Meson structure at JLab 22 GeV

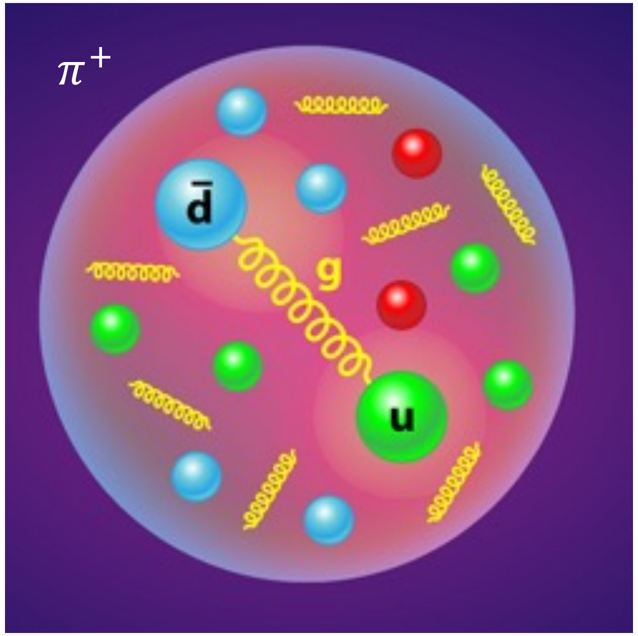
Patrick Barry, JLab

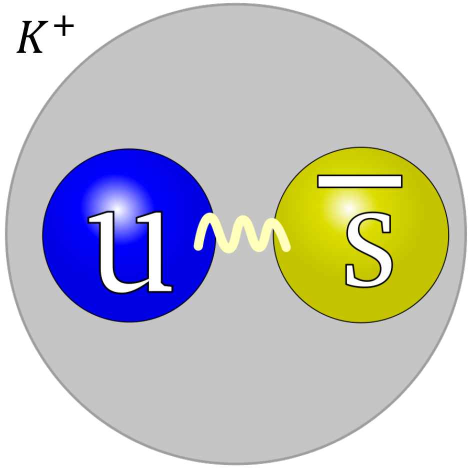
Science at the Luminosity Frontier: Jefferson Lab at 22 GeV Workshop

January 23th, 2023

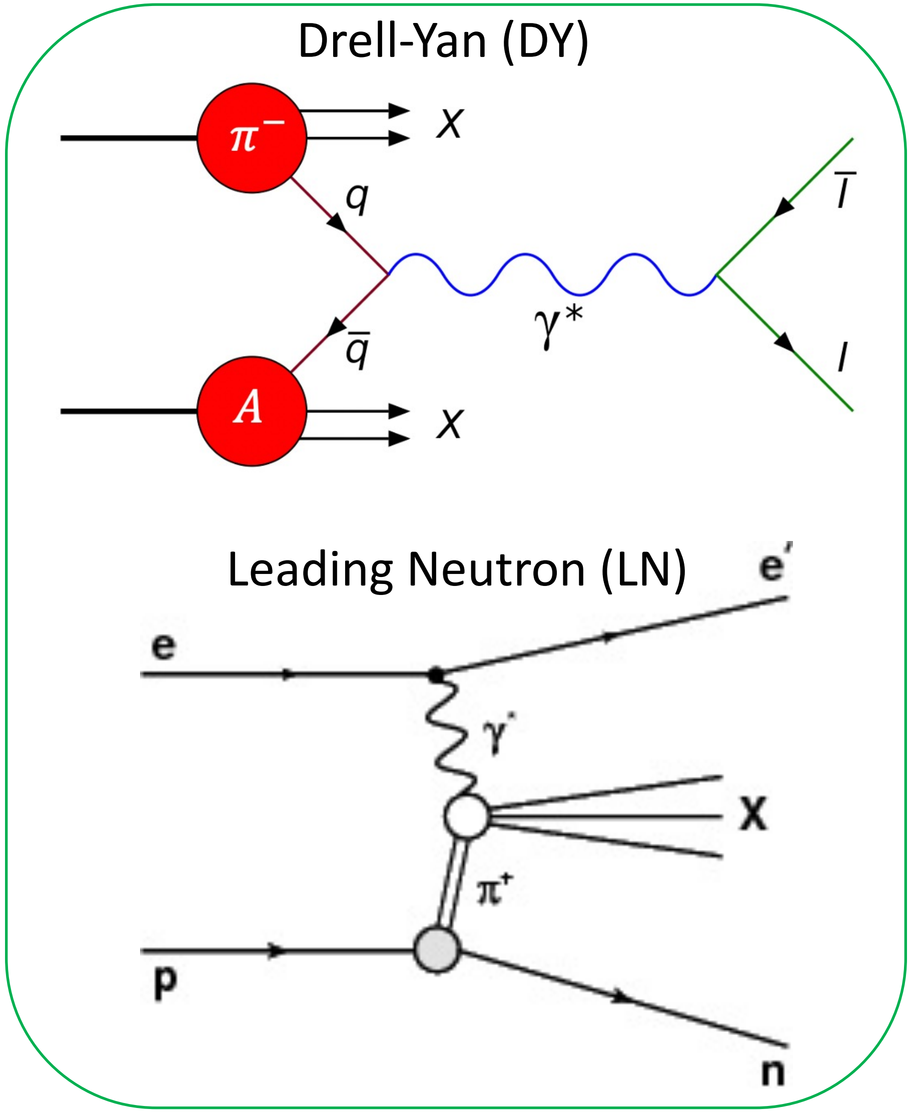
Mesons

- Pion is the Goldstone boson associated with SU(2) chiral symmetry breaking
- Kaon – SU(3)
- Simultaneously a $q\bar{q}$ bound state
- Studying these structures provides another angle to probe QCD and effective confinement scales
- More available data is desperately needed





Pion PDFs in JAM

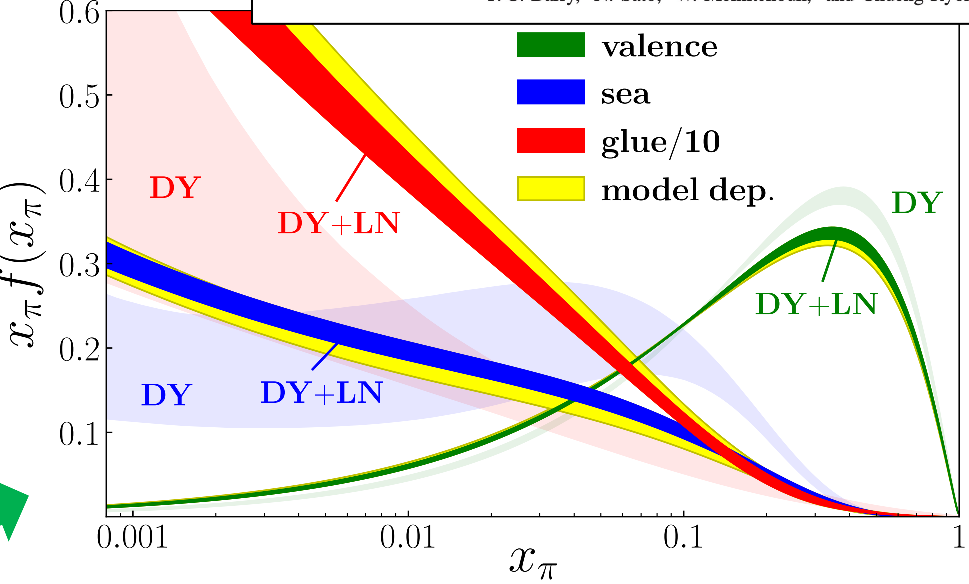


PHYSICAL REVIEW LETTERS **121,** 152001 (2018)

Featured in Physics

First Monte Carlo Global QCD Analysis of Pion Parton Distributions

P. C. Barry,[1] N. Sato,[2] W. Melnitchouk,[3] and Chueng-Ryong Ji[1]

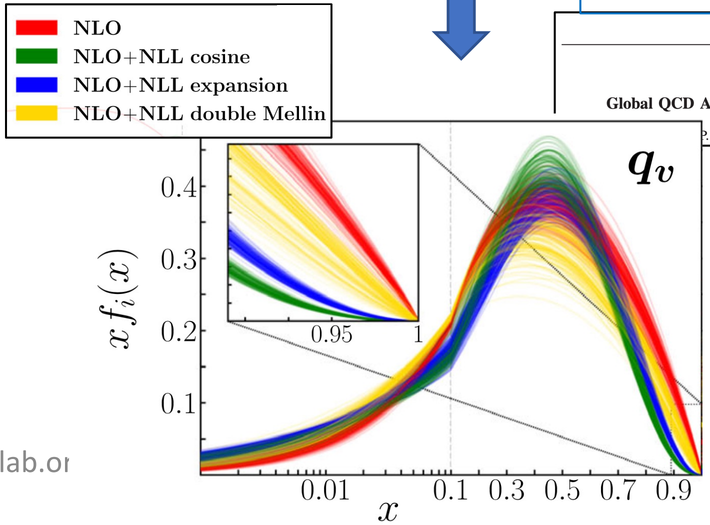


Threshold resummation in DY

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

Global QCD Analysis of Pion Parton Distributions with Threshold Resummation

P. C. Barry,[1] Chueng-Ryong Ji,[2] N. Sato,[1] and W. Melnitchouk[1]



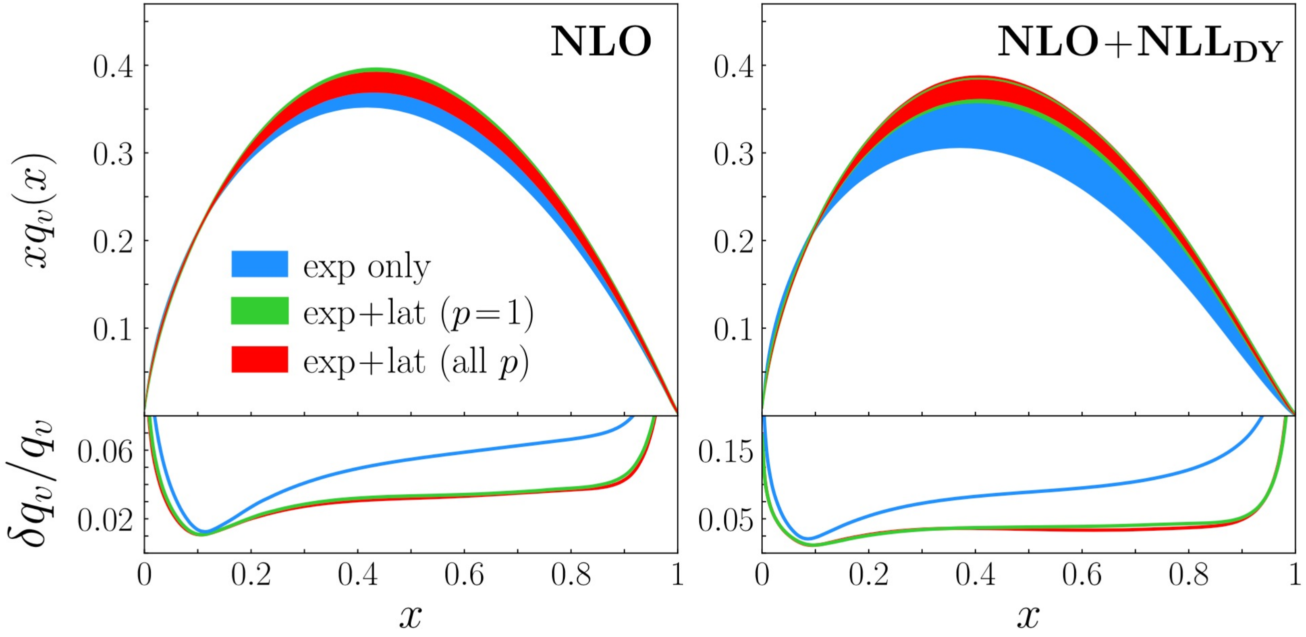
Pion PDFs from lattice + experimental data

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

Complementarity of experimental and lattice QCD data on pion parton distributions

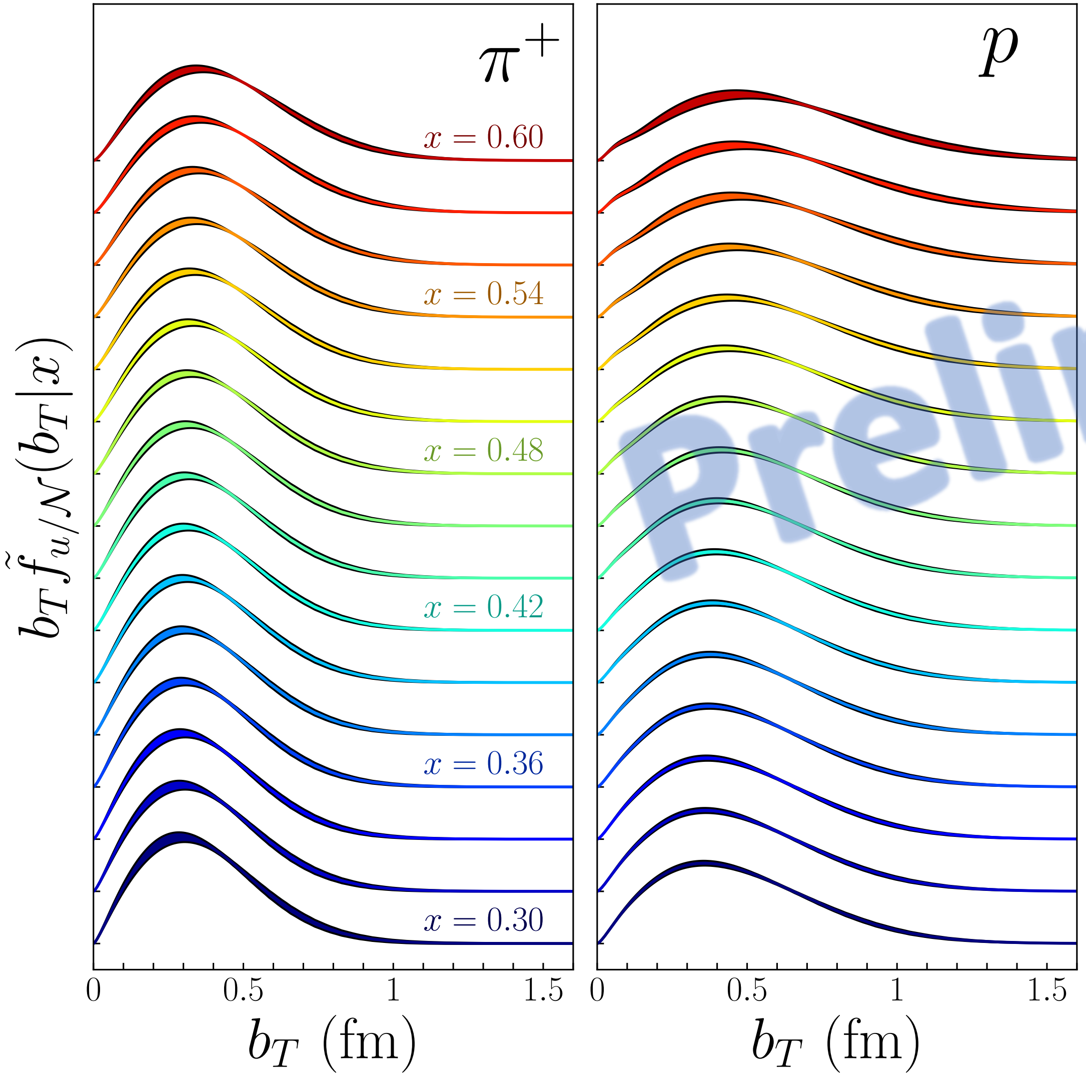
P. C. Barry,[1] C. Egerer,[1] J. Karpie,[2] W. Melnitchouk,[1] C. Monahan,[1,3] K. Orginos,[1,3] Jian-Wei Qiu,[1,3] D. Richards,[1] N. Sato,[1] R. S. Sufian,[1,3] and S. Zafeiropoulos[4]

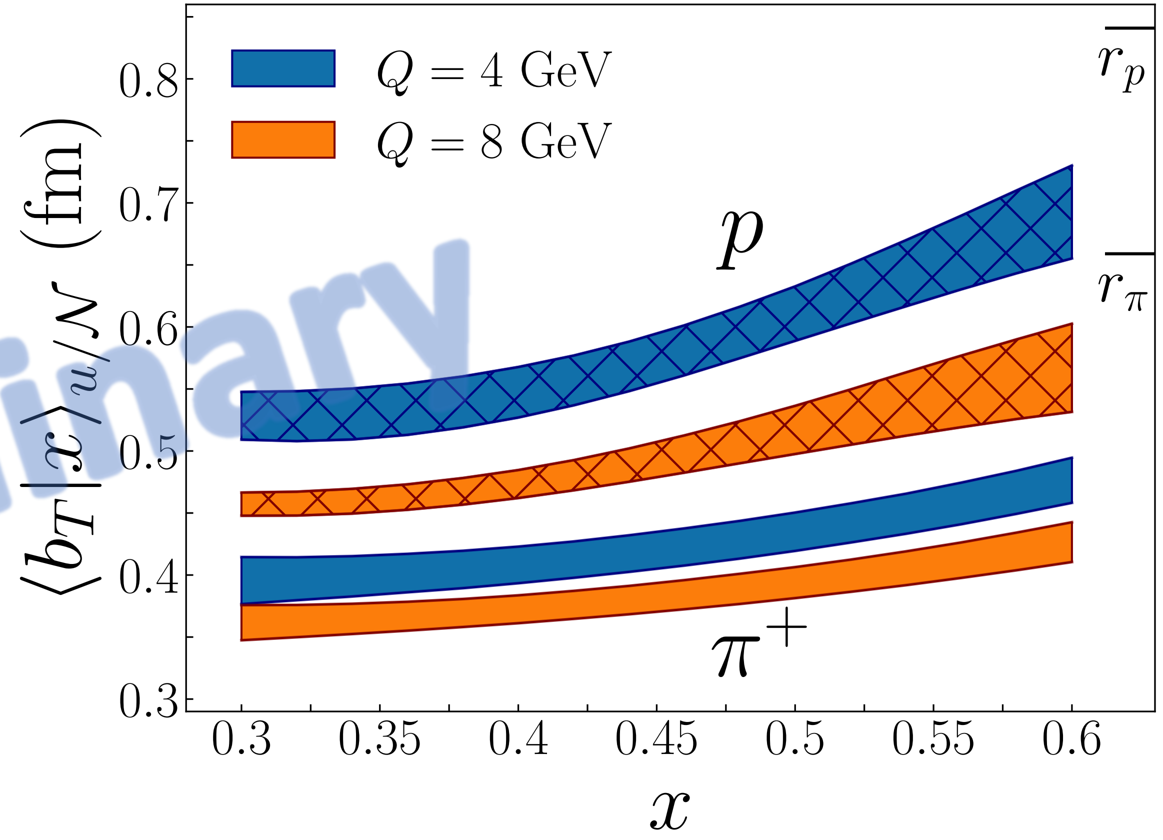
(Jefferson Lab Angular Momentum (JAM) and HadStruc Collaborations)



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

Pion vs proton TMDs

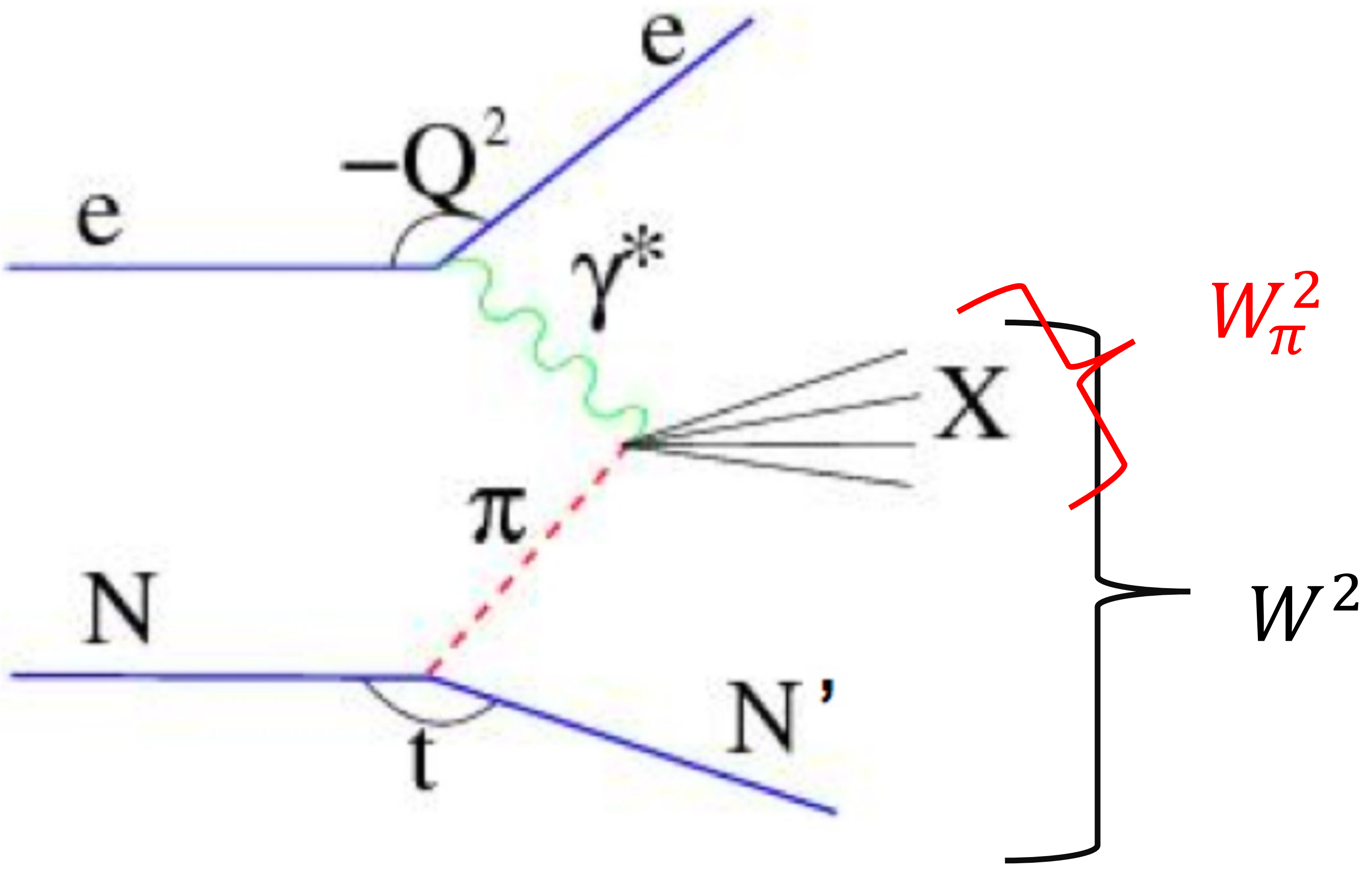




- Differences are purely non-perturbative TMDs
- Important to compare different hadronic systems

TDIS program: Sullivan process and W_π^2

- Impose kinematic cuts on experimental data
- What about the W_π^2?



Check the resonance regions

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

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) $I(J^{PC}) = 0,1(1^{--})$

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

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

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

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

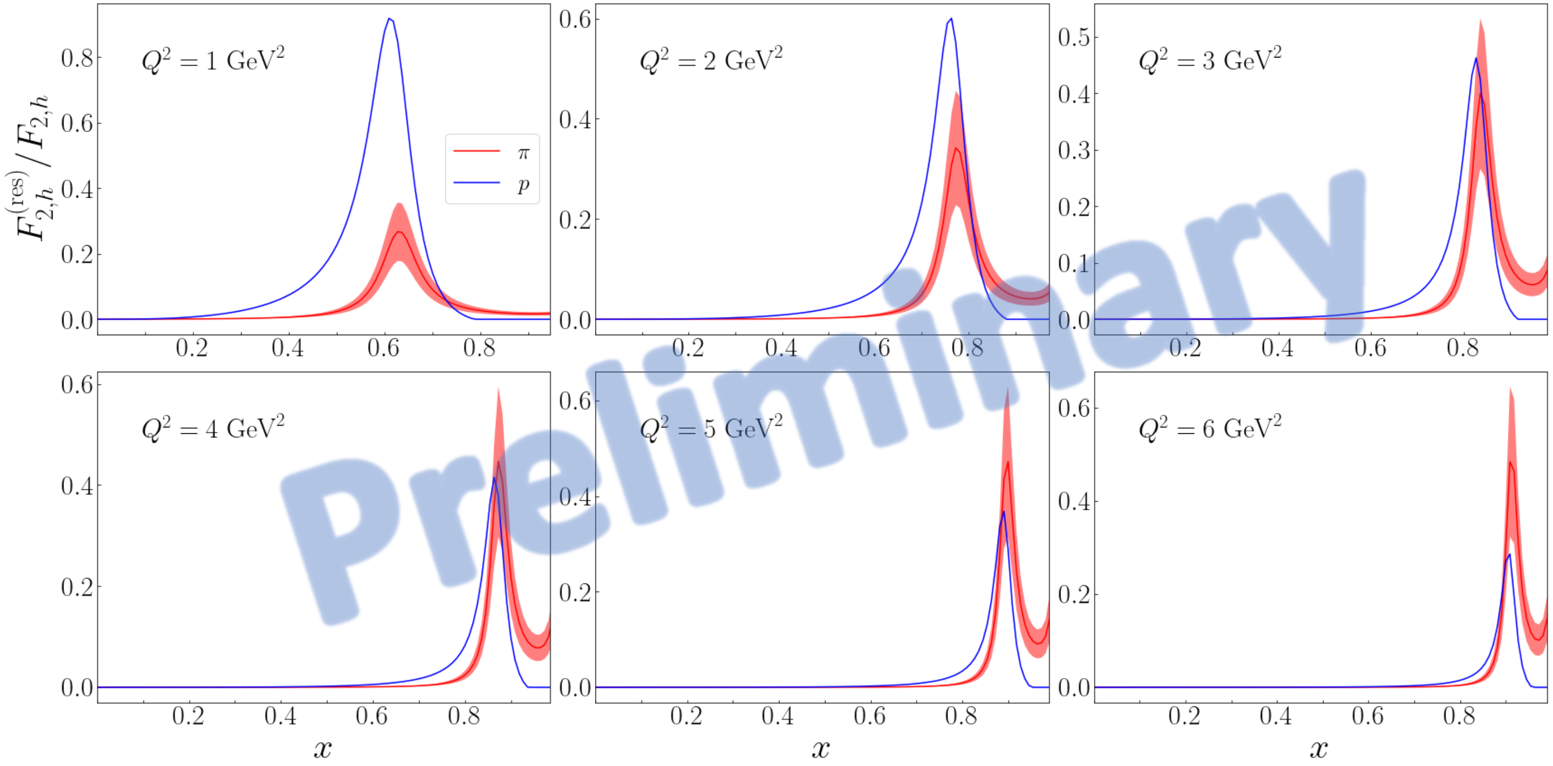
Mass $m = 1229.5 \pm 3.2$ MeV (S = 1.6)
Full width $\Gamma = 142 \pm 9$ MeV (S = 1.2)

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

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, here considered the ρ-meson

Contribution from ρ to F_2^π

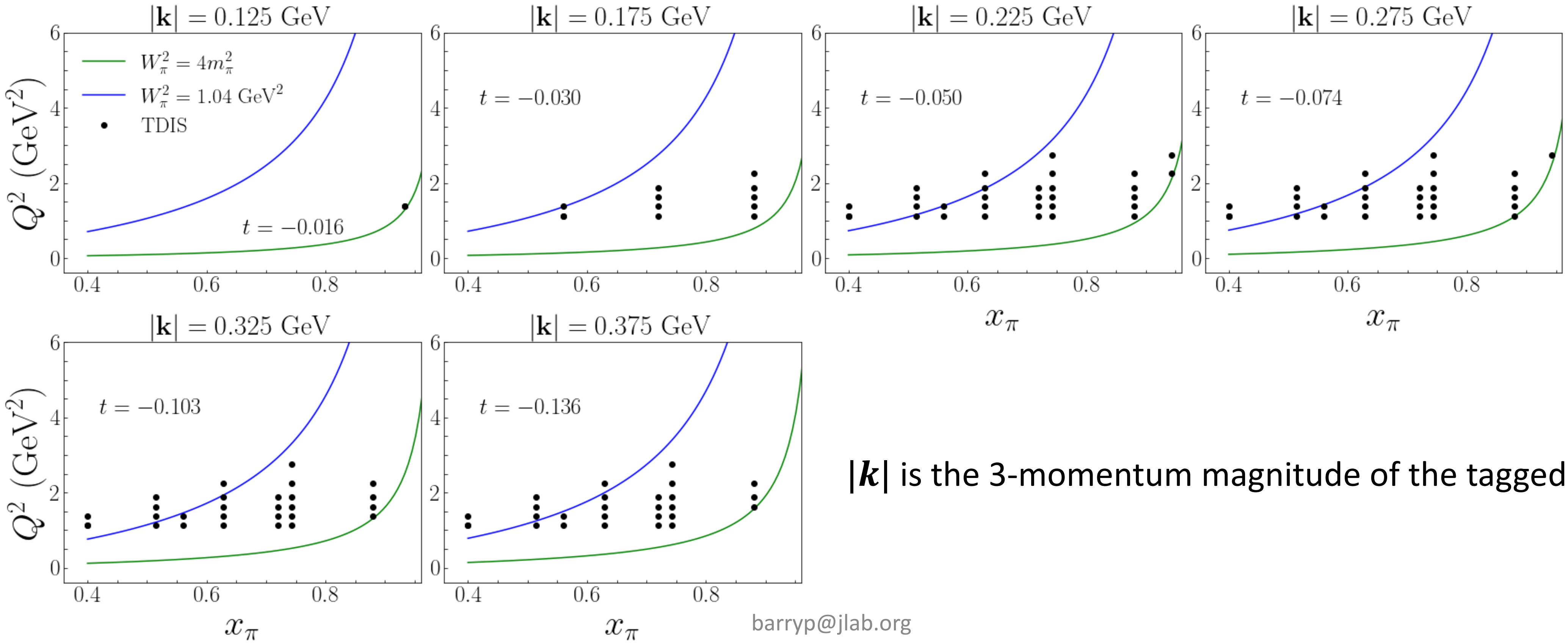


Δ resonance courtesy of Astrid Hiller Blin

- Comparing the Δ resonance in the nucleon to the ρ resonance in the pion
- Appreciable certainly at larger Q^2 – challenging to describe with partonic degrees of freedom – introduce a cut in W_π^2

Current 11 GeV TDIS kinematics

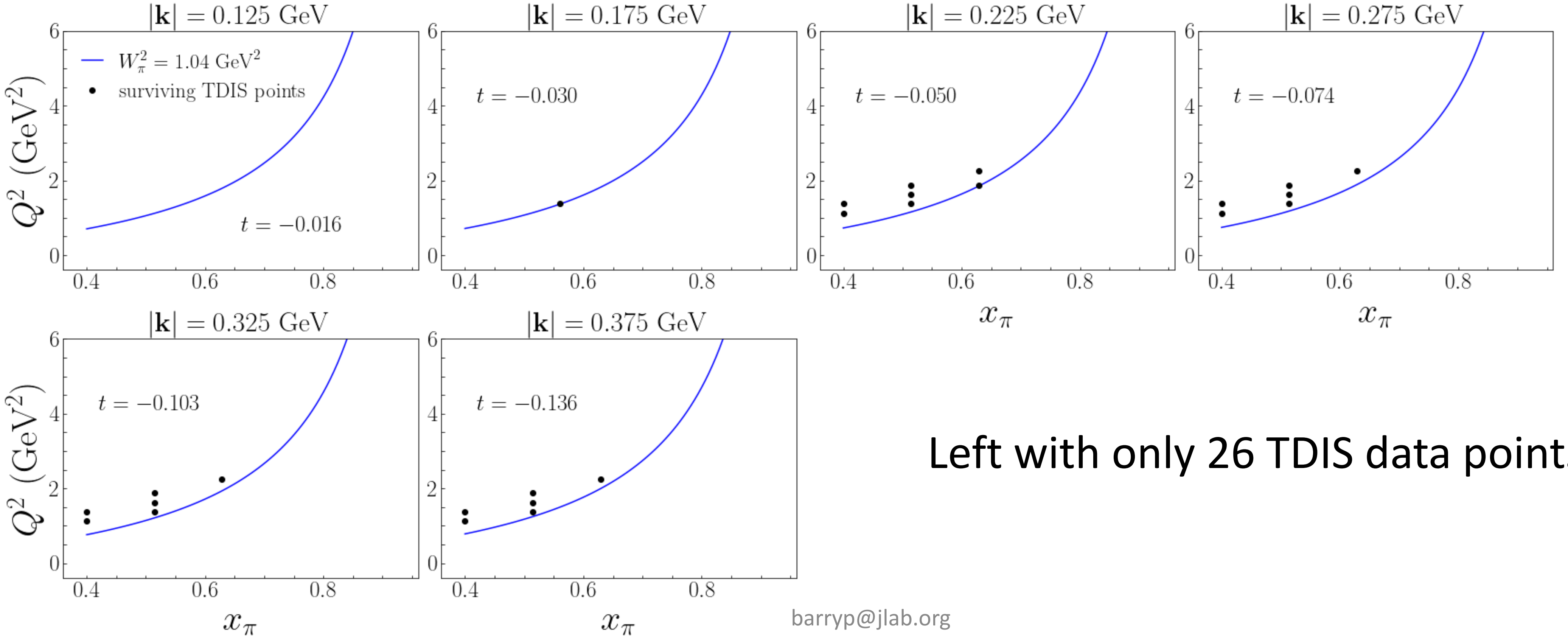
- Plotting available 11 GeV TDIS kinematics with a few representative W_π^2 curves



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

Choosing $W^2_{\pi,\max} = 1.04\ \mathrm{GeV}^2$

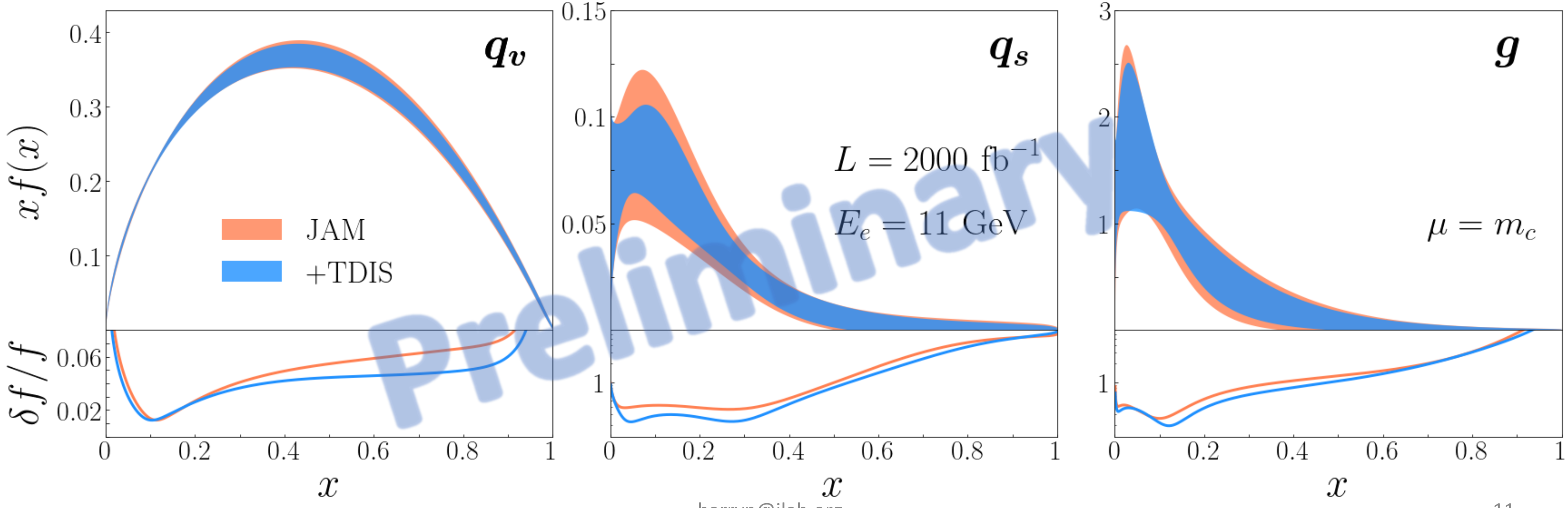
- Removing all data points that could be contaminated by ρ-resonance regions



Left with only 26 TDIS data points

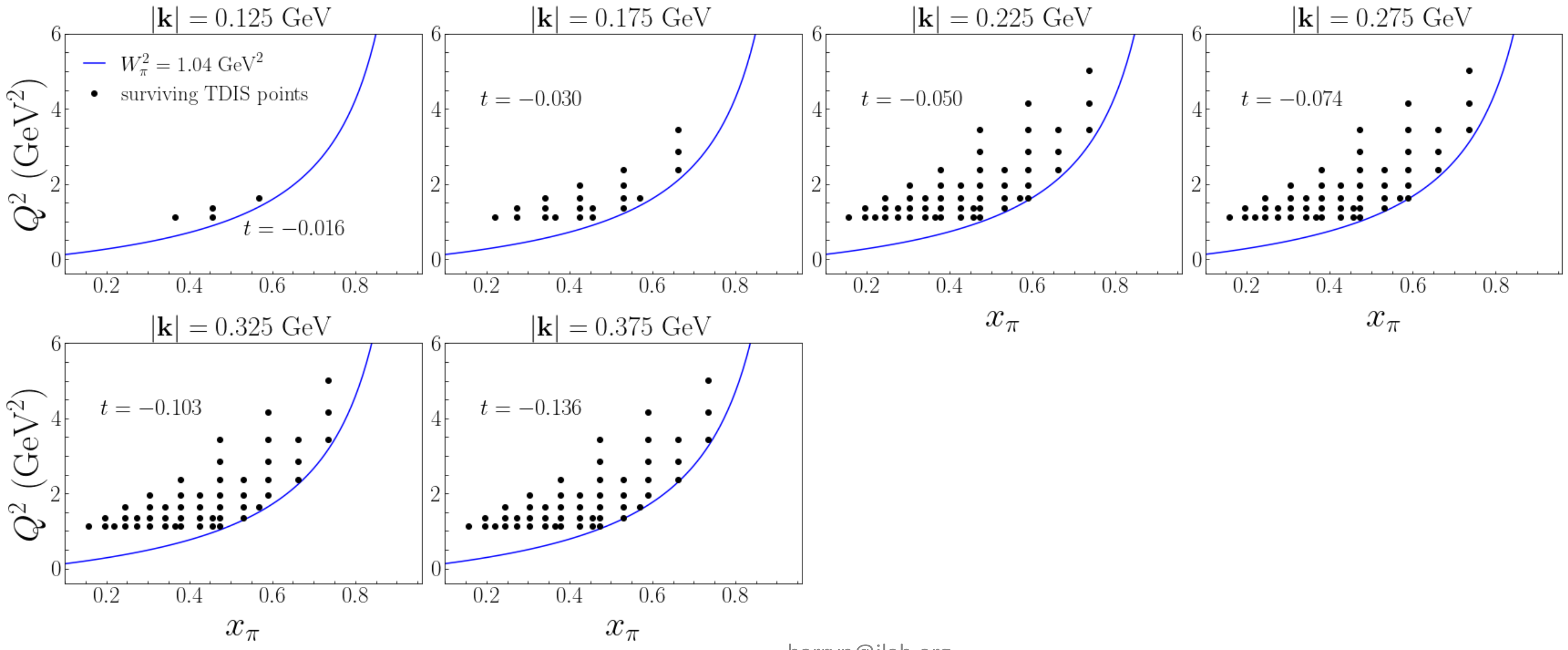
Performing impact study with 11 GeV

- Create pseudodata from these points and perform global analysis with available experimental data assuming 6.5% systematic uncertainty



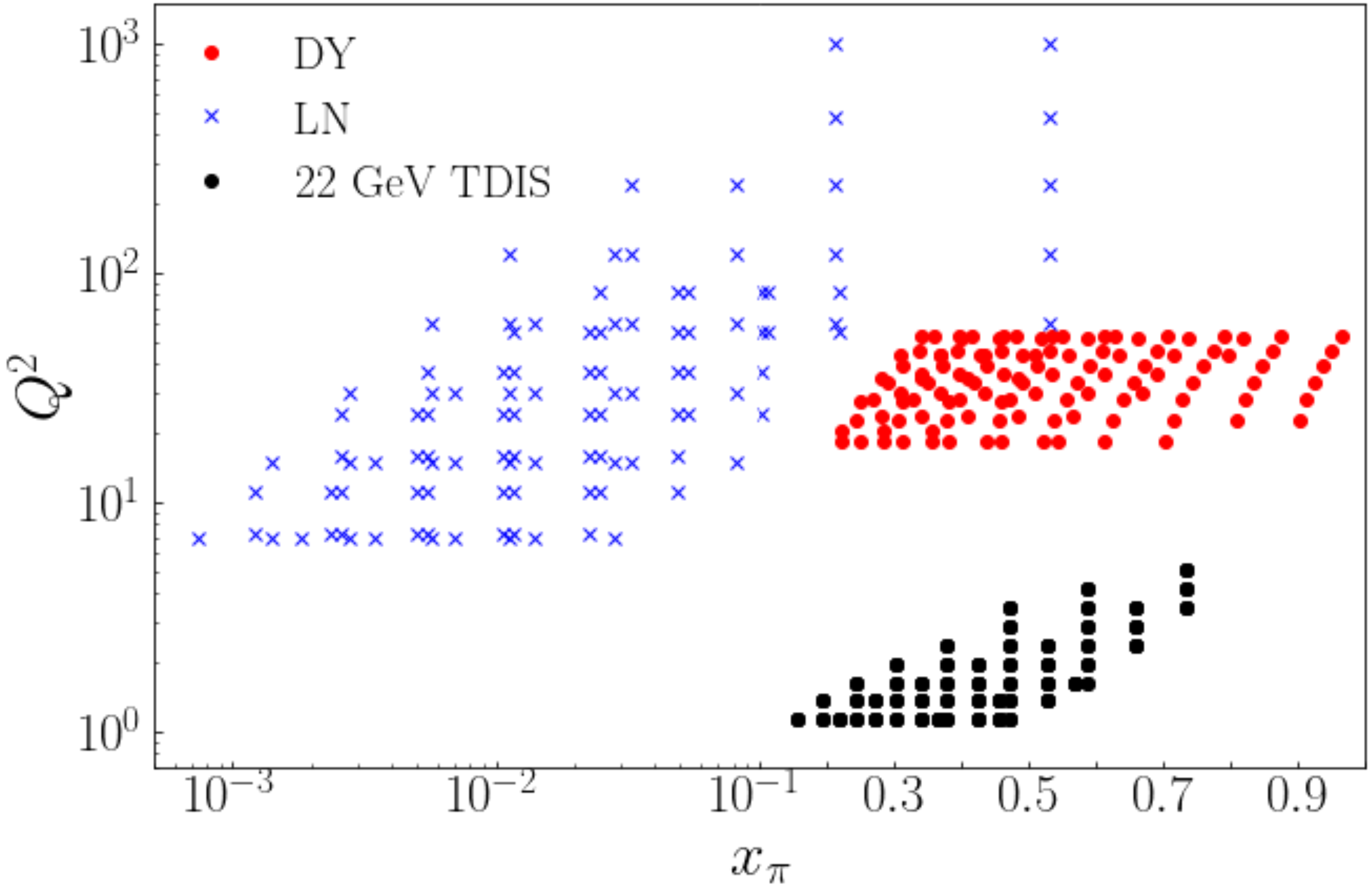
Kinematics with 22 GeV

- MASSIVE increase in available data points



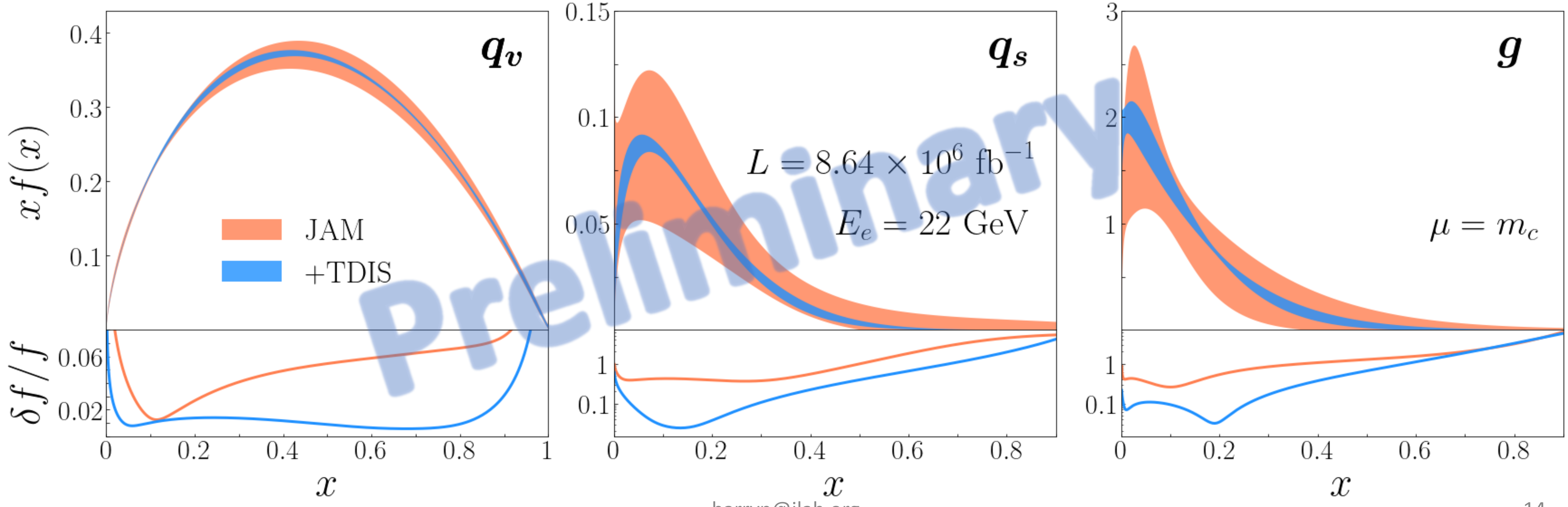
Total kinematics

- Much larger range in x_π and Q^2



Impact on pion PDFs with 22 GeV

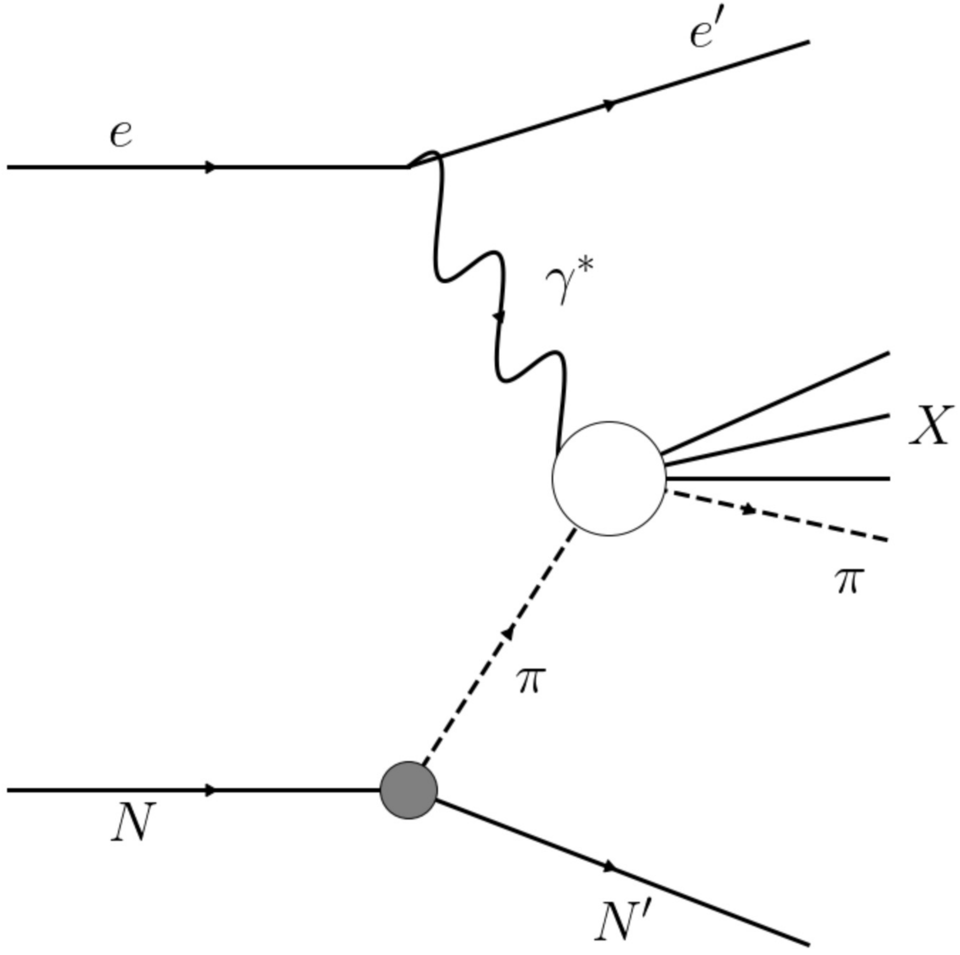
- Knowledge of pion PDFs increases dramatically with 22 GeV beam
- Assuming 1.2% systematic uncertainty



Pion SIDIS: access to TMDs

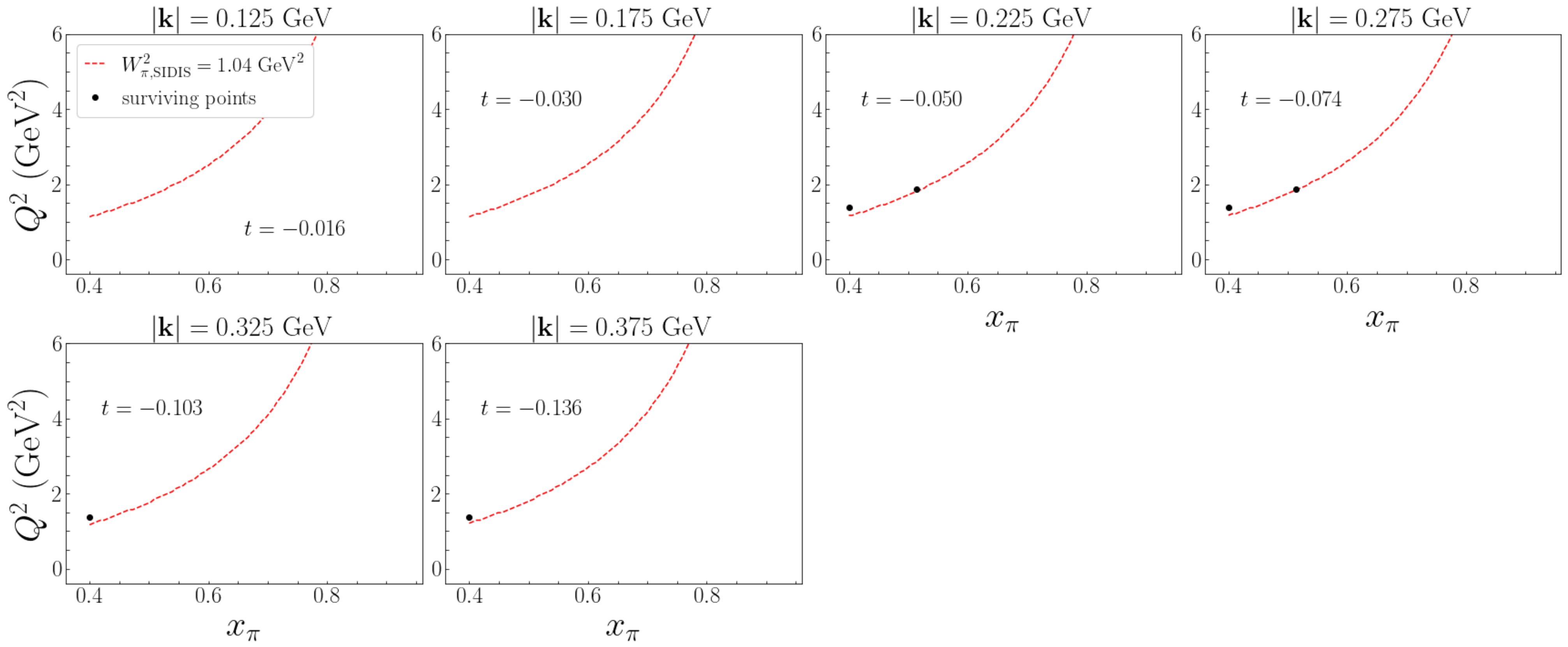
$$eN \to e'N'\pi X$$

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



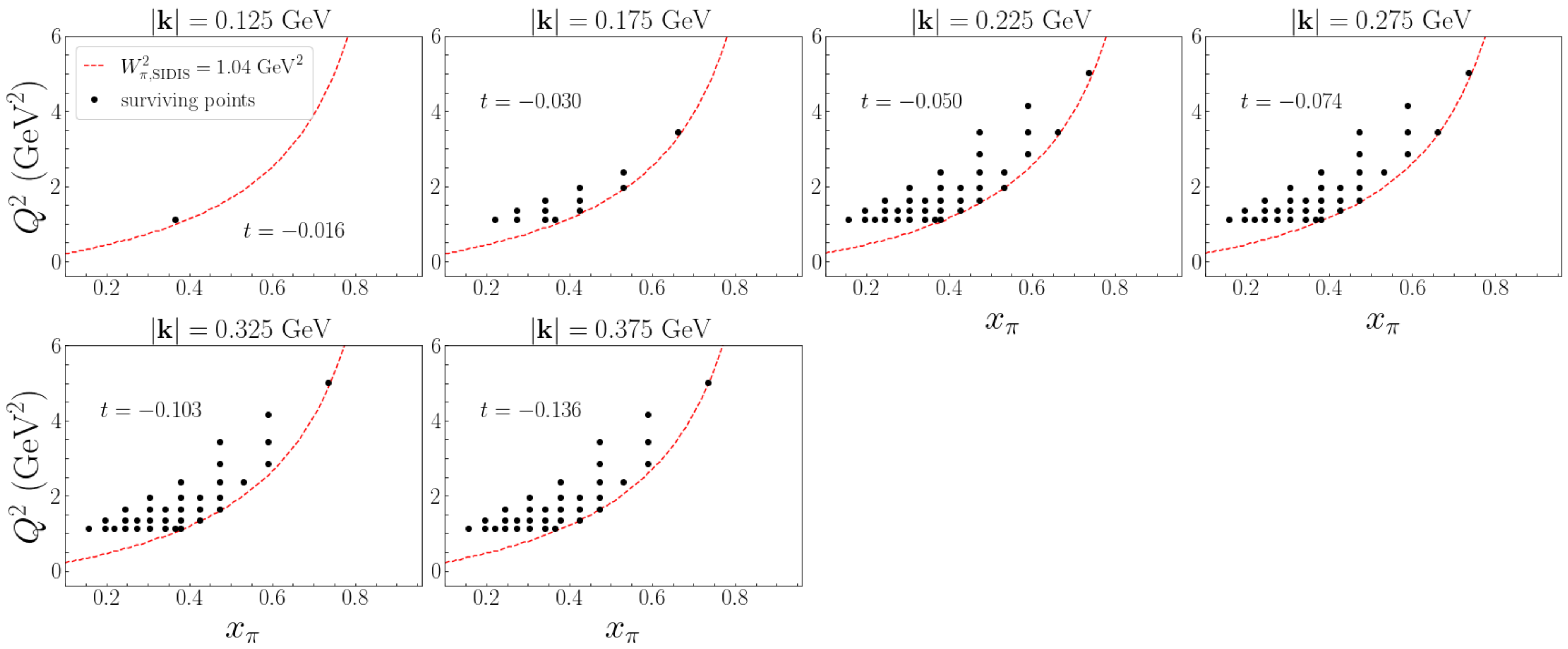
Kinematics with 11 GeV

- Still a cut on $W_\pi^2 = 1.04\ \text{GeV}^2$, but SIDIS requires more phase space
- Hardly anything available with $z = 0.2$, $P_{h,T} = 0.2$ GeV



Kinematics with 22 GeV

- Huge increase – TMD studies becomes possible!



Conclusion

- Impacts from the 11 GeV TDIS experiment on pion PDFs will be limited, but can test the large-x_π behavior inferred from the Drell-Yan data
- The 11 GeV TDIS can measure the low-W_π pion structure function
- **Much** more constraints will come from larger 22 GeV upgrade
- Compared with EIC, JLab can provide more precise data
- Kaon PDF analysis may be more realistic with energy upgrade

Backup Slides

Conditional density

- We define a quantity in which describes the ratio of the 2-dimensional density to the integrated, b_T-independent number density

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

Average b_T

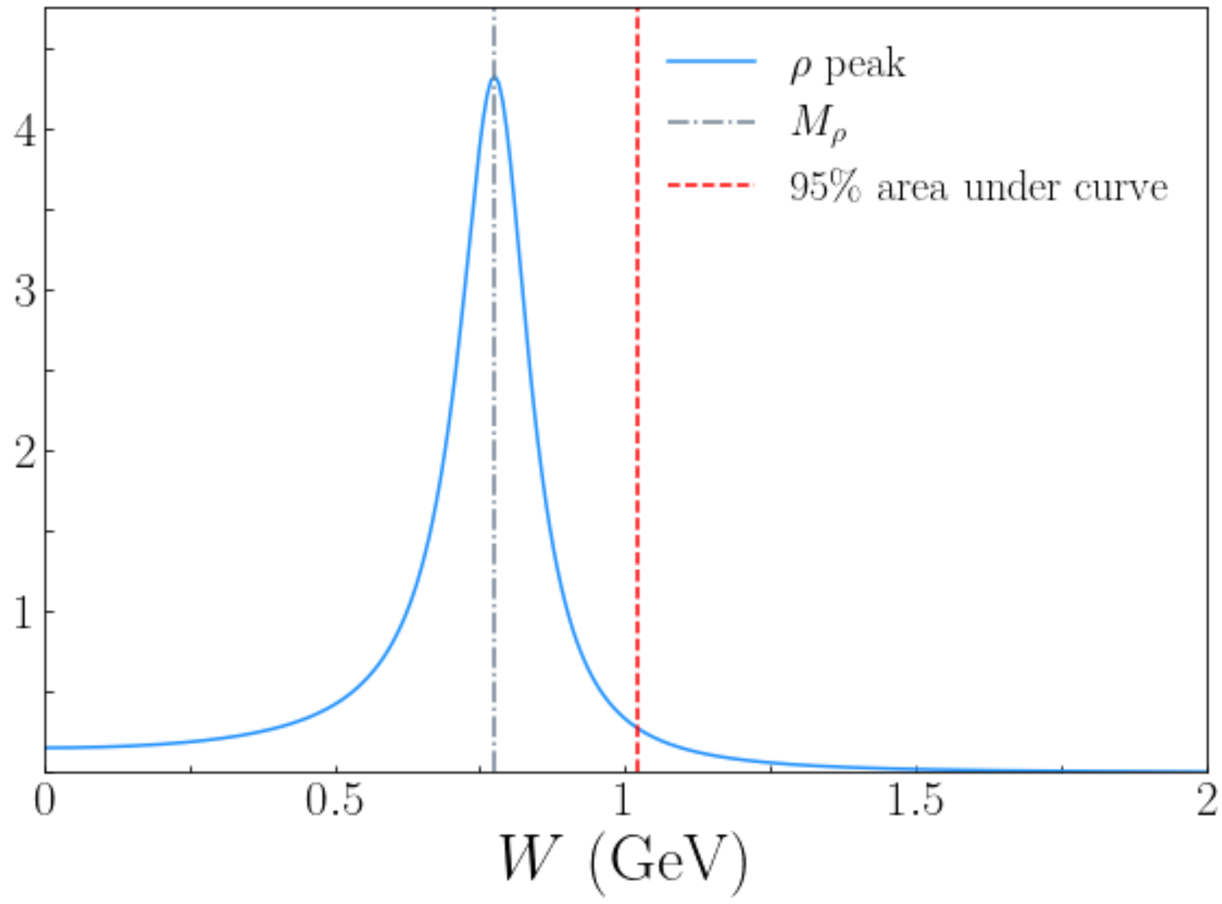
- The conditional expectation value of b_T for a given x

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

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

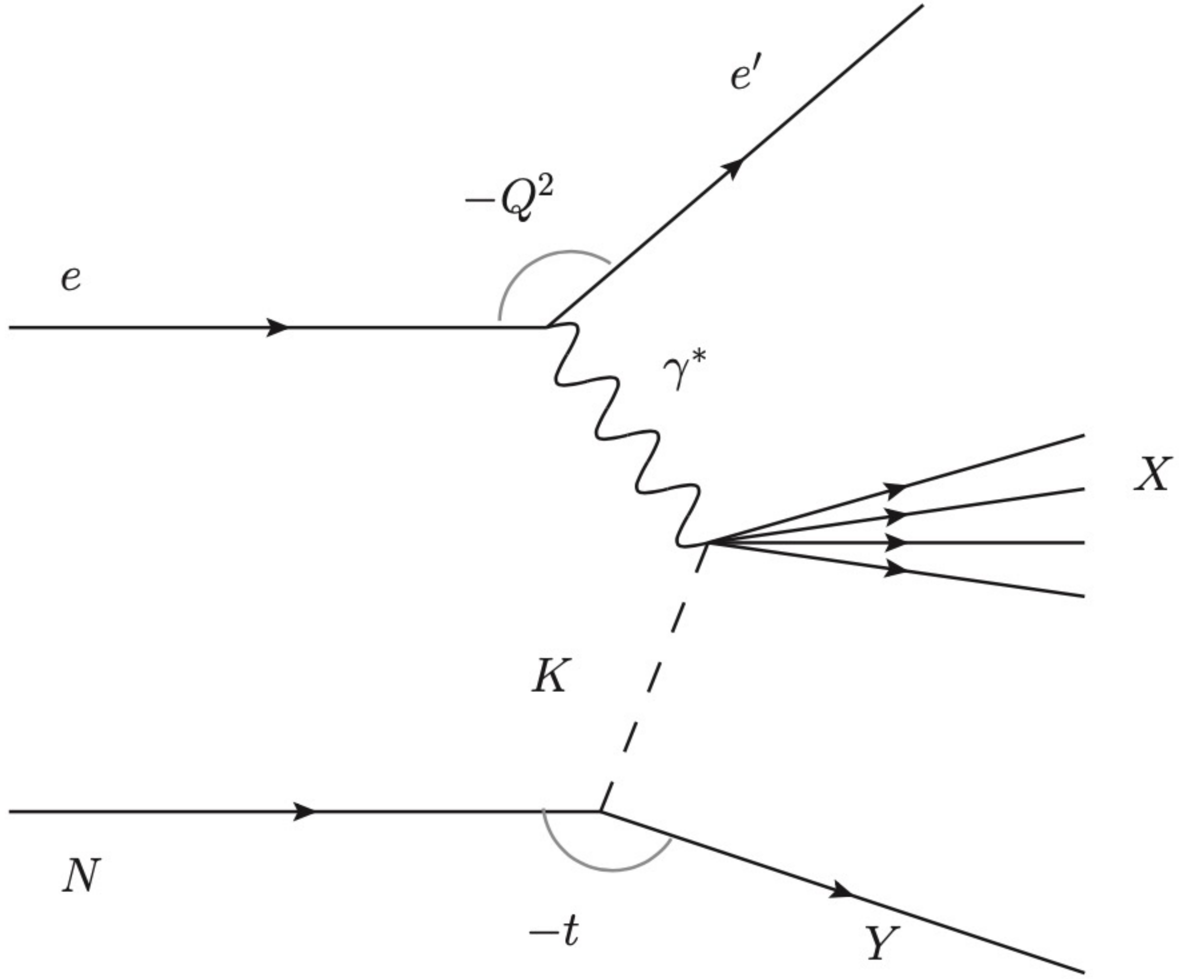
What to choose for W_π^2

- HERA did not measure the low-W_π^2 region
- Potentially largest resonance comes from the ρ-meson
- Must be well above the peak of the resonance
- Estimating the safe region to be an energy above 95% of the area under the curve



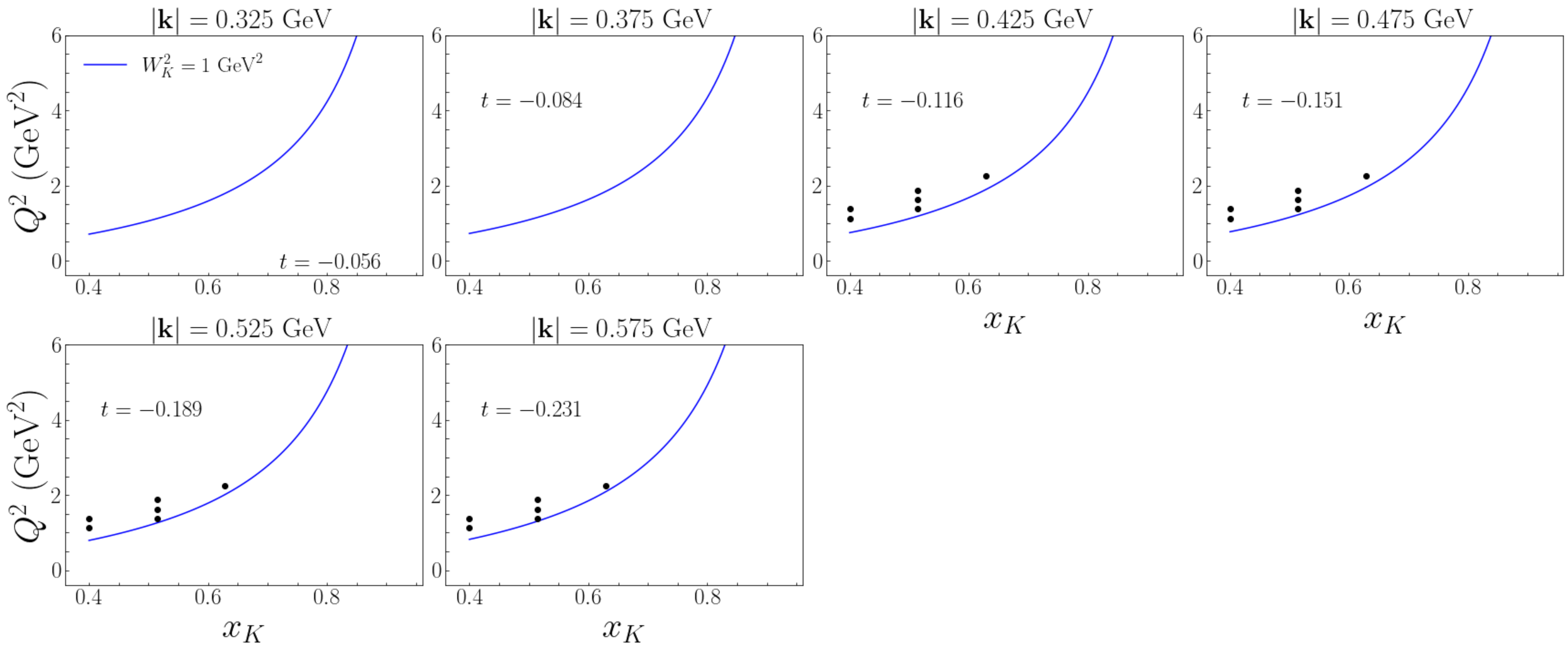
Brief words on kaon TDIS

- 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



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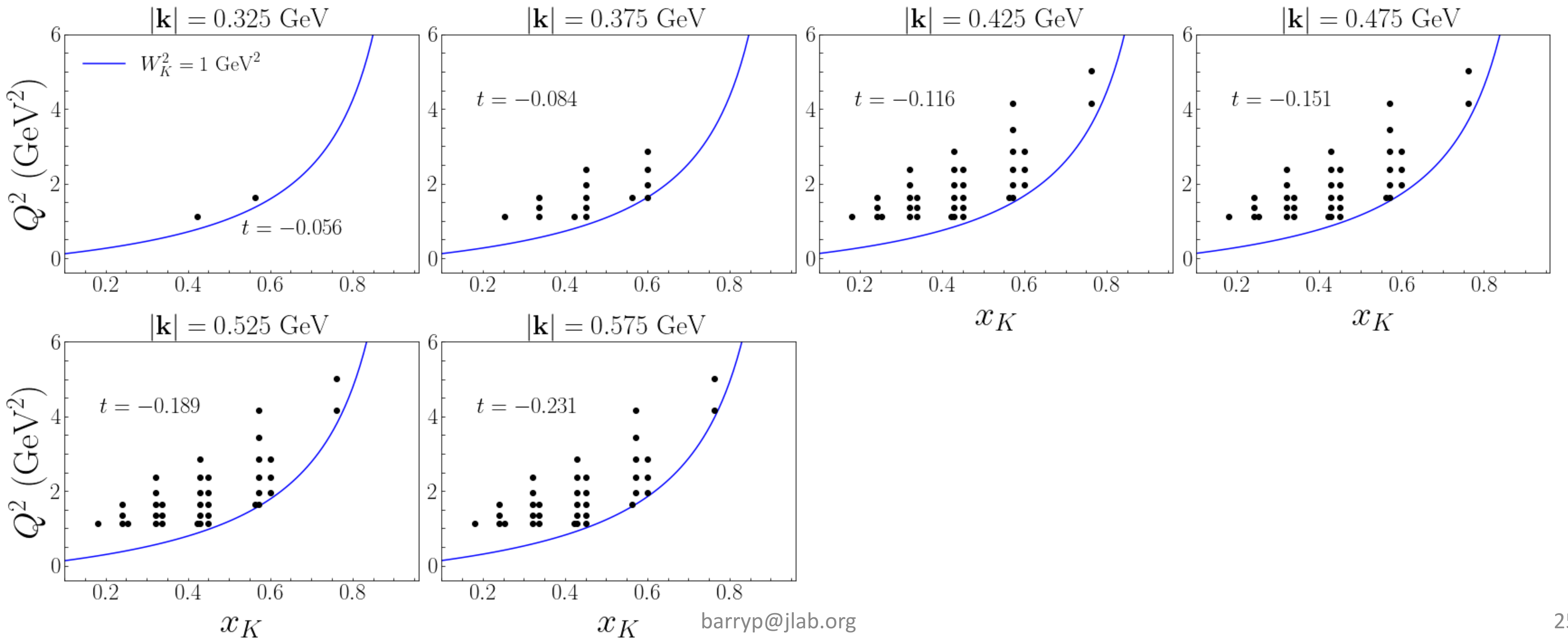
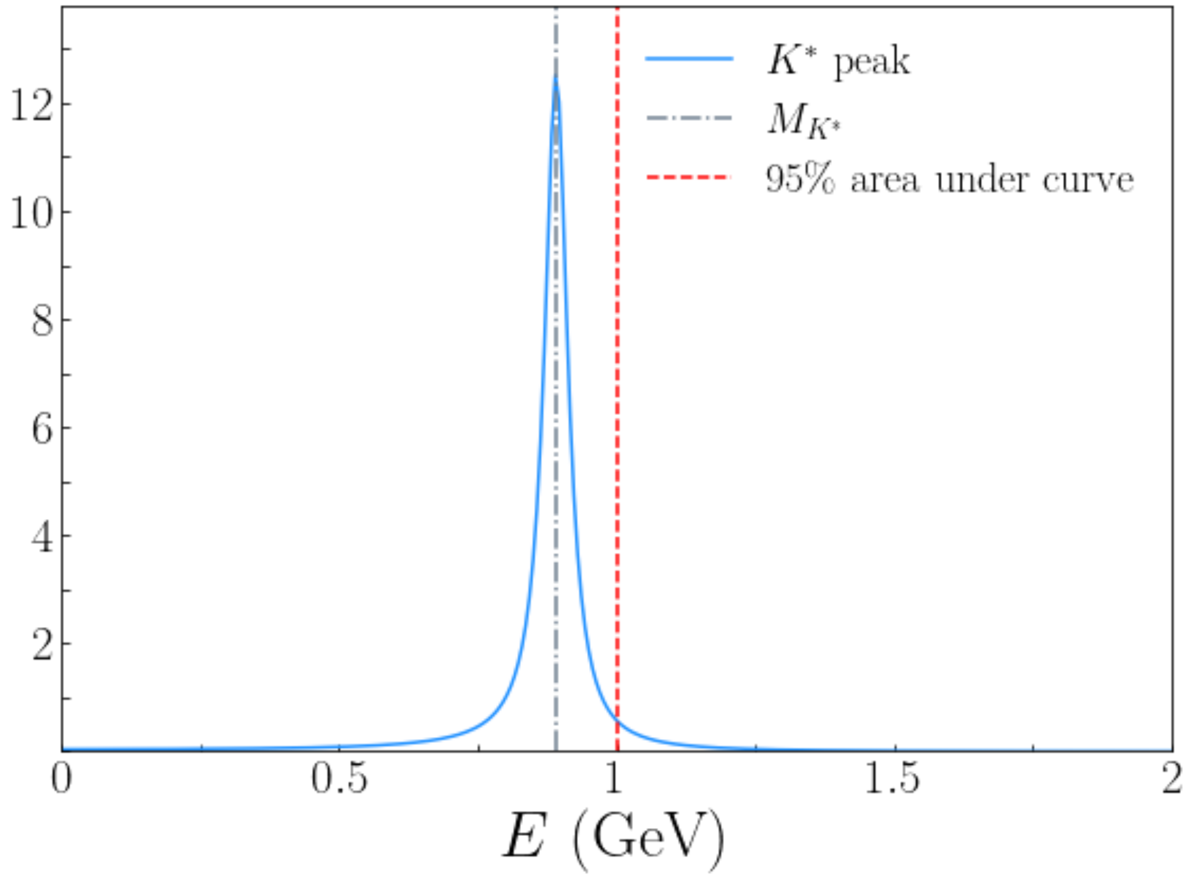
Kinematics for 22 GeV Kaon TDIS

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



Resonance from K^*

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



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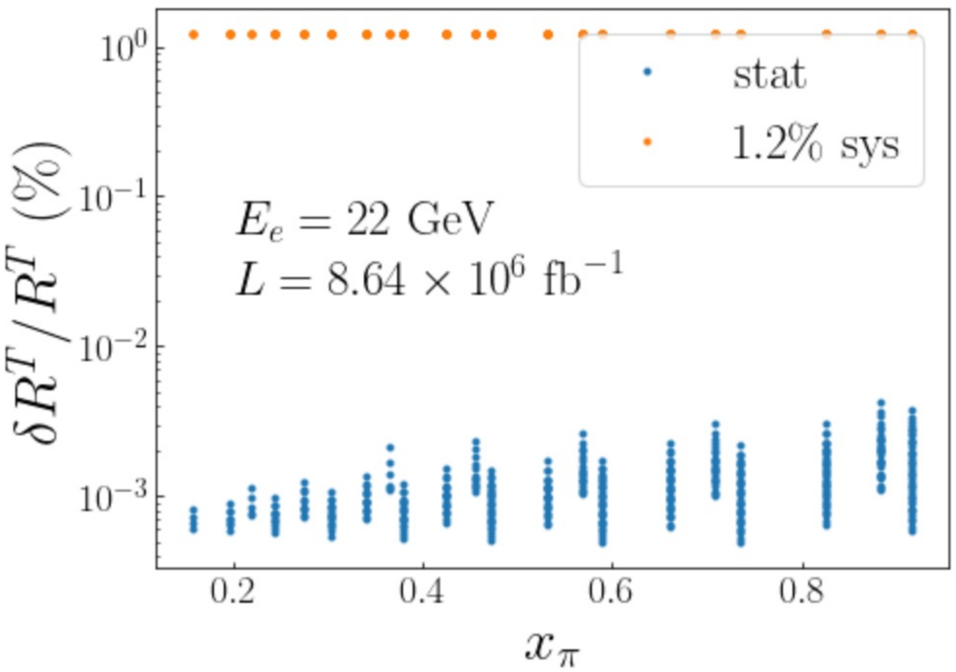
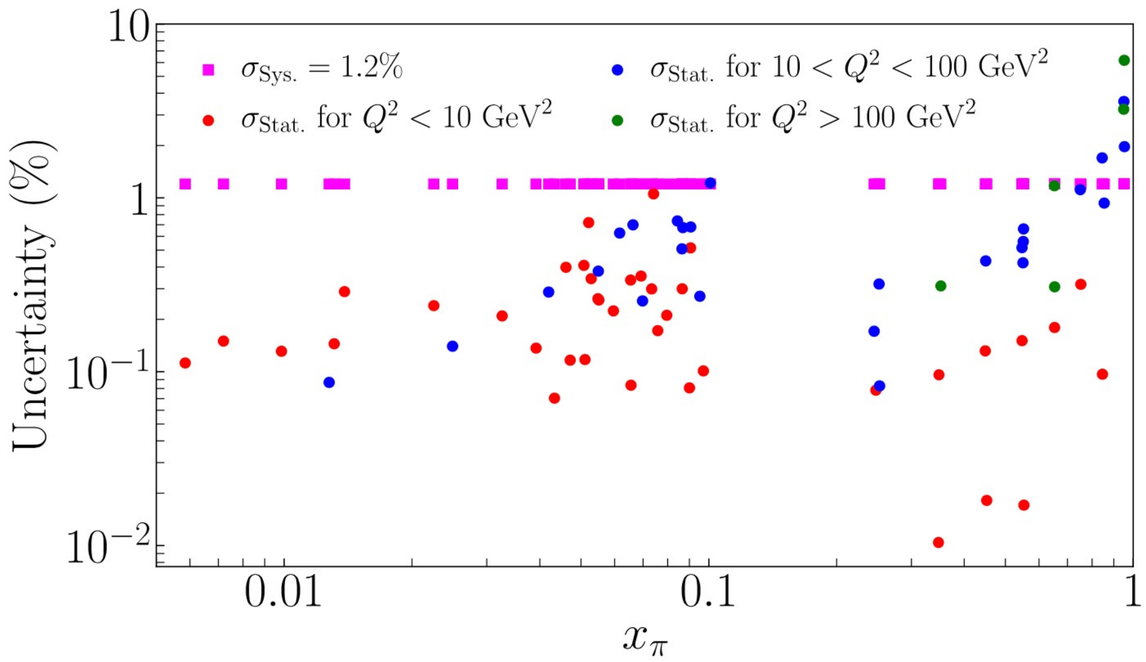
EIC vs JLab 22 GeV

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

<u>JLab</u>



<u>EIC</u>



Use of W^2 for SIDIS

The unobserved invariant mass-squared in inclusive DIS is

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

In SIDIS it is

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

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

- Replace M^2 with t