University of Glasgow

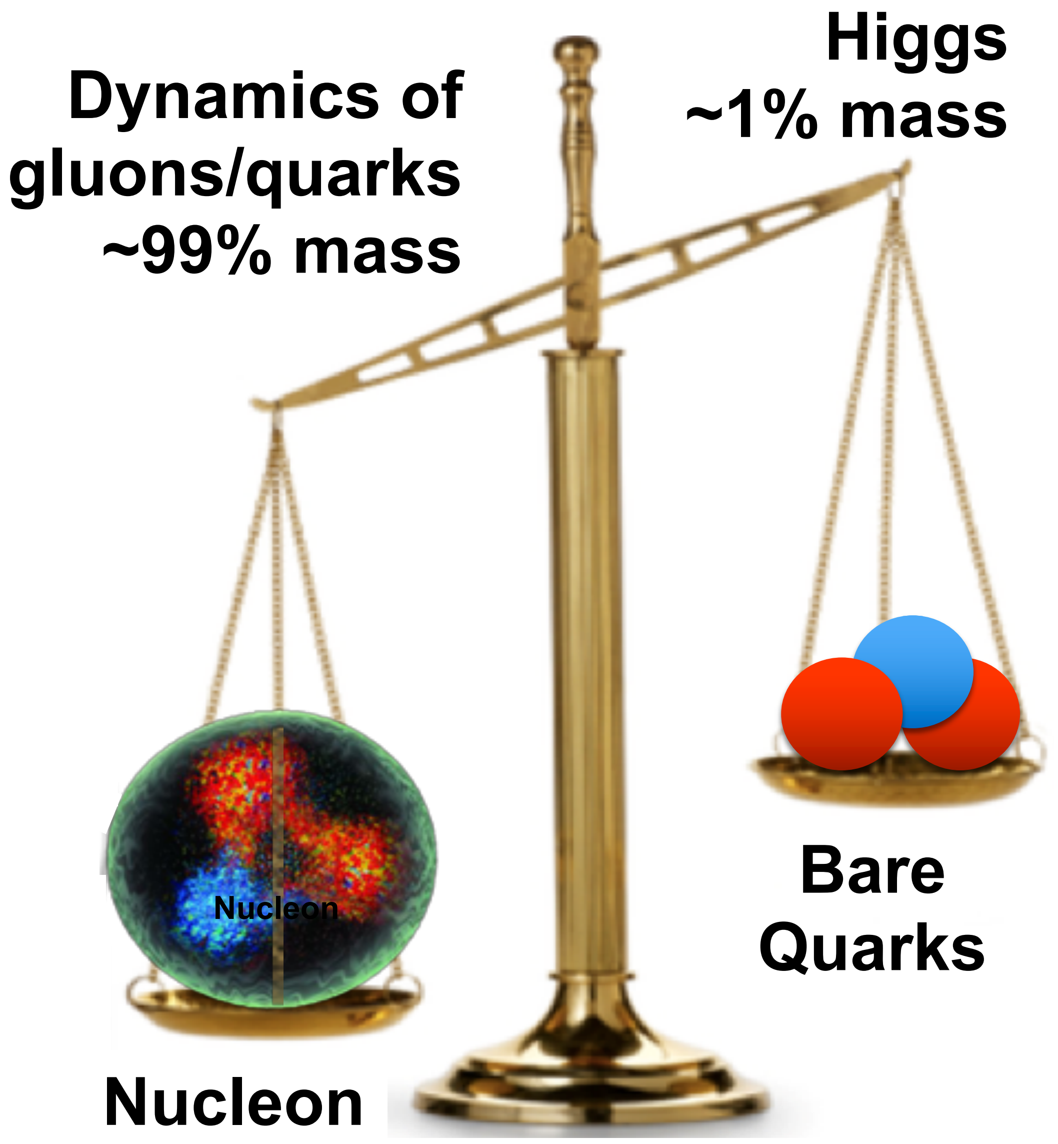
Measurements of Light Meson Structure via Tagged Deep Inelastic Scattering (TDIS)

Rachel Montgomery (UoG) on behalf of many colleagues from several institutions in the:

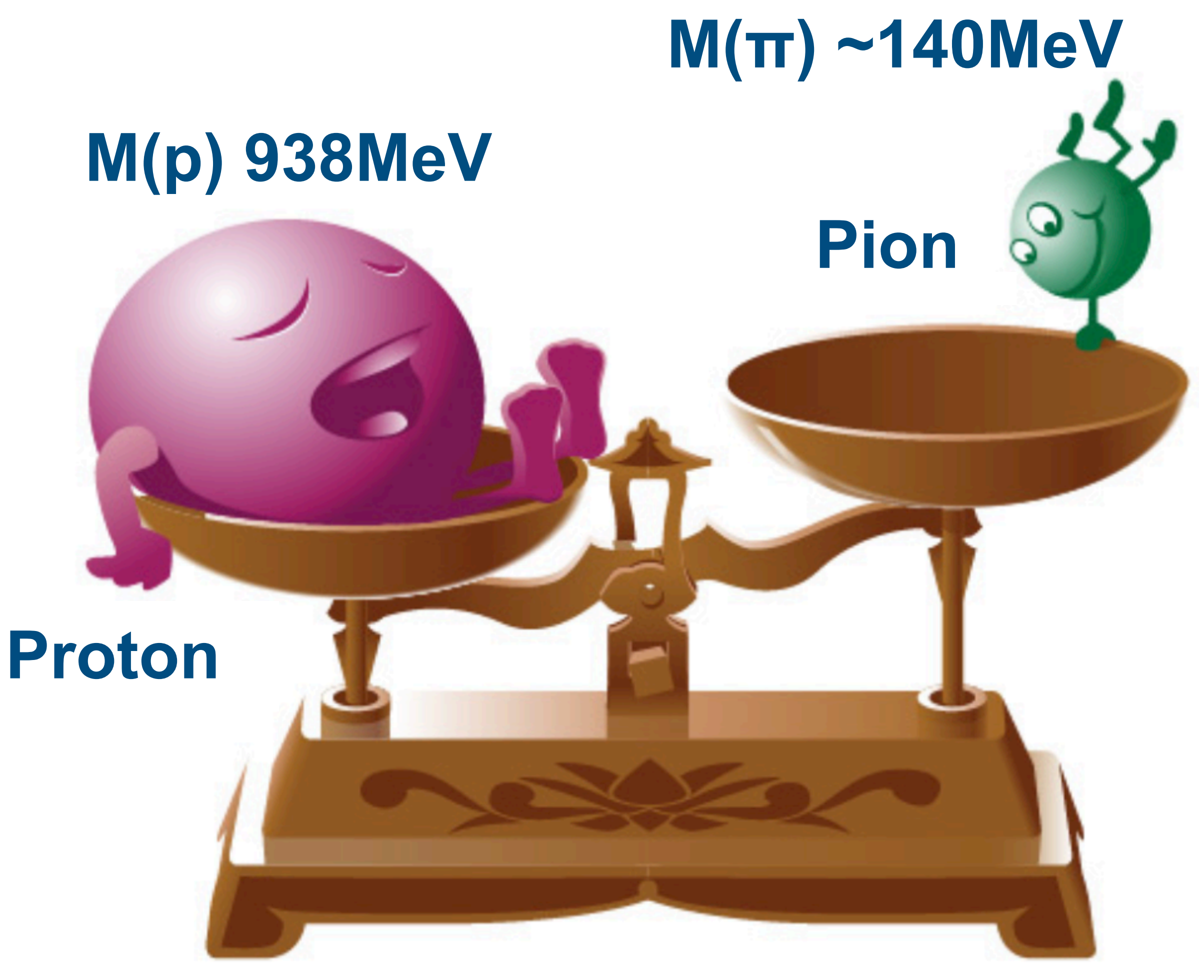
Jefferson Lab *Hall A, SBS and TDIS Collaborations*

10th Biennial Workshop of the APS Topical Group on Hadronic Physics
04/13/23

Why Meson Structure?



Hadron	Observed Mass (MeV)	Higgs Generated Mass (MeV)
Proton (uud)	~940	~10
Pion ($u\bar{d}$)	~140	~7
Kaon ($u\bar{s}$)	~490	~100

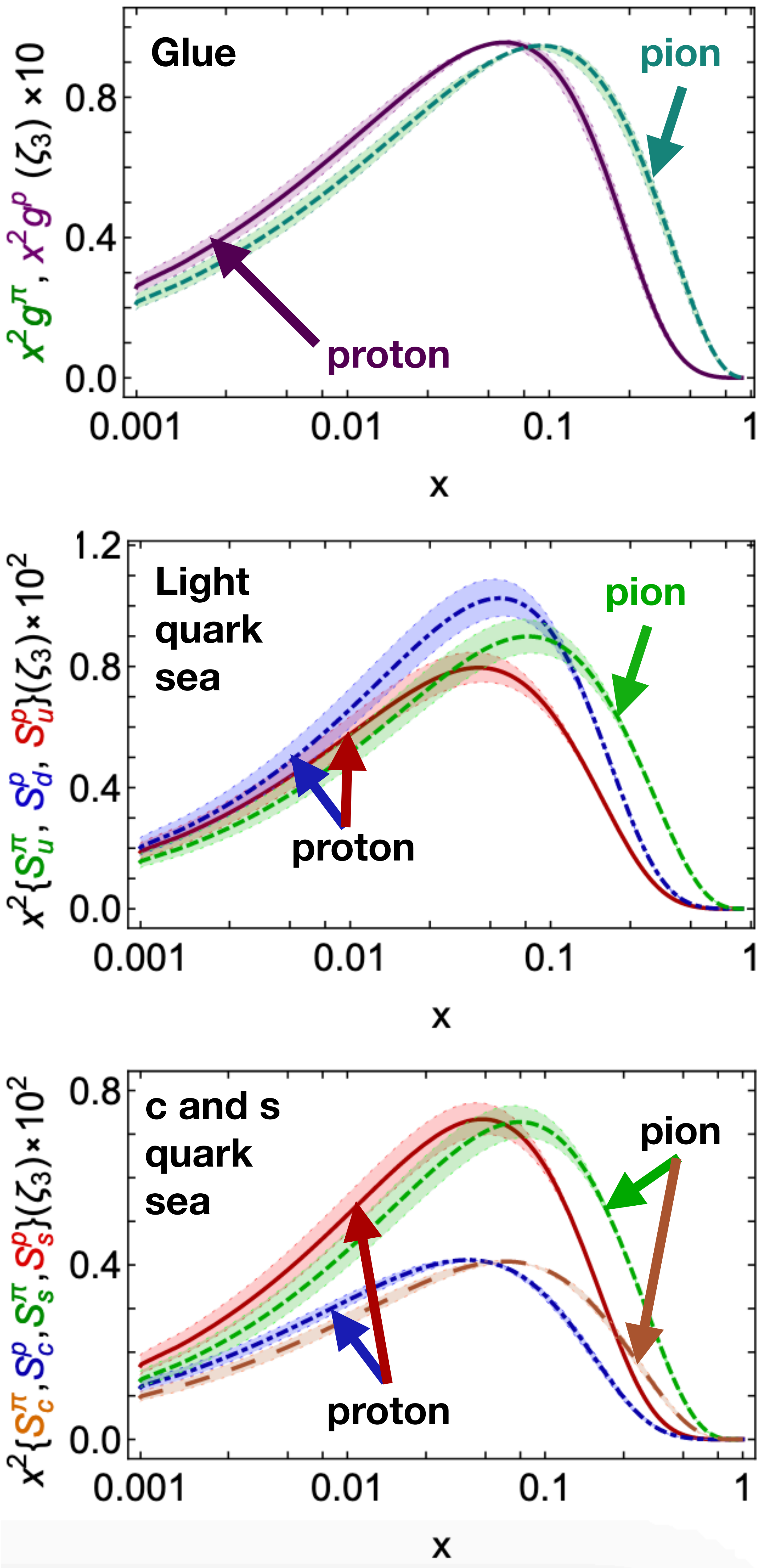


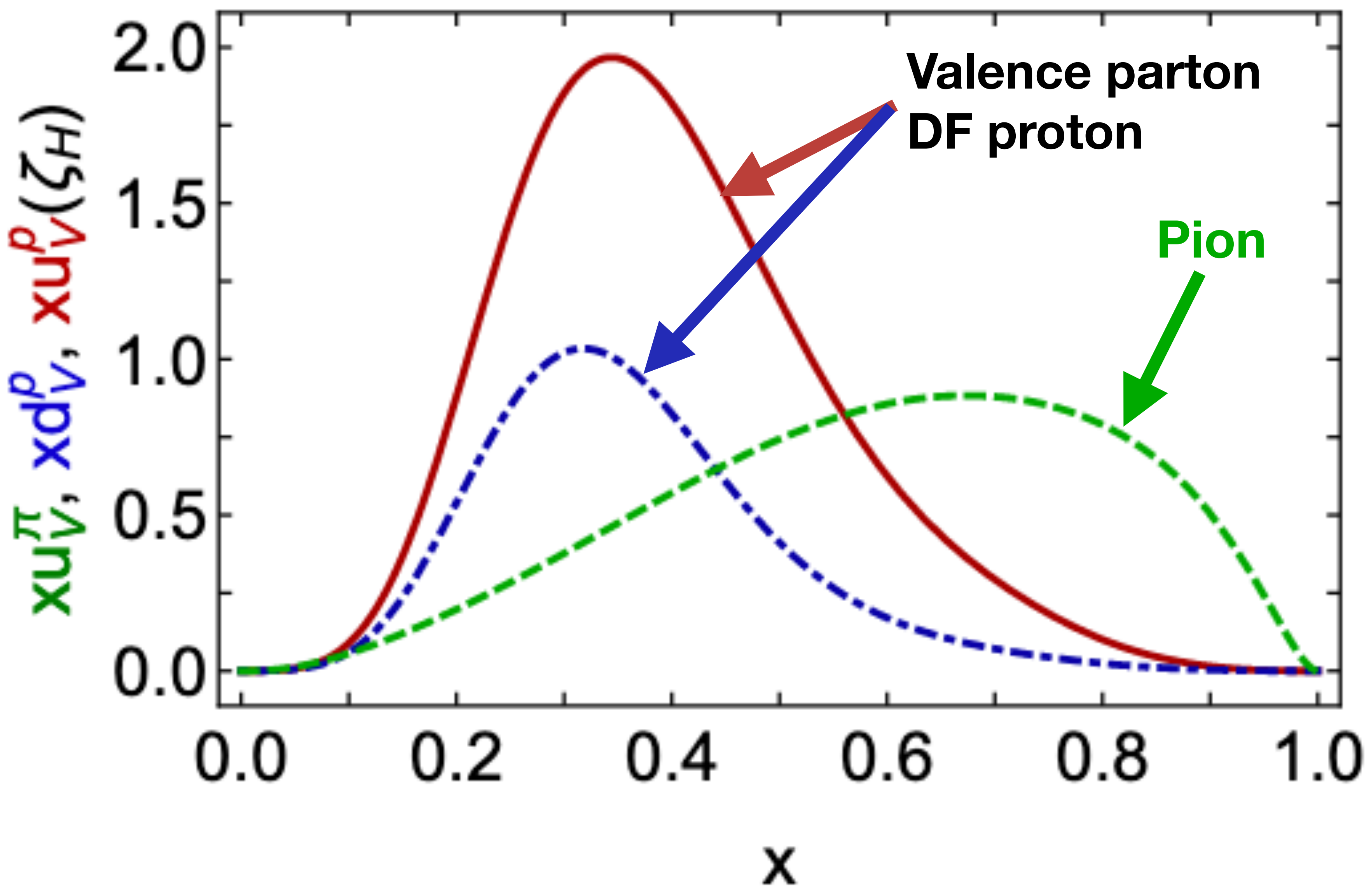
https://www.nobelprize.org/prizes/physics/2008/illustrated-information/

- Long list of motivations for studying π/K in nuclear physics…
- Dynamics of strong interactions in QCD ~99% nucleon mass
  - emergent hadronic mass (EHM)
- Unnaturally light π/K (Goldstone bosons) can offer unique insights into mass generation
- Comparing distributions of light quarks versus strange quarks within mesons
  - → measurable signals of EHM
- Substantial theoretical work…need data
- π/K structure not well known experimentally
- Interesting implications for PDFs

Pion vs Proton Valence PDF

From arxiv: 2203.00753 [hep-ph]





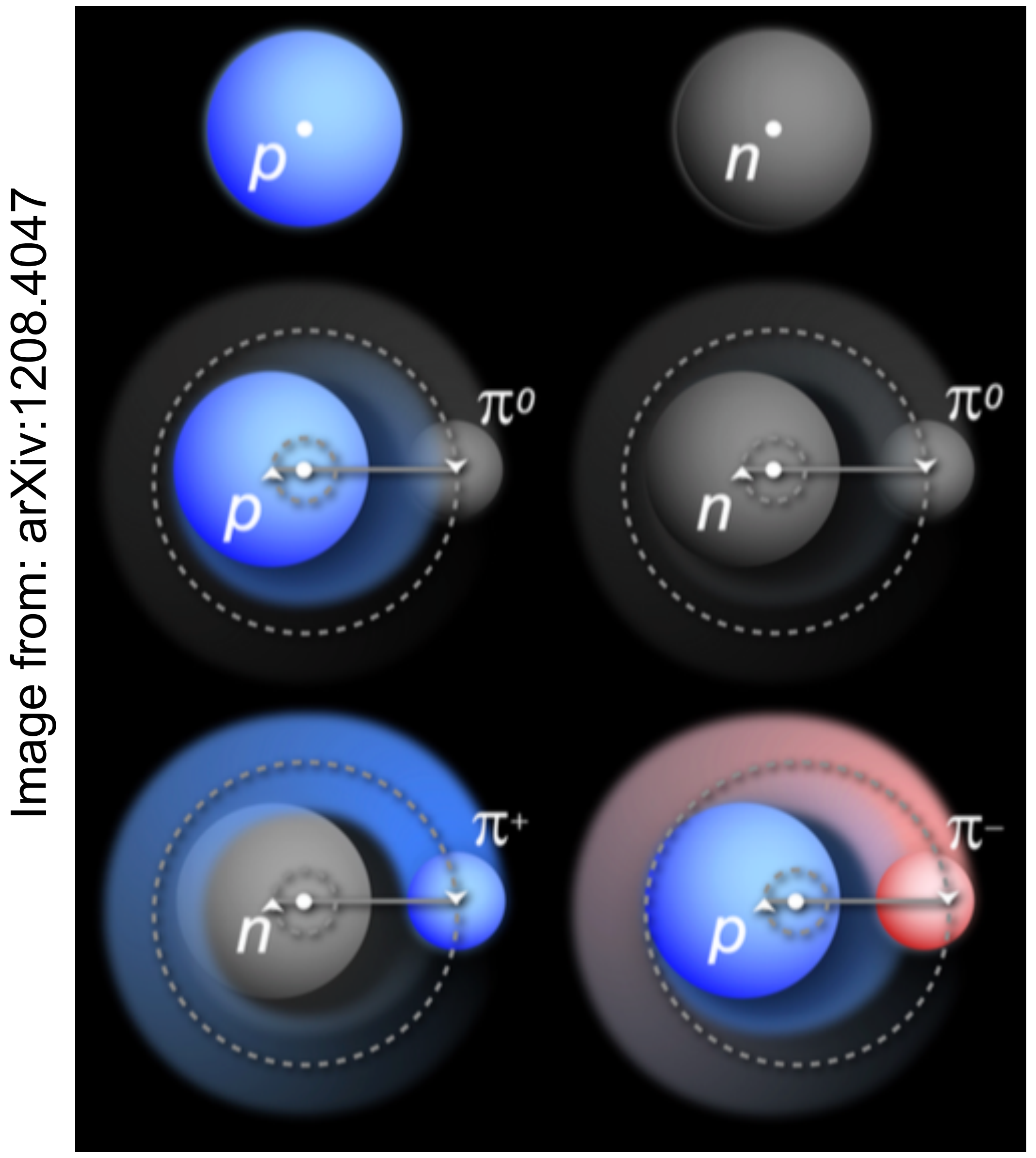
From C. Roberts (INP)

Continuum Schwinger function methods (DSE)

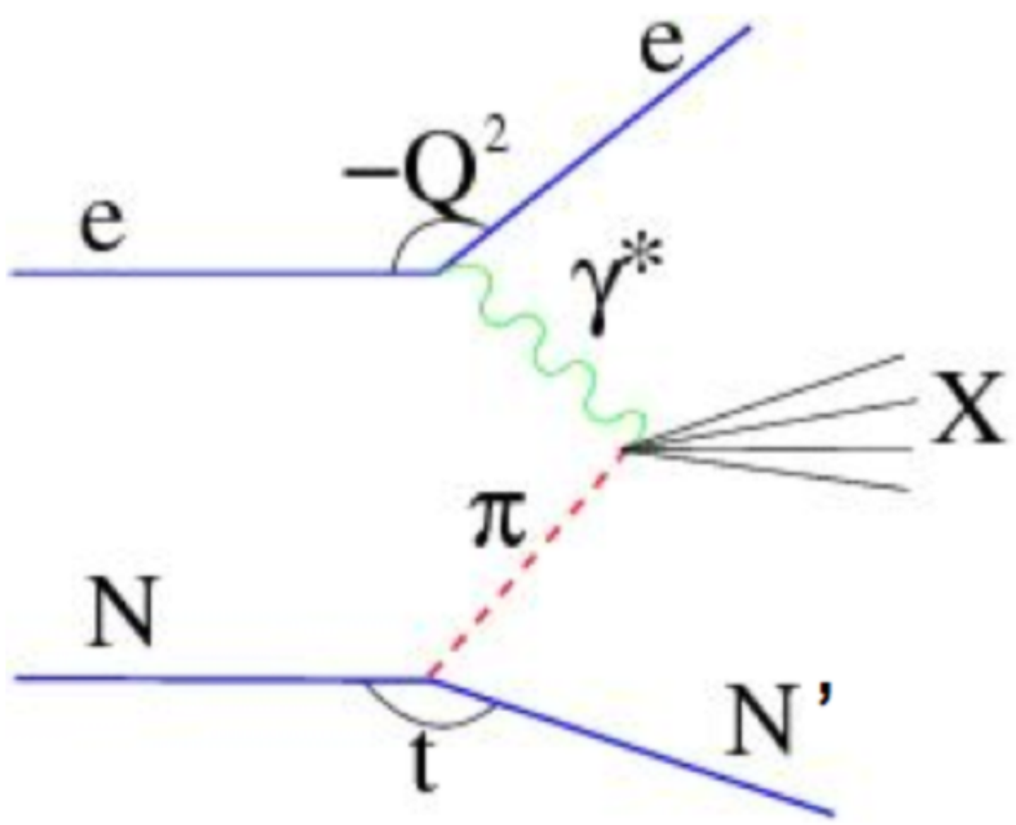
Ya Lu, Lei Chang, Khépani Raya, Craig Roberts, José Rodriguez-Quintero, 2203.00753 [hep-ph], Phys Lett B 830 (2022) 137130/1-7

- Marked difference between pion and proton valence PDF
- Differences translate into sea and glue DF
- “Much to be learnt before proton and pion structure understood in terms of DF… what is difference between distributions of partons within proton and pion?”

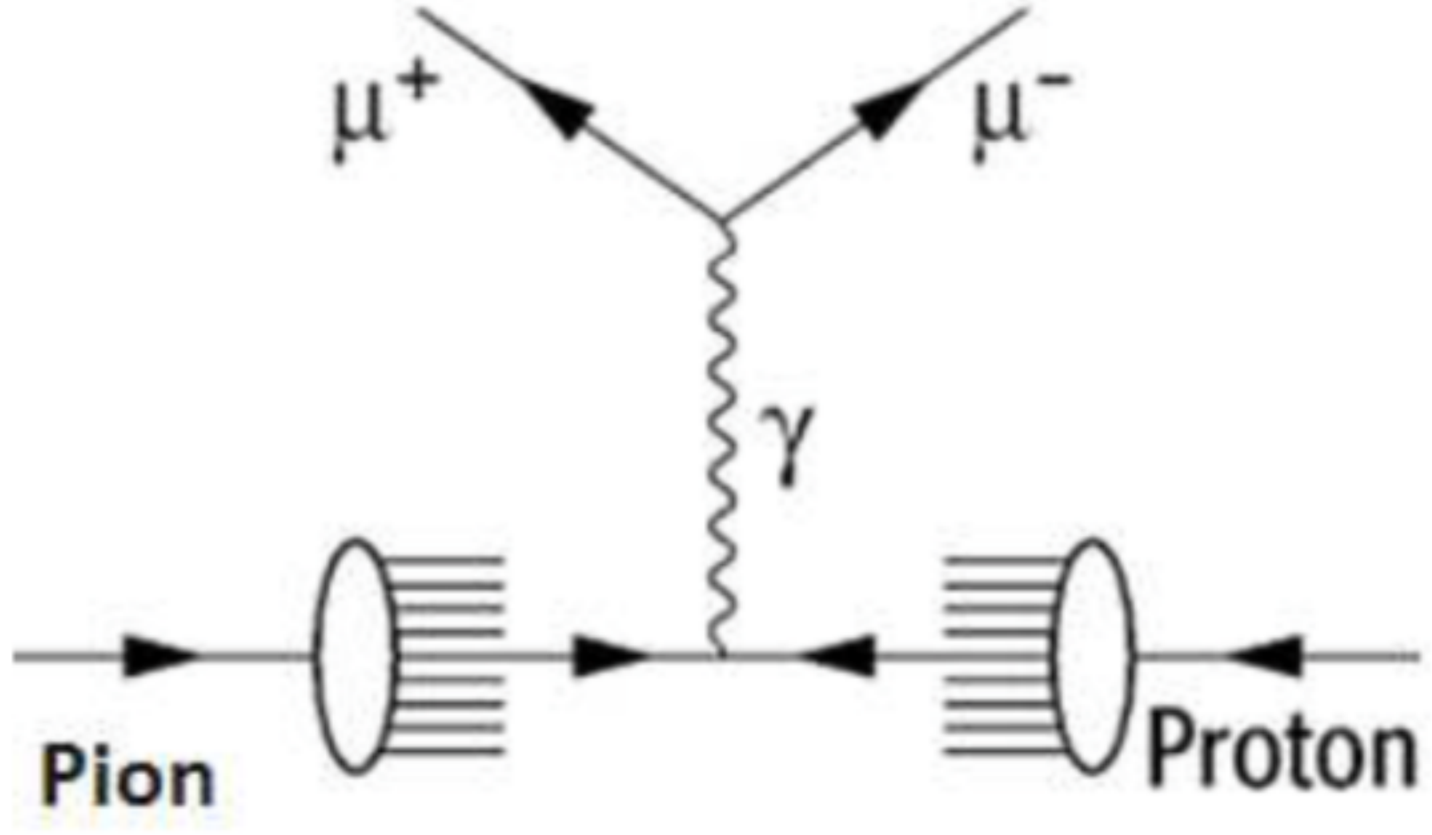
Sullivan Process



Hard scattering from virtual meson cloud of nucleon



Drell-Yan



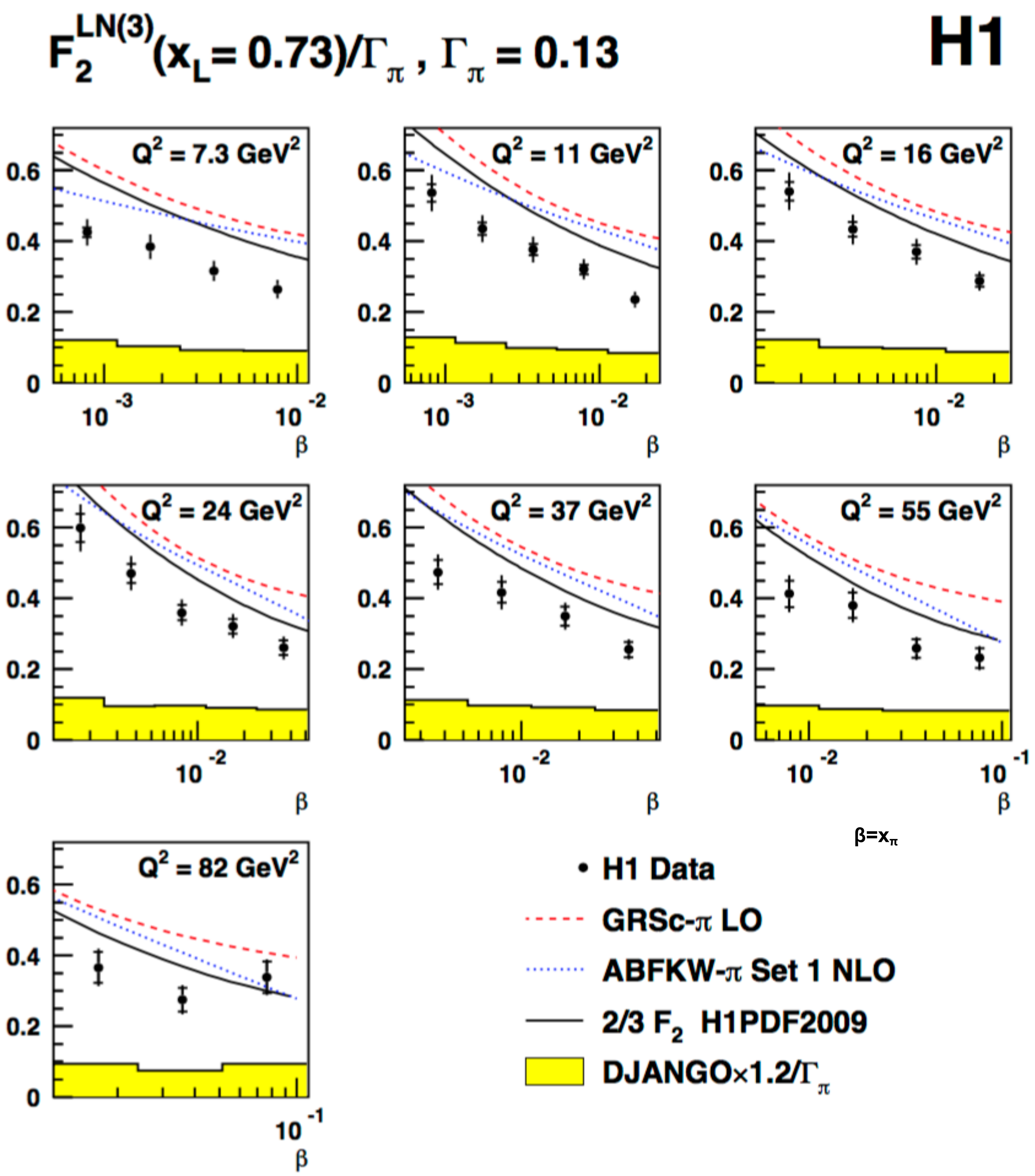
- Upcoming JLab TDIS experiment
  - DIS with spectator tagging
  - Directly tag mesonic content of nucleon
- Aims:
  - Pion and kaon F_2 in valence regime

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2{}_0 \sin^4\frac{\theta}{2}} \cos^2\frac{\theta}{2}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\frac{\theta}{2}\right]$$

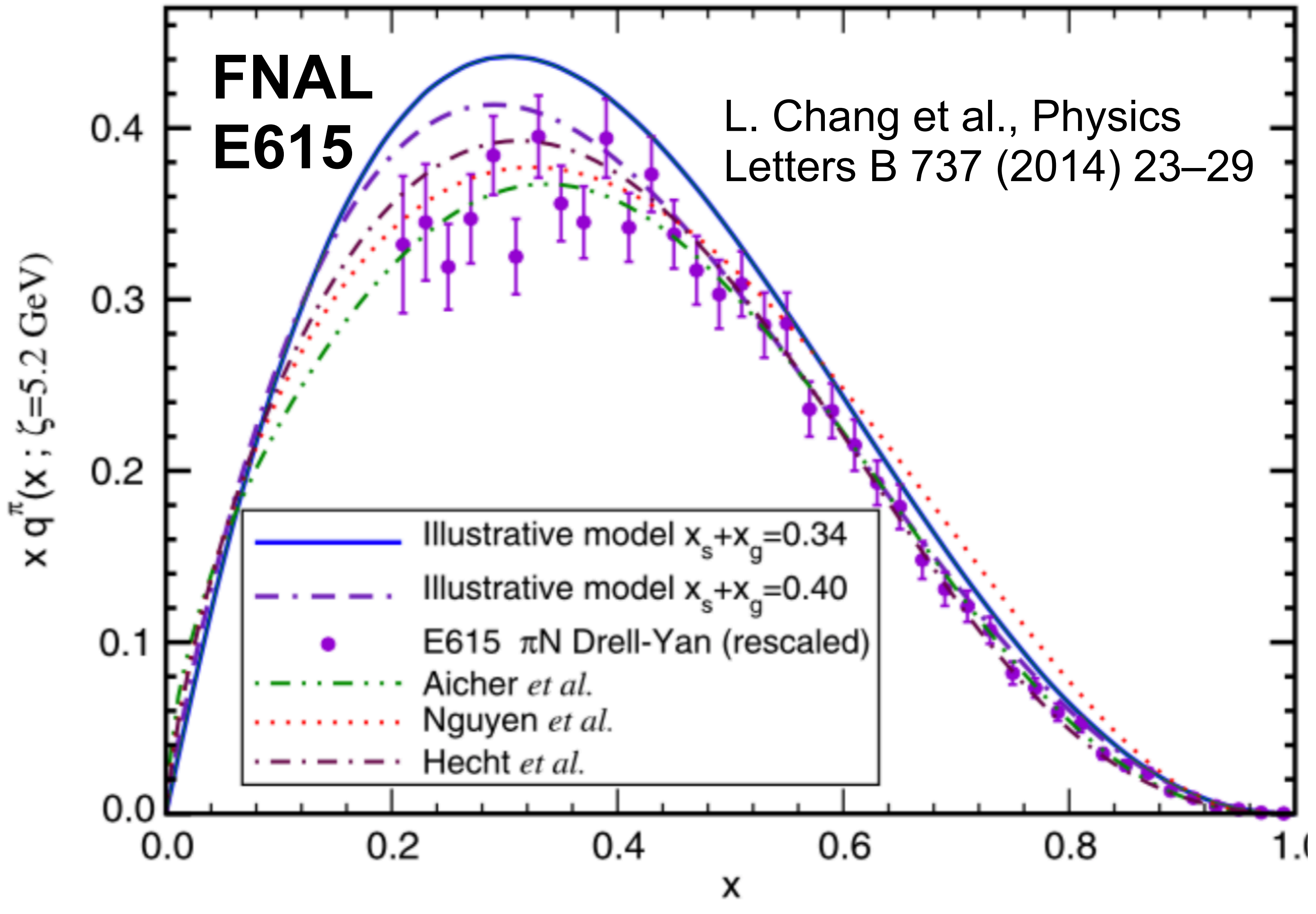
- F_1, F_2 structure functions (SF)
- SF → input for parton distribution functions

Example Previous Data

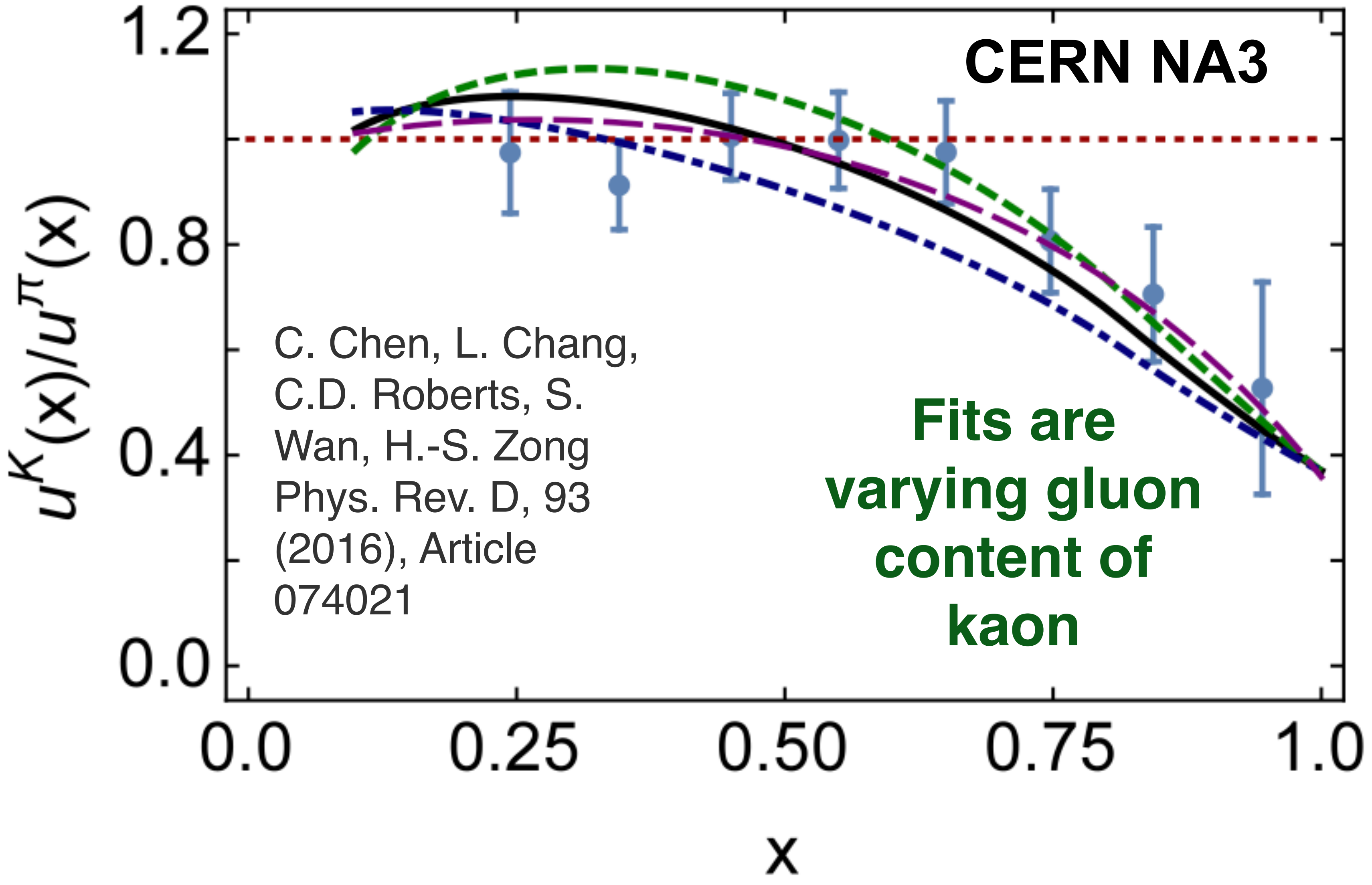
Eur. Phys. J. C (2010) 68: 381-399



Pion valence quark distribution function



Ratio K/pi u-quark distributions



<u>Sullivan Process at HERA:</u>

•Leading neutron tagged in ep → eXN

•6 < Q^2 < 100GeV^2; 1.5e^{-4} < x < 3.0e^{-2}

JLab TDIS:

- Higher x, lower Q^2
- Study evolution

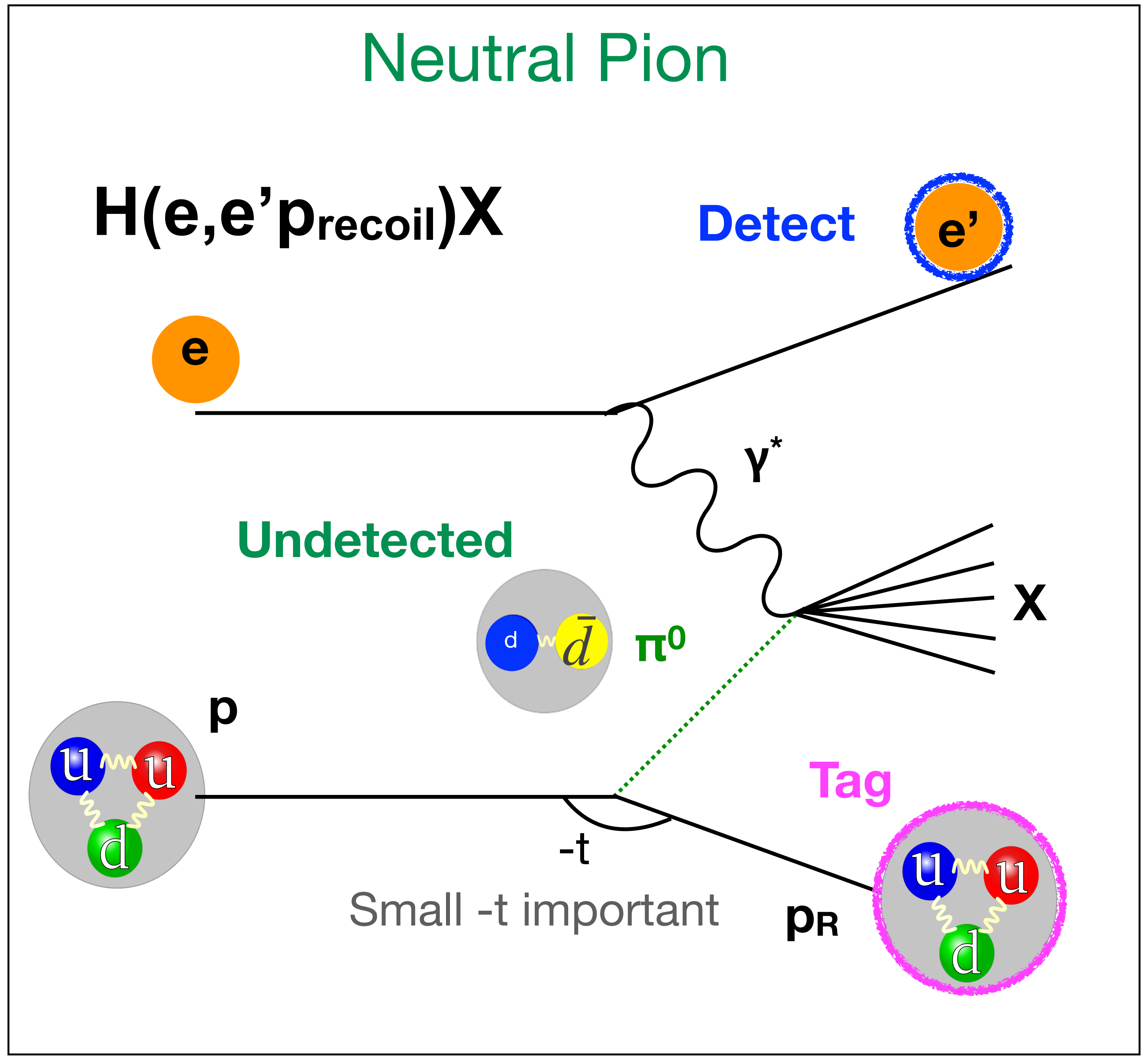
<u>Valence region - DY at CERN and FNAL:</u>

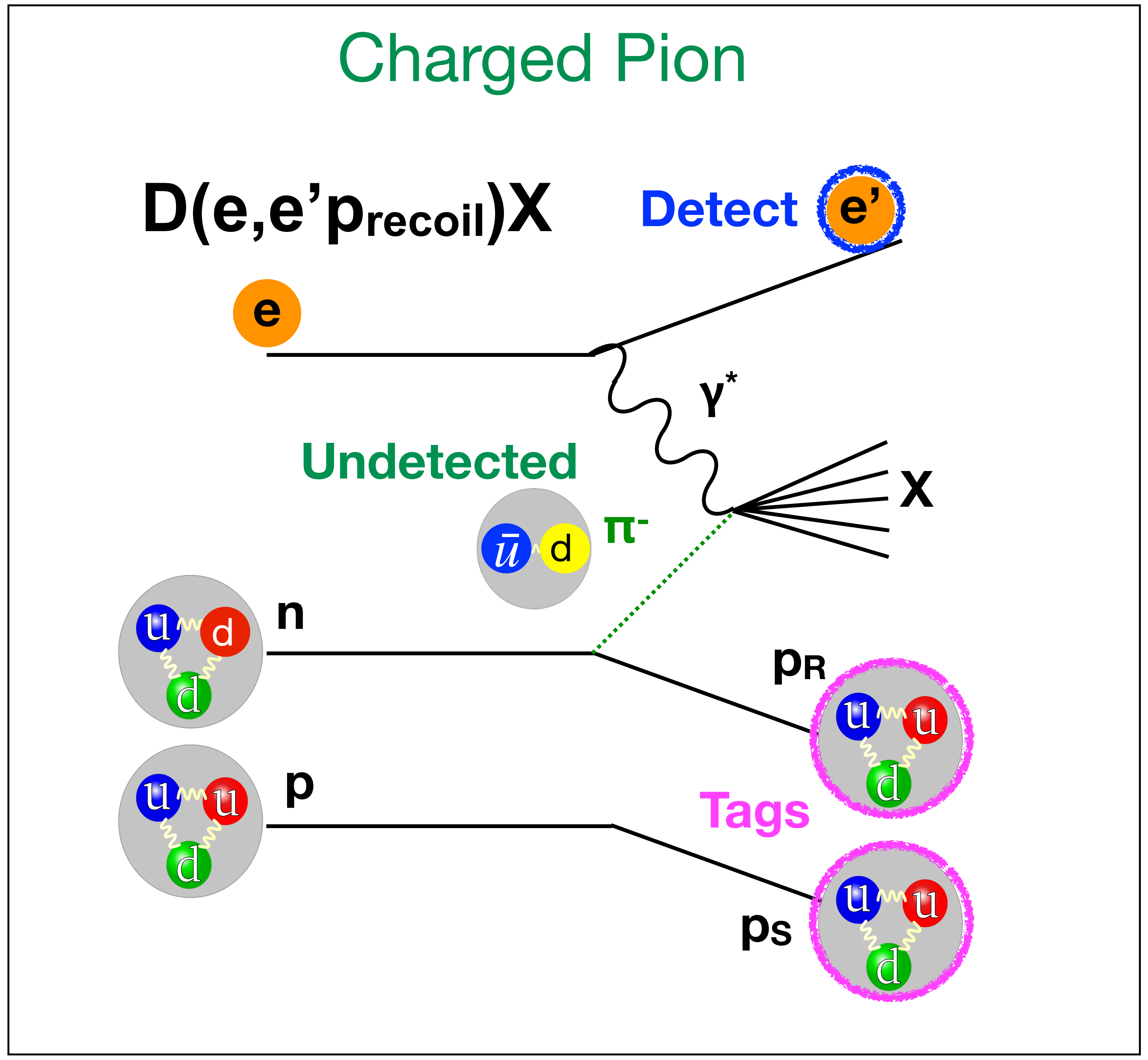
- Large-x interesting - substantial theory, pQCD, DSE, light-front, …
- More data needed to reduce uncertainties in global PDF fits
- DY data coming from AMBER at CERN - complementarity

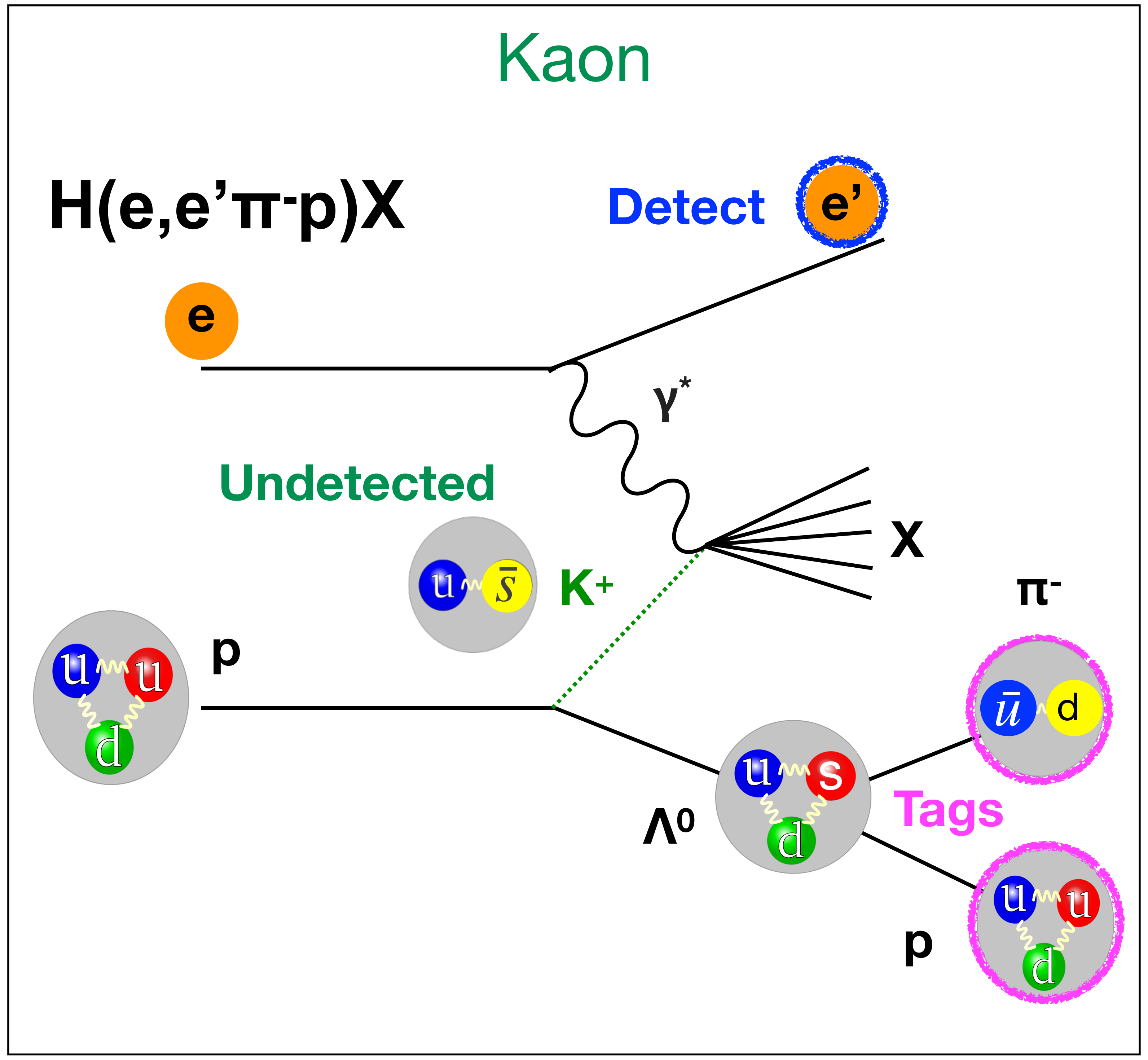
JLab TDIS:

- Test universality
- Extend to neutral pions and improve kaon situation

TDIS Measurements







$8 < W^2 < 18$ GeV^2
$1 < Q^2 < 3$ GeV^2
$0.05 < x < 0.2$

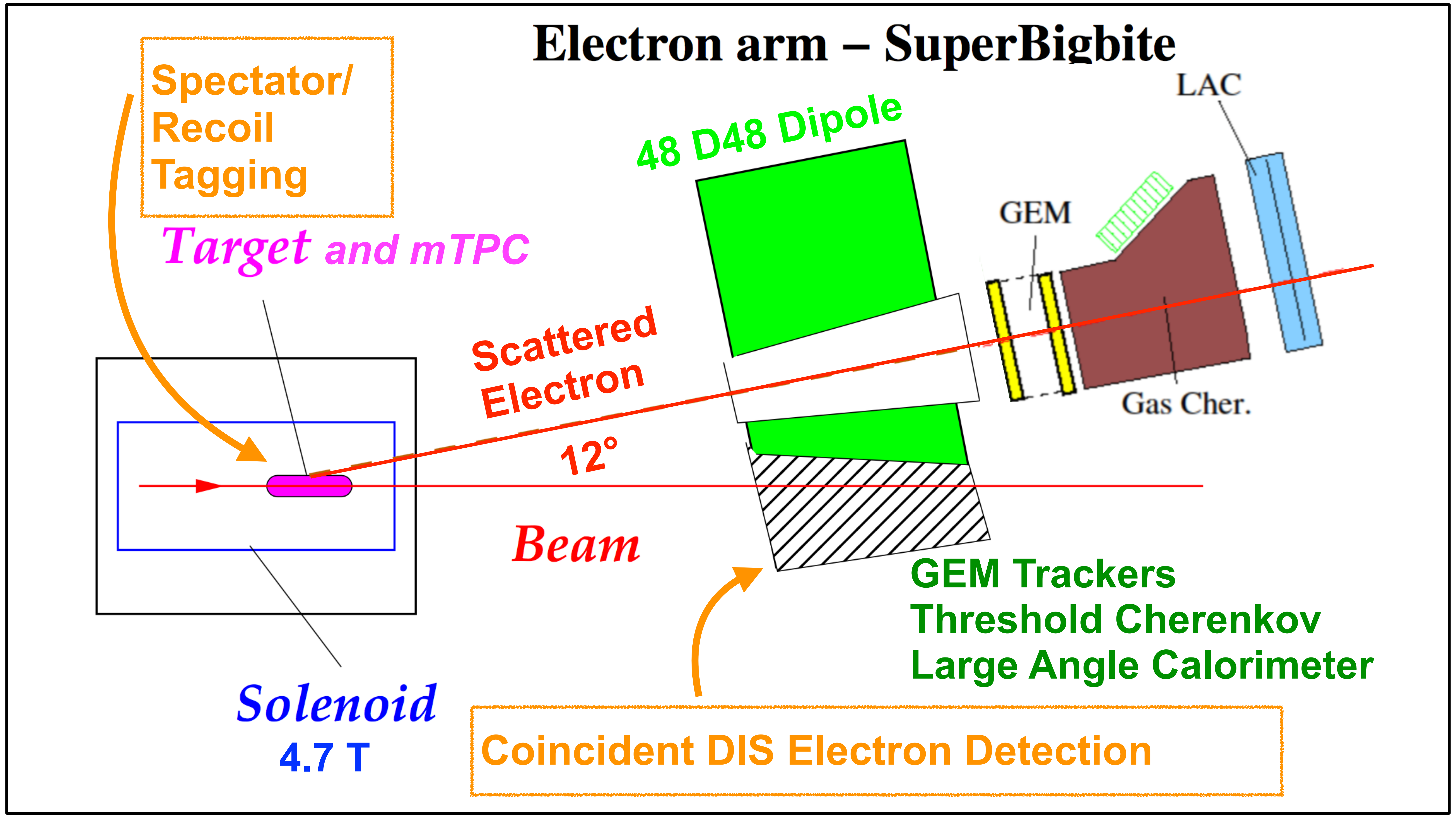
- Ratio of tagged to total inclusive cross-sections
- Tagged signal orders of magnitude smaller → need high luminosity

$$R^T = \frac{d^4\sigma(ep \to e'Xp')}{dxdQ^2dzdt} \Big/ \frac{d^2\sigma(ep \to e'X)}{dxdQ^2} \Delta z \Delta t \sim \frac{F_2^T(x,Q^2,z,t)}{F_2^p(x,Q^2)} \Delta z \Delta t$$

TDIS Measurements

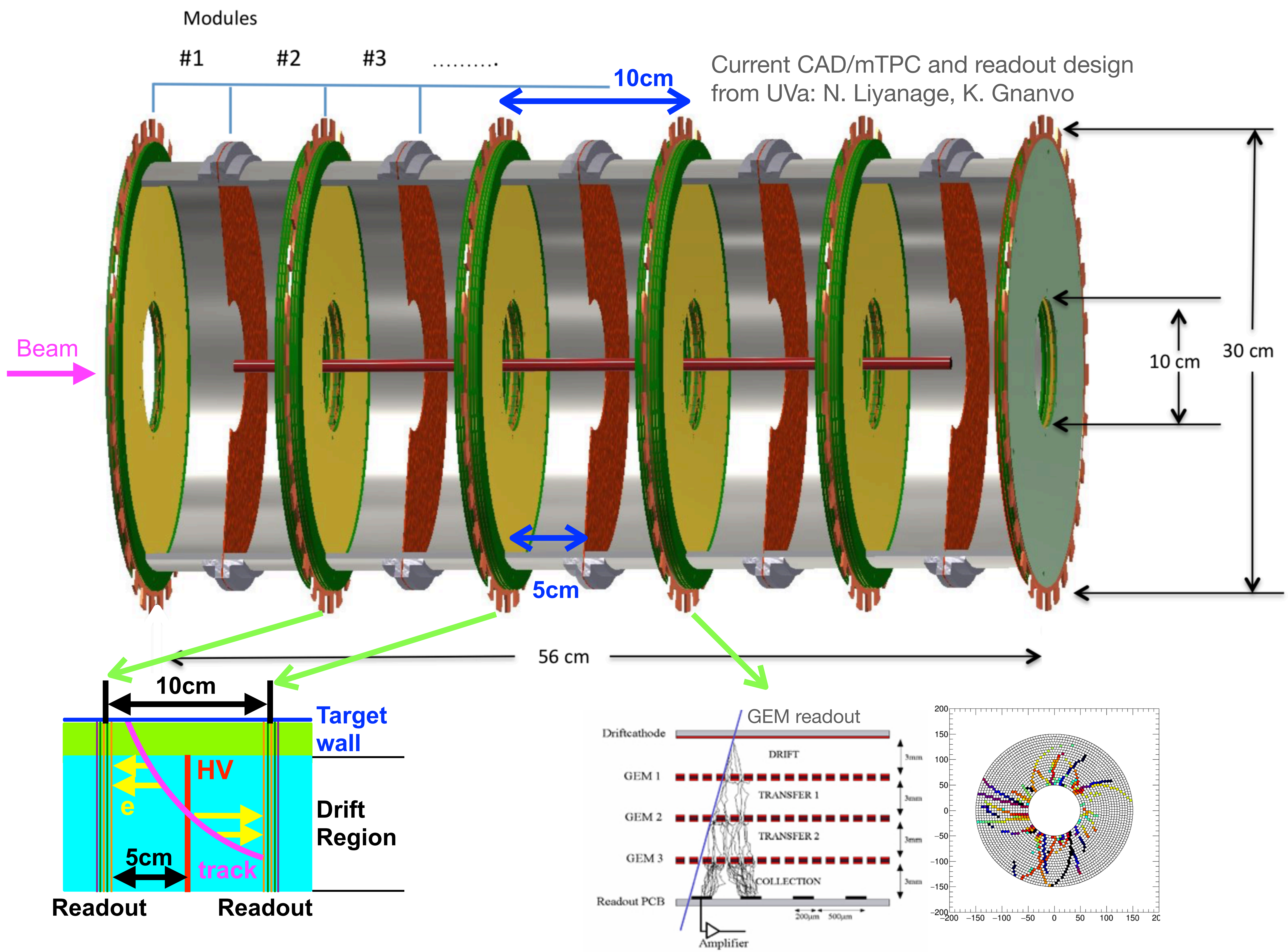
JLab high current Halls (A andC) operating at luminosity frontier

Ideal for rare TDIS process



- 50μA 11 GeV e^- and high density H/D targets
  - high luminosity 2.9 x 10^{36} $cm^{-2}s^{-1}$
- e' in reconfigured Super Bigbite Spectrometer
  - Configurable spectrometer
  - Electron PID and (L2) trigger, tracking and π rejection (~10^{-4})
- Multiple time projection chamber (mTPC) for tagging

High Rate mTPC



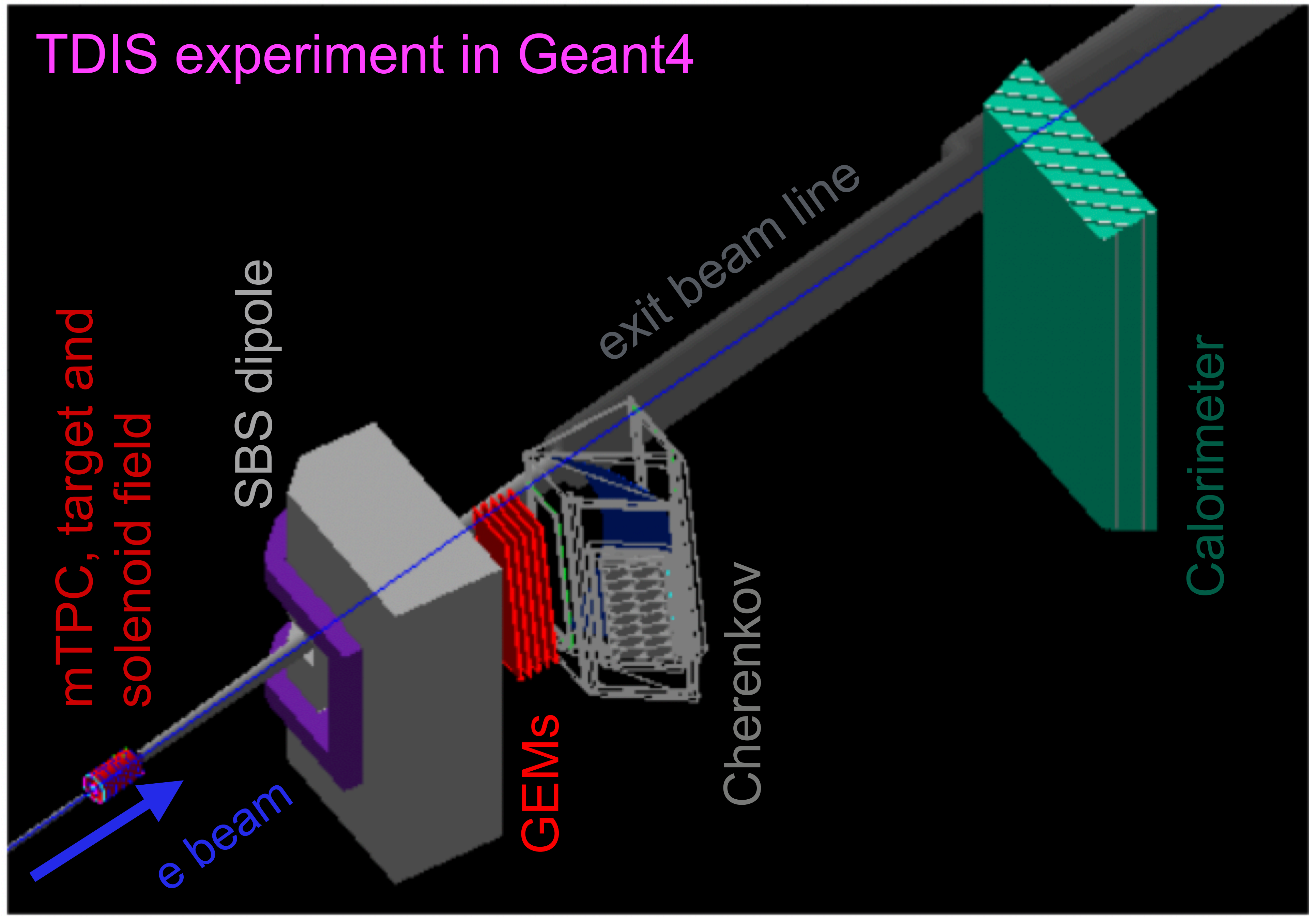
- Division into sub-chambers
- Reduces background rates

- TPC: filled with low density gas at STP

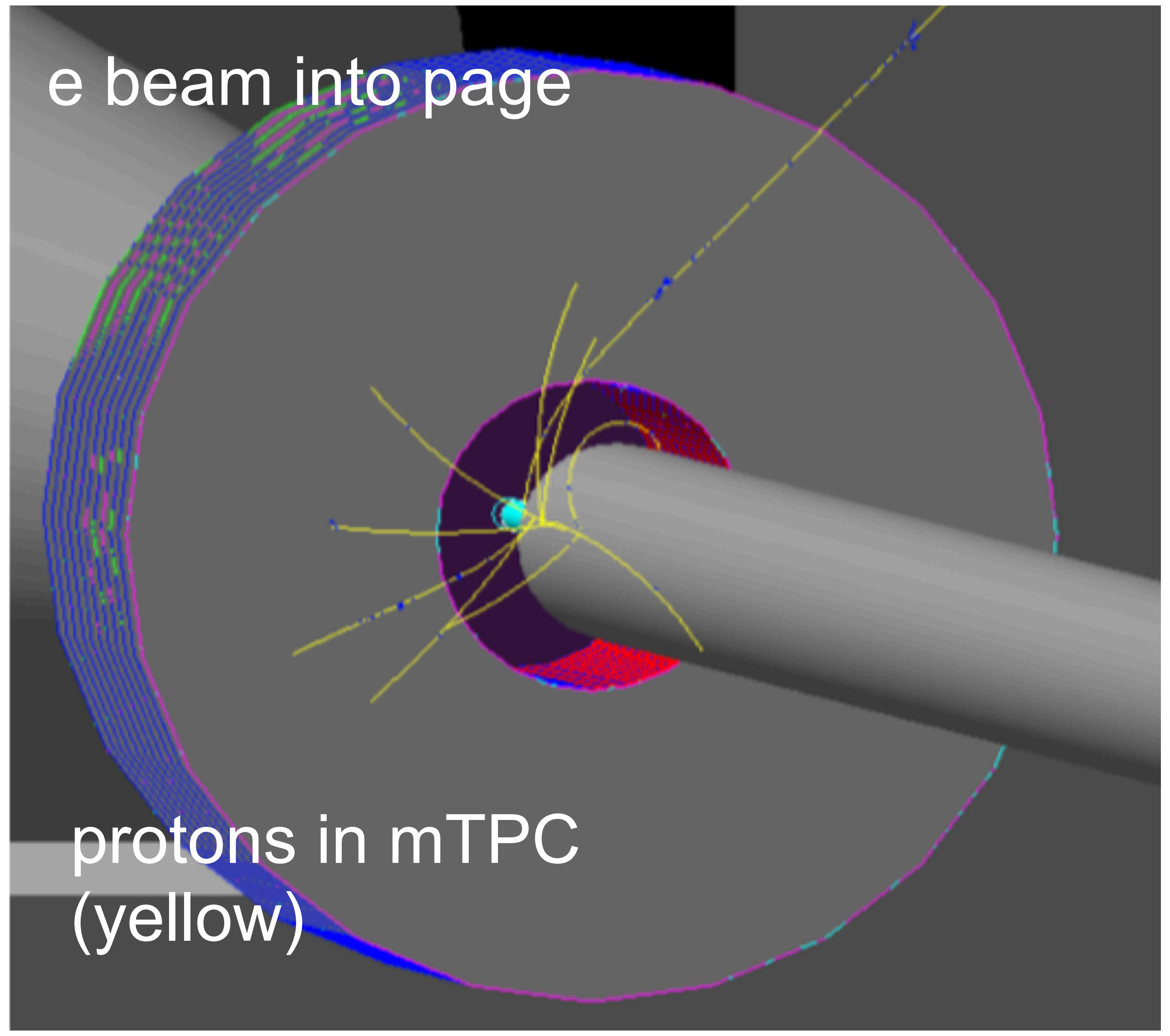
- Readout planes
  - Multi layer GEM foils
  - Segmented readout pads

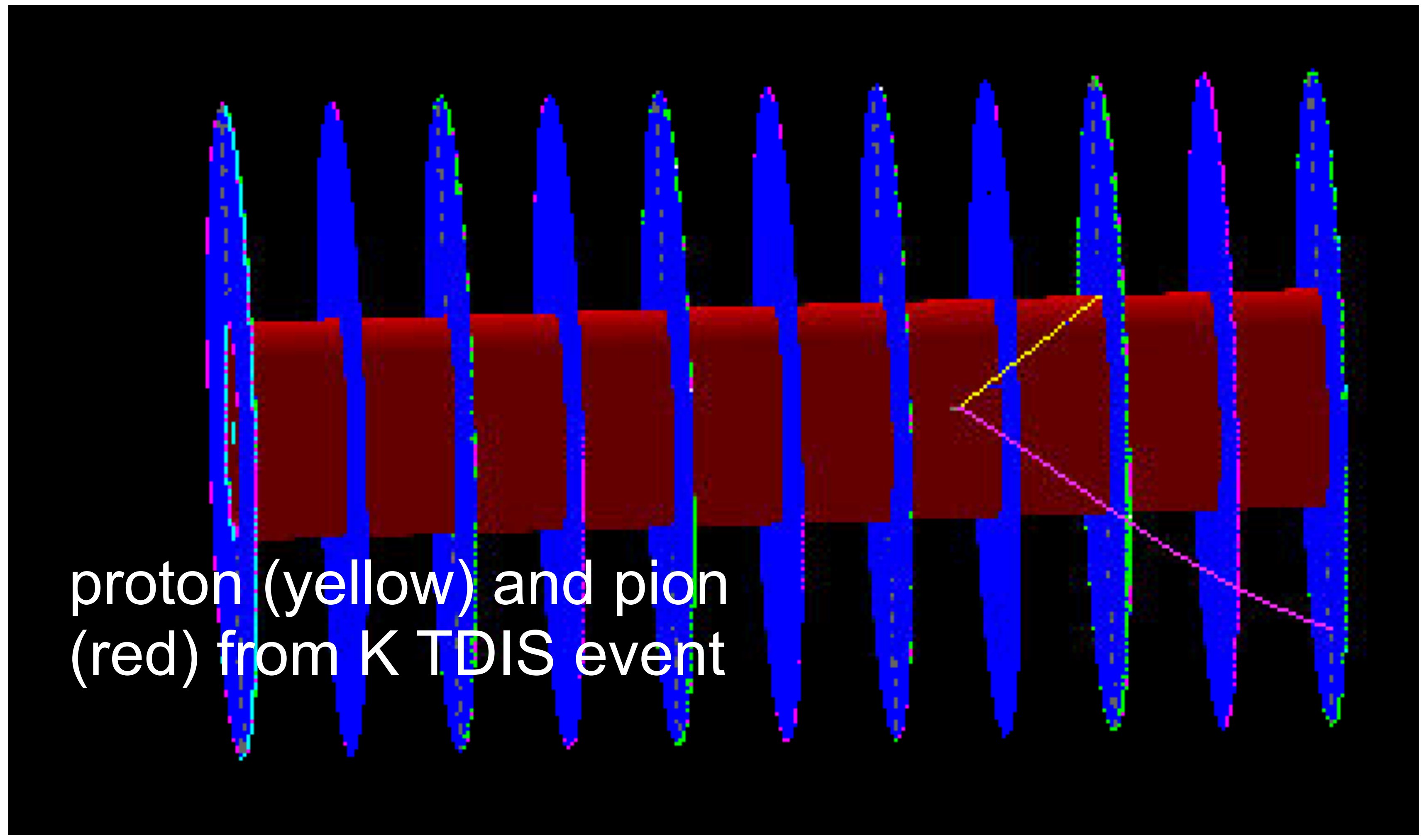
- Tag recoils/spectators (60 - 400MeV/c)
  - Vertex and tracking
  - Momentum reconstruction (solenoid)
  - PID by dE/dx

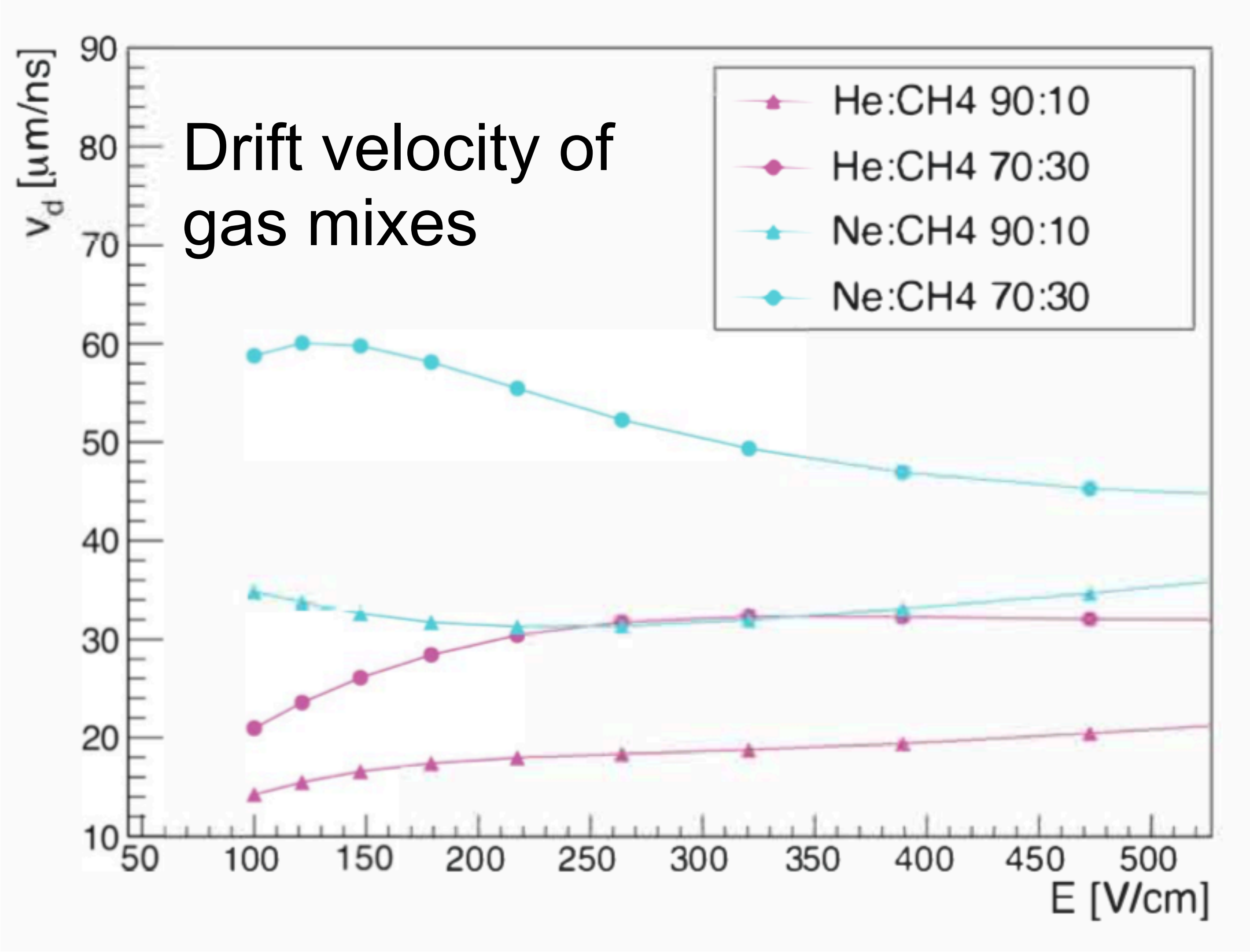
Simulation



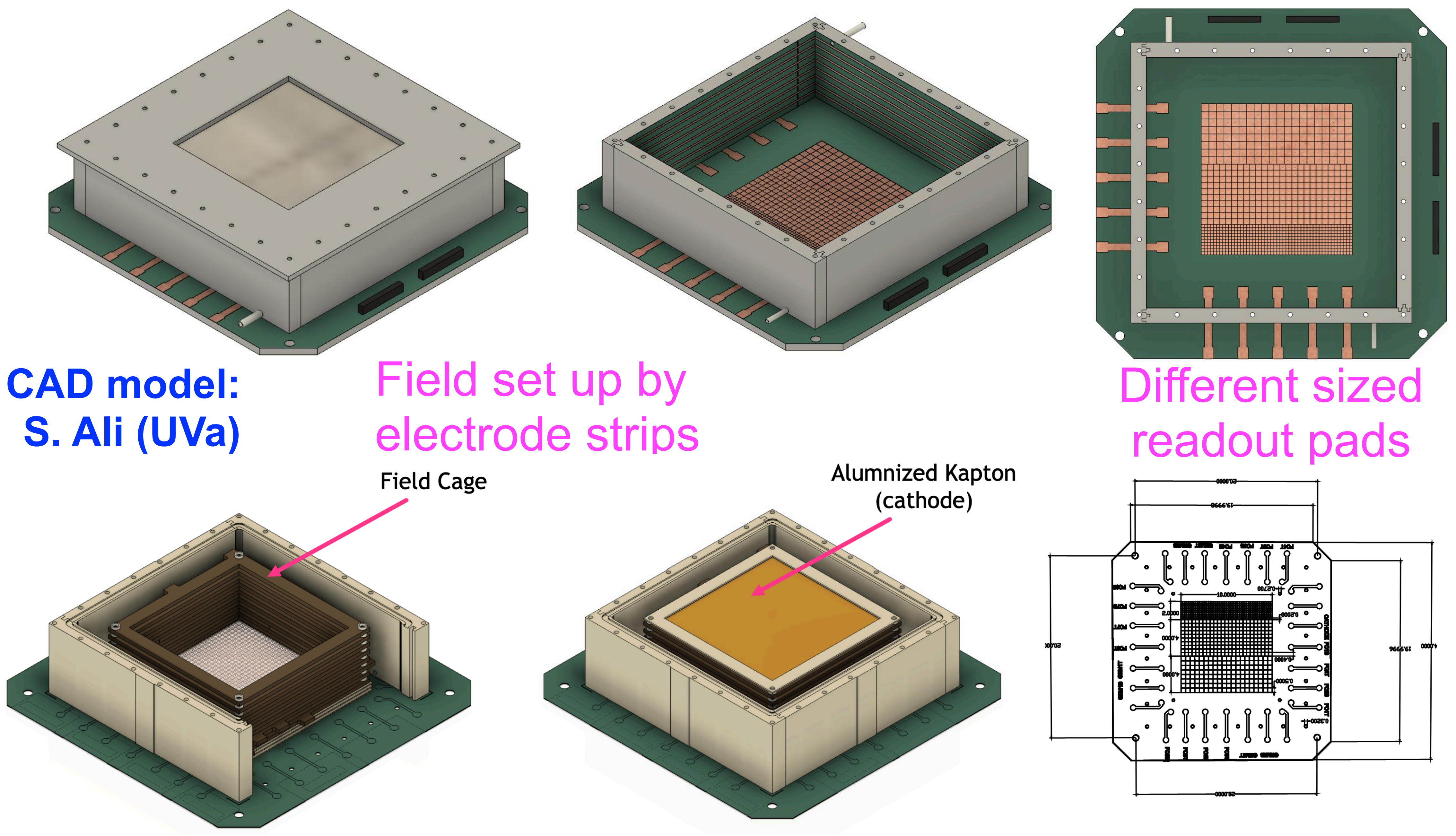
- In-depths studies within SBS collaboration's Geant4 framework
  - *Team* of contributors (e.g. C. Ayerbe, E. Fuchey, S. Wood, A. Tadepalli, D. Dutta, R. Montgomery, A. Puckett, M. Carmingotto…and more!)
- mTPC also simulated using CERN's magboltz/garfield
  - Gas mixtures; electric field…
- Updates to background/accidentals rate studies ongoing
- Tracking developments ongoing, especially for D target case







mTPC Prototyping

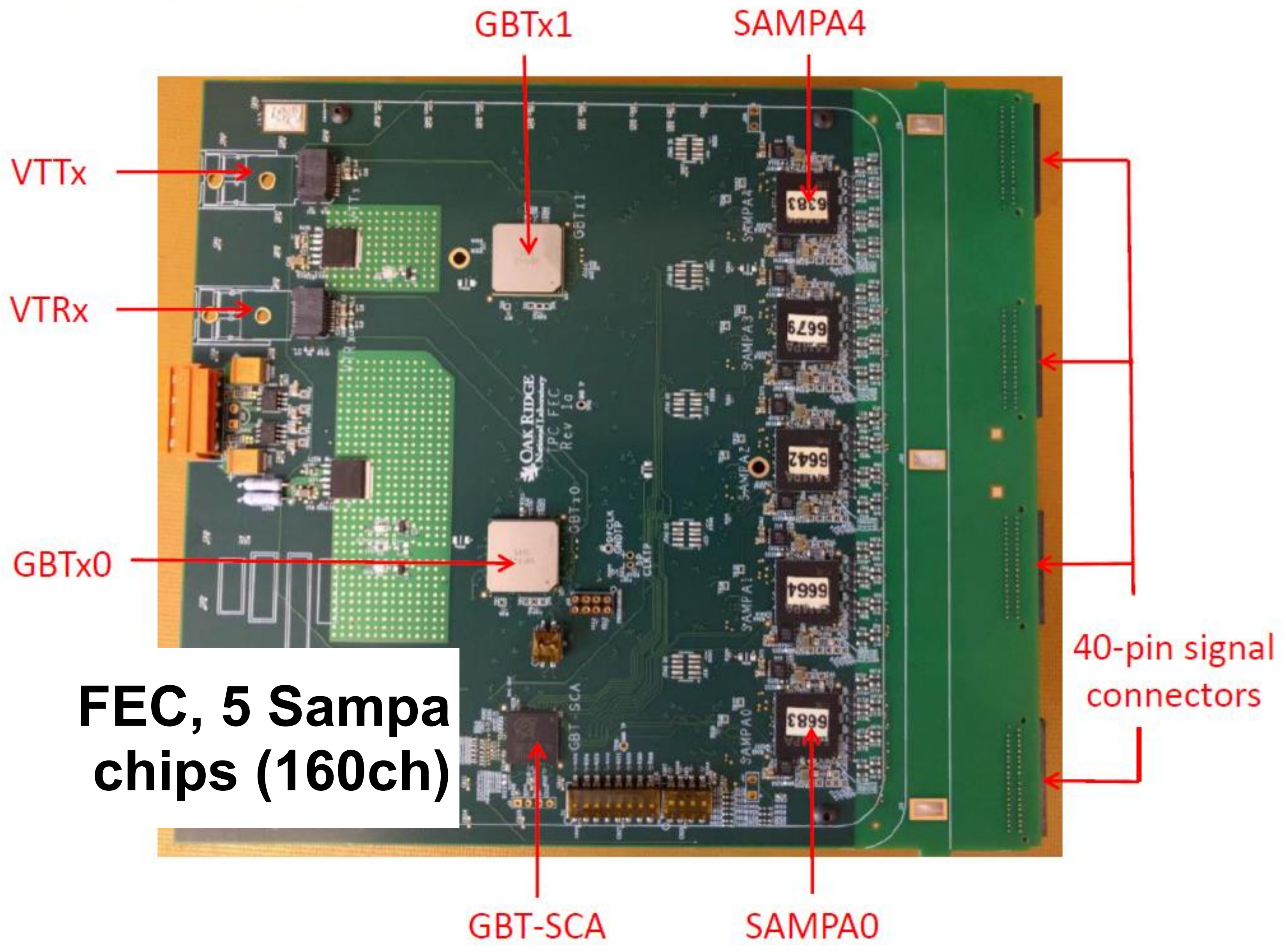


- University of Virginia recently completed 1st prototype
  - (N. Liyanage, H. Nguyen, S. Ali)
  - 10 x 10 cm^2 active area
  - Entrance window → cathode → 4.7cm drift in field cage → triple GEM foils (2mm between foils) → segmented anode PCB → Panasonic connectors/readout
- JLab/MSU (E. Christy, C. Cuevas, A. Nadeeshani, D. Dutta) preparing HV divider and readout

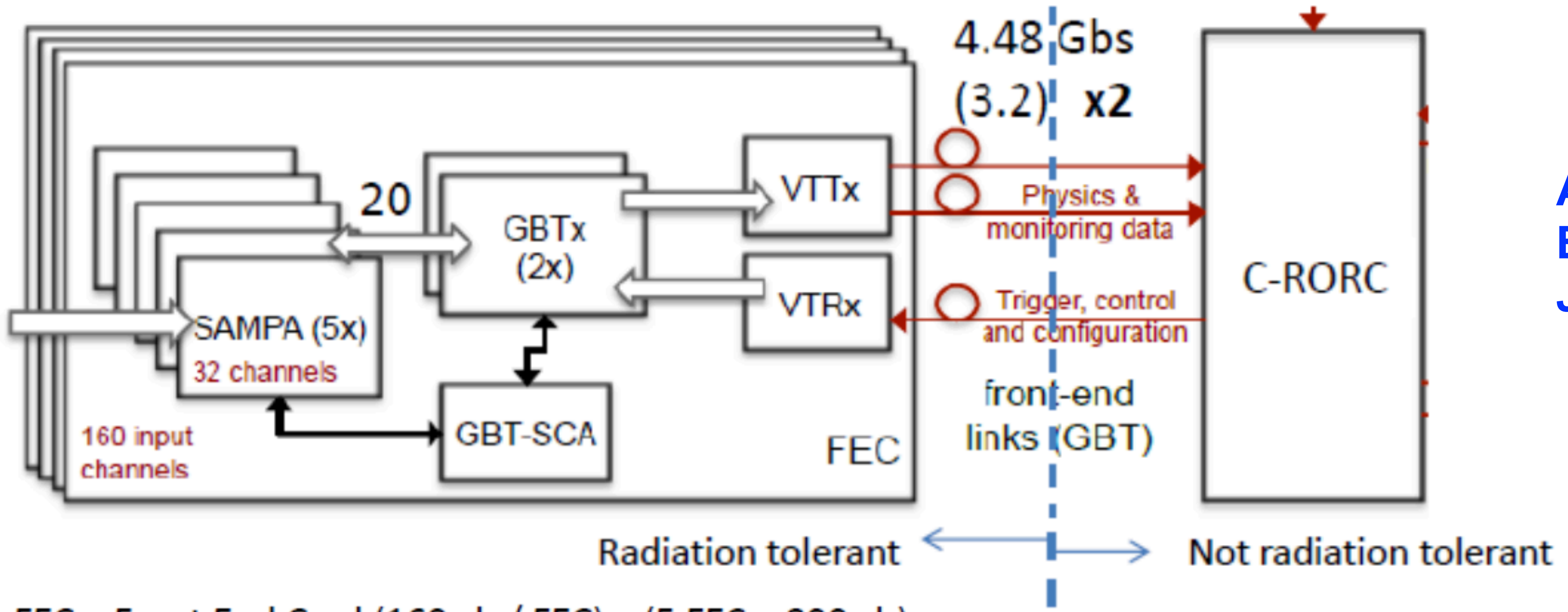
- Expect start of tests at JLab imminently

Construction images courtesy of Aruni Nadeeshani (MSU), Huang Nguyen (UVa)

Triggerless Readout at JLab



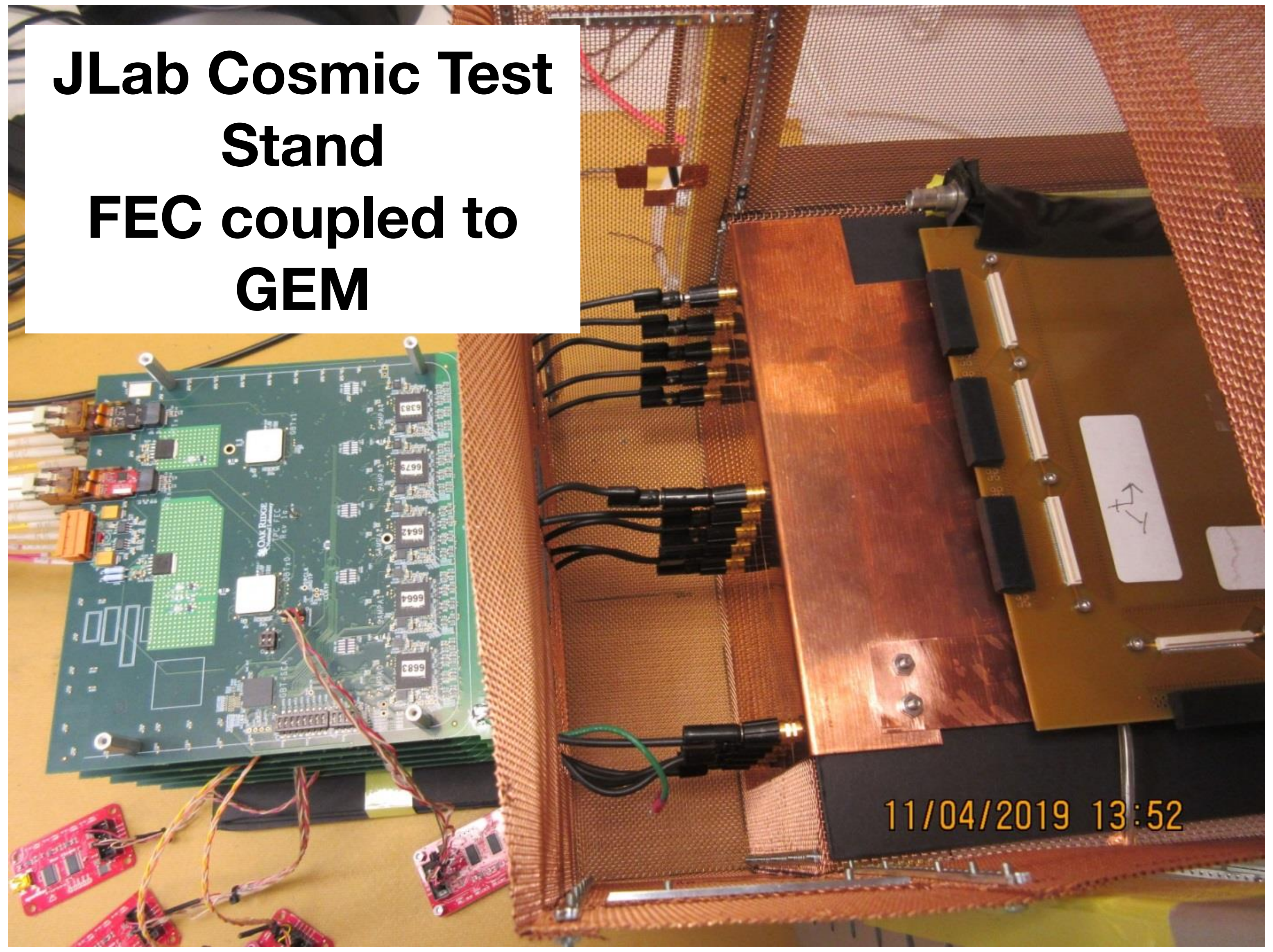
FEC, 5 Sampa chips (160ch)



FEC – Front End Card (160 ch / FEC) (5 FEC = 800 ch)
C-RORC – Common Read Out Receiver Card (PCIe)
GBTx – Giga Bit Transceivers
GBT-SCA – GBTx Slow Controls Adapter
VTTx, VTRx – Fiber optic transceivers

All pics:
E. Jastrzembski
JLab

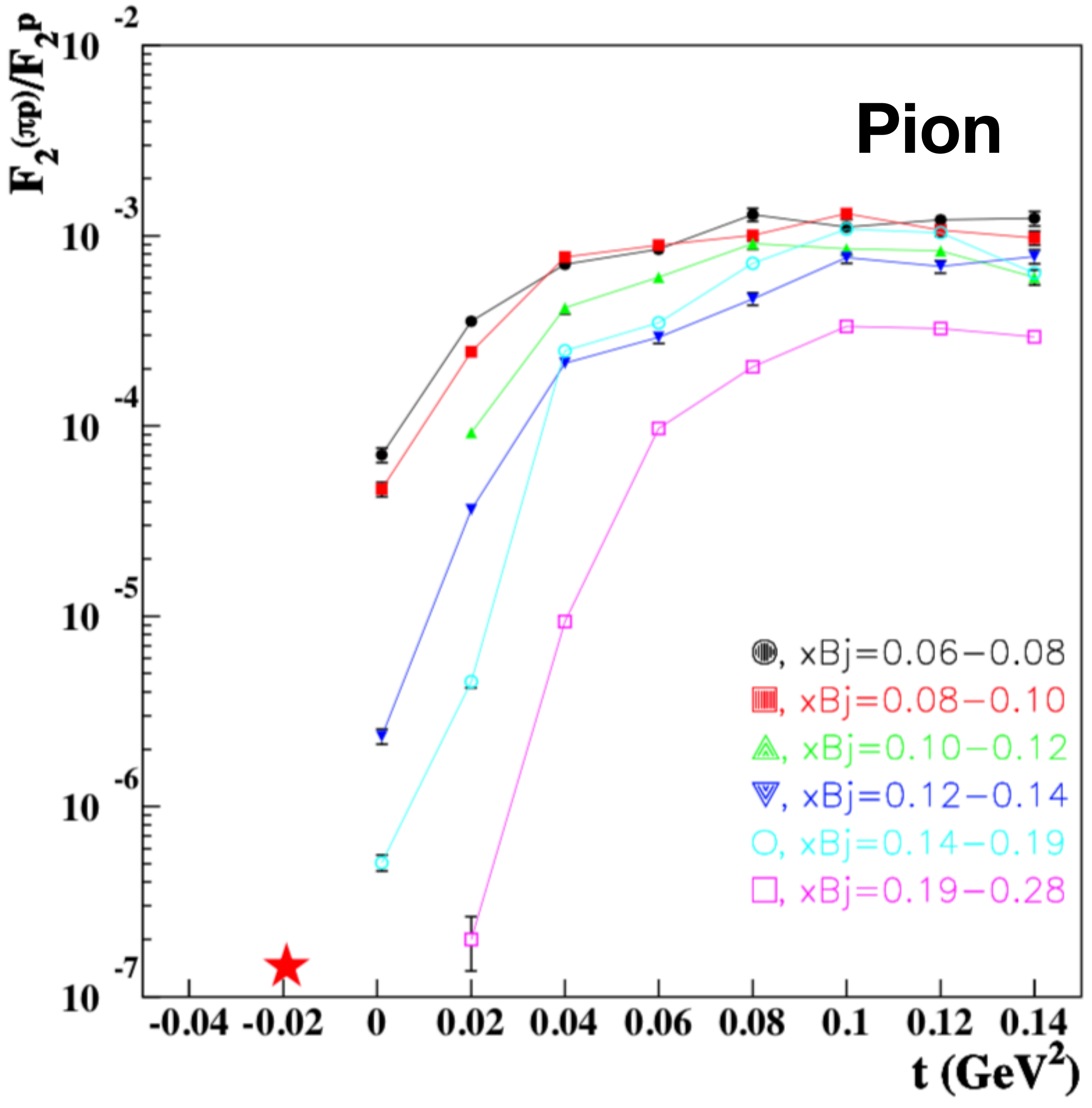
JLab Cosmic Test Stand
FEC coupled to GEM

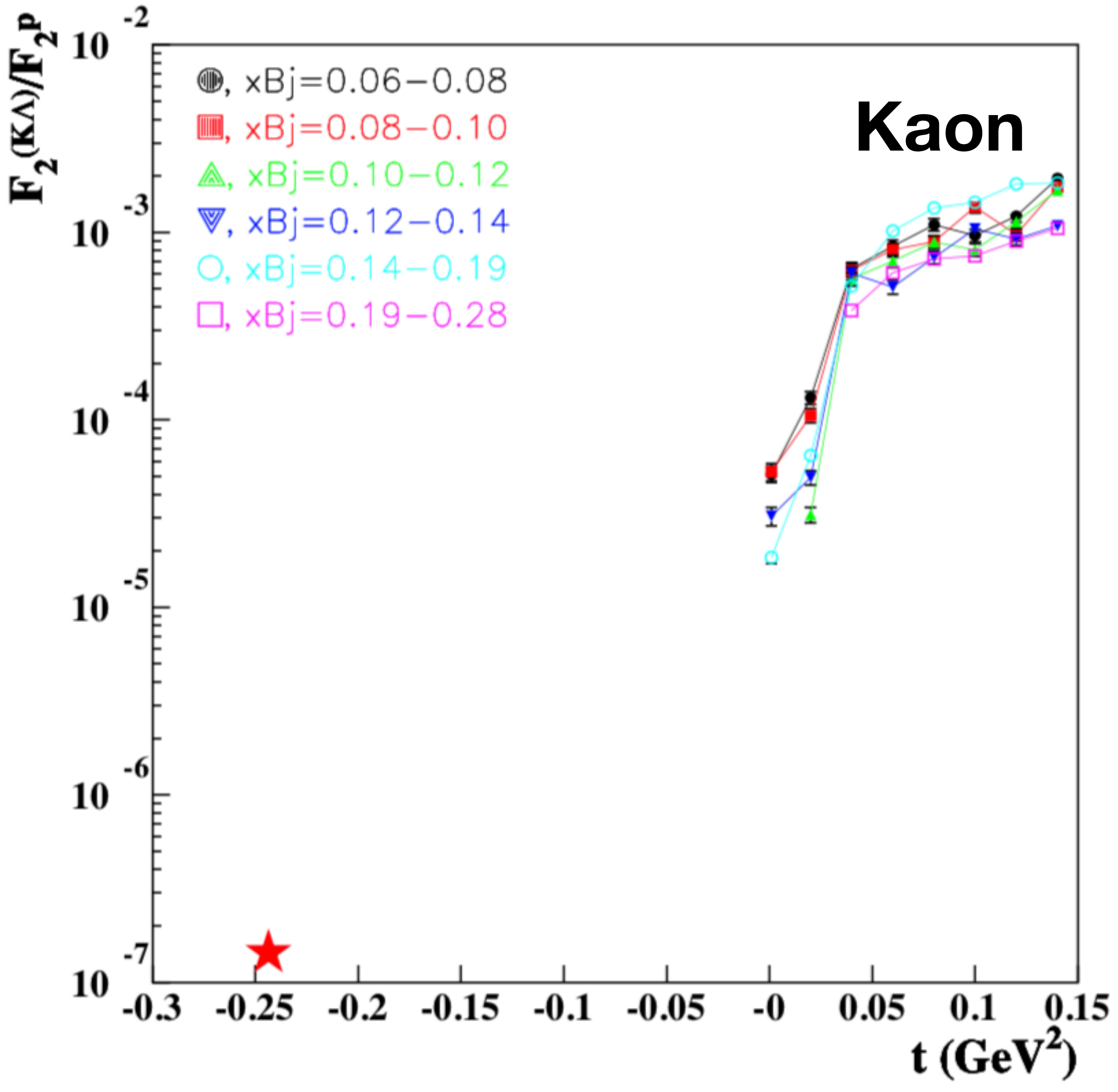


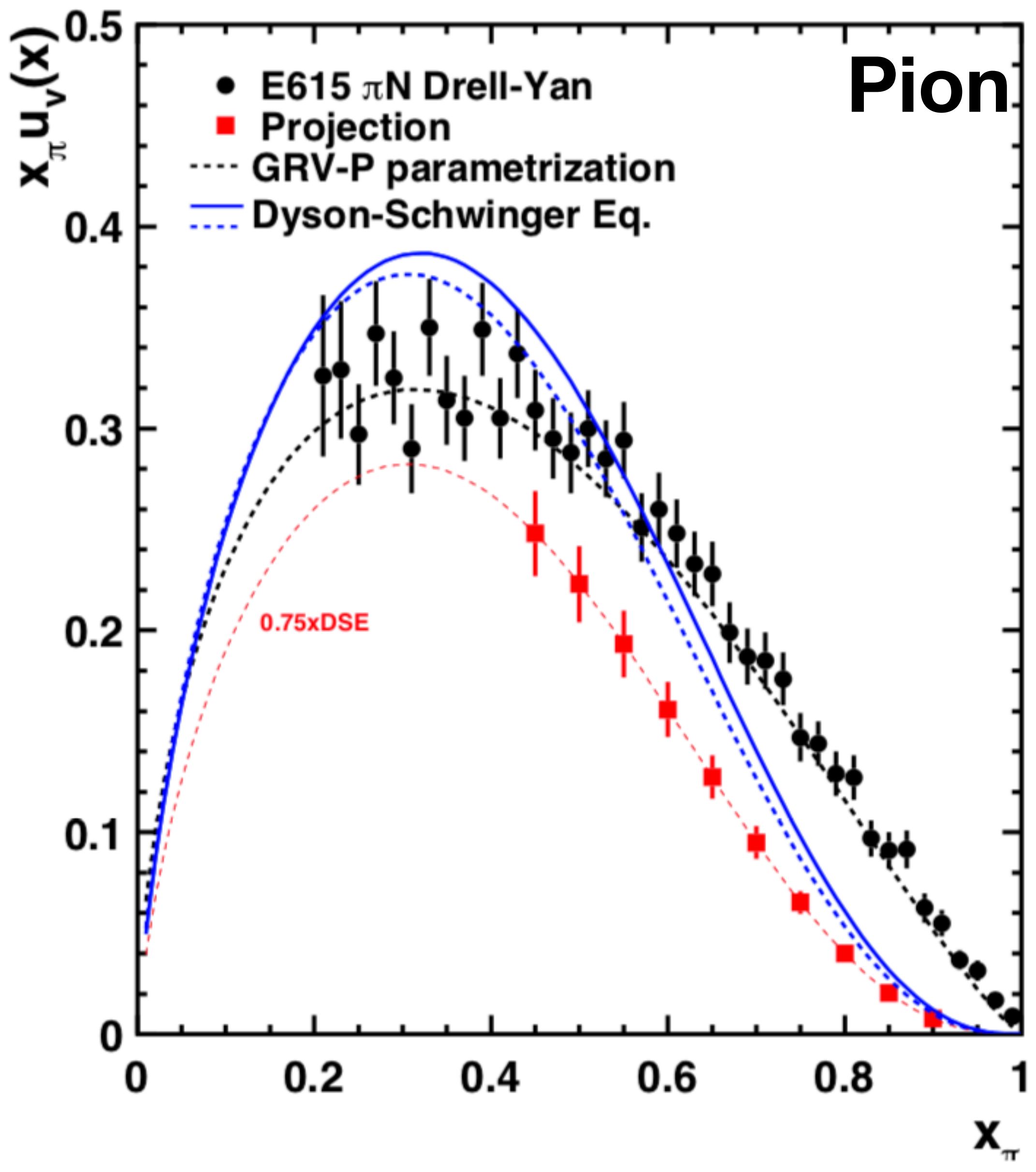
- Read data continuously from ≥35k channels
- Parallel data flow
- Event synch with triggered detectors (SBS)

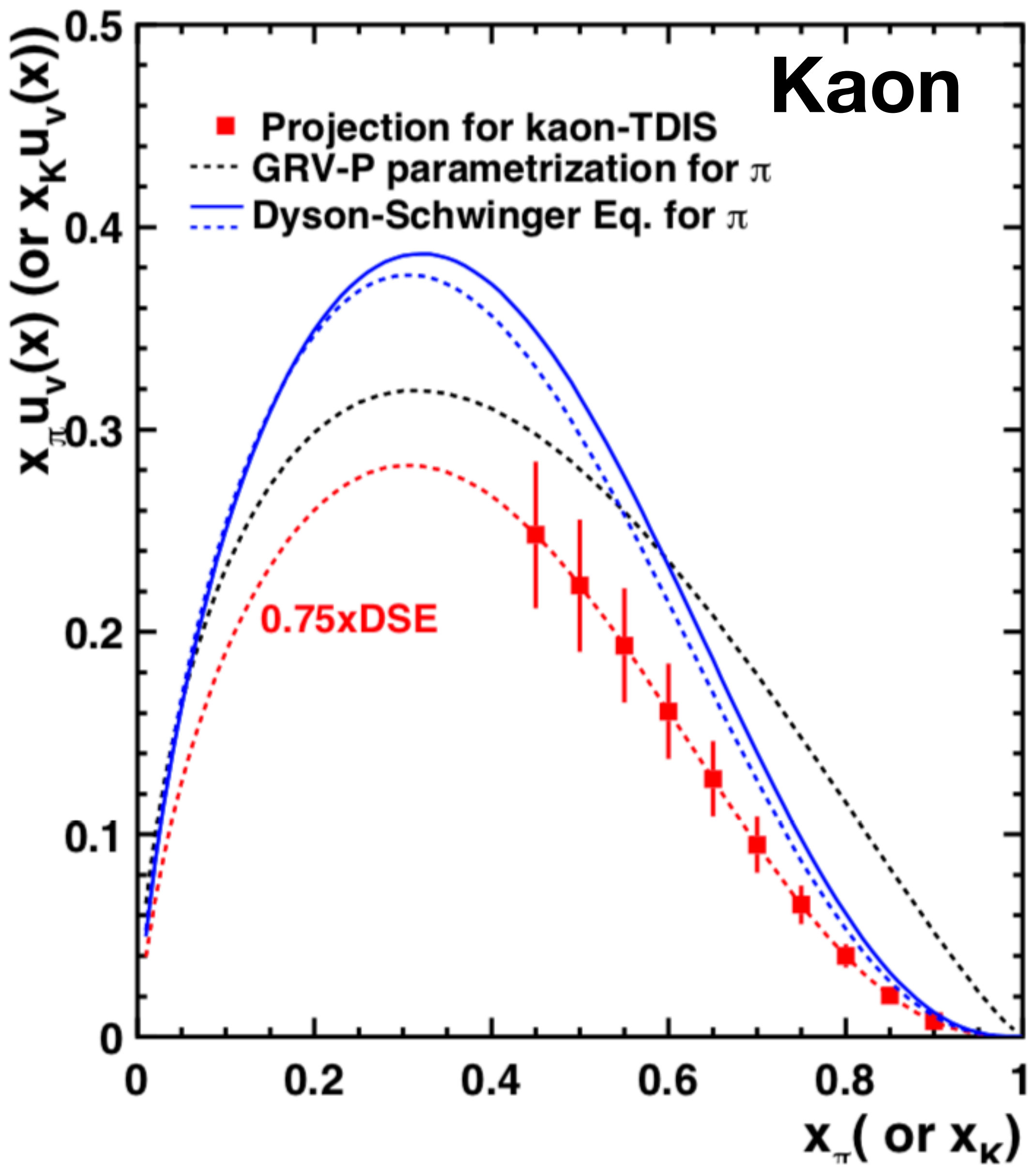
- Prototyping at JLab (E. Jastrzembski, G. Heyes, et al.)
- Using: Oak Ridge FEC developed for ALICE TPC
- SAMPA ASIC: pre-amp, ADC, zero-suppression… (M. Bregant, Sao Paolo)

Example Projected Results





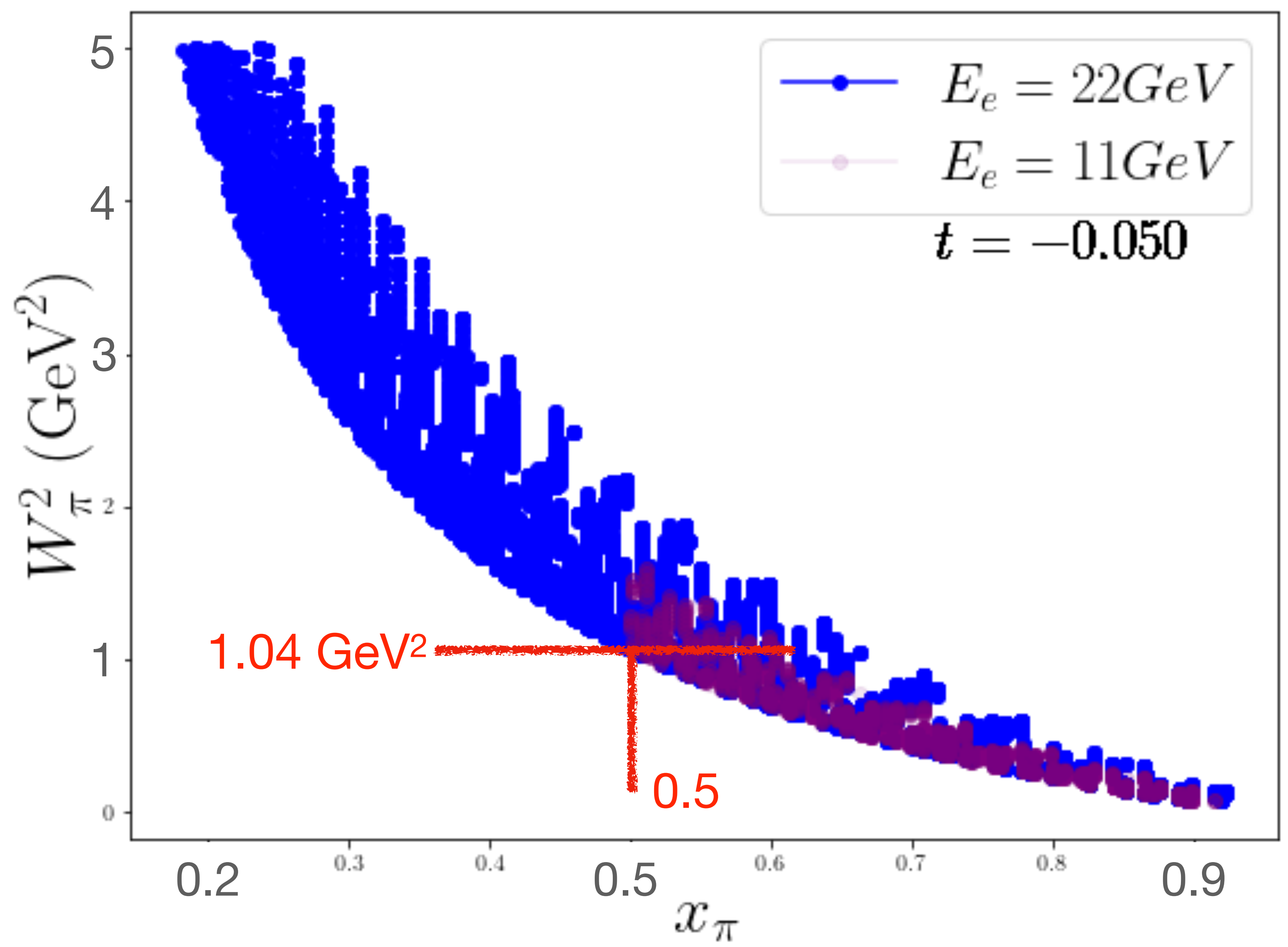




- Based on phenomenological pion cloud model
  - T.J. Hobbs, Few Body Syst. 56 (2015) no.6-9
  - J.R. McKenney et al., Phys. Rev. D93 (2016), 05011
- Kinematical mapping of F_2
- Low momentum reach of mTPC essential to obtain shapes of curves
- Shown: projected range of x_π relevant to valence quark distribution analyses
- Adds to sparse world data

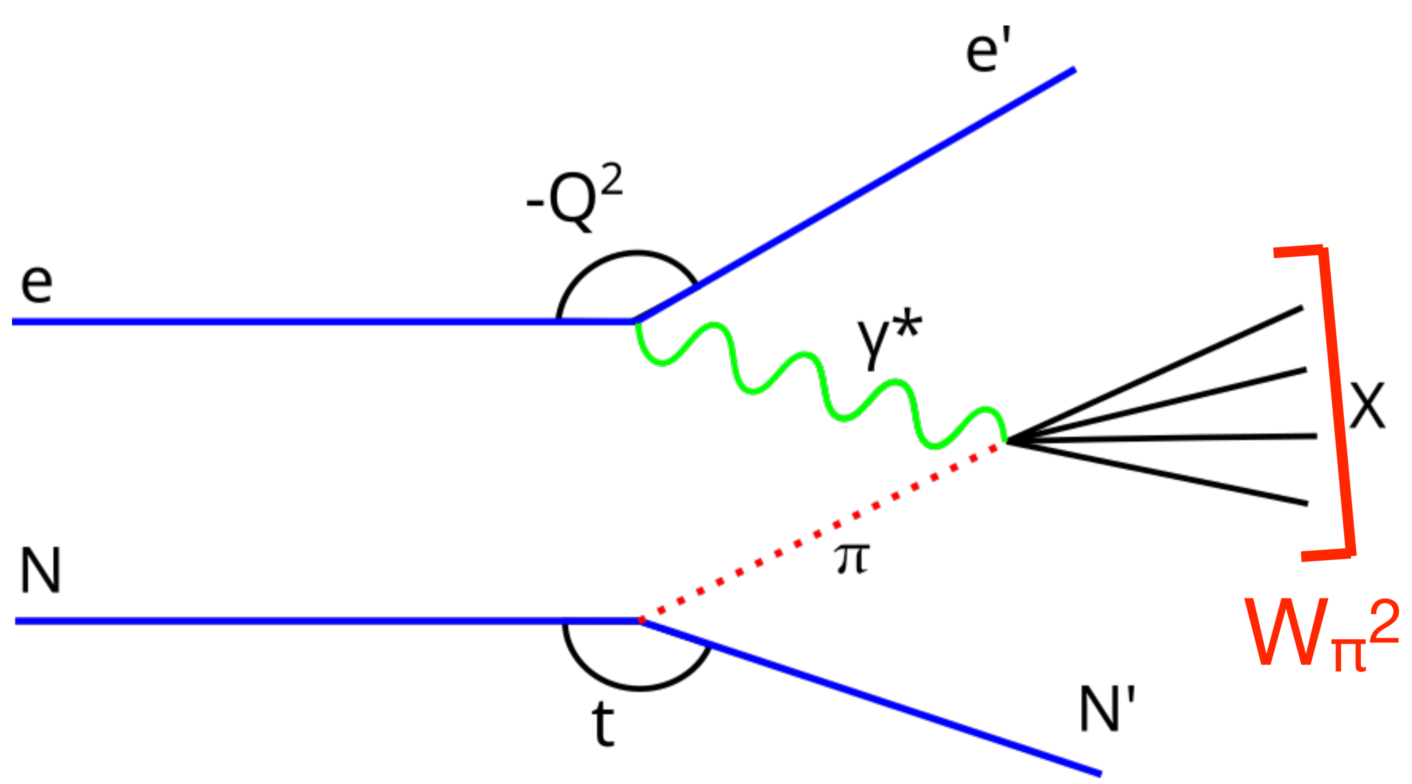
22GeV Extension

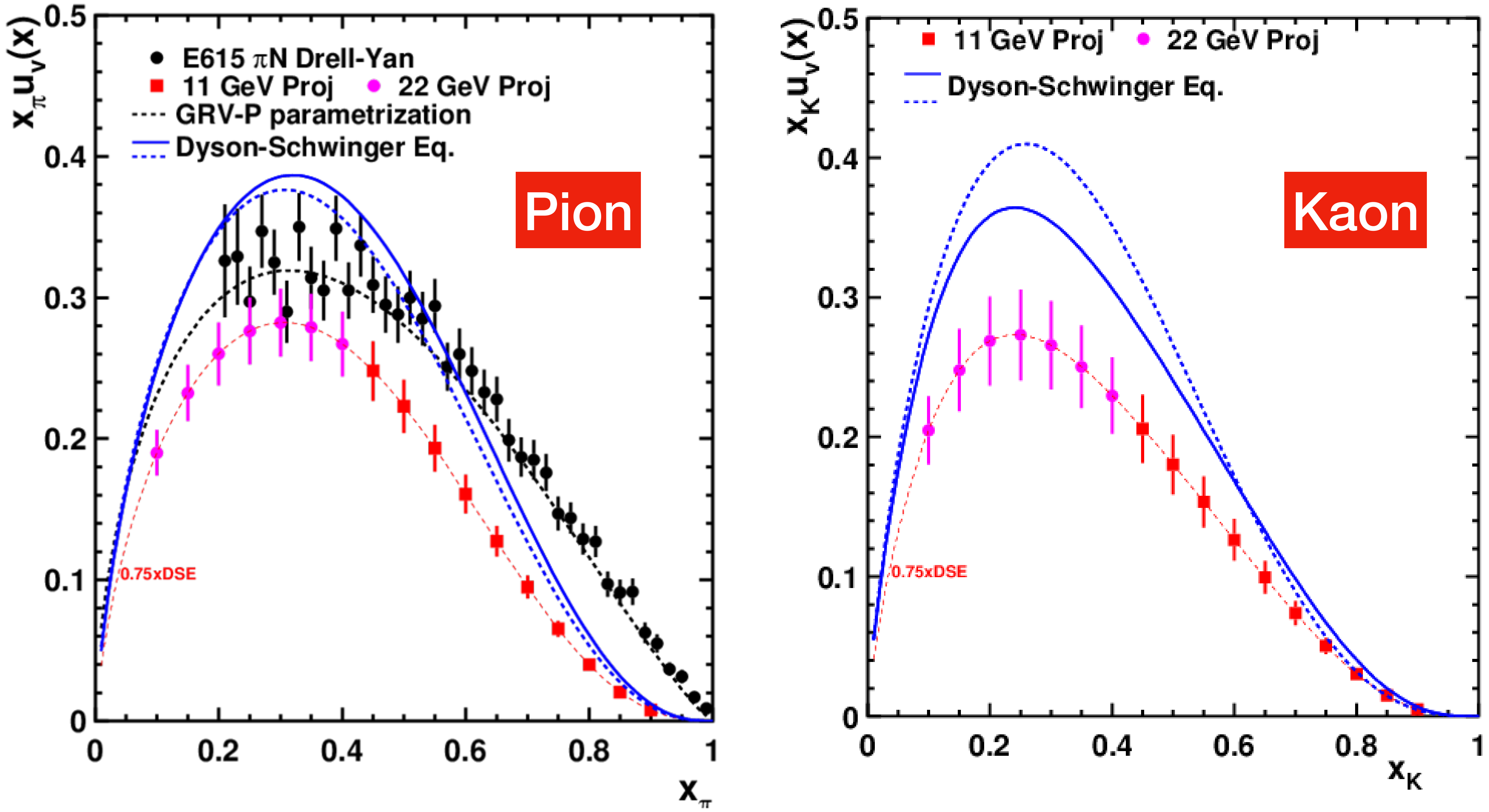
Plot: C. Ayerbe (W&M)



- Studied using phase space from Patrick Barry (JLab)
- Includes T.J. Hobbs' et al. F_2^π model and JAM PDFs

- Vastly expands kinematic phase space (e.g. Q^2, W^2, x_π, k_T)
- e.g. W_π^2 and x_π
- PDF studies: $W_\pi^2 > 1.04GeV^2$ to minimise ρ resonance
- More data available above $1.04GeV^2$
- 11GeV: still some data above $1.04GeV^2$
- 11GeV: novel studies of resonances at low W_π^2
- 11GeV: realise challenging experimental technique

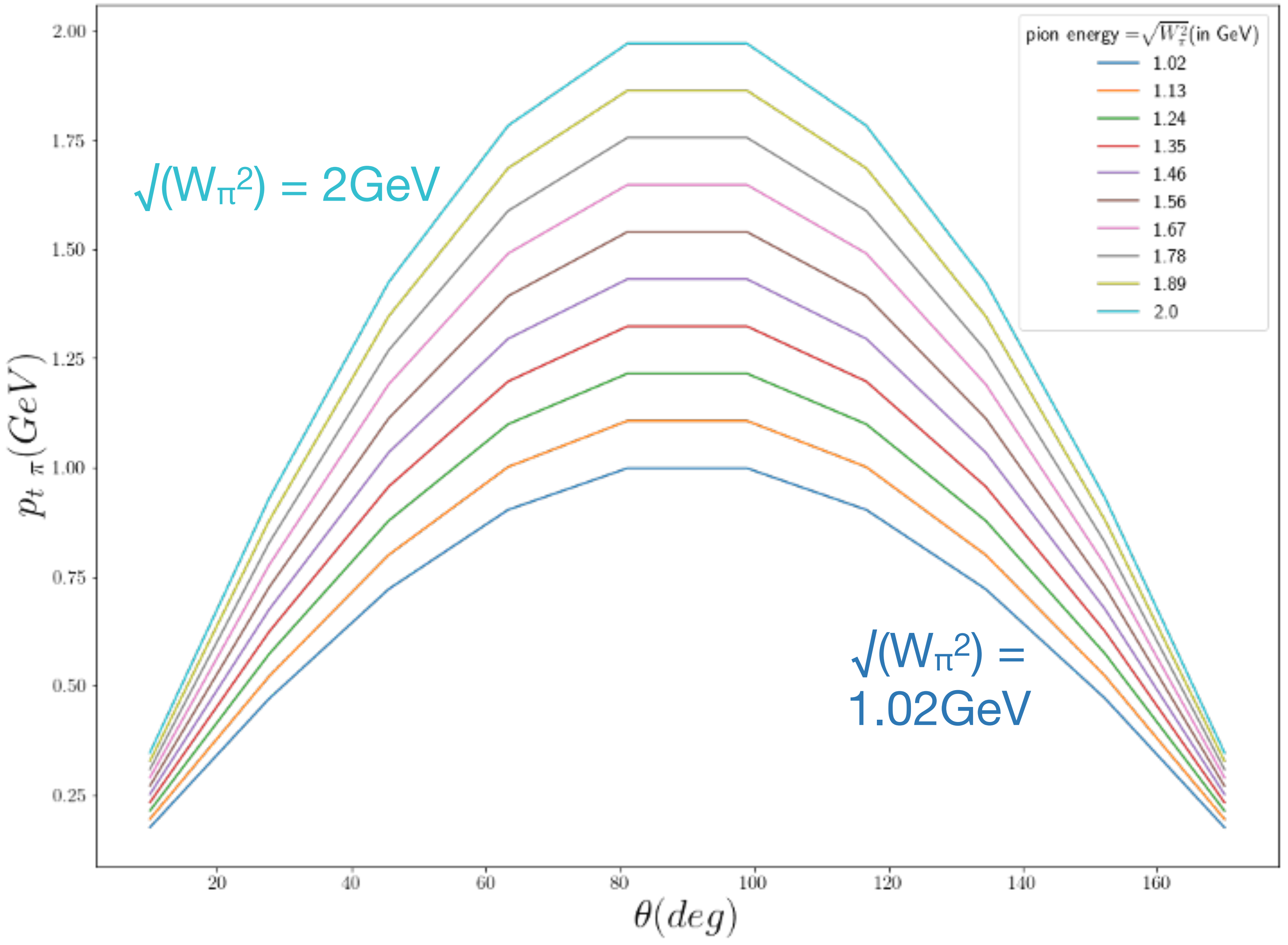




Plots:
D. Dutta (MSU),
T. Horn (CUA)

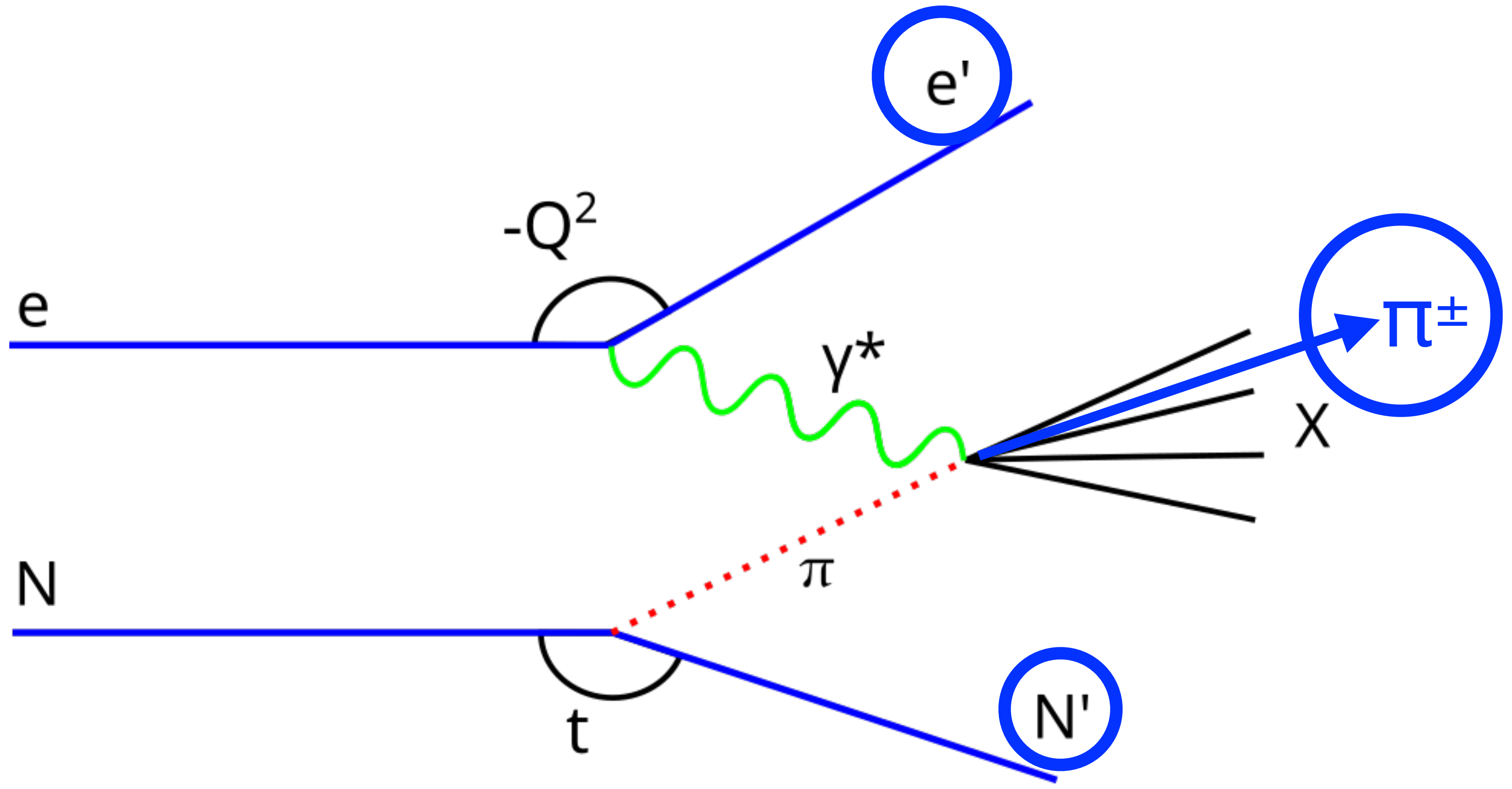
22GeV Extension

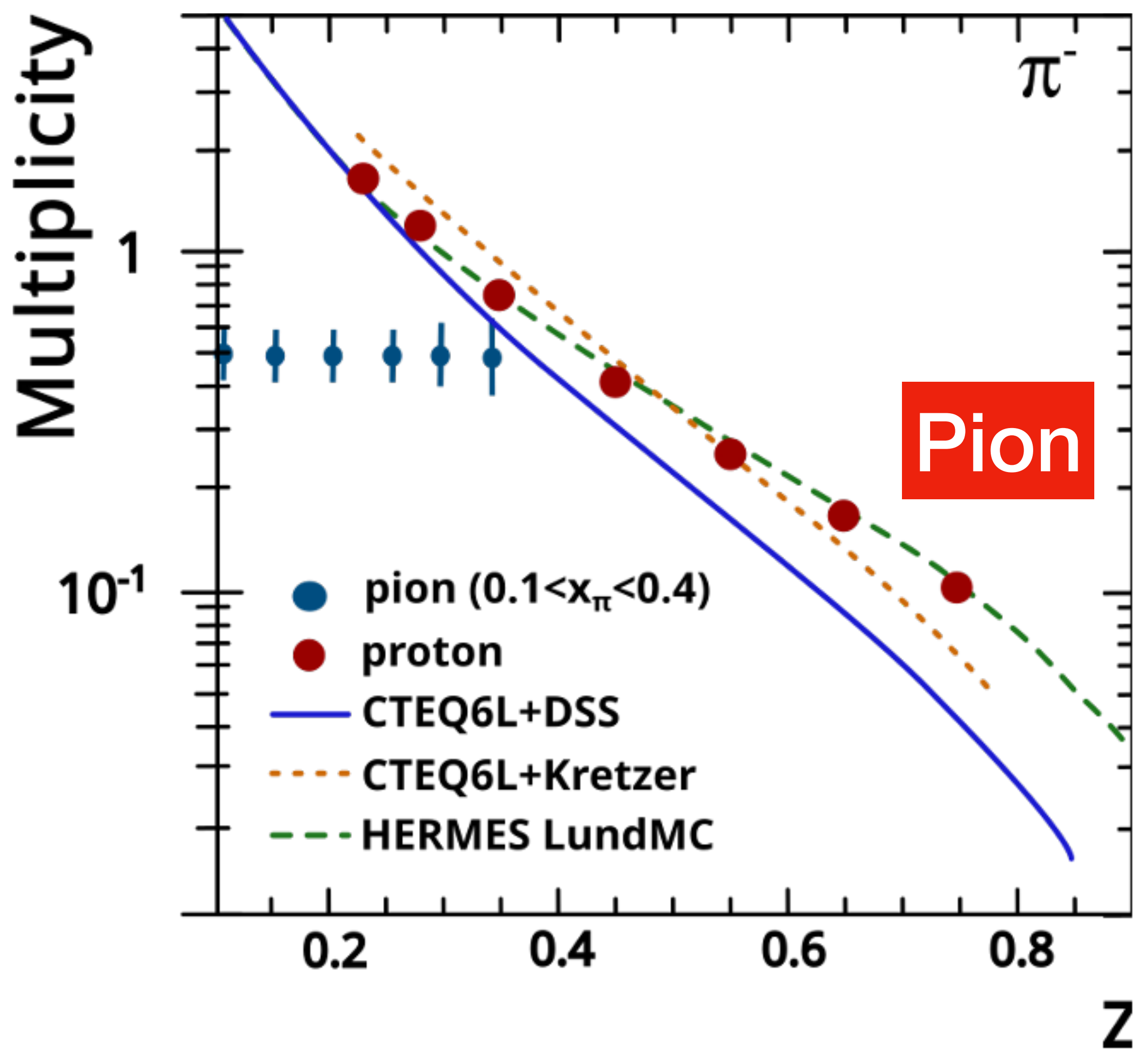
Plot: C. Ayerbe (W&M)

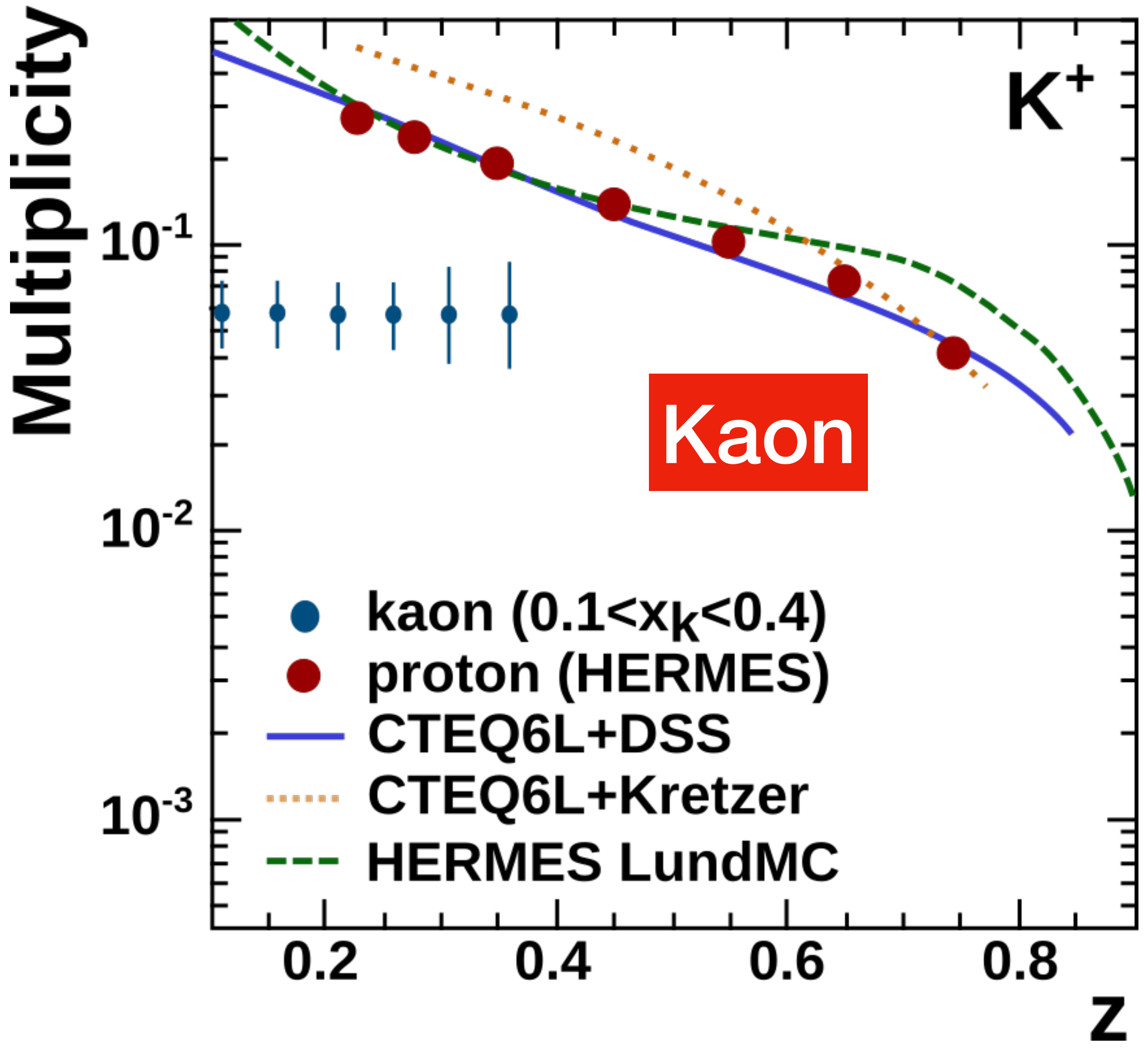


- Data available between W_π^2 1.04 and 4GeV^2
- SIDIS on virtual meson possibility → meson TMDs!
- Expect interesting differences between meson/nucleon TMDs

- Assume W_π^2 used to produce π
- Measure e', N' and π
- SIDIS pion p_T ranges: 0.25 GeV/c to 2GeV/c and ~20° to 160°
- Would need to add detector for π (under study)





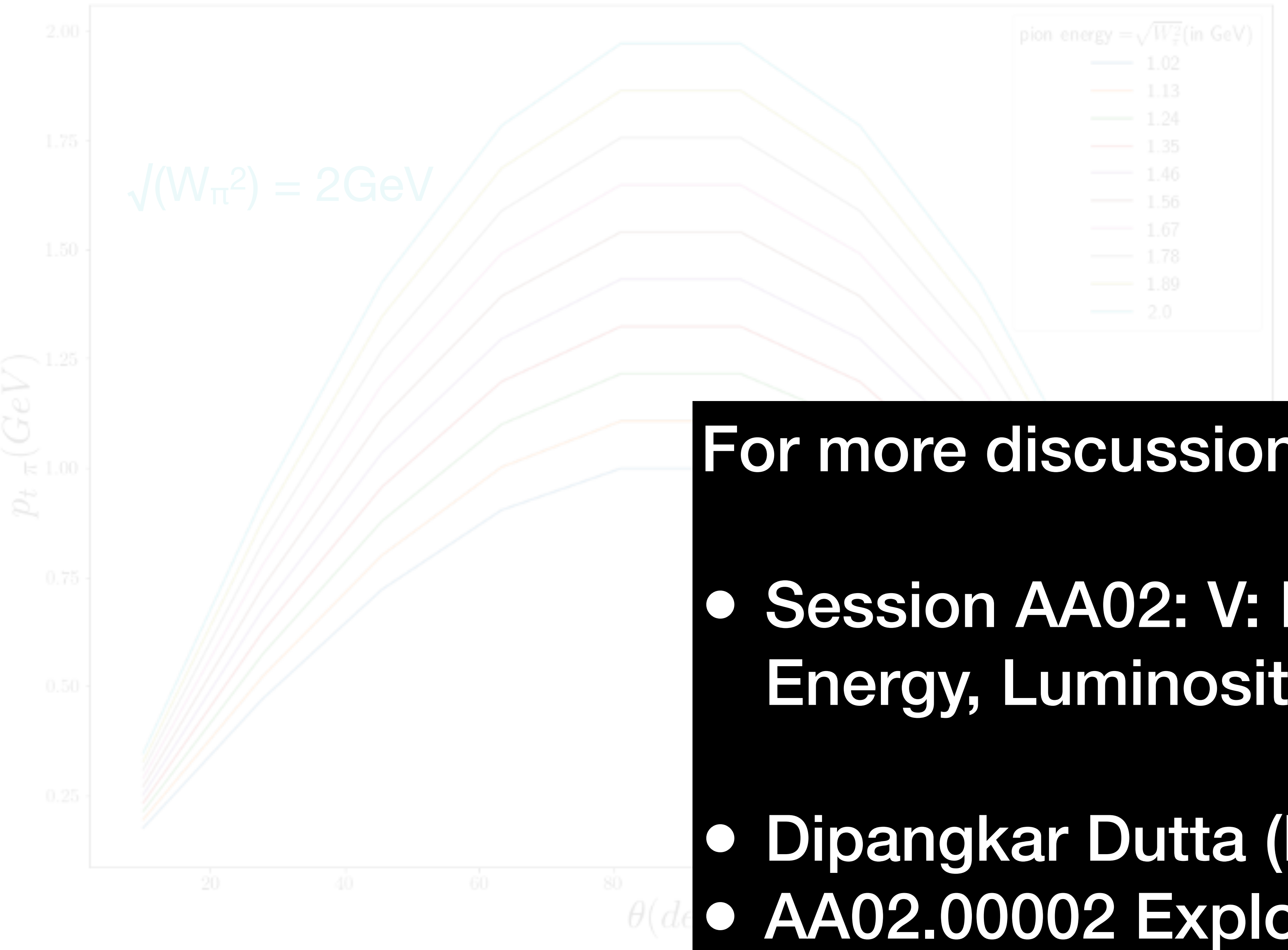


HERMES results from:
A. Airapetian et al. (HERMES Collaboration), Phys. Rev. D 87, 074029

Plots: D. Dutta (MSU), C. Ayerbe (W&M)

22GeV Extension

Plot: C. Ayerbe (W&M)



- Data now available between W_π^2 1.04 and 4GeV²
- SIDIS on virtual meson possibility → meson TMDs!
- Expect interesting differences between meson/nucleon TMDs from theory

- Assume W_π^2 used to produce π

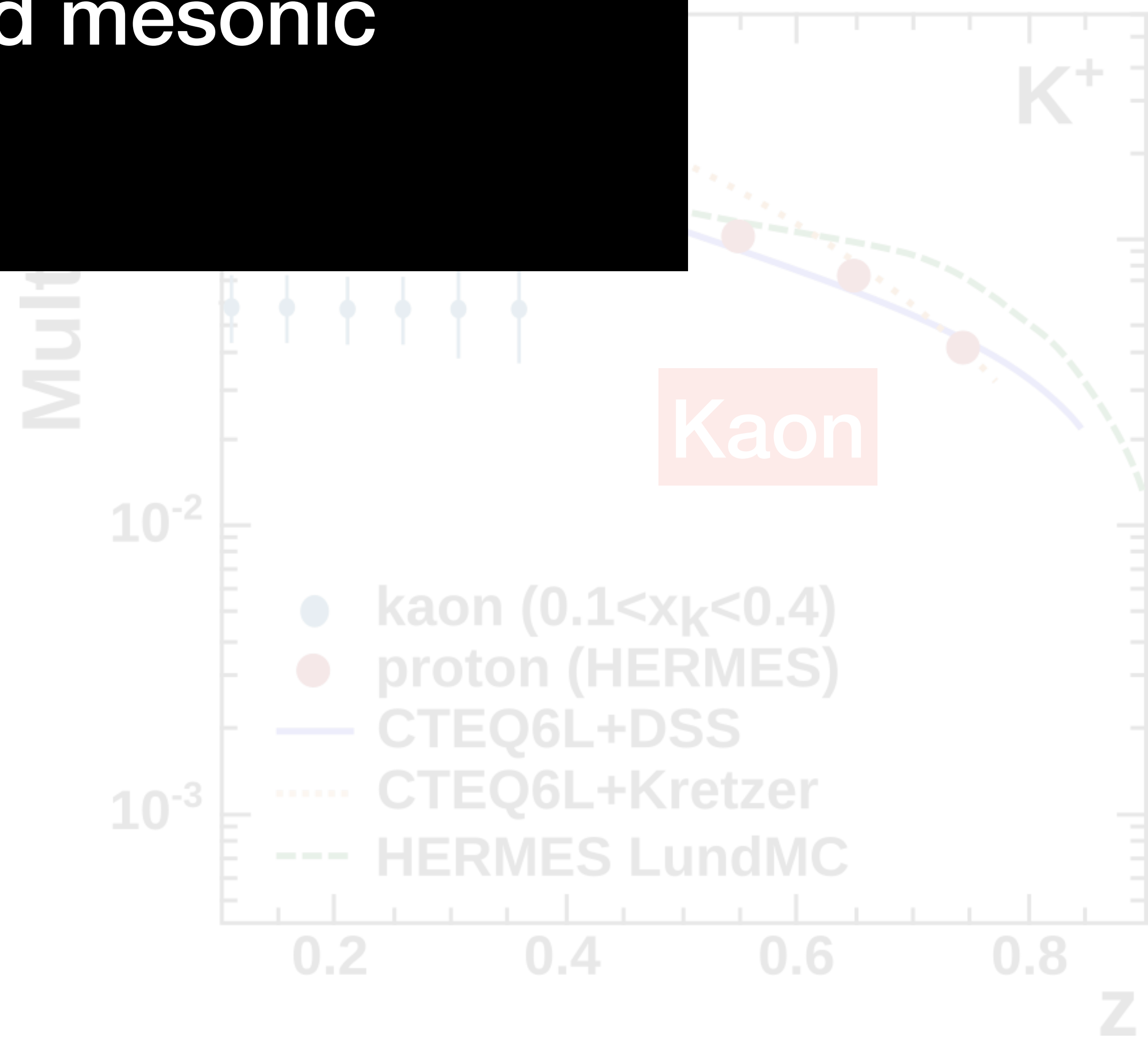
…nd ~20° to 160°

…tudy)

For more discussion on 22GeV, see:

- Session AA02: V: Mini-Symposium: Opportunities with JLab Upgrades in Energy, Luminosity, and a Positron Beam

- Dipangkar Dutta (Mississippi State University)
- AA02.00002 Exploring mesonic content of the nucleon and mesonic structure with 22GeV JLab
- 24th April 8:12am, virtual room 2



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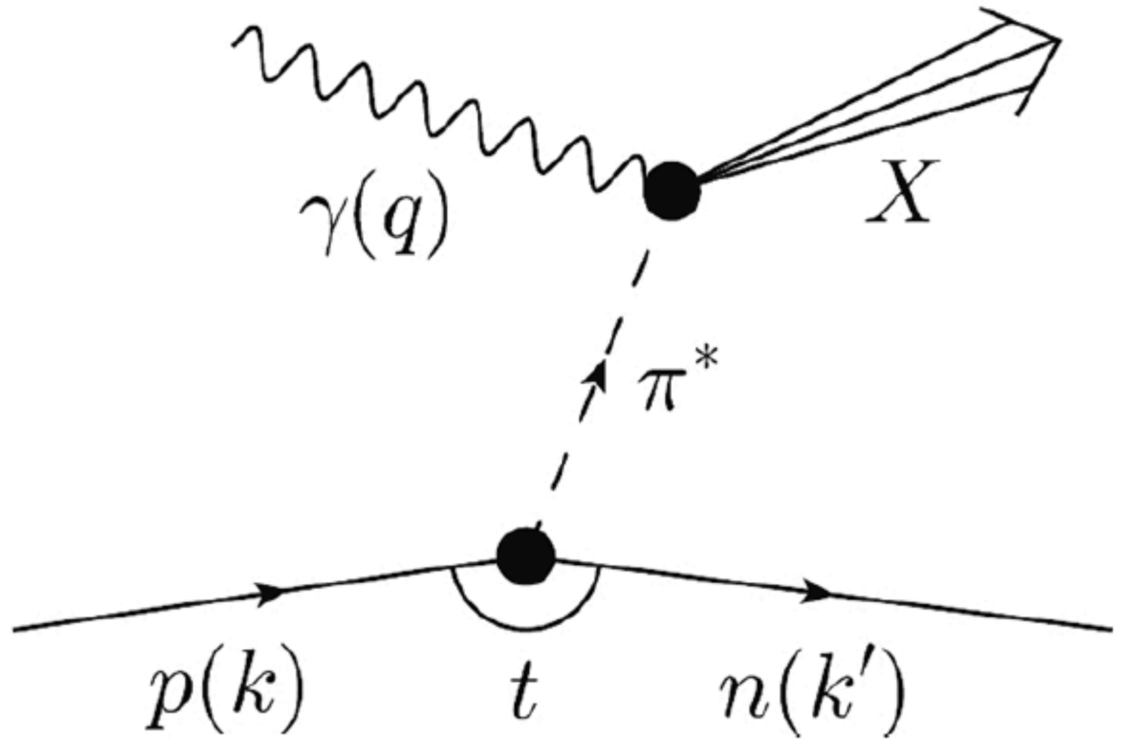
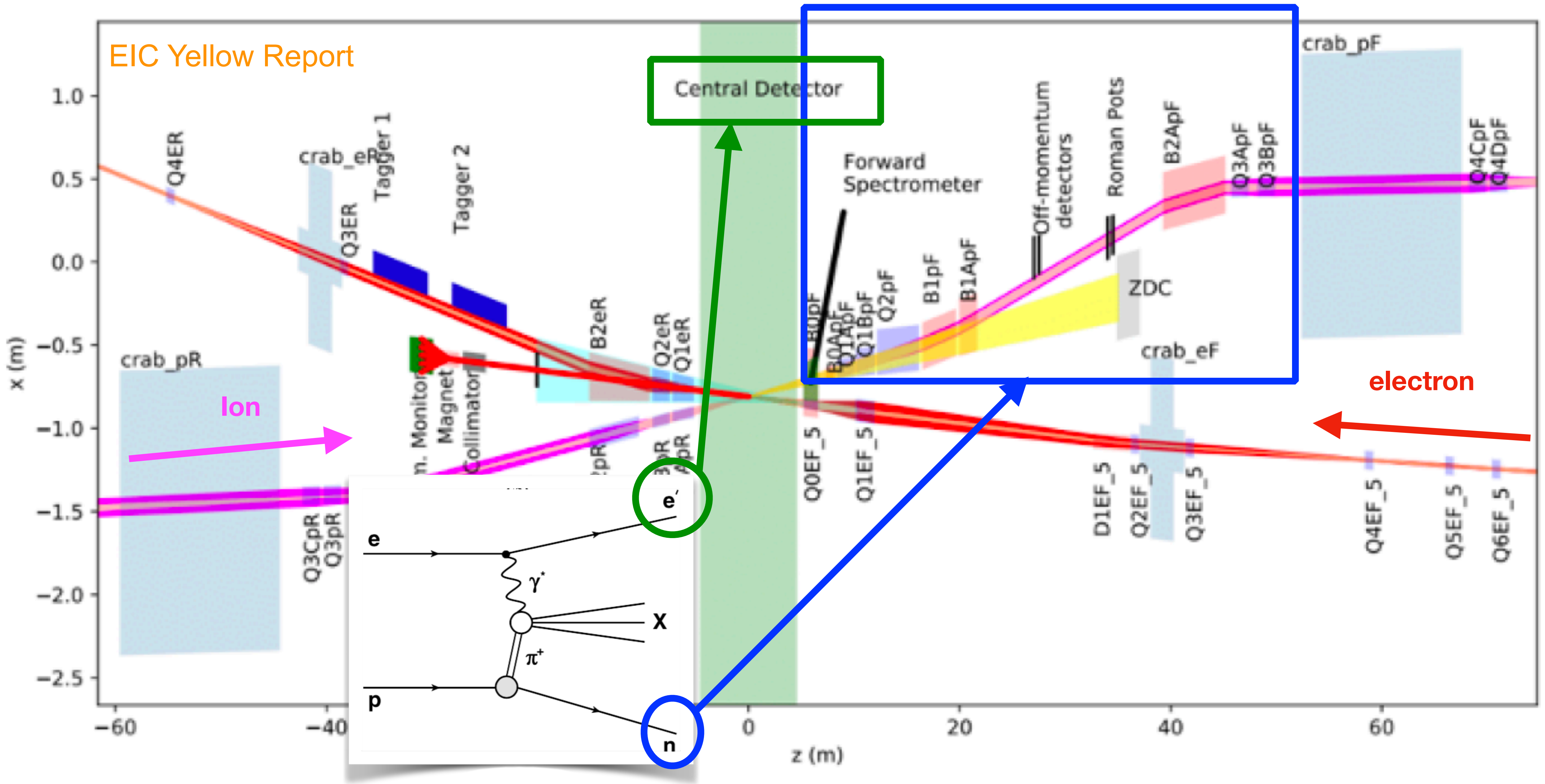
Summary and Outlook

- π/K structure can offer insights into EHM
- Experimental data for π/K structure functions extremely sparse

✓ TDIS program at JLab:
- New data - test universality in valence regime for PDF
- Kaon SF - almost empty world data set!
- Prototyping underway





- Precursor for meson structure via Sullivan at EIC
- High luminosity ($\mathscr{L}$=10^{34}Hz/cm^2 = 1000 * $\mathscr{L}_{HERA}$)
- Full acceptance
- Bridge HERA low x and JLab valence regime

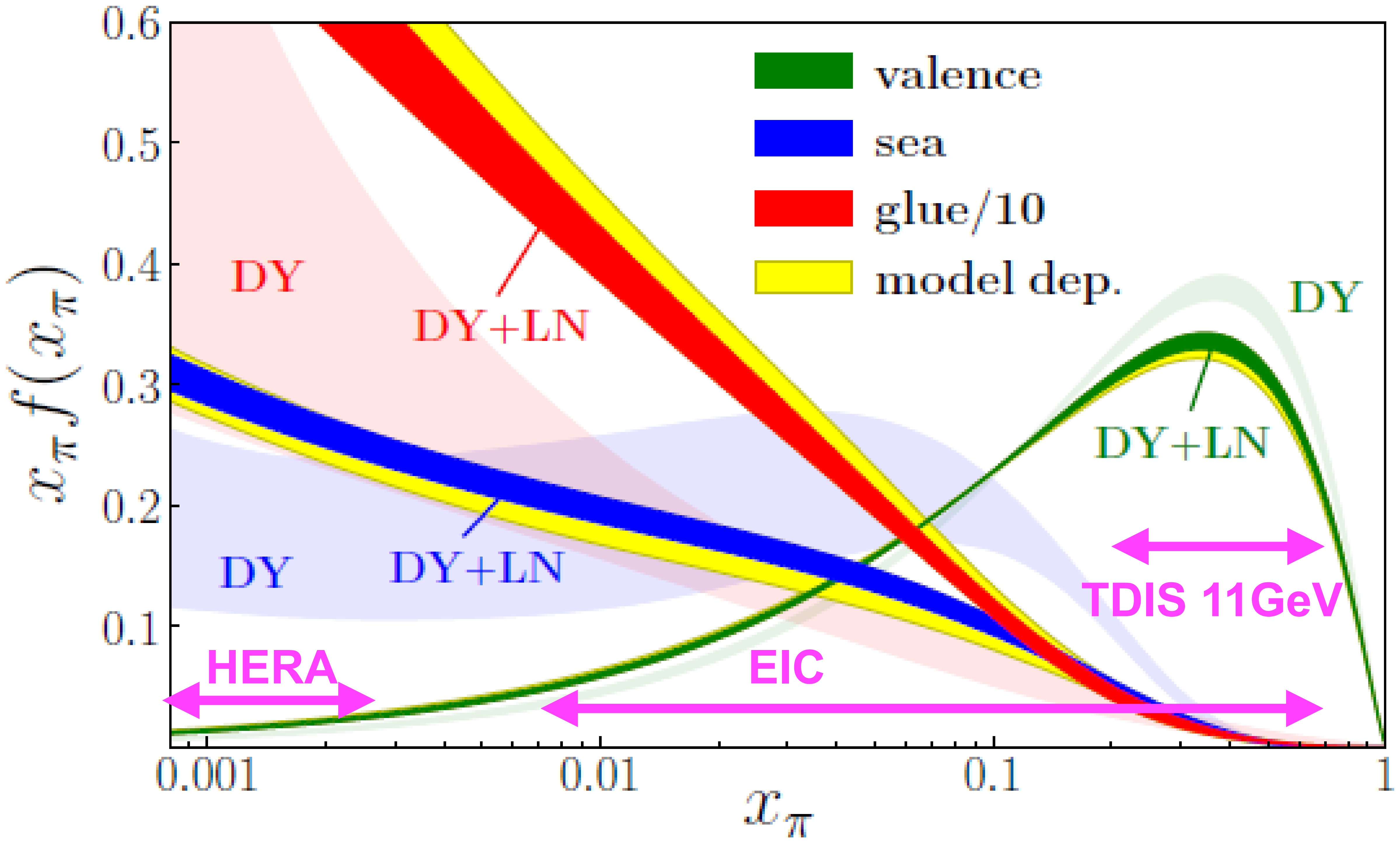
- EIC Meson Structure Working Group:
  - Aguilar *et al*, Eur. Phys. J. A. (2019) **55** 190
  - Arrington *et al* 2021 J. Phys. G: Nul. Part. Phys. **48** 075106

Thank You

Back Up Follows…

EIC Reach

Global PDF from JAM Collaboration, Phys. Rev. Lett. 121, 152001 (2018)



Pion and Proton Unpolarised Leading-Twist TMD

Tobias Frederico's slide from Light-Front Conference

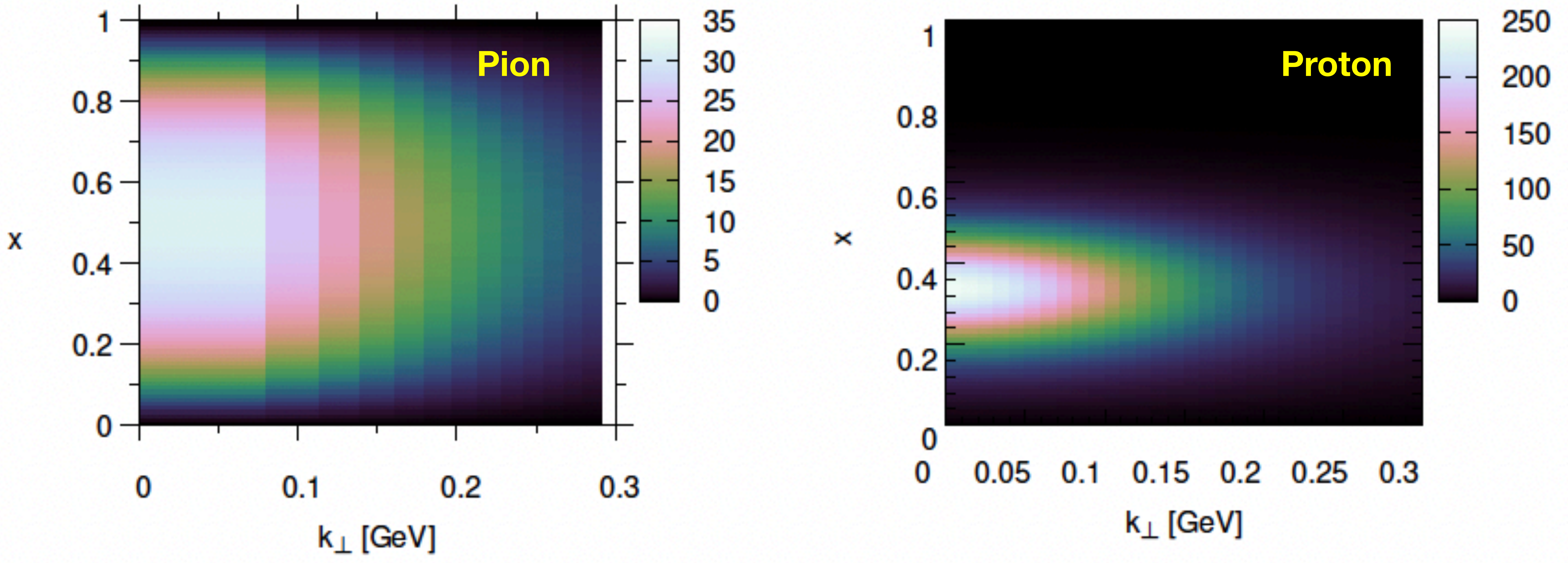


Figure: Leading twist unpolarized TMDs at the hadron scale. Left frame: Pion from Minkowski space Bethe-Salpeter equation model with constituent quarks, massive one-gluon exchange and quark-gluon form factor [1]. Right frame: Proton from a Light-front model with constituent quarks and a scalar diquark [2].

[1] W. de Paula, E. Ydrefors, J.H. Nogueira Alvarenga, T. Frederico, G. Salmè, PRD 105 (2022) L071505, and in preparation.

[2] E. Ydrefors, T. Frederico PRD 104 (2021) 114012; and arXiv: 2211.10959 [hep-ph].

- From:
- T. Frederico (Instituto Tecnologico de Aeronautica)
- E. Ydrefors (Chinese Academy of Sciences)

- Remarkable broadening of pion TMD in x compared to narrower proton
- Spread in $k_\perp$ similar (~200MeV)
- Expect interesting differences between meson and nucleon TMDs