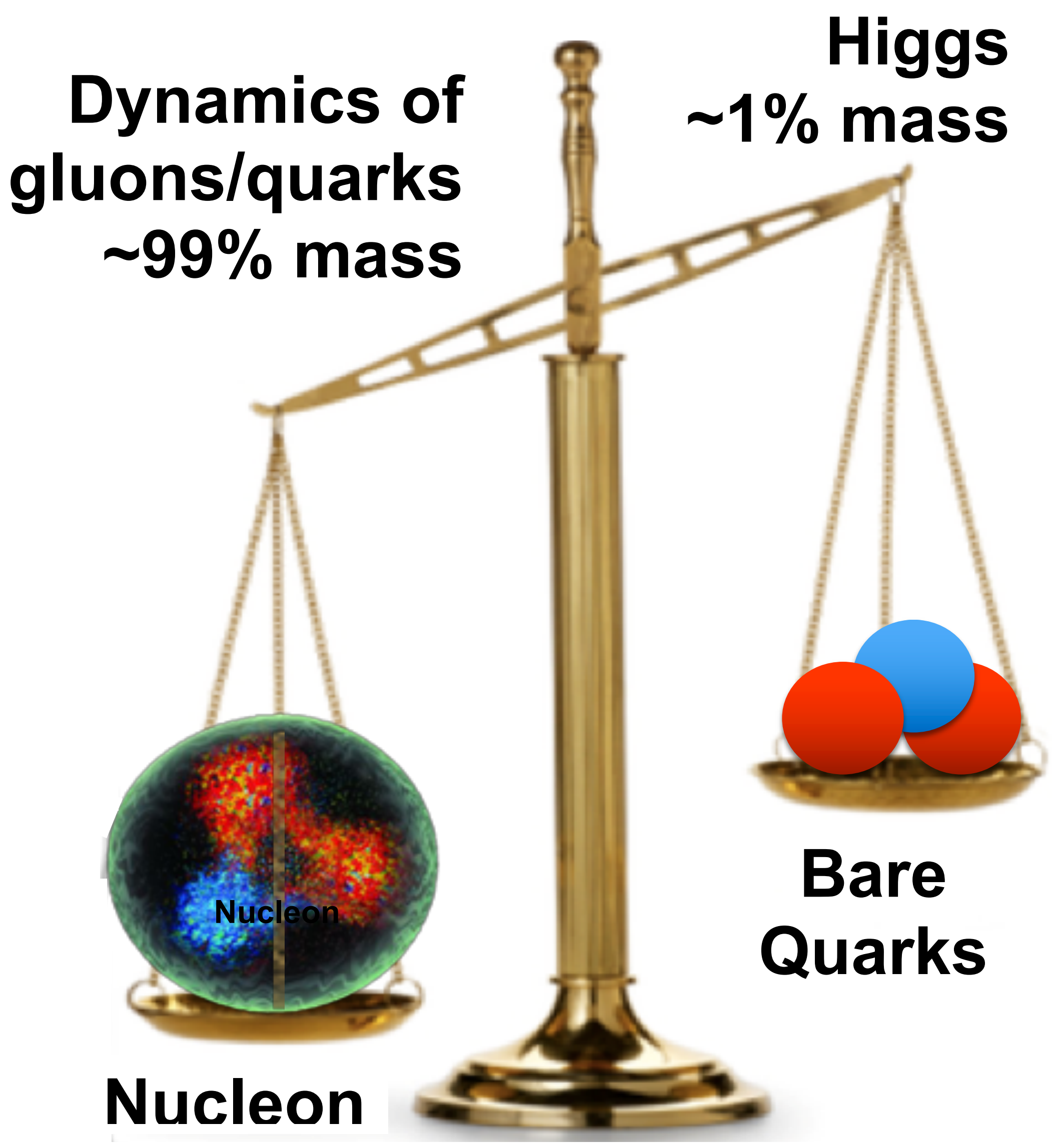
Meson Structure via Spectator Tagging

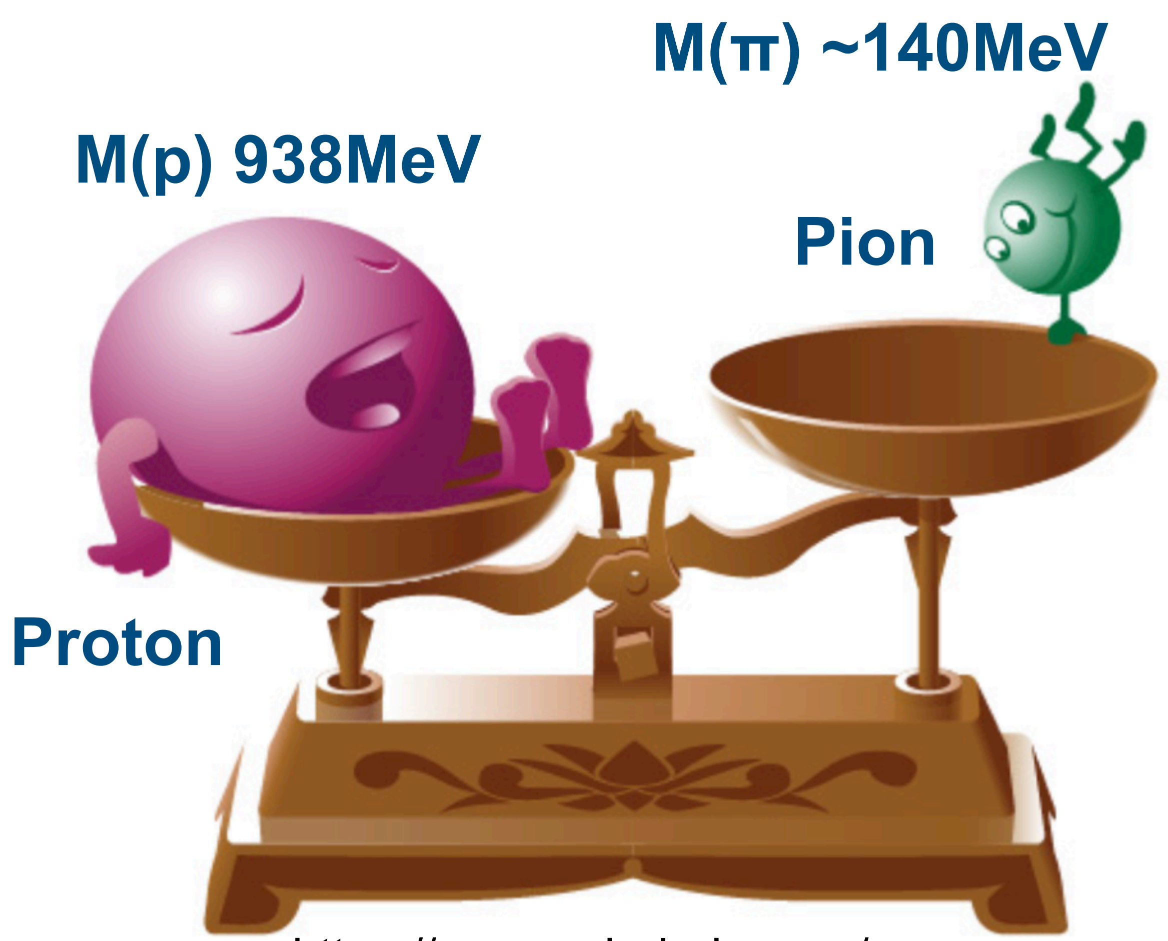
Science at the Luminosity Frontier: Jefferson Lab at 22GeV Workshop
23/01/23

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

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

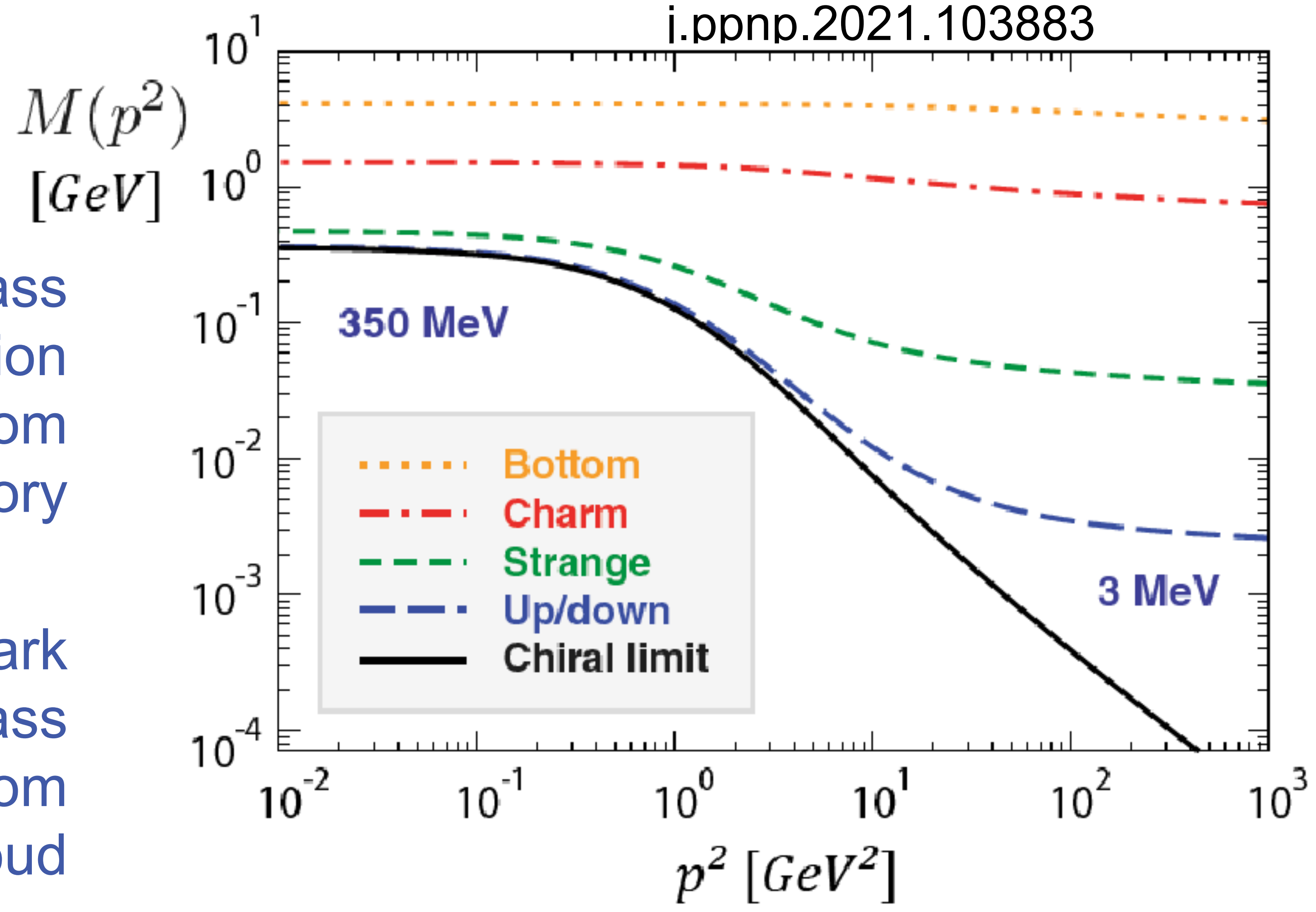
Why Meson Structure





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

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



Quark mass acquisition functions from QCD theory

Light quark dynamical mass generation from gluon cloud

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

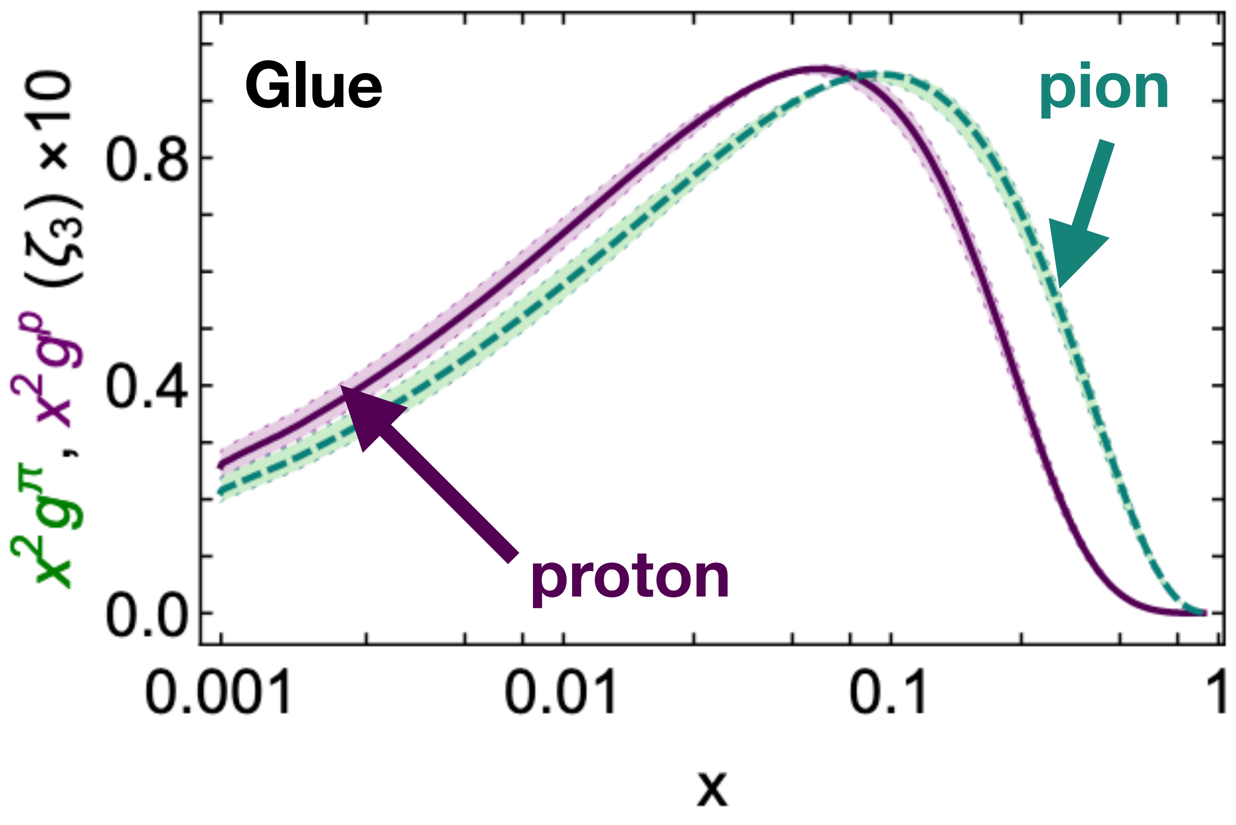
- Mass budgets for **light π/K** (Goldstone bosons) vastly different from **heavy nucleon,** and **each other**

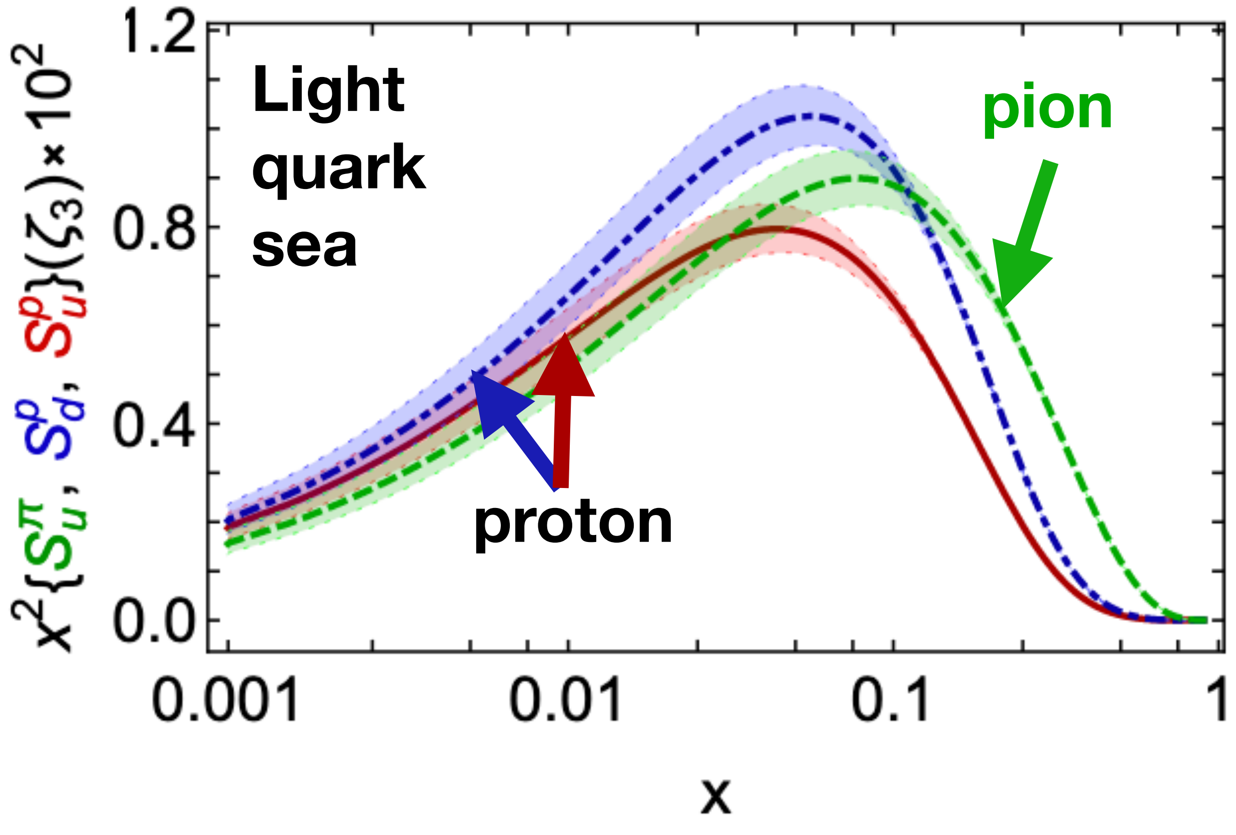
- Comparing distributions of light quarks versus strange quarks within mesons → measurable signals of EHM

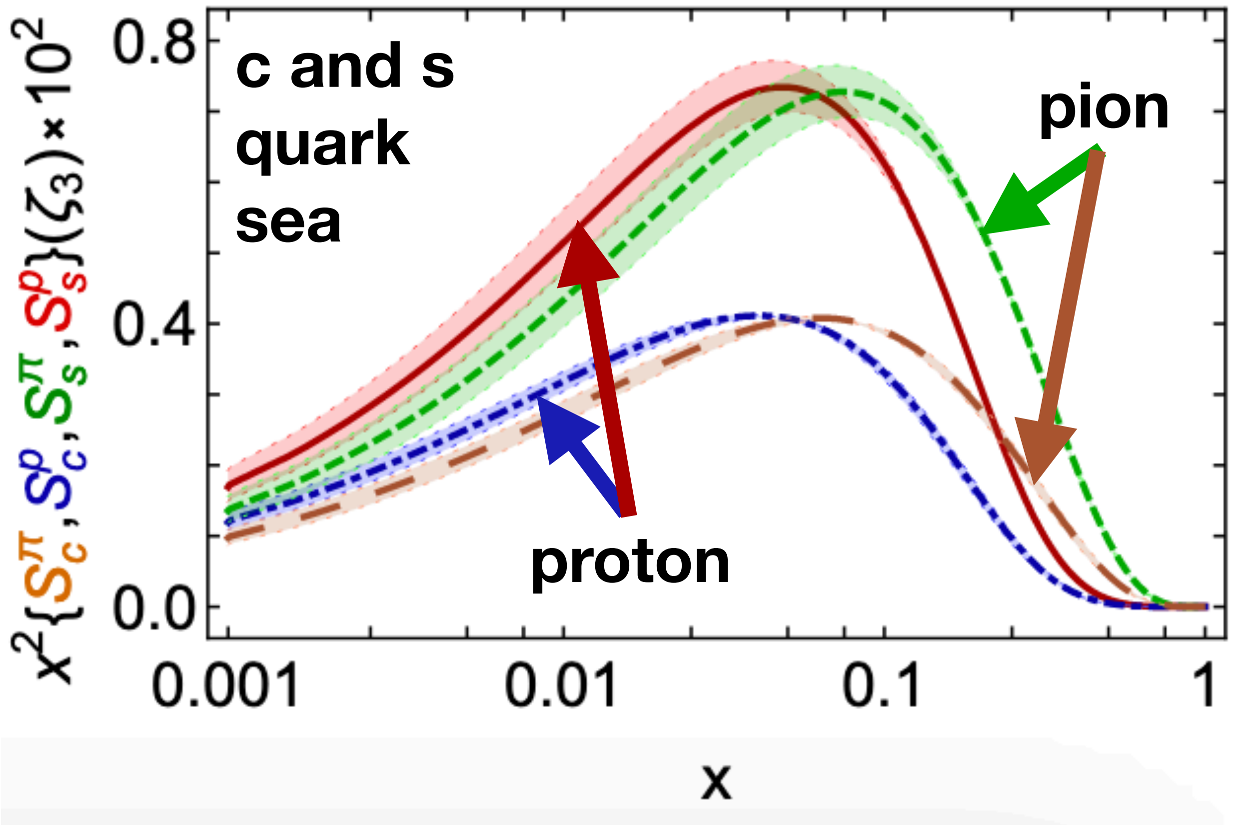
- π/K structure not well known experimentally
- Need data!
- Interesting implications for PDFs/TMDs…

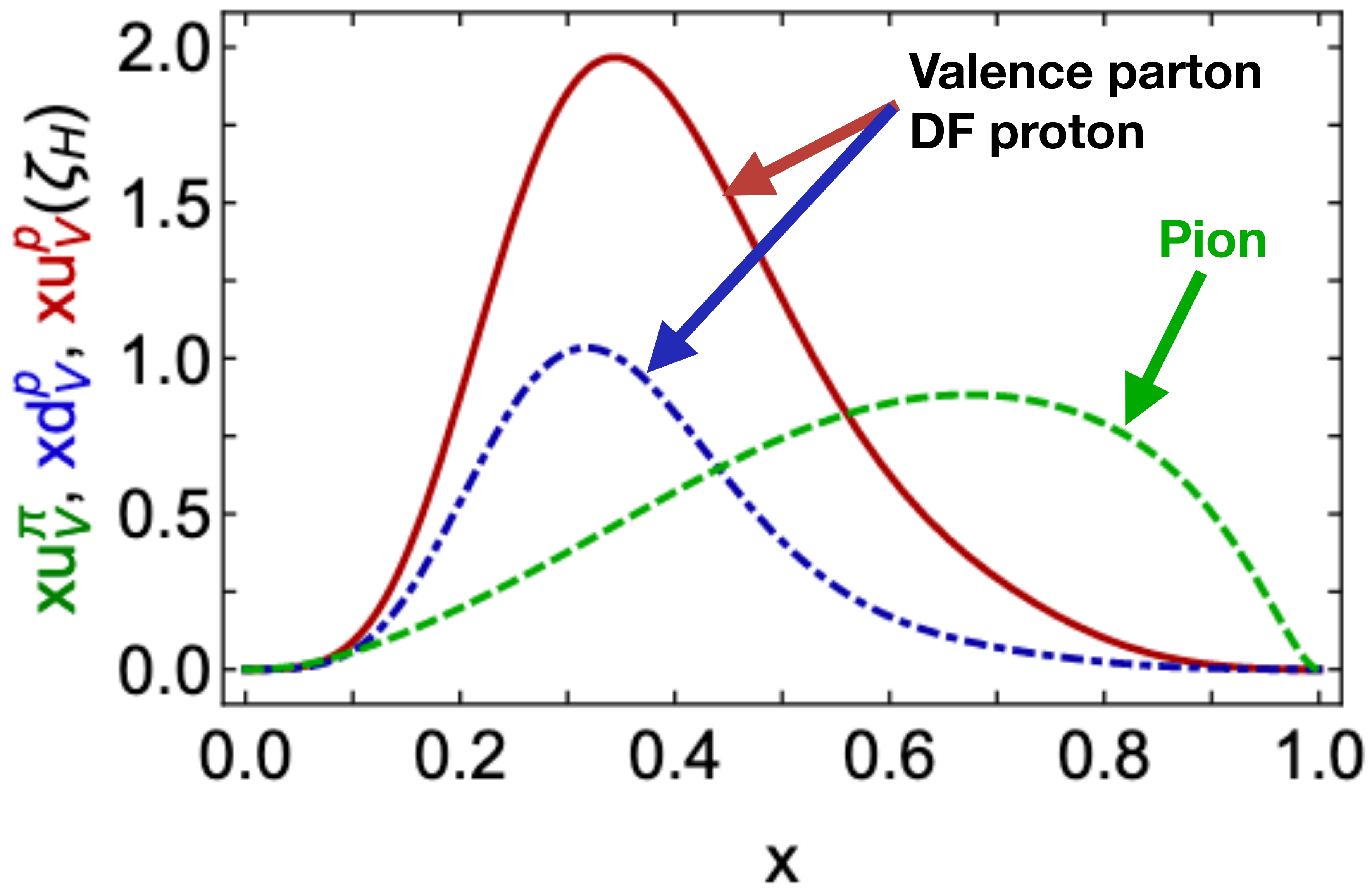
Pion vs Proton Valence PDFs

arxiv: 2203.00753 [hep-ph]









From C. Roberts (INP)

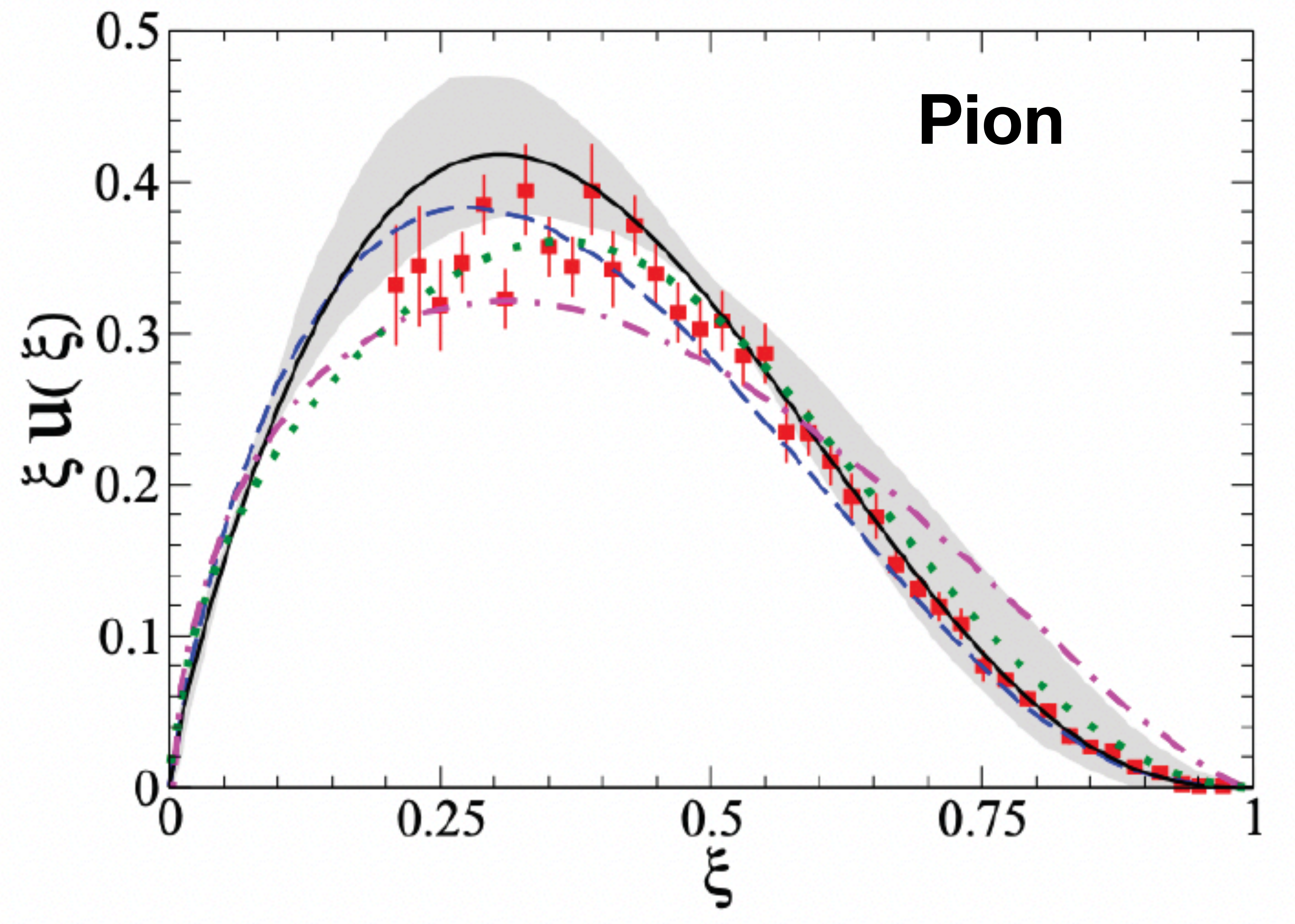
Continuum Schwinger function methods

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

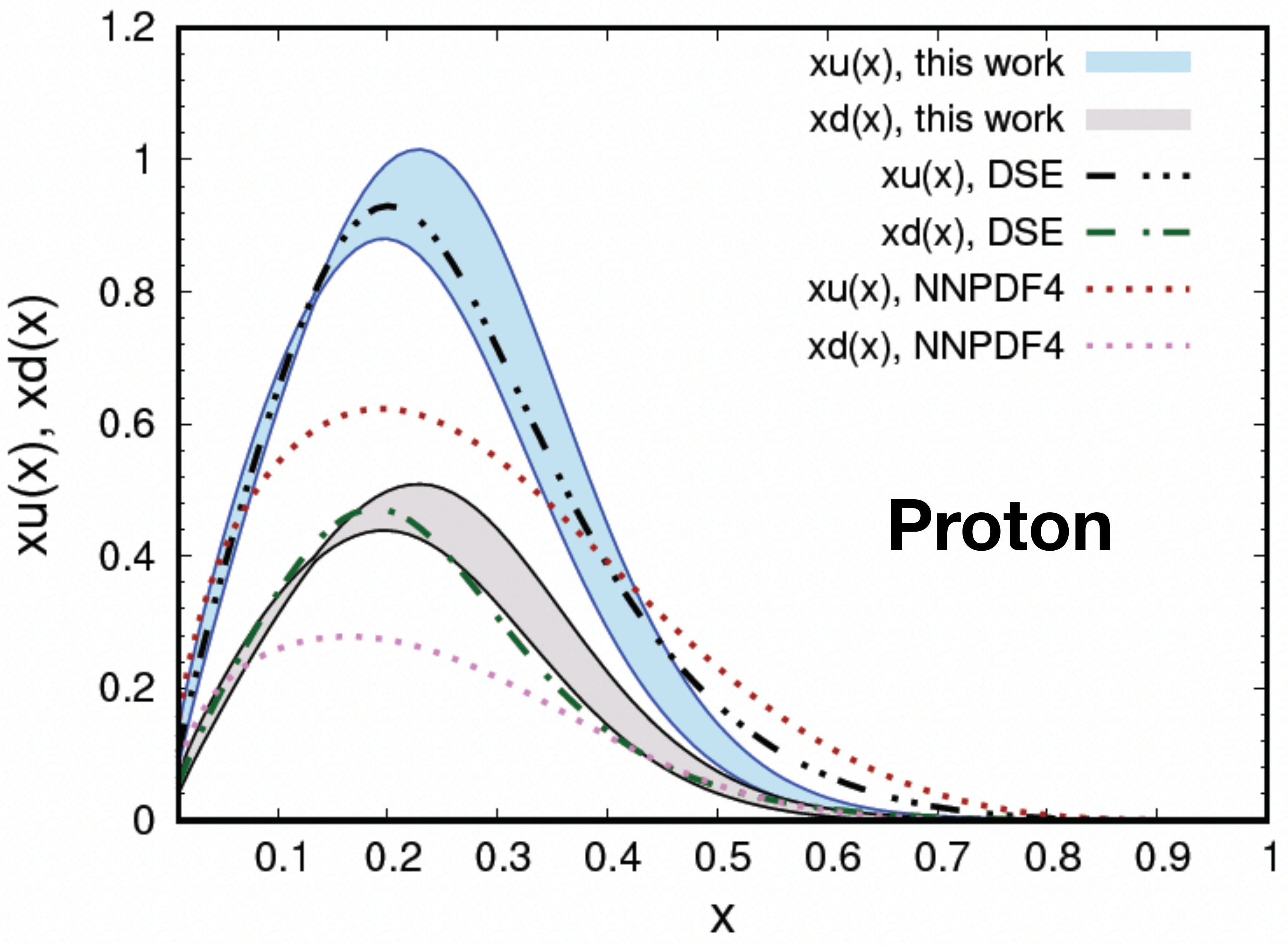
- Marked difference between pion and proton valence PDF
- Differences translate into sea and glue DF
- "Much to be learnt before proton and pion structure understood in terms of DF,… what is difference between distributions of partons within proton and pion?"

Pion and Proton Unpolarized PDFs

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



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



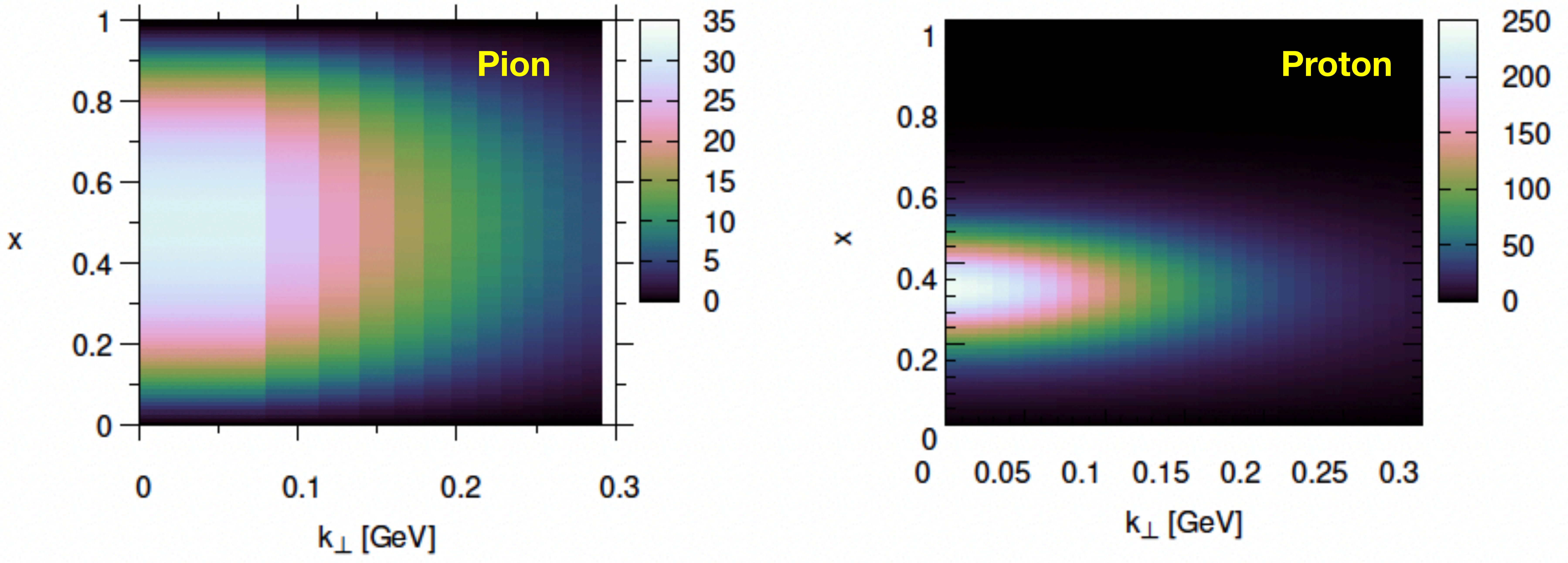
- From:
- T. Frederico (Instituto Tecnologico de Aeronautica)
- E. Ydrefors (Chinese Academy of Sciences)

- Minkowski space Bethe-Salepeter equation (pion)
- Light-front model (proton)
- See backup for details

- Broader pion PDF compared to proton

- Expect interesting differences between meson and nucleon PDFs

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.

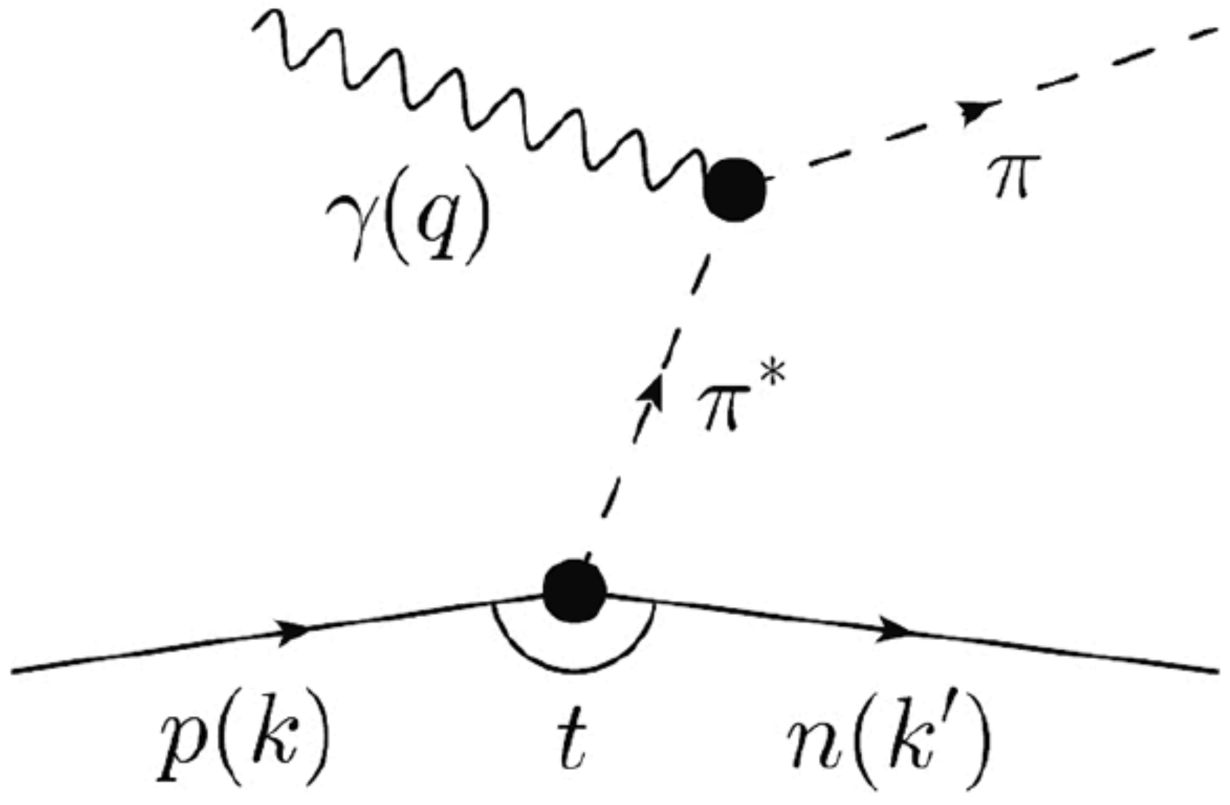
[2] E. Ydrefors, T. Frederico PRD 104 (2021) 114012; and arXiv: 2211.10959 [hep-ph].

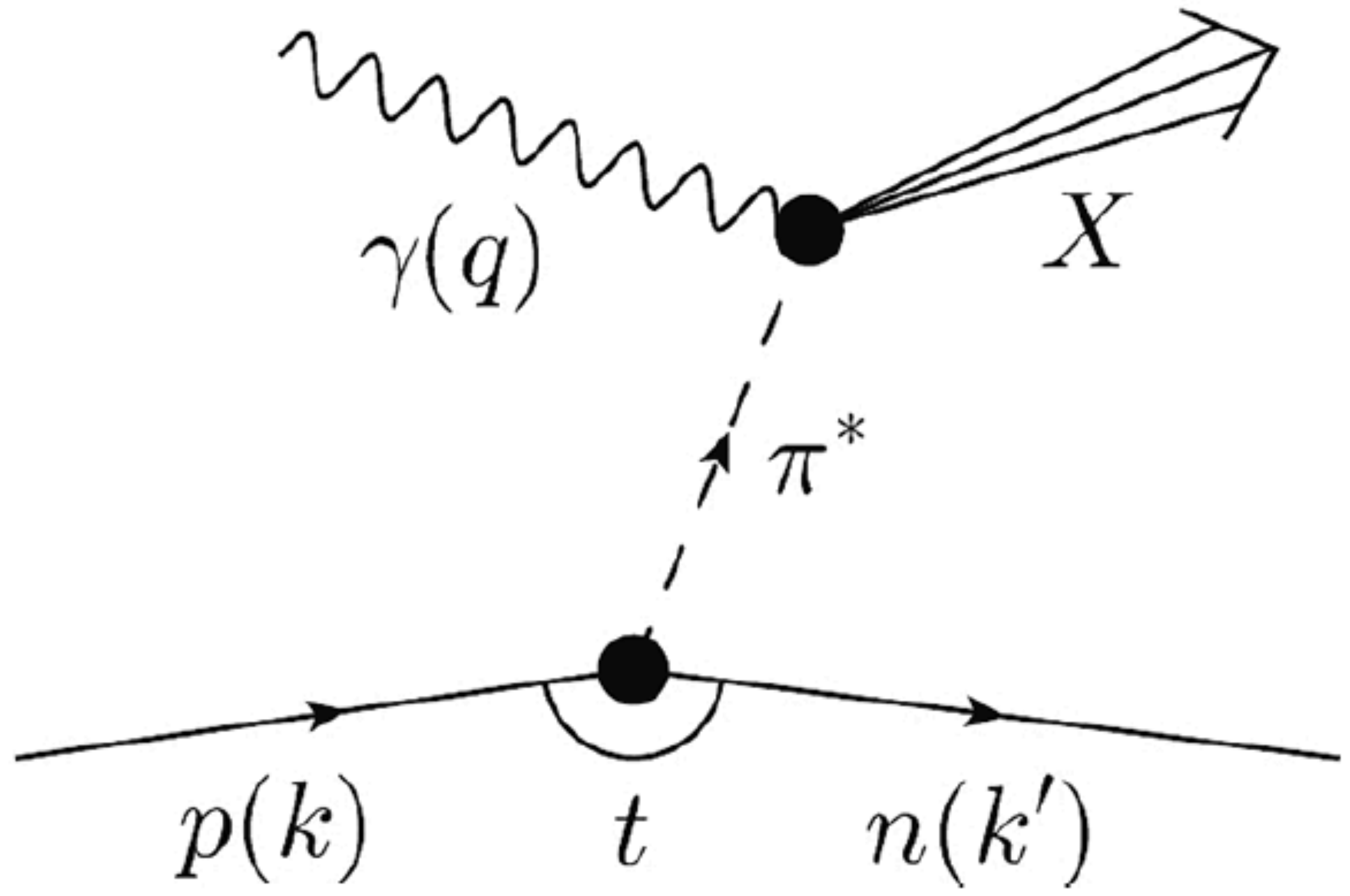
- From:
- T. Frederico (Instituto Tecnologico de Aeronautica)
- E. Ydrefors (Chinese Academy of Sciences)

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

Accessing Light Meson Structure

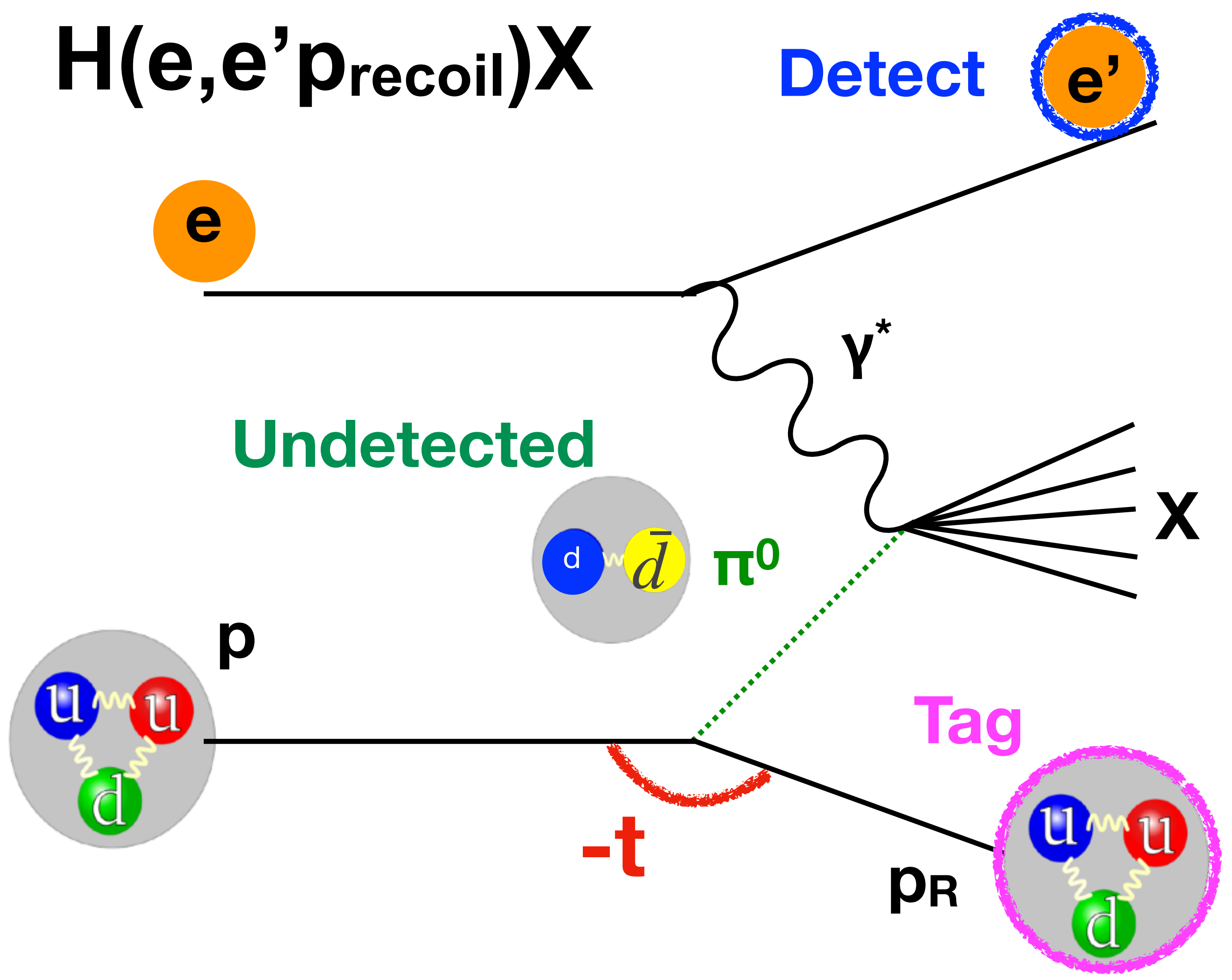
Sullivan Process - scattering from virtual meson cloud

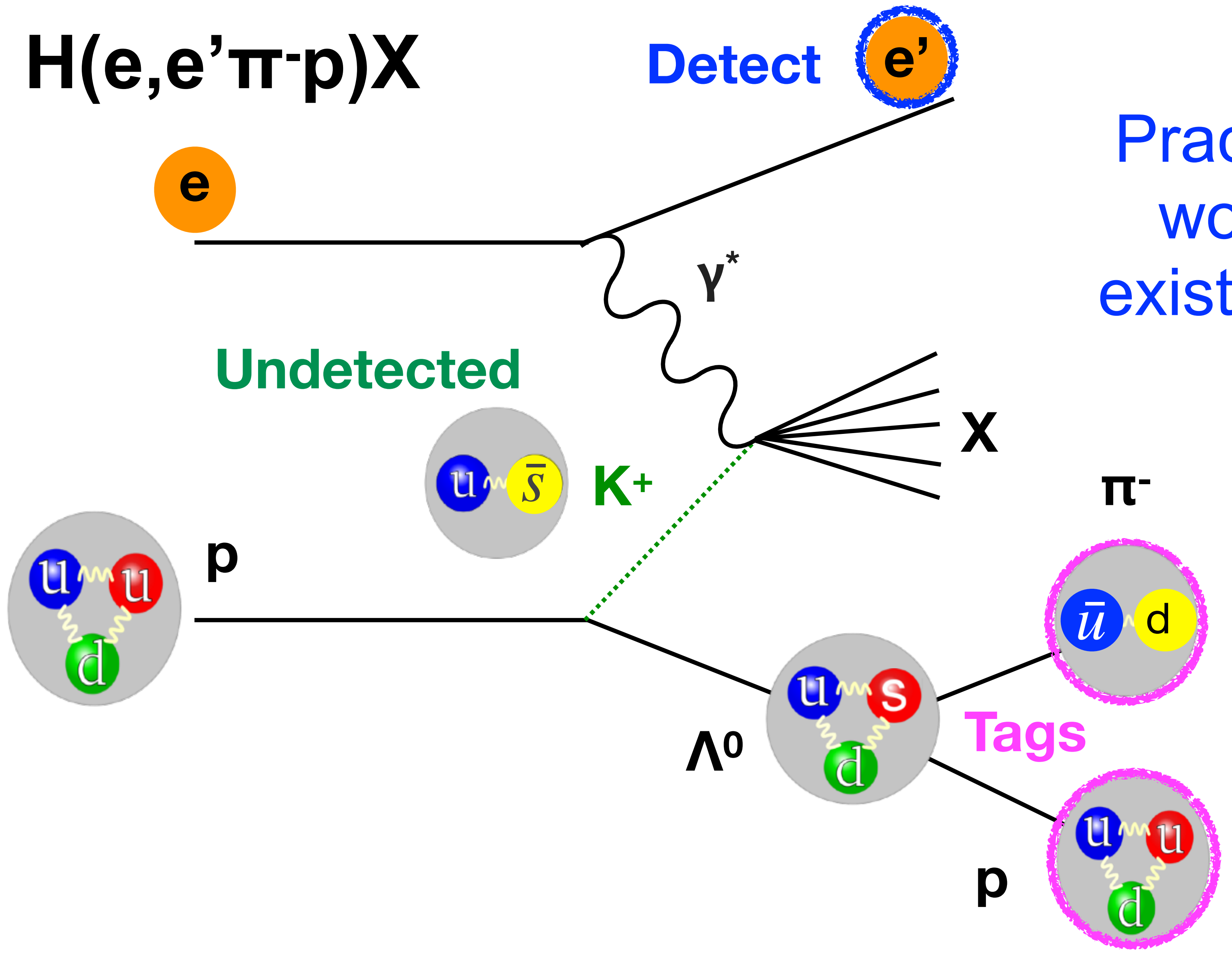




- Several "observables" for meson structure:
  - e.g. elastic EM form factors (FF), or **structure functions (SF)**
- Hall C successful history using meson cloud for electroproduction of pions/kaons for FF
- Upcoming Tagged Deep Inelastic Scattering (TDIS) program:
  - Meson SF via Sullivan process

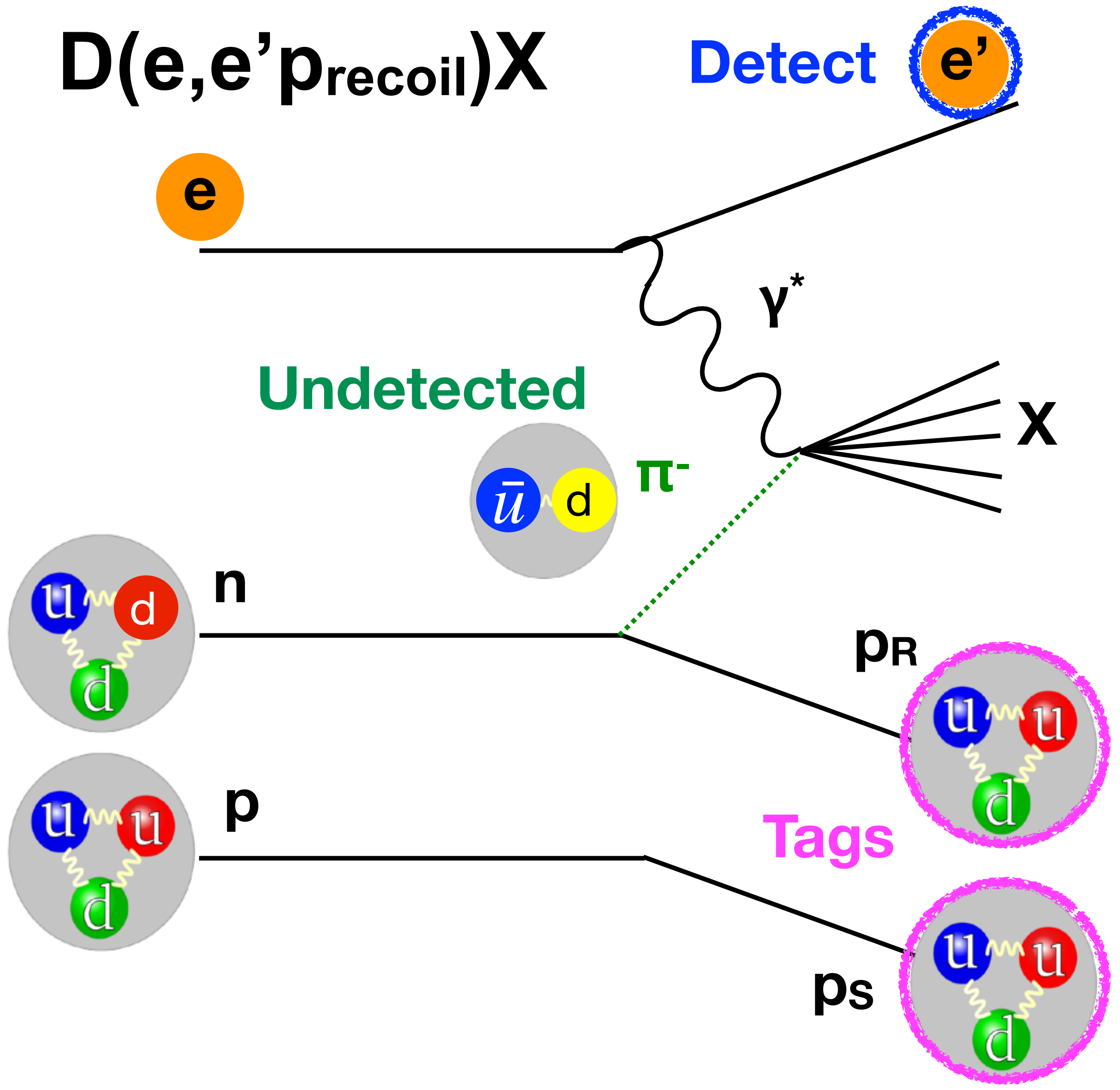
TDIS Plans at 11GeV





Practically no world data exists for kaon

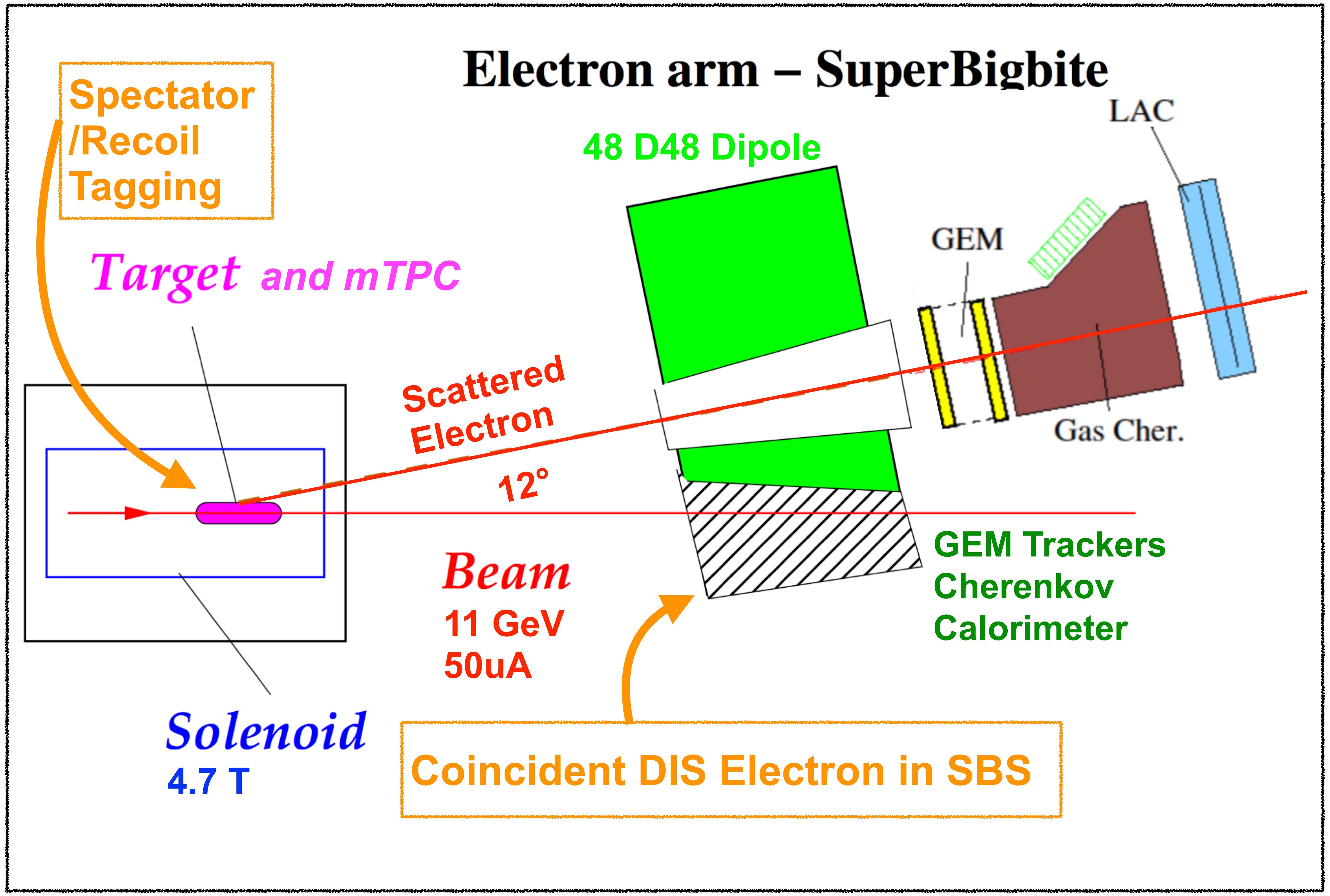
For reliable access to meson target, minimise |-t|



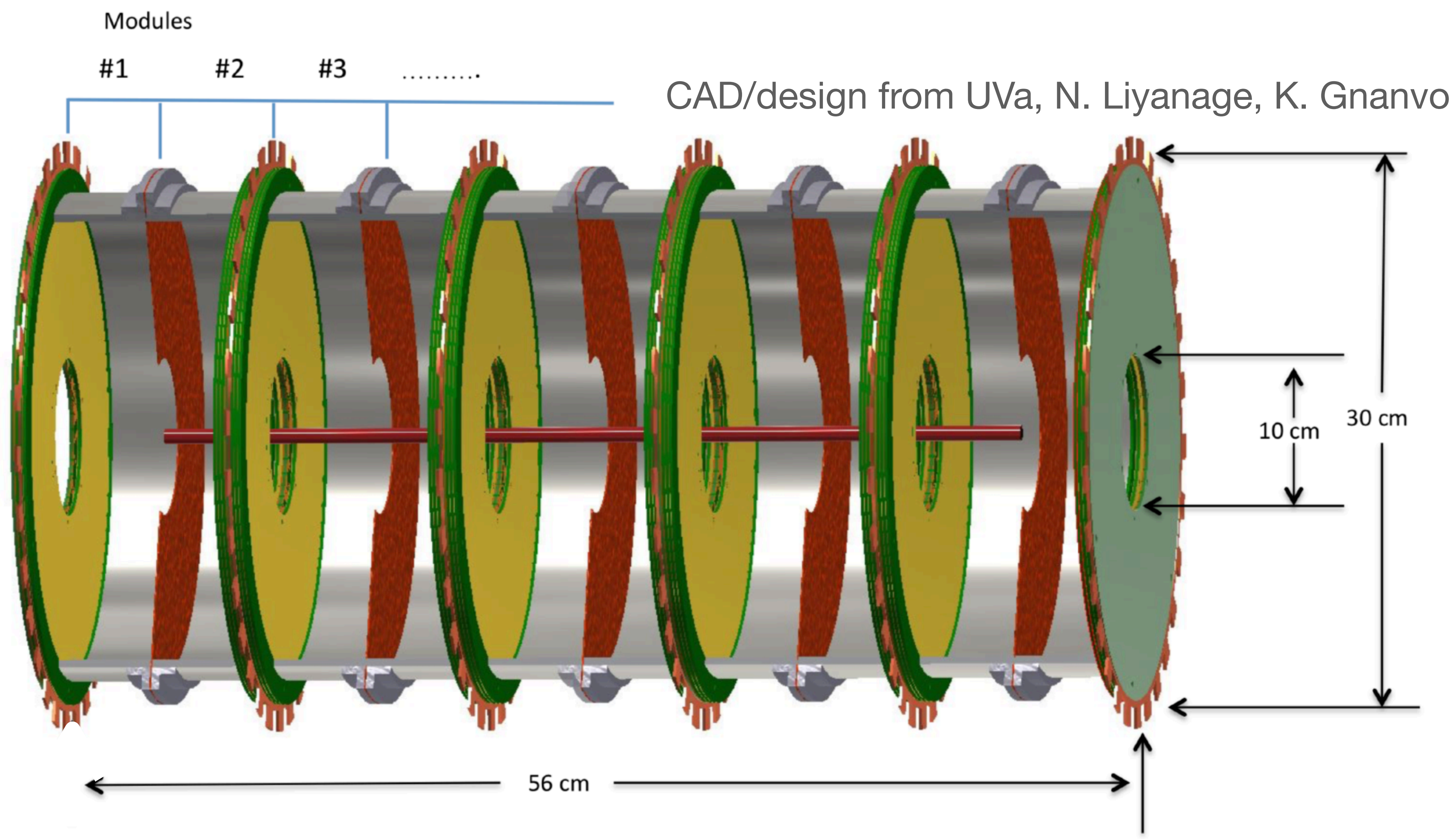
$8 < W^2 < 18$ GeV^2
$1 < Q^2 < 3$ GeV^2
$0.05 < x < 0.2$

- DIS with spectator tagging
  - effective free targets not easily found in nature
- TDIS:
  - Pion and kaon F_2 SF in valence regime
  - TDISn run group - neutron structure topics

TDIS Experimental Setup

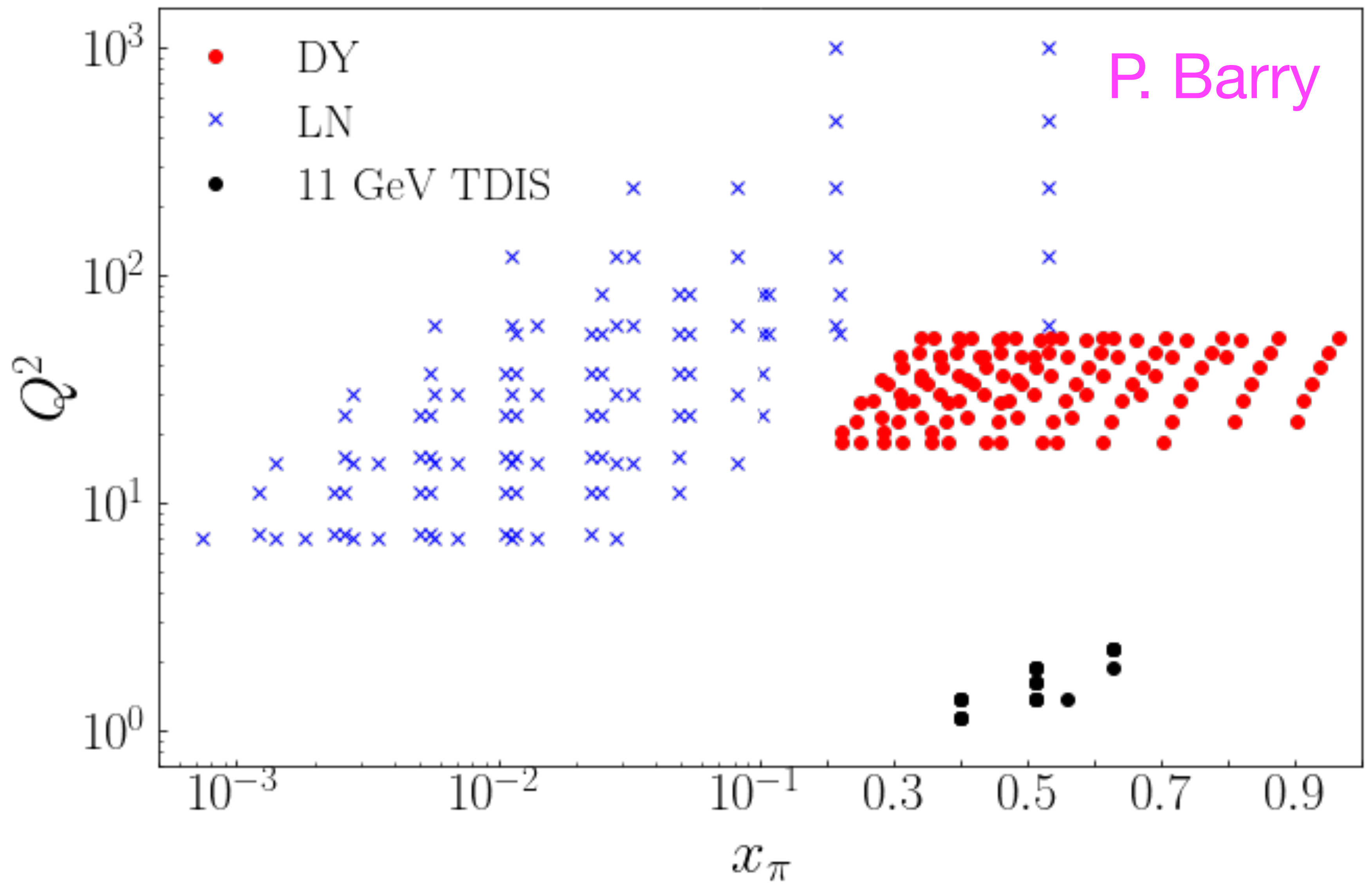


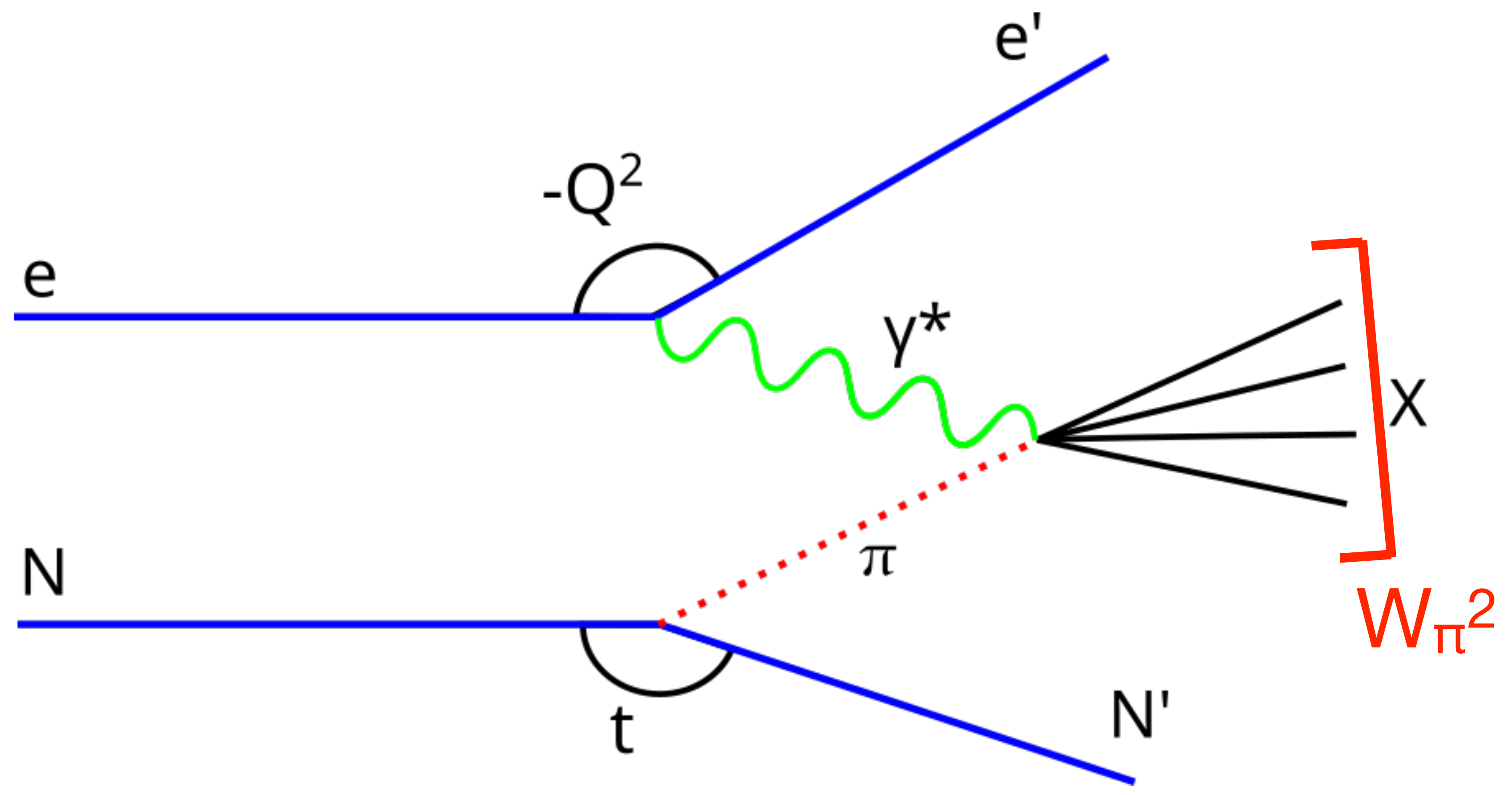
High rate multiple time projection chamber (mTPC) to tag recoiling/spectator hadrons

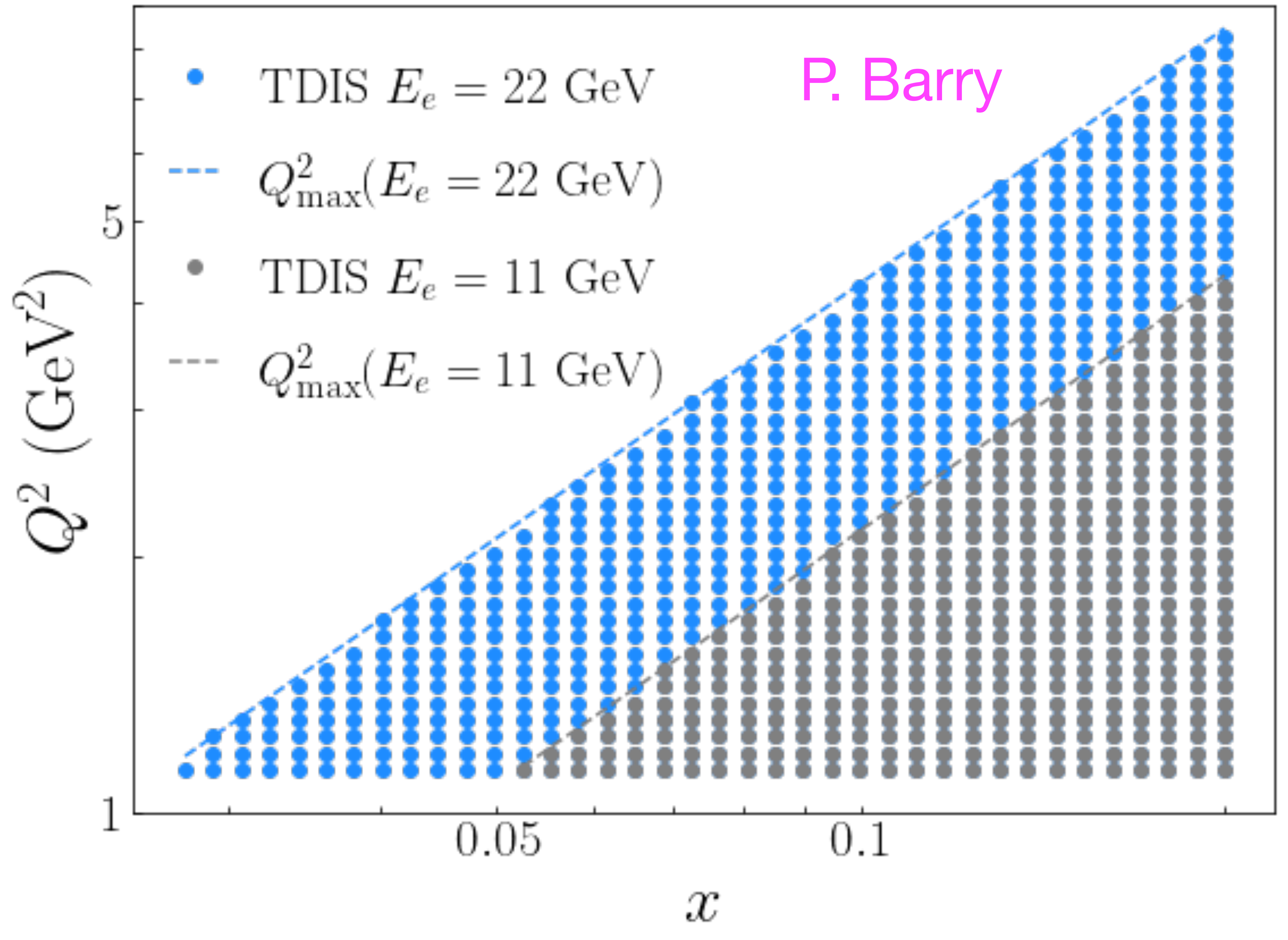


Tracking, dE/dx

TDIS at 22GeV





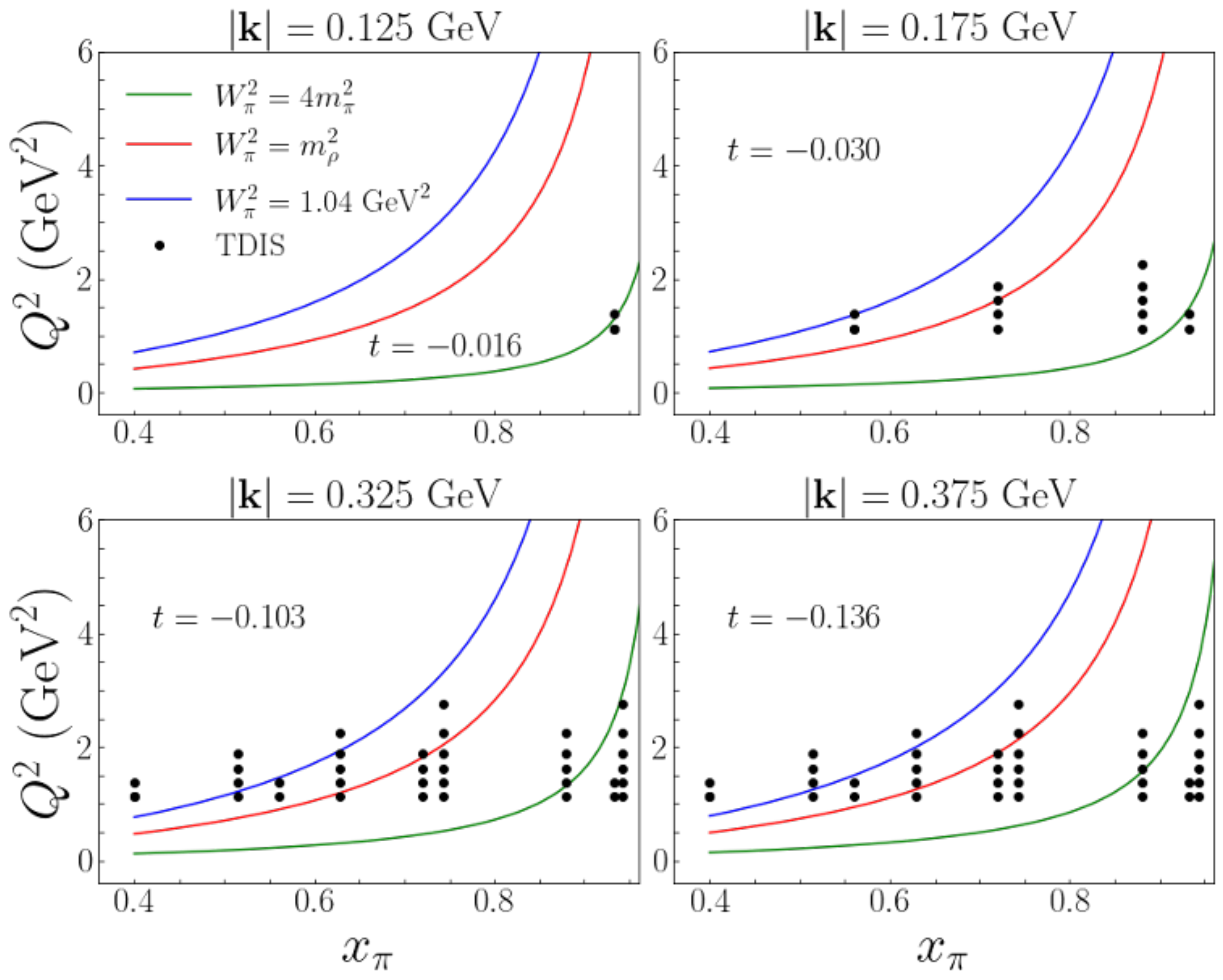


- P. Barry:
- TDIS useful to study resonances at low W_π^2
- Cut $W_\pi^2 > 1.04\text{GeV}^2$ to minimise ρ
- Much larger phase space at 22GeV

- 22GeV projections shown use P. Barry's phase space code
- Includes T.J. Hobbs' et al. F_2^π model and JAM PDFs

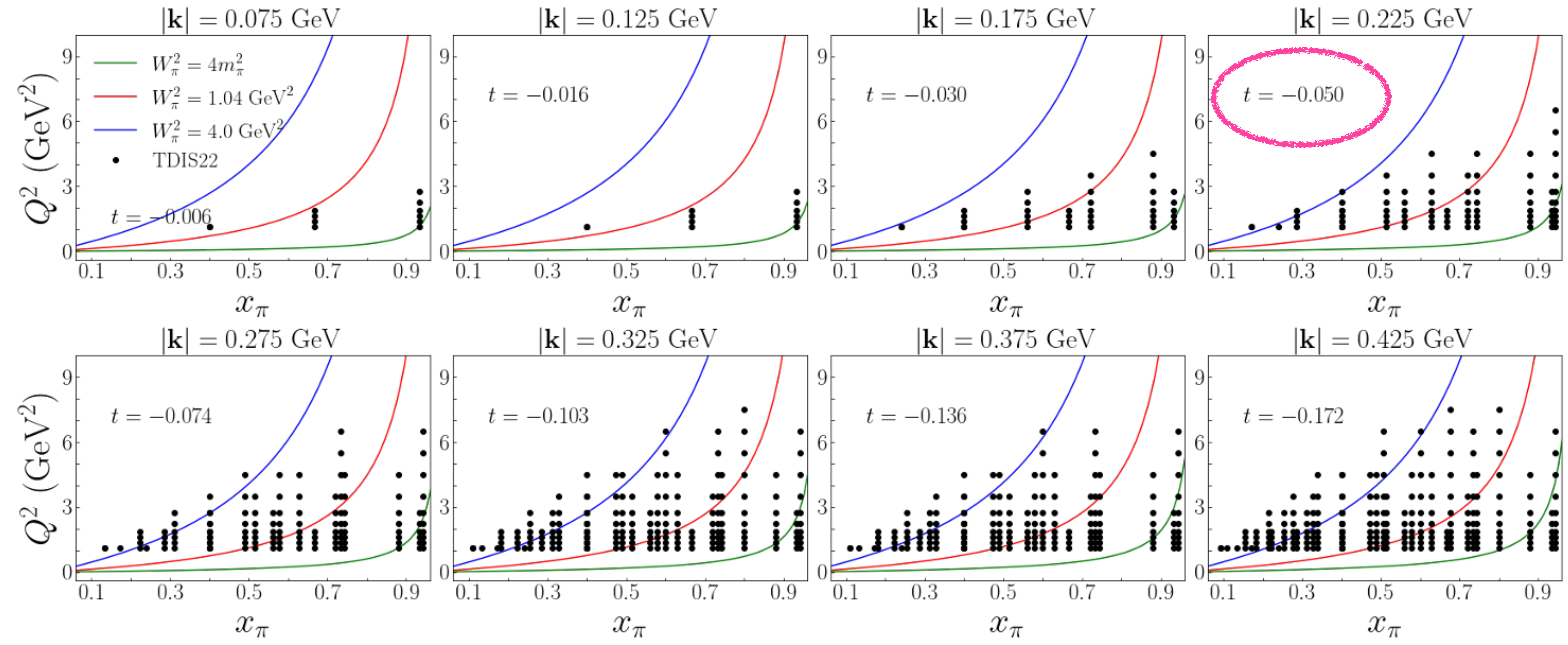
TDIS Phase Space for Pion SF

Plots: P. Barry and D. Dutta



11 GeV

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

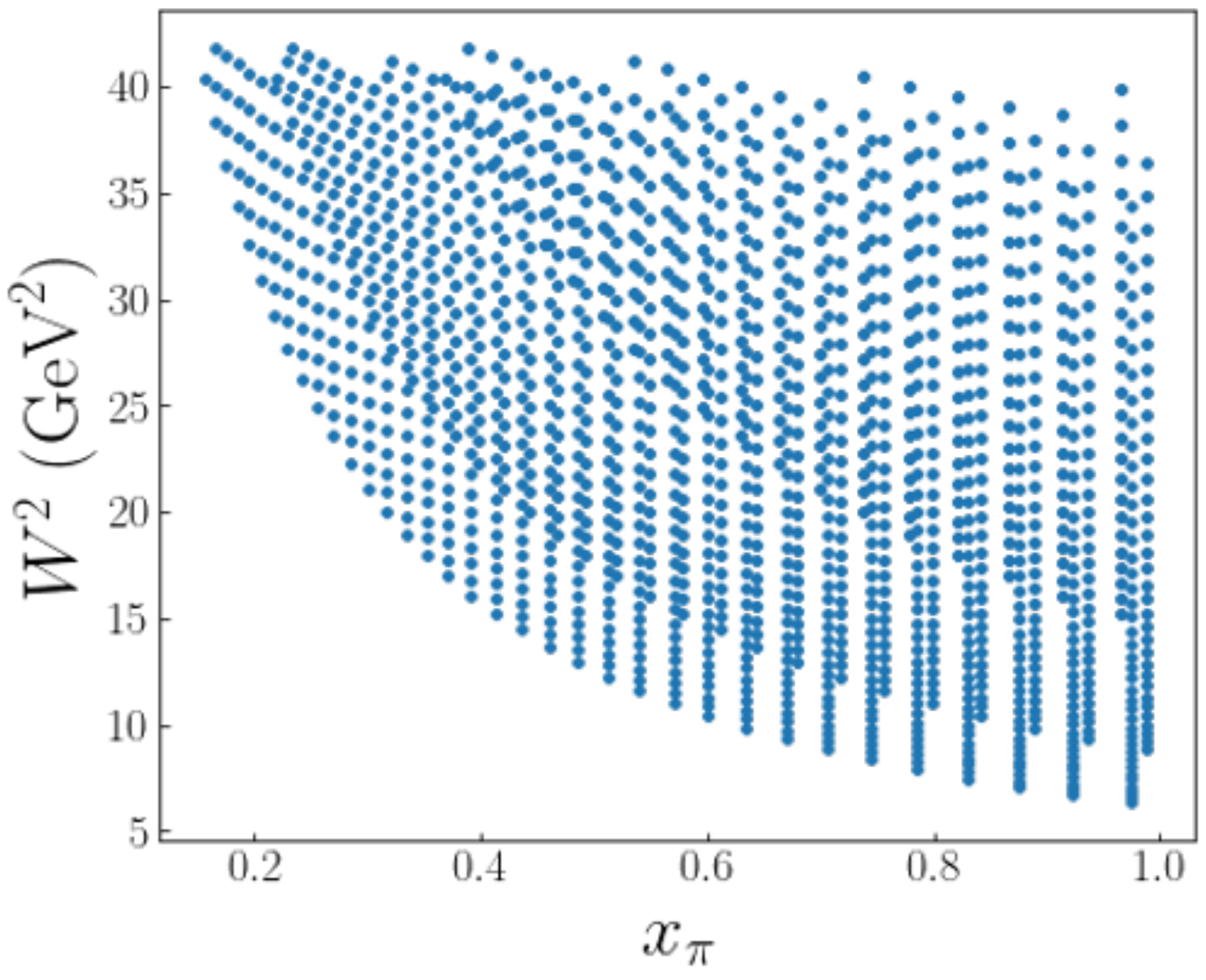


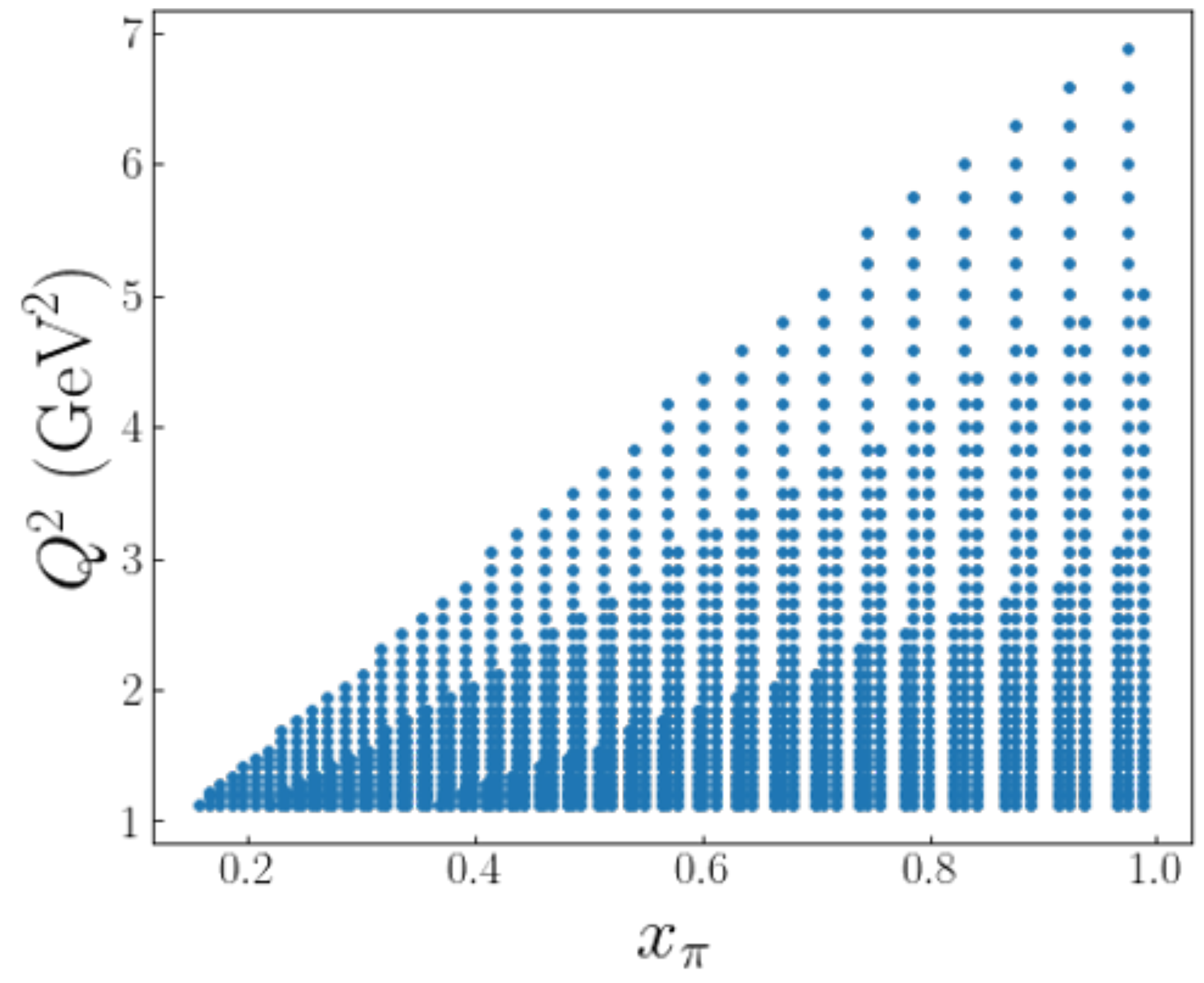
22 GeV

- 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**

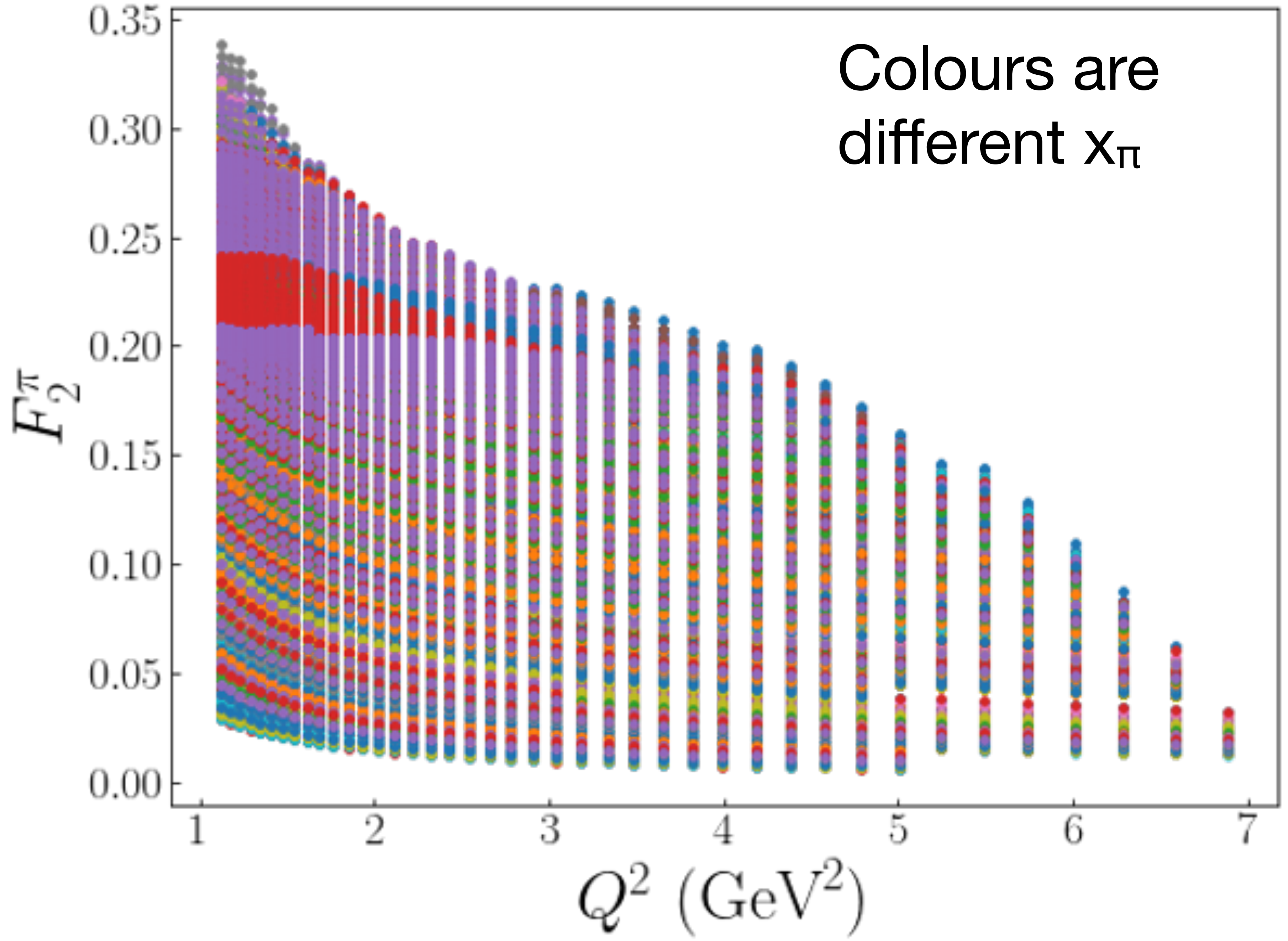
TDIS Phase Space 22GeV

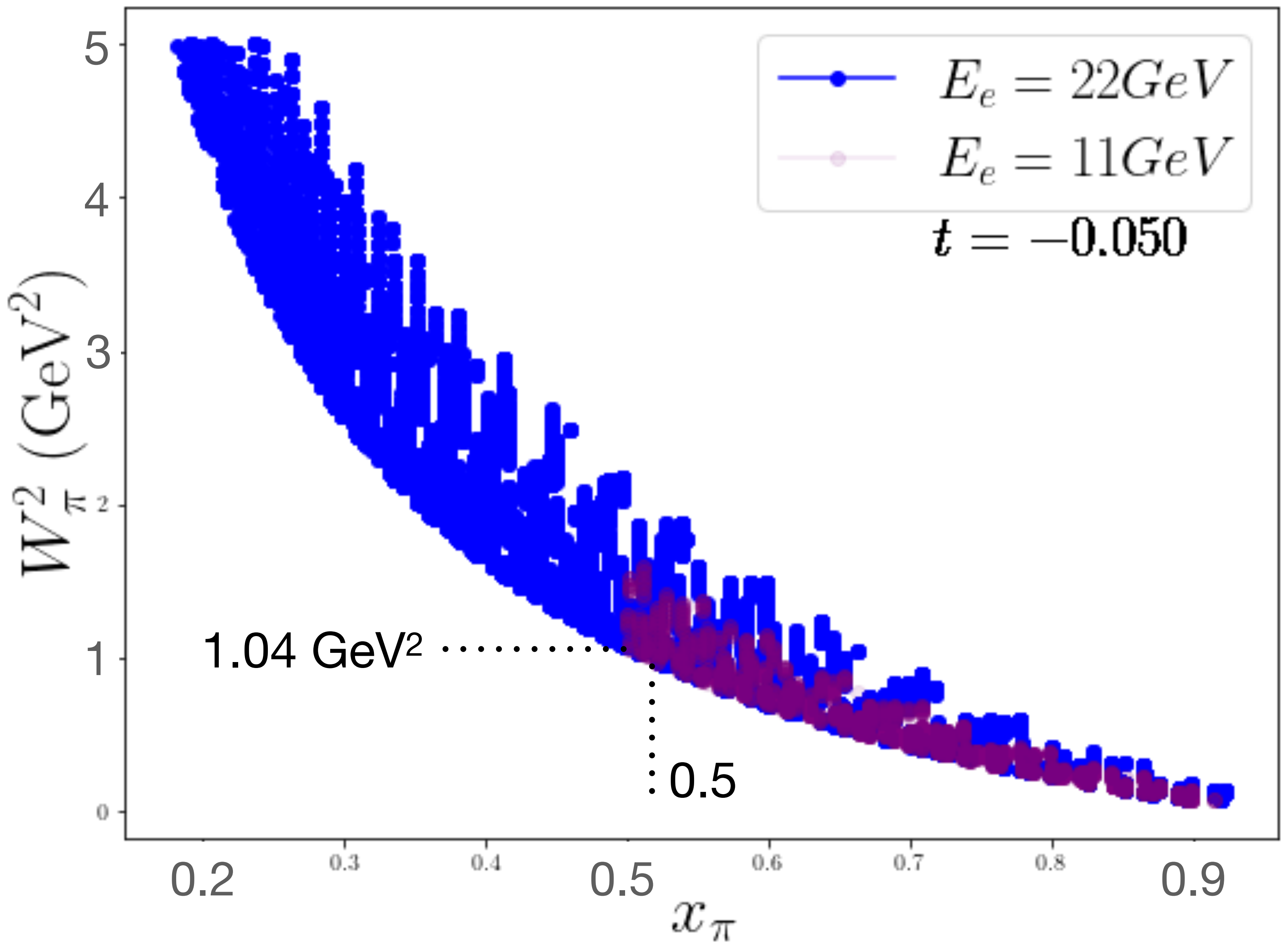




Plots: C. Ayerbe

Broad coverage in x_π





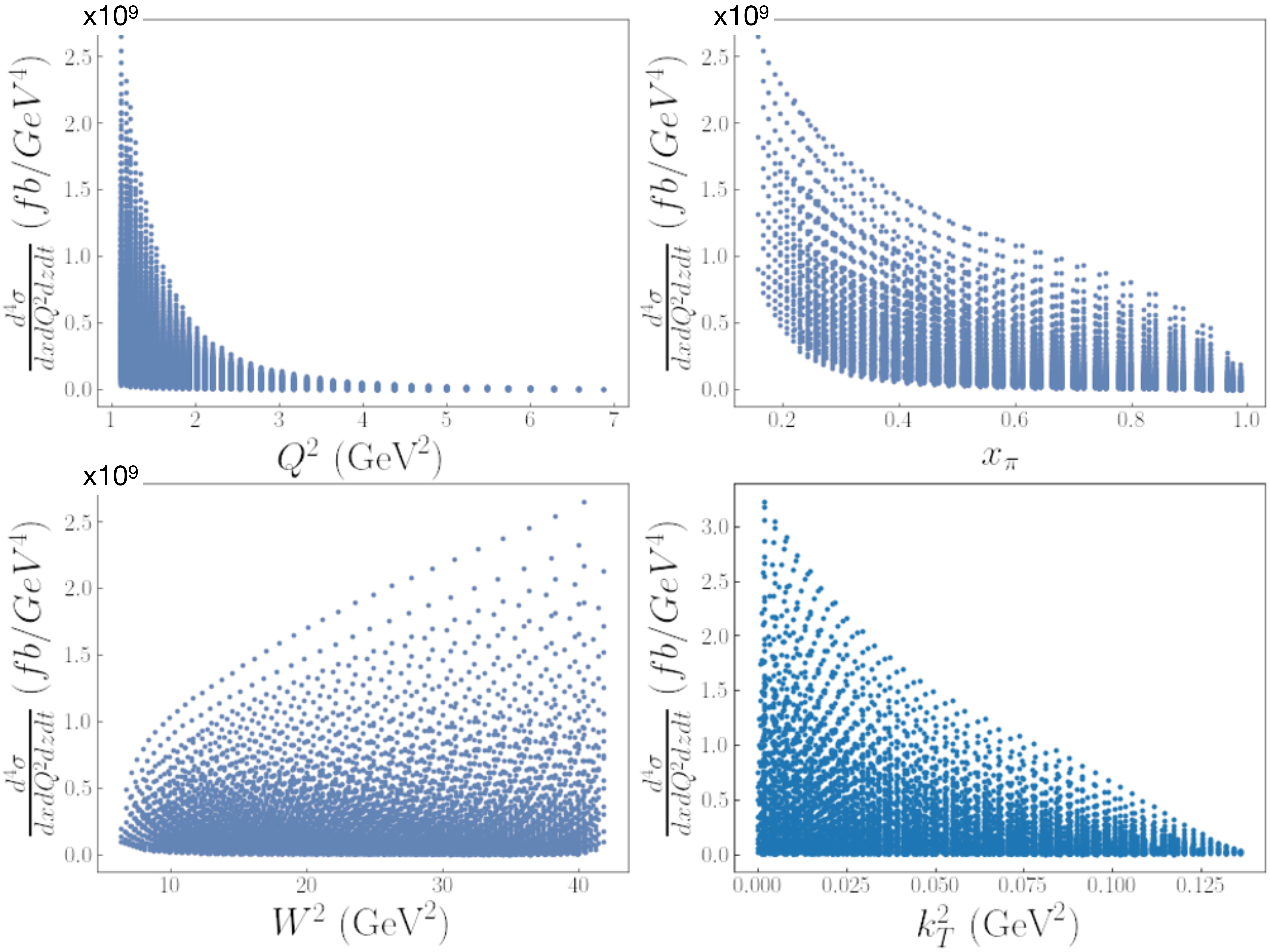
W_π^2 vs x_π plot at t=-0.05

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

11GeV, also cut x>0.5

Distinction between 11/22GeV
Much wider landscape @22GeV
Only 22GeV reaches W_π^2>2GeV^2

TDIS Cross Section 22GeV



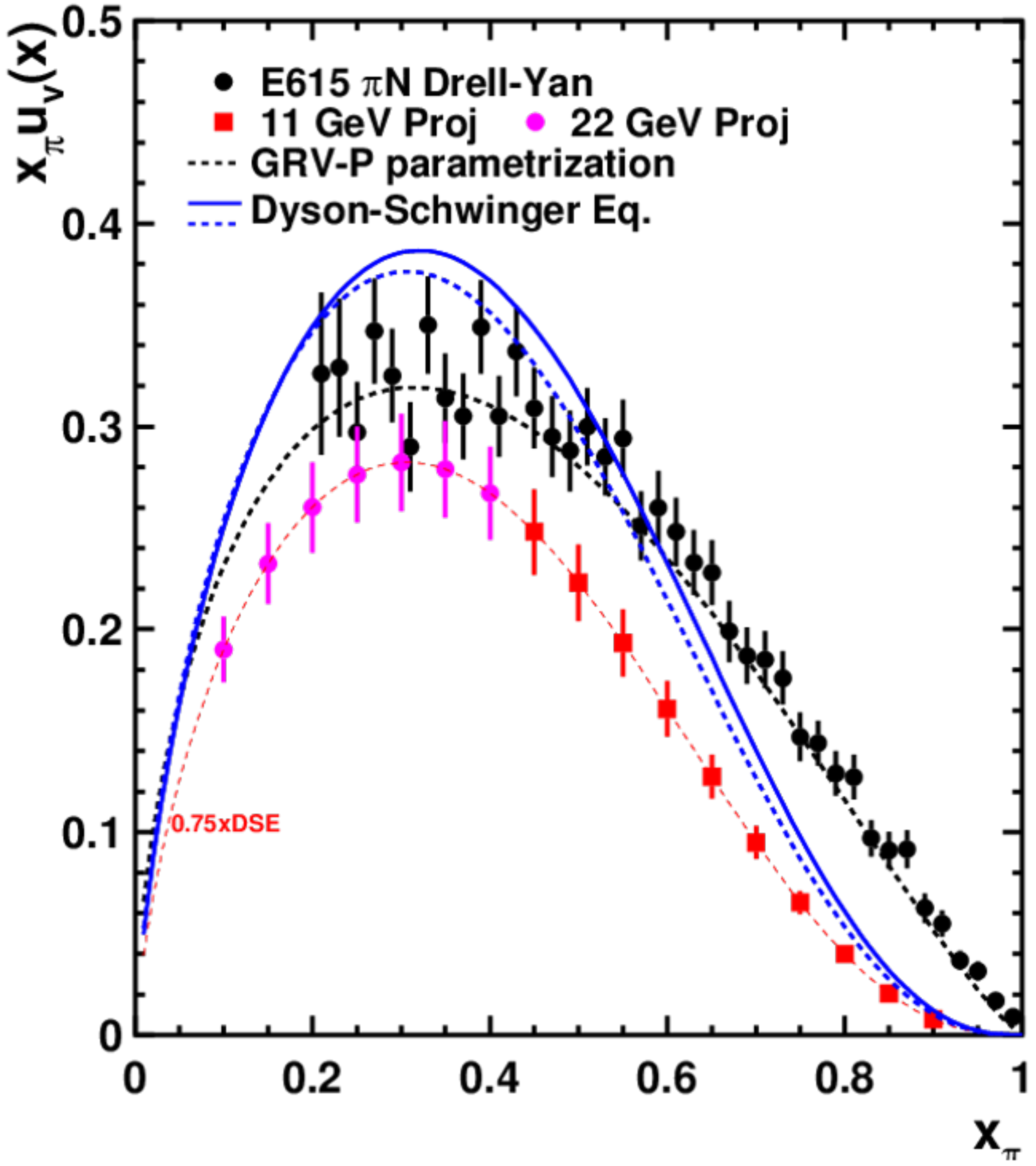
Plots: C. Ayerbe

Coverage in k_T^2, relevant for π SF

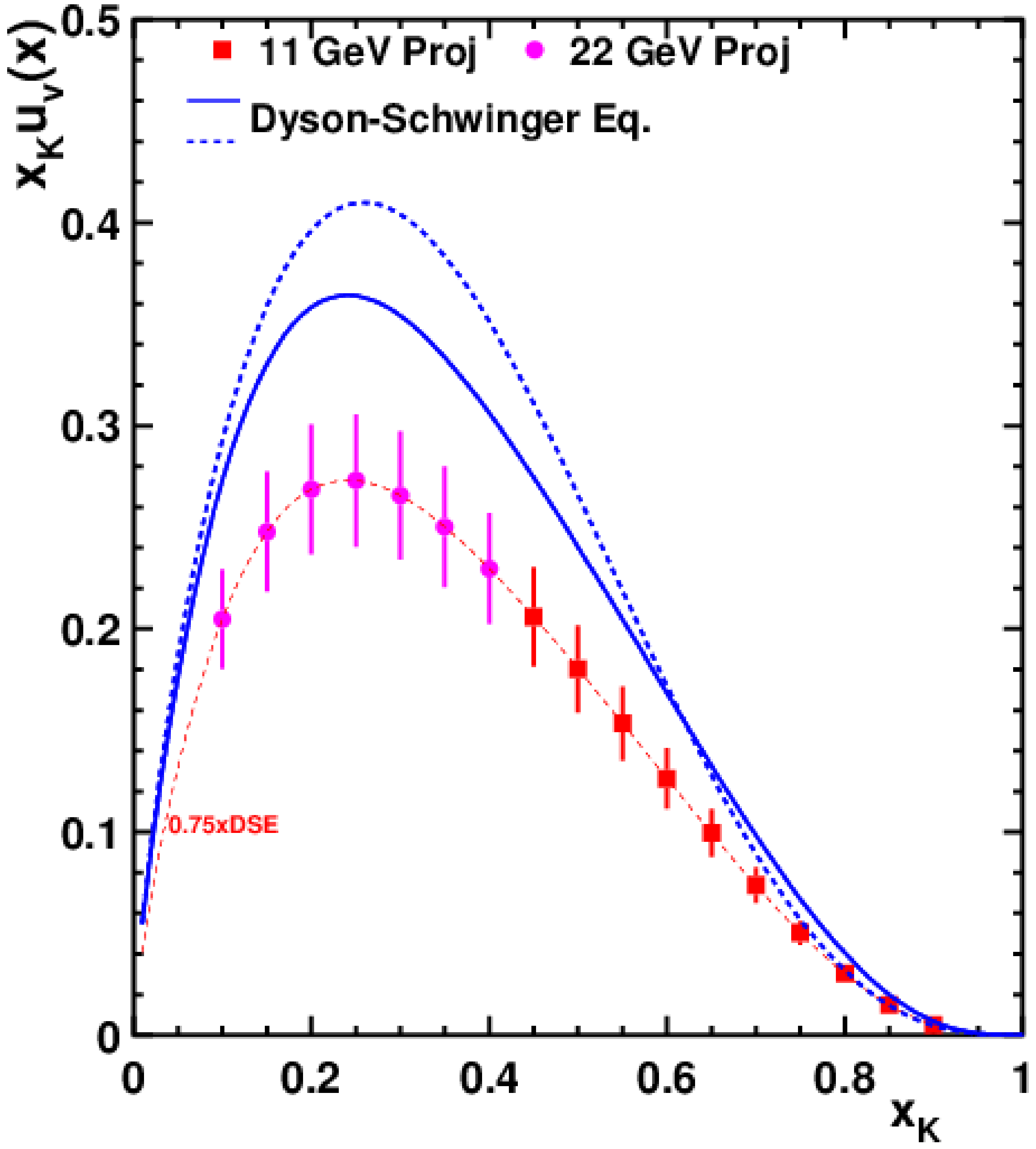
(transverse mom of virtual particle squared)

TDIS x_π Range and Projections

Pion



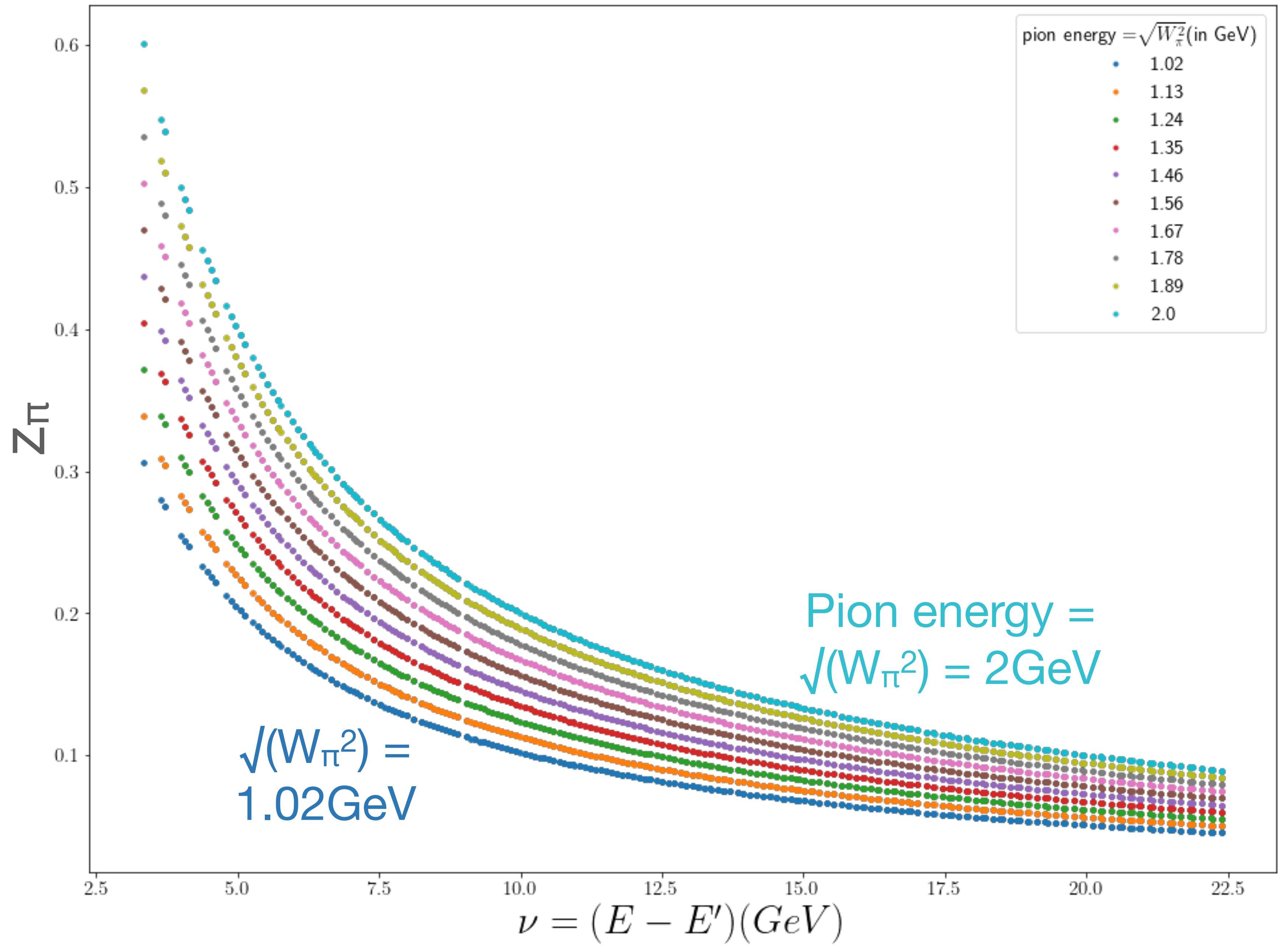
Kaon

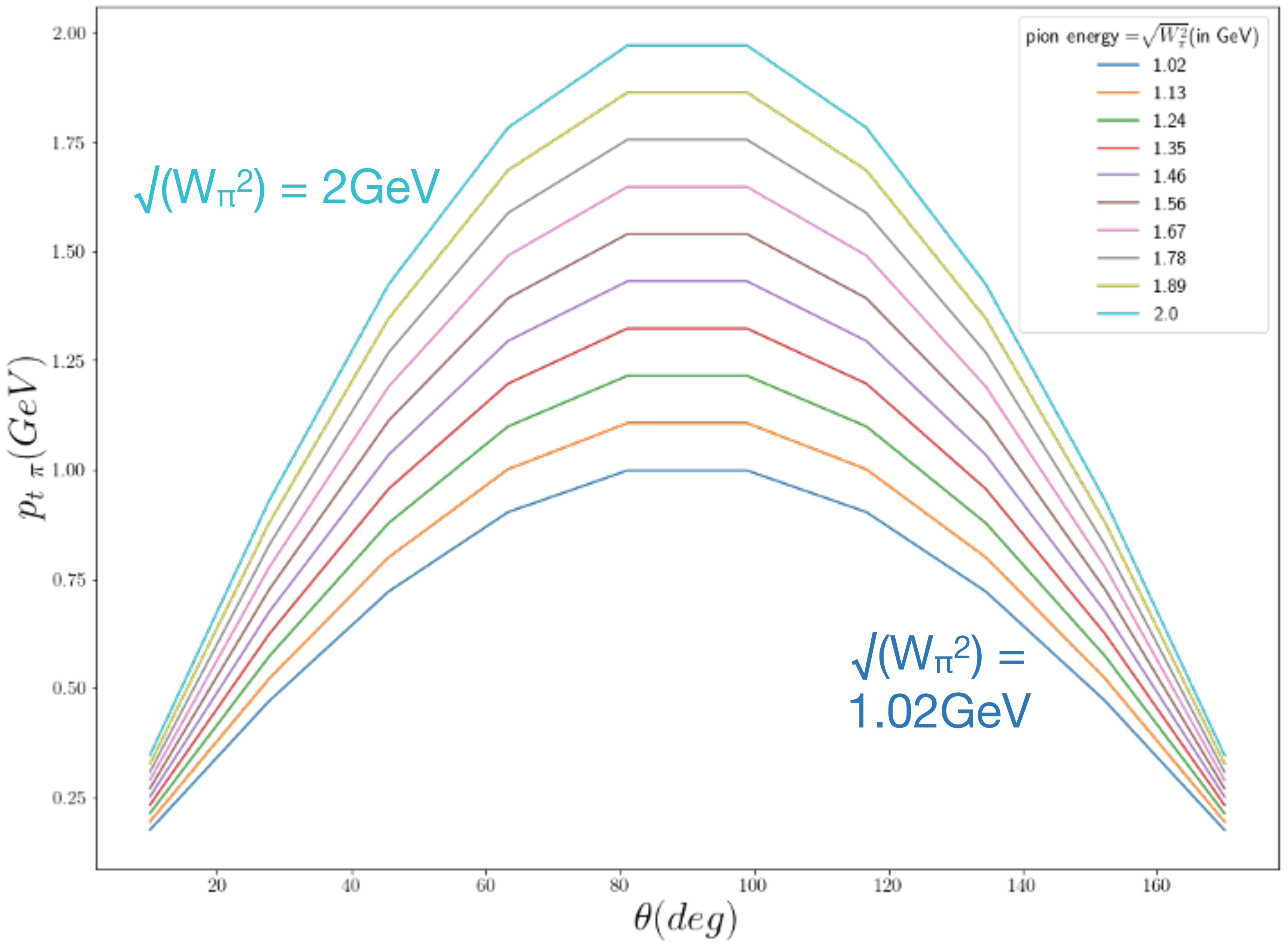


- 22GeV Projections:
  - 50 days' beam time
  - Time to keep error bars same as 11GeV proposals
- 11Gev limited $x_{\pi/K}$>=0.4
- 22GeV now $x_{\pi/K}$=0.1
- Same ranges for π and K
- 22GeV drastically expands x-range!
- Adds to sparse world data
- Especially kaon!

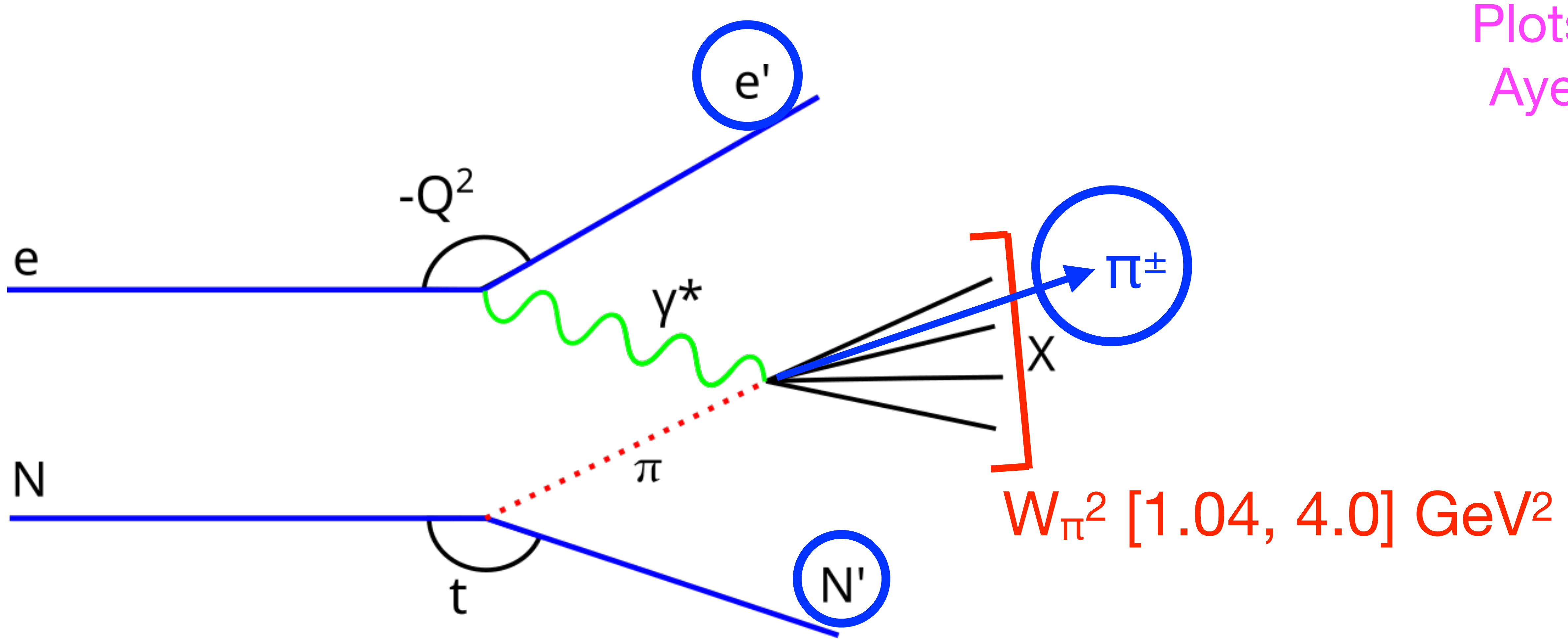
Plots: D. Dutta and T. Horn

SIDIS on Virtual Meson with TDIS at 22GeV





Plots: C. Ayerbe



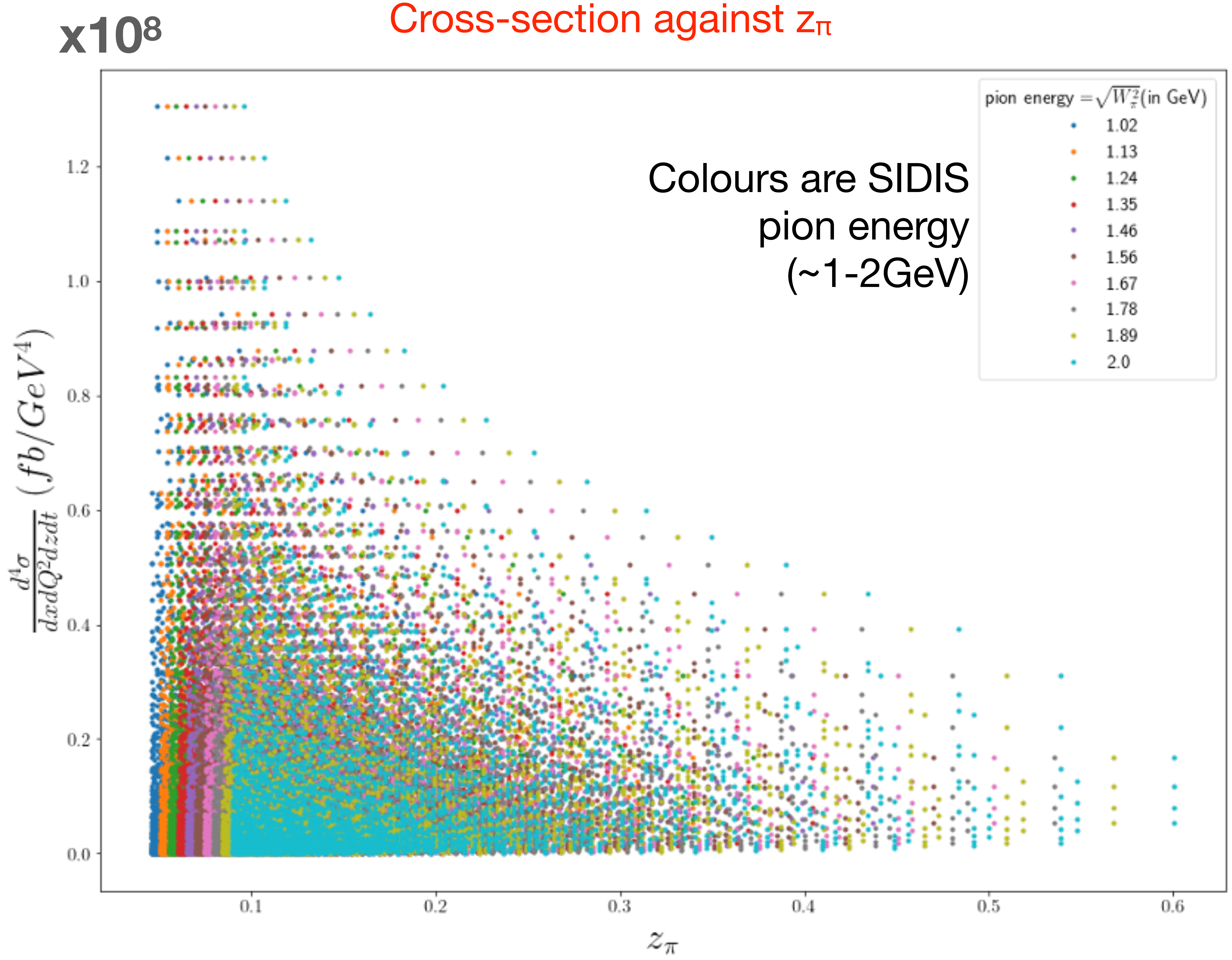
- 22GeV, TDIS available between 1.04 and 4GeV^2
- SIDIS on virtual meson possibility

- Assume W_π^2 used to produce π
- Measure e', N' and π

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

SIDIS Cross Section 22GeV

Cross-section against z_π

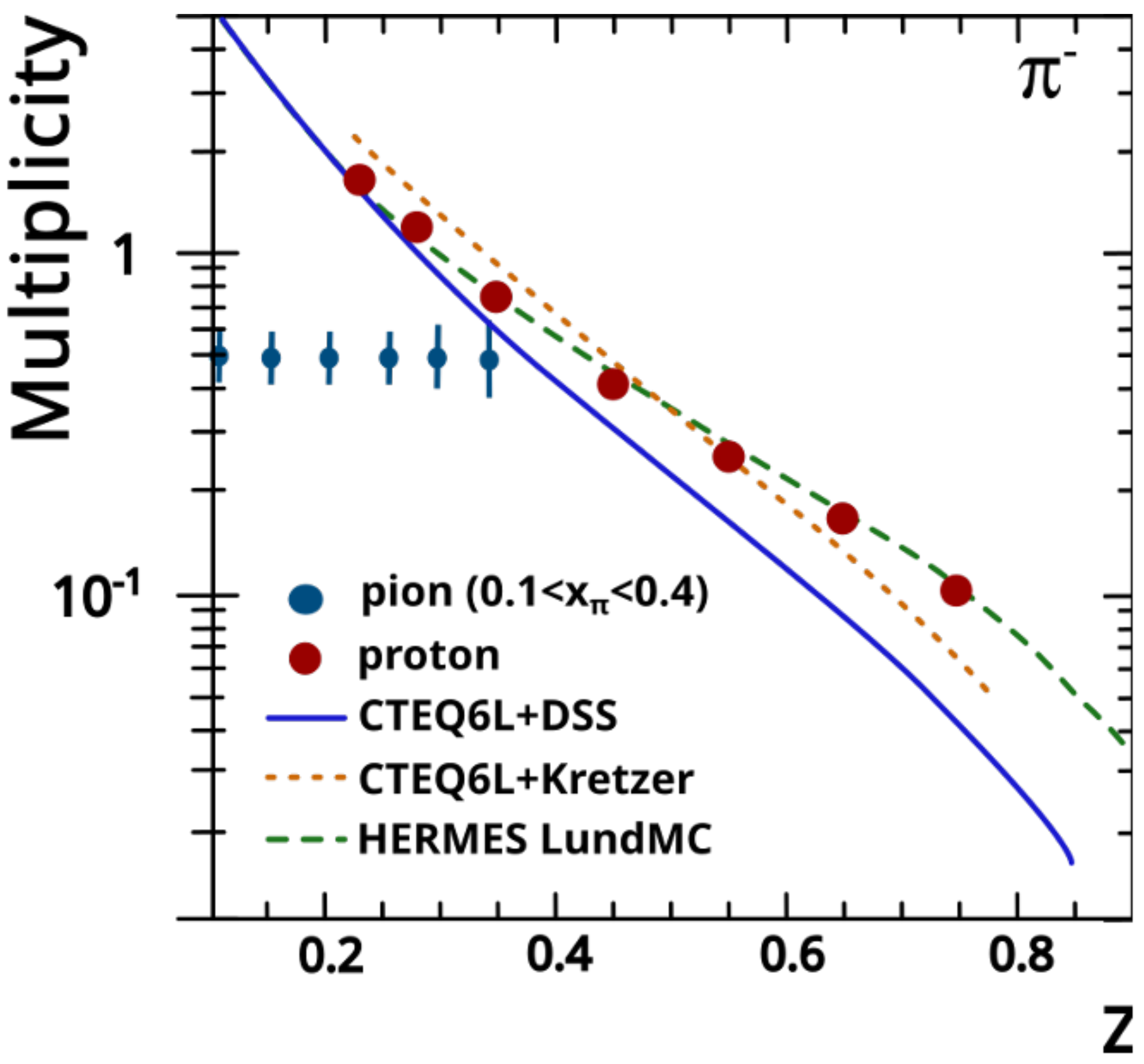


- Expected SIDIS rates scaled from TDIS cross section
- Assume SIDIS rates ~ 4% TDIS @11GeV

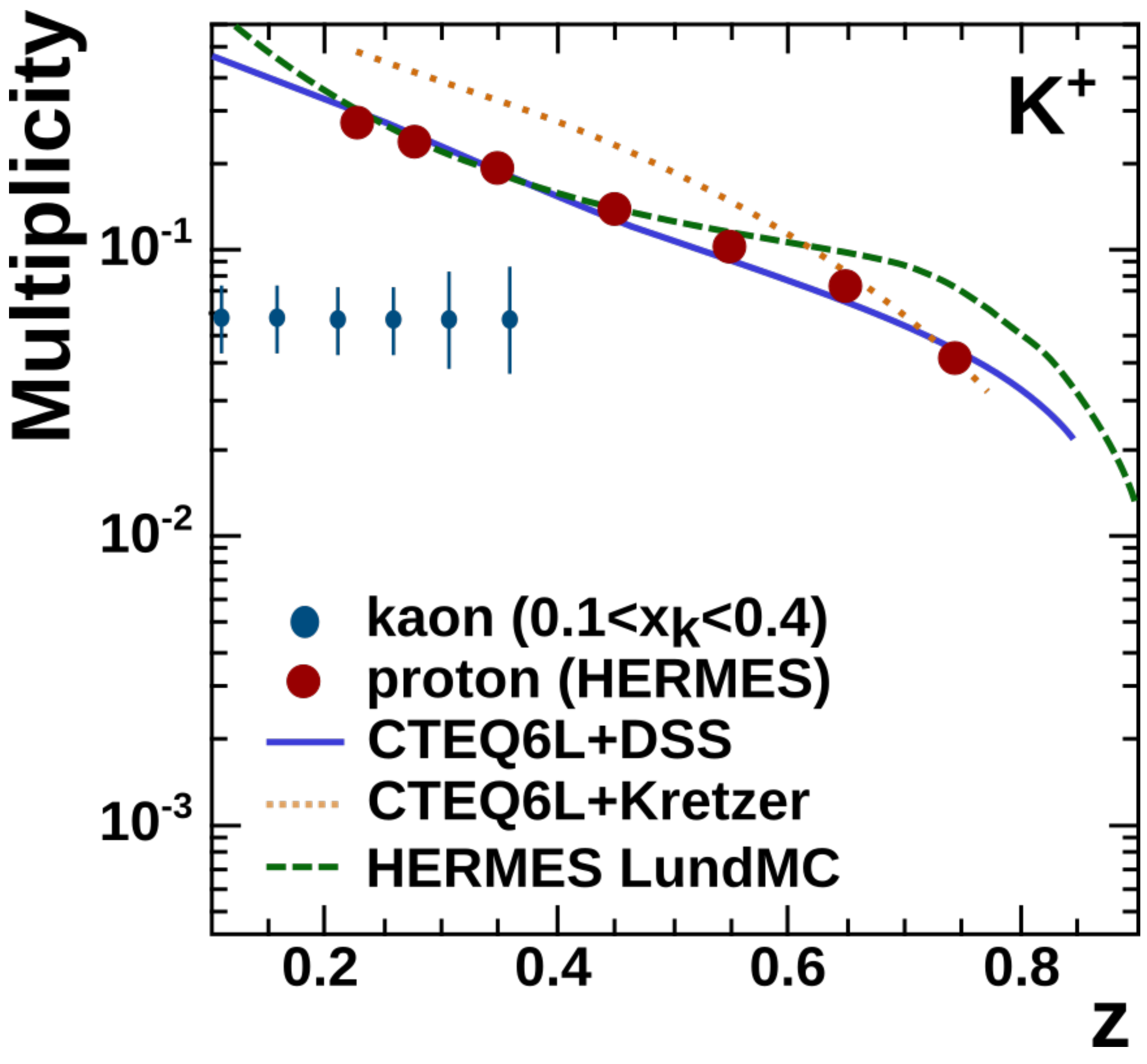
Plot/Calculation: C. Ayerbe and D. Dutta

SIDIS 22GeV Multiplicities

Pion



Kaon

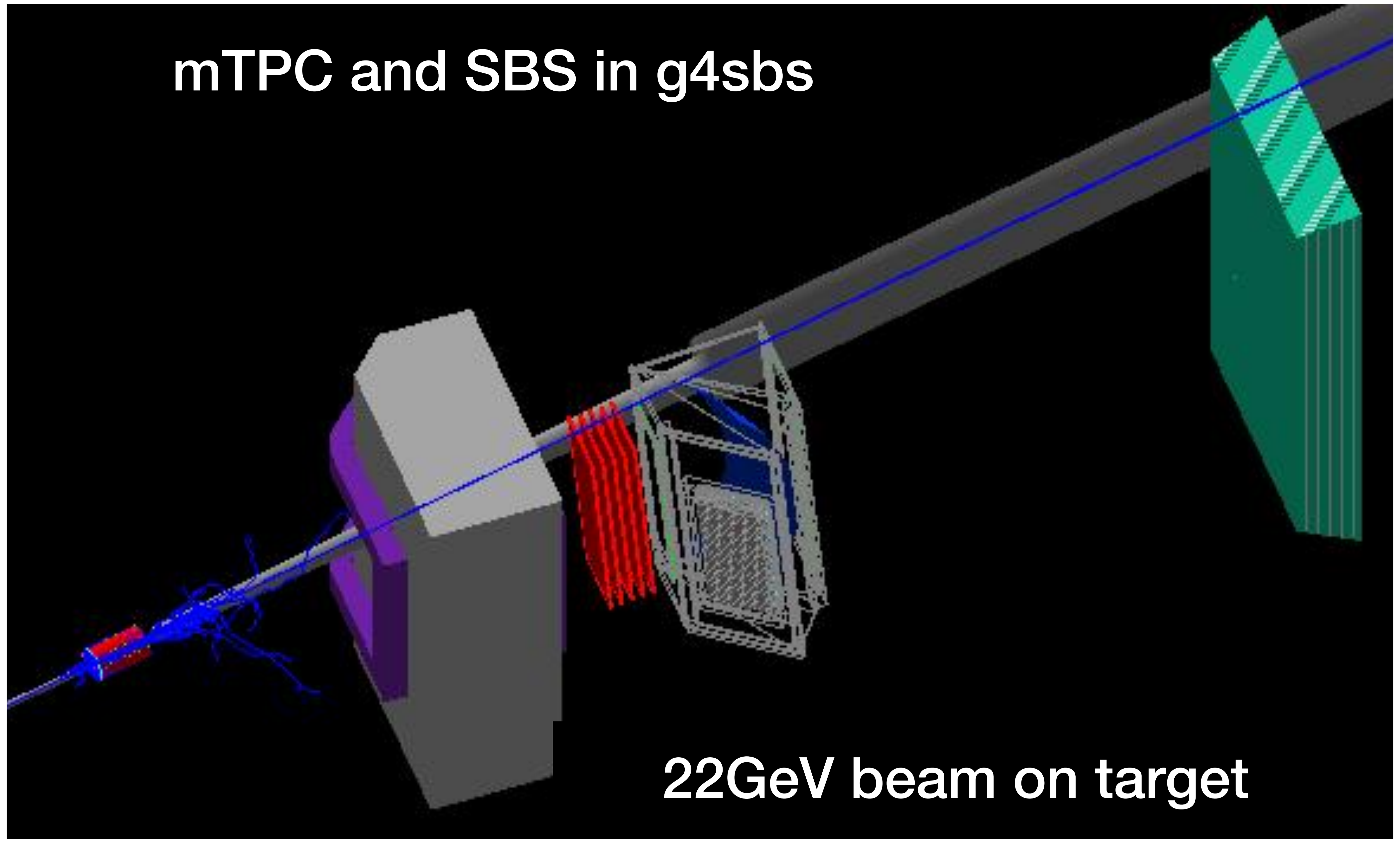


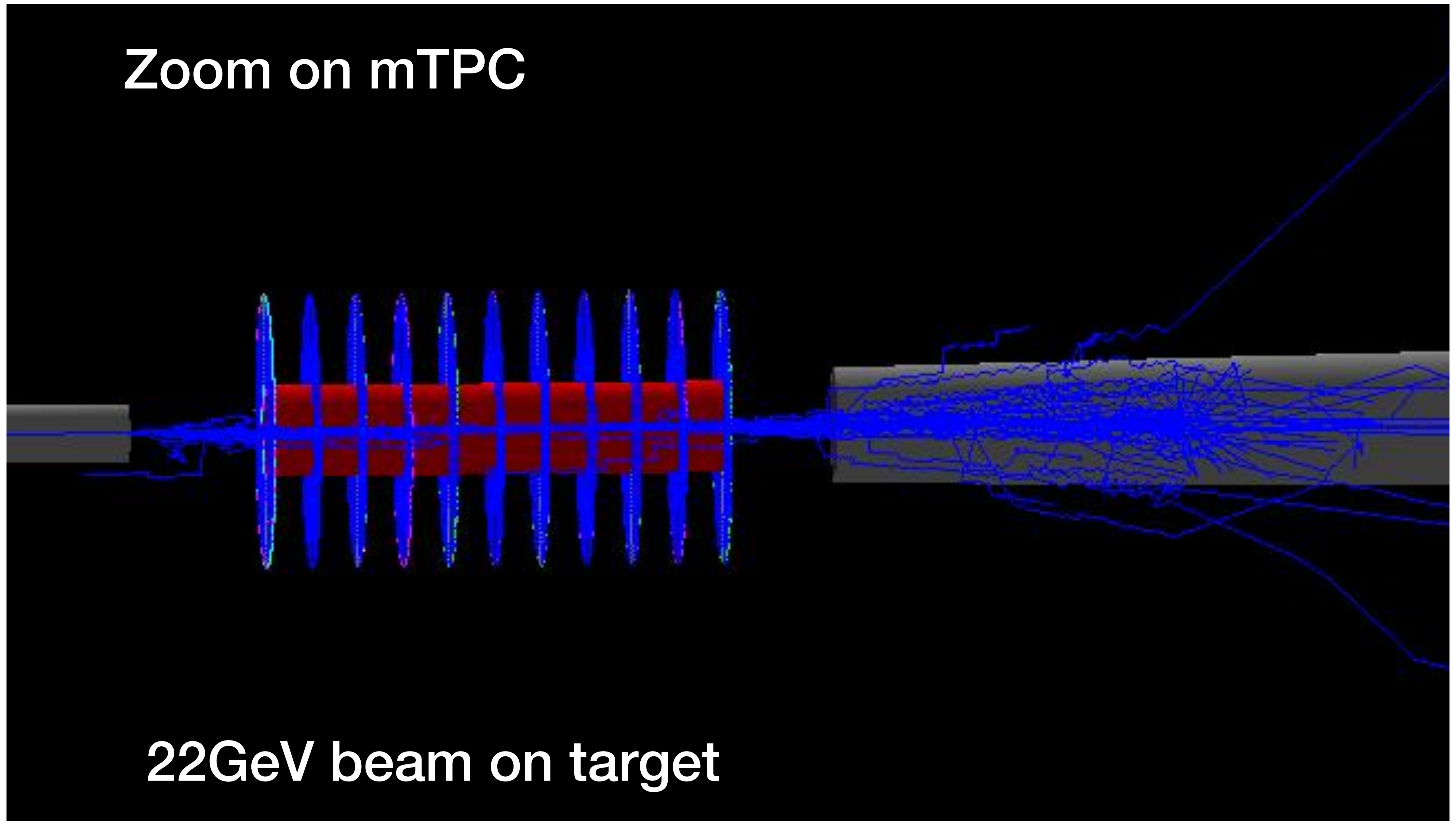
HERMES results from:
A. Airapetian et al. (HERMES Collaboration), Phys. Rev. D 87, 074029

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

Plots:
D. Dutta,
C. Ayerbe

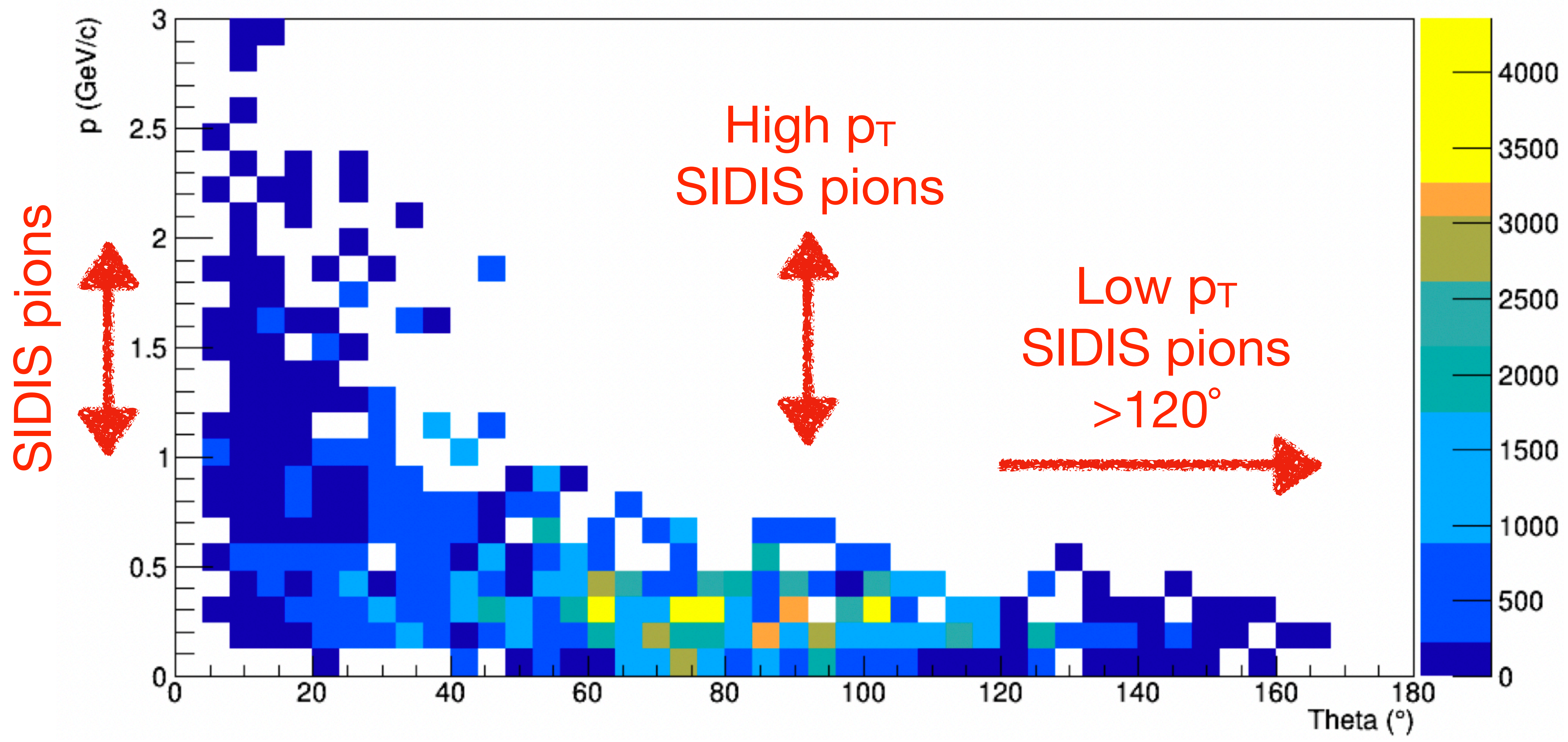
22GeV Simulation Status

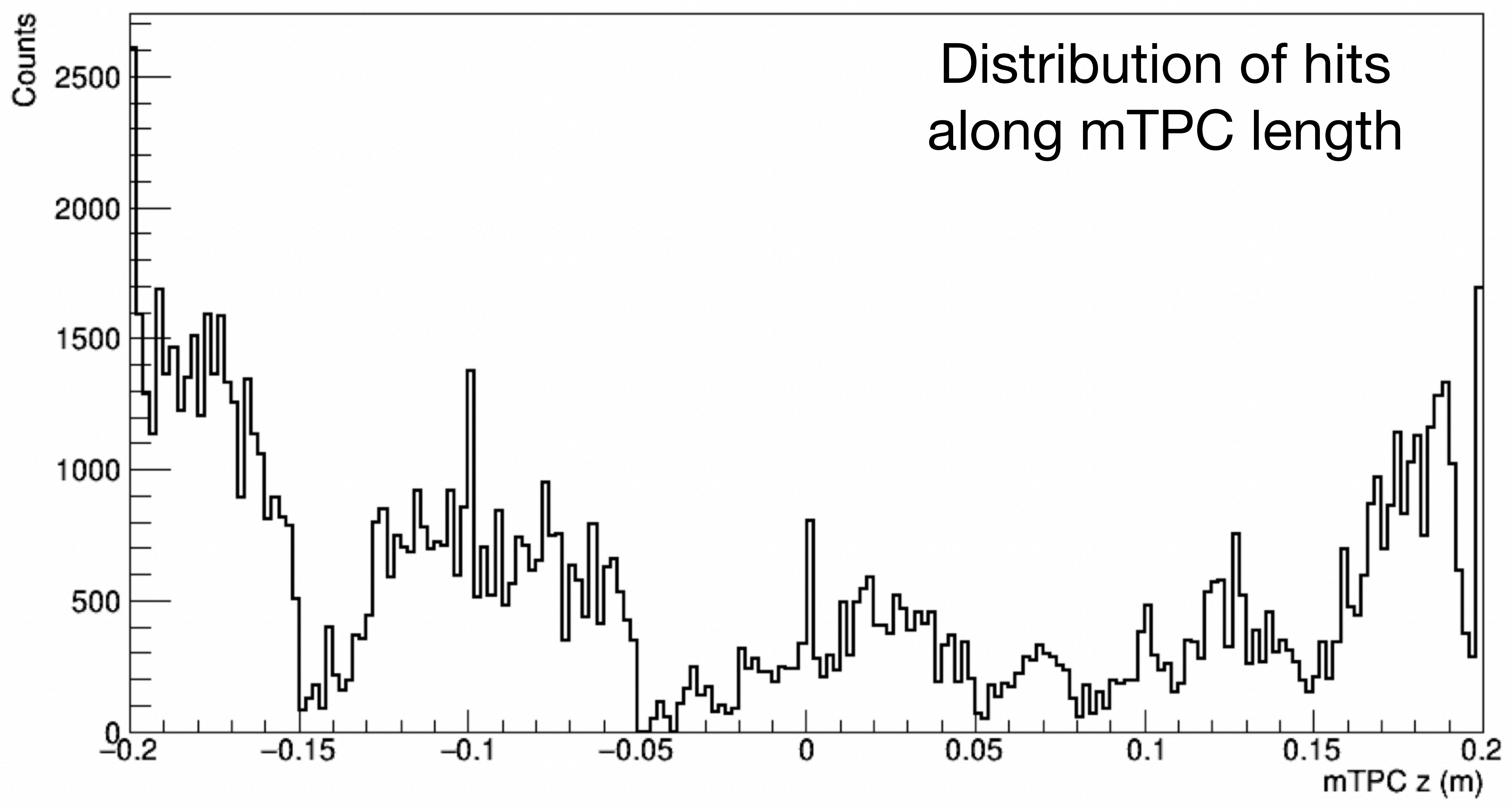




- mTPC/TDIS within SBS Geant4 framework g4sbs
- Can be used for initial studies
- Example next steps:
  - input TDIS/SIDIS events
  - evaluate backgrounds further (eg Pythia)

22GeV Simulation Status





- 22GeV beam on target and Geant4 physics
- Shown: background pions in mTPC

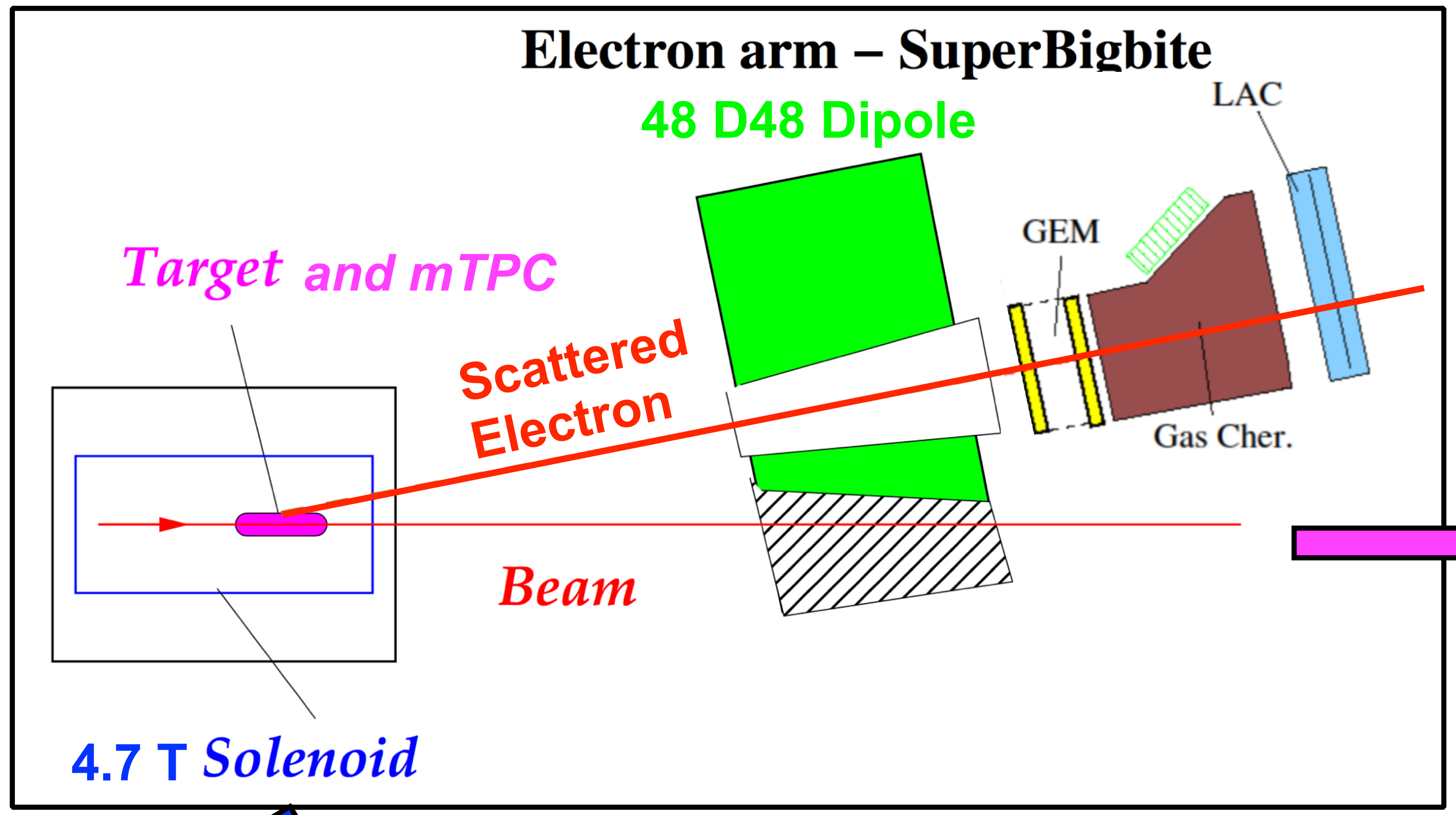
- n.b. SIDIS pions 1GeV < p_π < 2GeV

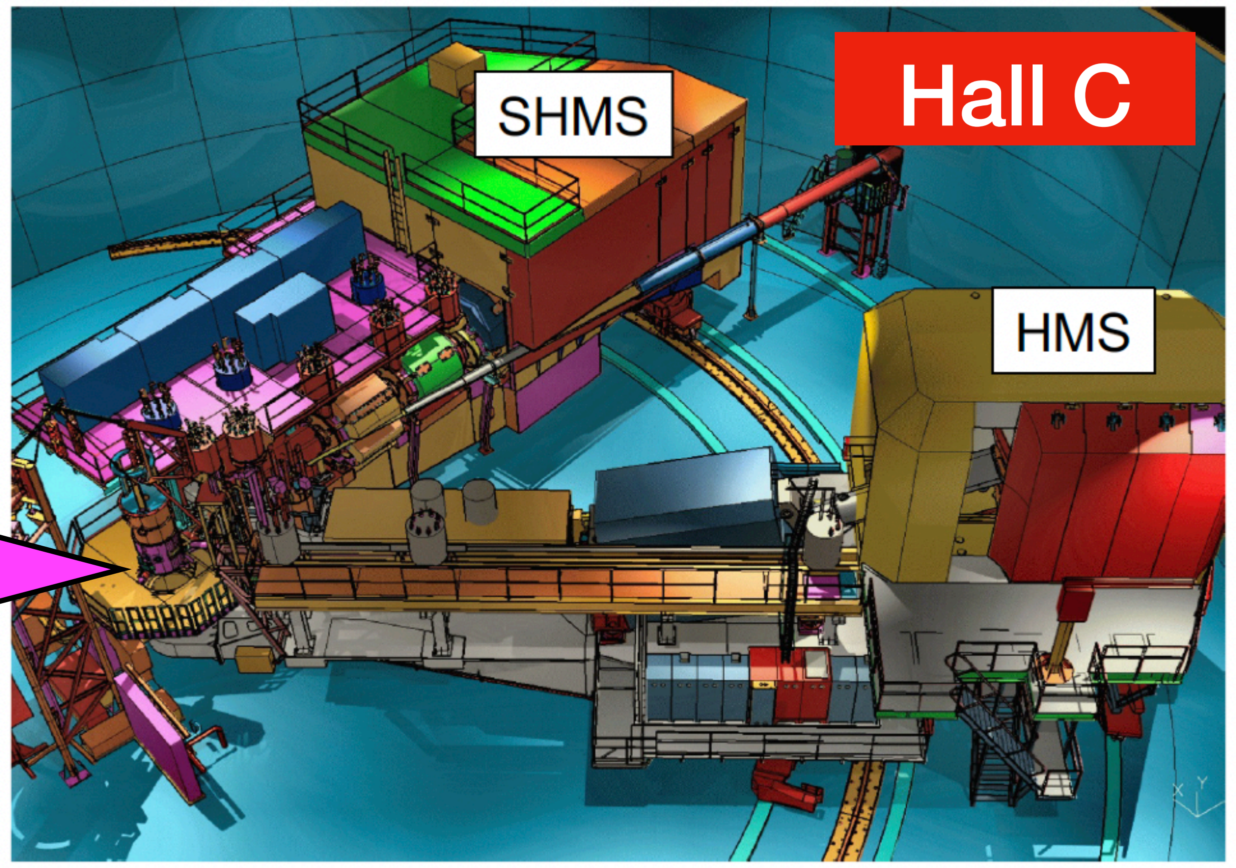
- Particularly interested in ~90° SIDIS pions for large p_T region

- For low p_T region have to rely on >120°

- Low angles <40° maybe more difficult

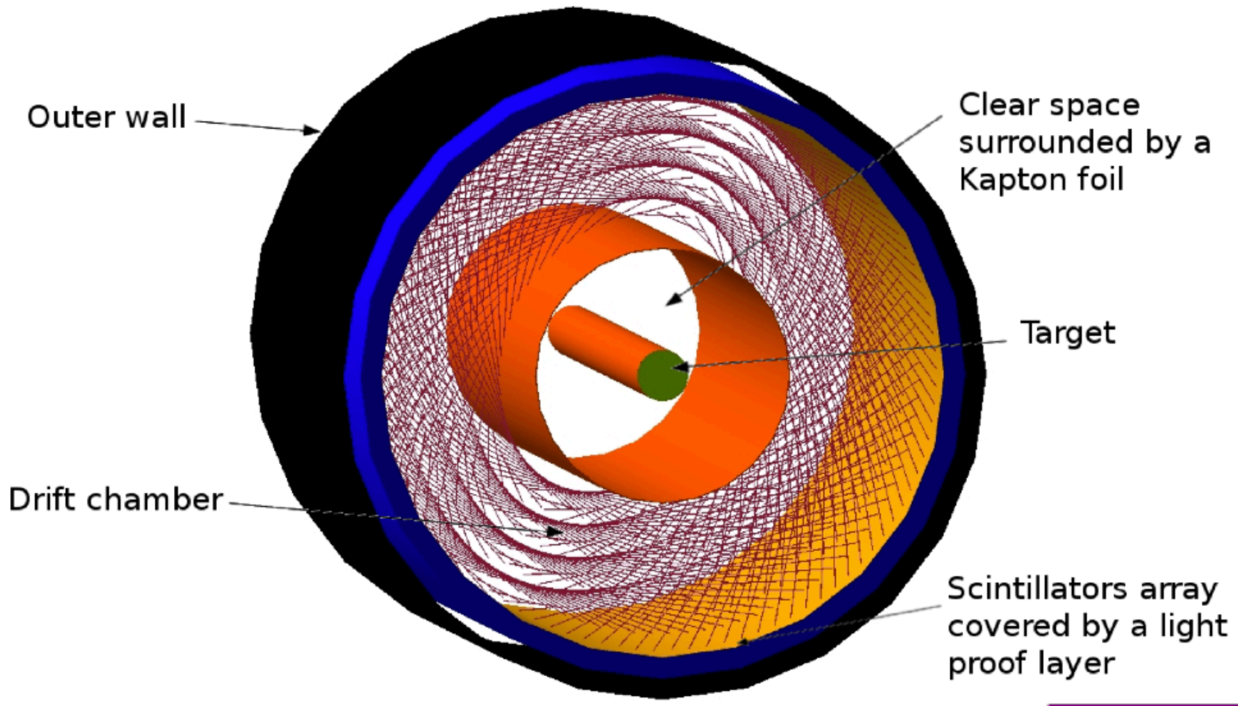
22GeV Experimental Considerations



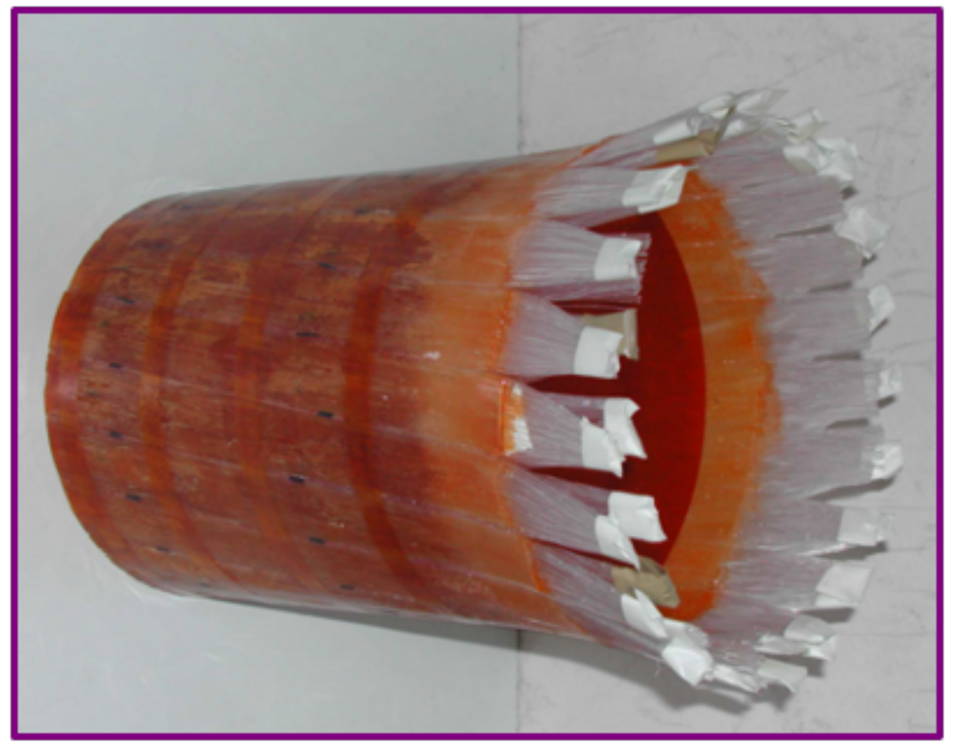


- **Considering practicalities**
- Have to tag extra SIDIS pion
- Highly segmented scintillating fibres surrounding mTPC
  - c.f. HERMES recoil/ALERT
- mTPC within solenoid
- mTPC outer radius needs reduced

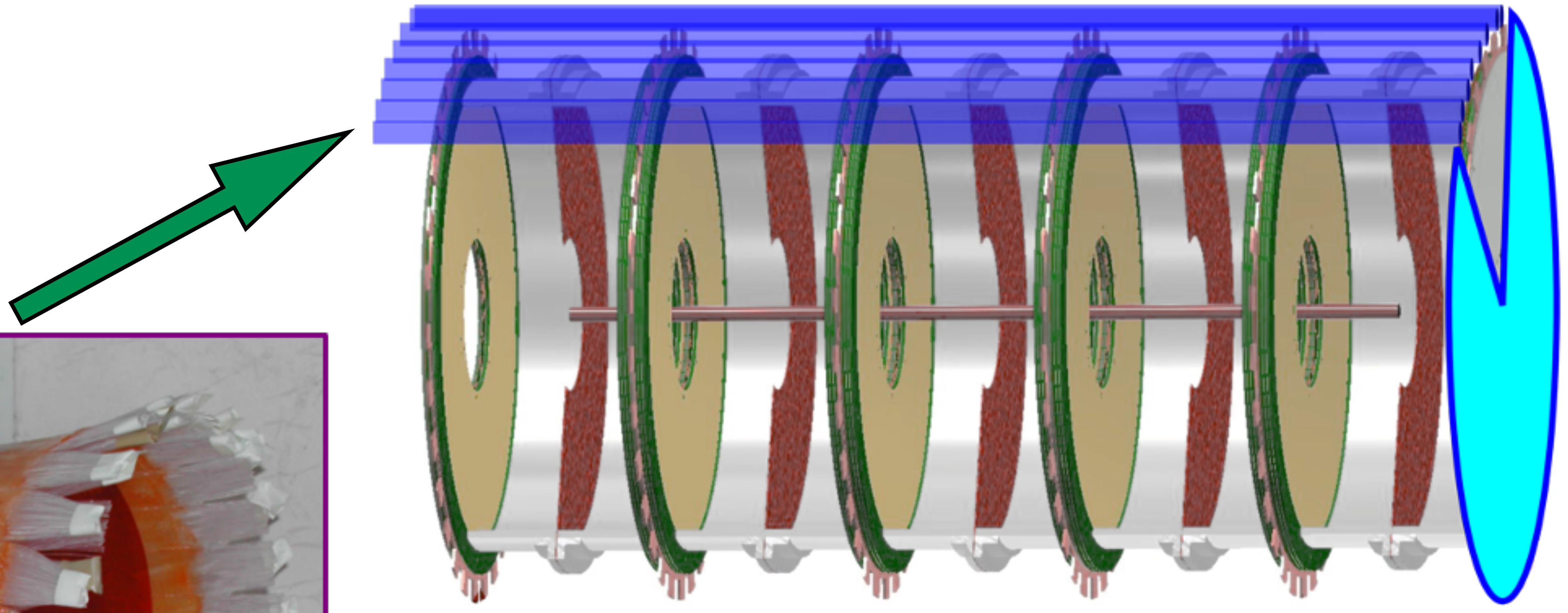
- UVa Solenoid
- 400mm warm bore
- Length 152.7cm



Detector from ALERT proposal, Hall B



HERMES Recoil Detector



mTPC plus scintillator

Speculative/In progress!

Summary…

- Pion, kaon, nucleon have very different, complicated, structures
- Meson structure → insights into EHM

- EIC → access gluons and sea quarks
  - Uncertainties increase for SF at EIC as $x \rightarrow 1$
  - see J. Phys. G: Nul. Part. Phys. 48 075106 2021
- High luminosity, fixed target JLab Halls ideal for meson structure (rare processes)
- TDIS 11GeV will impact sparse world data set in mid-high x_π range

- 22GeV
  - Expands significantly TDIS phase space for meson SF ($x_\pi \rightarrow 0.1$)
  - Offers possibility for SIDIS on virtual mesons and meson TMDs
    - Not available with 11GeV

- Expect differences in PDFs and TMDs of nucleon Vs light mesons
  - 22GeV would be gateway to this experimentally!

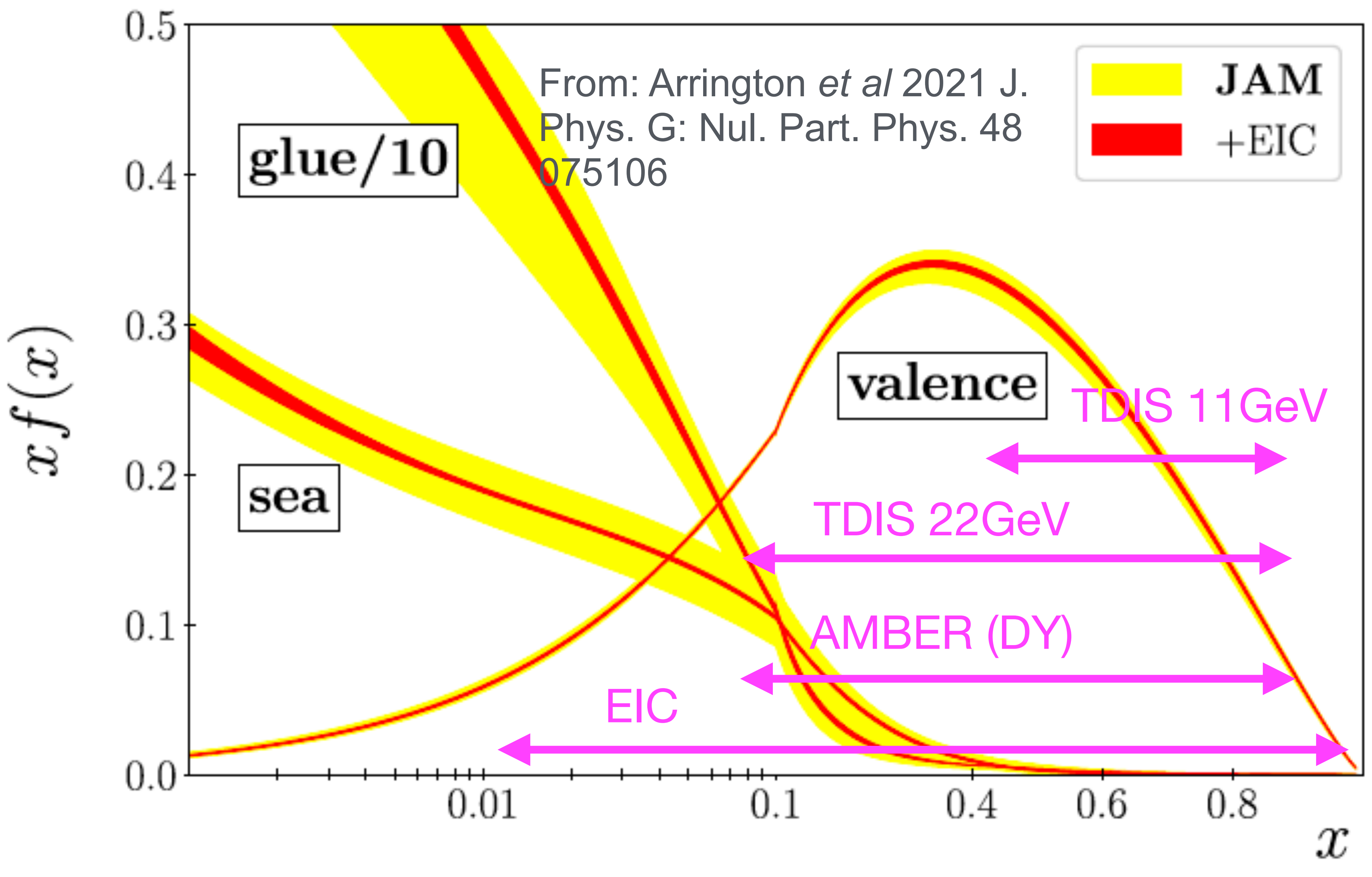
- Work in progress…
- Welcome any ideas for other processes on virtual meson?

…Thank you…

Back Up

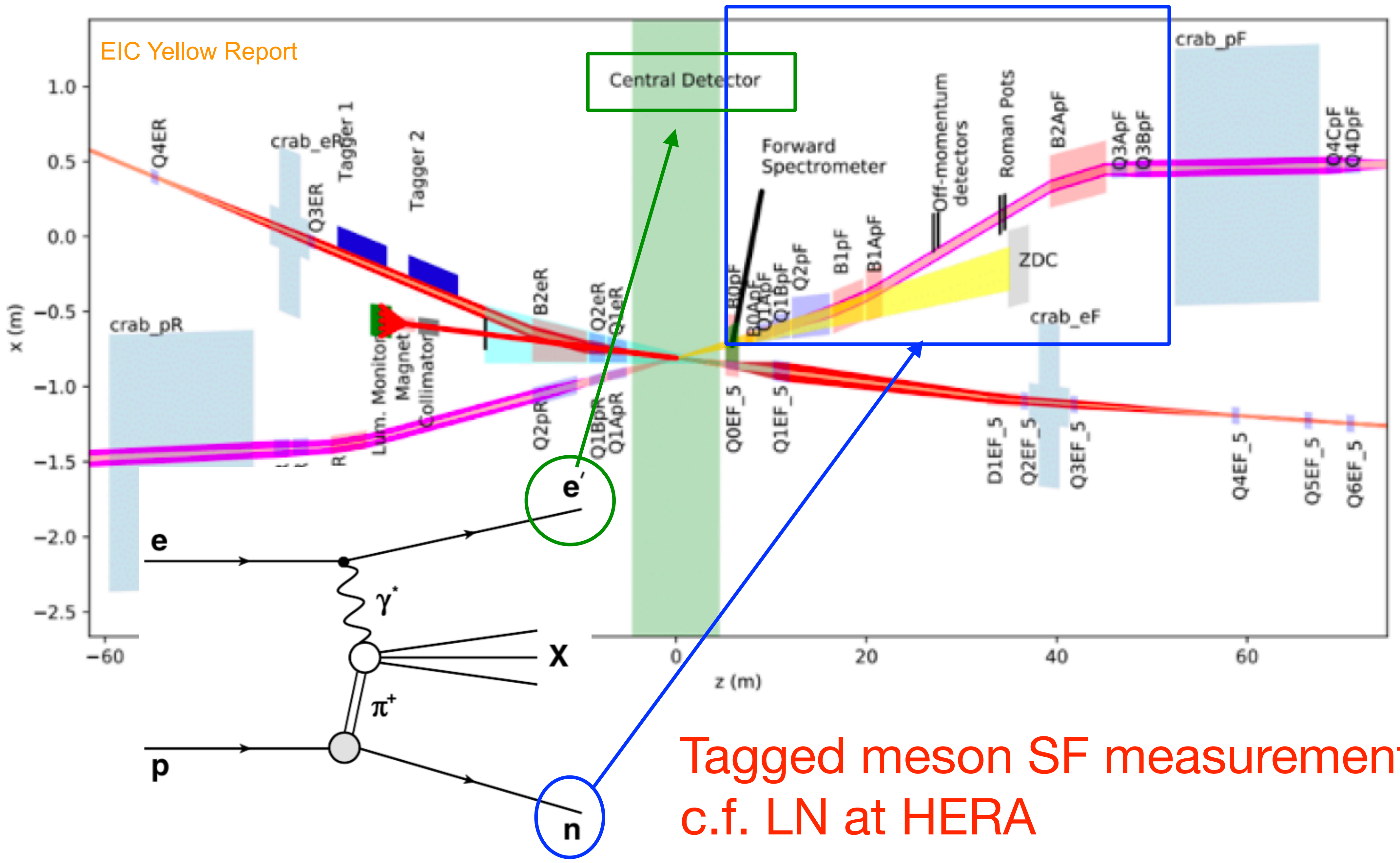
Meson Structure Functions at EIC

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 $\mathscr{L}$=10^{34}Hz/cm^2 = 1000 * $\mathscr{L}_{\mathrm{HERA}}$

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

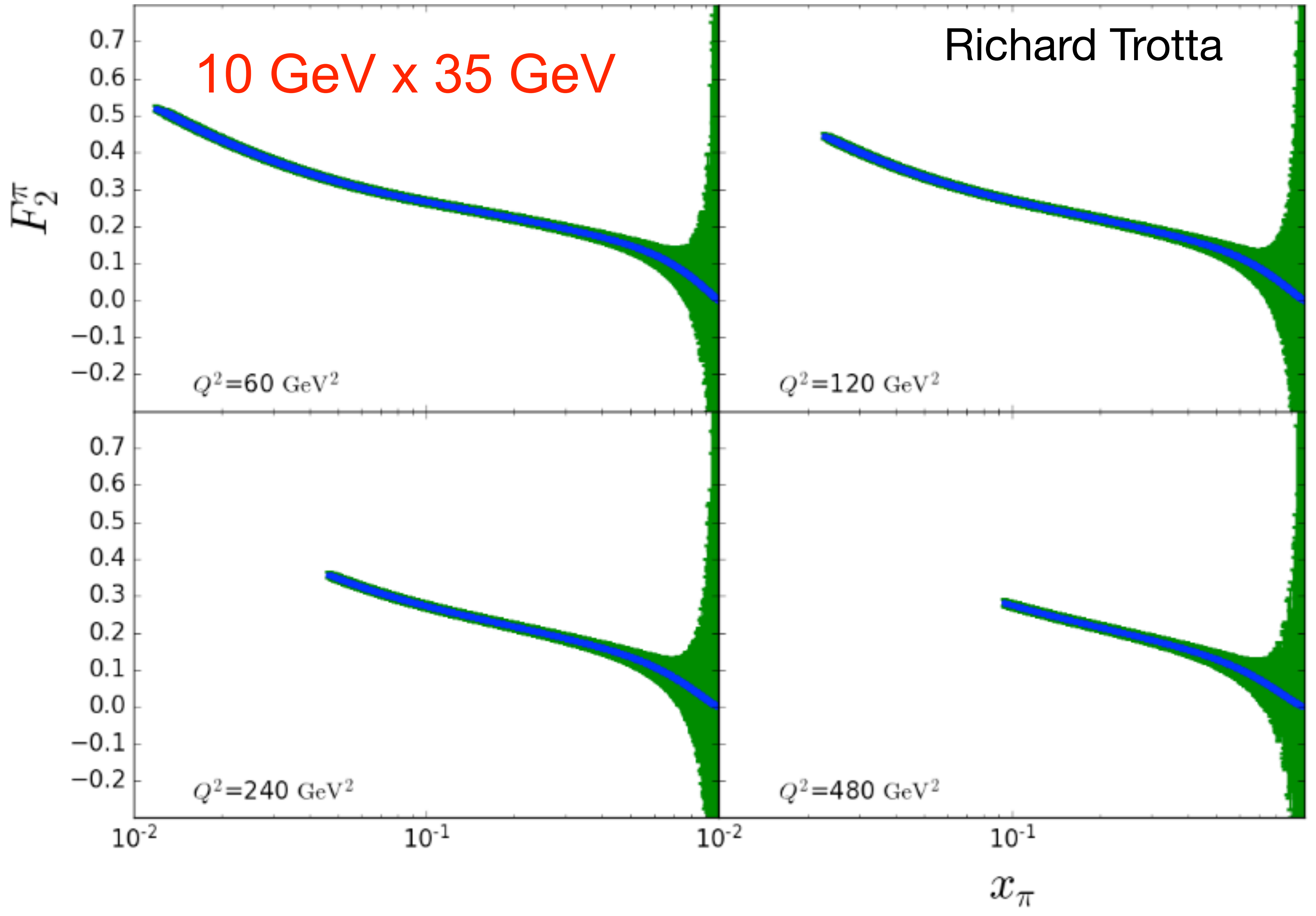


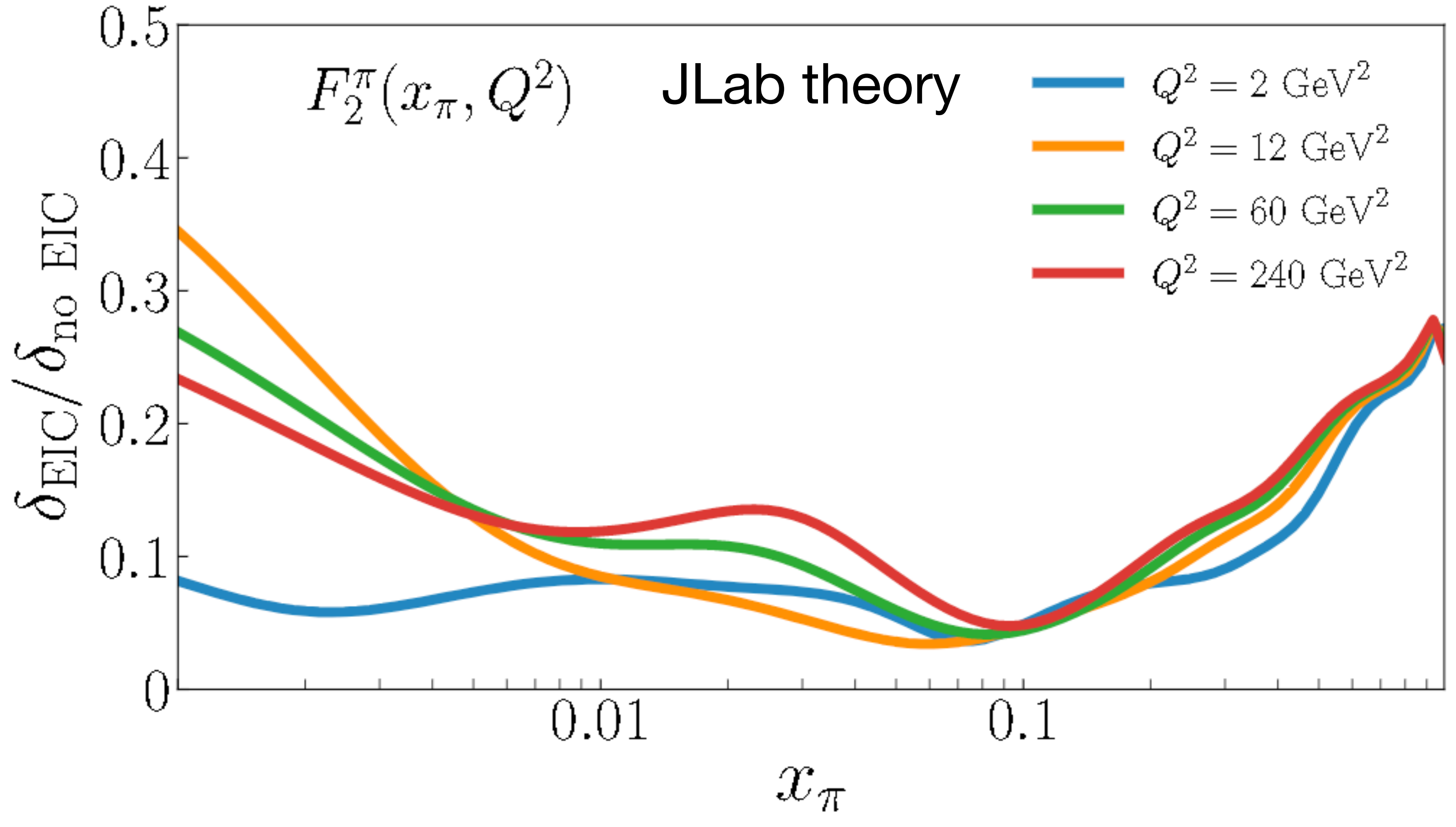
Tagged meson SF measurements planned
c.f. LN at HERA

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 $x_\pi \sim 3\times10^{-3} \rightarrow 0.4$)

- 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

Pion and Proton Unpolarized PDFs

Minkowski space Bethe-Salepeter equation

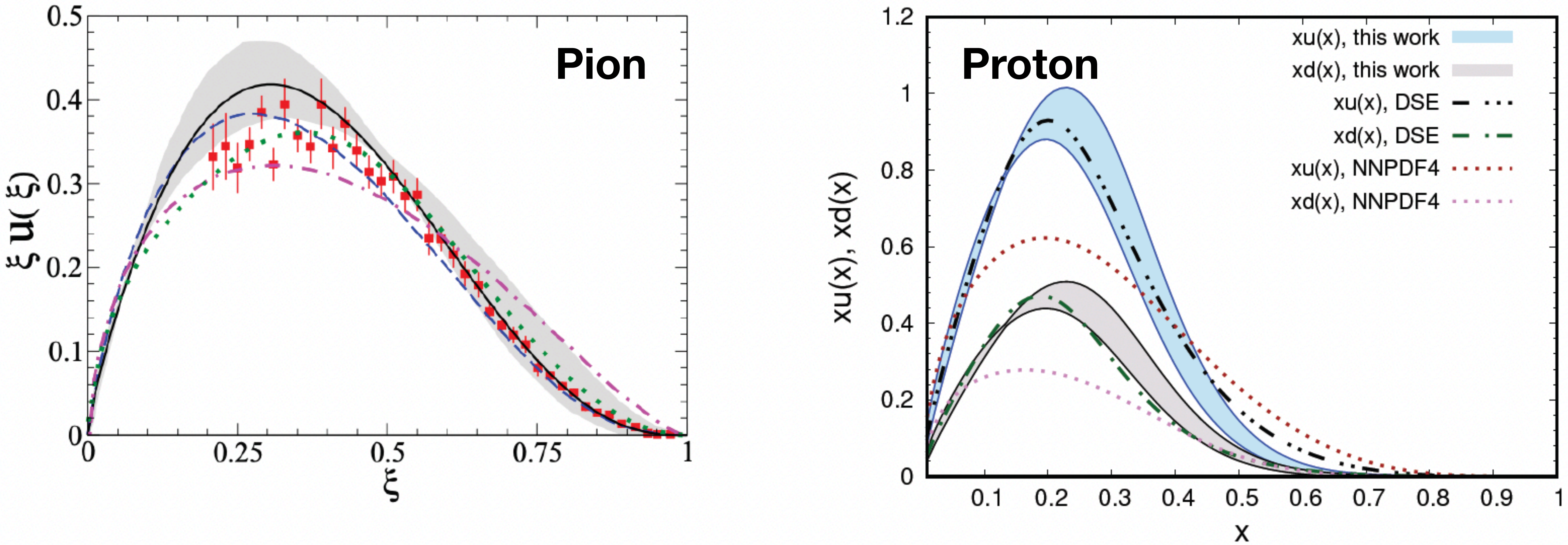


Figure: Unpolarized PDF. Left frame: Pion PDF at 5.2 GeV. Solid line: Minkowski space Bethe-Salpeter equation model with constituent quarks, massive one-gluon exchange and quark-gluon form factor from Ref. [1]; Dashed line: DSE calculation from Fig. 5 of Ref. [2]; Dash-dotted line: DSE calculation with dressed quark-photon vertex from Ref. [3]; Dotted line: BLFQ (Basis Light-Front Quantization) from Ref. [4]. Shaded area: Lattice QCD calculation extracted via Mellin moments from Ref. [5]. Red full circles: E615 Collaboration experimental data with soft-gluon resummation [6] evolved to 5.2 GeV. Right frame: Proton PDF at 3.097 GeV obtained with a Light-front model with constituent quarks and a scalar diquark from Ref. [7] blue and gray bans; Dashed-dot-dot from DSE [8]; Dotted lines NNPDF4.

[1] W. de Paula, E. Ydrefors, J.H. Nogueira Alvarenga, T. Frederico, G. Salmè, PRD 105 (2022) L071505, and in preparation.
[2] Z. F. Cui, M. Ding, J. M. Morgado, K. Raya, D. Binosi, L.Chang, J. Papavassiliou, C.D. Roberts, J. Rodríguez-Quintero, and S.M. Schmidt, EPJA 58 (2022) 10.
[3] K. D. Bednar, I. C. Cloët, and P. C. Tandy, PRL 124 (2020) 042002.
[4] J. Lan, K. Fu, C. Mondal, X. Zhao, and j. P. Vary (BLFQ), PLB 825 (2022) 136890.
[5] C. Alexandrou, S. Bacchio, I. Cloët, M. Constantinou, K. Hadjiyiannakou, G. Koutsou, and C. Lauer (ETM), PRD104 (2021) 054504.
[6] M. Aicher, A. Schäfer, and W. Vogelsang, PRL 105 (2010) 252003.
[7] E. Ydrefors, T. Frederico PRD 104 (2021) 114012; and arXiv: 2211.10959 [hep-ph].
[8] Y. Lu, L. Chang, K. Raya, C. D. Roberts, J. Rodríguez-Quintero, PLB 830 (2022) 137130.

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- Emanuel Ydrefors (Chinese Academy of Sciences)

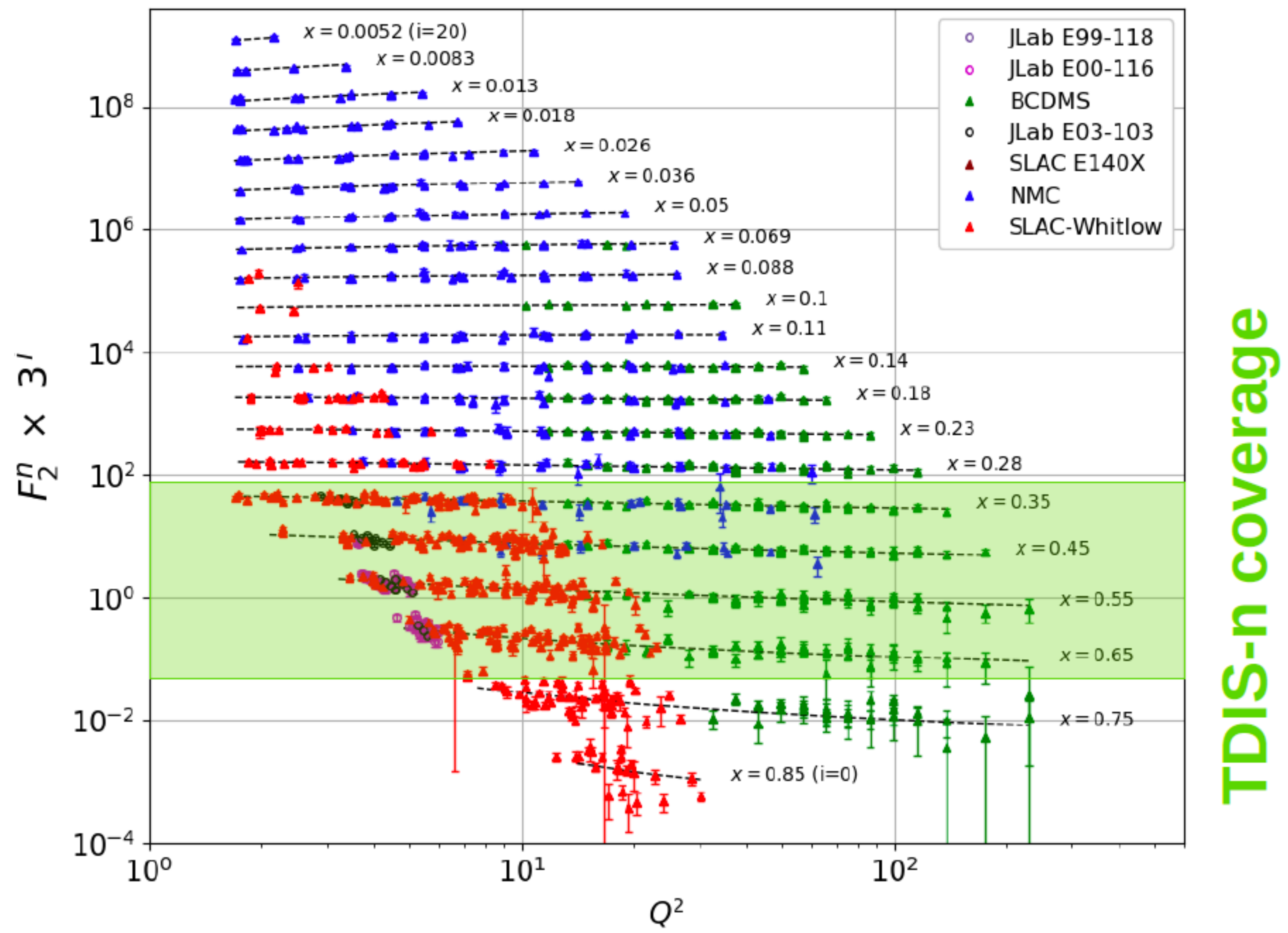
- Broader pion PDF compared to proton

- Pion:
  - Comparison between different theory practically within lattice QCD band
  - x→1 more sensitive to different continuum approaches
- Proton:
  - Striking that NNPDF4 more wider than for π

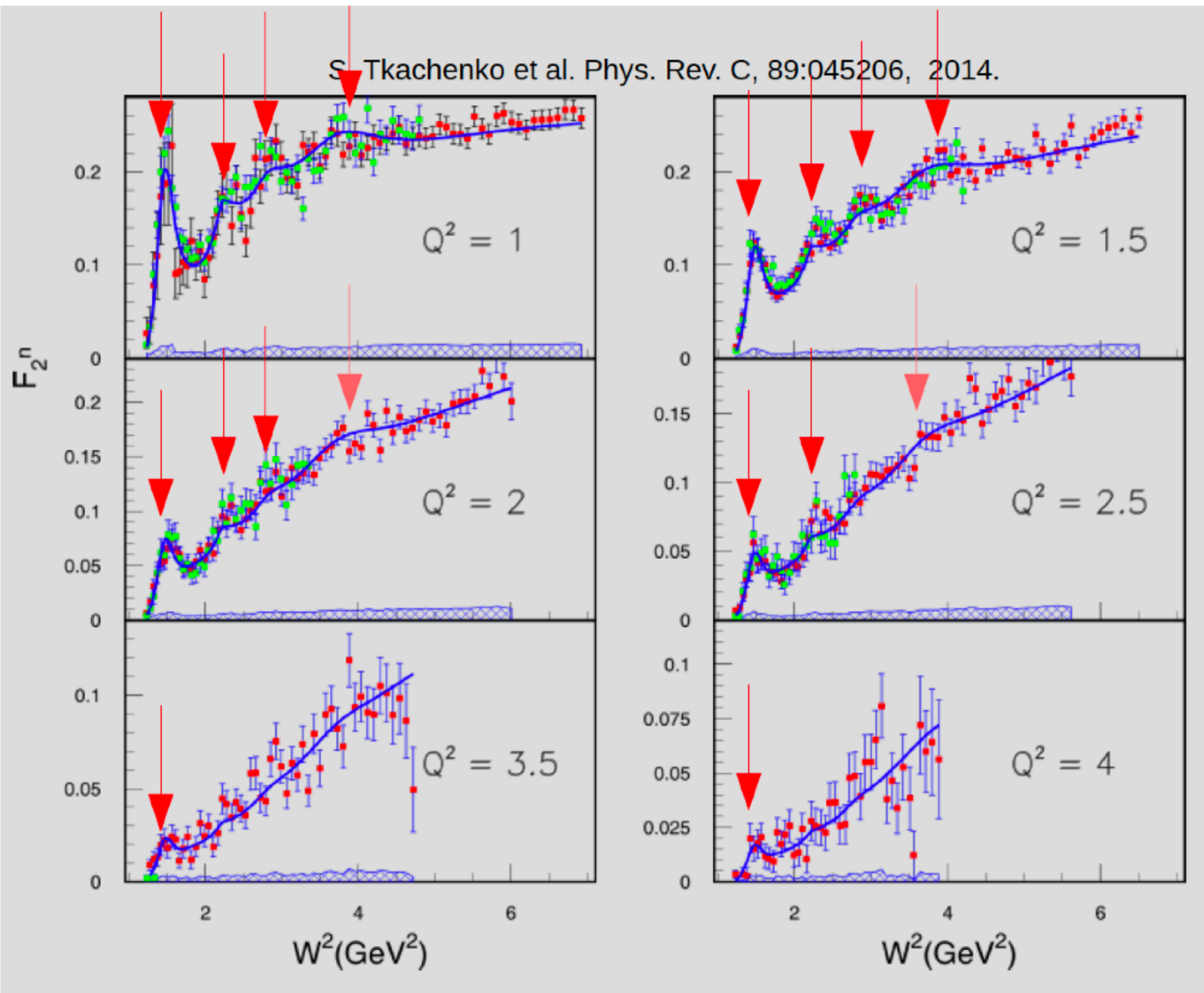
- Expect differences between meson and nucleon PDFs

11GeV TDISn at JLab

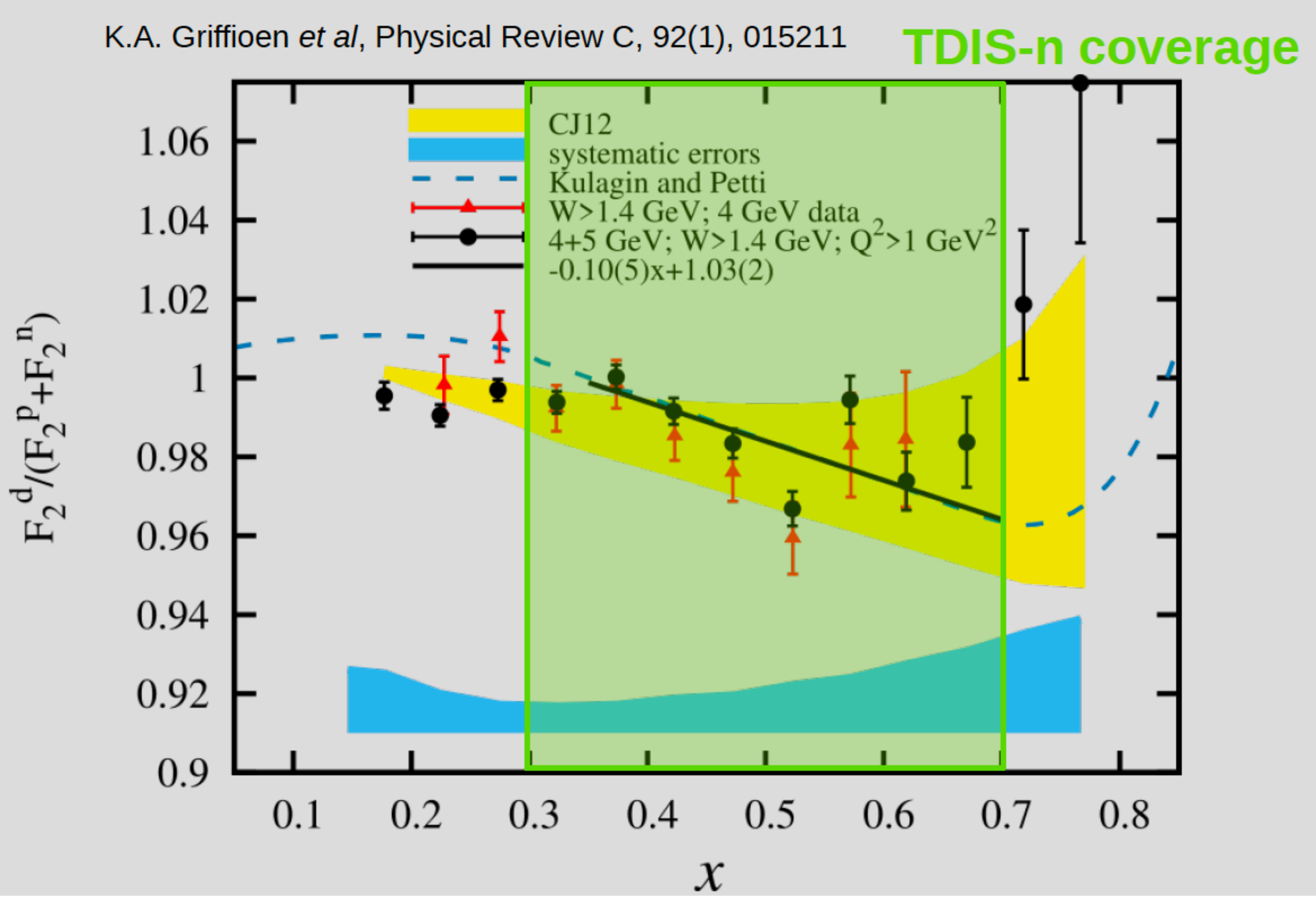
Neutron F_2 SF



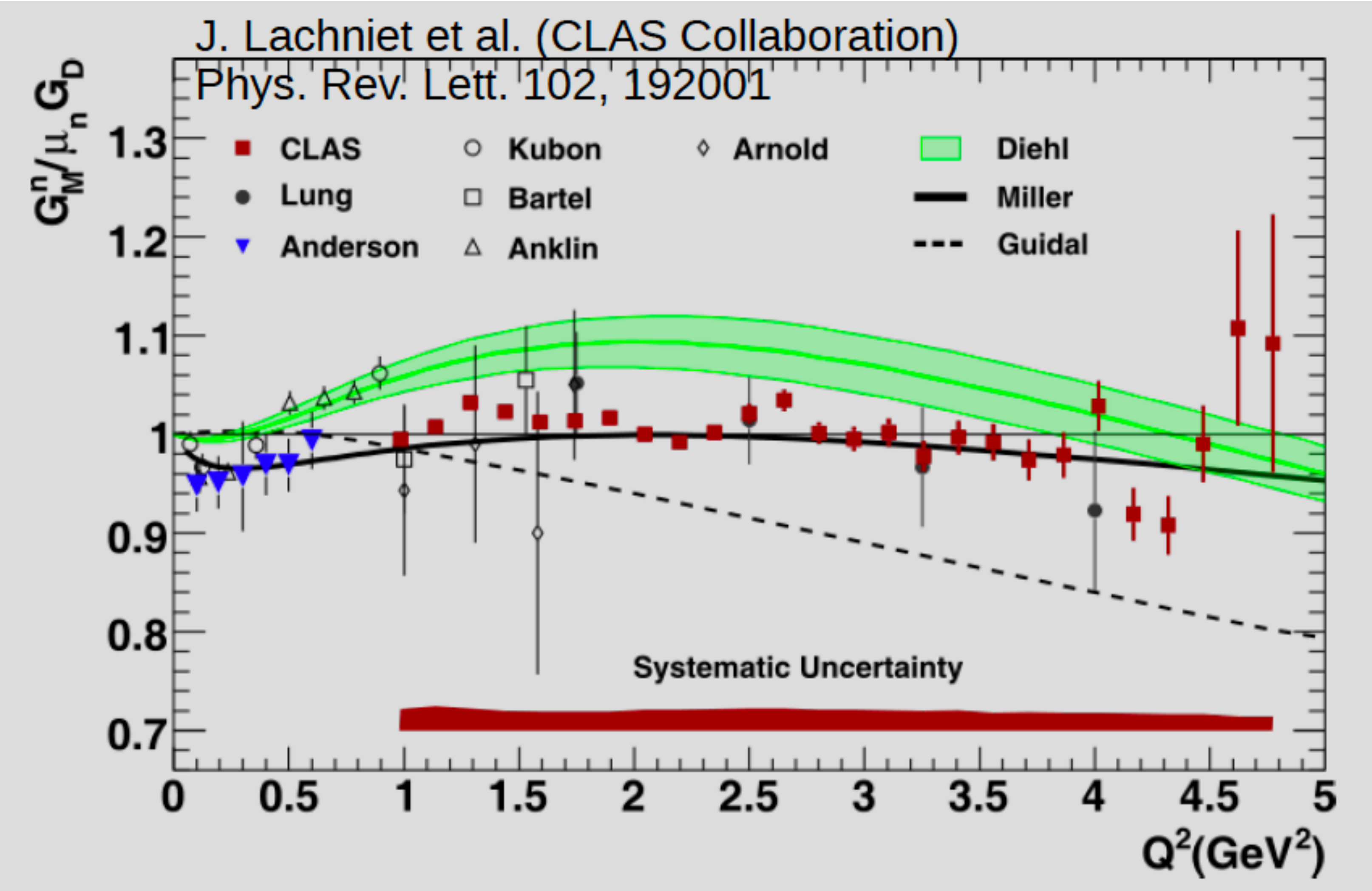
Resonance Region SF



EMC effect in deuteron



Elastic e-n scattering and EM form factor G_M^n

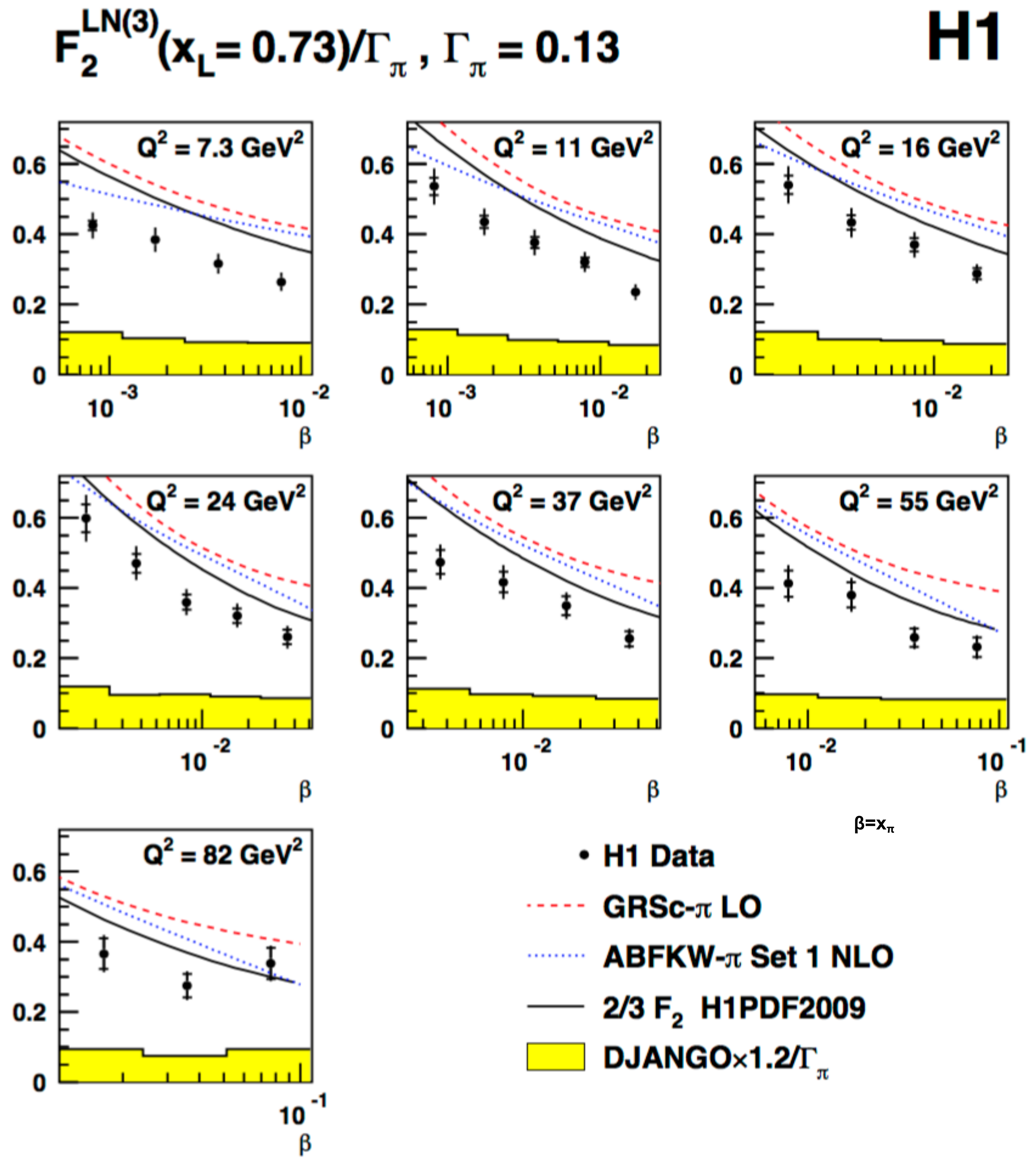


- TDIS-n: Tagged DIS measurement of the neutron SF
- TDIS Run Group Proposal PAC49 (2021)

- Measurements à la BONUS12 (e.g.) to provide independent cross-checks on neutron structure, more statistics, test of systematics, independent normalisation checks of tagging method

Previous Meson Structure Data

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

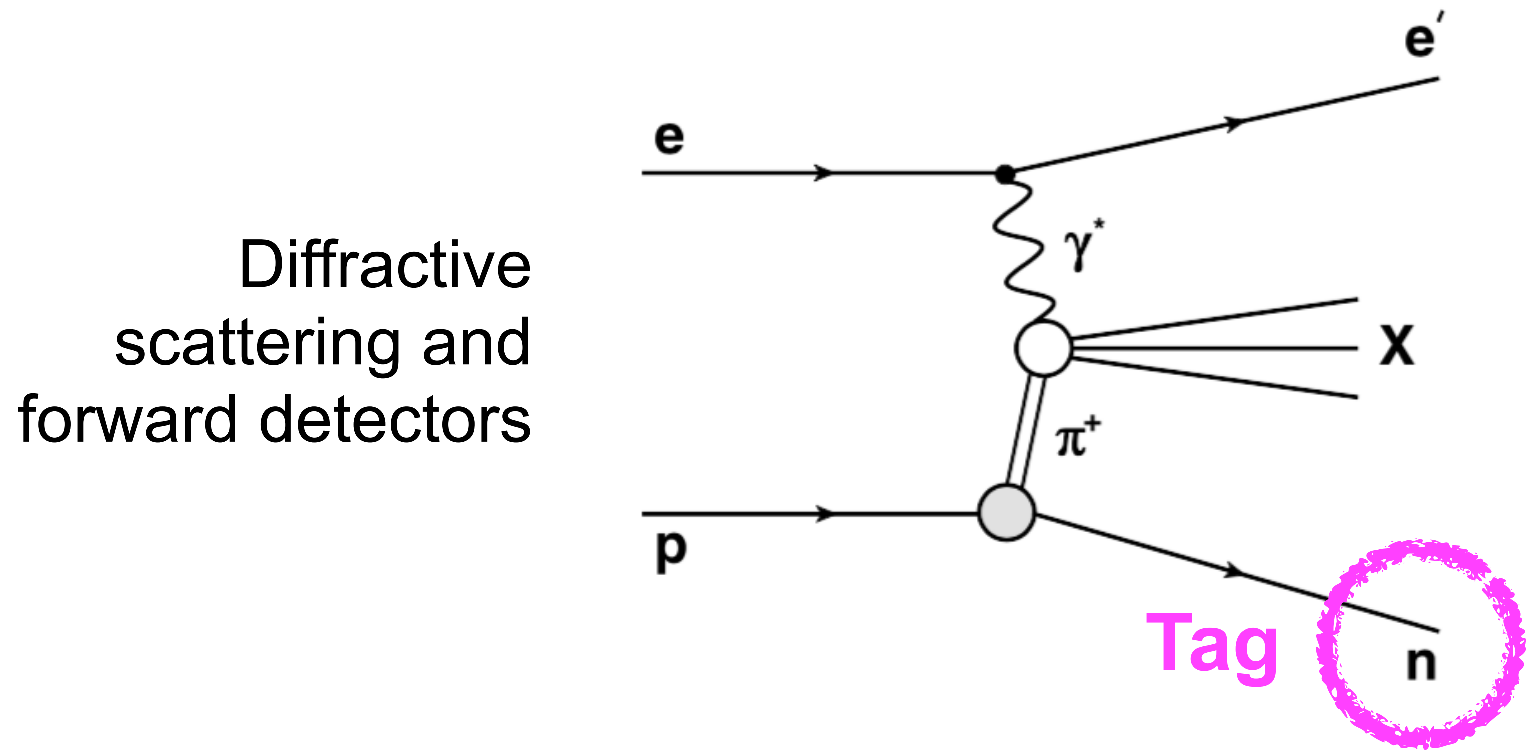


<u>HERA Tagged DIS</u>

- 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 → e'Xn
- Charged pion SF extracted

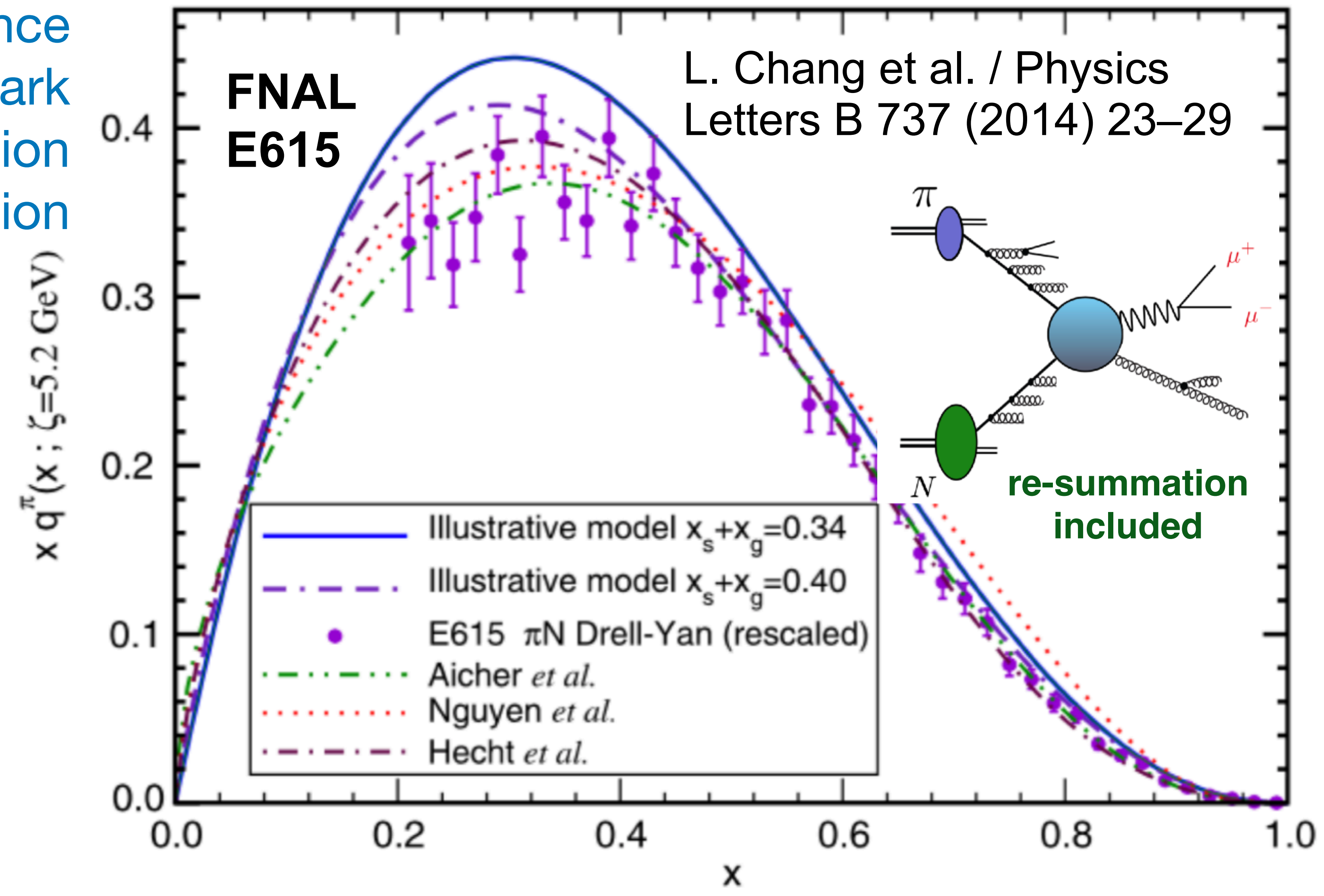


<u>TDIS:</u>

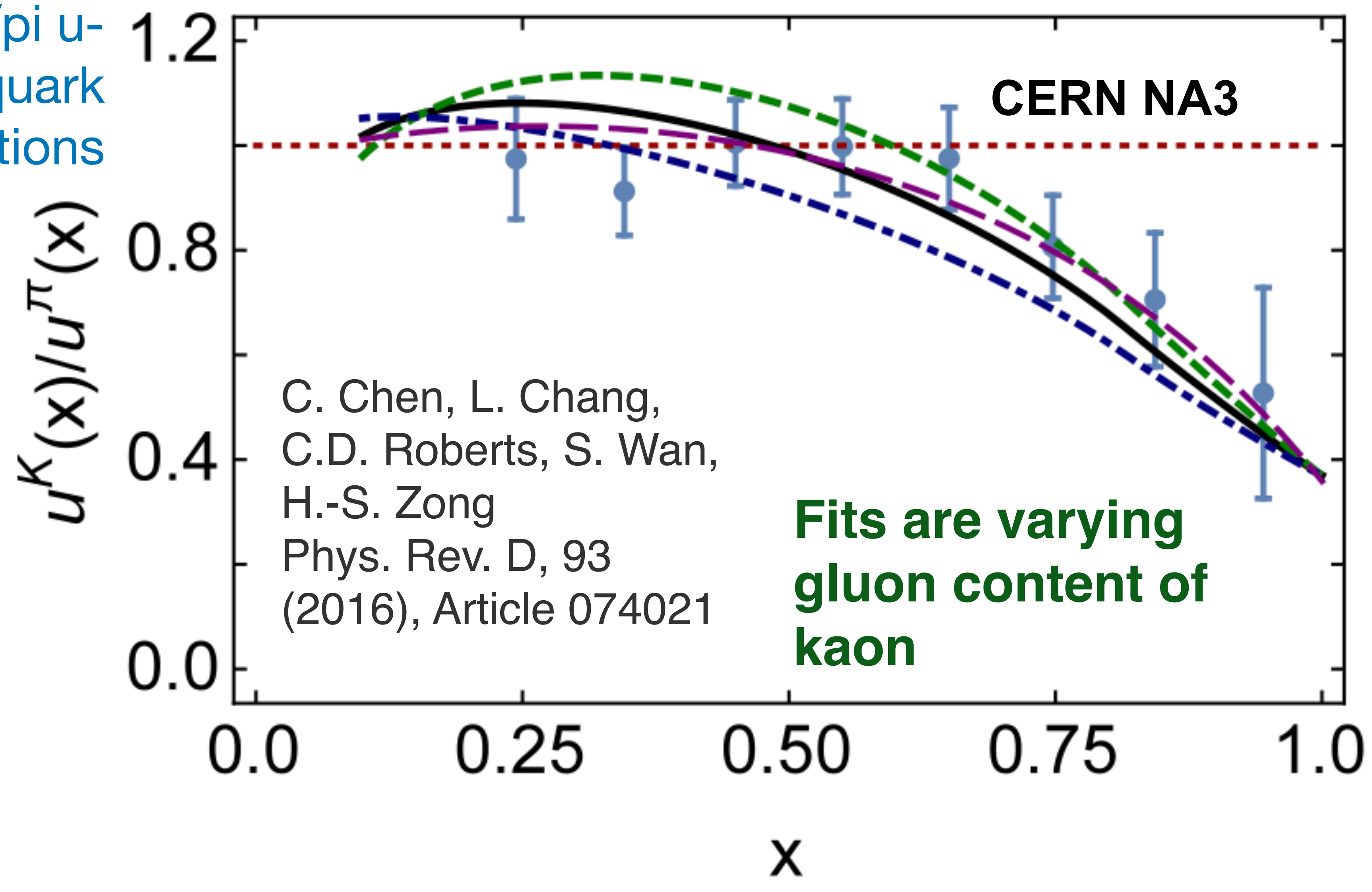
- Valence regime
- Higher x, lower Q^2
- Evolution between kinematics

Previous Meson Structure Data

Pion valence quark distribution function

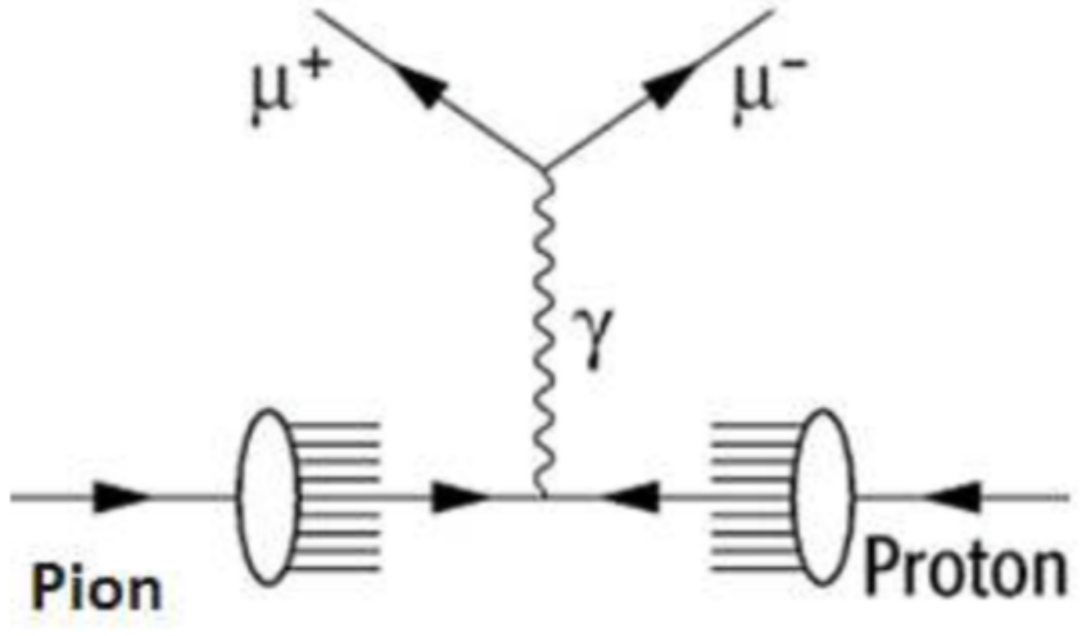


Ratio K/pi u-quark distributions



Valence region - Drell Yan

- CERN/Fermilab data



- 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

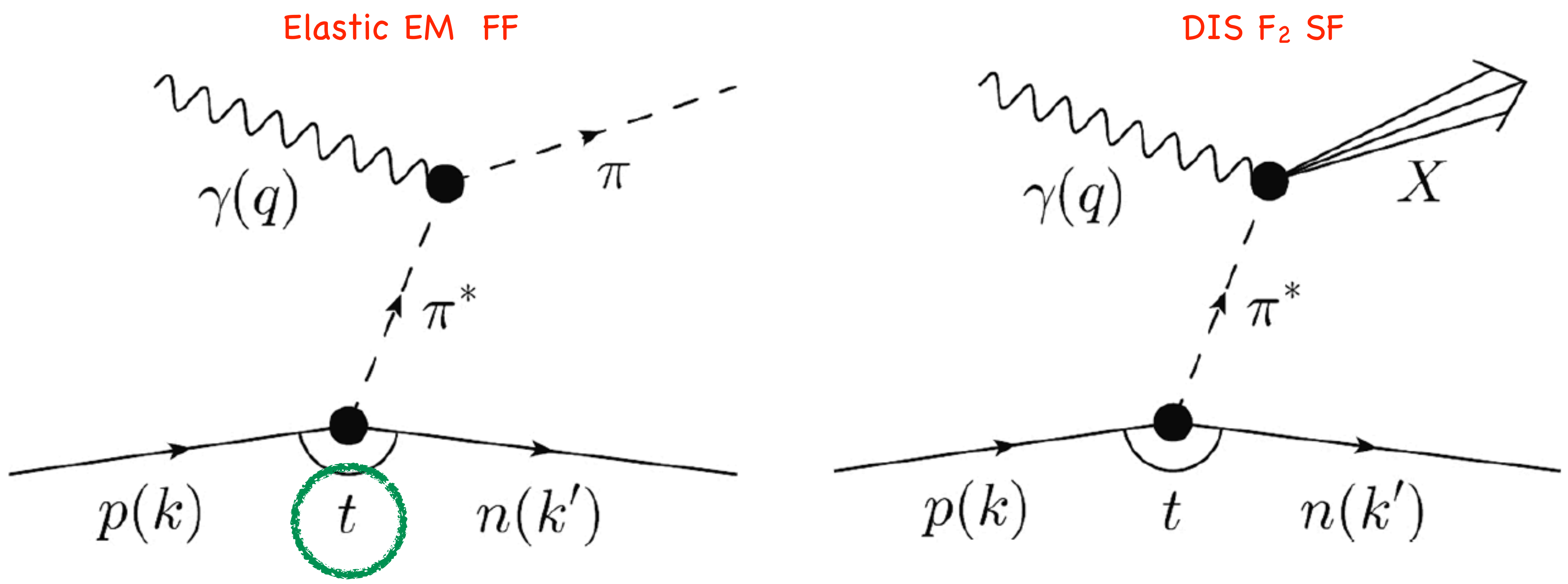
TDIS

- Independent cross-check
- Extend to neutral pions
- More data 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

Sullivan Process

Sullivan Process

Use the nucleon as a virtual laboratory!



<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