Impacts on the pion PDFs using the Sullivan process in future facilities

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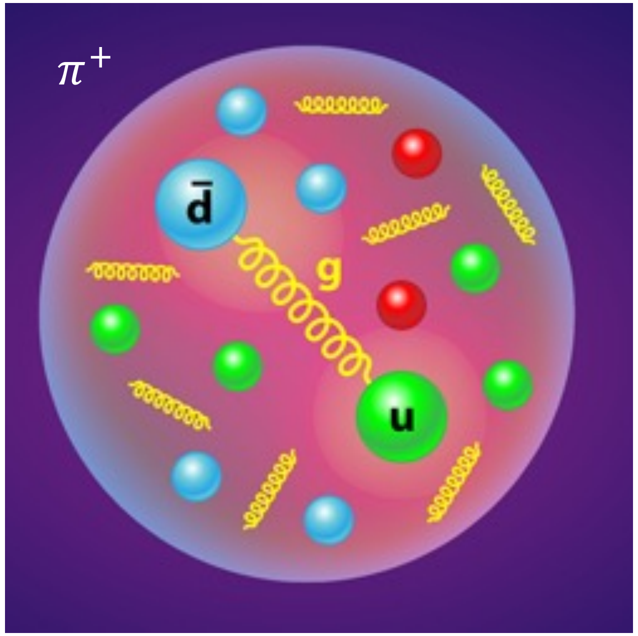
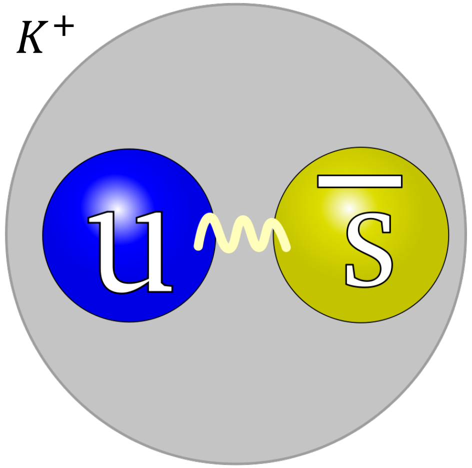
Mesons

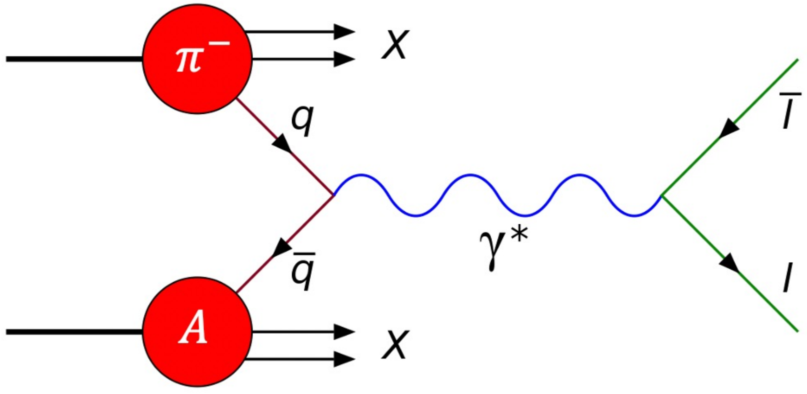
- Pion is the Goldstone boson associated with SU(2) chiral symmetry breaking
- Kaon – SU(3)
- Simultaneously a $q\bar{q}$ bound state
- Studying these structures provides another angle to probe QCD and effective confinement scales
- More available data is desperately needed



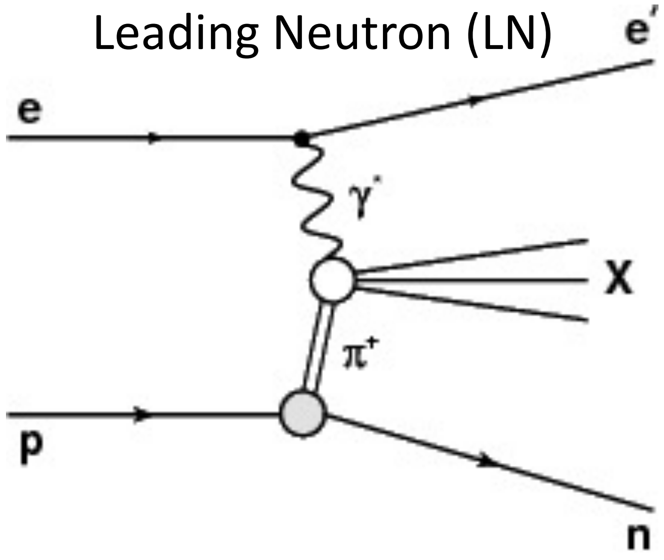


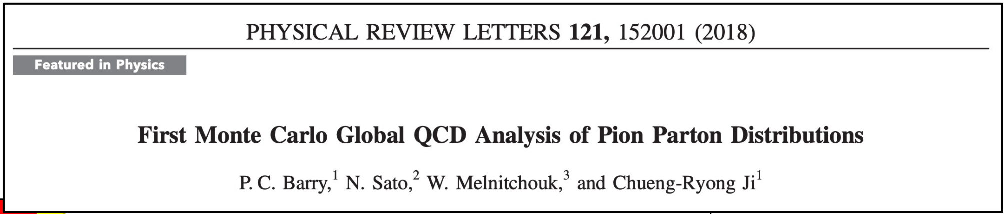
Pion PDFs in JAM

Drell-Yan (DY)



Leading Neutron (LN)



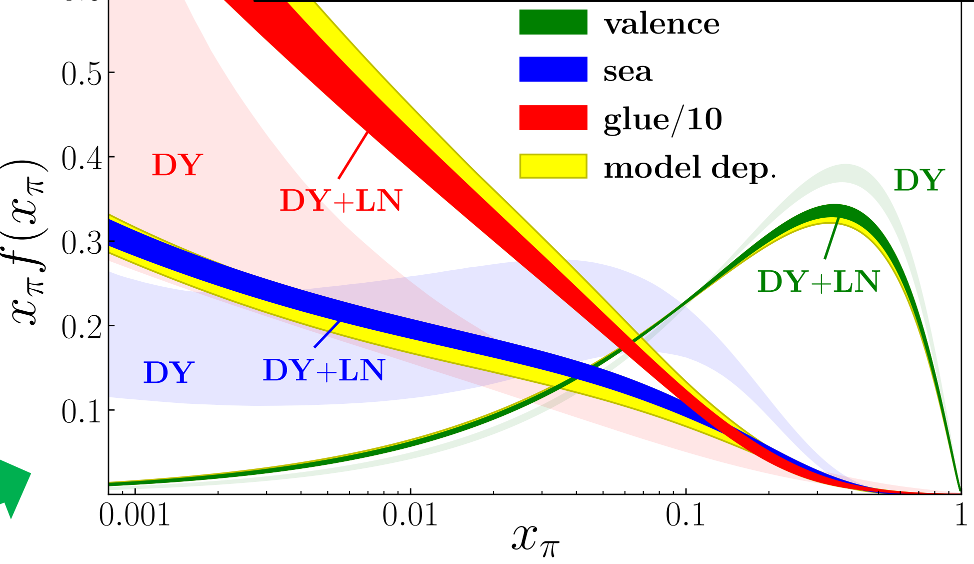


PHYSICAL REVIEW LETTERS **121,** 152001 (2018)

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]

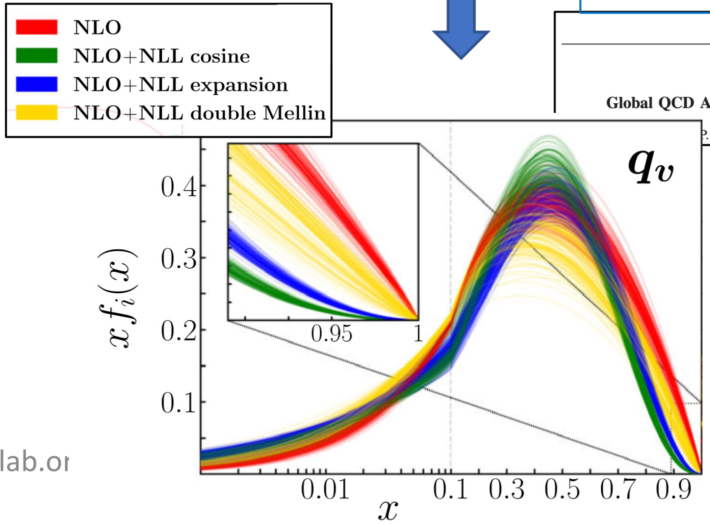


Threshold resummation in DY

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]



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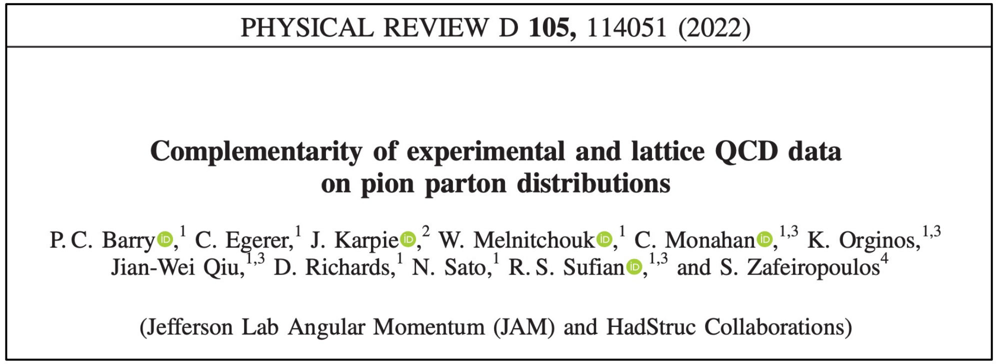
Pion PDFs from lattice + experimental data

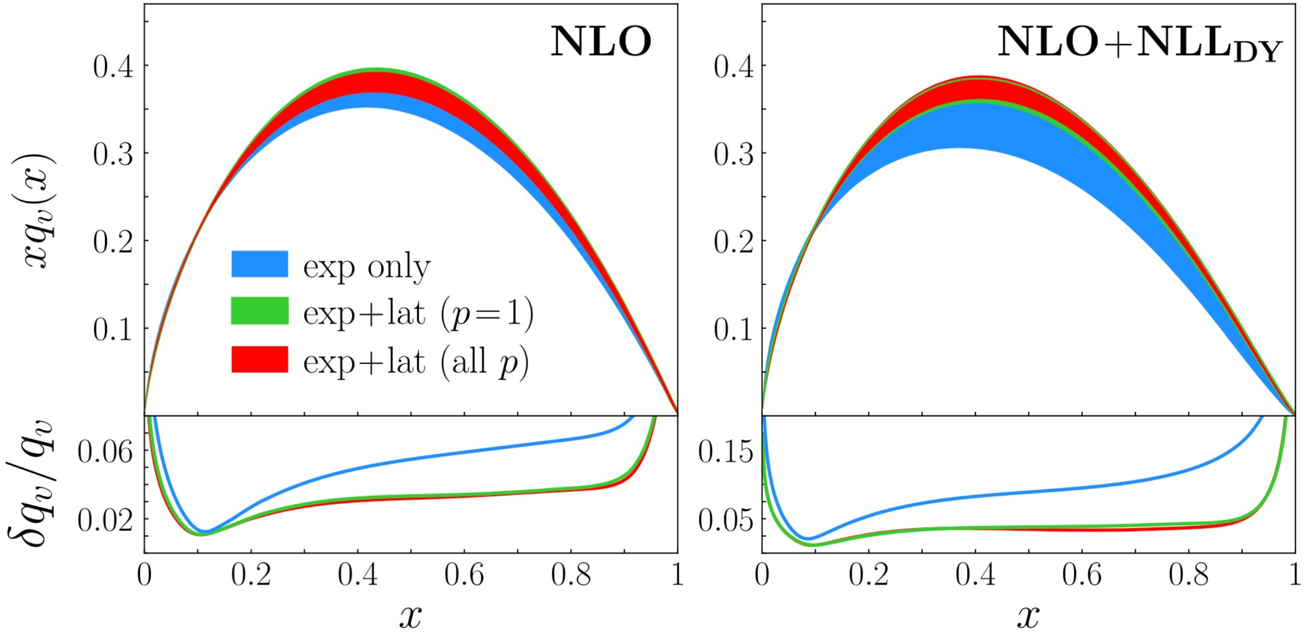


PHYSICAL REVIEW D **105,** 114051 (2022)

Complementarity of experimental and lattice QCD data on pion parton distributions

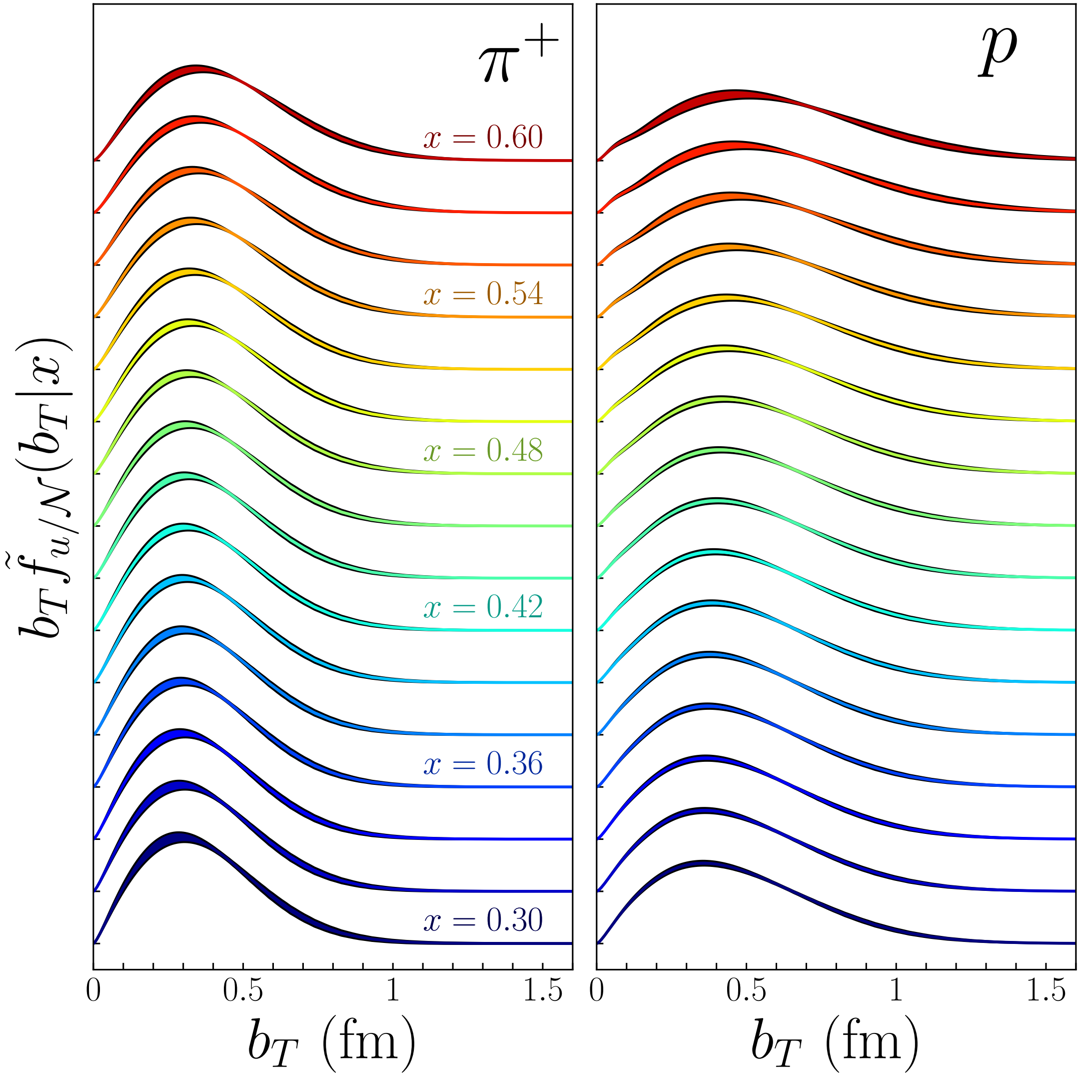
P. C. Barry,[1] C. Egerer,[1] J. Karpie,[2] W. Melnitchouk,[1] C. Monahan,[1,3] K. Orginos,[1,3]
Jian-Wei Qiu,[1,3] D. Richards,[1] N. Sato,[1] R. S. Sufian,[1,3] and S. Zafeiropoulos[4]

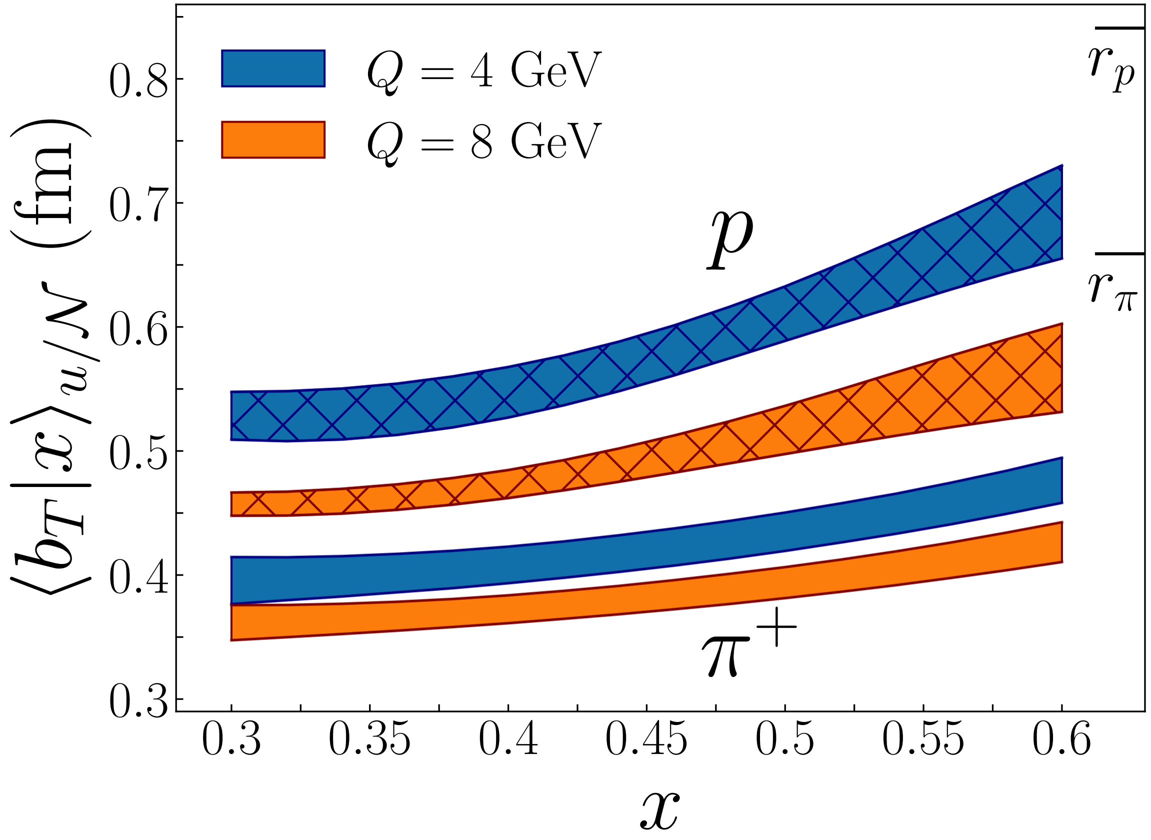
(Jefferson Lab Angular Momentum (JAM) and HadStruc Collaborations)



- 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

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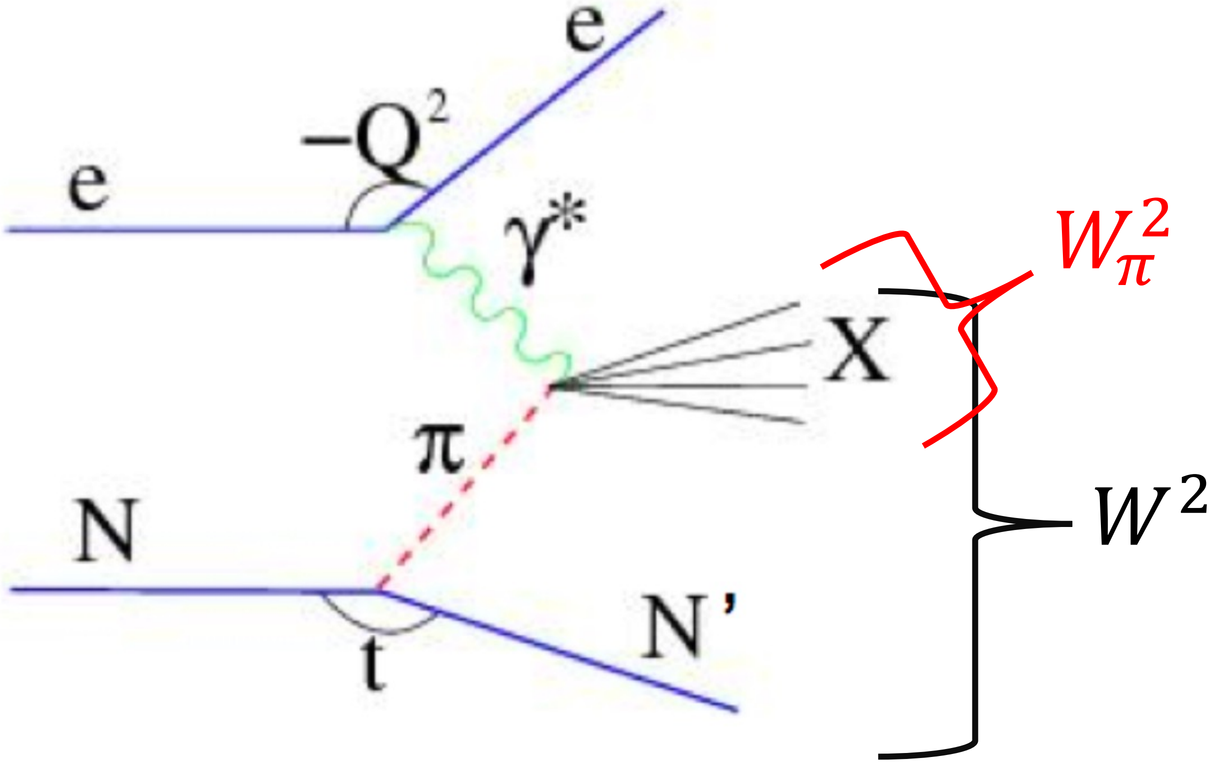
TDIS program: Sullivan process and W_π^2

- Measure $F_2^{\mathrm{T}(4)}(x, Q^2, x_L, t) = f_{\pi N}(x_L, t) F_2^{\pi}(x/\bar{x}_L, Q^2),$
- Impose kinematic cuts on experimental data
- What about the W_π^2?



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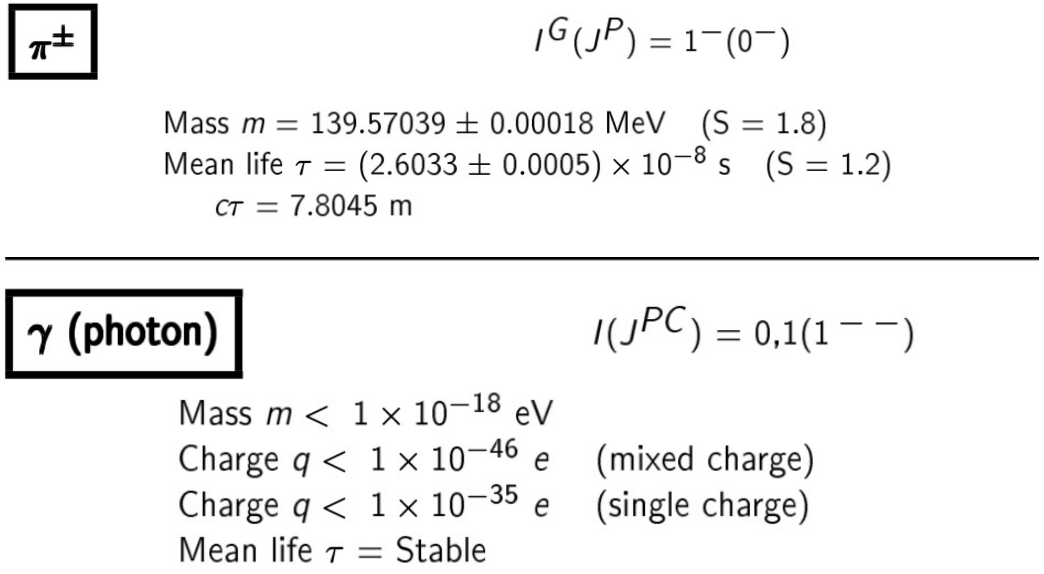
Check the resonance regions

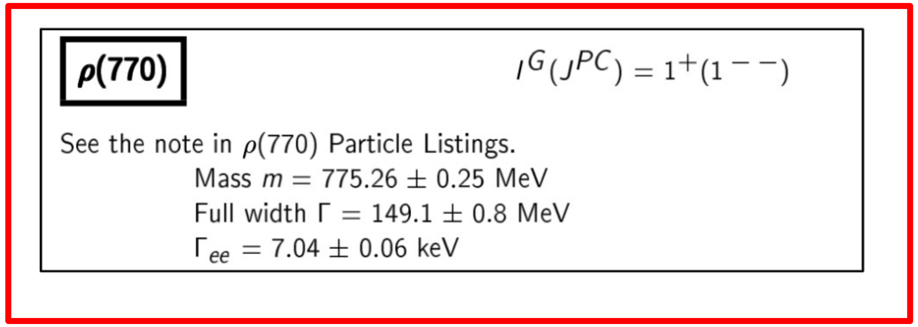


$\pi^\pm$ $I^G(J^P) = 1^-(0^-)$

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

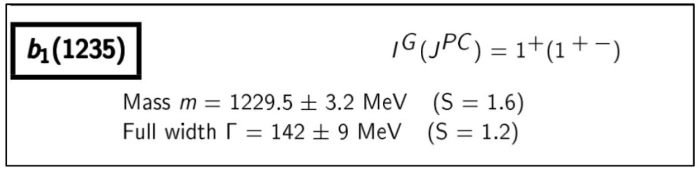
γ (photon) $I(J^{PC}) = 0{,}1(1^{--})$

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



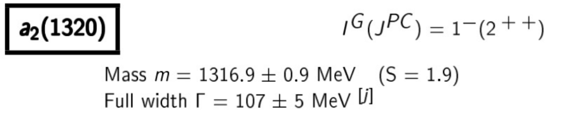
$\rho(770)$ $I^G(J^{PC}) = 1^+(1^{--})$

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

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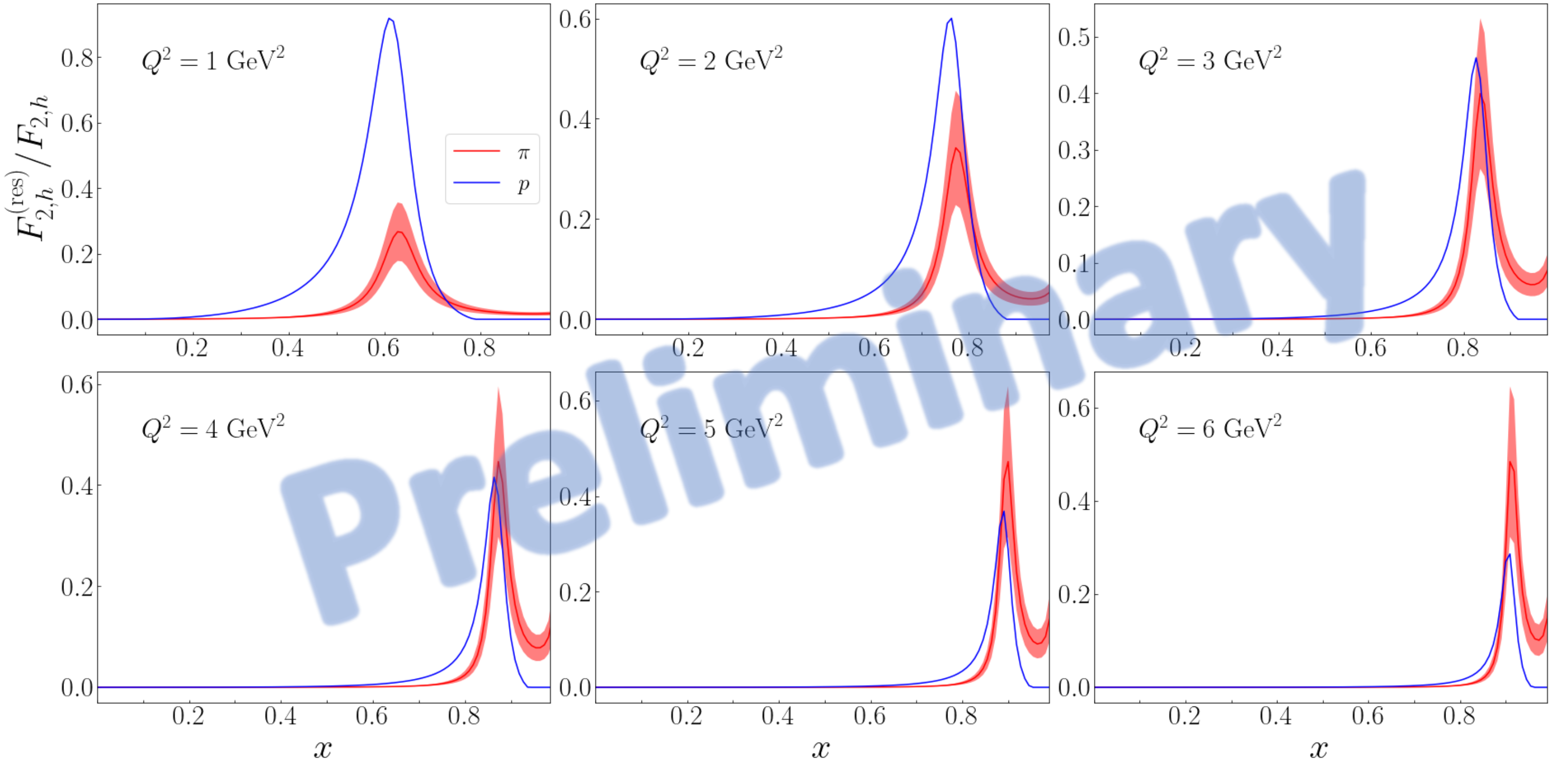
Contribution from ρ to F_2^π



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

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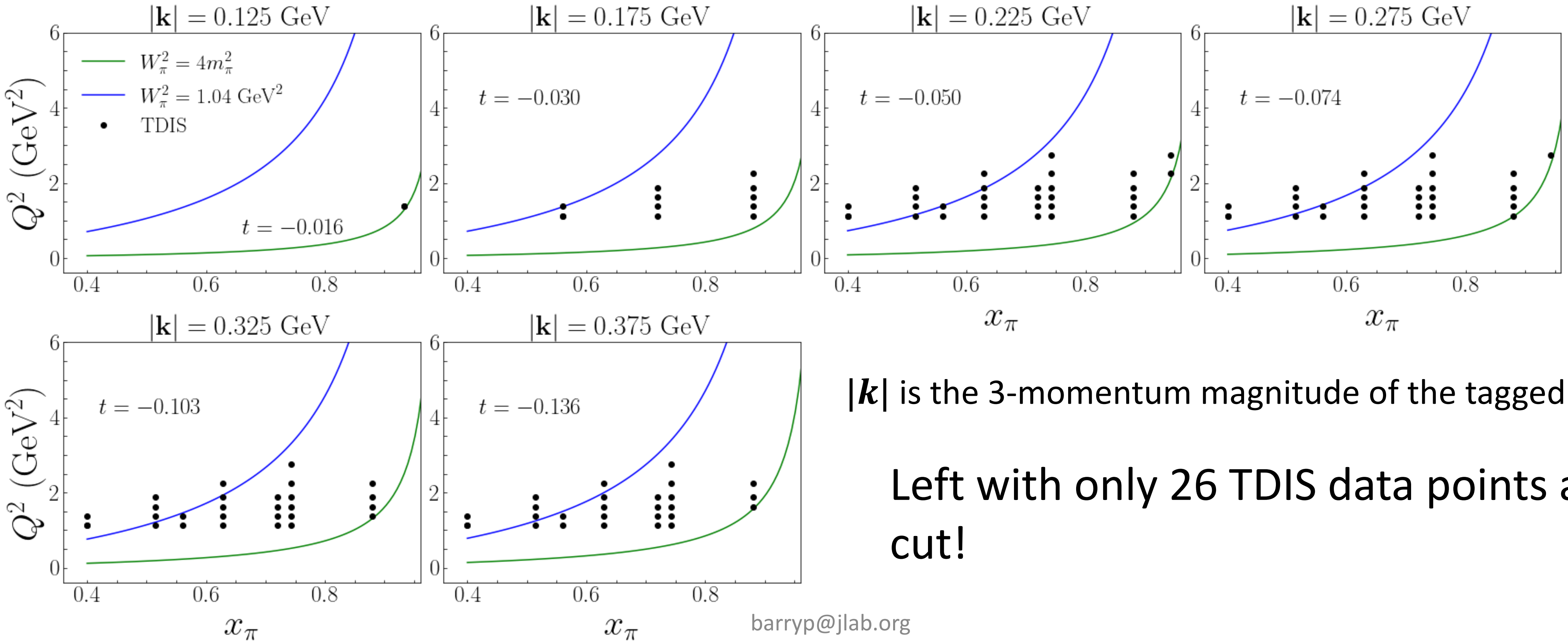
Current 11 GeV TDIS kinematics

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

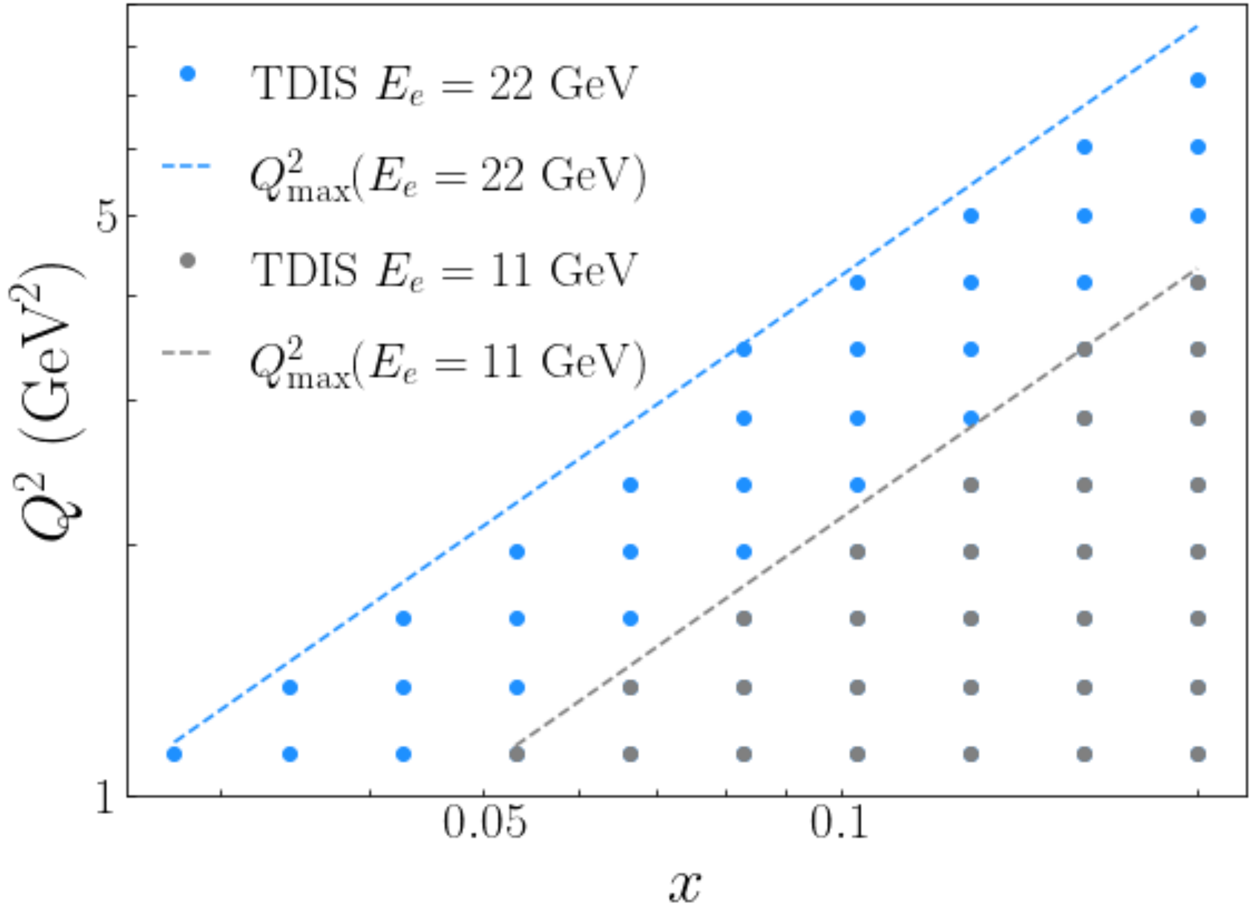


$|\boldsymbol{k}|$ is the 3-momentum magnitude of the tagged nucleon

Left with only 26 TDIS data points after cut!

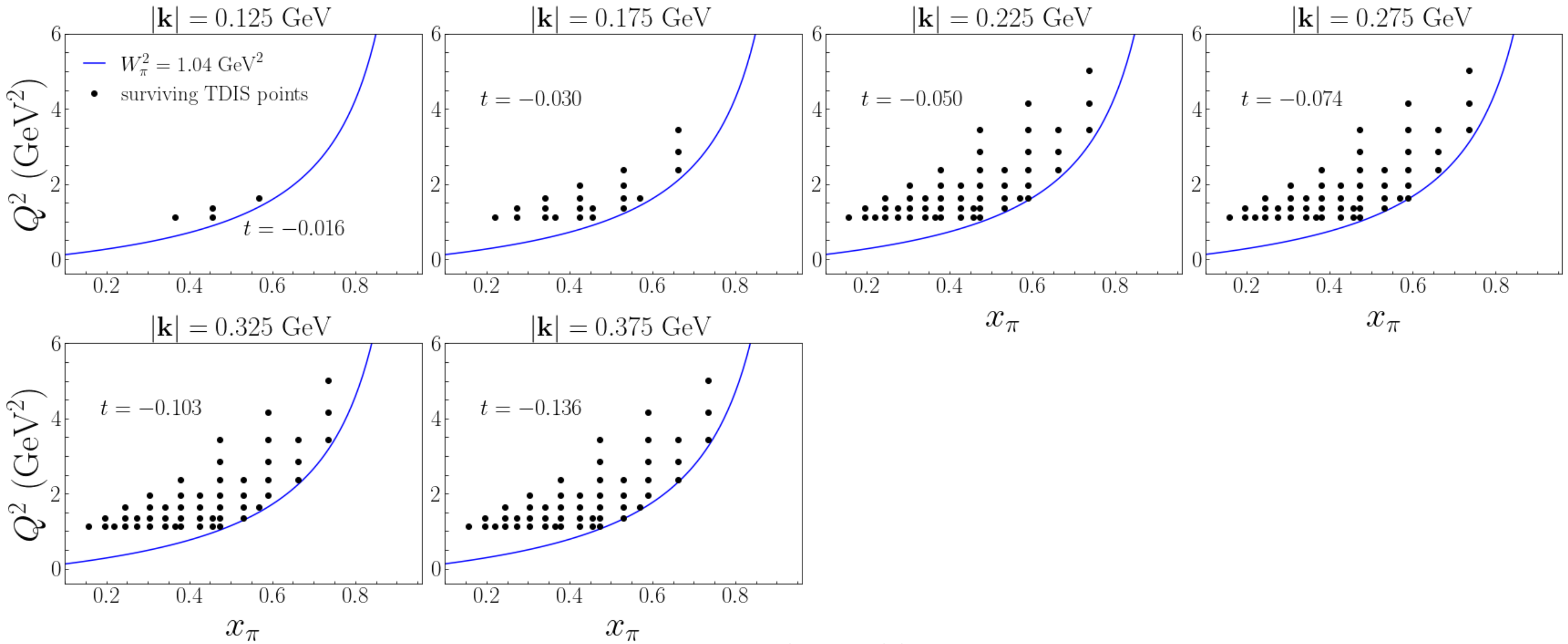
Upgrade to 22 GeV

- Much more available kinematic range in (x, Q^2)
- Recall the W_π^2 cut removed large x_π and small Q^2 data
- New blue points will survive the cut



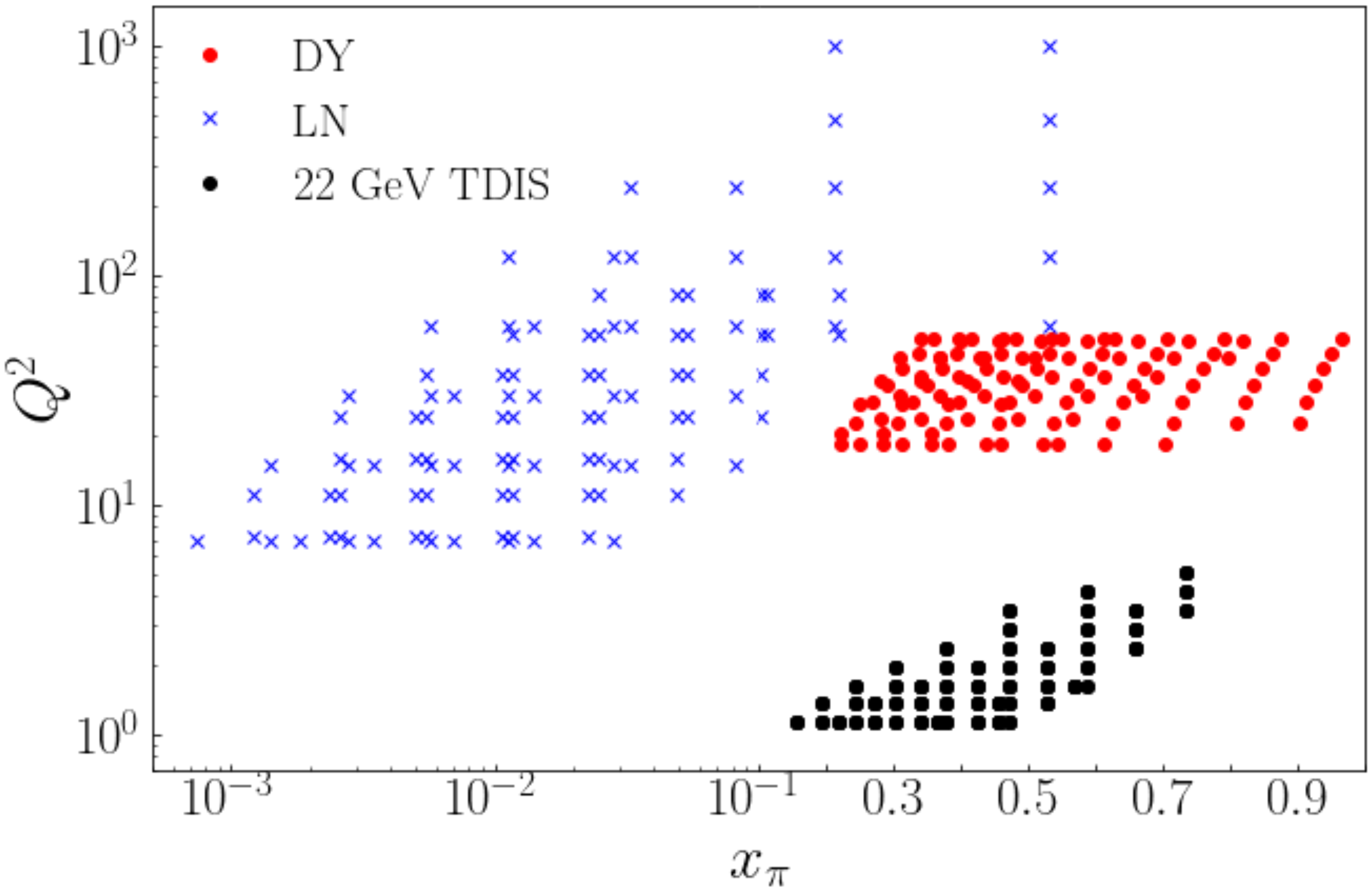
Kinematics with 22 GeV

- MASSIVE increase in available data points



Total kinematics

- Important overlap of TDIS points in the DY region
- Tests of universality of the PDFs!



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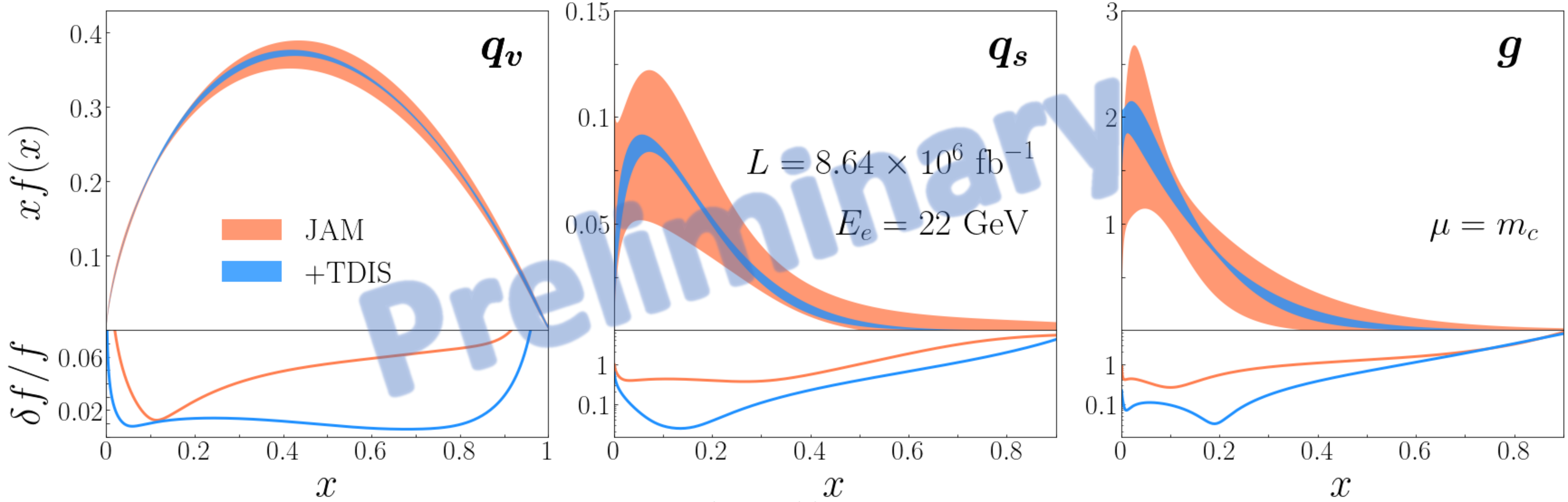
Impact on pion PDFs with 22 GeV

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



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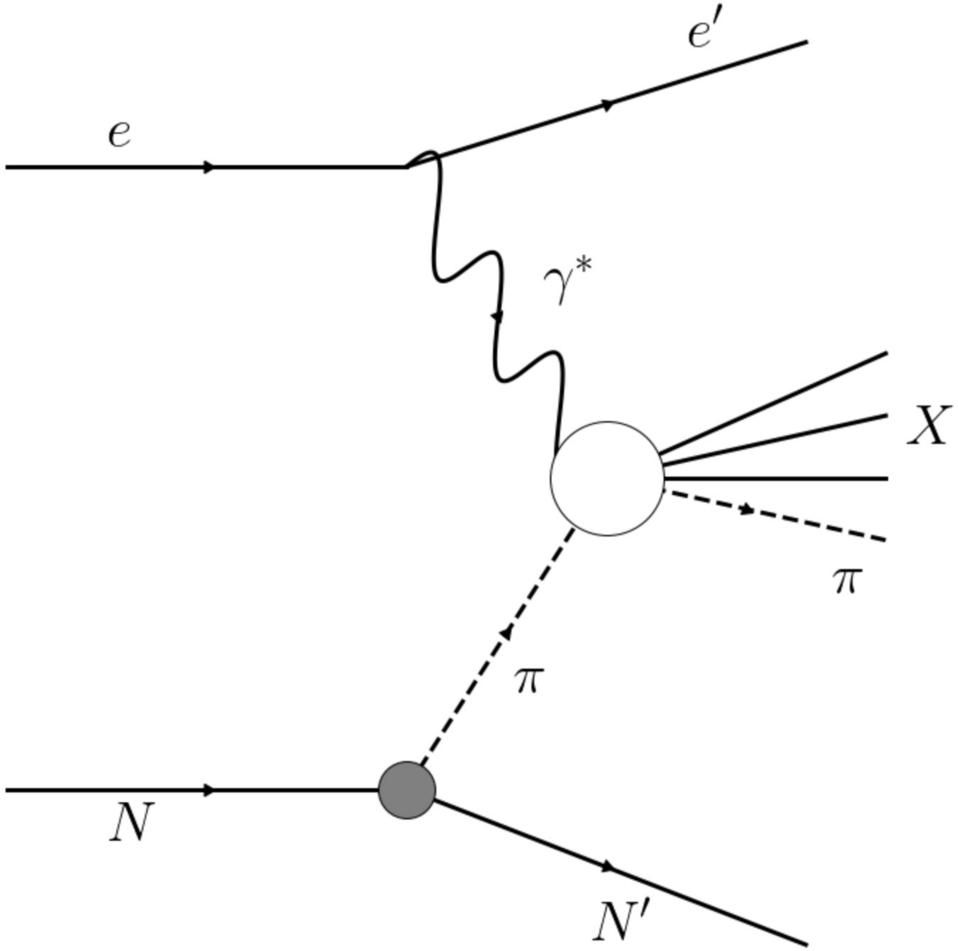
Pion SIDIS: access to TMDs

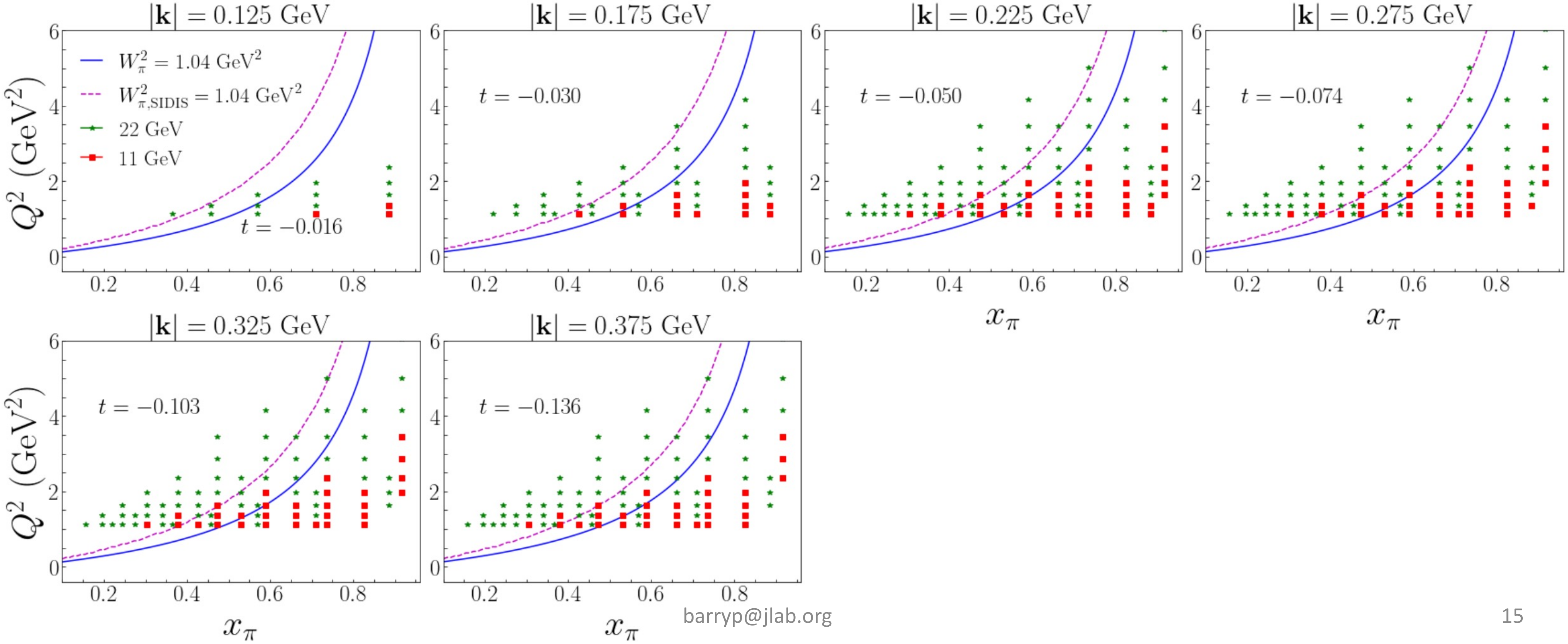
$$eN \to e'N'\pi X$$

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



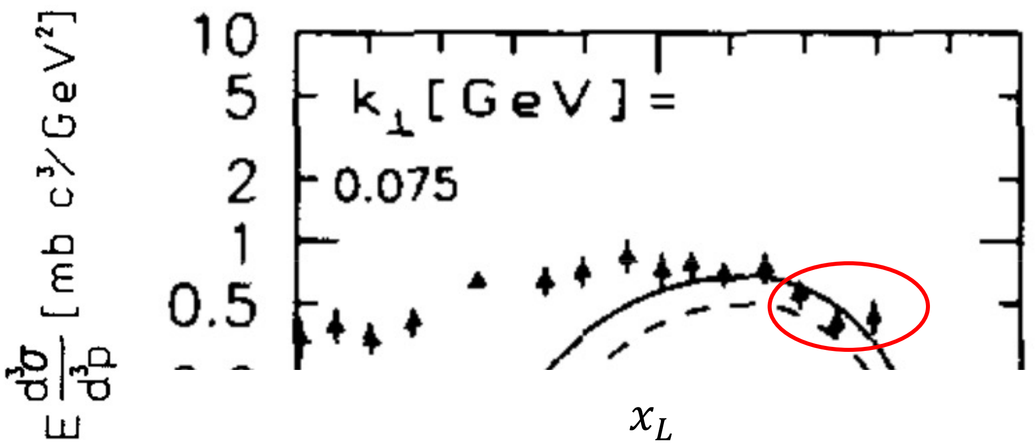
Available kinematics for JLab

- Can only use 22 GeV data for any TMD analysis



Kaons

- As a best estimate for tagged hyperon rates, we look to the splitting function ratios of the $f_{\pi N}$ to $f_{K\Lambda}$
- Estimate roughly an appropriate regulator through $pp \to \Lambda X$ data
- Preliminary fits indicate $f_{K\Lambda}/f_{\pi N} \approx 1\%$
- Rates in cross sections may be roughly the same!



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Conclusion

- Impacts from the 11 GeV TDIS experiment on pion PDFs will be limited
- The 11 GeV TDIS can measure the low-W_π pion structure function
- More constraints will come from larger 22 GeV upgrade
- JLab 22 upgrade analysis constraining the valence quark allows complementary measurements at EIC with more solid footing
- Kaon PDF analysis may be more realistic with energy upgrade and high luminosity

Backup Slides

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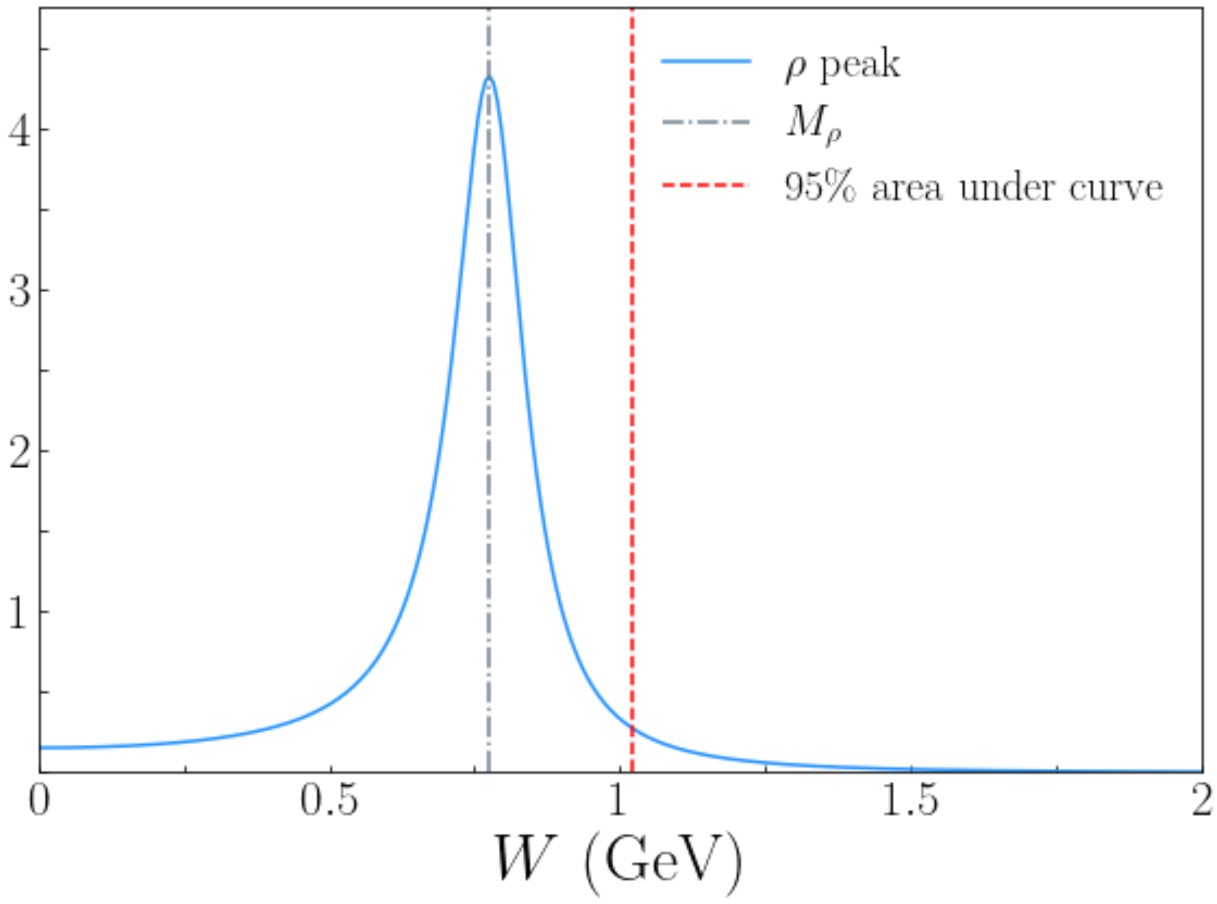
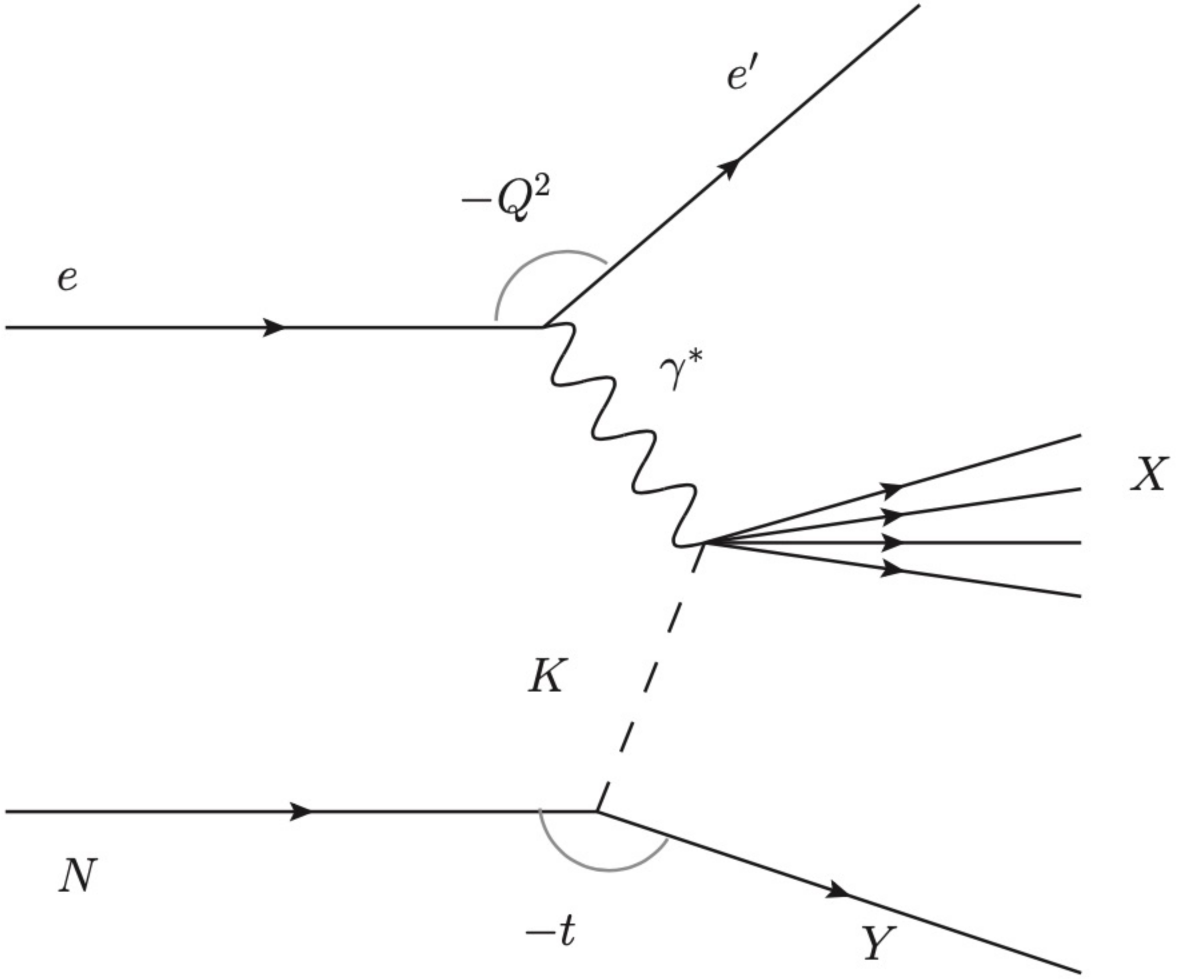
What to choose for W_π^2

- 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



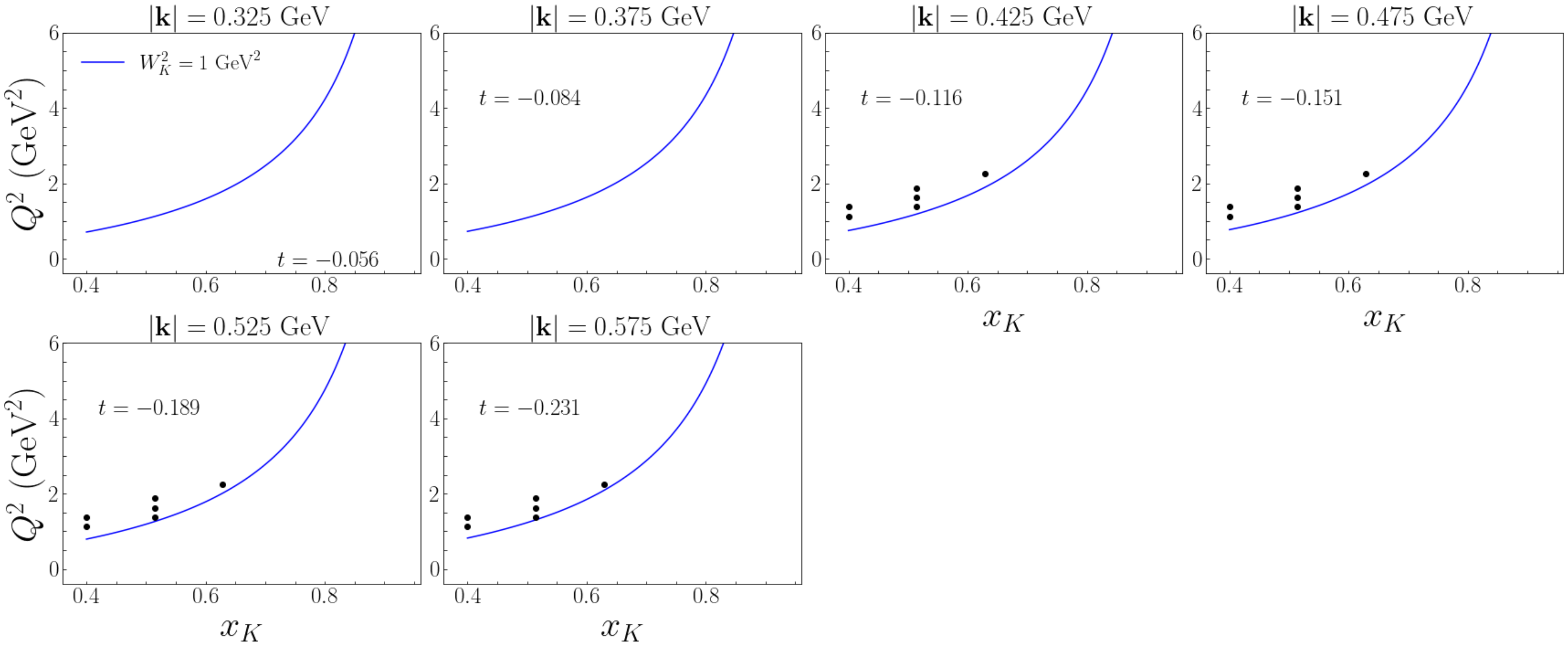
Brief words on kaon TDIS

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



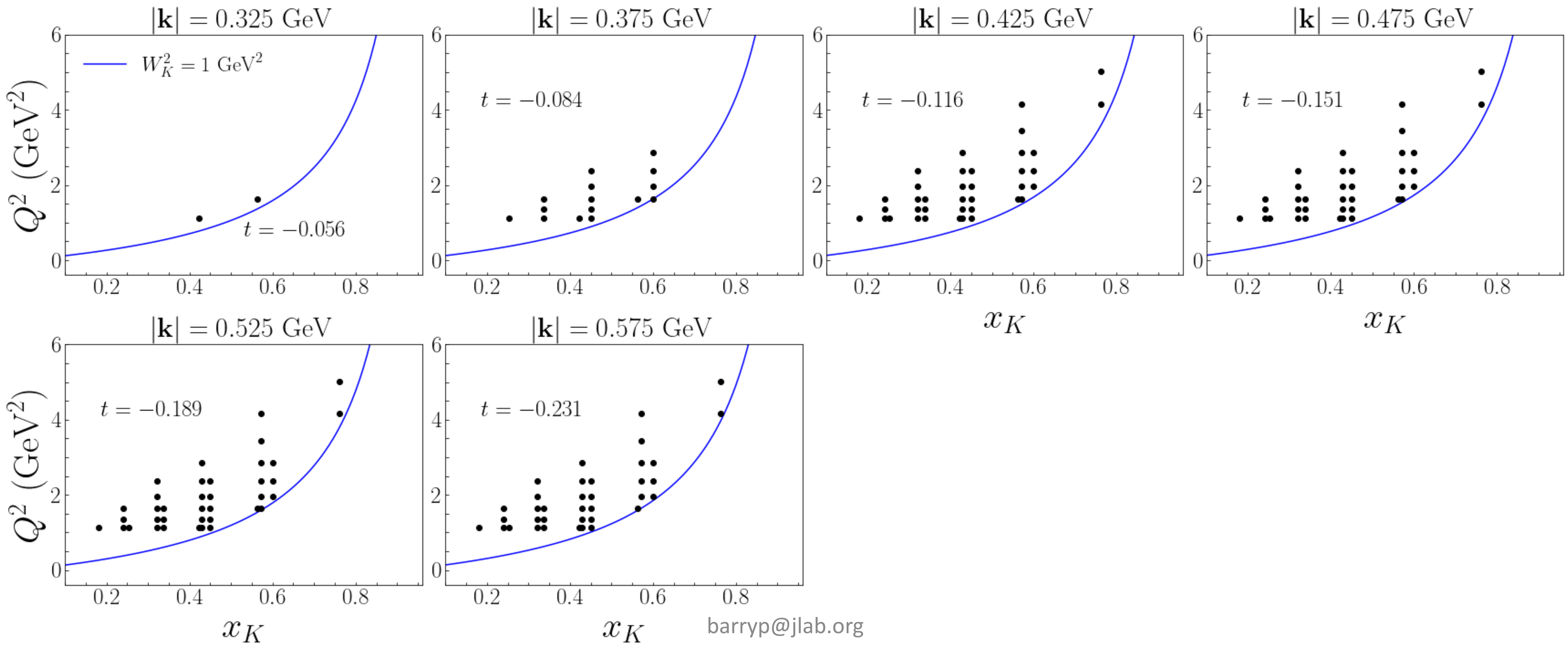
Kinematics for 11 GeV Kaon TDIS

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



Kinematics for 22 GeV Kaon TDIS

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



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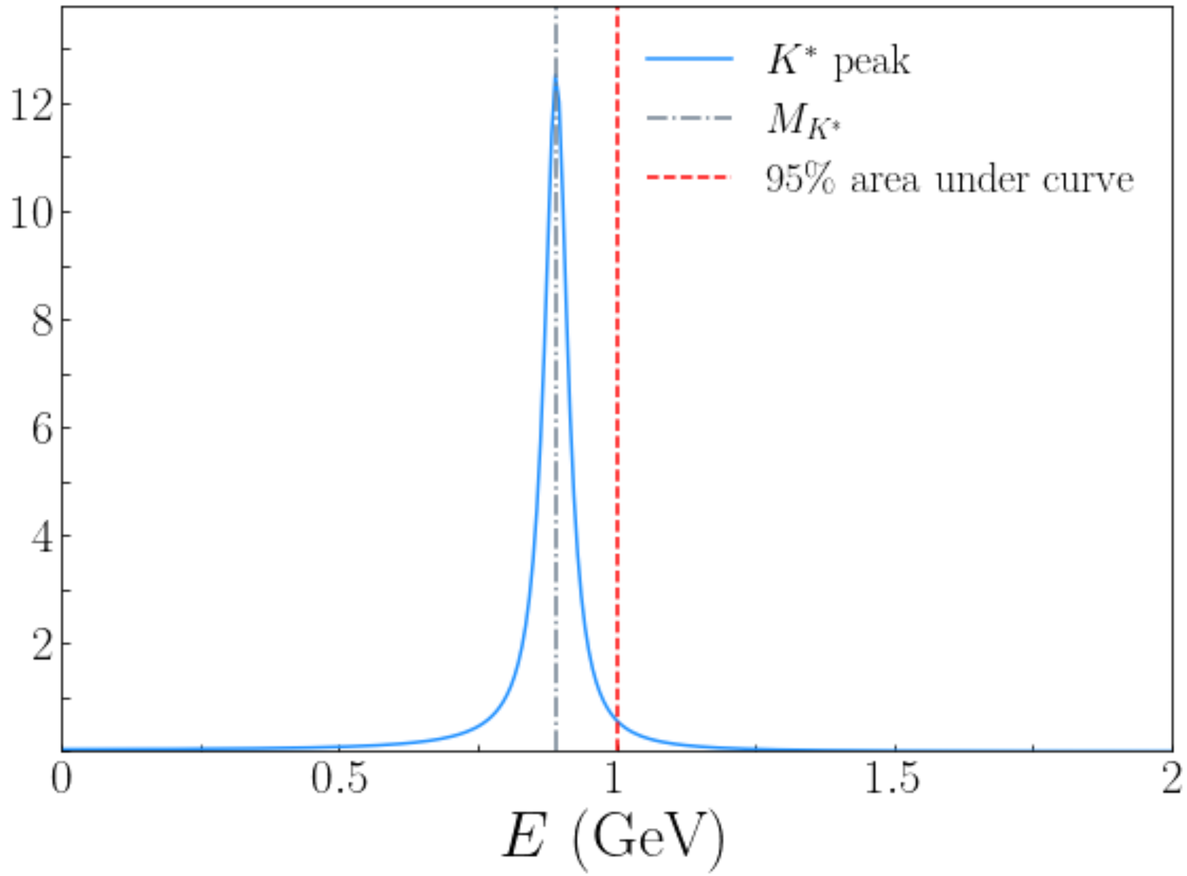
Resonance from K^*

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



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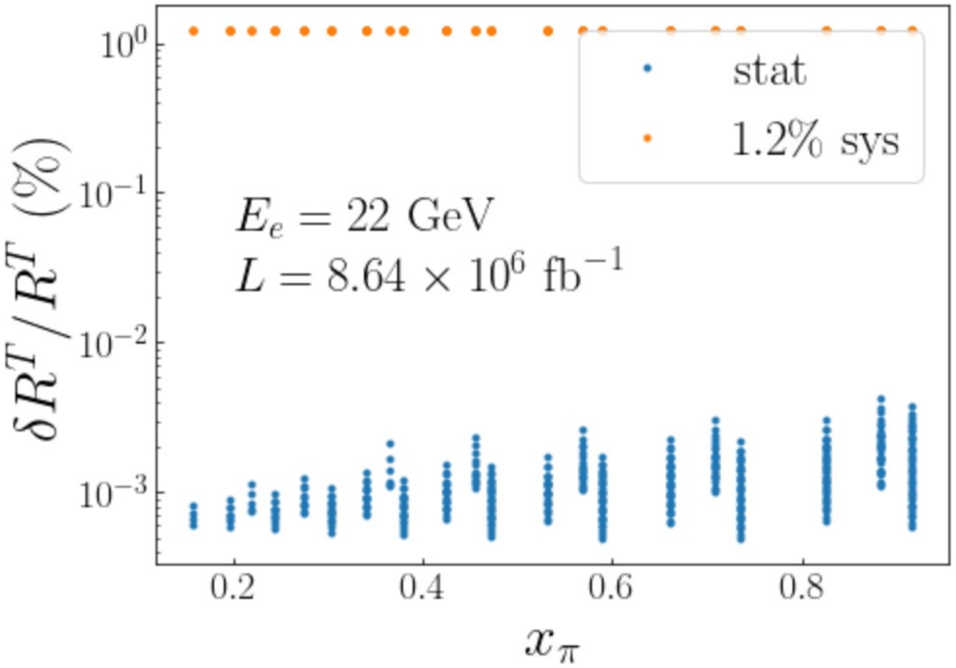
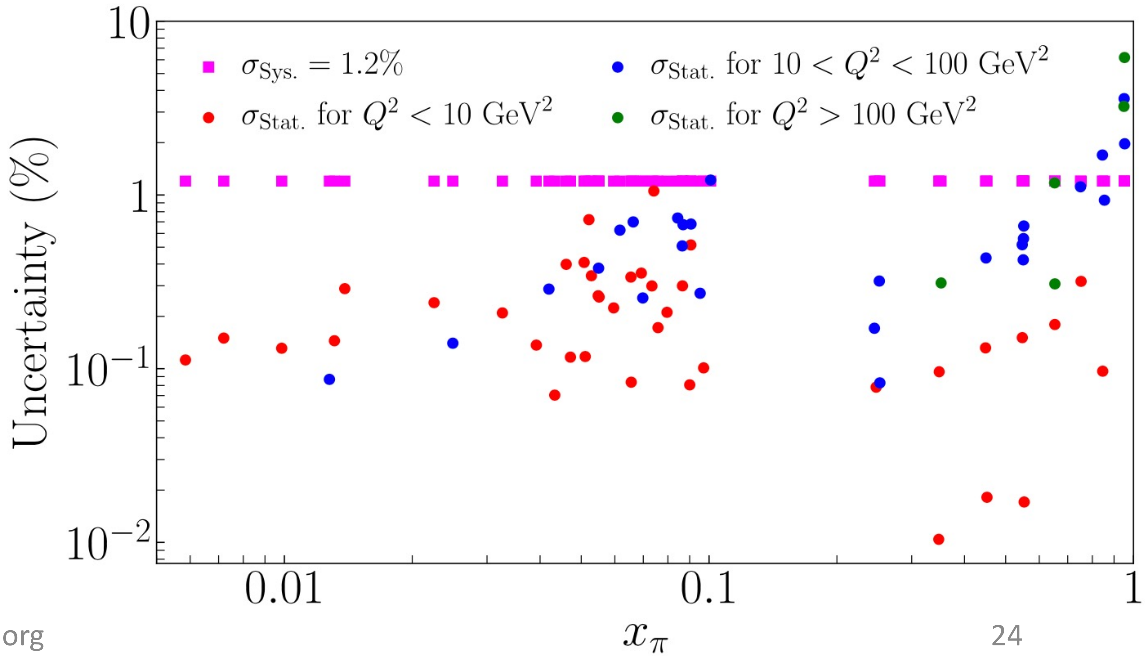
EIC vs JLab 22 GeV

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

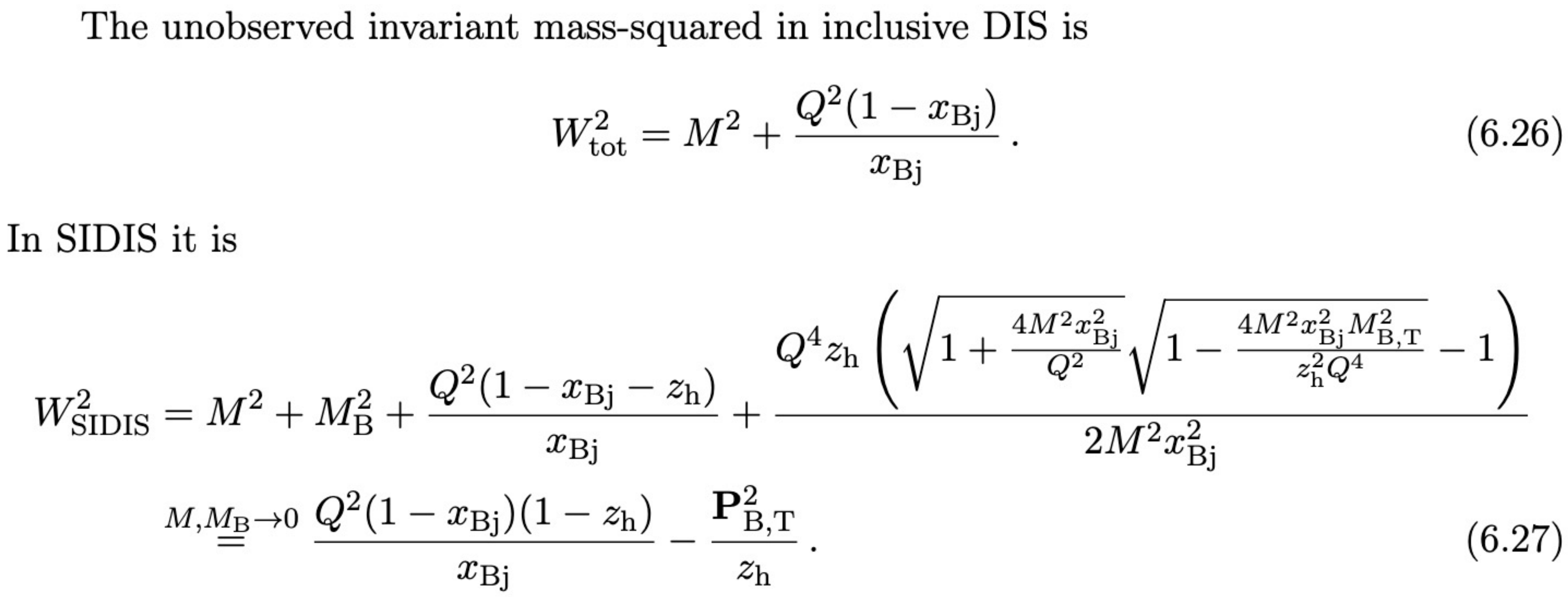
JLab



EIC



Use of W^2 for SIDIS



The unobserved invariant mass-squared in inclusive DIS is

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

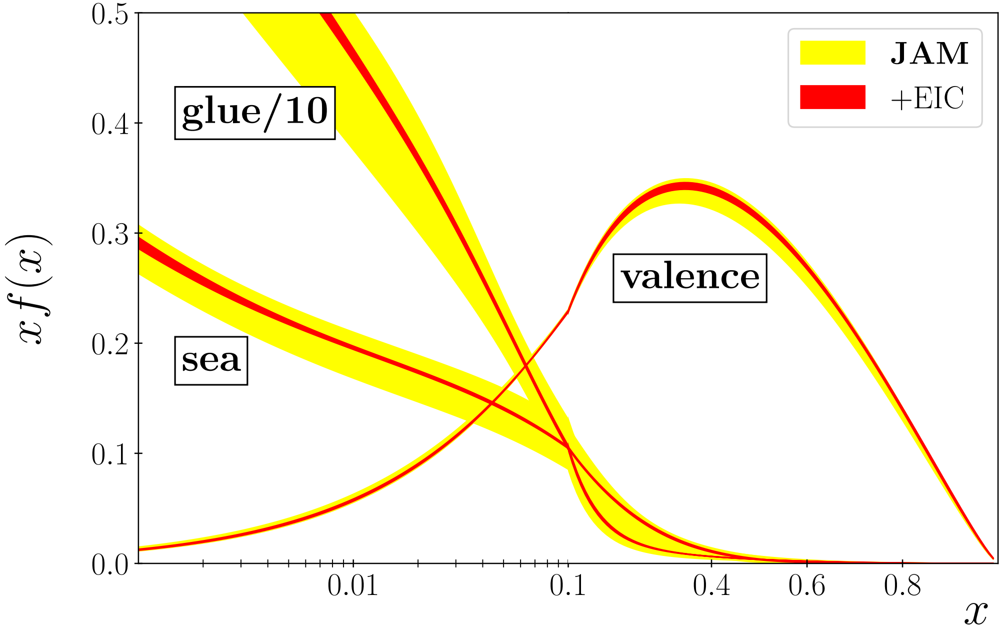
In SIDIS it is

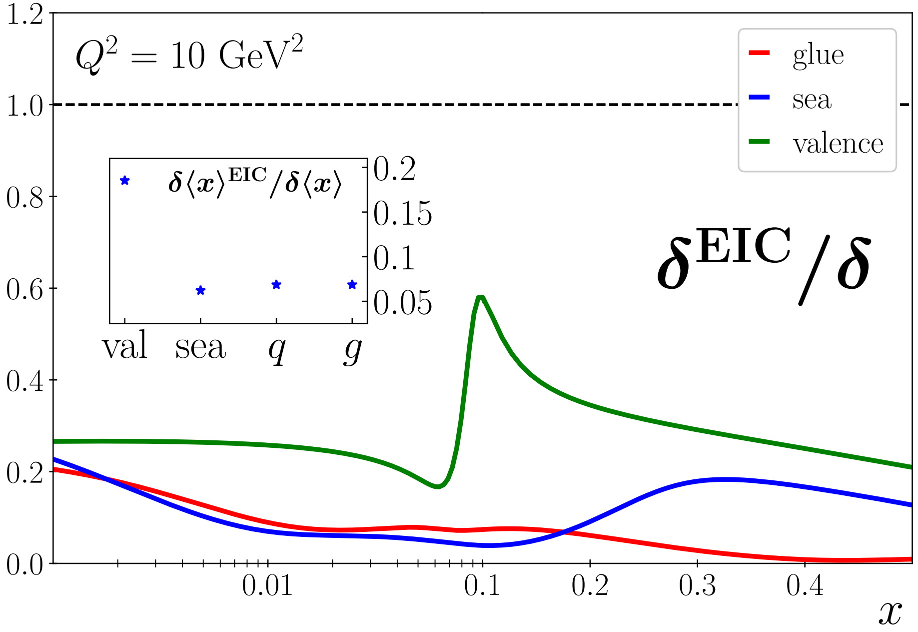
$$\begin{aligned} W_{\rm SIDIS}^2 &= M^2 + M_{\rm B}^2 + \frac{Q^2(1-x_{\rm Bj}-z_{\rm h})}{x_{\rm Bj}} + \frac{Q^4 z_{\rm h}\left(\sqrt{1+\frac{4M^2x_{\rm Bj}^2}{Q^2}}\sqrt{1-\frac{4M^2x_{\rm Bj}^2M_{\rm B,T}^2}{z_{\rm h}^2Q^4}}-1\right)}{2M^2x_{\rm Bj}^2} \\ &\overset{M,M_{\rm B}\to 0}{=} \frac{Q^2(1-x_{\rm Bj})(1-z_{\rm h})}{x_{\rm Bj}} - \frac{\mathbf{P}_{\rm B,T}^2}{z_{\rm h}}\,. \end{aligned} \tag{6.27}$$

- Replace M^2 with t

Future EIC

- We may also perform impact studies for the EIC





- Statistical uncertainties are small compared with HERA, and uncertainties will be dominated by systematics