The 3-D Structure of the Pion From Pion-induced Drell-Yan Scattering

HADRON 2021
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Leonard Gamberg

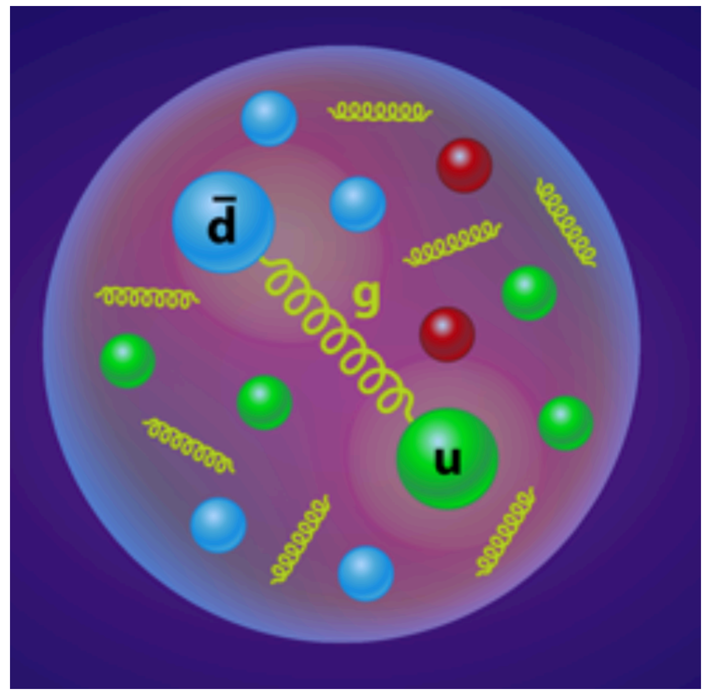
PennState Berks

w/ Patrick Barry, Eric Moffat, Alexei Prokudin
Wally Melnitchouk, Nobuo Sato, ……
"JAM 3-D"

U.S. DEPARTMENT OF ENERGY | Office of Science

TMD Collaboration

The Pion as bound state QCD



- Pion plays a central/"outsized" role in hadron physics
- As a nearly massless $\bar{q}q$ bound state Goldstone boson
  - ★ Chiral symmetry is explicitly broken by small current quark masses

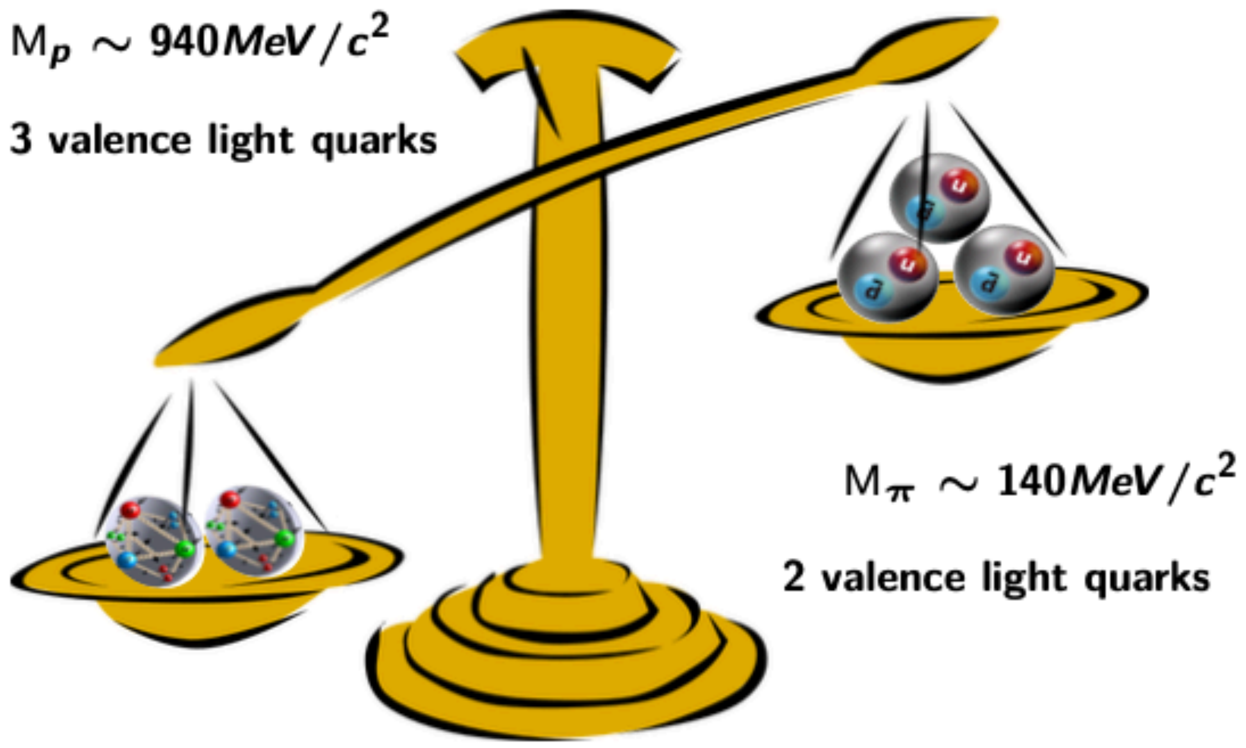
Pion pole condition from Bethe-Salpeter

$$m_\pi^2 = \frac{m}{2\,G_\pi\,M\,I(m_\pi^2)}$$

Gell Mann Reiner Oaks Relation

$$f_\pi^2\,m_\pi^2 = \tfrac{1}{2}\,(m_u + m_d)\,\langle \bar{u}u + \bar{d}d\rangle$$

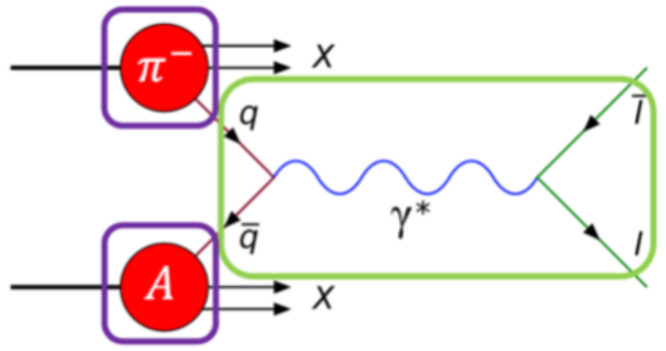
★ Mass without mass" bulk of pion mass due to quantum fluctuations of $\bar{q}q$ pairs, gluons, & energy associated with quarks moving at close to speed of light



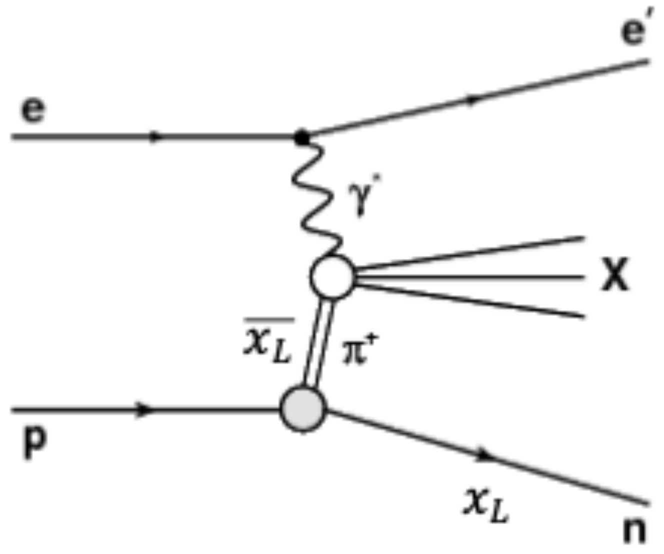
The Pion recent progress

- Also @ high energies pion reveals unique spectrum of momentum distributions, $f_{i/\pi}(x,\mu)$
  See talk of P.C. Barry Monday: DY & LN process as predicted from Collinear Factorization

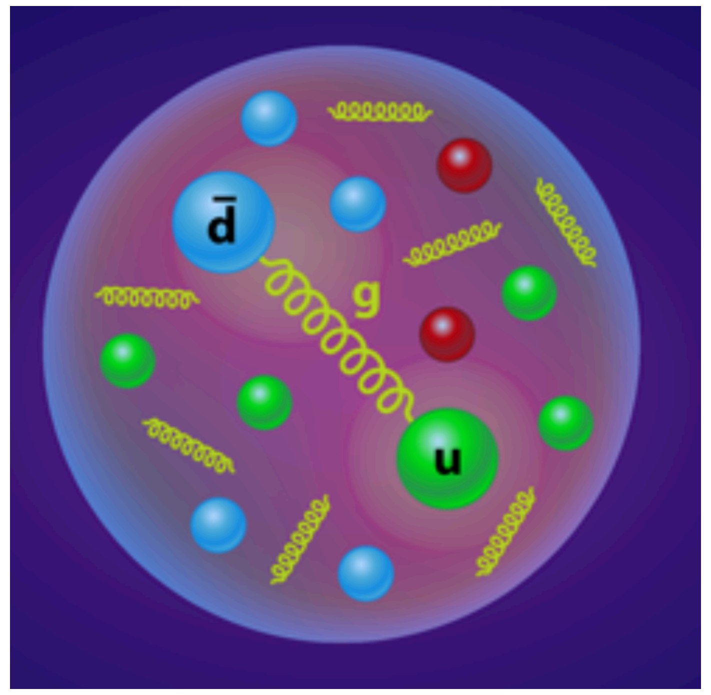
1) $$\frac{d\sigma^{DY}}{dQ^2 dy} = \sum_{a,b} \int dx_a\, dx_b\, H^{DY}_{a,b}(x_a, x_b, y, Q^2, \mu^2)\, f_{a/A}(x_a, \mu^2)\, f_{b/B}(x_b, \mu^2)$$



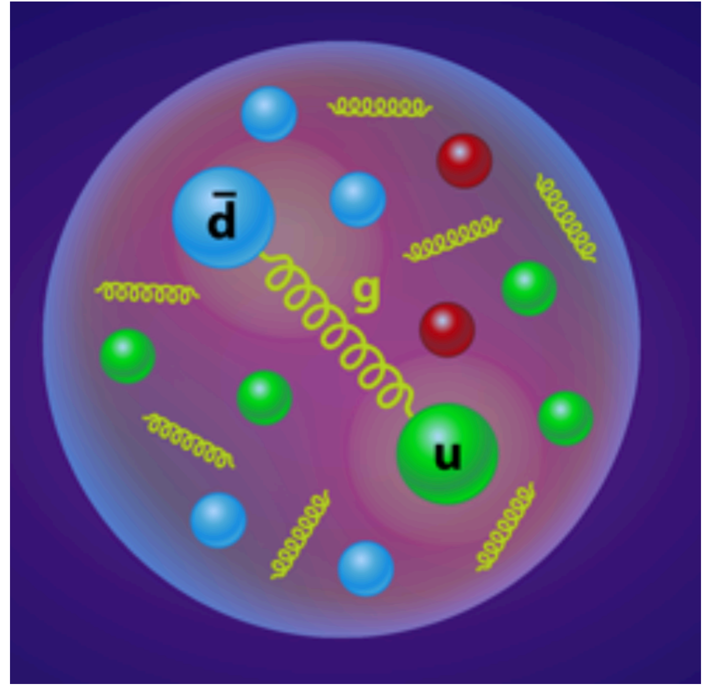
2) $$\frac{d^3\sigma^{LN}}{dx_B\, dQ^2\, dx_L} = \frac{4\pi\alpha^2}{x_B\, Q^4}\left(1 - y_e + \frac{y_e^2}{2}\right) F_2^{LN}(x_B, Q^2, x_L)$$



Understanding how these contrasting manifestations of the same $\bar{q}q$ bound state arise dynamically at different energy scales from first principles remains a major challenge in QCD



The Pion recent progress



- Also @ high energies pion reveals unique spectrum of momentum distributions, $f_{i/\pi}(x,\mu)$
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Jefferson Lab Angular Momentum (JAM)
Barry, Sato, Melnitchouk, C.R. Ji, PRL 2018

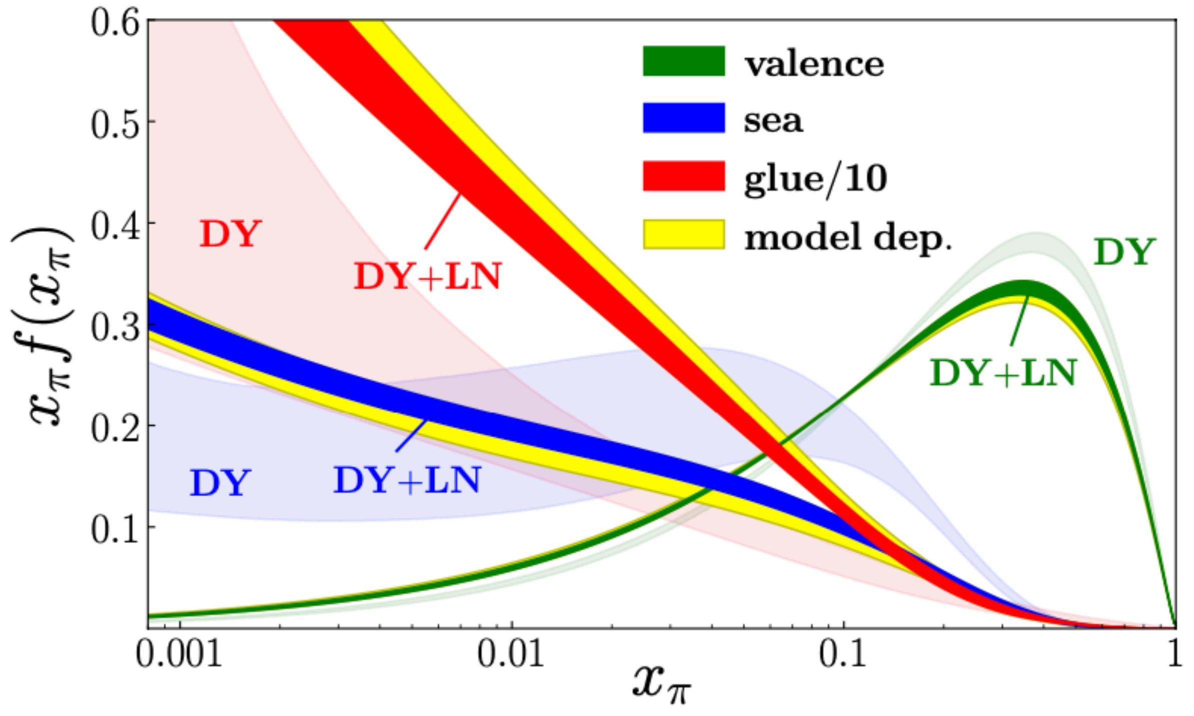
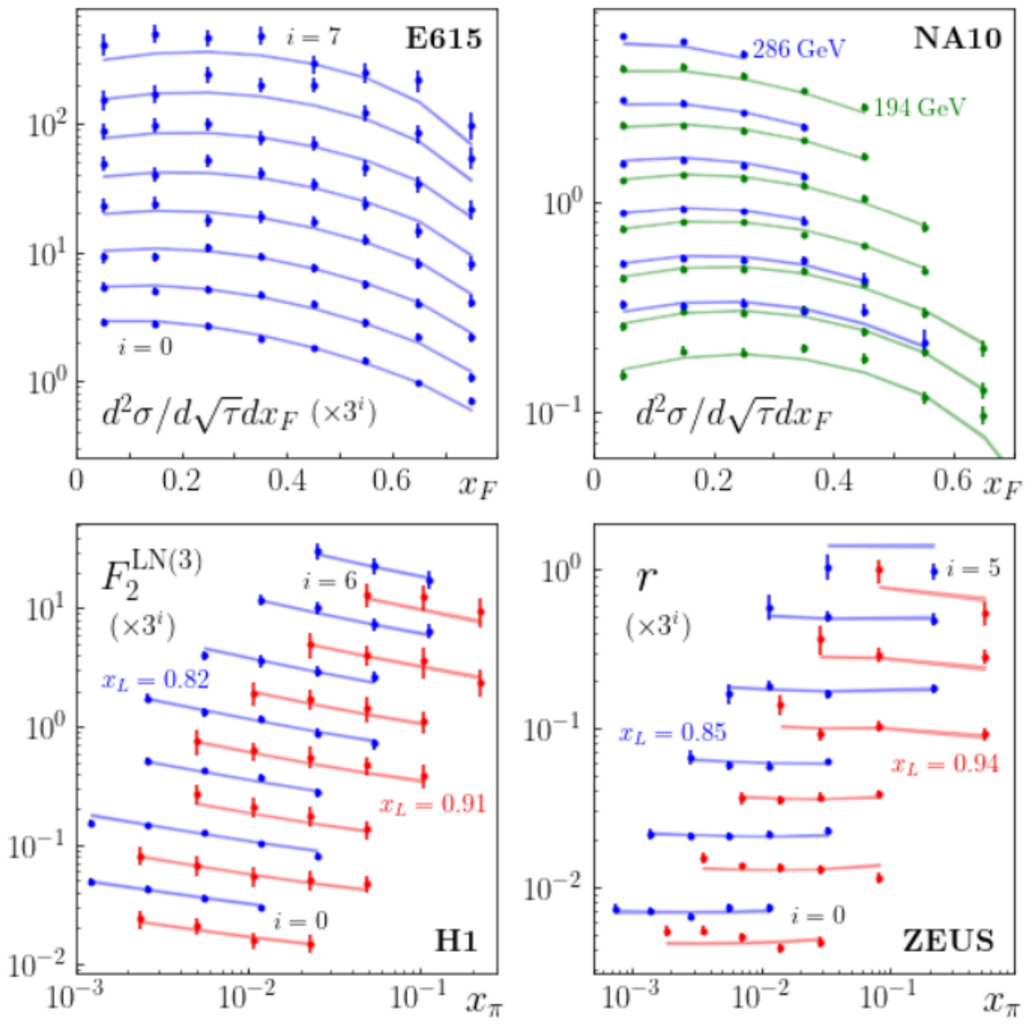


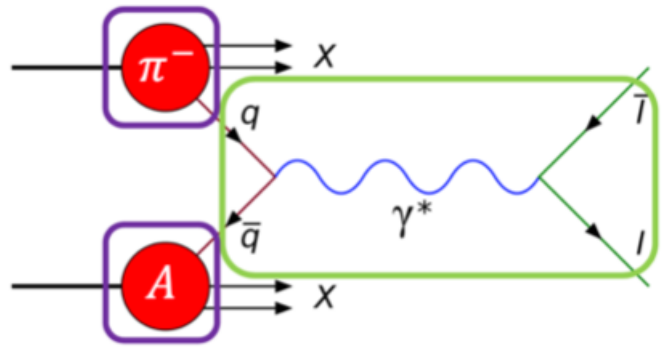
FIG. 2. Pion valence (green), sea quark (blue) and gluon (red, scaled by 1/10) PDFs versus x_π at $Q^2 = 10\ \text{GeV}^2$, for the full DY + LN (dark bands) and DY only (light bands) fits. The bands represent 1σ uncertainties, as defined in the standard Monte Carlo determination of the uncertainties [42] from the experimental errors. The model dependence of the fit is represented by the outer yellow bands.



- Top row – Drell-Yan
- Bottom row – Leading neutron
- Good agreement with data
- $\chi^2_{\text{npts}} = 0.979$

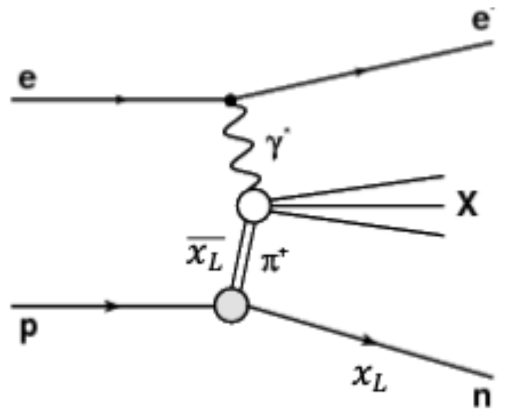
1)

$$\frac{d\sigma^{DY}}{dQ^2 dy} = \sum_{a,b}\int dx_a\, dx_b\, H^{DY}_{a,b}(x_a, x_b, y, Q^2, \mu^2)\, f_{a/A}(x_a,\mu^2)\, f_{b/B}(x_b,\mu^2)$$



2)

$$\frac{d^3\sigma^{LN}}{dx_B\, dQ^2\, dx_L} = \frac{4\pi\alpha^2}{x_B Q^4}\left(1 - y_e + \frac{y_e^2}{2}\right) F_2^{LN}(x_B, Q^2, x_L)$$



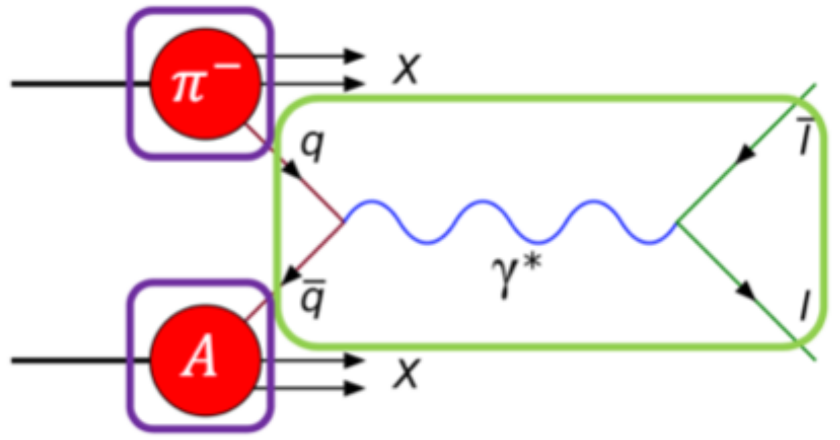
Extended fit to include “large” p_T Drell Yan data

Barry et al *Phys.Rev.D* 103 (2021), also included transverse momentum dependent Drell-Yan data in a global QCD analysis for the first time. These data were able to be described well by our $O(\alpha_s)$ framework, and new pion PDFs were extracted. The inclusion of the pT-dependent data helped in reduce the uncertainties of the gluon distribution at large x

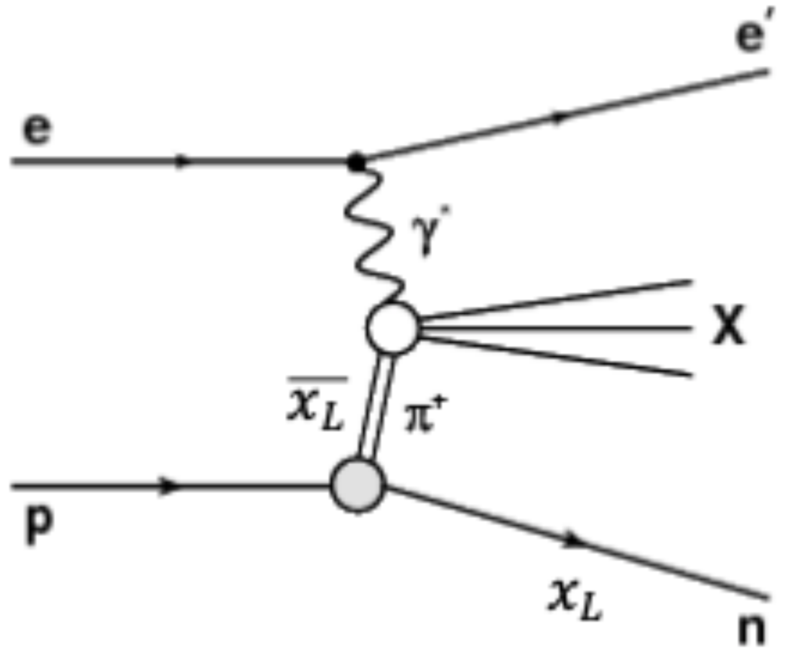
Extended fit to include "large" p_T Drell Yan data

Jefferson Lab Angular Momentum (JAM) Cao Barry, Sato, Melnitchouk, arXiv:2103.02159

1) $$\frac{d\sigma^{\rm DY}}{dQ^2 dy} = \sum_{a,b} \int dx_a\, dx_b\, H^{\rm DY}_{a,b}(x_a, x_b, y, Q^2, \mu^2)\, f_{a/A}(x_a, \mu^2)\, f_{b/B}(x_b, \mu^2)$$



2) $$\frac{d^3\sigma^{\rm LN}}{dx_B\, dQ^2\, dx_L} = \frac{4\pi\alpha^2}{x_B Q^4}\left(1 - y_e + \frac{y_e^2}{2}\right) F_2^{\rm LN}(x_B, Q^2, x_L)$$



$$F_2^{\rm LN}(x_B, Q^2, x_L) = 2 f_{\pi N}(\bar{x}_L) F_2^{\pi}(x_\pi, Q^2)$$

$$F_2^{\pi}(x_\pi, Q^2) = \sum_i \int d\xi H_i^{\rm DIS}(\xi, \mu^2, Q^2)\, f_{i/\pi}(x_\pi/\xi, \mu^2)$$

Collinear Factorization CSS NPB 1985

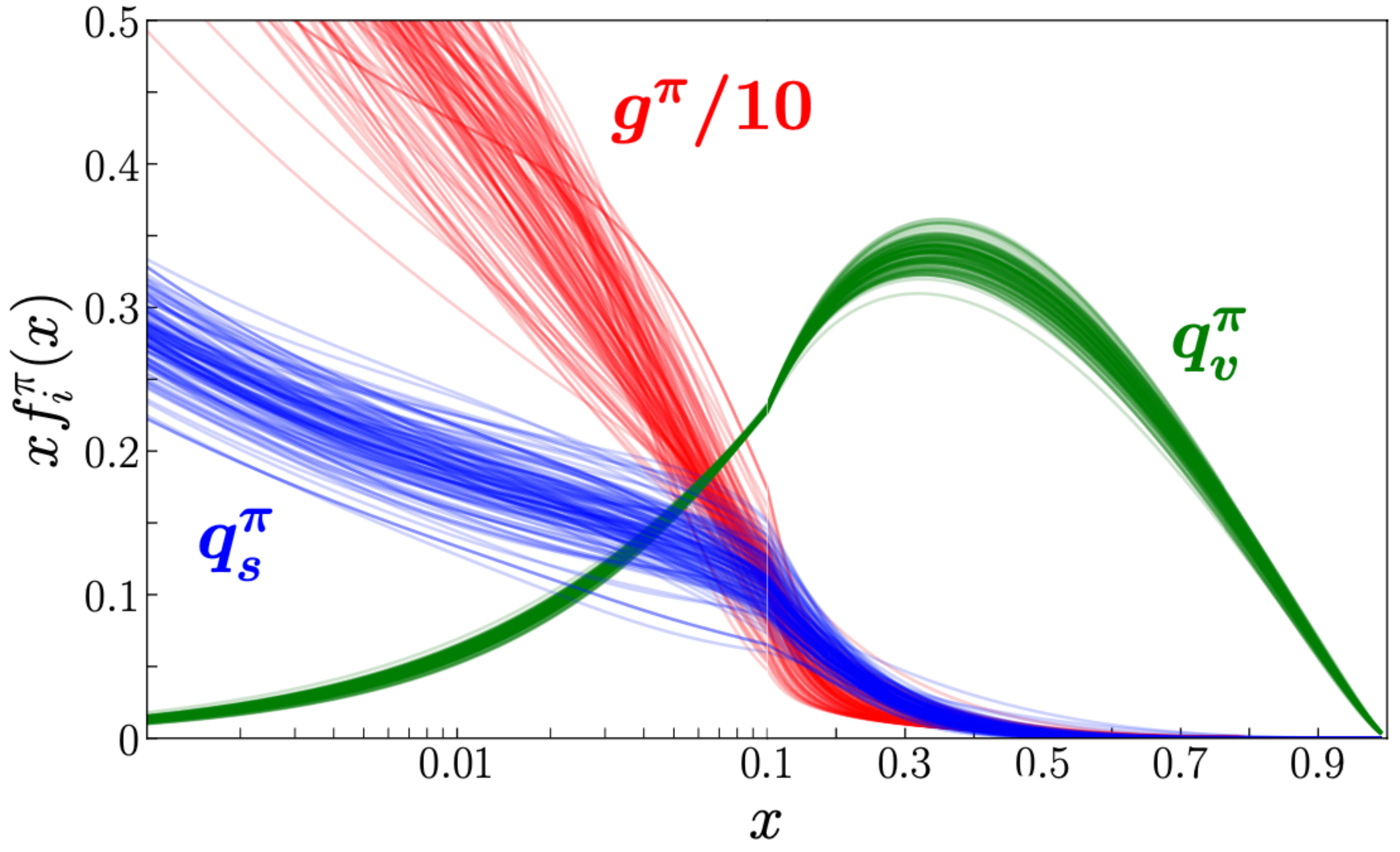
3) $$\frac{d\sigma^{\rm DY}}{dQ^2 dy dp_T} = \sum_{a,b} \int dx_a\, dx_b\, H^{\rm FO}_{a,b}(x_a, x_b, y, p_T, Q^2, \mu^2)\, f_{a/A}(x_a, \mu^2)\, f_{b/B}(x_b, \mu^2)$$

$p_T \lesssim Q$

Extended fit to include "large" p_T Drell Yan data

Jefferson Lab Angular Momentum (JAM) Cao Barry, Sato, Melnitchouk, arXiv:2103.02159

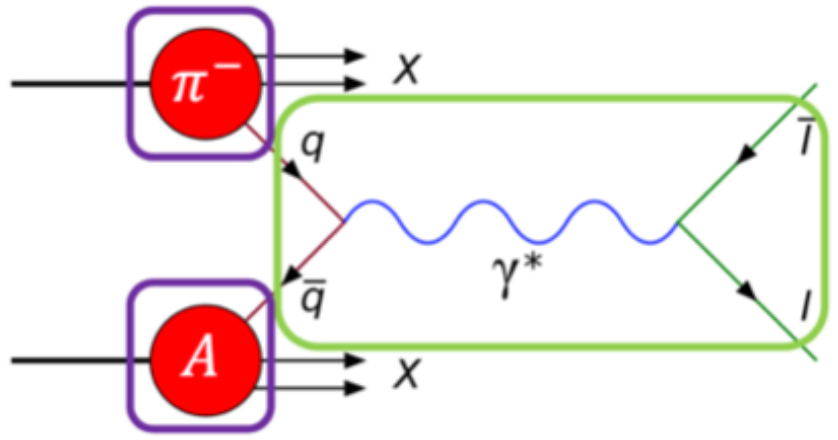
New Monte Carlo QCD analysis of pion parton distribution functions, including, for the first time, large transverse momentum dependent pion-nucleus Drell-Yan cross sections together with P_T-integrated Drell-Yan & leading neutron electroproduction data from HERA.



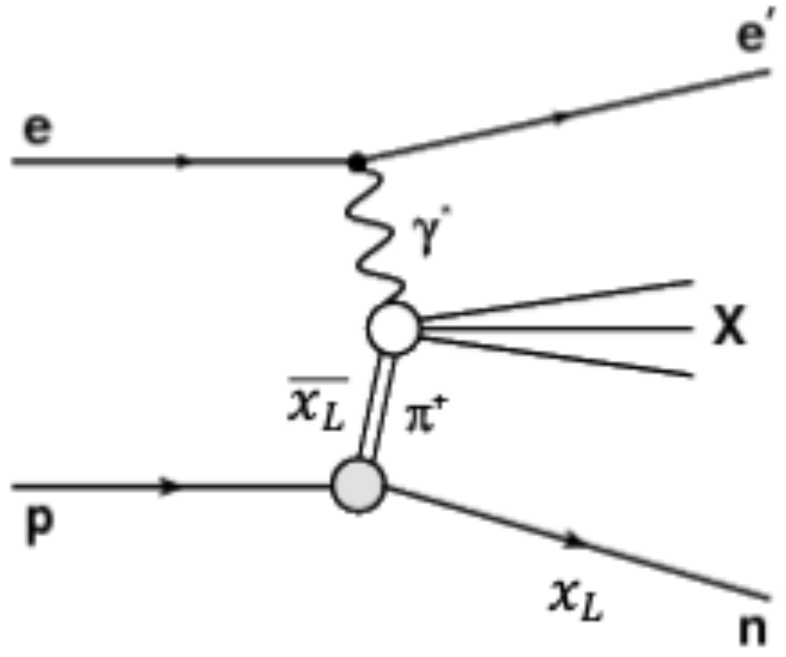
JAM20 Pion PDFs

Pion valence quark, sea quark, and gluon (scaled by a factor of 1/10) PDFs extracted from the JAM Monte Carlo analysis of DY (pT-integrated and pT-dependent) and leading neutron data at a scale of $\mu^2 = 10\ \mathrm{GeV}^2$

1)



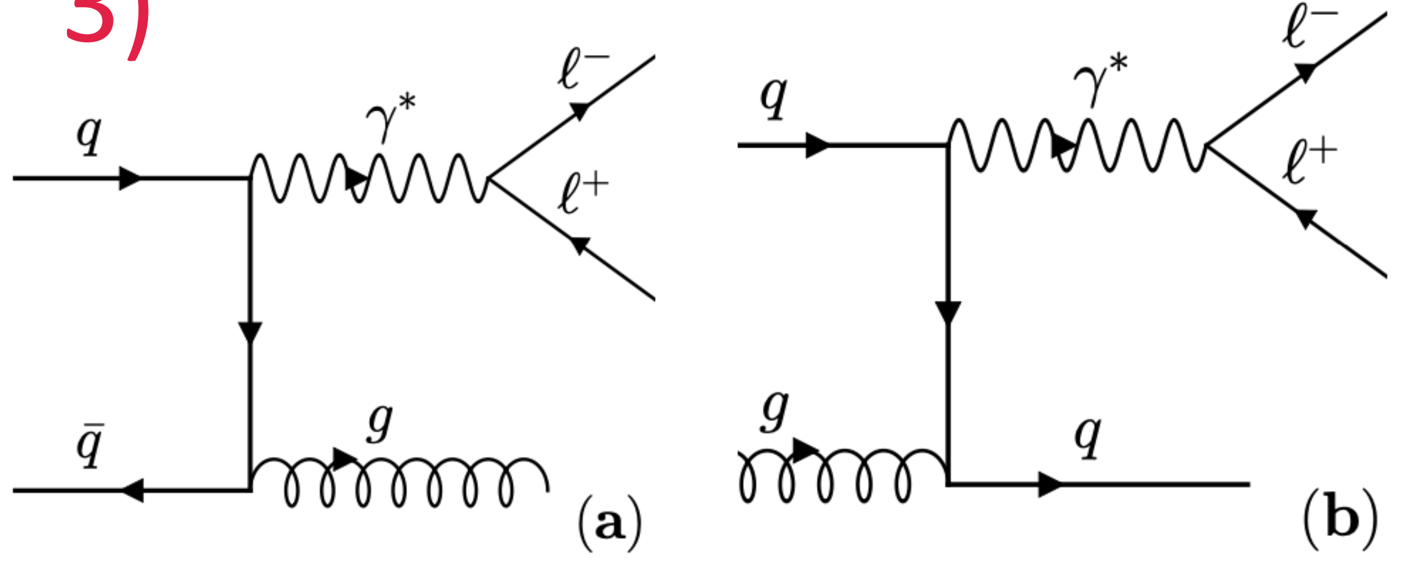
2)



3)

$$\frac{d\sigma^{\mathrm{DY}}}{dQ^2 dy dp_T} = \sum_{a,b} \int \mathrm{d}x_a\, \mathrm{d}x_b\, H^{\mathrm{FO}}_{a,b}(x_a, x_b, y, p_{\mathrm{T}}, Q^2, \mu^2)\, f_{a/A}(x_a, \mu^2)\, f_{b/B}(x_b, \mu^2)$$

3)



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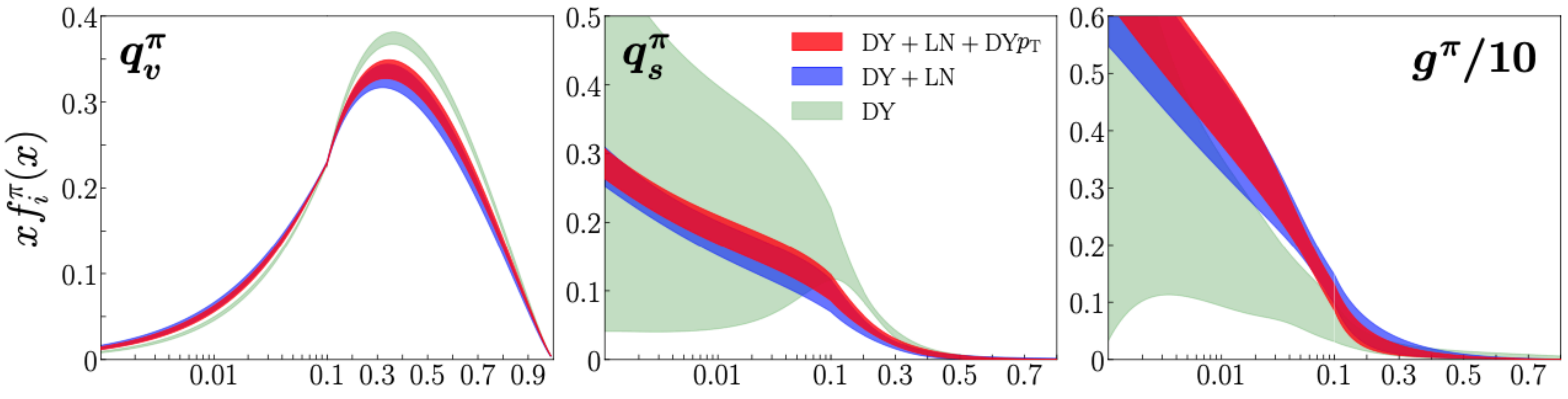
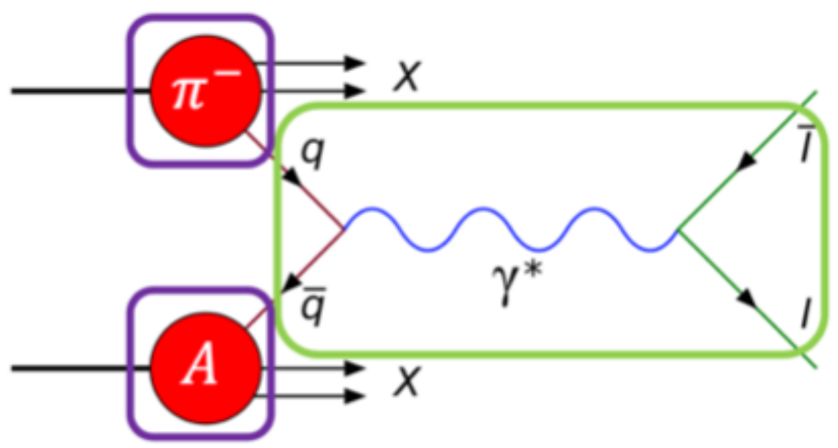
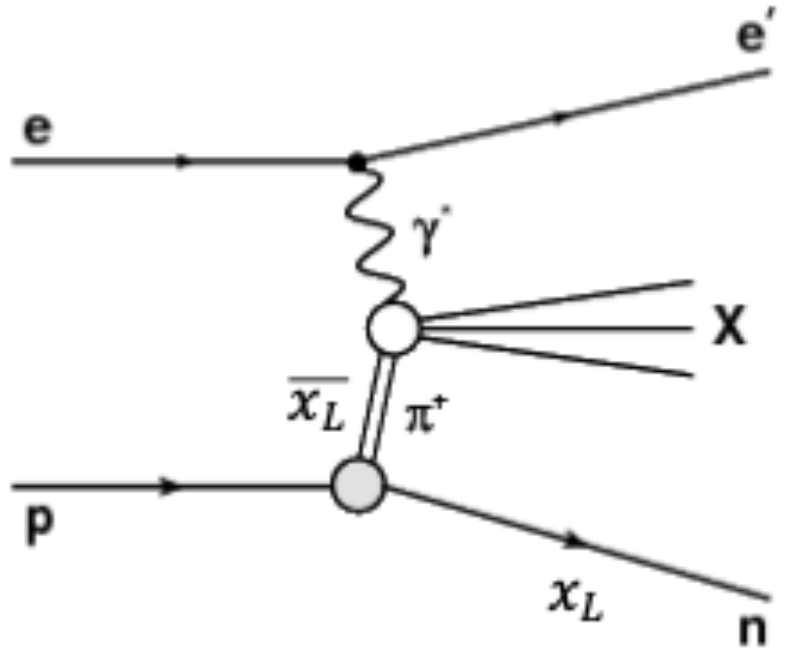


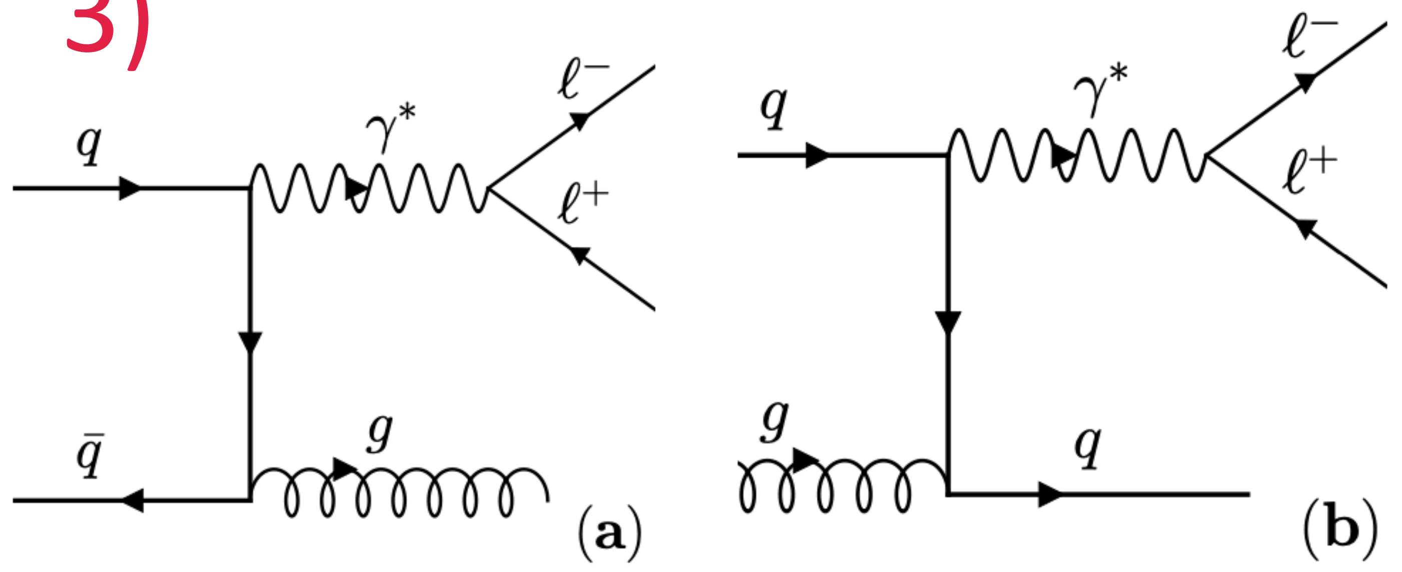
1)



2)



3)

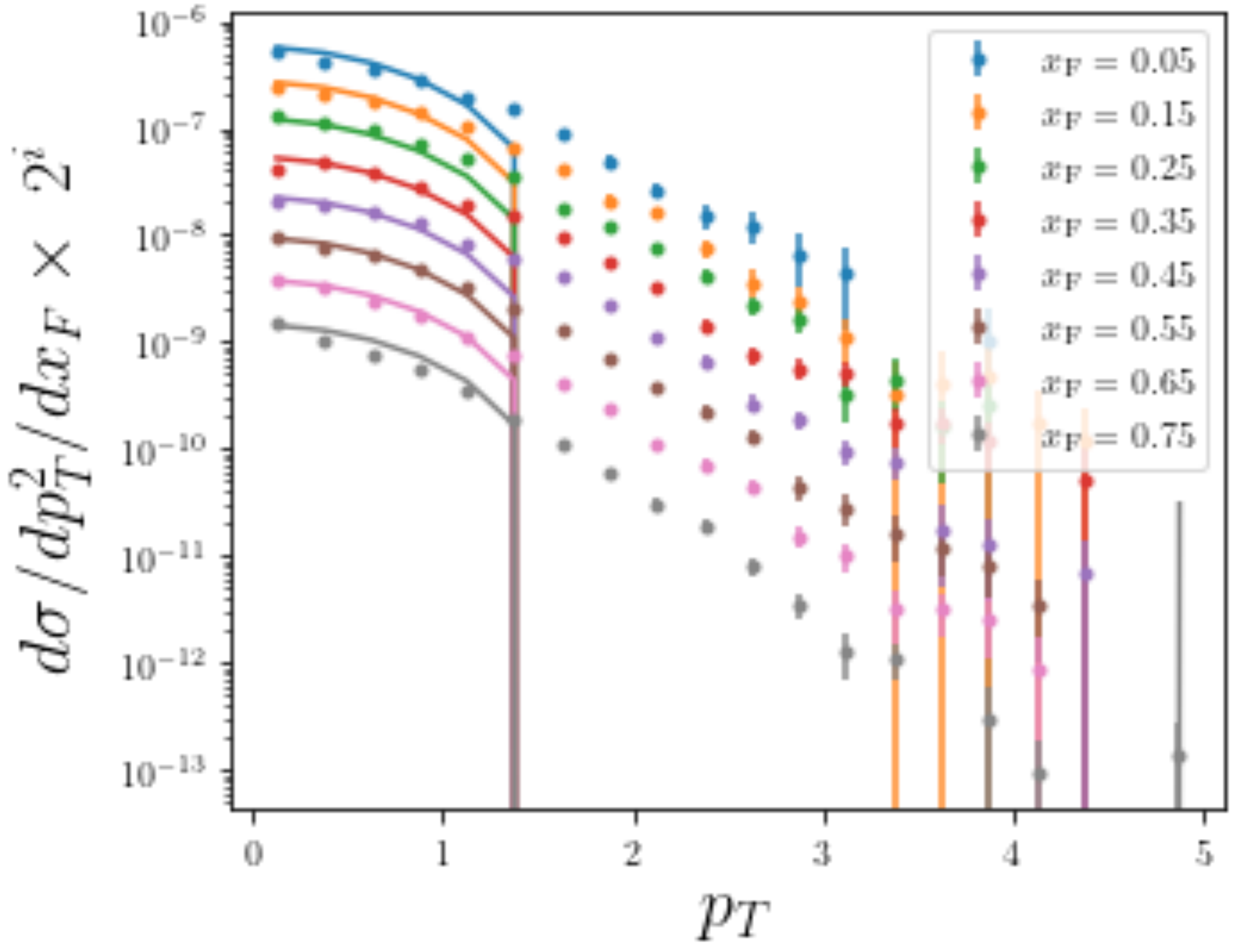


3) $$\frac{d\sigma^{\rm DY}}{dQ^2 dy dp_T} = \sum_{a,b} \int \mathrm{d}x_a\, \mathrm{d}x_b\, H^{\rm FO}_{a,b}(x_a, x_b, y, p_{\rm T}, Q^2, \mu^2)\, f_{a/A}(x_a, \mu^2)\, f_{b/B}(x_b, \mu^2)$$

"More granular" $p_T \sim k_T \ll Q$ access to the Pion TMDs

To describe the transverse momentum "region" $p_T \sim k_T \ll Q$ is the regime of TMDs of the pion

That require fitting "region" $p_T \sim k_T \ll Q$ differential pion-induced Drell-Yan cross section



TMD Factorization

$$\frac{d\sigma^W}{dQ^2\, dx_F\, dp_T^2} = \int \frac{d^2 \boldsymbol{b}_T}{(2\pi)^2}\, e^{i \boldsymbol{p}_T \cdot \boldsymbol{b}_T} \tilde{W}(x_F, b_T, Q)$$

$$\tilde{W}(x_F, b_T, Q) = \sum_j H^{DY}_{j\bar{j}}(Q, \mu, a_s(\mu)) \tilde{f}_{j/A}(x_A, b_T; \zeta_A, \mu) \tilde{f}_{\bar{j}/B}(x_B, b_T; \zeta_B, \mu)$$

TMD Factorization

- ***Collins Soper Sterman NPB 1985***
- ***Ji Ma Yuan PRD PLB …2004, 2005***
- ***Aybat Rogers PRD 2011***
- ***Collins 2011 Cambridge Press***
- ***Echevarria, Idilbi, Scimemi JHEP 2012***
- ***… many more refs***

Some earlier work on pion-hadron DY

- F. Ceccopieri, A. Courtoy , S. Noguera, S. Scopetta, EJP 2018 CSS Evolution w/ NJL
- Vladimirov JHEP 2019 Pion-induced DY processes within TMD factorization

The Pion TMDs & Factorization

TMD Factorization

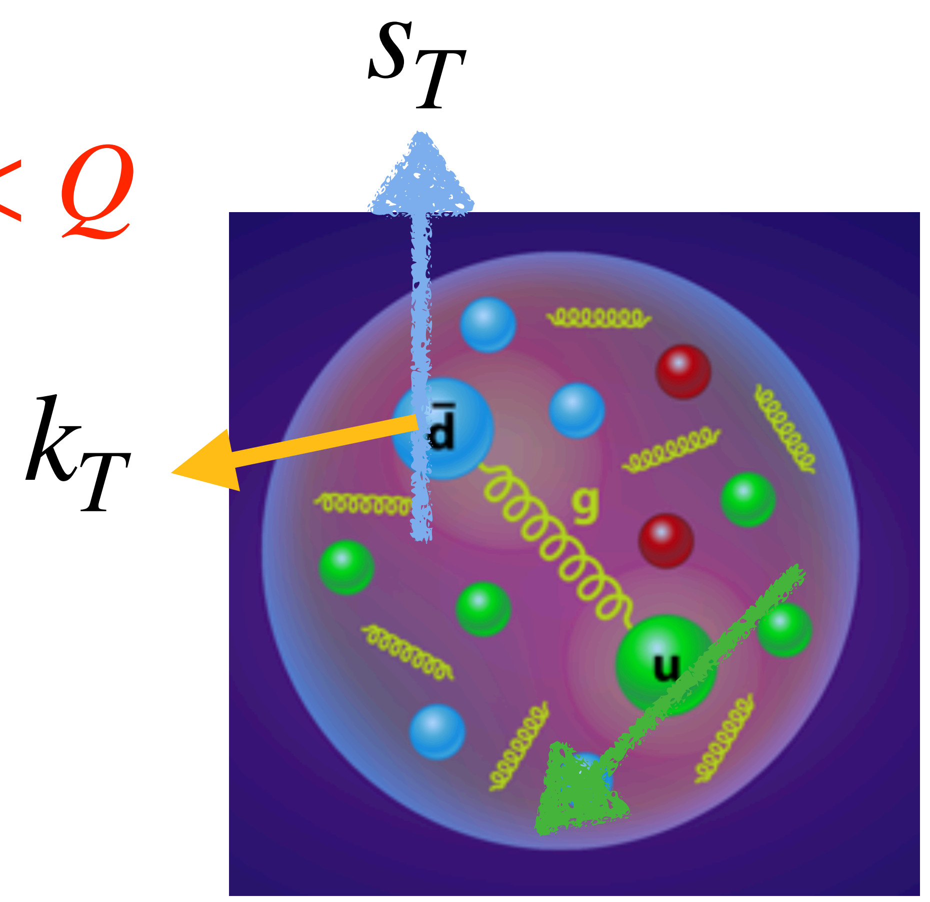
- ✦*Mulders Tangerman NPB 1995*
- ✦*Boer Mulders PRD 1997*

Leading Power TMDPDFs

Quark Spin

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
ion	U	f_1 = Unpolarized		$h_1^{\perp}$ = − Boer-Mulders

$q_T \sim k_T \ll Q$



$$f(x, k_T, s_T) = \frac{1}{2}\left[f_1^{\pi}(x, k_T^2) + \frac{s_T^i \epsilon^{ij} k_T^j}{m_\pi} h_1^{\pi\,\perp}(x, k_T^2)\right]$$

Factorization carried out Fourier b_T space FT TMDs $\tilde{f}(x, b_T; \zeta, \mu)$

Real QCD need QFT definitions of TMDs LC & UV divergences

TMD Evolution depends on rapidity ζ and RGE scales μ

4W) !!!

$$\frac{d\sigma^W}{dQ^2\, dx_F\, dp_T^2} = \int \frac{d^2\boldsymbol{b}_T}{(2\pi)^2}\, e^{i\boldsymbol{p}_T\cdot\boldsymbol{b}_T}\, \tilde{W}(x_F, b_T, Q)$$

$$\tilde{W}(x_F, b_T, Q) = \sum_j H_{j\bar{j}}^{DY}(Q, \mu, a_s(\mu))\, \tilde{f}_{j/A}(x_A, b_T; \zeta_A, \mu)\, \tilde{f}_{\bar{j}/B}(x_B, b_T; \zeta_B, \mu)$$

TMD Factorization

- ✦*Collins Soper Sterman NPB 1985*
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- ✦*Collins 2011 Cambridge Press*
- ✦*Echevarria, Idilbi, Scimemi JHEP 2012,*

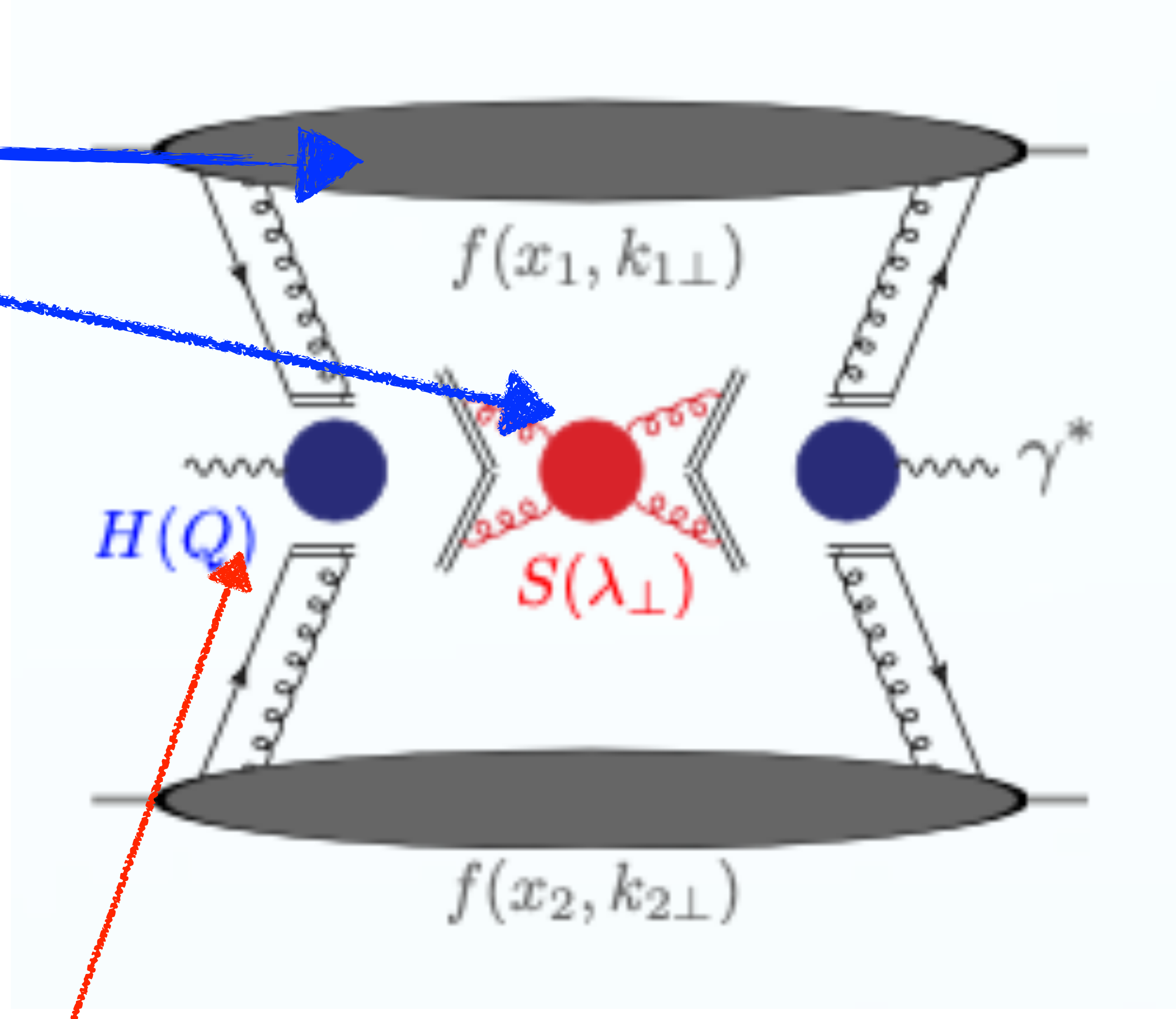
TMD factorization—Renormalization and Evolution

$$\tilde{f}^{\text{sub}}_{j/H}(x,\boldsymbol{b};\mu,\zeta_{\text{PDF}}) = \lim_{\substack{y_A\to+\infty\\ y_B\to-\infty}} \underbrace{\tilde{f}^{\text{unsub}}_{j/H}(x,\boldsymbol{b};\mu,n_B(y_B))} \sqrt{\frac{\tilde{S}(\boldsymbol{b};y_A,y_s)}{\tilde{S}(\boldsymbol{b};y_A,y_B)\tilde{S}(\boldsymbol{b};y_s,y_B)}} \times Z_2 Z_F$$

$$\Updownarrow$$

$$\tilde{f}^{\text{unsub}}_{j/H}(x,b_T;\mu,y_P-y_B) = \int \frac{db^-}{2\pi} e^{-ixP^+b^-} \langle P|\bar{\psi}(0)\gamma^+\mathcal{U}_{[0,b]}\psi(b)|P\rangle|_{b^+=0}$$

$$\zeta \equiv x^2 M_P^2 e^{y_P-y_s}, \quad \text{and} \quad n_B(y_B) \equiv y_P - y_B$$



- TMDs depend on two scales ζ and μ resulting from need to regulate light cone & UV divergences

- In full QCD, the ζ and μ dependence of TMDs reflected in solution to the
  - ✳Collins-Soper
  - ✳RG equations

$$\frac{d\sigma^W}{dQ^2\,dx_F\,dp_T^2} = \int \frac{d^2\boldsymbol{b}_T}{(2\pi)^2}\, e^{i\boldsymbol{p}_T\cdot\boldsymbol{b}_T}\tilde{W}(x_F,b_T,Q)$$

$$\tilde{W}(x_F,b_T,Q) = \sum_j H^{\text{DY}}_{j\bar{j}}(Q,\mu,a_s(\mu))\tilde{f}_{j/A}(x_A,b_T;\zeta_A,\mu)\tilde{f}_{\bar{j}/B}(x_B,b_T;\zeta_B,\mu)$$

Renormalization and Evolution- $\{\zeta, \mu\}$ TMD

- Collins Soper Eq. $$\frac{\partial \ln \tilde{f}_{j/H}(x, b_T; \mu, \zeta)}{\partial \ln \sqrt{\zeta}} = \tilde{K}(b_T, \mu)$$

$$\tilde{K}(b_T, \mu) \equiv \frac{1}{2} \frac{\partial}{\partial y_n} \ln \frac{S(b_T, y_n, -\infty)}{S(b_T, y_n, -\infty)}$$

- RGE for C.S. kernel $$\frac{d\tilde{K}(b_T; \mu)}{d \ln \mu} = -\gamma_k(\alpha_s(\mu))$$
- RGE for TMD $$\frac{d \ln \tilde{f}_{j/H}(x, b_T; \mu, \zeta)}{d \ln \mu} = -\gamma_F(\alpha_s(\mu), \zeta/\mu)$$

Solve simultaneously and get evolved renormalized TMD $\rightarrow \zeta = Q^2, \quad \mu = \mu_Q \sim Q$

$$\tilde{f}_1(x, b_T; Q^2, \mu_Q) \sim \left(\tilde{C}^{f_1}(x/\hat{x}, b_*(b_T); \mu_{b_*}^2, \mu_{b_*}, \alpha_s(\mu_{b_*})) \otimes f_1(\hat{x}; \mu_{b_*})\right)$$
$$\times \exp\left[-S_{pert}(b_*(b_T); \mu_{b_*}, Q, \mu_Q) - S_{NP}^{f_1}(b_T, Q)\right]$$

Collins (2011); ...

CSS evolution *F.T.*-TMD B.C. OPE & b_* prescript.

Solution w/ evolution

$$\tilde{f}_1(x, b_T, Q^2, \mu_Q) \sim \left[\tilde{C}^{f_1}\left(x/\hat{x}, \boldsymbol{b}_*; \mu_{b_*}^2, \mu_{b_*}, \alpha(\mu_{b_*})\right) \otimes f_1(\hat{x}, \mu_{b_*})\right]$$

$$\times \exp\left[-S_{pert}(\mu_{b_*}(b_T); \mu_{b_*}, Q^2) - S_{NP}(b_T, Q)\right]$$

perturbative Sudakov factor

non-perturbative Sudakov factor

$$\underbrace{-\ln(Q/\mu_{b_*})\tilde{K}(b_*, \mu_{b_*}) - \int_{\mu_{b_*}}^{\mu_Q} \frac{d\mu'}{\mu'}\left[\gamma(\alpha_s(\mu'); 1) - \gamma_K(\alpha_s(\mu'))\ln(Q/\mu')\right]}_{\text{same for unpol. and pol.}}$$

$$g_{f_1}(x, b_T) + g_K(b_T)\ln(Q/Q_0)$$

different for each TMD

universal

$$b_*(b_T) \equiv \sqrt{\frac{b_T^2}{1 + b_T^2/b_{\max}^2}} \qquad \mu_{b_*} = C_1/b_*(b_T)$$

TMD factorization

- In small-p_T region, Use the CSS formalism for TMD evolution

Aybat Rogers 2011 & Collins 2011

$$\frac{d\sigma}{dQ^2\,dy\,dq_T^2} = \frac{4\pi^2\alpha^2}{9Q^2 s} \sum_{j,j_A,j_B} H^{\mathrm{DY}}_{j\bar{j}}(Q,\mu_Q,a_s(\mu_Q)) \int \frac{d^2\boldsymbol{b}_T}{(2\pi)^2} e^{i\boldsymbol{q}_T\cdot\boldsymbol{b}_T}$$
$$\times\, e^{-\boxed{g_{j/A}(x_A,b_T;b_{\max})}} \int_{x_A}^{1} \frac{d\xi_A}{\xi_A} f_{j_A/A}(\xi_A;\mu_{b_*})\, \tilde{C}^{\mathrm{PDF}}_{j/j_A}\left(\frac{x_A}{\xi_A}, b_*;\mu^2_{b_*},\mu_{b_*},a_s(\mu_{b_*})\right)$$
$$\times\, e^{-\boxed{g_{\bar{j}/B}(x_B,b_T;b_{\max})}} \int_{x_B}^{1} \frac{d\xi_B}{\xi_B} f_{j_B/B}(\xi_B;\mu_{b_*})\, \tilde{C}^{\mathrm{PDF}}_{\bar{j}/j_B}\left(\frac{x_B}{\xi_B}, b_*;\mu^2_{b_*},\mu_{b_*},a_s(\mu_{b_*})\right)$$
$$\times \exp\left\{-\boxed{g_K(b_T;b_{\max})}\ln\frac{Q^2}{Q_0^2} + \tilde{K}(b_*;\mu_{b_*})\ln\frac{Q^2}{\mu^2_{b_*}} + \int_{\mu_{b_*}}^{\mu_Q}\frac{d\mu'}{\mu'}\left[2\gamma_j(a_s(\mu')) - \ln\frac{Q^2}{(\mu')^2}\gamma_K(a_s(\mu'))\right]\right\}$$

Non-perturbative TMDs to extract

$W - term$

- Perturbative content calculated from first principles of QFT
- Non-perturbative content (as for collinear case) to be fit to data

Non-perturbative Universal content

$$\boxed{g_k(b_T; b_{max})}$$

- Perturbative content calculated from first principles of QFT
- Non-perturbative content (as for collinear case) to be fit

❋ $$g_K(b_T; b_{max}) = \frac{g_2 b_{NP}^2}{2} \ln\left(1 + \frac{b_T^2}{b_{NP}^2}\right) = g_2 b_{NP}^2 \ln \frac{b_T}{b_*}$$

$$\lim_{b_T \to 0} g_K(b_T; b_{max}) \approx \frac{g_2}{2} b_T^2$$

Aidala, Field, Gamberg, Rogers PRD 2014 “Large b_T “

❋ $$g_k(b_T; b_{max}) = g_0 \left(1 - \exp\left[-\frac{C_F \alpha_s(\mu_{b*}) b_T^2}{\pi g_0(b_{max}) b_{max}^2}\right]\right)$$

Collins Rogers PRD 2015 “Large b_T “

❋ $$g_k(b_T; b_{max}) = \frac{g_2}{2} b_T b_*$$

Vladimirov JHEP 2019 “Large b_T “

Non-perturbative “intrinsic” content

$$\boxed{g_j(x, b_T)}$$

- Perturbative content calculated from first principles of QFT
- Non-perturbative content (as for collinear case) to be fit

- $$g_j(x, b_T) = b_T^2 \left(\frac{g_1}{2} + g_1 g_3 \log \left(\frac{10 x x_0}{(x + x_0)} \right) \right)$$ Aybat Rogers 2011

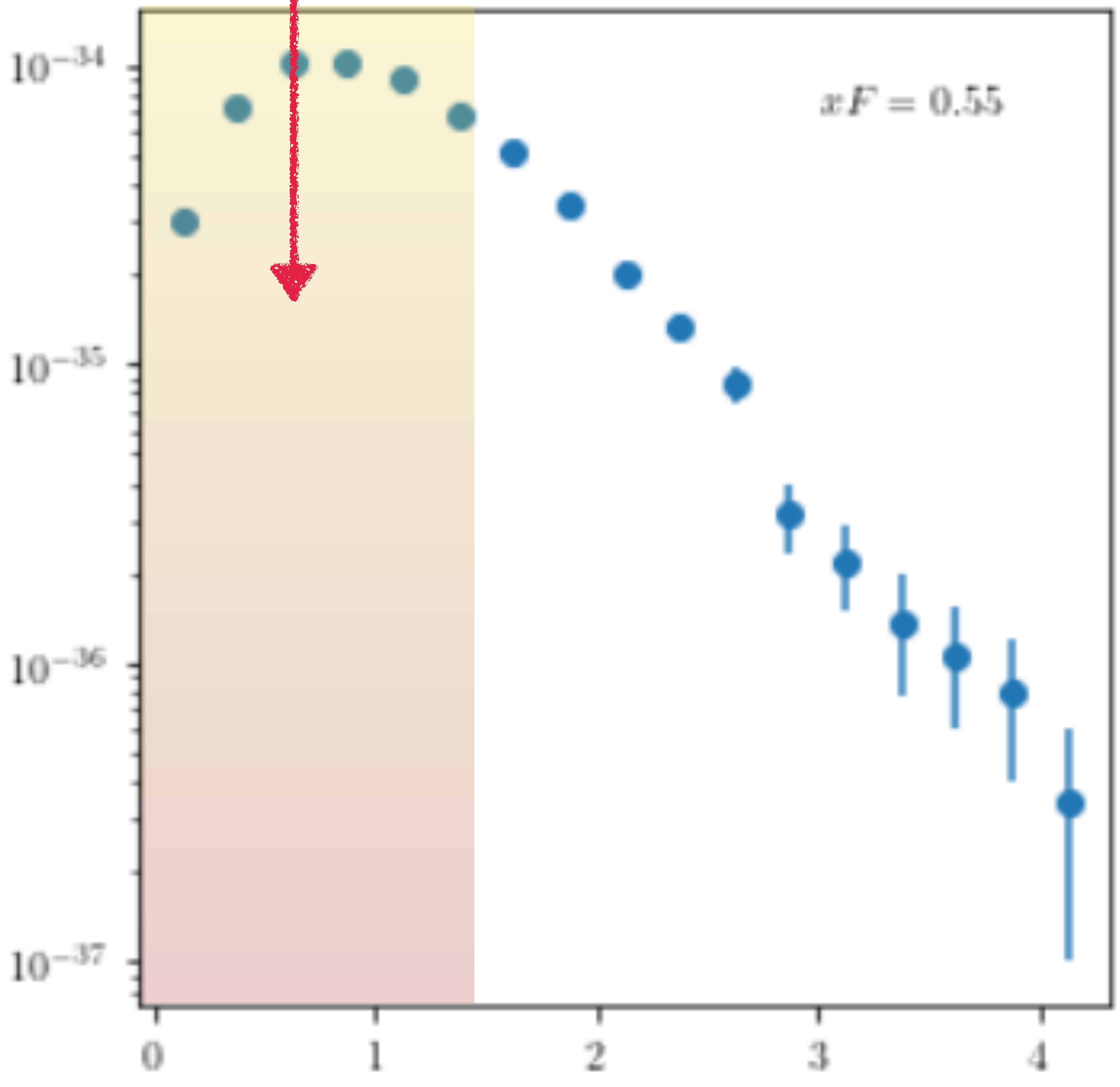
- $$g_j(x, b_T) = \frac{(g_1 + g_3 x) b_T^2}{\sqrt{1 + |g_4| x^2 b_T^2}}$$ Vladimirov JHEP 2019

- $$F_{QZ}^{NP}(b, Q, x_A, x_B; b_{max}) = \exp\left\{ -\ln\left(\frac{Q^2 b_{max}^2}{c^2} \right) \{ g_1 [(b^2)^\alpha - (b_{max}^2)^\alpha] + g_2 (b^2 - b_{max}^2) \} - \bar{g}_2 (b^2 - b_{max}^2) \right\}$$ Qiu & Zhang PRL 2001

- $$\tilde{f}(b_T, x, Q) = N \frac{\frac{M^{1+\nu}}{b_T \Gamma(\nu)} \left(\frac{2}{b_T} \right)^{1-\nu} k_{1-\nu}\left(M b_T \frac{10 x x_0}{(x+x_0)}\right) \times (1 + A b_T + B/b_T)}{\frac{M^{1+\nu}}{b_{T*} \Gamma(\nu)} \left(\frac{2}{b_{T*}} \right)^{1-\nu} k_{1-\nu}\left(M b_{T*} \frac{10 x x_0}{(x+x_0)}\right) \times (1 + A b_{T*} + B/b_{T*})}$$ Bessel parametrization has large exponential behavior in b_T

$$\frac{d\sigma(m \lesssim q_T \lesssim Q, Q)}{dy\,dq^2\,dp_T^2} = W(p_T, Q) + FO(p_T, Q) - AY(p_T, Q) + O\left(\frac{m}{Q}\right)^c$$

$Y = F0 - AY$



E615 DY Data
(E537 also)
also need proton data
E288
E605
E772

Fixed Target Data only!

1) We have fit the NP parameters will show in simultaneous fit

2) Open TMD & collinear params to all pion data

Preliminary *Vladimirov's NP content*

Open proton and pion TMDs and pion collinear

Fit all pT-integrated DY, LN, low-pT DY data from pions and protons

Includes now a fit of the universal NP TMD parameter

reaction: DYpT
filters: Q<9
filters: xF<0.8
filters: pTmax<0.4*Qmin
reaction: DYpT

idx	col	obs	tar	npts	chi2	chi2/npts	[redacted]	nchi2
12881	E288	Ed3sigma/dp3	pp	52.00	86.43	1.66	[redacted]	0.01
12882	E288	Ed3sigma/dp3	pp	54.00	73.36	1.36	[redacted]	0.01
12883	E288	Ed3sigma/dp3	pp	51.00	95.59	1.87	[redacted]	0.09
10605	E605	Ed3sigma/dp3	pp	25.00	63.89	2.56	[redacted]	0.25
10772	E772	Ed3sigma/dp3	pp	39.00	105.65	2.71	[redacted]	0.04
1001	E615	d2sigma/dpTdm	pi-p	59.00	210.18	3.56	[redacted]	4.93
1002	E615	d2sigma/dpTdx	pi-p	48.00	112.10	2.34	[redacted]	0.01
15371	E537	d2sigma/dpT2dm	pi-p	61.00	50.59	0.83	[redacted]	1.77
15372	E537	d2sigma/dpT2dx	pi-p	45.00	43.28	0.96	[redacted]	0.49

reaction: dy-pion
filters: Q2>4.16**2
filters: Q2<59.0
filters: xF>0
filters: xF<0.9
reaction: dy-pion

idx	col	obs	tar	npts	chi2	chi2/npts	[redacted]	nchi2
10001	E615	dsig/drtau/dxF	pi-W	61.00	50.23	0.82	[redacted]	0.00
10002	NA10	dsig/drtau/dxF	pi-W	36.00	22.34	0.62	[redacted]	11.96
10003	NA10	dsig/drtau/dxF	pi-W	20.00	21.05	1.05	[redacted]	6.30

reaction: ln
filters: y<0.2
reaction: ln

idx	col	obs	tar	npts	chi2	chi2/npts	[redacted]	nchi2
1000	H1	F2LN	ep->e'nX	58.00	21.72	0.37	[redacted]	13.57
2000	ZEUS	R	ep->e'nX	50.00	69.84	1.40	[redacted]	0.36

2) Open TMD & collinear params to all pion data

Preliminary

Open proton and pion TMDs and pion collinear

idx	dist	type	value
1	pdf-pion	g1 N	3.75e-01
2	pdf-pion	g1 a	-1.03e+00
3	pdf-pion	g1 b	2.65e+00
4	pdf-pion	u1 a	-9.12e-01
5	pdf-pion	u1 b	5.49e+00
6	pdf-pion	ubv1 a	-3.13e-01
7	pdf-pion	ubv1 b	9.70e-01
8	p->pi,n	lambda	1.37e+00
9	universal	g2	9.61e-03
10	tmd	g1	2.55e-02
11	tmd	g3	7.81e-01
12	tmd	g4	-5.27e+00
13	tmd-pion	g1	4.65e-02
14	tmd-pion	g3	5.89e-01
15	tmd-pion	g4	-2.24e+00
16	DYpT	12881	1.03e+00
17	DYpT	12882	1.03e+00
18	DYpT	12883	1.08e+00
19	DYpT	10605	1.07e+00
20	DYpT	10772	9.80e-01
21	DYpT	1001	1.36e+00
22	DYpT	1002	9.81e-01
23	DYpT	15371	1.17e+00
24	DYpT	15372	9.09e-01
25	dy-pion	10001	1.00e+00
26	dy-pion	10002	8.27e-01
27	dy-pion	10003	7.74e-01
28	ln	1000	1.18e+00
29	ln	2000	9.76e-01

2) Open TMD & collinear params to all pion data

Preliminary

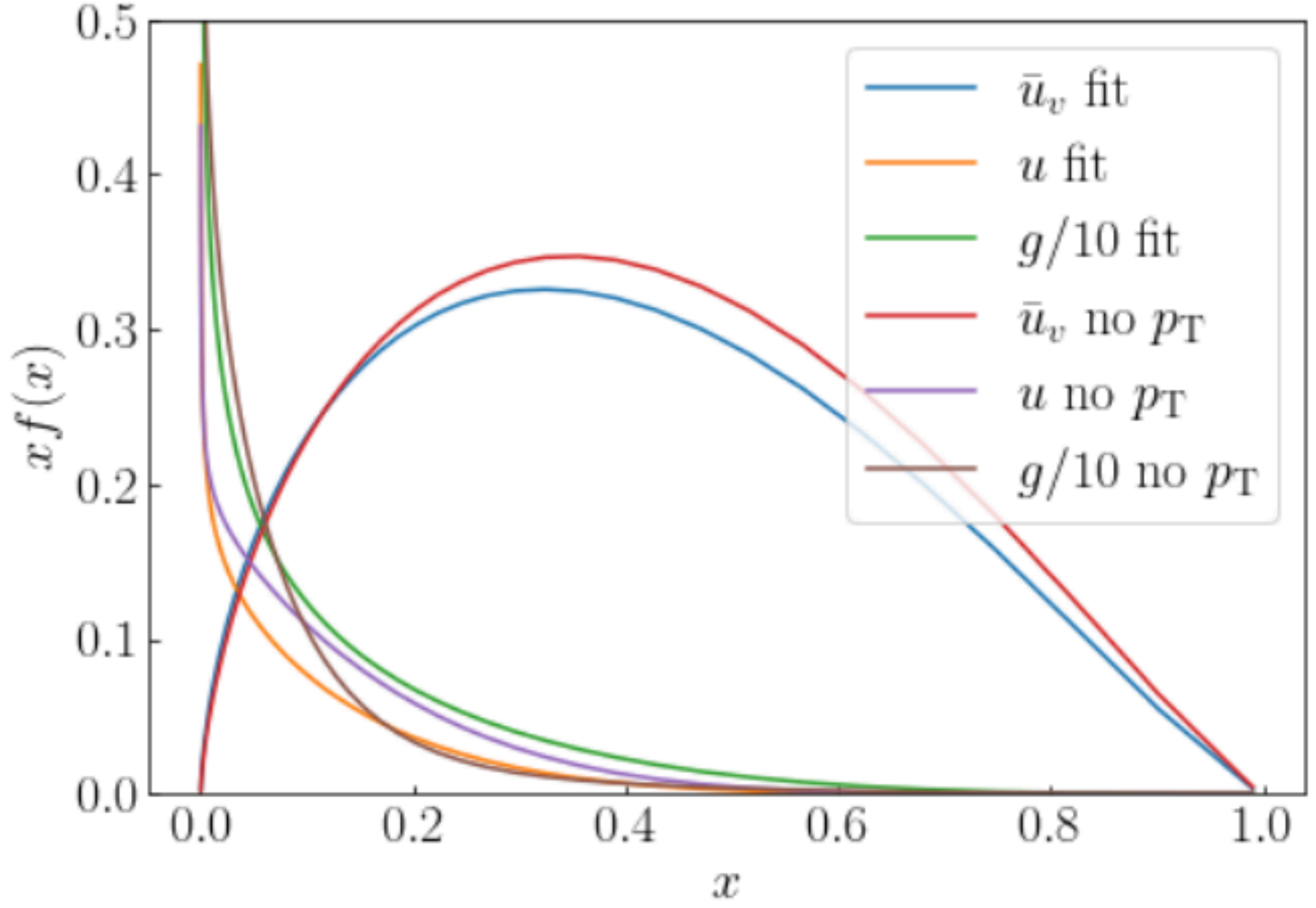
nb. fixed target DY experiments, the expected constraints will be on the collinear valence distribution.

Open proton and pion TMDs and pion collinear

PDFs look somewhat different with the inclusion of pT data.

Gluon is larger at higher x, while sea is smaller

Valence has some reduction at larger x



2) Open TMD & collinear params to all pion data

Preliminary

Open proton and pion TMDs and pion collinear

Proton data -- E288

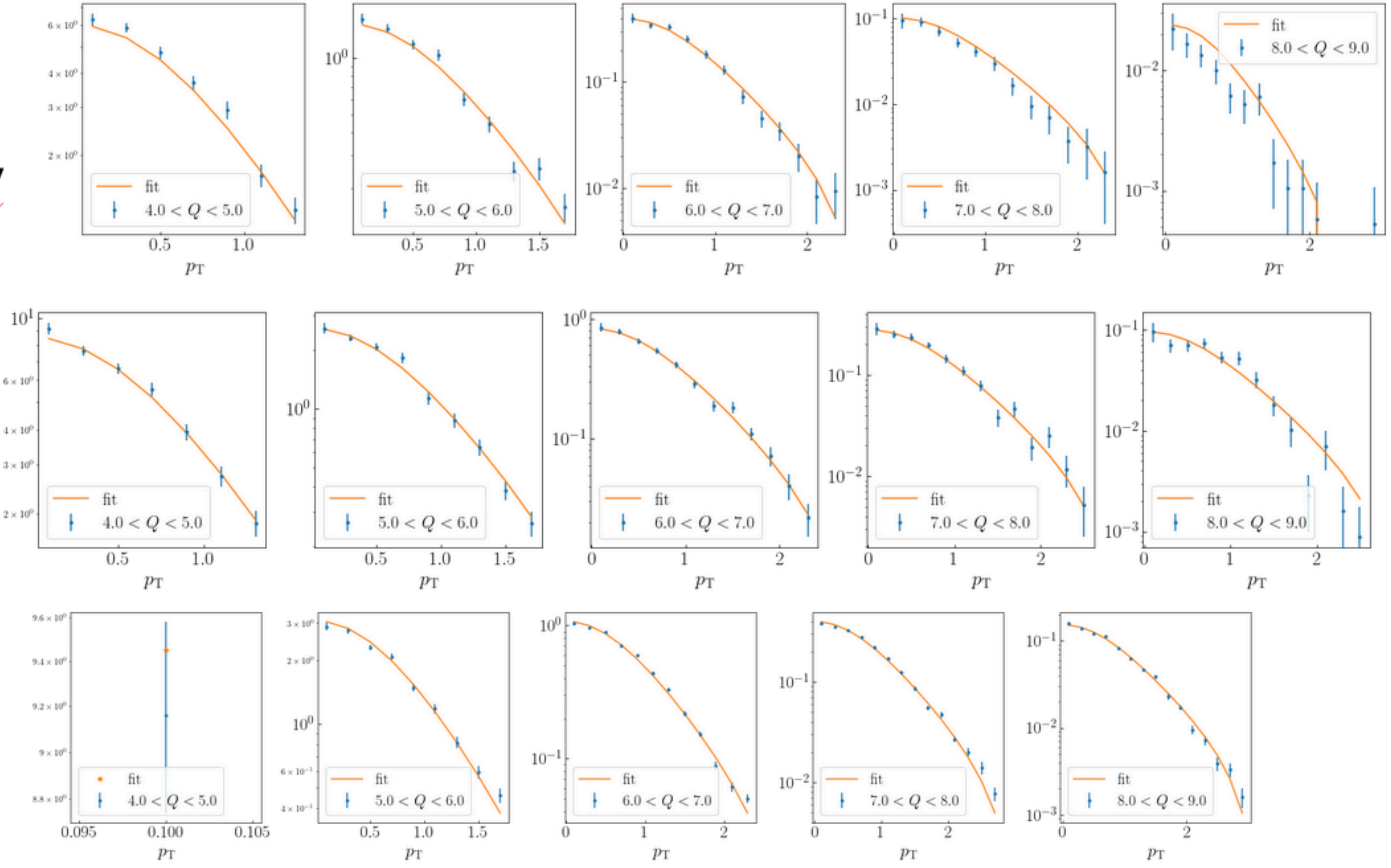
Observable:

$$E\frac{d^3\sigma}{dp^3}$$

E=200GeV

E=300GeV

E=400GeV



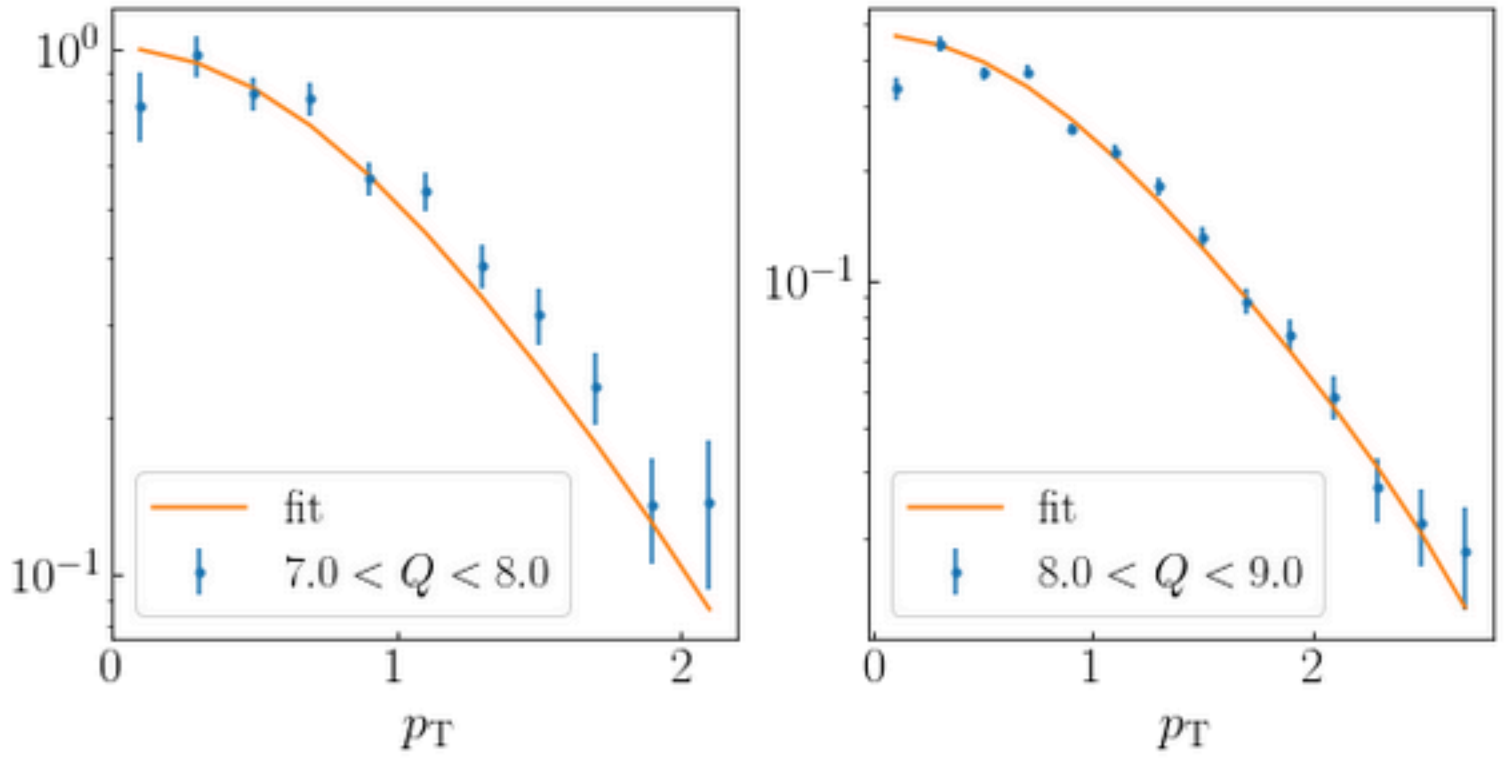
2) Open TMD & collinear params to all pion data

Preliminary

Open proton and pion TMDs and pion collinear

Proton data

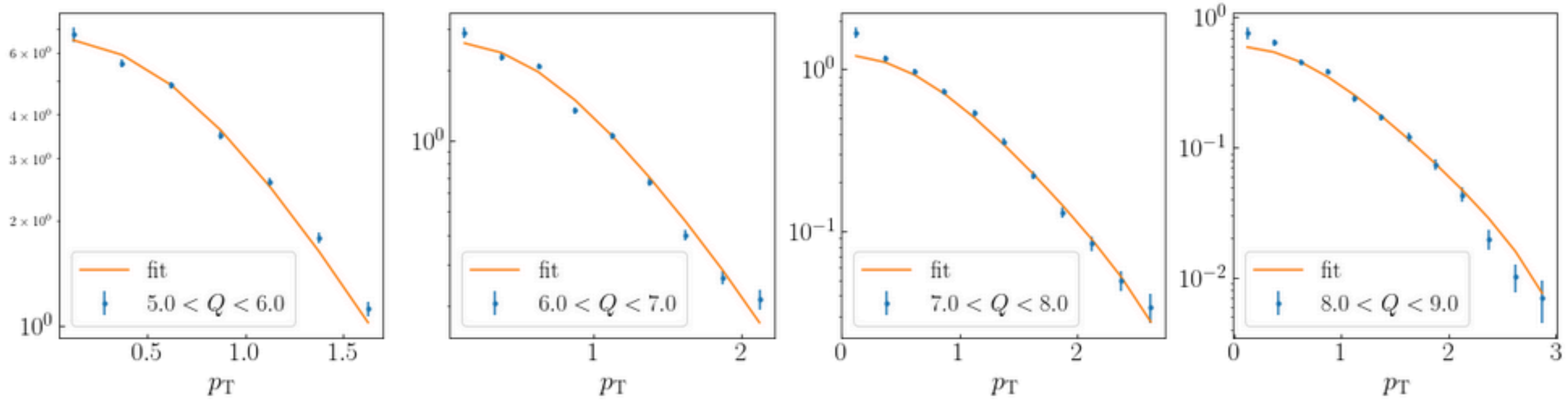
E605



Observable:

$$E\frac{d^3\sigma}{dp^3}$$

E772

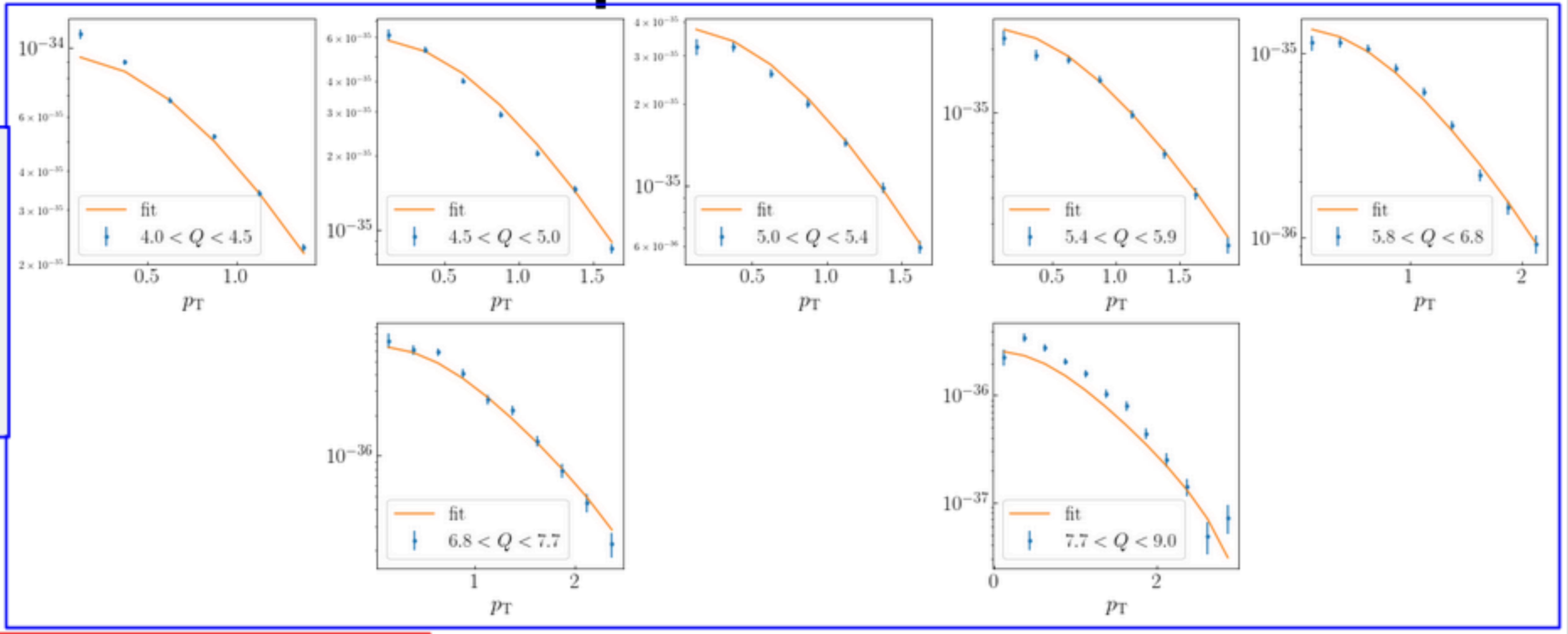


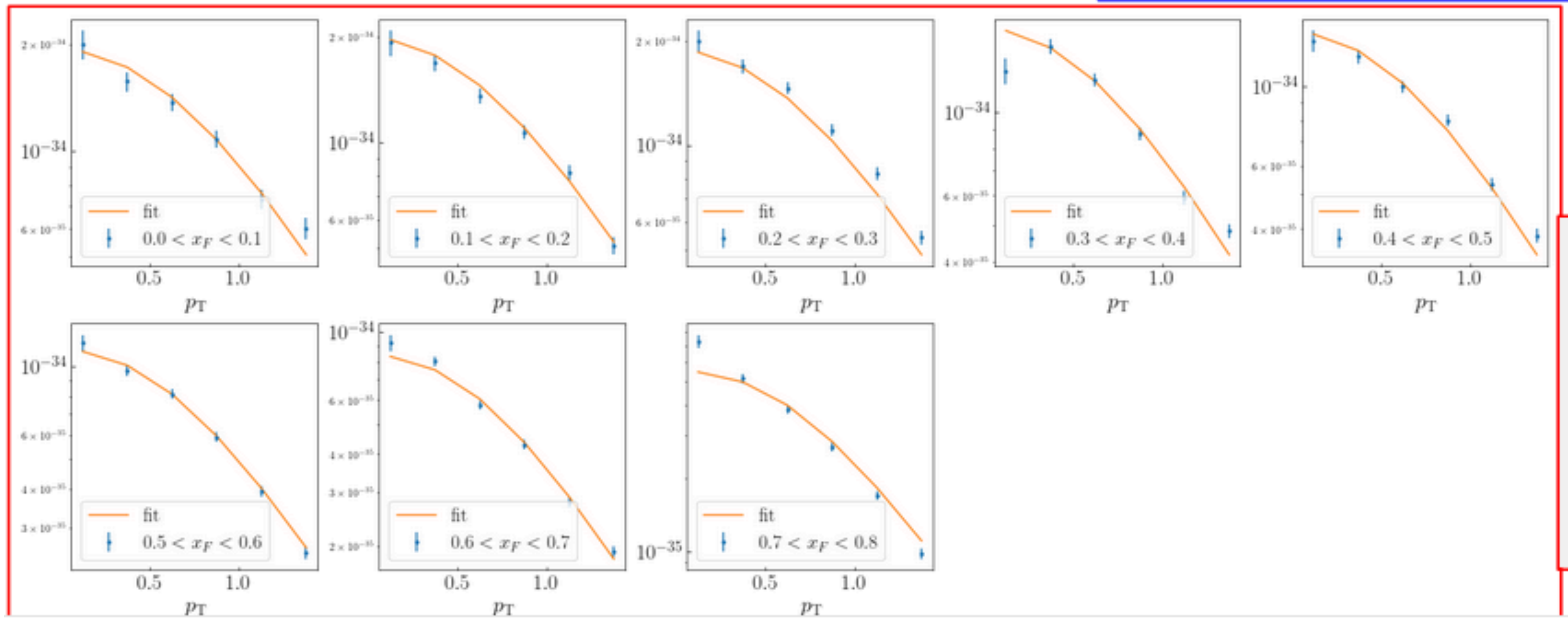
2) Open TMD & collinear params to all pion data

Open proton and pion TMDs and pion collinear

Pion data - E615

$$\frac{d^2\sigma}{dp_{\mathrm{T}}^2\, dQ}$$





$$\frac{d^2\sigma}{dp_{\mathrm{T}}^2\, dx_F}$$

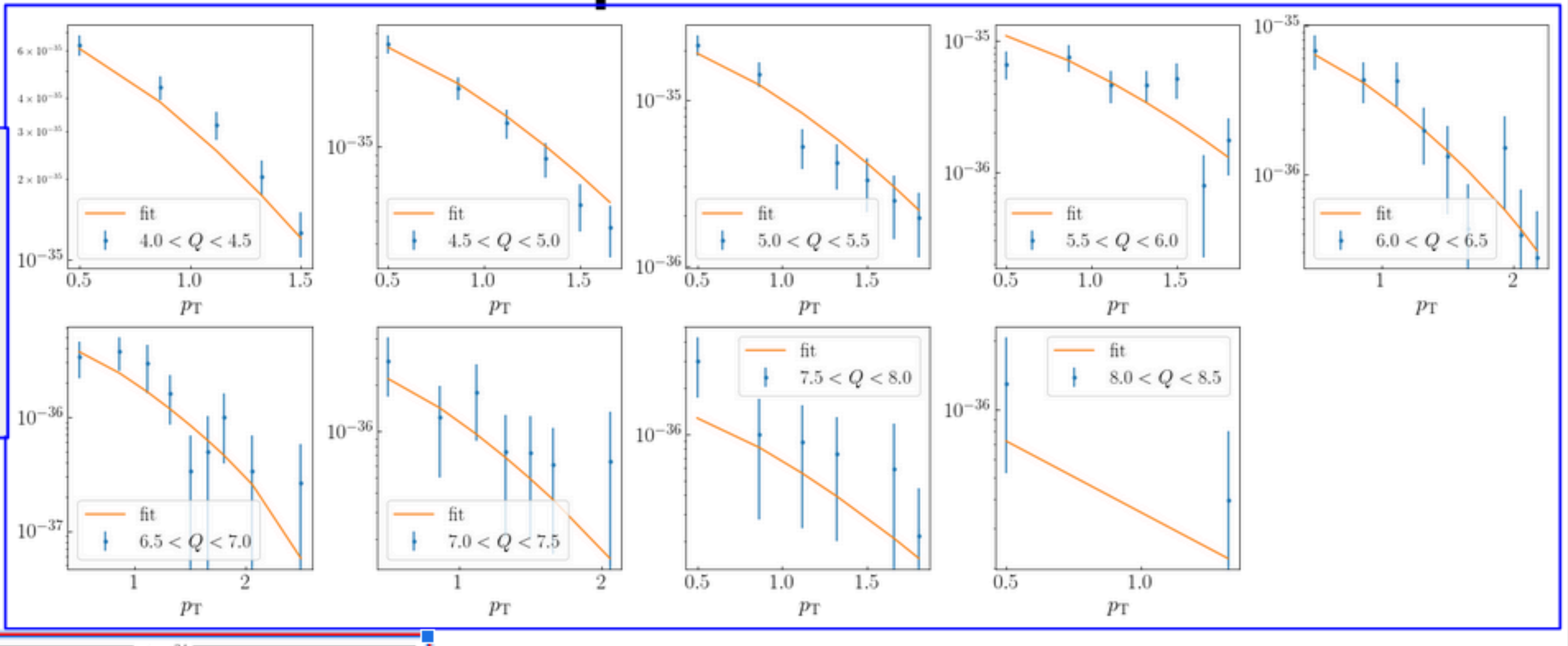
2) Open TMD & collinear params to all pion data

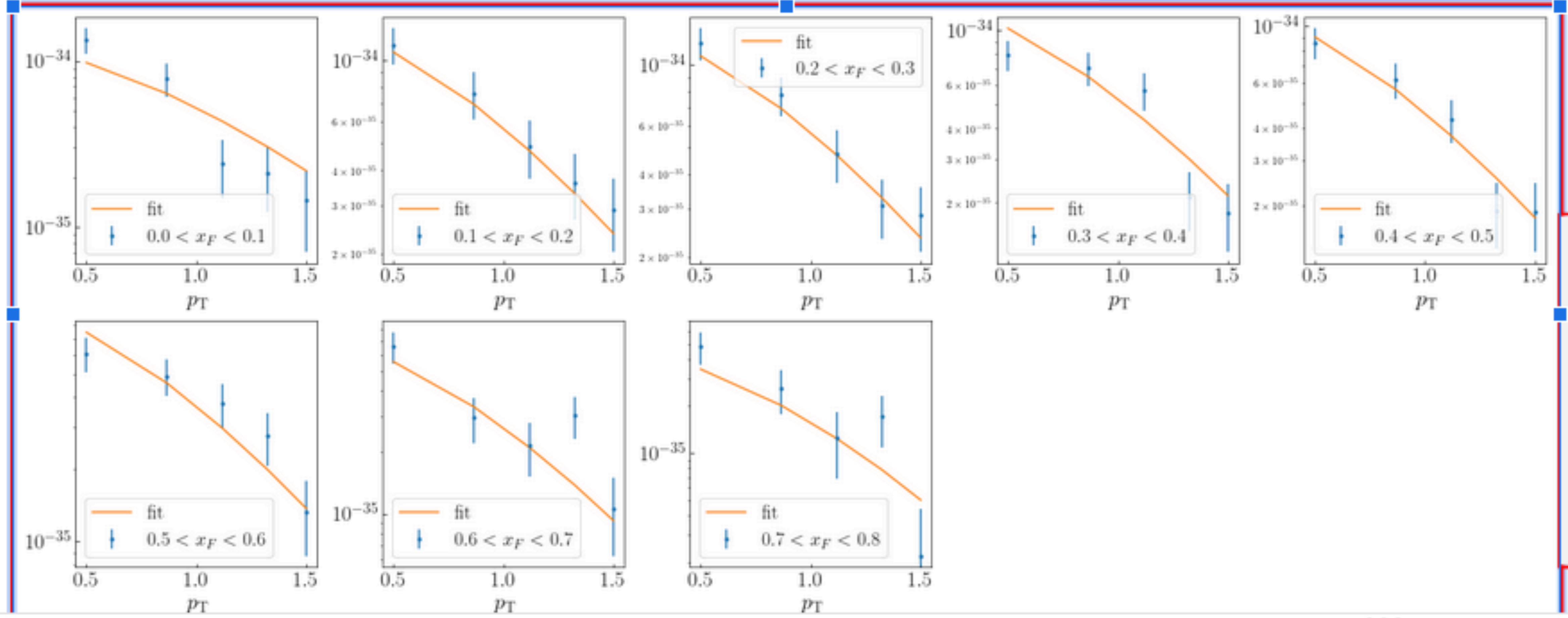
Preliminary

Open proton and pion TMDs and pion collinear

Pion data - E537

$$\frac{d^2\sigma}{dp_{\rm T}^2 dQ}$$





$$\frac{d^2\sigma}{dp_{\rm T}^2 dx_F}$$

Open TMD & collinear params to all pion data

Preliminary

Simultaneous fit for CSS and Bessel

1) Fit both proton and pion to only DYpT data -- get proton parameters
2) Fit collinear and TMD to pion DYpT data
3) Fit collinear and TMD to all data

Open TMD & collinear params to all pion data

Preliminary

Bessel and CSS -- fit proton and pion to DYpT

reaction: DYpT
filters: Q<9
filters: xF<0.8
filters: pTmax<0.4*Qmin
reaction: DYpT

idx	col	obs	tar	npts	chi2	chi2/npts	rchi2	nchi2
12881	E288	Ed3sigma/dp3	pp	52.00	105.90	2.04	0.00	0.03
12882	E288	Ed3sigma/dp3	pp	54.00	70.32	1.30	0.00	0.07
12883	E288	Ed3sigma/dp3	pp	51.00	87.94	1.72	0.00	0.02
10605	E605	Ed3sigma/dp3	pp	25.00	62.44	2.50	0.01	0.02
10772	E772	Ed3sigma/dp3	pp	39.00	124.68	3.20	0.68	2.10
1001	E615	d2sigma/dpTdm	pi-p	59.00	202.03	3.42	0.00	3.35
1002	E615	d2sigma/dpTdx	pi-p	48.00	155.19	3.23	0.00	0.13
15371	E537	d2sigma/dpT2dm	pi-p	61.00	49.93	0.82	0.00	1.51
15372	E537	d2sigma/dpT2dx	pi-p	45.00	41.67	0.93	0.00	0.62

idx	dist	type	value
1	universal	g0	6.44e-02
2	tmd	CA	5.18e+00
3	tmd	CB	1.33e-03
4	tmd	M	1.98e+00
5	tmd	nu	3.17e+00
6	tmd	x0	5.30e-02
7	tmd-pion	CA	3.22e+00
8	tmd-pion	CB	9.28e-02
9	tmd-pion	M	1.02e+00
10	tmd-pion	nu	1.85e+00
11	tmd-pion	x0	6.62e-02
12	DYpT	12881	9.56e-01
13	DYpT	12882	9.33e-01
14	DYpT	12883	9.63e-01
15	DYpT	10605	9.77e-01
16	DYpT	10772	8.55e-01
17	DYpT	1001	1.29e+00
18	DYpT	1002	9.41e-01
19	DYpT	15371	1.16e+00
20	DYpT	15372	8.98e-01

Open TMD & collinear params to all pion data

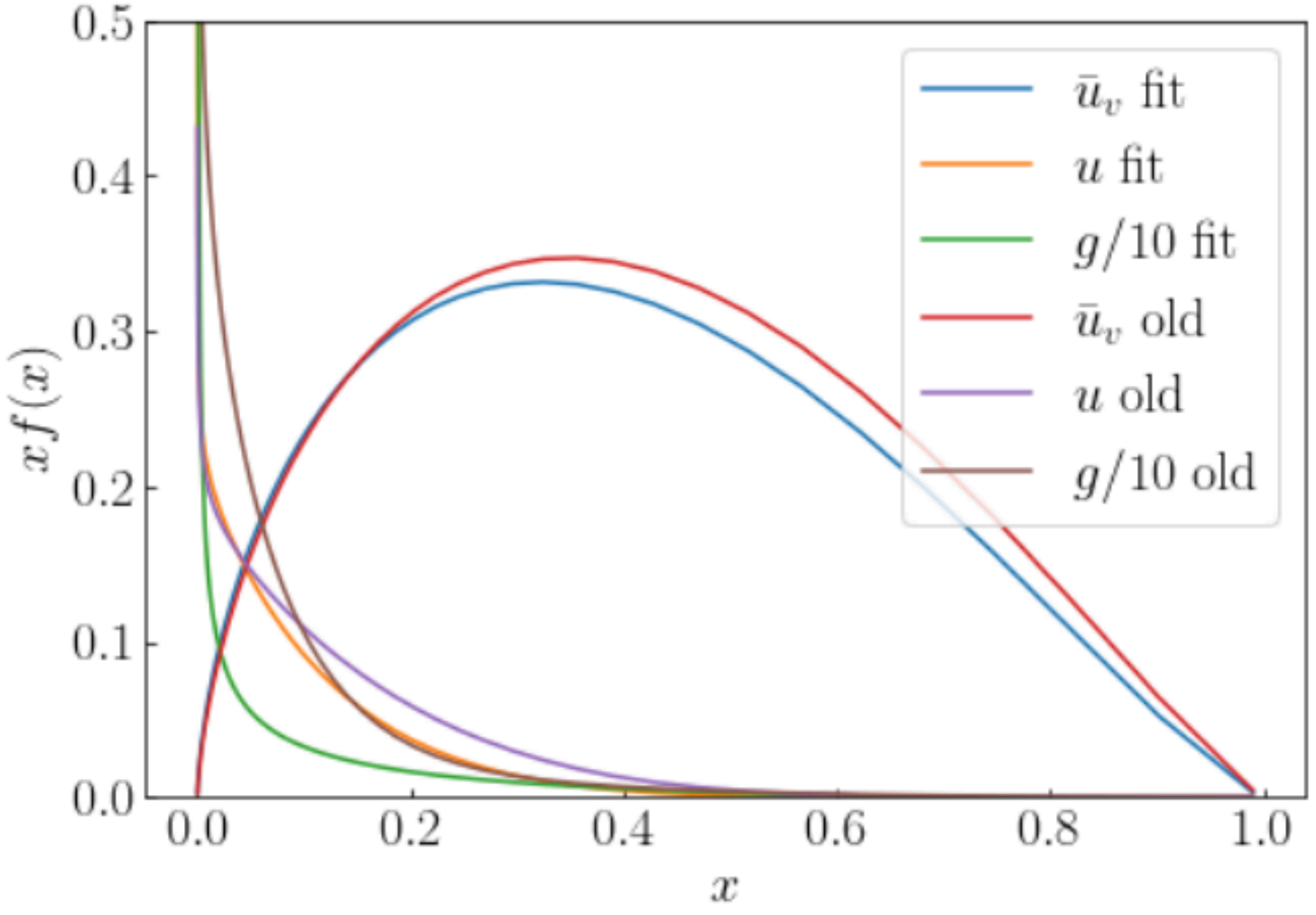
Preliminary

Bessel and CSS -- fit collinear and NP pion to pion data

Collinear PDFs

Noticable change in gluon distributions at lower x

Valence does not change too much



Open TMD & collinear params to all pion data

Preliminary

Bessel and CSS -- fit collinear and NP pion to pion data

Click to add text

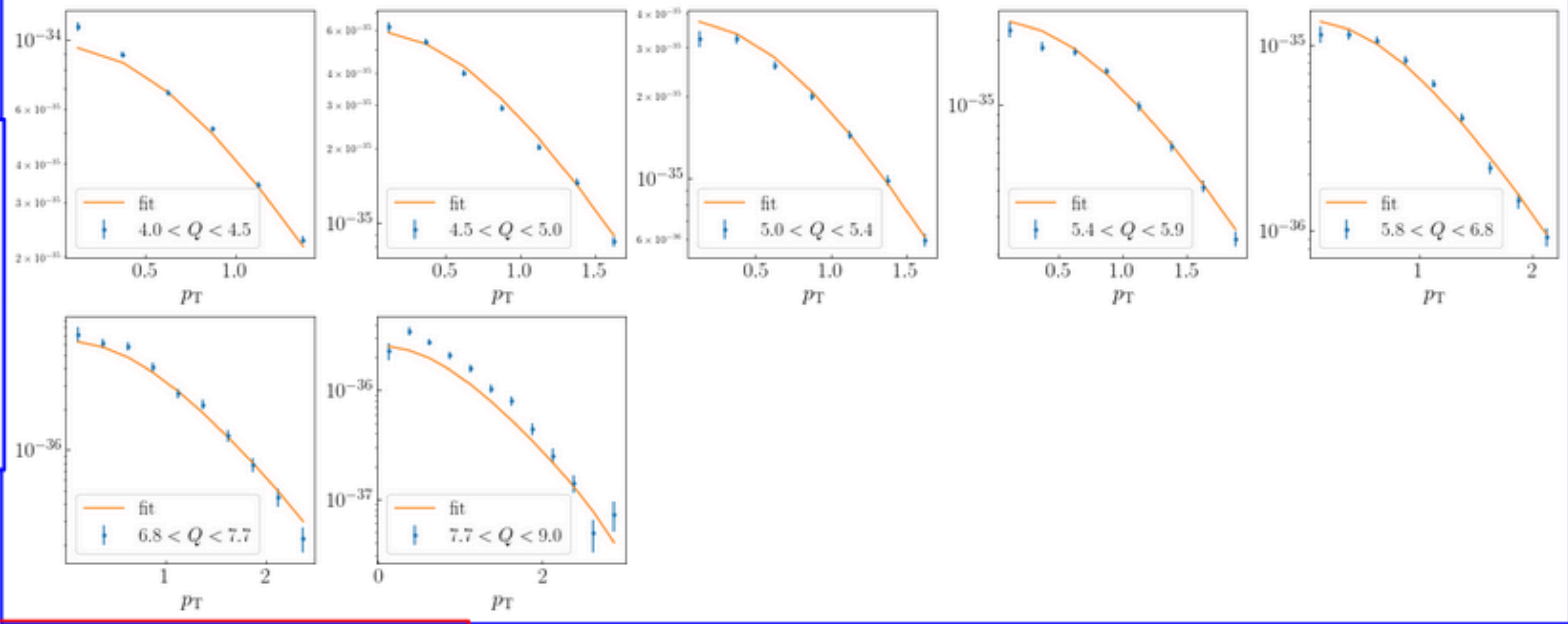
idx	dist	type	value
1	pdf-pion	g1 N	3.13e-01
2	pdf-pion	g1 a	-1.90e+00
3	pdf-pion	g1 b	1.49e-08
4	pdf-pion	u1 a	-9.54e-01
5	pdf-pion	u1 b	6.89e+00
6	pdf-pion	ubv1 a	-2.91e-01
7	pdf-pion	ubv1 b	1.01e+00
8	p->pi,n	lambda	1.40e+00
9	tmd-pion	CA	1.00e+01
10	tmd-pion	CB	4.29e-01
11	tmd-pion	M	2.71e+00
12	tmd-pion	nu	1.74e+00
13	tmd-pion	x0	2.40e-02
14	DYpT	1001	1.20e+00
15	DYpT	1002	8.61e-01
16	dy-pion	10001	1.01e+00
17	dy-pion	10002	8.33e-01
18	dy-pion	10003	7.80e-01
19	ln	1000	1.17e+00
20	ln	2000	9.72e-01

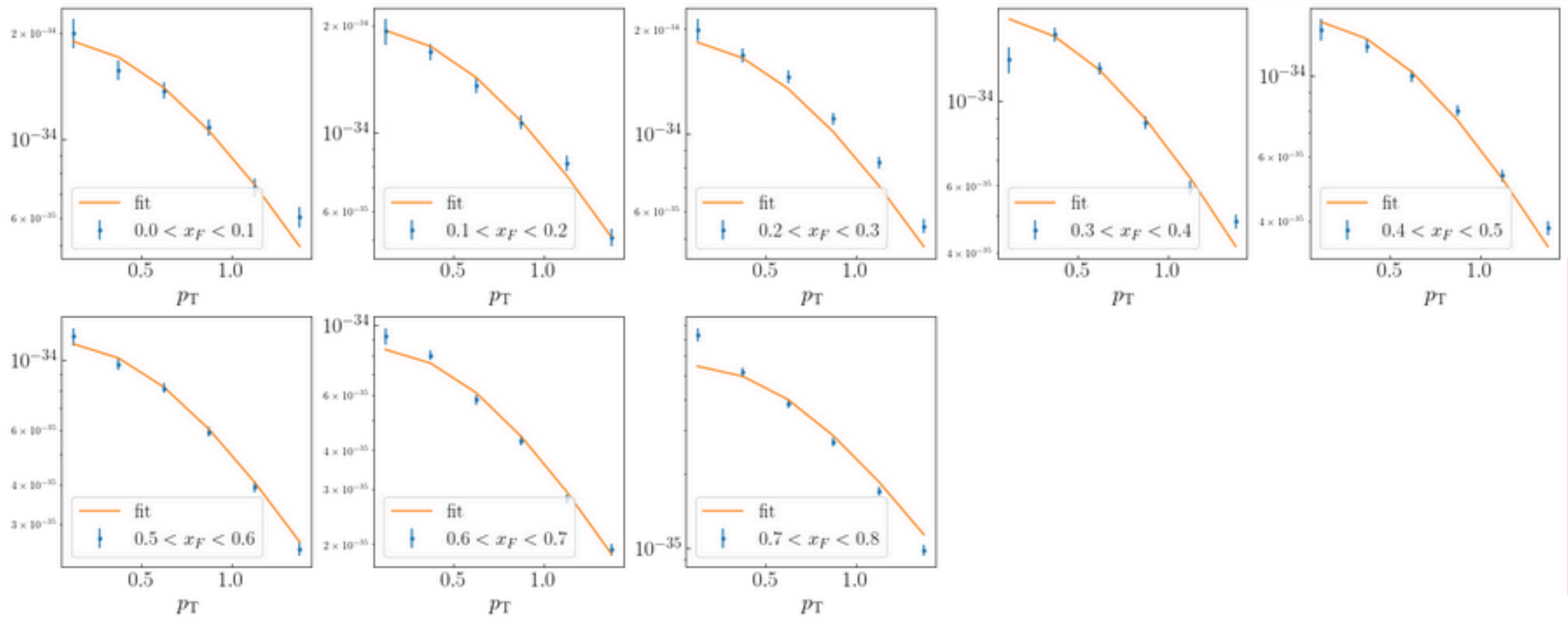
Open TMD & collinear params to all pion data

Bessel and CSS -- fit collinear and NP pion to pion data

E615 data

$$\frac{d^2\sigma}{dp_{\mathrm{T}}^2 dQ}$$





$$\frac{d^2\sigma}{dp_{\mathrm{T}}^2 dx_F}$$

Next step(!) Toward 3-D Pion structure

- **3-D imagining / TMDs using Drell Yan**

★ Entails the study of TMD factorization & Matching in Drell Yan

$\sigma(p_T) \sim W(p_T) + Y(p_T)$ - Collins Soper Sterman NPB 1985

- Goal to use p_T (q_T) data over full range &
- simultaneous fit of pion pdfs & TMDs

- **<u>Cross section different "regions"-"two scales"</u>**

- W valid for $\Lambda_{QCD} \sim p_T \ll Q$ TMD factorization
- FO valid for $\Lambda_{QCD} \ll p_T \sim Q$ Collinear factorization

Beyond the W term MATCHING p_T in CSS

✦ *Collins Soper Sterman NPB 1985*

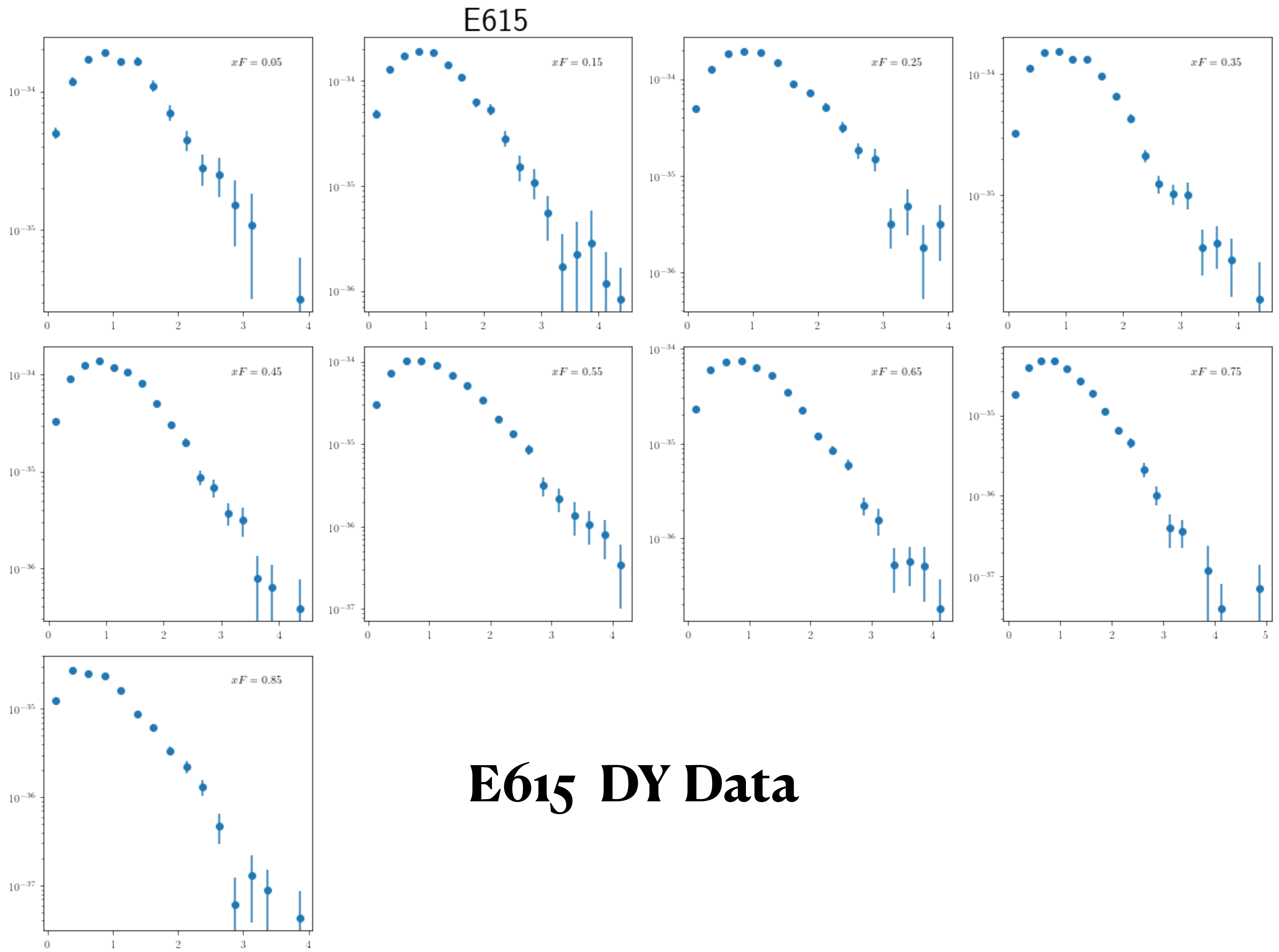
✦ *Collins 2011 Cambridge Press*

✦ **Collins, Gamberg, Prokudin, Sato, Rogers, Wang PRD 2016 - improved matching**

$$\frac{d\sigma(m \lesssim q_T \lesssim Q, Q)}{dy dq^2 dp_T^2} = \left.\frac{d\sigma^W(q_T, Q)}{dy dq^2 dp_T^2}\right|_{m \lesssim q_T \ll Q} + \left.\frac{d\sigma^{FO}(q_T, Q)}{dy dq^2 dp_T^2}\right|_{m \ll q_T \lesssim Q} - \left.\frac{d\sigma^{ASY}(q_T, Q)}{dy dq^2 dp_T^2}\right|_{m \lesssim q_T \ll Q}$$

$$\equiv W(p_T, Q) + FO(p_T, Q) - AY(p_T, Q) + O\left(\frac{m}{Q}\right)^c$$

$$\equiv W(p_T, Q) + Y(p_T, Q) + O\left(\frac{m}{Q}\right)^c$$



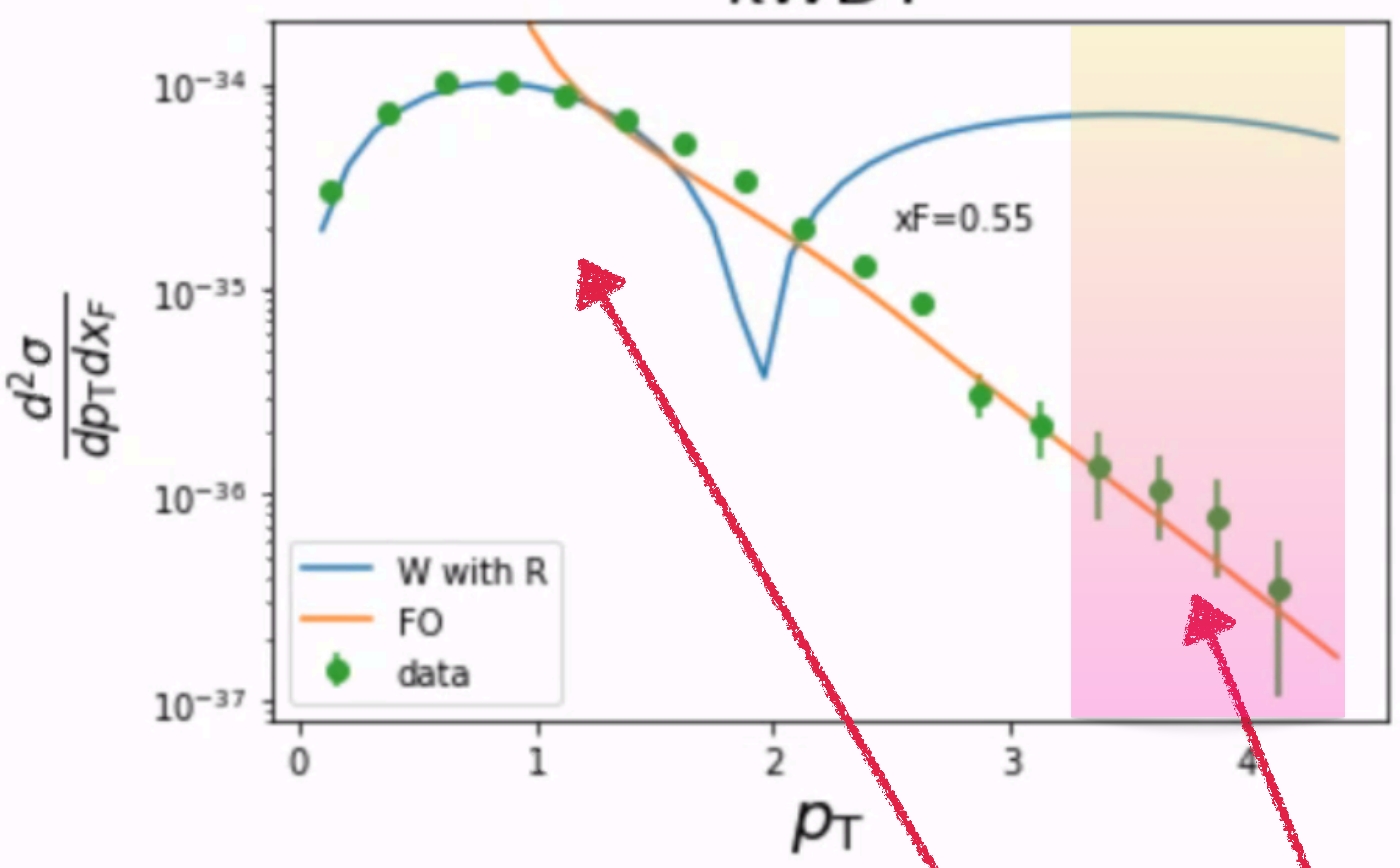
E615 DY Data

- **<u>Cross section in terms of different "regions"</u>**
- W valid for $q_T \sim k_T \ll Q$ TMD factorization
- FO valid for $k_T \ll p_T \sim Q$ Collinear factorization
- ASY subtracts d.c. & in principle
- $ASY \to W,\ p_T \to \infty$ and $ASY \to FO, p_T \to 0$

Drill down ⟶

A first glimpse matching $W + Y$

E615 DY Data



Key Elements

- Normalization control Thru W term
  - S_{NP} , while S_{pert} preserved

$$\tilde{f}_1(x, b_T, Q^2, \mu_Q) \sim \left[\tilde{C}^{f_1}\left(x/\hat{x}, \boldsymbol{b}_*; \mu_{b_*}^2, \mu_{b_*}, \alpha(\mu_{b_*})\right) \otimes f_1(\hat{x}, \mu_{b_*})\right]$$

$$\times \exp\left[-S_{pert}(\mu_{b_*}(b_T); \mu_{b_*}, Q^2) - S_{NP}(b_T, Q)\right]$$

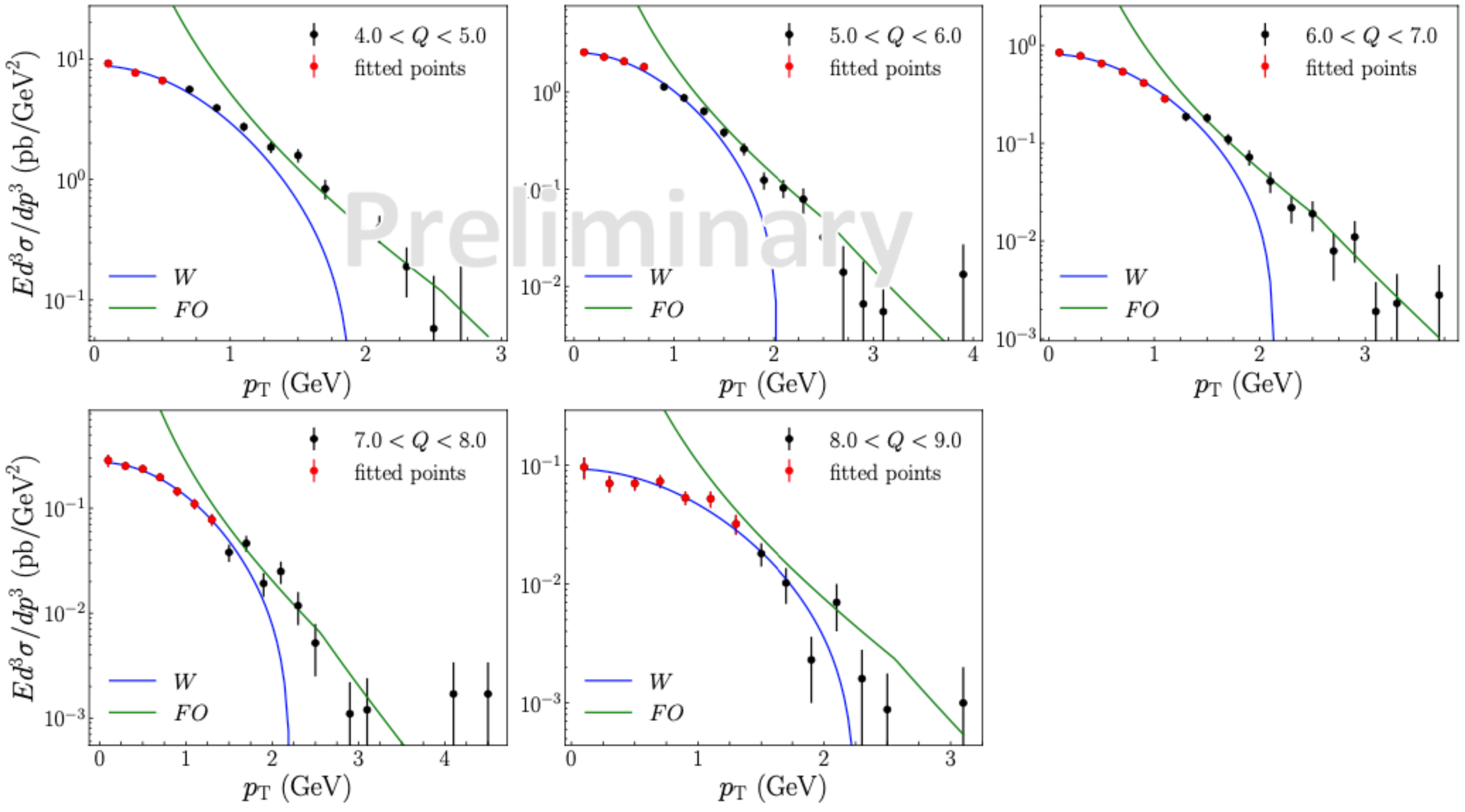
- FO from Barry et al. $f_{i/\pi}(x, \mu)$ @ $\mu = p_T/2$

$$\frac{d\sigma(m \lesssim q_T \lesssim Q, Q)}{dy dq^2 dp_T^2} = W(p_T, Q) + FO(p_T, Q) - AY(p_T, Q) + O\left(\frac{m}{Q}\right)^c$$

A first glimpse of matching $W + Y$ Hard scale $\mu \sim p_T$

Results – E288 pp data

- Perform simultaneous fit of small-p_{T} TMDs to E288 (pp) and E615 (πA) data
- FO is prediction using collinear PDFs and scale $\mu = p_{\mathrm{T}}/2$



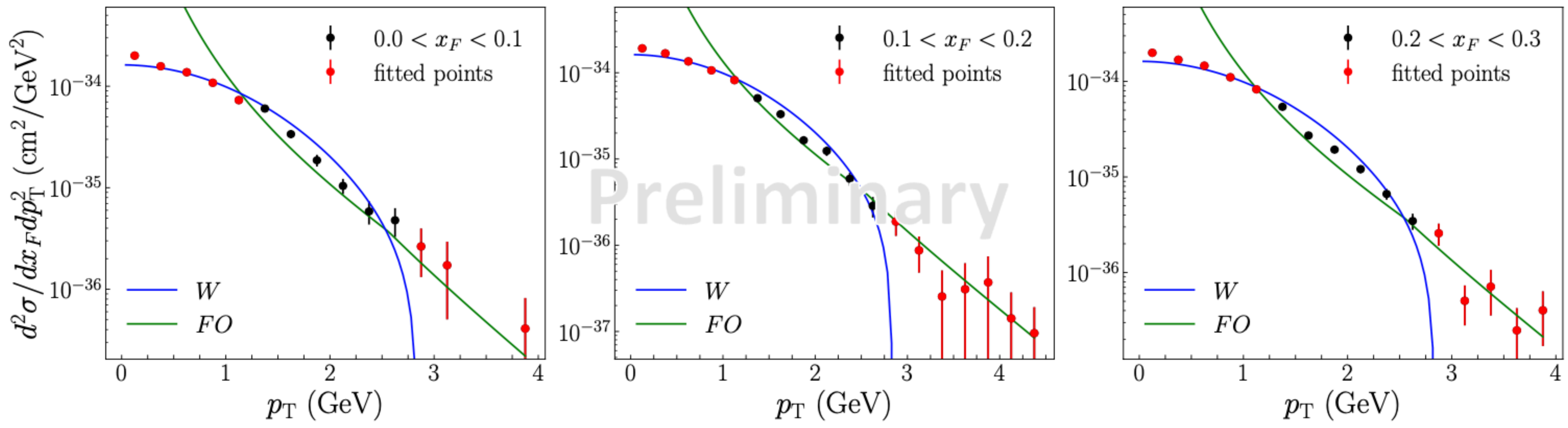
Hard scale $\mu \sim C\, p_T\ , \quad C \sim 1$

$$\frac{d\sigma(m \lesssim q_T \lesssim Q, Q)}{dy dq^2 dp_T^2} = W(p_T, Q) + FO(p_T, Q) - AY(p_T, Q) + O\left(\frac{m}{Q}\right)^c$$

A first glimpse of matching $W + Y$ Hard scale $\mu \sim p_T$

Results – E615 πW data

- Proton and pion TMDs are different, but g_K are same
- Perform simultaneous fit of small-p_{T} TMDs to E288 (pp) and E615 (πA) data



$$\frac{d\sigma(m \lesssim q_T \lesssim Q, Q)}{dy dq^2 dp_T^2} = W(p_T, Q) + FO(p_T, Q) - AY(p_T, Q) + O\left(\frac{m}{Q}\right)^c$$

Summary

- We've used pdfs extracted from JAM 20 to describe the full p_T cross section for DY
- First simultaneous fit of pion collinear PDFs & TMDs
- Generally diagnosed challenges of matching $\sigma(p_T) \sim W(p_T) + Y(p_T)$
  - ★ Entails the study of factorization & Matching

★ Perform simultaneous fit of pion (and nucleon/nuclear) pdfs from

1) $$\frac{d\sigma^{\rm DY}}{dQ^2 dy} = \sum_{a,b} \int dx_a\, dx_b\, H^{\rm DY}_{a,b}(x_a, x_b, y, Q^2, \mu^2)\, f_{a/A}(x_a, \mu^2)\, f_{b/B}(x_b, \mu^2)$$

2) $$\frac{d^3\sigma^{\rm LN}}{dx_B\, dQ^2\, dx_L} = \frac{4\pi\alpha^2}{x_B\, Q^4}\left(1 - y_e + \frac{y_e^2}{2}\right) F_2^{\rm LN}(x_B, Q^2, x_L)$$

3) $$\frac{d\sigma^{DY}}{dQ^2 dy dp_T} = \sum_{a,b} \int dx_a\, dx_b\, H^{\rm FO}_{a,b}(x_a, x_b, y, p_T, Q^2, \mu^2)\, f_{a/A}(x_a, \mu^2)\, f_{b/B}(x_b, \mu^2)$$

4 (W+Y)) $$\frac{d\sigma}{dQ^2\, dx_F\, dp_T^2} = \frac{d\sigma^{W}}{dQ^2\, dx_F\, dp_T^2} + \frac{d\sigma^{\rm DY}}{dQ^2\, dx_F\, dp_T^2} - ASY(\text{double count})$$

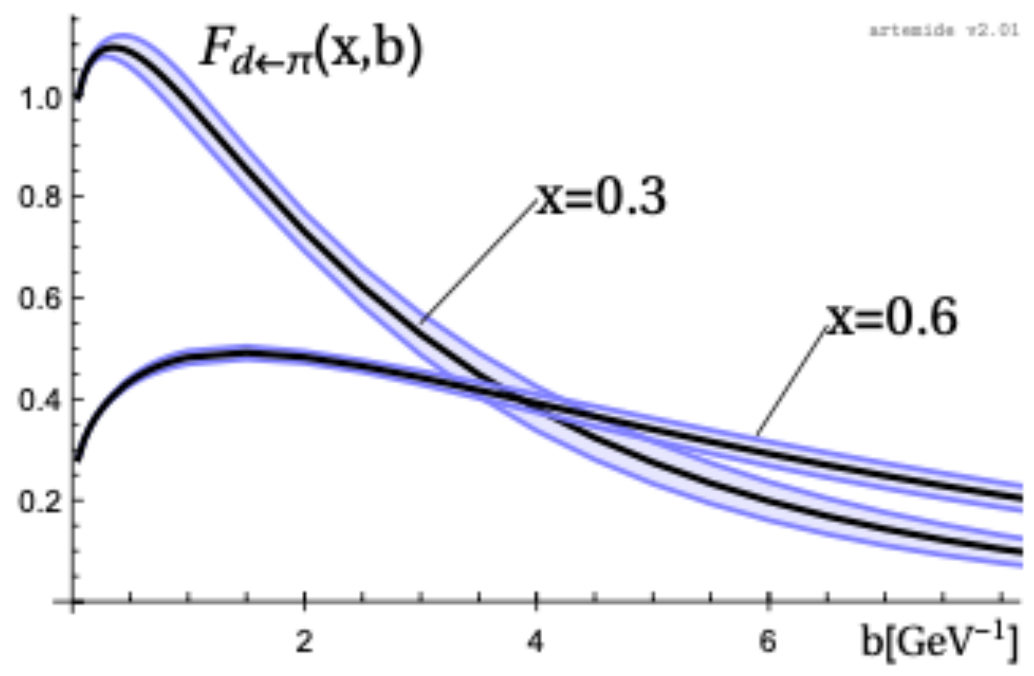
$$W(x_F, p_T, Q) \to \tilde{f}(x, b_T, Q^2, \mu_Q) \sim \left[\tilde{C}^f\left(x/\hat{x}, \mathbf{b}_*; \mu^2_{b_*}, \mu_{b_*}, \alpha(\mu_{b_*})\right) \otimes f_1(\hat{x}, \mu_{b_*})\right]$$
$$\times \exp\left[-S_{pert}(\mu_{b_*}(b_T); \mu_{b_*}, Q^2) - S_{NP}(b_T, Q)\right]$$

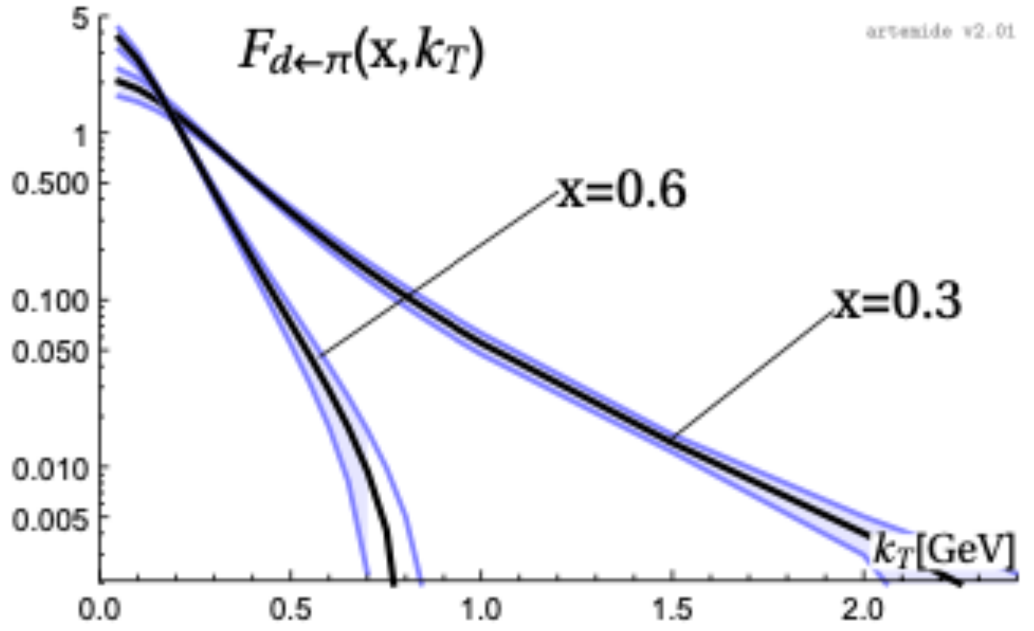
Extras

First Studies

Vladimirov JHEP 2019

Pion-induced DY processes within TMD factorization





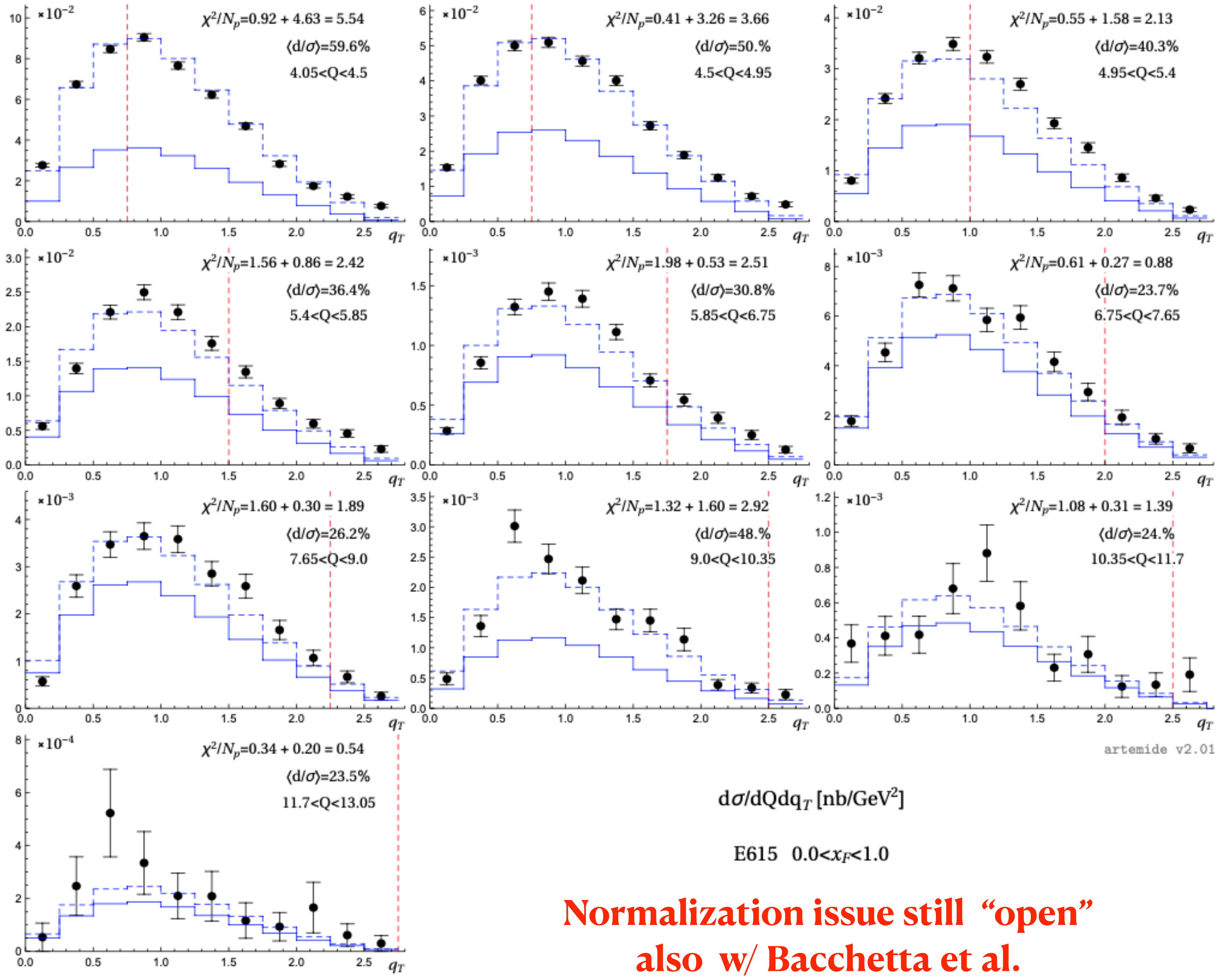
Pion TMDPDF for d-quark in b-space. (Right) Pion TMDPDF for d-quark in kT -space.
The bands are the 1σ uncertainty band related to the data error-bands and calculated by the replica method.

$$\frac{d\sigma^W}{dQ^2\, dx_F\, dp_T^2} = \frac{4\pi^2\alpha^2}{9Q^2 s}\sum_j H_{j\bar{j}}^{\rm DY}(Q,\mu_Q,a_s(\mu_Q))$$

$$\times \int \frac{d^2\boldsymbol{b}_T}{(2\pi)^2}\, e^{i\boldsymbol{p}_T\cdot\boldsymbol{b}_T}\, \tilde{f}_{j/\pi}(x_A,b_T;Q^2,\mu_Q)\, \tilde{f}_{\bar{j}/H}(x_B,b_T;Q^2,\mu_Q)$$

W – term only

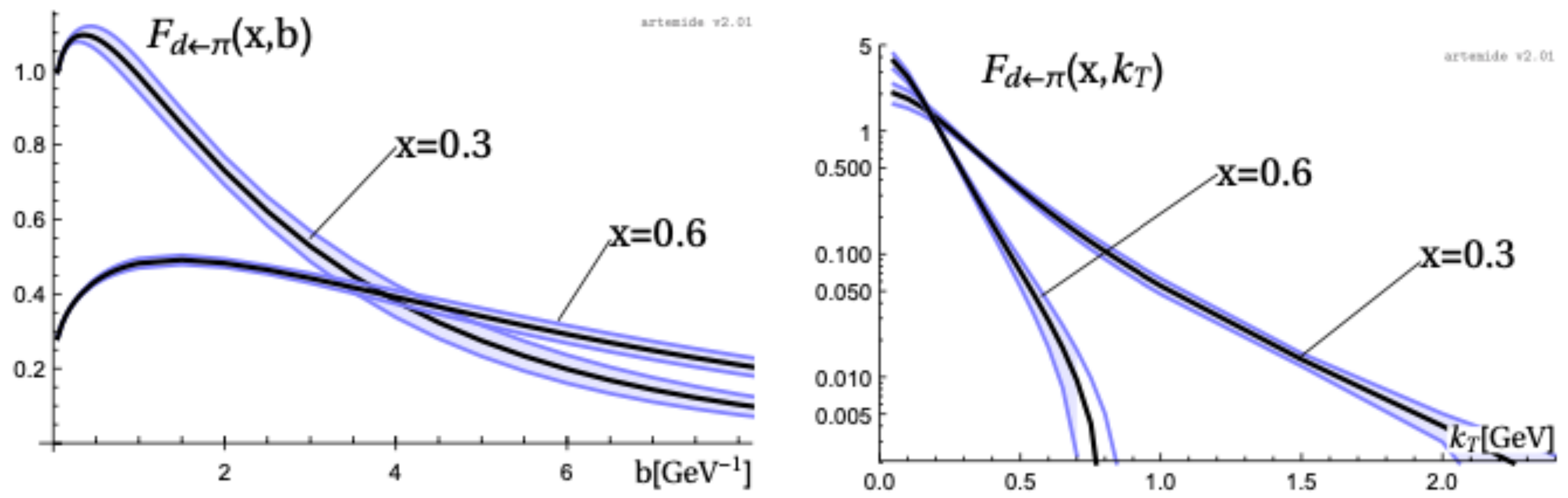
E615 DY Data



Normalization issue still "open" also w/ Bacchetta et al.

Figure 5. Comparison of the theory prediction (solid line) to E615 differential in Q. The dashed line is the theoretical prediction after the addition of systematic shifts d_i. The values of the χ^2 and d_i are calculated for the each Q-bin with 16% correlated error. The vertical dashed line shows the estimation of the boundary for TMD factorization approach.

JHEP 2019 Vladimirov
Pion-induced DY processes within TMD factorization



Pion TMDPDF for d-quark in b-space. (Right) Pion TMDPDF for d-quark in kT -space.
The bands are the 1σ uncertainty band related to the data error-bands and calculated by the replica method.

Extracted from E615 DY Data

COMMENTS

Alot of engineering in the non perturbative TMD parametrization
and modeling χ^2 on normalization

Vladimirov JHEP 2019
Bacchetta et al. 2019 Pavia 19 (DY TMD analysis)
Scimemi & Vladimirov JHEP 2020 (DY + SIDIS TMD analysis)
....
We diagnose W+FO @ Leading order simple NP

PHYSICAL REVIEW LETTERS **122,** 082301 (2019) Chao Shi and Ian C. Cloët

Bethe-Salpeter LC Wave Function methods for TMDs

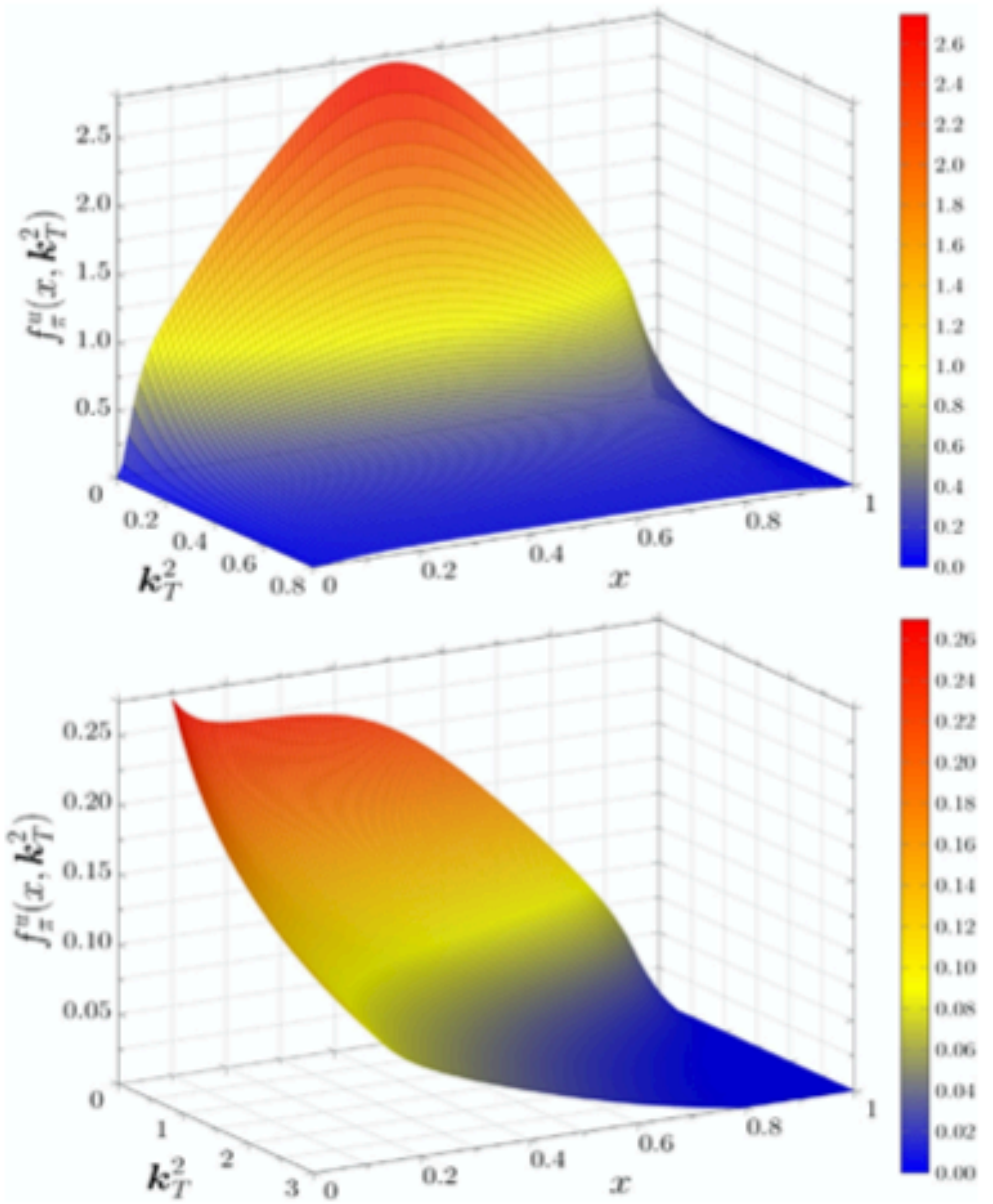


FIG. 2. Upper panel: DSE result for the time-reversal even u-quark TMD of the pion, $f_\pi^u(x, k_T^2)$, at the model scale of $\mu_0^2 = 0.52$ GeV^2. Lower panel: Analogous result evolved to a scale of $\mu = 6$ GeV using TMD evolution with the b^* prescription and $g_2 = 0.09$ GeV [51]. The TMDs are given in units of GeV^{-2} and k_T^2 in GeV^2.

Recent work *FO* DY calculations

Alessandro Bacchetta,[1,2,*] Giuseppe Bozzi,[1,2,†] Martin Lambertsen,[3,‡] Fulvio Piacenza,[1,2,§]
Julius Steiglechner,[3,∥] and Werner Vogelsang[3,¶]

The predicted cross sections fall significantly short of the available data even at the highest accessible values of q_T

DIFFICULTIES IN THE DESCRIPTION OF DRELL-YAN PROCESSES … PHYS. REV. D **100,** 014018 (2019)

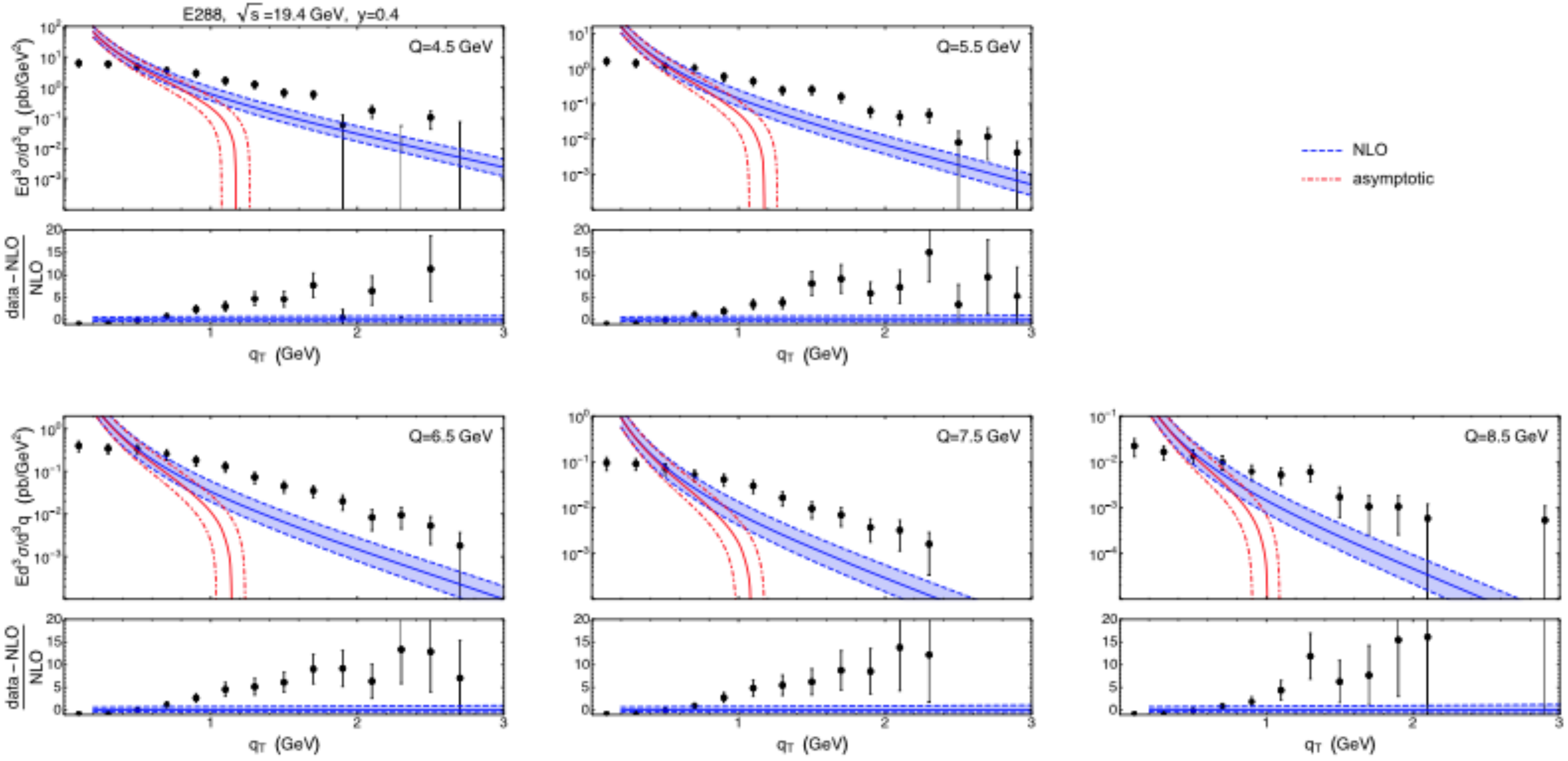


FIG. 6. E288. Experimental data vs NLO QCD predictions for $y = 0.4$ and different invariant mass bins.