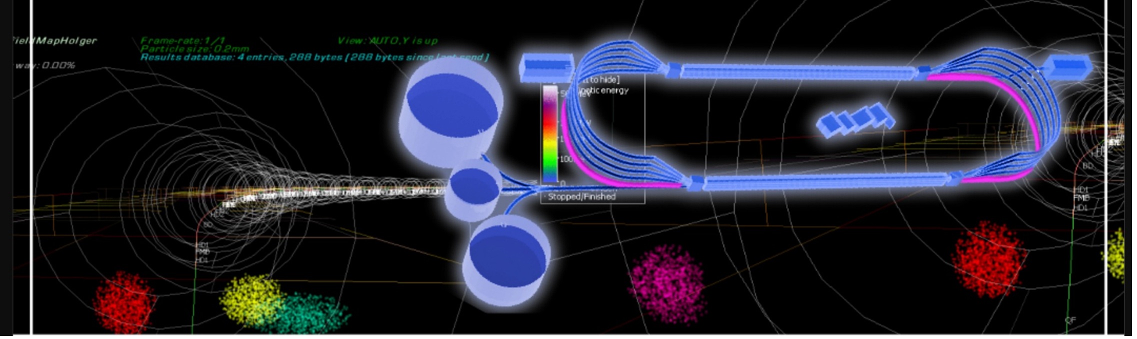

Meson parton distributions at 22 GeV

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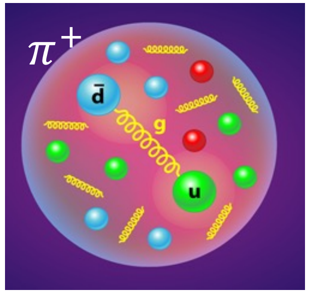
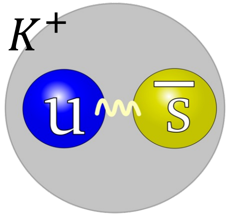
Science at the Luminosity Frontier: Jefferson Lab at 22 GeV

December 9th, 2024

Argonne NATIONAL LABORATORY

Motivation

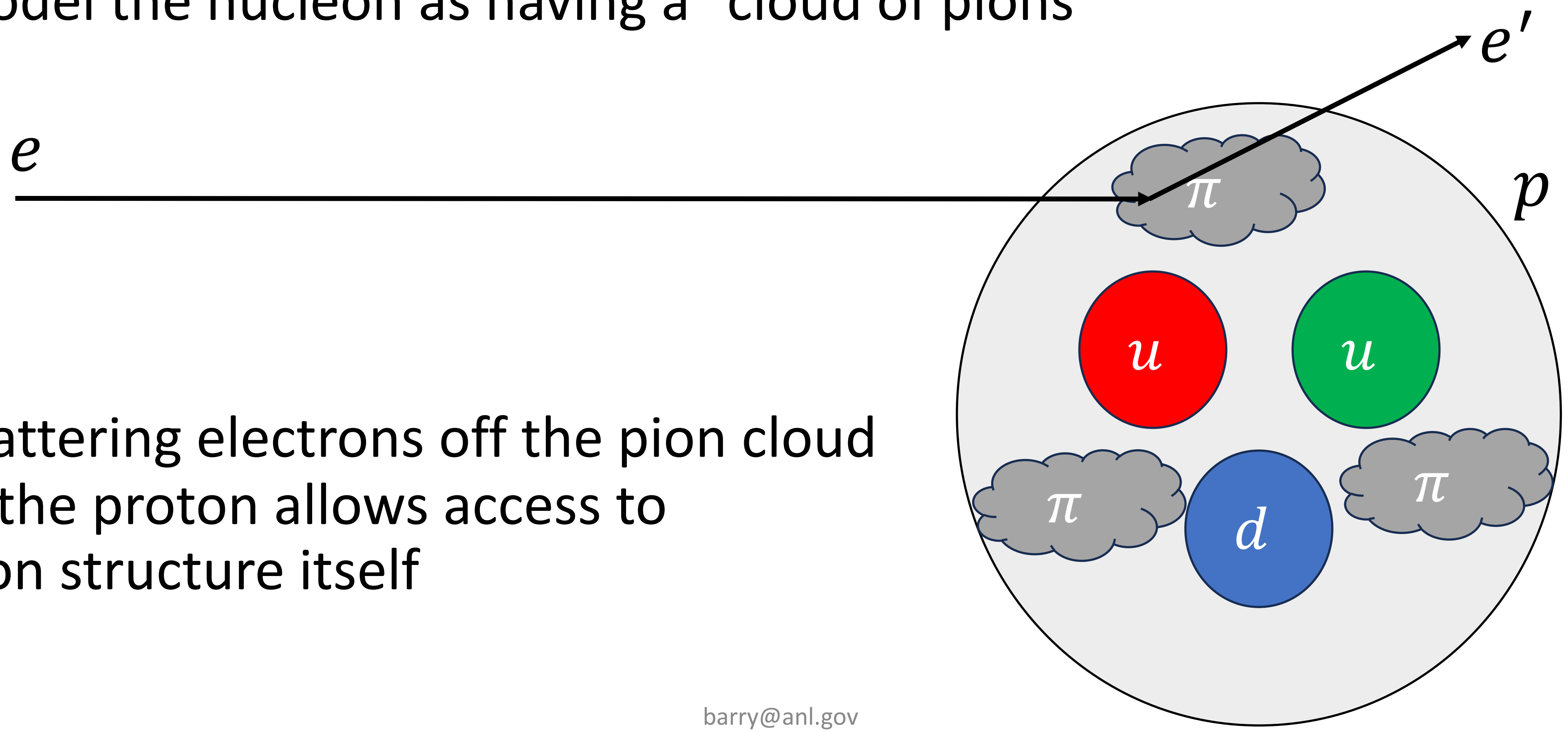




- We want to learn about QCD through the structure of hadrons
- Does it make sense to *only* study proton structure? **NO!**
- **Mesons** offer importance of emergent phenomena of QCD such as
  - How is mass generated?
  - How do quarks and gluons arrange themselves within hadrons?
  - Why is there confinement?
- Allows for another probe of confinement scales in quark-gluon bound systems

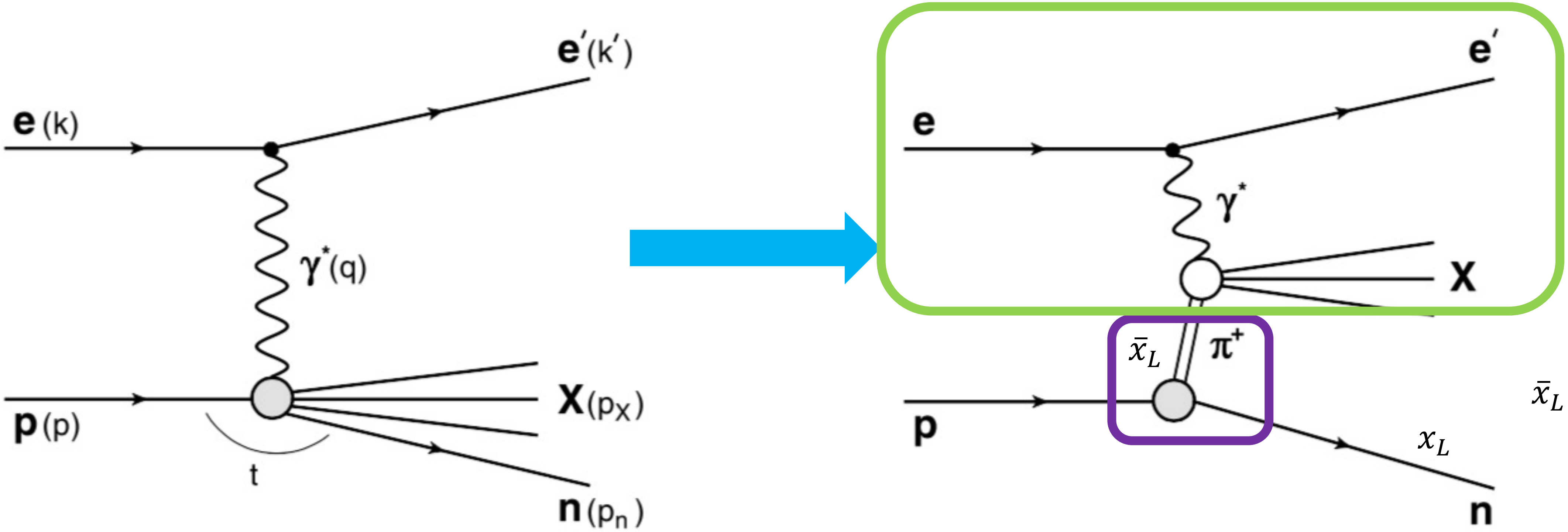
Accessing pions indirectly

- 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

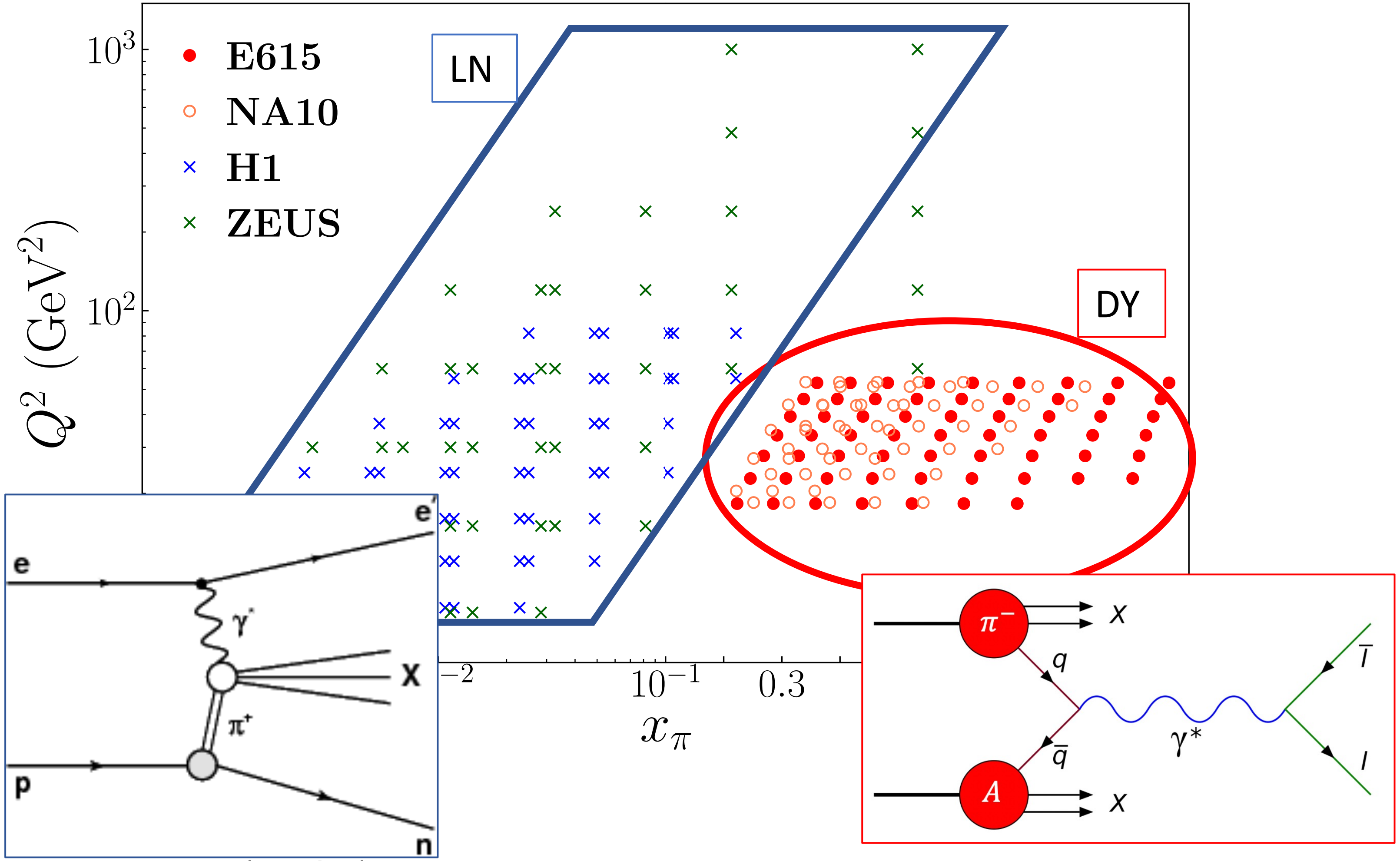


$\bar{x}_L = 1 - x_L$

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

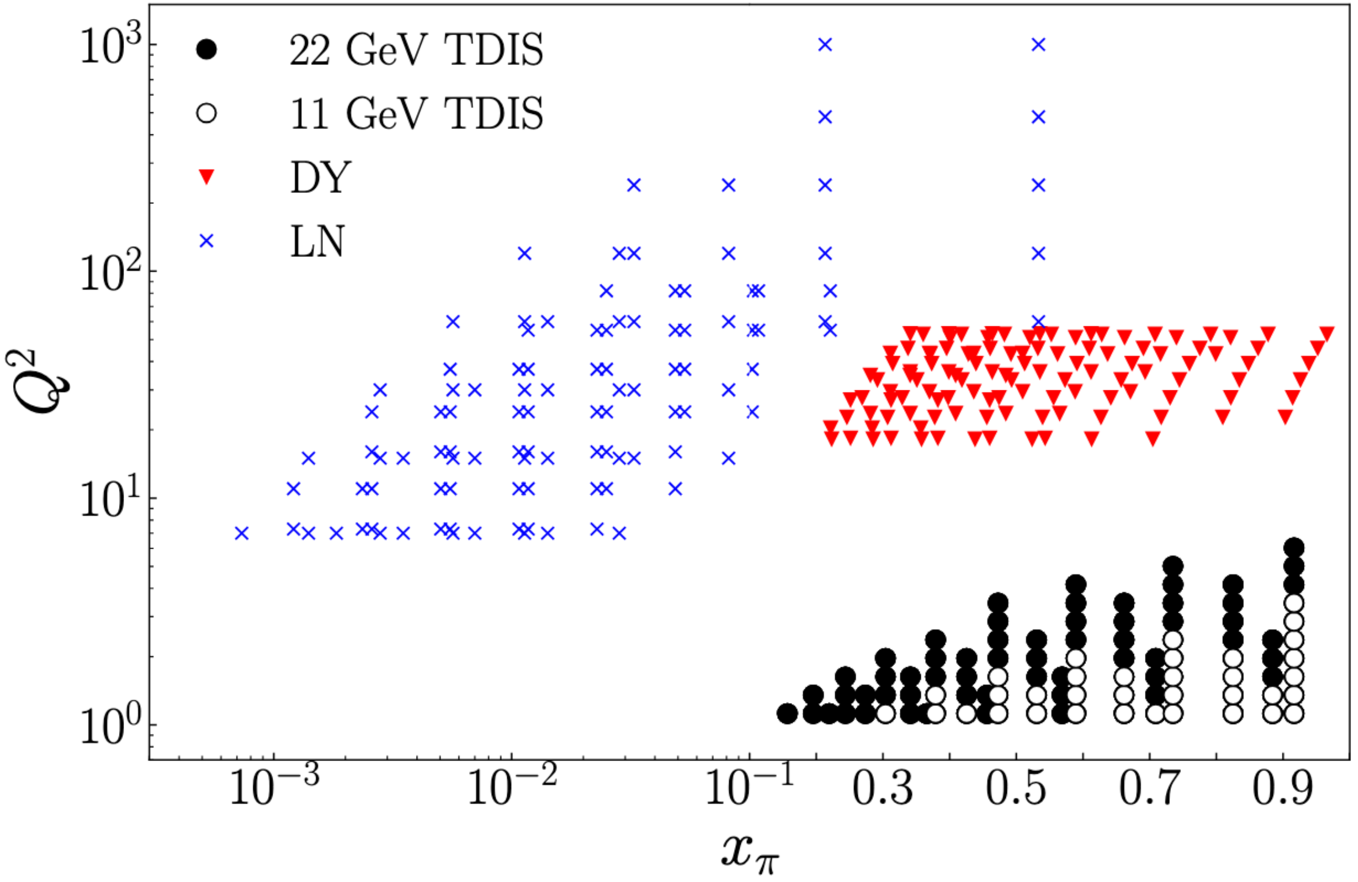
Available datasets for pion structures

- Little kinematic overlapping region
- How can we validate our results with independent measurements in separate kinematic regions?
- Need overlap at large x_π

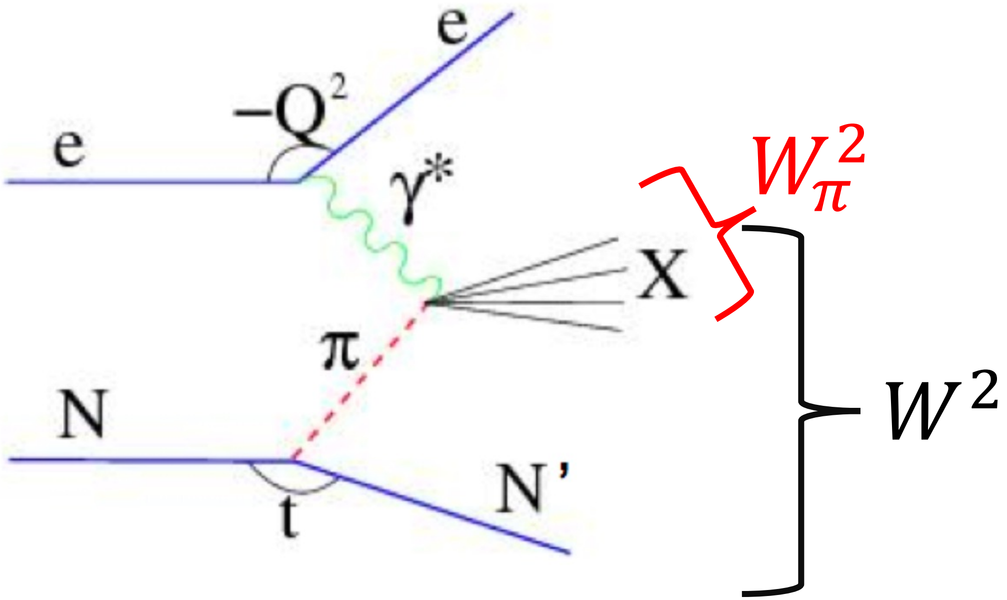


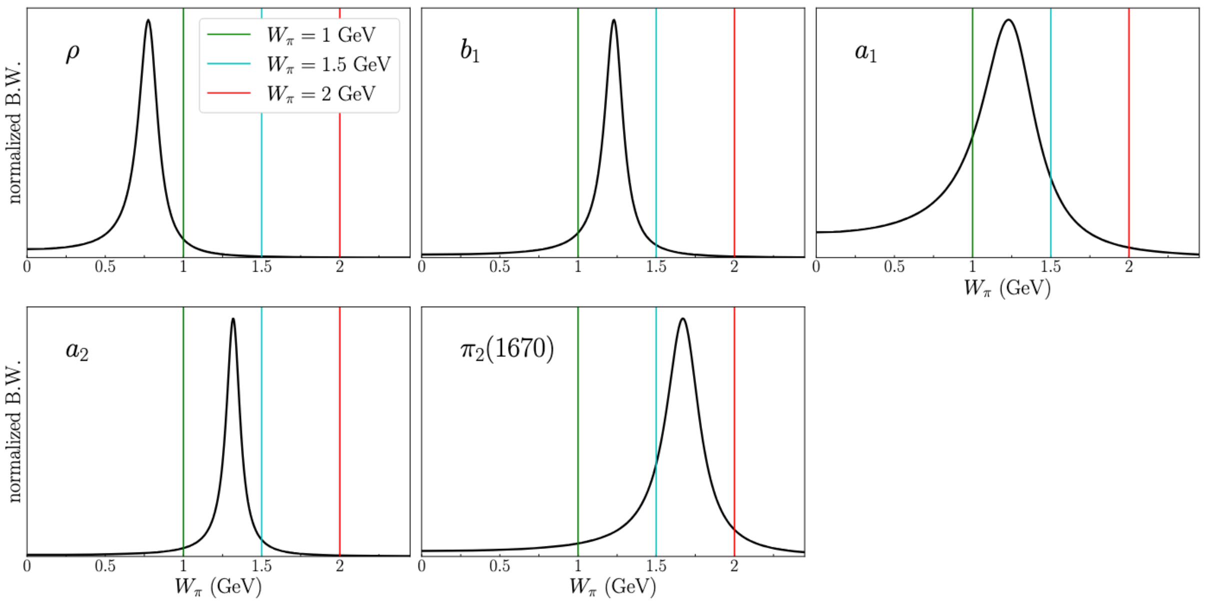
Future kinematics

- With JLab 11 and 22 GeV, we can achieve overlap between DY and TDIS measurements
- However, we must be **careful** how to interpret these data!



Small W_π^2: resonance region

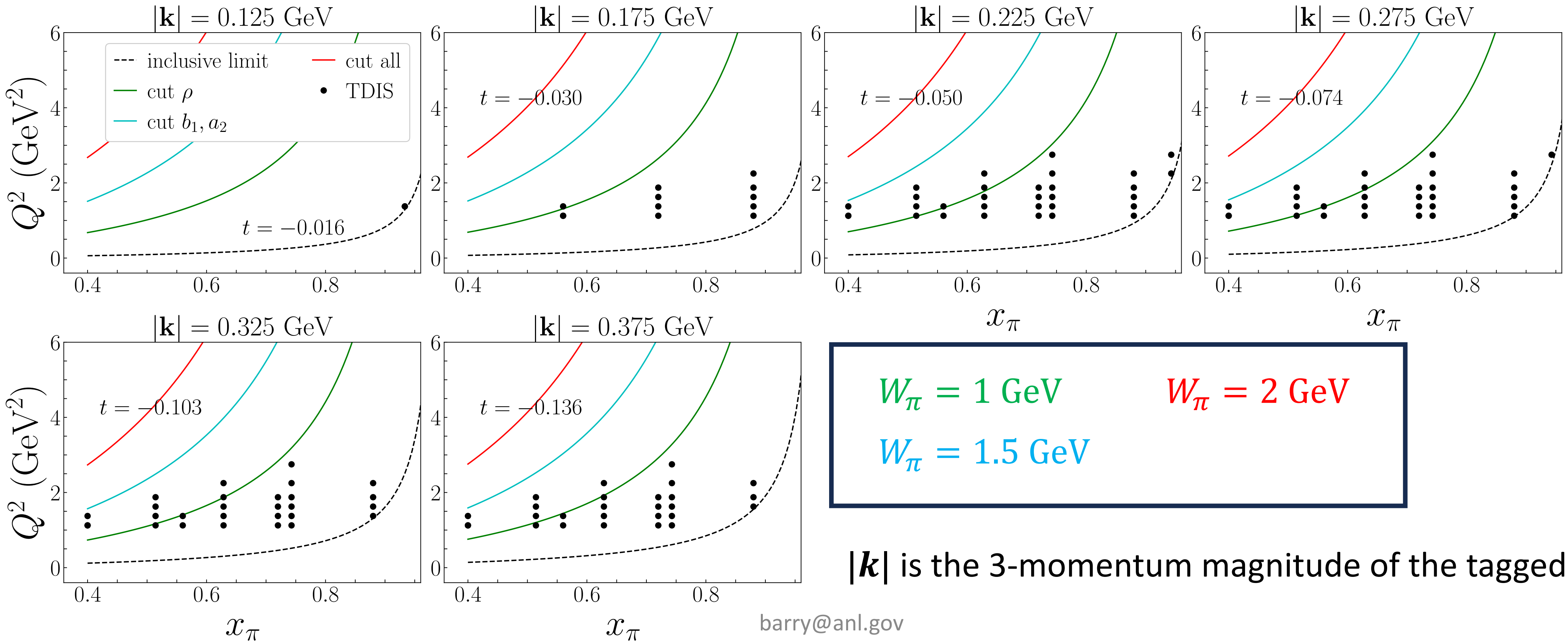




- Have to impose proper cuts on the W_π^2 to interpret in terms of parton densities

Current 11 GeV TDIS kinematics

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



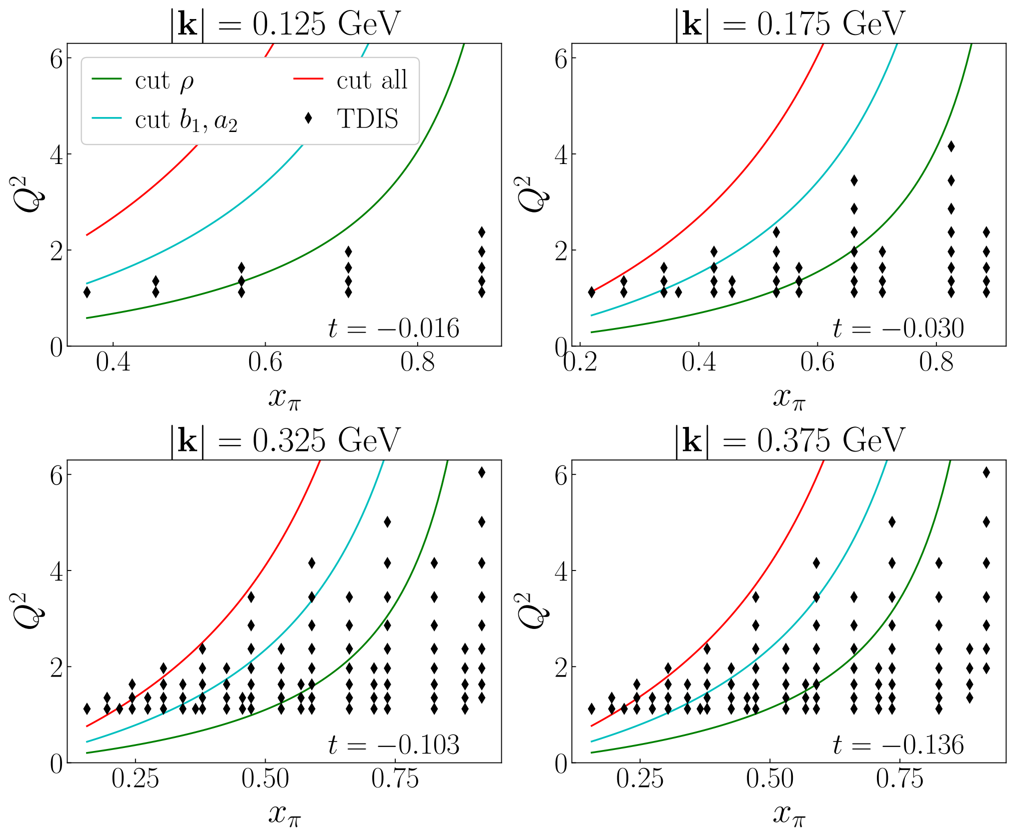
$W_\pi = 1$ GeV $\quad W_\pi = 2$ GeV

$W_\pi = 1.5$ 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



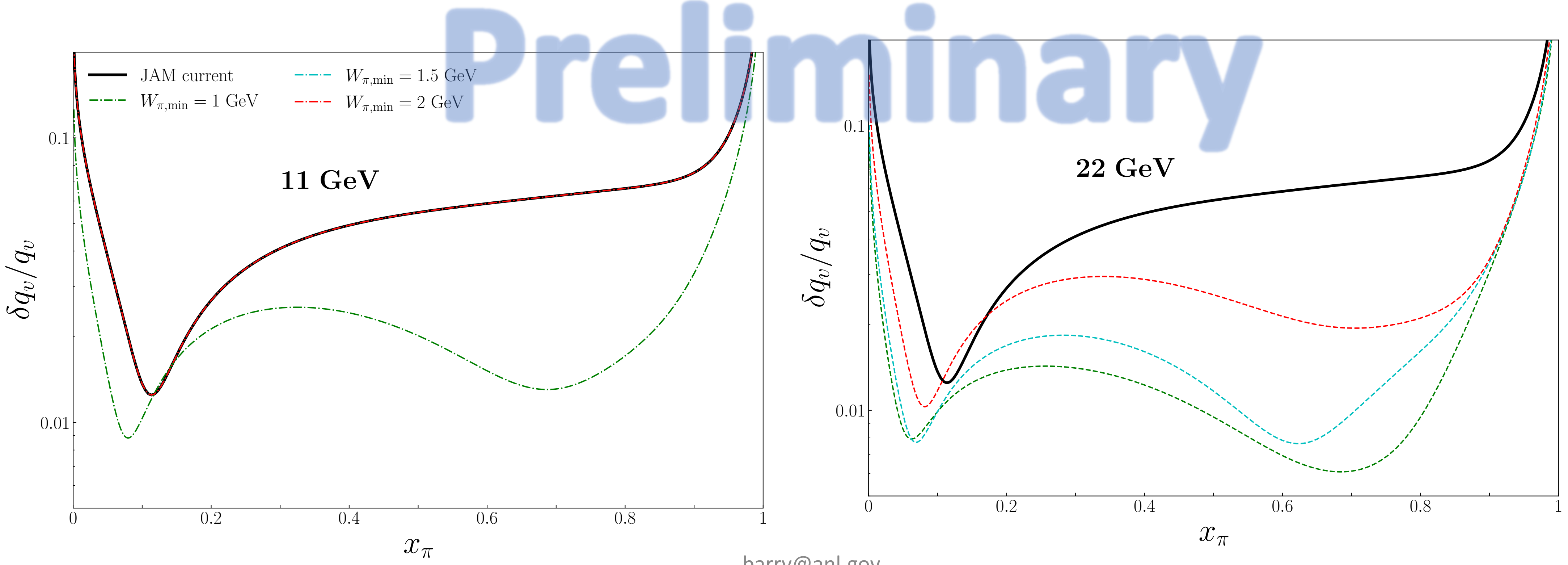
$W_\pi = 1$ GeV

$W_\pi = 2$ GeV

$W_\pi = 1.5$ GeV

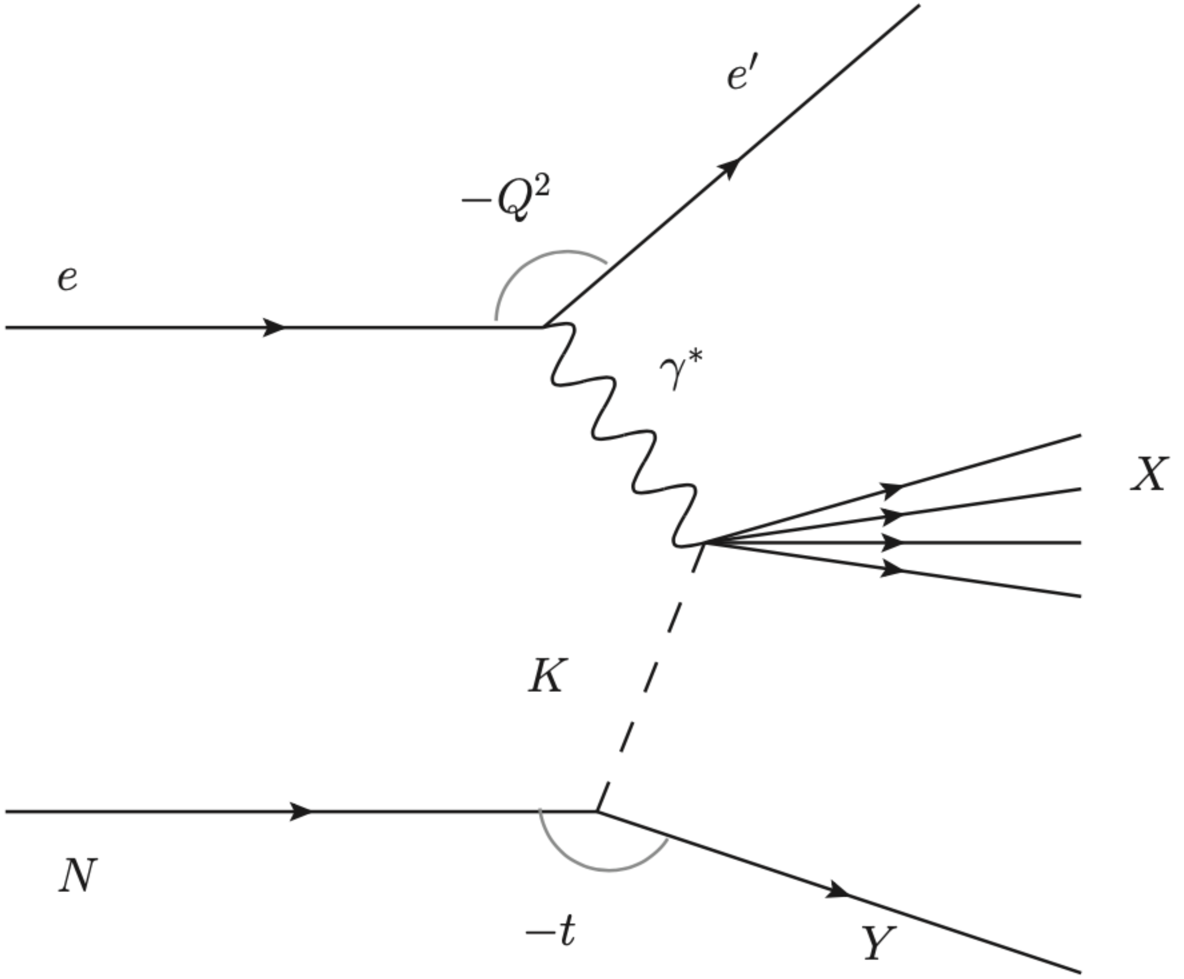
Impact on pion PDFs with 22 GeV

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



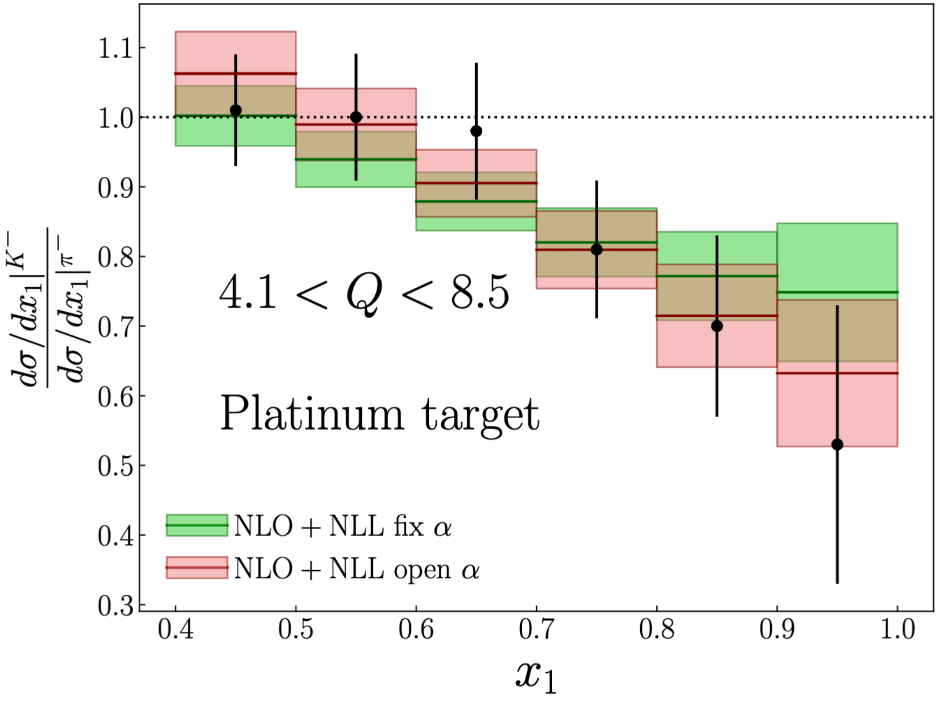
Kaons at JLab

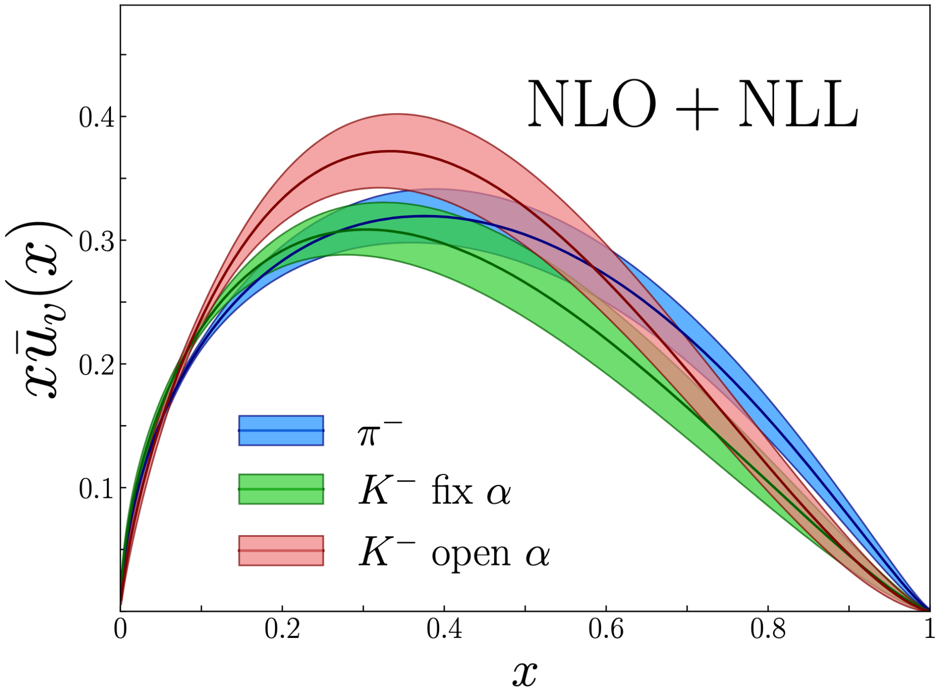
- Sullivan process applies, but a *hyperon* must be tagged
- Consider again, not only inclusive W^2 but W_K^2
- Resonances can appear from K^* mesons



What do we know about kaons?

- Ratio of K^- induced to π^- induced DY from NA3 in 1980





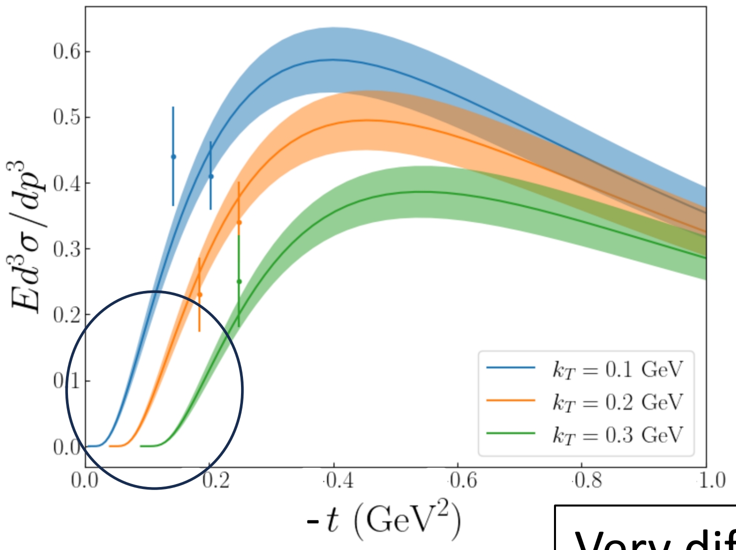
Constraints on the kaon splitting function

- We look at $pp \to \Lambda X$ data from CERN

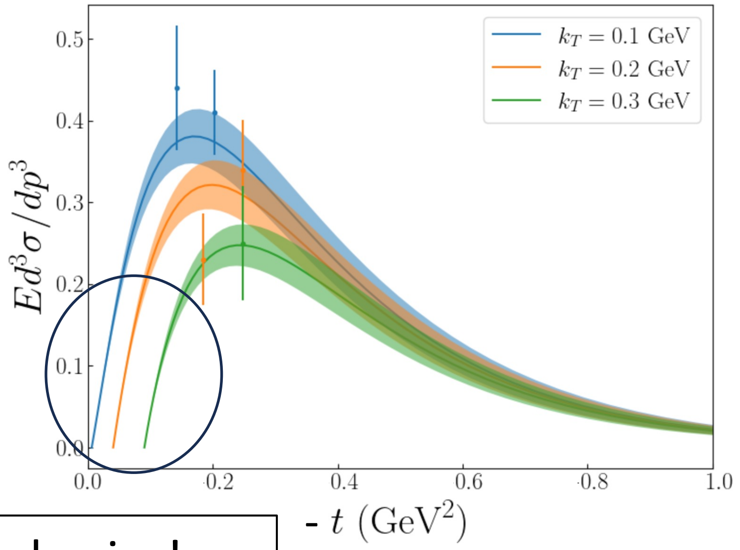
Splitting of $p \to K\Lambda$; has model dependence

$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}^3p}(pp \to \Lambda X) = f_{K\Lambda}(\bar{x}_L, k_T^2)\,\sigma_{\mathrm{tot}}^{pK^+}(s\bar{x}_L),$$

s-dependent exponential model



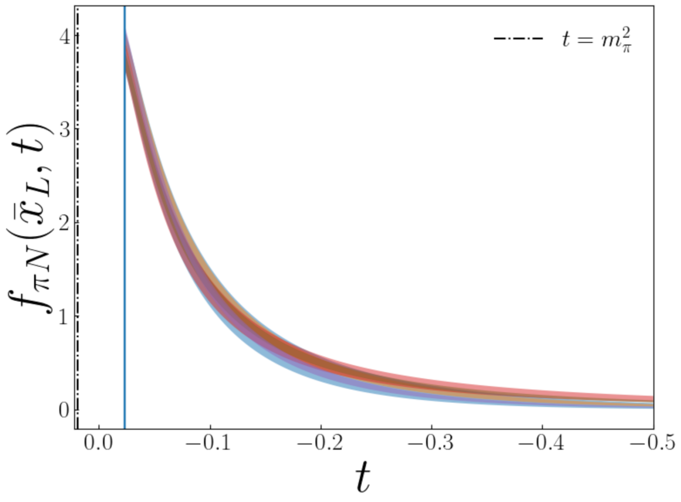
t-dependent exponential model

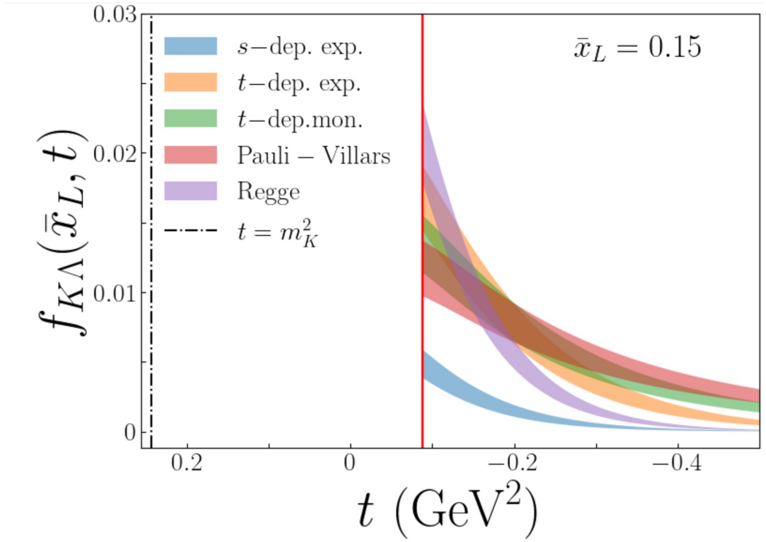


Very different small t behavior!
JLab data can help us resolve this.

Resulting splitting function comparisons

- The TDIS cross section is proportional to the splitting function





- The counts for the kaon TDIS will be ≈ 2 orders of magnitude less than for pions
- Need high luminosity machine!

Final thoughts

- 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
- JLab 22 GeV can validate the meson structure where DY measurements are performed

<u>Other topics not discussed here</u>

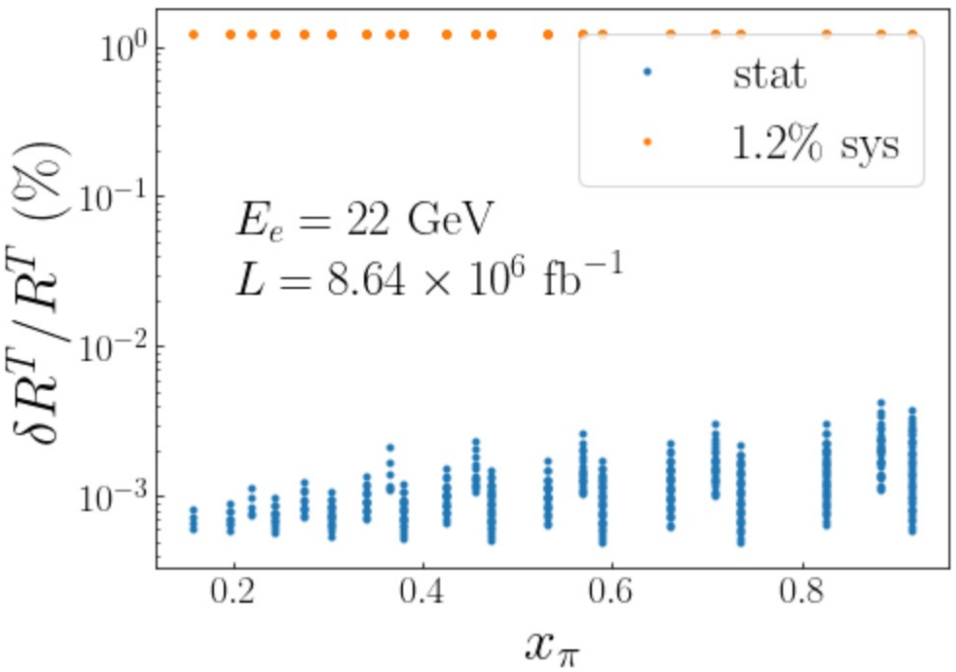
- The 11 GeV TDIS can map out the low-W_π resonance region and may allow for F_L constraints
- SIDIS at 22 GeV can offer another observable for pion TMDs in the large-x_π region

Backup Slides

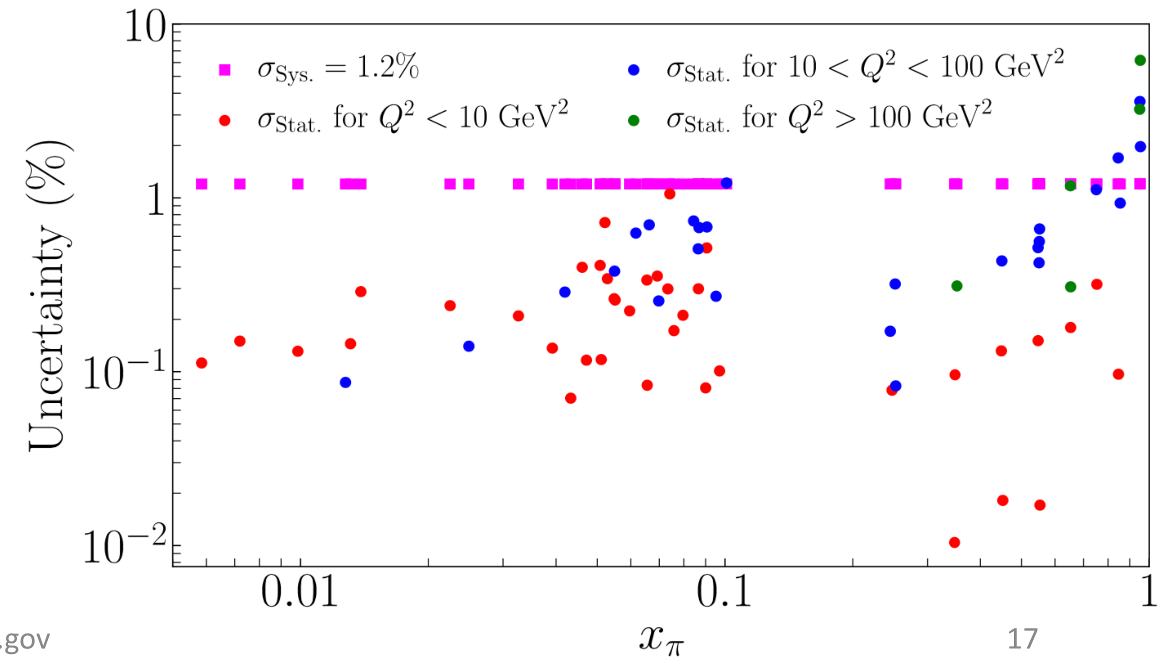
EIC vs JLab 22 GeV

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

JLab

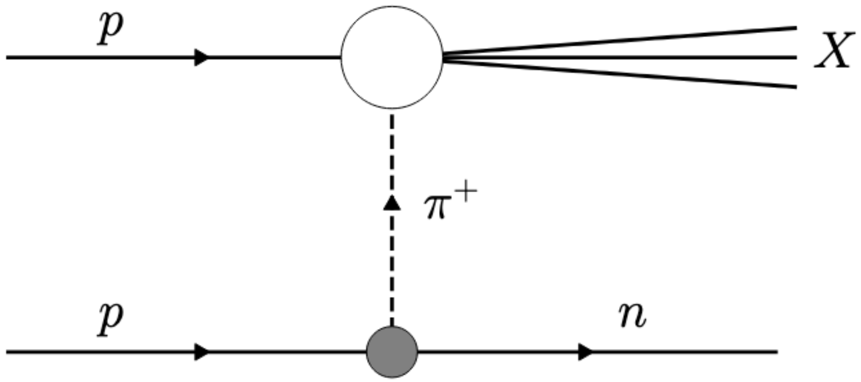


EIC



Testing systematics of the Sullivan process

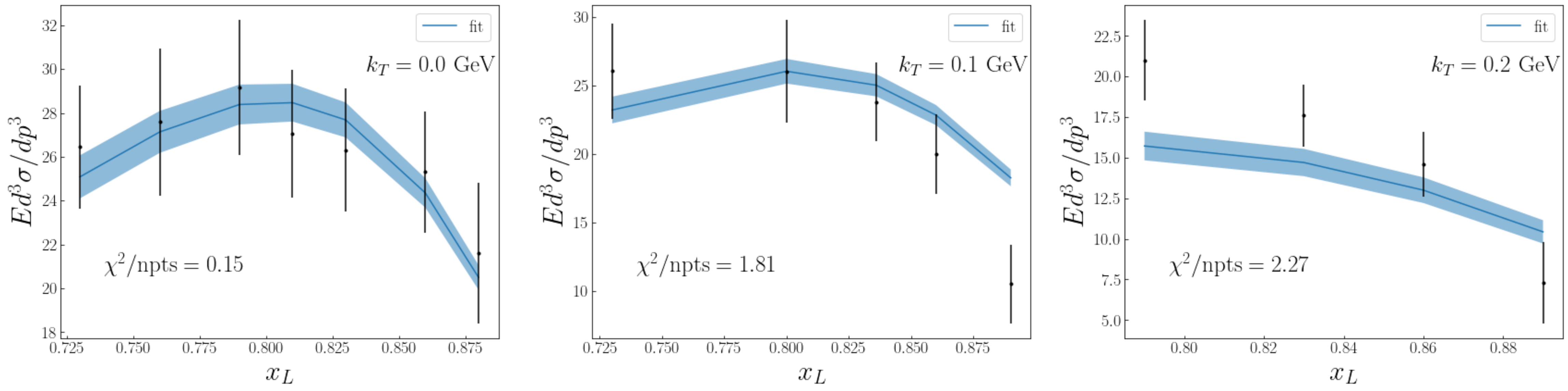
- We look to $pp \to nX$ data as well



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

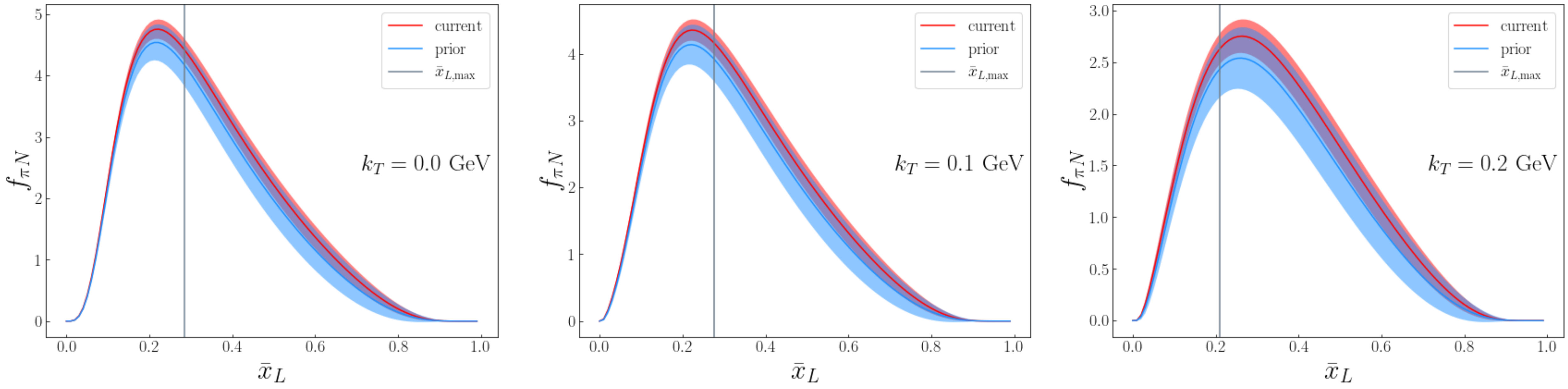
Data and theory comparisons

- Perform cut on $|t| < 0.1\ \mathrm{GeV}^2$



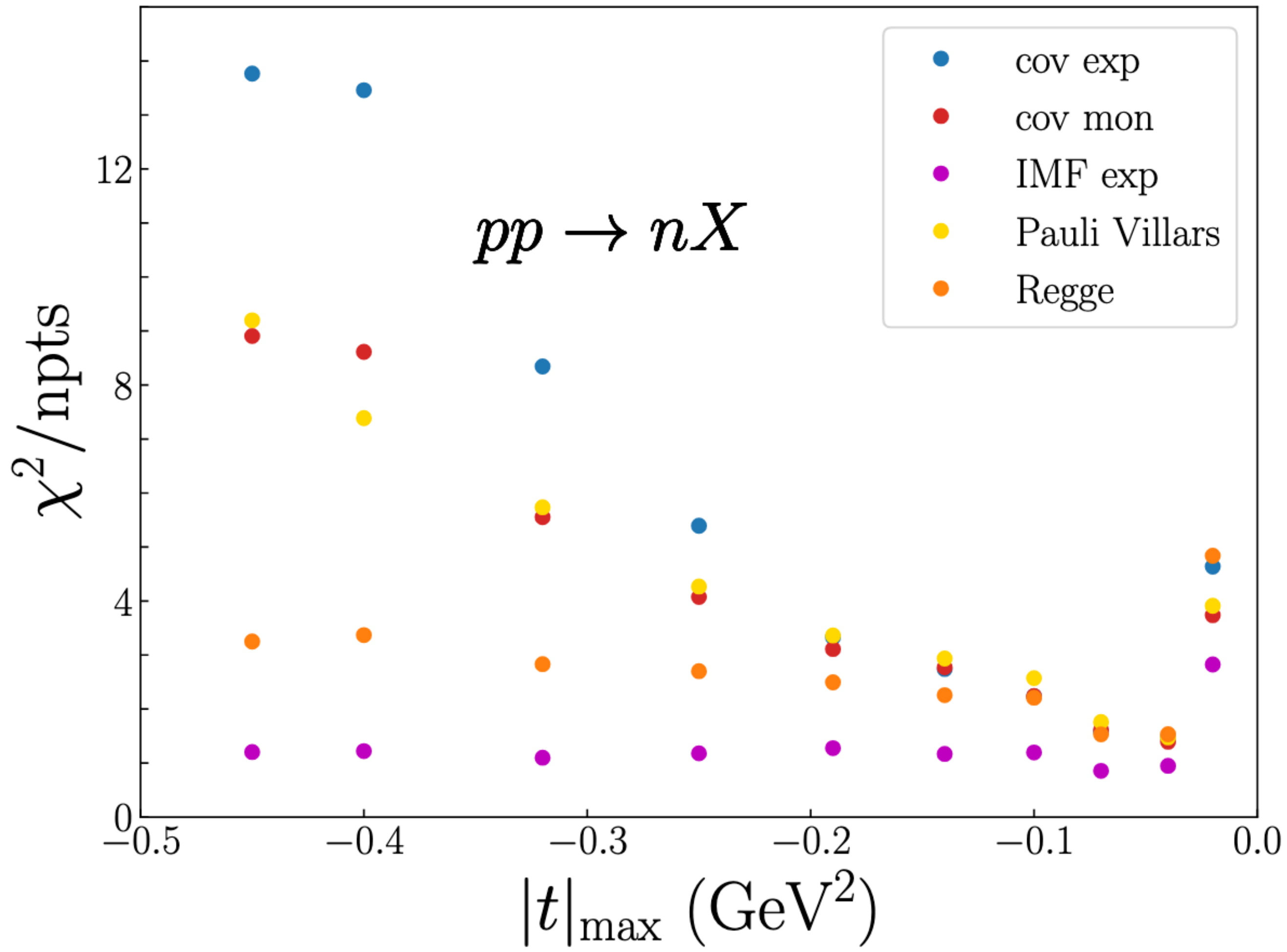
Resulting splitting function

- 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



Definition of W_π^2

- Derived from kinematics

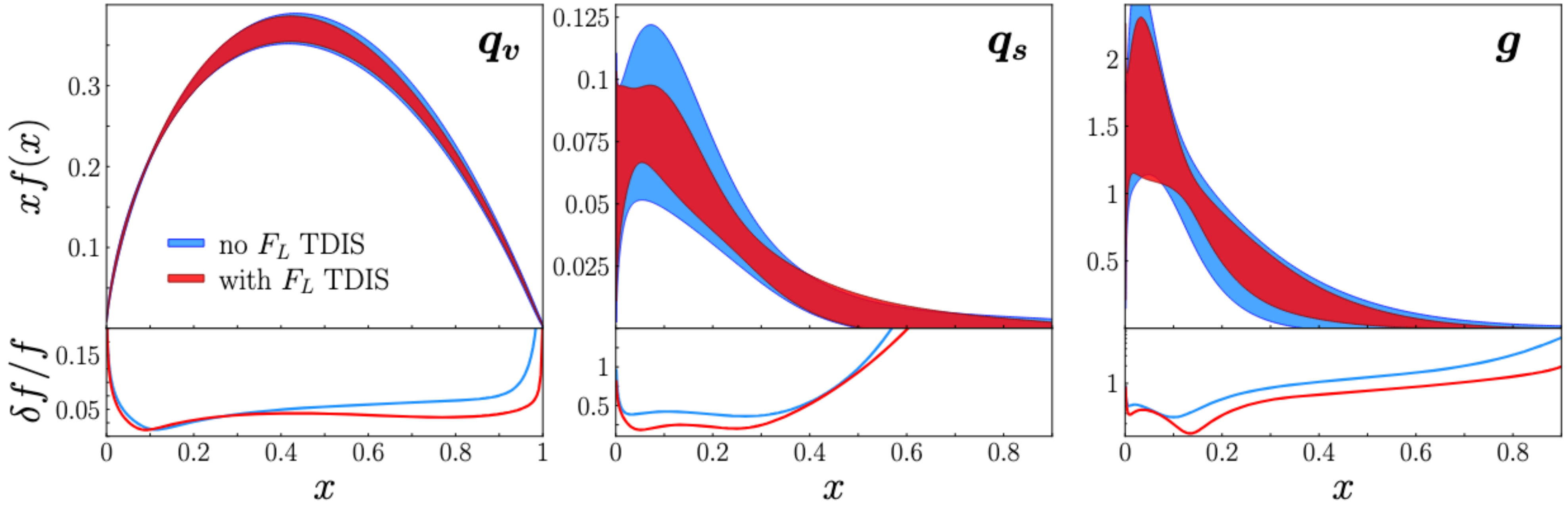
$$W_\pi^2 = t - Q^2 \left(1 - \frac{\bar{x}_L}{x}\right) = t - Q^2 \left(1 - \frac{1}{x_\pi}\right).$$

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



Impact study details

- We created pseudodata in the form of

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

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

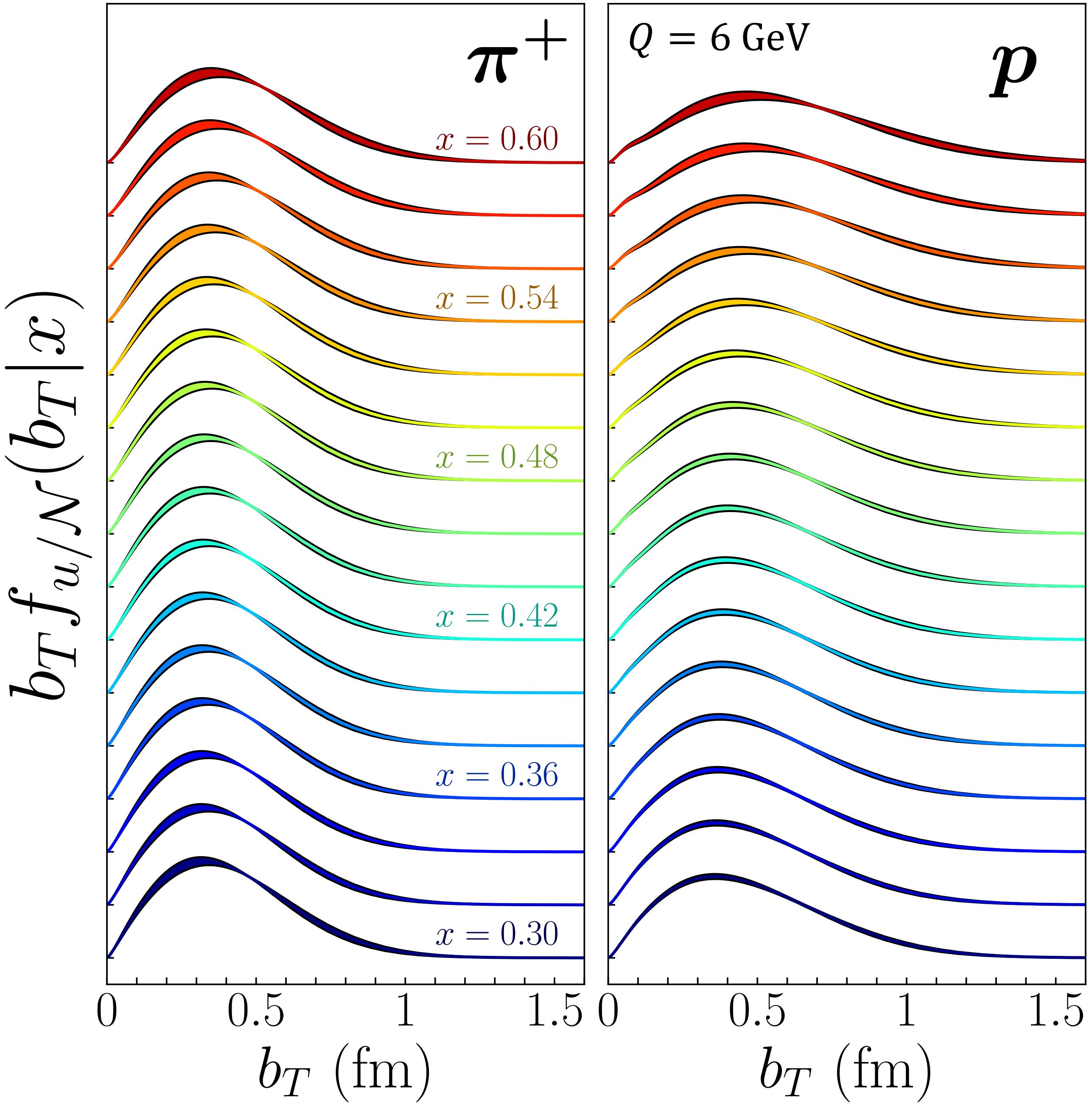
Transverse momentum structure

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

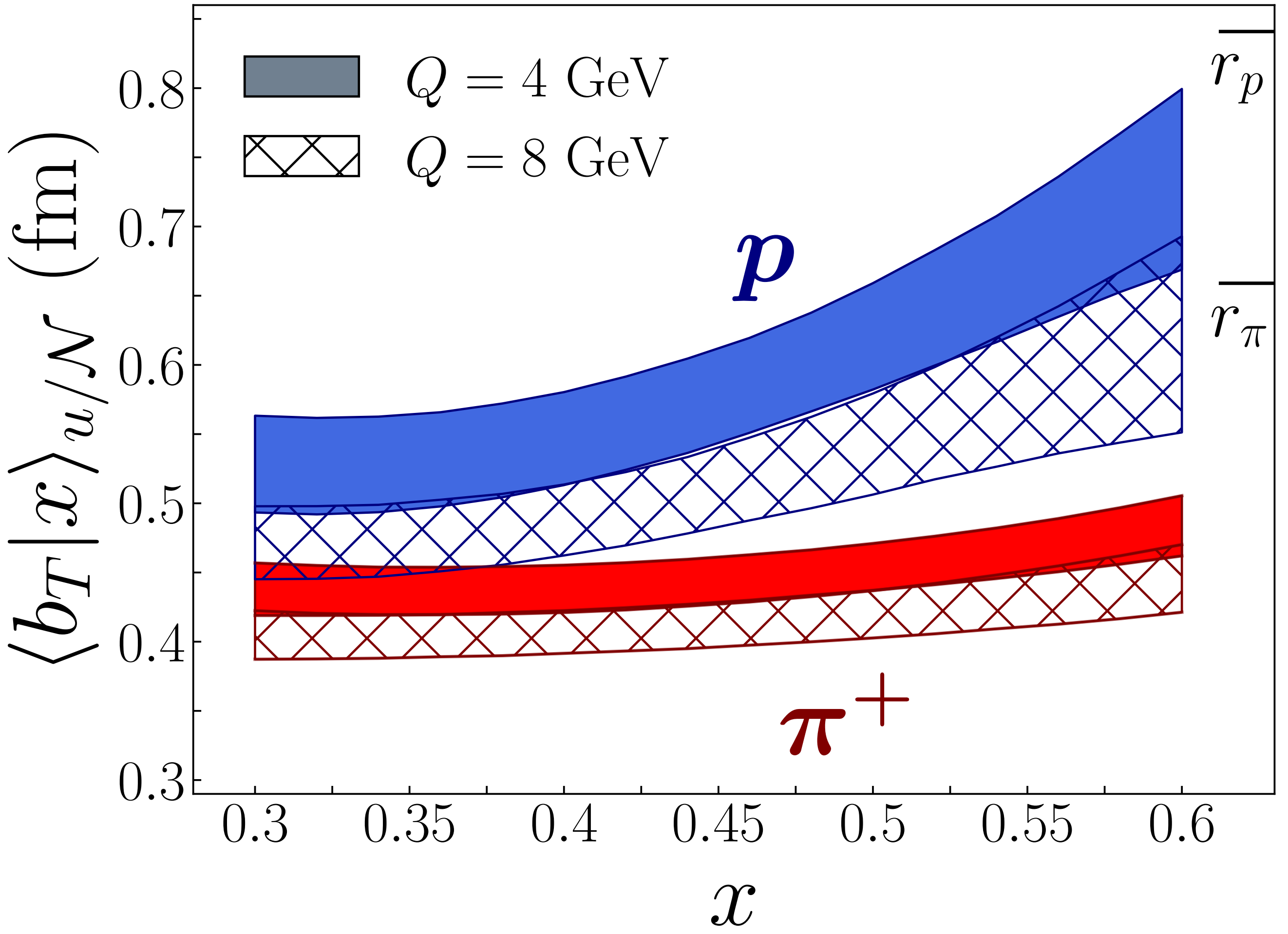


Average b_T

- 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



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

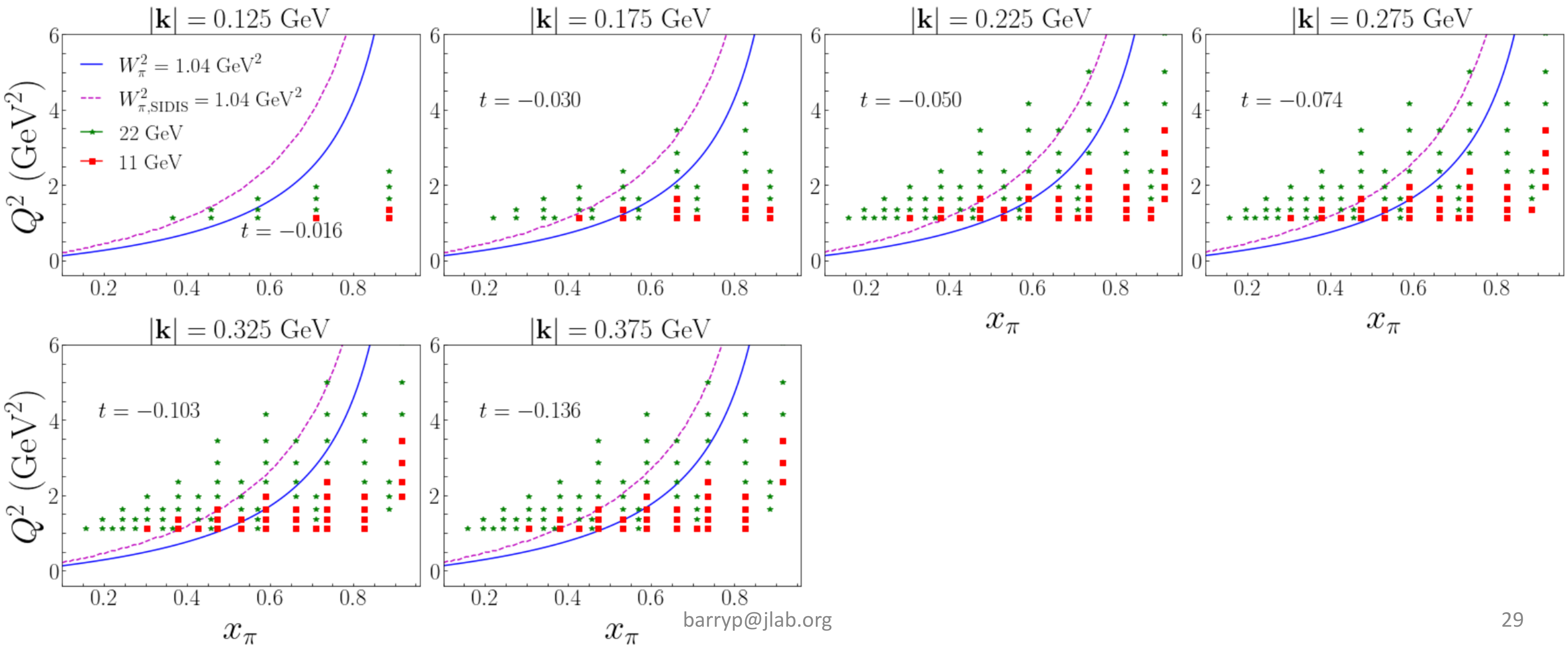
$$W_{\rm SIDIS}^2 = M^2 + M_{\rm B}^2 + \frac{Q^2(1-x_{\rm Bj}-z_{\rm h})}{x_{\rm Bj}} + \frac{Q^4 z_{\rm h}\left(\sqrt{1+\frac{4M^2x_{\rm Bj}^2}{Q^2}}\sqrt{1-\frac{4M^2x_{\rm Bj}^2M_{\rm B,T}^2}{z_{\rm h}^2Q^4}}-1\right)}{2M^2x_{\rm Bj}^2}$$

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

- Replace M^2 with t

Available kinematics for JLab

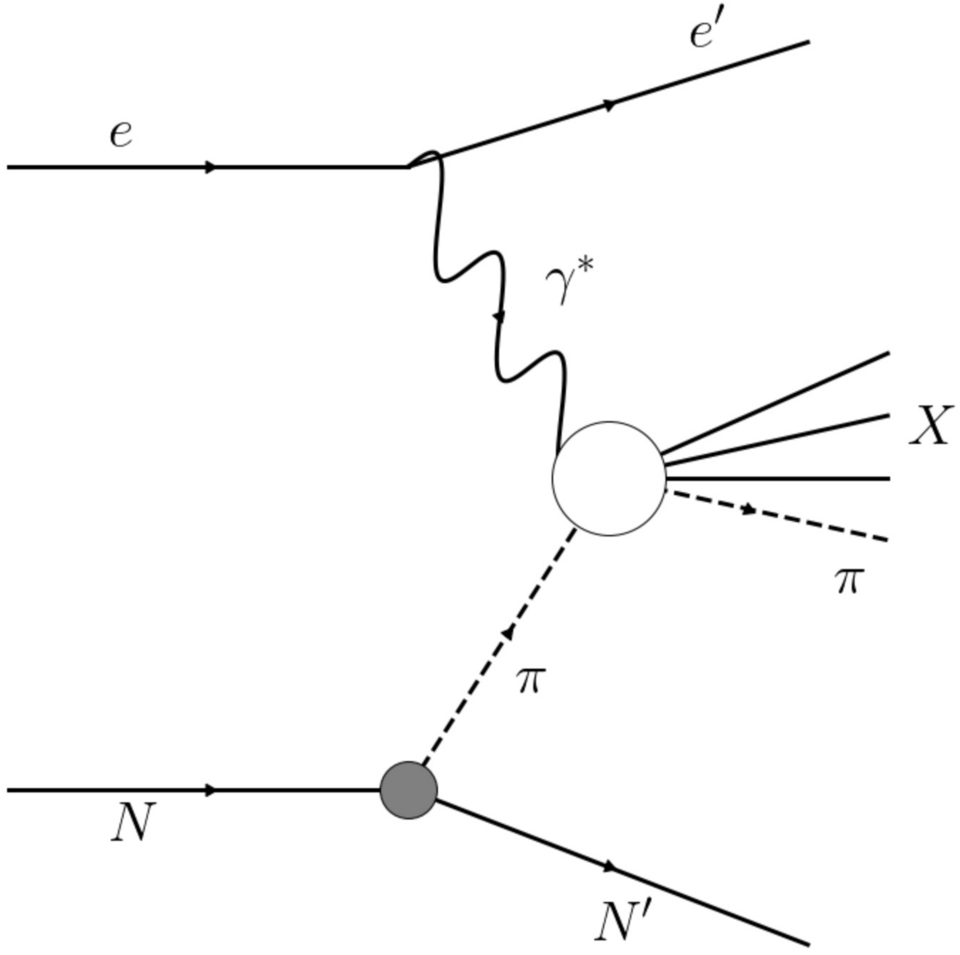
- Can only use 22 GeV data for any TMD analysis



Pion SIDIS: access to TMDs

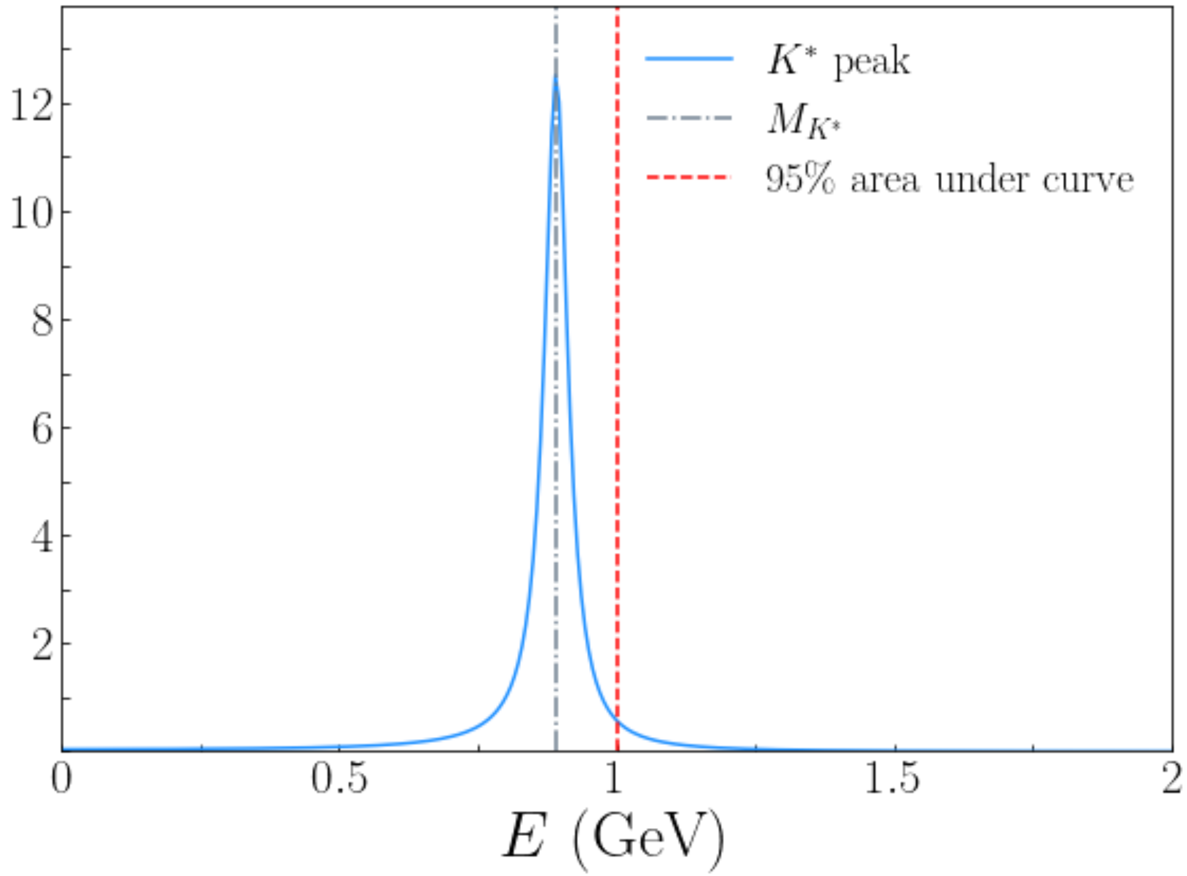
$$eN \to e'N'\pi X$$

- Measure an outgoing pion in the TDIS experiment
- Gives us another observable sensitive to pion TMDs
  - Needed for tests of universality
  - Optimal range of x_π to be sensitive to non-perturbative TMDs



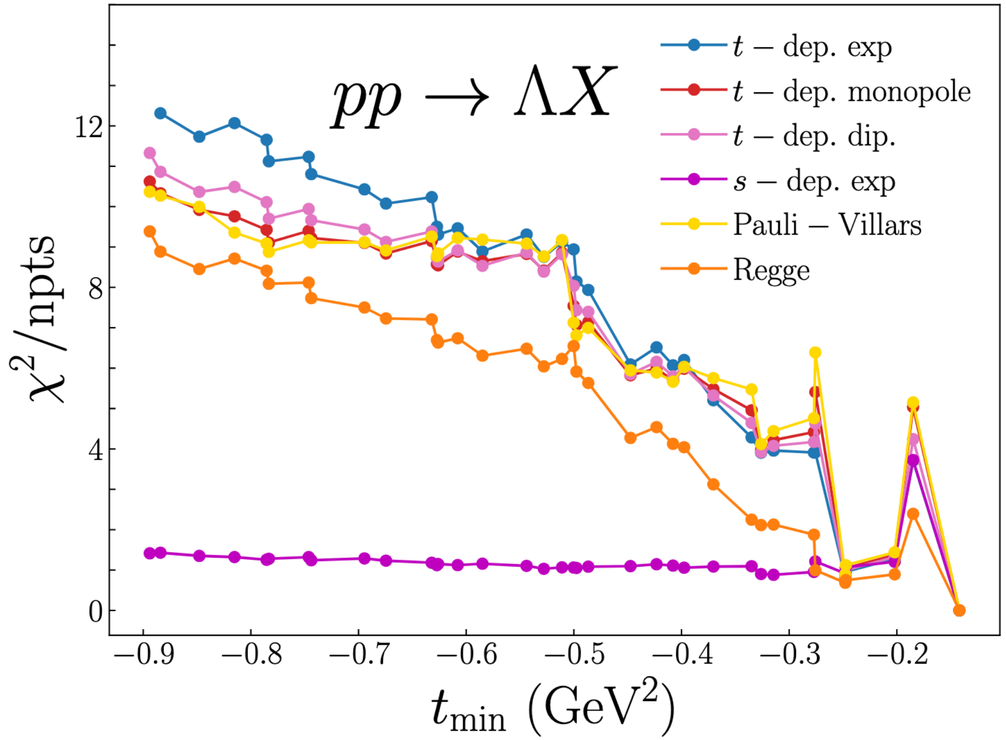
Resonance from K^*

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



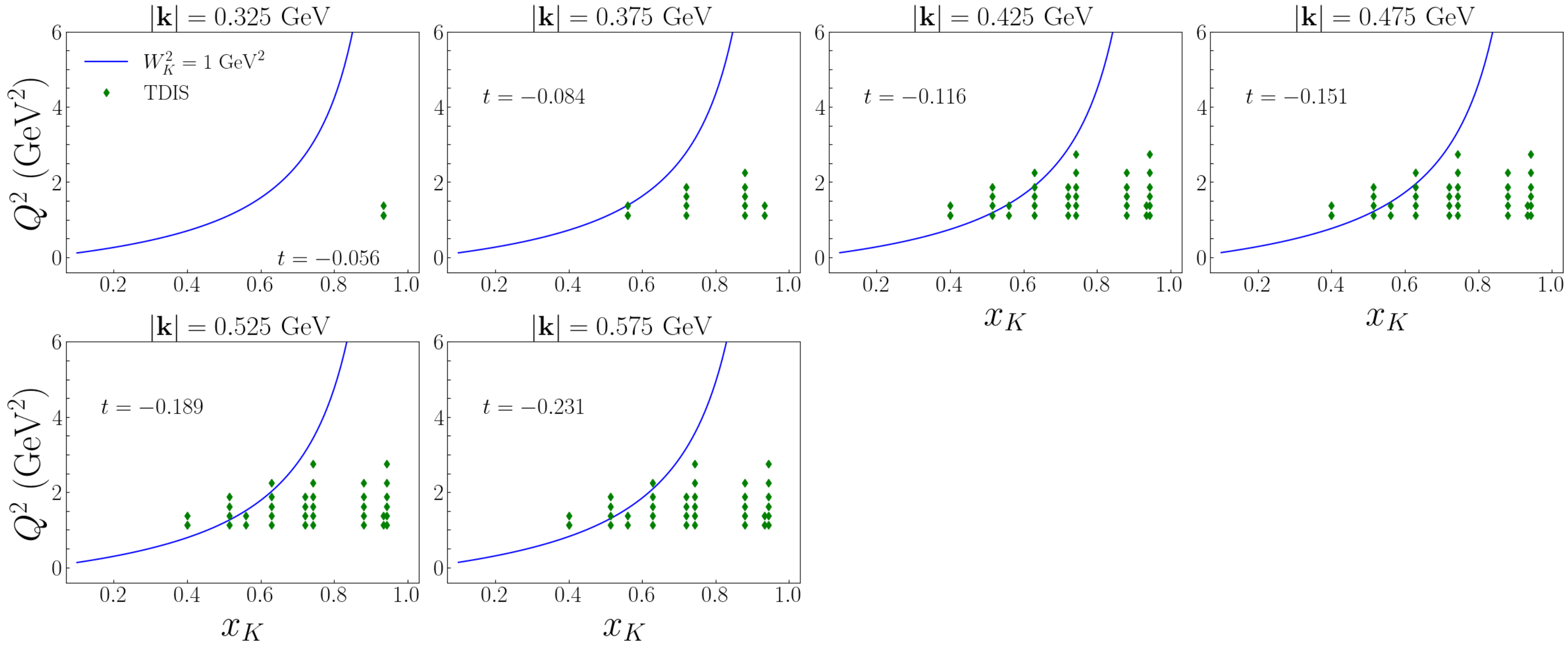
Analysis results for the $pp \to \Lambda X$ data

- Limit ourselves to a $t_{\rm min} = -0.25\ \mathrm{GeV}^2$



Kinematics for 11 GeV Kaon TDIS

- Region of t satisfies our $t_{\min}$ cut from the $pp \to \Lambda X$ analysis



Kinematics for 22 GeV Kaon TDIS

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