Pion Parton Distributions at 22 GeV

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Jefferson Lab 22 GeV Open Discussion

November 18, 2024

Studying hadron structure

Should we only study the structure of protons to learn about QCD?

NO!

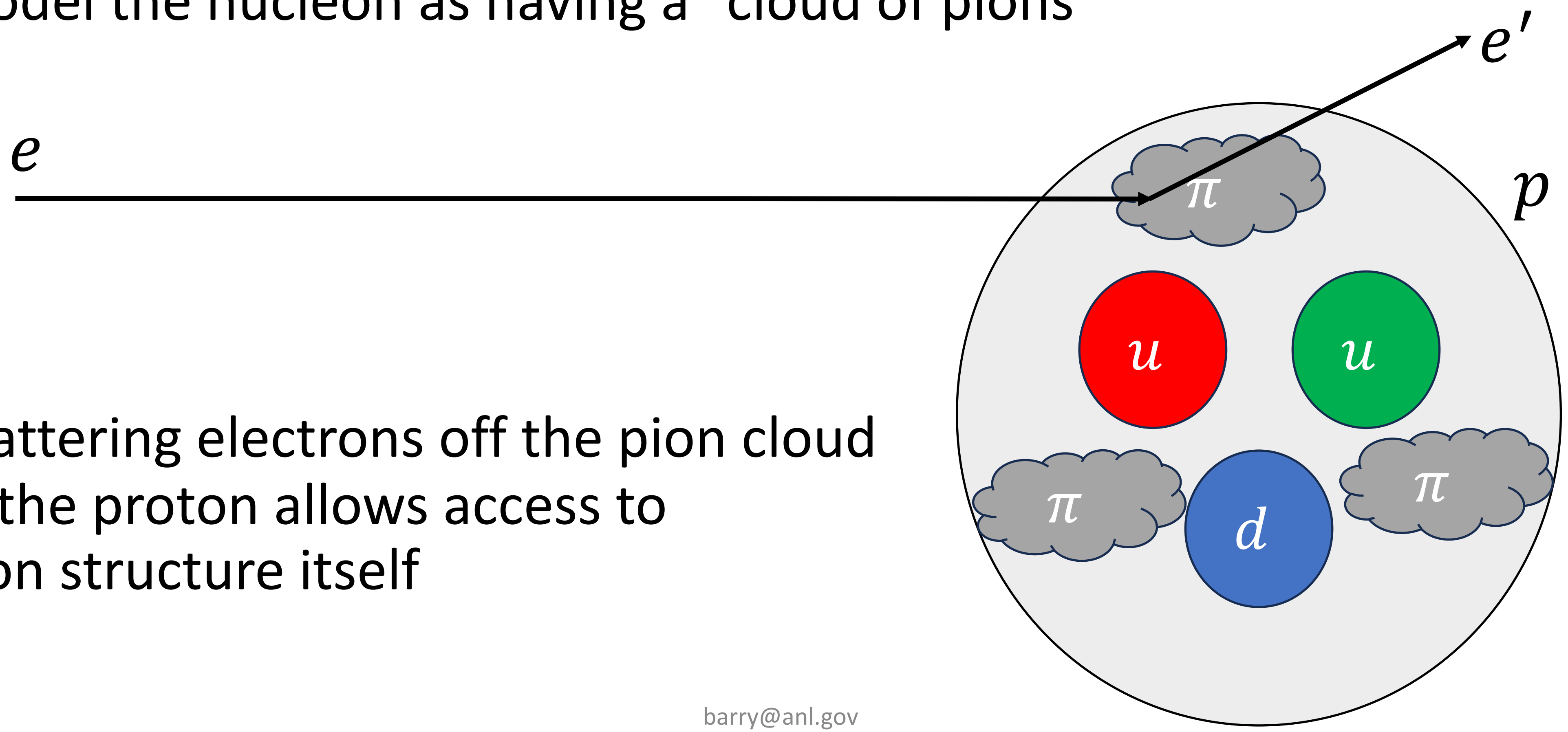
- **Mesons** offer importance of emergent phenomena of QCD such as
  - How is mass generated?
  - How do quarks and gluons arrange themselves within hadrons?
  - Why is there confinement?
- Allows for another probe of confinement scales in quark-gluon bound systems

Questions in meson structure

1. How to test universality of PDFs?
2. What is the gluonic content of pions compared with protons?
3. What is the transverse momentum structure of pions, and how does it relate to confinement scales?

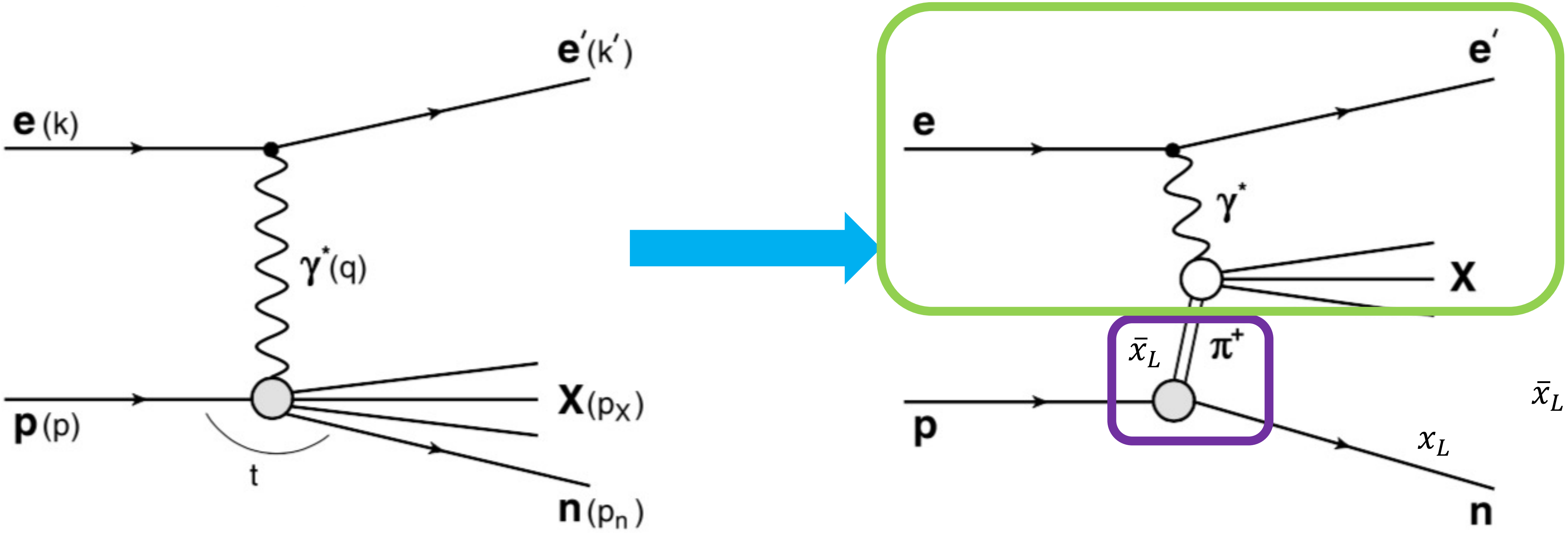
Accessing pions indirectly

- Exchange of pions among nucleons keep the nucleus intact
- Model the nucleon as having a “cloud of pions”



- Scattering electrons off the pion cloud in the proton allows access to pion structure itself

Leading Neutron (LN) electroproduction



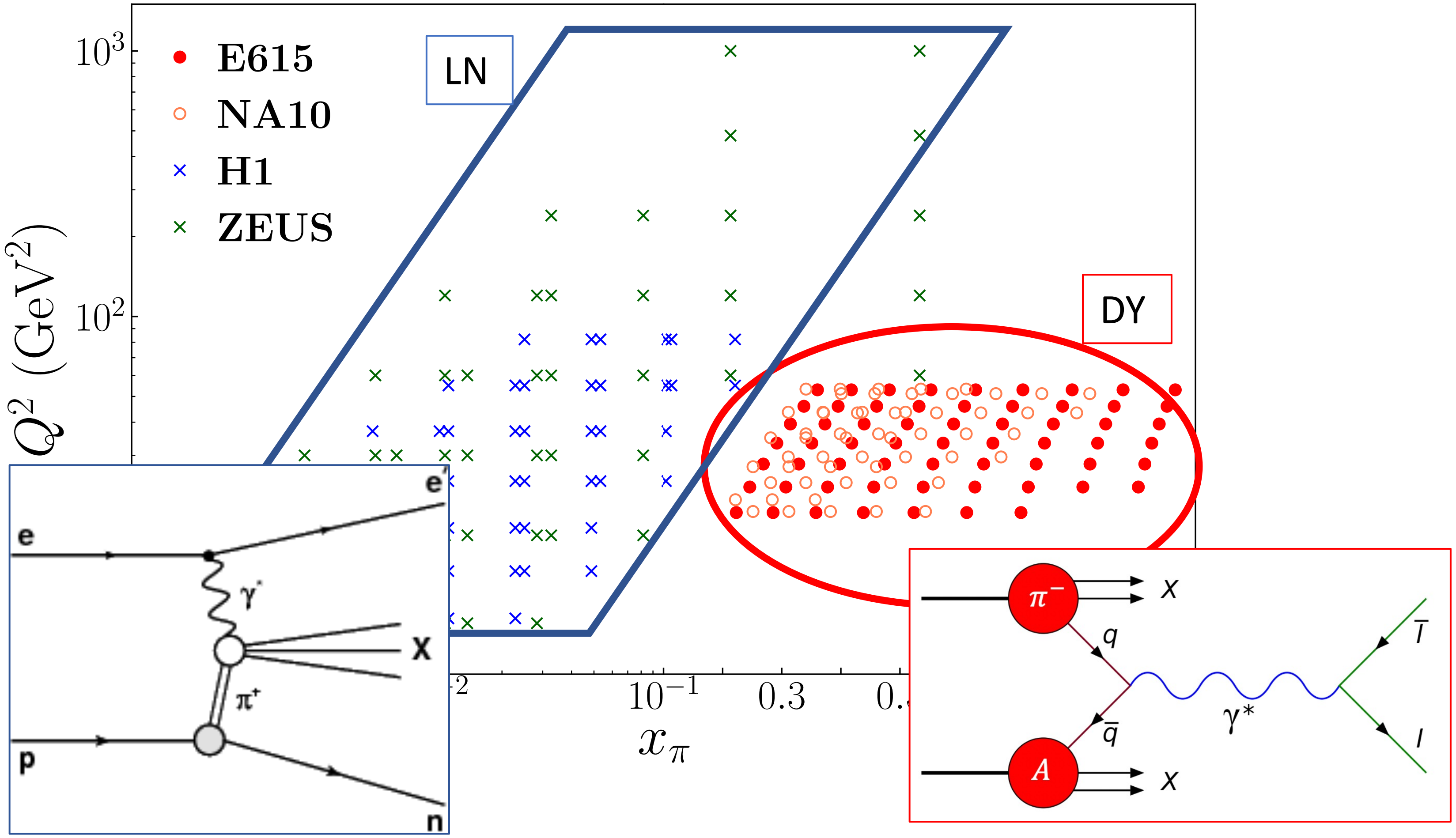
$\bar{x}_L = 1 - x_L$

$$\frac{d\sigma}{dx\,dQ^2\,d\bar{x}_L} \propto f_{p\to\pi^+ n}(\bar{x}_L) \sum_i \int_{x/\bar{x}_L}^{1} \frac{d\xi}{\xi} \mathcal{C}_i(\xi)\, f_i^{\pi}\left(\frac{x/\bar{x}_L}{\xi}, \mu^2\right)$$

Available datasets for pion structures

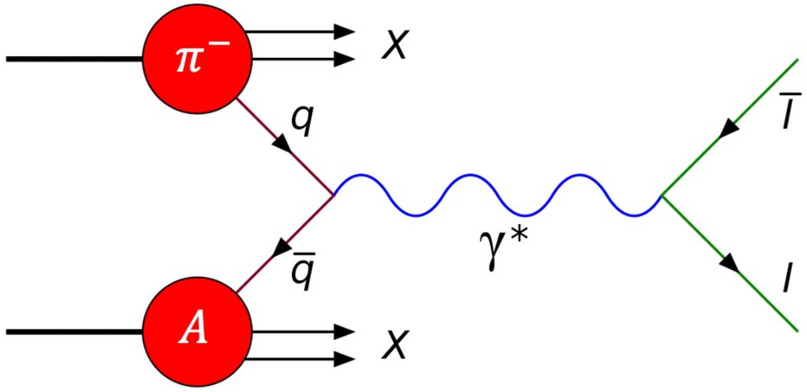
- Less available data than in the proton case

- Little kinematic overlapping region!

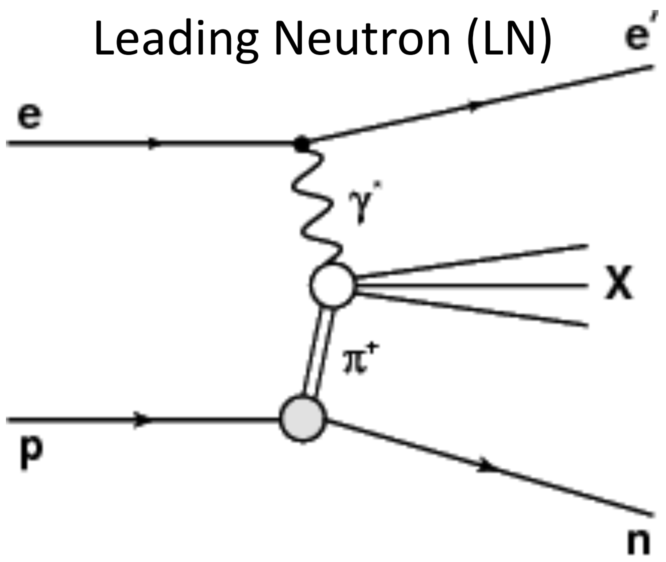


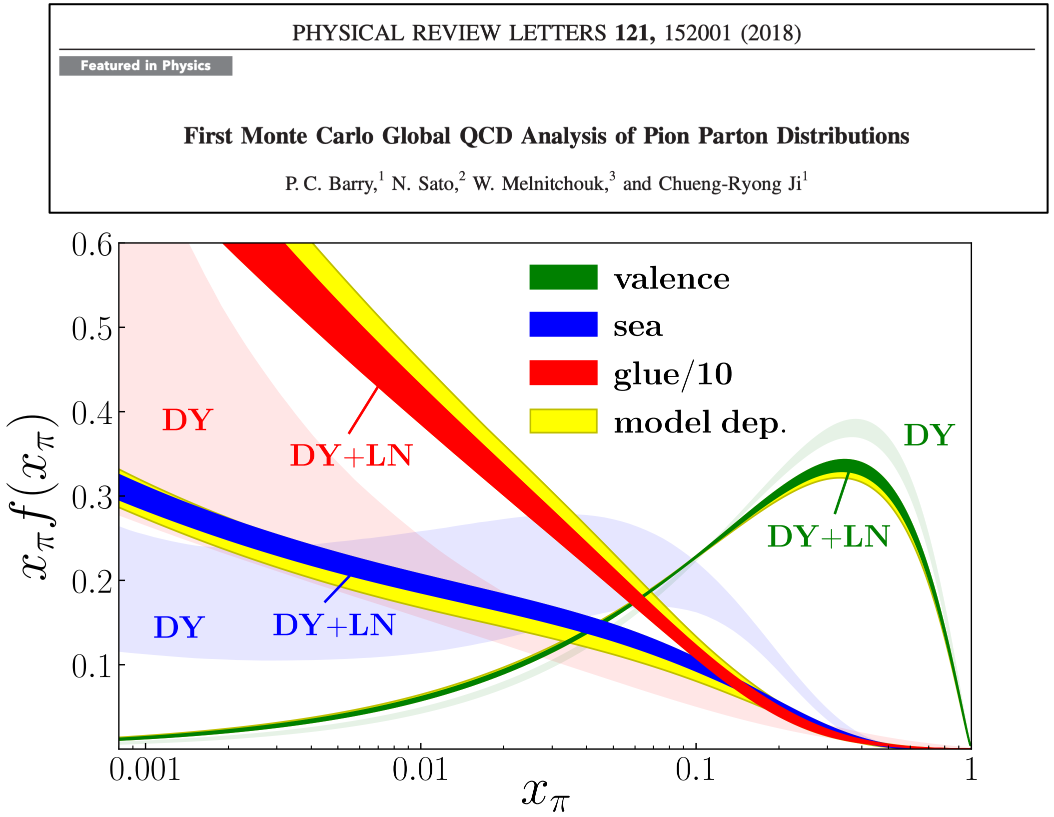
Pion PDFs in JAM

Drell-Yan (DY)



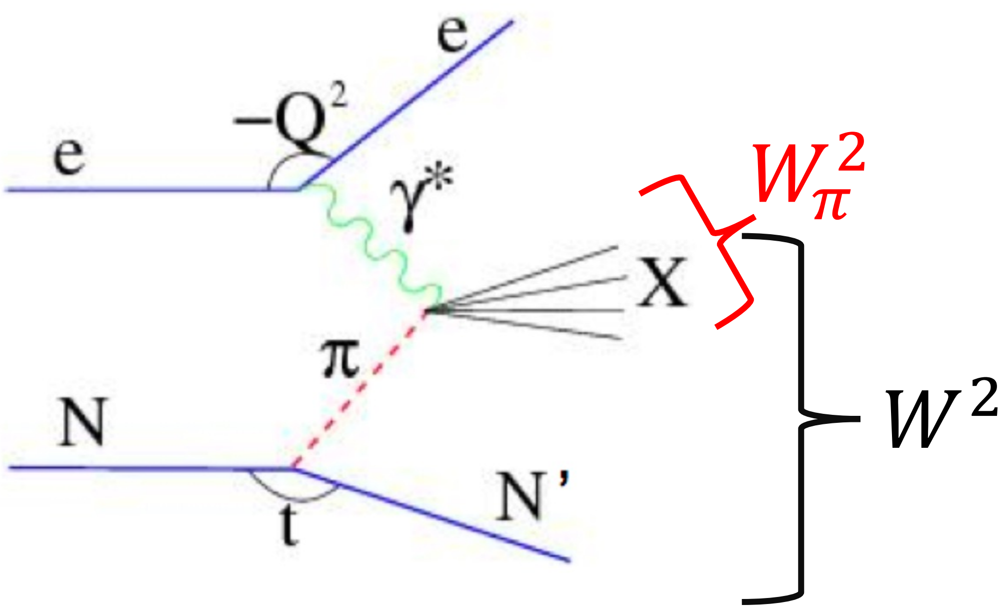
Leading Neutron (LN)





1. How to test universality of pion PDFs?

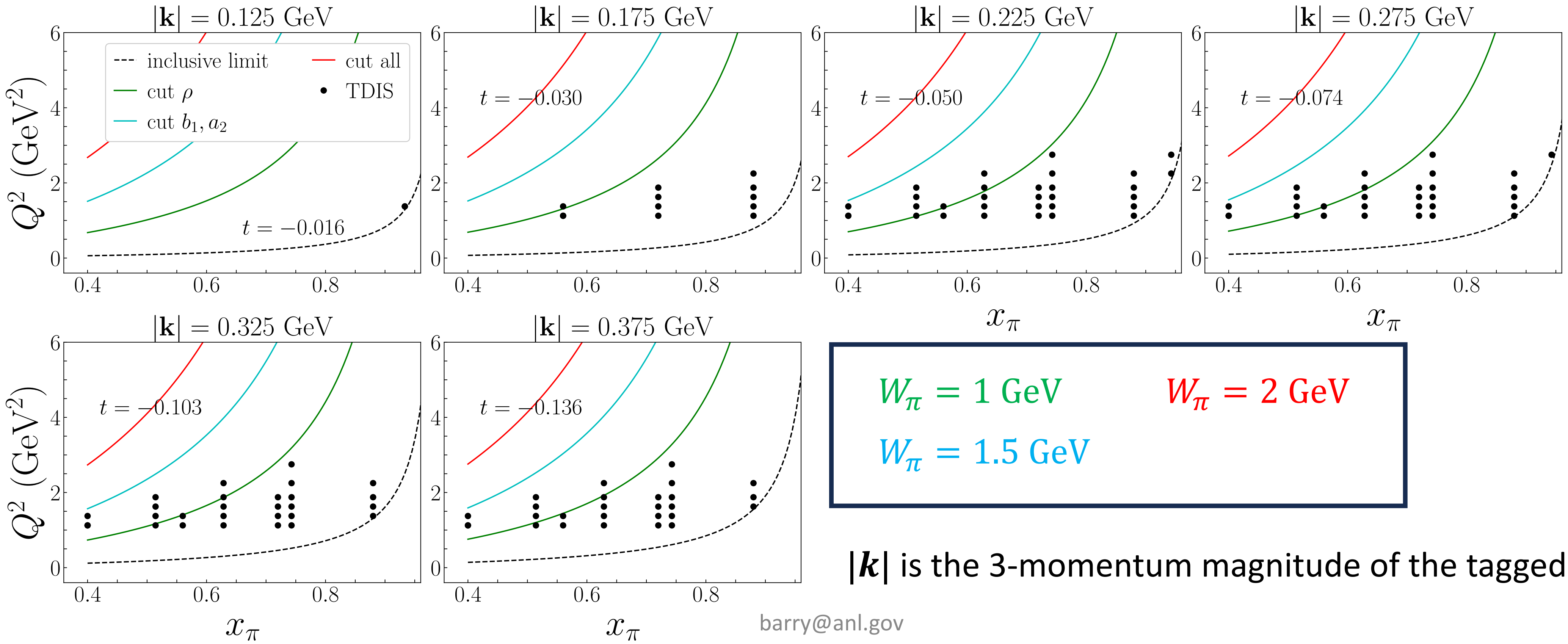
- The tagged deep inelastic scattering (TDIS) program at JLab offers overlapping kinematics with DY
- But how reliable are these kinematics with 11 GeV? – resonance region



Meson	Mass (MeV)	Decay width (MeV)
ρ	775.26 ± 0.23	149.1 ± 0.8
b_1	1229.5 ± 3.2	142 ± 9
a_1	1230 ± 40	425 ± 175
a_2	1318.2 ± 0.6	107 ± 5
$\pi(1670)$	$1670.6^{+2.9}_{-1.2}$	258^{+8}_{-9}

Current 11 GeV TDIS kinematics

- Plotting available 11 GeV TDIS kinematics with a few representative W_π curves



W_π = 1 GeV

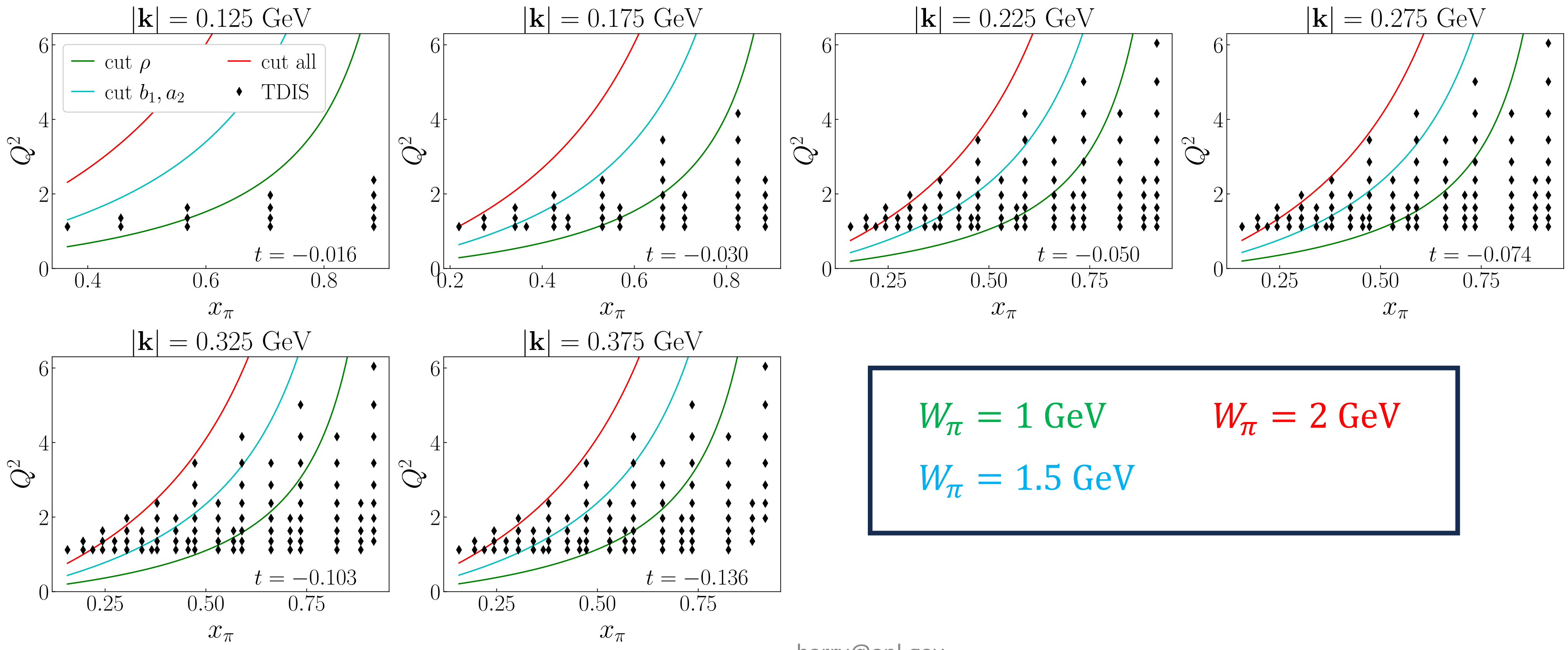
W_π = 2 GeV

W_π = 1.5 GeV

$|\boldsymbol{k}|$ is the 3-momentum magnitude of the tagged nucleon

Kinematics with 22 GeV

- We keep some data points above the $W_\pi = 2$ GeV cut



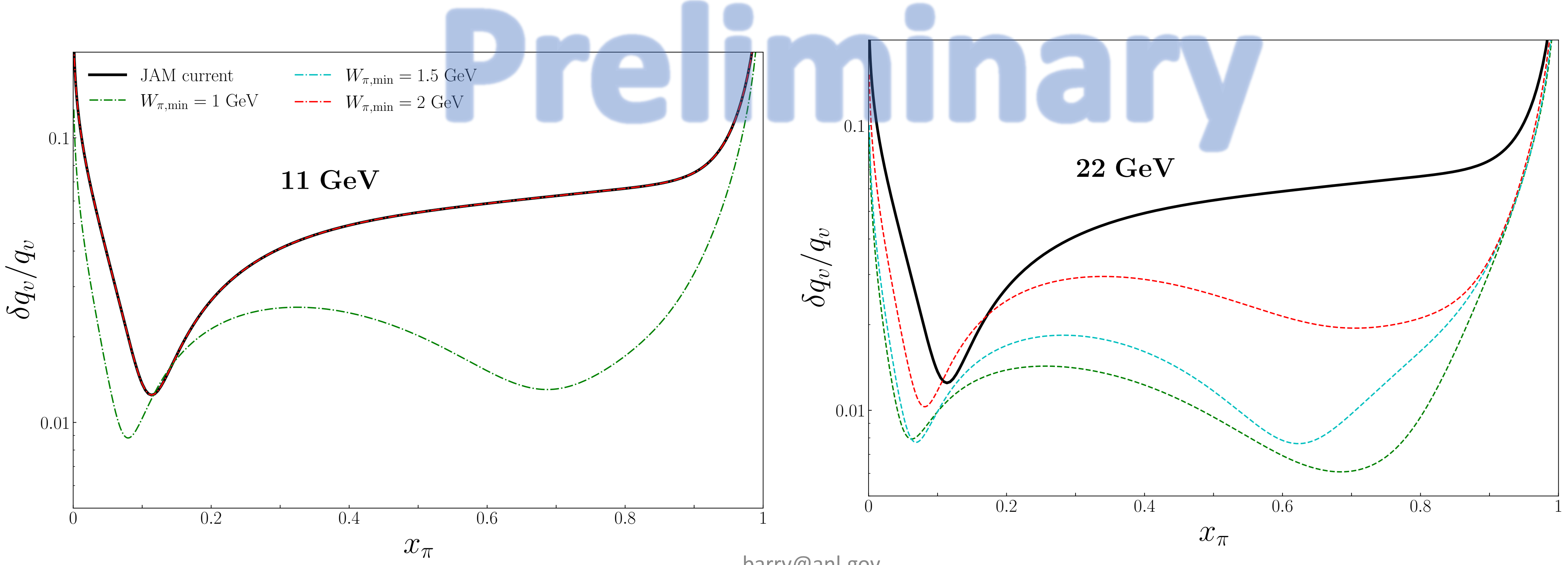
$W_\pi = 1$ GeV

$W_\pi = 2$ GeV

$W_\pi = 1.5$ GeV

Impact on pion PDFs with 22 GeV

- Knowledge of pion PDFs increases dramatically with 22 GeV beam
- Assuming 1.2% systematic uncertainty and 200 days of data-taking



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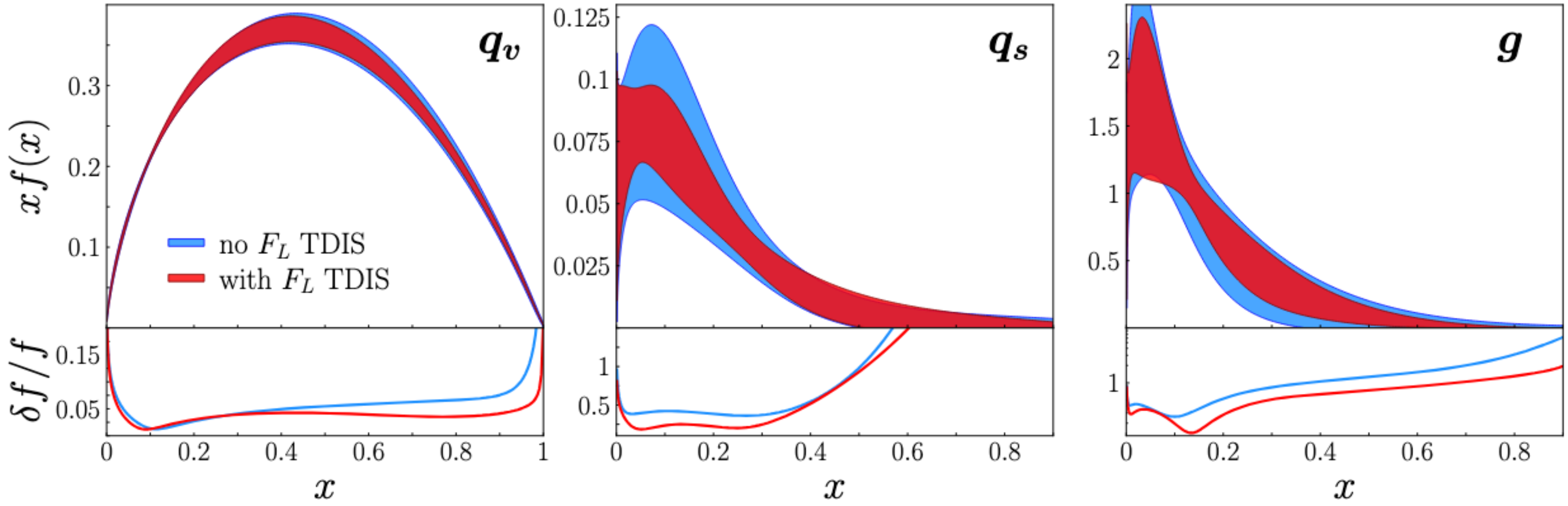
2. Gluonic content of the pion

- The gluon has sensitivity to F_2^π at next-to-leading order (NLO)
- However, it comes in at leading order (LO) for F_L^π
- If we can perform L-T separation in regions of kinematics, we may be able to access g_π
- Because the ρ meson does *not* contribute to F_L, we analyze the region in $2m_\pi < W_\pi < 1\ \mathrm{GeV}$

Impact of F_L studies

- We look only at 11 GeV kinematics that overlap with 8.8 GeV beam kinematics
- Reduction in the gluon uncertainty at large x



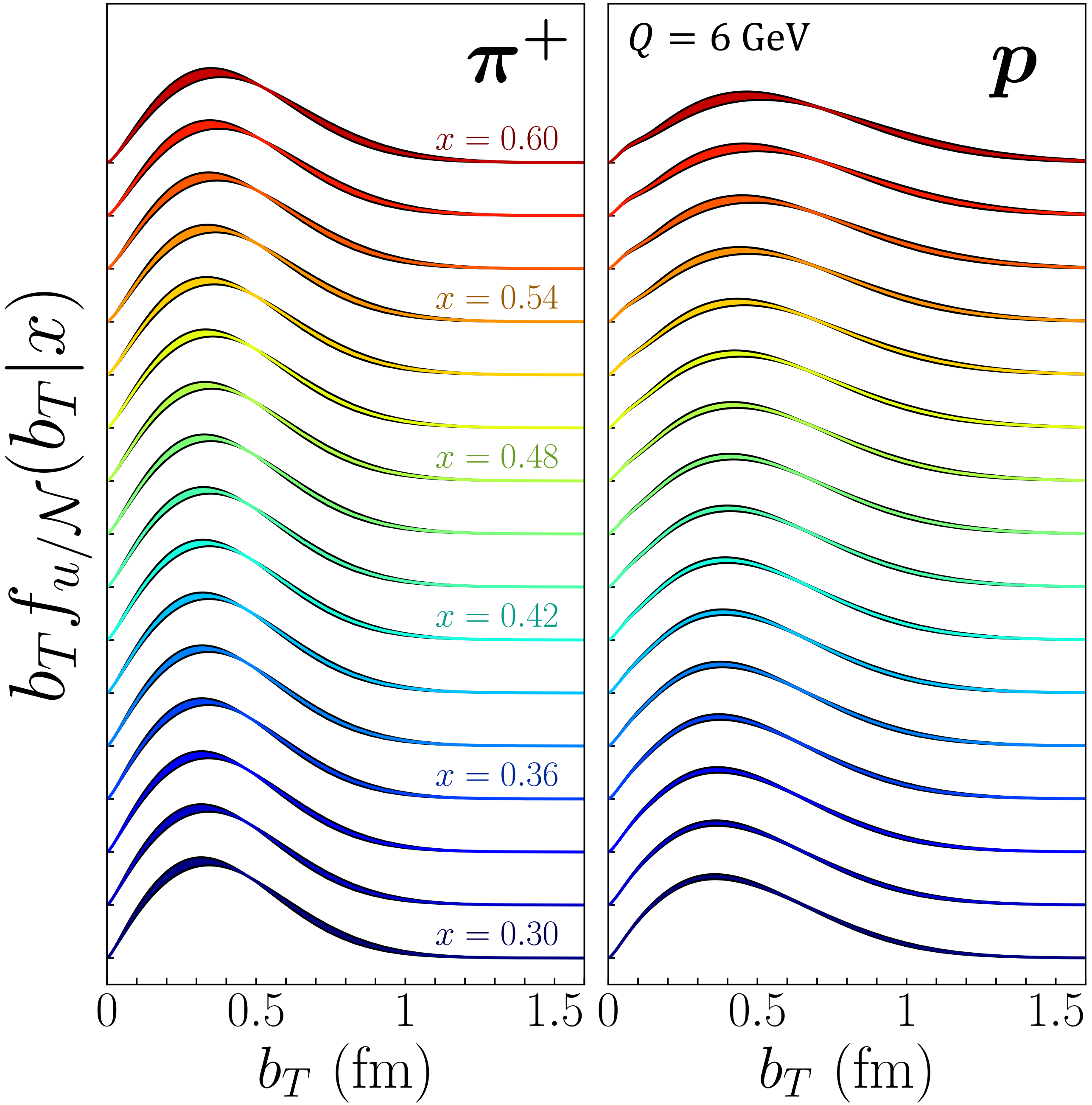
3. Transverse momentum structure

Relation to k_T-space TMD

$$\tilde{f}_{q/\mathcal{N}}(x, b_T) = (2\pi)^2 \int d^2\boldsymbol{k}_T e^{-i\boldsymbol{b}_T\cdot\boldsymbol{k}_T} f_{q/\mathcal{N}}(x, k_T)$$

$$\tilde{f}_{q/\mathcal{N}}(b_T|x; Q, Q^2) \equiv \frac{\tilde{f}_{q/\mathcal{N}}(x, b_T; Q, Q^2)}{\int d^2\boldsymbol{b}_T \tilde{f}_{q/\mathcal{N}}(x, b_T; Q, Q^2)}.$$

- Broadening in b_T-space appearing as x increases
  - $\Longrightarrow$Narrowing in k_T-space
- Up quark in pion is narrower than up quark in proton in b_T-space
  - $\Longrightarrow$ Broader in k_T-space



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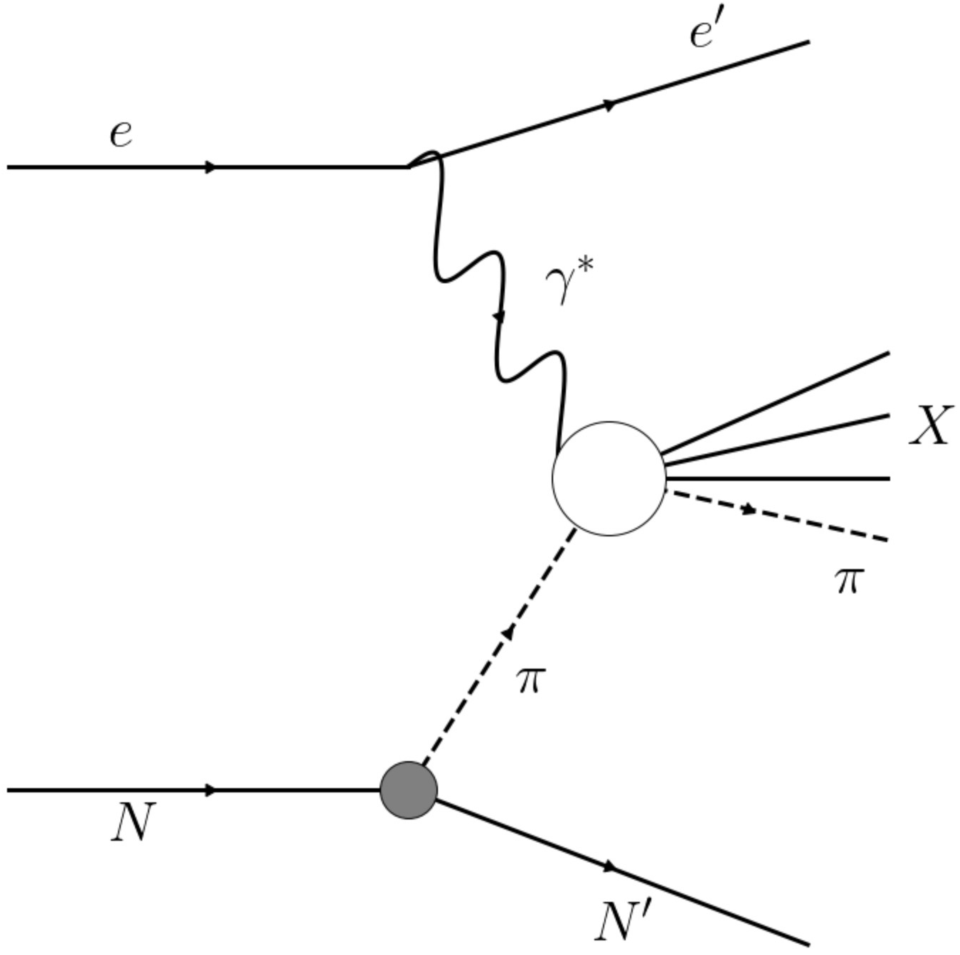
Pion SIDIS: access to TMDs

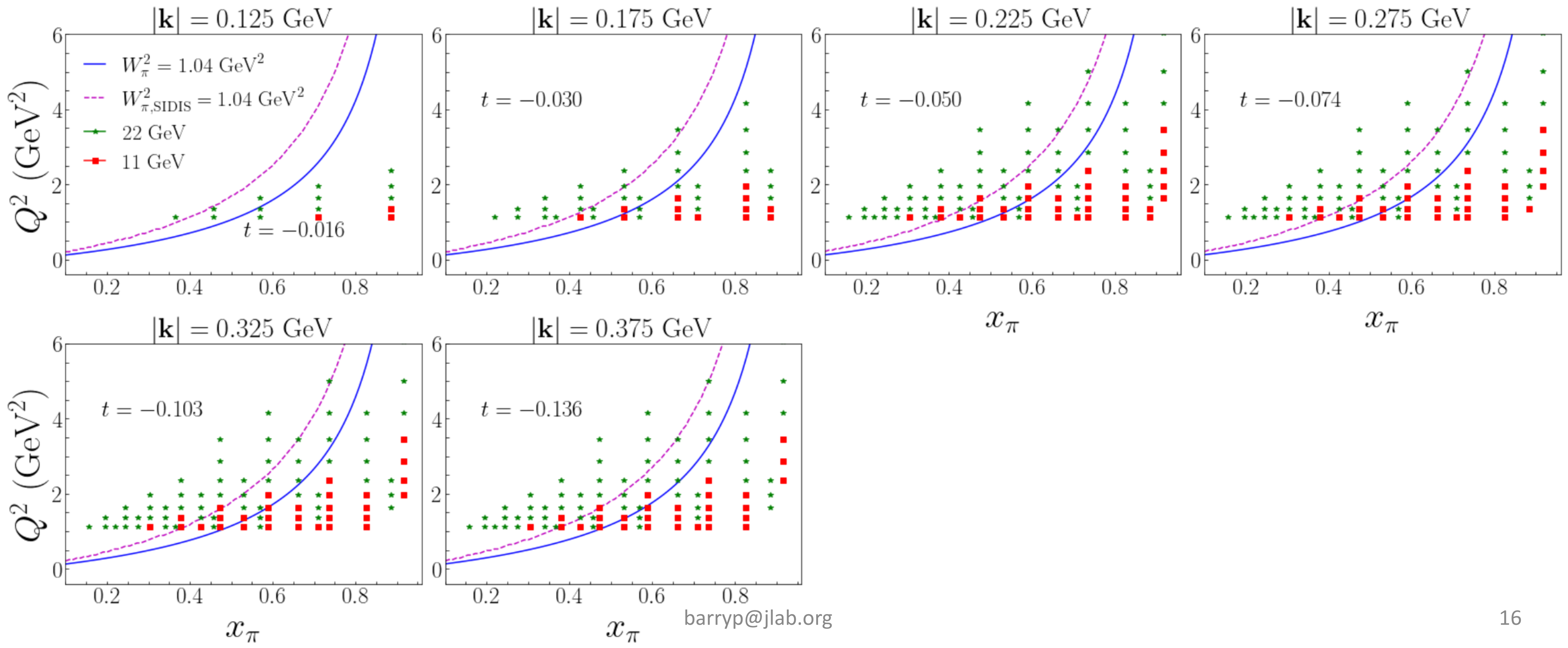
$$eN \to e'N'\pi X$$

- Measure an outgoing pion in the TDIS experiment
- Gives us another observable sensitive to pion TMDs
  - Needed for tests of universality



Available kinematics for JLab

- Can only use 22 GeV data for any TMD analysis



Conclusion

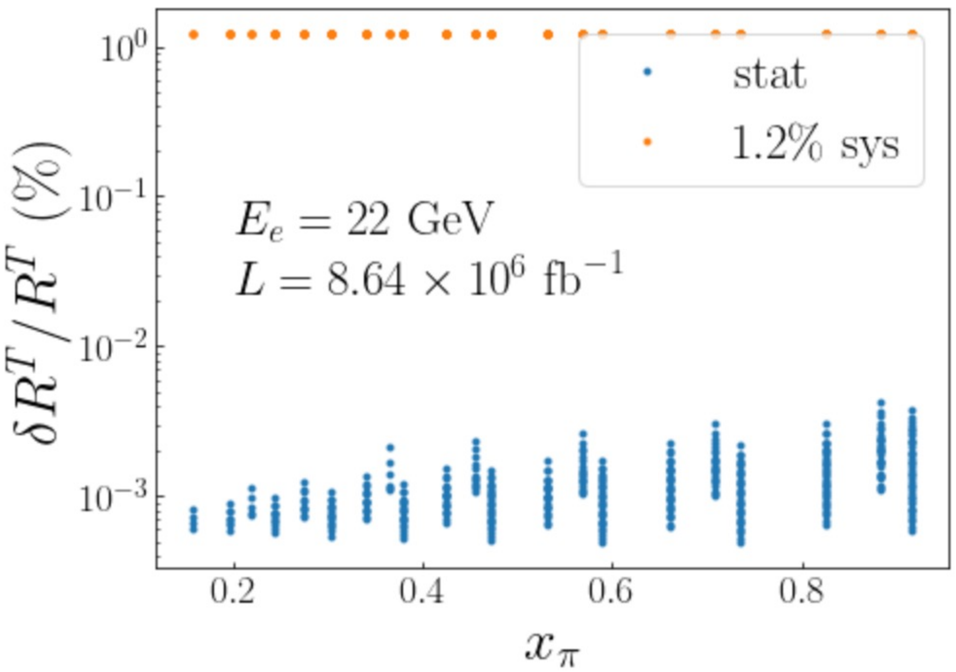
- Impacts from the 11 GeV TDIS experiment on pion PDFs will be limited
- Tests of universality in “clean” DIS regions are needed at 22 GeV
- The 11 GeV TDIS can map out the low-W_π resonance region and may allow for F_L constraints
- SIDIS at 22 GeV can offer another observable for pion TMDs

Backup Slides

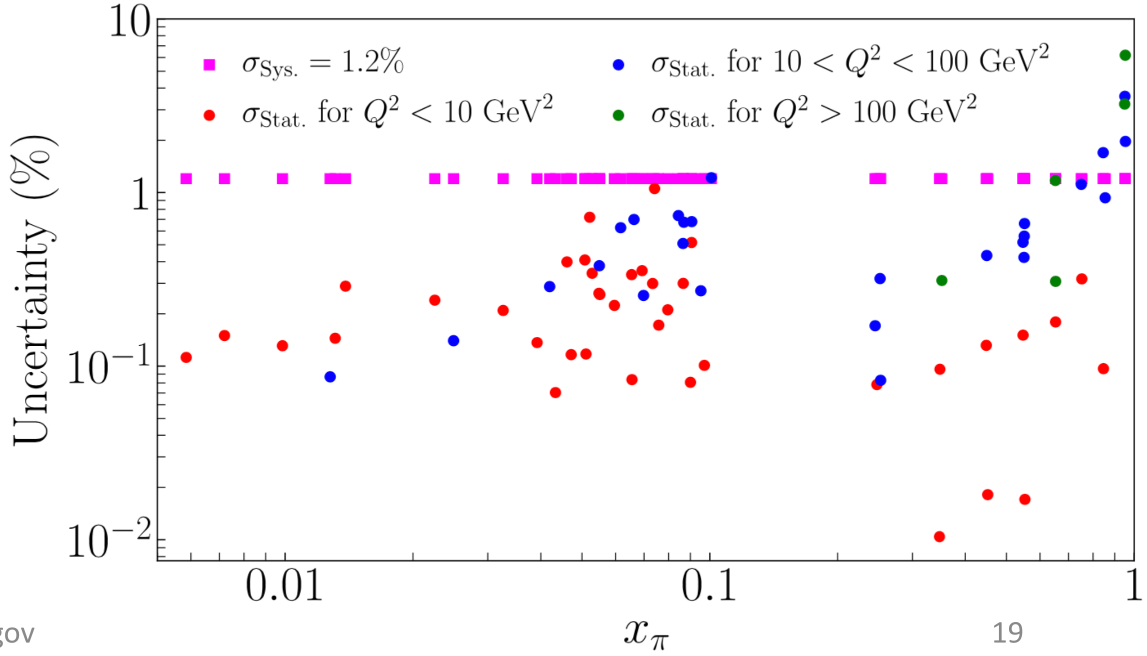
EIC vs JLab 22 GeV

- JLab measurements will be much more precise with a 200 day beam run – luminosity plays a big role

JLab

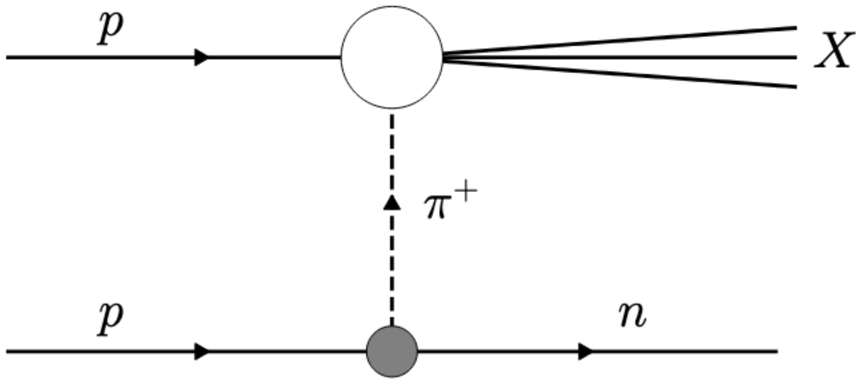


EIC



Testing systematics of the Sullivan process

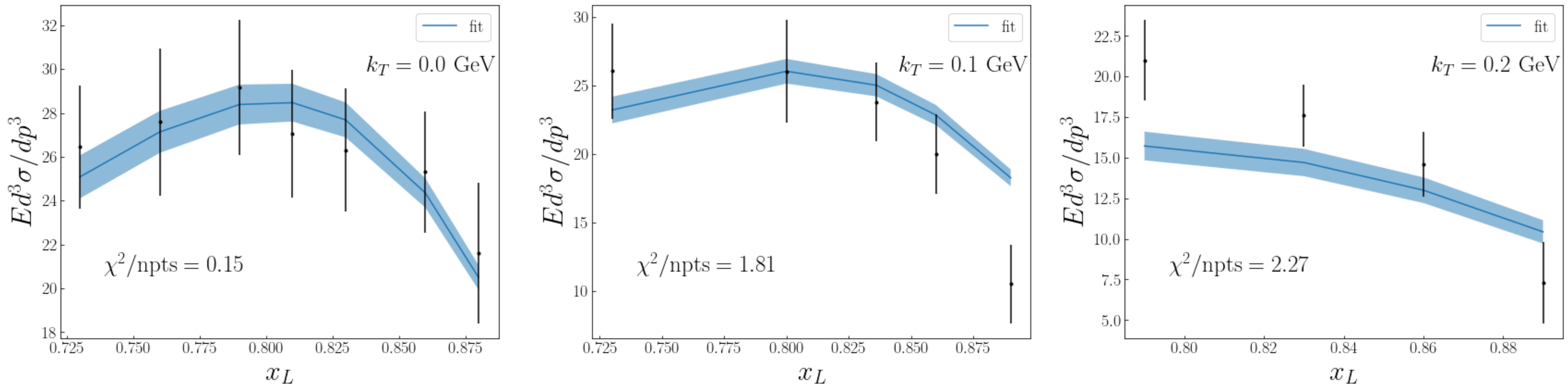
- We look to $pp \to nX$ data as well



- Here, sensitive as well to the $f_{\pi N}$ splitting function
  - Additional observable to test the universality

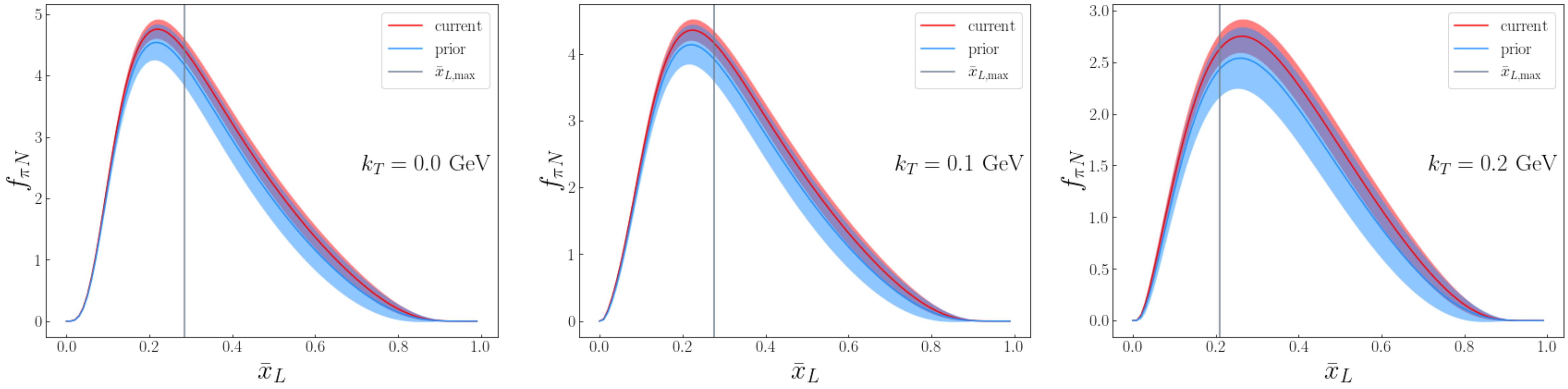
Data and theory comparisons

- Perform cut on $|t| < 0.1$ GeV^2



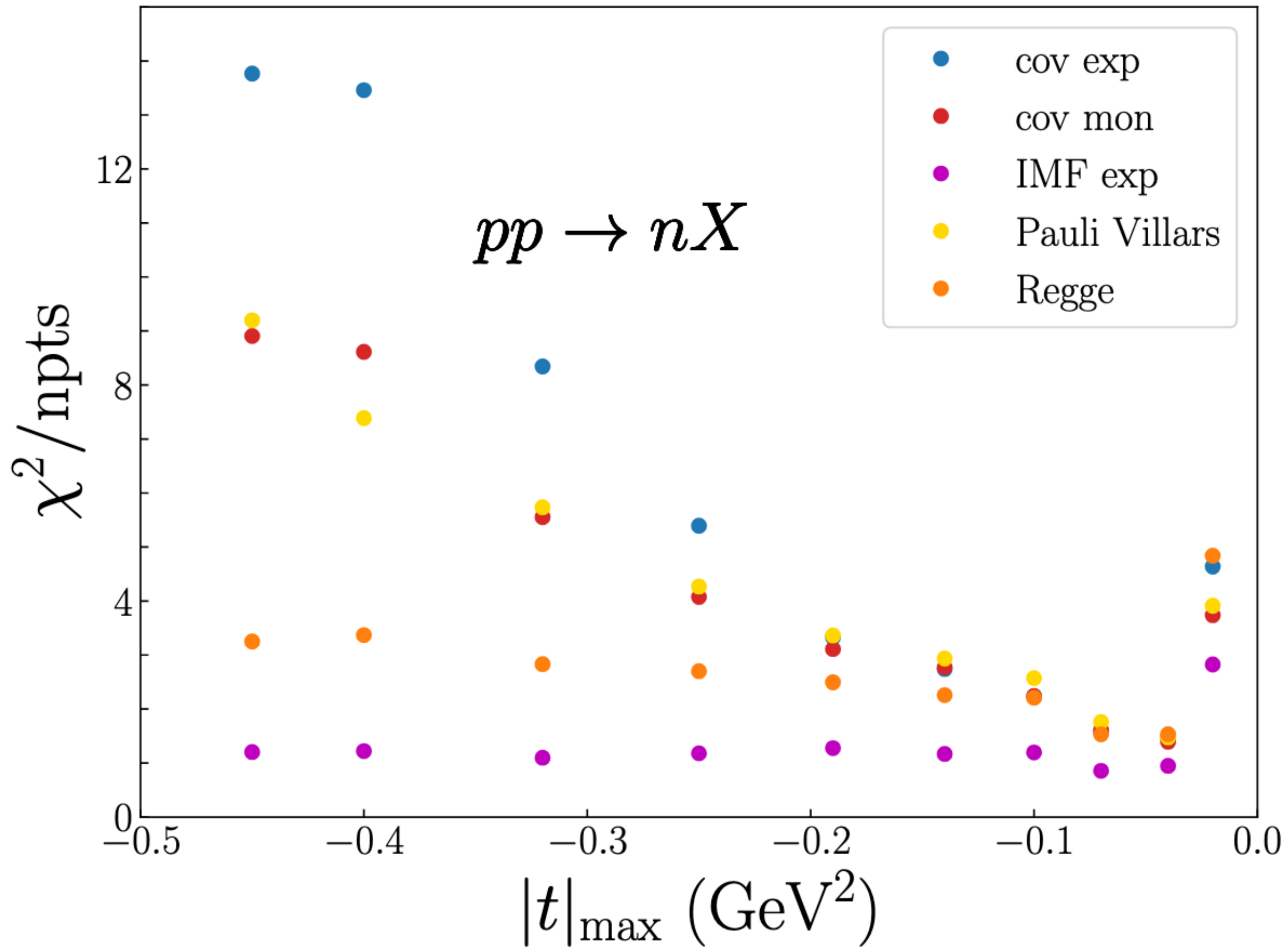
Resulting splitting function

- Agrees with the prior within the uncertainty bands



Resulting χ^2 for the $pp \to nX$ data

- All models as a function of the cut on $|t|$
- $|t|_{\max} = 0.1\ \mathrm{GeV}^2$ is ideal as it gives good description of data for all models



JAM analysis with threshold resummation

PHYSICAL REVIEW LETTERS **127,** 232001 (2021)

Global QCD Analysis of Pion Parton Distributions with Threshold Resummation

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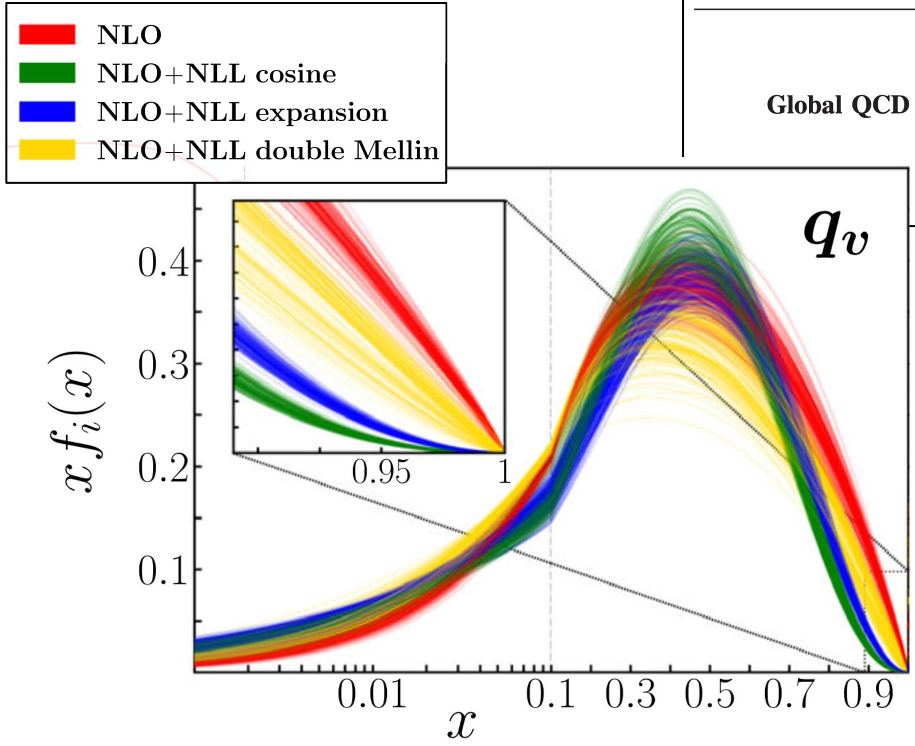
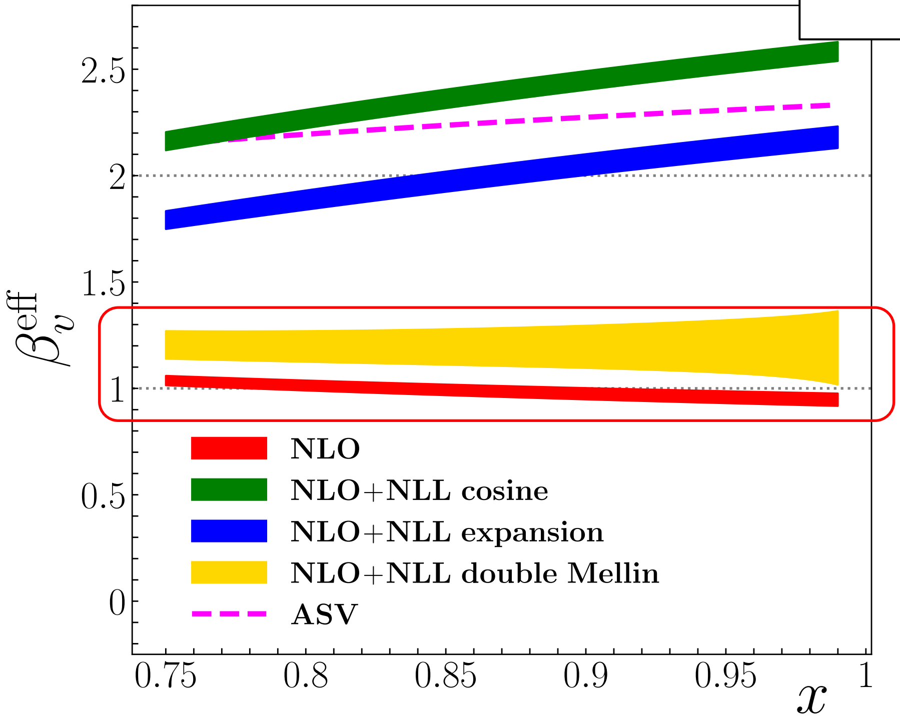
(JAM Collaboration)



$$\beta_{\rm eff}(x,\mu) = \frac{\partial \log |q_v(x,\mu)|}{\partial \log(1-x)}$$



- Highly dependent on perturbative approach
- NLO and NLO+NLL double Mellin methods better on theoretical grounds

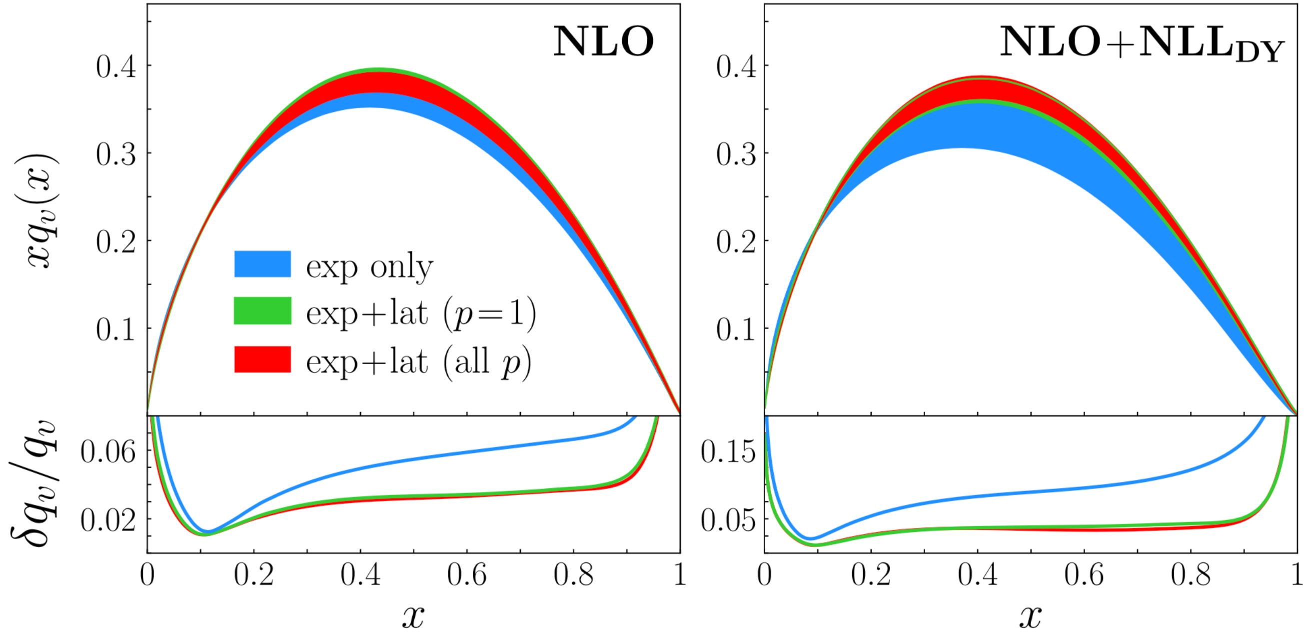
Pion PDFs from lattice + experimental data

PHYSICAL REVIEW D **105,** 114051 (2022)

Complementarity of experimental and lattice QCD data on pion parton distributions

P. C. Barry,[1] C. Egerer,[1] J. Karpie,[2] W. Melnitchouk,[1] C. Monahan,[1,3] K. Orginos,[1,3] Jian-Wei Qiu,[1,3] D. Richards,[1] N. Sato,[1] R. S. Sufian,[1,3] and S. Zafeiropoulos[4]

(Jefferson Lab Angular Momentum (JAM) and HadStruc Collaborations)



- The inclusion of lattice QCD data along with experimental data can also help us to reveal pion structure

Check the resonance regions

$\pi^{\pm}$ $\quad I^G(J^P) = 1^-(0^-)$

Mass $m = 139.57039 \pm 0.00018$ MeV (S = 1.8)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

γ (photon) $\quad I(J^{PC}) = 0,1(1^{--})$

Mass $m < 1 \times 10^{-18}$ eV
Charge $q < 1 \times 10^{-46}$ e (mixed charge)
Charge $q < 1 \times 10^{-35}$ e (single charge)
Mean life τ = Stable

$\rho(770)$ $\quad I^G(J^{PC}) = 1^+(1^{--})$

See the note in $\rho(770)$ Particle Listings.
Mass $m = 775.26 \pm 0.25$ MeV
Full width $\Gamma = 149.1 \pm 0.8$ MeV
$\Gamma_{ee} = 7.04 \pm 0.06$ keV

$b_1(1235)$ $\quad I^G(J^{PC}) = 1^+(1^{+-})$

Mass $m = 1229.5 \pm 3.2$ MeV (S = 1.6)
Full width $\Gamma = 142 \pm 9$ MeV (S = 1.2)

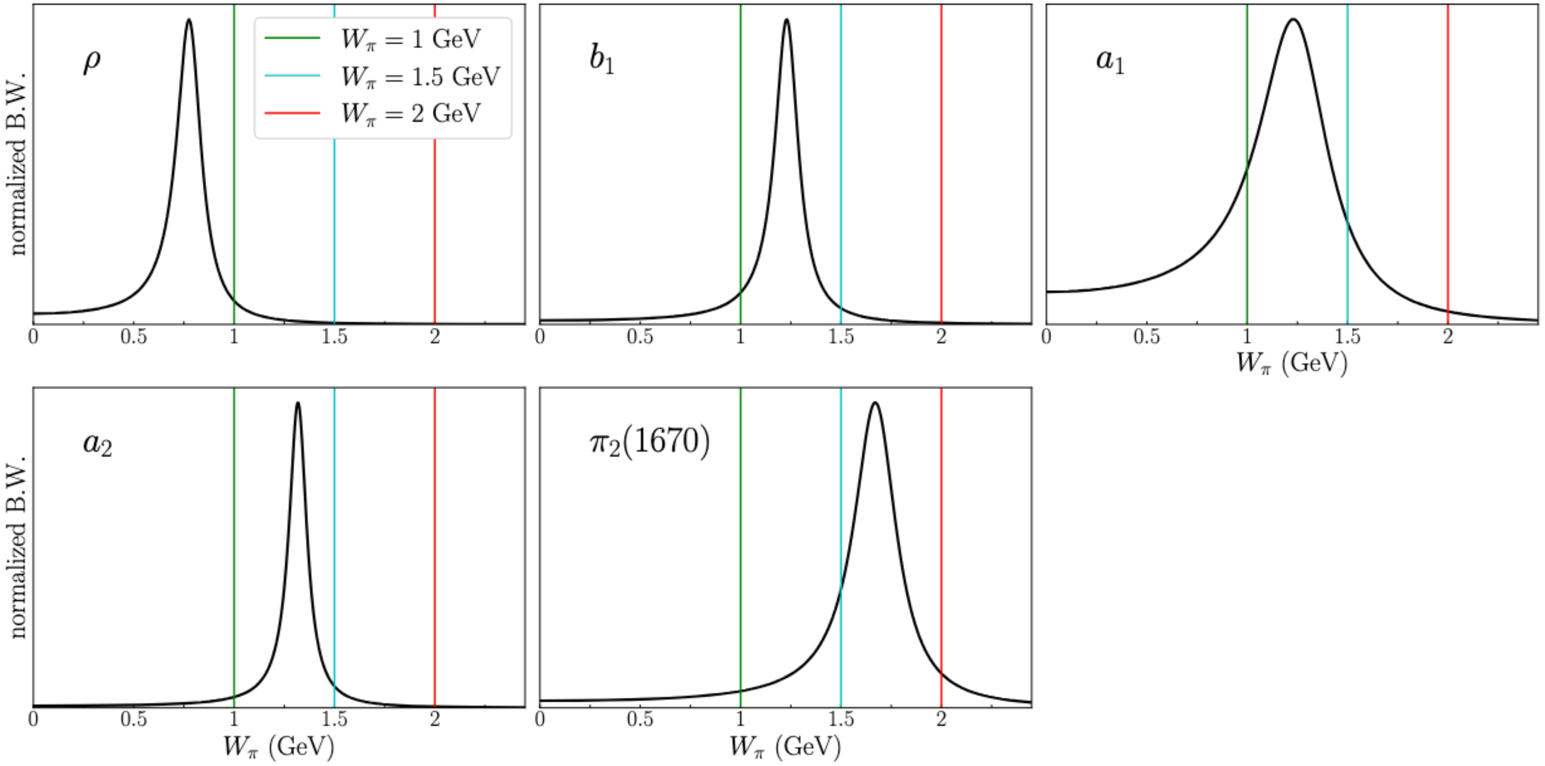
$a_2(1320)$ $\quad I^G(J^{PC}) = 1^-(2^{++})$

Mass $m = 1316.9 \pm 0.9$ MeV (S = 1.9)
Full width $\Gamma = 107 \pm 5$ MeV [j]

The quantum numbers of a charged π and photon result in specific outgoing mesons

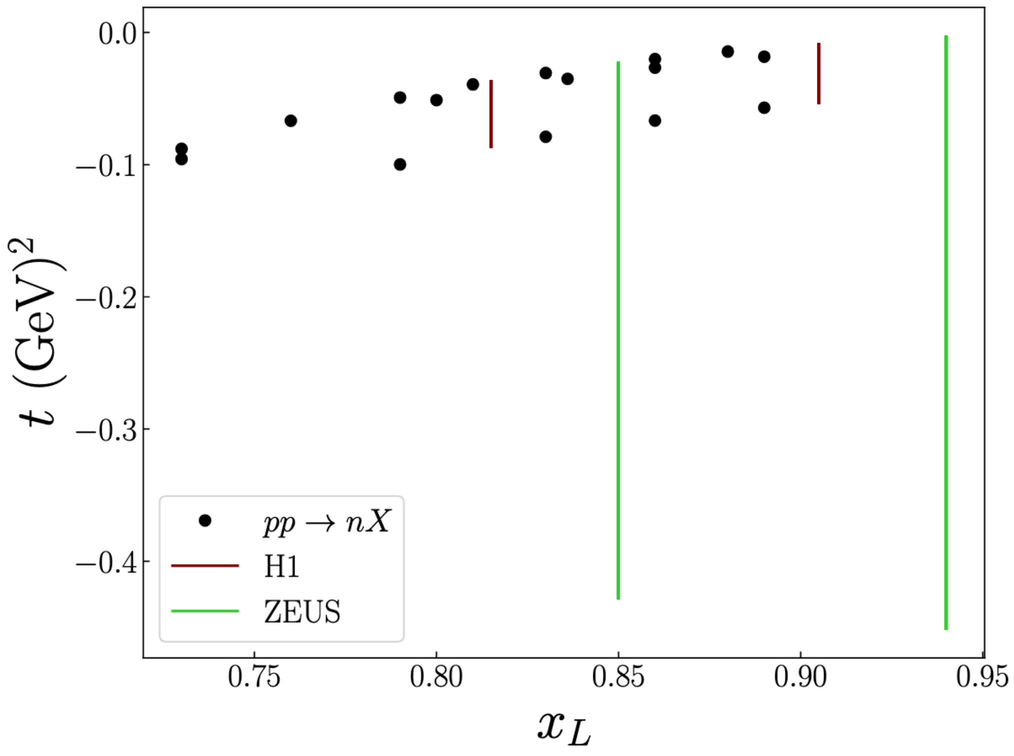
Resonances

- Possible low-lying resonances from $\gamma^*\pi$



Kinematics of Sullivan-variables

- Cuts on the $pp \to nX$ data at $|t| > 0.1\ \mathrm{GeV}^2$



Definition of W_π^2

- Derived from kinematics

$$W_\pi^2 = t - Q^2\left(1 - \frac{\bar{x}_L}{x}\right) = t - Q^2\left(1 - \frac{1}{x_\pi}\right).$$

Impact study details

- We created pseudodata in the form of

$$R^{\mathrm{T}} = \frac{\mathrm{d}^4\sigma(eN \to e'N'(\Lambda)X)}{\mathrm{d}x\mathrm{d}Q^2\mathrm{d}x_L\mathrm{d}t} / \frac{\mathrm{d}^2\sigma(eN \to e'X)}{\mathrm{d}x\mathrm{d}Q^2} \Delta x_L \Delta t$$

- We used a luminosity of: $d\mathcal{L}/dt - 5 \times 10^{38}/\mathrm{cm}^2/\mathrm{s}$

Use of W^2 for SIDIS

The unobserved invariant mass-squared in inclusive DIS is

$$W_{\rm tot}^2 = M^2 + \frac{Q^2(1-x_{\rm Bj})}{x_{\rm Bj}}\,. \tag{6.26}$$

In SIDIS it is

$$W_{\rm SIDIS}^2 = M^2 + M_{\rm B}^2 + \frac{Q^2(1-x_{\rm Bj}-z_{\rm h})}{x_{\rm Bj}} + \frac{Q^4 z_{\rm h}\left(\sqrt{1+\frac{4M^2x_{\rm Bj}^2}{Q^2}}\sqrt{1-\frac{4M^2x_{\rm Bj}^2M_{\rm B,T}^2}{z_{\rm h}^2Q^4}}-1\right)}{2M^2x_{\rm Bj}^2}$$

$$\overset{M,M_{\rm B}\to 0}{=} \frac{Q^2(1-x_{\rm Bj})(1-z_{\rm h})}{x_{\rm Bj}} - \frac{\mathbf{P}_{\rm B,T}^2}{z_{\rm h}}\,. \tag{6.27}$$

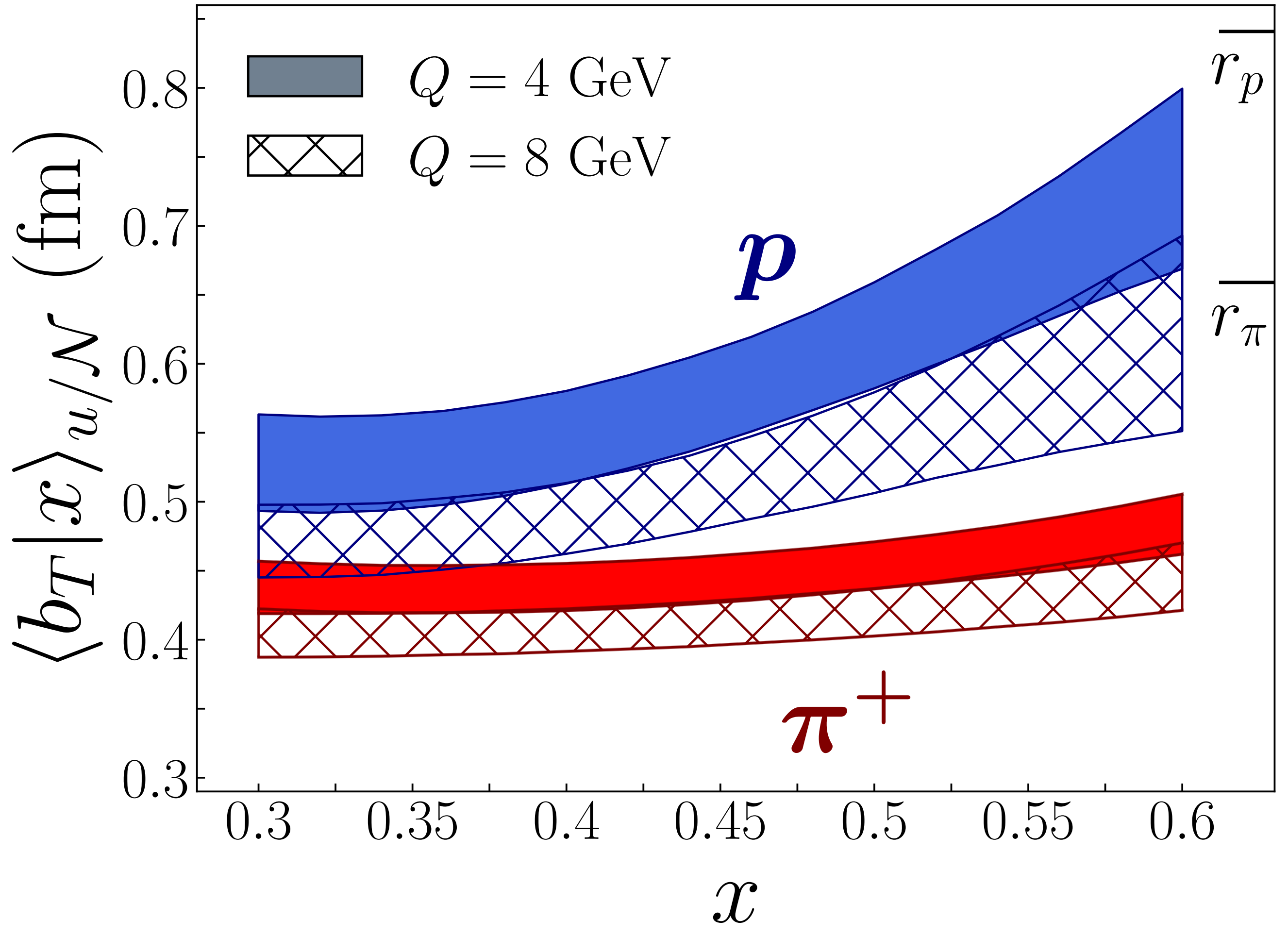
- Replace M^2 with t

Average b_T

- The conditional expectation value of b_T for a given x

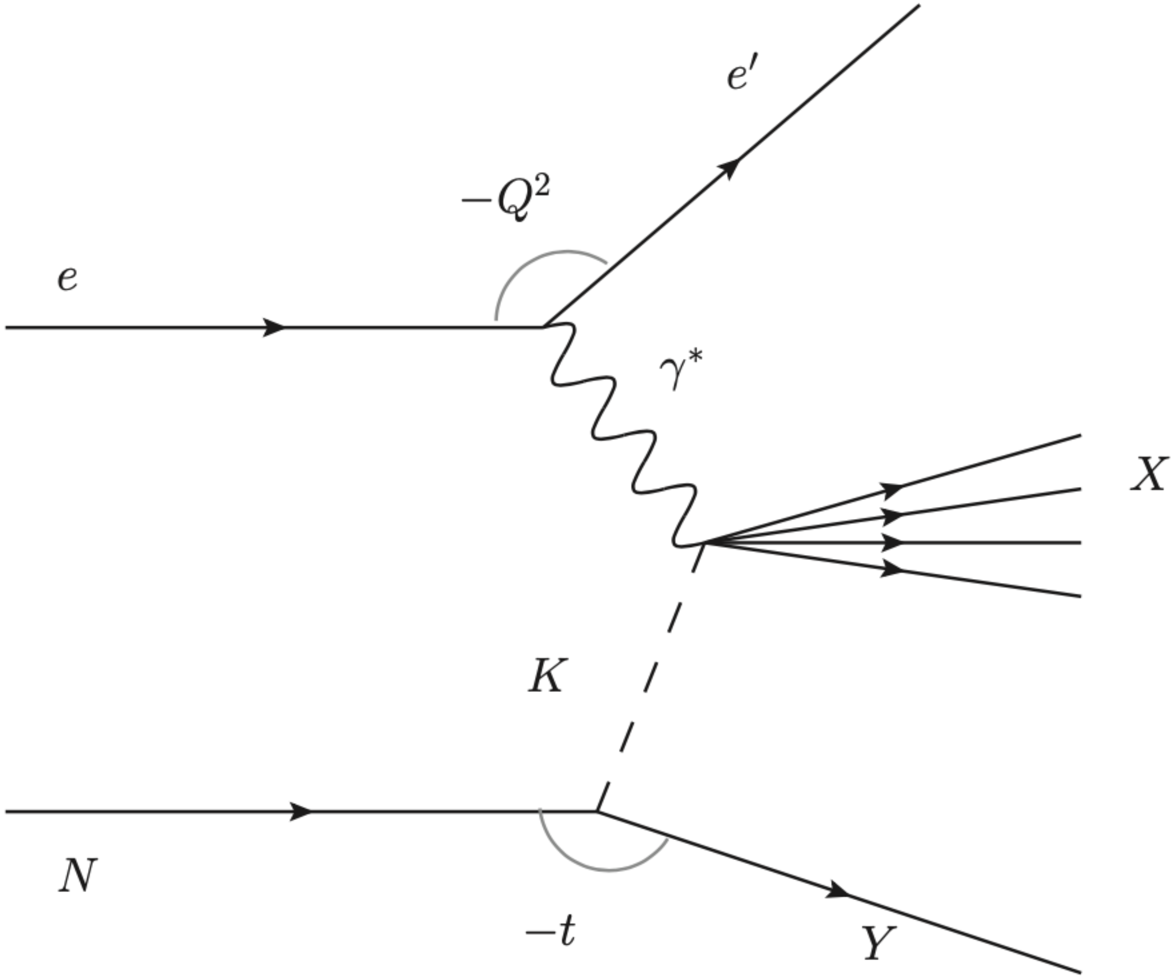
$$\langle b_T|x\rangle_{q/\mathcal{N}} = \int \mathrm{d}^2\boldsymbol{b}_T\, b_T\, \tilde{f}_{q/\mathcal{N}}(b_T|x;Q,Q^2)$$

- Shows a measure of the transverse correlation in coordinate space of the quark in a hadron for a given x



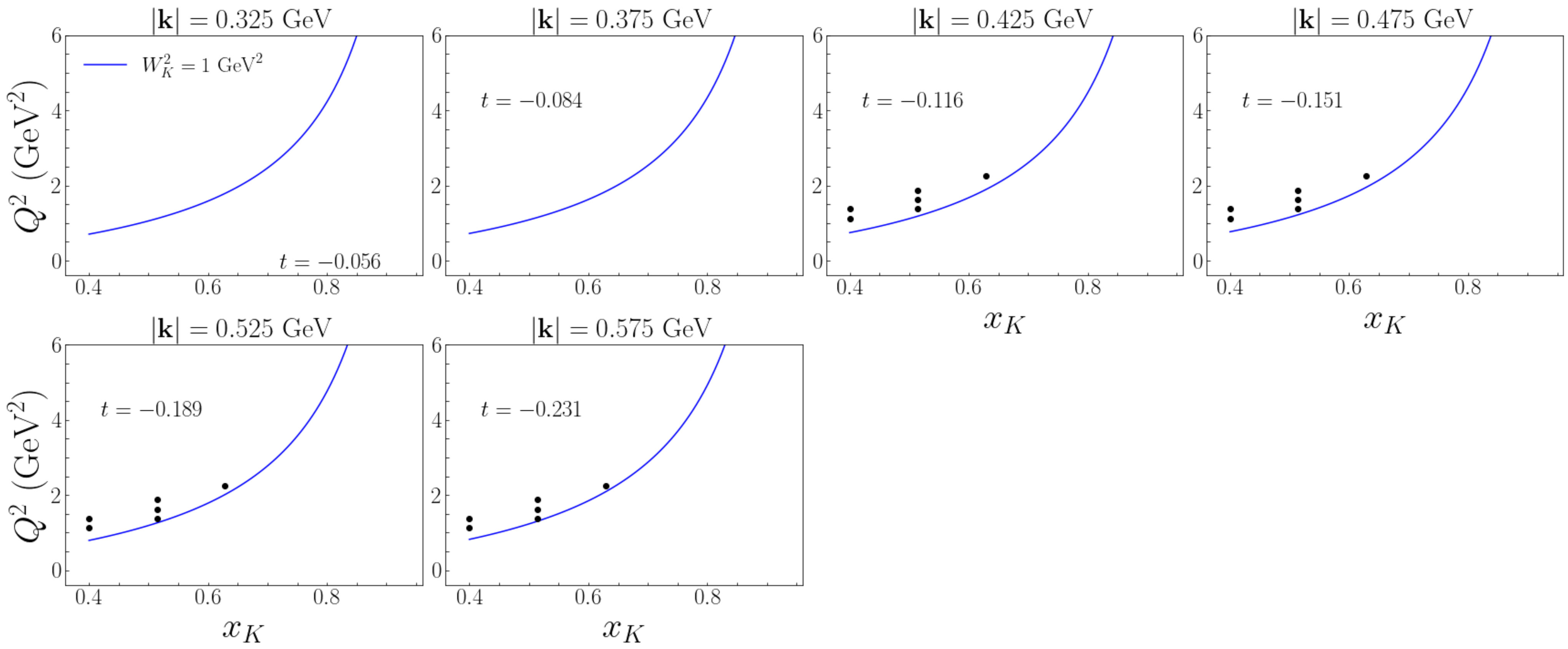
Brief words on kaon TDIS

- Sullivan process applies, but a *hyperon* must be tagged
- Consider again, not only inclusive W^2 but W_K^2



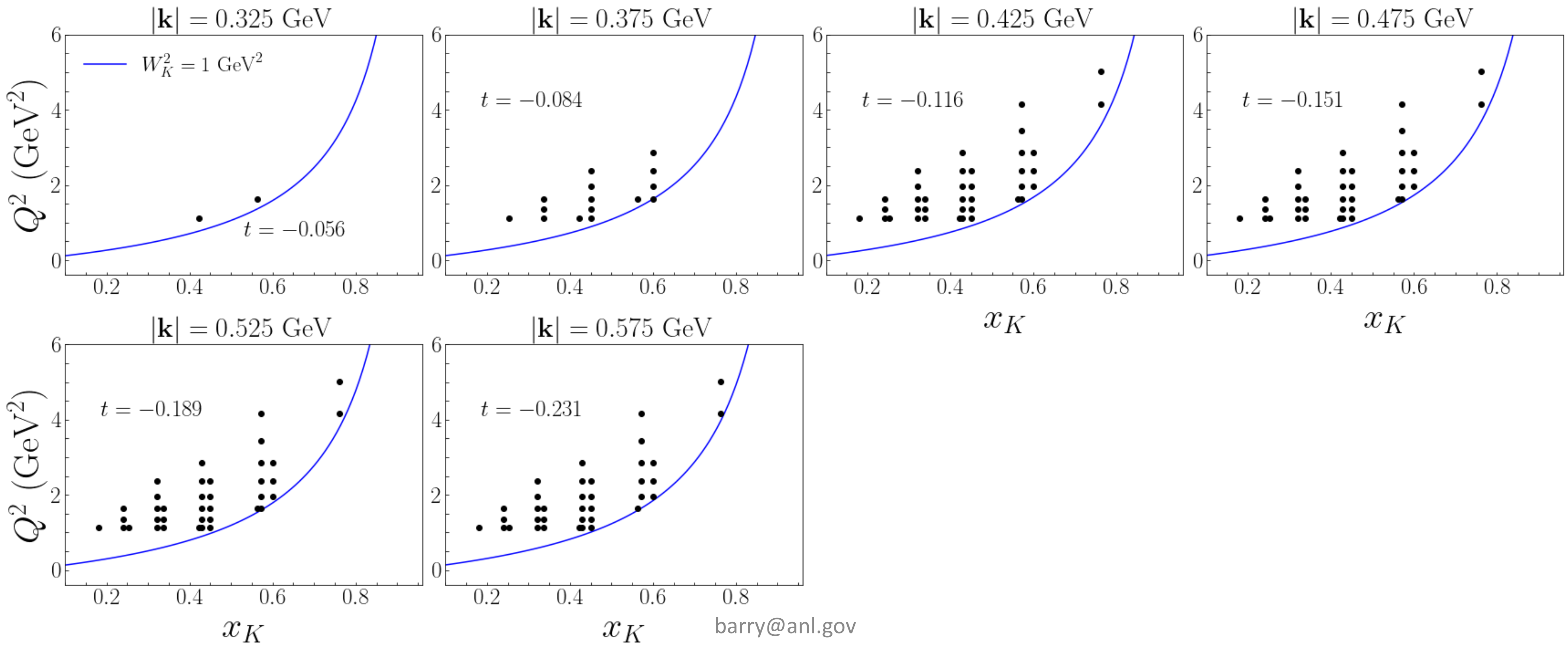
Kinematics for 11 GeV Kaon TDIS

- Beware of such large $|t|$ further away from kaon pole



Kinematics for 22 GeV Kaon TDIS

- Accepting of more points at smaller $|\boldsymbol{k}|$



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Resonance from K^*

- The K^* resonance is much more narrow than for ρ meson
- $W^2_{K,\mathrm{max}} = 1\ \mathrm{GeV}^2$