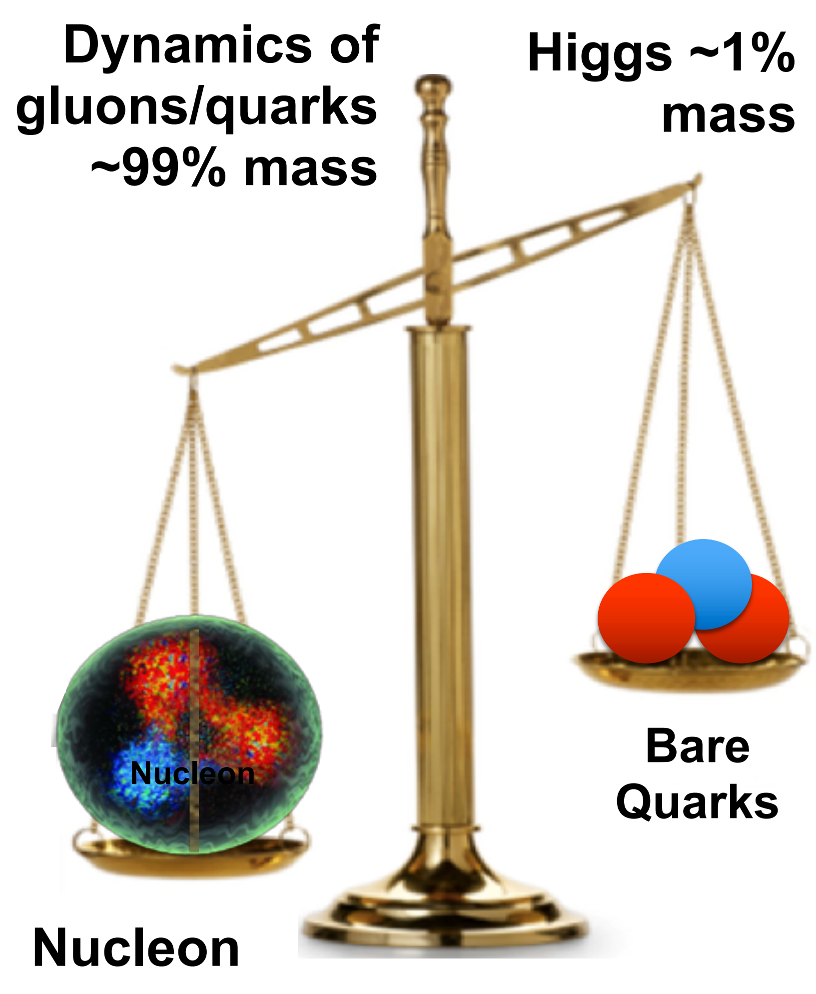
Opportunities for Meson Structure via Tagged Deep Inelastic Scattering (TDIS) with a 22GeV Beam at JLab

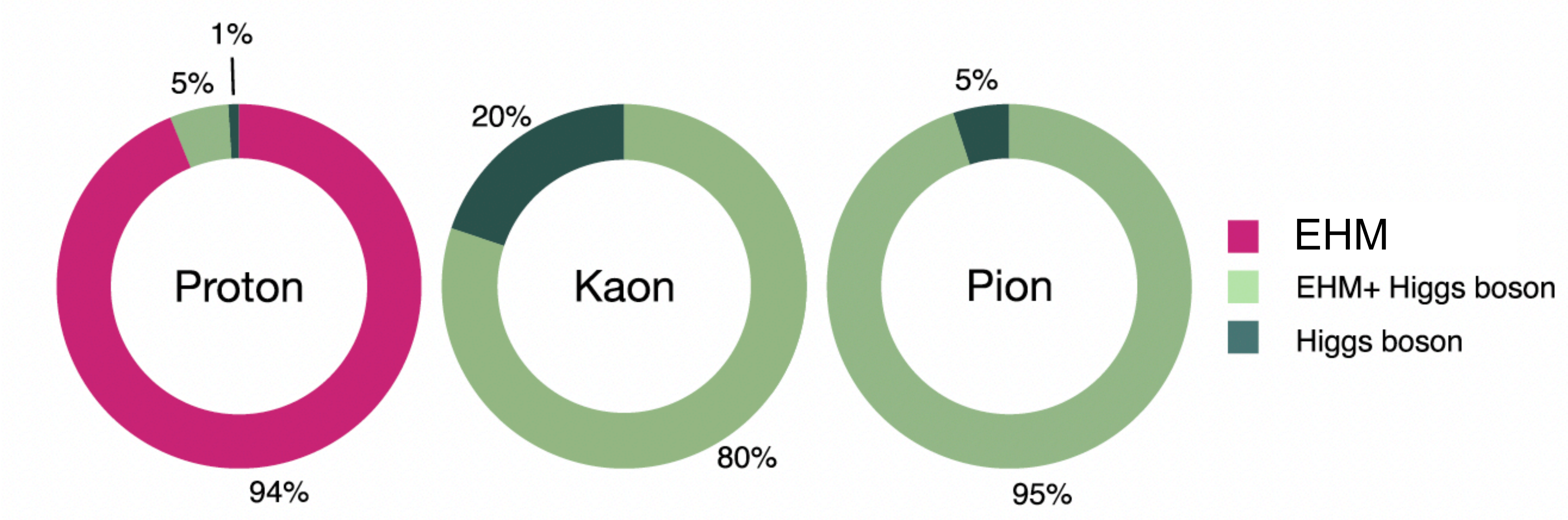
*Rachel Montgomery (UoG) on behalf of **many**:*

C. Ayerbe (W&M); P. Barry (JLab); M. Defurne (CEA Saclay); D. Dutta (MSU); R. Ent (JLab); T. Horn (CUA); C. Keppel (JLab); P. King (OU); A. Tadepalli (JLab) … and others also from:
Hall A, SBS and TDIS Collaborations and EIC Meson SF Working Group

Science at the Luminosity Frontier: Jefferson Lab at 22GeV Workshop
INFN LNF Frascati
11th Dec 2024

Why Light Meson Structure



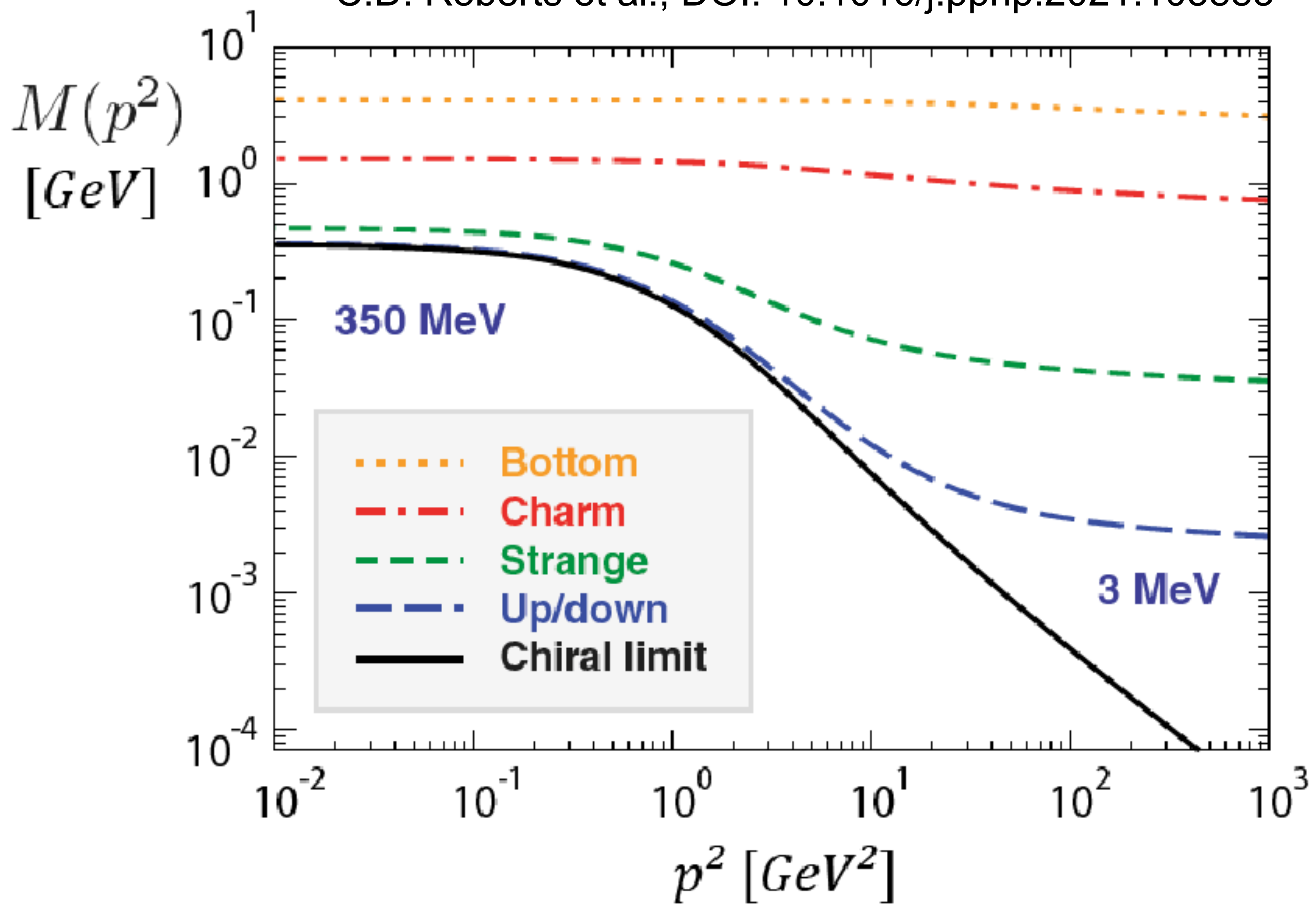


D. Binosi, DOI: 10.1007/s00601-022-01740-6

C.D. Roberts et al., DOI: 10.1016/j.ppnp.2021.103883

Quark mass acquisition functions from QCD theory

Light quarks: dynamical mass generation from gluon cloud



- Numerous motivations to study π/K meson structure
  - e.g. NN interaction, access strangeness
- π/K are a key facet of nucleon structure

- They also provide unique information for nucleon mass enigma

- Dynamics of strong interactions in QCD → ~99% nucleon mass
  - emergent hadronic mass (EHM)

- Mass budgets for **π/K** (Goldstone bosons) vastly different from **nucleon,** and **each other**

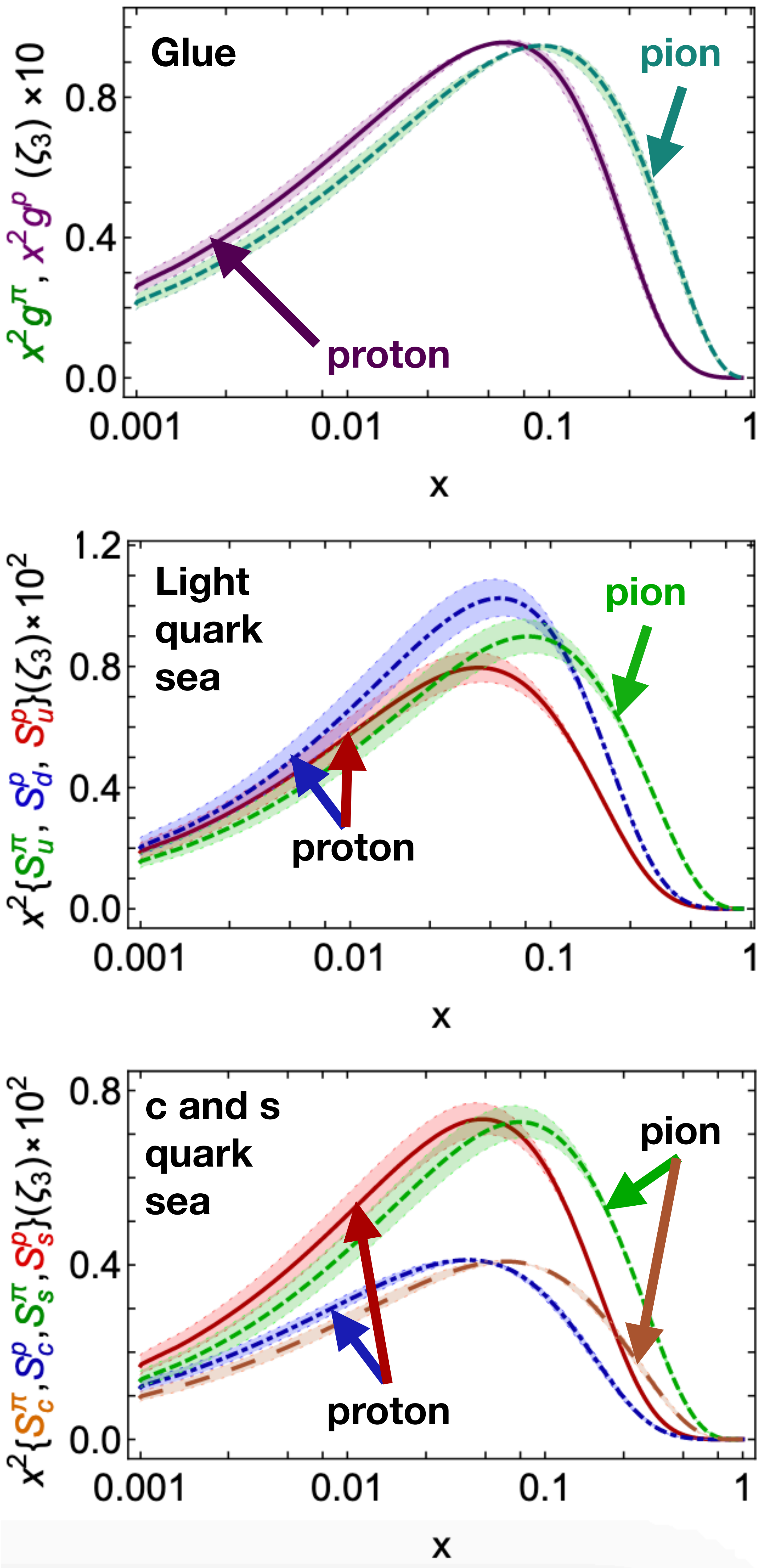
- Comparing distributions of light quarks versus strange quarks within mesons → directly measurable signals of EHM

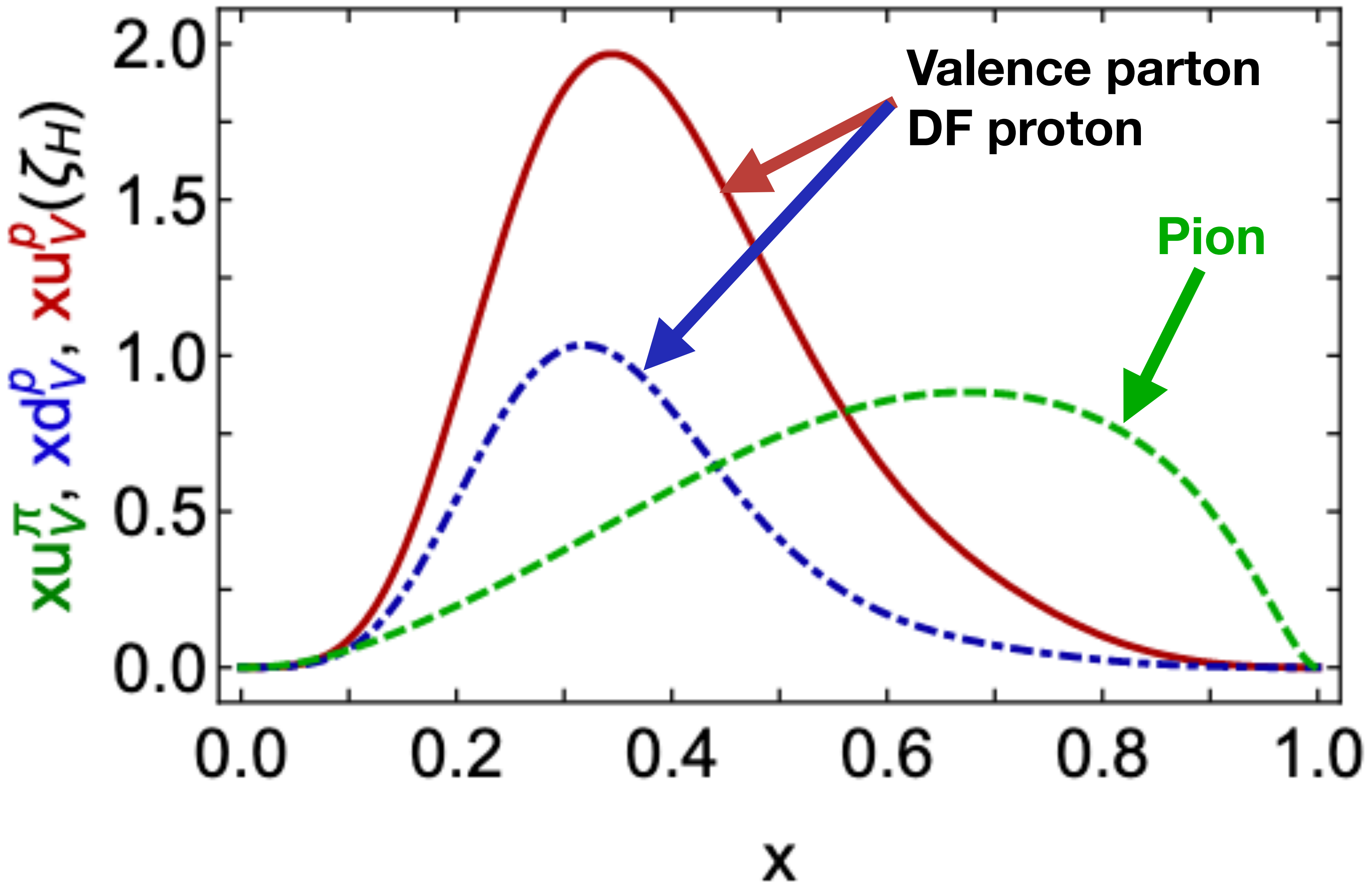
- π/K structure not well known experimentally
- We desperately need data!

- Interesting implications for PDF/TMD…

Pion vs Proton Valence PDFs

arxiv: 2203.00753 [hep-ph]





From C. Roberts (INP)

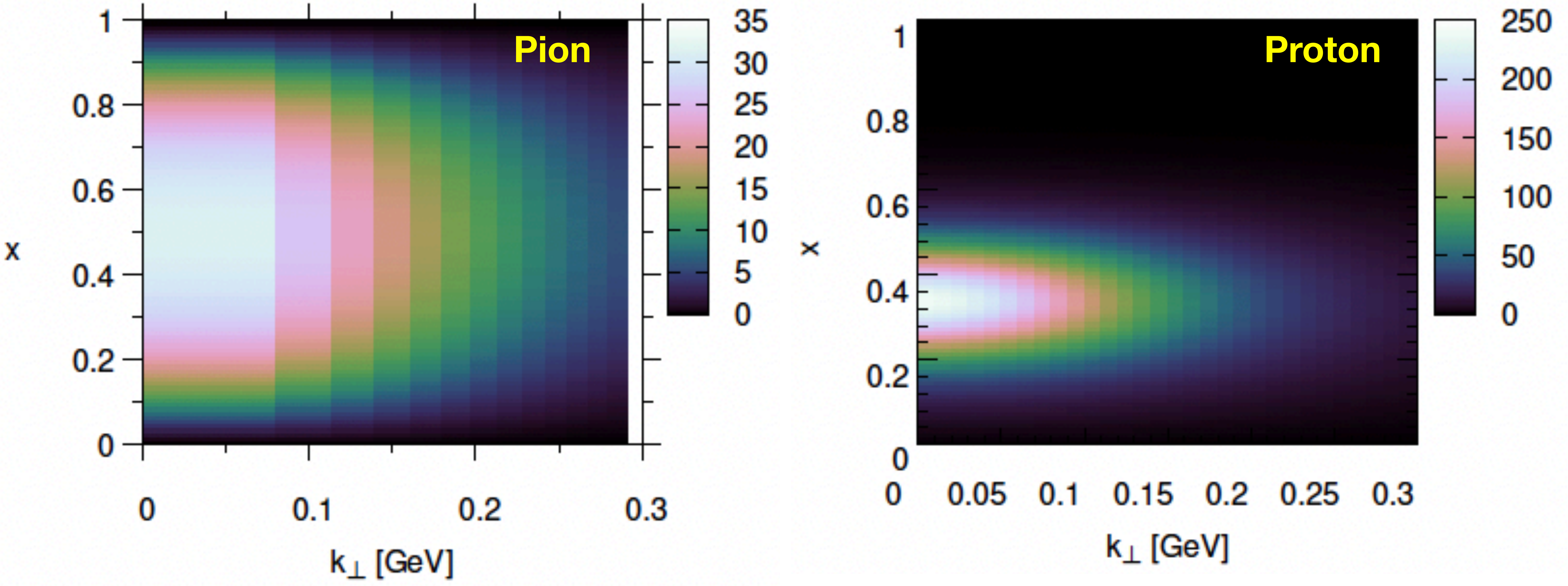
Continuum Schwinger function methods

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

Pion vs Proton TMD Theory Very Active

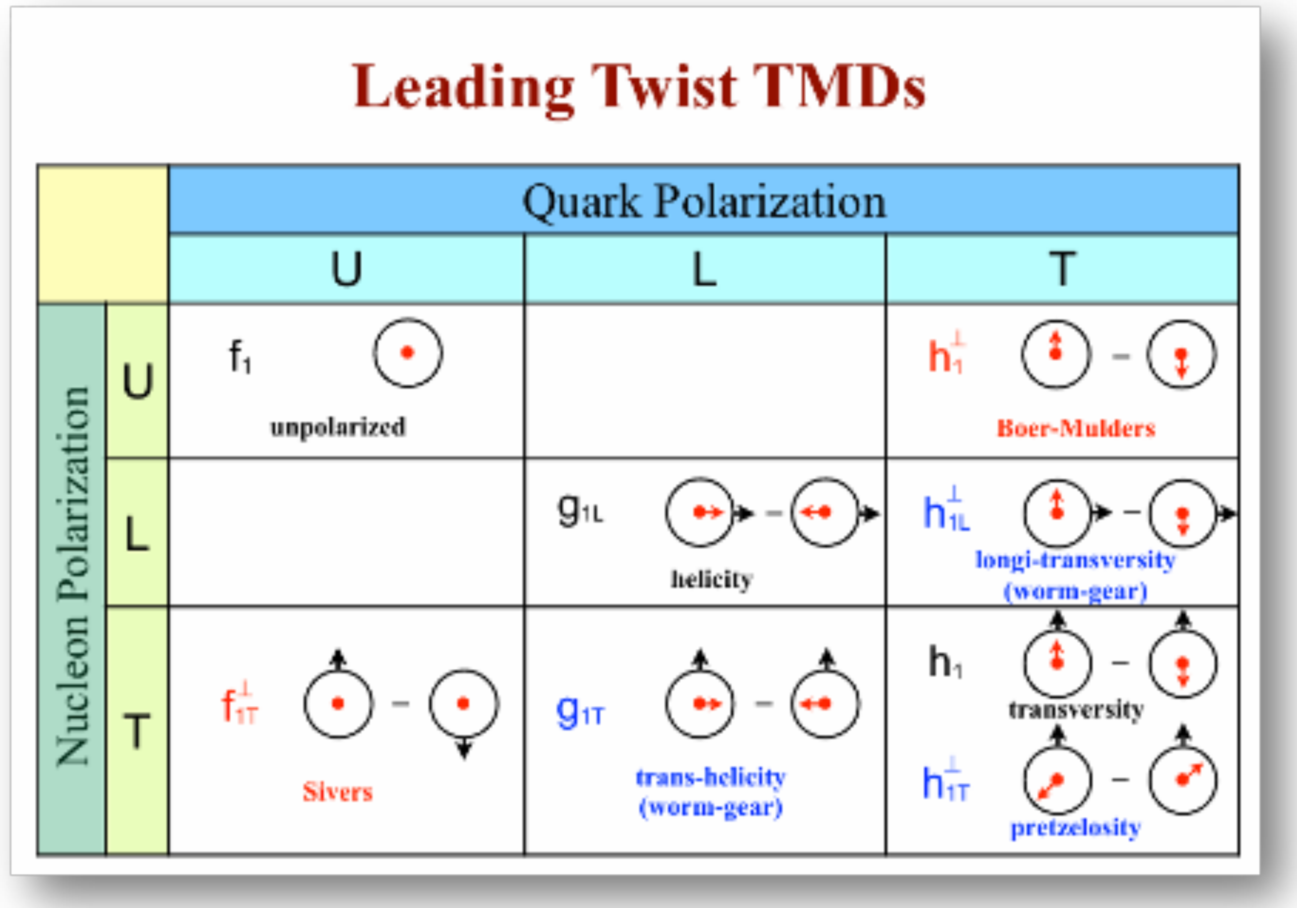
From: T. Frederico (Instituto Tecnologico de Aeronautica) E. Ydrefors (Chinese Academy of Sciences)



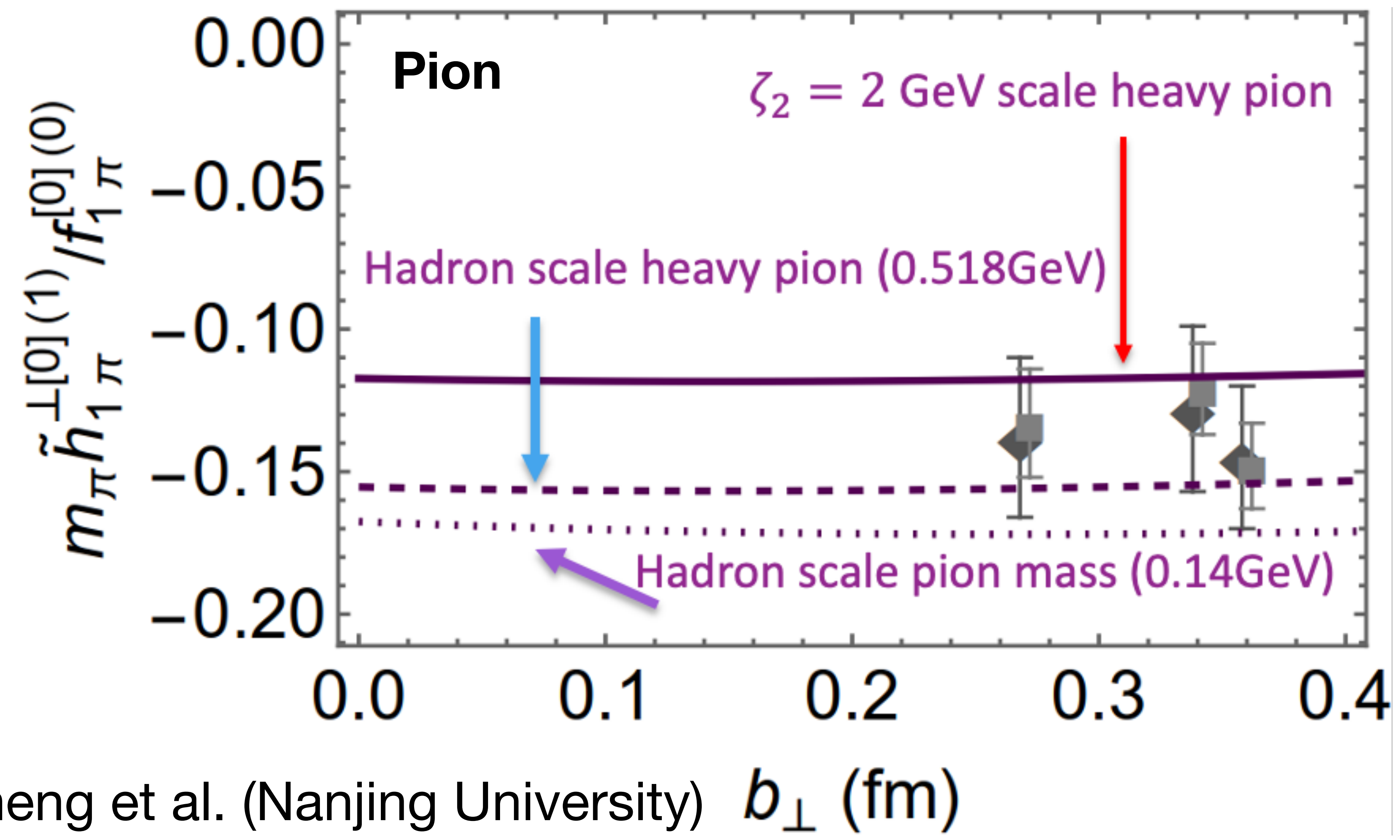
- Unpolarised leading twist TMDs

- Calculated using Minkowski space Bethe-Salepeter equation methods
- More details/references in back up

- Remarkable broadening for pion in x compared to proton
- Spread in k⊥ similar (~200MeV)



arXiv:2409.11568v2 [hep-ph] 21 Sep 2024



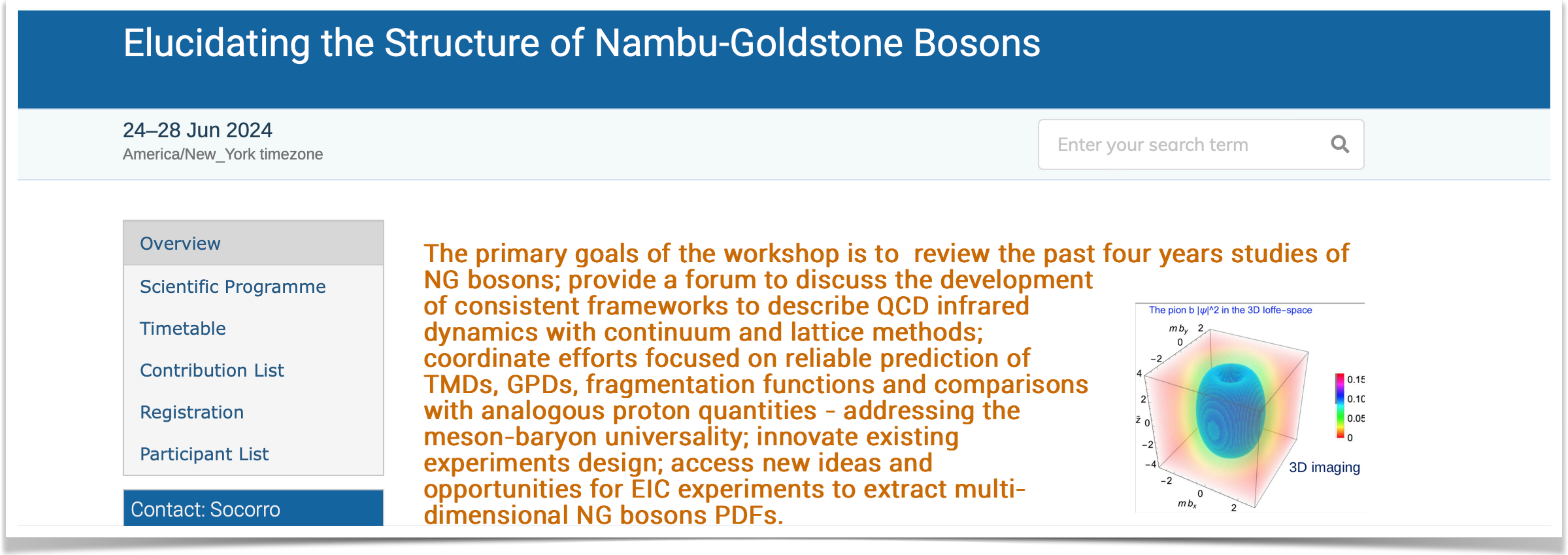
From: Dan-Dan Cheng et al. (Nanjing University)

- Two non-zero TMDs and generalised Boer-Mulders shift calculated for pion
- Boer-Mulders shift - TMD observable related to Boers-Mulders effect

- Dyson Schwinger methods
- Results compared with lattice
- Allows to study e.g. quark current mass dependence of pion TMD
- See arXiv:2409.11568v2

We Need More Data

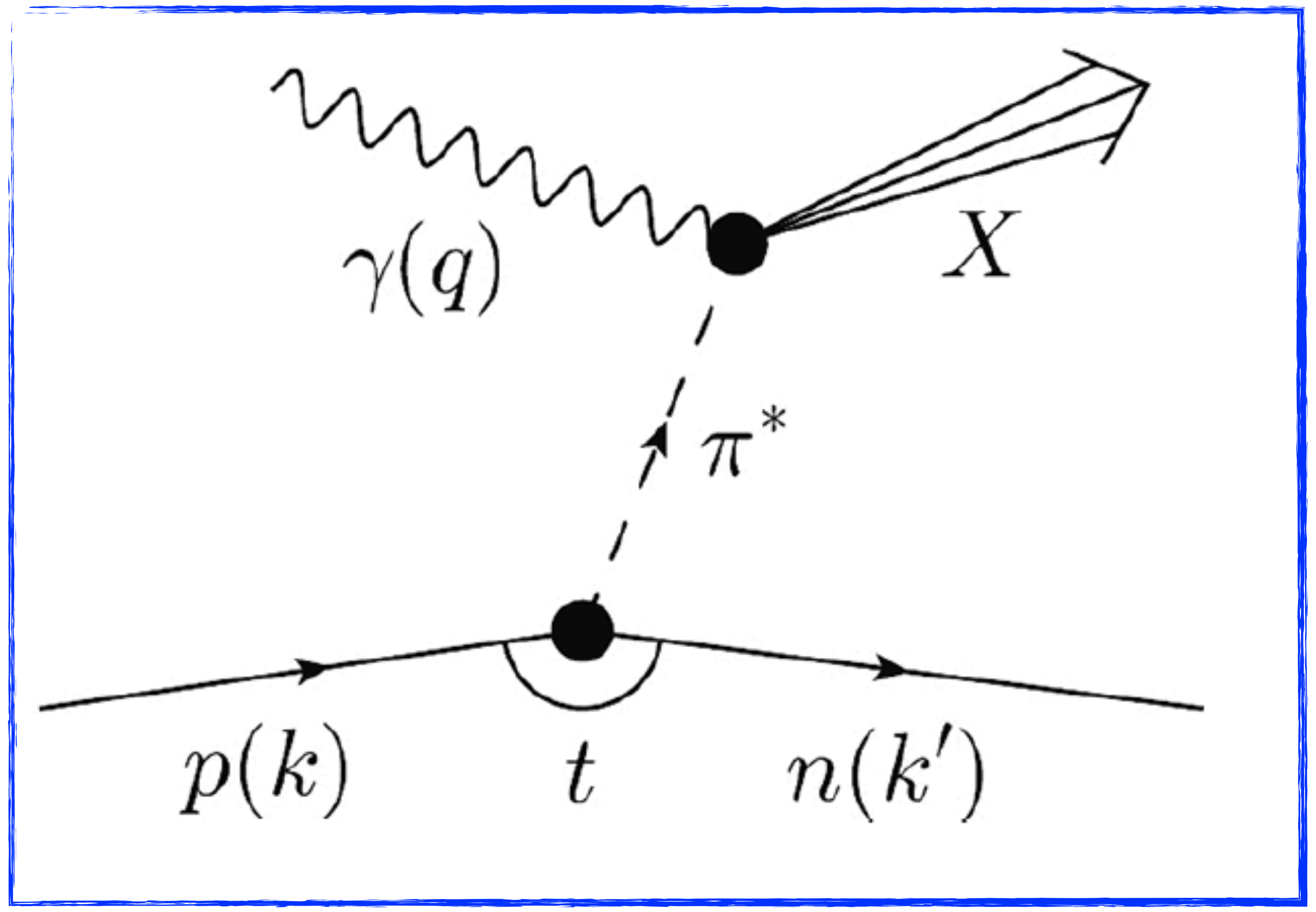
- Wealth of recent exciting theoretical developments on light meson structure
- Eg see many more reports at recent CFNS workshop



- Extracting meson PDF and TMDs from data will be very complicated
- We desperately need more experimental data
- TDIS data in valence regime will
  - Add to very sparse world data set (especially for kaon)
  - Offer tests of universality when combined with existing and future Drell Yan data
  - Be a direct probe of the elusive meson cloud

Accessing Light Meson Structure

Sullivan Process - scattering from virtual meson cloud



- Upcoming Tagged Deep Inelastic Scattering (TDIS) program → light meson structure functions (SF) via Sullivan process

- JLab TDIS program is anticipated in community

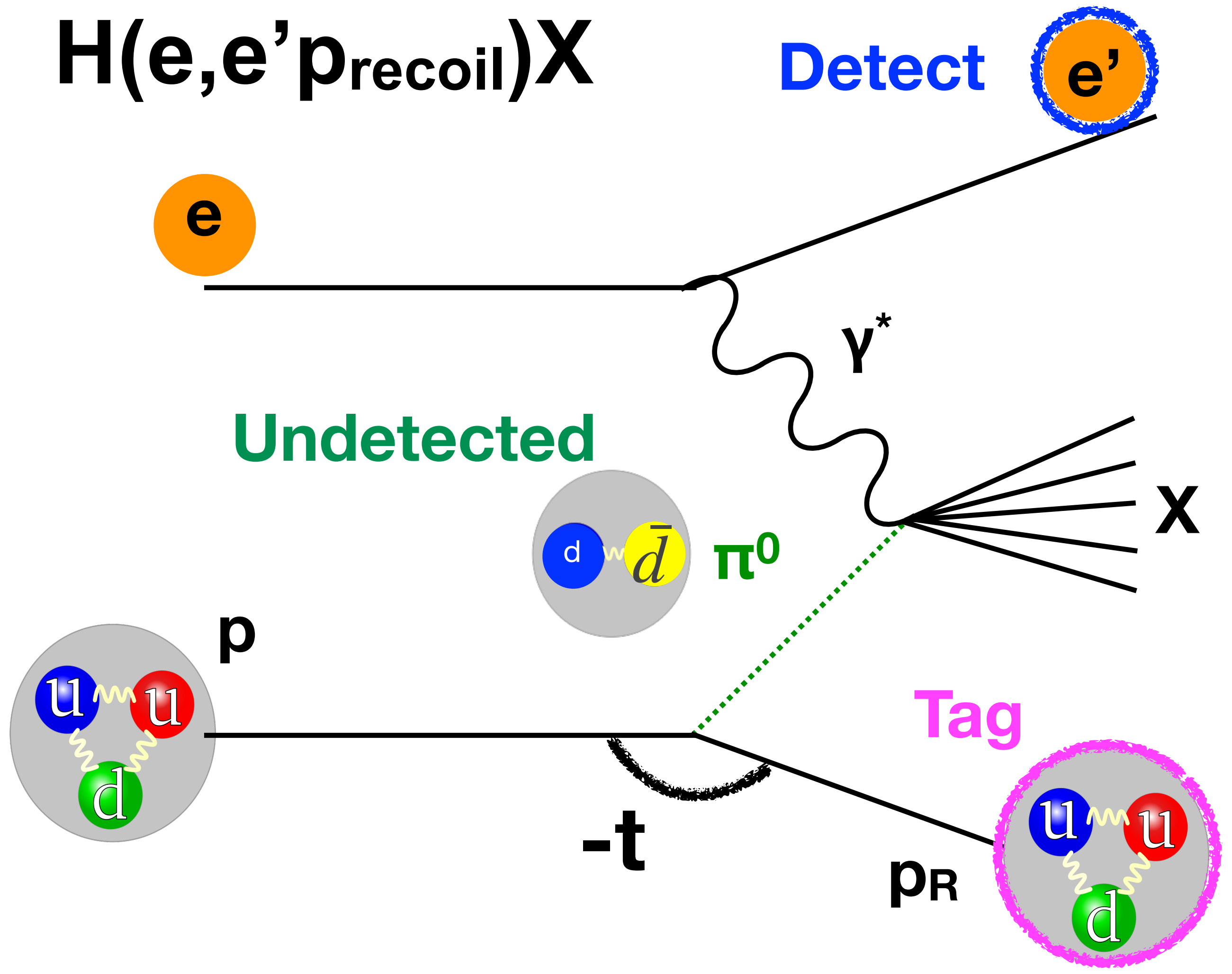
- Significant number of recent publications advocating for new tagged meson SF measurements like TDIS
  - e.g. last July (2023) >50 publications with >1200 citations (including 2023 LRP white paper and EIC YR)

- TDIS capabilities to probe nucleon's elusive virtual meson cloud directly in mid to high-x region are completely unique to JLab's high current Halls

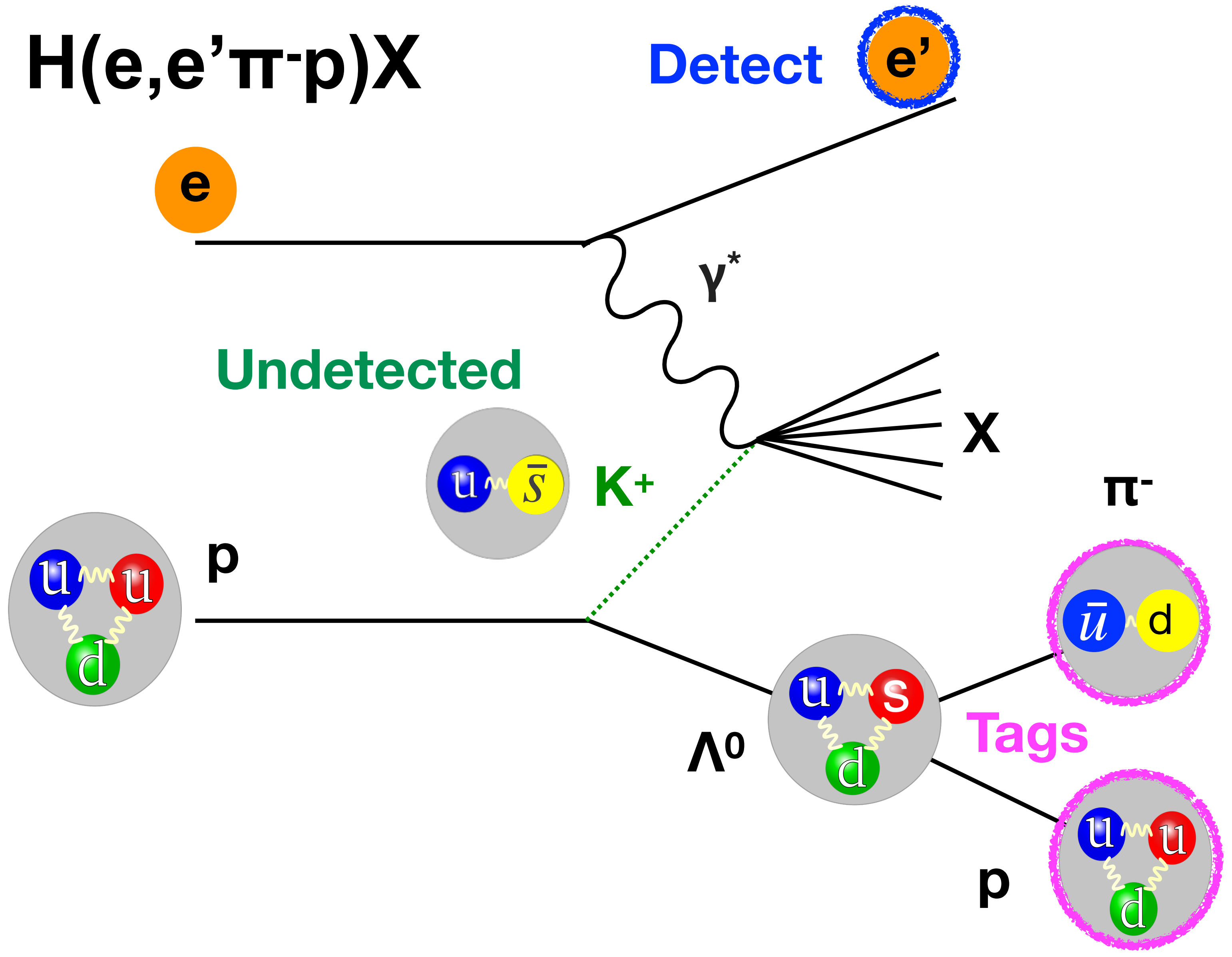
TDIS Plans at 11GeV

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

World first

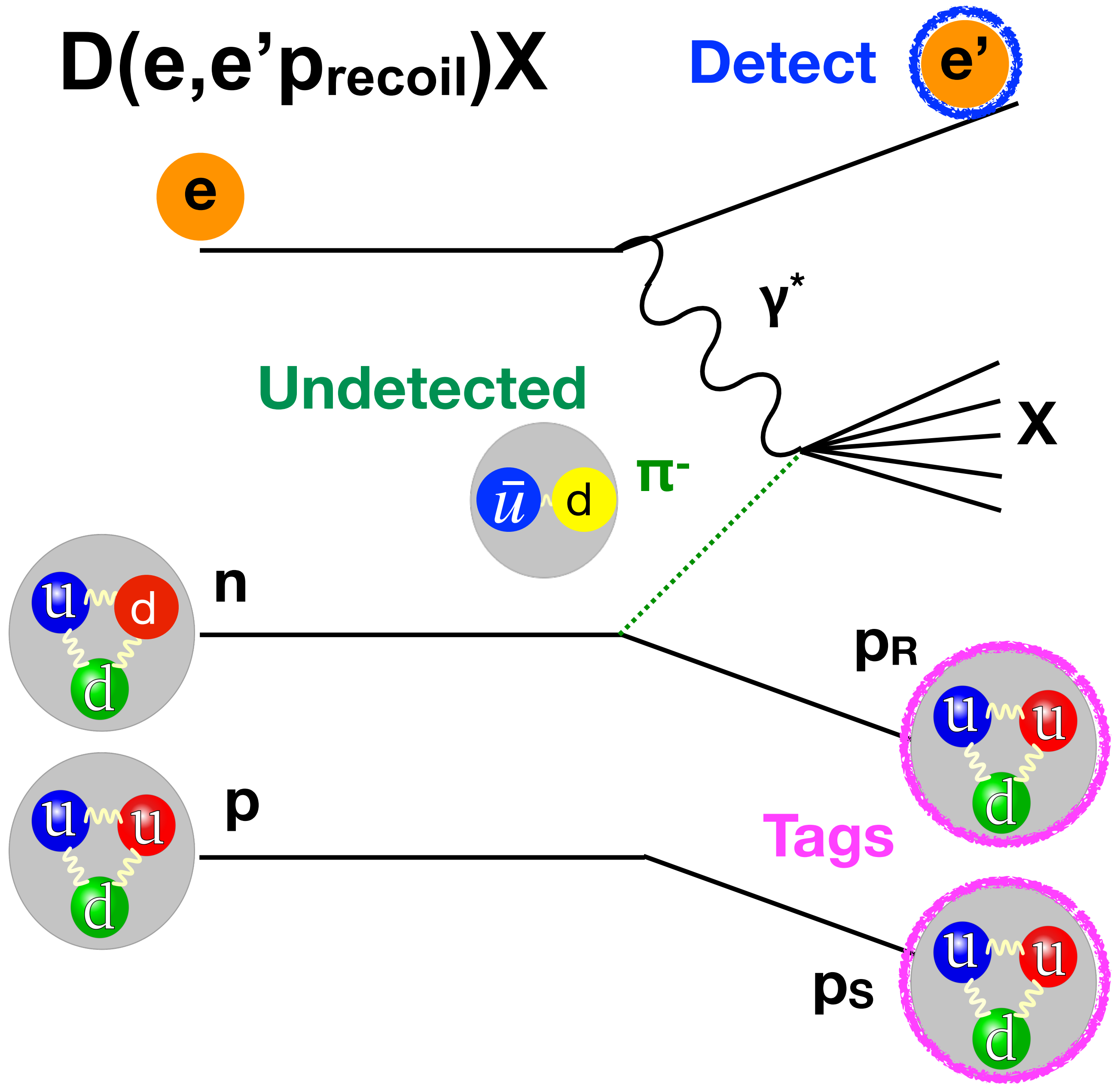


For reliable access to meson target need to, minimise |-t|



Practically no world data exists for kaon

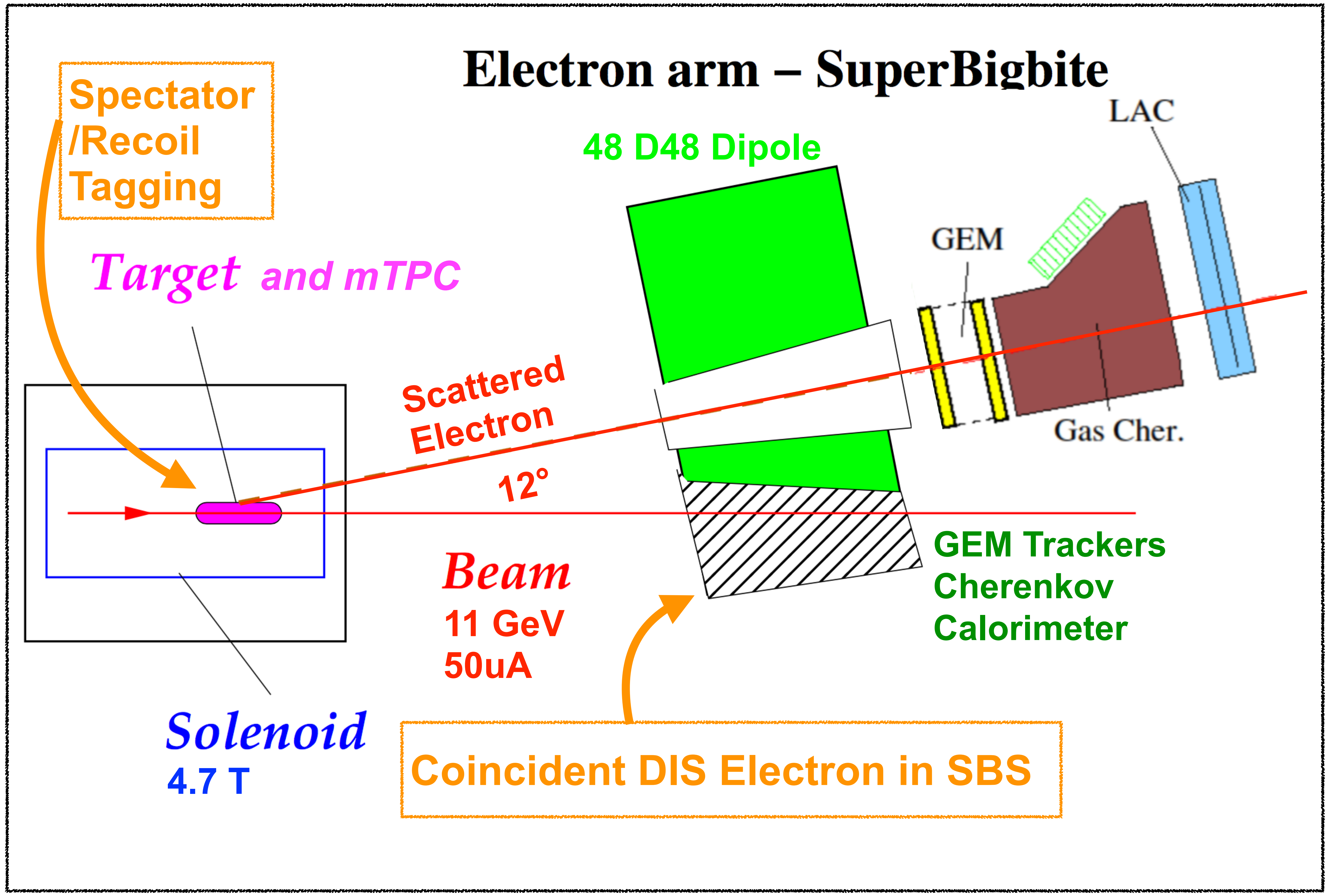
World first

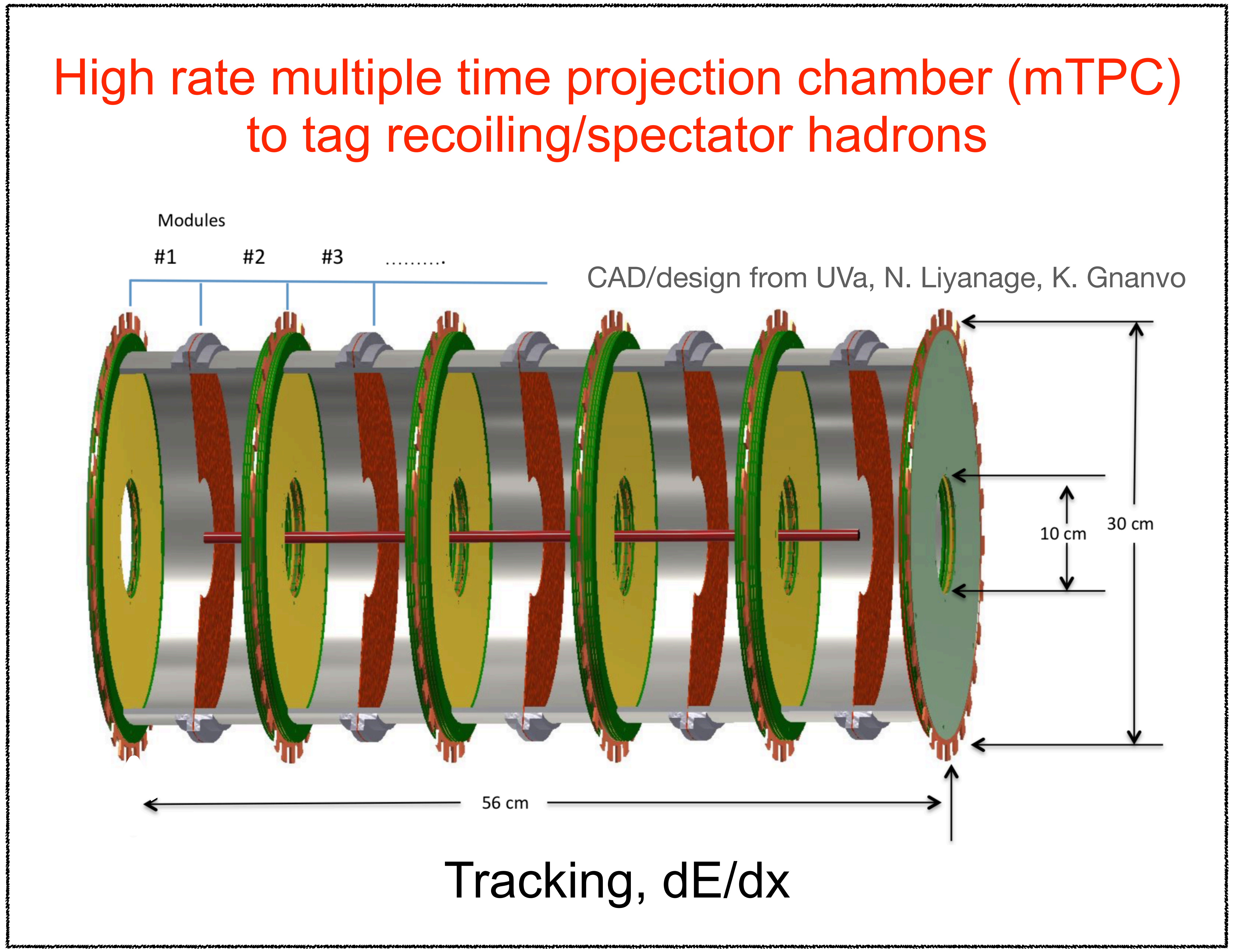


Resolve model tensions and uncertainties at large x

- DIS with spectator tagging
- TDIS:
  - Pion and kaon F_2 SF in valence regime
  - (TDISn run group - neutron structure topics)
  - (nDVCS LOI - neutron GPDs)
- Latest updates:
  - Passed jeopardy July 2023 (PAC51)
  - Lots of work on-going on recoil detector prototyping and demonstrating high rate tracking using AI techniques

TDIS Experimental Setup

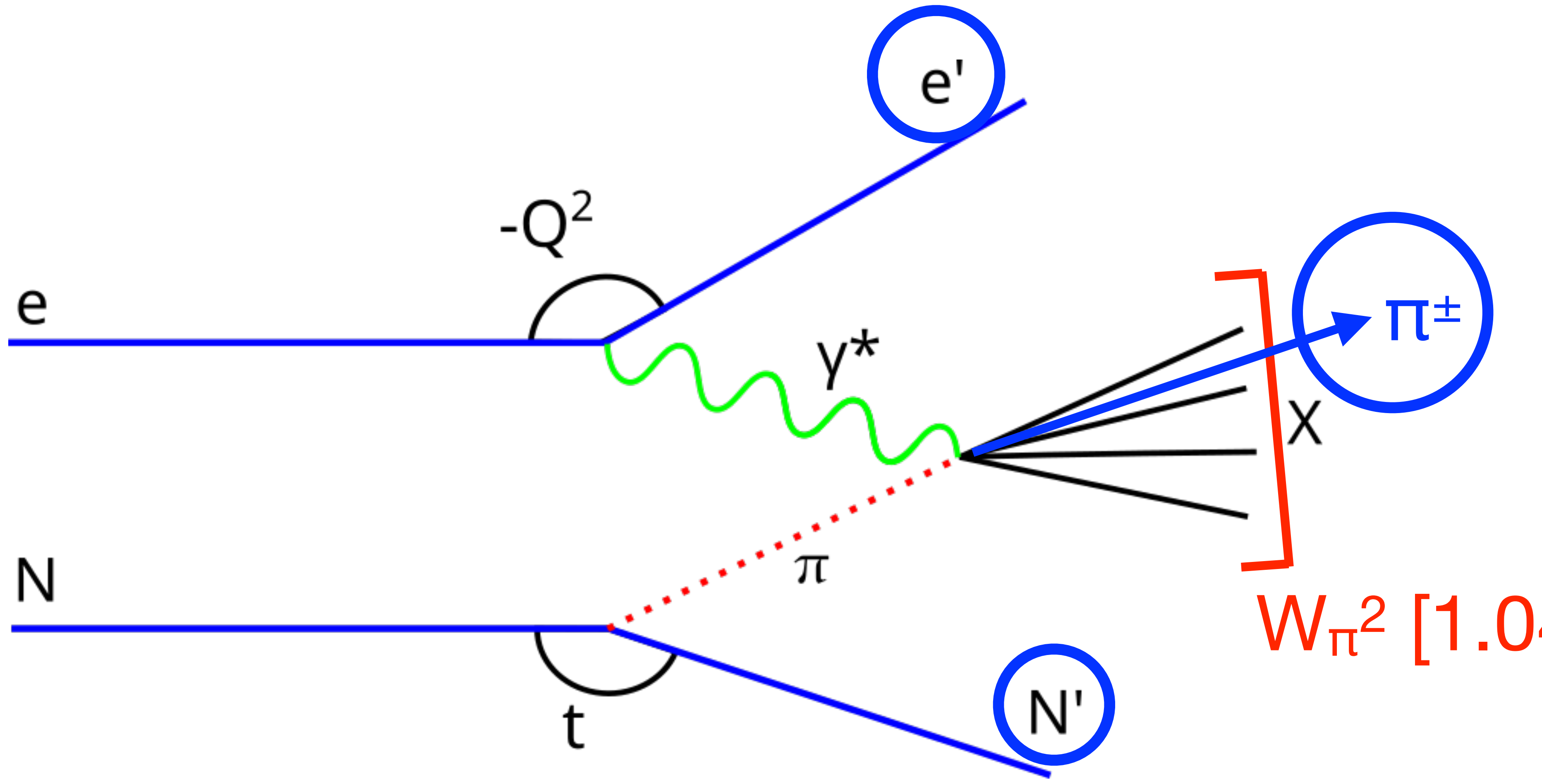




TDIS Set up could be deployed in either Hall A or C

22GeV Unlocks Possibility of Pion SIDIS via Sullivan Process

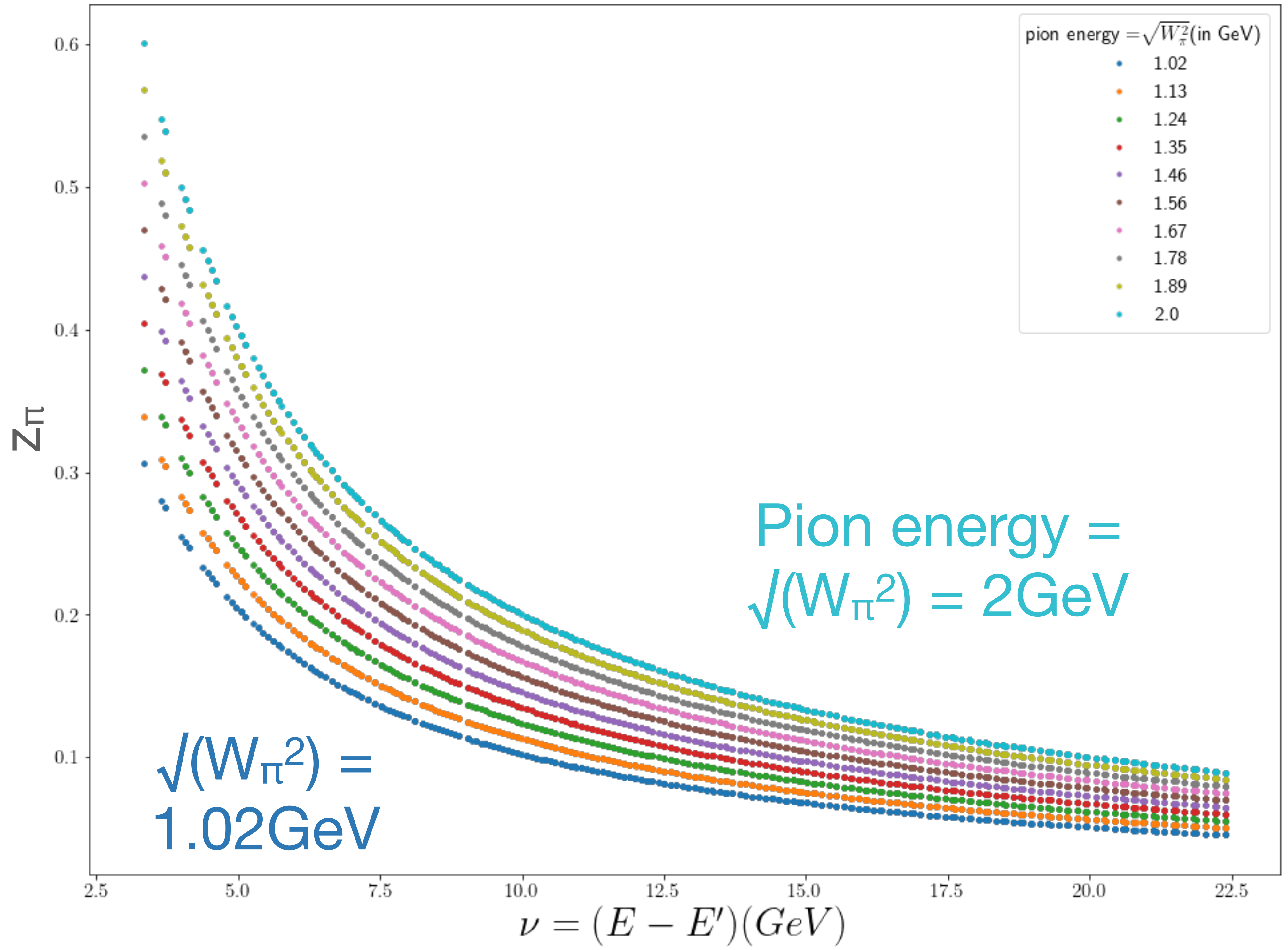
SIDIS on Virtual Meson with TDIS at 22GeV

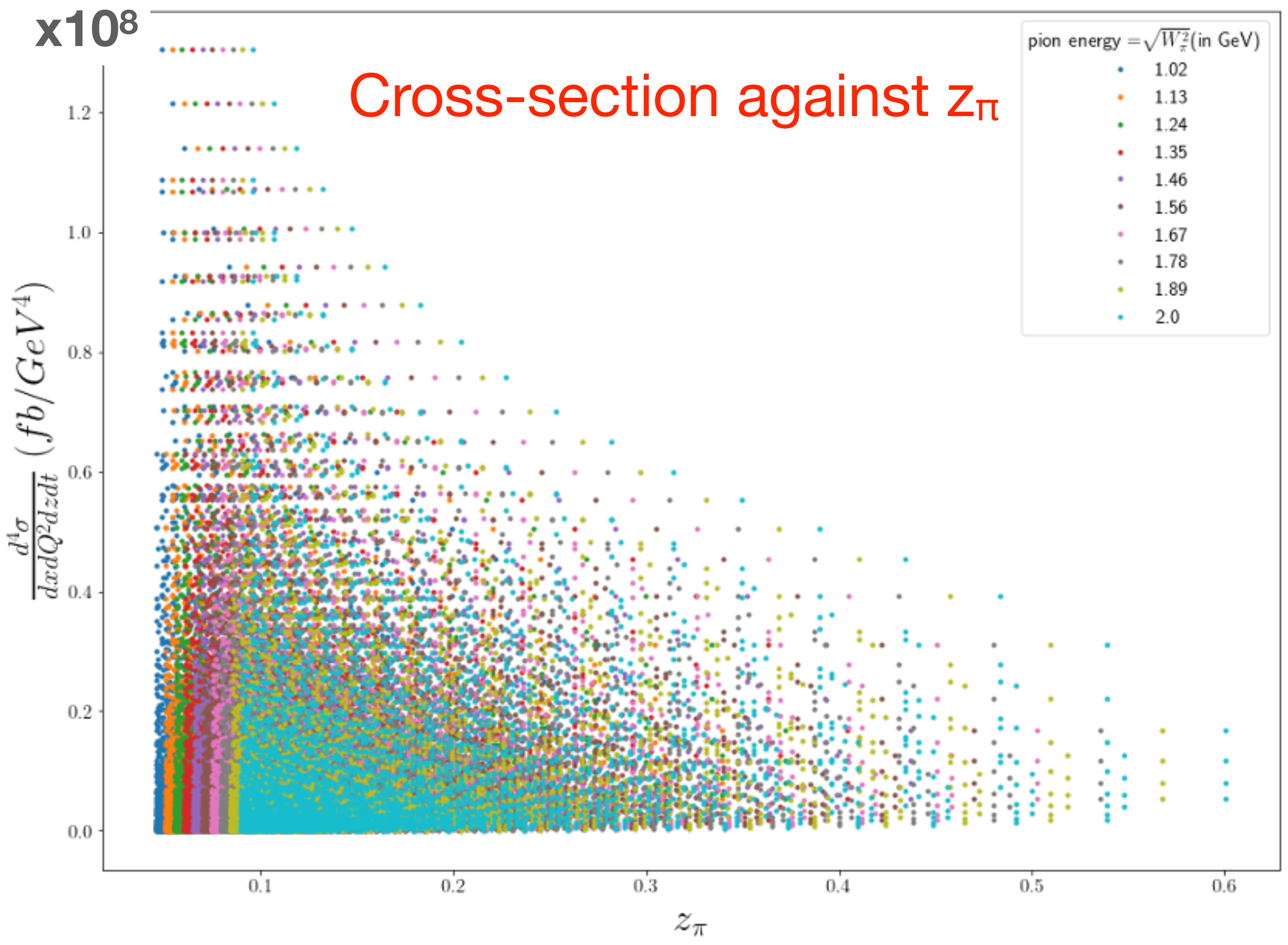


W_π^2 [1.04, 4.0] GeV^2

- Data now available for W_π^2 between 1.04 and 4GeV²
- SIDIS on virtual meson now a possibility!

- Assume W_π^2 used to produce π
- Measure e', N' and π
- Will need a new detector for π



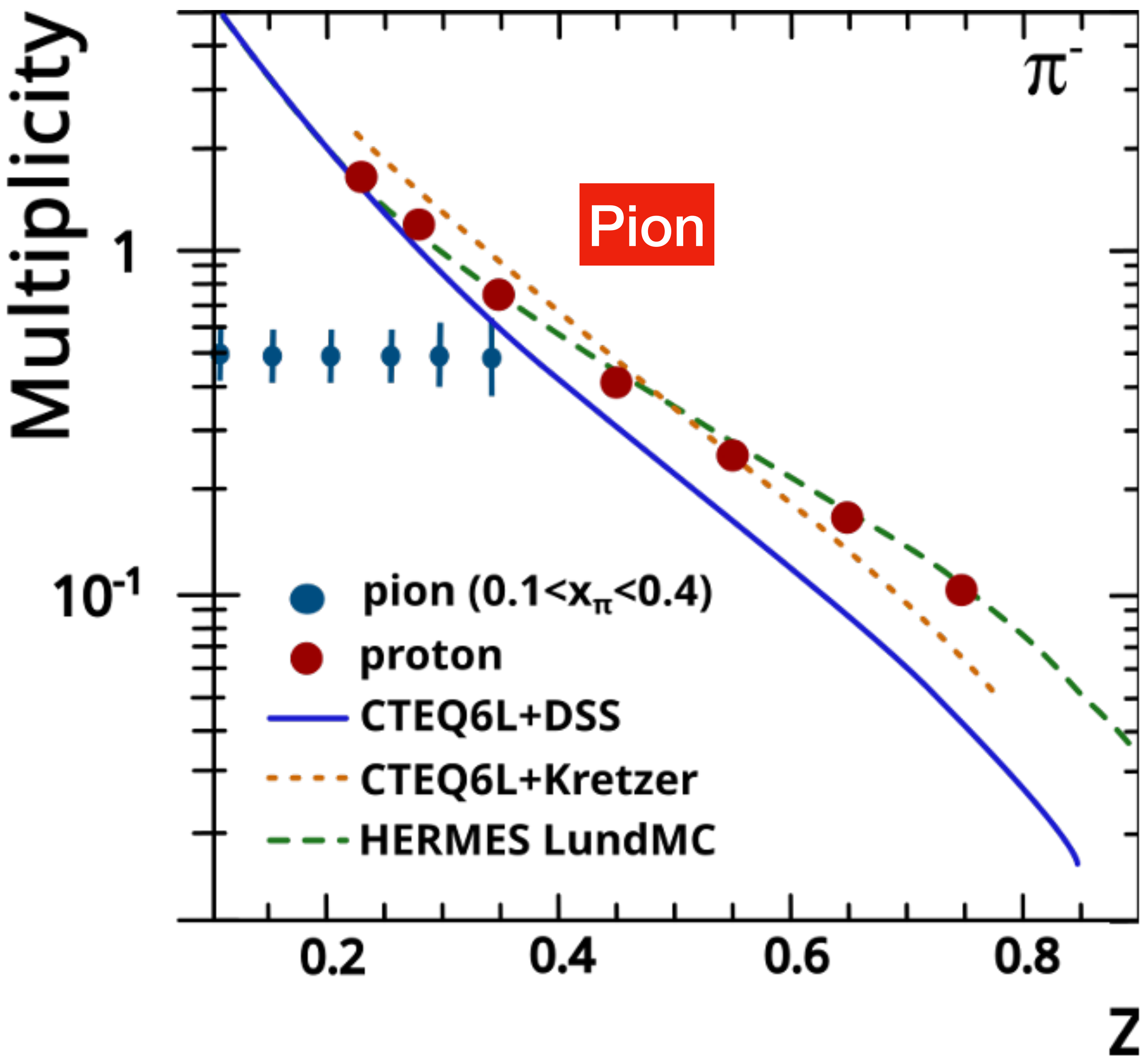


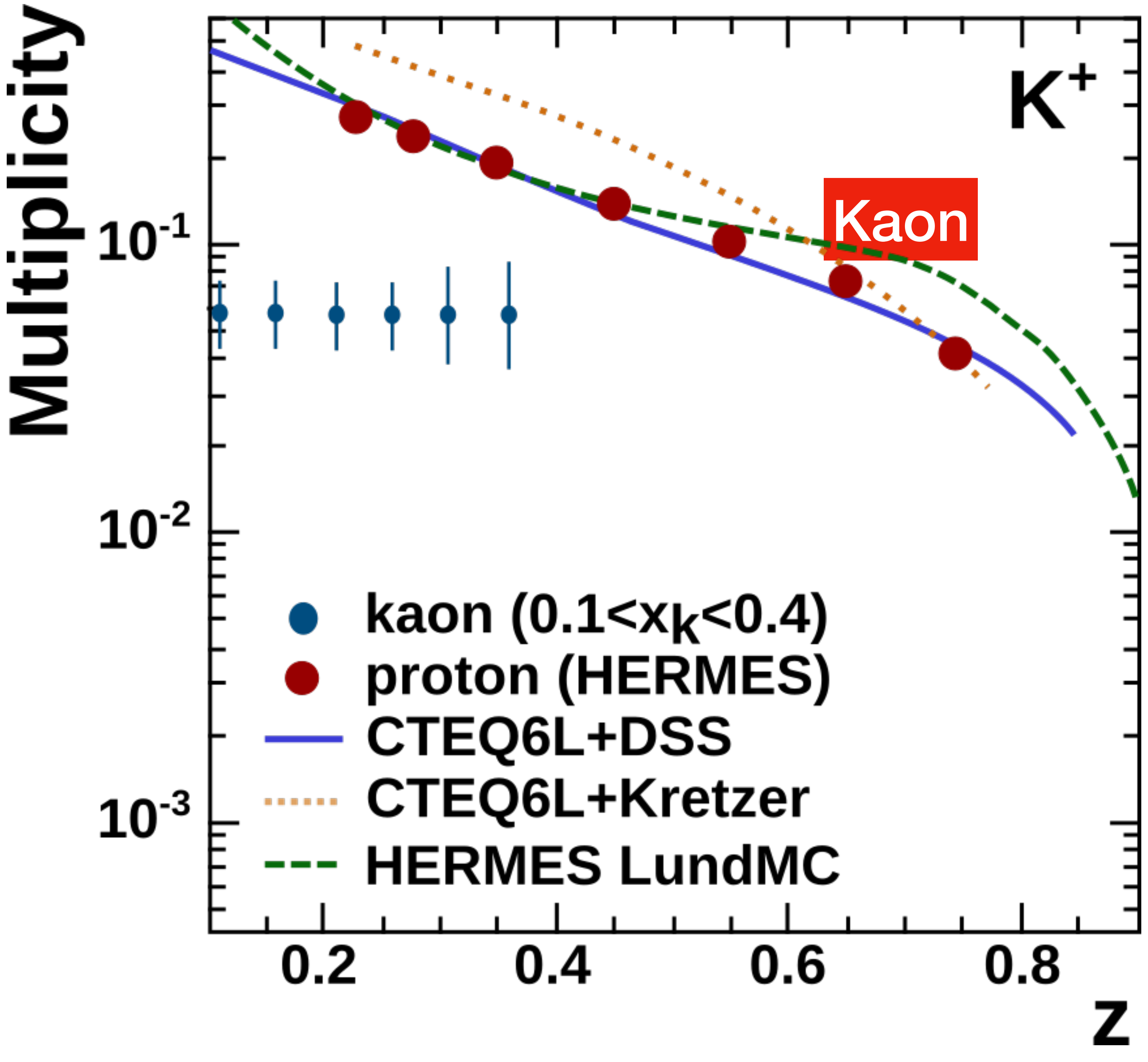
- Expected SIDIS rates scaled from TDIS cross section
- Assume SIDIS rates ~ 4% TDIS @11GeV
- Colours are SIDIS pion energy (~1-2GeV)

Plots: C. Ayerbe and D. Dutta

Using phase space code from Patrick Barry

SIDIS 22GeV Multiplicities



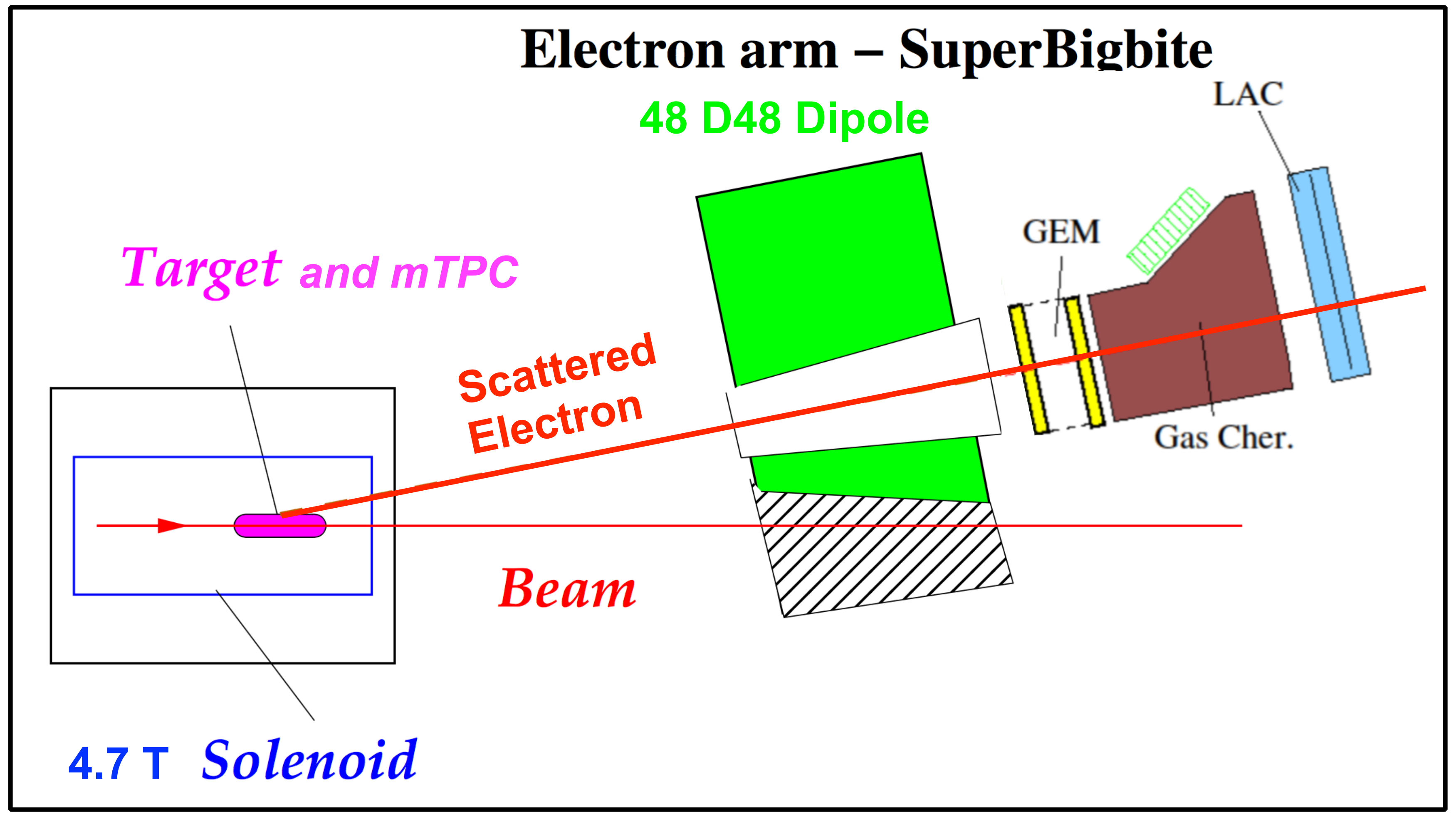


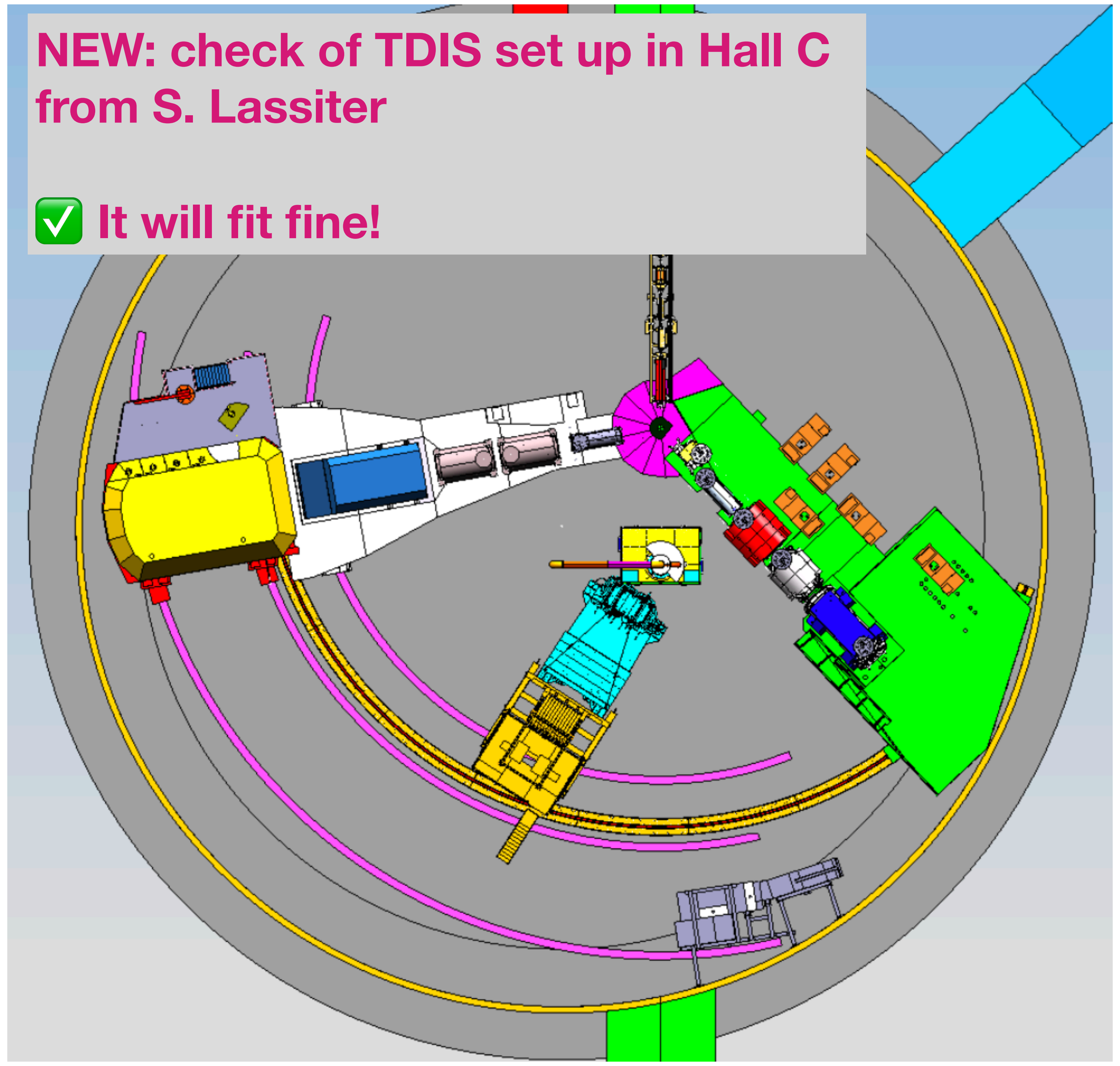
- Projections based on 50 days' beam time
- Meson TMD observables via SIDIS on virtual meson become a possibility at 22GeV

Plots:
D. Dutta,
C. Ayerbe

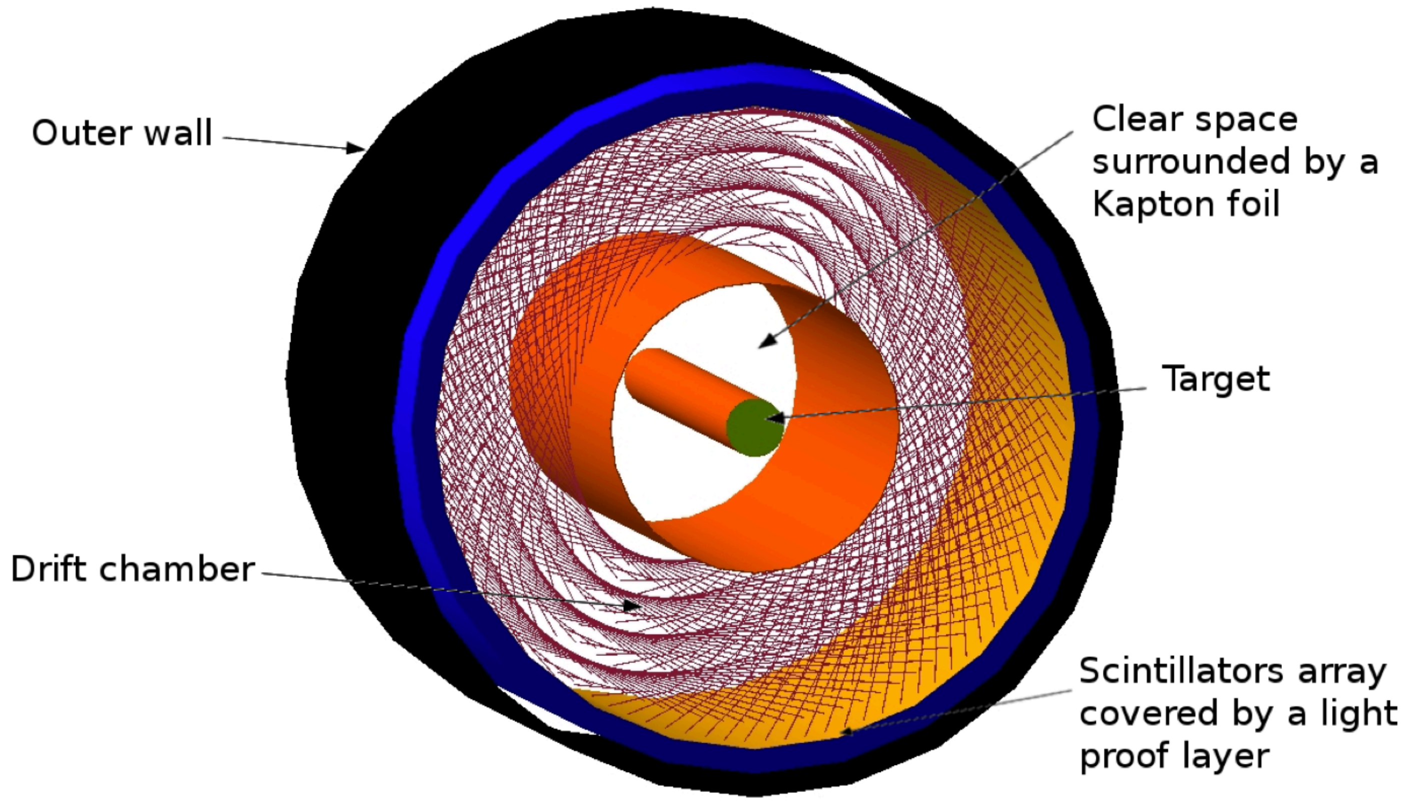
Nb HERMES results from: A. Airapetian et al. (HERMES Collaboration), Phys. Rev. D 87, 074029 for demonstration of existing proton data, not for comparison with pion projections

22GeV Experimental Considerations





- UVa Solenoid
- 400mm warm bore
- Length 152.7cm



- Detector from ALERT proposal, Hall B
- Barrel geometry drift chamber surrounding by supplementary detector

- Have to tag extra SIDIS pion → need a new pion detector
- Its design is the next major “to-do”

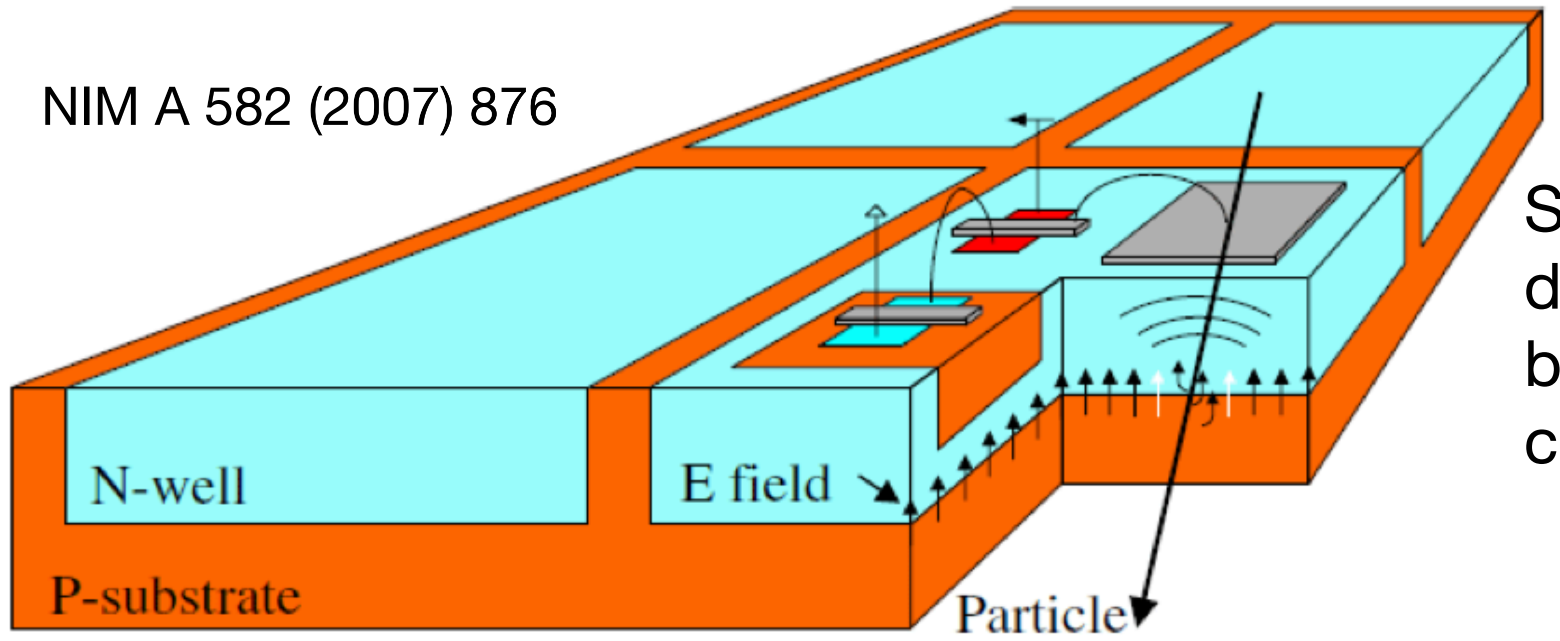
- mTPC enclosed within solenoid - restricts space for any additional detectors
- One option could be to replace the solenoid for a new one, with a larger bore
  - Several pion detector designs could be considered
  - May also be useful for 11GeV set up

- Alternatively, keep UVa solenoid and add thin tracking detectors
  - e.g. HVMAPS → this will be our next route of study

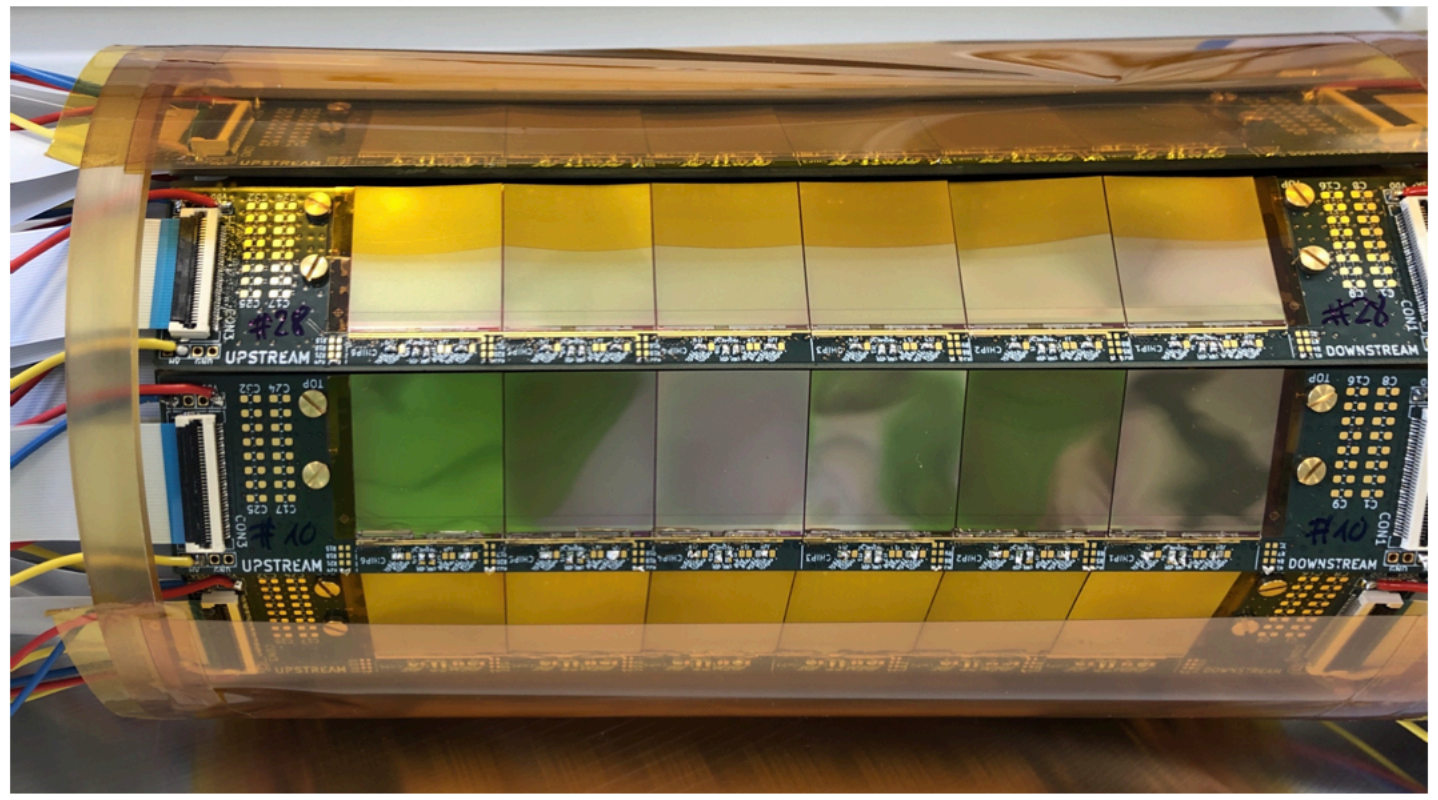
High Voltage Monolithic Active Pixel Sensors (HVMAPS) for SIDIS Pions

HVMAPS

NIM A 582 (2007) 876

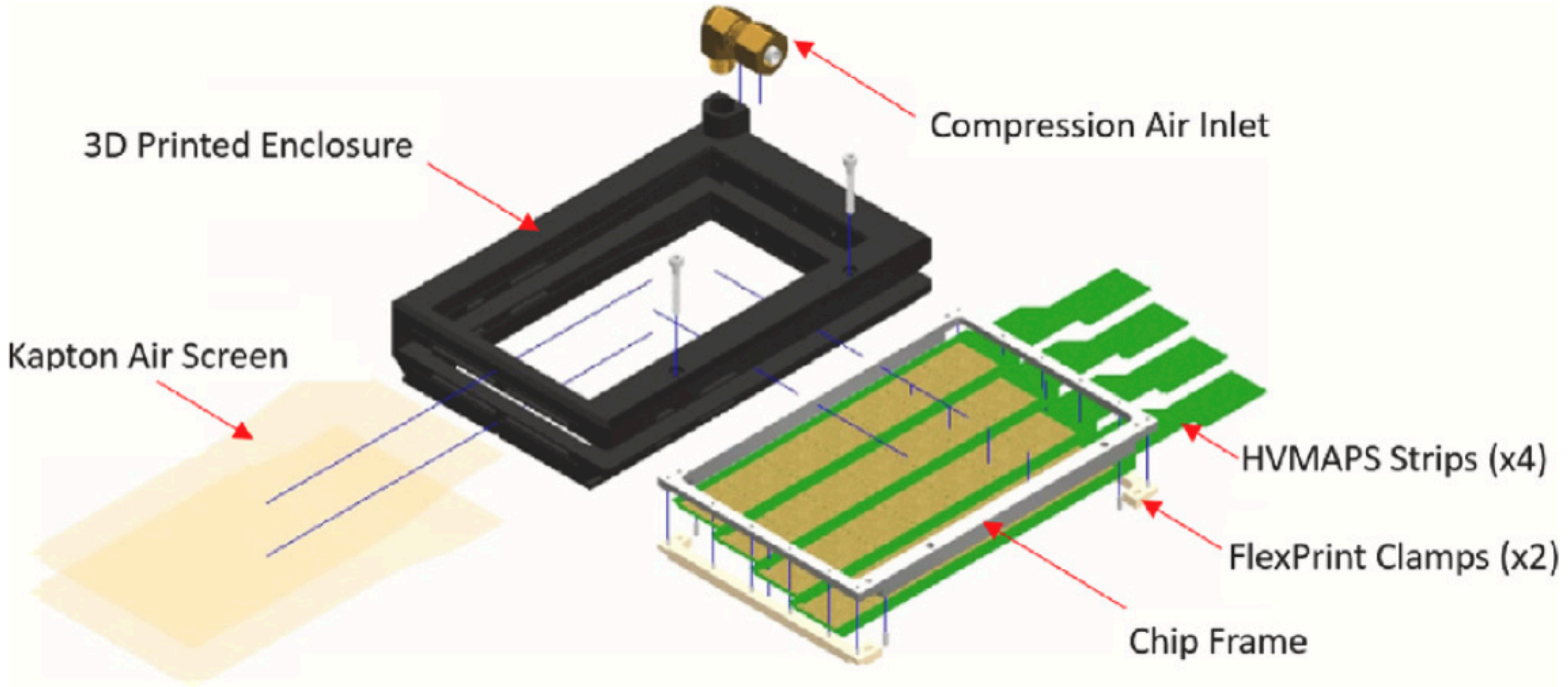


Strong electric field in depletion zone of reverse biased diode leads to fast current signal



Vertex detector prototype with MuPix10 chips for Mu3e

From: arXiv:2106.03534v1 [physics.ins-det]



HVMAPS for Hall A MOLLER Compton Polarimeter (From U. Manitoba group)

- Silicon sensor with hit processing circuitry integrated on a single silicon wafer - simplified monolithic design
- Highly granular; very thin/low material thickness; low cost; low power; high efficiency; improved radiation tolerance; work in magnetic field; standard commercial CMOS processes

- HVMAPS collect charge via drift, compared with diffusion in standard MAPS → faster signals
- Can be operated in high rate environments (up to 30MHz)
- Can be readout in continuous mode

- HVMAPS will be used for Mu3e tracking (barrel config, 4 layers)
- Active area 2cm x 2cm, pixel size 80 μm x 80 μm, sensors thinned to ~50μm (X/X_0=0.054%), commercial 180nm HV-CMOS process, time resolution <20ns

- HVMAPs also to be used at JLab in MOLLER for particle tracking, some real time monitoring of event profile, and for Compton polarimetry (will use P2Pix, a modified version of MuPix10)

- Proposal for TDIS → system of barrel layers of HVMAPS placed immediately surrounding mTPC, within solenoid, for SIDIS pions

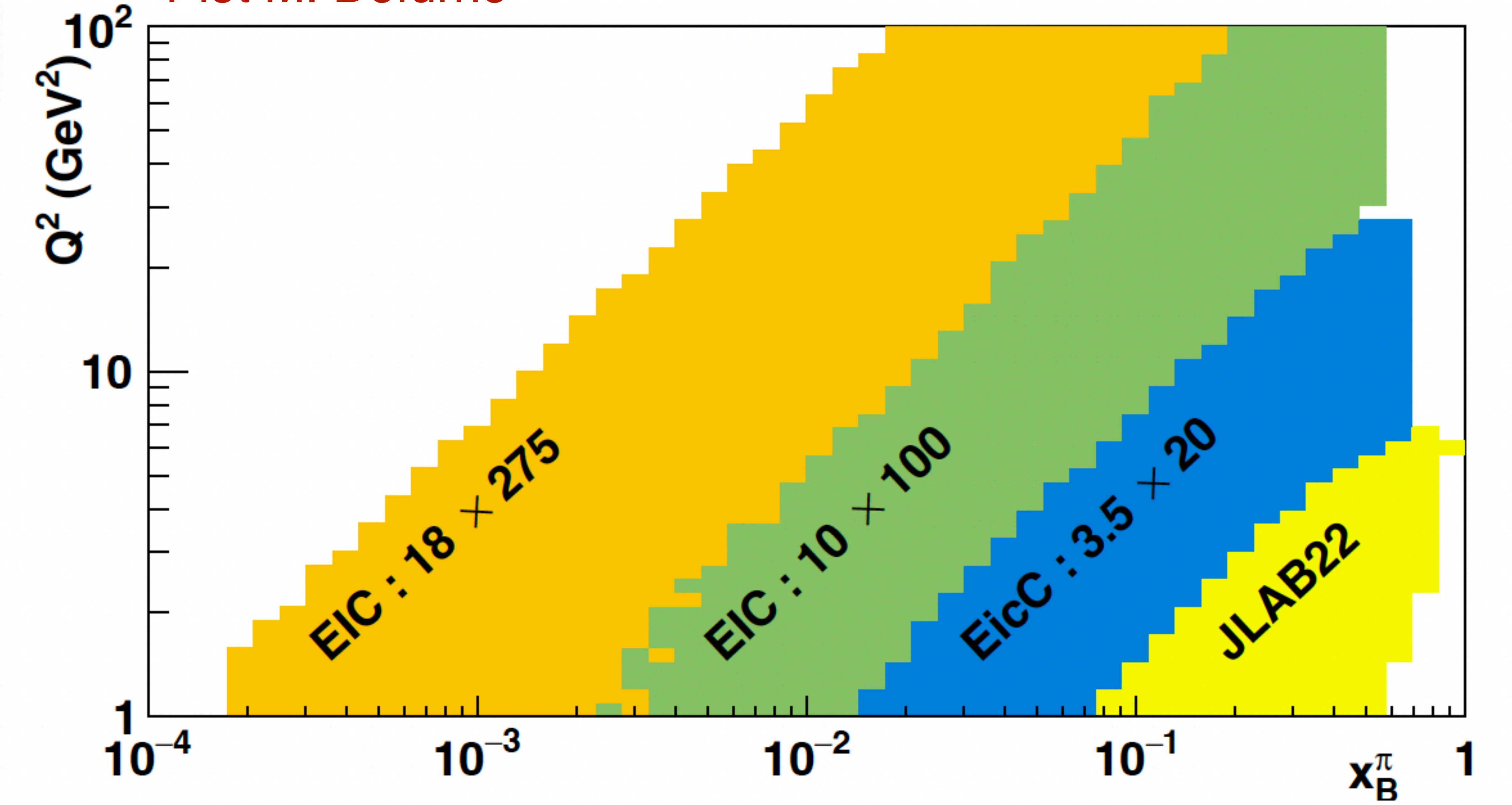
- **Concept, research and design in progress**

https://doi.org/10.1016/j.nima.2024.169874

22GeV Unlocks Possibility of Pion DVCS via Sullivan Process

Pion DVCS via Sullivan Process Unlocked at 22GeV

Plot M. Defurne



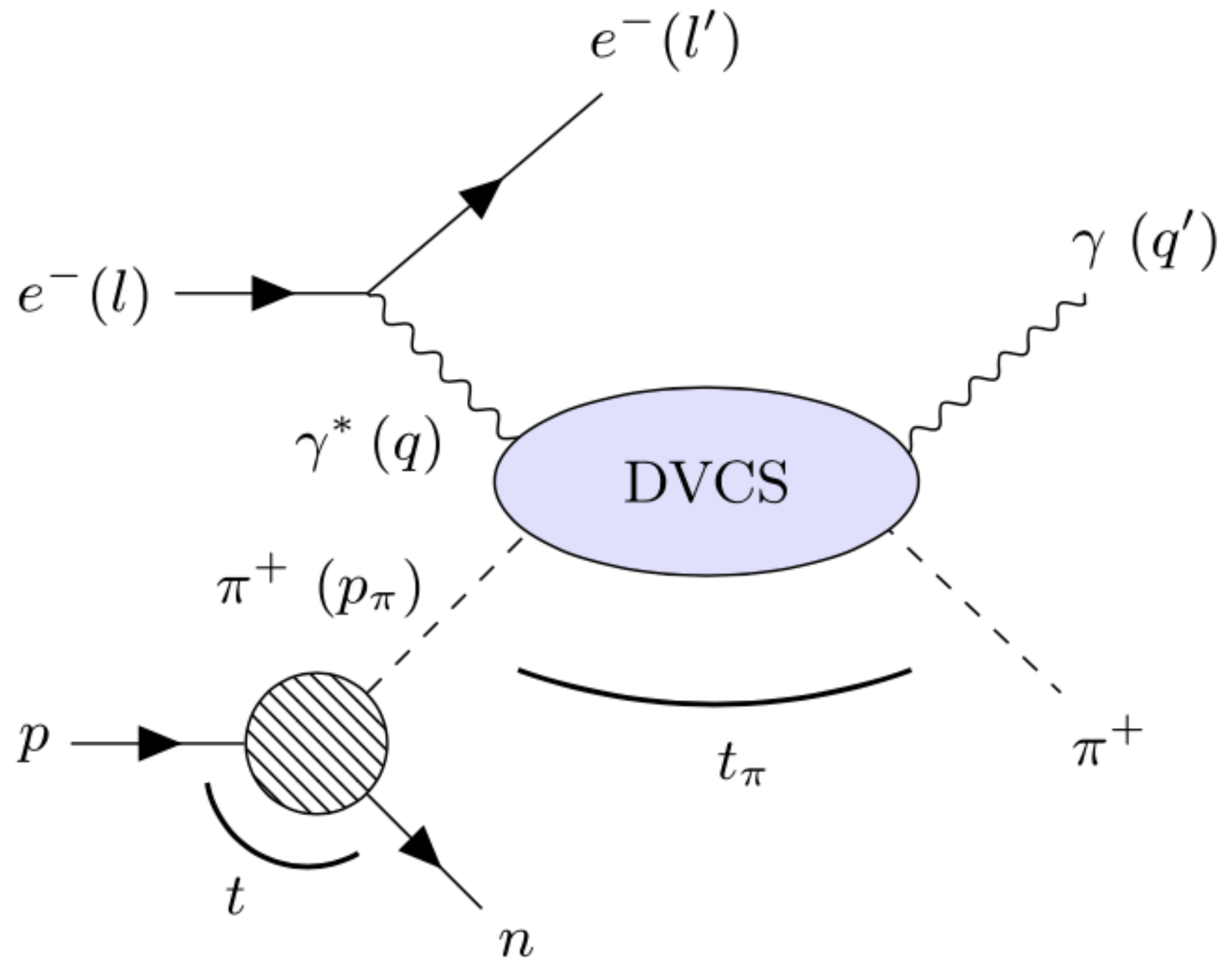
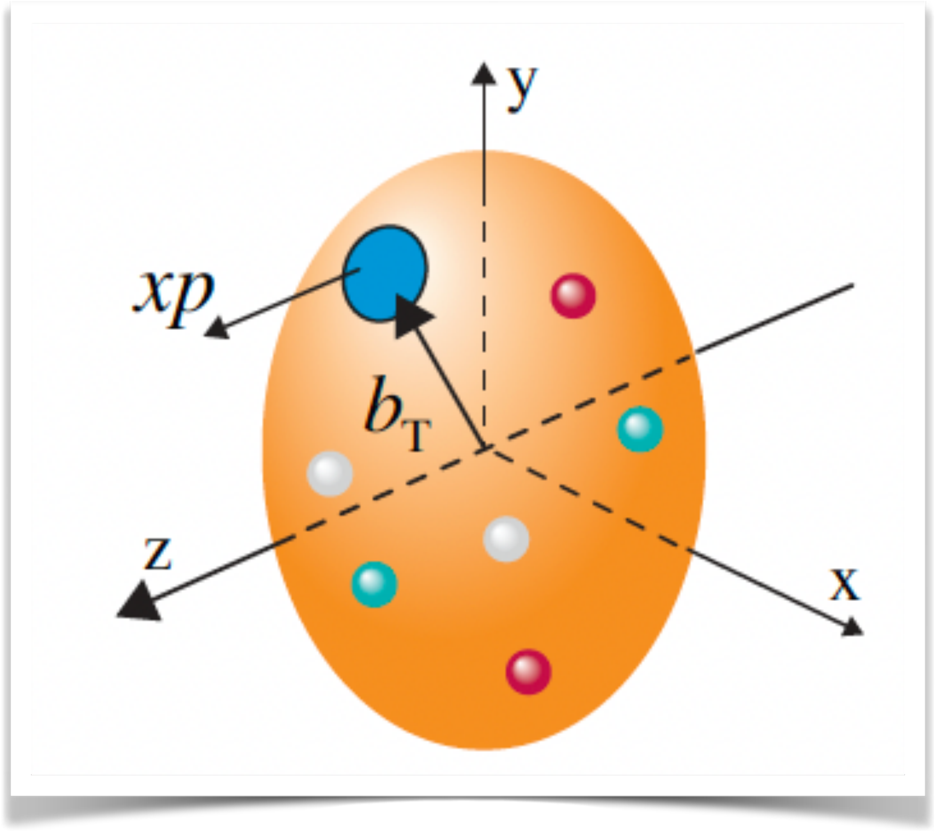


Image and more info on Sullivan DVCS:
J. Chavez et al, PRL 128, 202501 (2022)



- Studies by M. Defurne (CEA Saclay)

- DVCS and GPDs → correlations between x and b_T of partons; quark orbital angular momentum; GFF for mechanical properties…
- *Many* theoretical studies of pion GPDs, but severe lack of data!

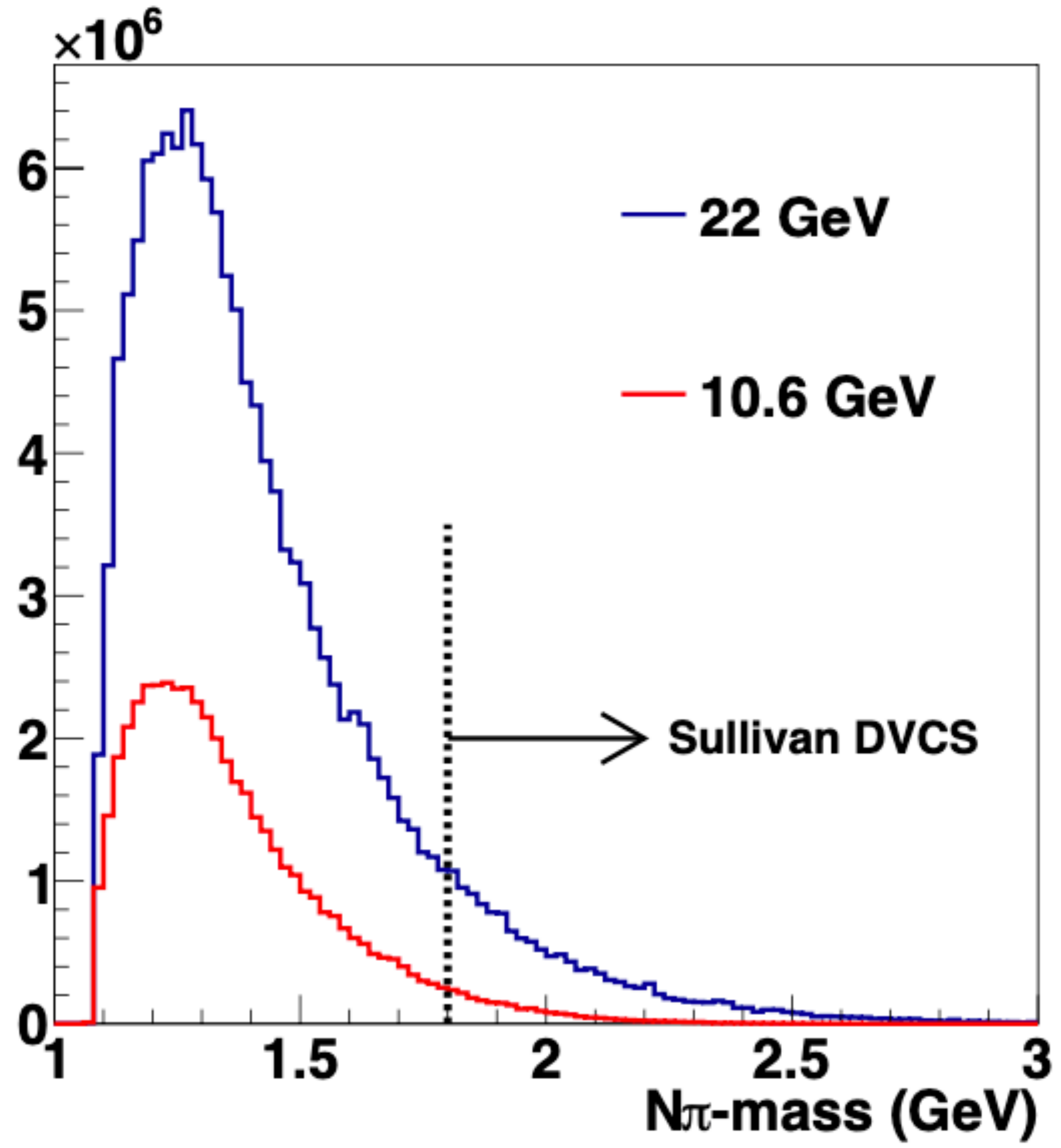
- 22 GeV unlocks pion DVCS via Sullivan process with TDIS, which is not possible at 11GeV
- Phase space at 22GeV completely complimentary to future collider data!
  - JLab 22GeV extends the reach far into the valence regime, which is not accessible at future colliders
- JLab 22GeV combined with colliders would enable a pion GPD program spanning $x_B^\pi \sim 10^{-4}$ to ~ 1

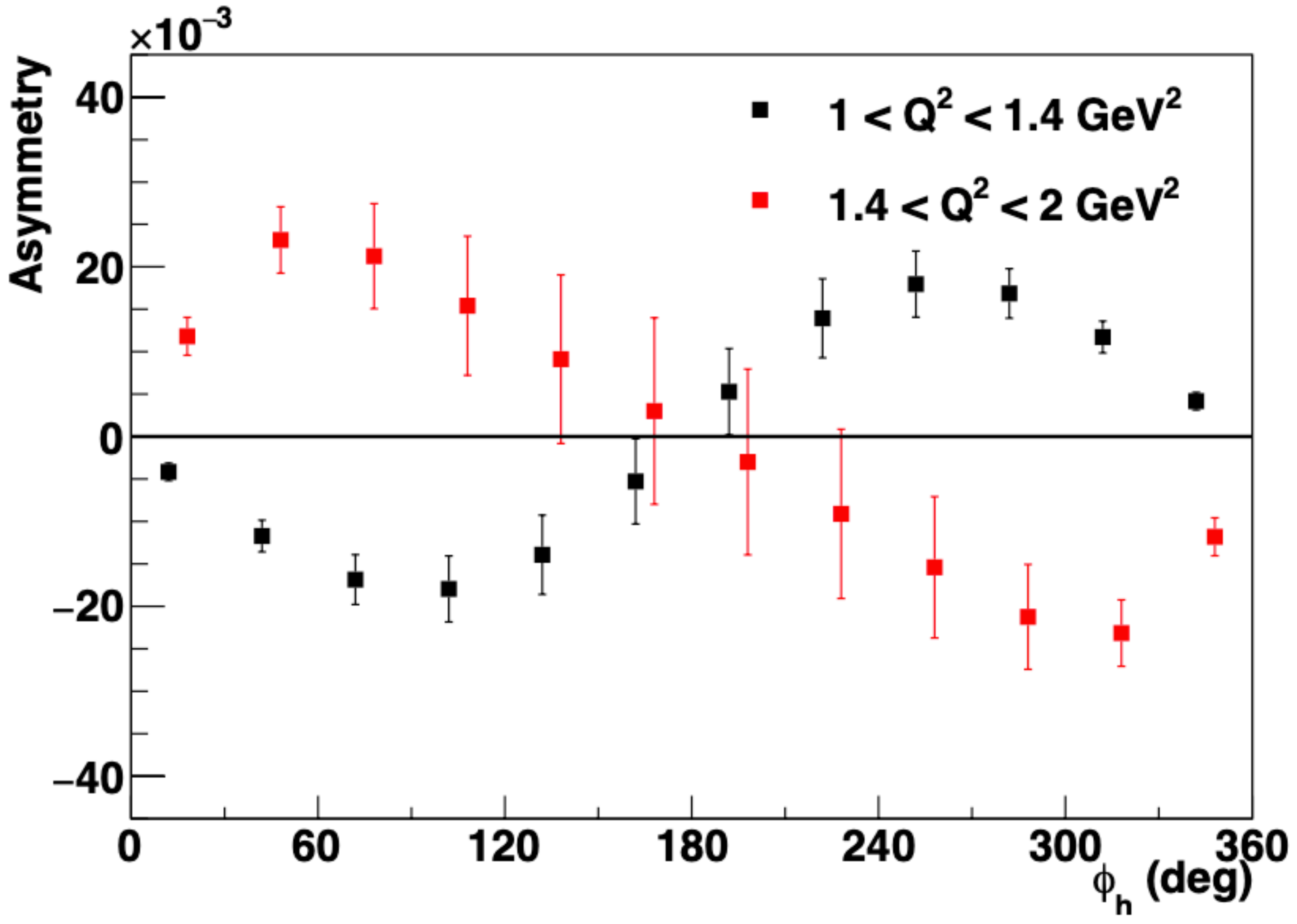
- To realise this measurement, we need to figure out how to measure the final state π and γ in the TDIS set up

Pion DVCS via Sullivan Process Unlocked at 22GeV

More stats above nucleon resonances cut

Assumed luminosity 3000fb^{-1}





Plots M. Defurne

Only accessible for TIDS with 22GeV electron beam

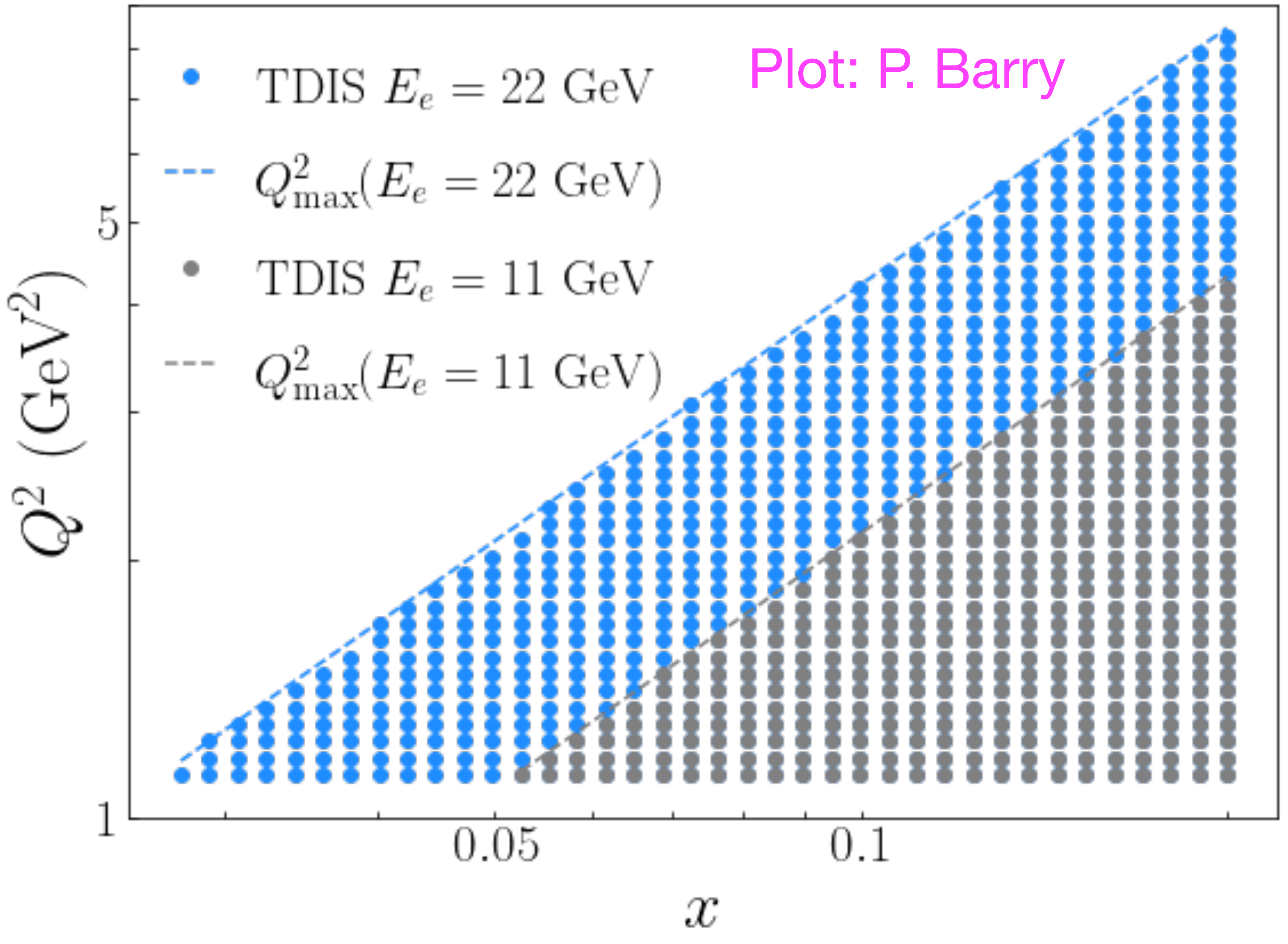
- Need mass of spectator nucleon and recoil pion > 1.8 GeV (< 1.8 GeV nucleon resonances contribute to scattering)
- 22GeV → phase space extends to lower x_π → higher cross sections → more events > 1.8 GeV

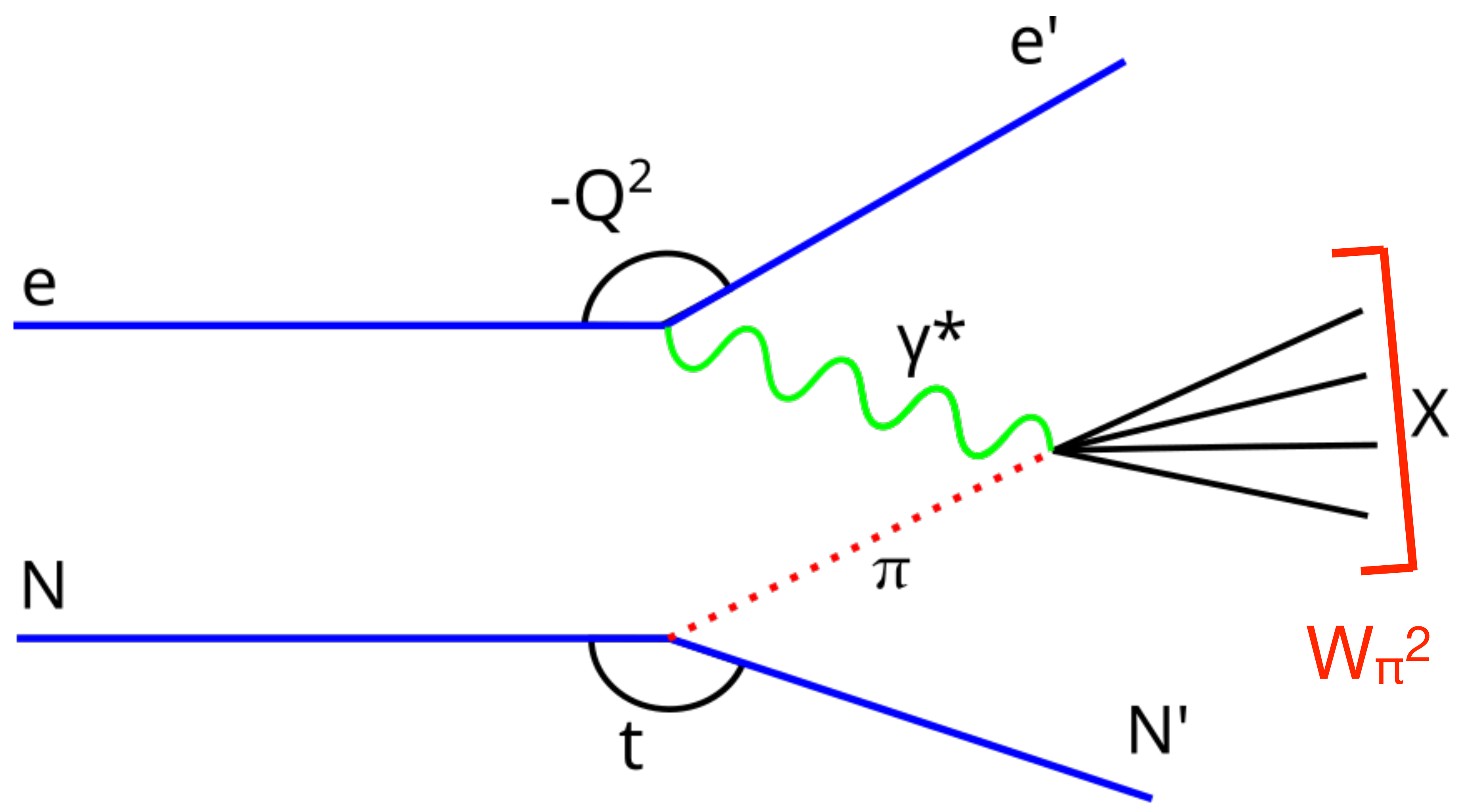
- BSA calculated with predicted statistics for integrated luminosity 3000fb^{-1} and $x_\pi \in [0.1, 0.2]$
- Sign change in BSA predicted across all tested GPD models as Q^2 increases
- Gluon and quark contributions to imaginary part of CFF have opposite signs
  - as Q^2 increases gluon contribution decreases and gets smaller than quark contribution

- Locating zero crossing between quark and gluon driven regimes would improve understanding of DVCS
- BSA would be a clear observable for mapping regime of gluon superiority in pion → crucial info for EHM topics
- Important role of gluons in valence region of pions is expected → TDIS at 22GeV will shed new light on this

22GeV Expands Phase Space for Meson Structure Function Extractions

TDIS at 22GeV





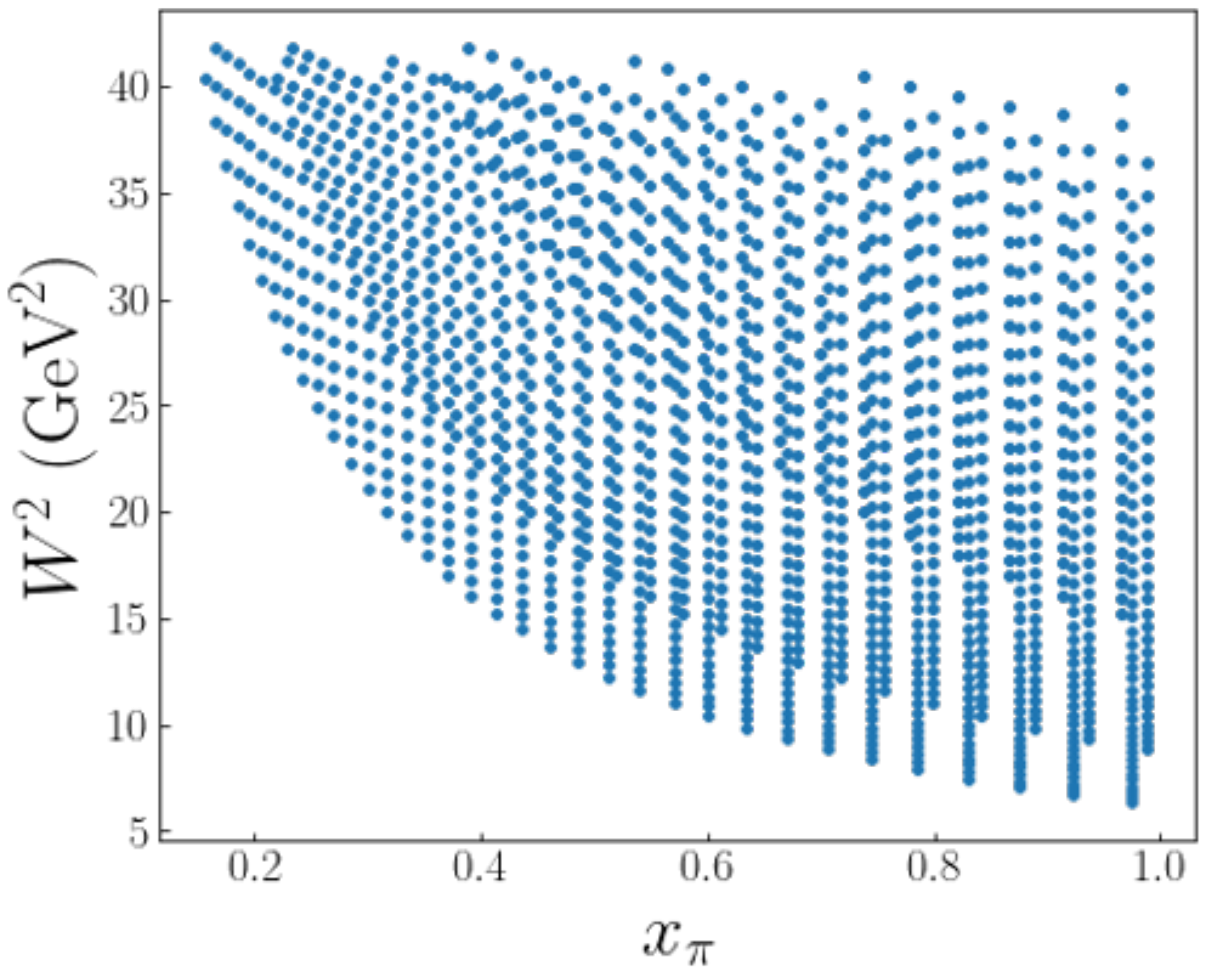
- See P. Barry's talk on Monday
- To maximise impact on PDF fits, W_π^2 > 1.04GeV^2 cut will minimise ρ resonance contributions
- Much larger phase space available for this at 22GeV compared to 11 GeV

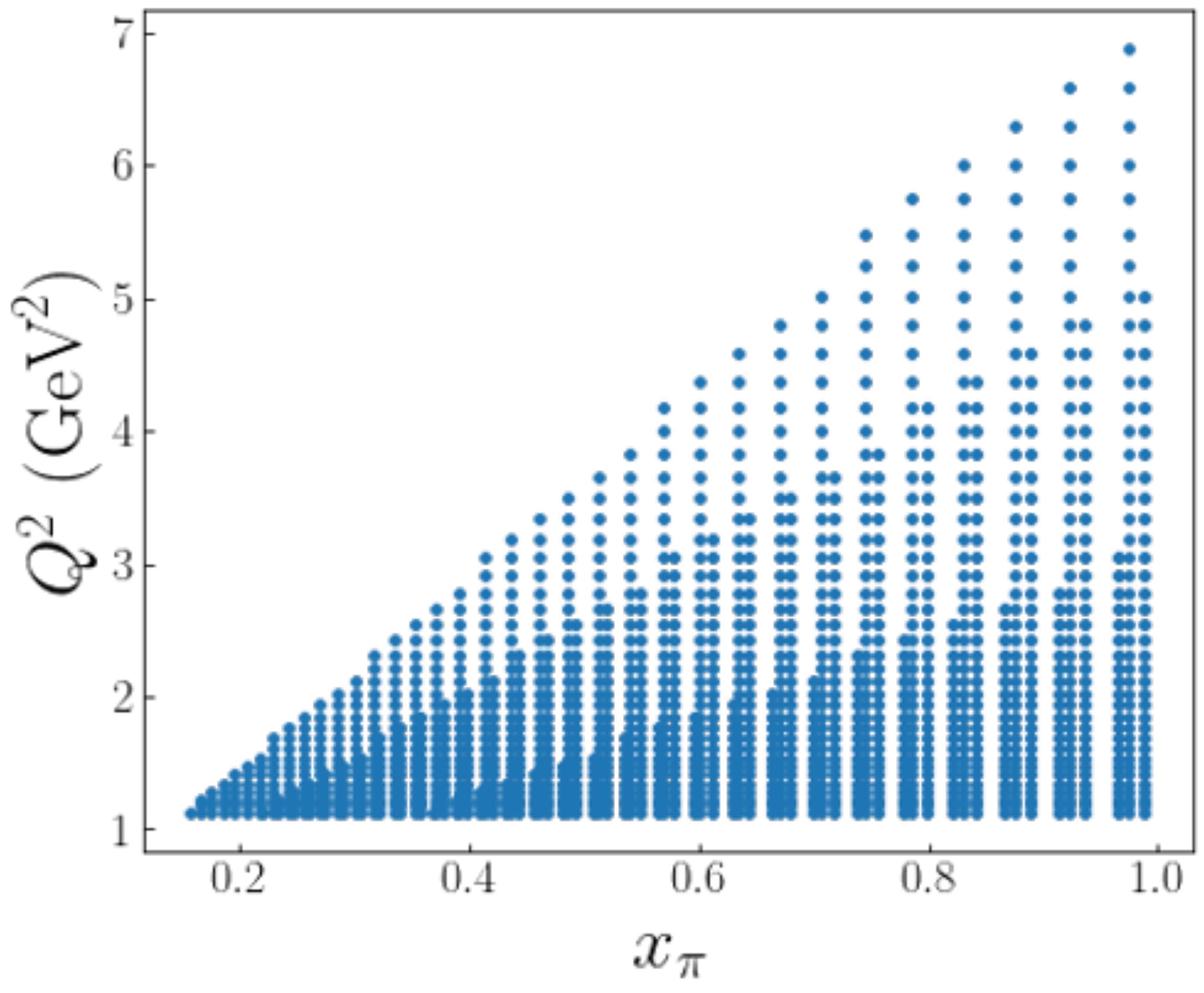
- 11GeV remains crucial
  - Needed to establish and validate the challenging tagging technique, both experimentally and in analysis
  - Needed to commission the novel very high-rate equipment
  - Mapping out pion resonances is important - they have not been measured before so we do not know what to expect
  - 11GeV data is important to help improve and tune model predictions for 22GeV and beyond (e.g. EIC, EIcC)

TDIS Example Phase Space Plots for 22GeV

22GeV projections calculated using P. Barry's phase space code

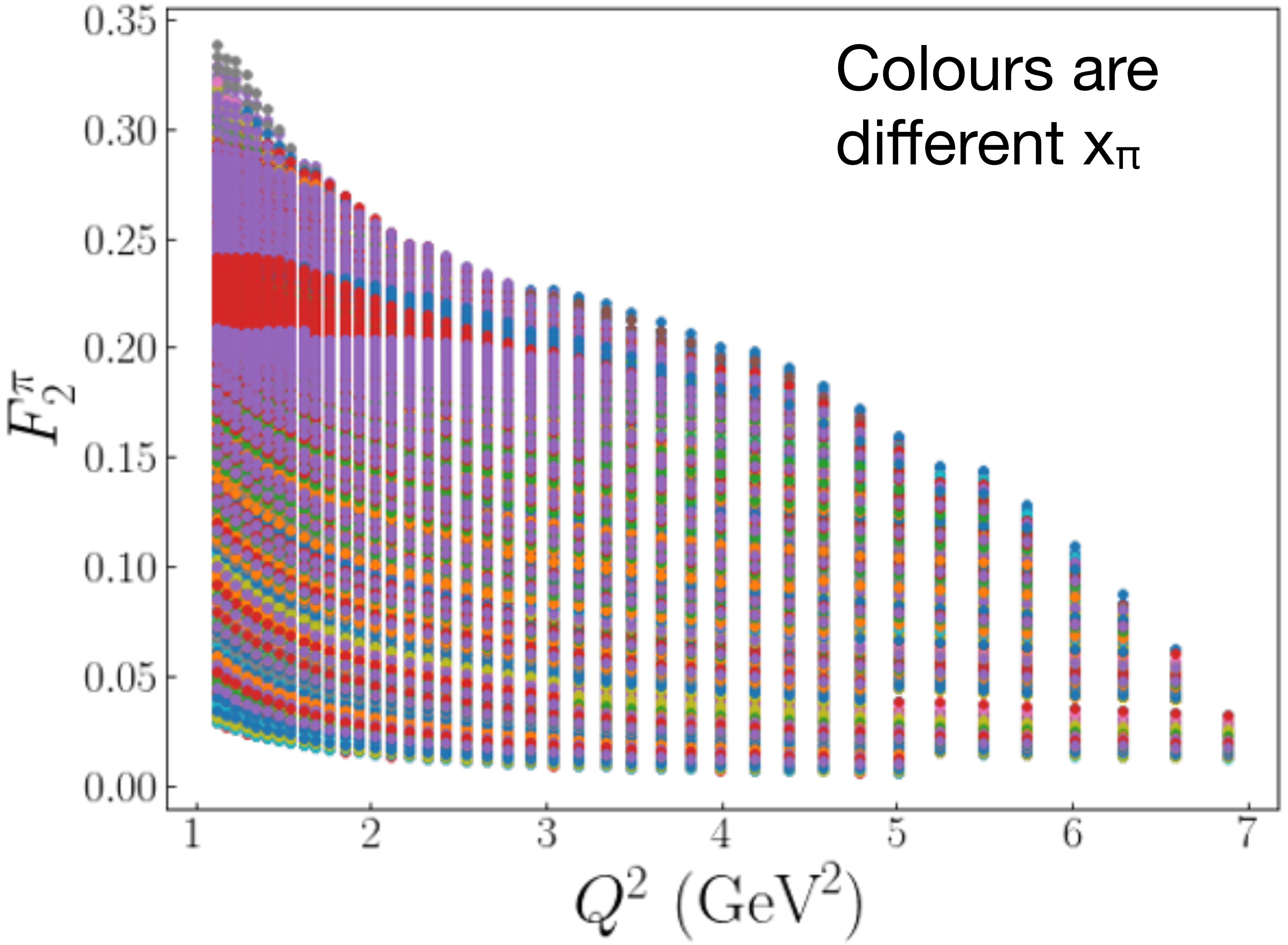
Includes T.J. Hobbs' et al. F_2^π model and JAM PDFs

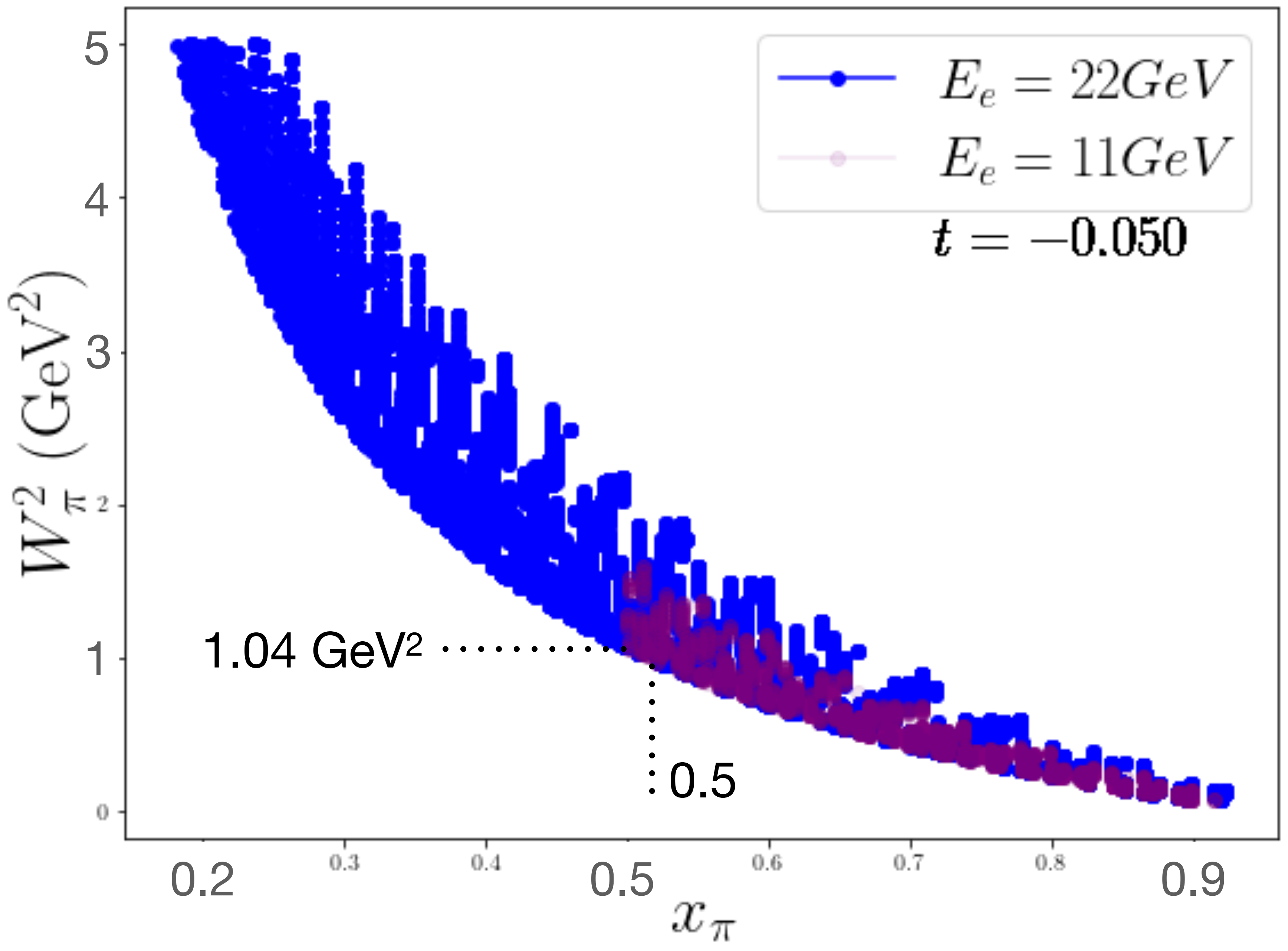




Plots: C. Ayerbe

Broad coverage in x_π





W_π^2 vs x_π plot at t=-0.05

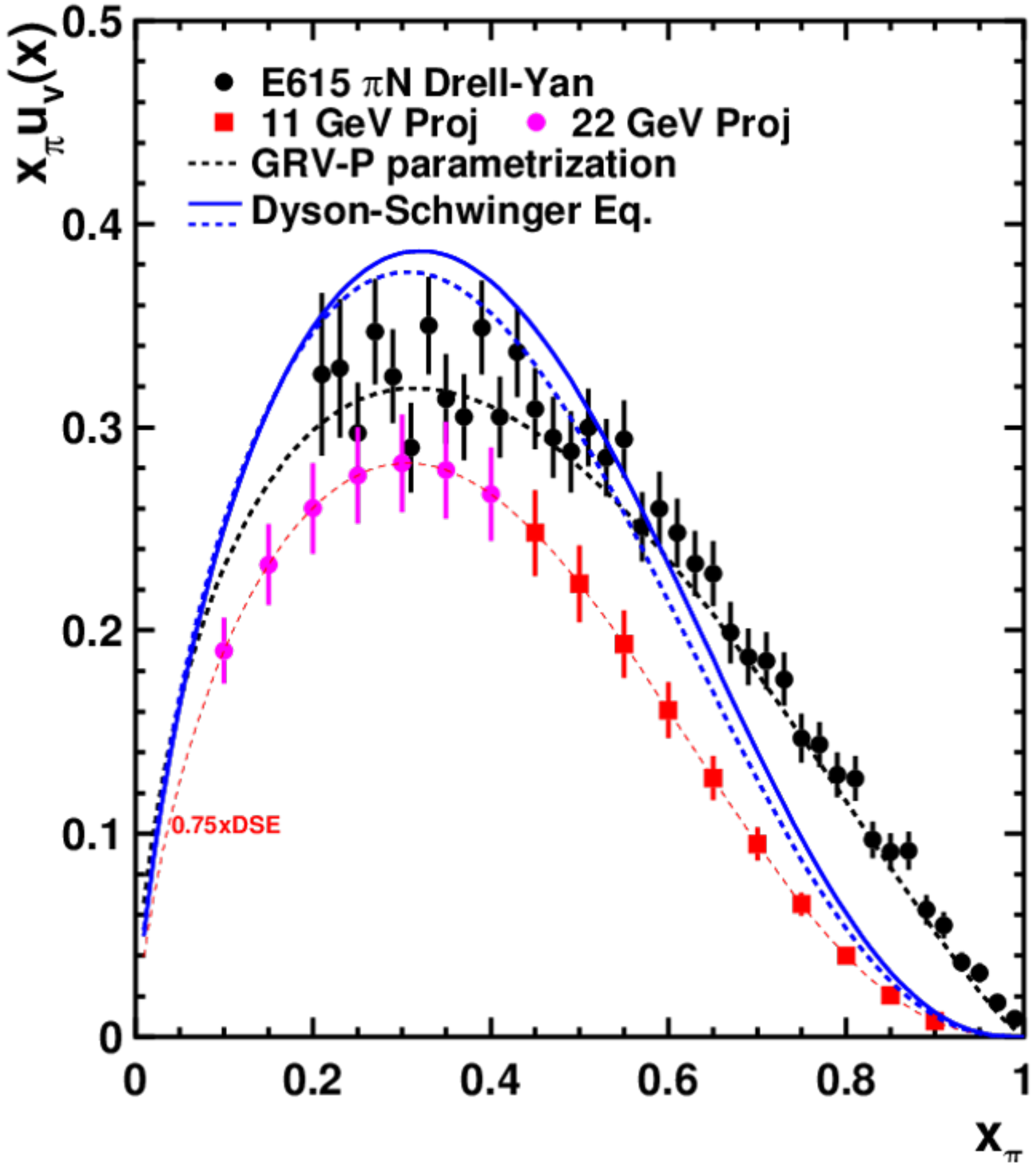
$4m_\pi^2 < W_\pi^2 < 5GeV^2$

11GeV, also cut x>0.5

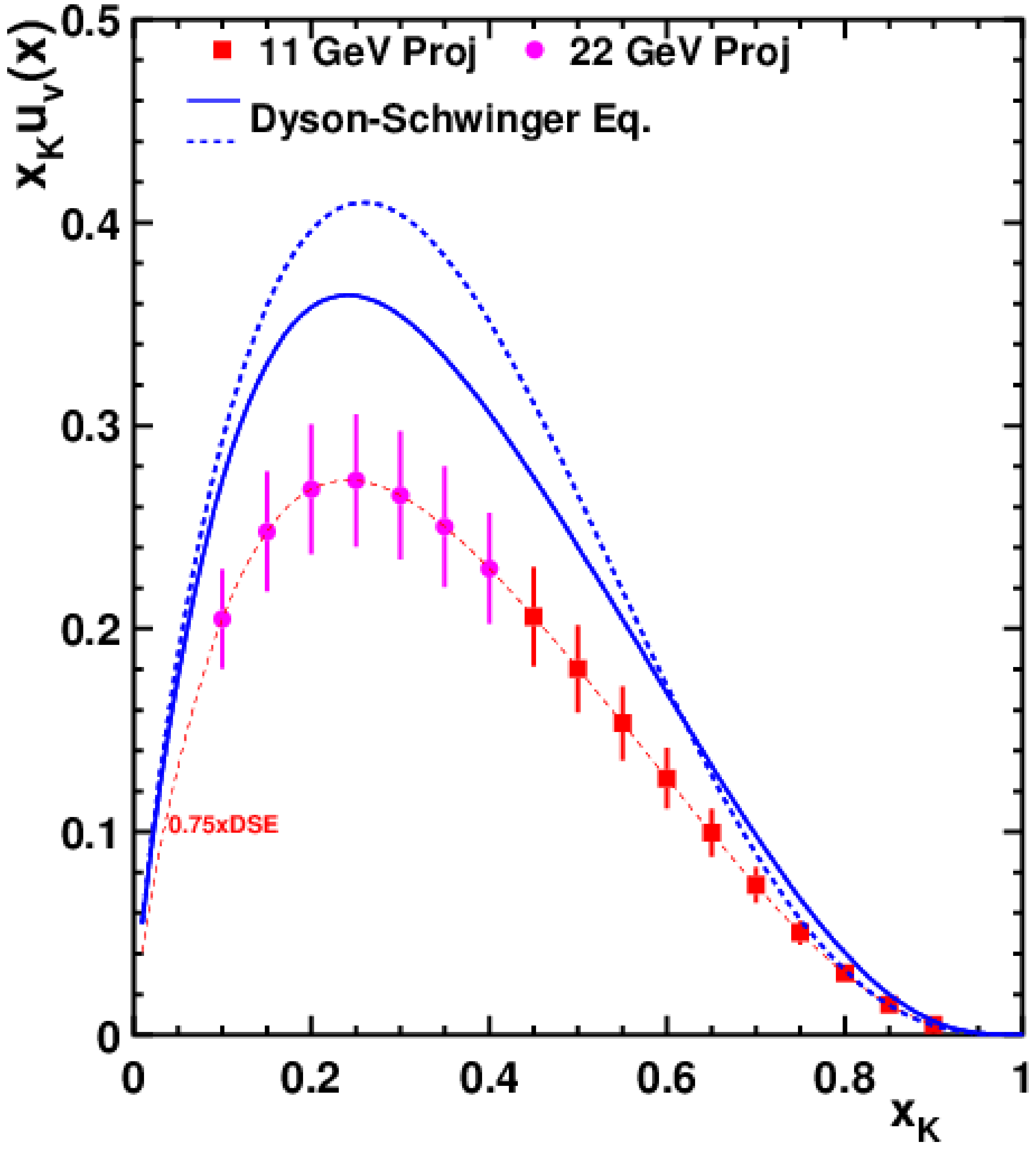
Much wider landscape @22GeV
Only 22GeV reaches W_π^2>2GeV^2

TDIS x_π Range

Pion



Kaon



- 22GeV Projections:
  - 50 days' beam time
  - Time to keep error bars same as 11GeV proposals
- 22GeV drastically expands x-range!
- Adds to sparse world data
- Especially kaon!

Plots: D. Dutta and T. Horn

Plan Moving Forward

Immediate Next Steps for 22GeV TDIS

Phase space extension for meson SF and PDF studies is very significant, but also understood at the moment

Next steps will be focussed on demonstrating further the feasibility of the new SIDIS and DVCS measurements

☑ Pion SIDIS
- Pion TMD model developments within theory community are very active → theoretical study of pion SIDIS with 22GeV TDIS is possible
- Next step → show extracting TMDs from TDIS data, with all experimental considerations included, is feasible:
  - Design SIDIS pion detector (eg HVMAPS)
  - Implement pion detector in TDIS Geant4 → determine realistic acceptances, efficiencies and resolutions
  - Convert phase space model from JAM into event generator
  - Study pion SIDIS events in TDIS simulation with new pion detector
  - …

☑ Pion DVCS
- Pion GPD model developments also very active
- Next steps → further check feasibility with TDIS simulation:
  - Work on detector designs for π and γ, implement them in Geant4 and check simulated performances
  - (Current idea → same pion detector as SIDIS, with NPS for photon detection)
  - Convert phase space model from CEA Saclay into event generator
  - Pass events through simulation with new detectors in place and demonstrate BSA extraction with realistic simulation
  - …

Summary

- Meson structure function measurements with TDIS can provide crucial insights for EHM

- EIC will provide access to meson structure in gluon and sea quark regime
  - Uncertainties increase for meson SF at EIC as $x \rightarrow 1$ (see J. Phys. G: Nul. Part. Phys. 48 075106 2021)

- JLab is the only place to realise a TDIS program which can impact a sparse world data set for pion and kaon SF in high x_π range
- It is crucial that we run TDIS 11GeV prior to 22GeV to validate and establish the technique

- 22GeV TDIS
  - Expands phase space for meson SF ($x_\pi \rightarrow 0.1$), which will strongly impact PDF fits
  - Offers new possibility for SIDIS on virtual pion for pion TMD observables - not available with 11GeV TDIS
    - Large x_π data in which non-perturbative TMD structures are more sensitive than in small x_π and large $\sqrt{s}$ data (ie EIC)
  - Offers new possibility for DVCS on virtual pion for pion GPD studies with TDIS - not available with 11GeV

- SIDIS and DVCS via Sullivan process with TDIS would enable a novel multi-dimensional meson imaging program at mid-high x

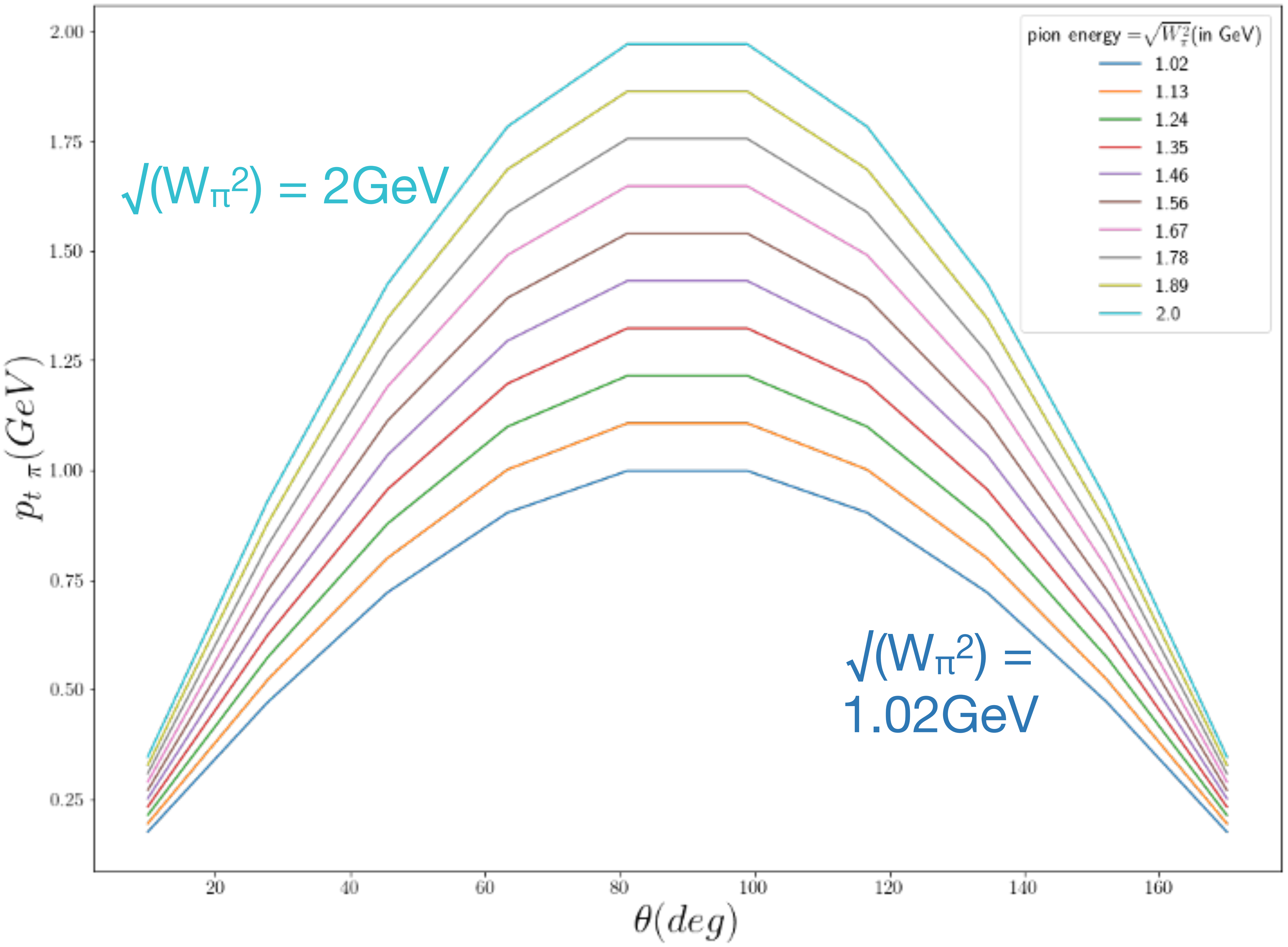
- This is a work in progress…

Thank you

Back-up follows

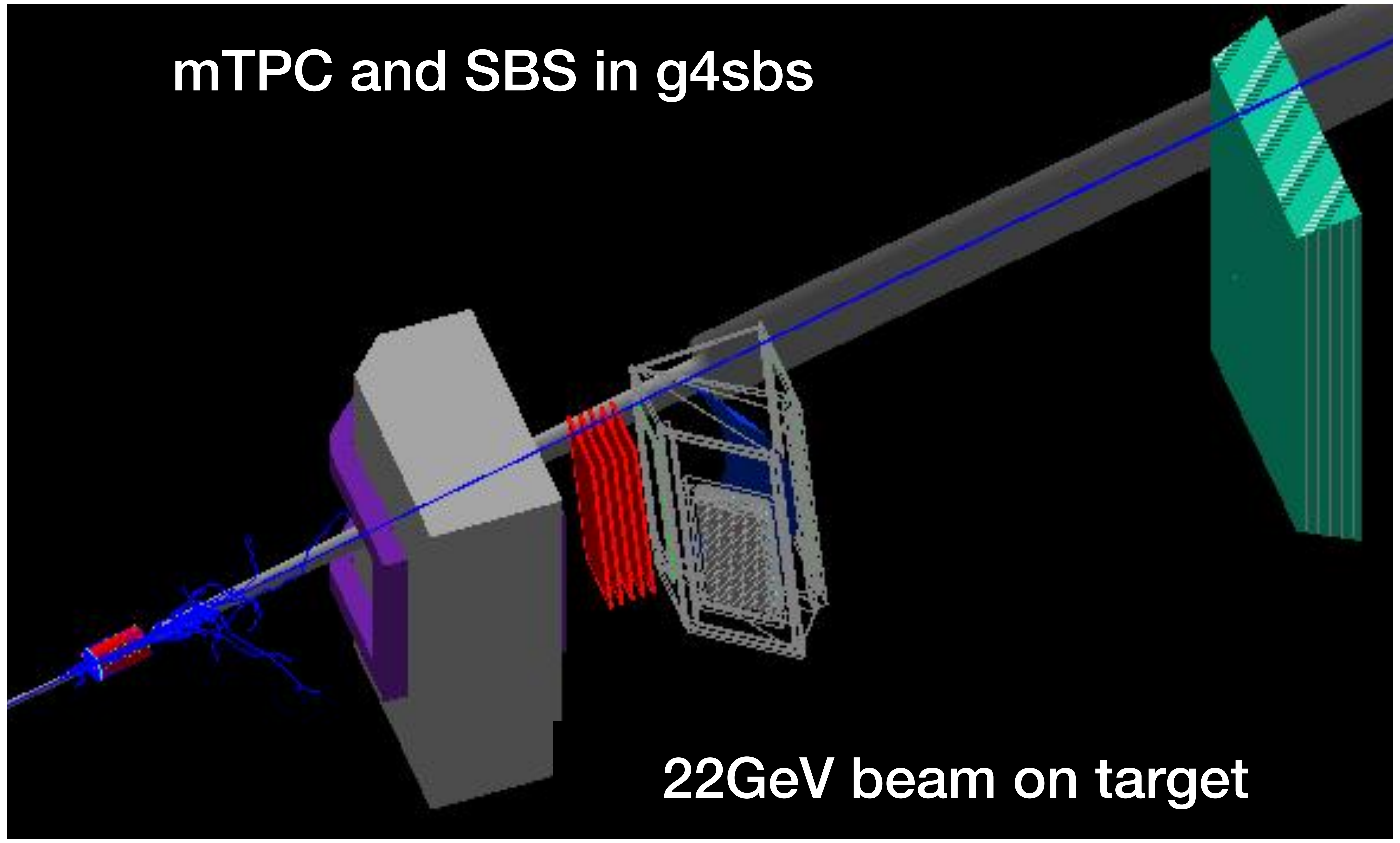
SIDIS on Virtual Meson with TDIS at 22GeV

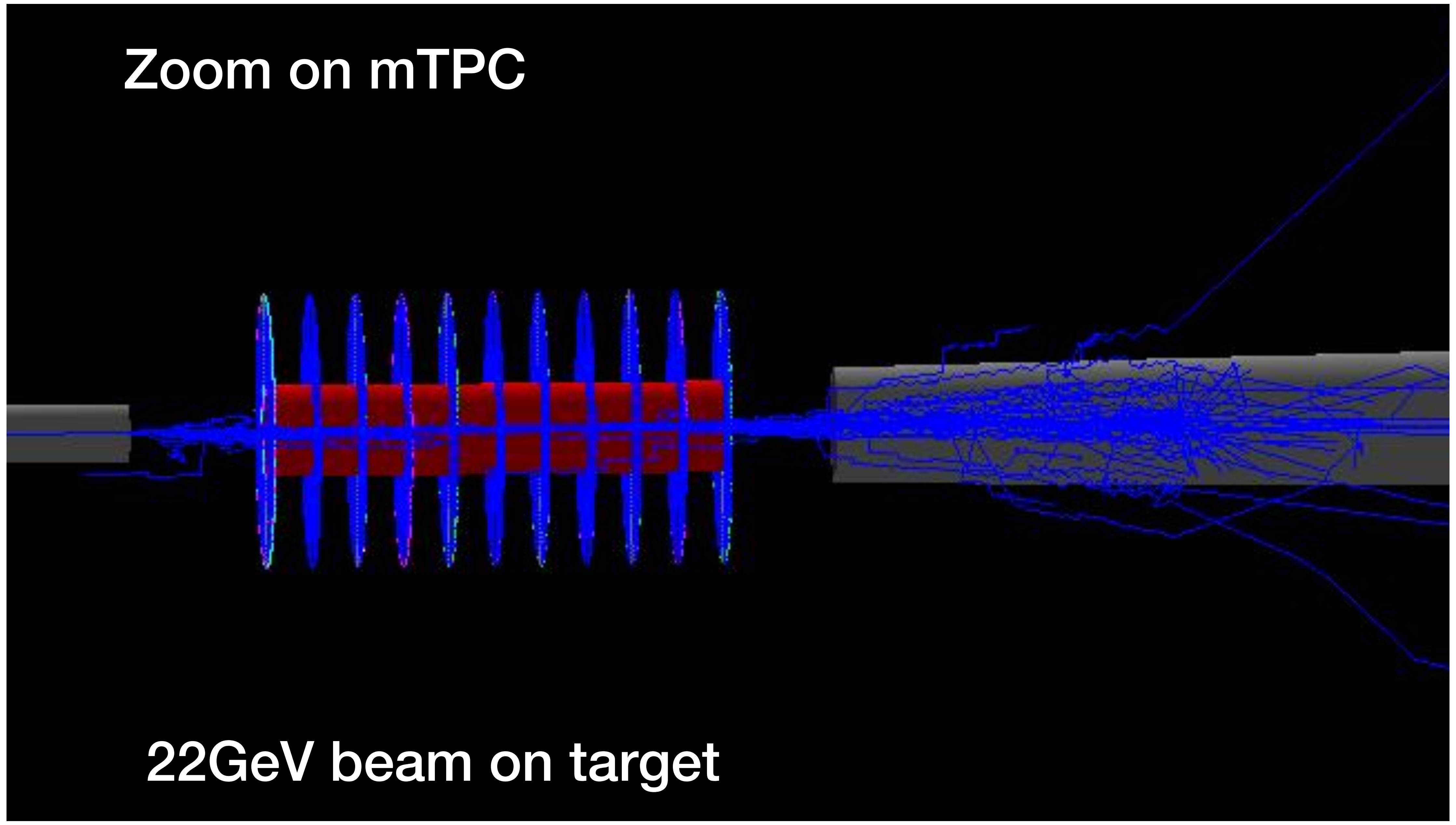
Plot: C. Ayerbe



- SIDIS pion p_T ranges from
  - 0.25 GeV/c at 20° and 160°
  - 2GeV/c at 90°

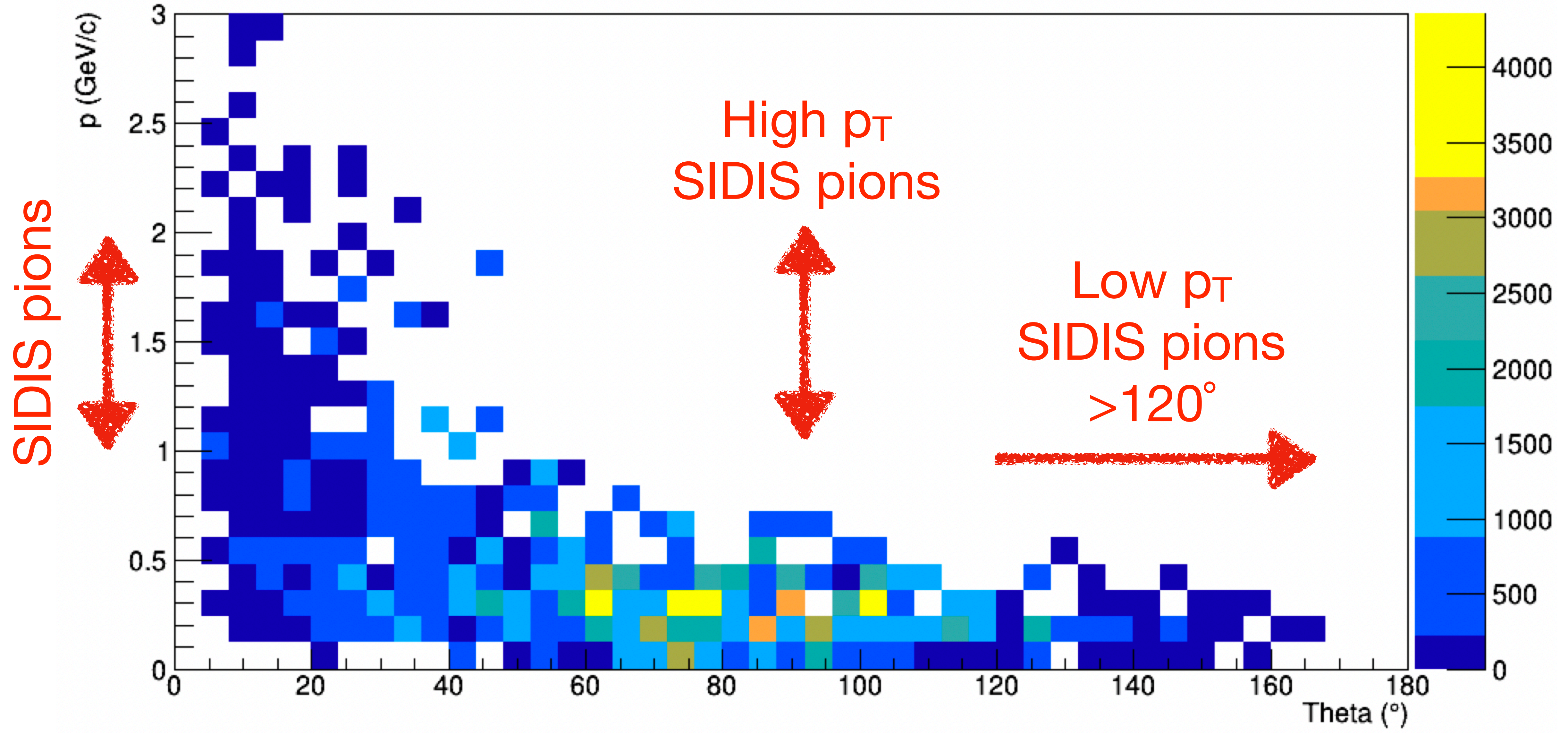
22GeV Simulation Status

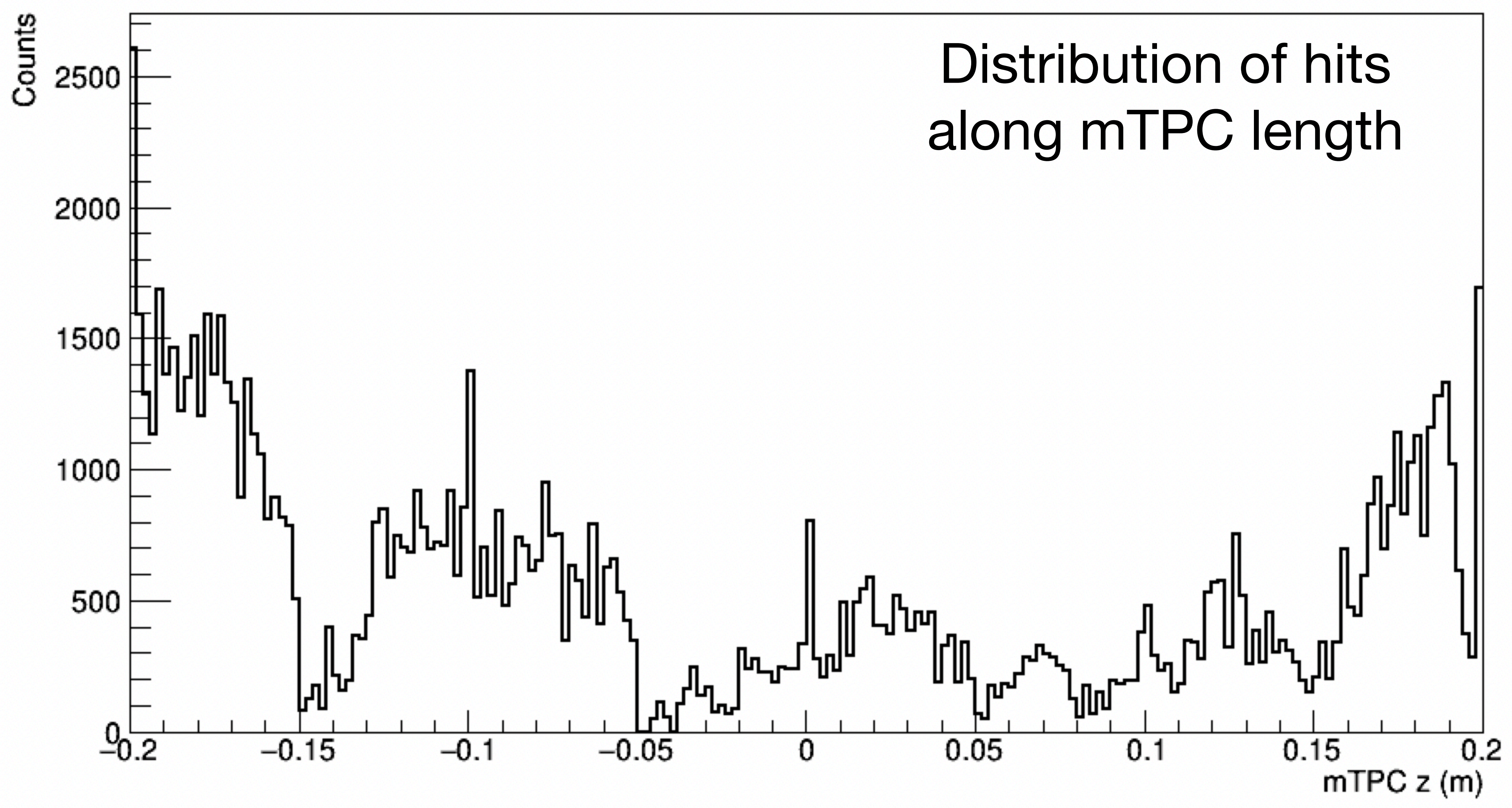




- mTPC/TDIS within SBS Geant4 framework g4sbs
- Can be used for initial studies
- Example next steps:
  - input TDIS/SIDIS events
  - evaluate backgrounds further (eg Pythia)

22GeV Simulation Status

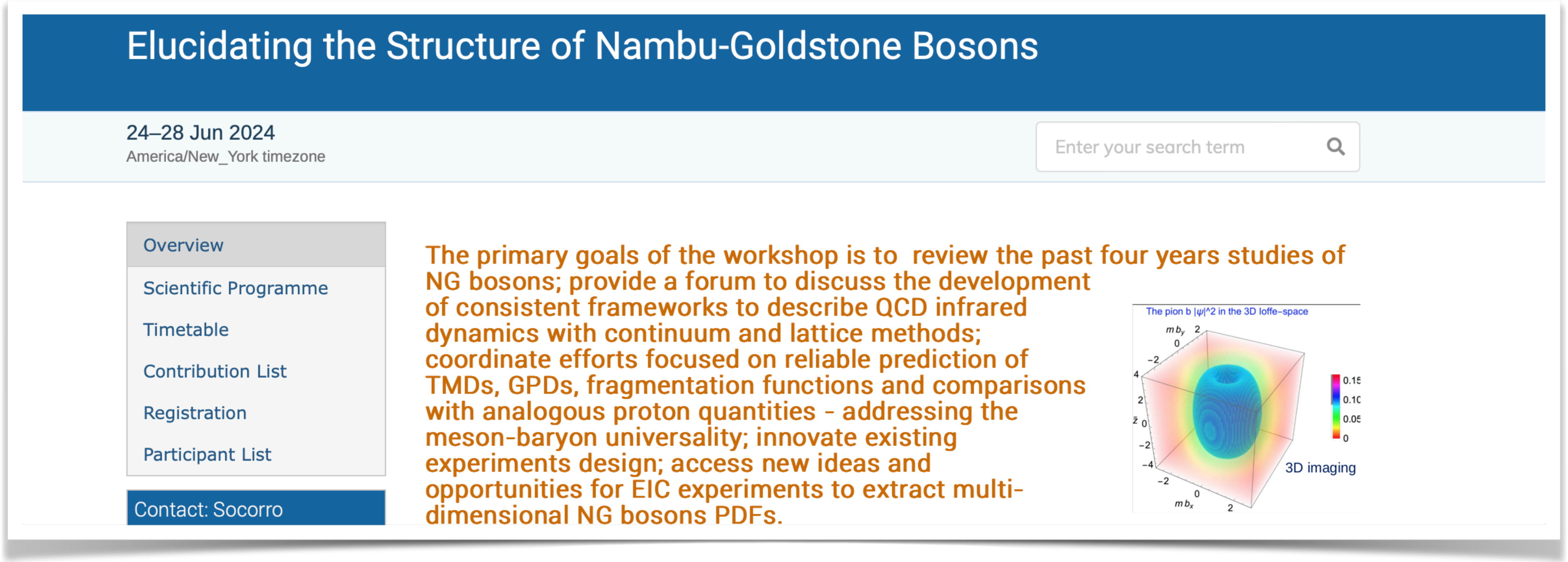




- 22GeV beam on target and Geant4 physics
- Shown: background pions in mTPC
- n.b. SIDIS pions 1GeV < p_π < 2GeV
- Particularly interested in ~90° SIDIS pions for large p_T region
- For low p_T region have to rely on >120°
- Low angles <40° maybe more difficult

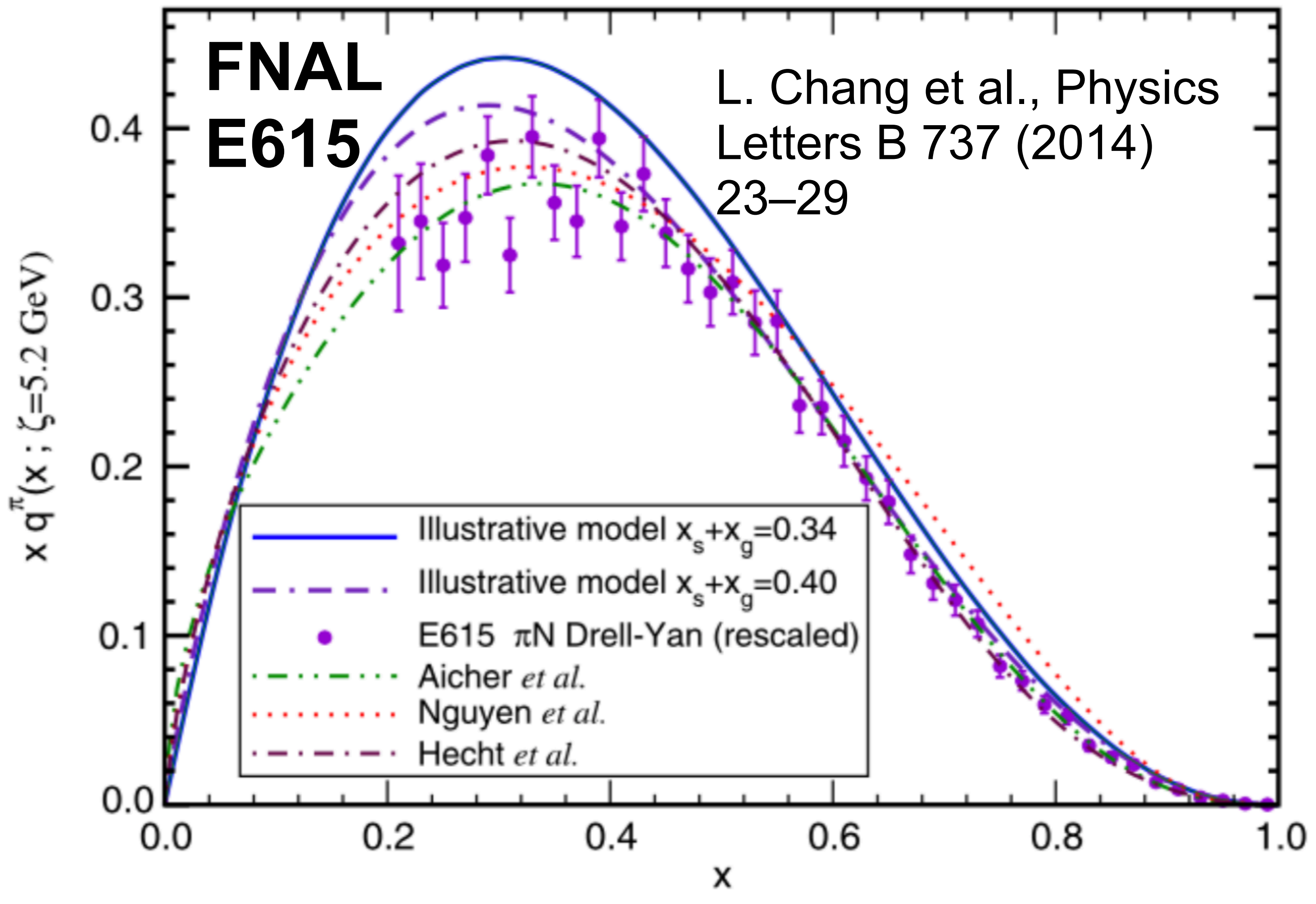
We Need More Data

- Wealth of recent exciting theoretical developments on light meson structure
- Eg see many more reports at recent CFNS workshop

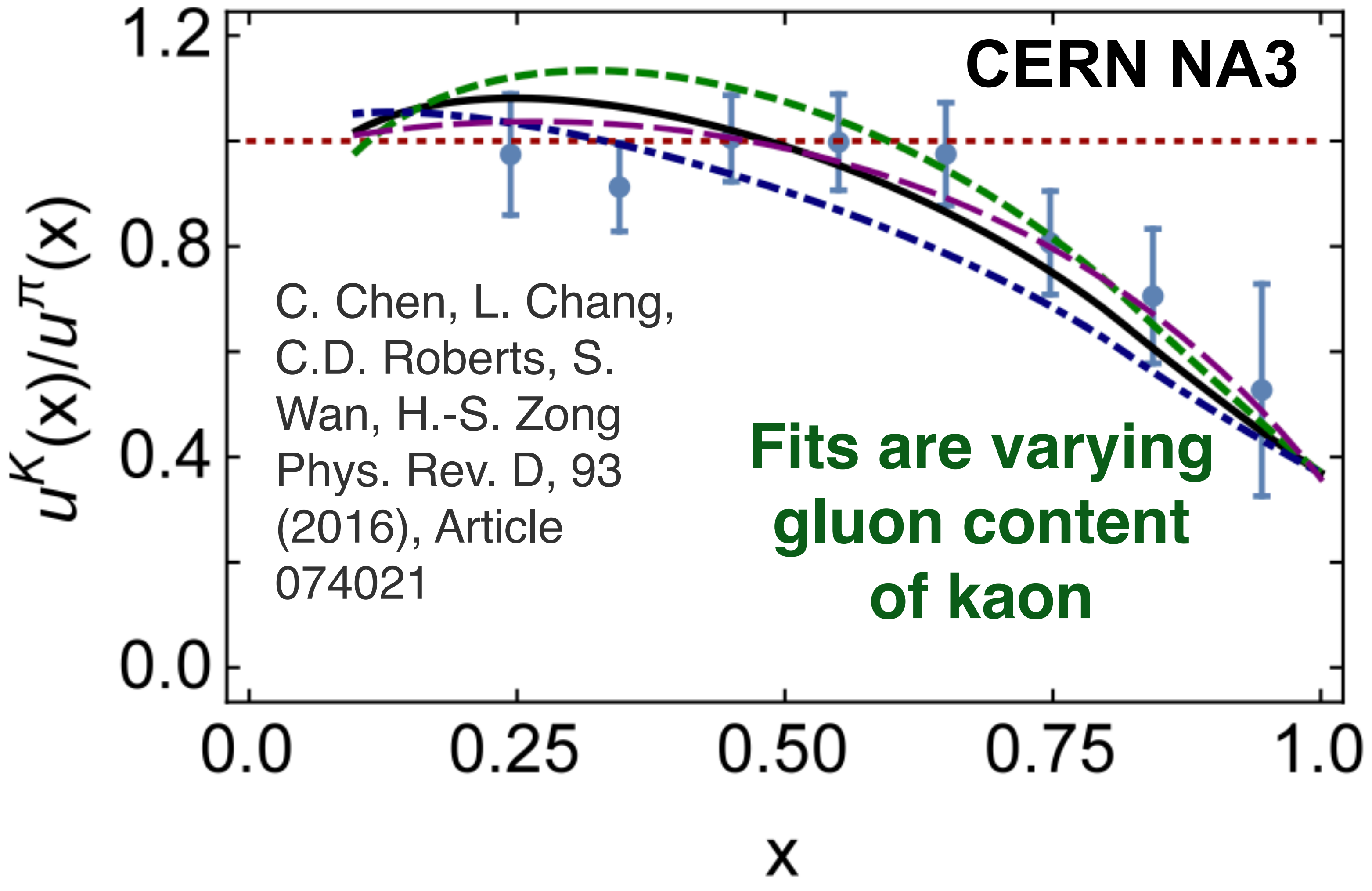


- Extracting meson PDF and TMDs from data will be very complicated
- Demand for experimental data very strong

Pion valence quark distribution function



Ratio K/pi u-quark distributions



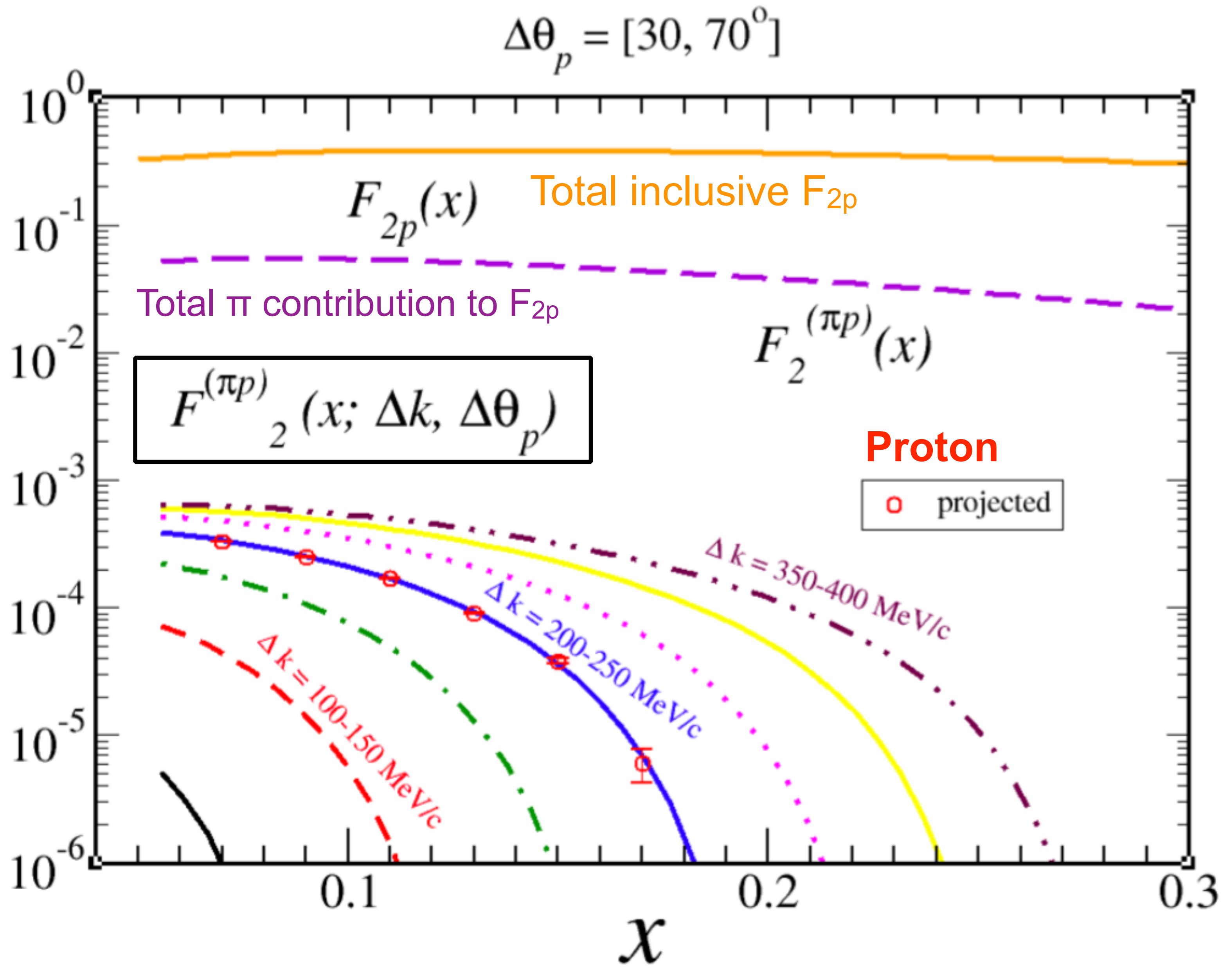
- Very low-x: leading neutron data from HERA
- Valence region: limited DY data from CERN/Fermilab
- More data needed to reduce uncertainties in global PDF fits
- More DY coming from AMBER - complimentarity

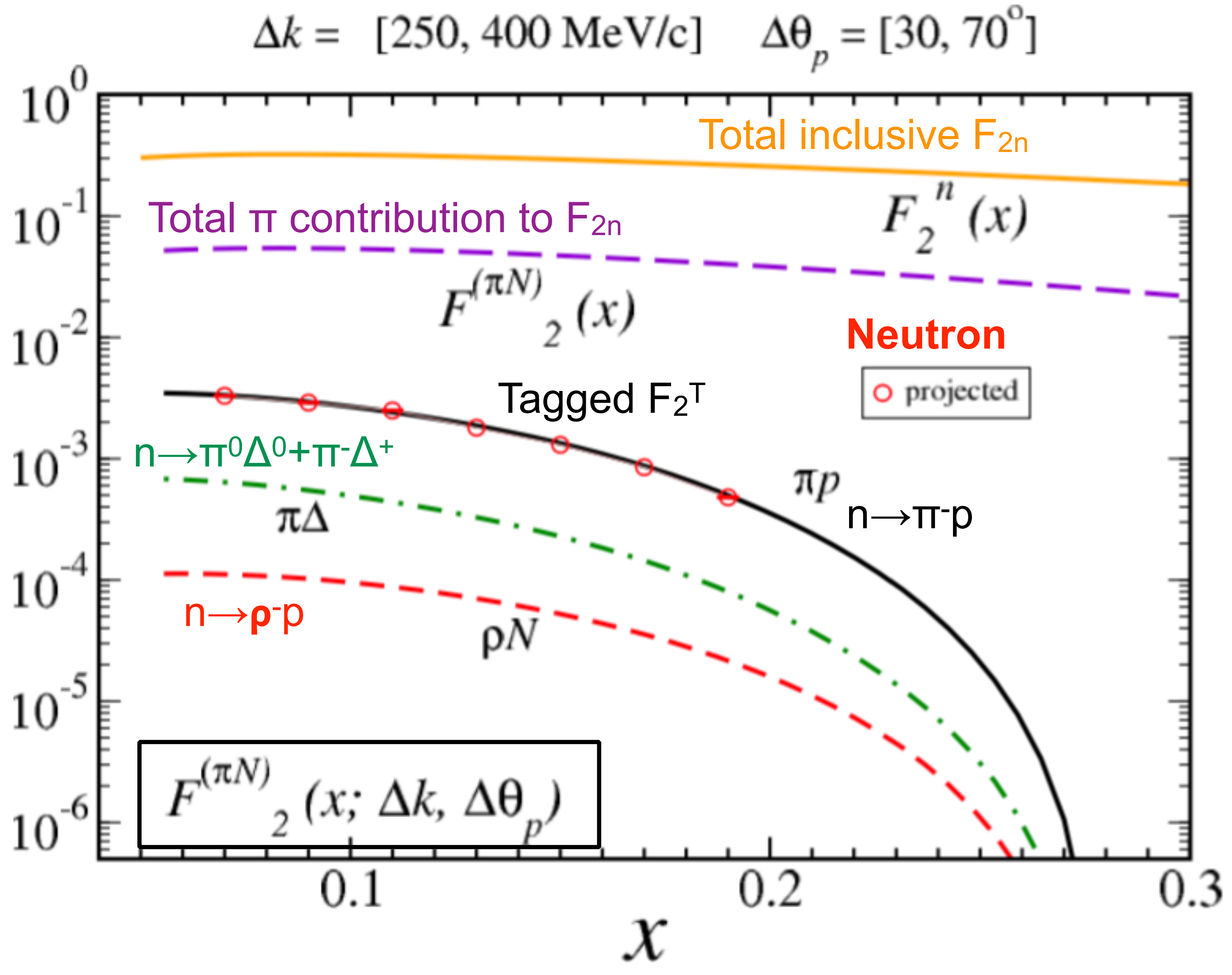
JLab TDIS:

- Direct probe of meson cloud
- Test universality
- Extend to neutral pions and drastically improve kaon situation

Need the Unique Luminosity Available at JLab

T.J. Hobbs, Few-Body Syst 56, 363 (2015)





- Predictions based on phenomenological pion cloud model (T.J. Hobbs)
- Tagged orders of magnitude smaller than DIS signal → need high luminosity!
- Measure ratio of tagged to total inclusive DIS cross-sections (reduce systematic uncertainties)

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

$$F_2^T(x, Q^2, z, t) = \frac{R^T}{\Delta z \Delta t} F_2^p(x, Q^2)$$

TDIS Method

- Projected rates/beam time/results used phenomenological pion cloud model
  - T.J. Hobbs, Phenomenological implications o the Nucleon's Meson Cloud, Few-Body Syst 56, 363 (2015)
  - H. Holtmann et al., Nucl. Phys. A 596, 631 (1996)
  - W. Melnitchouk, A.W. Thomas, Z. Phys. A 353, 311 (1995)

- Contribution to inclusive nucleon F_2 from scattering off virtual pion:

$$F_2^{(\pi N)}(x) = \int_x^1 dz\, f_{\pi N}(z)\, F_{2\pi}\left(\frac{x}{z}\right)$$

(z = light cone momentum fraction of initial nucleon carried by pion)

- Unintegrated distribution function (light-cone momentum distribution of π in nucleon):

$$f_{\pi N}(z) = \frac{1}{M^2} \int_0^\infty dk_\perp^2\, f_{\pi N}(z, k_\perp^2)$$

$k_\perp$ = transverse momentum of pion

- Semi-inclusive tagged SF is un-integrated product:

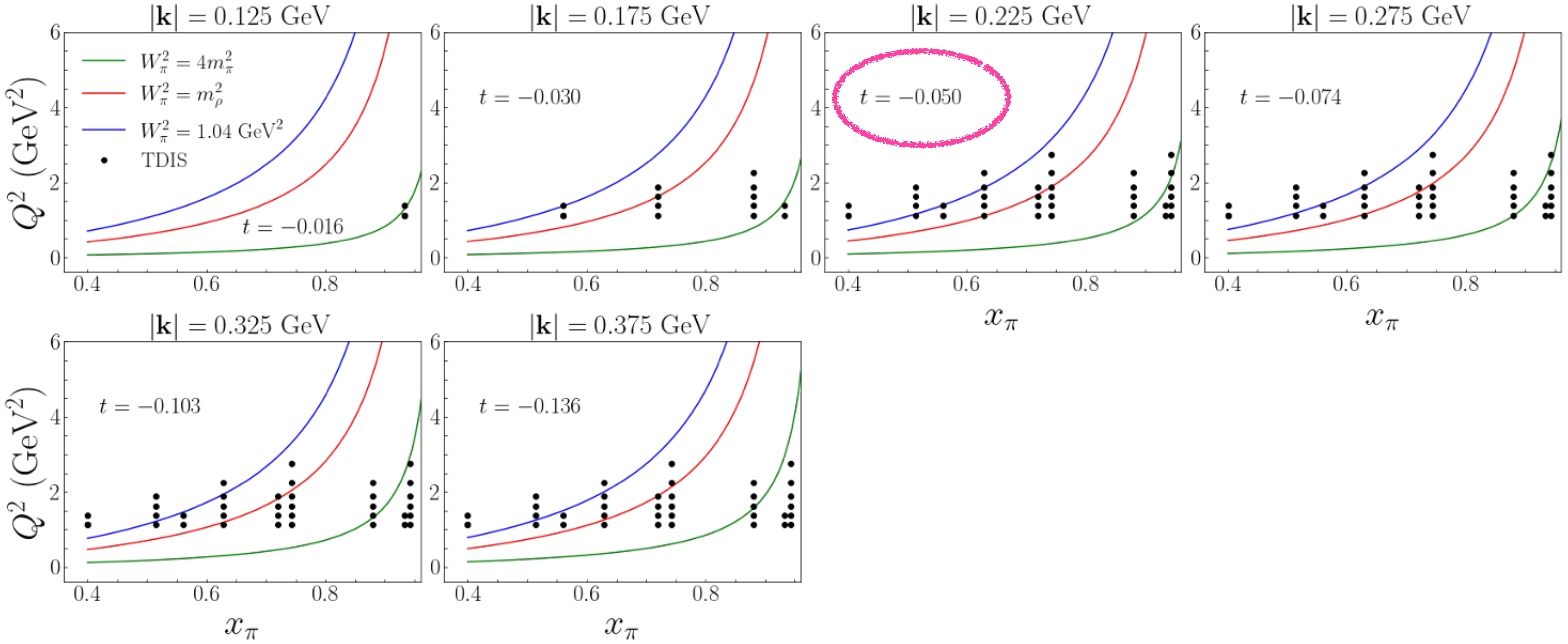
$$F_2^{(\pi N)}(x, z, k_\perp) = f_{\pi N}(z, k_\perp)\, F_{2\pi}\left(\frac{x}{z}\right)$$

Pion "flux" **Pion SF**

- Interested in $z \lesssim 0.2$; $x<z$ → defines maximum x, Q^2 (beam 11GeV)

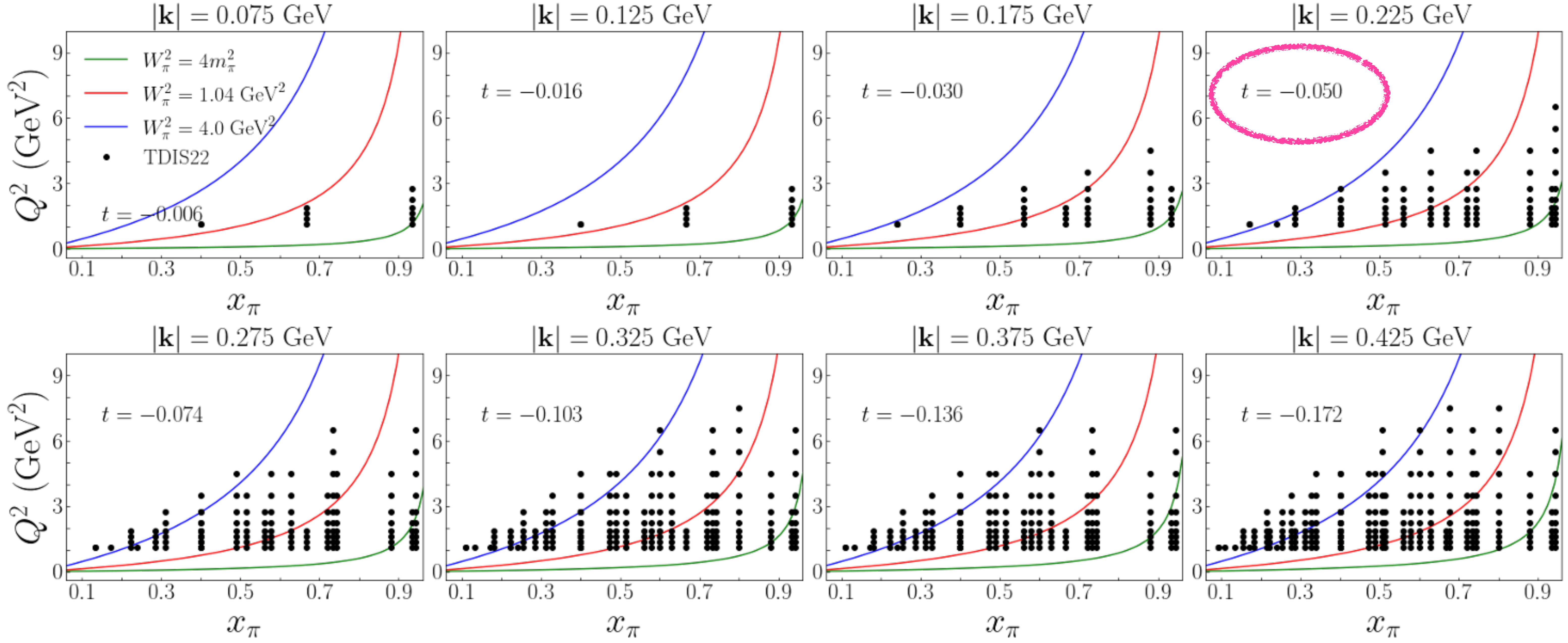
TDIS Phase Space for Pion SF

Plots: P. Barry and D. Dutta



11 GeV

- 11GeV
- Blue line $W_\pi^2 = 1.04$GeV^2
- TDIS proposal Binning



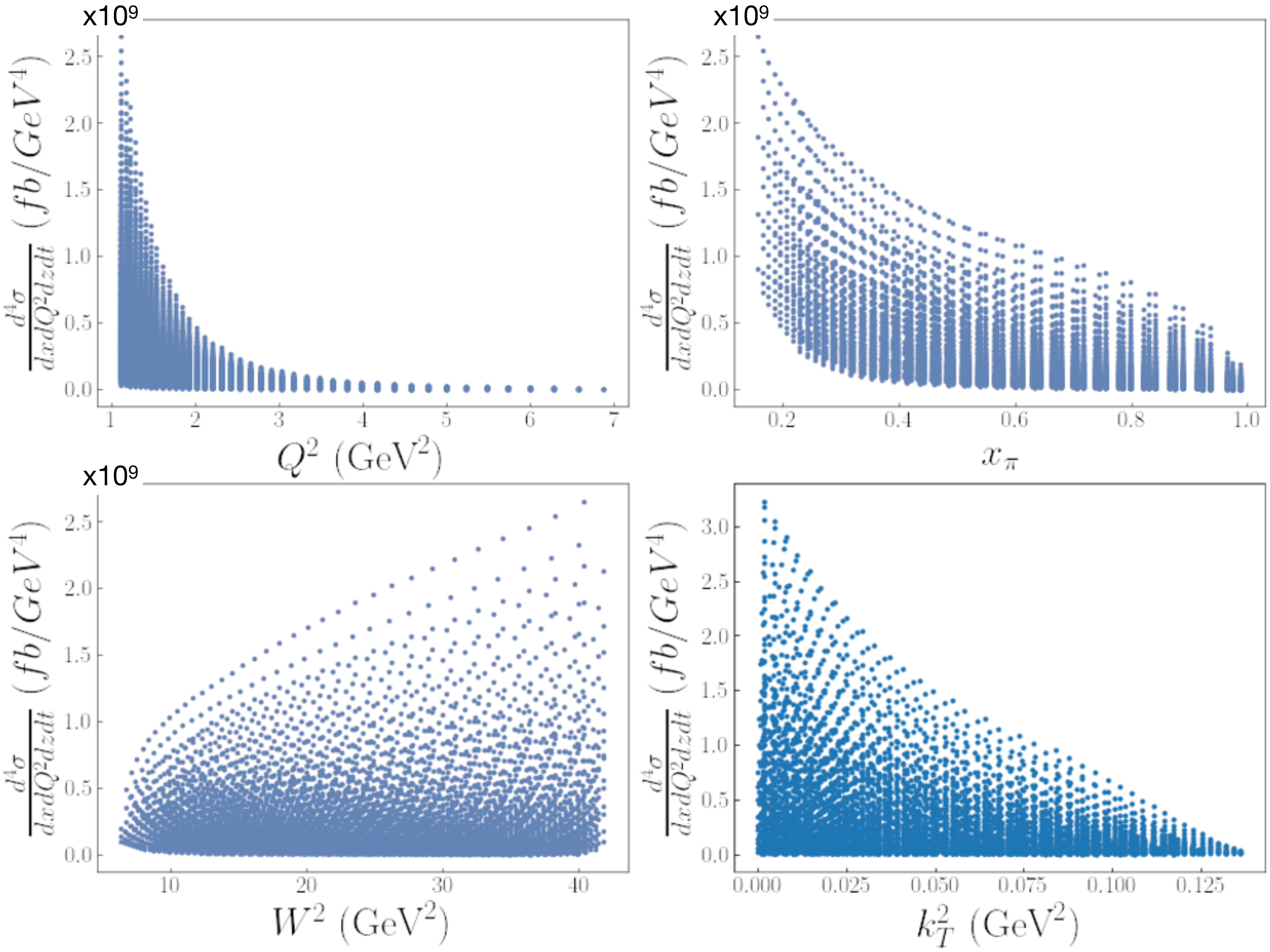
22 GeV

- 22GeV
- **Much more phase space!**

- Red line $W_\pi^2 = 1.04$GeV^2
- Blue line $W_\pi^2 = 4$GeV^2
- Data now available between 1.04GeV^2 and 4GeV^2
- **→ SIDIS now a possibility**

TDIS Cross Section 22GeV

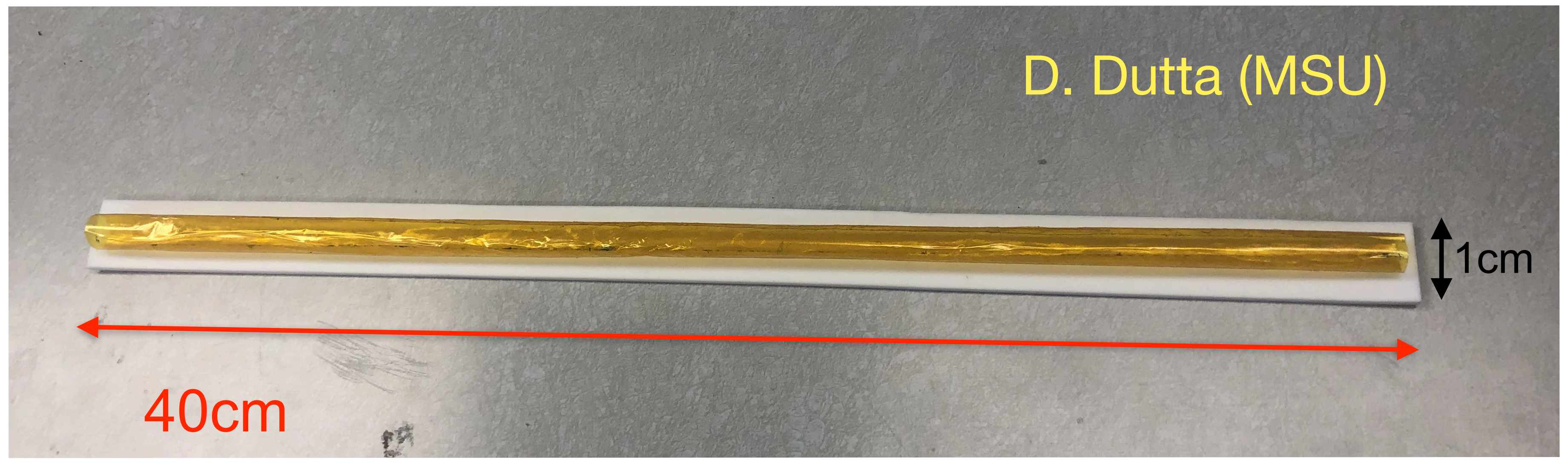
Plots: C. Ayerbe



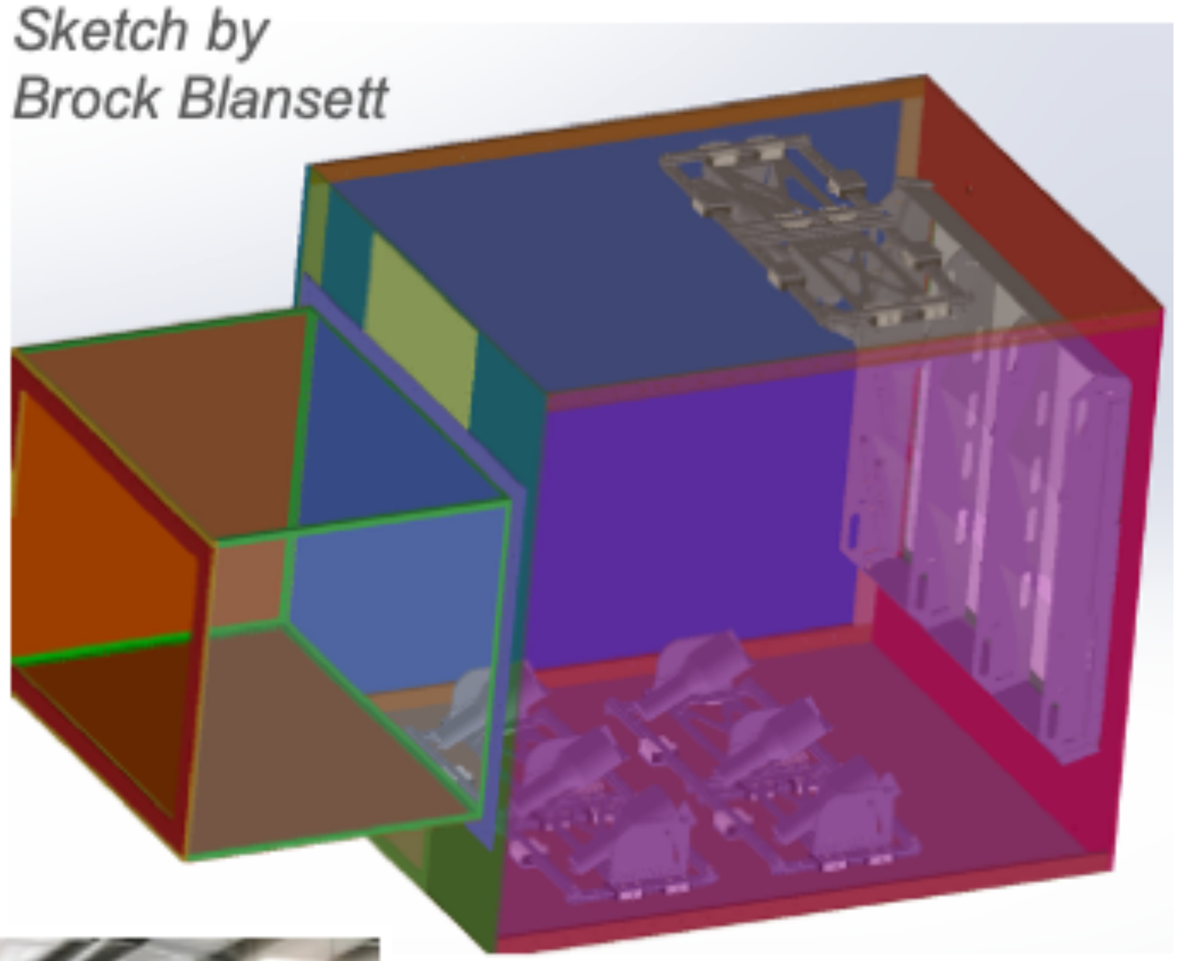
Coverage in k_T^2, relevant for π SF

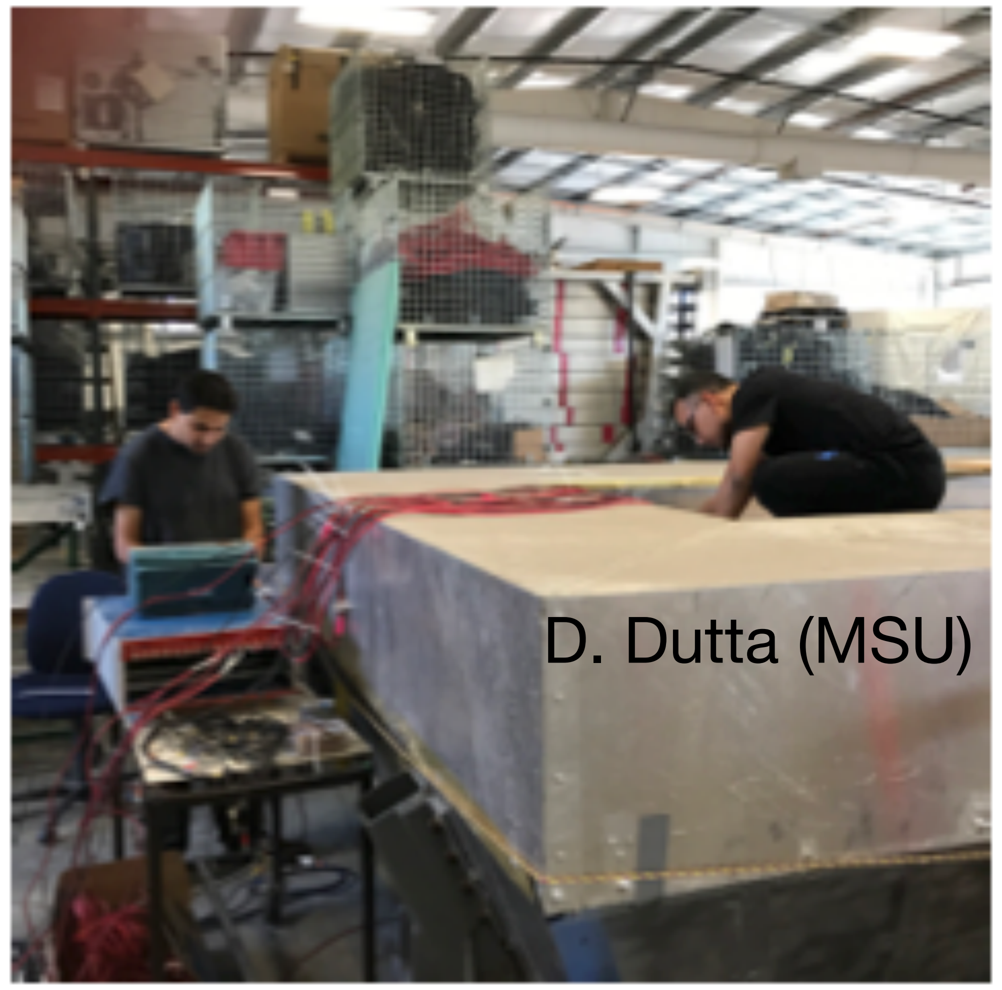
(transverse mom of virtual particle squared)

TDIS Set Up - On-going Developments



Sketch by
Brock Blansett

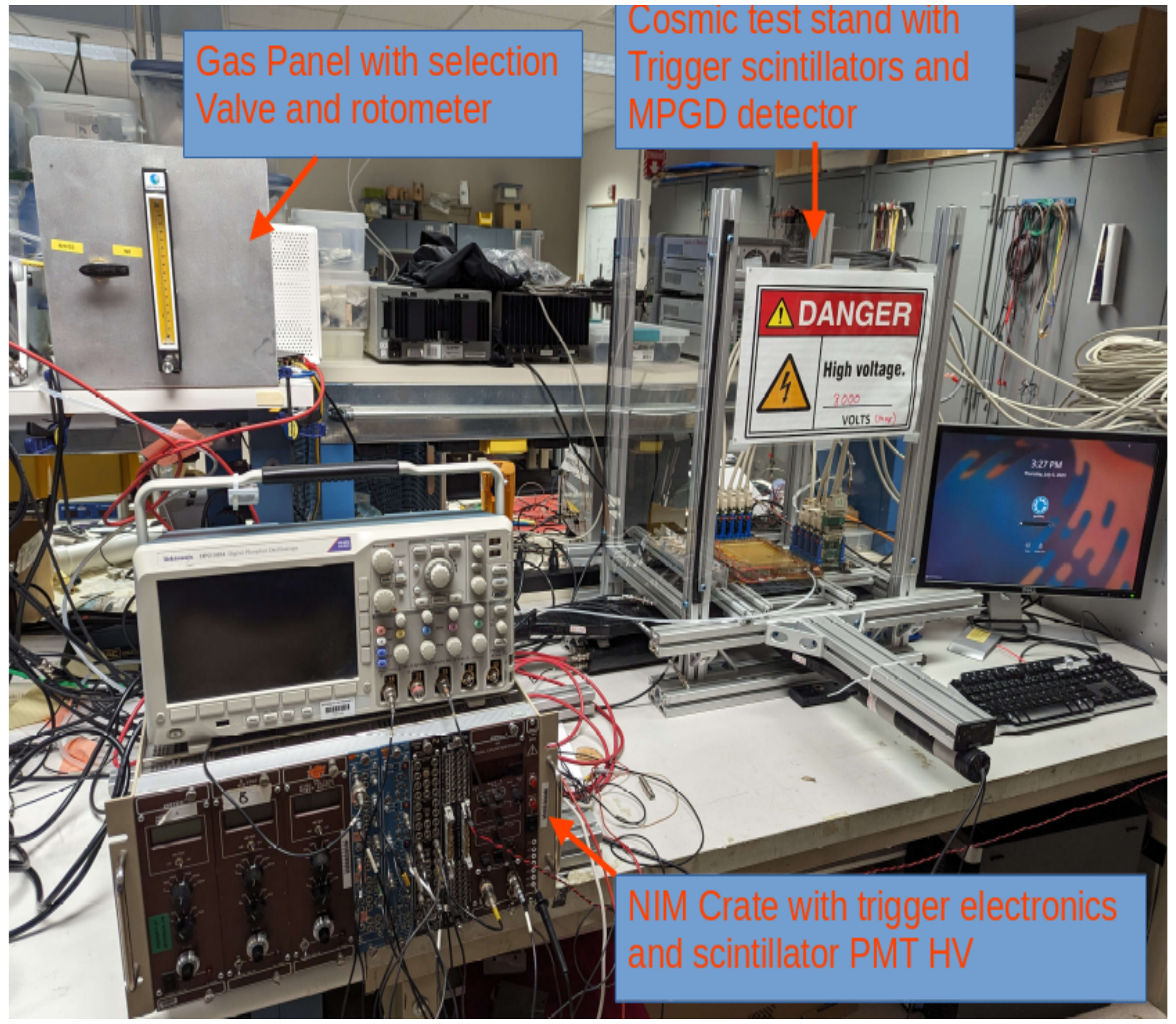




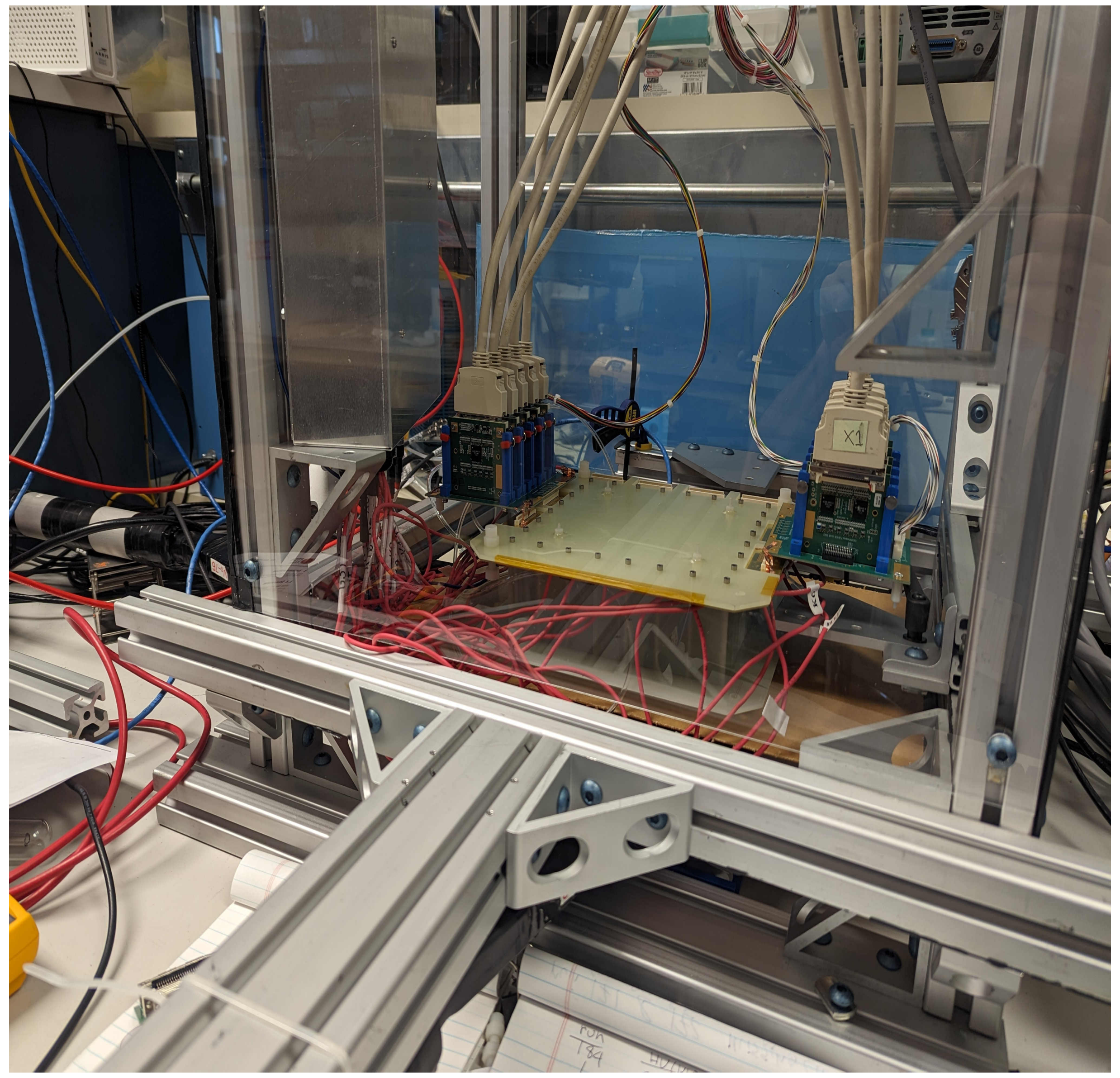
- Straw target prototyping (MSU)
  - 25μm Kapton walls; spiral wound; 3atm; room temp
- Recent theory suggests TDIS signal ~30% larger and less sensitive to pion flux factor than expected
  - J. R. McKenney et al. Phys. Rev. D 93, 054011 (2016) and P. Barry (JLab)
  - Potential to run at lower beam current
- New hadron blind gas Cherenkov under design (UT)
  - 4m Neon or Ne/Ar, 1atm
  - Distinguish e/π over 2-11GeV
- LAC refurbished and under test (MSU, JLab)
  - Plans to develop FPGA electron trigger
- mTPC prototyping (UVa, JLab)
- Front-end electronics development and prototyping at JLab (JLab, Univ. Sao Paolo)

mTPC Prototyping Tests at JLab

From E. Christy (JLab)

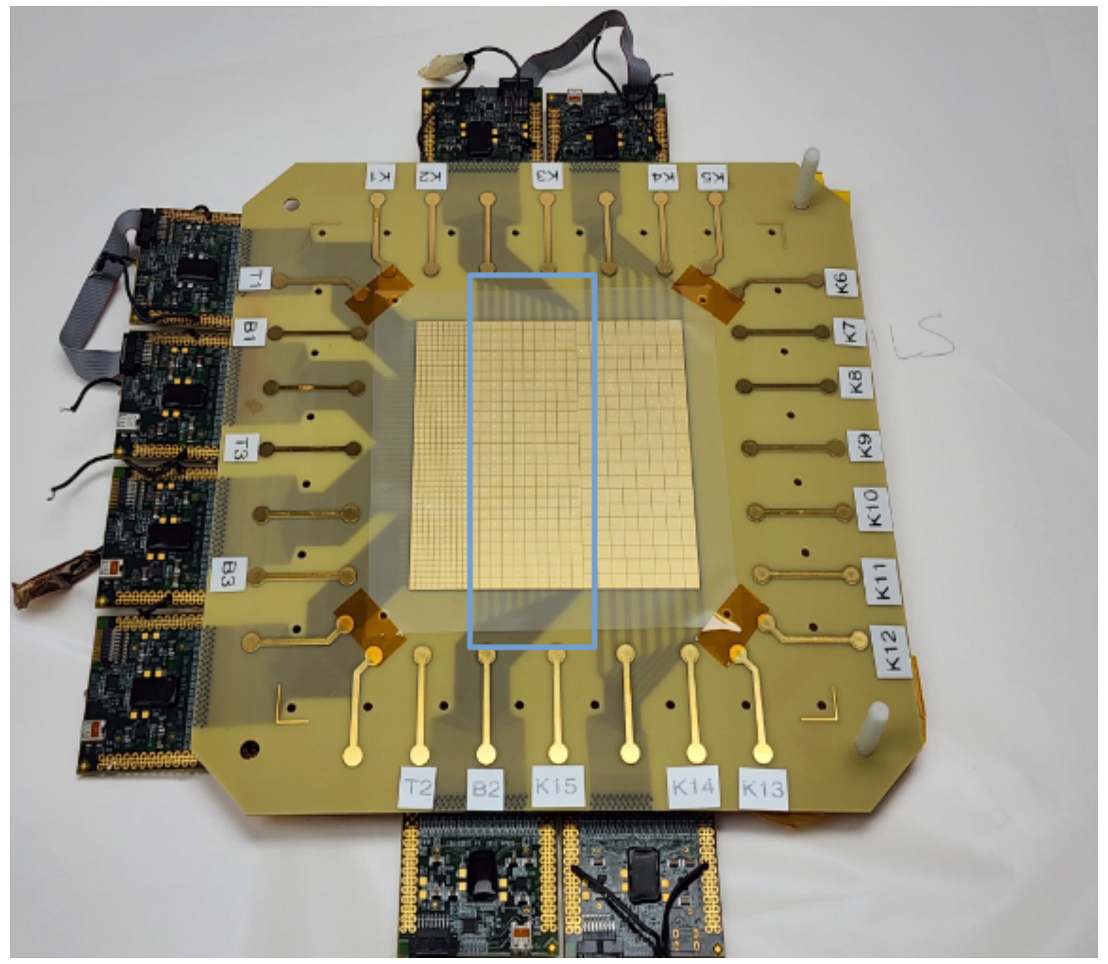


Preamp cards with shaper
24 channels per card / 5 cards per baseboard

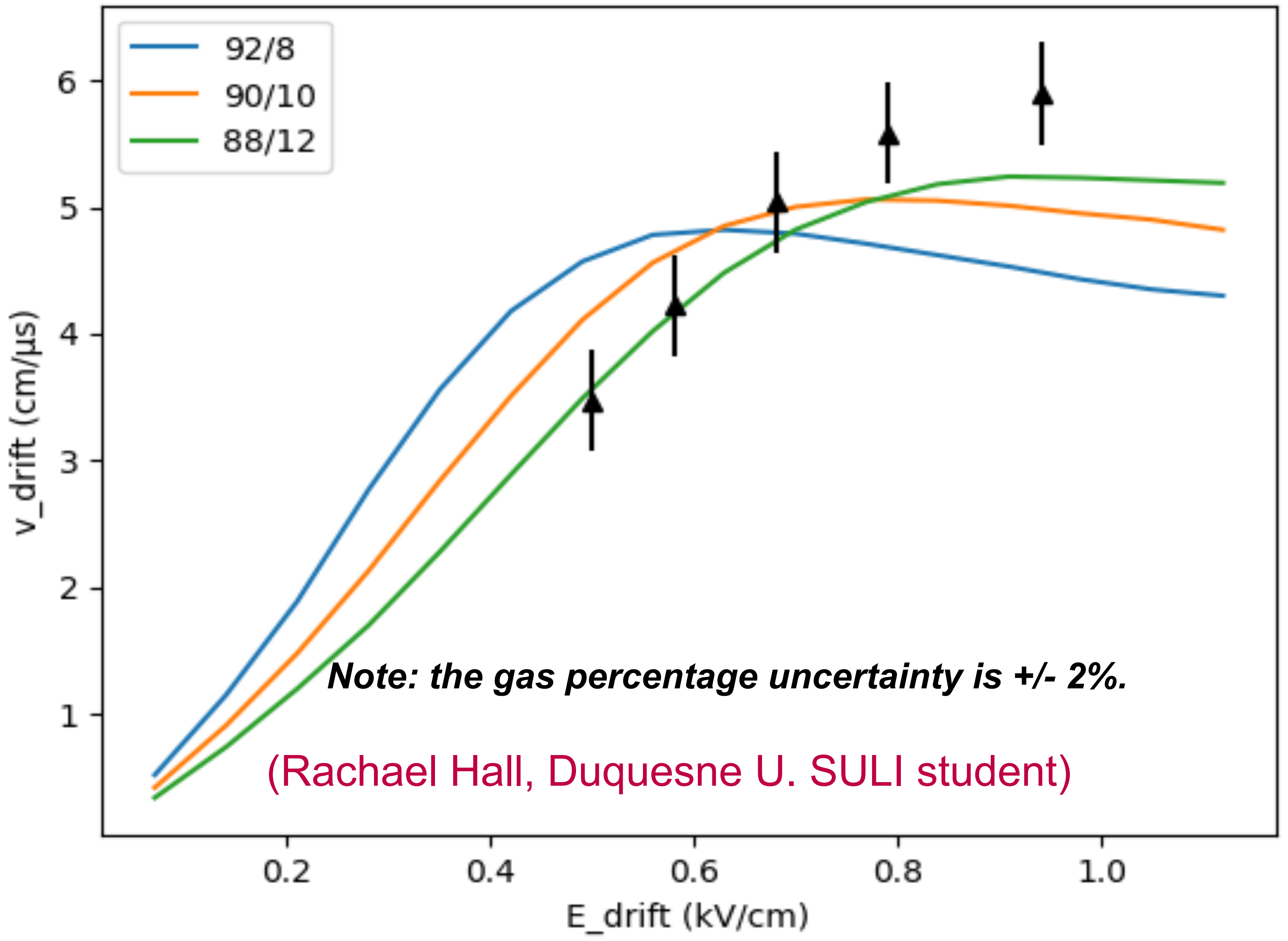


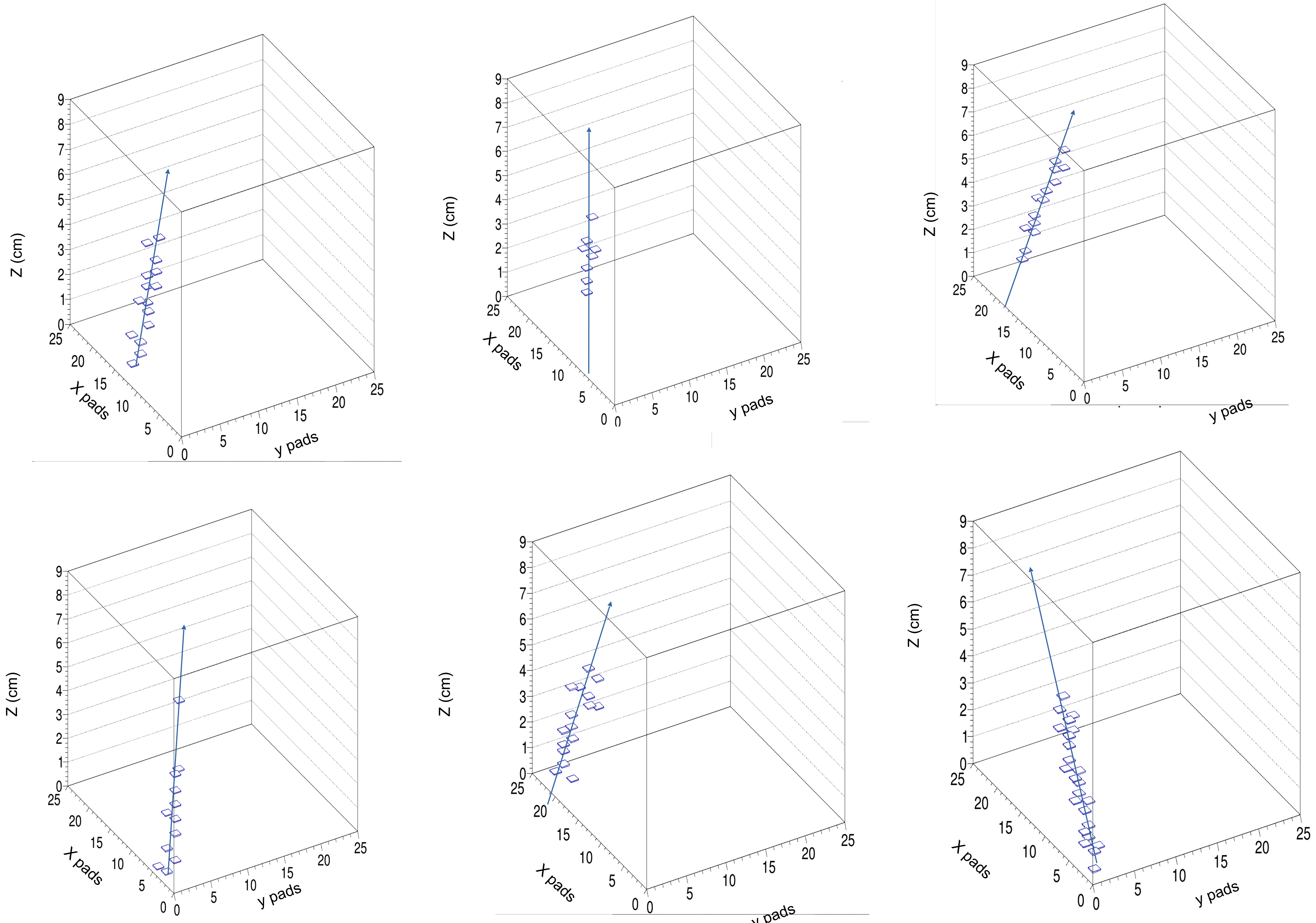
- Tests on-going with JLab FA125 VME system
- Will move to TDIS electronics in future

- Cosmics triggers of orthogonal directions:
  - Testing drift times of charge in field cage
  - Recording tracks
  - (Horizontal orientation shown, as in left pic, 5cm drift)
- Reported some HV discharges in initial testing, now solved



Data shown taken with medium sized pads

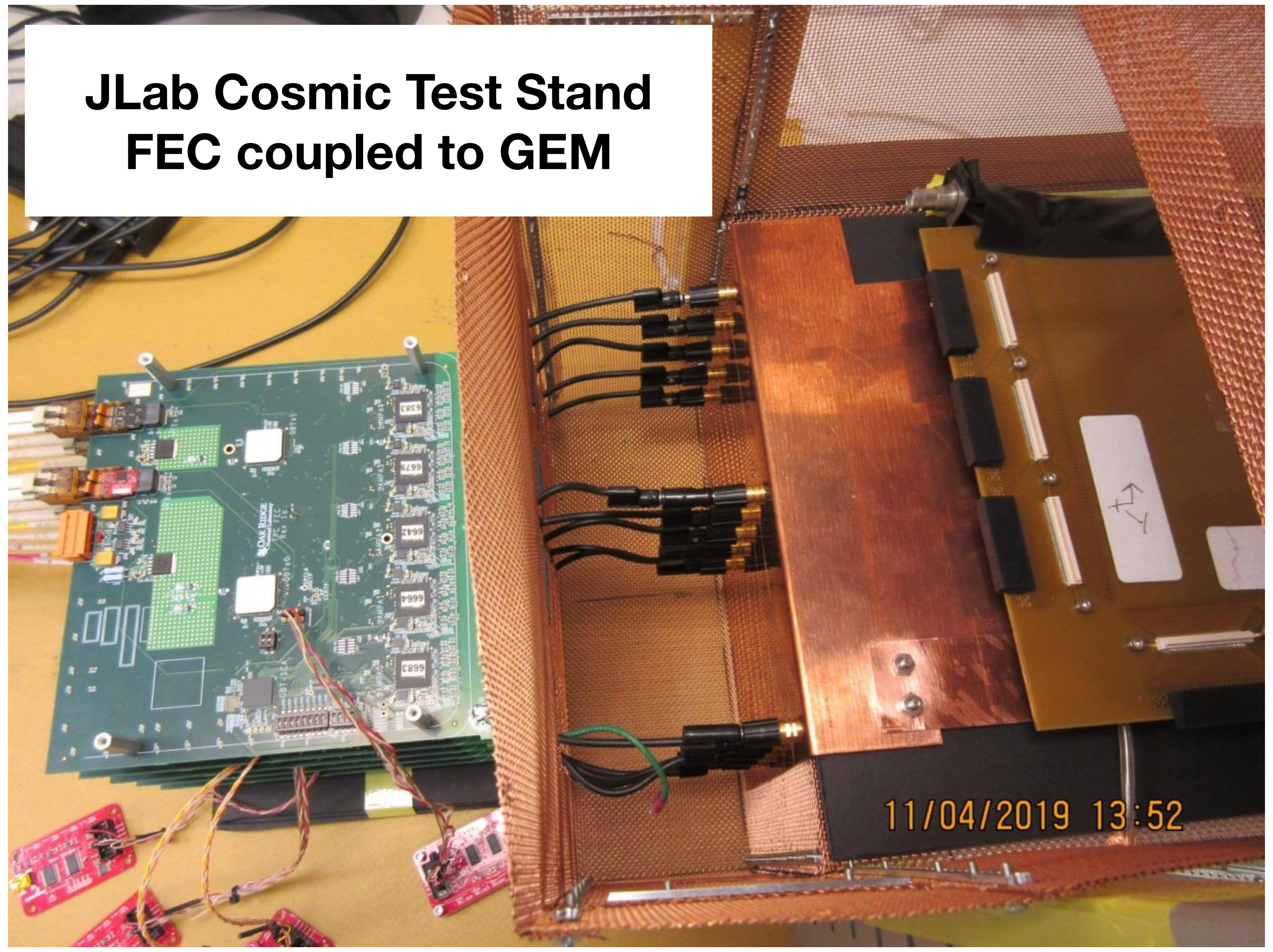


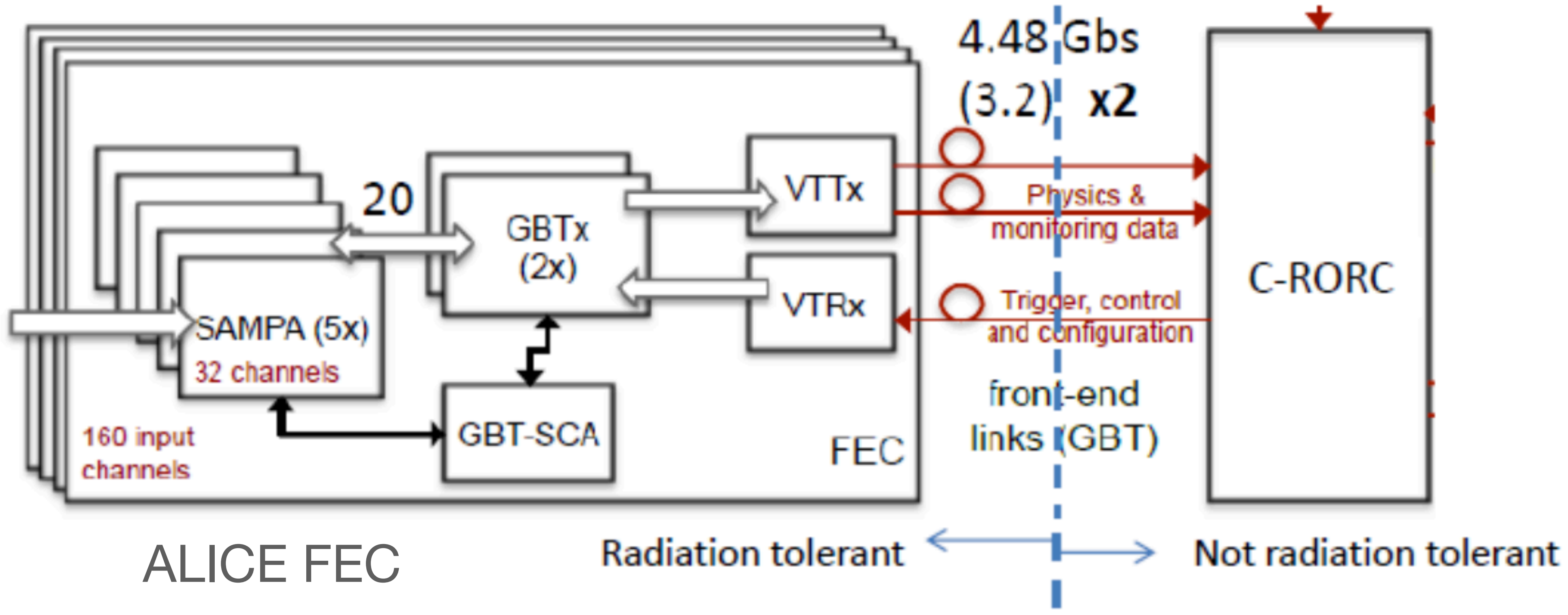


(Sudipta Saha, JLab)

Front-End Readout

All pics: E. Jastrzembski (JLab)





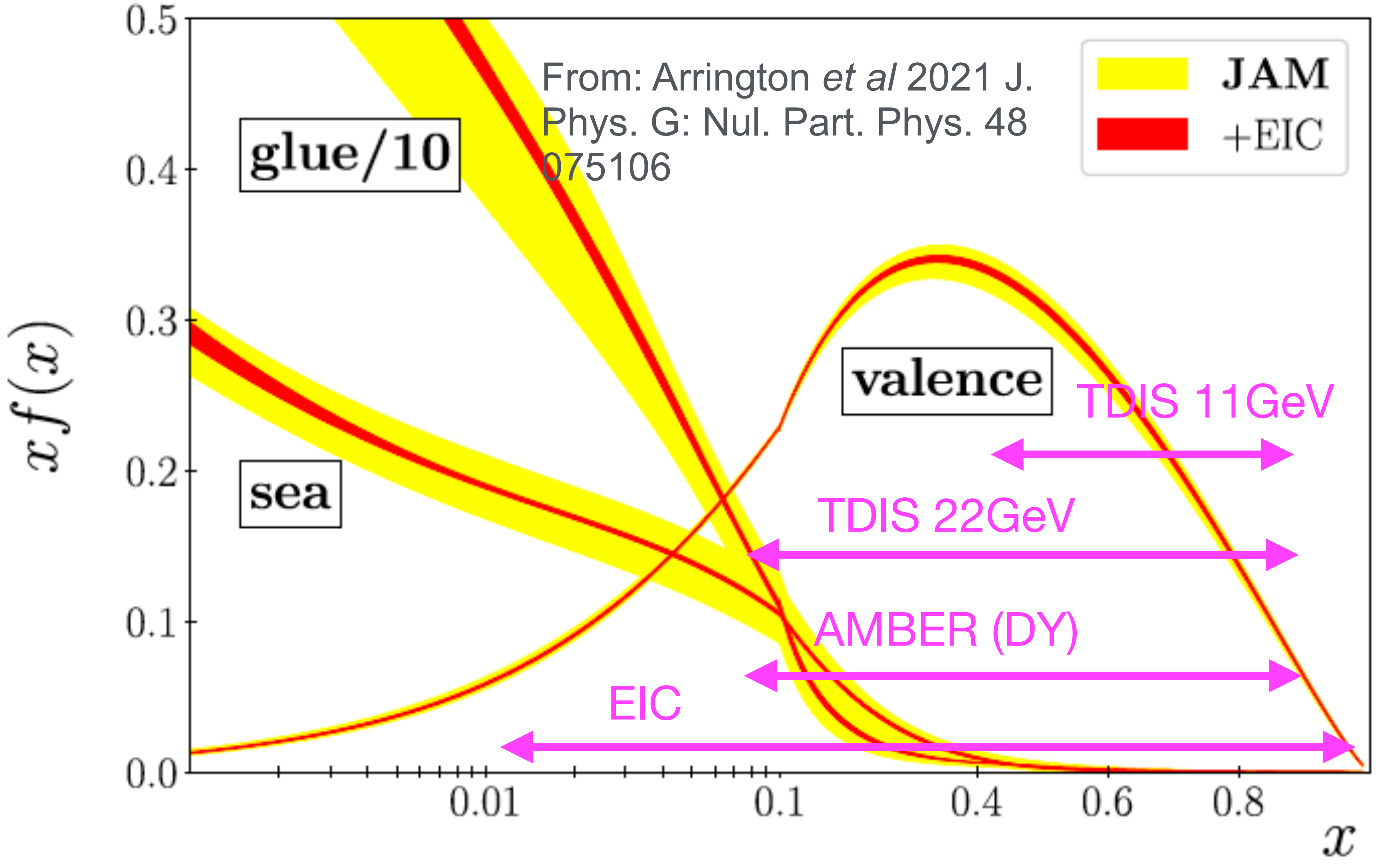
FEC – Front End Card (160 ch / FEC) (5 FEC = 800 ch)
C-RORC – Common Read Out Receiver Card (PCIe)
GBTx – Giga Bit Transceivers
GBT-SCA – GBTx Slow Controls Adapter
VTTx, VTRx – Fiber optic transceivers

- SAMPA ASIC:
  - Pre-amp, ADC, zero-suppression…
  - (M. Bregant, Sao Paolo)

- Prototyping stand at JLab (E. Jastrzembski et al.) - originally stand used Oak Ridge SAMPA FEC for ALICE TPC
- mTPC prototype will use sPHENIX TPC FEC and SAMPA v5 (80ns shaping time)

- SAMPA FECs can be operated in triggered or continuous mode
- TDIS has been a driver for streaming readout at JLab

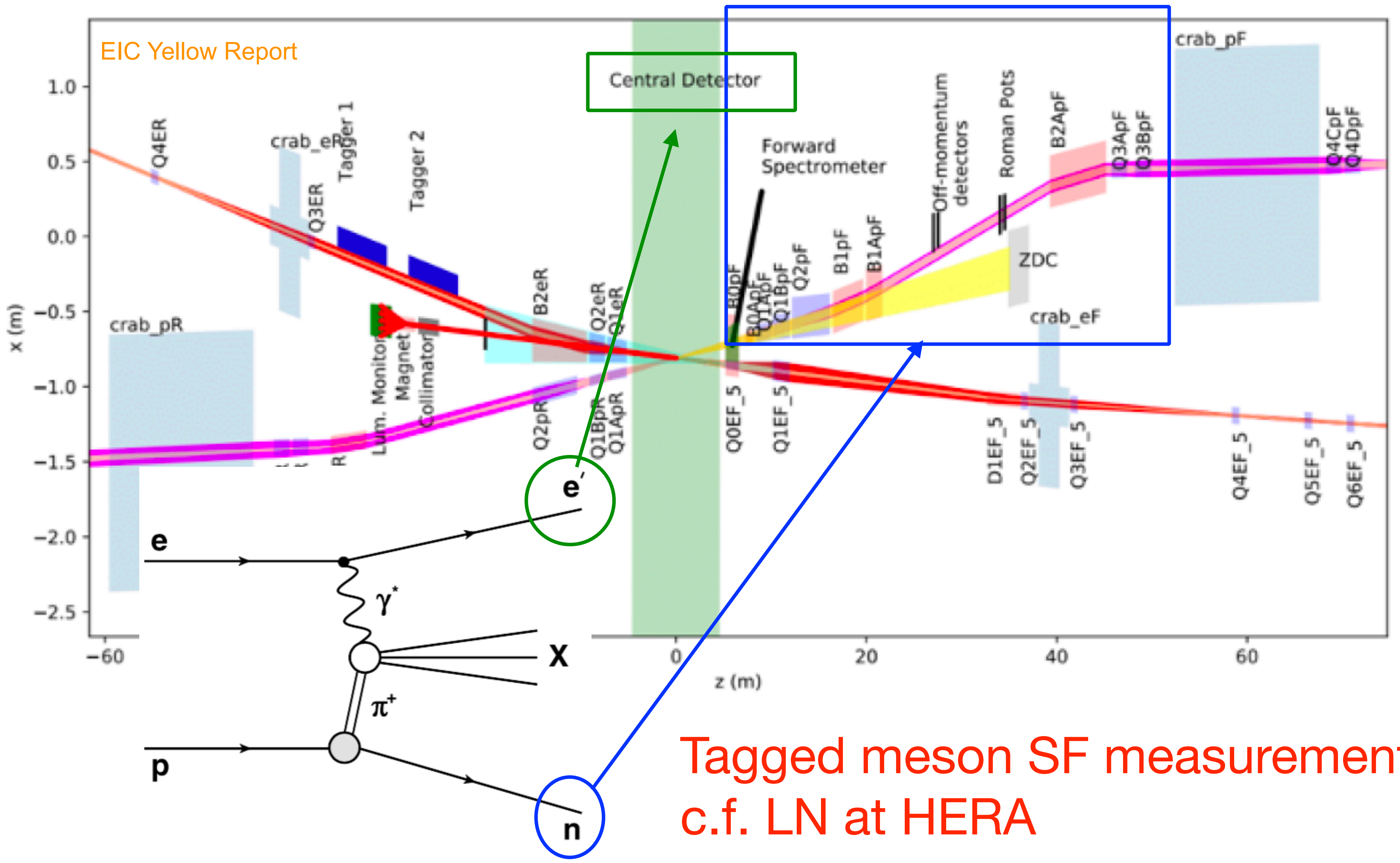
Meson Structure Functions at EIC



Barry P C, Ji C-R, Melnitchouk W and Sato N Threshold resummation effects on pion PDFs at large x

- Excellent opportunity for bridge between HERA and high-x
- Wide CM energy range (20-140GeV), large (x,Q^2) landscape
- High luminosity, full acceptance
- Gain >=decade compared to HERA
  - e-nucleon $\mathcal{L}=10^{34}$Hz/cm^2 = 1000 * $\mathcal{L}_{HERA}$

- Improve uncertainties for pion's valence, sea quark and gluon PDFs with inclusion of EIC data

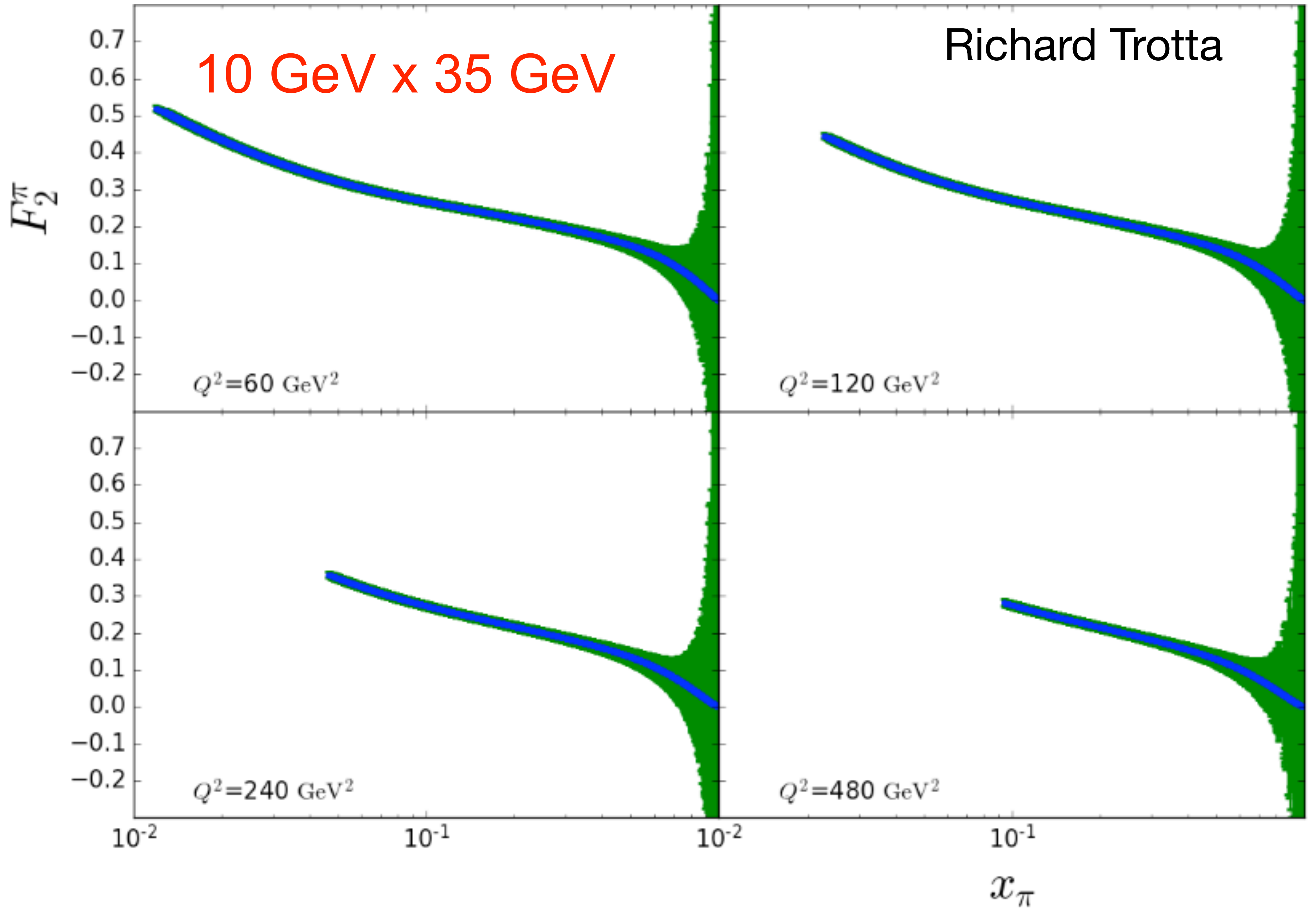


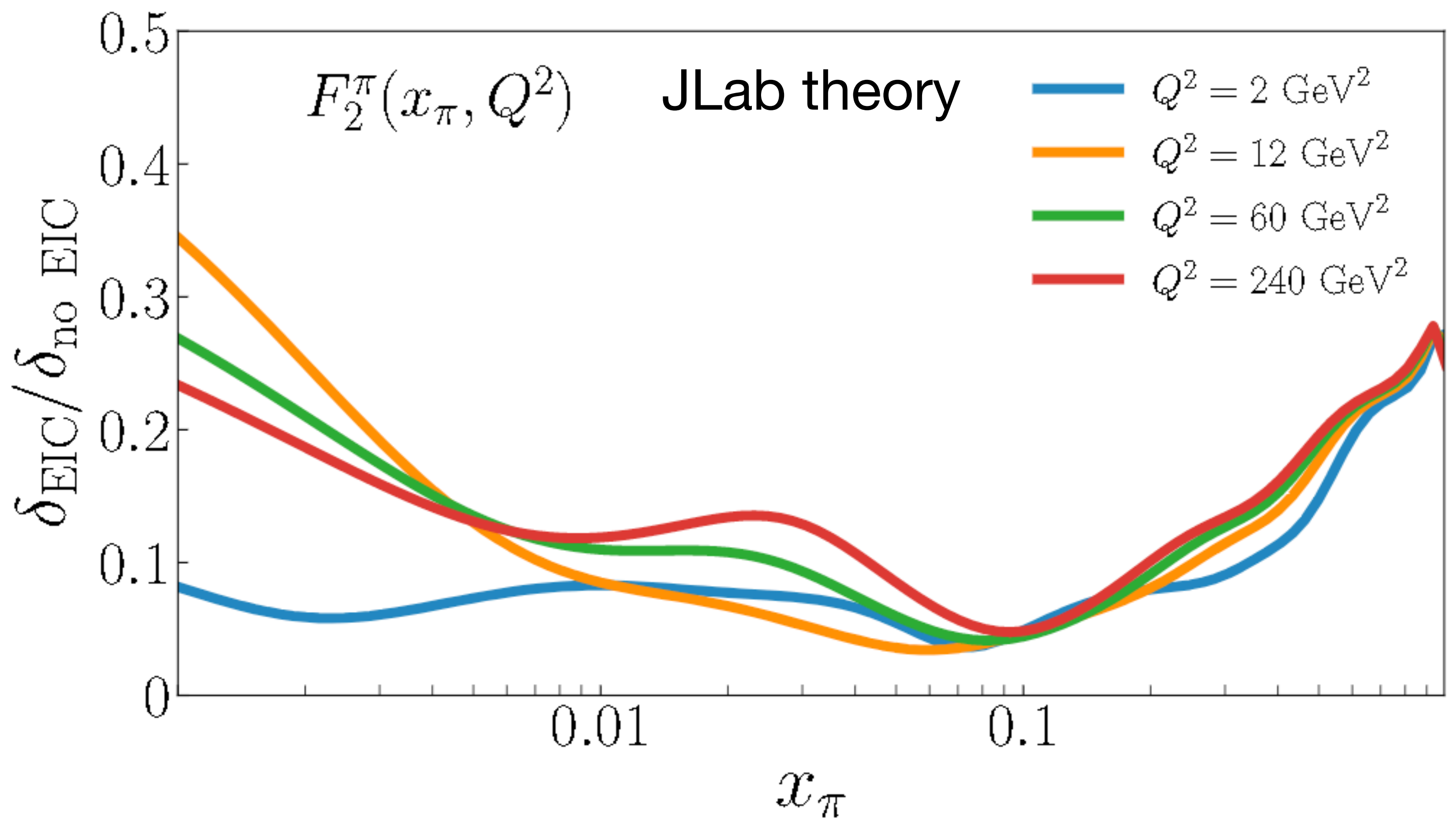
Tagged meson SF measurements planned
c.f. LN at HERA

EIC Meson SF Working Group

For more info see:
Aguilar *et al*, Eur. Phys. J. A. (2019) **55**
Arrington *et al* 2021 J. Phys. G: Nul. Part. Phys. 48 075106

Meson Structure Functions at EIC





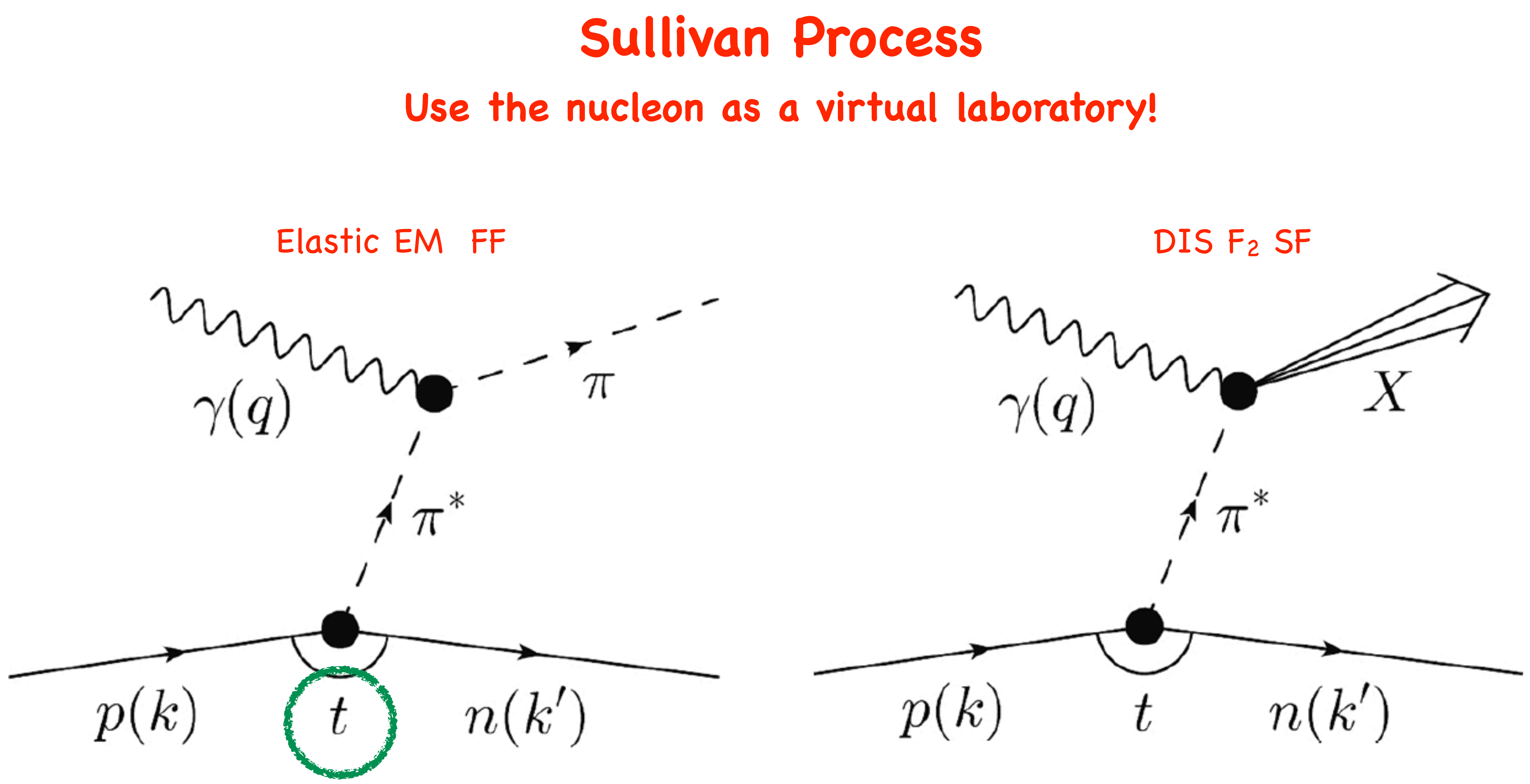
Ratio of uncertainty of $F_2^\pi(x,Q^2)$ from global fit with/without EIC
Data impactful over large x, Q^2 (80-90% reduction $x_\pi \sim 3\text{x}10^{-3} \rightarrow 0.4$)

- Results from EIC Meson SF working group and from Arrington *et al* 2021 J. Phys. G: Nul. Part. Phys. 48 075106

- SF shown calculated at NLO using pion PDFs
- Projected data binned in x(0.001), Q^2 (10GeV^2)
- Blue = projections, green = uncertainty for luminosity 100fb^{-1}
- x-coverage down to 10^{-2}
- Uncertainties increasing towards x~1
- Similar SF analysis can be extended to kaon

- Detailed comparison between pion/kaon and gluon contents possible
- Reduce uncertainties in global PDF fits

Sullivan Process



<u>Sullivan Process Confidence (from T. Horn)</u>

- At small -t (four mom transfer squared at nucleon vertex):
  - cross-section behaviour characteristic of meson pole dominance
- S-X Qin, C. Chen, C. Mezrag, C.D. Roberts, Phys. Rev. C 97 (2018) 015203:
  - "Reliable access to meson target as t becomes space like if pole associated with meson remains dominant feature of reaction, and structure of related correlation evolves slowly/smoothly with virtuality"
  - → pion $-t \leq 0.6 GeV^2$, kaon $-t \leq 0.9 GeV^2$
- Can be checked empirically - data taking at range of t-values
- Experiments at JLab have studied this: electroproduction for physical pion form factor, over decade of experience

T. Horn, C.D. Roberts, J. Phys. G43 (2016) no.7, 073001
G. Huber et al, PRL 112 (2014) 182501
R.J. Perry et al, PRC 100 (2019) 2, 025206

Pion TMD Activities

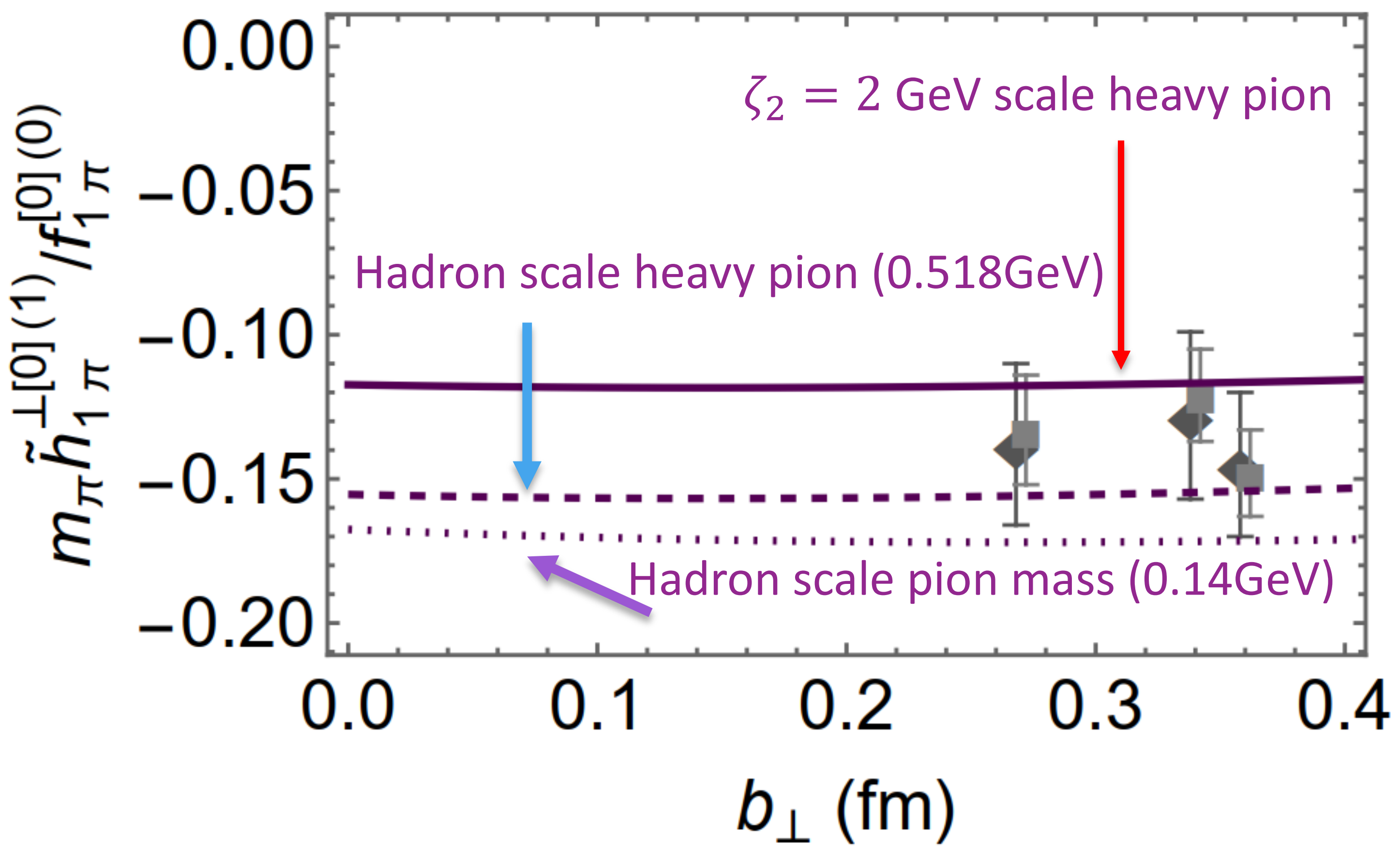
Generalized Boer-Mulders shift

- The so called "generalized Boer-Mulders shift" is defined in an appropriate way to be safely evaluated on the lattice

$$\langle k_y \rangle_{UT}(b_T^2;\zeta_2) \equiv m_\pi \frac{\tilde{h}_1^{\perp[0](1)}(b_T^2;\zeta_2)}{\tilde{f}_1^{[0](0)}(b_T^2;\zeta_2)}$$

  - ✓ The denominator is unity, independent of the resolving scale
  - ✓ The numerator is directly related to the first $k_\perp$ moment of BM function

$$H_0(\zeta_2^2) = H_0(\zeta_1^2)\left[\frac{\alpha_{LO}(\zeta_2^2)}{\alpha_{LO}(\zeta_1^2)}\right]^{\frac{1}{4}(C_F-2\mathcal{S})\gamma_m}$$



- The magnitude of the shift decreases slowly with increasing meson mass
- The impact of evolution is noticeable, but not dramatic

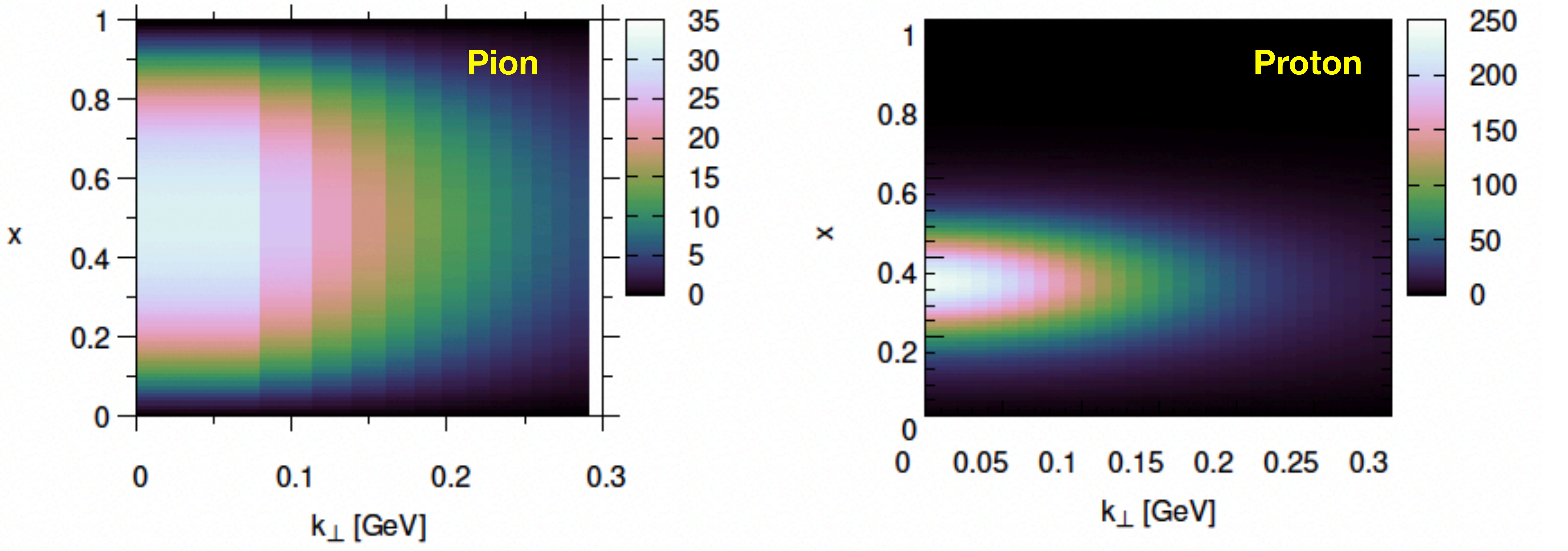
ddcheng@smail.nju.edu.cn, Pion Boer-Mulders function using a contact interaction, Total Pages (24)

Slide from Dan-Dan Cheng (Nanjing University)
For more details see paper:
arXiv:2409.11568v2 [hep-ph] 21 Sep 2024

Generalised Boer-Mulders shift

- defined by x-moments of generic Fourier Transformed TMDs
- TMD observable related to Boer-Mulders effect

Pion and Proton Unpolarised Leading-Twist TMD



Tobias' slide from Light-Front

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⊥ similar (~200MeV)
- Expect interesting differences between meson and nucleon TMDs