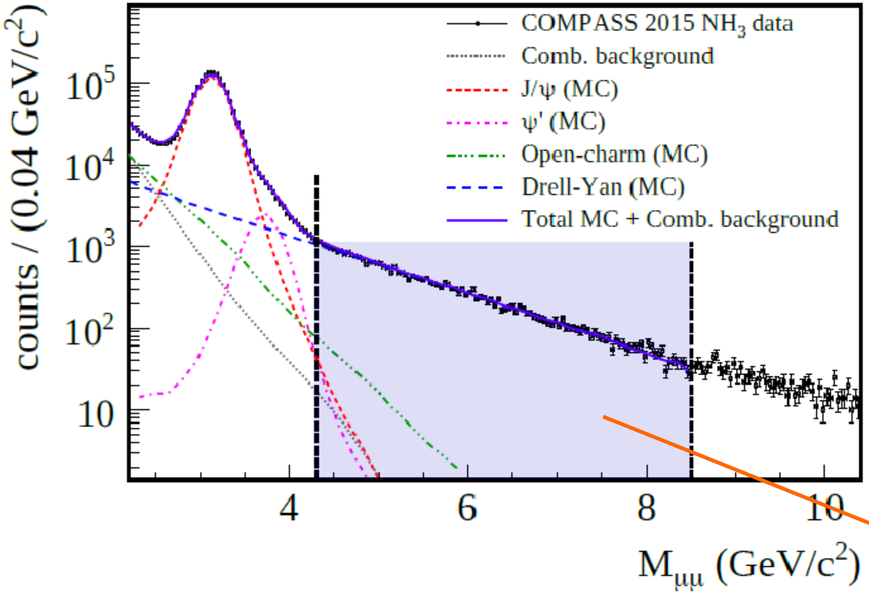
Dimuon trigger system



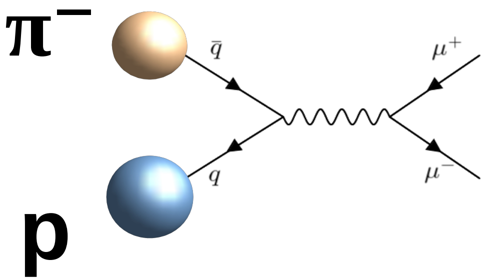
2 triggers, based on hodoscope pairs:

- 2 muons emitted at large angle (LAS-LAS)
- 1 muon at large angle, 1 muon at small angle (LAS-OUTER)





Drell-Yan process



u-quark dominance

Several sources of dimuons:

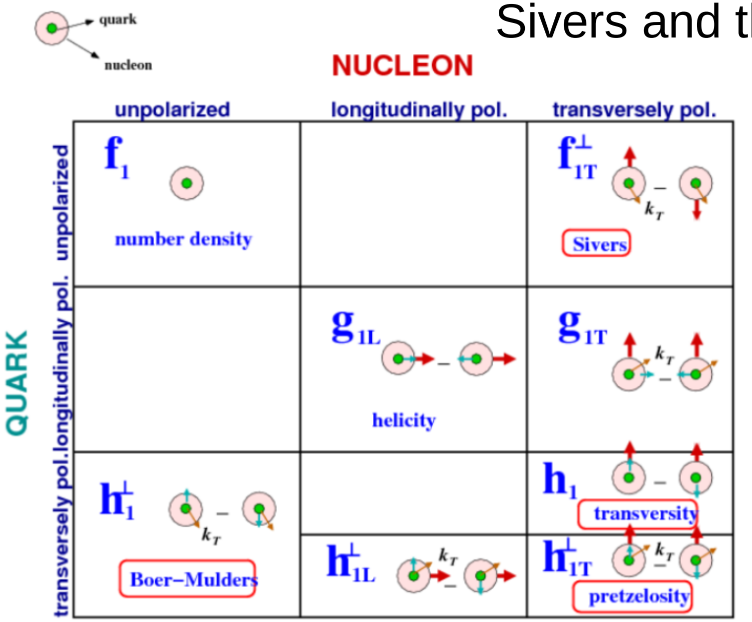
- Charmonia resonances: J/ψ and ψ(2S)
- Semi-leptonic decays of D-meson pairs (open-charm)
- Combinatorial of uncorrelated muons
- Drell-Yan

The mass range 4.3 – 8.5 GeV/c^2 is almost pure Drell-Yan

The purity of the process is accounted for in the Drell-Yan analyses.

Transverse Momentum Dependent PDFs

Sivers and the expected sign-change between SIDIS and DY



3 collinear PDFs used to describe the proton and its dependences (x, Q^2)

- Unpolarized
- Helicity
- Transversity

If considering also the transverse motion, at leading twist

8 quark TMD PDFs are needed to describe the proton (x, k_T, Q^2).

- **Sivers function**: non-vanishing orbital angular momentum
- **Sivers** and **Boer-Mulders** are time-reversal odd: opportunity for a crucial test of the TMD approach of QCD ($q_T << Q^2$):

$$h_1^{\perp}\text{(SIDIS)} = -\, h_1^{\perp}\text{(DY)}$$

$$f_{1T}^{\perp}\text{(SIDIS)} = -\, f_{1T}^{\perp}\text{(DY)}$$

Transverse Spin Asymmetries

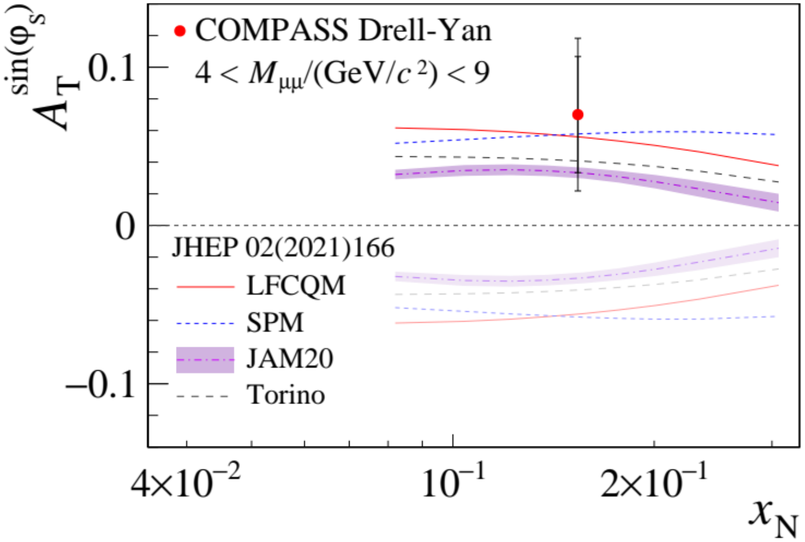
Final results now at ArXiv: 2312.17379

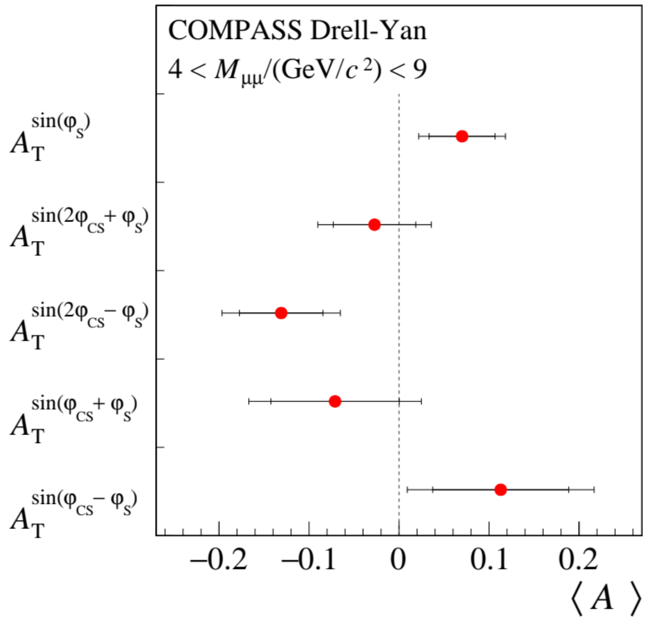
Extended mass range: 4 – 9 GeV/c². Contamination from other processes is taken into account as a dilution effect to the asymmetries.

Theory curves based on S. Bastami et al, JHEP 02 (2021) 166.

Sivers asymmetry in SIDIS measured by COMPASS, with nearly same spectrometer, and also in the same mass range.

Data favors the sign change scenario of the Sivers TMD PDF, between SIDIS and DY





These asymmetries relate to convolutions of the TMD PDFs:

$$A_T^{\sin(\phi_S)} \propto \bar{f}_1^{\,\pi}(x_\pi, k_{T,\pi}) \otimes f_{1T}^{\perp,p}(x_N, k_{T,p})$$
$$A_T^{\sin(2\phi+\phi_S)} \propto \bar{h}_1^{\perp,\pi}(x_\pi, k_{T,\pi}) \otimes h_{1T}^{\perp,p}(x_N, k_{T,p})$$
$$A_T^{\sin(2\phi-\phi_S)} \propto \bar{h}_1^{\perp,\pi}(x_\pi, k_{T,\pi}) \otimes h_1^{p}(x_N, k_{T,p})$$

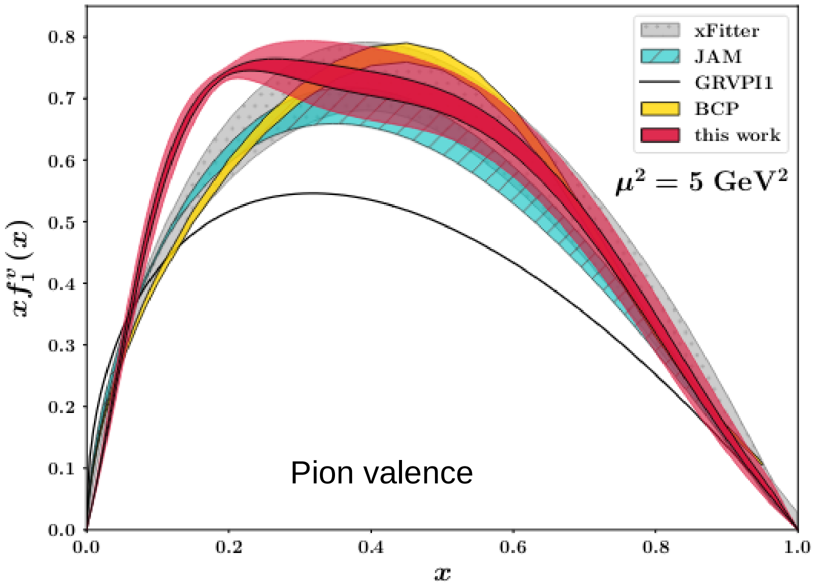
Pion structure

Pion-induced Drell-Yan provides an access to both proton and pion structure.

In COMPASS Drell-Yan there is mostly sensitivity to the u-quark PDFs in the valence region.

Proton PDFs are known to a good accuracy. Not the case for pion PDFs!

MAP Coll., Phys.Rev.D 107, 114023 (2023)



Available pion-induced DY data is more than 30 years old

Most relevant statistics from E615 (Fermilab) and NA10 (CERN), but using W target
– non-negligible nuclear effects.

Only π^- beam, thus little sensitivity to sea quarks.

A normalization issue between E615 and NA10 data, by up to 20%

Very limited information on systematic uncertainties was provided by past experiments.

Wen-Chen Chang talk

Drell-Yan cross sections

COMPASS

$$\frac{d^n\sigma}{dx_n} = \frac{1}{\mathcal{L}} \times \frac{1}{\varepsilon} \times \frac{d^n N_{\mu\mu}}{dx_n}$$

L is the luminosity
ε contains efficiencies, acceptance and lifetimes
x_n are the variable dependences of the differential measurement

$\tau = M^2_{\mu\mu}/s = x_\pi x_N$

q_T, q_L } Transverse and longitudinal momentum of the dimuon in the Hadrons collision frame

$x_F = q_L/(\sqrt{s}/2)$

$x_\pi = [\, x_F + \sqrt{x_F^2 + 4\tau}]/2$

$x_N = [-x_F + \sqrt{x_F^2 + 4\tau}]/2$

Statistics :

	Target length (cm)	Beam fraction	DY events 4.3 < M < 8.5 GeV/c²
NH_3-He	55+55	0.99	36000
Al	7	0.57	6000
W	20	0.49	43000

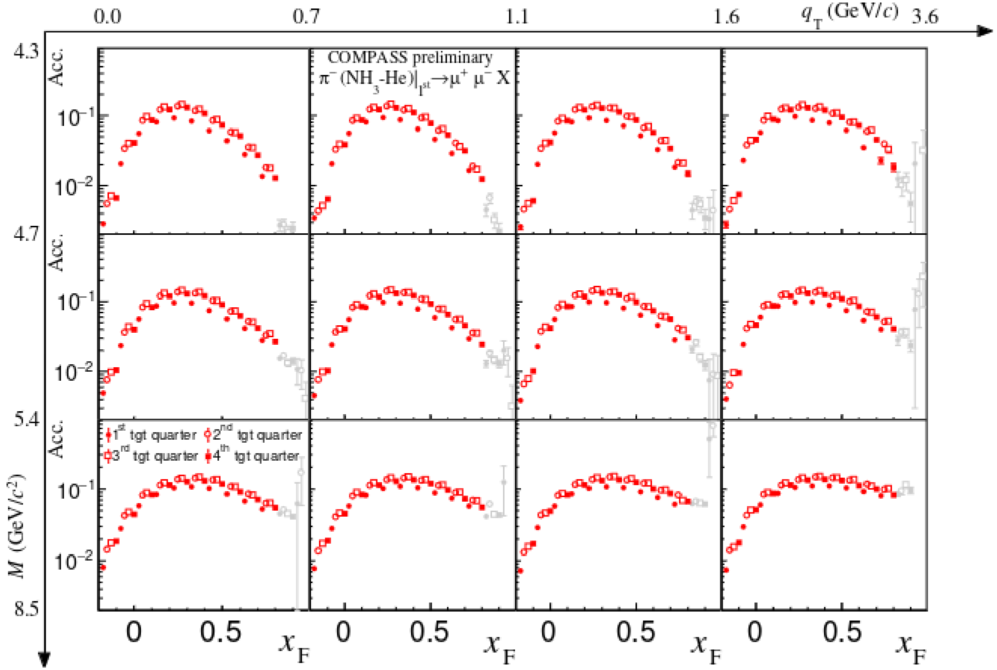
Measurement of cross section requires good control of luminosity and efficiencies systematics. For this reason, only 2018 data is used in this analysis.

Dimuon Acceptance

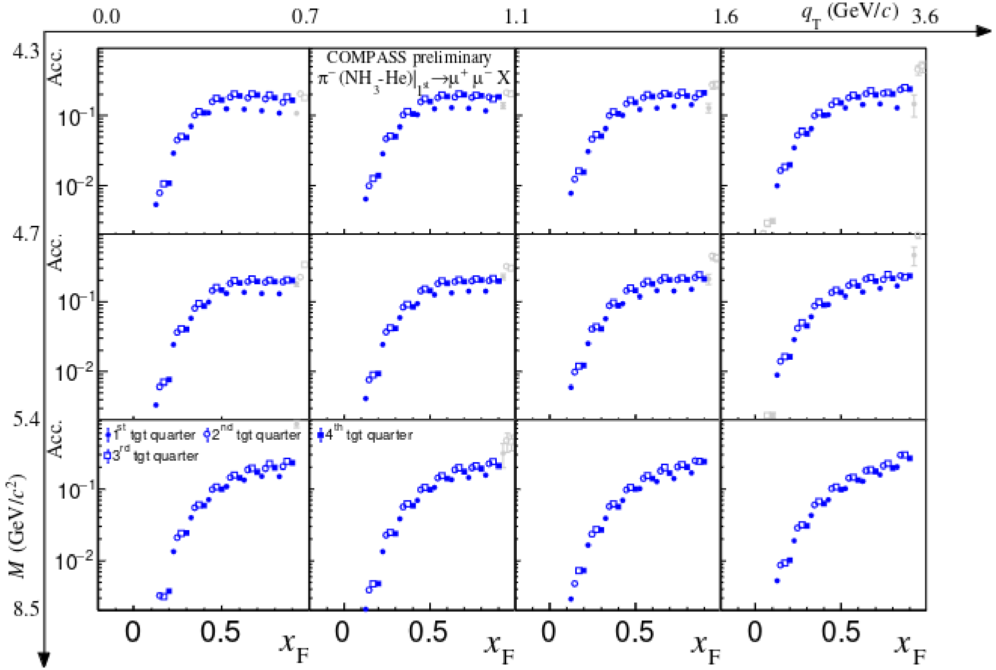
Evaluated in 4 dimensions (M, q_T, x_F, Z_{vertex}) and separately per dimuon trigger

Example: (NH_3-He) target

LAS-LAS



LAS-OUTER



Measurement restricted to the range where the acceptance relative accuracy is better than 10%

Acceptance ranges from ~1% to ~15%

Drell-Yan process purity

The DY purity in the mass range 4.3 – 8.5 GeV/c² is evaluated from a cocktail fit to the dimuon mass spectrum, and taken into account in the final cross section.

Study done in (q_T, x_F) bins, separately per target and trigger.

The purity is above 90% for:

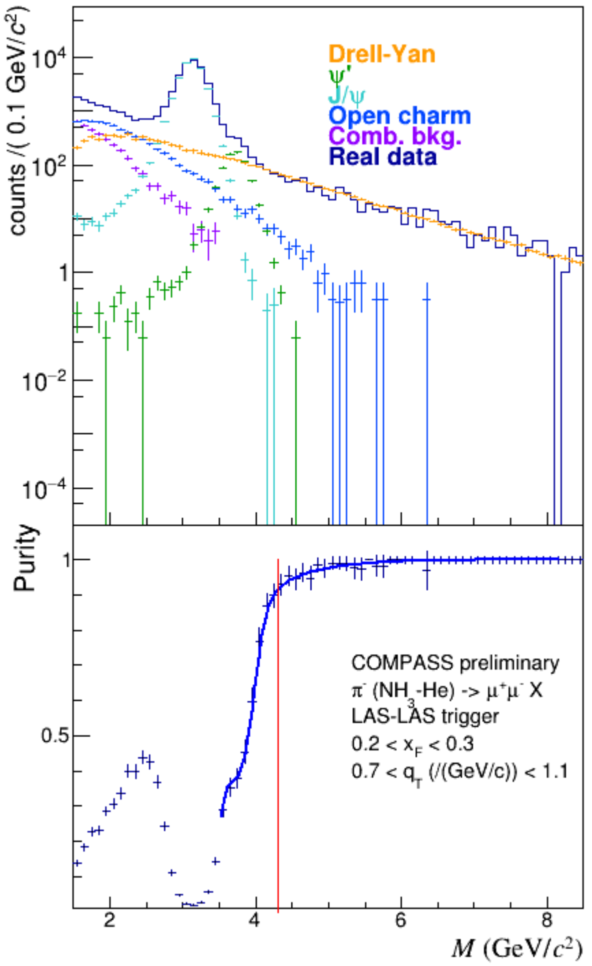
- NH3-He : M > 4.3 GeV/c²
- Al: M > 4.7 GeV/c²
- W: M > 5.5 GeV/c²

The purity is affected by the mass resolution, worse for W.

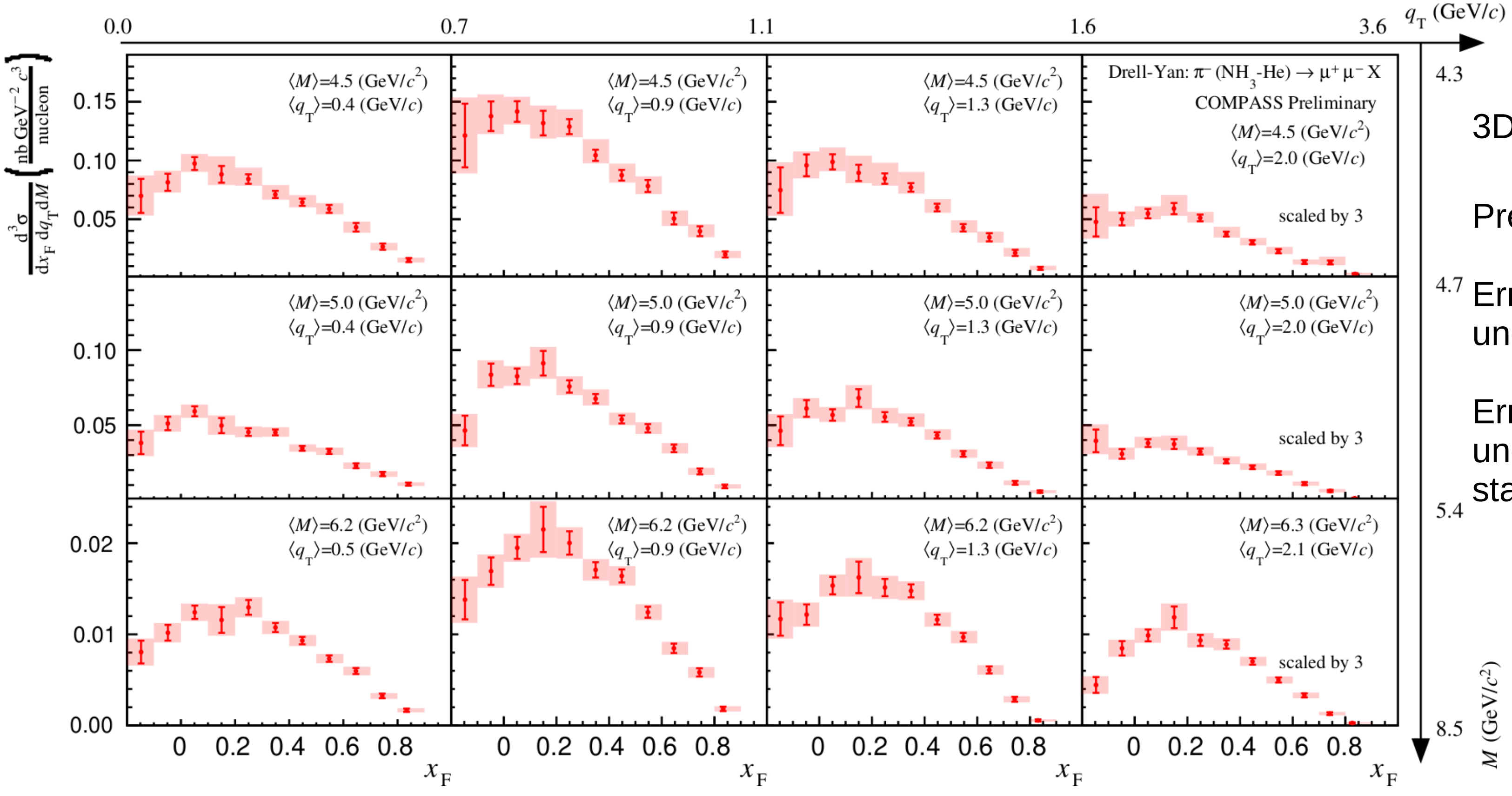
The resolutions are also evaluated from Monte Carlo:

Target	δx_F	δq_T (MeV/c)	$\delta M/M$
NH3-He	0.03	150	3.5%
Al	0.03	245	4.5%
W	0.03	340	6.5%

Example:



Drell-Yan cross section per nucleon from the **ammonia-mix target** in bins of mass and q_T, as function of Feynman-x



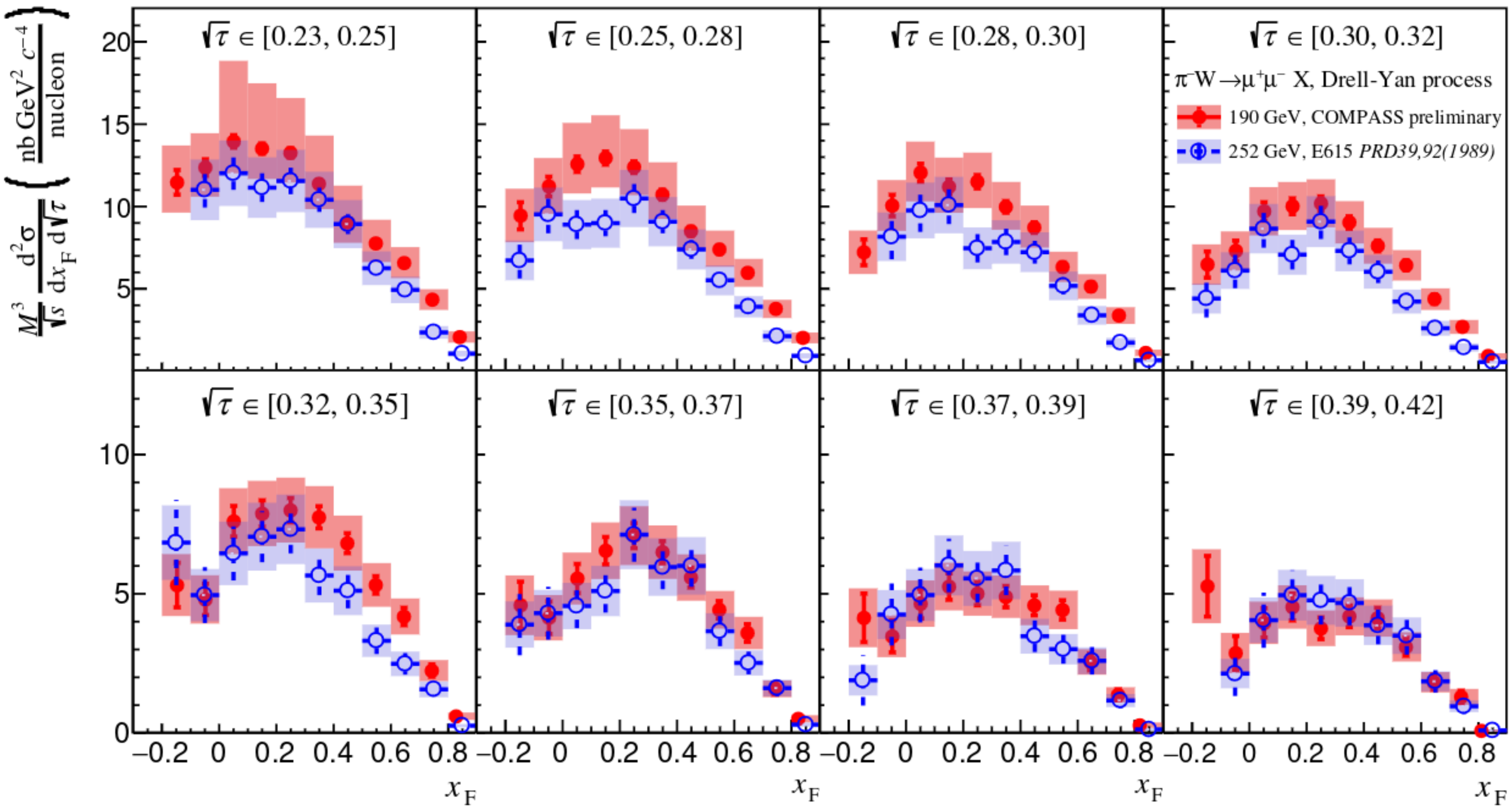
3D cross sections (M, q_T, x_F)

Preliminary results

Error bars are statistical uncertainty

Error bands are the total uncertainties (quadratic sum of stat. and syst. error)

Drell-Yan cross section per nucleon from the **tungsten target** in bins of √τ, as function of Feynman-x: comparison with E615



2D cross section ($\sqrt{\tau}$, x_F)

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

COMPASS is systematically higher, for $\sqrt{\tau}<0.32$

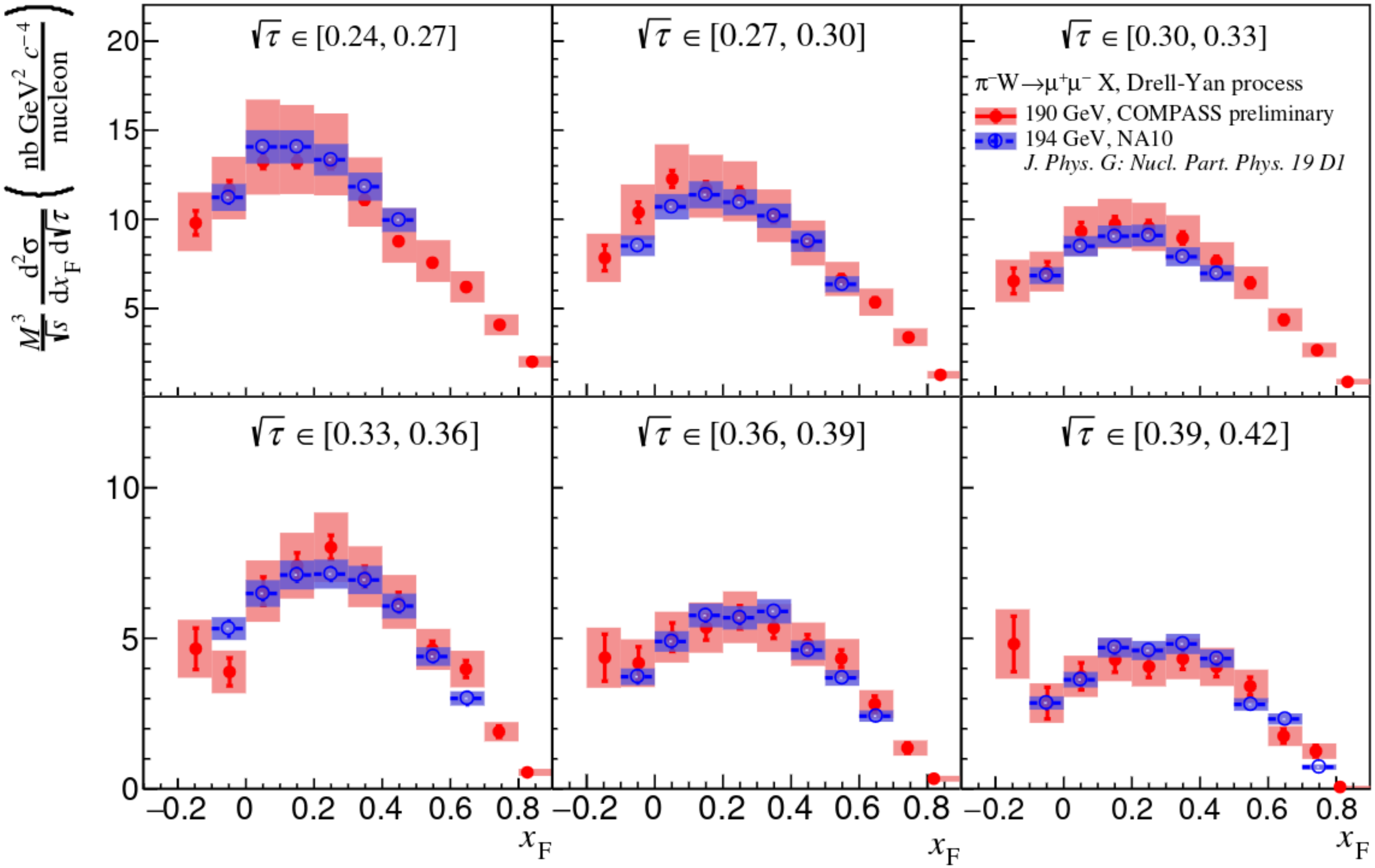
Preliminary results

Error bars are statistical uncertainties

Error bands are the total uncertainties (quadratic sum of stat. and syst. errors)

E615 coll., Phys. Rev. D 39, 92-122 (1989)

Drell-Yan cross section per nucleon from the **tungsten target** in bins of √τ, as function of Feynman-x: comparison with NA10



2D cross section ($\sqrt{\tau}$, x_F)

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

Compatibility between COMPASS and NA10

Preliminary results

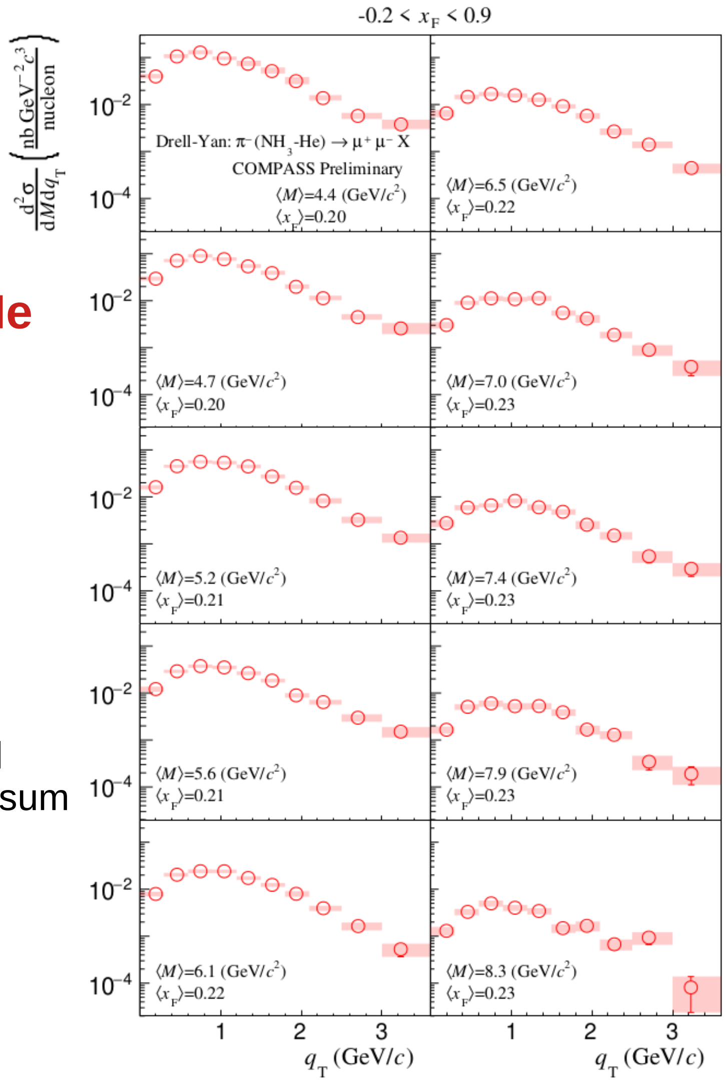
Error bars are statistical uncertainty only

Error bands are the total uncertainties (quadratic sum of stat. and syst. errors)

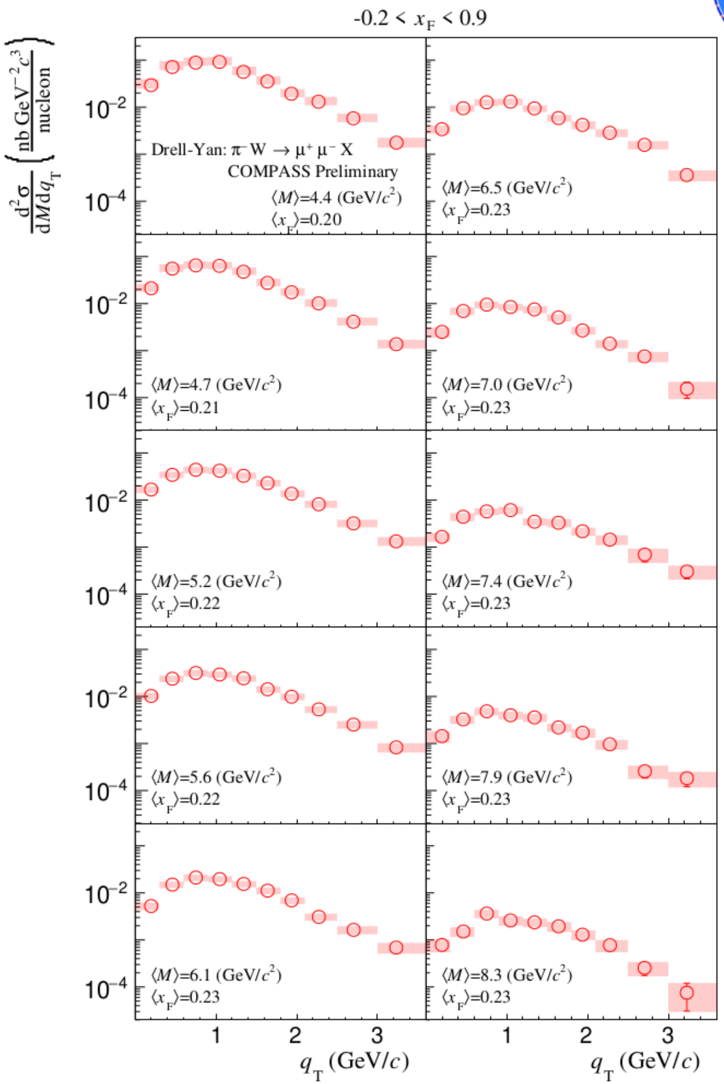
NA10 coll., Z. Phys. C 28, 9 (1985)

Drell-Yan cross section per nucleon, in bins of mass, as function of q_T

NH_3-He



W



2D cross section (M, q_T)

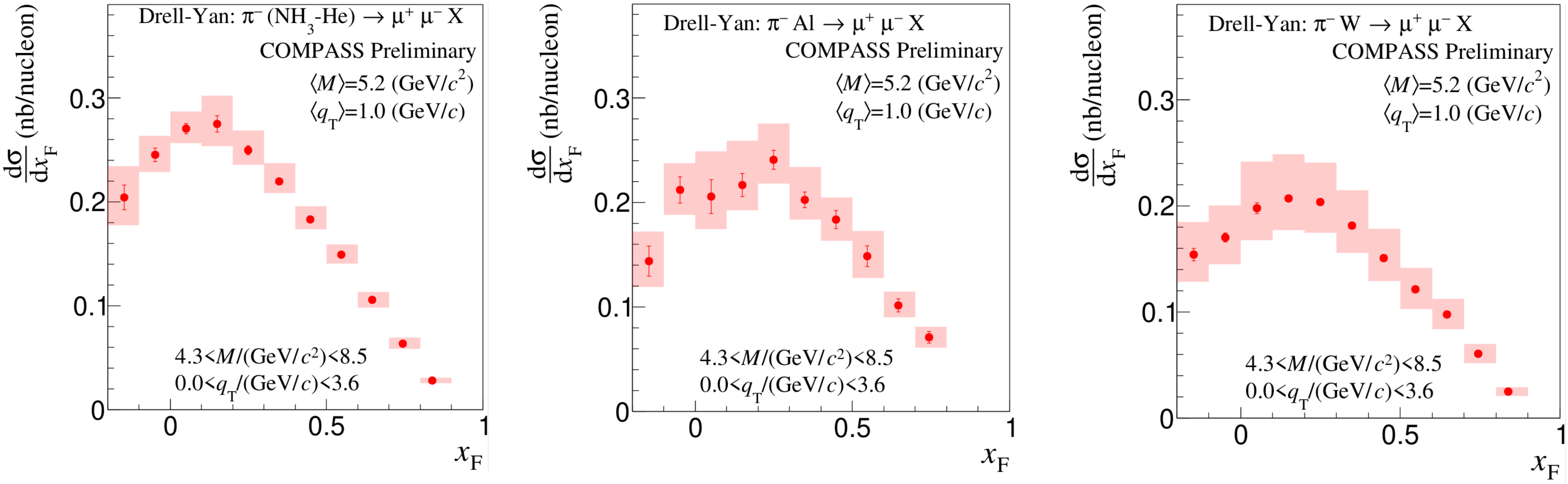
Preliminary results

Error bars are statistical Uncertainty

Error bands are the total uncertainties (quadratic sum of stat. and syst. error)

Drell-Yan cross section per nucleon as a function of Feynman-x

NH_3-He **Al** **W**



Preliminary results.

Error bars are the statistical uncertainties.

Error bands are the total uncertainties (quadratic sum of stat. and syst. error)

Also studies of nuclear effects (not shown this time):

- EMC effect
- q_T broadening
- partonic energy loss

Preliminary summary on uncertainties

The systematics of the COMPASS measurement include:

- Luminosity uncertainty ~4% (normalization uncertainty)
- Trigger, purity and acceptance-related uncertainties depending on target and kinematics

	Statistics (#events)	Systematic uncertainty	#datapoints in (M, x_F)
COMPASS			
NH3-He	36000	~5%	110
Al	6000	~15%	50
W	43000	~15%	50
NA10			
W	155000	6.5%	59
E615			
W	36000	16%	168

Ongoing work to evaluate the fraction of correlated and uncorrelated systematics, and provide a full covariance matrix for cross-section results.

Conclusion

COMPASS studied for the first time the transversely polarized Drell-Yan process, collecting data in 2015 and 2018.

Measurement of transverse spin asymmetries in the Drell-Yan process, from the data of both years:

- Sivers asymmetry at 1.5σ above zero;
- Transversity-related asymmetry at 2σ below zero;
- Pretzelosity-related asymmetry compatible with zero.

The measured Sivers asymmetry in Drell-Yan is compatible with the sign-change hypothesis with respect to the SIDIS one, also measured in COMPASS. These asymmetries are an important input for the extraction of the proton transversely polarized TMD PDFs.

The pion-induced Drell-Yan cross section is measured from the 2018 data, in a multidimensional analysis (M, q_T, x_F). These results are an important input for the extraction of the pion PDF and unpolarized TMD PDF.

Kun Liu talk

Paving the way for AMBER pion structure studies!