Pion-induced Drell-Yan muon pair production on various nuclear targets at COMPASS

Workshop on PDF in EIC Era @ Academia Sinica, Taipei

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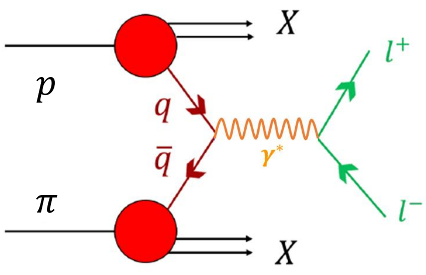
on behalf of the COMPASS collaboration

Processes for Pion PDF

$\boldsymbol{Drell-Yan}$

$\pi^- p \to \mu^+ \mu^- X$



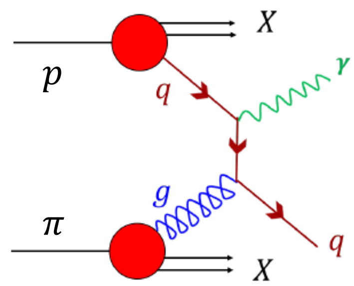
sensitive to valence
moderate-x to large-x

Pro : Physics model is solid

Con : Only E615, NA10 from 30yrs ago
Tension between two data sets
Fixed target data w/ large uncertainty

$\boldsymbol{prompt-gamma}$

$\pi^- p \to \gamma X$



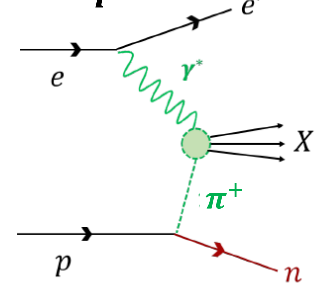
sensitive to gluon
moderate-x

Pro : was the only process set to constrain gluon

Con : WA70 data also from 30yrs ago
Large uncertainty due to the background

leading-neutron DIS
(*Sullivan process*)

$p \to \pi^+ n_{e'}$



sensitive to low-x valence
➔ better constrain gluon and sea
(future EIC plan to extend the x region)

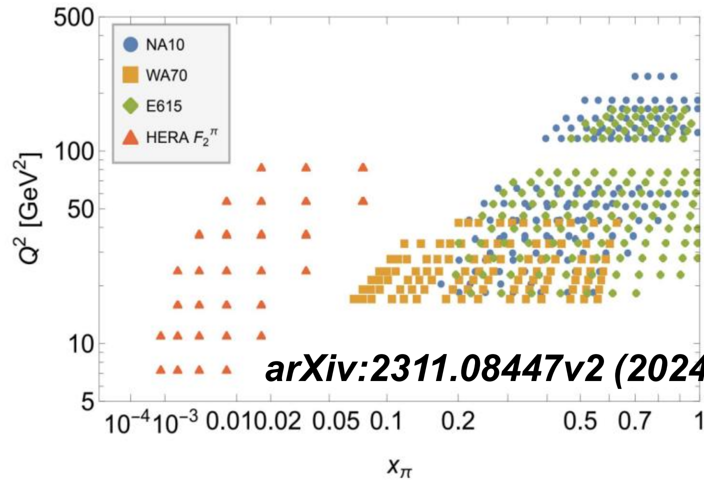
Pro : No pion beam data required
High statistic data from DIS

Con : theoretical description remains uncertain.

Drell-Yan data and leading-neutron DIS data are considered two most important and complimentary processes to extract pion PDF.

Data for Pion PDF

Pion PDFs		Data for Valence: Drell-Yan NA10	Data for Valence: Drell-Yan E615	Data for Gluon: Prompt-gamma WA70	Data for Gluon: *leading-neutron DIS* HERA
1992	SMRS	O	O	O	
1992	GRV	O	O	O	
2018	JAM	O	O		O
2020	xFitter	O	O	O	
2024	Fantômas	O	O	O	O



arXiv:2311.08447v2 (2024)

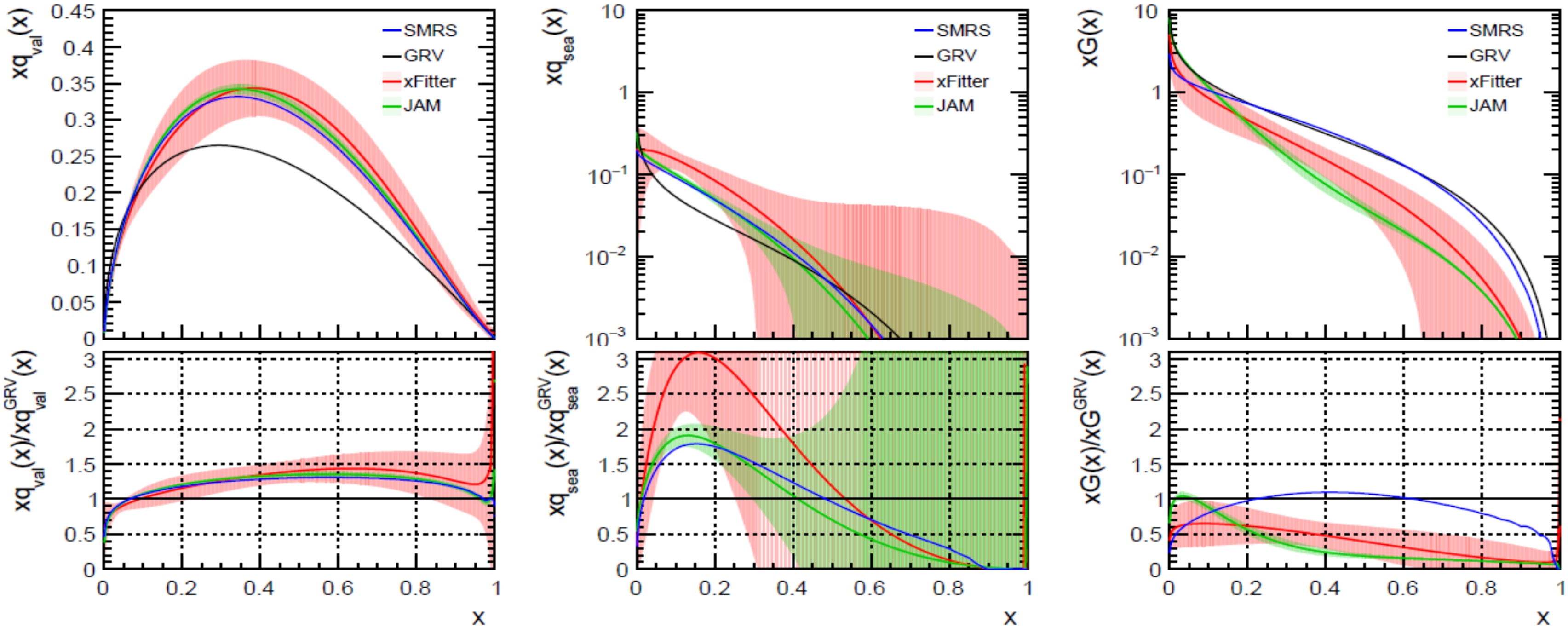
COMPASS 2018 data is new input of DY data since 30 yrs.

① **E615 (Fermilab) and NA10 (CERN) are more than 30 years old**. A normalization issue between E615 and NA10 data, by up to 20%.

② We have not only W target but only from $NH_3 - He$ **target which gives less nuclear effects.**

Pion PDF

$\boxed{Q^2 = 9.6GeV}$ **Valence** **Sea** **Gluon**



GRV is lower than the others by 30%-50% for valence PDF

Poorly constrained for sea PDF.

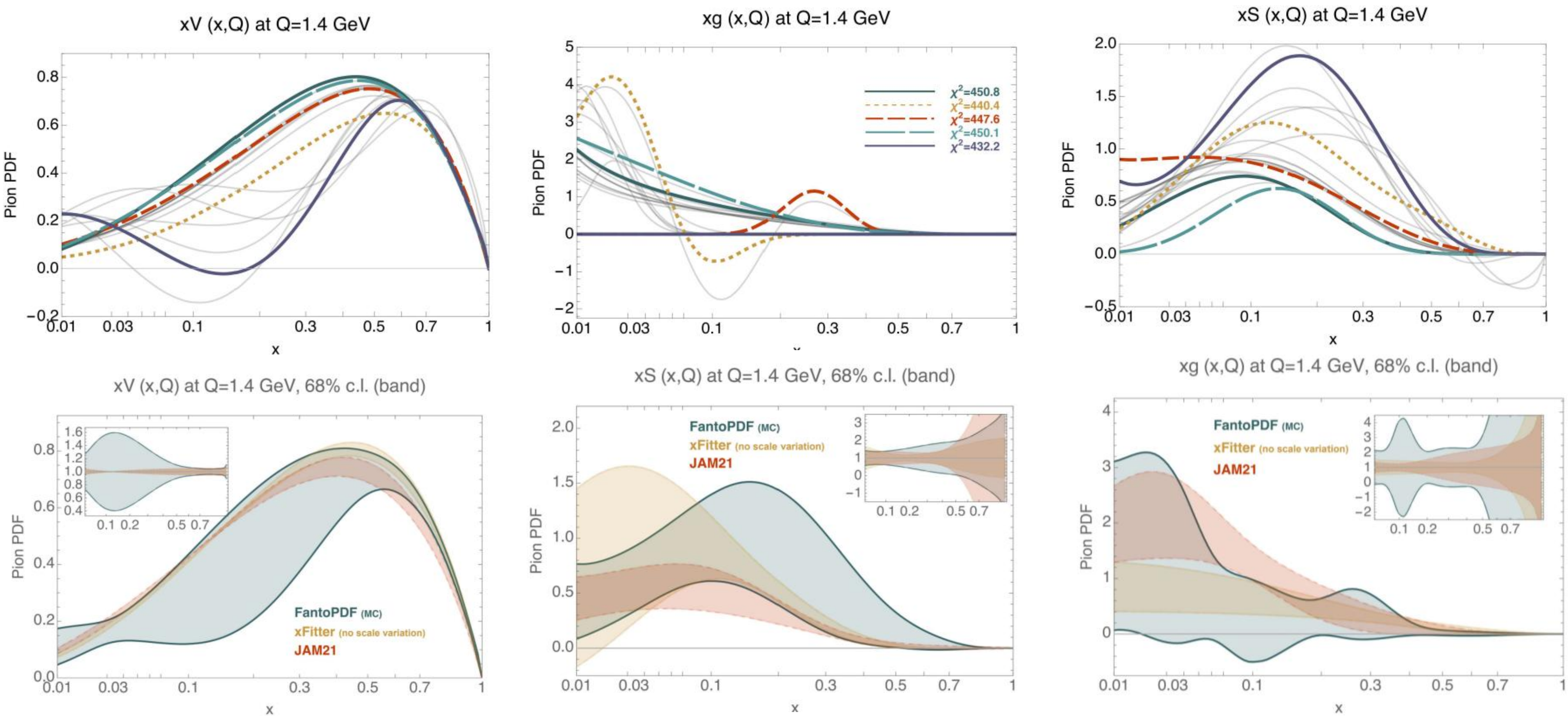
GRV and SMRS has larger gluon strength than JAM and xFitter at $x > 0.1$

Phys. Rev. D 102, 054024 (2020)

Pion PDF has still large discrepancy between different PDF sets.

Pion PDF

arXiv:2311.08447v2 (2024)

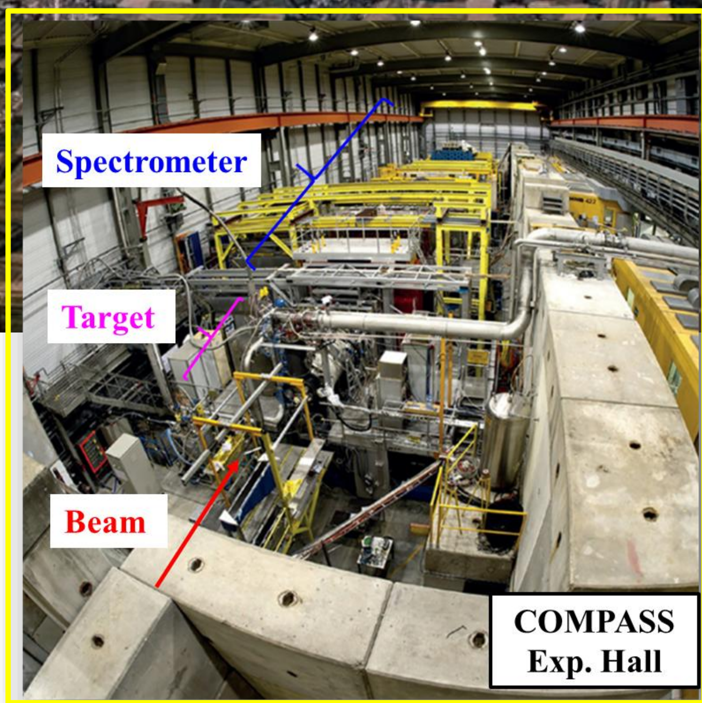


The Fantômas PDF study shows that the instability of the fit leads to large uncertainties in the pion PDF, partly due to the choice of functional form. However, the primary source of instability originates from the large uncertainties in the existing data sets.

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

- Nucleon structure
- Hadron structure
- Hadron spectroscopy

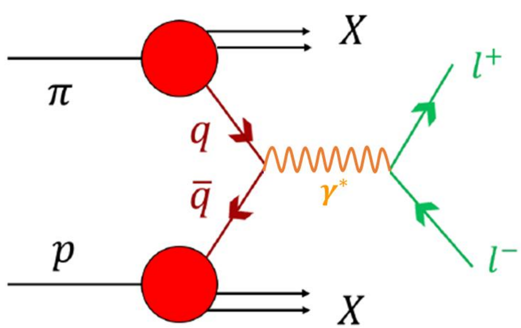
- Common spectrometer
- High intensity muon and hadron beams



- **COMPASS**
  - A fixed target experiment at CERN
  - A 60m-long spectrometer
  - Multiple beam choices : muon, proton, pion
  - Multiple target choices : nuclear target and polarized ammonia target

Physics Variables and Studied Physics

$LO\quad : q\bar{q} \rightarrow \gamma^* \rightarrow l^+ l^-$



- $Dimuon\ mass\ :\ M^2 = (p_{\mu+} + p_{\mu-})^2$
- $Dimuon\ transverse\ momentum\ :\ q_T$
- $Dimuon\ lontitutinal\ momentum\ :\ q_L$
- $Feynman - x : x_F = q_L / \left(\frac{\sqrt{s}}{2}\right)$ $in\ hadron\ collison\ frame$
- $Bjorken - x : x_{\pi/N} = \frac{1}{2}\left(\sqrt{x_F^2 + 4\frac{M^2}{s}} \pm x_F\right)$

PDF

S.D. Drell and T.M. Yan
PRL 25 (1970) 316

$$\frac{d^2\sigma}{dM_{ll'}dx_F} = \frac{2\pi\alpha^2}{9M_{ll'}^3}\left(\frac{x_\pi x_p}{x_\pi + x_p}\right)\sum Q_q^2\,[q(x_\pi)\bar{q}(x_p) + \bar{q}(x_\pi)q(x_p)]$$

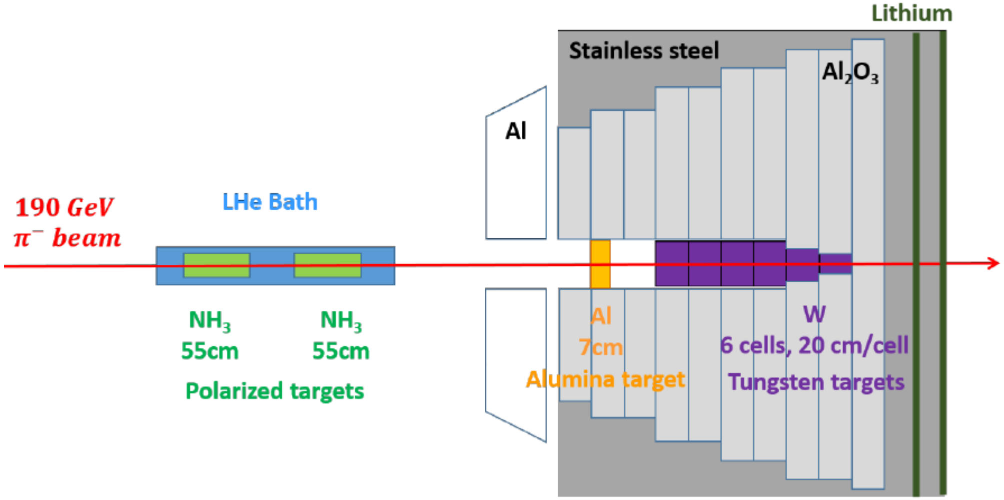
TMD

Journal of High Energy Physics
Article number: 90 (2019)

$$\frac{d^3\sigma}{dM_{ll}dx_F\boldsymbol{dq_T}} = \sigma_0 \sum_{f_\pi, f_p} H_{f\pi fp}(M_{ll}, \mu)\int \frac{d^2\boldsymbol{b}}{4\pi} e^{i(\boldsymbol{b}.\boldsymbol{p_T})} F_{h\pi\to f\pi}(x_\pi, \boldsymbol{b}; \mu, \zeta_1) F_{hp\to fp}(x_p, \boldsymbol{b}; \mu, \zeta_1)$$

- For PDF and TMD study, differential cross section in $M, x_F, and\ q_T$ are important
- For nuclear effect study, differential cross section in x_F, q_T, x_N are of interest.

2015 and 2018
Drell-Yan Data Taking COMPASS



$$\pi^- + p \rightarrow \mu + \mu^- + X$$

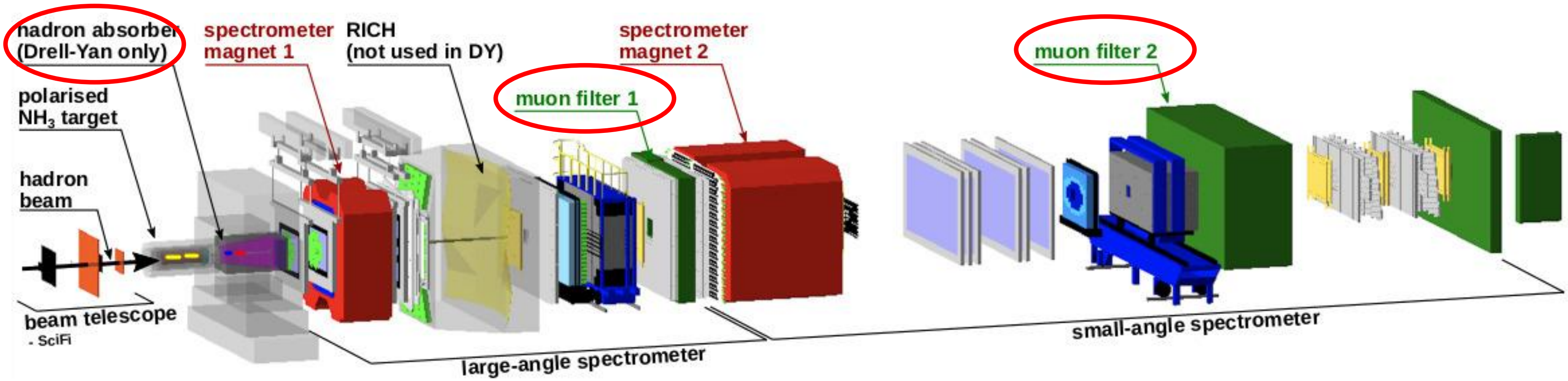
π^- beam

$NH_3 - He,$ Al W

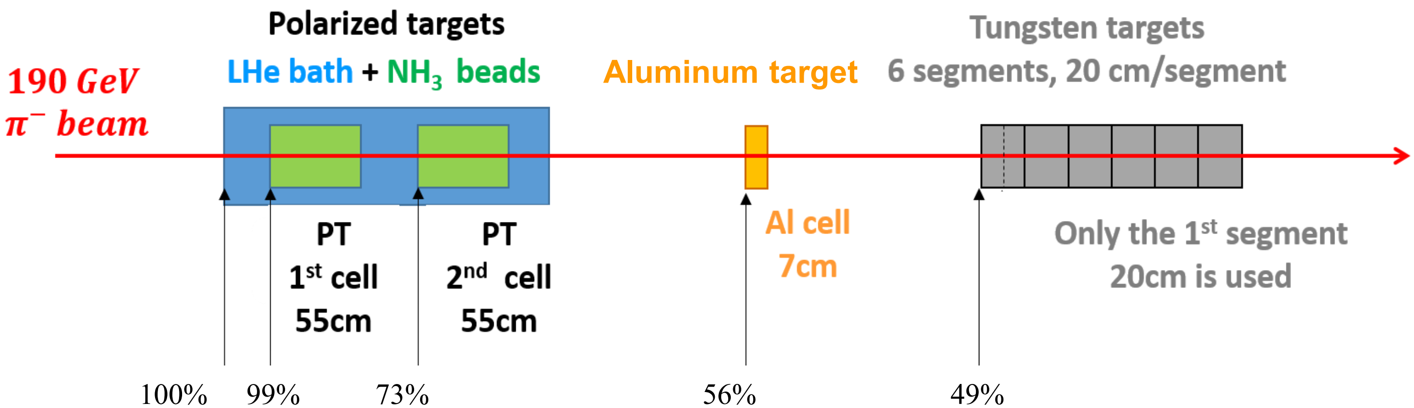
$Dimuon\ events$

$stopped\ by\ absorber$

- **Ensure clean dimuon sample**
- Hadron absorber
- Two stages muon filter
- Dimuon triggers

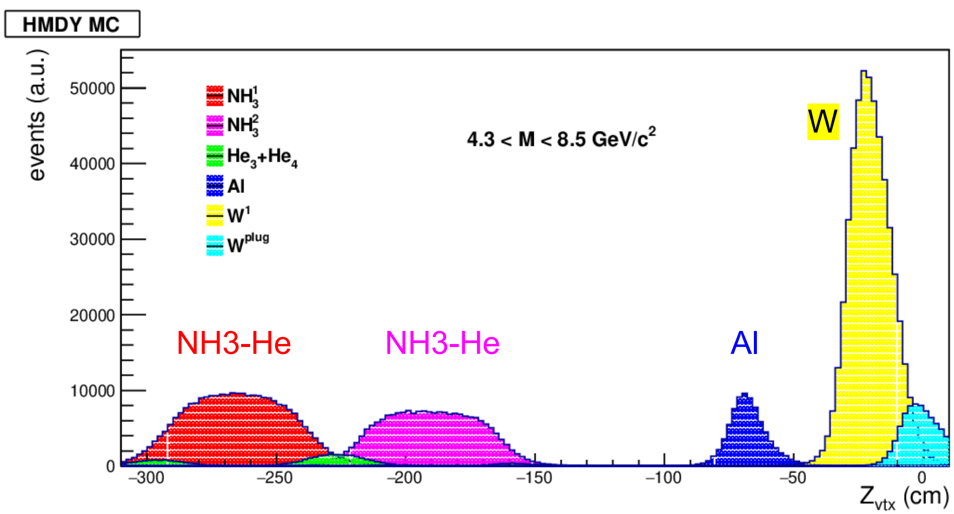


Target Composition



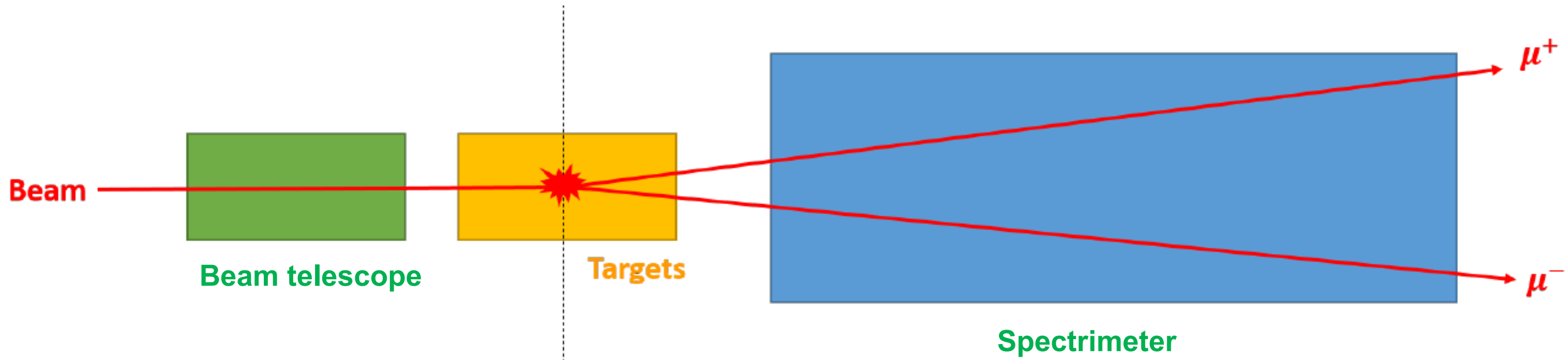
- $\boldsymbol{NH_3 - He}$ **target**
- Solid NH3 beads immersed in liquid He
- Two 55cm segments
- **Molar fraction of nucleon : 15.7 % H, 11.1 % He, 73.2 % N**

- **W target**
- Beam dump
- **first 20cm to avoid high probability of secondary reinteractions.**



Event migration from the neighboring material is estimated less than 4% for all the targets.

Measurement of Differential Cross Section



$\mathcal{L}$: ***Luminosity***
$=$ ***Num. of collisions***

$N_{\mu\mu}$: ***Measured physics events***

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

Differential cross section

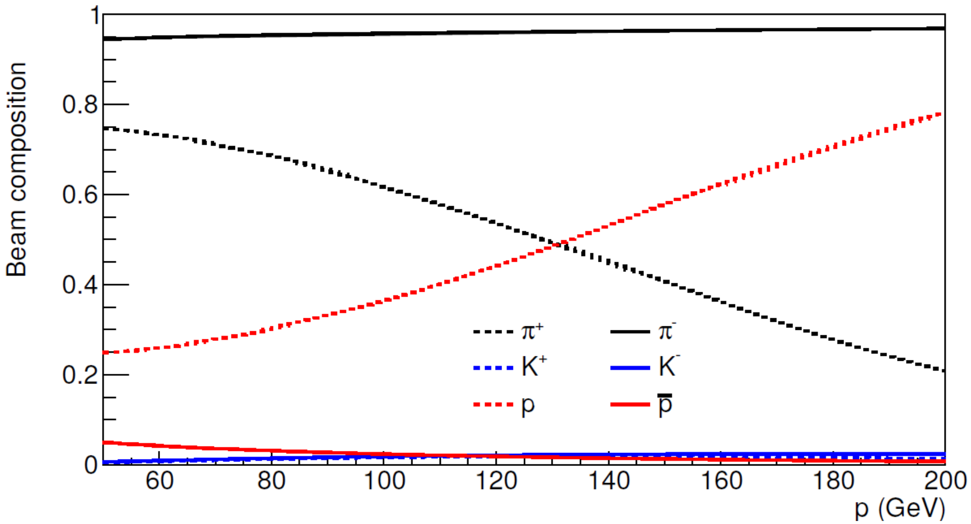
Measured physics events
— *Event selections*
— ***Purity extraction***

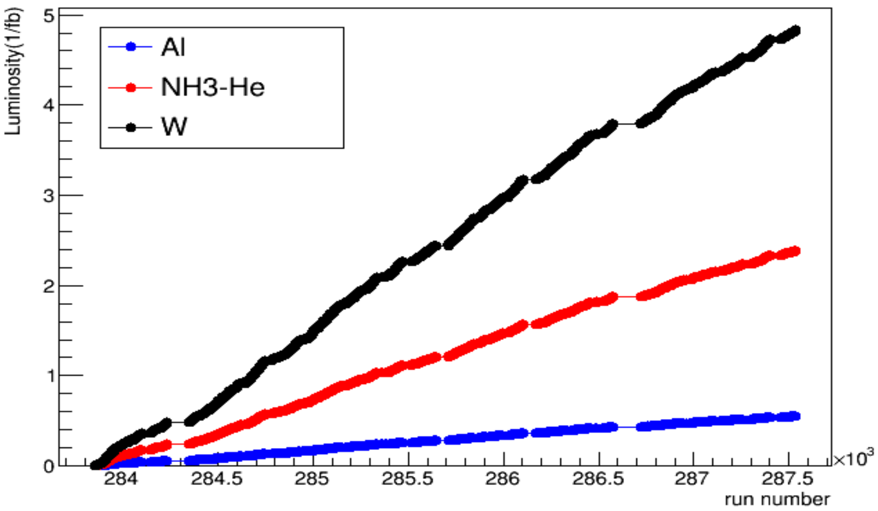
Luminosity
— *Beam flux*
— *Taget density*

Efficiency
— ***Geometry coverage (Acceptance)***
— ***Trigger efficiency (Acceptance)***
— *DAQ lifetime*
— *Veto lifetime*

Only some of the topics will be presented today, ex. Luminosity, acceptance, purity extraction.

Beam Composition and Luminosity



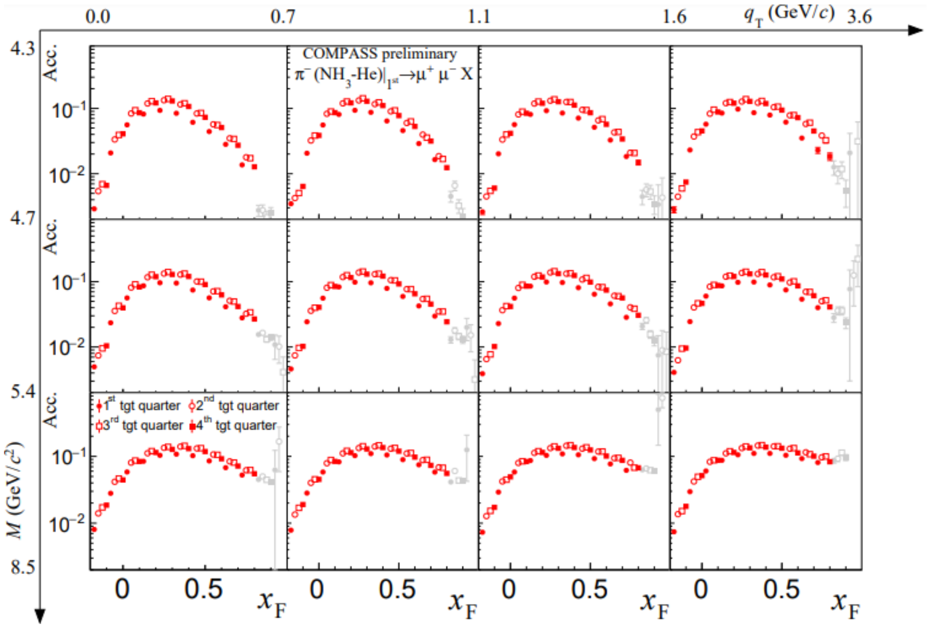


- **Beam condition**
- average intensity 70 MHz
- High energy: 190 GeV
- Negative hadron beam composition:
  97% pions, 2% kaons, 1% anti proton
- No PID for beam contamination (neglected and accounted for in the systematic uncertainties.)

- **Luminosity**
- 20 cm W : $\sim 5\ fb^{-1}$
- 110 cm NH3-He : $\sim 2\ fb^{-1}$
- 7 cm Al : $\sim 0.5\ fb^{-1}$

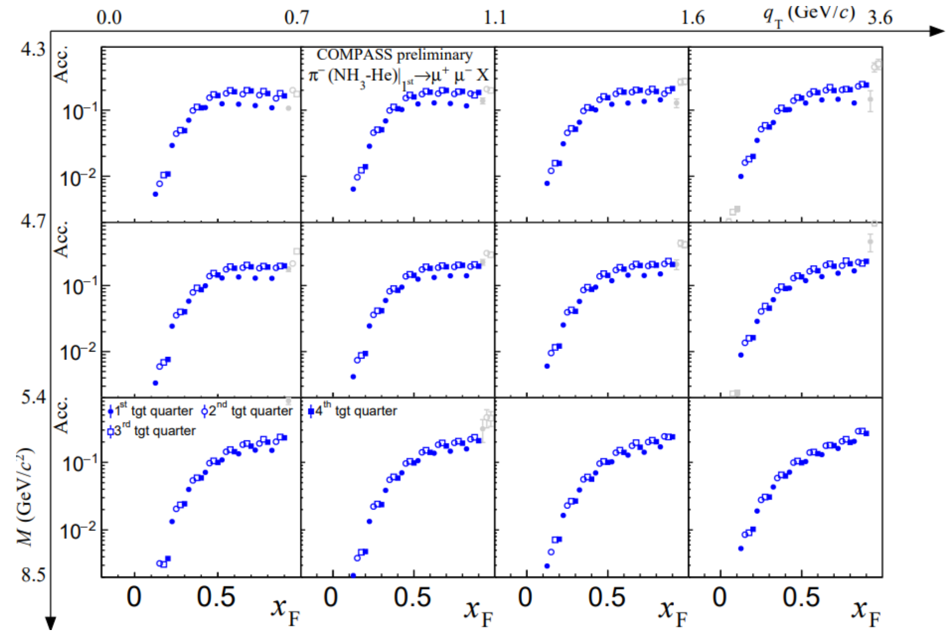
Acceptance of Dimuon Triggers

NH3-He cell1, LASxLAS



Also backward coverage ($-0.2 < x_F < 0$)

NH3-He cell1, LASxOUT



Increase the statistics in forward angle

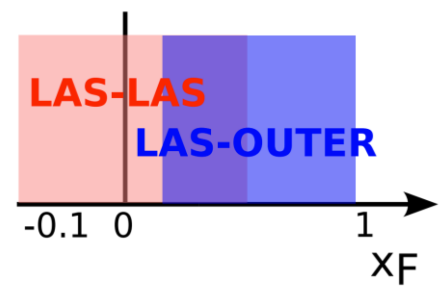
- Kinematic range and bins

① 12 bins in x_F=[-0.2, 1.0]

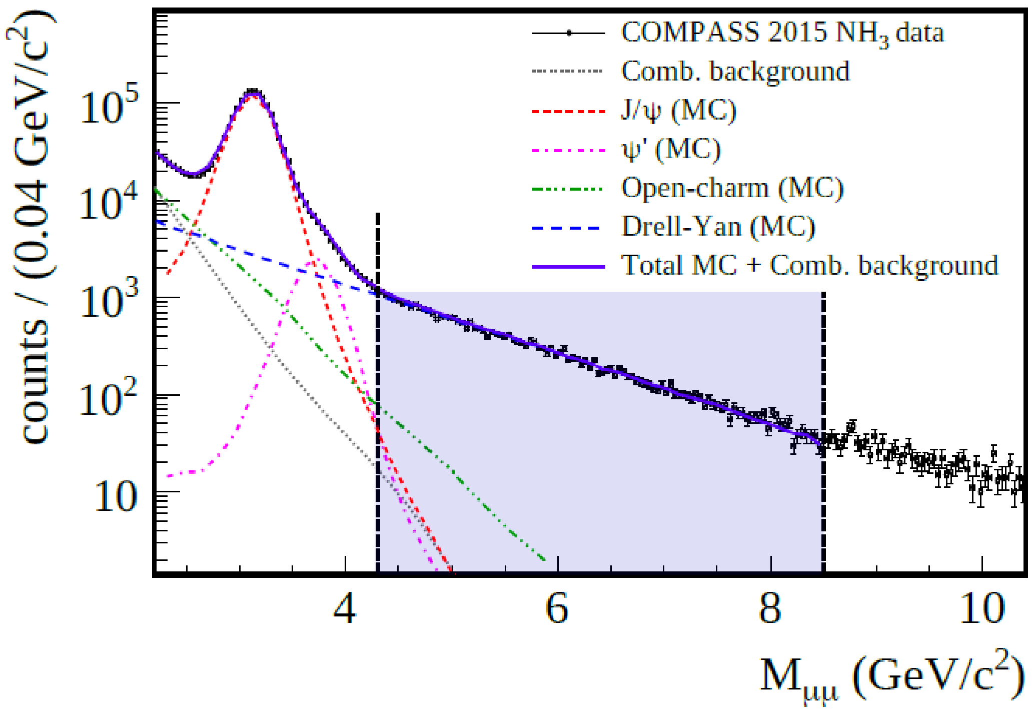
② 3 bins in $M(\frac{GeV}{c^2})$= [4.3, 8.5]

③ 4 bins in $q_T(\frac{GeV}{c})$= [0, 3.6]

- Acceptance
- around 1% to 10%.
- Only bins statistical error < 10%



HMDY Sample



- High mass Drell-Yan (HMDY) data is selected to analyze in the mass region of 4.3<mass<8.5 GeV.
- Number of dimuon pair selected (after all event selections but not include purity correction) :

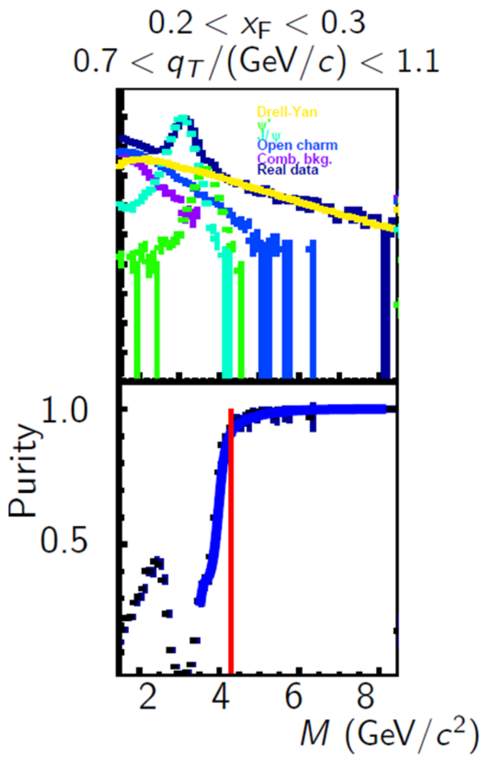
① W : 43, 000 evens

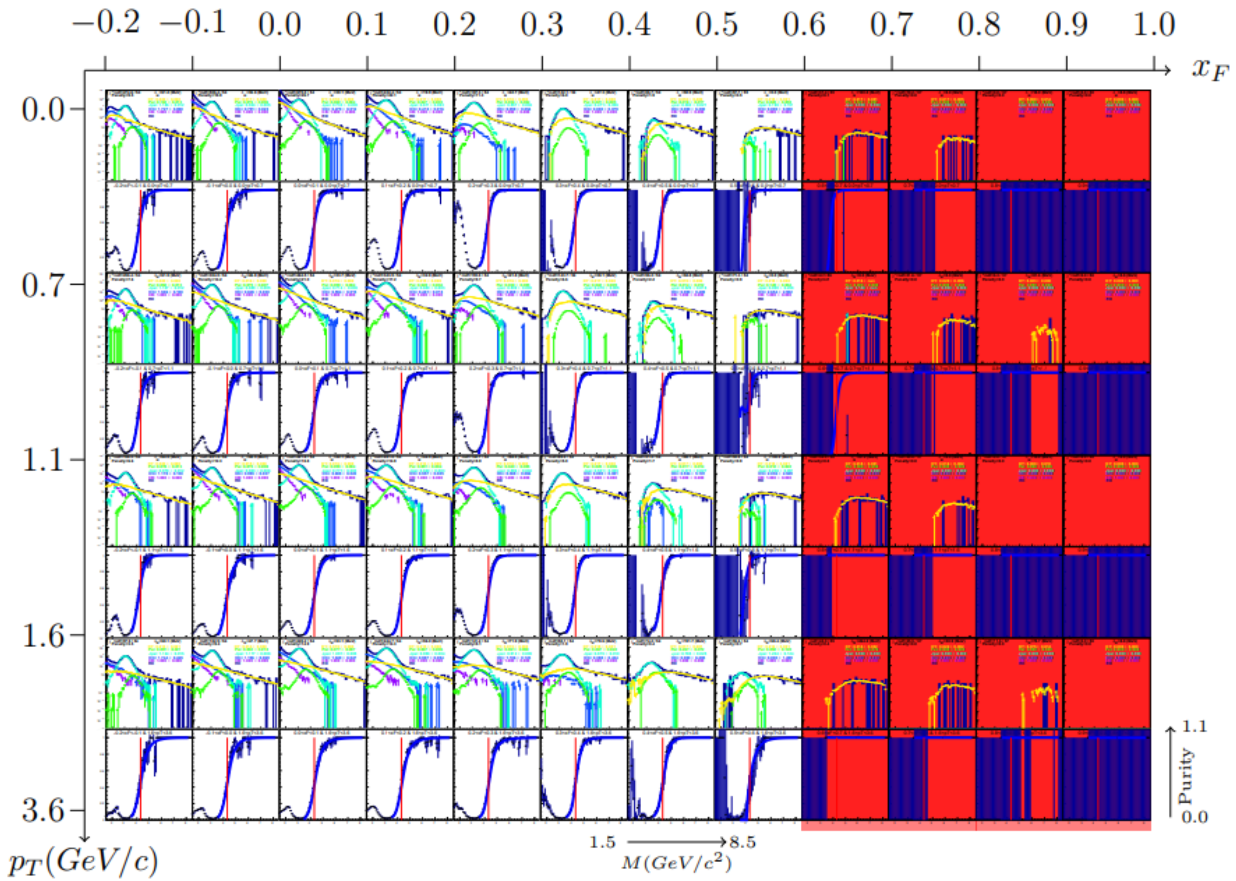
② NH3-He : 36, 000 events

③ Al : 6, 000 events

Purity Extraction

W, LL trigger



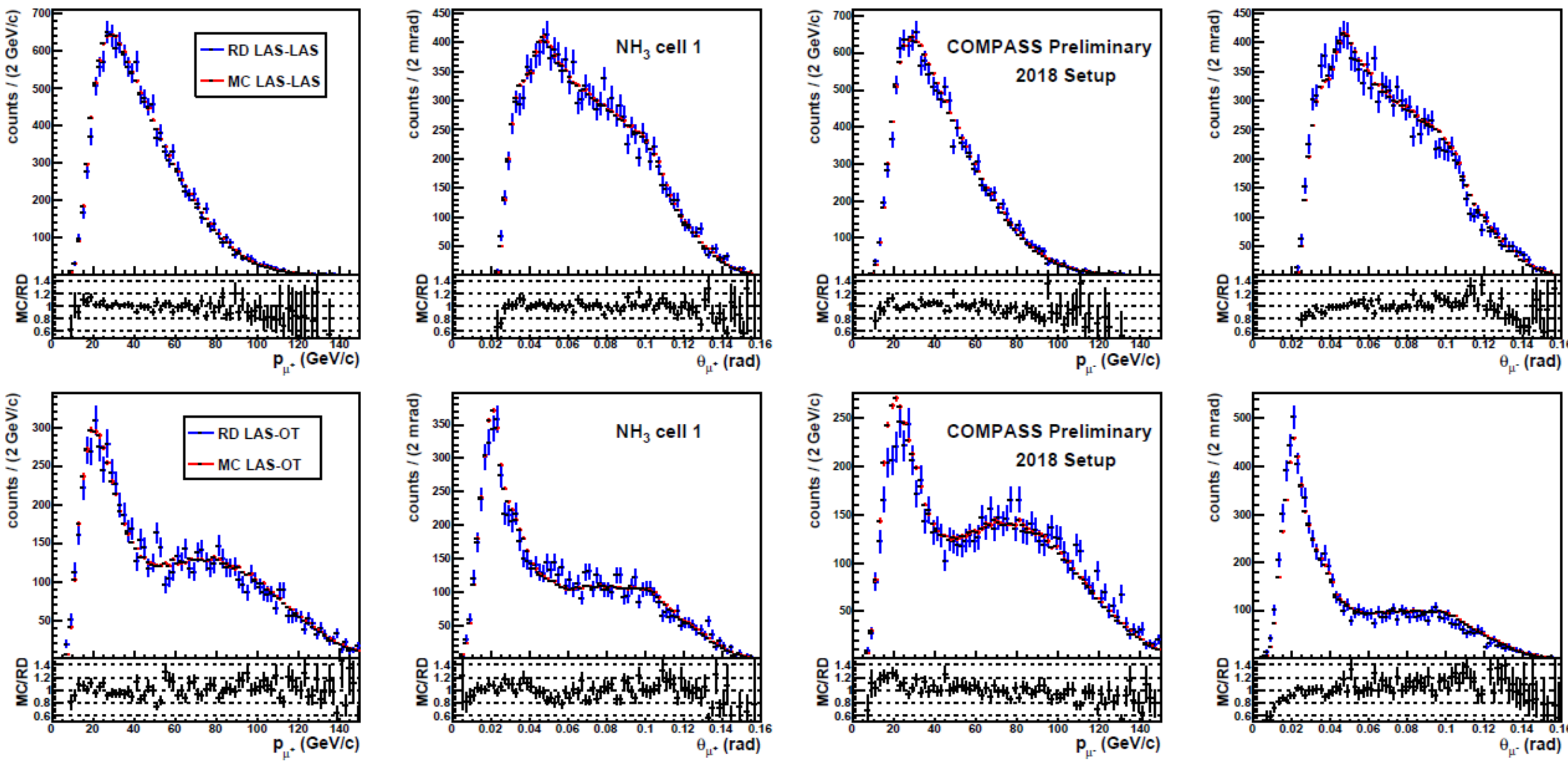


- Extraction is done with kinematic dependence (bin-by-bin).
- Purity increased with the increasing of mass and x_F, but decreased with higher q_T.

RD and MC Comparison (NH_3)

NH3-He cell1
LASxLAS

NH3-He cell1
LASxOUT

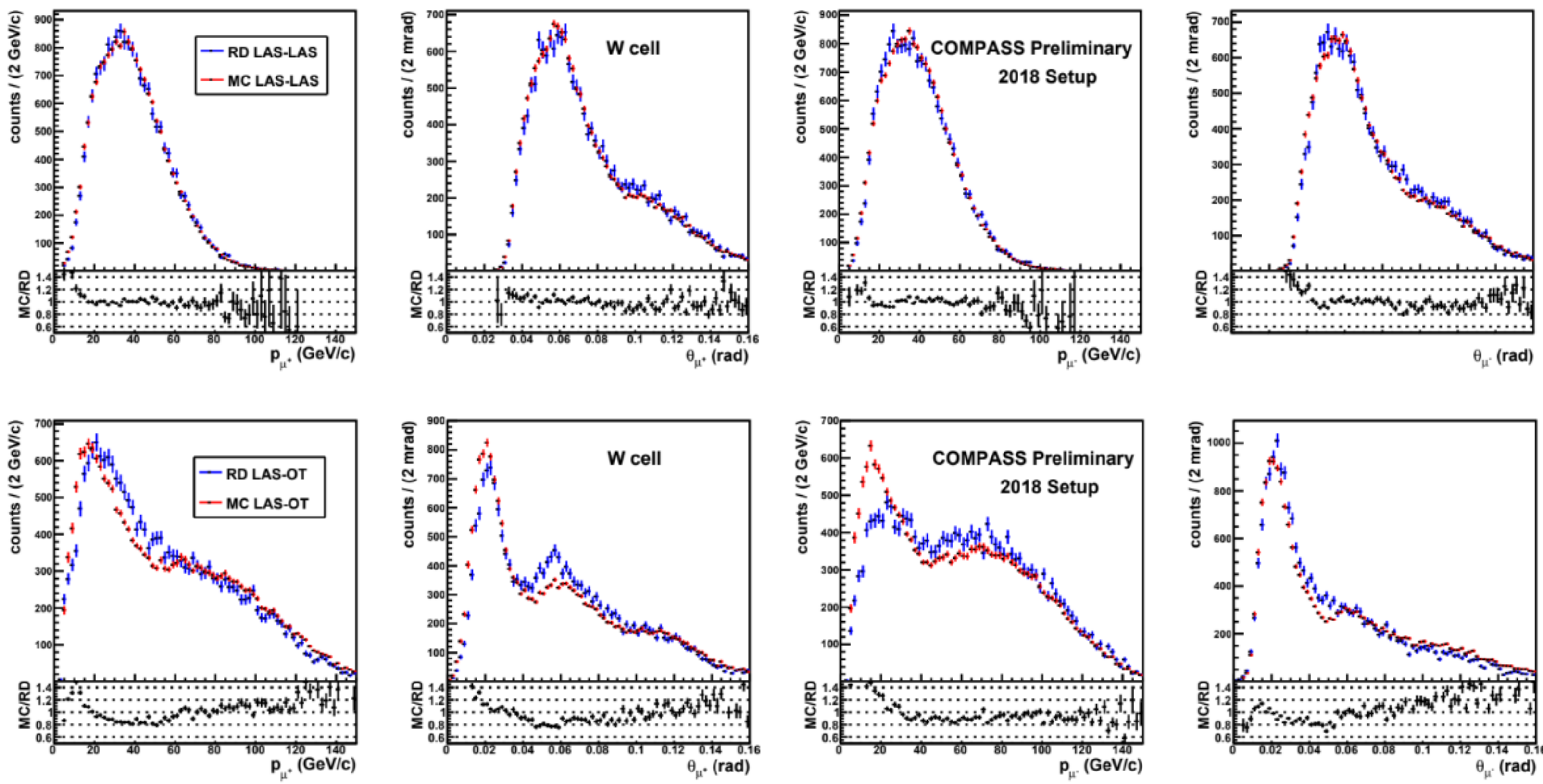


Nice agreement between RD and MC for NH3-He cells.

RD and MC Comparison (W Target)

W target
LASxLAS

W target
LASxOUT



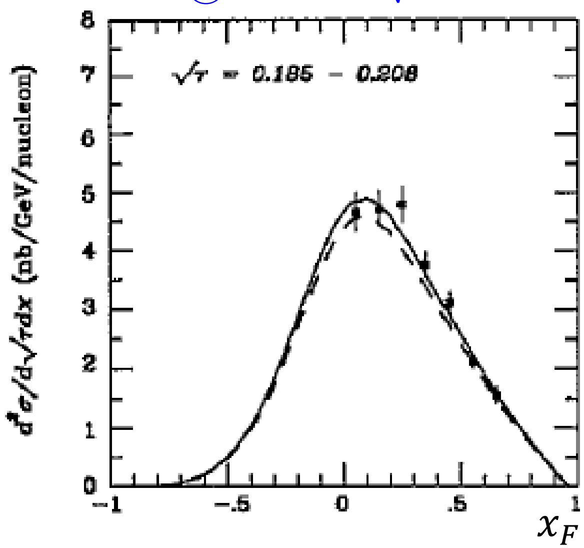
However, slightly worse for W cells.

Normalization Issue from E651 Data

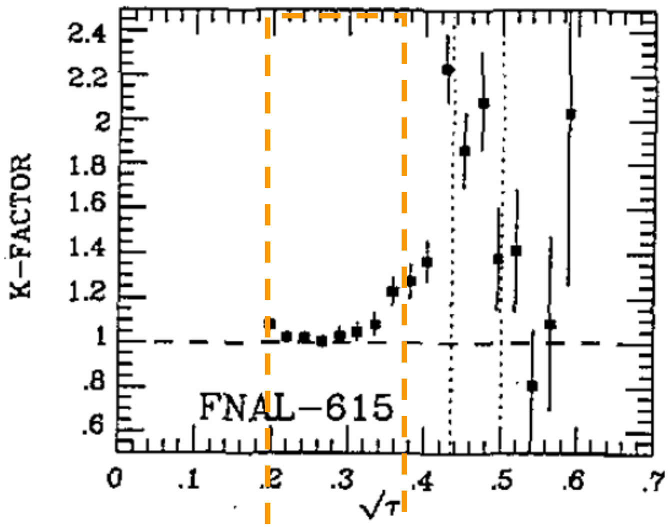
J. Phys. G: Nucl. Part. Phys. 19 D1 (1993)

The **pQCD calculation in NLO** is performed with nucleon PDF of MRS and pion PDF of SMRS in this paper.

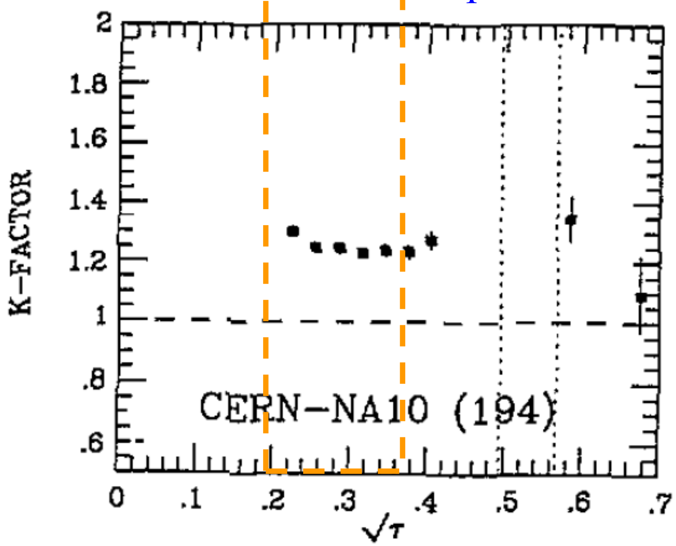
E615 @$0.185 < \sqrt{\tau} < 0.208$



E615 252 GeV pion + W



NA10 194 GeV pion + W



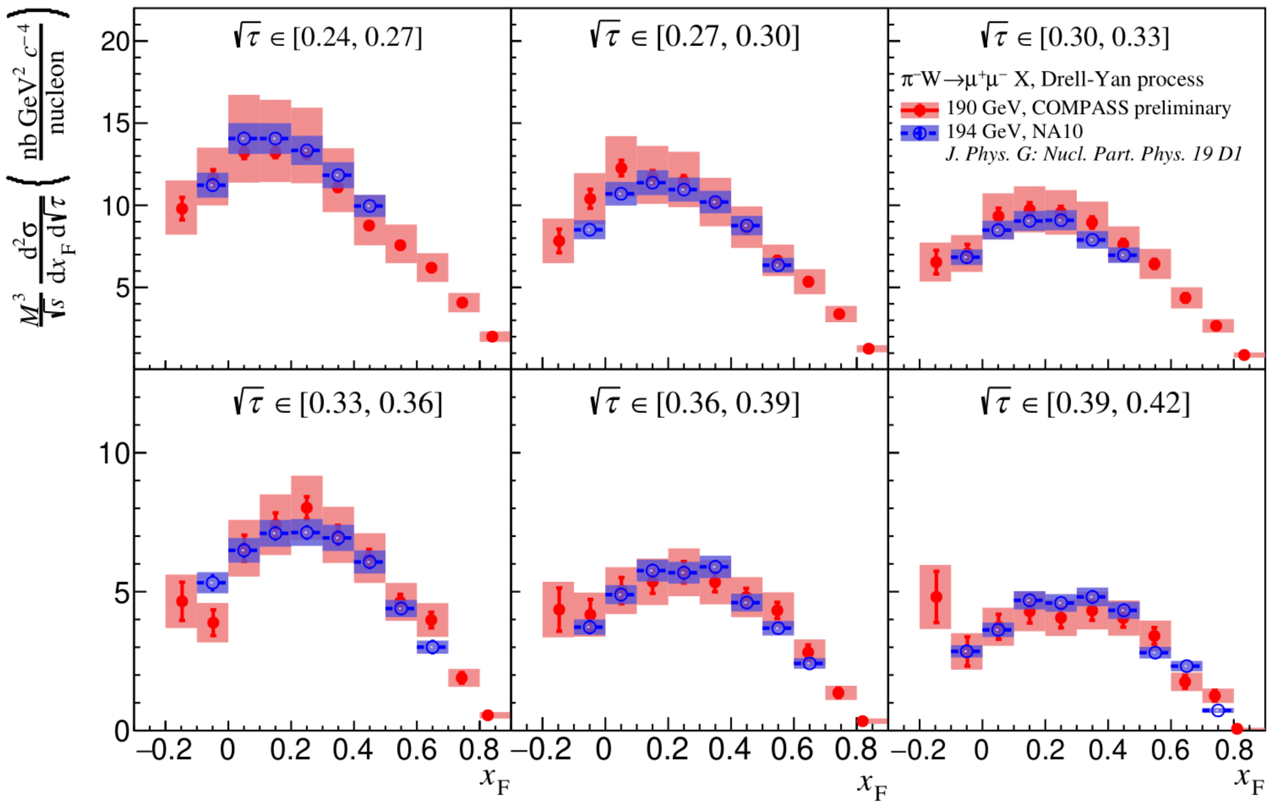
A nice agreement achieved between data and calculation with a small deviation defined as K-factor equal to the ratio between data and calculation :

$$\boxed{K\ factor = Data/pQCD_{NLO}}$$

There is a obvious normalization issue around 20% between the results given by E615 and NA10 which are the ones used the most in pion PDF global analysis.

COMPASS Results Compare to NA10 Experiment (W Target)

$$\tau = \frac{M^2}{s}$$



- Dot: data point
- Error bar : statistical error
- Shield : total error (systematics + statistics)

Systematic of NA10 = 6.5% (no kinematic dep.)

- Compared with with NA10 experiment

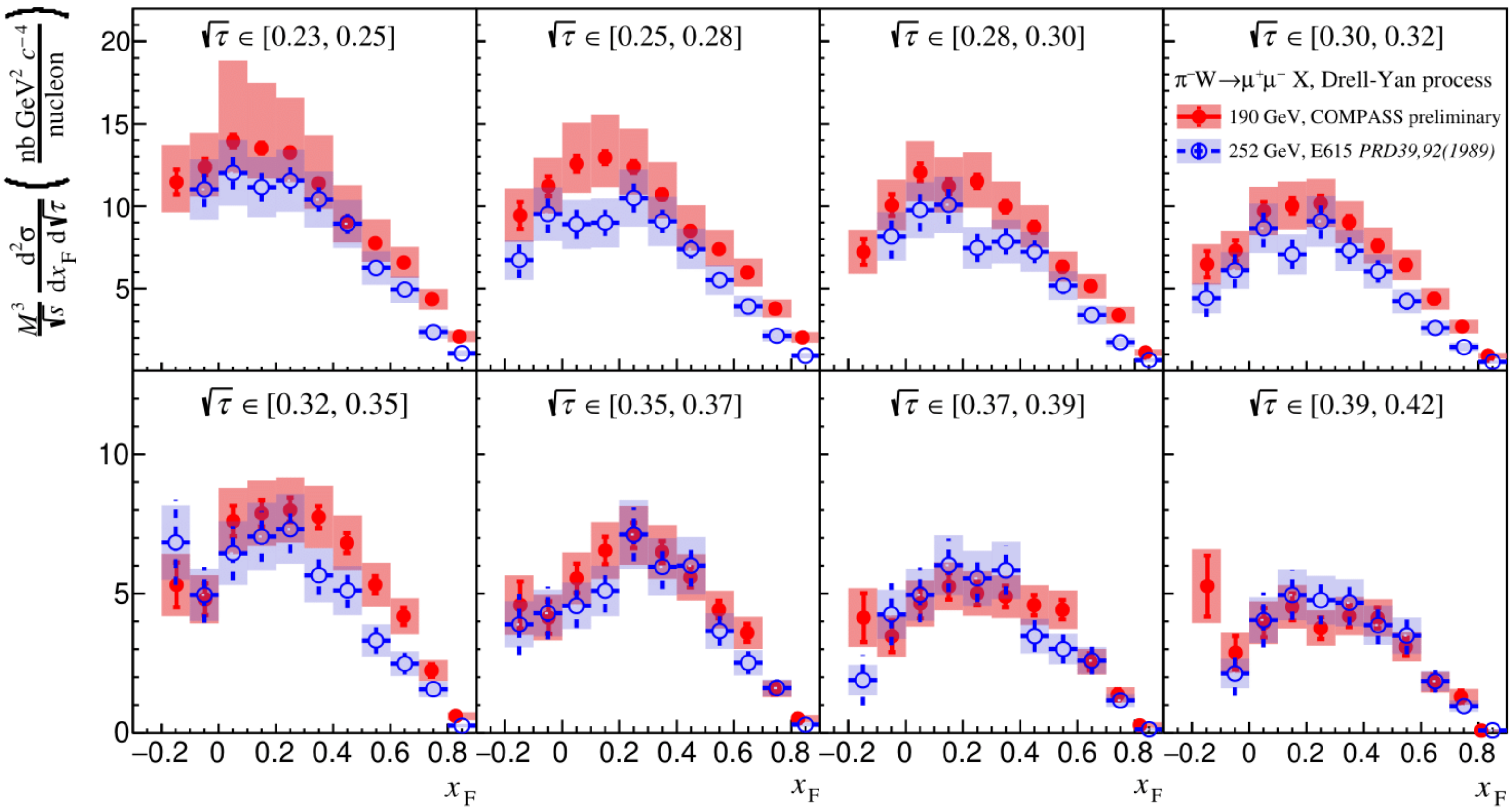
① The normalization is at the same level for all the $\sqrt{\tau}$ bins.

② COMPASS has larger kinematic coverage.

③ NA10 has better both statistics and systematics uncertainty.

COMPASS Results Compare to E615 Experiment (W Target)

$\tau = \frac{M^2}{s}$



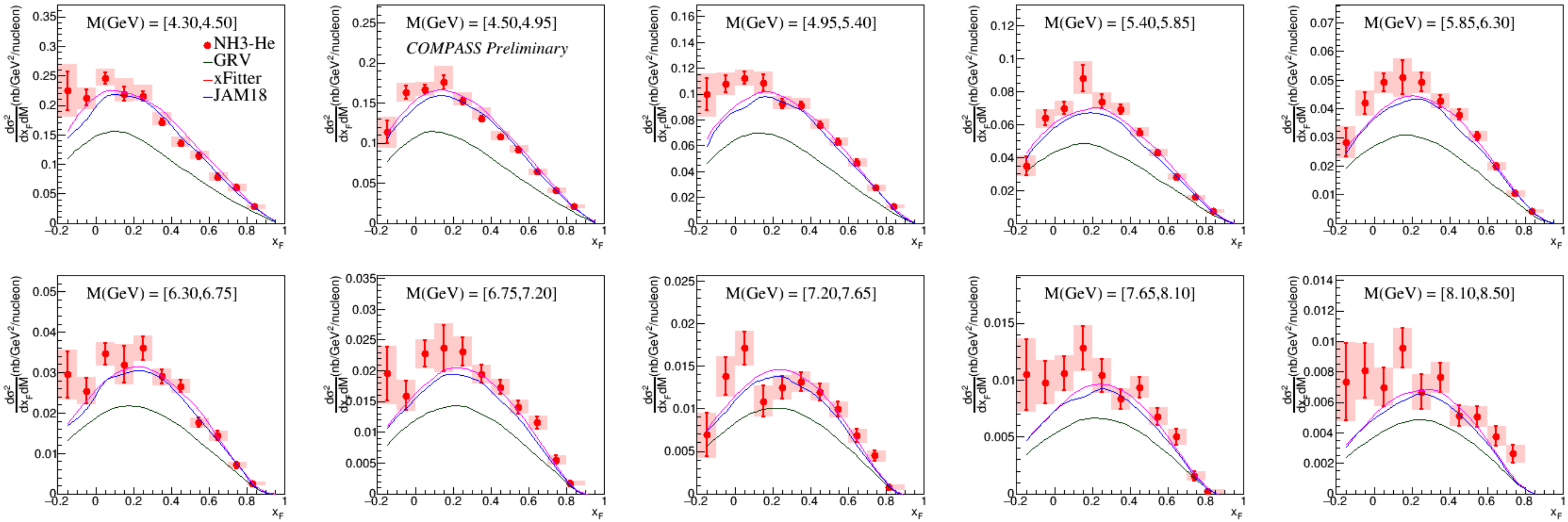
Systematic of E615 = 16% (no kinematic dep.)

- Compared with E615 experiment

① The normalization of COMPASS data is higher at low mass but the same level in high mass.

② The uncertainty is overall similar, but COMPASS's is worse at low mass (due to worse resolution).

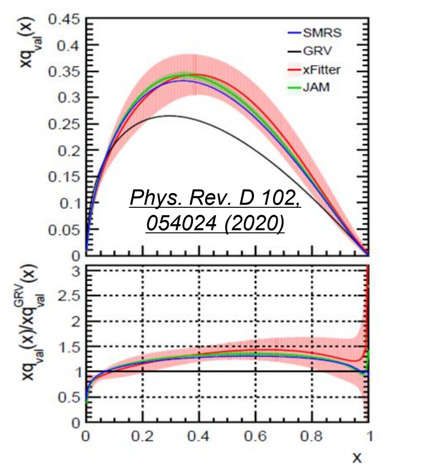
COMPASS Results Compare to DYNLO Calculation



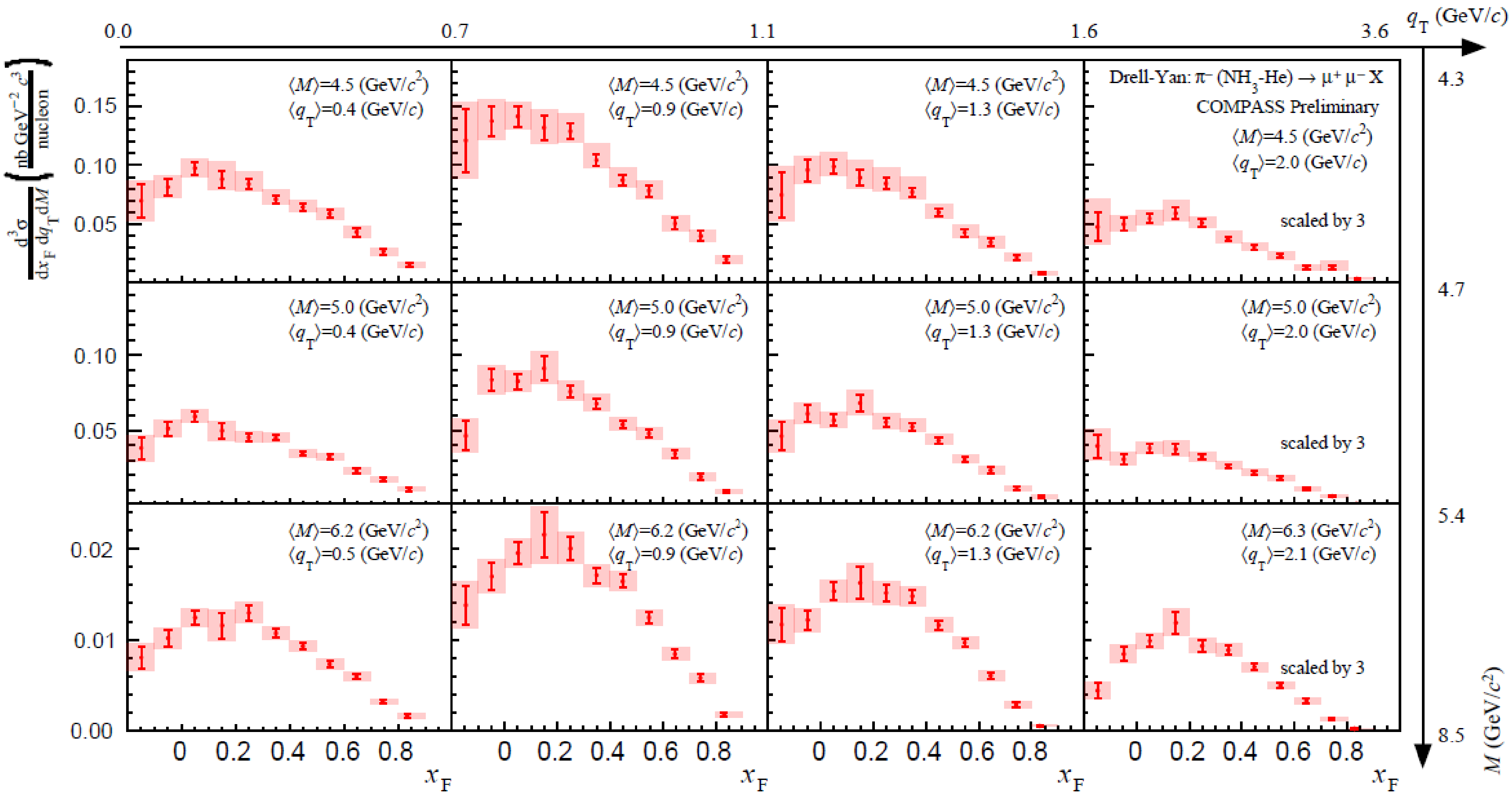
- **DYNNLO Calculation (**Phys.Rev.Lett.103:082001,2009**)**
- For Al and W target, use nCTEQ nuclear PDF
- **For NH3-He target, use the molar mixture of proton and neutron PDF from nCTEQ with the fraction 15.7 % H, 11.1 % He, 73.2 % N**
- For pion PDF, use GRV, xFitter, and JAM21

- **COMPASS data has nice agreement w/ DYNNLO calculation of xFitter and JAM. The normalization from GRV is low. The reason could be the low valence contribution from GRV.**

$valence\ @\ Q^2 = 9.6\ (GeV)$

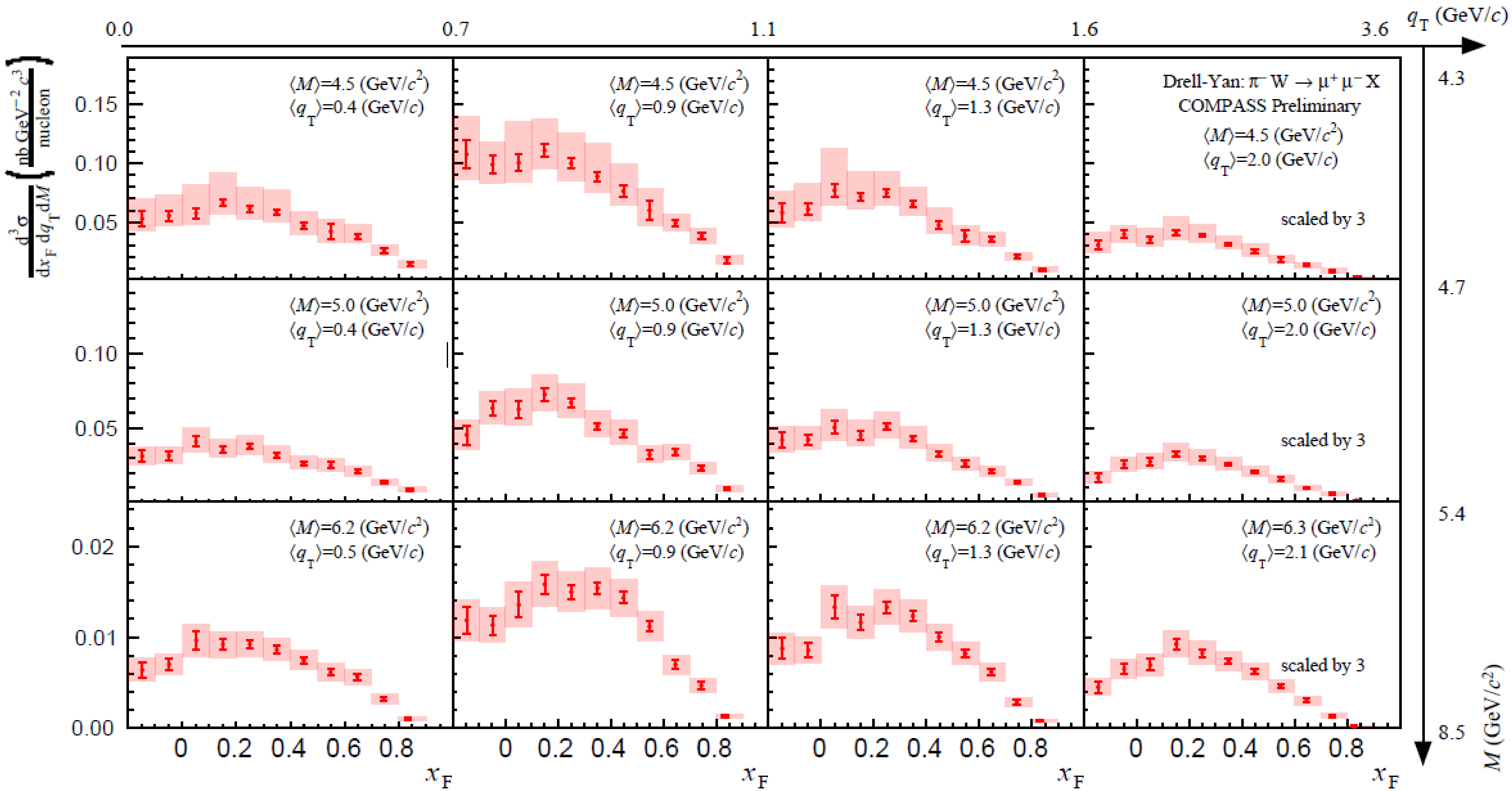


3 Dimensional Drell-Yan Cross Section



- **First pion-induced DY experiment provides three dimensional cross section.**
- Light NH3-He target could avoid the impact of nuclear effect.

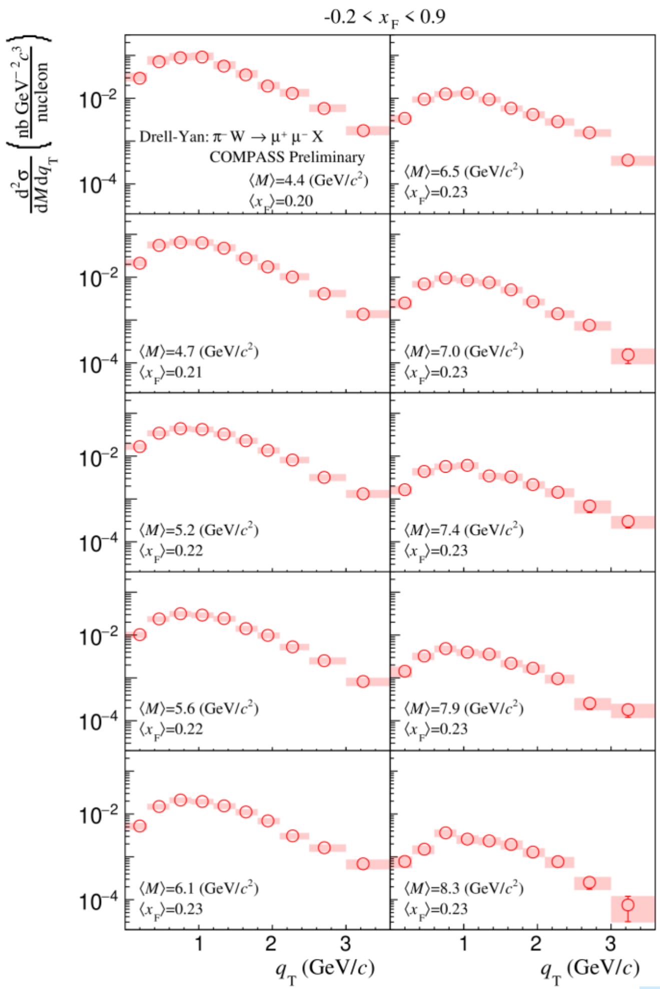
3 Dimensional Drell-Yan cross section on W target



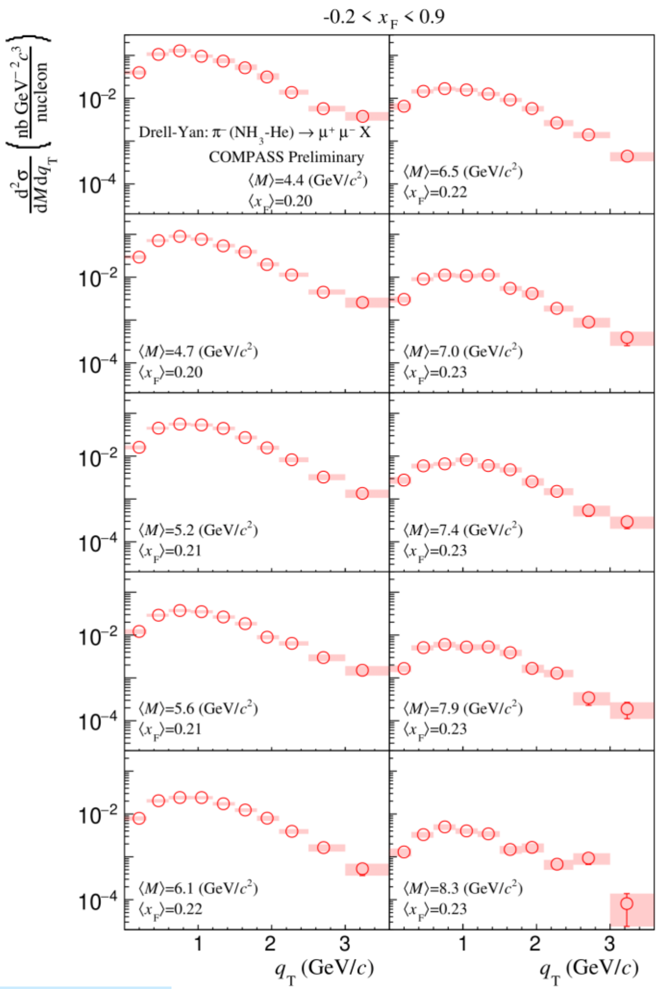
For W target, the uncertainty is mainly dominated by systematics of purity and acceptance, especially in the low mass.

Differential Cross Section in q_T

W

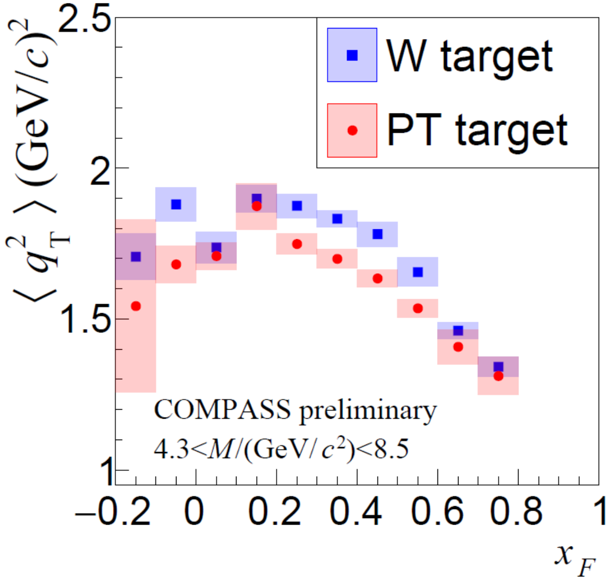


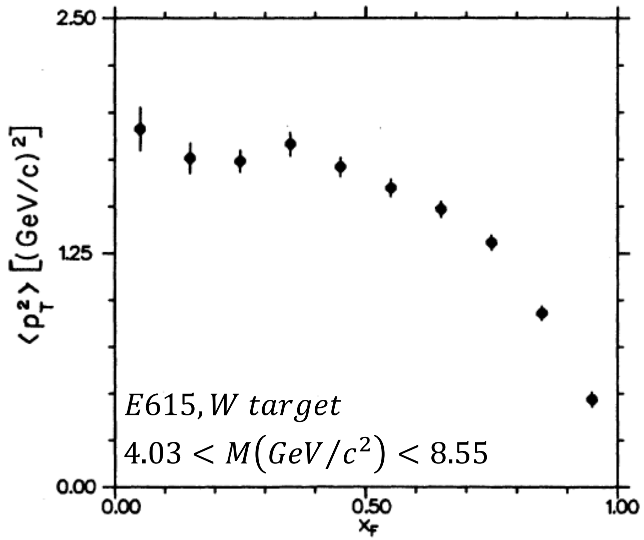
$NH_3 - He$



TMD extraction.

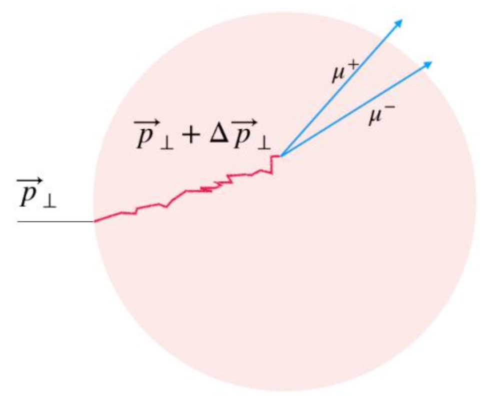
Average Transverse Momentum Square
Study Nuclear Effect



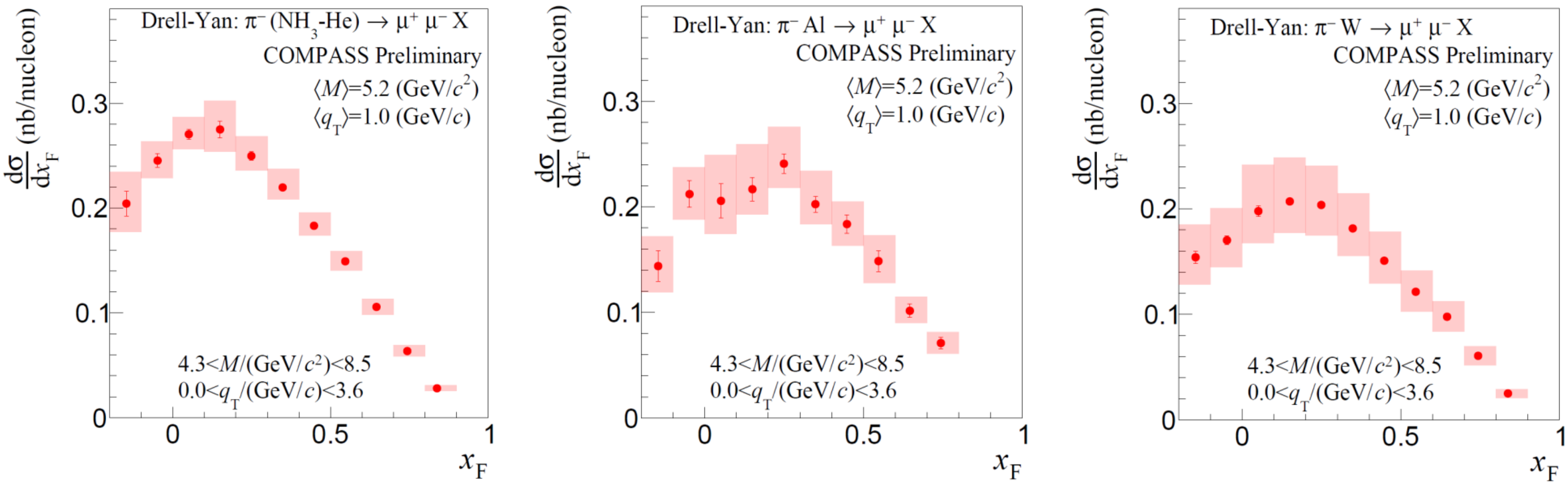


Phys.Rev.D **39 (1989) 92-122**

Parton crossing nuclear medium, looses energy due to multiple scattering and gluon emission. It reflects a gain of transverse momentum for heavier nuclei, so called q_T broadening.

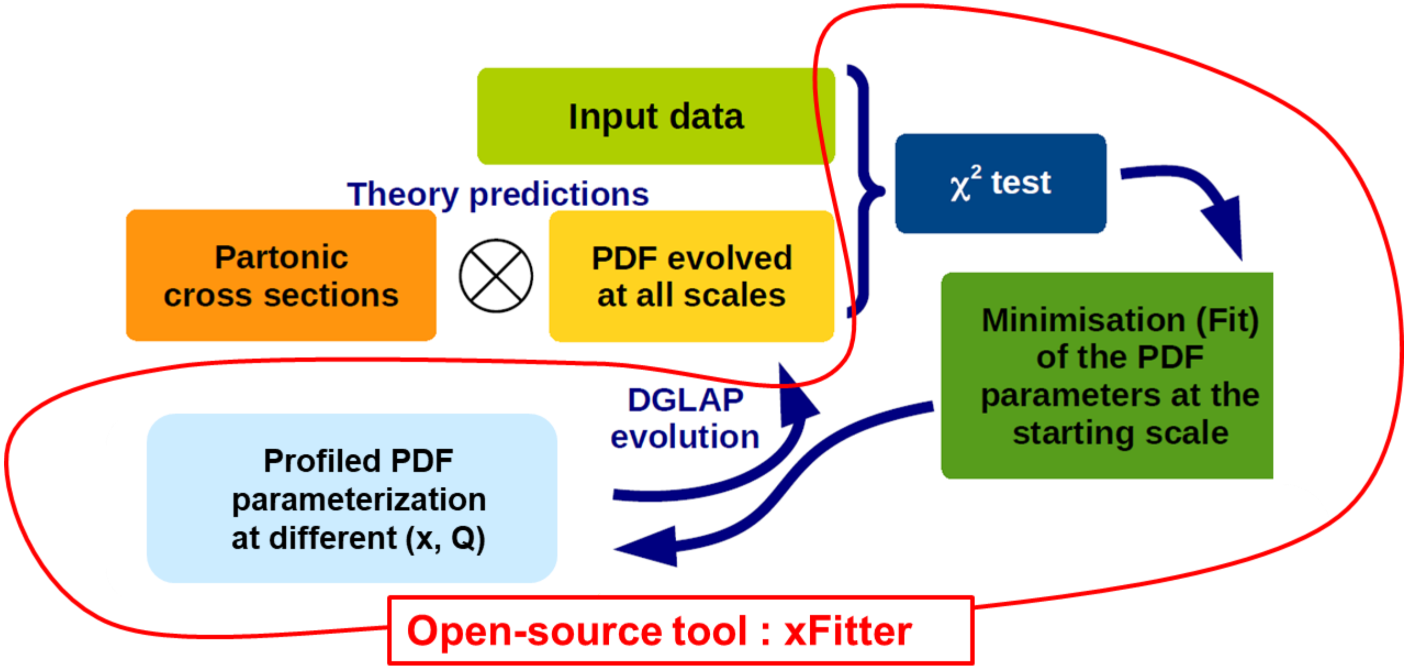


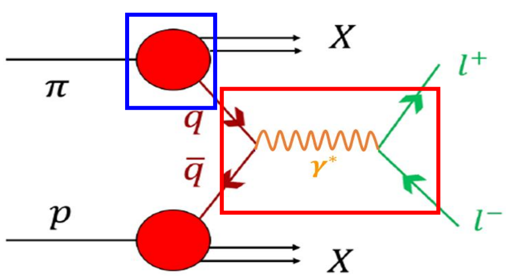
Differential Cross Section for Light and Heavy Targets Material to Study Nuclear Effect



The ratio of Drell-Yan cross sections between heavy and light nuclear targets provides an access to cold nuclear effects.

Estimate the Impact of COMPASS Data to Pion PDF Using xFitter Tool





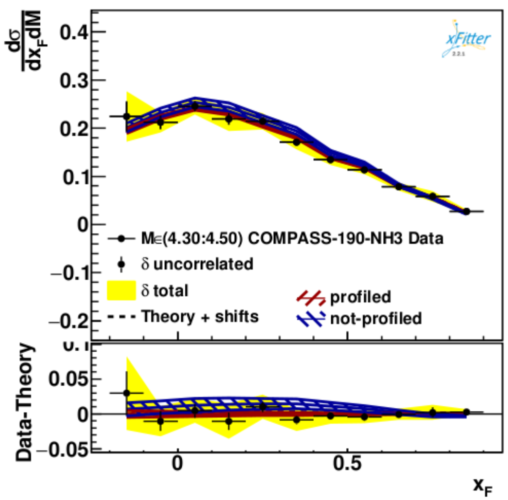
$$\boxed{\frac{d^2\sigma}{dM_{ll'}dx_F}} = \boxed{\frac{2\pi\alpha^2}{9M_{ll'}^3}\left(\frac{x_\pi x_p}{x_\pi + x_p}\right)} \boxed{\sum Q_q^2\,[q(x_\pi)\bar{q}(x_p) + \bar{q}(x_\pi)q(x_p)]}$$

Input data COMPASS — Theoretical prediction — Access unknown pion PDF

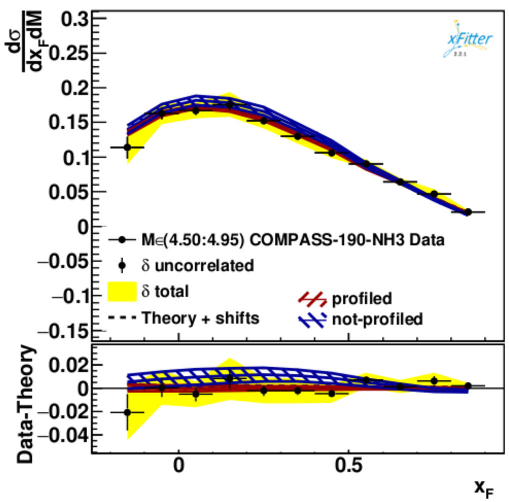
We use open source tools, xFitter(fitting) and MCFM (calculation), to estimate the impact of COMPASS data to pion PDF.

Fitting Qualify

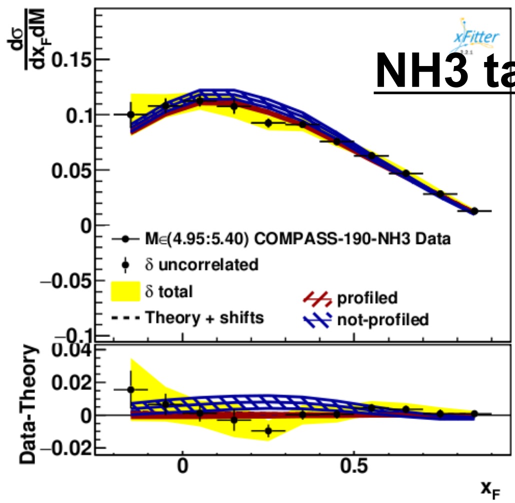
$4.30 < m < 4.50$



$4.50 < m < 4.95$

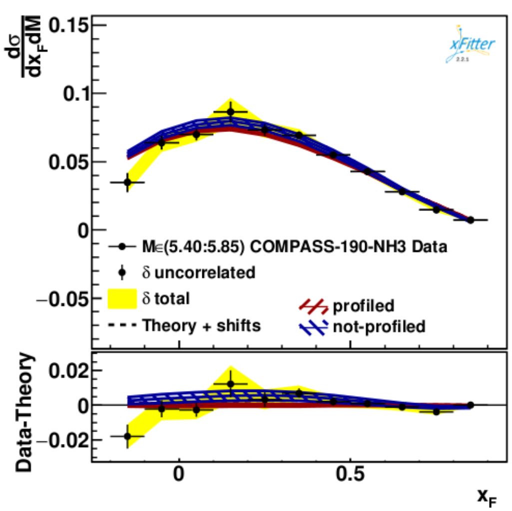


$4.95 < m < 5.40$

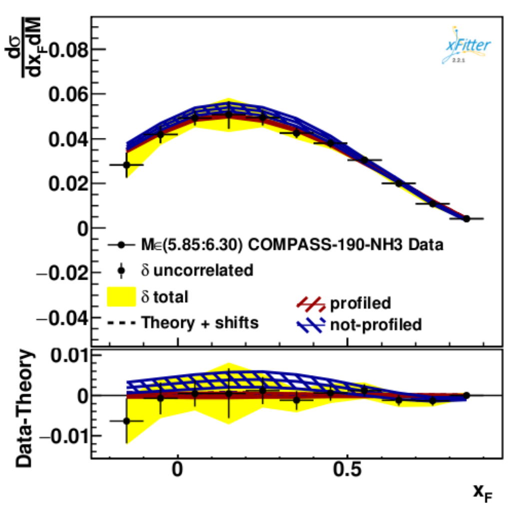


NH3 targets

$5.40 < m < 5.85$



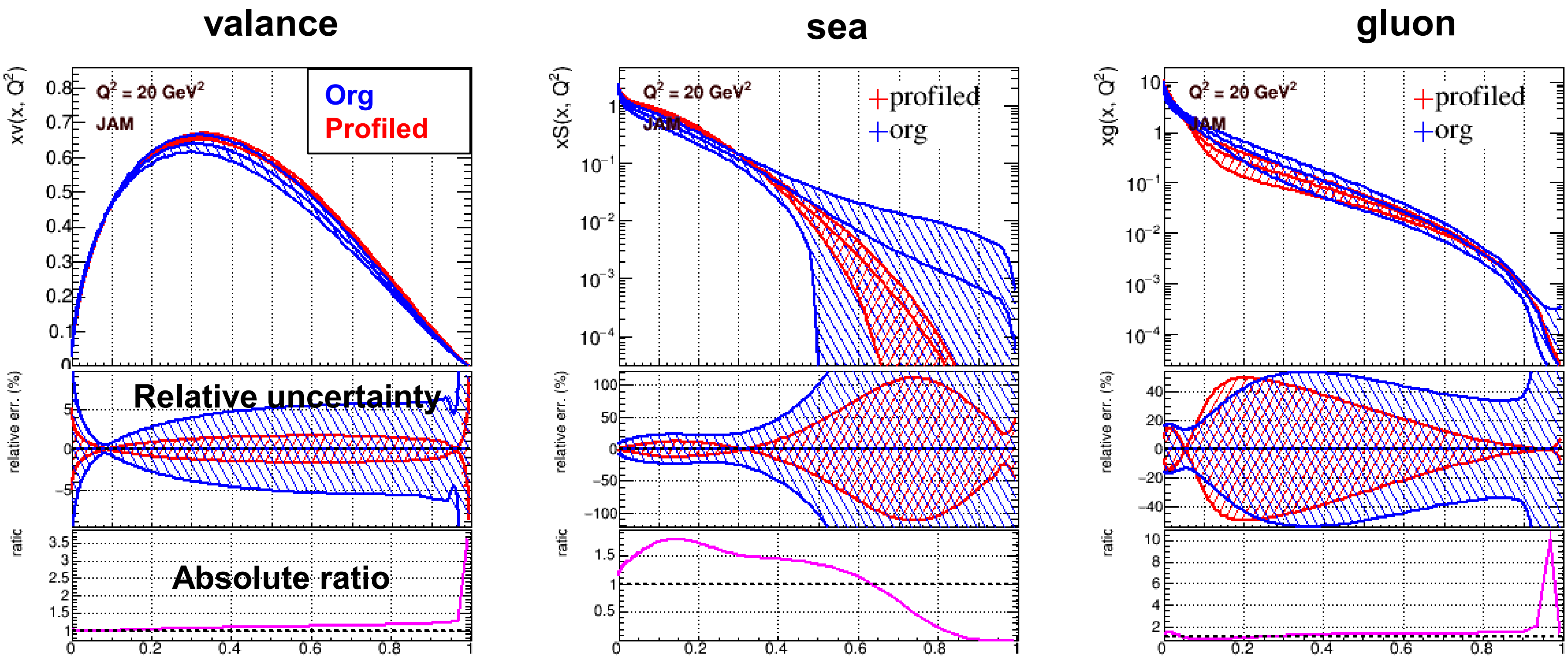
$5.85 < m < 6.30$



	not-profiled	profiled
$4.30 < m < 4.50$	32.20/11	10.97/11
$4.50 < m < 4.95$	54.10/11	17.26/11
$4.95 < m < 5.40$	40.46/11	14.58/11
$5.40 < m < 5.85$	20.15/11	24.99/11
$5.85 < m < 6.30$	10.09/11	5.22/11

Fitting quality looks reasonable.

Impact to JAM PDF

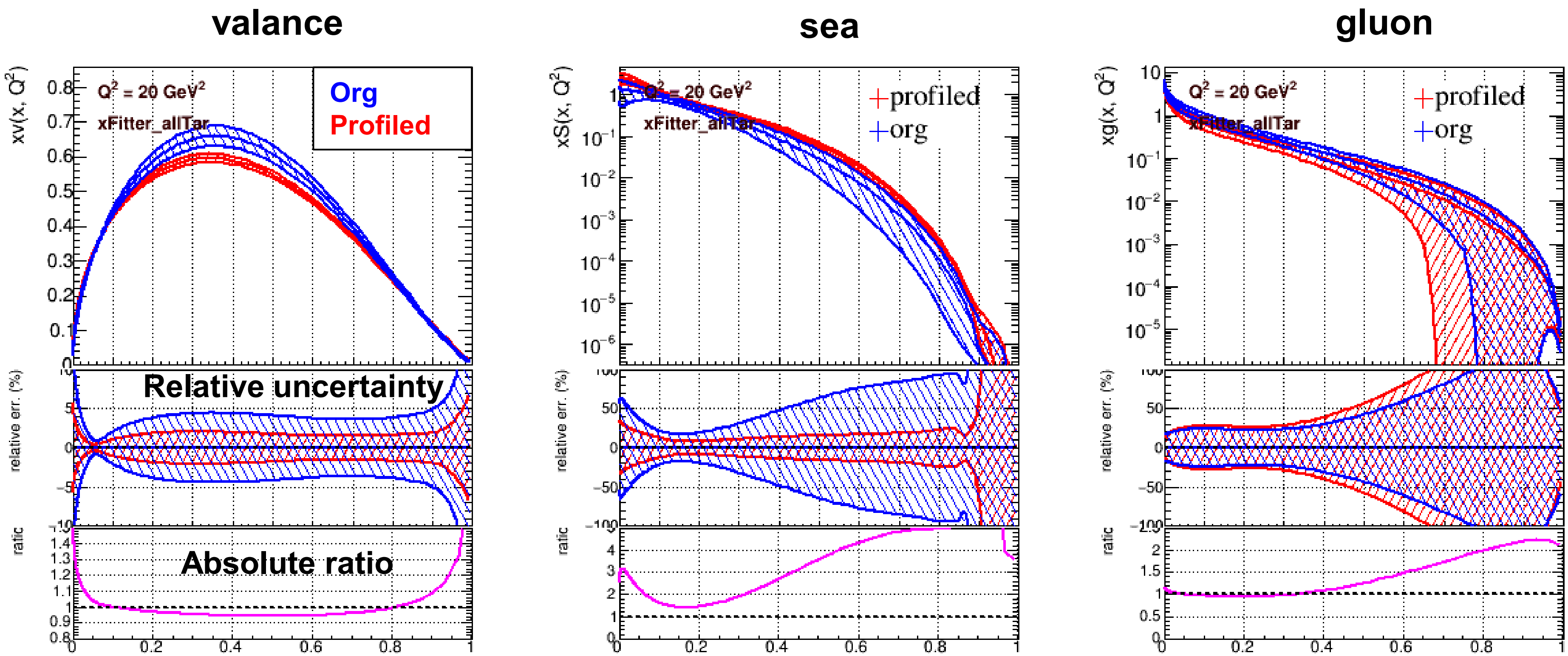


Preliminary test

JAM21PionPDFnlo
Phys. Rev. Lett. 127, 232001 (2021)

- Reduce the uncertainty >50%.
- Contribution of valence, sea, glue stays at the same level.

Impact to xFitter PDF



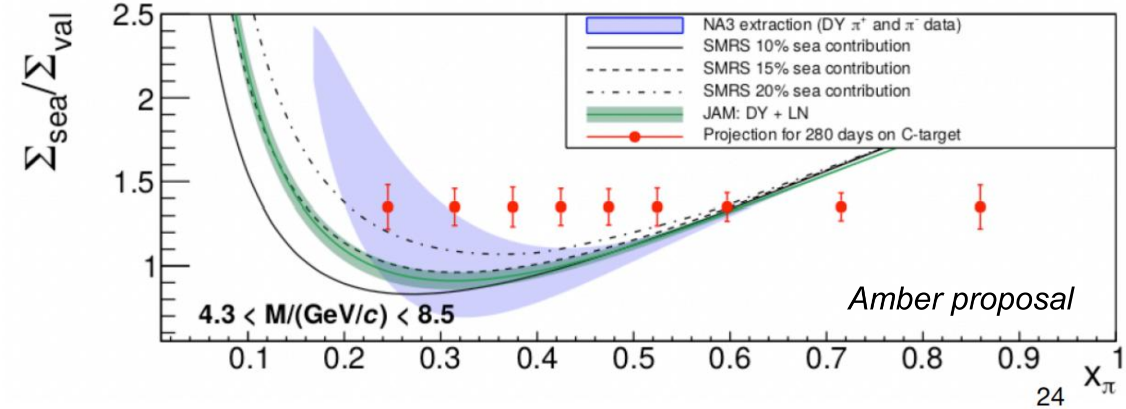
Preliminary test

xFitterPI_NLO_EIG
Phys. Rev. D
102, 014040 (2020)

- Reduce the uncertainty >50%.
- Valence contribution is less.
- Sea is increased.

Future Projects for Pion PDF Study

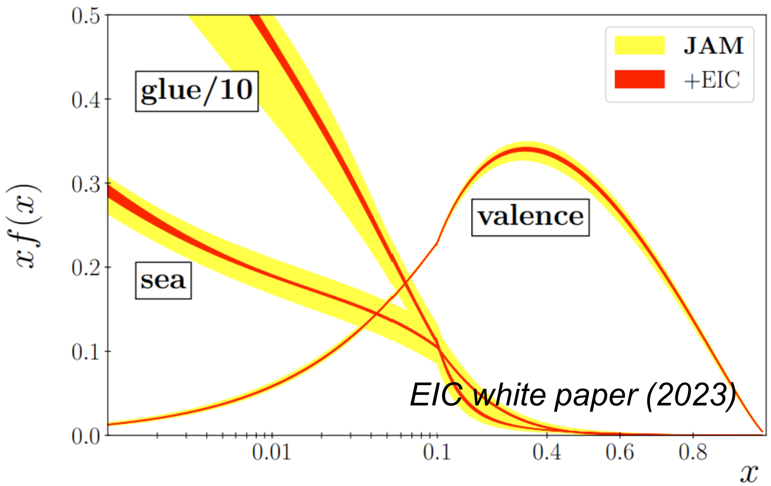
- **Amber (2029): Pion induced Drell-Yan process. Positive and negative pion** beam on Carbon and Tungsten target.



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

Tag sea quark.

- **EIC : Leading-neutron DIS process.** 5 GeV electron beam collides with 50 GeV proton.



Wide kinematic coverage to not just better constrain of gluon (and sea), but also valence.

Summary

- Pion-induced DY data and Leading-neutron DIS data are two complimentary data sets to extract pion PDF.

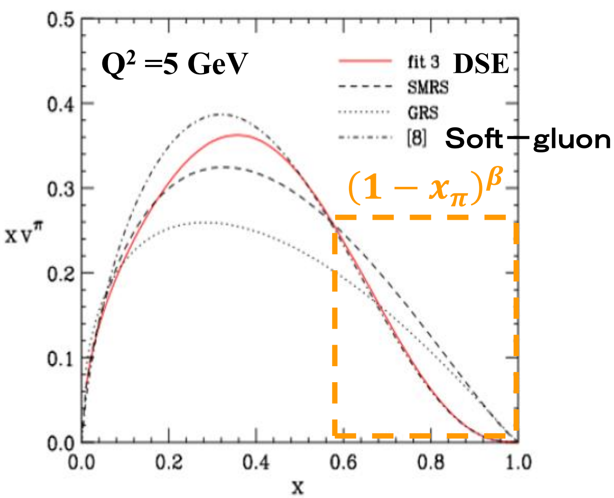
- The latest pion-induced Drell-Yan data was published 30 years ago by E615 and NA10 experiments. **New pion-induced Drell-Yan data from COMPASS will be new input to constrain of pion PDF/TMDPDF and the study of nuclear effect.**

- The preliminary estimate of the impact of the **COMPASS data on the pion PDF suggests a reduction of the uncertainty of JAM valence and xFitter valence by approximately 50%**. The normalization and statistical uncertainties have been finalized. **Work is ongoing to determine the correlation matrix of the various systematic uncertainties in order to provide improved input for pion PDF extraction.**

Back up

Large Valence Region of Pion PDF

Phys. Rev. Lett. 105, 252003



$$v_{\pi^-}(x_{\pi^-}) = A^v x^\alpha (1-x)^\beta (1+\gamma x^\delta)$$

NJL and pQCD NLO : $\beta \sim 1$

DSE and soft-gluon : $\beta \sim 2$

There is a great interest on the large valence region. Difference QCD model gives different prediction. On large x region valance of pion $\sim(1-x_\pi)^\beta$

- Model dependent

① $\beta \sim 1$:

- Nambu-Jona-Lasinio models.
- global fits based on partonic pQCD NLO calculation (GRV, SMRS, JAM, xFitter).

① $\beta \sim 2$:

- Dyson-Schwinger equations.
- soft-gluon threshold resummation.

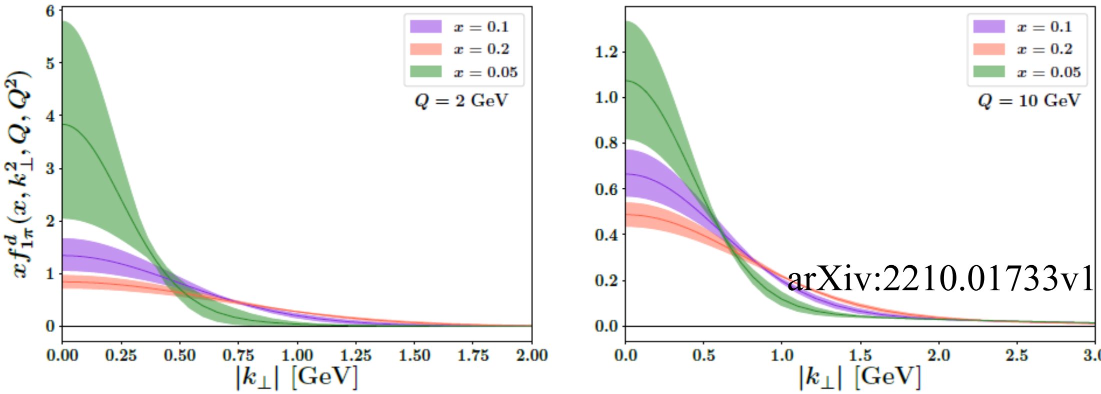
In large x region, the contribution of soft-gluon radiation increases. (usually consider x > 0.6.)

- Low statistics data :

① Contributed from pion induced Drell-Yan data. Only one data set from E615-256GeV was analyzed.

② Besides, the cross section in large x is rather small with large uncertainty.

Pion TMD PDF



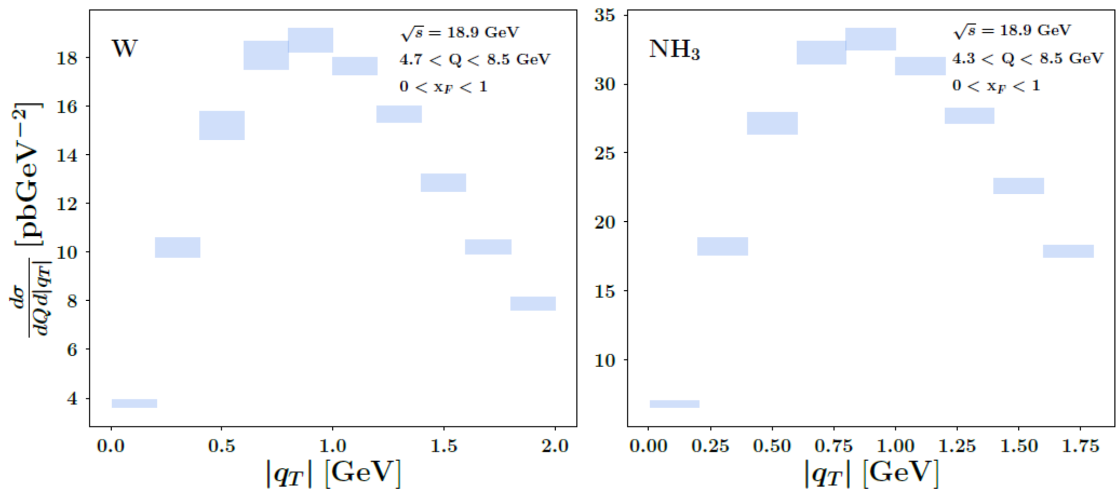


FIG. 5: Theoretical predictions based on our fit for the unpolarized pion–nucleus DY cross section as function of the virtual vector boson transverse momentum $|q_T|$. Left panel for tungsten (W) nucleus, right panel for ammonia molecule (NH_3). Uncertainty bands correspond to 68% CL.

MAP group using the current pion TMD (fit E615 and E537 data) to predict the COMPASS Drell-Yan cross section along qT. Our input will help the global fit of pion TMD.