COMPASS Pion-Induced Drell-Yan Cross Section and Its Impact to Pion PDFs

2nd TIDC EIC workshop

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Outline

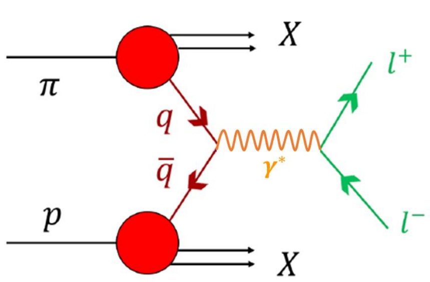
- Introduction of Pion Parton Distribution Function (PDF)
- Results of COMPASS Pion-induced Drell-Yan Data
- Impact of COMPASS Data to Pion PDF

Pion Parton Distribution Function (PDF)

Pion PDFs		Data			Theory
		Valence	Gluon	Sea	
1992	SMRS	**Pion-induced Drell-Yan** NA10(1985) E615(1989)	**Pion-induced Prompt-gamma** WA70(1988)	**Momentum sum rule**	**pQCD NLO**
1992	GRV				
2020	xFitter				
2018	JAM		**Leading-neutron DIS** HERA(2018)		

$\boldsymbol{Drell-Yan}$

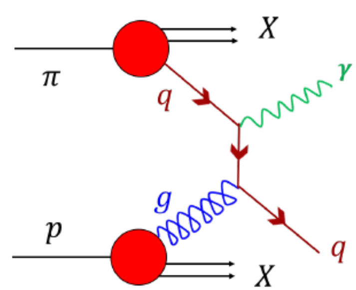
$\pi^{\pm}p \rightarrow \mu^{+}\mu^{-}X$



sensitive to valance

$\boldsymbol{prompt-gamma}$

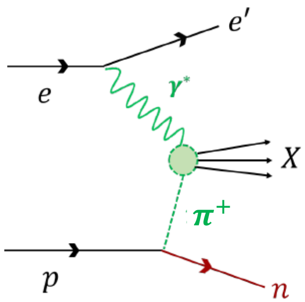
$\pi^{\pm}p \rightarrow \gamma X$



sensitive to gluon

$\boldsymbol{Leanding-neutron\ DIS}$

$p \rightarrow \pi^{+}n$



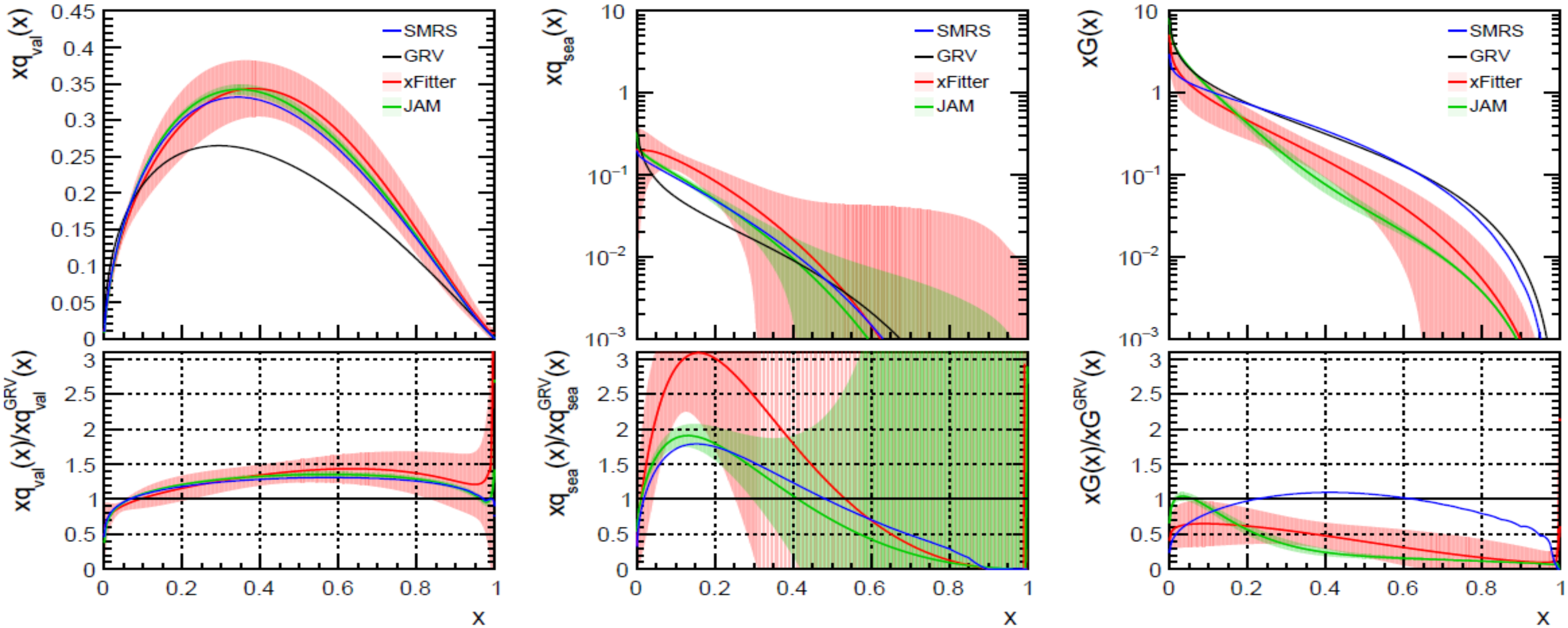
sensitive to gluon

- Due to the lack of static pion target, data used to extract pion PDF is very limited. The most update pion-induced Drell-Yan data used to constrain valence quark was E615 which was 30 years ago. COMPASS data could bring a new contribution to constrain pion valence.
- JAM group uses HERA which measures leading-neutron DIS process brings a new idea.

Pion Parton Distribution Function (PDF)

$Q^2 = 9.6GeV$

Valence **Sea** **Gluon**



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

Poorly constrained for sea PDF.

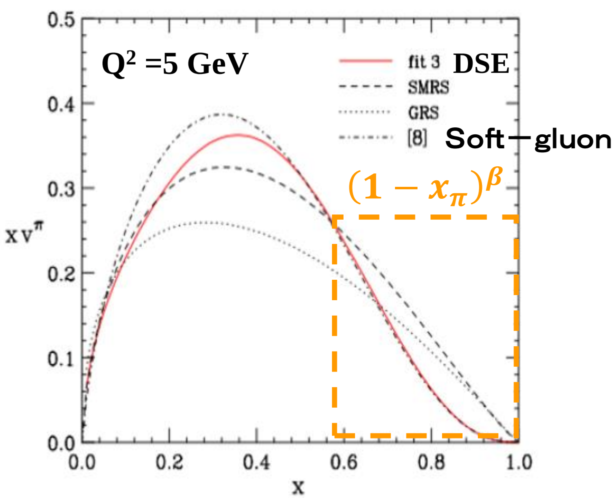
GRV and SMRS has larger gluon contamination than JAM and xFitter at $x_\pi > 0.1$

Phys. Rev. D 102, 054024 (2020)

- Pion PDF is not as well constrained due to the lack of data.
- Only the morden PDFs, JAM and xFitter gives uncertainty.

Large Valence Region

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 :

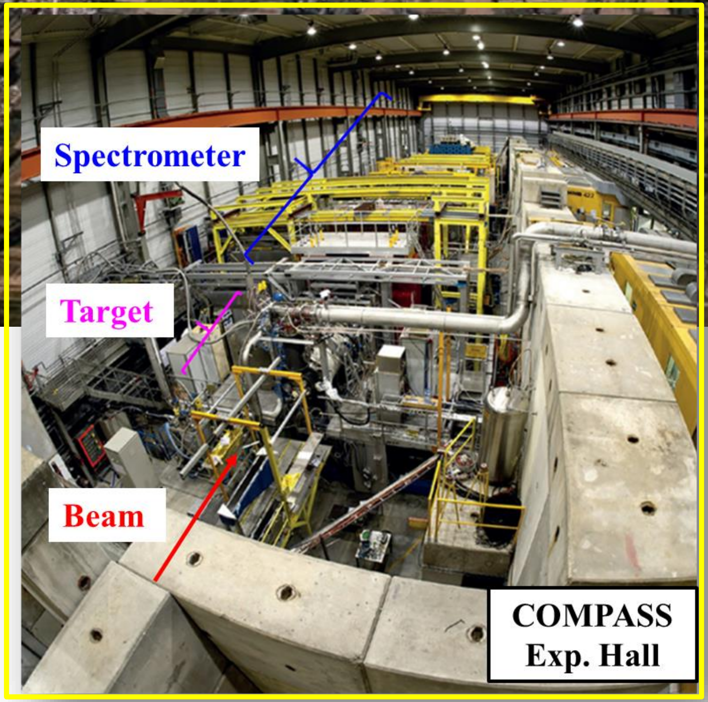
① Contributed from pion induced Drell-Yan data. Only one data set from E615-256GeV was analyzed.

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

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

- Nucleon structure
- Hadron structure
- Hadron spectroscopy

- Common spectrometer
- High intensity muon and hadron beams

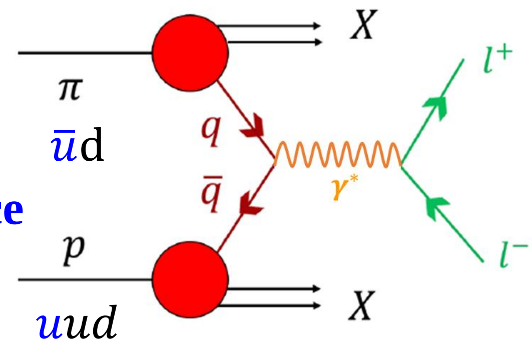


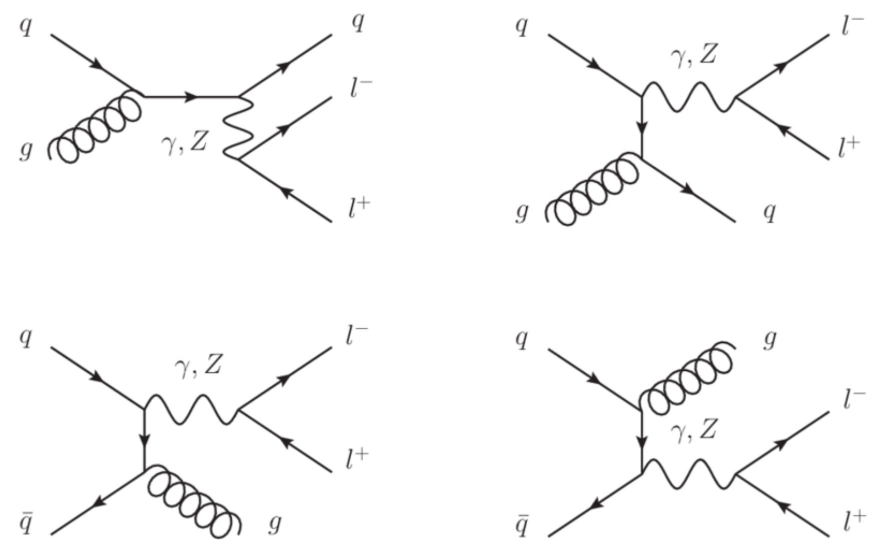
- **COMPASS**
- A fixed target experiment at CERN
- A 60m-long spectrometer
- Multiple beam choices : muon, proton, pion
- Multiple target choices : nuclear target and polarized ammonia target

Pion-Induced Drell-Yan Process
Physics Program of COMPASS in 2018

Pion-induced Drell-Yan Process (DY)

pion valence





$\boldsymbol{LO} : \boldsymbol{q\bar{q} \to \gamma^* \to l^+ l^-}$

$\boldsymbol{NLO} : \boldsymbol{q\bar{q}g \to \gamma^* \to l^+ l^- g}, \quad \boldsymbol{qg \to \gamma^* \to l^+ l^- q}$

PDF

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

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

TMD

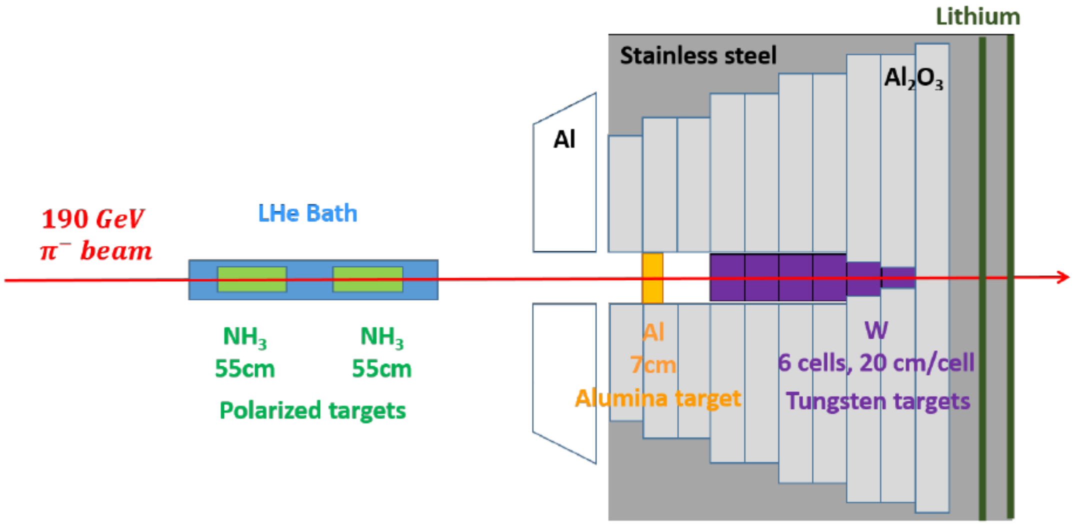
Journal of High Energy Physics
Article number: 90 (2019)

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

$*$ ***transverse momentum*** $\boldsymbol{k_T, q_T, p_T}$

Drell-Yan process is an power tool to probe PDF and TMD of hadron.

2018 Drell-Yan Data Taking COMPASS



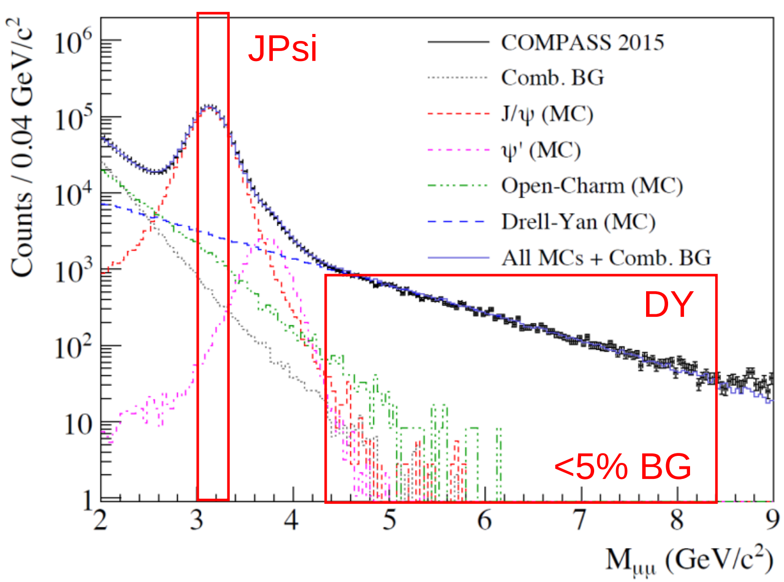
$$\pi^- + p \rightarrow \mu + \mu^- + X$$

π^- beam — NH_3, Al, W targets — *Dimuon events* — *Hadron absorber*

- **Beam** : 190 GeV π^-
- **Target :**

Polarized ammonia targets (spin physics)

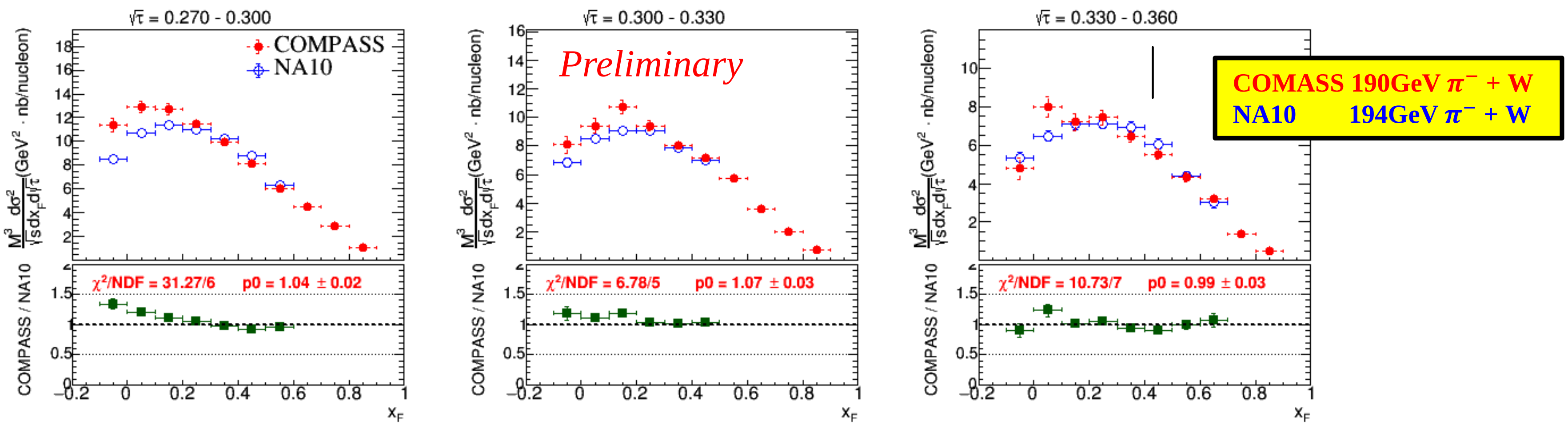
Nuclear target : Al, W (nuclear effect)

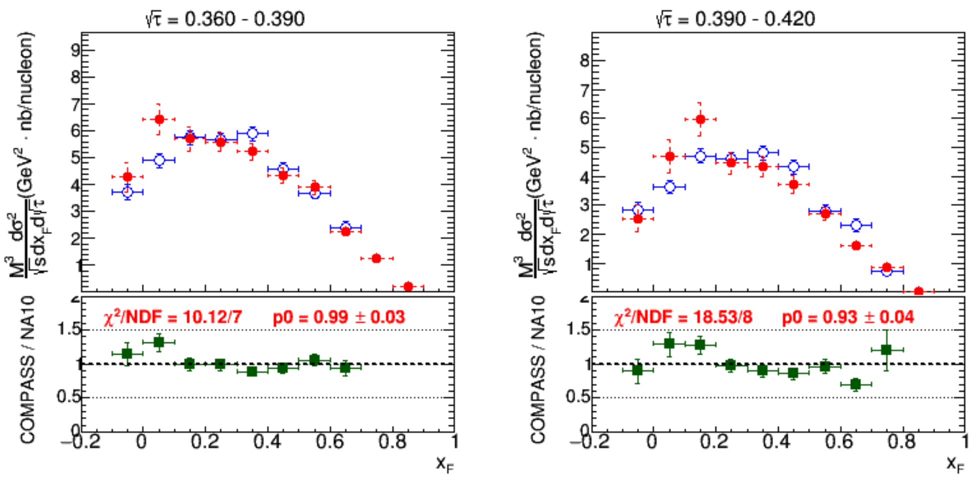


COMPASS data could contributes to

- Pion valence PDF
- Pion TMD
- Nuclear effect (3 targets)

Pion-Induced Drell-Yan Cross Section from 2018 COMPASS Data





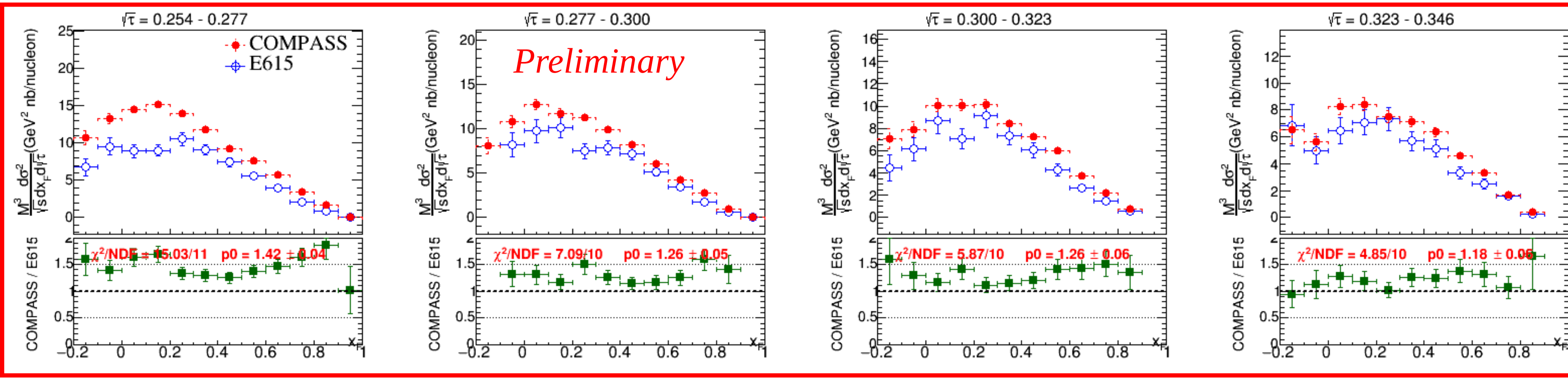
- $\sqrt{\tau} = M_{\mu\mu}/\sqrt{s}$; $x_F = x_\pi - x_p$
- Inconsistent for xf<0.2. Could be the highe background contamination. systematic uncertainty< 15%.
- NA10 VS COMPASS
- COMPASS has larger kinematic
- But larger systematic uncertainty (5% VS 10%-15%).

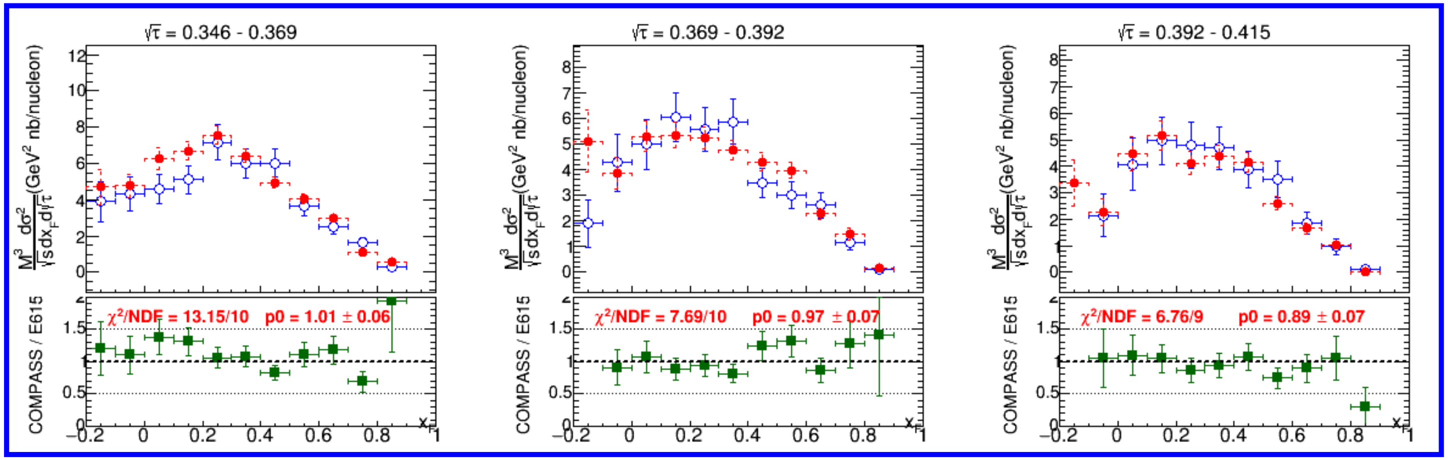
NA10 data :
Z. Phys. C - Particles and Fields 28 (1985)
J. Phys. G - Nucl. Part. Phys. 19 D1(1993)

Pion-Induced Drell-Yan Cross Section from 2018 COMPASS Data

Different normalization

E615 data : *Phys. Rev. D 39 (1989) 92*





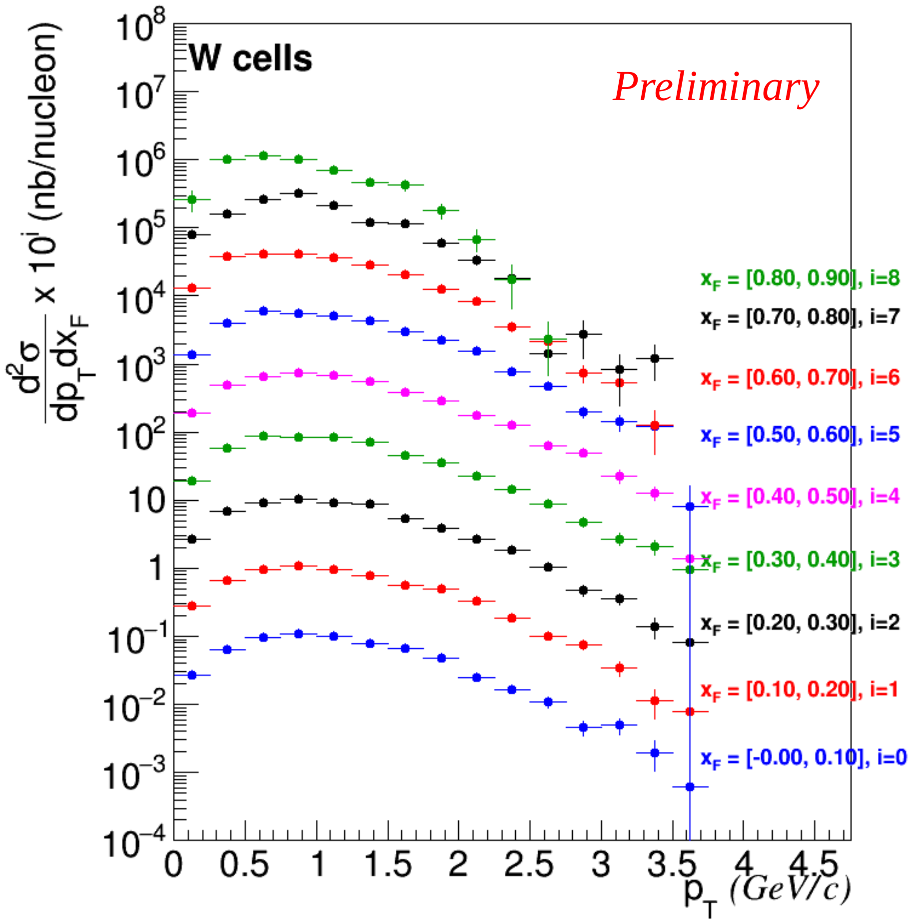
Same normalization

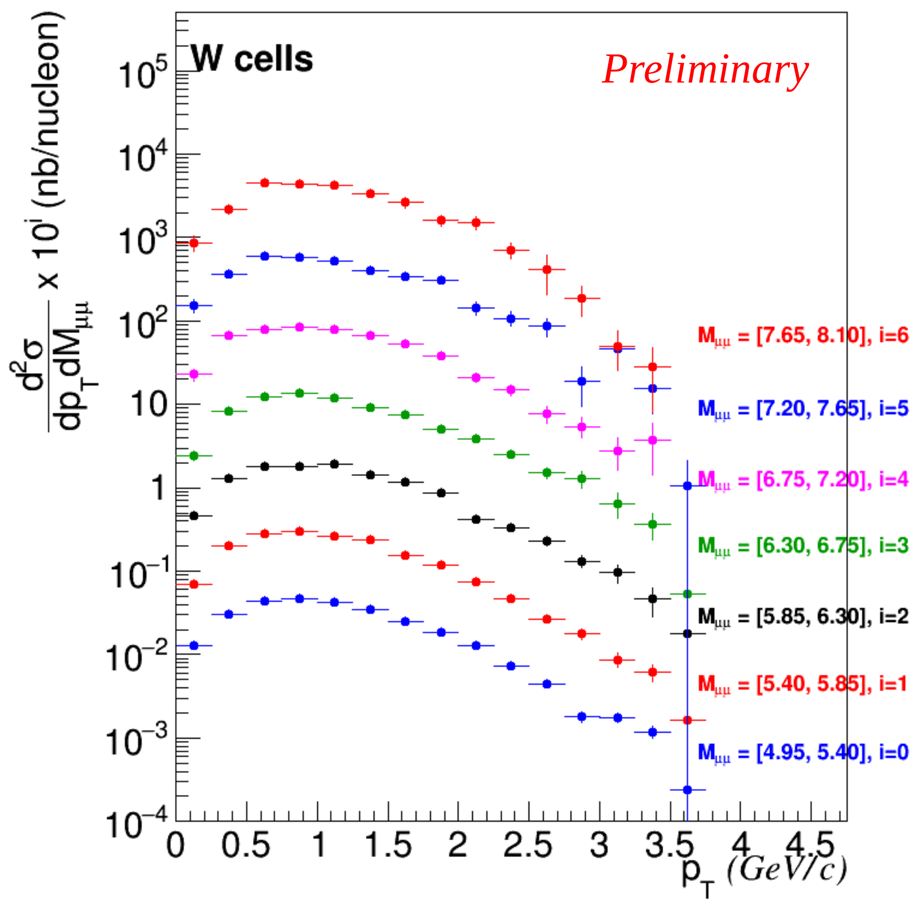
COMASS	**190GeV π^- + W**	
E615	**252GeV π^- + W**	

Compare to E615 data, the advantage of COMPASS data is better statistical uncertainty (similar systematics ~ 10%-15%).

Normalization issue of E615 data had been reported in articles from Alexey Vladimirov and MAP group.

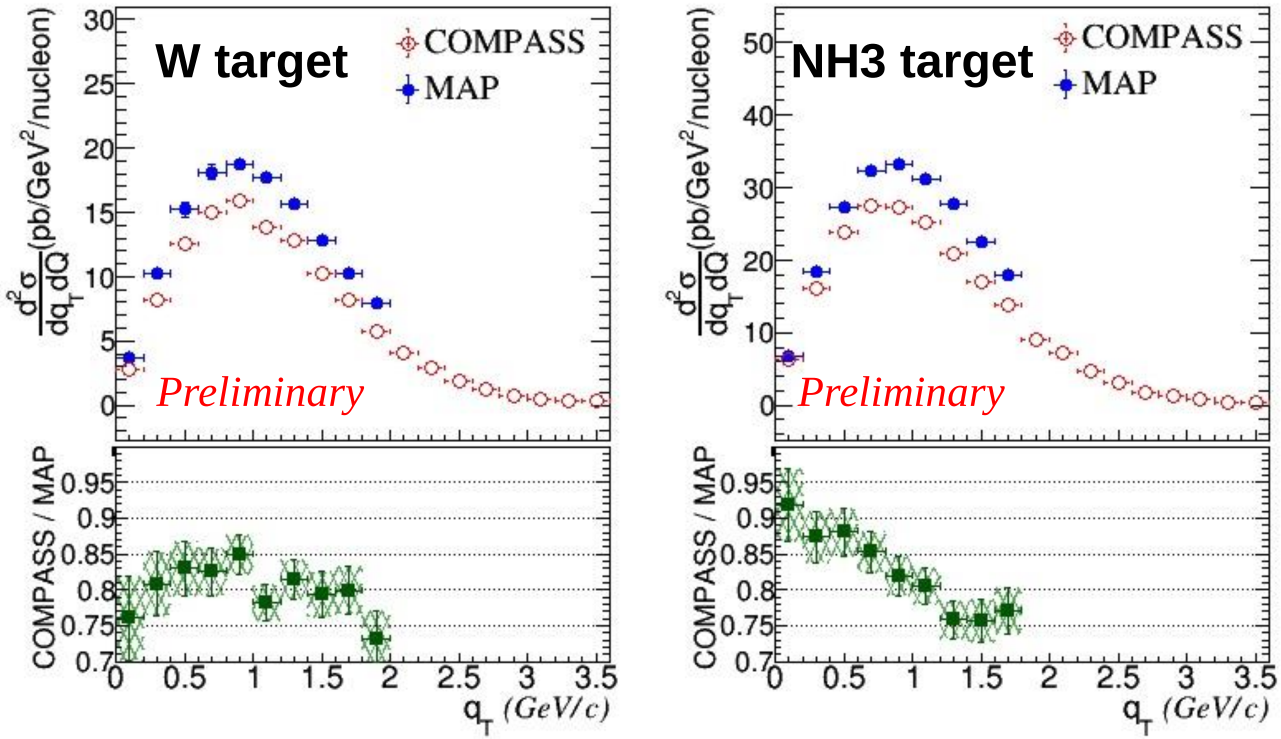
Pion-Induced Drell-Yan Cross Section from 2018 COMPASS Data





Drell-Yan cross section in the kinematics of transverse momentum could make contribution to TMD of pion. The global analysis of it is rather little(Alexey Vladimirov , MAP group). The problem is also lack of data (only E615 data contributed before).

Pion-Induced Drell-Yan Cross Section from 2018 COMPASS Data



MAP : https://arxiv.org/pdf/2210.01733.pdf

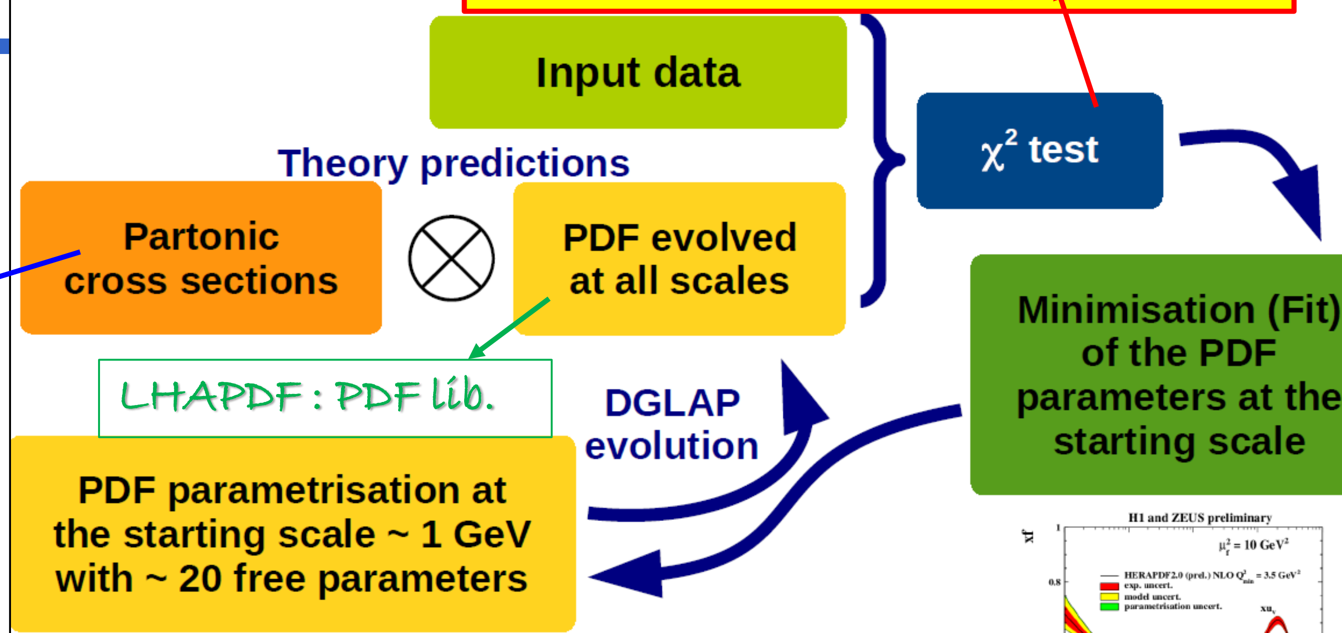
MAP group made a prediction (2022) for COMPASS data.
The comparison shows that

(1) There is a overall 0.85 factor in normalization
(2) qT dependence is stronger for NH3.

PDF Fit

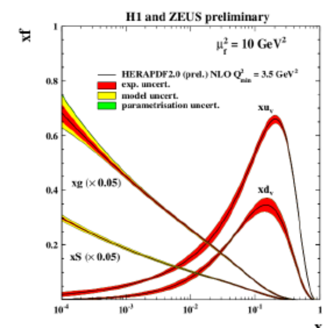
xFitter : Fitting tool
Main functions : fitting, profiler, draw

- MCFM :
partonic cross section calculation
- APPLgrid :
patch of MCFM, theoretical calculation in grid form. One can use different PDFs + grid files to calculate cross section

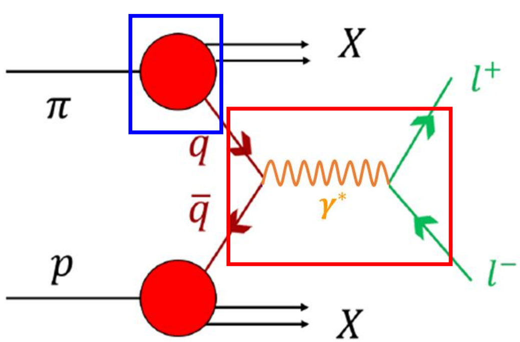


http://www.physics.smu.edu/olness/ftp/misc2/cteq/2016/lectures2016/XFITTER/Camarda.pdf

Result:
$f(x,Q^2)$
at all scales



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



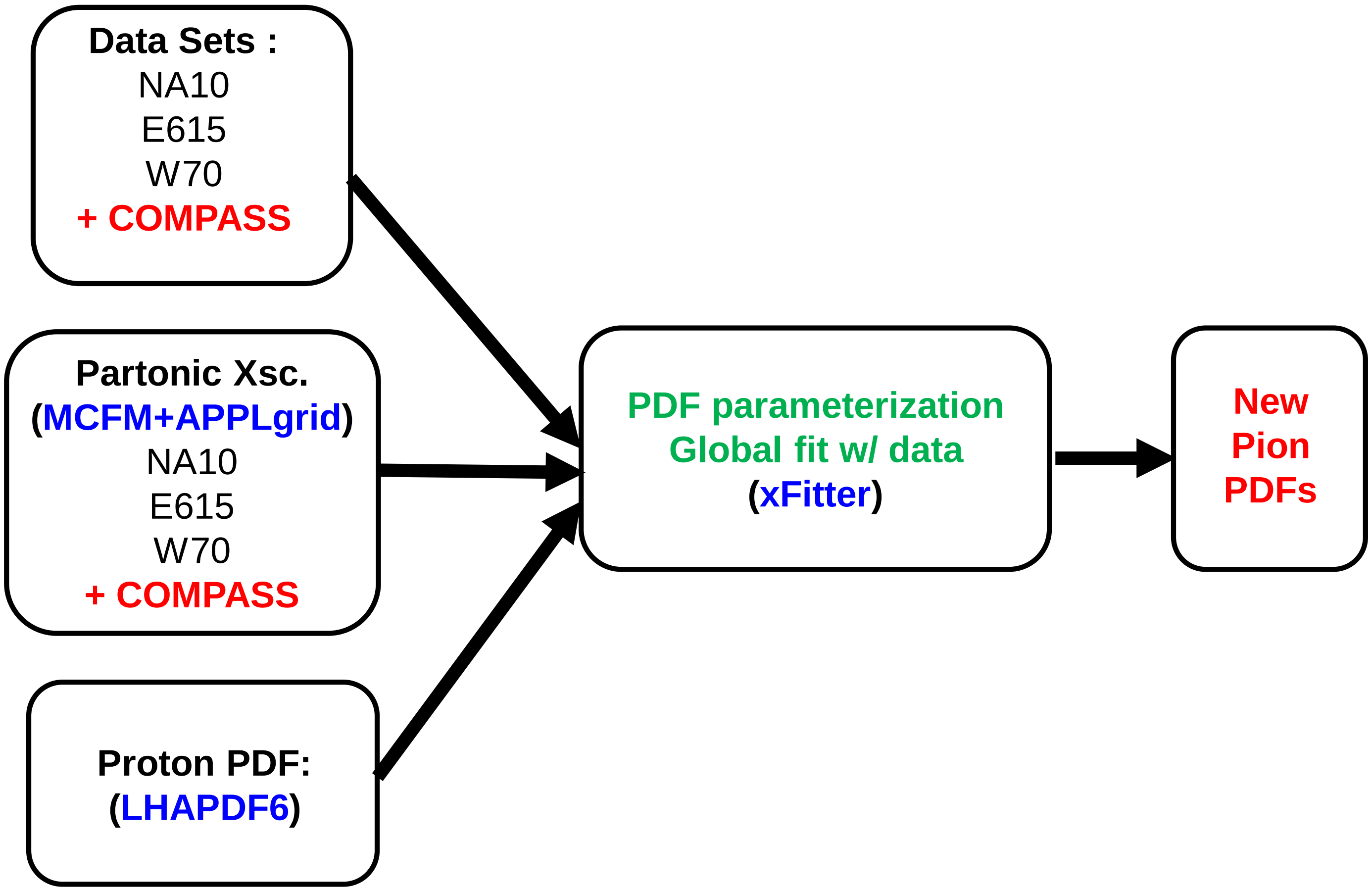
$$\frac{d^2\sigma}{dM_{ll'}dx_F} = \frac{2\pi\alpha^2}{9M_{ll'}^3}\left(\frac{x_\pi x_p}{x_\pi + x_p}\right)\sum Q_q^2\,[q(x_\pi)\bar{q}(x_p) + \bar{q}(x_\pi)q(x_p)]$$

Input data

partonic cross section calculation

Proton PDF (known)
Pion PDF Form (unknow)
➔ parameterization
➔ fit data to extract pars.

Global Fit of xFitter



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Parton distribution functions of the charged pion within the xFitter framework

TABLE I. Fitted parameter values and χ^2. The first column corresponds to the fit with $D_v = 0$. The second column shows results of the fit with free D_v and $\alpha = \frac{5}{2}$. The uncertainties of parameter values do not include scale variations. The valence and gluon normalization parameters A_v and A_g were not fitted, but were determined based on sum rules [Eq. (2)] and values of the fitted parameters.

	$D_v = 0$		free D_v	
χ^2/N_{DoF}	$444/373 = 1.19$		$437/372 = 1.18$	
A_v	2.60	Sum rule	1.72	
$\langle xv \rangle$	0.56		0.54	Sum rule
B_v	0.75 ± 0.03		0.63 ± 0.06	
C_v	0.95 ± 0.03		0.26 ± 0.13	
D_v	0	fix	-0.93 ± 0.06	free
$A_S = \langle xS \rangle$	0.21 ± 0.08		0.25 ± 0.09	
B_S	0.5 ± 0.8		0.3 ± 0.7	
C_S	8 ± 3		6 ± 3	
$A_g = \langle xg \rangle$	0.23	Sum rule	0.20	Sum rule
C_g	3 ± 1		3 ± 1	

My work is based on the work published by xFitter group. The results published can be reproduced.

Definition of SU3-pion

The π^- PDF $xf(x, Q^2)$ is parametrized at an initial scale $Q_0^2 = 1.9\ \mathrm{GeV}^2$, just below the charm mass threshold $m_c^2 = 2.04\ \mathrm{GeV}^2$. Neglecting electroweak corrections and quark masses, charge symmetry is assumed: $d = \bar{u}$, and SU(3)-symmetric sea: $u = \bar{d} = s = \bar{s}$. Under these assumptions, pion PDFs are reduced to three distributions: total valence v, total sea S, and gluon g:

v= 2dv

$$v = d_v - u_v = (d - \bar{d}) - (u - \bar{u}) = 2(d - u) = 2d_v,$$

$$S = 2u + 2\bar{d} + s + \bar{s} = 6u,$$ S= 6dbar

$$g = g,$$ g=g

which we parametrize using a generic form:

$$xv(x) = A_v x^{B_v} (1 - x)^{C_v} (1 + D_v x^{\alpha}),$$
$$xS(x) = A_S x^{B_S} (1 - x)^{C_S} / \mathcal{B}(B_S + 1, C_S + 1),$$
$$xg(x) = A_g (C_g + 1)(1 - x)^{C_g}, \quad (1)$$

where $\mathcal{B}$ is the Euler beta function, which ensures that the A_S parameter represents the total momentum fraction carried by the sea quarks. The B-parameters determine the low-x behavior, and C-parameters determine the high-x behavior. Quark-counting and momentum sum rules have the following form for π^-:

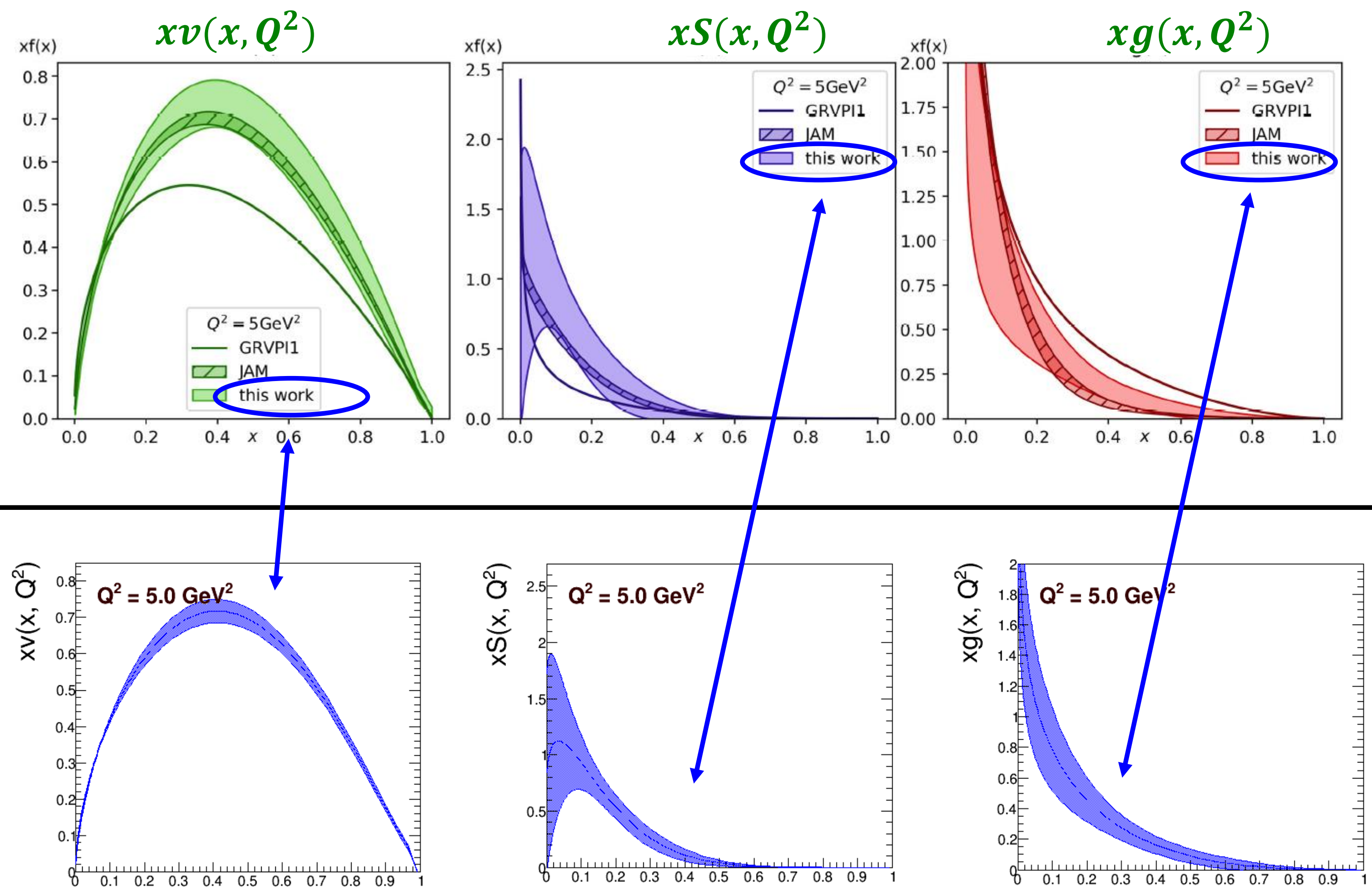
$$\int_0^1 v(x)\mathrm{d}x = 2, \quad \int_0^1 x(v(x) + S(x) + g(x))\mathrm{d}x = 1. \quad (2)$$

PDF parameterization and sum rule

Reproduce xFitter Group's Work
Verify the Framework

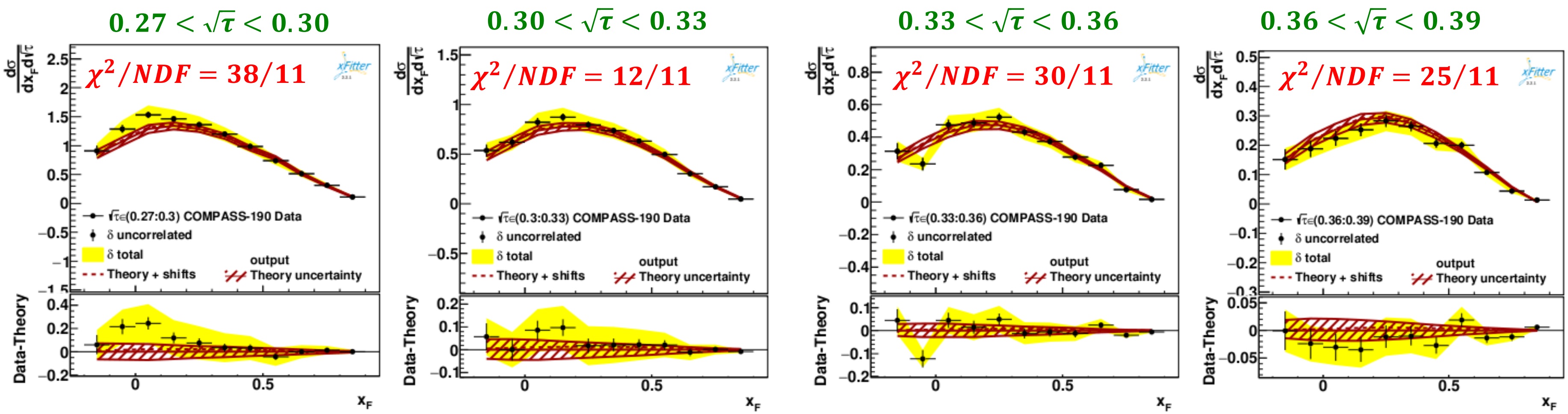
paper

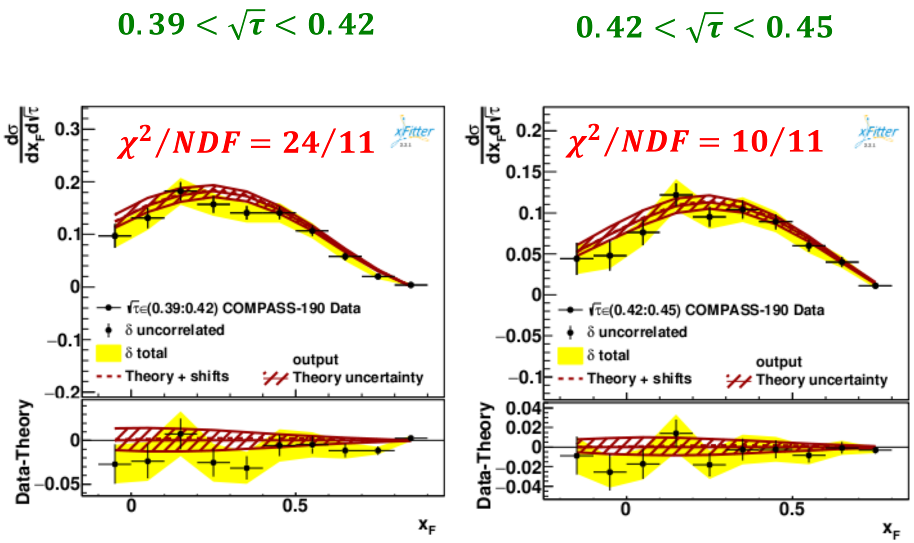
Reproduced



Results are well reproduced.

Include COMPASS Data to Global Fit



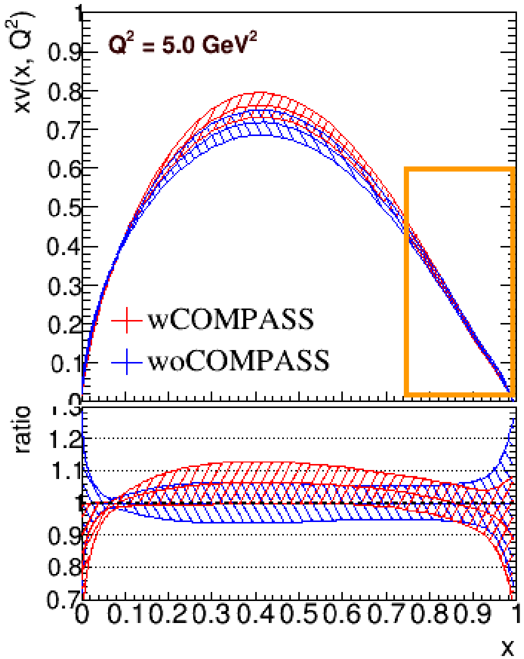


After verifying the framework, we include our COMPASS data to the global fit of pion PDFs.

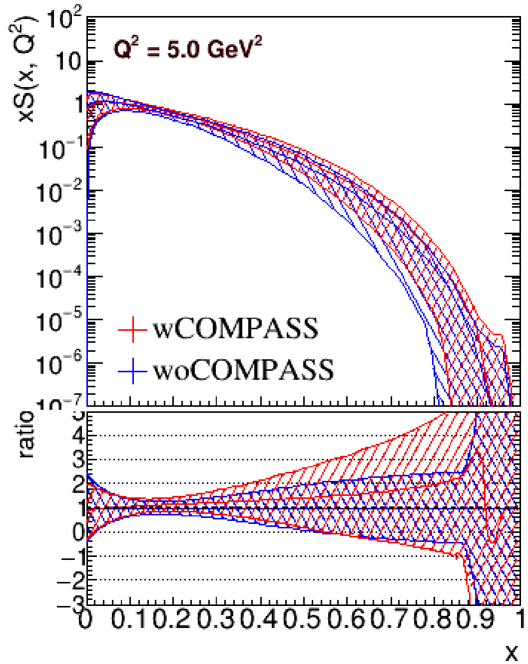
Here only the fit of COMPASS data is shown. If you are also interested in the ftting of other data sets. Please fine the results here : https://drive.google.com/file/d/1KN9GPa2cj0s_H-2fgiq9yaVywTlgWrDQ/view?usp=sharing

Pion PDFs Include COMPASS Data

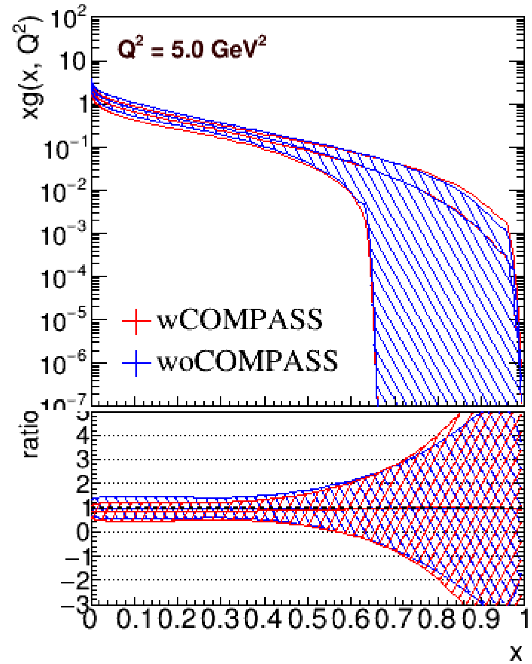
$xv(x, Q^2)$

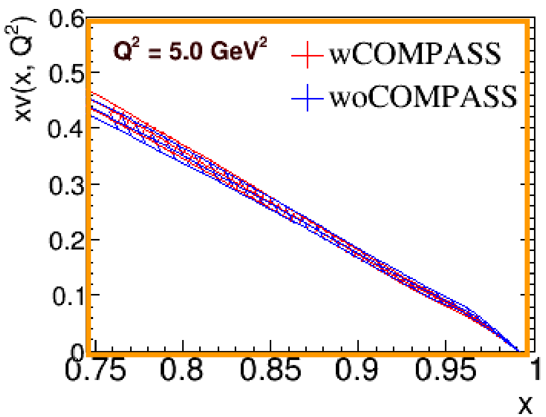


$xS(x, Q^2)$



$xg(x, Q^2)$

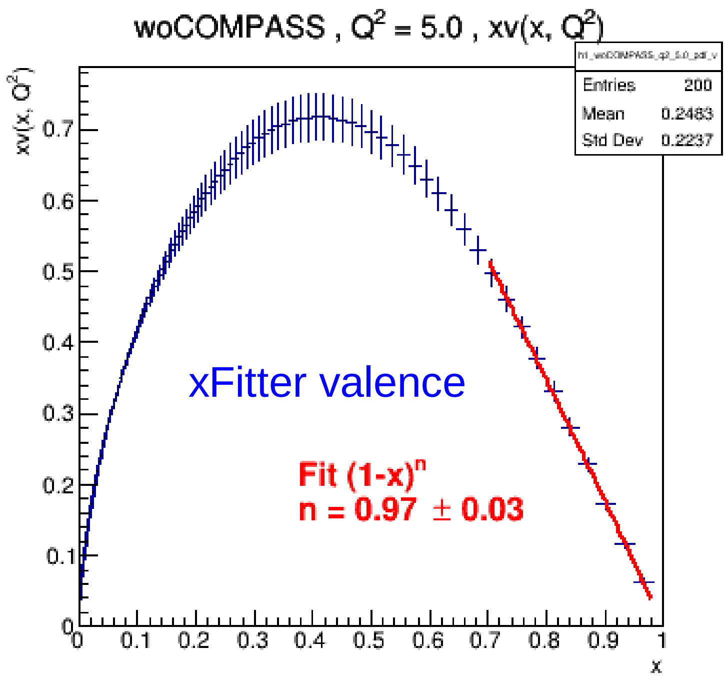




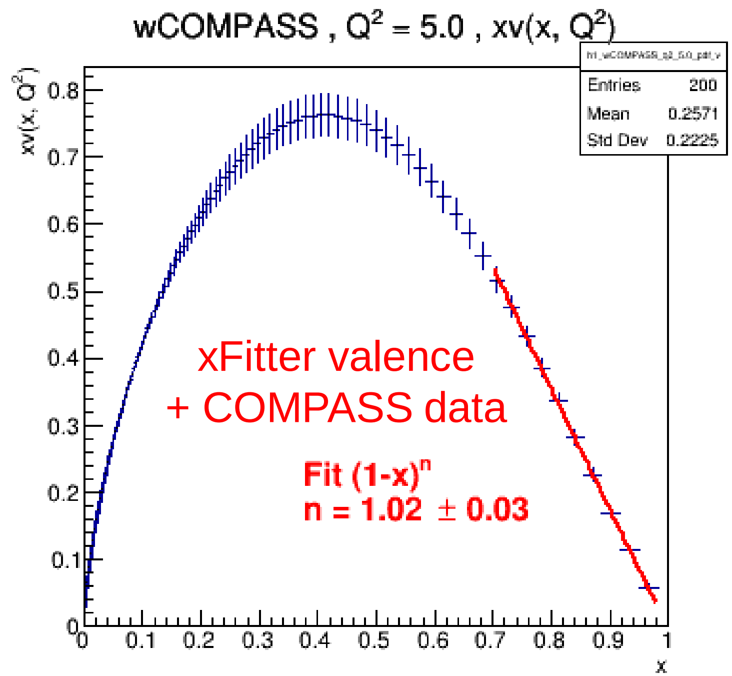
- Pion PDFs includes COMPASS data is consistent w/ the original xFitter pion PDFs.
- There is no specific improvement in the uncertainty of pion PDFs.

Valence in large x region

w/o COMPASS



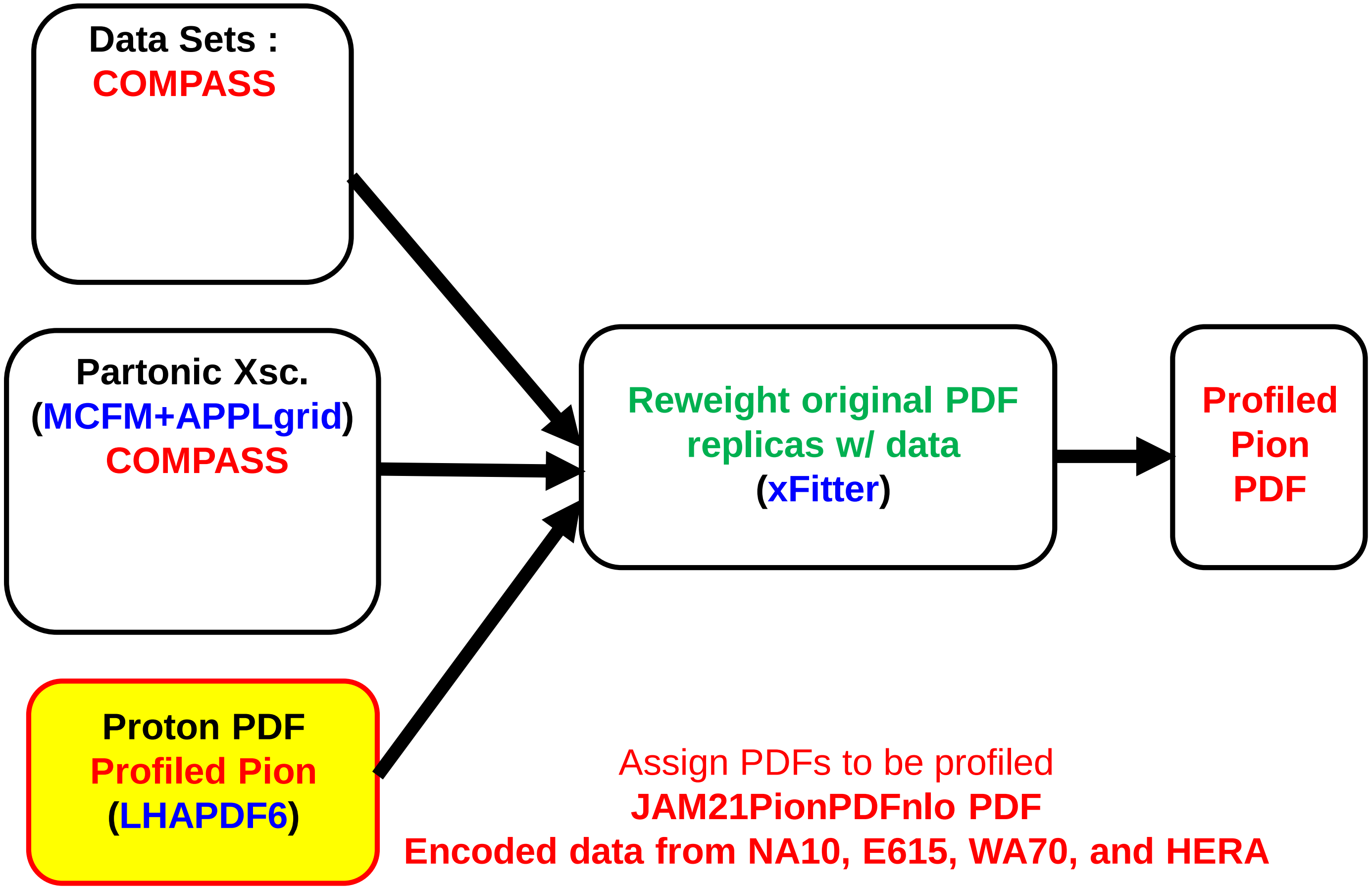
w COMPASS



In large x region of valence distribution, COMPASS data gives a faster drop in large xf region. (But still, the statistics is still not enough to give a firm conclusion.)

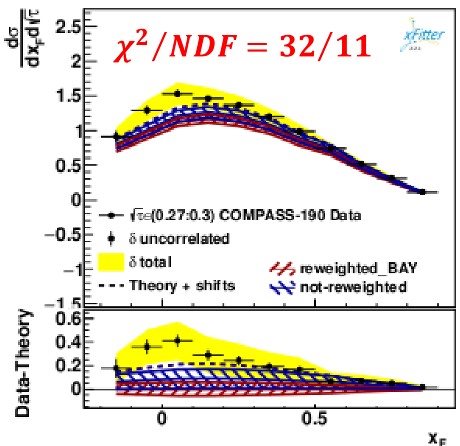
Profiler Function of xFitter

Profiler : Profiler is not exactly the global analysis. In this method, profiled PDF sets are assigned. xFitter tool fits each PDF replica with the given cross section data. Based on the difference of the cross section ratio between data and PDF replica, the PDF replica is updated. This tool is to estimate the impact of new data to the existing PDF.

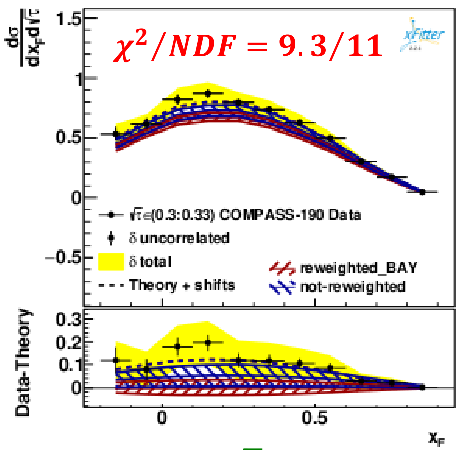


Profiler "JAM21PionPDFnlo" with COMPASS Data

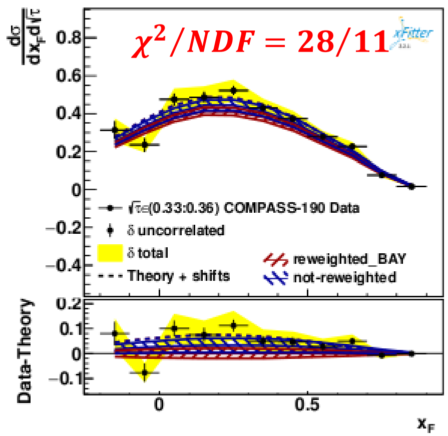
$0.27 < \sqrt{\tau} < 0.30$



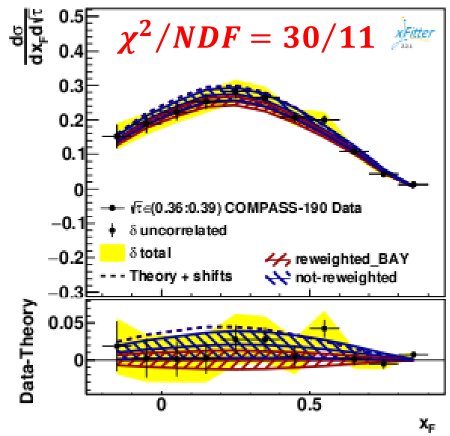
$0.30 < \sqrt{\tau} < 0.33$



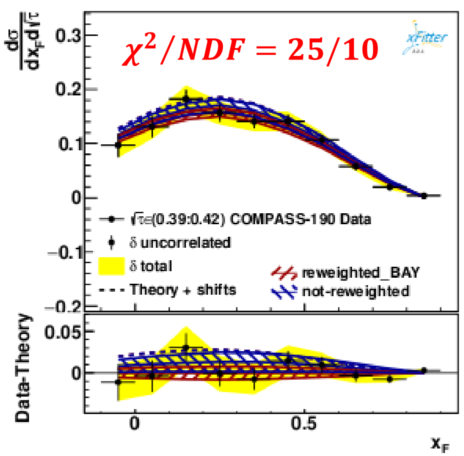
$0.33 < \sqrt{\tau} < 0.36$



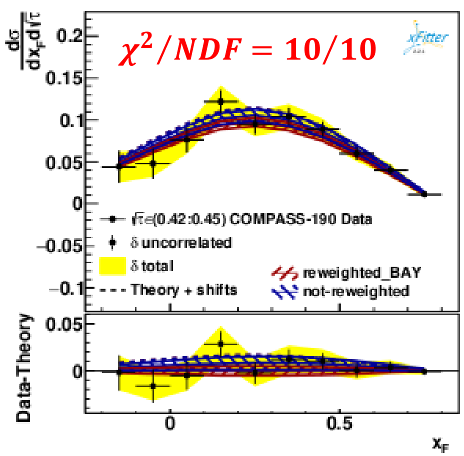
$0.36 < \sqrt{\tau} < 0.39$



$0.39 < \sqrt{\tau} < 0.42$



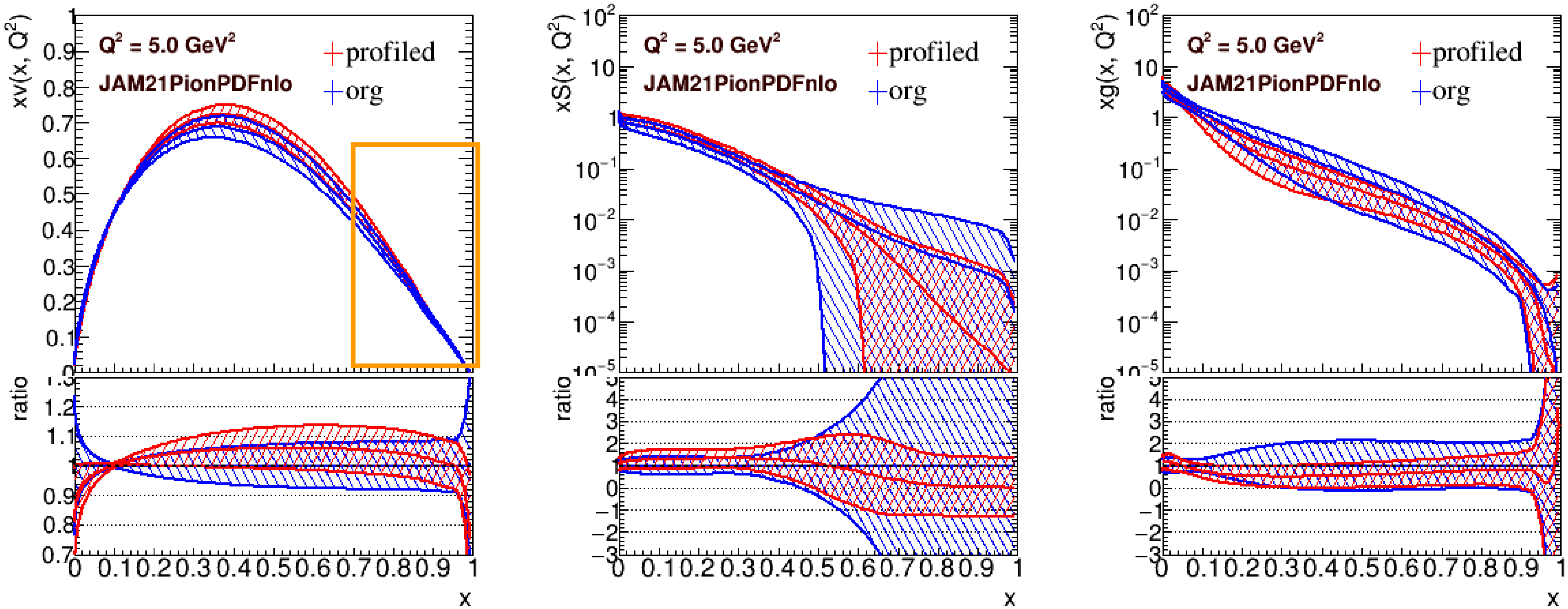
$0.42 < \sqrt{\tau} < 0.45$

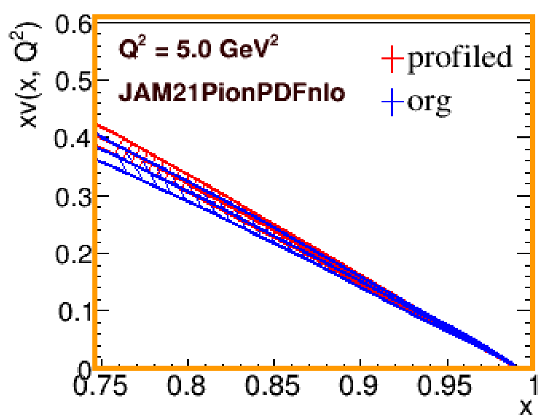


In all the sqrt(tau) ranges, the theoretical calculation is smaller than COMPASS data. +shits are applied in all bins.

Profiled "JAM21PionPDFnlo" PDFs

$xv(x, Q^2)$ $xS(x, Q^2)$ $xg(x, Q^2)$



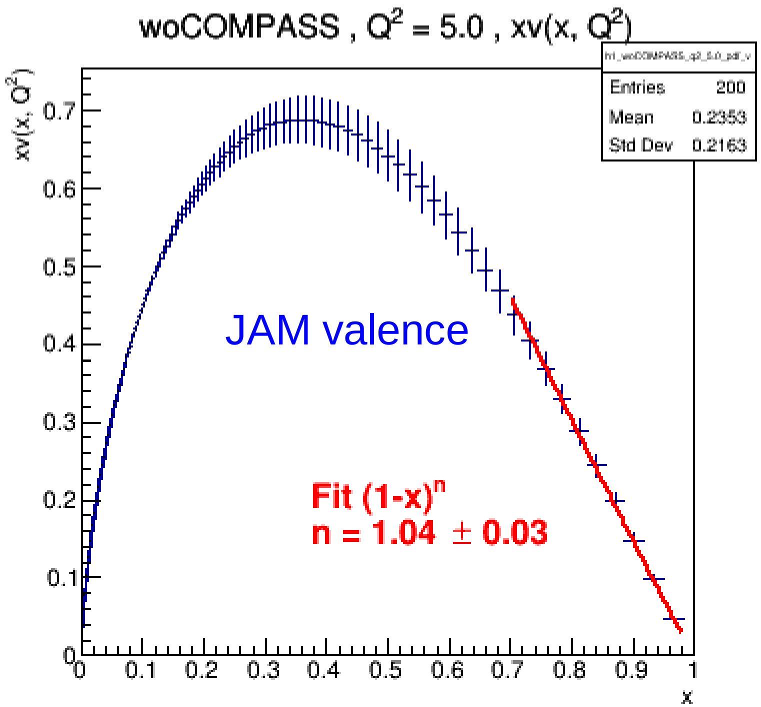


JAM Pion PDF is profiled w/ COMPASS data

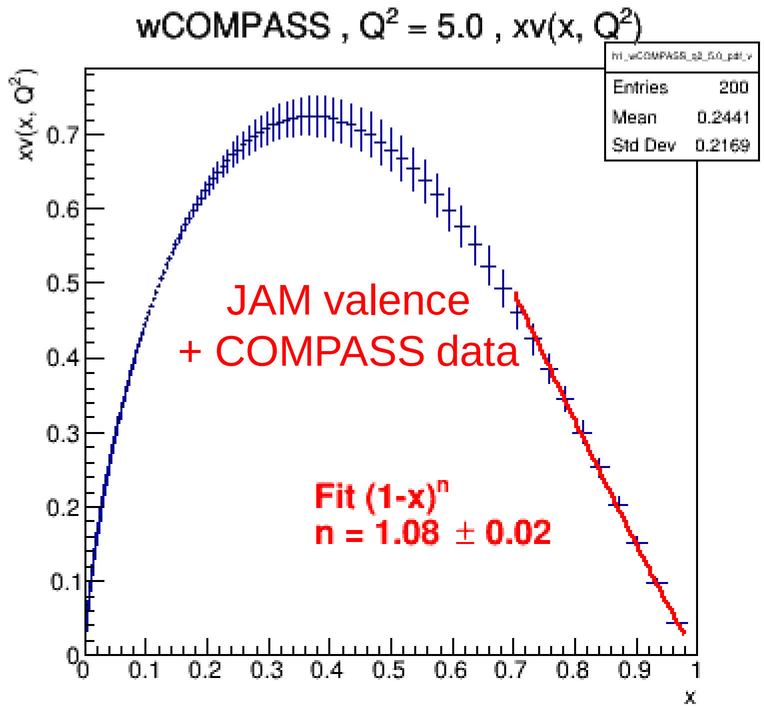
- Profiled PDF is consistent w/ the original PDF.
- COMPASS data improve the uncertainty of PDF of sea and gluon in xf>0.6.

Valance Dis. In Large xf

w/o COMPASS



w COMPASS



Consistent w/ the previous studies.

Summary

- Pion PDFs is poorly known till this days due to the lack of data.
- COMPASS carried the measurement of pion-induced Drell-Yan cross section which could bring impact to the knowledge of pion PDFs and pion TMDs. We analyze the data and it shows a great consistency with the passed measurements, E615 and NA10.
- Utilize then open-source tool xFitter, we perform the global fit/profiler to see the impact of COMPASS data towards the current pion PDF sets, xFitter PDFs and JAM PDFs.

  (1) No big impact on JAM and xFitter PDFs.

  (2) improve the uncertainty of sea and gluon when x>0.6.