Drell-Yan and charmonium results from COMPASS

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on behalf of the COMPASS Collaboration

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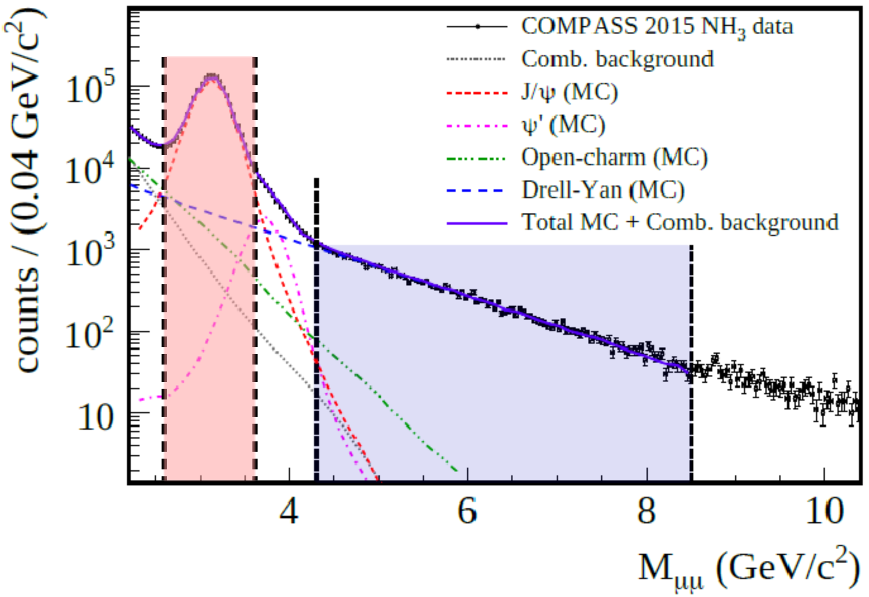
LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS
OE, FCT-Portugal, CERN/FIS-PAR/0016/2021

Goals of the COMPASS Drell-Yan programme



Pion-induced Drell-Yan:
- Transversely polarized target (NH3)
- Unpolarized targets (NH3+He; Al; W)

Charmonium production:
- Cross section
- Polarization
- J/psi pair production

➔ Studies of the transversely polarized TMD PDFs of the nucleon, complementary to SIDIS ones.

➔ Unique access to the (TMD) PDFs of the pion.

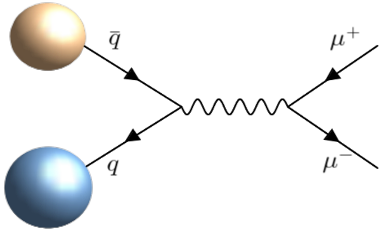
➔ Charmonium production at intermediate energies – study of production mechanisms.

COMPASS Drell-Yan measurement

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

π^-

p



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

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

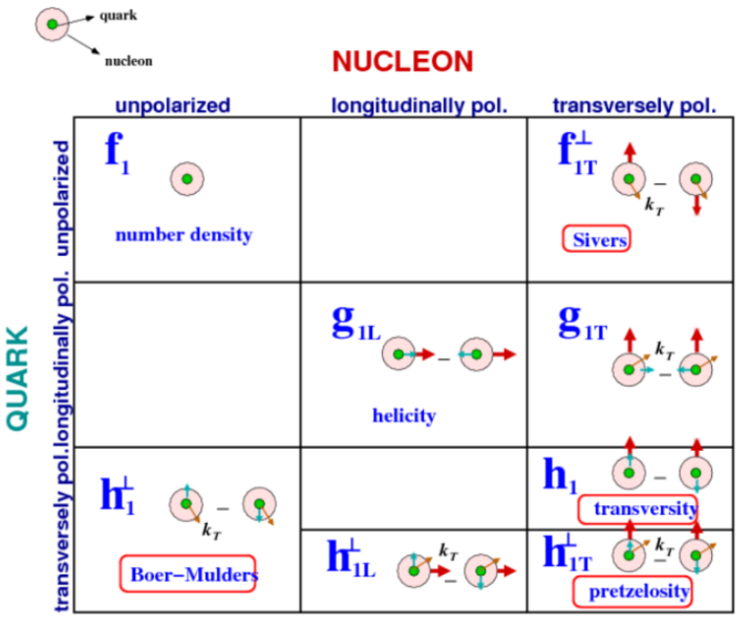
$f_{a,b}$ are the parton distribution functions from beam and target.

The cross section can be interpreted in terms of:

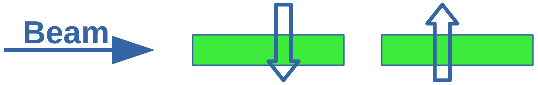
- $f_{a,b}\ (x_{N,\pi},\ \mu_f^2) \rightarrow$ **PDFs**
- $f_{a,b}\ (x_{N,\pi},\ k_T,\ \mu_f^2) \rightarrow$ **TMD PDFs**

3 collinear PDFs used to describe the proton and its dependences (x, Q^2):
Unpolarized; Helicity; Transversity.

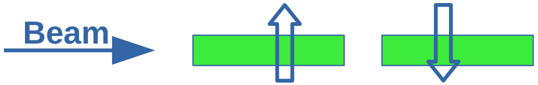
If considering also the transverse motion, at leading twist
8 quark TMD PDFs are needed to describe the proton (x, k_T, Q^2).



Spin Asymmetries



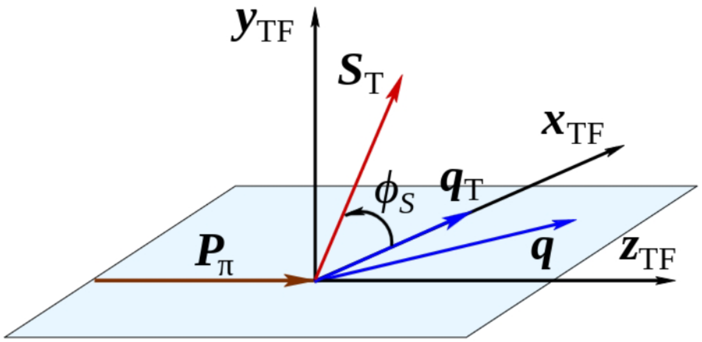
or



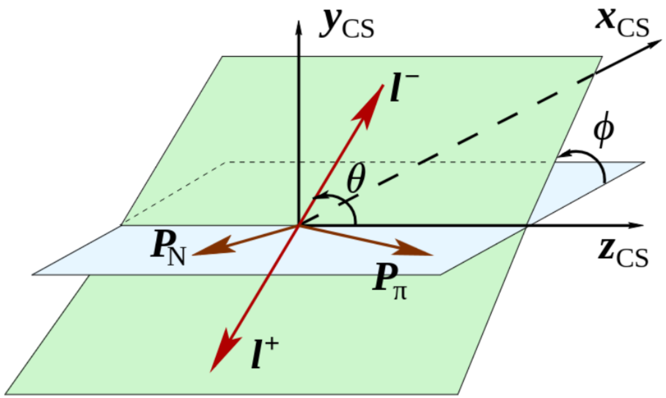
Transversely polarized target in 2 different spin configurations

$$\textbf{Asymmetry} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\downarrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\downarrow\uparrow}}$$

Target rest frame



Collins-Soper frame



Transverse Momentum Dependent PDFs

Sivers and the expected sign-change between SIDIS and DY

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

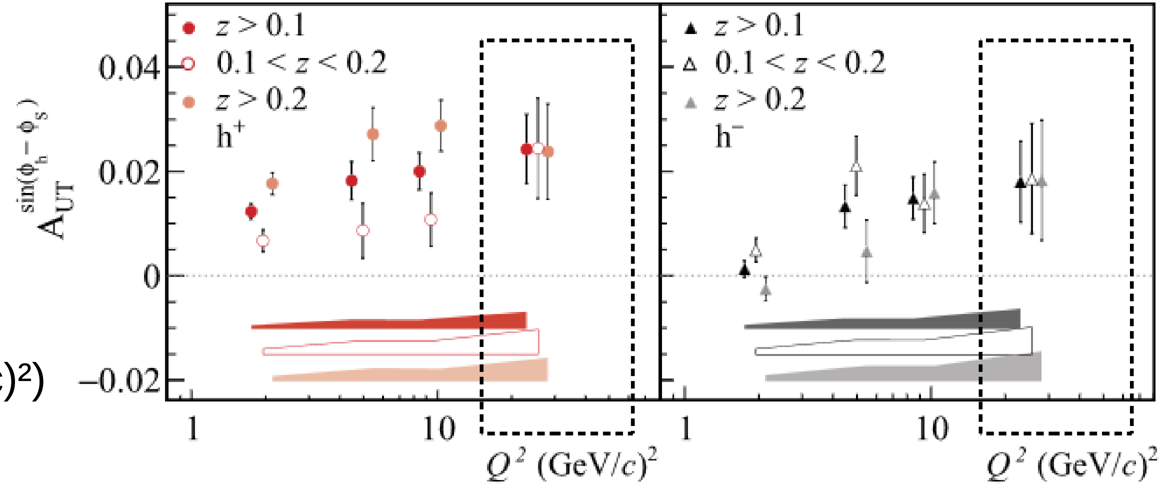
$$\boxed{h_1^{\perp}\,(\mathrm{SIDIS}) = -\,h_1^{\perp}\,(\mathrm{DY})}$$

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

In Drell-Yan, q_T is the transverse momentum of the final state dimuon, while Q is the dimuon invariant mass.

COMPASS **Sivers asymmetry** in **SIDIS**:
PLB 770 (2017) 138-145

Measured in a range common to Drell-Yan (16 < Q^2 < 81 $(\mathrm{GeV}/c)^2$)



Drell-Yan measurements at COMPASS

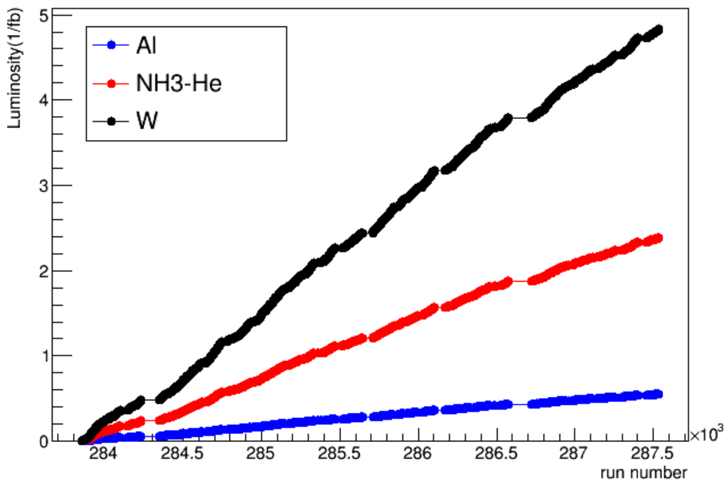
At the M2 beamline @ CERN

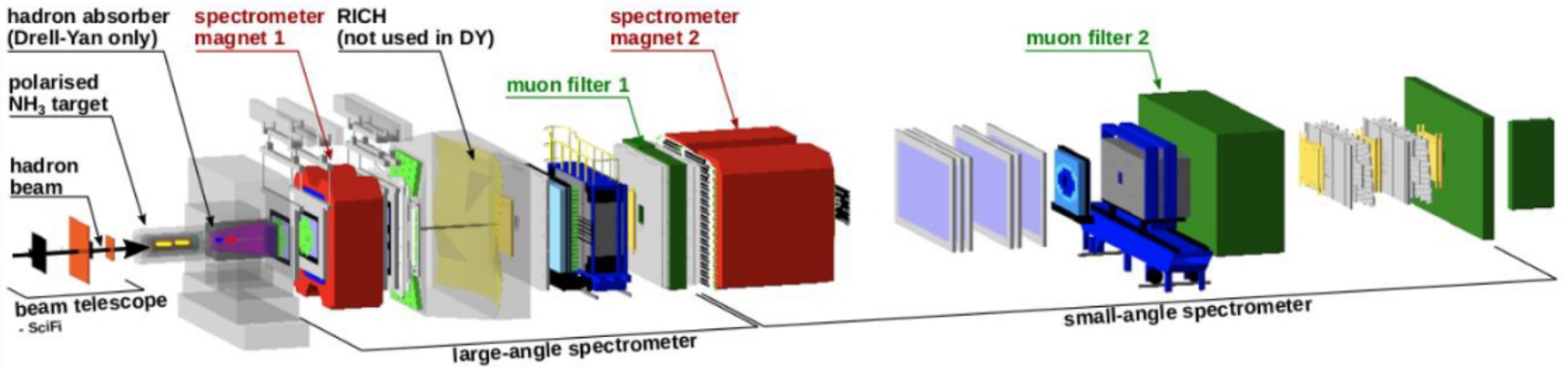
Negative hadron beam, 190 GeV/c:

- 96.8% π^-
- 2.4% K^-
- < 1% $\bar{p}$

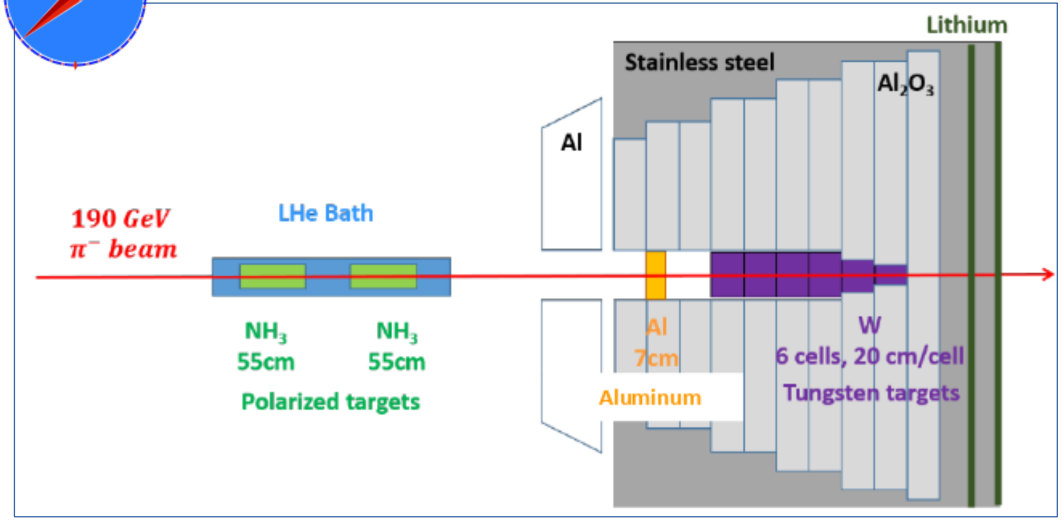
No beam PID. All beam is considered as pions, beam contamination accounted for in the systematics for π-induced Drell-Yan cross section.

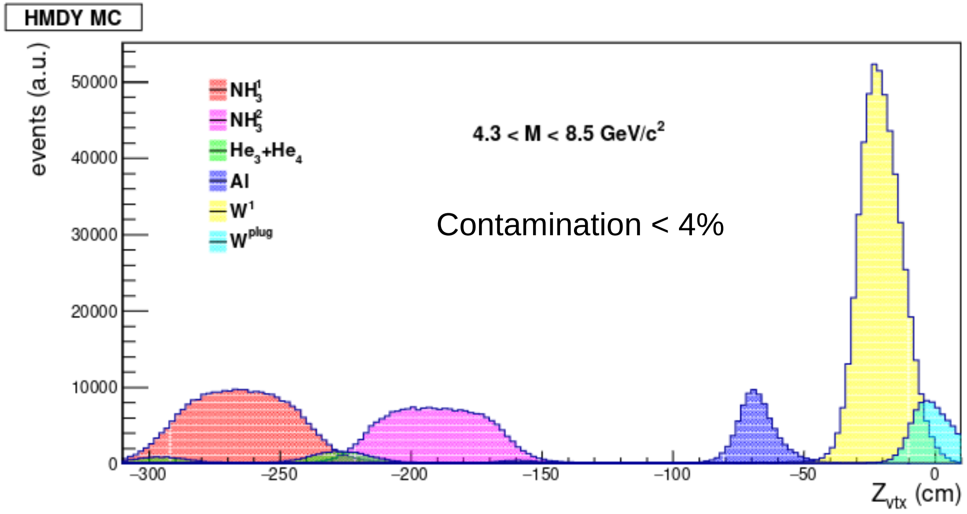
2018 integrated luminosity, per target





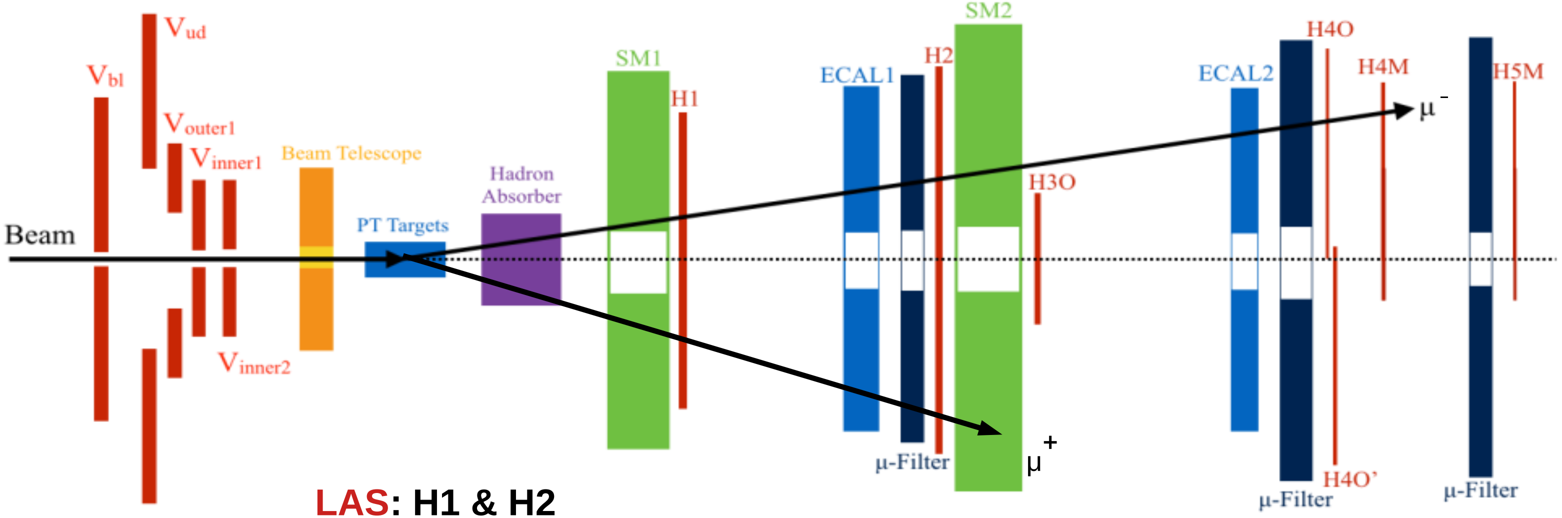
COMPASS targets





- Transversely polarized target: a mixture of NH_3 beads immersed in He.
- The 2 ammonia target cells are oppositely polarized.
- 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 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
- The contamination from other materials into the considered volumes for each target is <4% .

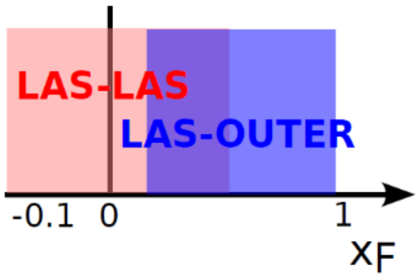
Dimuon trigger system



LAS: H1 & H2
OUTER: H3O & H4O

2 triggers, based on the time coincidence of hodoscope pairs:

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



Transverse Spin Asymmetries from DY

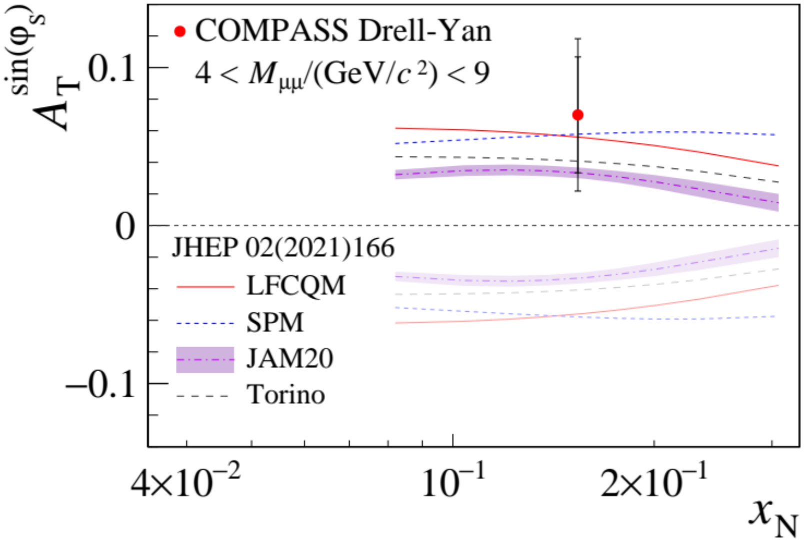
Final results now in: PRL 133 (2024) 071902

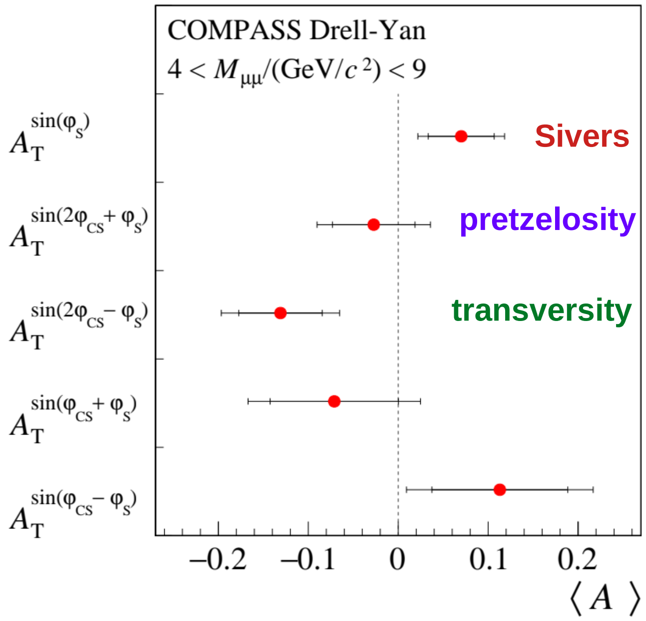
Extended mass range: 4 – 9 GeV/c². Contamination from other processes is taken into account as a dilution effect to the asymmetries.

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 Q² 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:

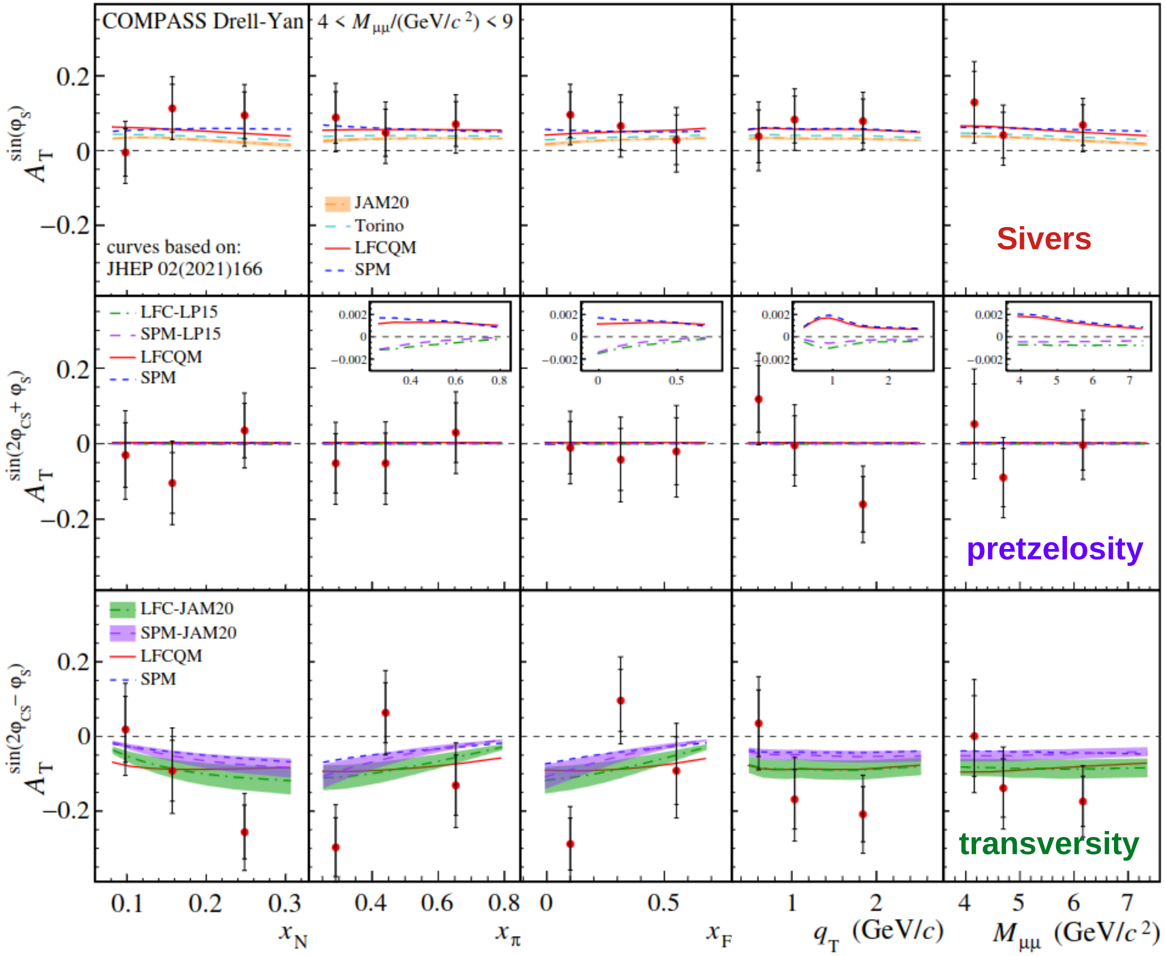
$$A_T^{\sin(\phi_S)} \propto \bar{f}_1^{\,\pi}(x_\pi, k_{T,\pi}) \otimes f_{1T}^{\perp,\,p}(x_N, k_{T,p})$$

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

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

Drell-Yan TSAs (standard)

Final results now in: PRL 133 (2024) 071902



Full data samples: 2015 + 2018

~100K dimuon events, after selection

Extended mass range:
4 < $M_{\mu\mu}/(\mathrm{GeV}/c^2)$ < 9

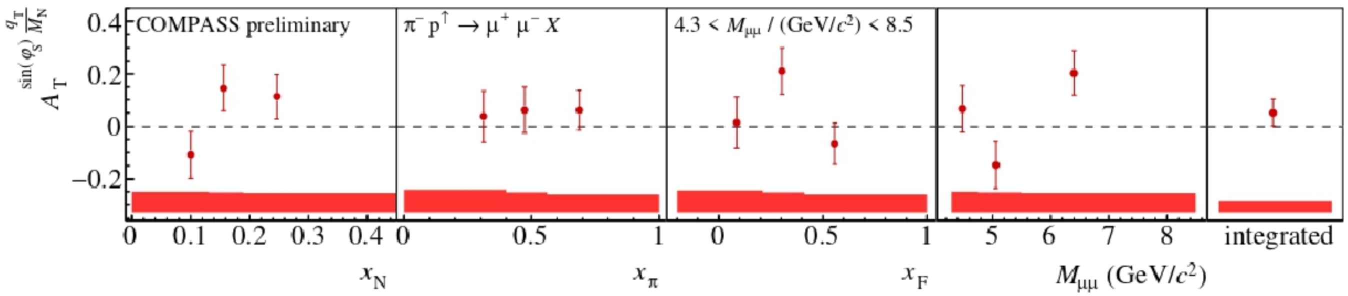
Results consistent with first publication (based on 2015 data only)
PRL 119 (2017) 112002.

q_T-weighted transverse Spin Asymmetries from DY

With respect to the standard analysis, it has the advantage of giving direct access to the n-th moments of the TMD PDFs:

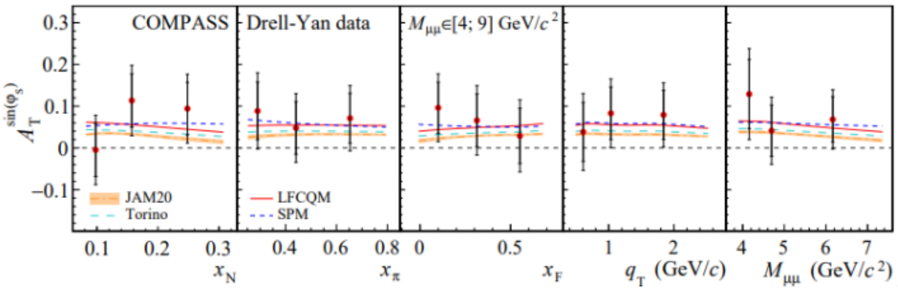
Standard		**q_T-weighted**
$A_T^{\sin(\phi_S)} \propto \bar{f}_1^{\pi} \otimes f_{1T}^{\perp,p}$	$\longleftrightarrow$	$A_T^{\sin(\phi_S)\, q_T/M_N} \propto \bar{f}_1^{\pi} \times f_{1T}^{\perp(1),p}$
$A_T^{\sin(2\phi+\phi_S)} \propto \bar{h}_1^{\perp,\pi} \otimes h_{1T}^{\perp,p}$	$\longleftrightarrow$	$A_T^{\sin(2\phi+\phi_S)\, q_T^3/M_N^2/M_\pi} \propto \bar{h}_1^{\perp(1),\pi} \times h_{1T}^{\perp(2),p}$
$A_T^{\sin(2\phi-\phi_S)} \propto \bar{h}_1^{\perp,\pi} \otimes h_1^{p}$	$\longleftrightarrow$	$A_T^{\sin(2\phi-\phi_S)\, q_T/M_\pi} \propto \bar{h}_1^{\perp(1),\pi} \times h_1^{p}$

Sivers q_T-weighted



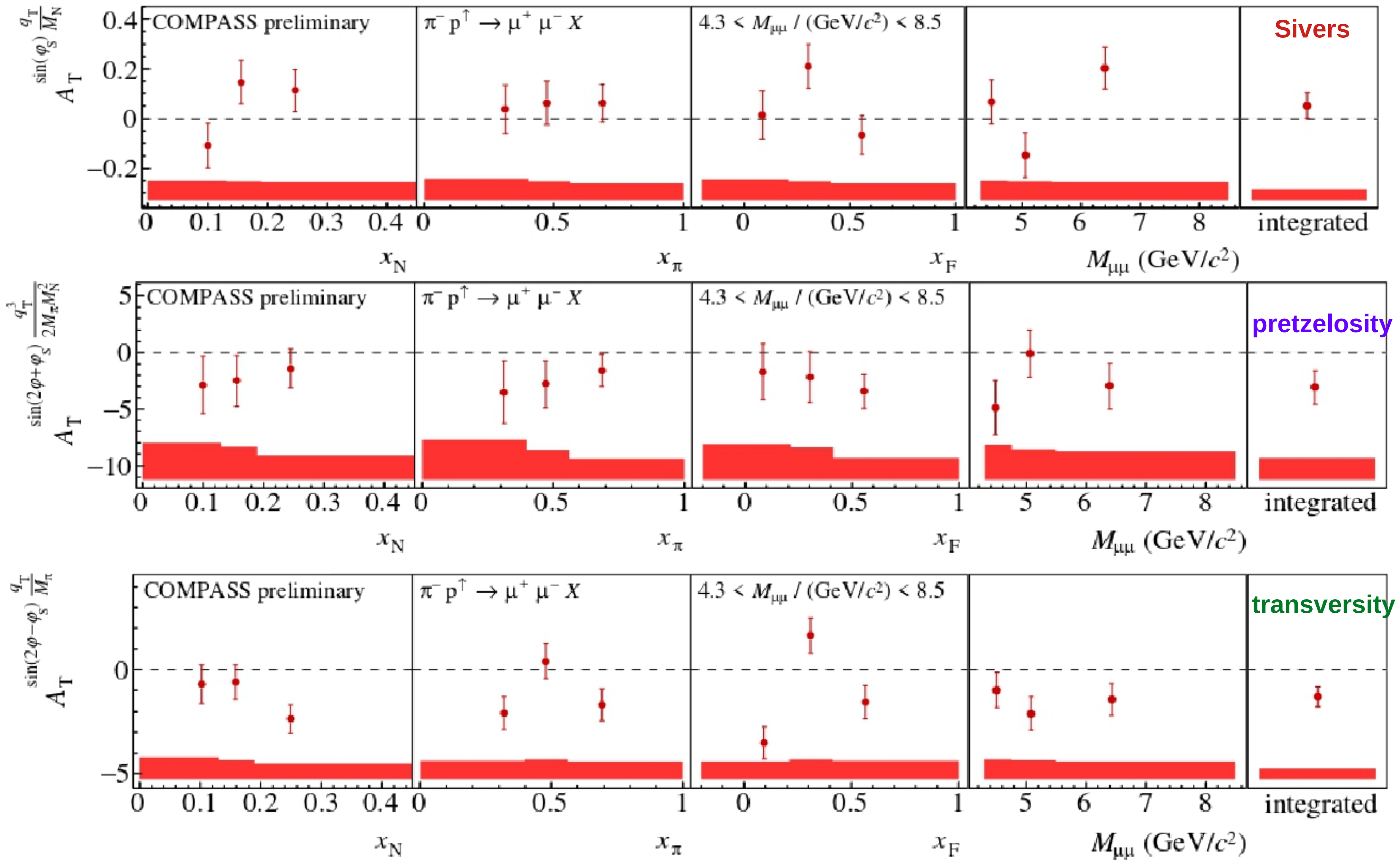
Sivers TSA (standard)

(PRL 133 (2024) 071902)



1σ positive Sivers WTSA, compatibility TSA ↔ WTSA

Drell-Yan q_T-weighted TSAs



1σ positive

2σ negative

2σ negative

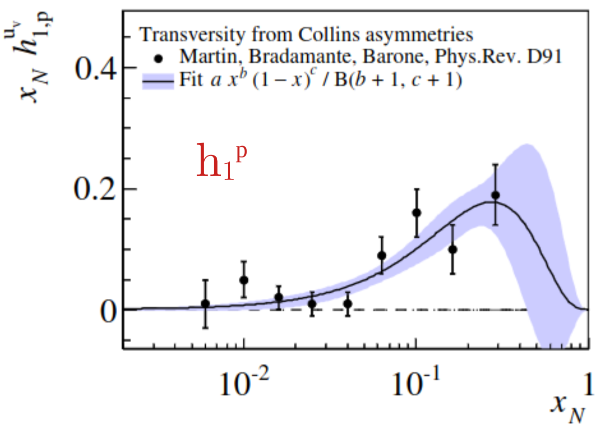
Pion Boer-Mulders TMD PDF: a recipe

Transversity-related WTSA: $A_T^{\sin(2\phi-\phi_S)\, q_T/M_\pi} \propto \bar{h}_1^{\perp(1),\pi} \times h_1^p$

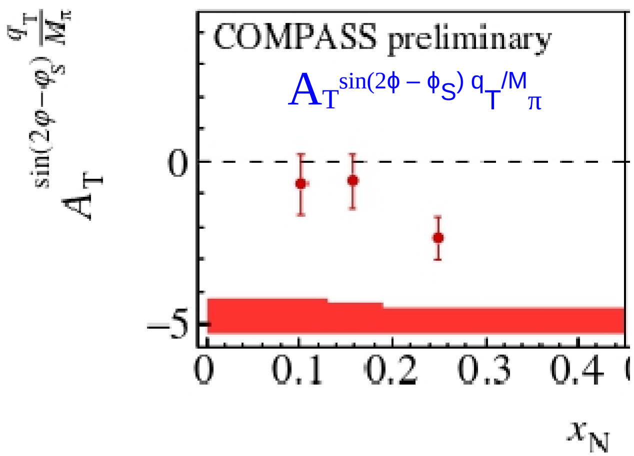
$$\approx -2 \frac{e_u^2\, h_{1,\pi}^{\perp(1)\bar{u}}(x_\pi)\, h_{1,p}^{u}(x_N)}{\sum_{q=u,d,s} e_q^2 \left[f_{1,\pi}^{\bar{q}}(x_\pi)\, f_{1,p}^{q}(x_N) + (q \leftrightarrow \bar{q})\right]}$$

- f_1^p and f_1^π are the unpolarized TMD PDFs of nucleon and pion, taken from CTEQ5D and GRV-PI, respectively.
- h_1^p is the transversity TMD PDF of the nucleon, interpolated by a simple fit to the Collins asymmetry
  A. Martin et al, PRD 91 (2015) 014034
- $\bar{h}_1^{\perp(1),\pi}$ is 1st k_T^2 moment of the Boer-Mulders TMD PDF of the pion.

From SIDIS:



From π-induced DY:



Access the 1st moment of the pion Boer-Mulders

$\bar{h}_1^{\perp(1),\pi}$

Pion structure

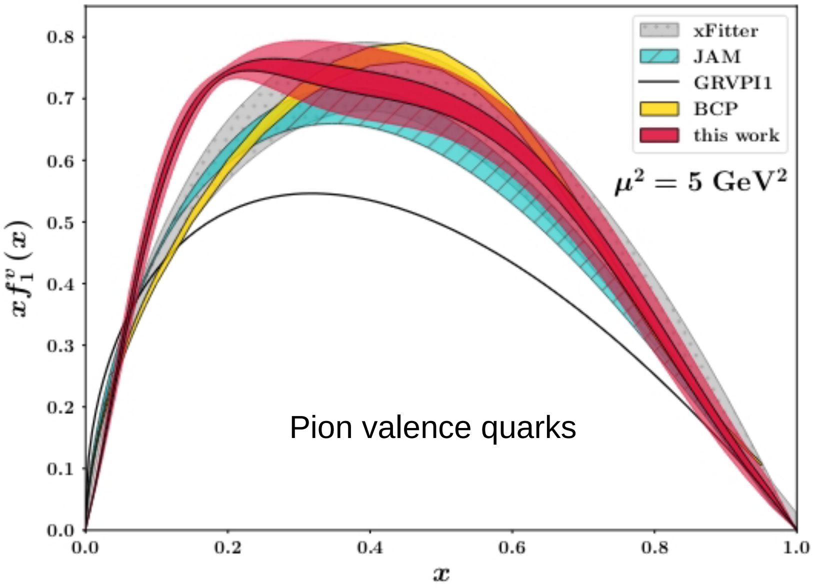
$$\sigma_{\pi p} = \sum_{a,b} \int_0^1 dx_\pi \; dx_N \; f_a(x_N, \mu_F^2) \; f_b(x_\pi, \mu_f^2) \; \hat{\sigma}_{ab}$$

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.

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

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

Boer-Mulders TMD PDF

The unpolarized Drell-Yan cross section angular dependence gives us also an access to the Boer-Mulders TMD PDFs:

Spin independent

$$\frac{d\sigma}{dq^4 d\Omega} \propto \hat{\sigma}_U \left\{ 1 + A_U^1 \cos^2\theta_{CS} + \sin 2\theta_{CS}\, A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + \sin^2\theta_{CS}\, A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \right.$$

or

$$\frac{d\sigma}{d\Omega} \propto \frac{3}{4\pi}\frac{1}{\lambda+3}\left[1 + \lambda\cos^2\theta_{CS} + \mu \sin 2\theta_{CS}\cos\varphi_{CS} + \frac{\nu}{2}\sin^2\theta_{CS}\cos 2\varphi_{CS}\right]$$

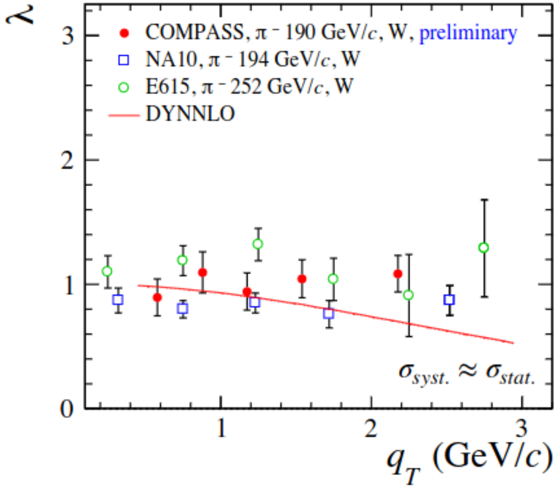
where: $\lambda = A_U^1$, $\mu = A_u^{\cos\phi}$, $\nu = 2\,A_U^{\cos 2\phi}$

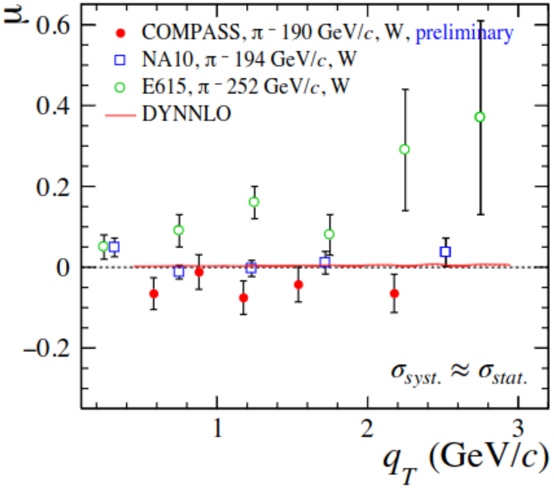
$$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$$

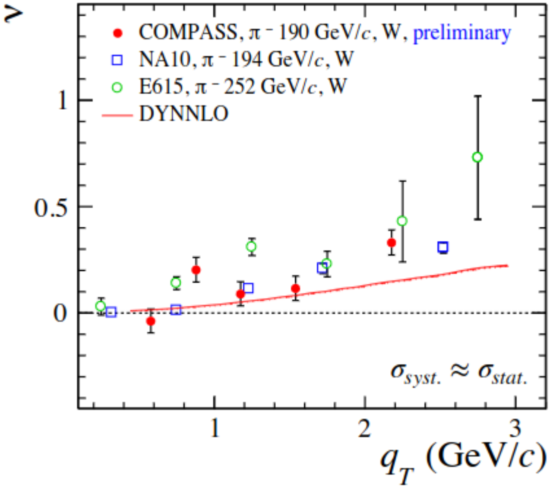
Convolution of the Boer-Mulders TMD PDFs of pion and nucleon

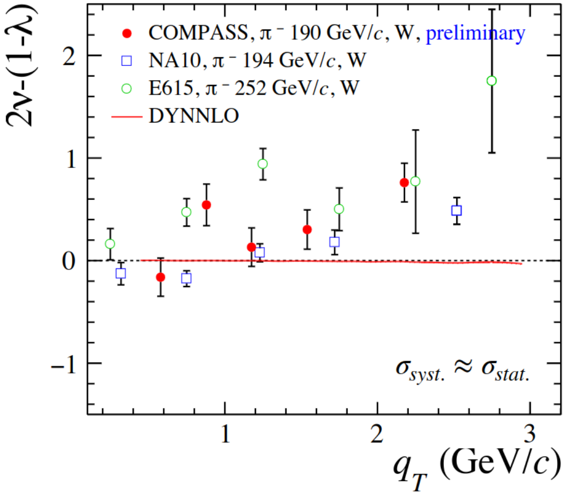
- In the naive Drell-Yan parton model , expect $\lambda=1$, $\nu=\mu=0$ (LO)
- At NLO, there might be a non-zero ν (cos $2\phi_{CS}$ dependence)
- Lam-Tung relation: $1 - \lambda = 2\,\nu$

Drell-Yan unpolarized asymmetries







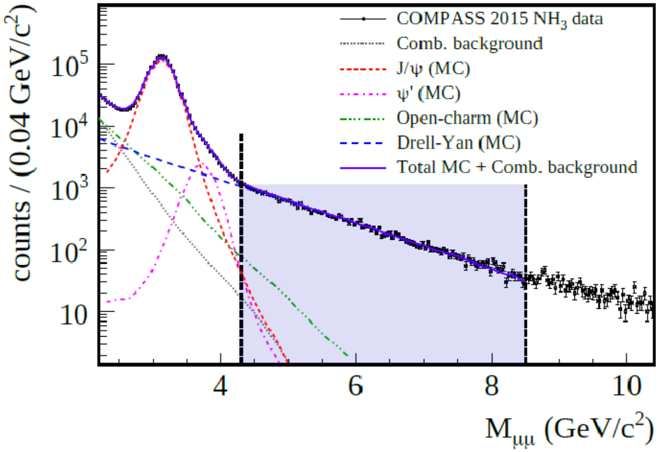


The Boer-Mulders-related coefficient ν tends to be larger than expected from pQCD

Hint for the presence of non-negligible Boer-Mulders effect

Possible violation of Lam-Tung relation.

Differential Drell-Yan cross sections



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

L is the luminosity

ε contains efficiencies, acceptance and lifetimes

x_n are the different observables

The dimuon mass range $4.3 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 8.5$ is considered as Drell-Yan dominated.

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

Acceptance ranges from ~1% to ~15%.
It varies mostly with x_F (weak dependence with q_T and mass).

Contamination from other physics processes (purity) is taken into account.

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

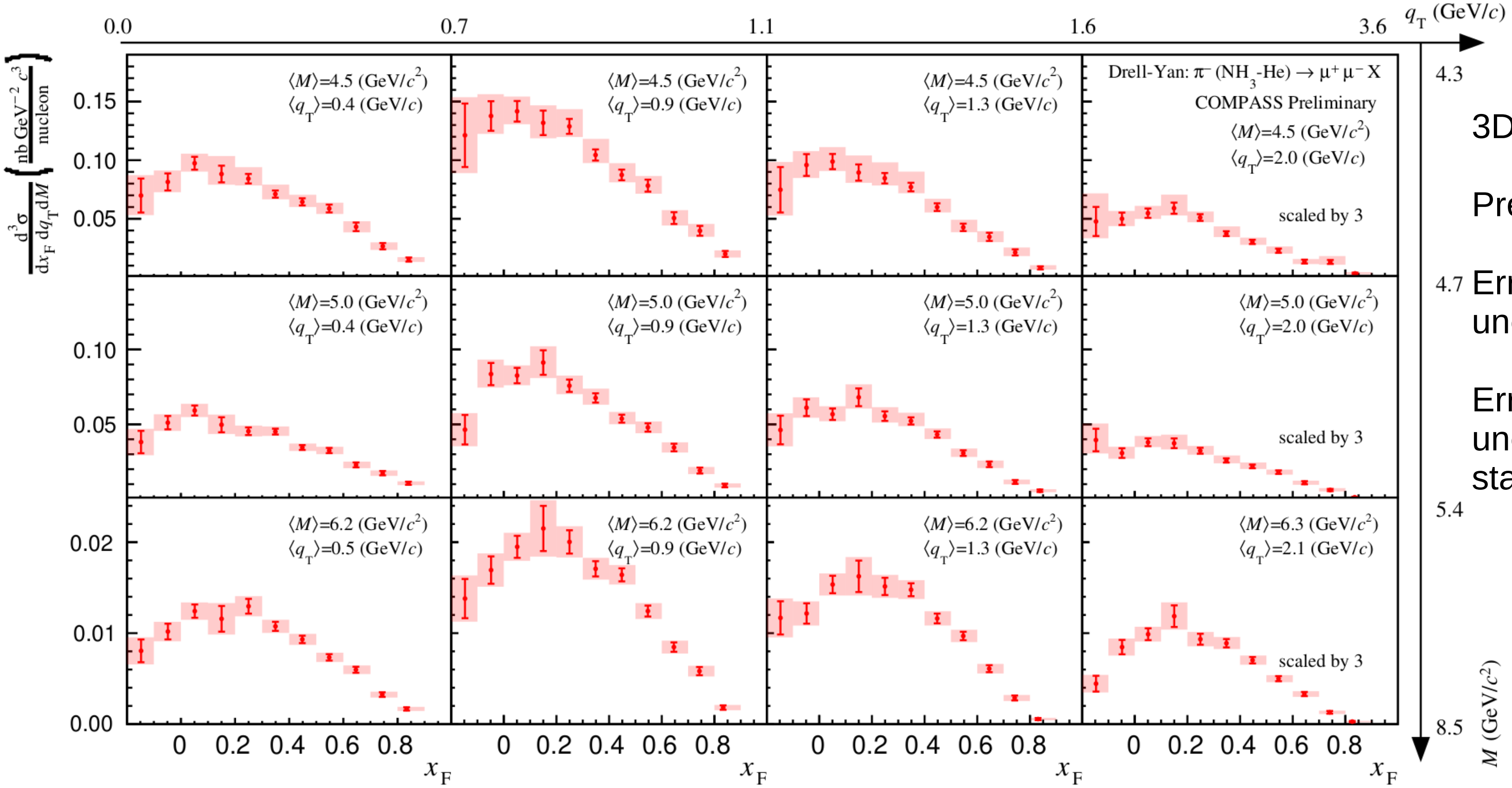
q_T, q_L : Transverse and longitudinal momentum of the dimuon in the Hadrons collision frame

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

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

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

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

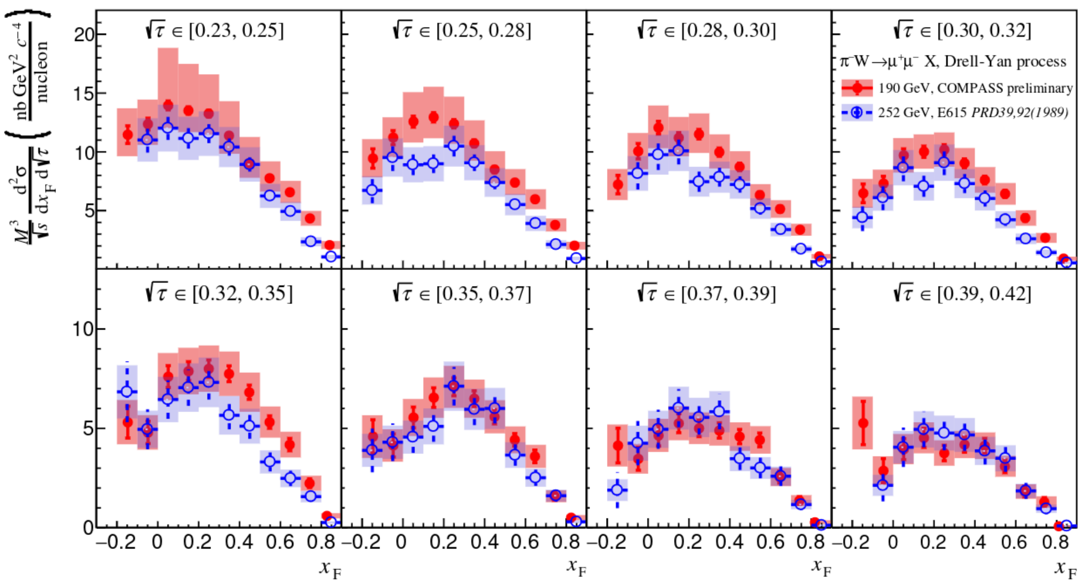
Error bars are statistical uncertainty

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

Input to global extraction of PDF and TMD PDF of the pion

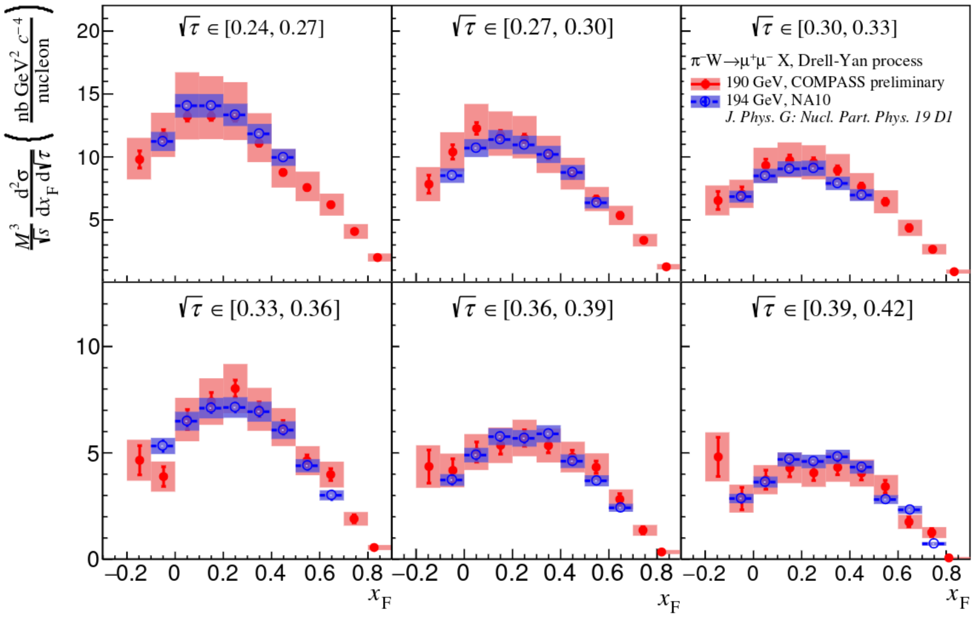
Drell-Yan cross section per nucleon from the **tungsten target** in bins of √τ, as function of Feynman-x

COMPASS versus E615



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

COMPASS versus NA10



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

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

Beam energy-independent DY cross section: $M^3/\sqrt{s}$ factor

Better agreement with NA10 than with E615,
namely at lower masses.

Drell-Yan cross section statistics and systematics

The systematics of the COMPASS measurement include:

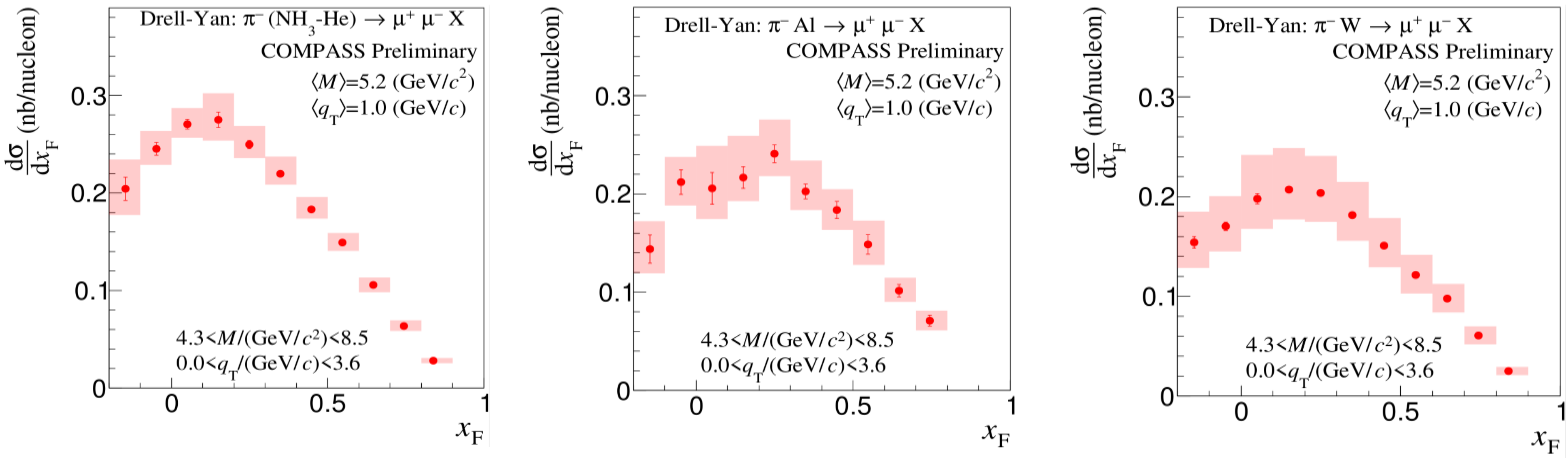
- Luminosity uncertainty ~4% (normalization uncertainty)
- Trigger, purity and acceptance-related uncertainties depending on target and kinematics

	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.

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)

→ Input for the extraction of nuclear PDFs and study of nuclear effects

From COMPASS to AMBER

COMPASS is providing much-awaited pion-induced Drell-Yan data (after a gap of 30 years).

At COMPASS Drell-Yan, mostly **valence quarks** are probed – **u-quark dominance**, since π^- beam.

AMBER is the next step to learn about pion structure:

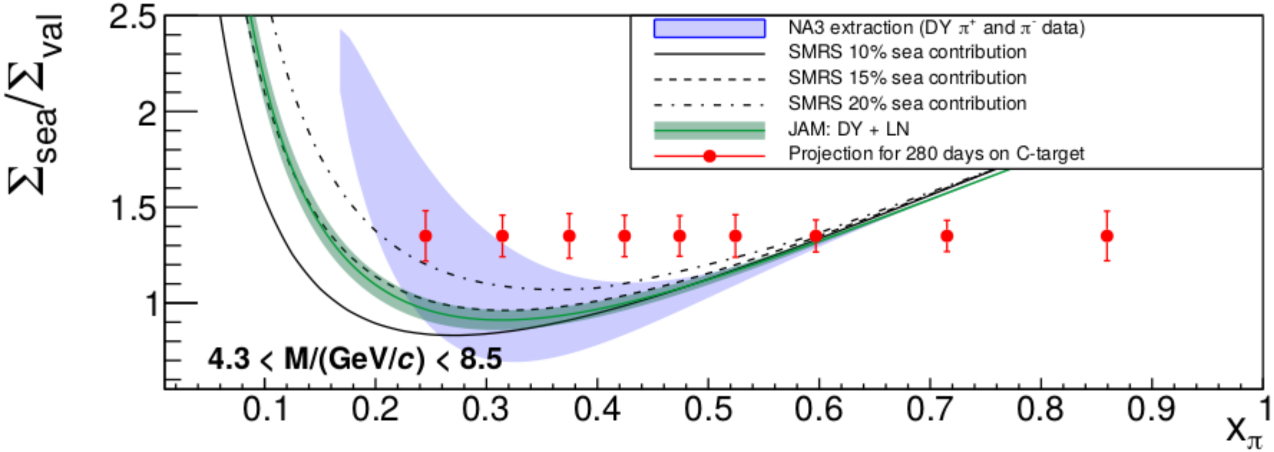
- Pion beam of both charges → **sea-valence separation**
- Benefit from the gained experience at COMPASS:
  - Light isoscalar target: **carbon**
  - Thinner and isolated **tungsten** target
  - Beam particle identification: CEDARs at beam high intensity
  - Improve vertexing and resolutions: vertex detector
  - Triggerless DAQ, with higher-level dimuon trigger – including online trigger efficiency control

AMBER

Apparatus for Meson and Baryon Experimental Research

AMBER
Apparatus for Meson and Baryon Experimental Research

Future: π-induced Drell-Yan with both beam charges



Valence composition:

$$u_{val}^{\pi^+} = u^{\pi^+} - \bar{u}^{\pi^+} \text{ and } d_{val}^{\pi^-} = d^{\pi^-} - \bar{d}^{\pi^-}$$

Flavour symmetry:

$$u_{val}^{\pi^+} = \bar{d}_{val}^{\pi^+} = \bar{u}_{val}^{\pi^-} = d_{val}^{\pi^-}$$

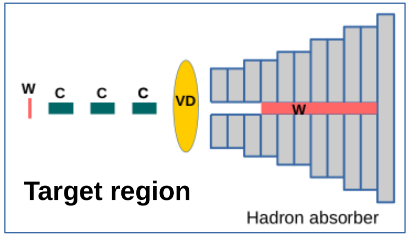
$$\bar{u}_{sea}^{\pi} = u_{sea}^{\pi} = \bar{d}_{sea}^{\pi} = d_{sea}^{\pi} = \bar{s}_{sea}^{\pi} = s_{sea}^{\pi}$$

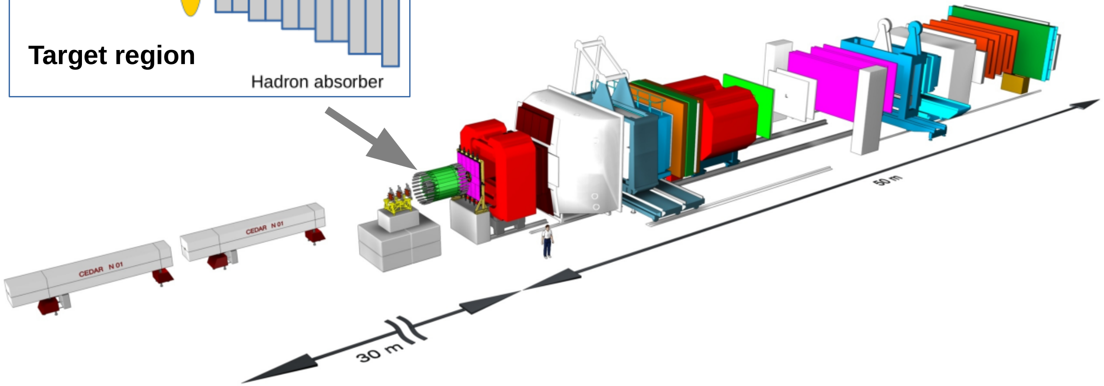
Sea/valence separation (LO) from ratio of cross-section combinations:

$$\boxed{\frac{\Sigma_{sea}}{\Sigma_{valence}} = \frac{4\sigma^{\pi^+C} - \sigma^{\pi^-C}}{-\sigma^{\pi^+C} + \sigma^{\pi^-C}}}$$

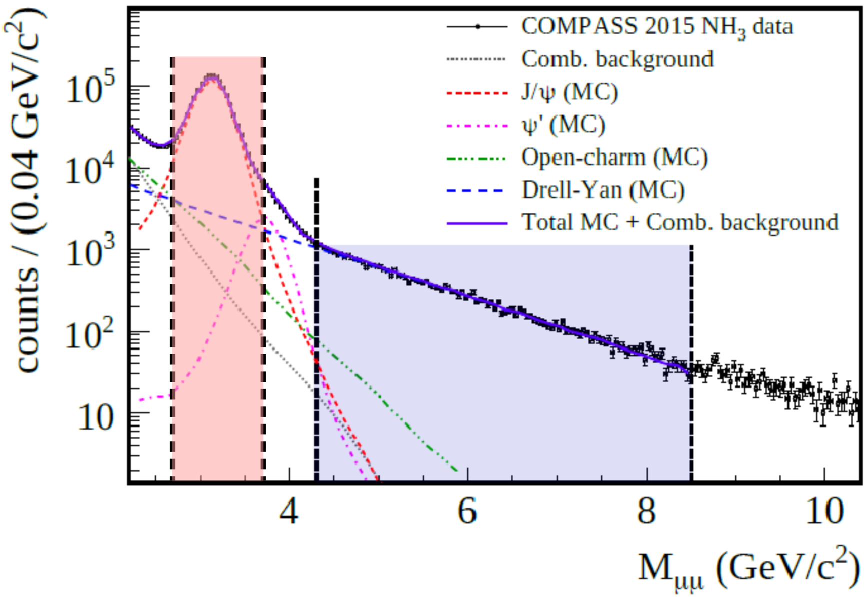
LO: only sea-val and val-sea terms

LO: only val-val terms





Hadro-production of charmonium in COMPASS



J/ψ and ψ(2S) data collected simultaneously with Drell-Yan.

Due to the limited mass resolution, ψ(2S) is hardly visible.

Due to the presence of hadron absorber, only access <u>inclusive charmonium production</u>.

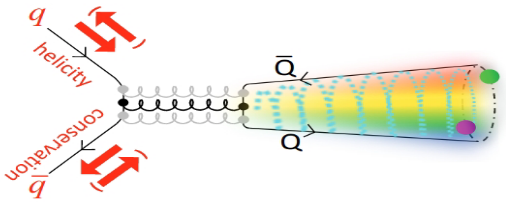
$$\pi^- A \to J/\psi\, X \to \mu^+\mu^-\, X$$

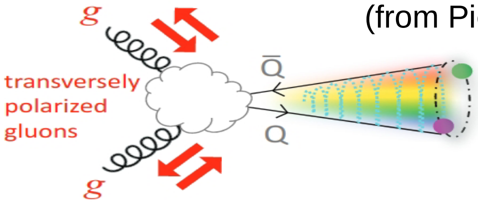
J/ψ-related analyses in COMPASS:

- Transverse spin asymmetries
- Unpolarized asymmetries (not yet released)
- Differential cross sections
- J/ψ-pair production

Charmonium production mechanisms

(from Pietro Faccioli)

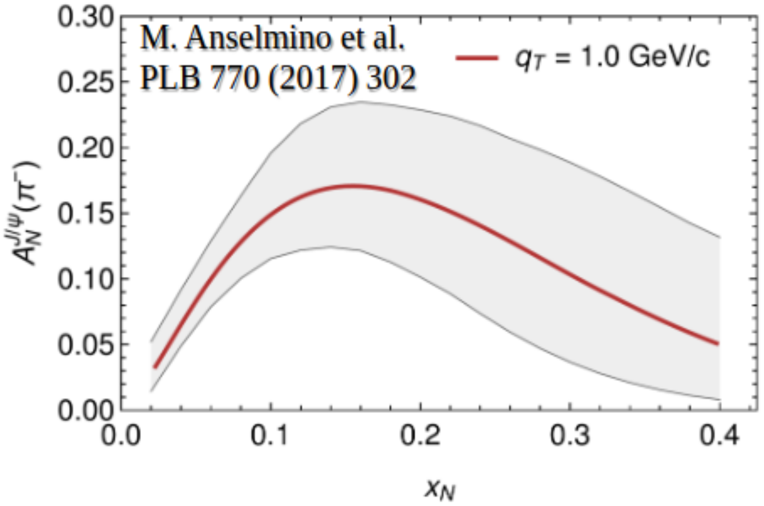




$q\bar{q}$ annihilation **gluon-gluon fusion**

...and also qg contributions possible.

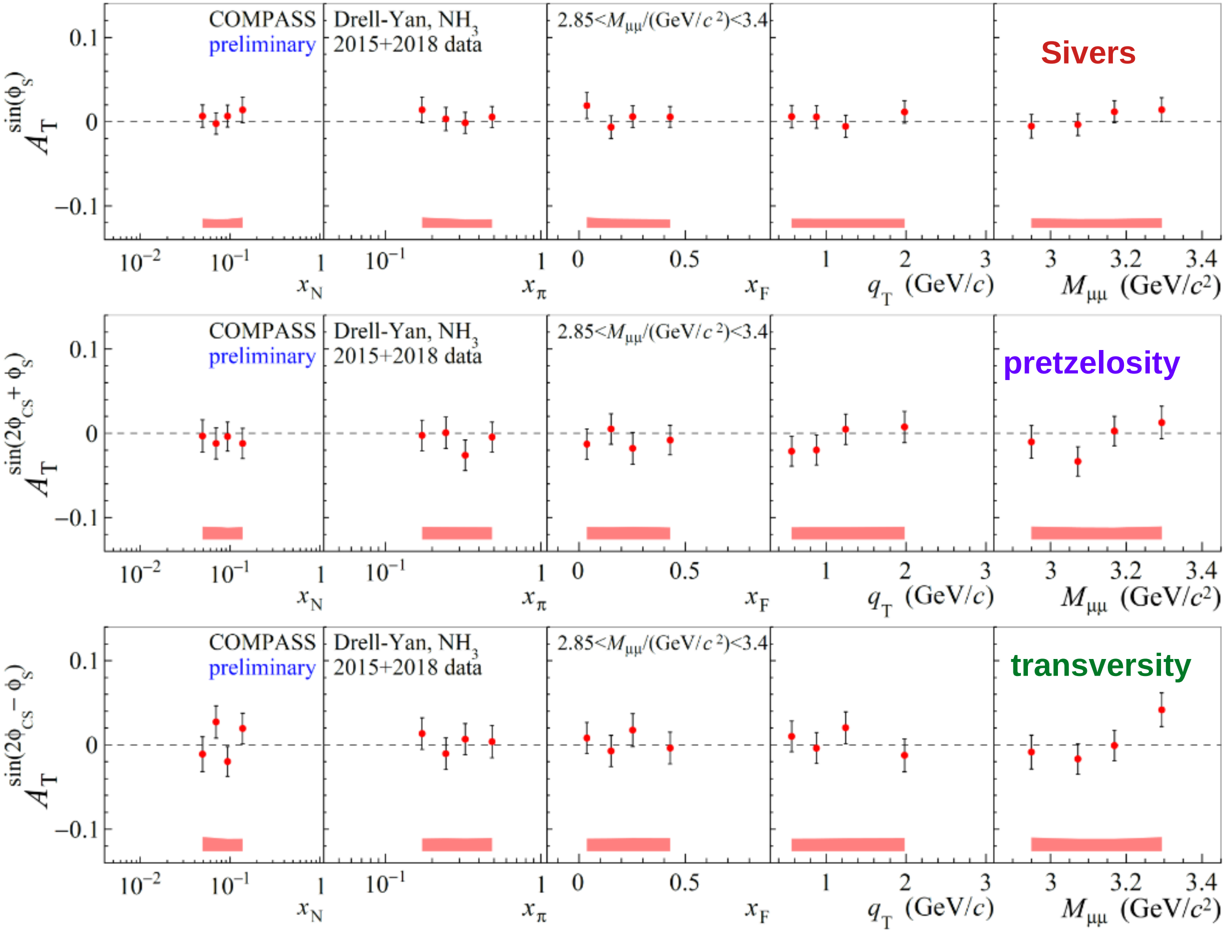
At COMPASS energies, the $q\bar{q}$ mechanism is expected to contribute significantly, while at LHCb gluon-gluon fusion is dominant.



Assuming $q\bar{q}$ annihilation dominance,
M. Anselmino et al, PLB 770 (2017) 302

predicted large J/ψ transverse spin asymmetry and sensitivity to u-quark Sivers TMD PDF of the nucleon.

Transverse spin asymmetries in the J/ψ mass range



J/ψ-dominated dimuon mass interval:

$2.85 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 3.4$

Lower $\langle x_N \rangle$ and $\langle x_\pi \rangle$ as compared to high mass Drell-Yan

Worse position resolution as compared to high mass Drell-Yan – small leakage from one cell into another.

All TSAs compatible with zero

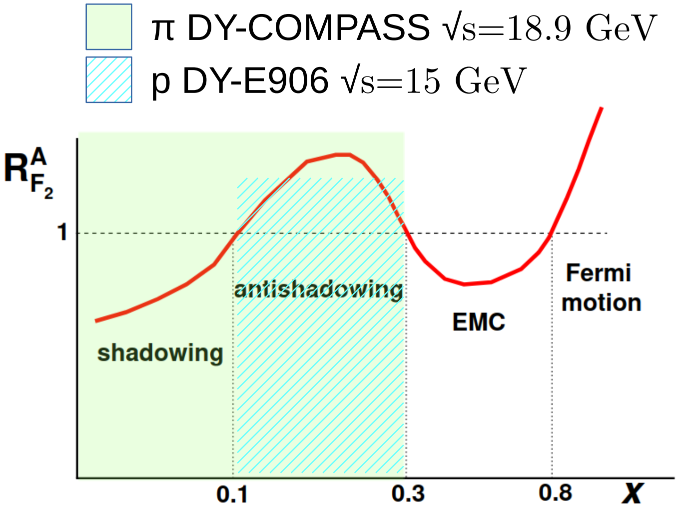
Study of “cold nuclear matter” effects

Different phenomena observed. At low x driven by partons multiple scattering.

A useful observable is the **Nuclear modification factor:**

$$R_{hA} = \frac{dN_{hA}^{J/\psi}}{\langle N_{coll}\rangle \; dN_{hh}^{J/\psi}}$$

If no nuclear effects: R_{hA} =1



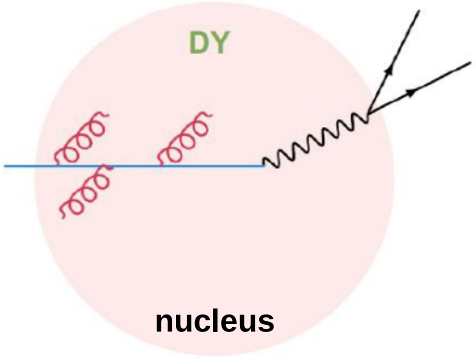
(from N. Armesto, 2006)

Try to encode it all in process-independent **nPDF**s

Partons may also lose energy via soft gluon emissions when crossing the cold nuclear matter

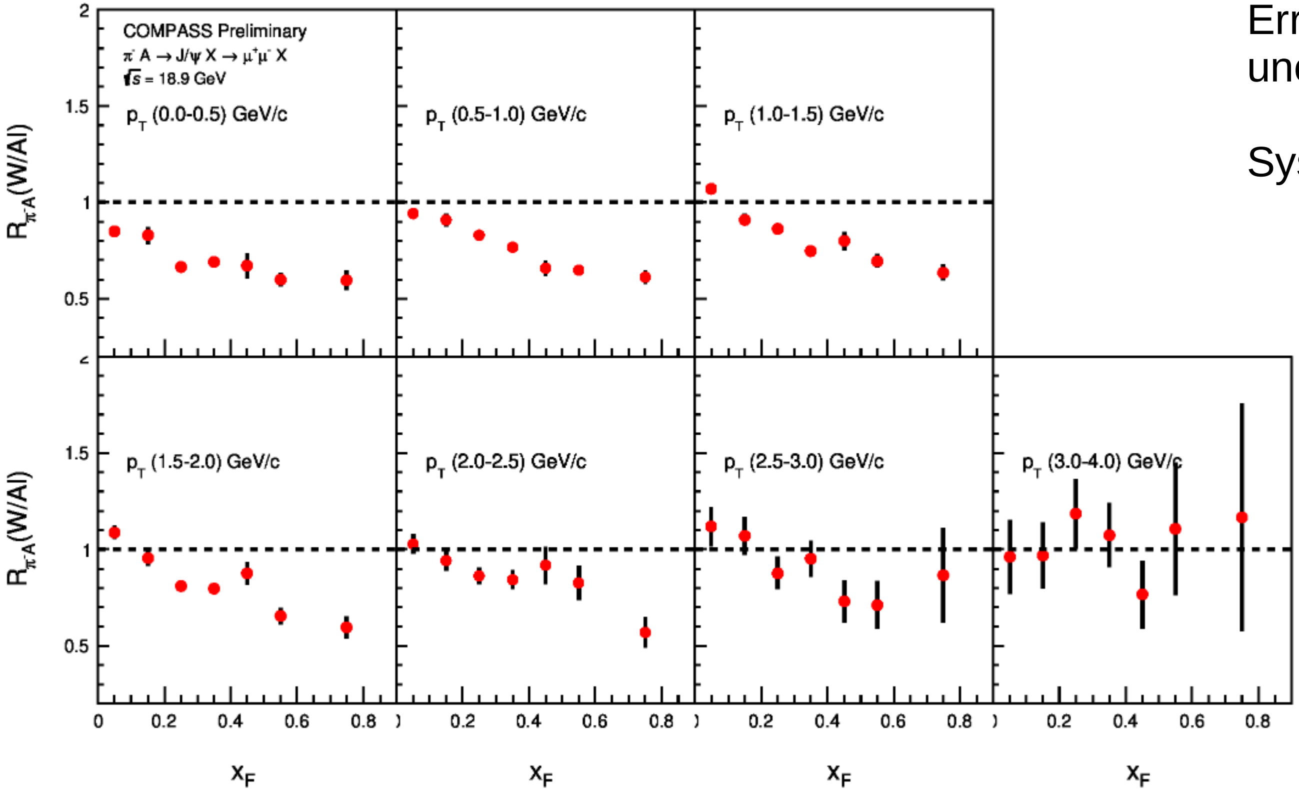
Different hard processes allow to study the **energy loss effect**:

- Drell-Yan → initial state radiation
- J/ψ production → initial and final state radiation, interference



J/ψ production cross-section ratios

$R_{\pi A}$(W/Al) (x_F, p_T) : ratio of J/ψ production cross sections per nucleon between W and Al targets in (x_F,p_T) bins.



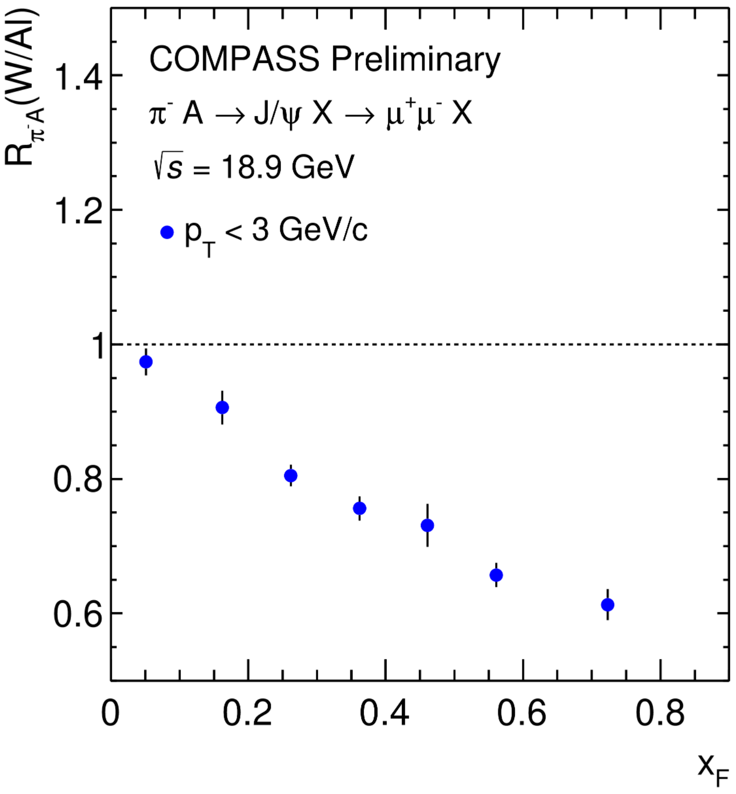
Error bars show the statistical uncertainty.

Systematic uncertainty <10%

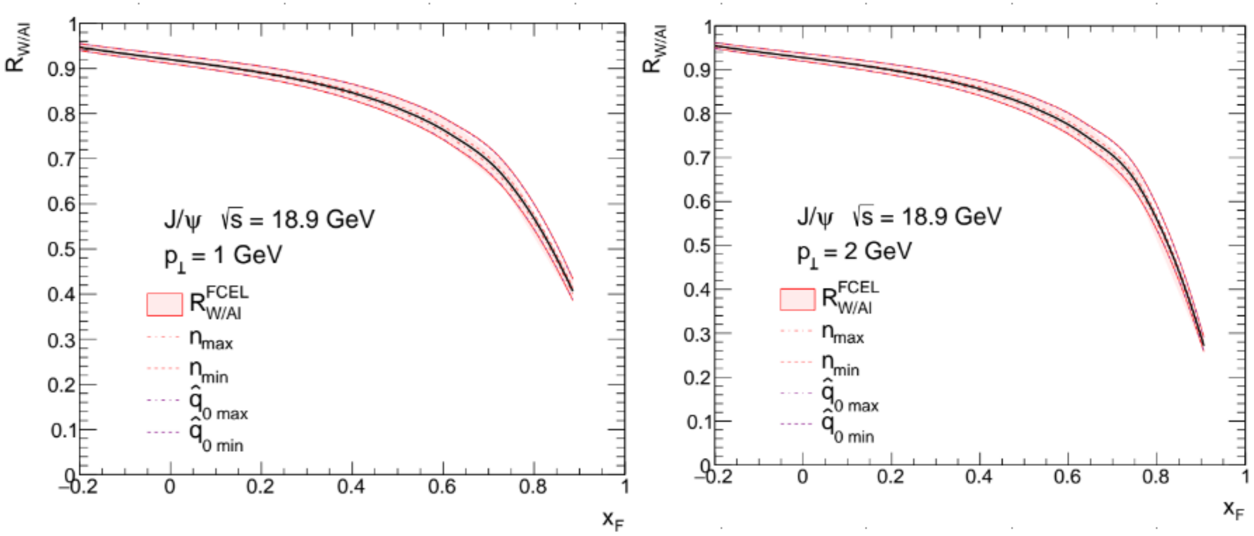
Suppression towards high x_F , more prominent at low p_T.

This 2D analysis provides additional insight, not possible from past experiments.

J/ψ nuclear modification factor and parton energy loss



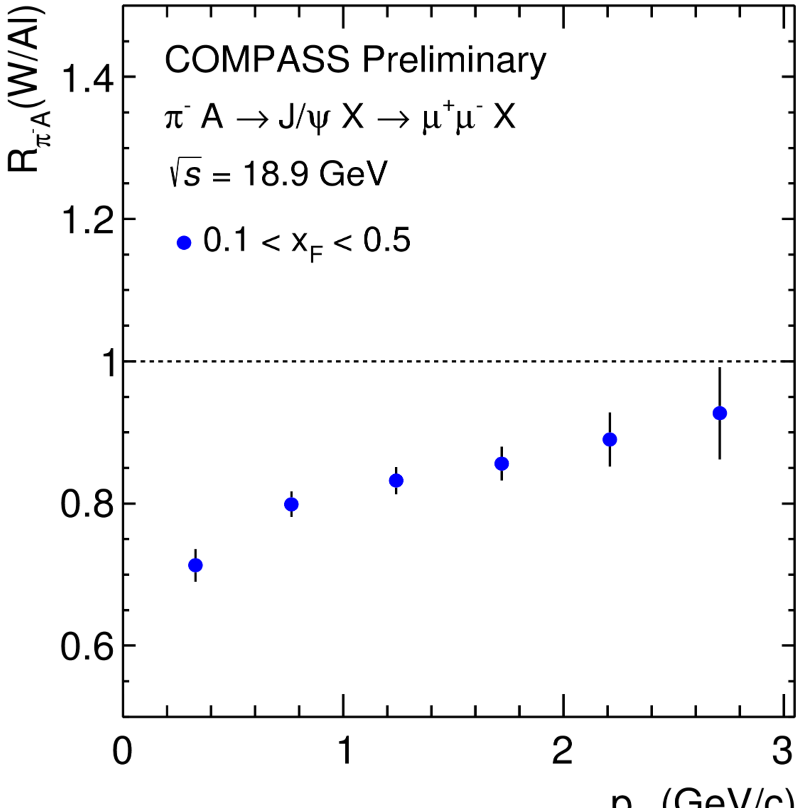
Using a model of energy loss, with transport coefficient q_o, by F. Arléo and S. Peigné, as in JHEP 03 (2013) 122.



F. Arléo, private communication, preliminary

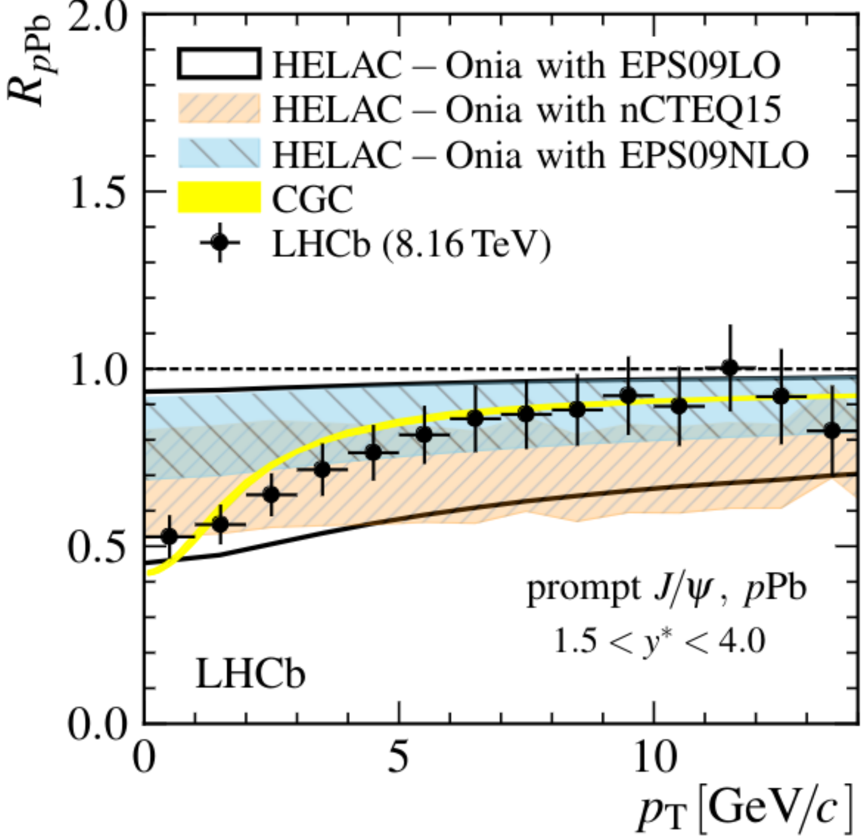
J/ψ nuclear modification factor: Comparing to LHCb

πW/πAl



(3.2 < y* < 4.2)

pPb/pp

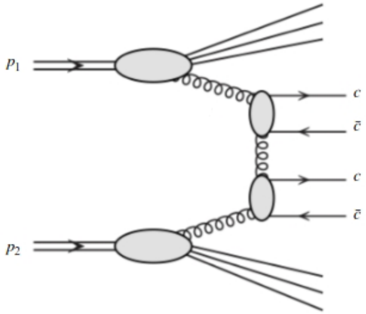


LHCb, PLB 774 (2017) 159-178

J/ψ pair production

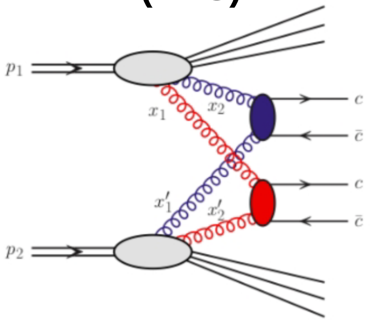
COMPASS, PLB 838 (2023) 137702

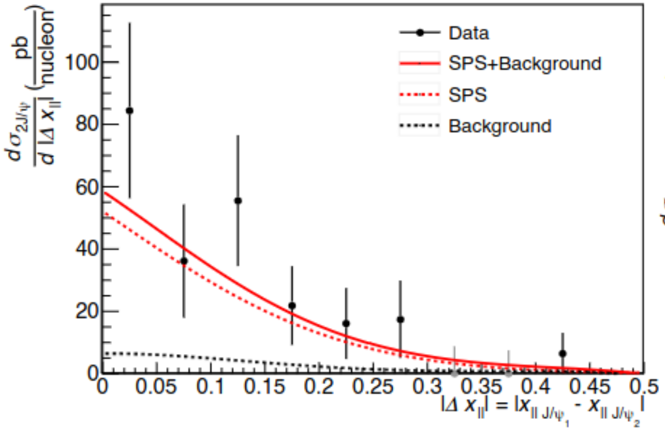
Single parton scattering (SPS)

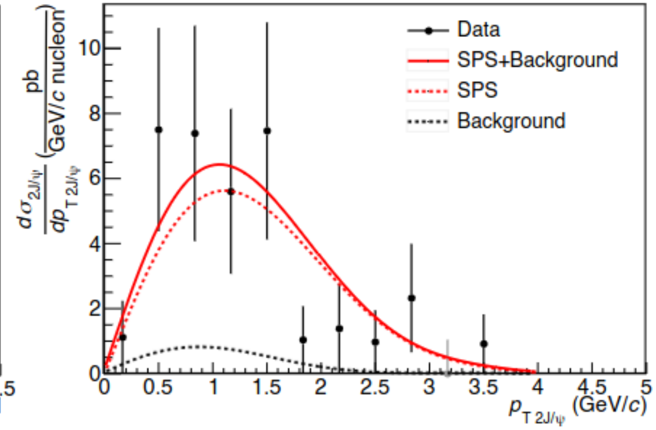


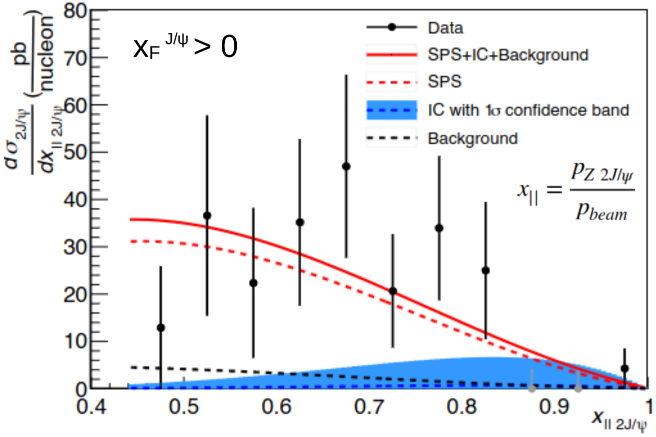
SPS expected to dominate at COMPASS energies

Double parton scattering (DPS)









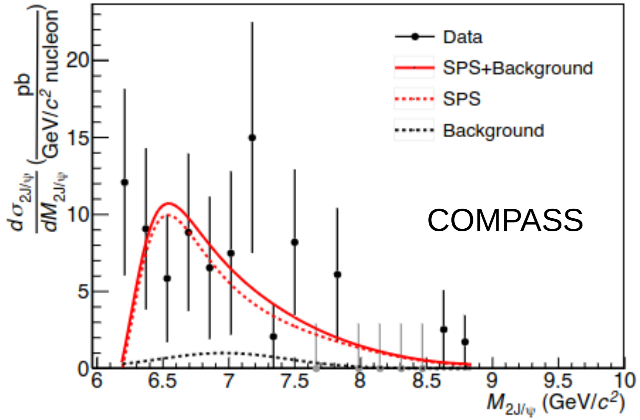
COMPASS results are consistent with pure SPS hypothesis

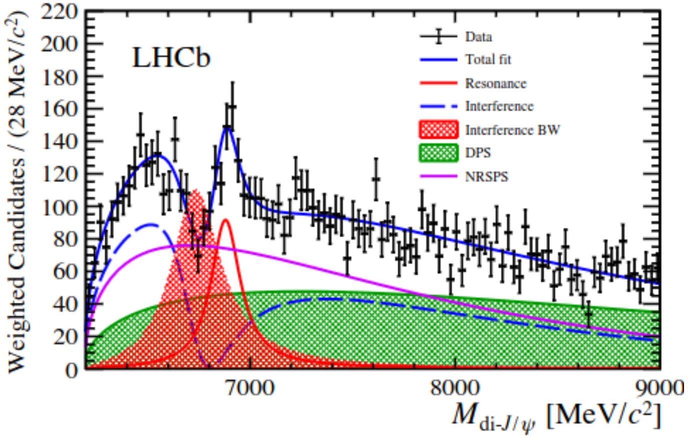
An upper limit on **intrinsic charm** (IC) production mechanism is obtained:

$$\sigma^{IC}_{2J/\psi}/\sigma_{2J/\psi}\Big|_{x_F>0} < 0.24\ (CL = 90\%)$$

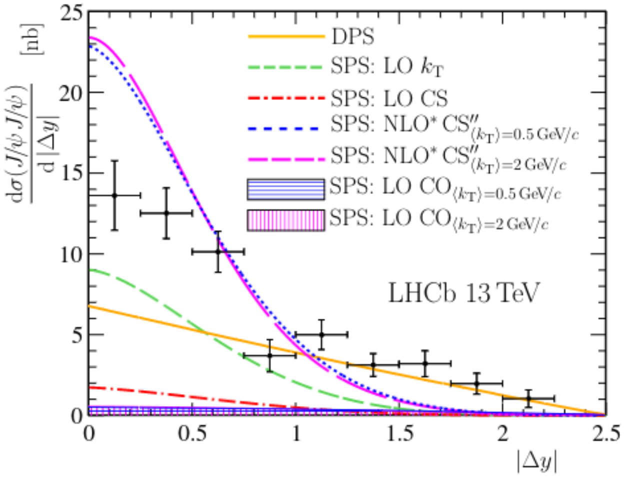
J/ψ pair production

COMPASS, PLB 838 (2023) 137702





M[X(6900)] = 6886 ± 11 ± 11 MeV
Γ[X(6900)] = 168 ± 33 ± 69 MeV



COMPASS sees no evidence for the exotic state reported by LHCb, Sci. Bull. 65 (2020) 1983-1993

Enhanced contribution of DPS at LHC energies allows LHCb to separate SPS and DPS in J/ψ pair production
LHCb, JHEP 06 (2017) 047.

J/ψ pair production from isolated SPS contribution

access to the **gluon TMD PDFs**

Modulations extracted are so-far consistent with zero
LHCb, JHEP 03 (2024) 088

In summary:

- COMPASS studied for the first time the transversely polarized Drell-Yan process, collecting data in 2015 and 2018.
- The measured Sivers asymmetry in Drell-Yan is compatible with the sign-change hypothesis with respect to SIDIS, (also measured in COMPASS).
- The pion-induced Drell-Yan cross section is measured from the 2018 data, in a multidimensional analysis (M, q_T, x_F).
- Visible hint for a non-zero Boer-Mulders effect in the angular dependence of the Drell-Yan cross section.
- Inclusive J/ψ production is studied in parallel. All measured transverse spin asymmetries are compatible with zero.
- Evidence for cold nuclear matter effects, visible in the J/ψ cross-section ratio W/Al.
- J/ψ pair production in COMPASS is measured to be compatible with pure SPS contribution.
- No evidence in COMPASS for the *X*(6900) exotic previously observed by LHCb.

Conclusion

Good harvest of results from the COMPASS Drell-Yan campaign.

Most of these are not yet published $\rightarrow$ publications should follow soon!

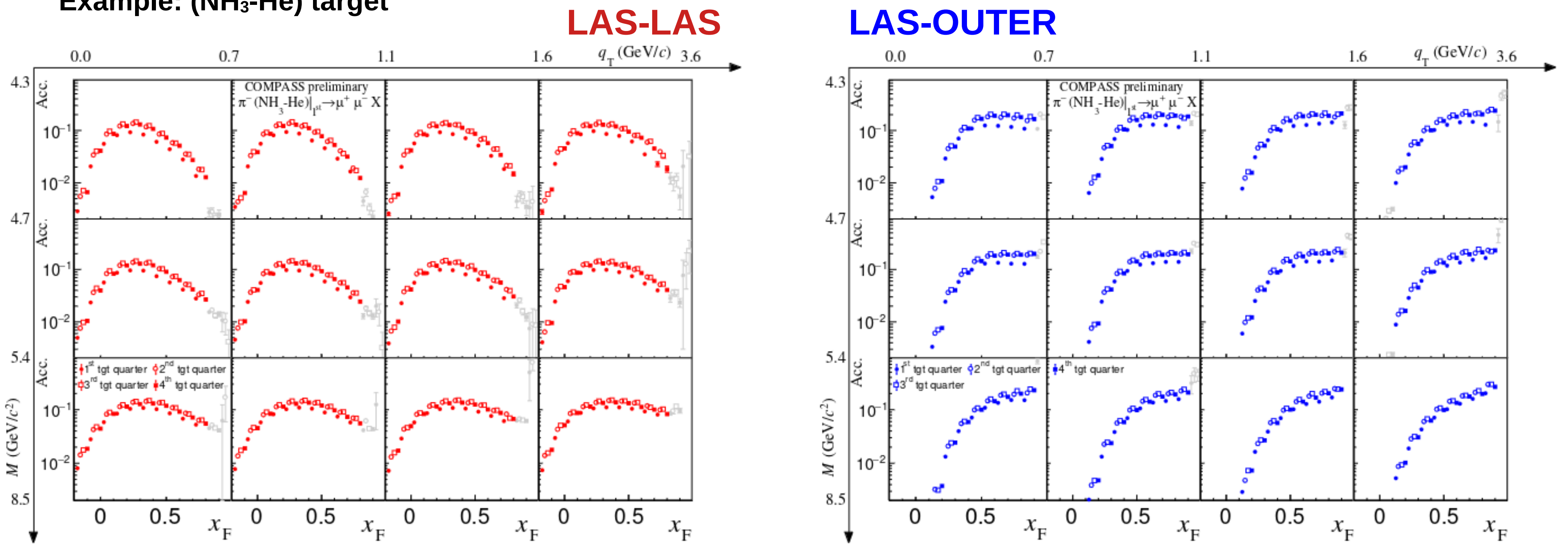
Learning curve getting steeper, with many ideas on how one could improve experimentally $\rightarrow$ AMBER

SPARES

High mass Drell-Yan Acceptance

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

Example: (NH_3-He) target



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:

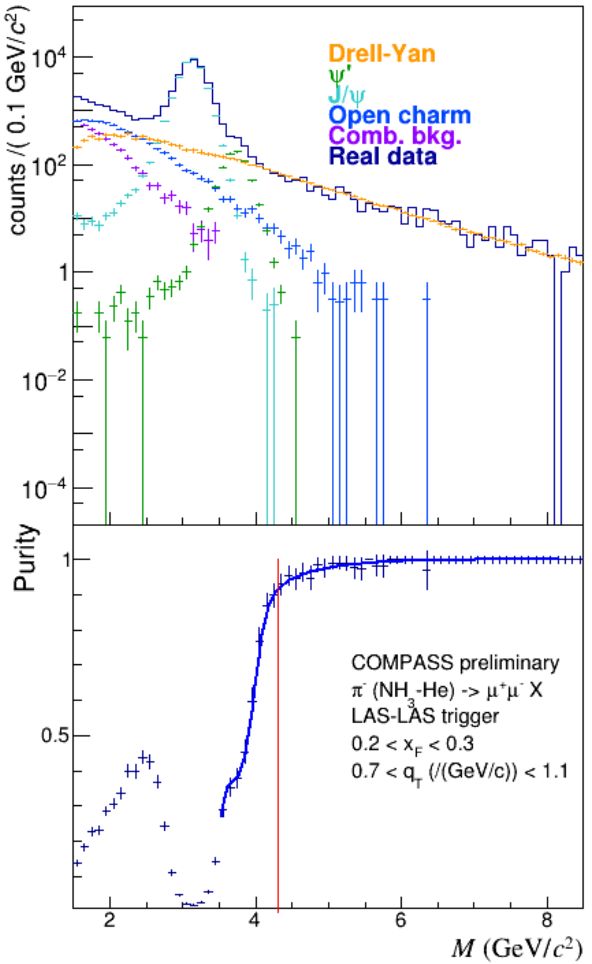
- NH3-He : M > 4.3 GeV/c²
- Al: M > 4.7 GeV/c²
- W: M > 5.5 GeV/c²

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, in bins of mass, as function of q_T

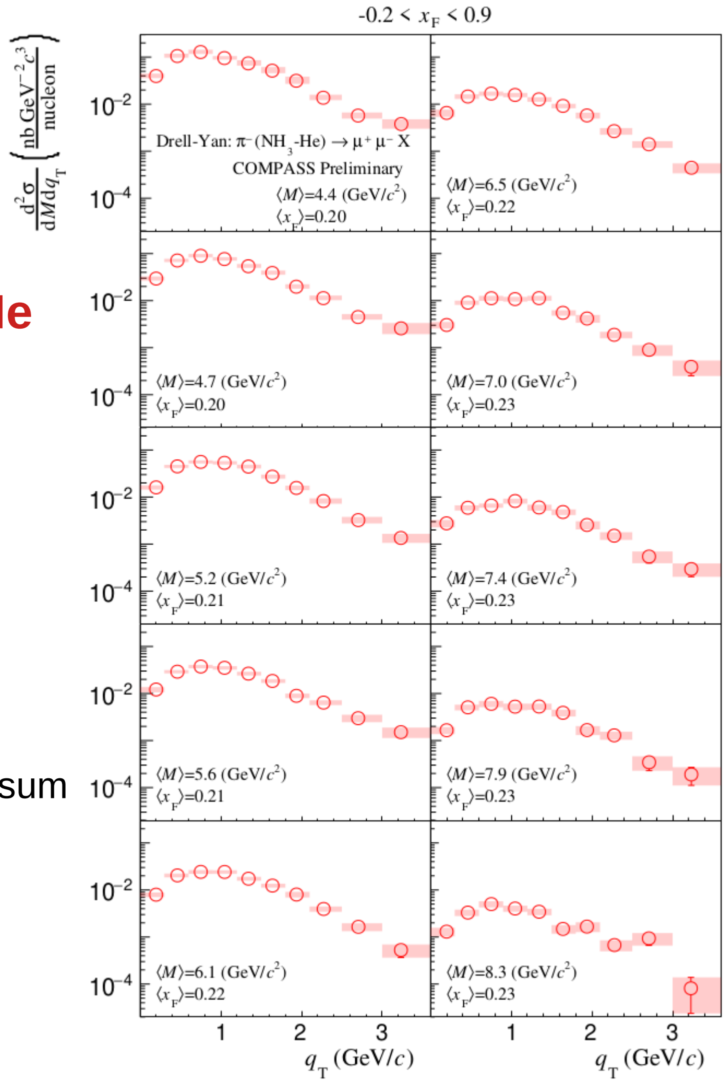
2D cross section (M, q_T)

Preliminary results

Error bars are statistical Uncertainty

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

NH_3-He



W