Meson Structure (SI)DIS

IR2@EIC

March 18th, 2020

Richard Trotta and the meson structure working group

Jefferson Lab

THE CATHOLIC UNIVERSITY OF AMERICA

Pion and Kaon Structure

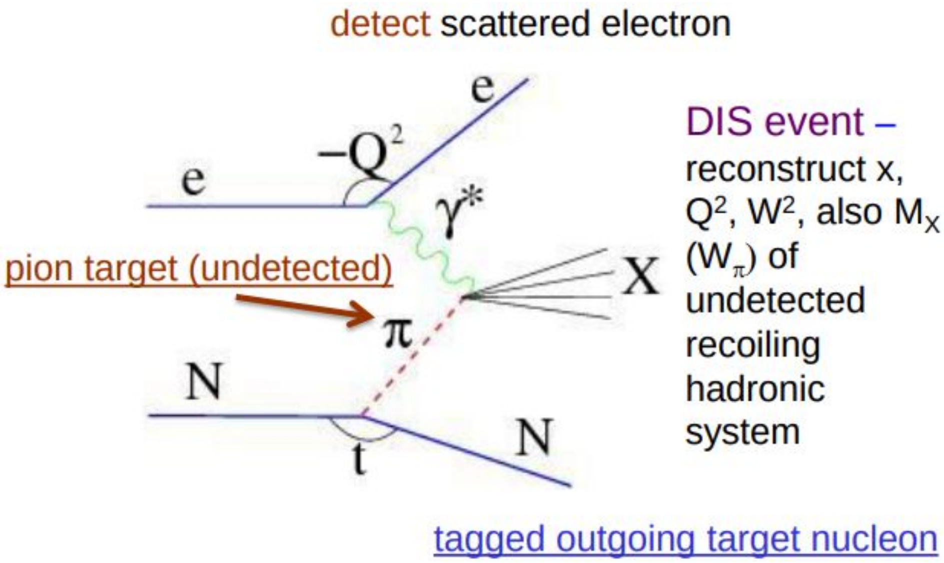
- The pion is both the lightest bound quark system with a valence $\bar{q}q$ structure and a Nambu-Goldstone boson

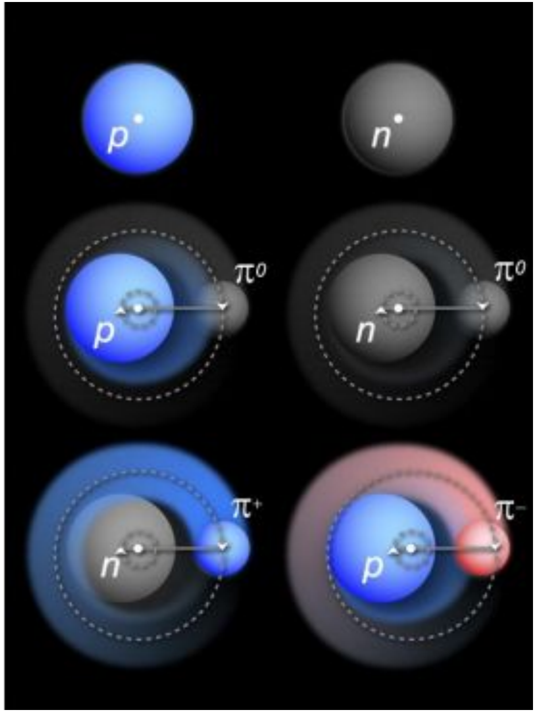
- There are exact statements from QCD in terms of current quark masses due to PCAC
  [Phys. Rep. 87 (1982) 77; Phys. Rev. C 56 (1997) 3369; Phys. Lett. B420 (1998) 267]
  - From this, it follows the mass of bound states increase as $\sqrt{m}$ with the mass of the constituents
  - In contrast (e.g. the CQM), bound state mass rises linearly with constituent mass - in the nucleon $m_Q \sim ⅓\, m_N \sim 310$ MeV, in the pion $m_Q \sim ½\, m_\pi \sim 70$ MeV, in the kaon (with one s quark) $m_Q \sim 200$ MeV (This is not real)
  - In both DSE and lQCD, the mass function of quarks is the same, regardless of what hadron the quarks reside in (This is real). It is the DCSB that makes the pion and kaon masses light.

- Pseudoscalar masses are generated dynamically

Deep Inelastic Scattering (DIS)

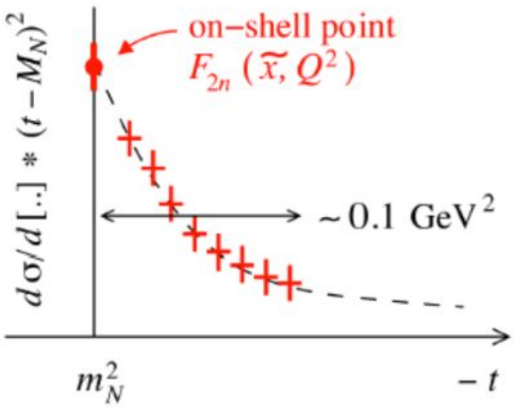
- Using the Sullivan process – scattering from nucleon-meson fluctuations





Off-Shell Considerations

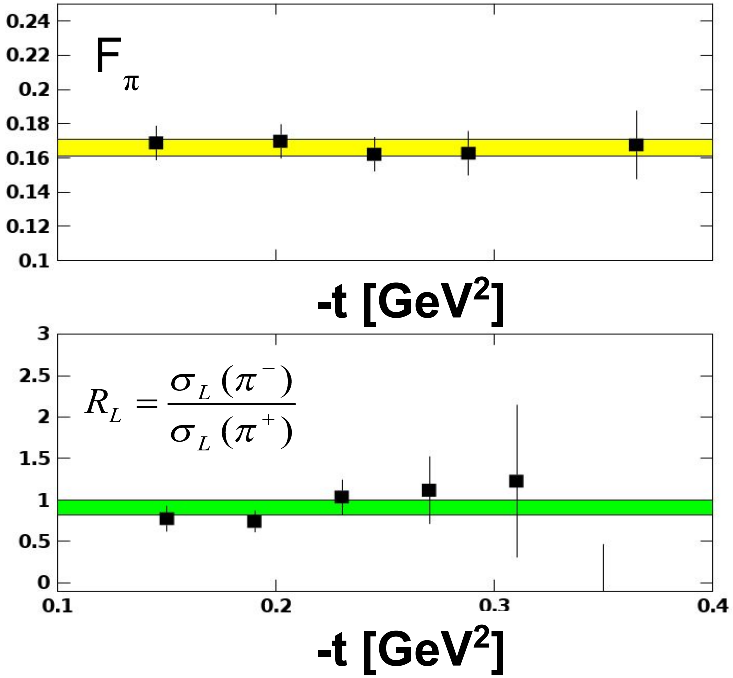
- The Sullivan process can provide reliable access to a meson target as t becomes space-like
- If the pole associated with the ground-state meson remains the dominant feature of the process
  - the structure of the related correlation evolves slowly and smoothly with virtuality
- Recent theoretical calculations found that changes in pion structure are modest so that a well-constrained experimental analysis should be reliable
  - For the pion when -t ≤ 0.6 GeV^2
  - For the kaon when -t ≤ 0.9 GeV^2



S-X Qin, C. Chen, C. Mezrag, C.D. Roberts, Phys. Rev. C 97 (2018) 015203

Experimental Validation

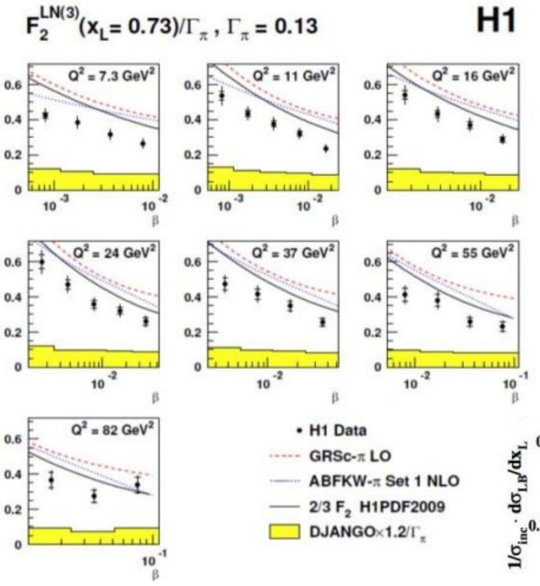
- To check these conditions are satisfied empirically...
  - data is taken covering a range in t
  - comparing this data with phenomenological and theoretical expectations
    - F_π values do not depend on -t to give confidence in applicability of model to the kinematic regime of the data
  - Verify that the pion pole diagram is the dominant contribution in the reaction mechanism
    - R_L (= $\sigma_L(\pi^-)/\sigma_L(\pi^+)$) approaches the pion charge ratio, consistent with pion pole dominance



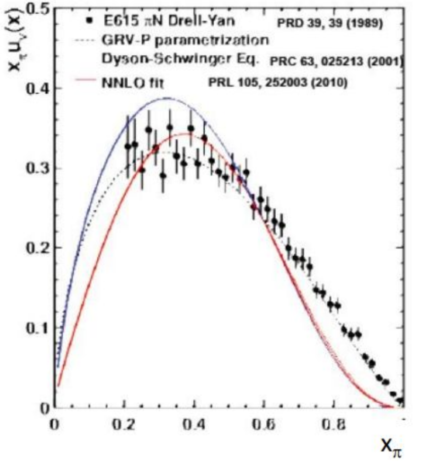
T. Horn, C.D. Roberts, J. Phys. G43 (2016) no.7, 073001
G. Huber et al, PRL112 (2014)182501
R. J. Perry et al., arXiV:1811.09356 (2019)

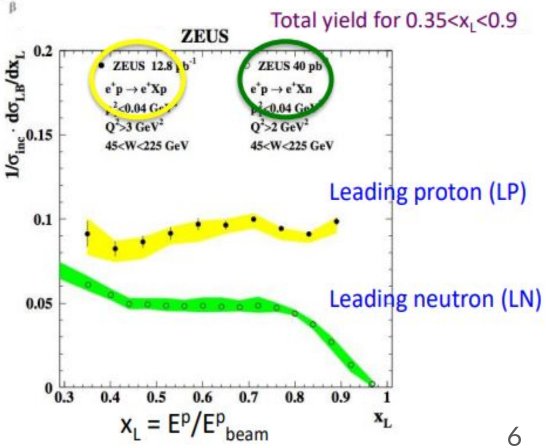
Pion Structure Function Measurements

- Knowledge of the pion structure function is very limited...
  - HERA TDIS data - at low x through Sullivan process (left)
  - Pionic Drell-Yan from nucleons in nuclei - at large x (right)
- One pion exchange is the dominant mechanism
  - Can extract pion structure function
  - In practice use in-depth model and kinematic studies to include rescattering, absorption...



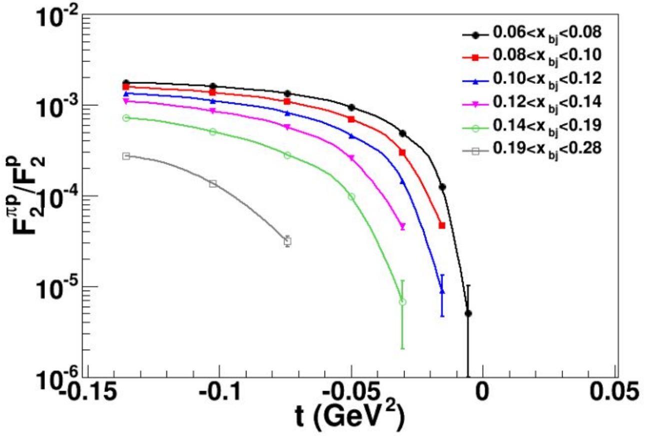
DESY 08-176 JHEP06 (2009) 74





EIC Capabilities

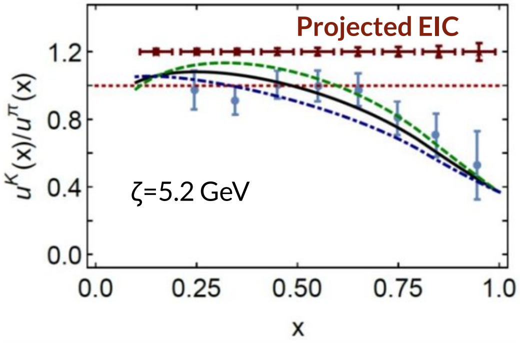
- $L_{EIC} = 10^{34}$ e-nucleons/cm²/s = 1000 x L_{HERA}
- Fraction of proton wave function related to pion Sullivan process is roughly 10^{-3} for a small −t bin (0.02)
  - pion data at EIC should be comparable or better than the proton data at HERA, or the 3D nucleon structure data at COMPASS
- By mapping pion (kaon) structure for −t < 0.6 (0.9) GeV², we gain at least a decade as compared to HERA/COMPASS
- Consistency checks with complementary COMPASS++/AMBER Drell-Yan data can show process-independence of pion structure information

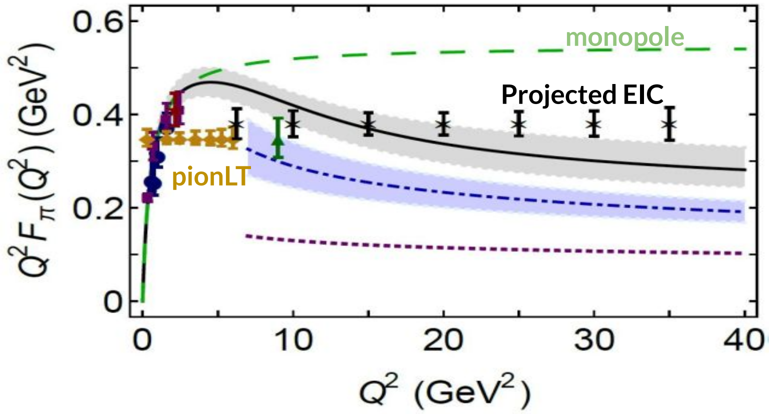


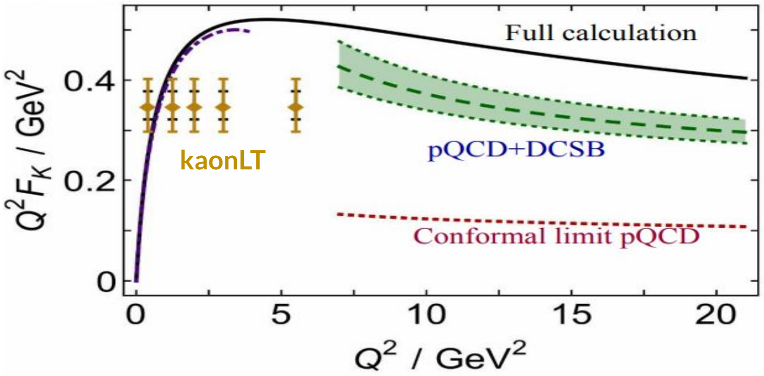
Jefferson Lab TDIS Collaboration, JLab Experiment C12-15-005 Proposal

2019 EPJA Pion and Kaon Structure Projections

- The EPJA paper projects a wide range of structure function data
- Projected Q^2 pion FF data up to 35 GeV^2
- Ratio of valence quark data projected at 1.2

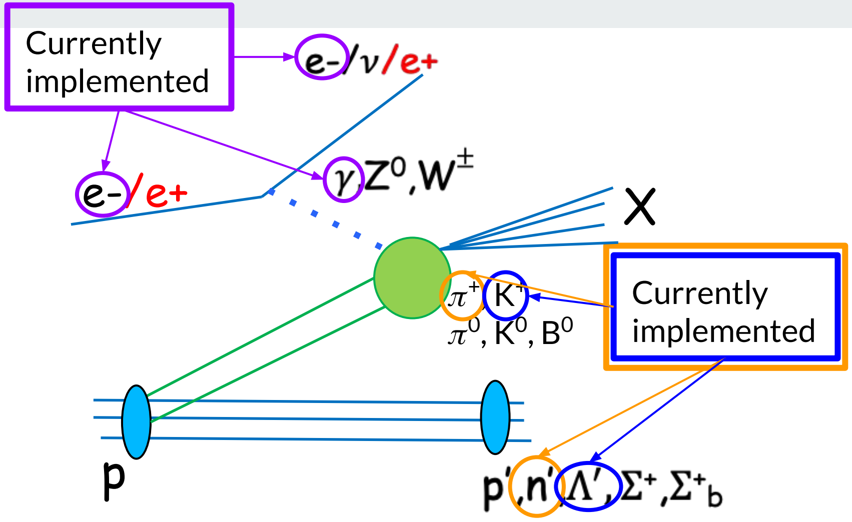






Arlene C. Aguilar, et al., Eur. Phy. J. A (2019) DOI:10.1140/epja/i2019-12885-0

Structure Functions



- For projections use a Fast Monte Carlo that includes the Sullivan process
  - PDFs, form factor, fragmentation function projections

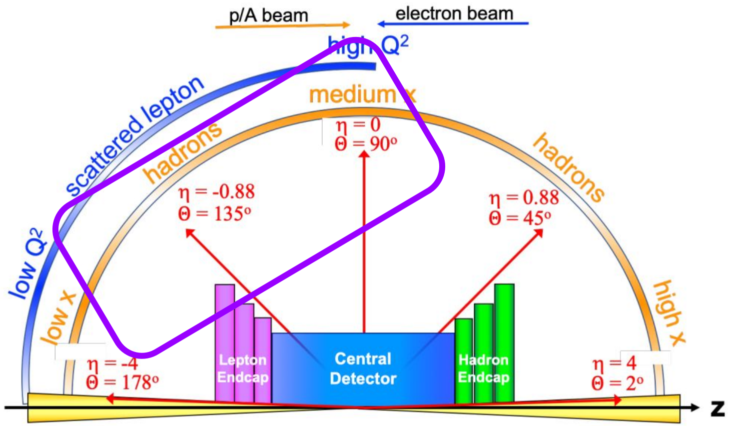
- Progress with generator development since 2019 EPJA article:
  - now can make pion structure function (pion SF) projections
  - paper currently under review in JPhysG (arXiv:2102.11788)

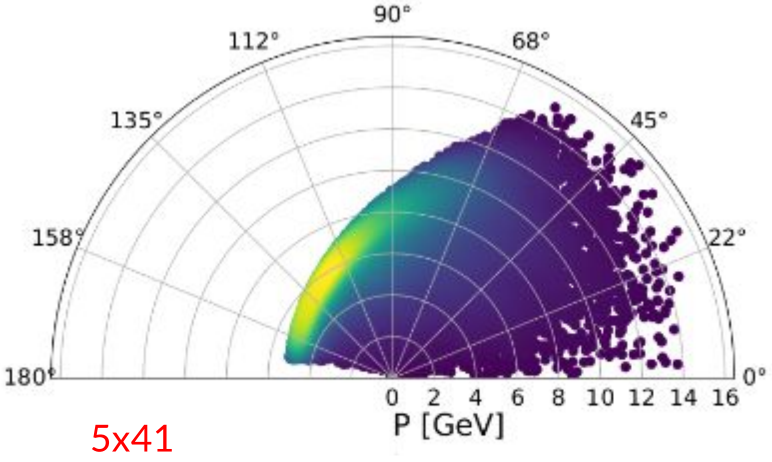
- π structure function: Measure DIS cross section with tagged neutron at small -t
- K structure function: Measure DIS cross section with tagged Λ/Σ at small -t
- Beam energies: 5 on 41, 5 on 100, 10 on 100, 10 on 135, 18 on 275
  - Only e-P currently implemented, but want to incorporate e-D

π^+ Form Factors

- Exclusive reactions are of interest
  - p(e,e'π^+n) exclusive reaction particular with p(e,e'π^+n)X SIDIS events as the background
  - A clean sample of p(e,e'π^+n) events needs to be isolated by detecting the neutron
- Measurements of the p(e,e'π^+n) reaction at the EIC have the potential to extend the Q^2 reach of F_π measurements even further
- A difficult measurement to make
  - Using the events generated from DEMP, the EIC software framework can assess the feasibility of the study with updated design parameters

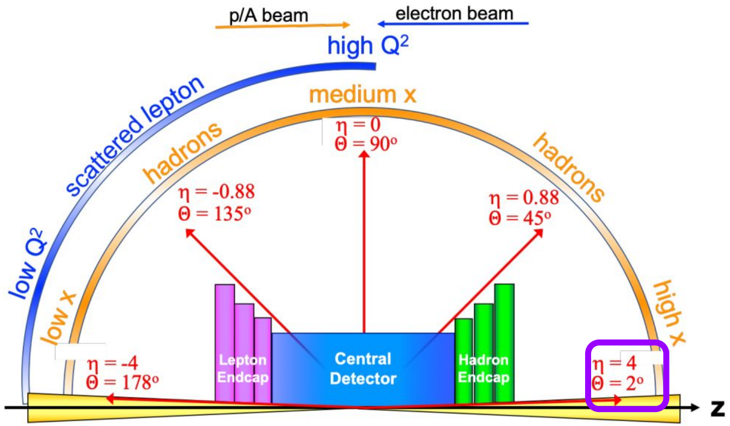
Meson Structure Functions – Scattered Electron

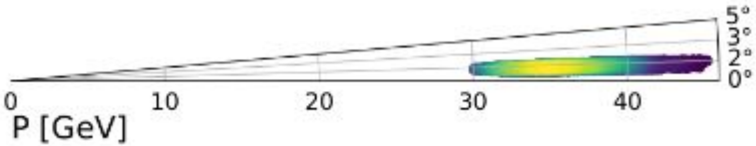




- Scattered electrons can be detected in the central detector

Meson Structure Functions – Forward Baryon

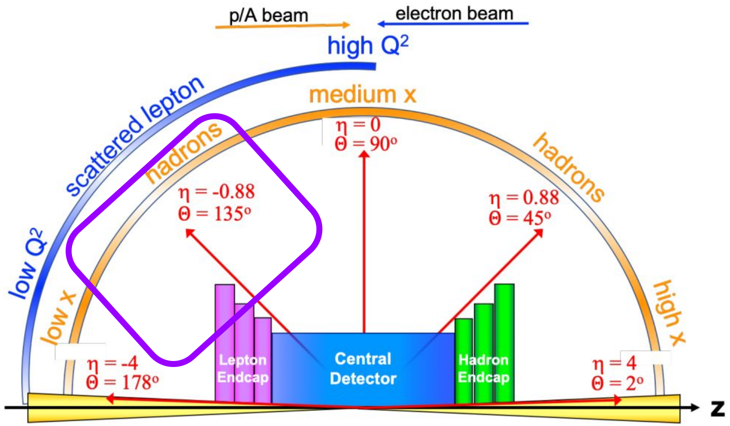


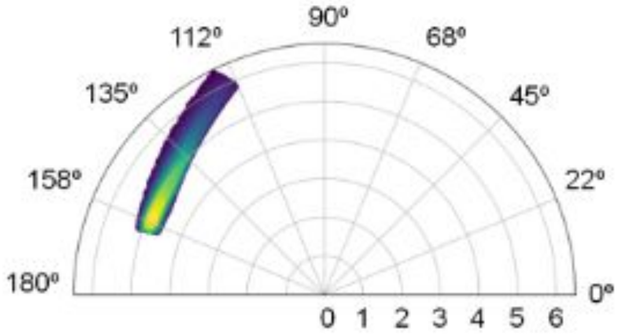


5x41

- Baryon (neutron, lambda) at very small forward angles and nearly the beam momentum

Meson Form Factor - Scattered Electron





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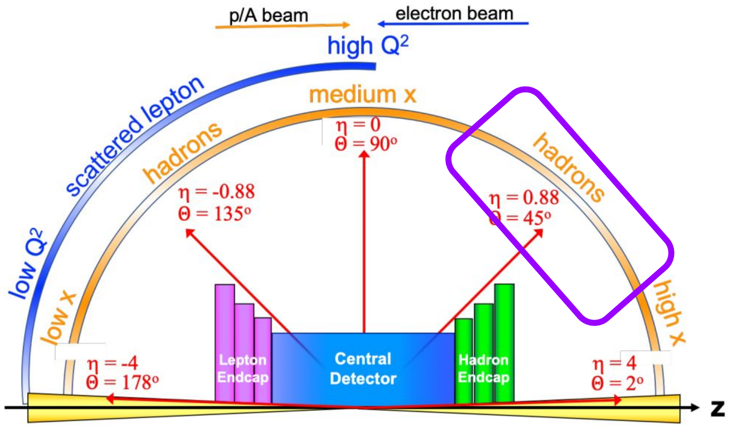
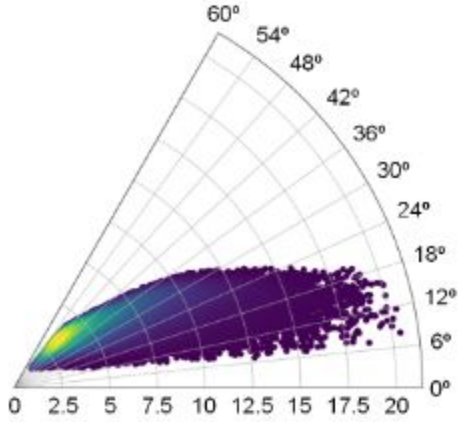
- The exclusive electron are stuck to a tighter band

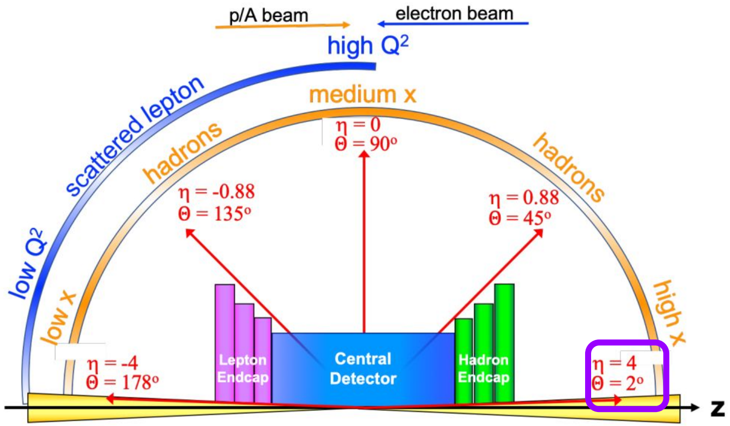
Meson Form Factor - Scattered π^+

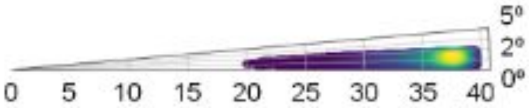




5x41

Meson Form Factor - Forward Neutron



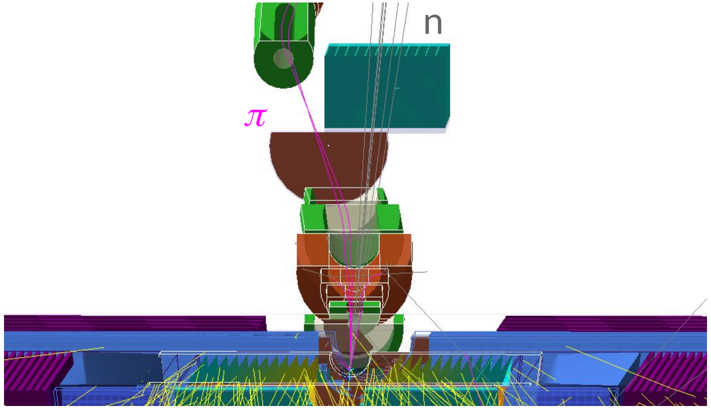


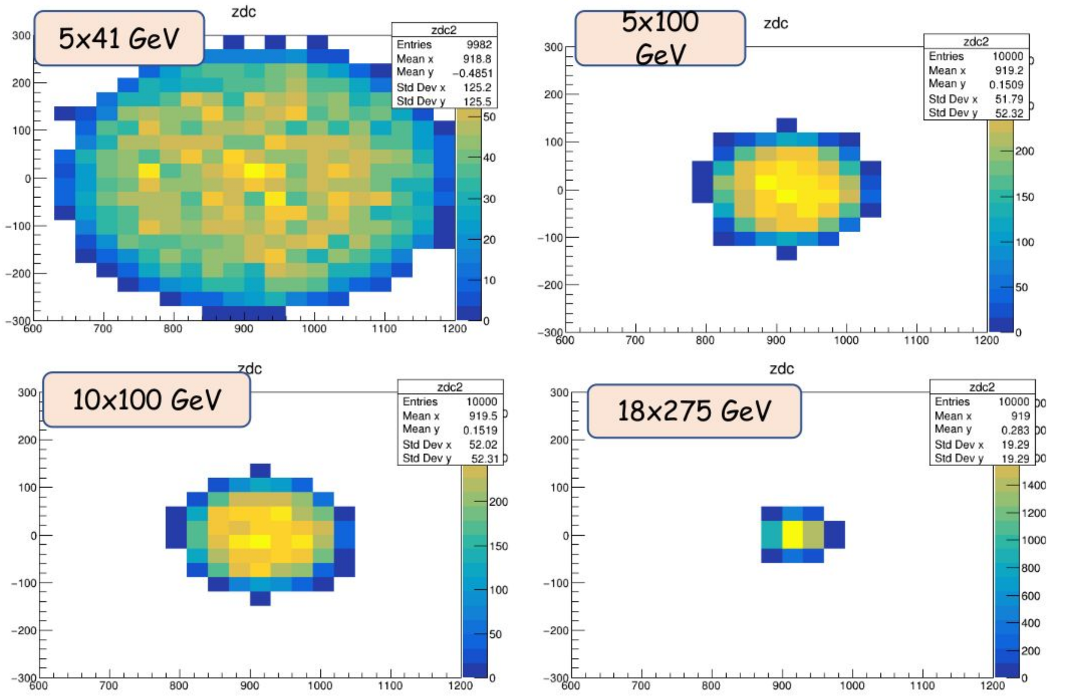
5x41

- Neutron carries ~80% of the momentum within 0.2° of outgoing proton

Neutron Final State

- For neutron final state use ZDC
  - detection fractions ~100% for 60x60 cm ZDC size
  - Need good ZDC angular resolution for required t resolution





- ZDC: [60x60 cm, 20 bins → 3 cm towers]
- The 60x60 cm ZDC allows for high detection efficiency for wide range of energies (K-Λ detection benefits from 5 on 41, 5 on 100)
  - Higher energies (10 on 100, 18 on 275) show too coarse of a distribution at this resolution

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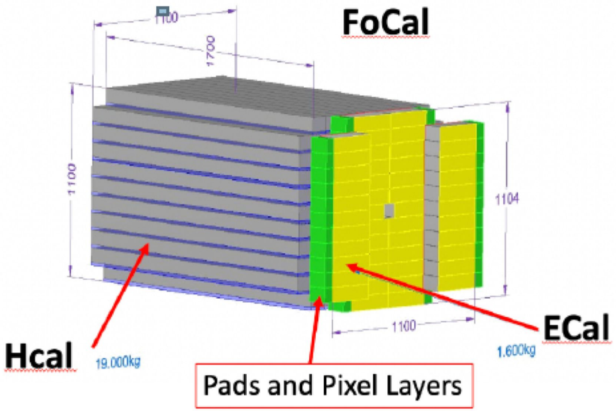
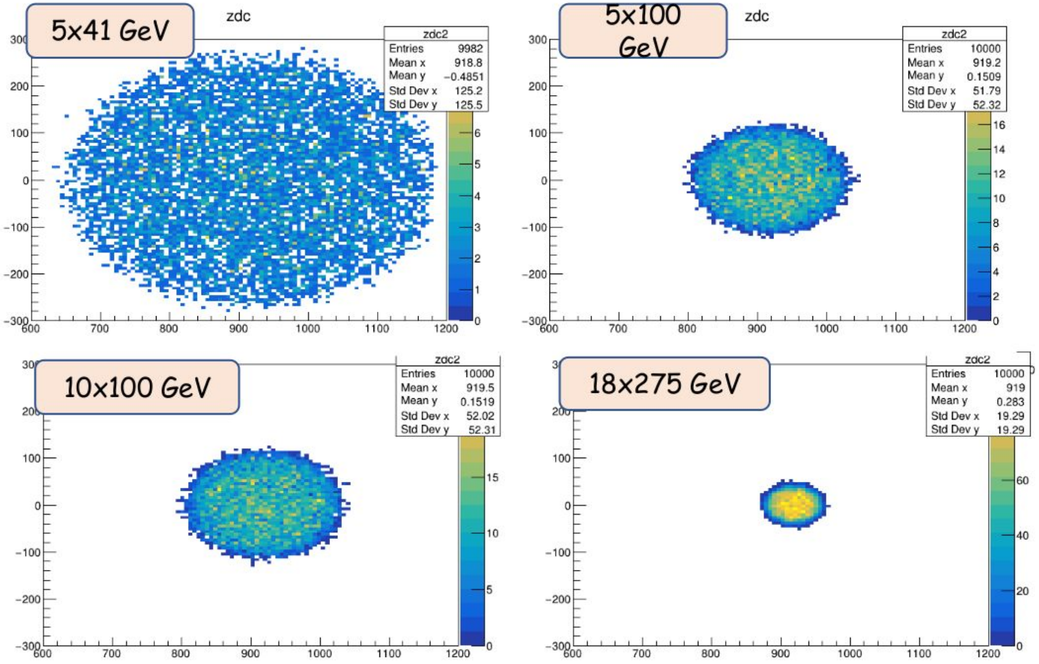




- ZDC: [60x60 cm, 100 bins → 0.6 cm towers]
- If we want energies over 100 GeV, we will need resolution of ~1 cm or better

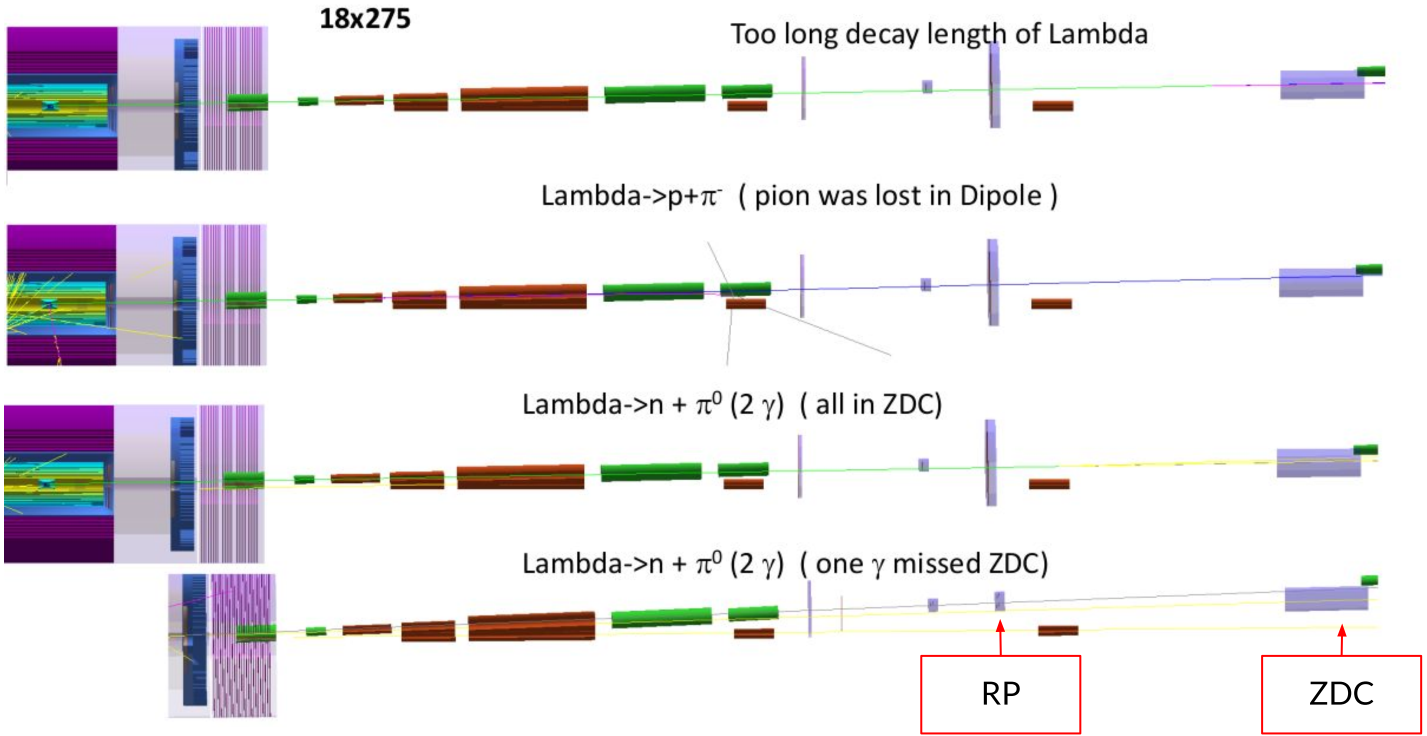
Lambda Final State

$\Lambda \rightarrow p+\pi^-$: very challenging!

- need additional particle tracking between dipoles and ZDC

$\Lambda \rightarrow n+\pi^0$: looks promising

- need additional high-res/granularity EMCal+tracking before ZDC



Summary

Full talk at 2020 Pion/Kaon Workshop

1. Produced initial physics deliverables, physics objects, and kinematic plots/coverage
    - Physics deliverables: π/K structure function plots, π form factor plot
    - Physics objects:
        - scattered electron
        - Measure π and tagged neutron (π form factor)
        - Measure "X" and tagged neutron (π structure function)
        - Measure "X" and tagged Λ/Σ (K structure function)

2. Evaluated with simulations detector performance/requirements
    - Standard detection requirements
    - For the tagged neutron at all energies: ~100% detection efficiency
        - Low energies [5 on 41, 5 on 100] **require at least 60cmx60cm size** to access wider range of energies
        - High energies [10 on 100, 10 on 135, 18 on 275] **requires resolution of 1 cm or less**
    - For measuring the tagged Λ benefits from low energies [5 on 41, 5 on 100] and needs...
        - $\Lambda \rightarrow n + \pi^0$: additional high-res/granularity
            - **EMCal+tracking before ZDC** (seems doable)
        - $\Lambda \rightarrow p + \pi^-$: additional trackers/veto in opposite charge direction on path to ZDC (more challenging)
    - [In progress] Good hadronic calorimetry to obtain good x resolution at large x

Looking Forward

- See our full paper currently under review in JPhysG (arXiv:2102.11788)
- Check out the upcoming ECT* April conference

FONDAZIONE BRUNO KESSLER

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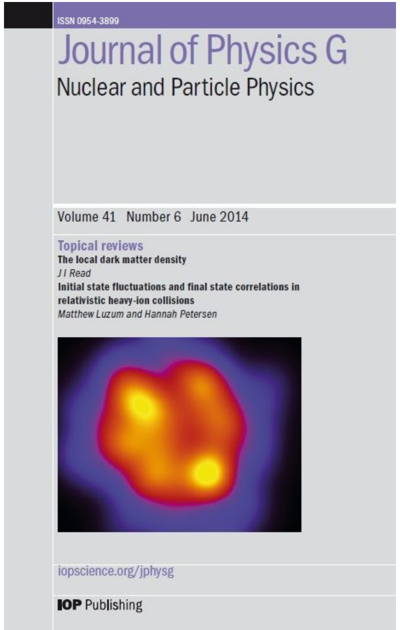
EUROPEAN CENTRE
FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREA

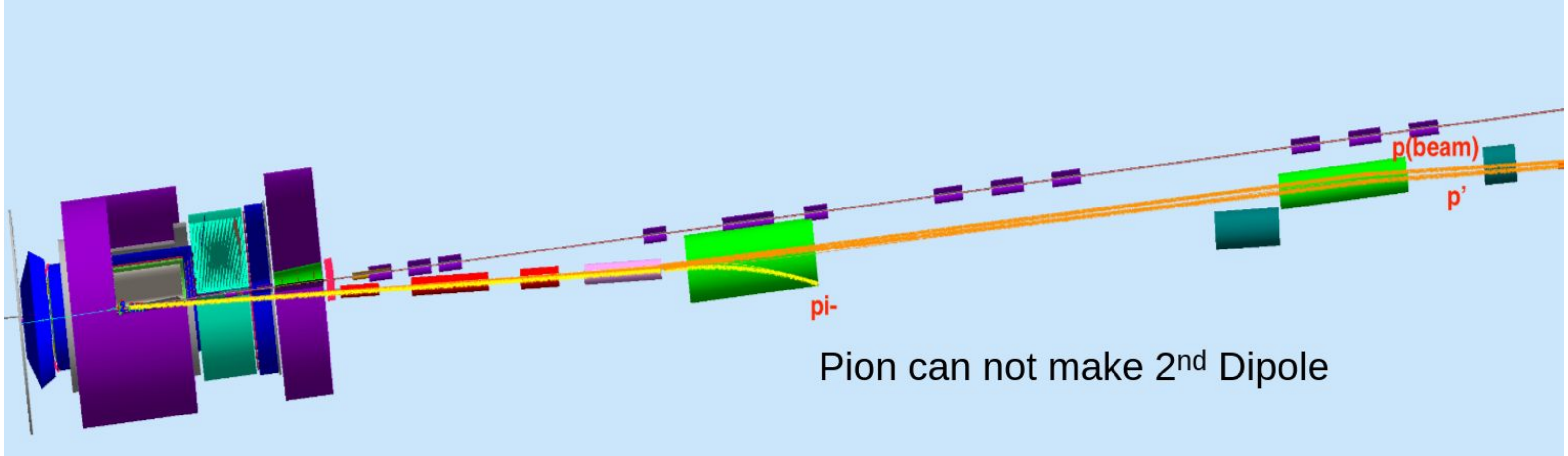


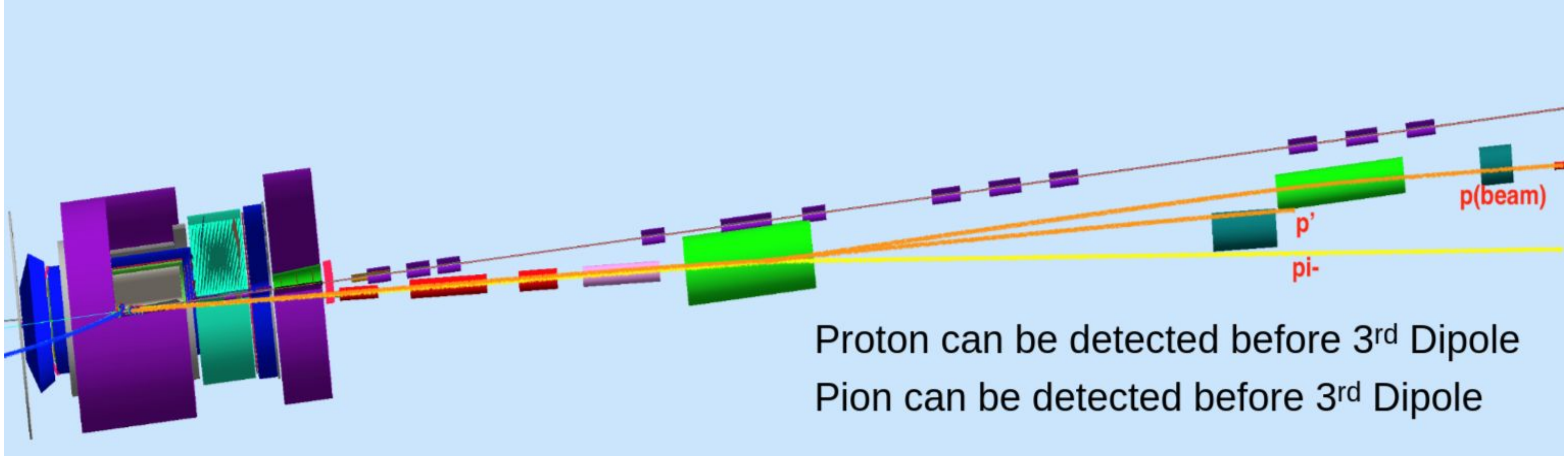
Meson structure working group members!

Daniele Binosi , Huey-Wen Lin, Timothy Hobbs, Arun Tadepalli, Rachel Montgomery, Paul Reimer, David Richards, Rik Yoshida, Craig Roberts, Garth Huber, Thia Keppel, John Arrington, Lei Chang, Stephen Kay, Ian L. Pegg, Jorge Segovia, Carlos Ayerbe Gayoso, Bill Li, Yulia Furletova, Dmitry Romanov, Markus Diefenthaler, Richard Trotta, Tanja Horn, Rolf Ent, Tobias Frederico

EXTRA

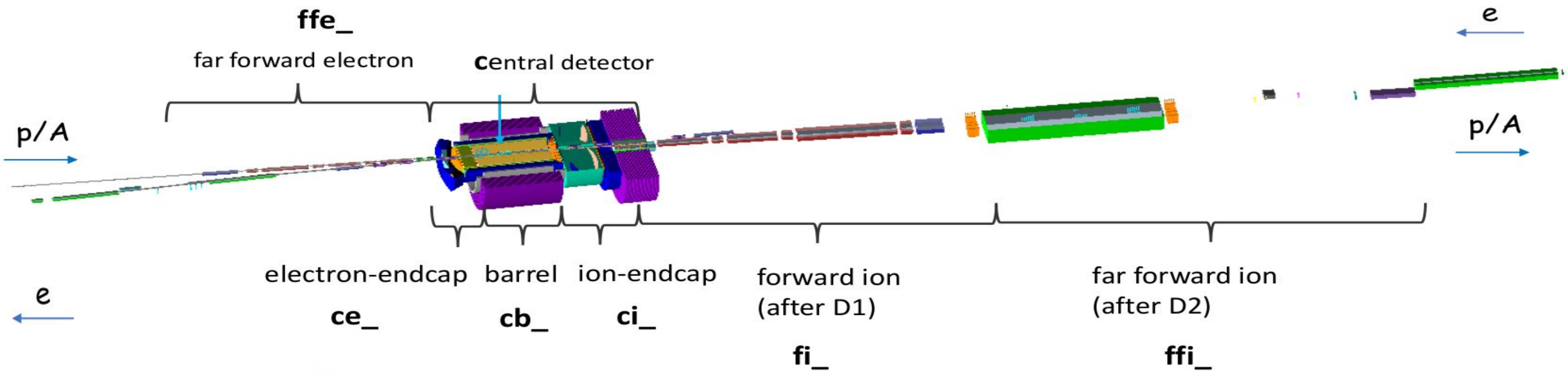
Detection of $^1H(e,e'K^+)\Lambda$, Λ decay to p + π^-





GEANT4 for EIC

- Meson structure MC outputs lund files for use in GEANT4
- Detector MC updated with eRHIC specifics (crossing angle changes primarily)
- Updates to electron beam line
  - Solenoid centered at zero - this cannot be changed as it affects the beamline
  - IR region was the same size for JLEIC and eRHIC design, so can use JLEIC detector in eRHIC beam line.
  - Modulo beam line required changes in end caps, crossing angles



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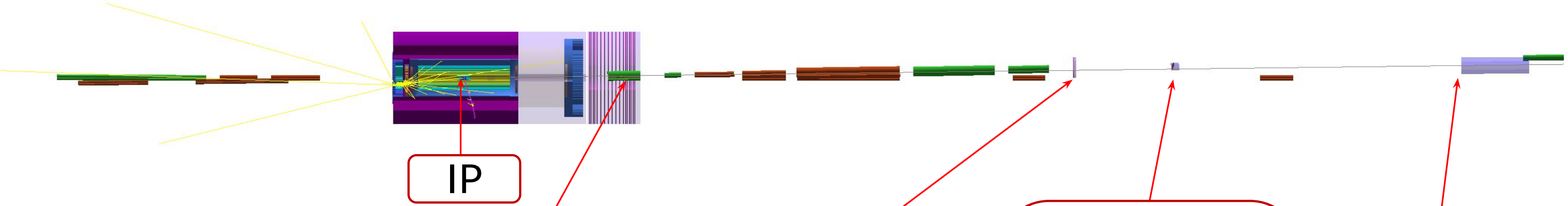


B0 sensors:
Rin ~ 3.4 cm
Rout ~ 20 cm
50x50 um^2 pixel pitch

Zpos= 5.9 m
Xpos =15 cm

Off momentum tracker :
Rin ~ 10 *cm (?) ,
10x30cm
500x500 um^2 pixel pitch

Zpos = 22.5 m
Xpos = 75 cm

Roman Pots:
Rin ~ 10σ
20x10 cm^2
500x500 um^2 pixel pitch

Zpos = 26.2 m
Xpos = 82 cm

RP2 (not seen):
Zpos = 28.2 m
Xpos = 91 cm

ZDC:
60x60cm EMCAL
LG: 1x1cm^2
HG: 100x100um^2
HCAL: 10x10 cm

Zpos = 38 m
Xpos = 90 cm

Lambda Final State

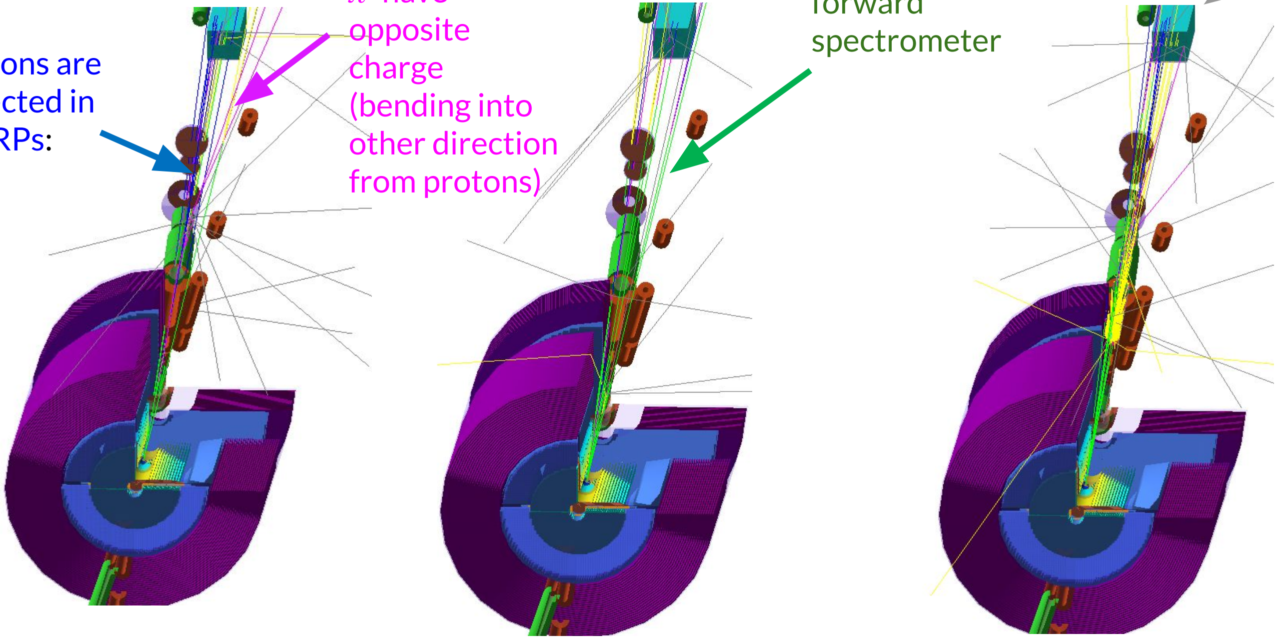
$$\Lambda \rightarrow p + \pi^{-}$$
$$\Lambda \rightarrow n + \pi^{0}$$

Protons are detected in the RPs:

π^{-} have opposite charge (bending into other direction from protons)

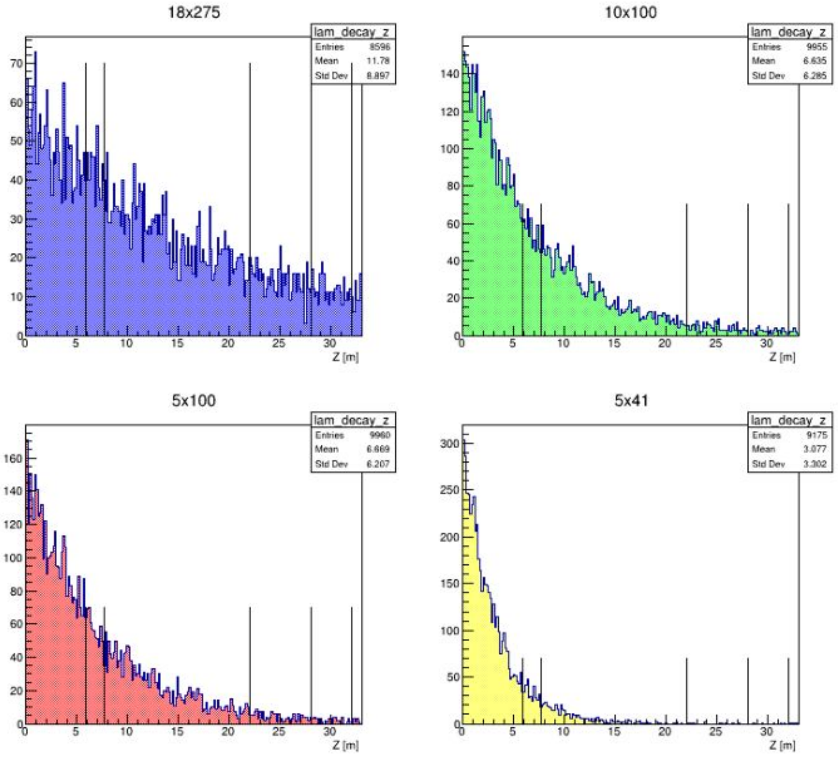
30% of Λ at high energy does not decay before forward spectrometer

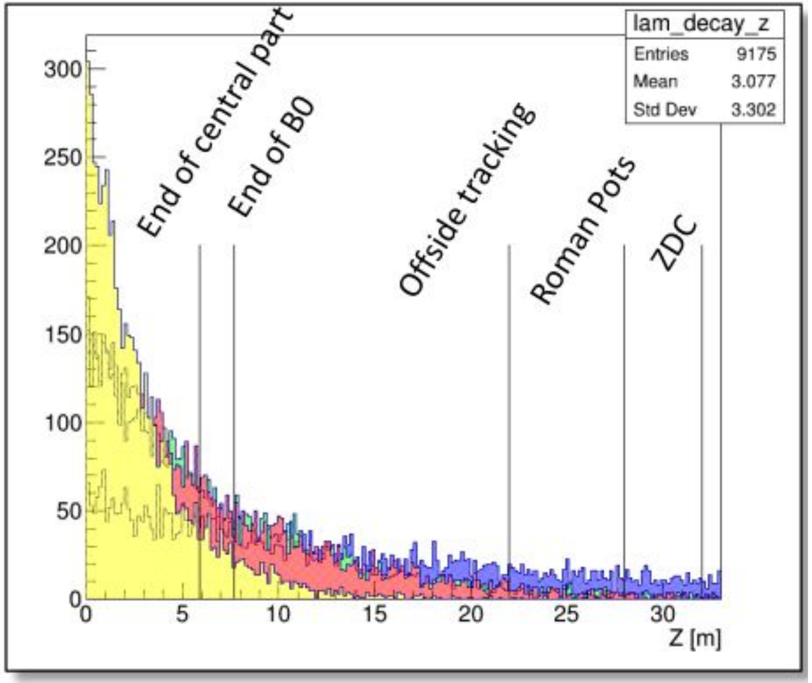
Neutrons and a fraction of π^{0} goes into ZDC



18 x 275

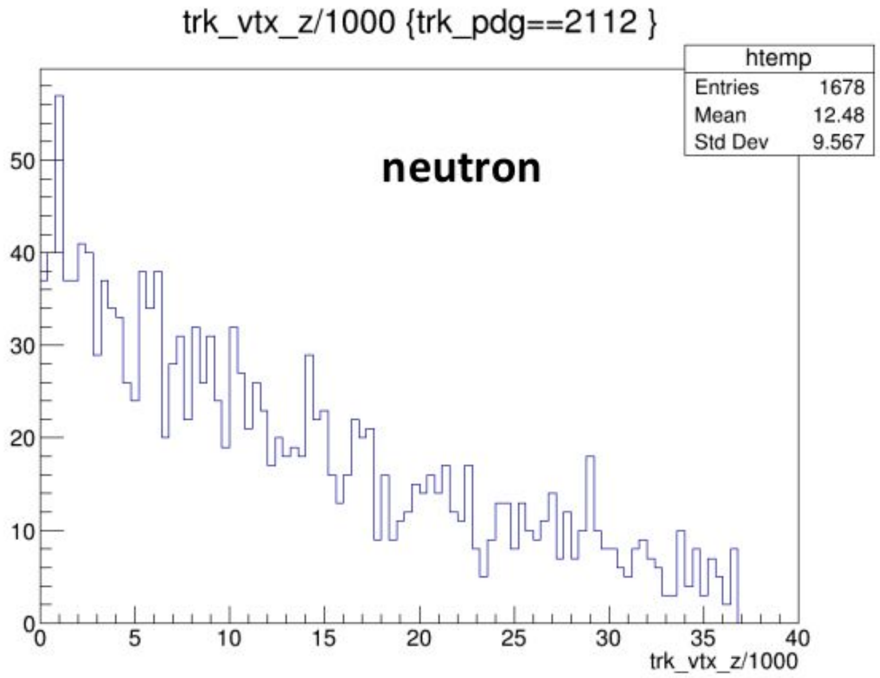
Decay Length

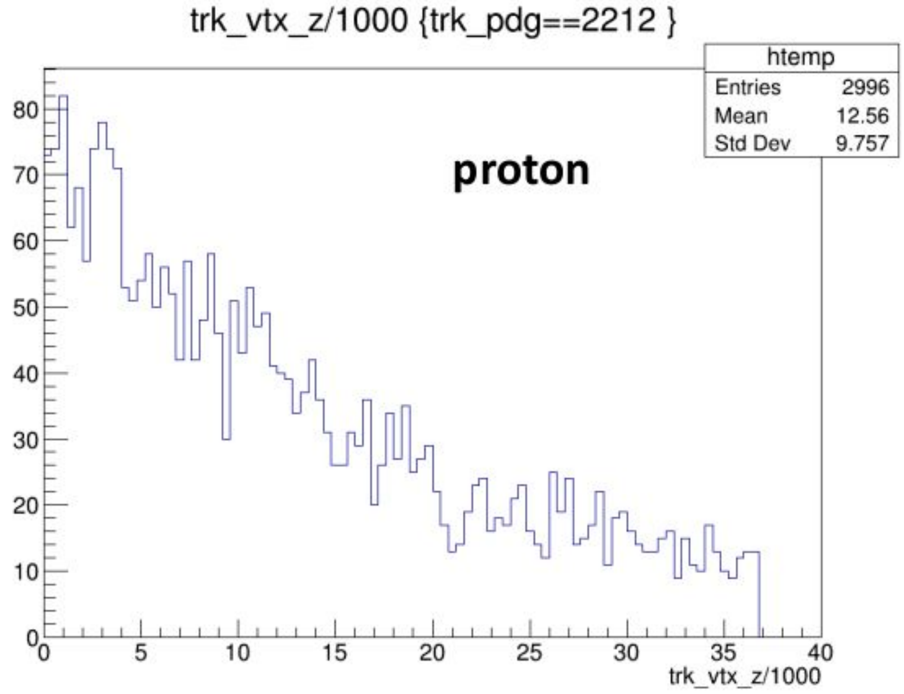




- There are some advantages for lower proton energy for K-Λ detection

Decay Length [p(e,e'K$^+\Lambda^0$)X]

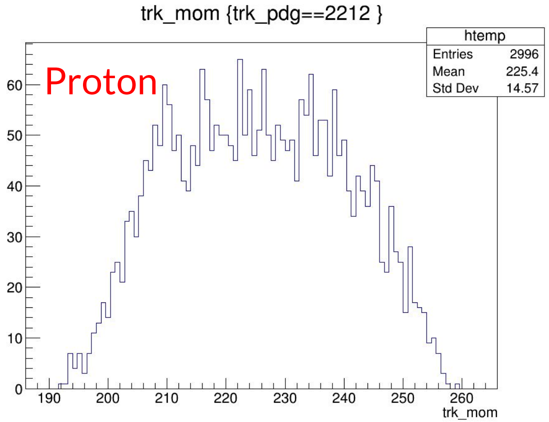


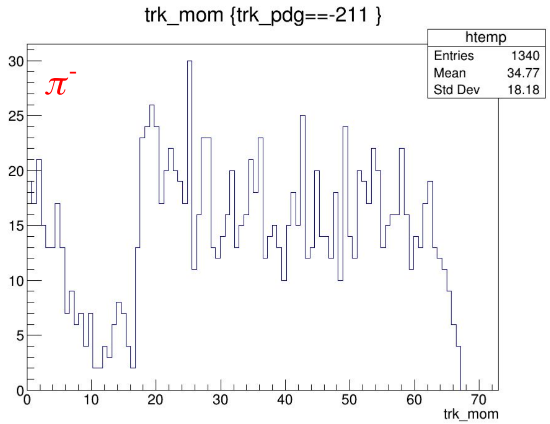


- 10k events → 3580 neutrons → ~47%
  - Need to add π^0 efficiency
- 10k events → 6390 protons → ~47%
  - Need to add π^- efficiency

Virtual planes [p(e,e'$K^+\Lambda^0$)X]

- Next step: Switch from virtual planes to the real size detector and check detector efficiency





Angular distribution for Proton