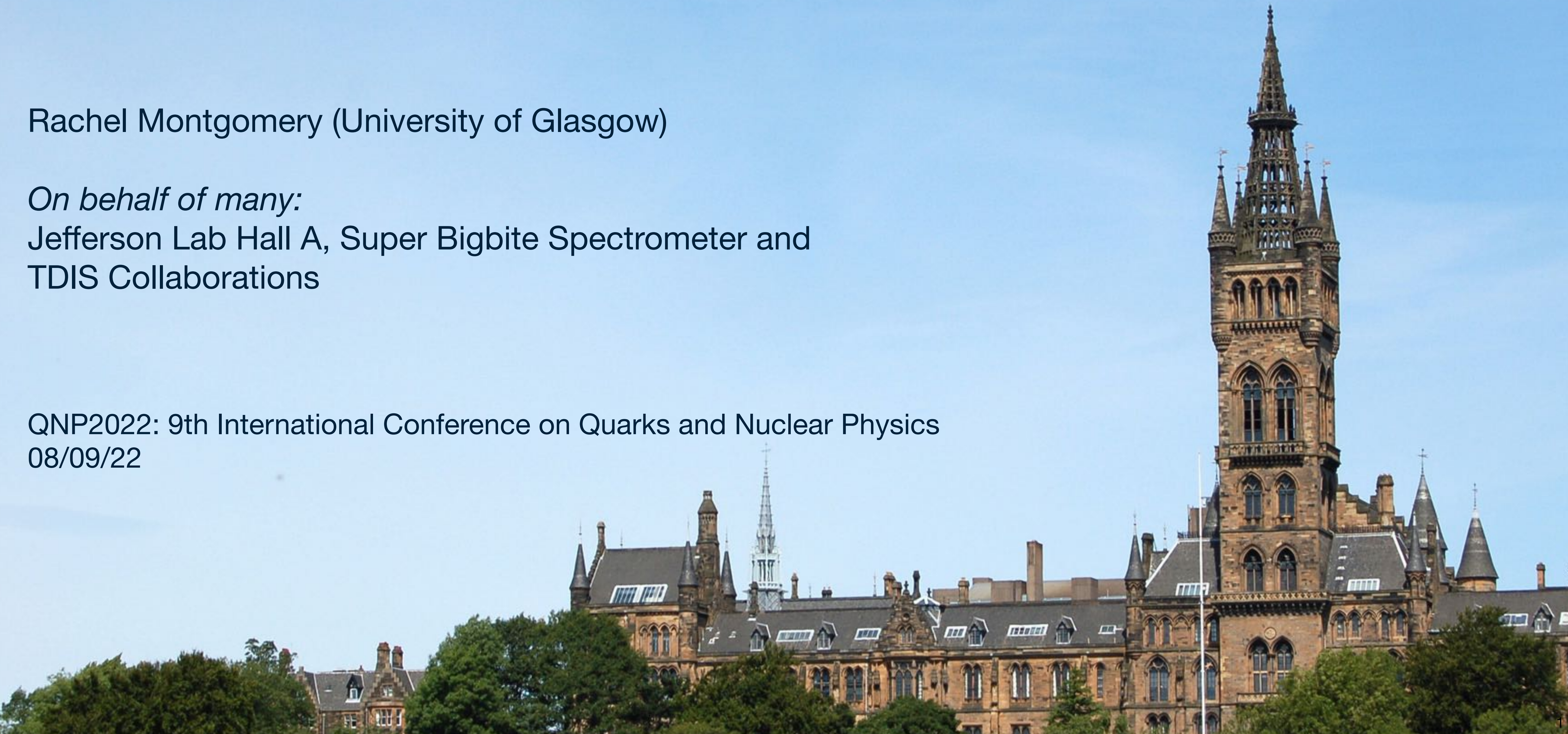


Probing Light Meson Structure via Tagged Deep Inelastic Scattering (TDIS)

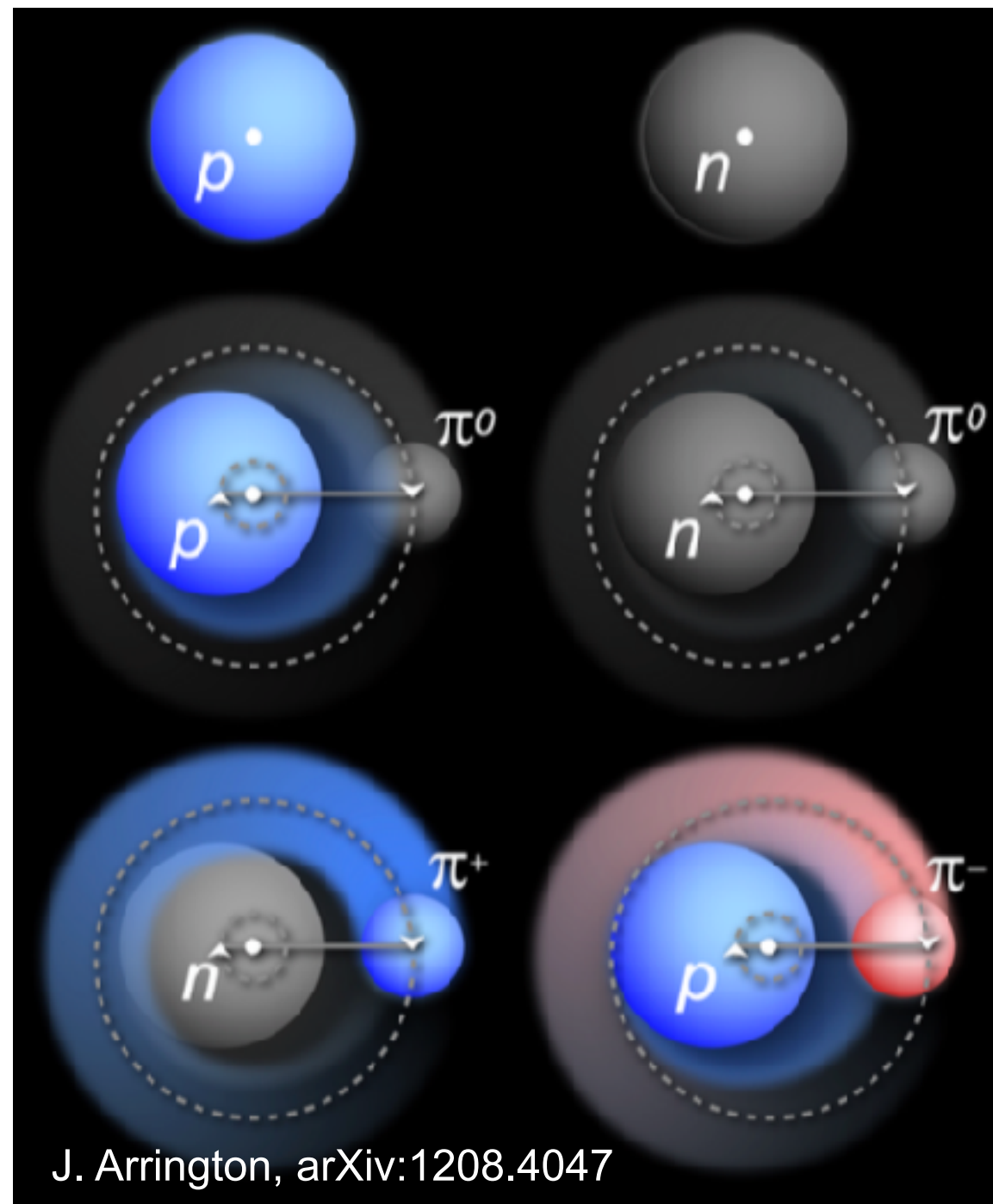
Rachel Montgomery (University of Glasgow)

On behalf of many:
Jefferson Lab Hall A, Super Bigbite Spectrometer and
TDIS Collaborations

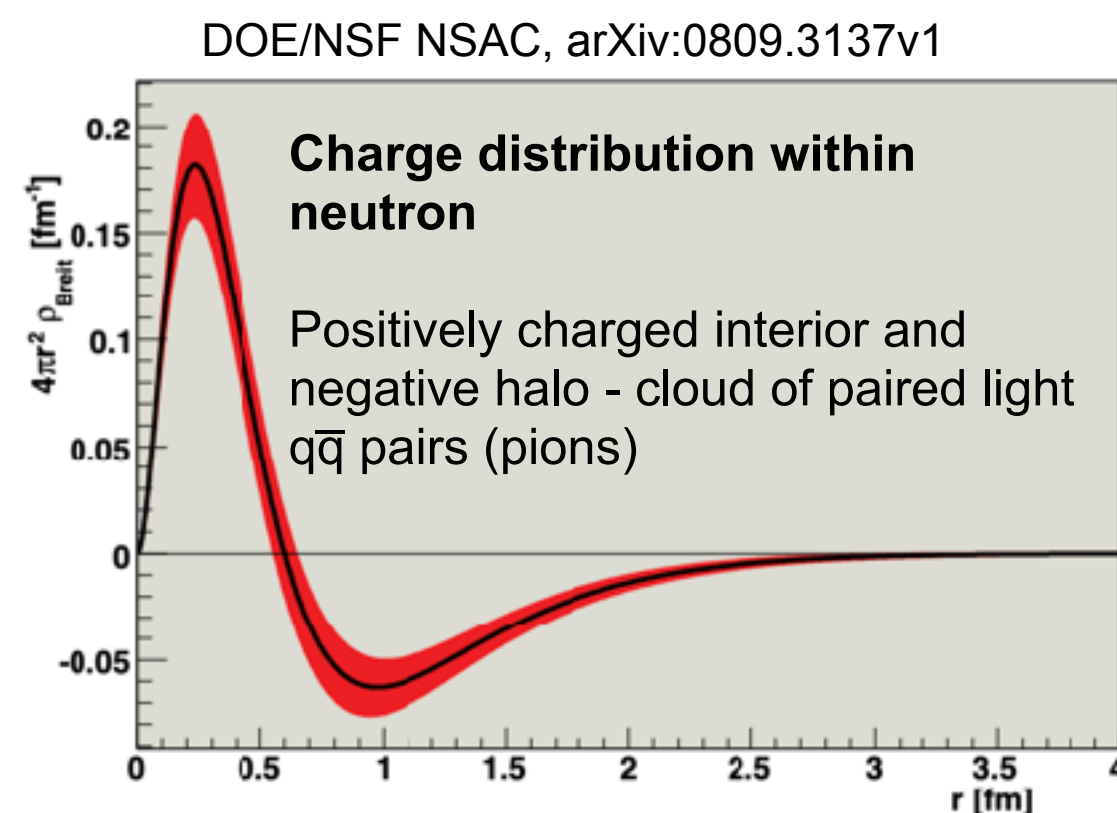
QNP2022: 9th International Conference on Quarks and Nuclear Physics
08/09/22



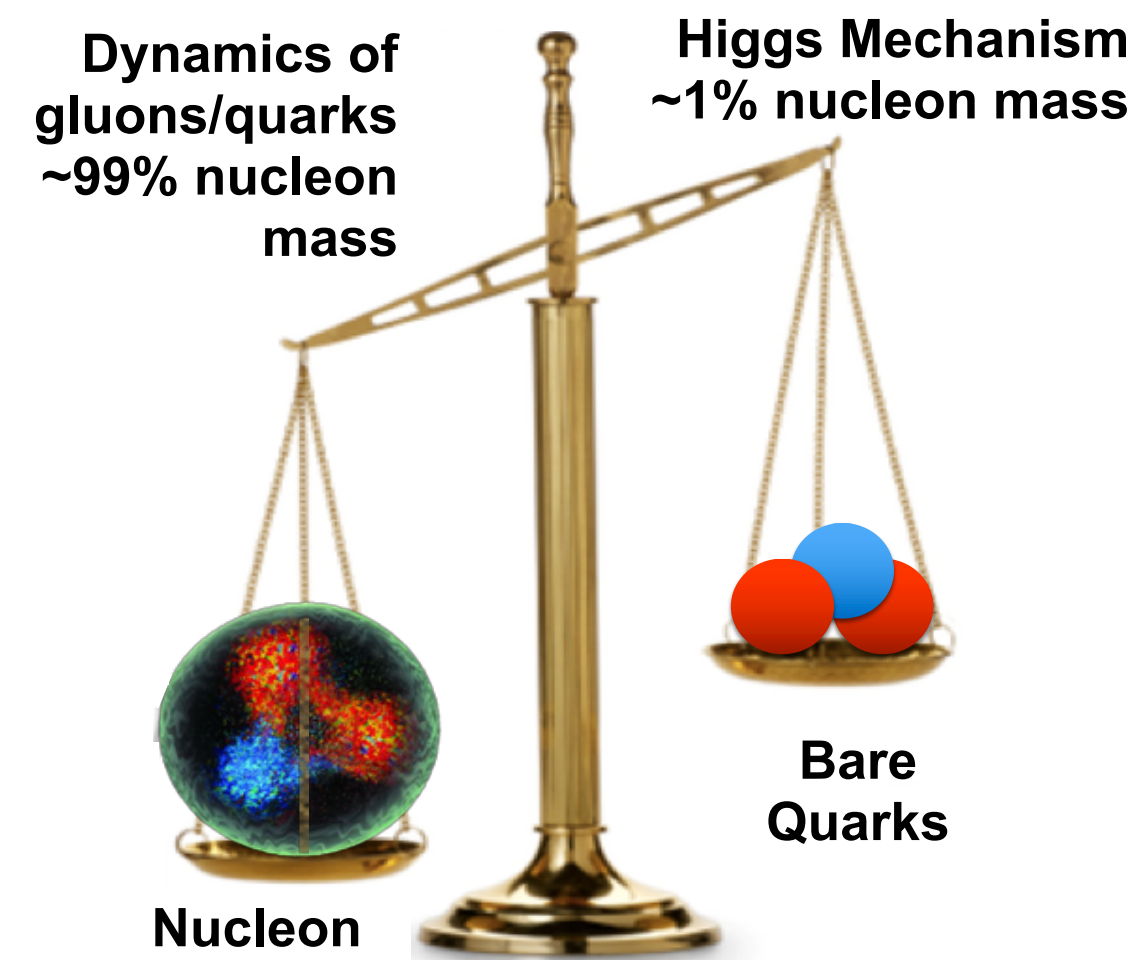
Why Meson Structure?



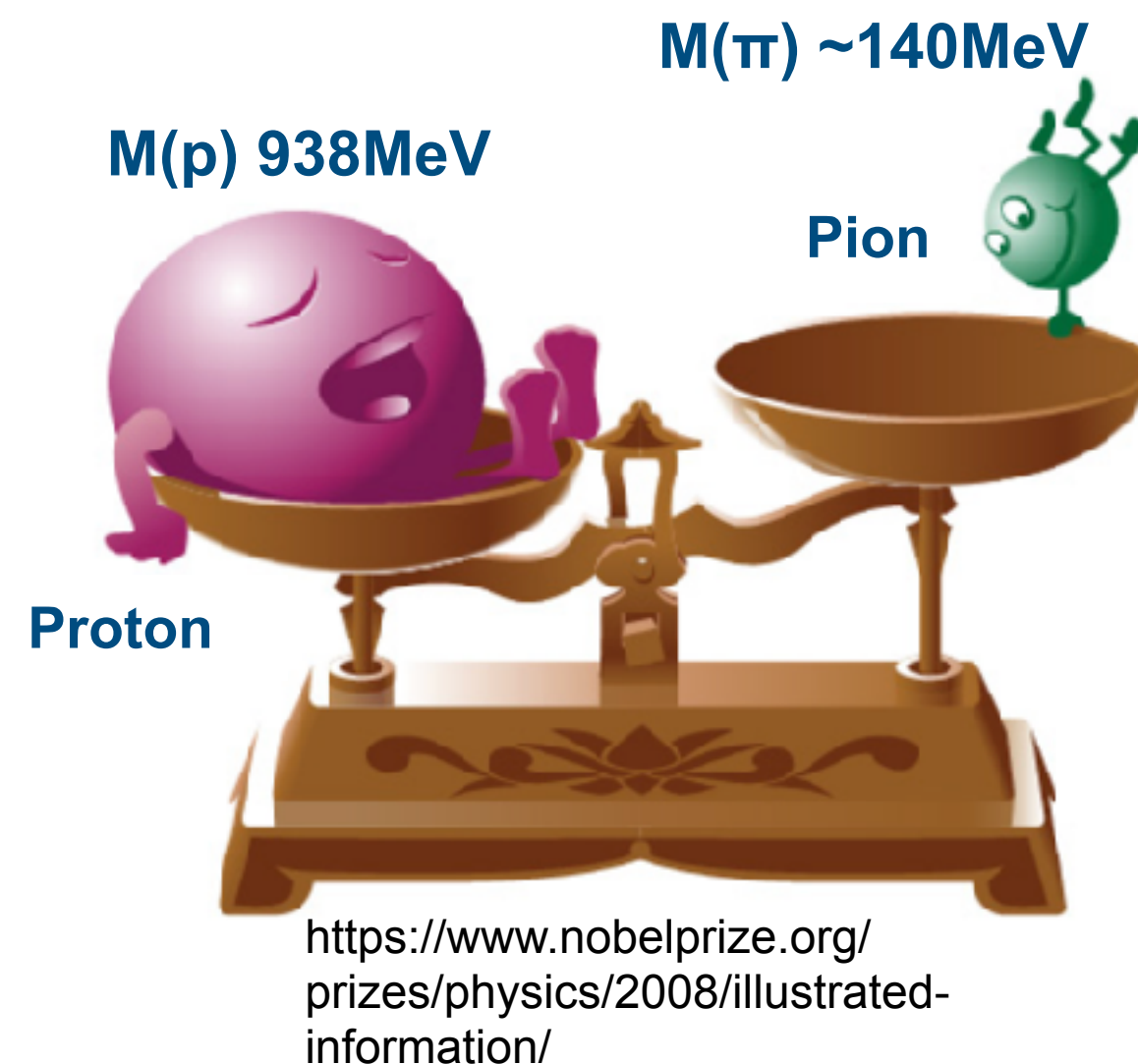
- Understanding structure of light mesons (pions/kaons) key for full understanding of nucleon
- Experimental evidence for mesonic content of nucleon exists
 - e.g. nucleon charge densities; pion/kaon form factors from electroproduction off nucleon...
 - **Exact mesonic content of nucleon unknown!**
- **Pion and kaons are key topics in nucleon/nuclear structure**
- Pion
 - Long range NN interaction; simplest QCD state; dynamical mass generation; nucleon/nuclear parton distribution functions (PDF)...
- Kaon
 - Momentum fractions carried by sea/gluon; different gluon content than pion, combine with valence quark for full PDF evolution...
- **Comparing structure of different light mesons provides unique insights into nucleon mass enigma**



Why Meson Structure?



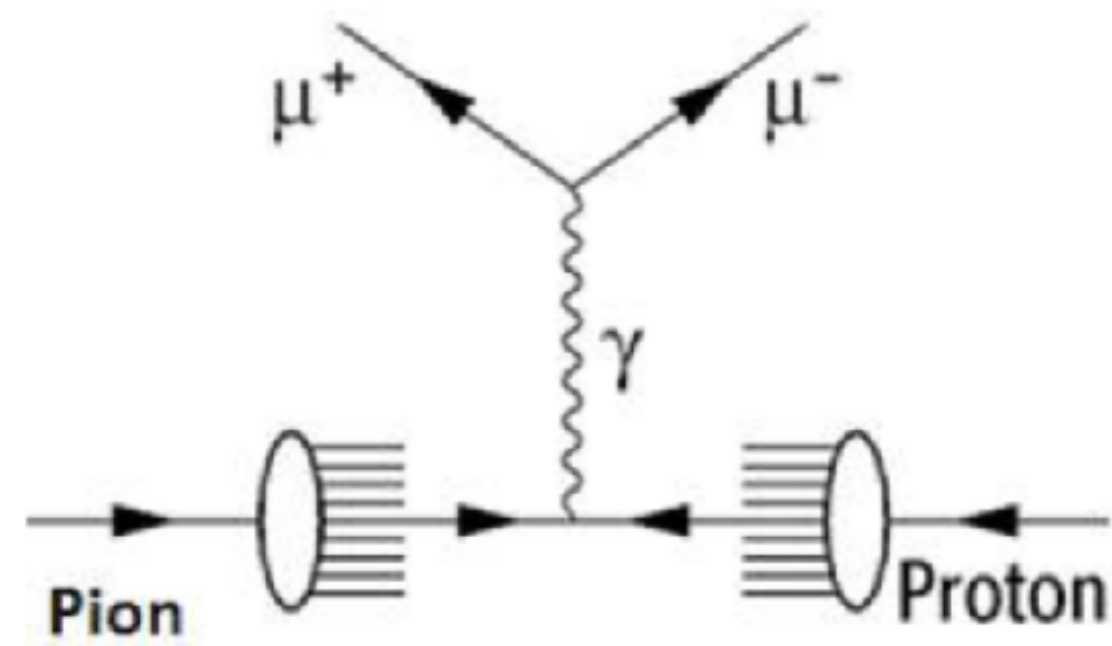
- Standard model and mass generation via Higgs ~1% nucleon mass
- Strong interactions in QCD ~99% nucleon mass: emergent hadronic mass (EHM)
- Mass scale of nucleon defined by QCD mechanisms



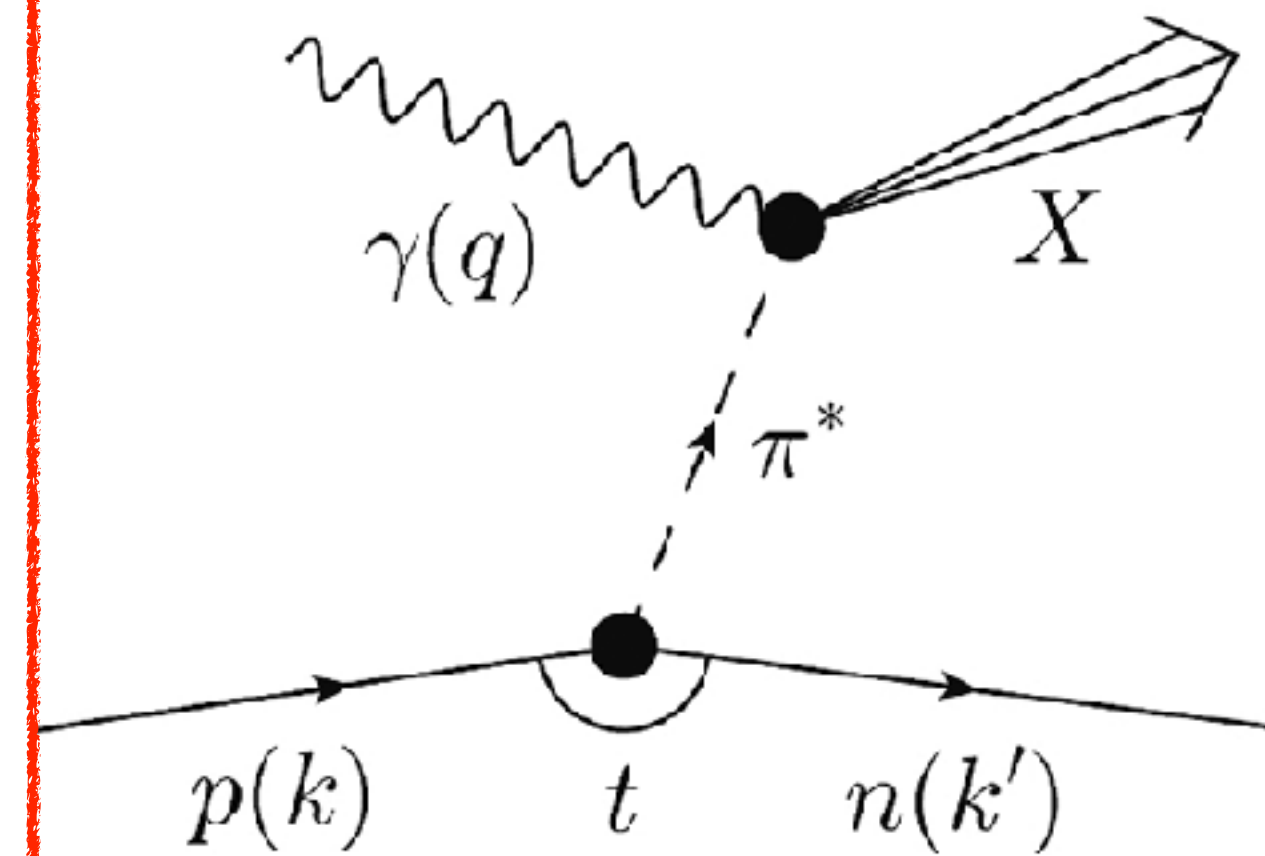
- Mass budgets for **light pion and kaon** vastly different from **heavy nucleon**, and each other
- Comparing distributions of light quarks versus strange quarks within mesons → measurable signals EHM
- Understanding pion/kaon structure one key tool for understanding EHM
- π/K structure practically unknown experimentally!
- Several observables:
 - e.g. elastic EM form factors, or **structure functions (SF)**

How Can We Access Pions/Kaons?

Drell-Yan



Sullivan



Hard scattering
from virtual meson
cloud of nucleon

Upcoming TDIS at Jefferson Lab

Measurement of Tagged Deep Inelastic Scattering (TDIS)

May 18, 2015

Hall A and SBS Collaboration Proposal

Dusuni Adikaram, Alexandre Camsonne, Dave Gaskell, Doug Higginbotham, Mark Jones, Cynthia Keppel (Spokesperson)¹, Wally Melnitchouk, Christian Weiss, Bogdan Wojtsekhowski (Spokesperson)¹
JEFFERSON LAB

John Arrington, Roy Holt, Paul Reimer
ARGONNE NATIONAL LAB

Paul King (Spokesperson), Julie Paschos
OHIO UNIVERSITY

Krishna Adhikari, Tim Dunne, Dipankar Dutta (Spokesperson), Lamin El Fassi, and Li Ye
MISSISSIPPI STATE UNIVERSITY

Charles Hyde, Sebastian Kuhn, Lawrence Weinstein
OLD DOMINION UNIVERSITY

John Annand (Spokesperson), David Hamilton, Derek Glazier, Dave Ireland, Kenneth Livingston,
UNIVERSITY OF GLASGOW

Ian MacGregor, Bryan McKinnon, Bjoern Seitz, Daria Sokhan
UNIVERSITY OF ILLINOIS AT URBANA CHAMPAIGN

Jen-Chieh Peng
UNIVERSITY OF VIRGINIA

Gordon Cates, Kondo Gaurav, Richard Lindgren, Nilanga Liyanage, Jixie Zhang
(Spokesperson)
COLLEGE OF WILLIAM AND MARY

Todd Averett, Keith Griffioen
INDIANA UNIVERSITY

Tim Hobbs, Thomas Londergan
LOS ALAMOS NATIONAL LABORATORY

Xiaokang Jiang
HAMPTON UNIVERSITY

Michael Christy, Narbe Kalantarians, Michael Kohl, Peter Monaghan, Ligang Tang
JAMES MADISON UNIVERSITY

Ioana Niculescu, Gabriel Niculescu
UNIVERSIDAD TECNICA FREDERICO SANTA MARIA

Doris Kopelovich, Nuruzzaman, I. Potashnikova
UNIVERSITY OF CONNECTICUT

Andrew Puckett
Garth Huber
UNIVERSITY OF REGINA

¹ Contact person

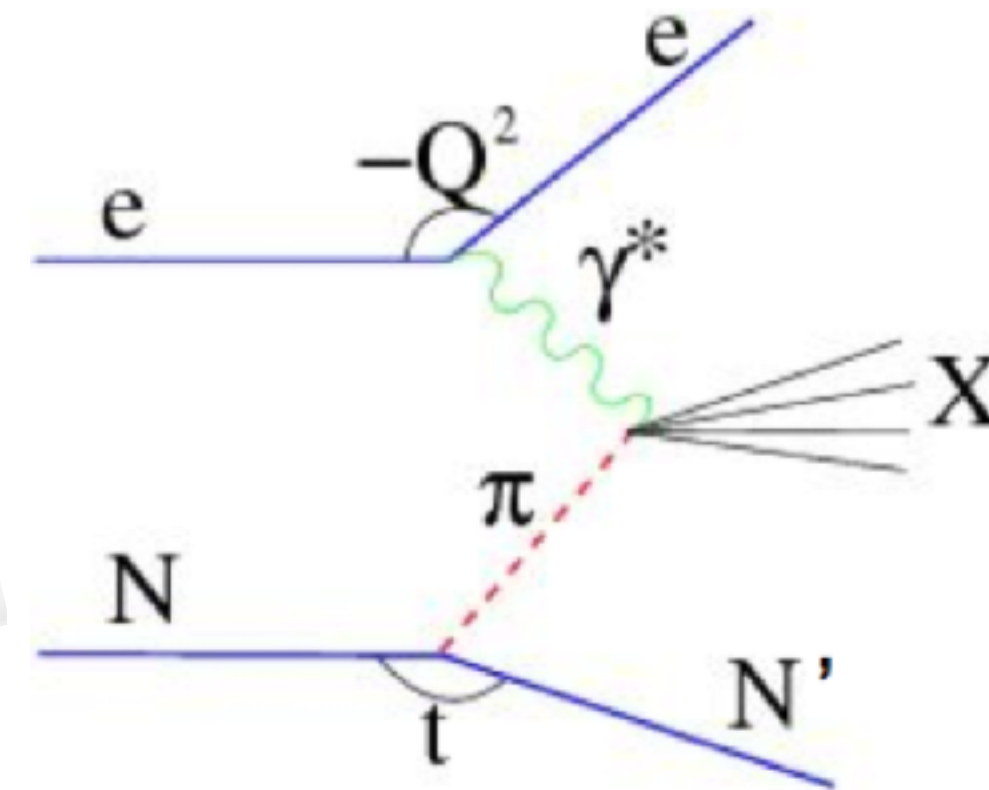
2

Measurement of Kaon Structure Function through Tagged Deep Inelastic Scattering (TDIS)

Kijun Park^{1,†,*}, Cynthia Keppel¹, Dave Gaskell¹, Alexandre Camsonne¹, Rachel Montgomery^{2,†}, John Annand², David Hamilton², Bjoern Seitz², Daria Sokhan², Kieran Hamilton², Tanja Horn^{3,†}, Dipanka Dutta⁴, Garth Huber⁵, Narbe Kalantarians⁶, Charles Hyde⁷, Sixue Qin⁸, Craig D. Robert⁸, Paul King⁹

¹ Jefferson Lab, Newport News, VA 23606, USA
² University of Glasgow, Glasgow G12 8QQ, United Kingdom
³ Catholic University of America, Washington, DC 20064, USA
⁴ Mississippi State University, MS 39762, USA
⁵ University of Regina, Regina, SK S4S 0A2, Canada
⁶ Virginia Union University, Richmond, VA 23220, USA
⁷ Old Dominion University, Norfolk, VA 23529, USA
⁸ Argonne National Laboratory, Argonne, IL 60439, USA
⁹ Ohio University, Athens, OH 45701, USA

* Contact Person
† Spokesperson



- DIS with spectator tagging:
→ effective free targets not easily found in nature
→ directly tag mesonic content of nucleon!

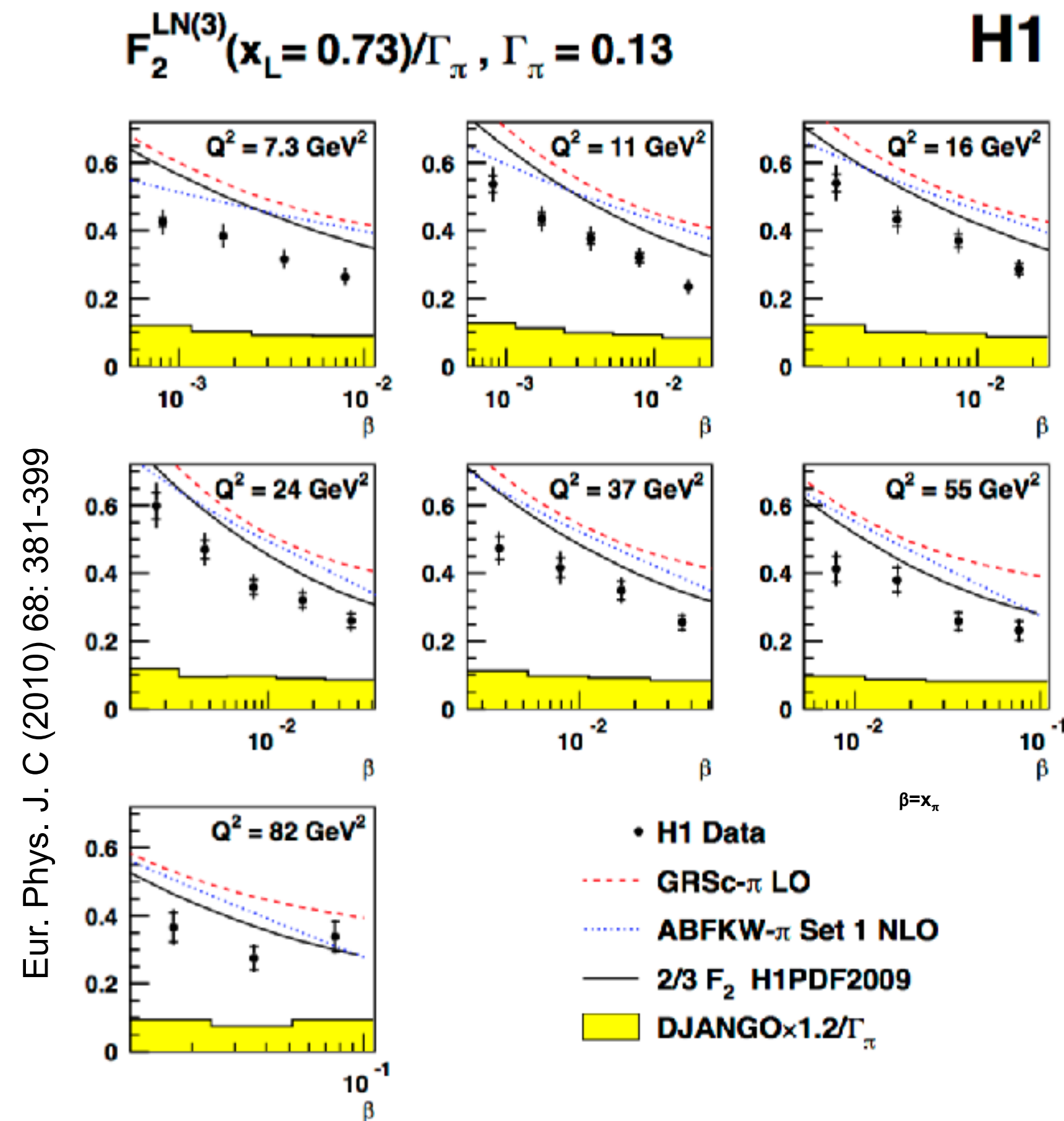
- Measure ratio of full inclusive to tagged DIS cross sections:
 - Access SF (i.e. hadron sub-structure)
 - SF → input for parton distribution functions

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E_0^2 \sin^4 \frac{\theta}{2}} \cos^2 \frac{\theta}{2} \left[\frac{1}{v} F_2(x, Q^2) + \frac{2}{M} F_1(x, Q^2) \tan^2 \frac{\theta}{2} \right]$$

- x = fraction of hadron's longitudinal momentum carried by struck quark
- $Q^2 = (4\text{-mom transferred by } \gamma^*)^2$

- TDIS aims:
 - Pion and kaon F_2 SF in valence regime

- Where will TDIS lie amongst existing meson SF data?



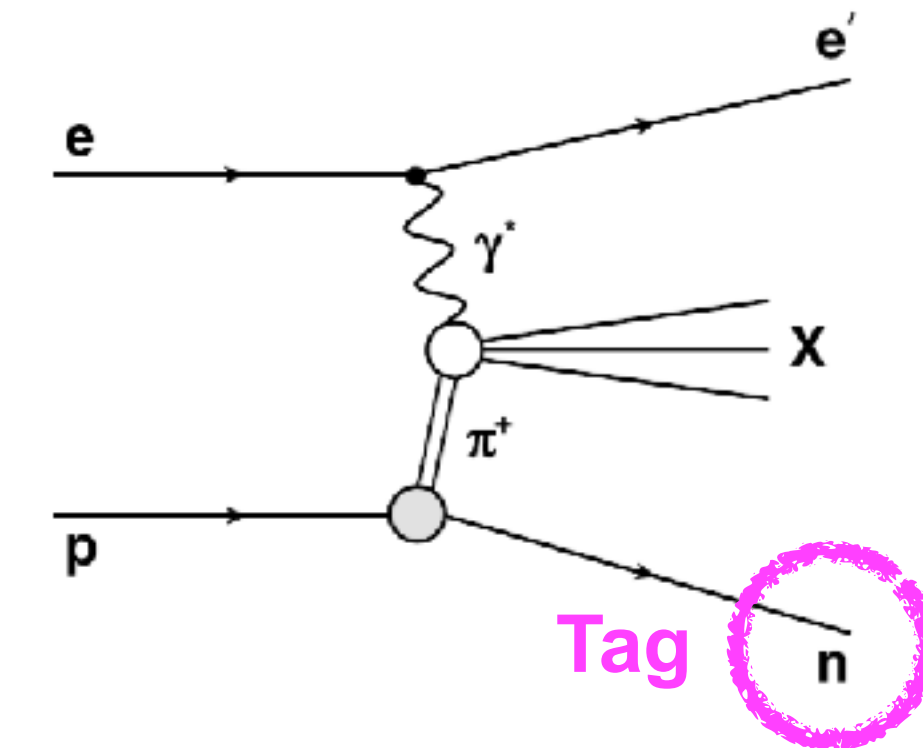
HERA Tagged DIS

- Sullivan process and meson cloud virtual target

- Pion sea region, low Bjorken x , high Q^2
- $6 < Q^2 < 100 \text{ GeV}^2$; $1.5e^{-4} < x < 3.0e^{-2}$

- Leading neutron tagged in $ep \rightarrow e'Xn$
- Charged pion SF extracted

Diffractive scattering and forward detectors

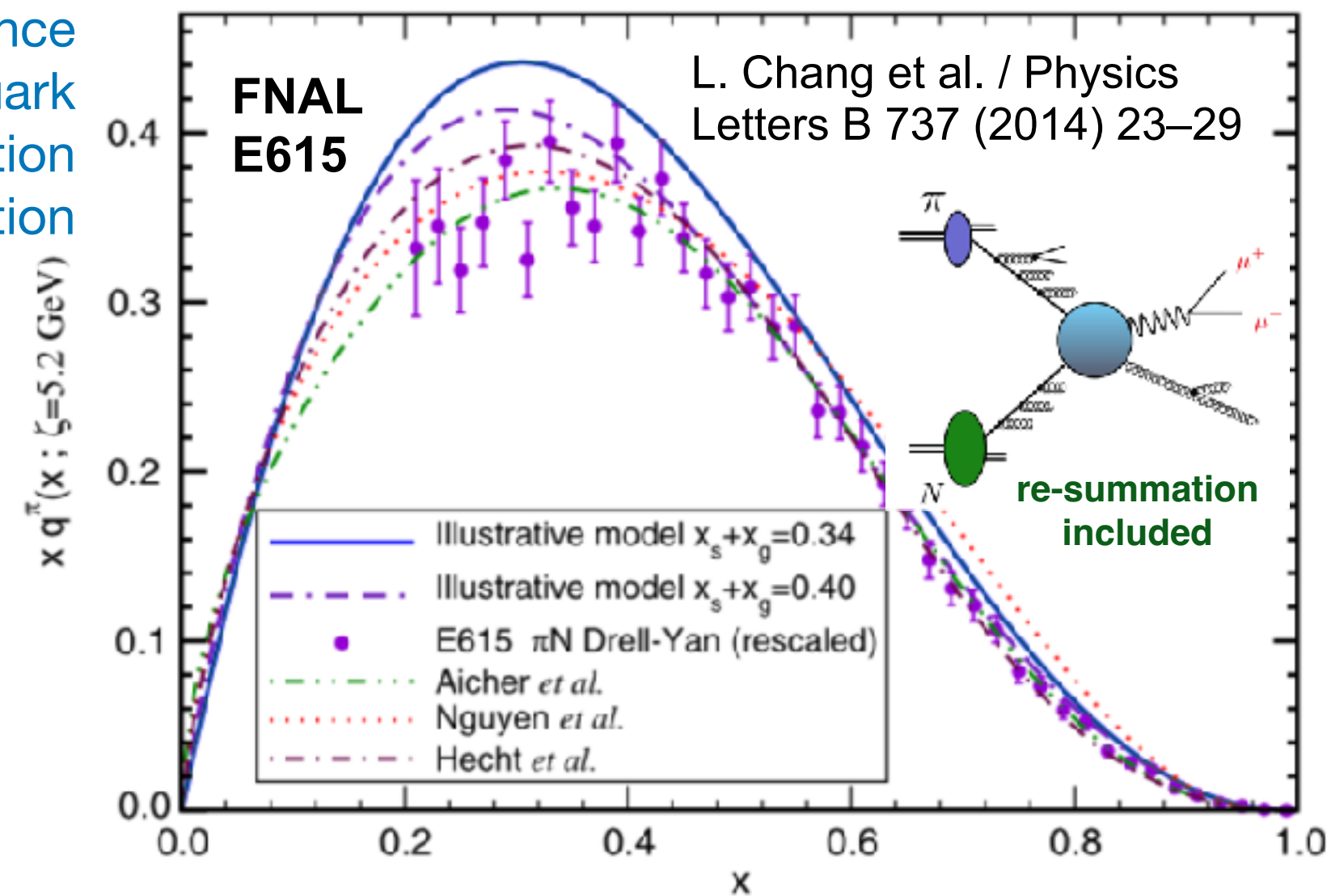


TDIS:

- Valence regime
- Higher x , lower Q^2
- Evolution between kinematics

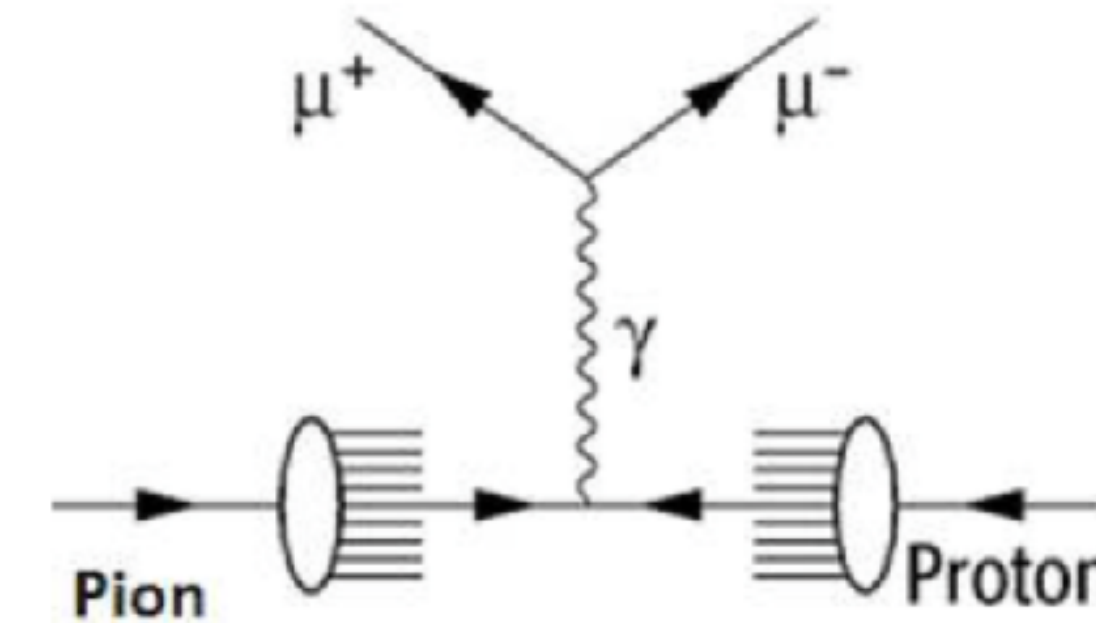
Previous Data

Pion valence
quark
distribution
function

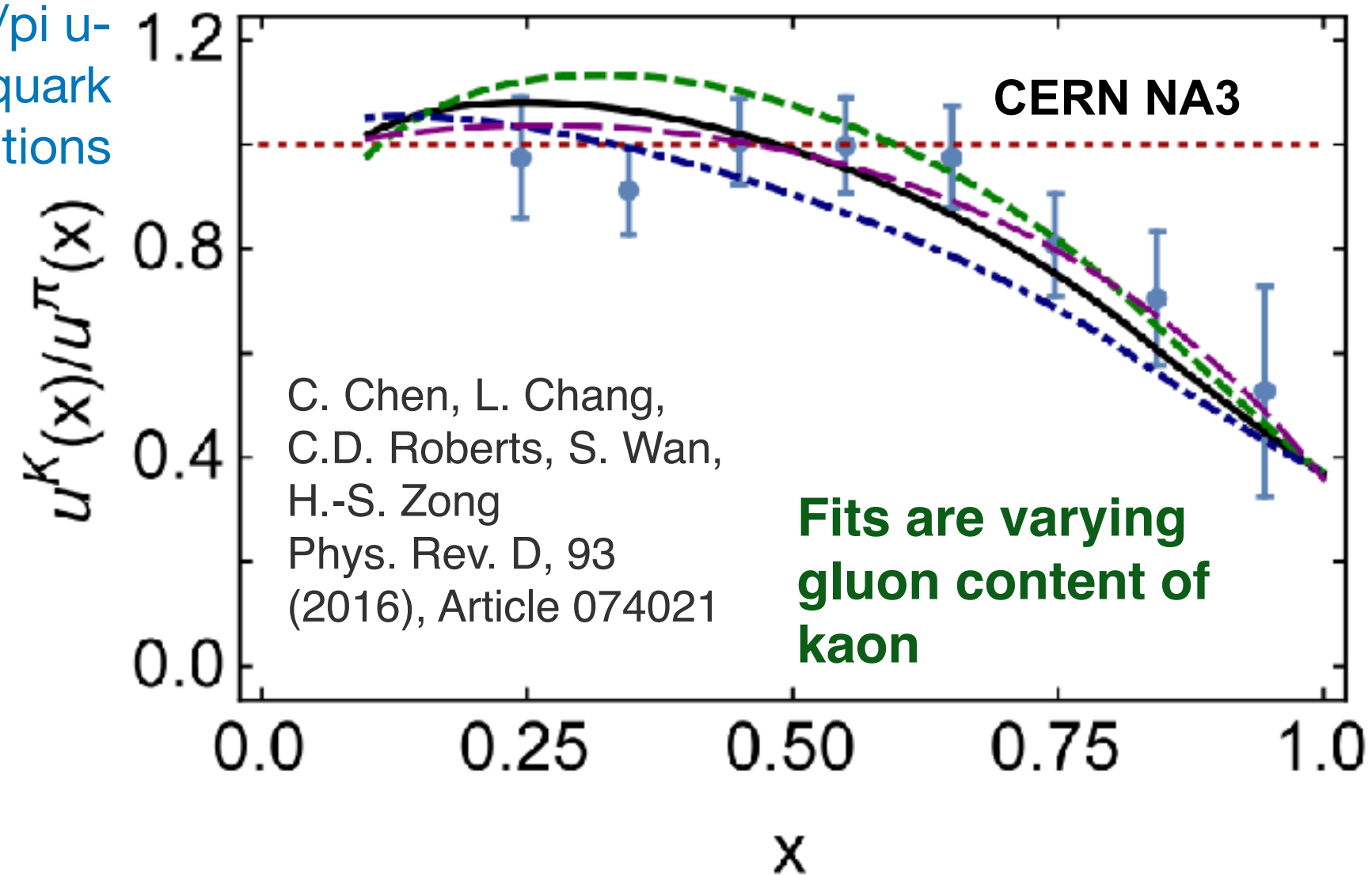


Valence region - Drell Yan

- CERN/Fermilab data



Ratio K/pi u-
quark
distributions



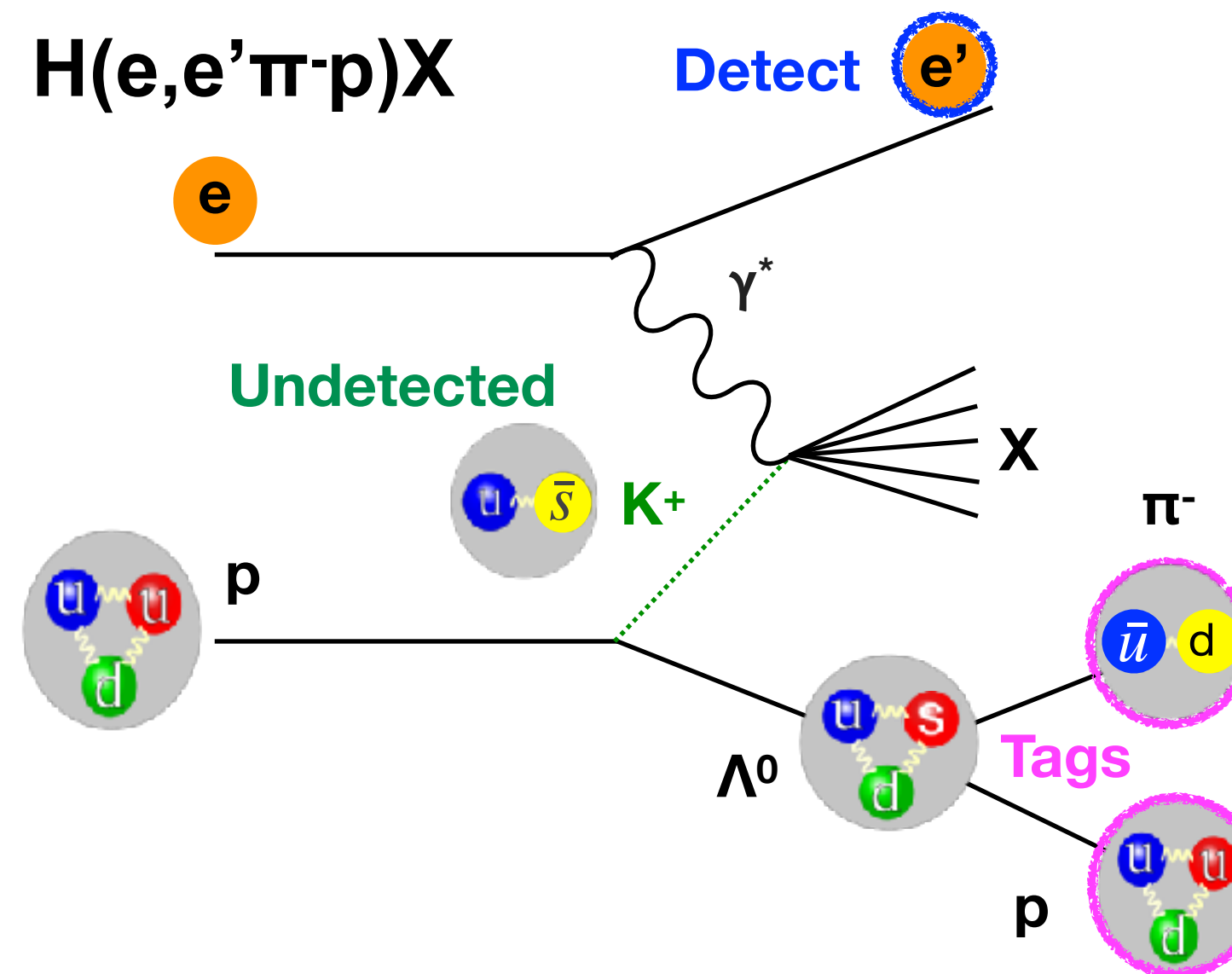
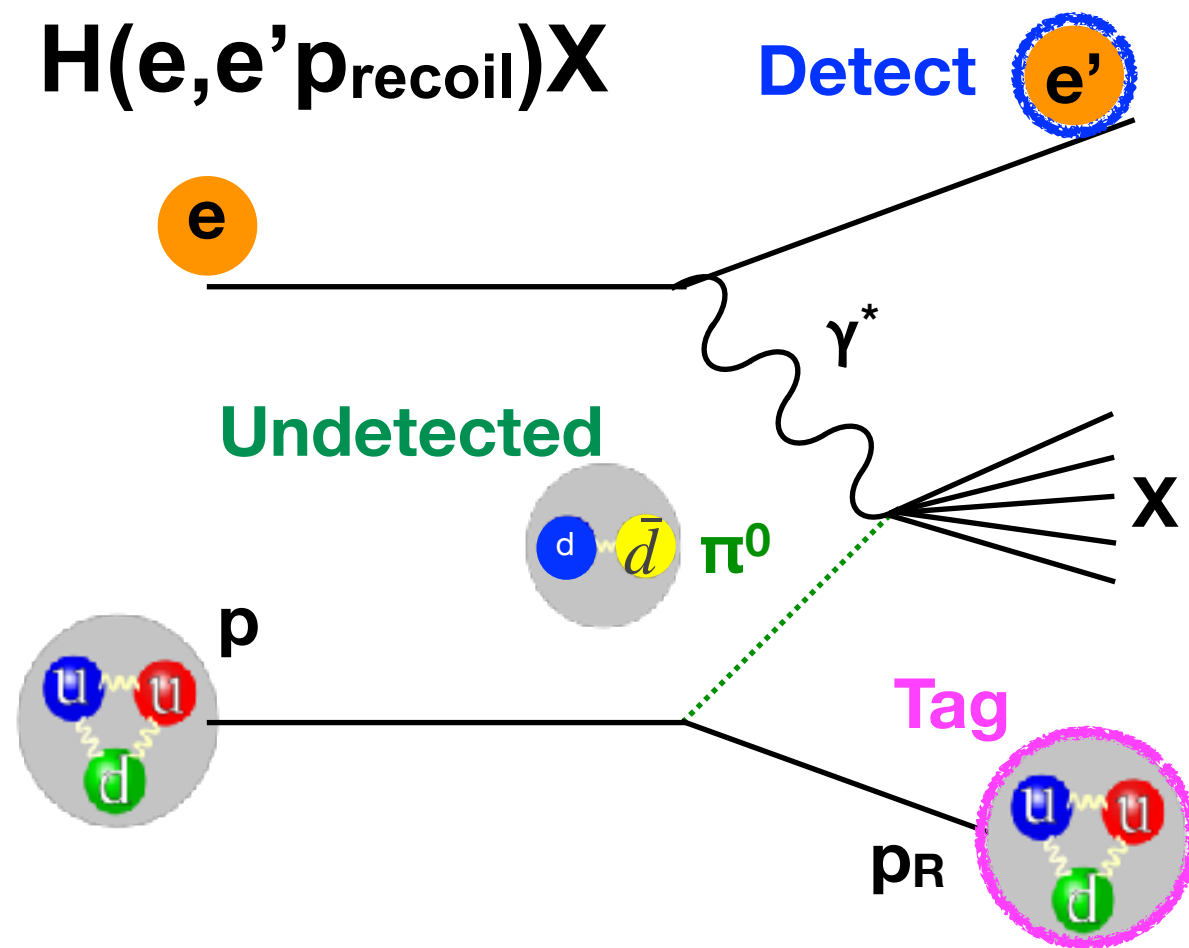
- Large-x region - QCD model tensions (pQCD, DSE, light-front), gluon re-summation and non overlapping uncertainties in some global PDF analyses
- Practically non-existent data for kaon

TDIS

- Independent cross-check
- Extend to neutral pions
- More data also coming from Drell Yan with COMPASS++/AMBER at CERN SPS (see 2019 LOI arXiv:1808.00848, pion beams on tungsten/carbon targets)
- More data essential

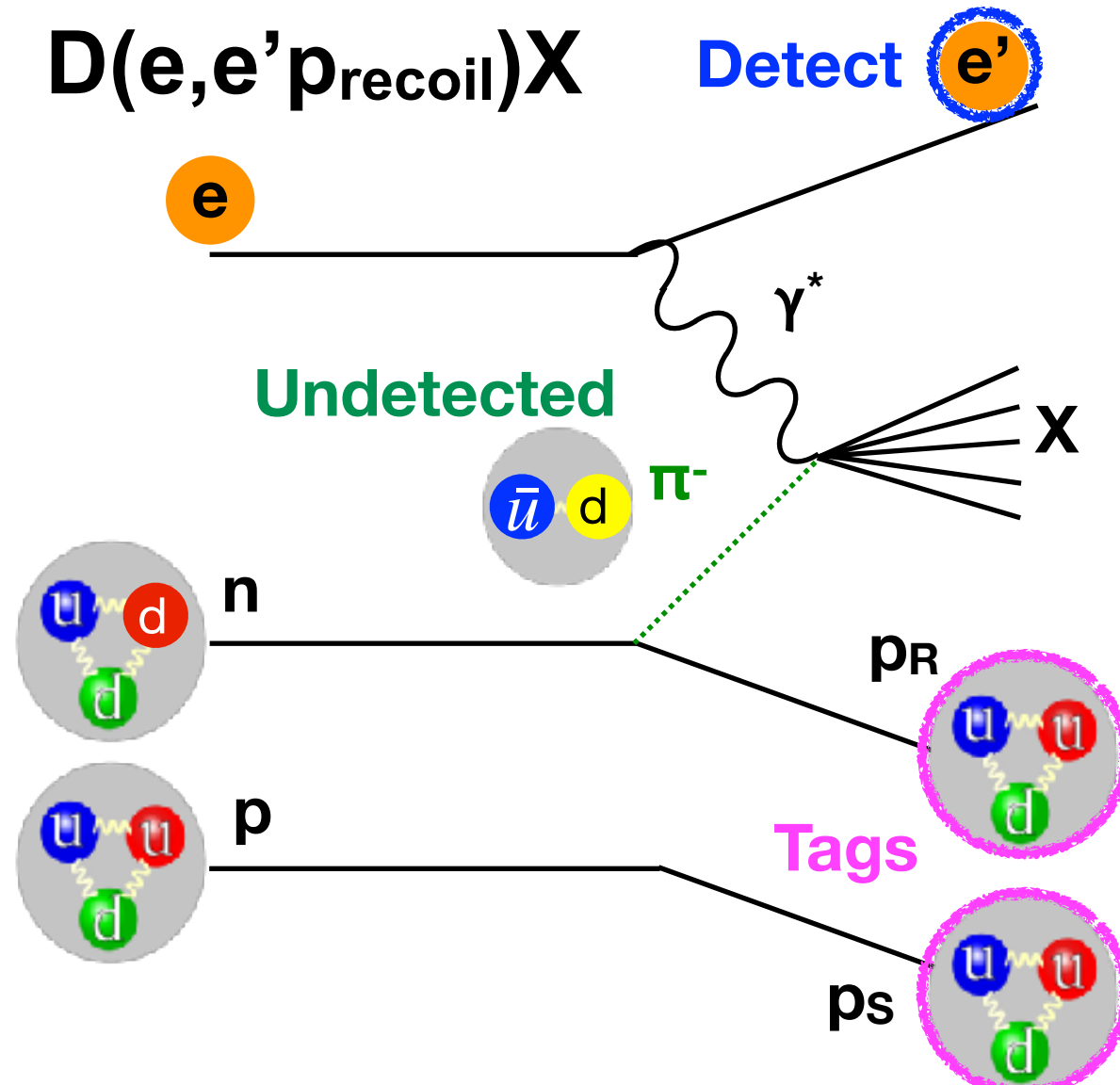
TDIS Measurements

1st direct
neutral
pion
extraction



1st direct
kaon
extraction

Resolve
QCD model
tensions/
add data for
charged
pion



$8 < W^2 < 18 \text{ GeV}^2$
 $1 < Q^2 < 3 \text{ GeV}^2$
 $0.05 < x < 0.2$
 DIS Regime

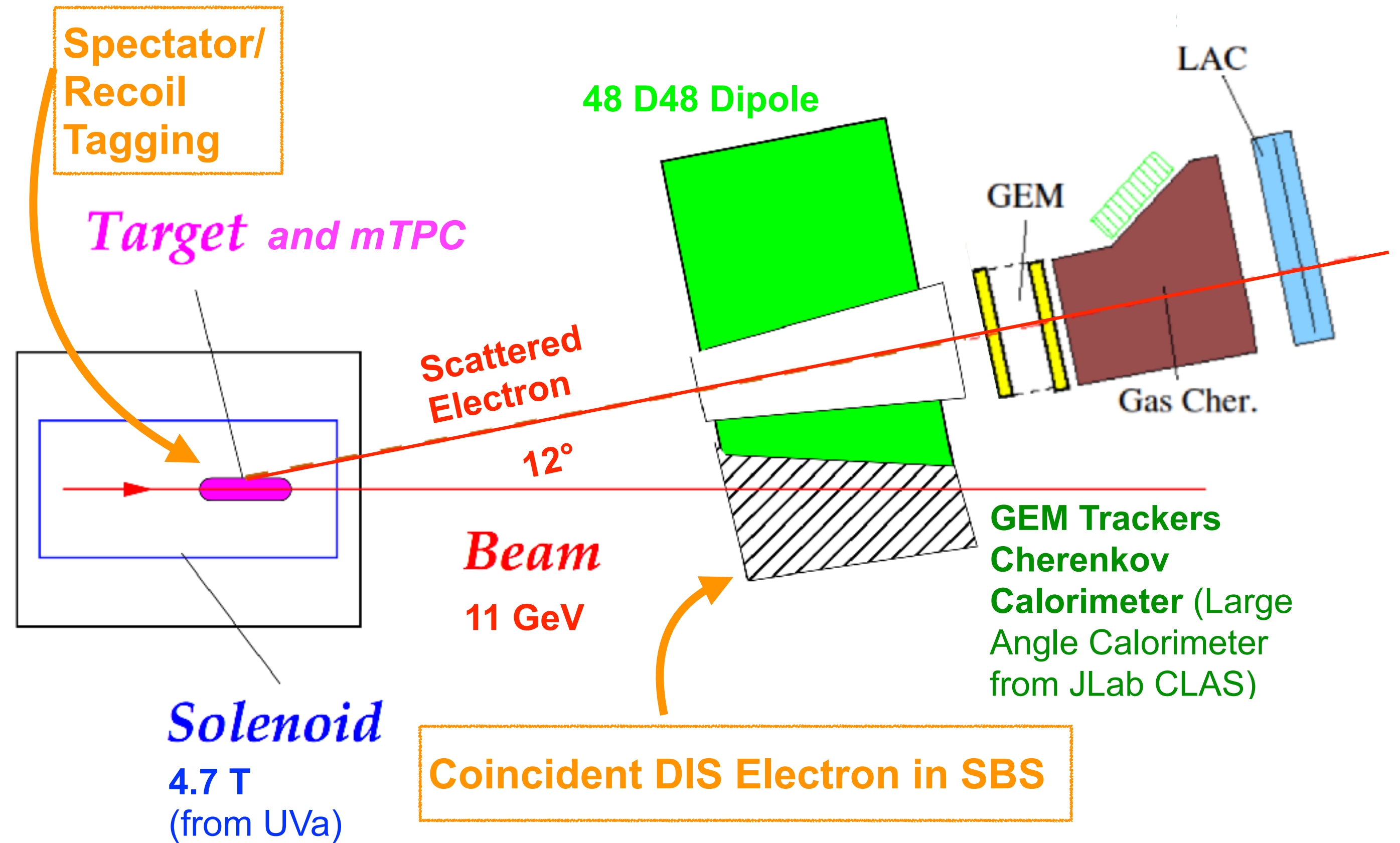
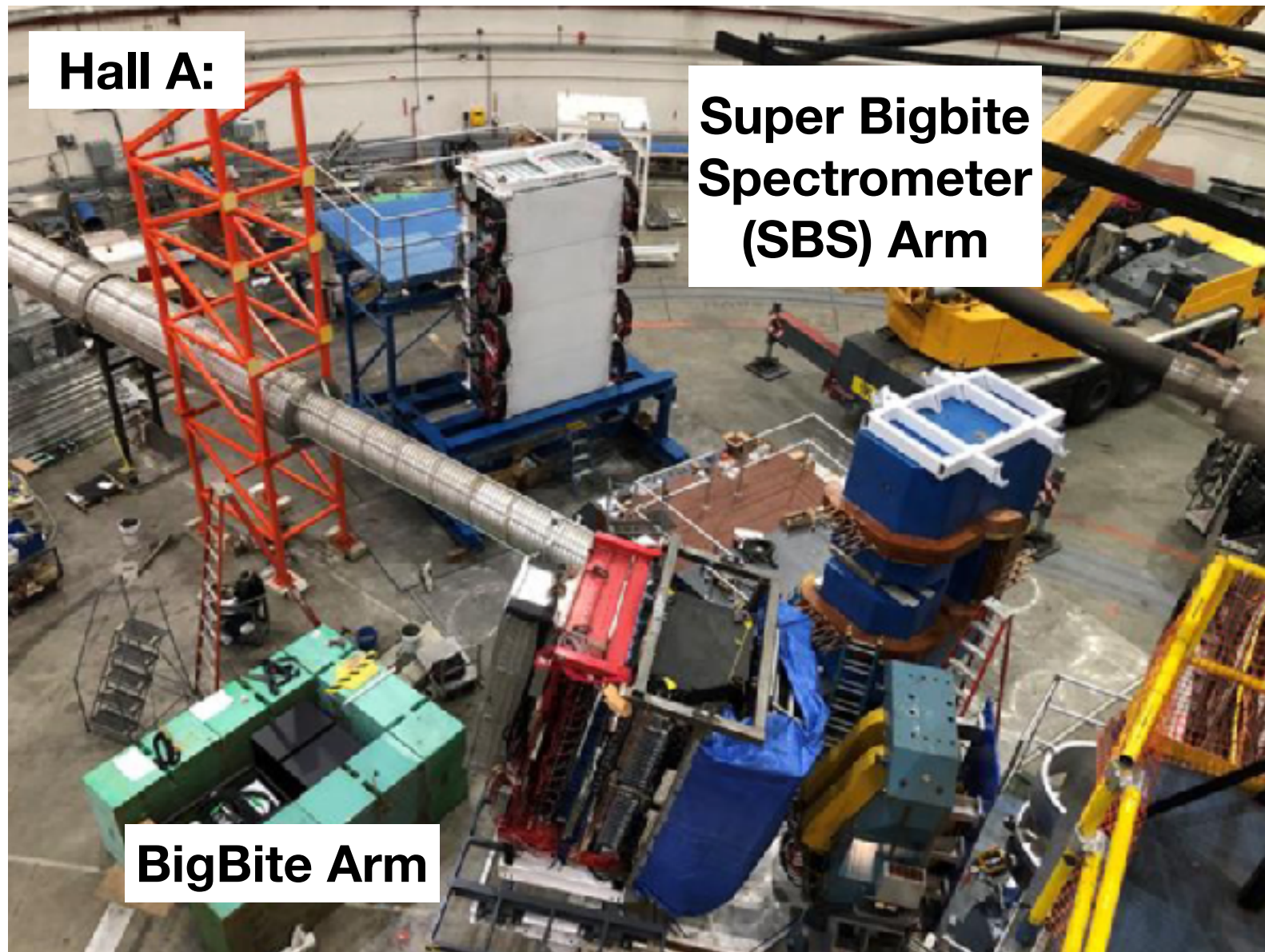
Novel detector essential for tagging
very low momentum recoiling
hadrons (60 - 400 MeV/c)...

Experimental Setup



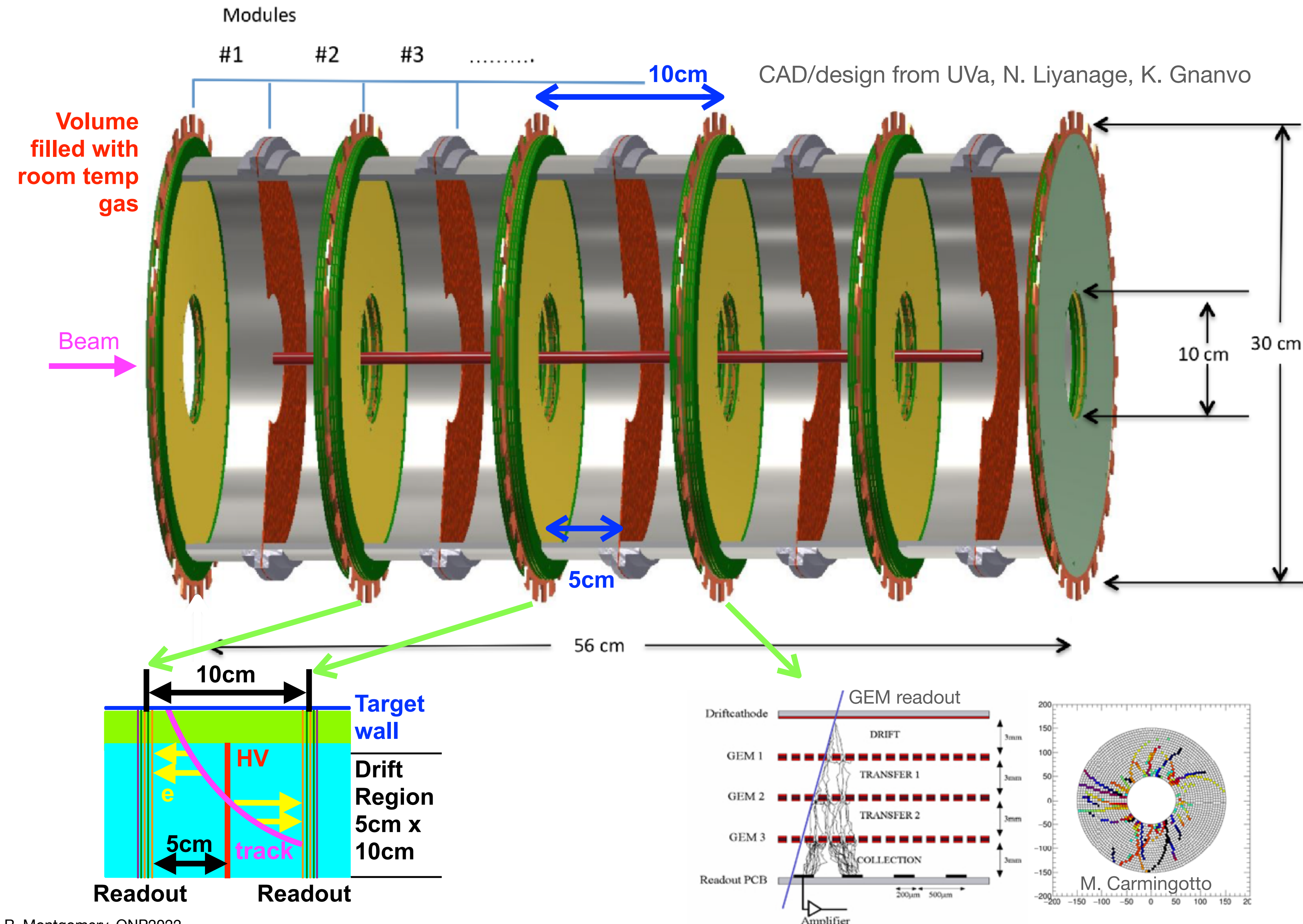
Jefferson Lab, VA, USA:

- Hall A:
 - New open geometry spectrometers
 - Higher luminosities
 - 10^{38-39}Hz/cm^2
 - Increased acceptance
 - Decreasing cross-sections at higher Q^2 ($>10\text{GeV}^2$)
- Rare DIS processes



- **SBS**: Refurbishments/upgrades underway (MSU (D. Dutta)/UConn (A. Puckett)/JLab (S. Malace)/U Tenn (N. Fornin)....)
- High density room temperature H/D **target**; 40cm length; 1cm diameter; 4atm
 - Development and prototyping: D. Dutta (MSU) with JLab
- 11 GeV e^- beam, $50\mu\text{A}$, **high luminosity** $\sim 3 \times 10^{36}\text{Hz/cm}^2$
- Multiple Time Projection Chamber (mTPC)...

High Rate mTPC

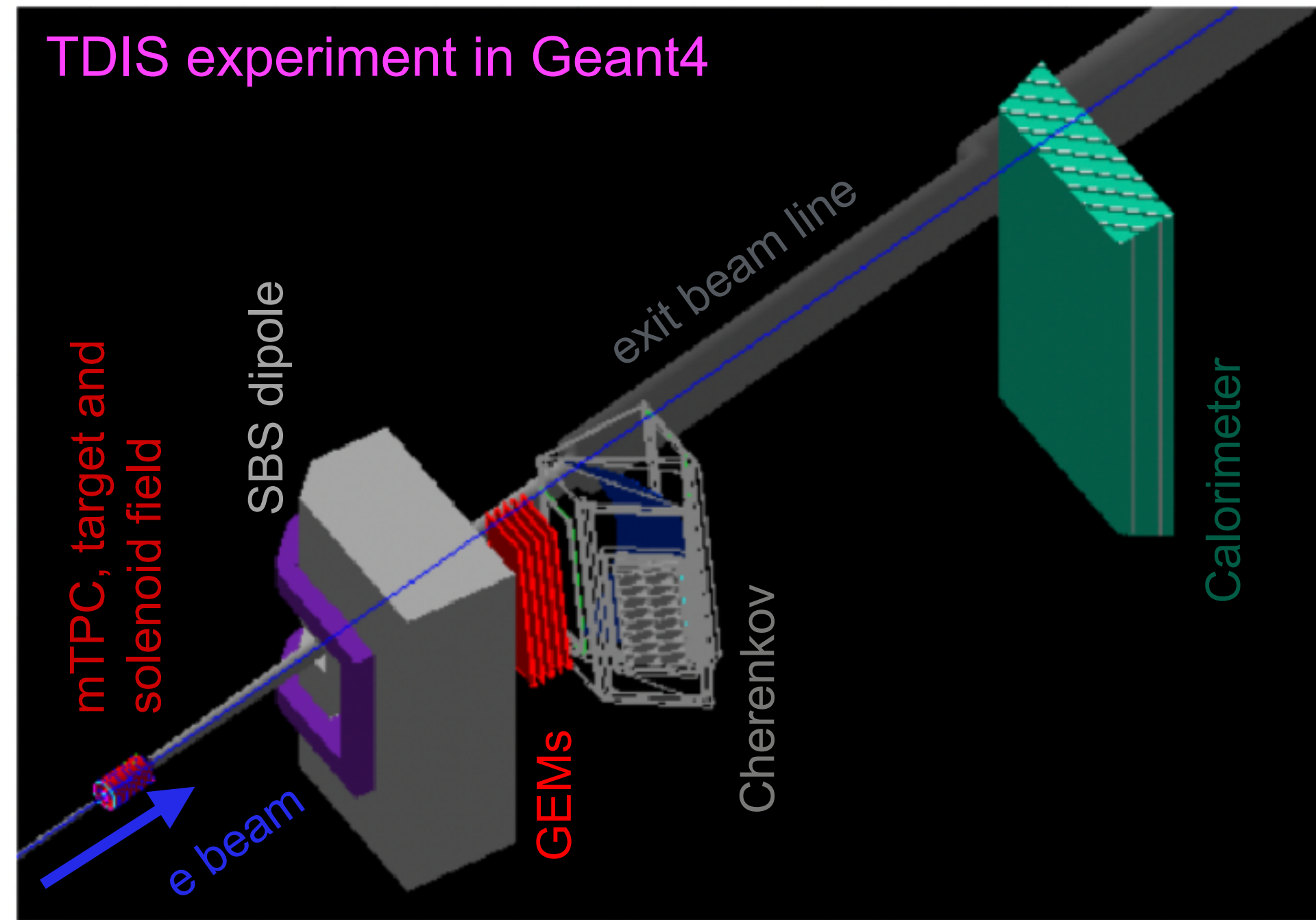


CAD/design from UVa, N. Liyanage, K. Gnanvo

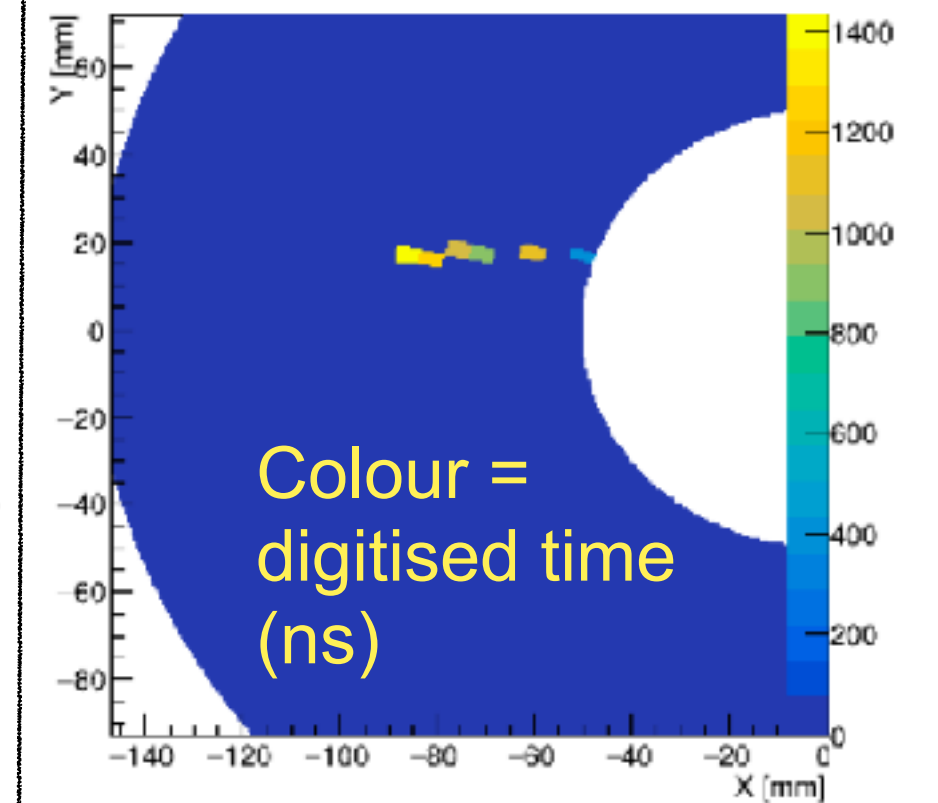
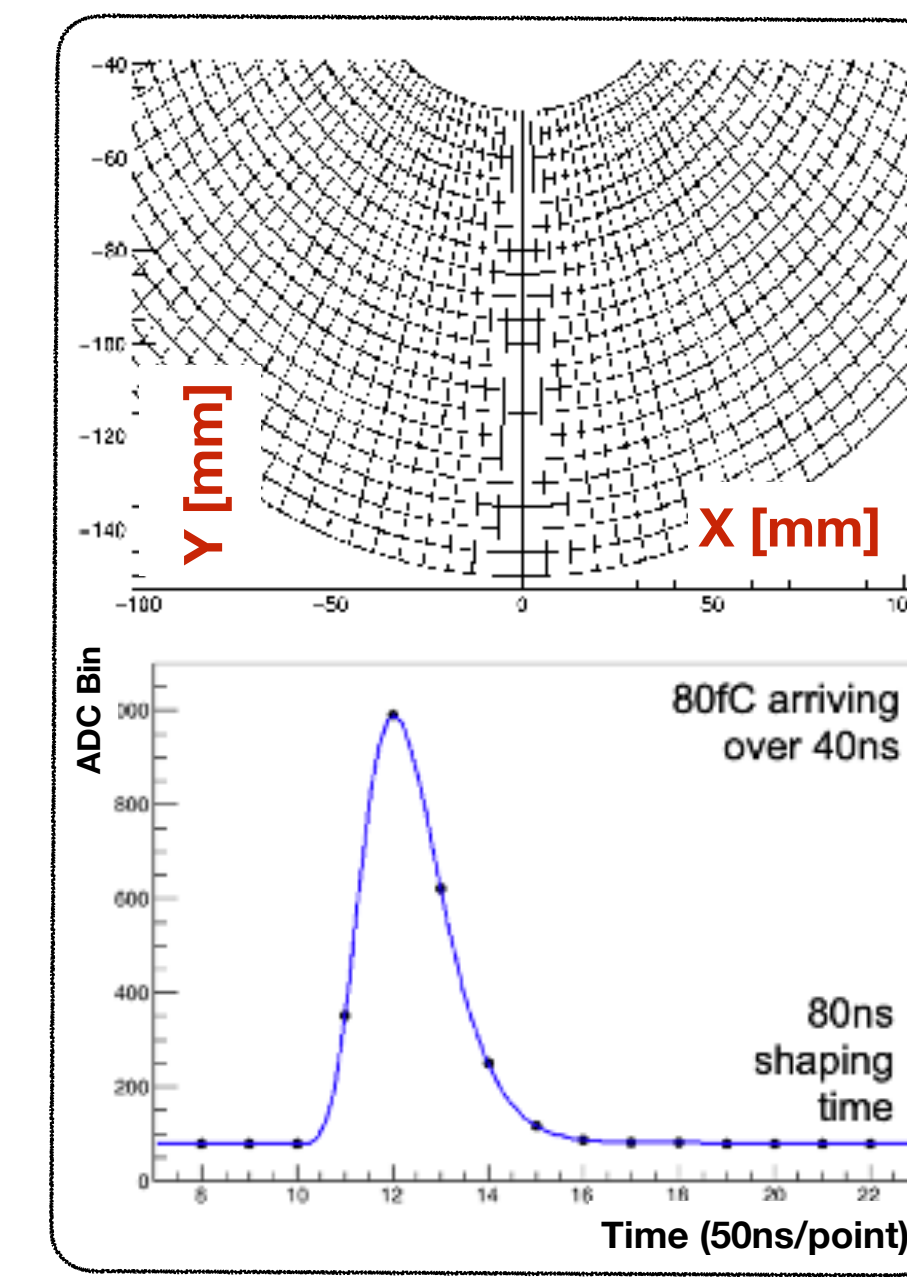
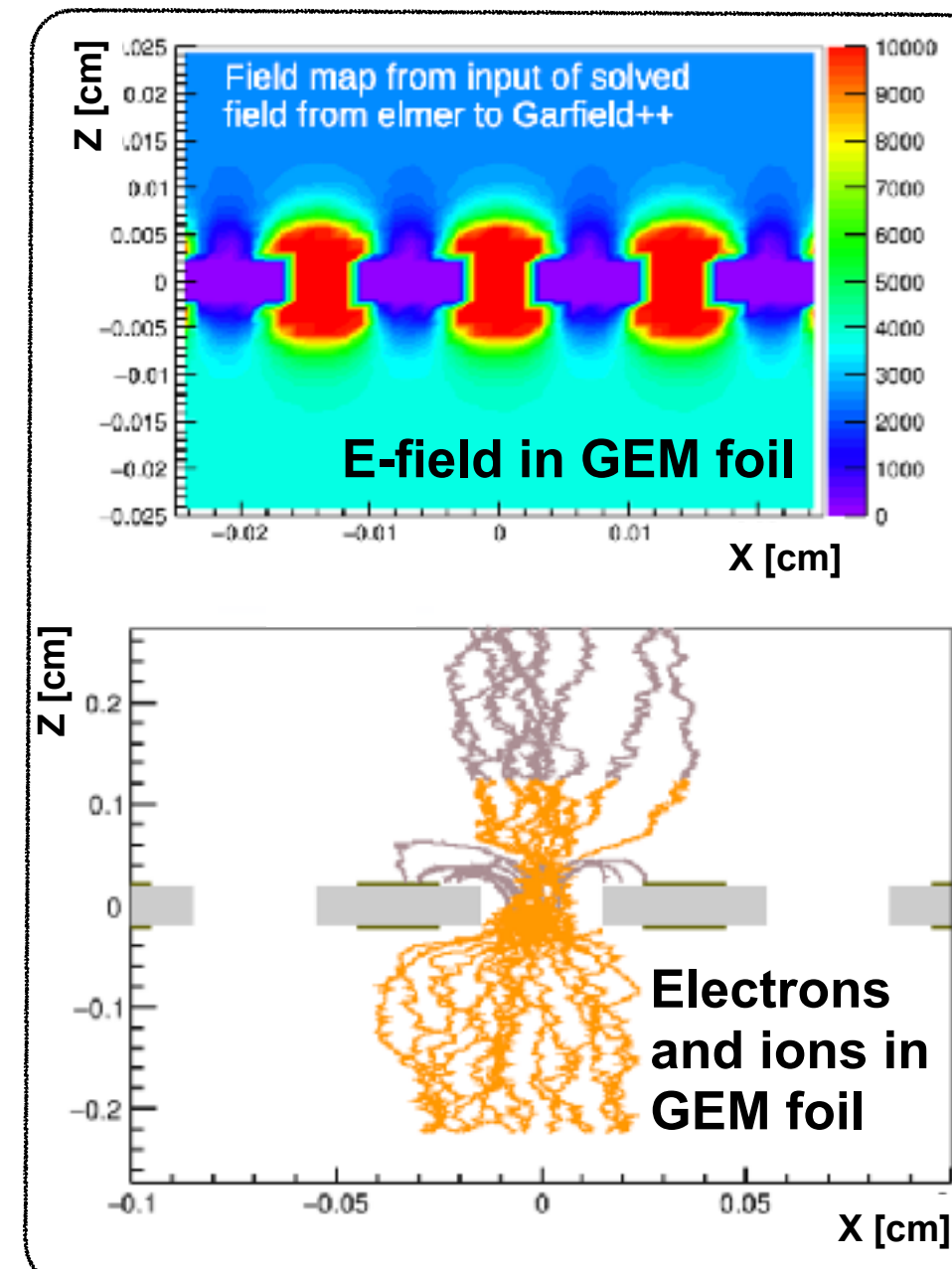
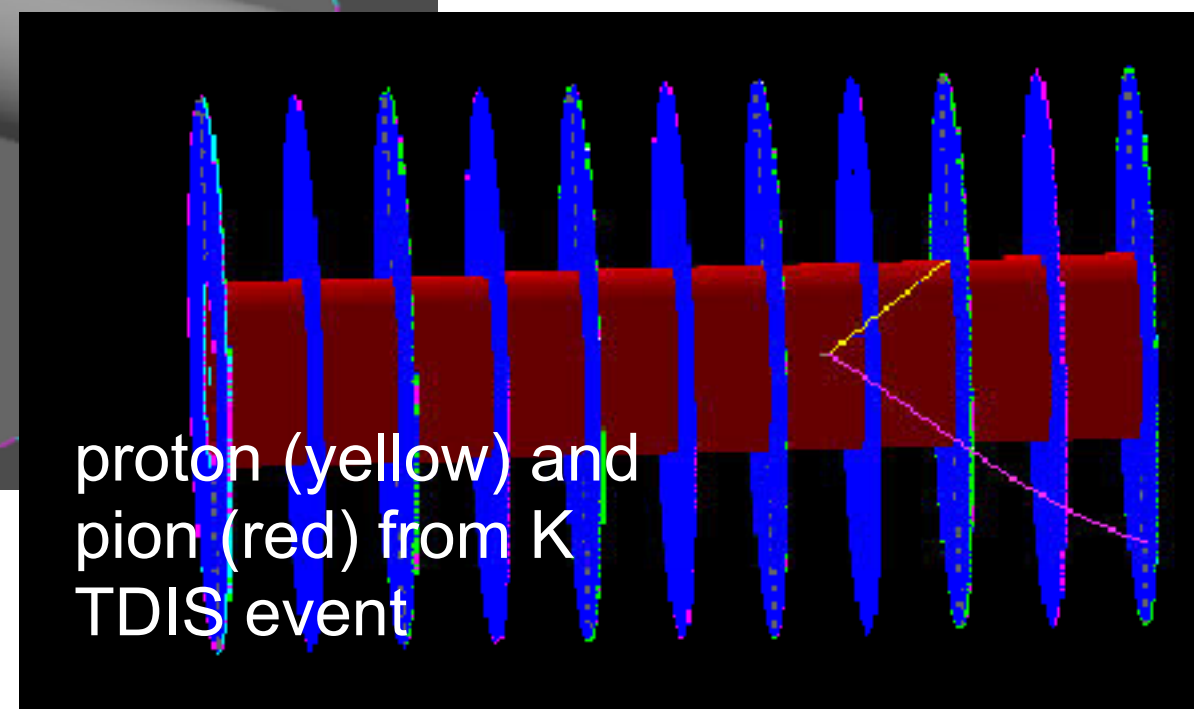
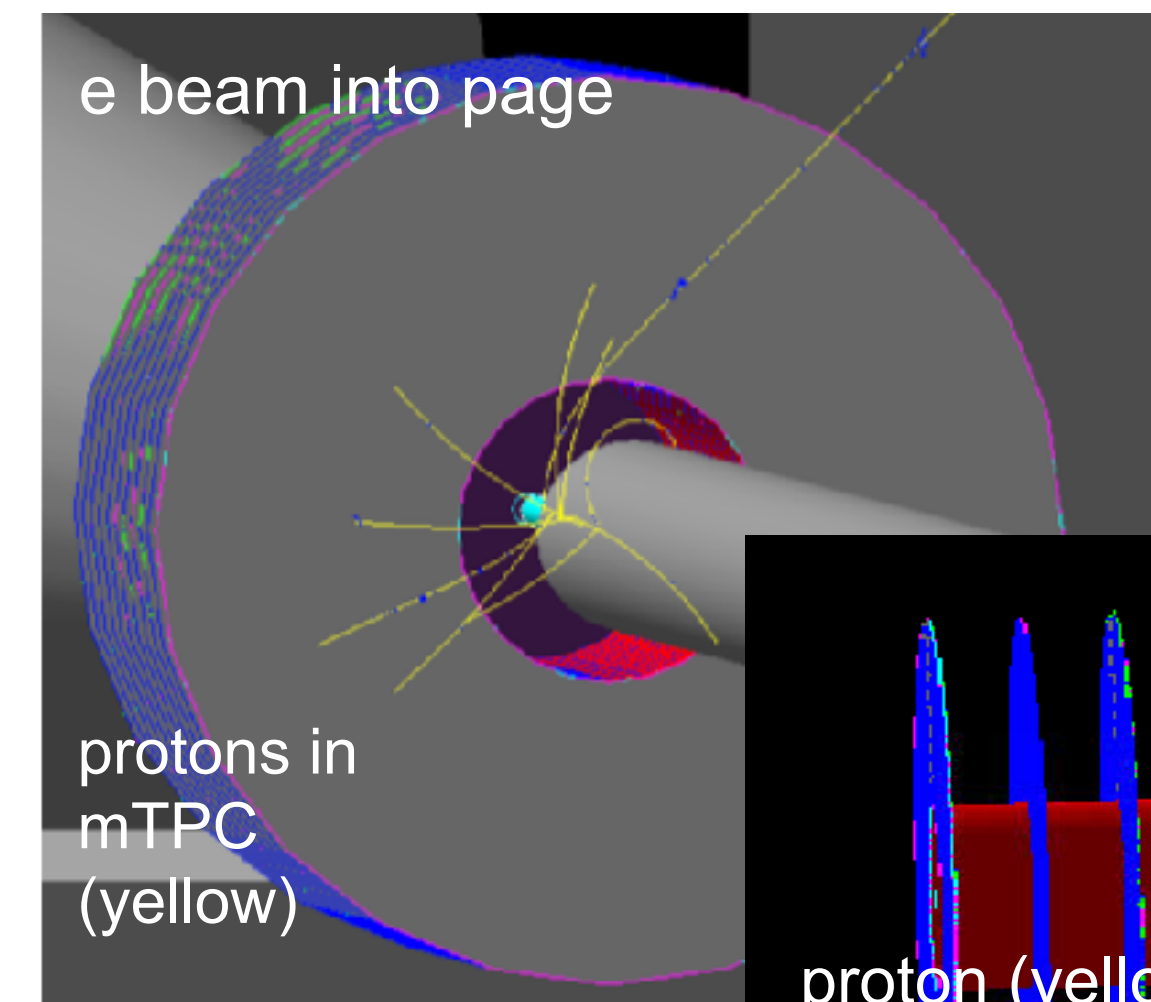
- Tagging recoils/spectators
 - Vertex and momentum analysis
 - PID by dE/dx
- Division of volume into chambers **reduces background rates**
 - e.g. $\sim 700\text{MHz} \rightarrow 70\text{MHz/module}$
- Readout planes
 - Multi layer GEM foils
 - Segmented readout pads

TDIS Simulations

TDIS experiment in Geant4

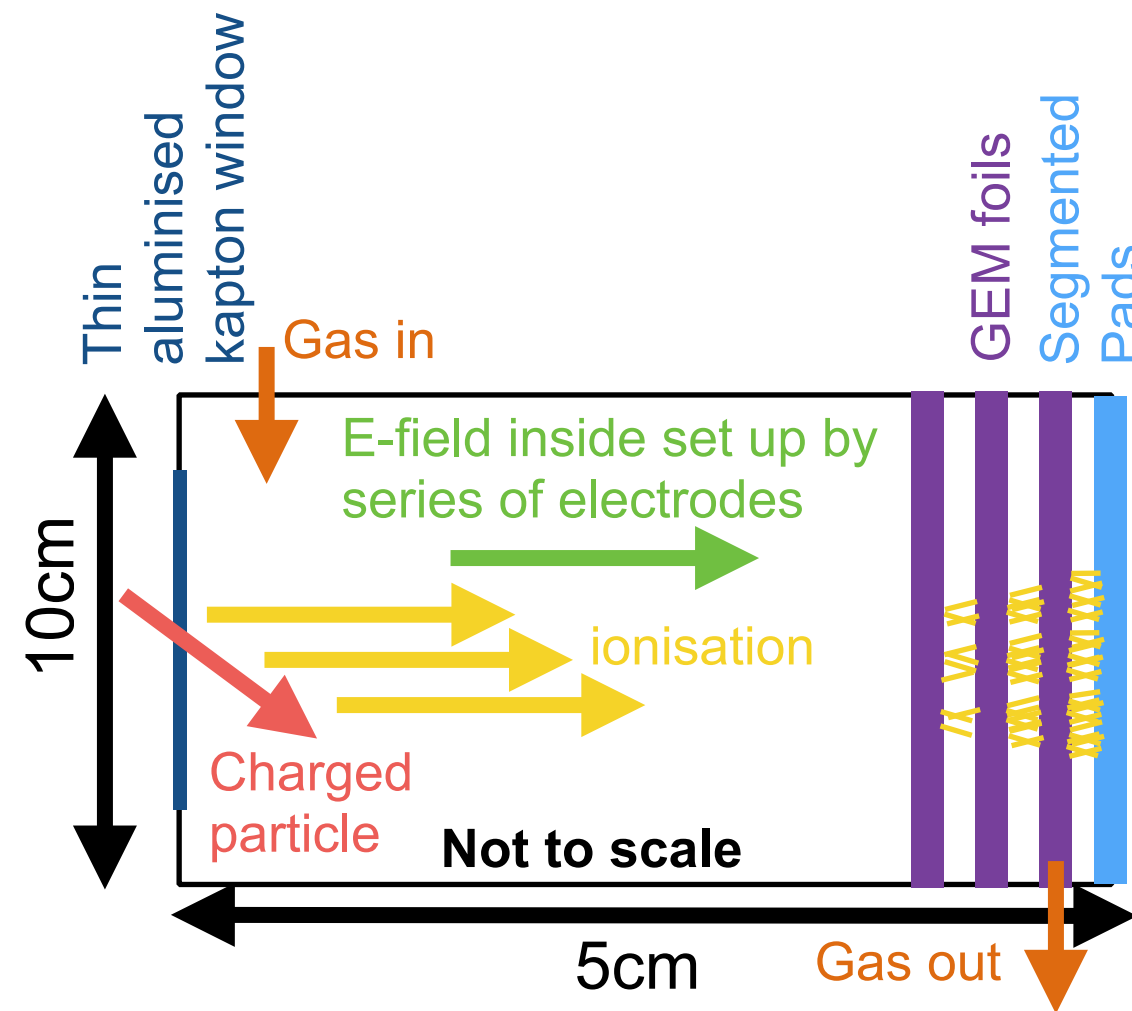


- Fully described in **Geant4** (within SBS collaboration framework)
- Team of contributors (e.g. C. Gayoso, E. Fuchey, S. Wood, A. Tadeipalli, D. Dutta, S. Ali, M. Carmingotto, R. Montgomery...and more)
- **mTPC simulated using CERN's magboltz/garfield**
 - Gas mixtures; electric field; drift properties
- **Event generators and background/accidentals rate studies**
 - H2 - elastic protons; D2 - photodisintegration/QE scattering/delta production
- **Digitisation and tracking underway**
 - Initial chain finding algorithm demonstrated mTPC capability for challenging TDIS high rate demands

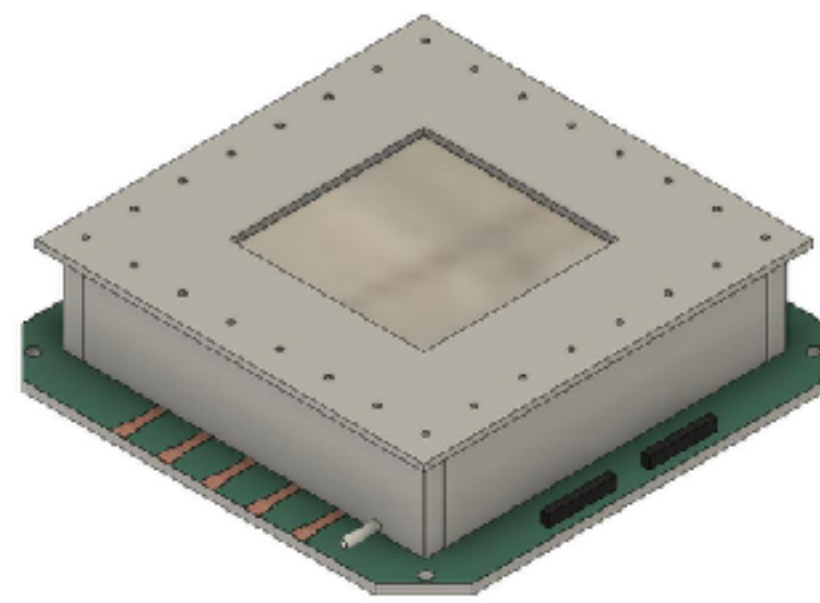


Example pad configuration
22 rings
122 pads/ring

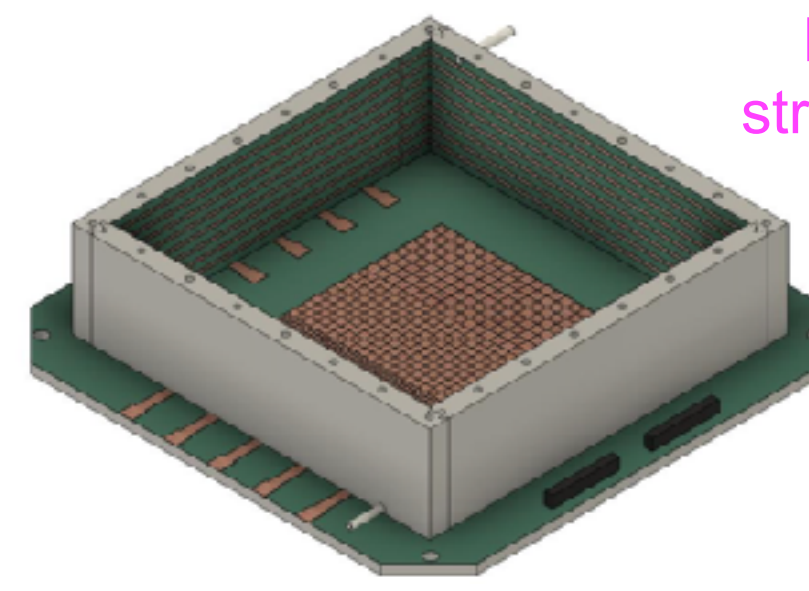
mTPC Prototyping



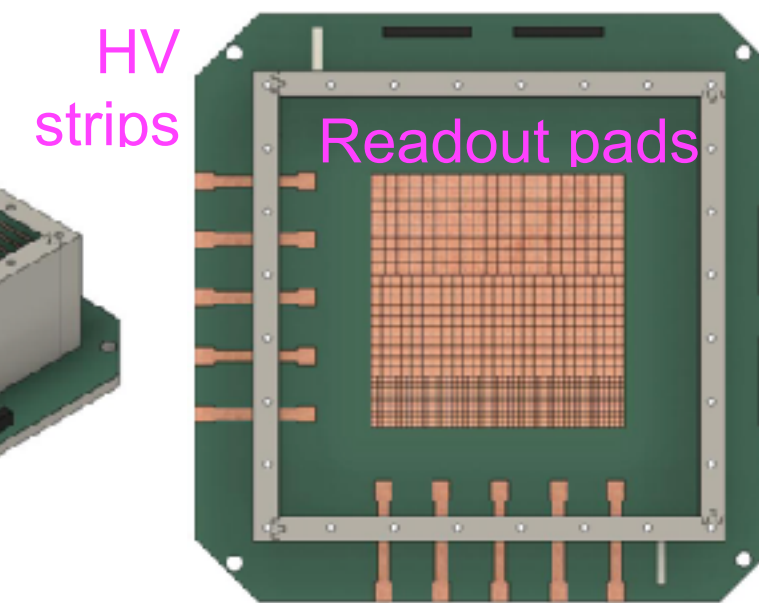
- Currently University of Virginia constructing **1st prototype mTPC chamber**
 - S. Ali, N. Liyanage,...
 - Square design; 10 x 10 cm² GEM active area
 - Three GEM foils stacked with 2mm spacing
 - 5cm drift
- Aims: tune simulation, test readout pads, electronics, gas mix choice, field, ion back flow...
- Further prototyping planned



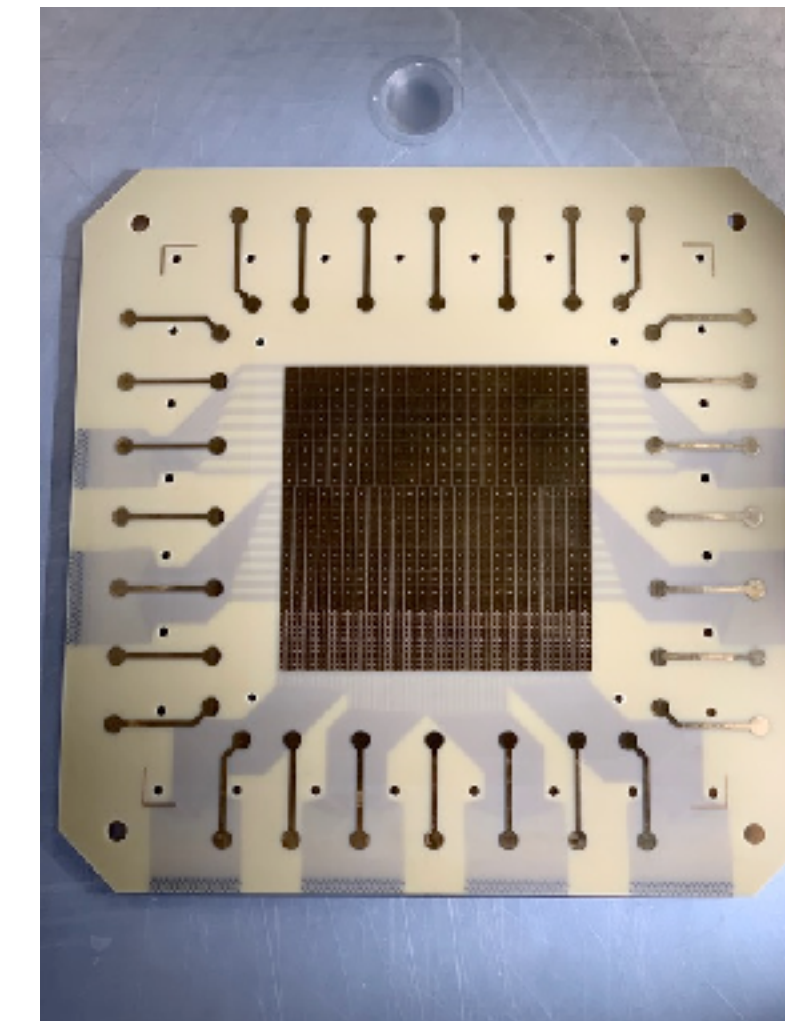
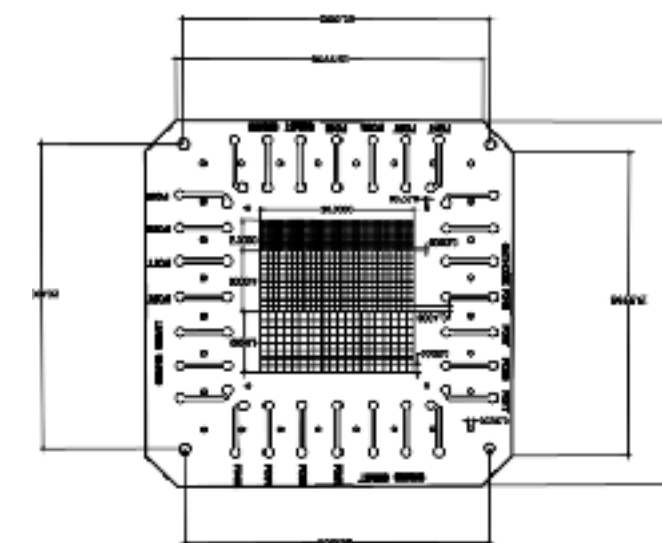
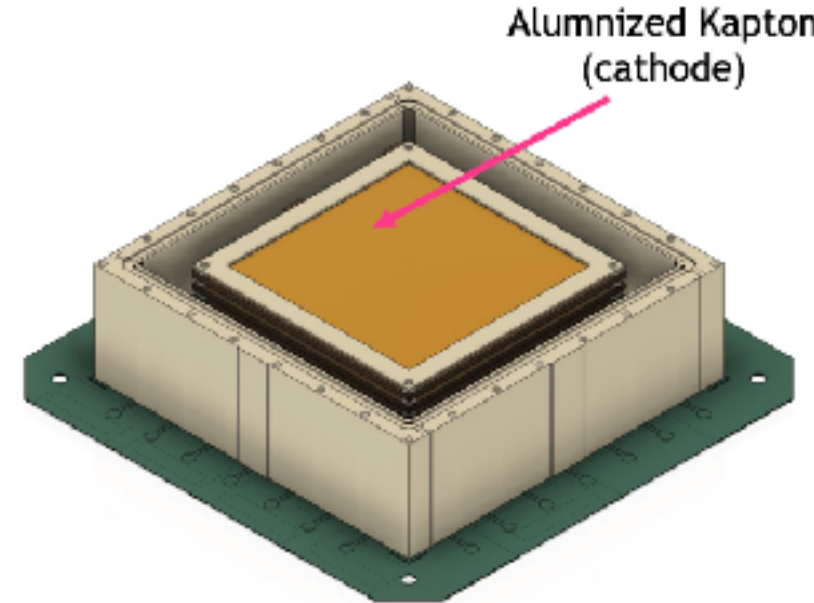
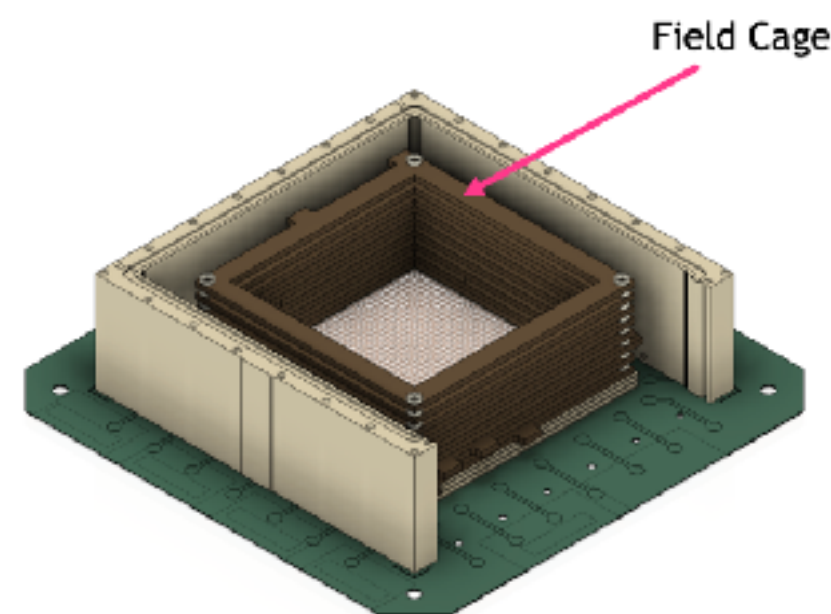
Design and CAD model:
S. Ali, UVa



Field set up by
electrode strips

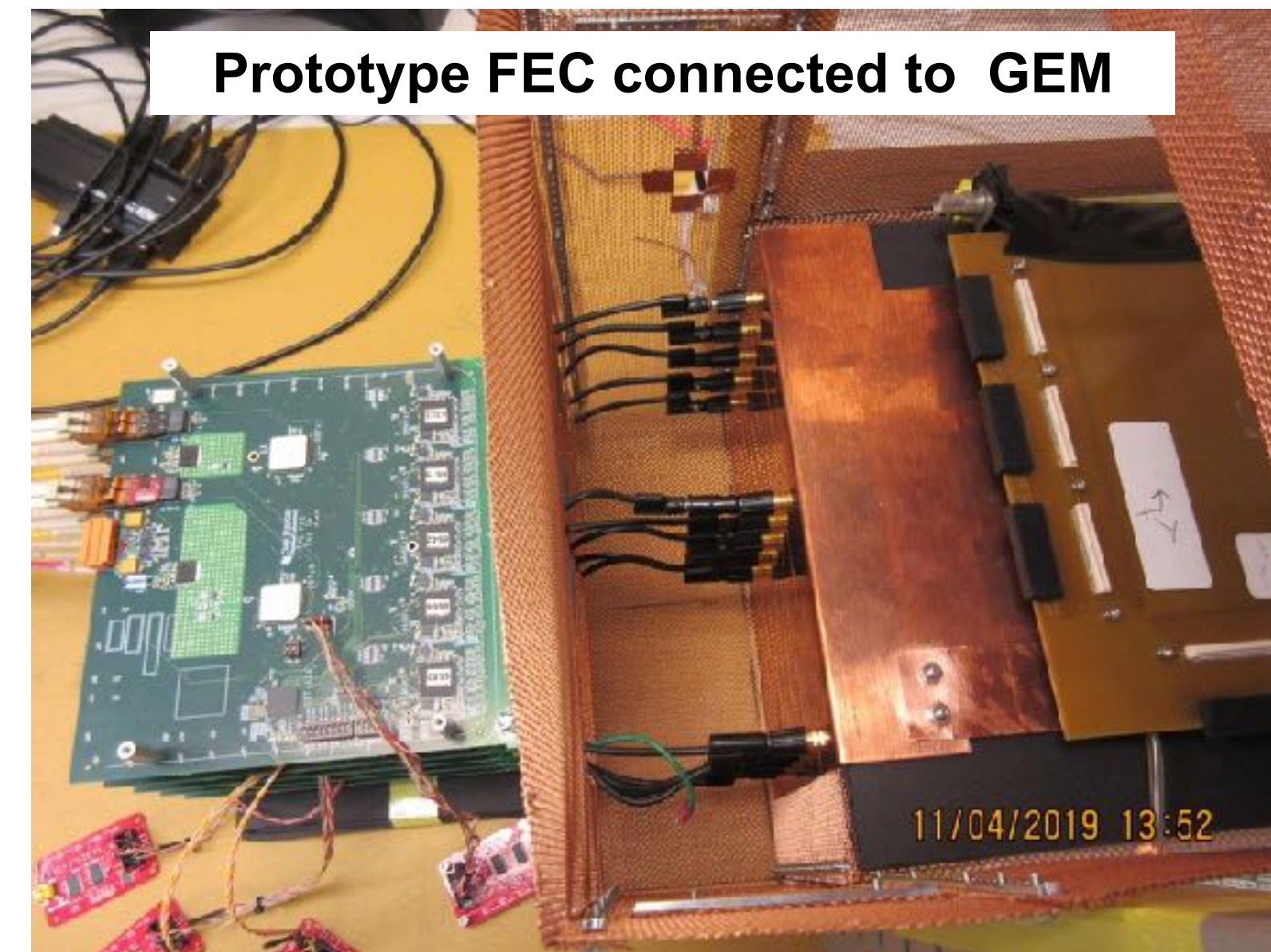
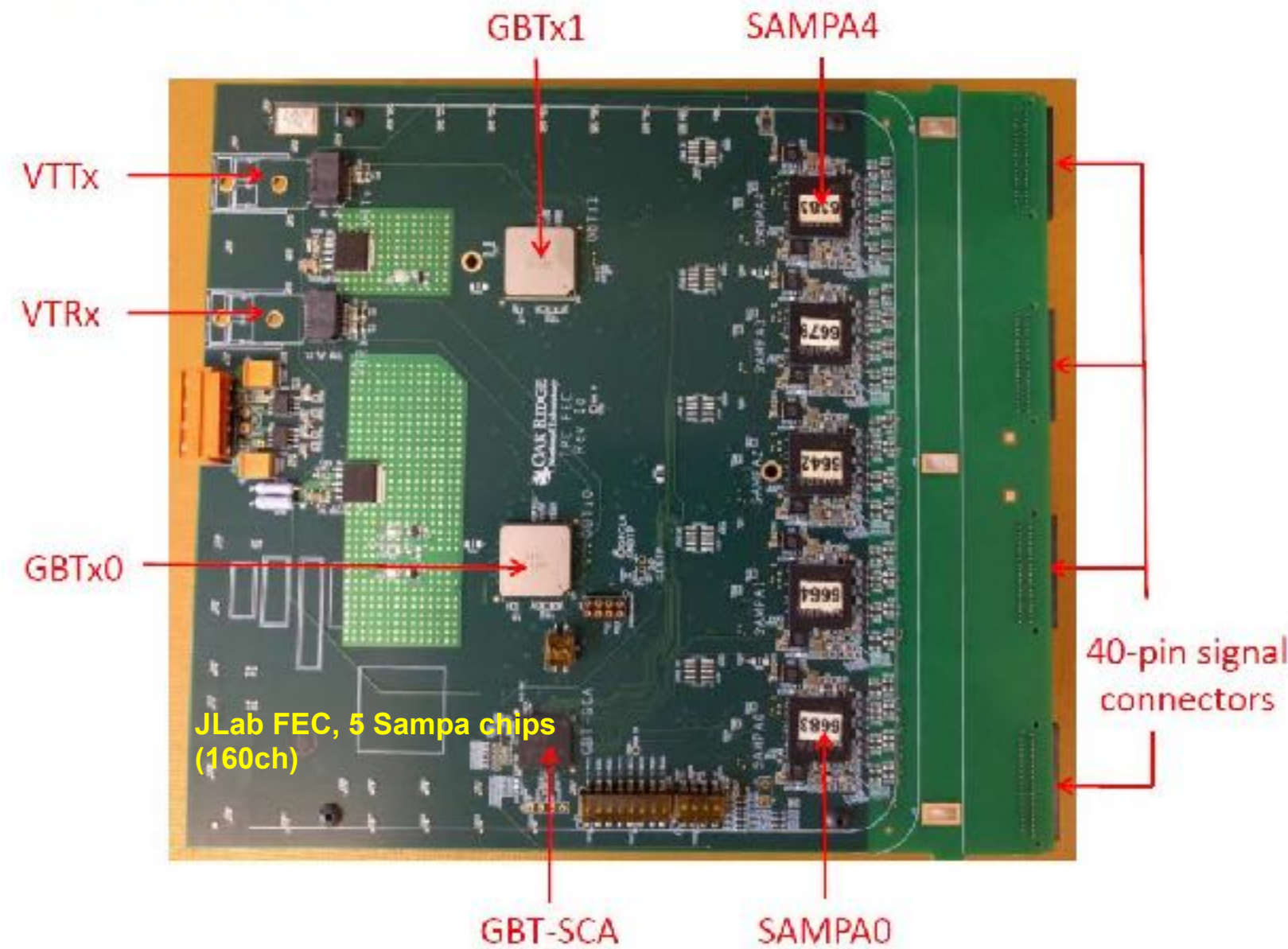


Different sized
pads

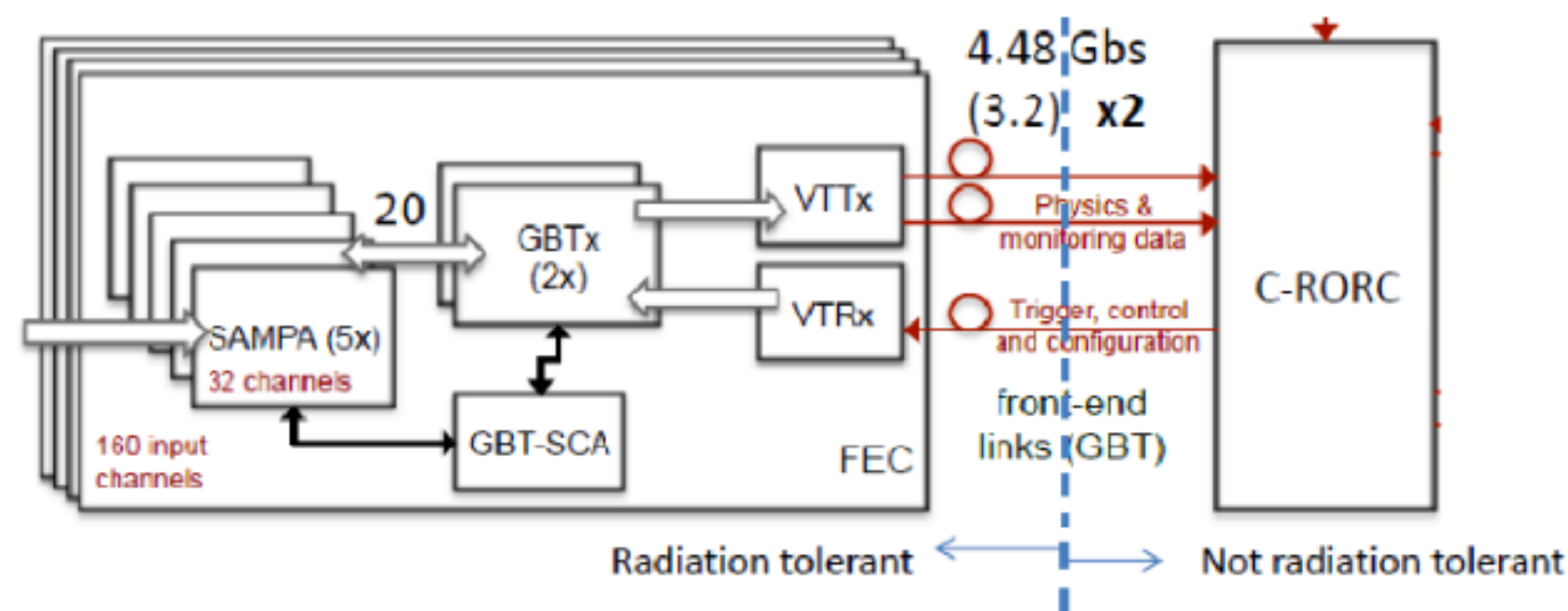


All images: S. Ali (UVa)

Streaming Readout Development



All pics:
E. Jastrzembski
JLab



FEC – Front End Card (160 ch / FEC) (5 FEC = 800 ch)

C-RORC – Common Read Out Receiver Card (PCIe)

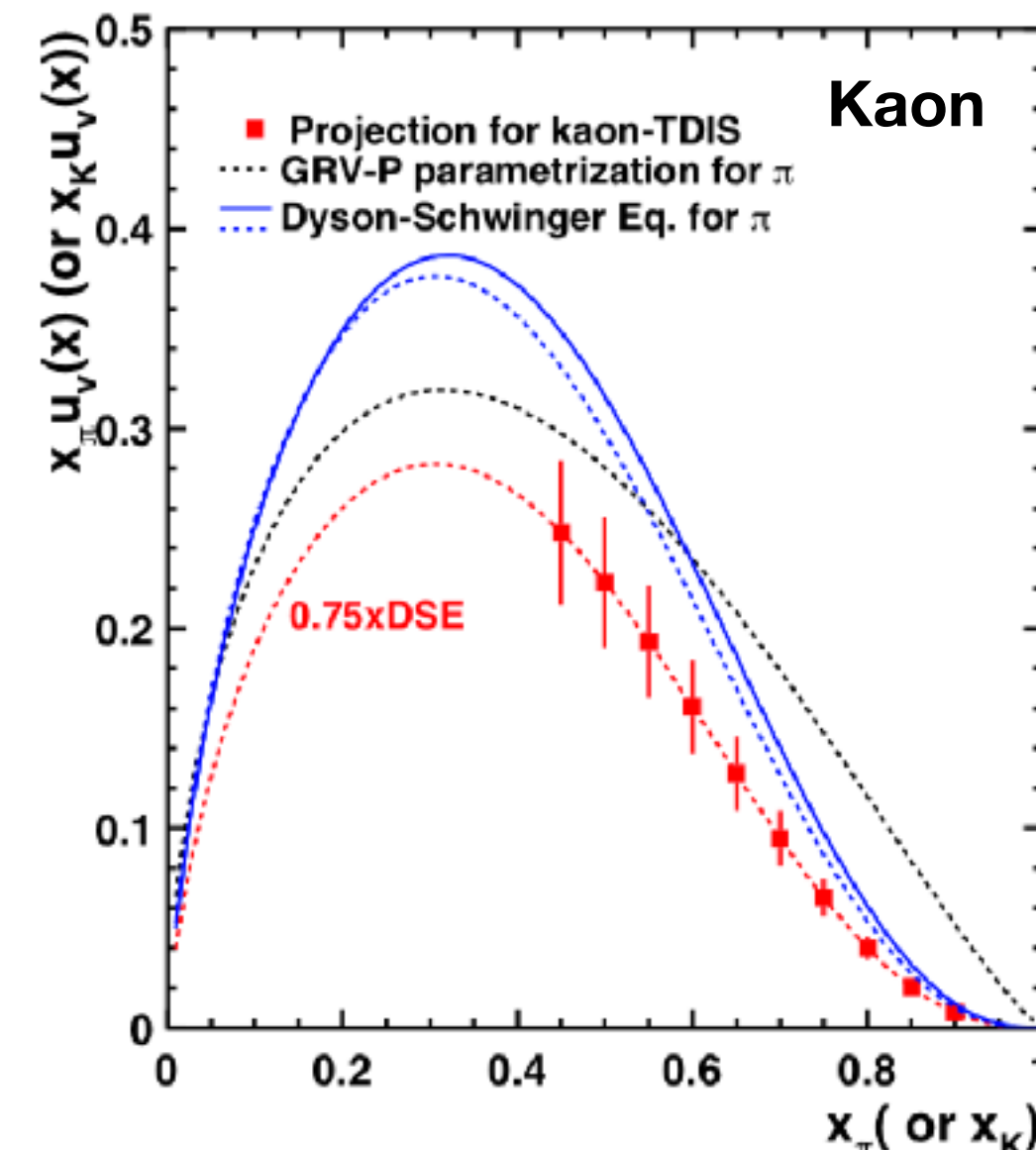
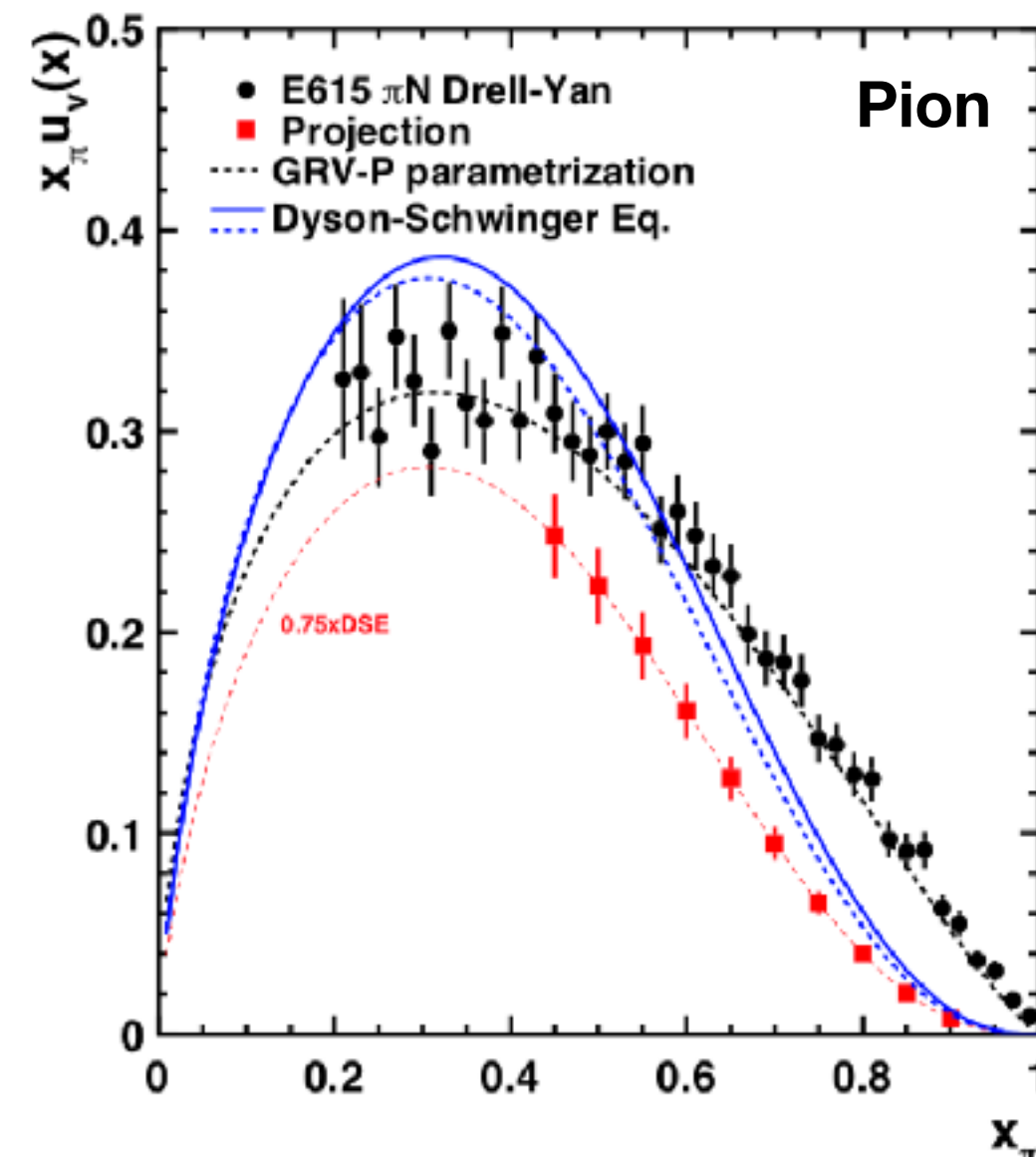
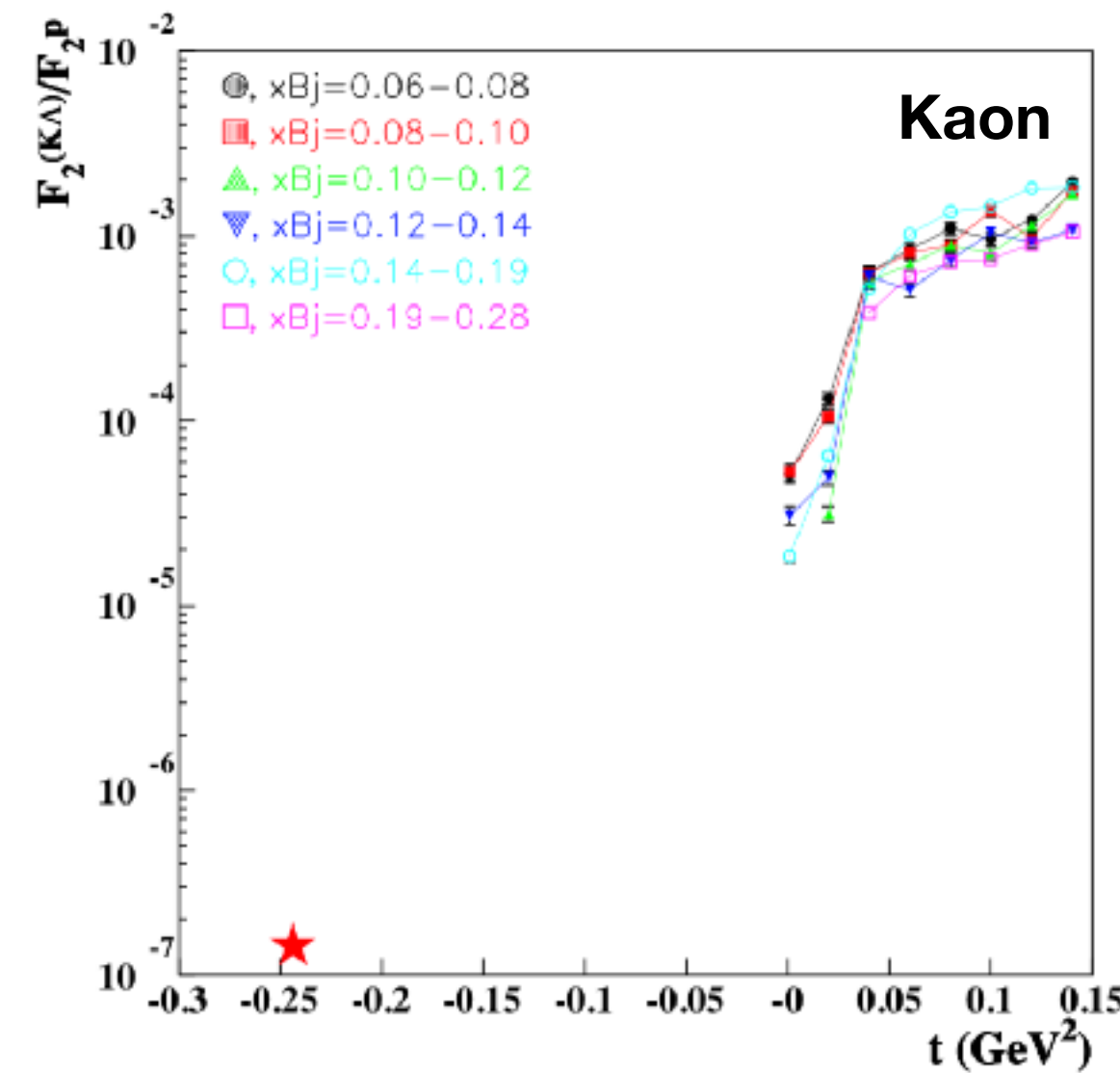
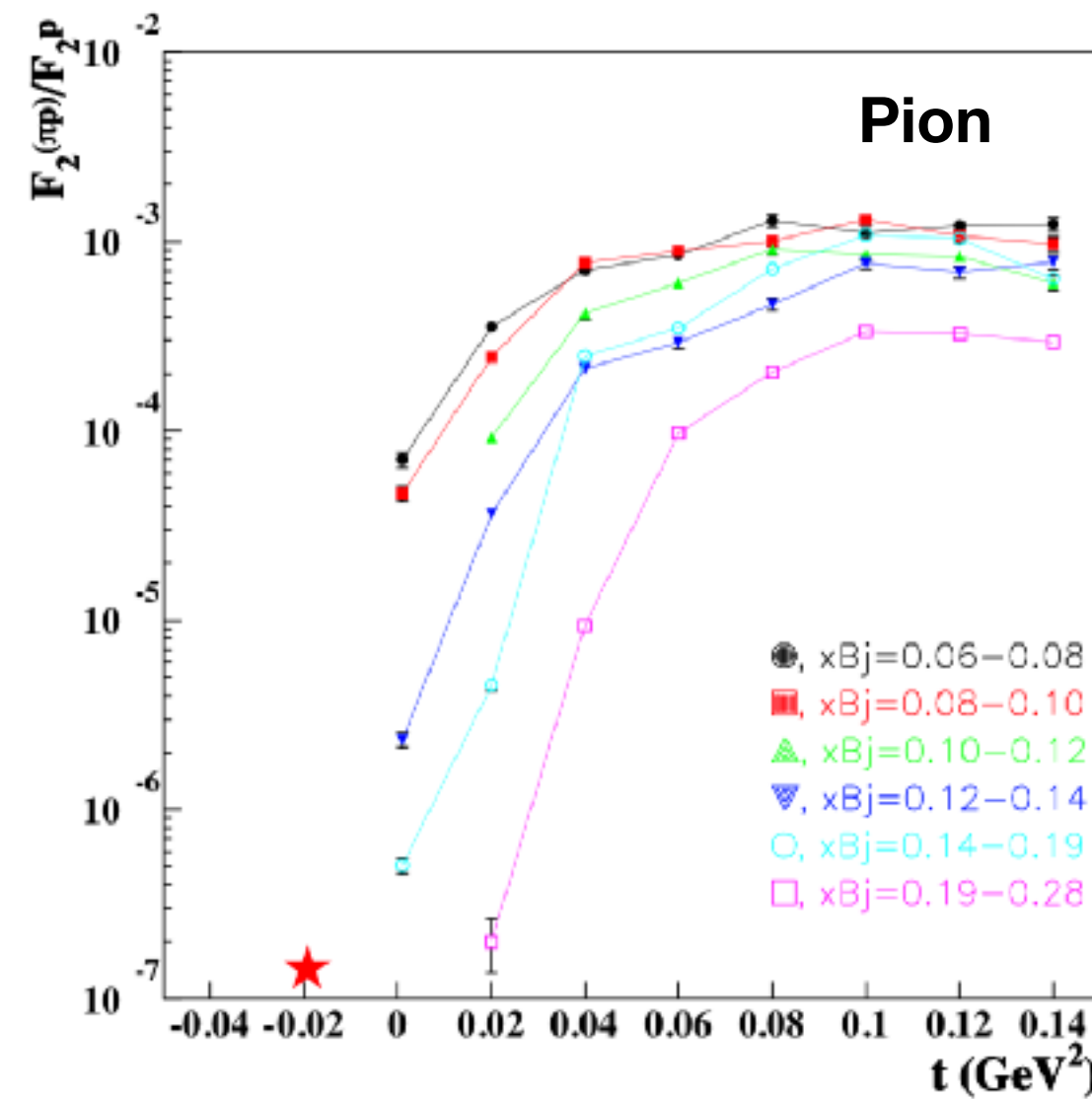
GBTx – Giga Bit Transceivers

GBT-SCA – GBTx Slow Controls Adapter

VTTx, VTRx – Fiber optic transceivers

- Goals:
 - data read continuously from **all channels (~35k)**
 - local digitisation/zero-suppression/noise rejection
 - parallel data flow to storage
 - event synch with data from other triggered detectors
- Testing/prototyping on-going @JLab** (E. Jastrzembski, G. Heyes et al.)
- SAMPA ASIC
 - charge-sensitive pre-amp, ADC, zero-suppression...
 - streaming readout developed for ALICE TPC (M. Bregant, Univ. Sao Paolo)
 - continuous sampling w/ high data readout speed (~1TB/s post zero-supp)
- Trigger-less mode successfully tested @ JLab (5 chips, ~160 chans)**
- Obtaining components for mTPC

Example Projected Results



- Kinematical mapping of SF
- Low momentum reach of mTPC essential to obtain shape of curve
- Projected **valence quark distributions**
- 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
- TDIS will serve as valuable input for global PDF analyses

Summary

- Meson structure important for understanding fundamental structure of nucleon
- Experimental data for pion/kaon structure functions, and mesonic content of nucleon, extremely sparse
- ✓ TDIS at JLab:
 - New data in valence regime
 - Understand nucleon + meson structure on deeper level
 - Kaon SF extraction in almost empty world data set!
 - First prototyping underway...
- TDIS will pave way for spectator tagging and meson structure at EIC
 - Model input, simulation/analysis, validation of Sullivan process, advanced instrumentation
 - 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
- Also (not covered):
 - TDIS-n run group for independent checks of neutron structure (e.g. F_2^n ...)

Thank you

