Monte Carlo simulation of pion and kaon structure functions at JLEIC

TRIESTE (ITALY)

Jul. 18-22, 2017

Kijun Park

Possibility of measurement for pi/K structure functions at EIC

Motivation

- **Protons, neutrons, pions and kaons are the main building blocks of nuclear matter !!**

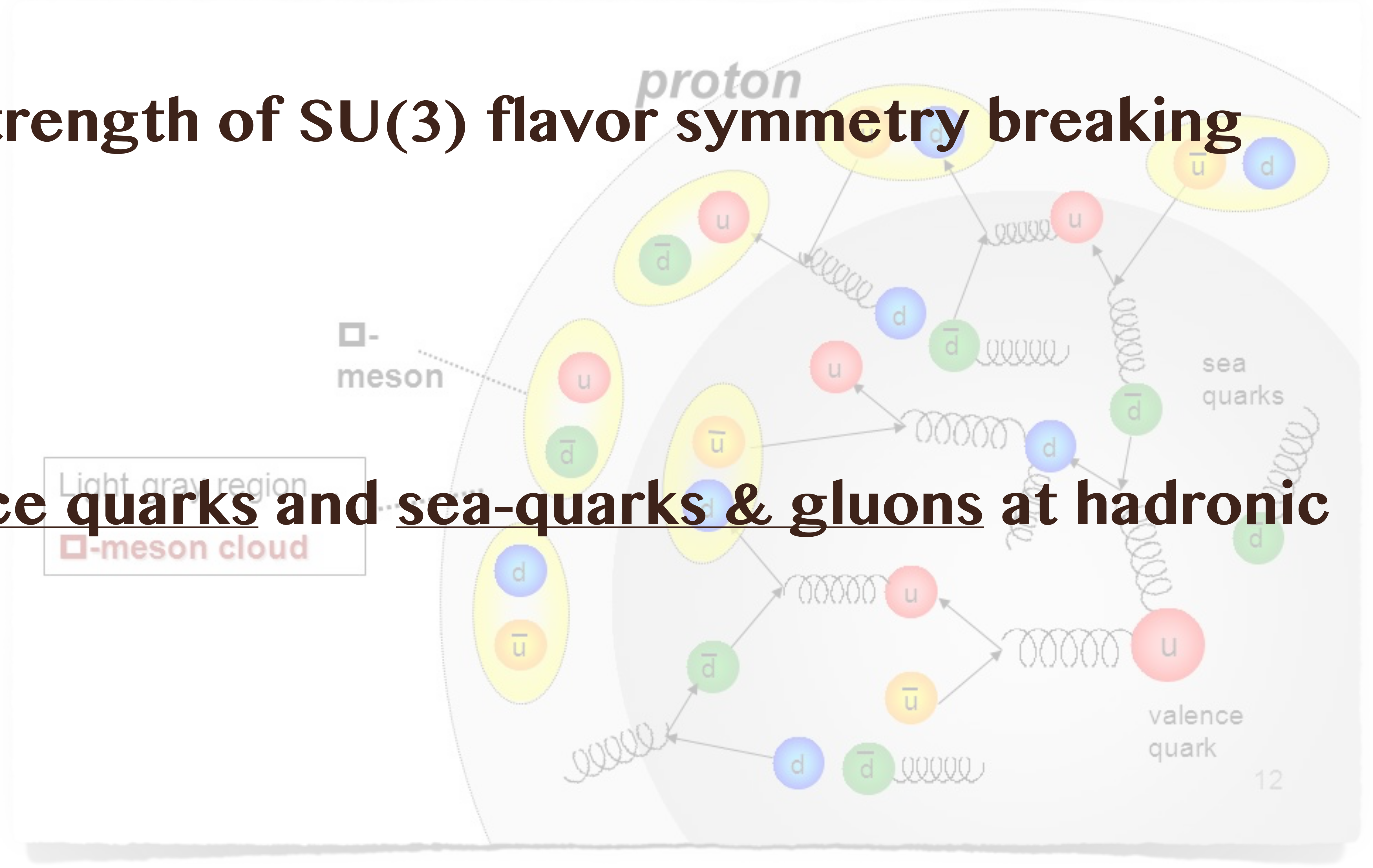
  1) The pion, or a meson cloud, explains light-quark asymmetry in the nucleon sea
  2) Pions are the Yukawa particles of the nuclear force – but no evidence for excess of nuclear pions or anti-quarks
  3) Kaon exchange is similarly related to the LambdaN interaction
  4) Mass is enigma – cannibalistic gluons vs massless Goldstone bosons

- **Flavor dependence of DCSB modulates the strength of SU(3) flavor symmetry breaking in meson PDFs**

  Origin of the mass: see Craig's Talk

- **Evolution of PDFs, it <u>must</u> include both <u>valence quarks</u> and <u>sea-quarks & gluons</u> at hadronic scale**

  PDFs: see Alberto's Talk



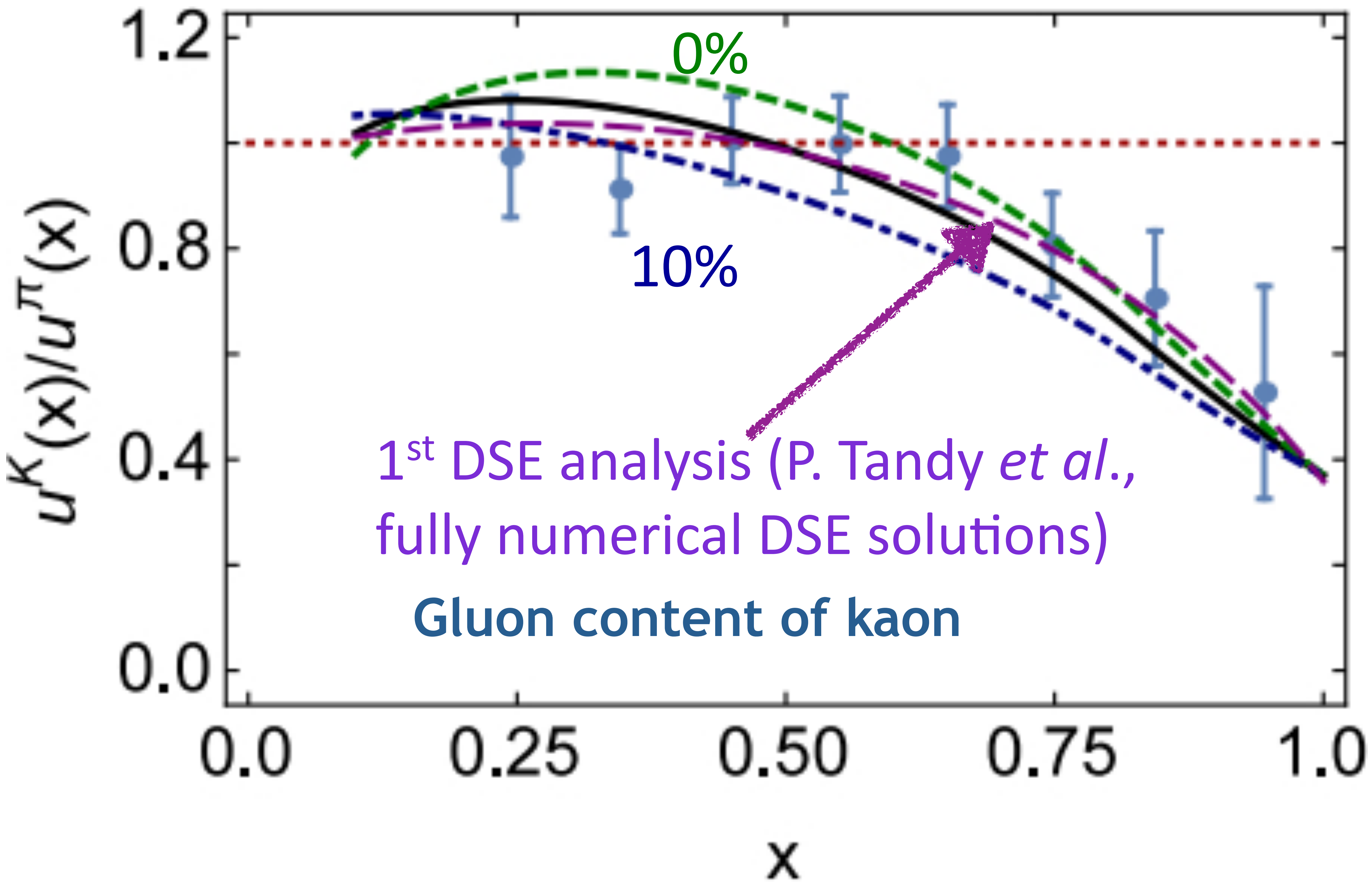
Why pi/K structure function is interesting ?

Origin of the mass: see Craig's Talk

Kaon structure function & Gluon content of kaon

- ✦ Valence quarks carry 95% of kaon's momentum at perturbative hadronic scale (in LQCD&DSE)
- ✦ Owing to heavier mass of intermediate states that can introduce sea-quarks, therefore sea-quark content of kaon is effectively zero !!
- ✦ LF-momentum fraction carried by glue as a parameter through u-quark ratio in K/pi

NA3 Collaboration @ CERN (1980)



DSE prediction for the ratio of u-quark distributions in the kaon and pion

Tagged DIS (TDIS) technique optimized to probe the partonic components of the meson cloud of the nucleon

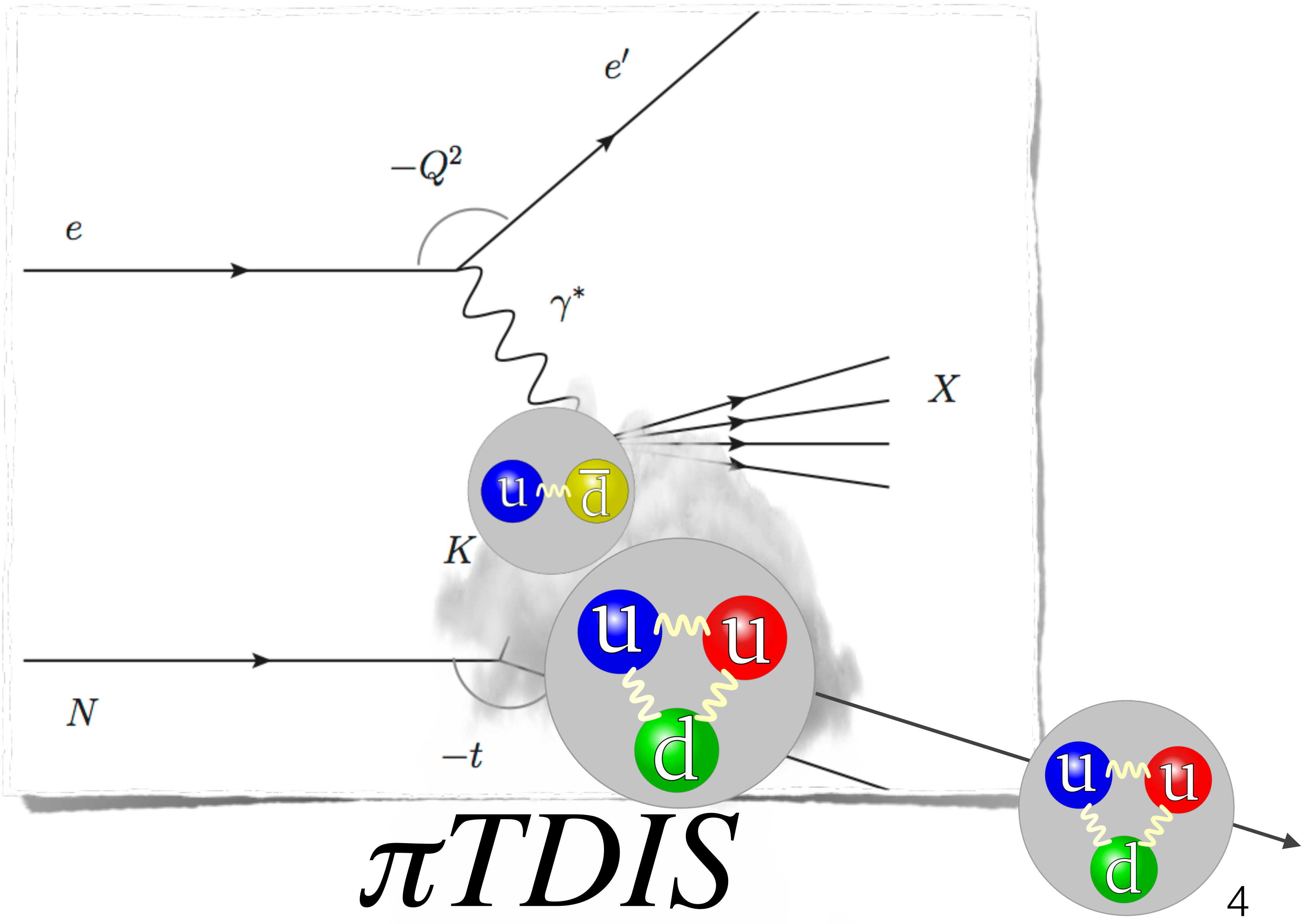
- ✦ Extraction of the pion/kaon structure function
- ✦ Testing of fundamental QCD
- ✦ No kaon data at all !
- ✦ The pi/k data crucial complimentary for understanding of the important background

only Drell-Yan data !!!
OLD DATA

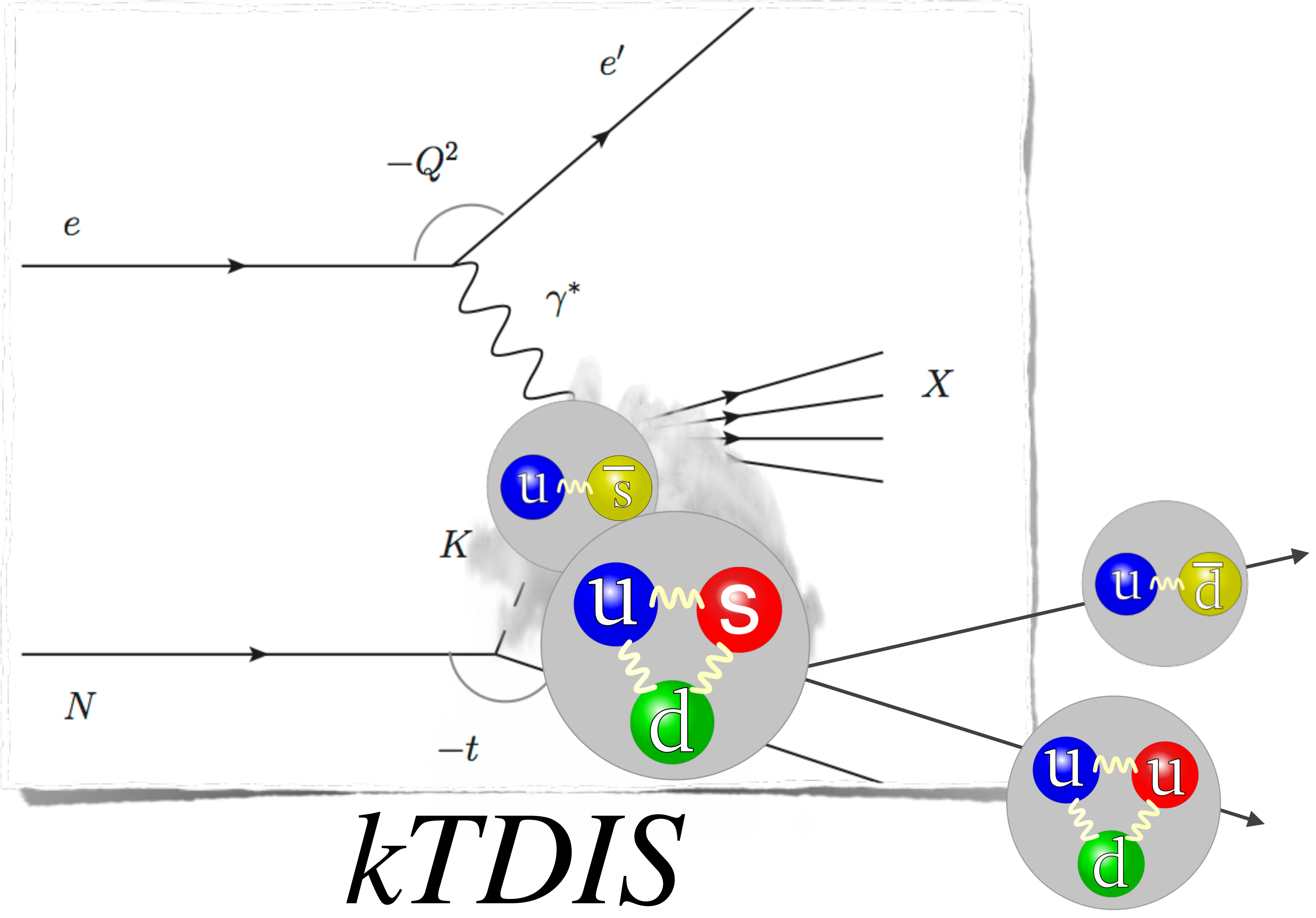
How do we want to measure ?

Tagged Deep Inelastic Scattering (TDIS)

- Sullivan Process
  .. provides reliable access to a meson target as t becomes space-like (the meson pole dominance of the process)
- Direct measure the mesonic-nucleon content



$\pi TDIS$



$kTDIS$

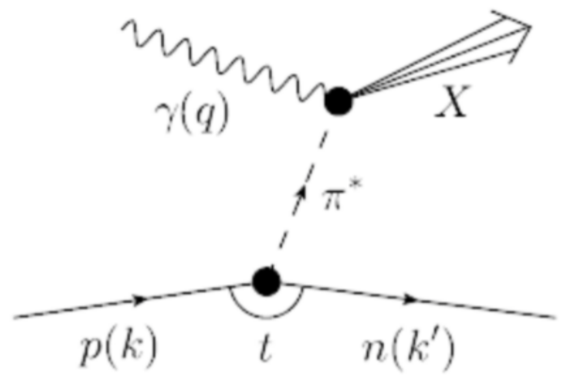
k/pi workshop

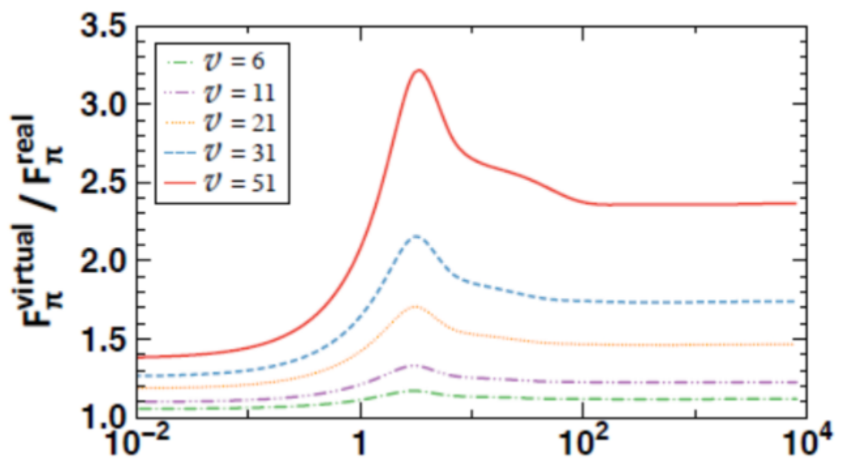
Pion and Kaon Structure at an Electron-Ion Collider

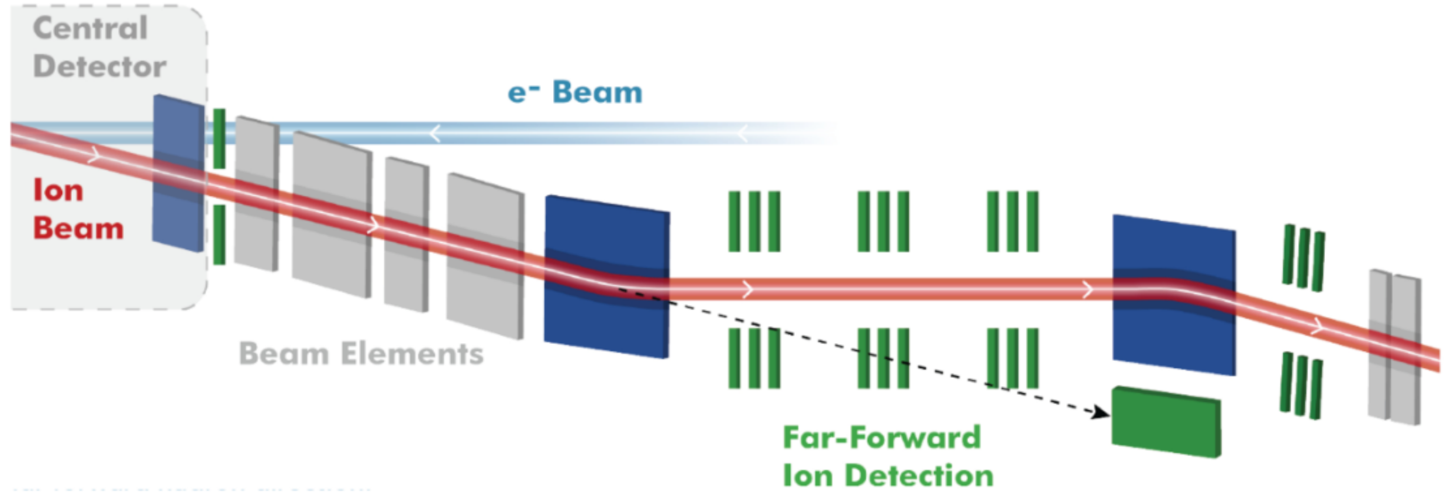
1–2 June 2017, Physics Division, Argonne National Laboratory

Argonne NATIONAL LABORATORY

HOME ACCOMMODATION PARTICIPANTS PROGRAM REGISTRATION







Introduction

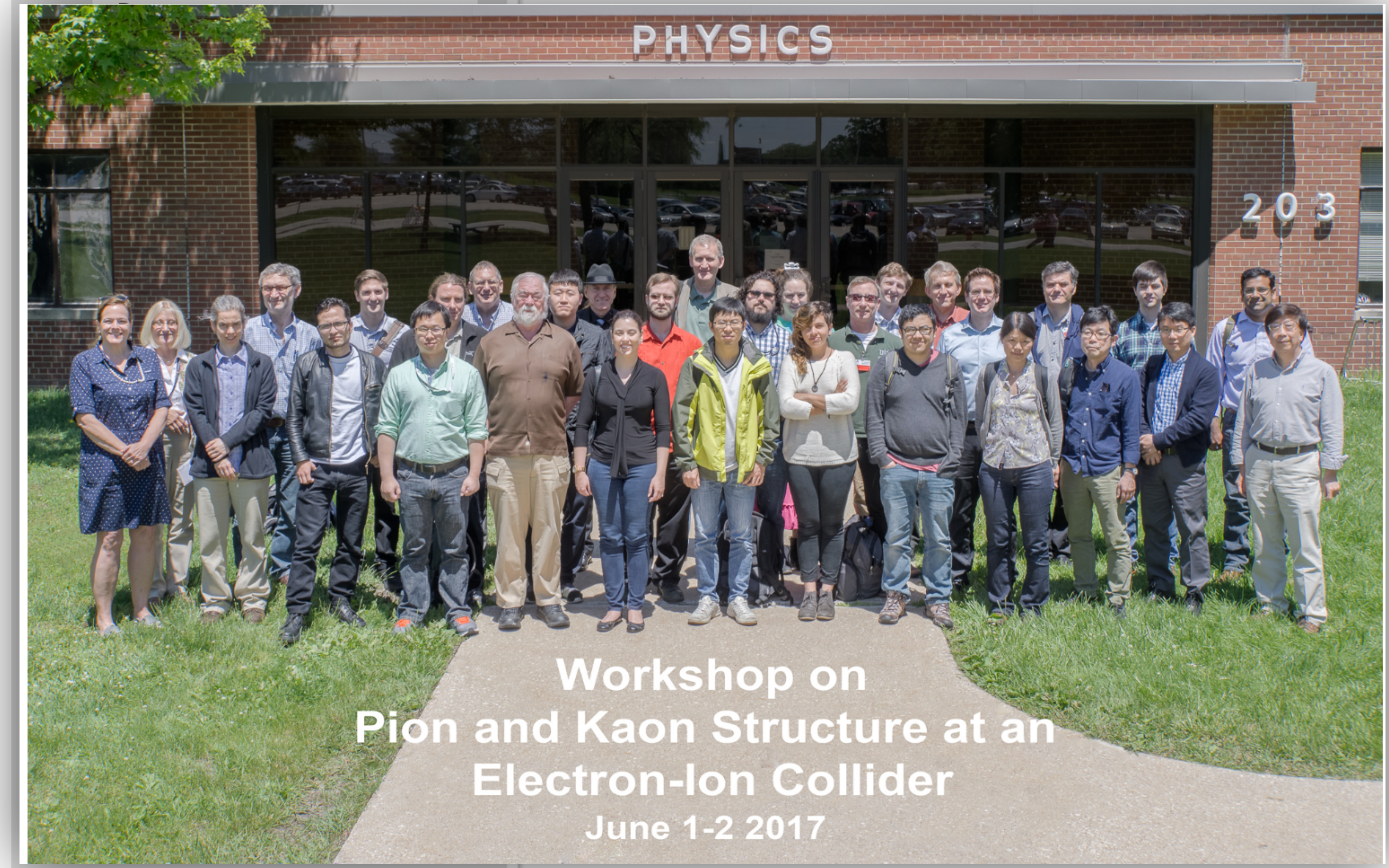
This workshop at Argonne National Laboratory will explore opportunities provided by an EIC to study the quark and gluon structure of the pion and kaon.

Invited Speakers:

- Whitney Armstrong (Argonne National Laboratory) [talk]
- Tanja Horn (The Catholic University of America) [R. Trotta] [T. Horn]
- Garth Huber (University of Regina) [talk]
- Huey-Wen Lin (Michigan State University) [talk]
- Wally Melnitchouk (Jefferson Lab) [talk]
- Pavel Nadolsky (Southern Methodist University) [talk]
- Kijun Park (Jefferson Lab) [talk]
- Jen-Chieh Peng (University of Illinois at Urbana-Champaign) [talk]
- Stephane Platchkov (CERN) [talk]

Navigate

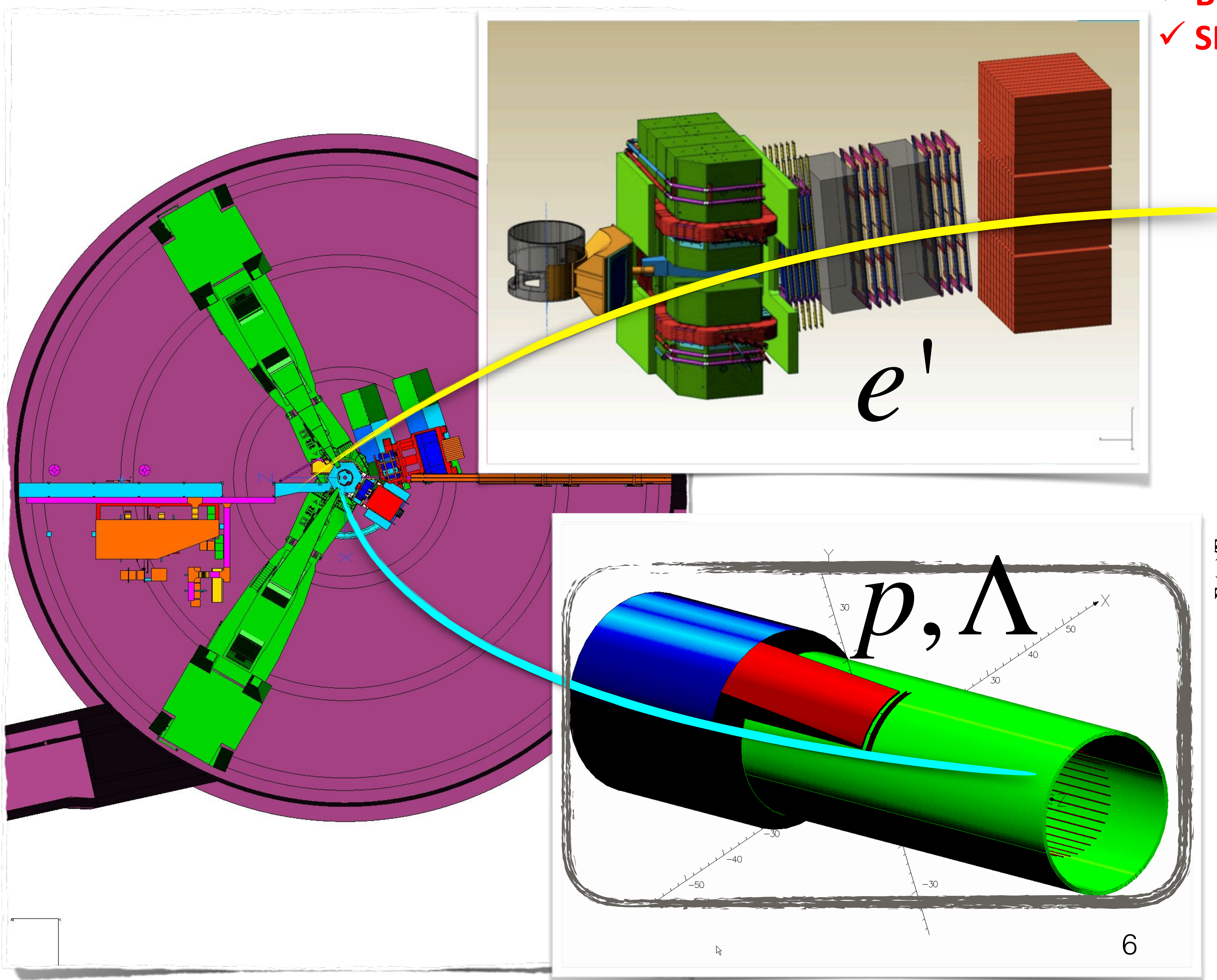
- Home
- Accommodation
- Participants



PAC45-JLAB12GeV

Jul.10-14, 2017

Program Advisory Committee

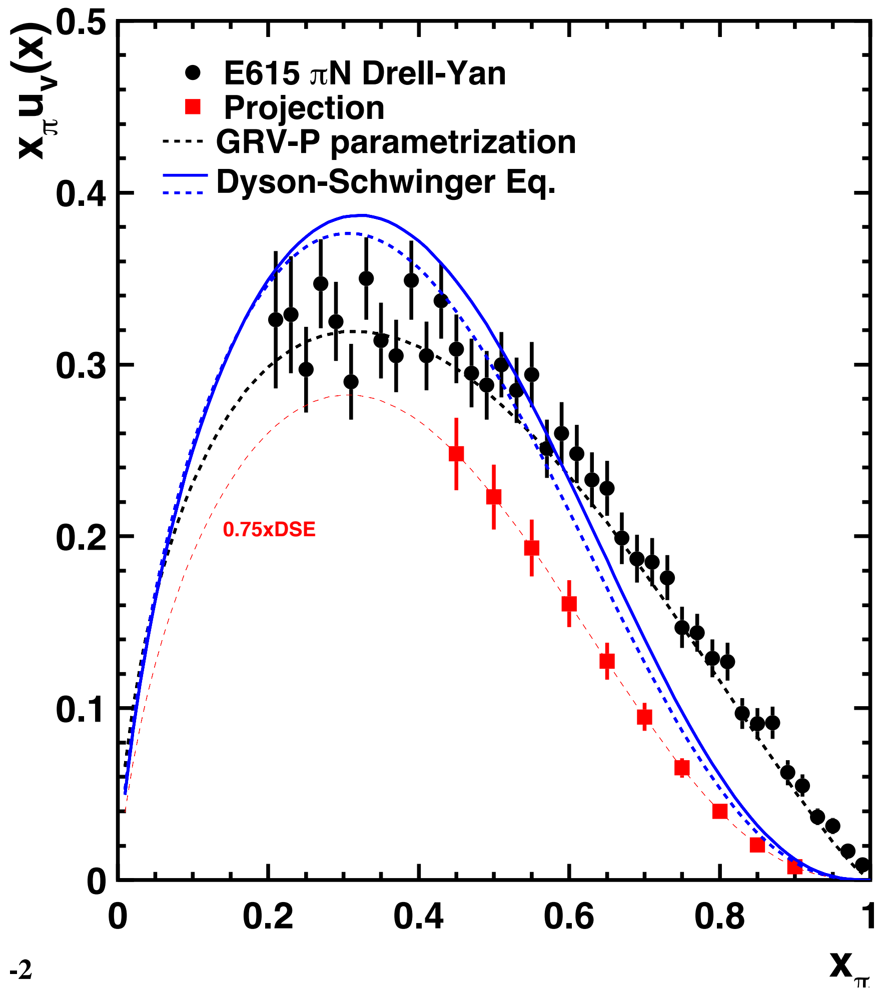


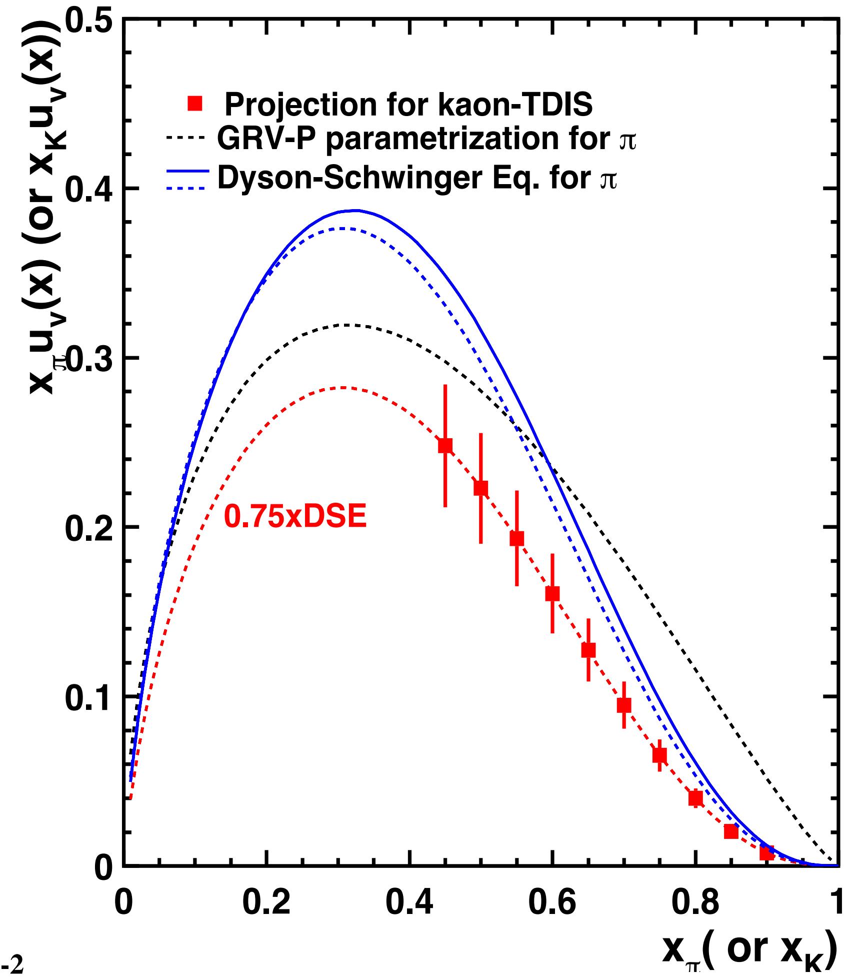
Hall A with Super Bigbite:

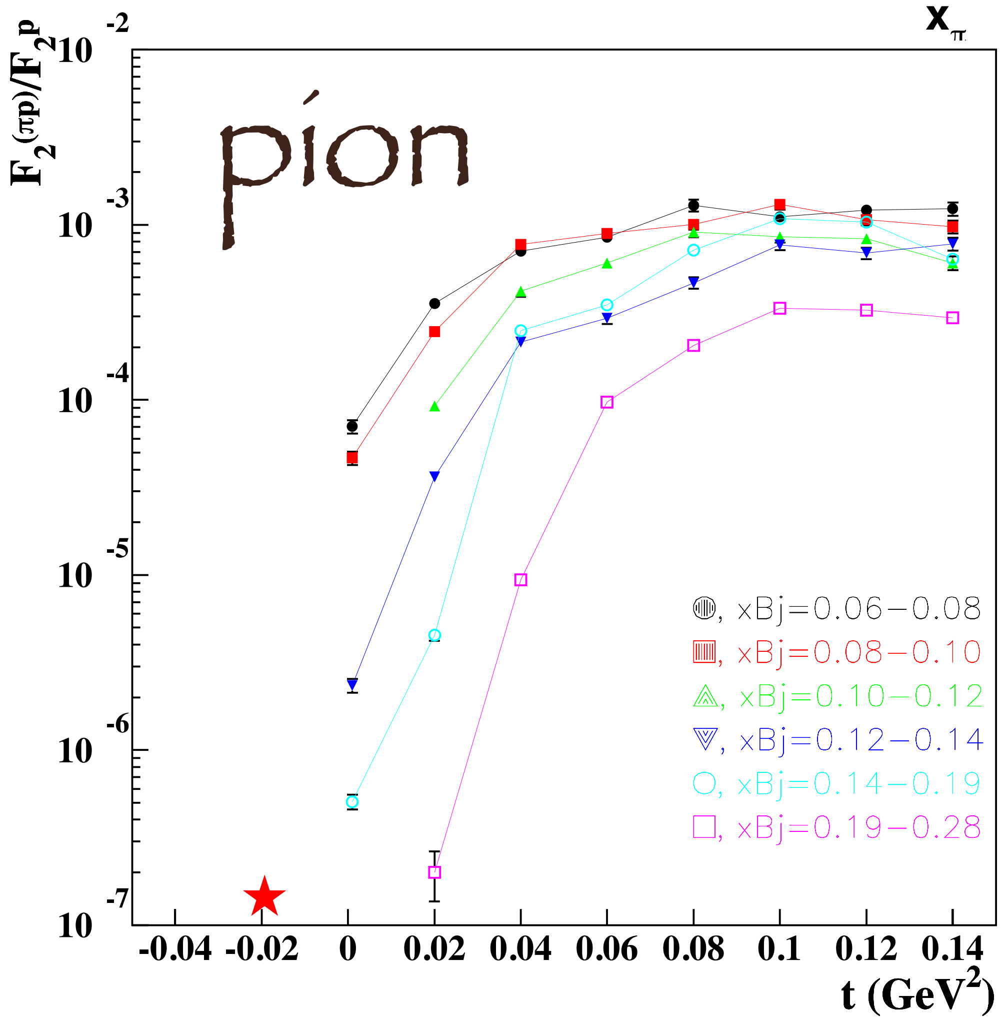
- ✓High luminosity,
  50 μAmp, $\mathcal{L}$ = 3 x 10^{36}/cm^2 s
- ✓Large acceptance
  Super Bigbite ~70 msr, hadron spectrometer
- ✓HCAL will be used in RTPC calibration
- ✓ **BONUS-type RTPC, requires Solenoid B-field**
- ✓ **SBS for electron detection**

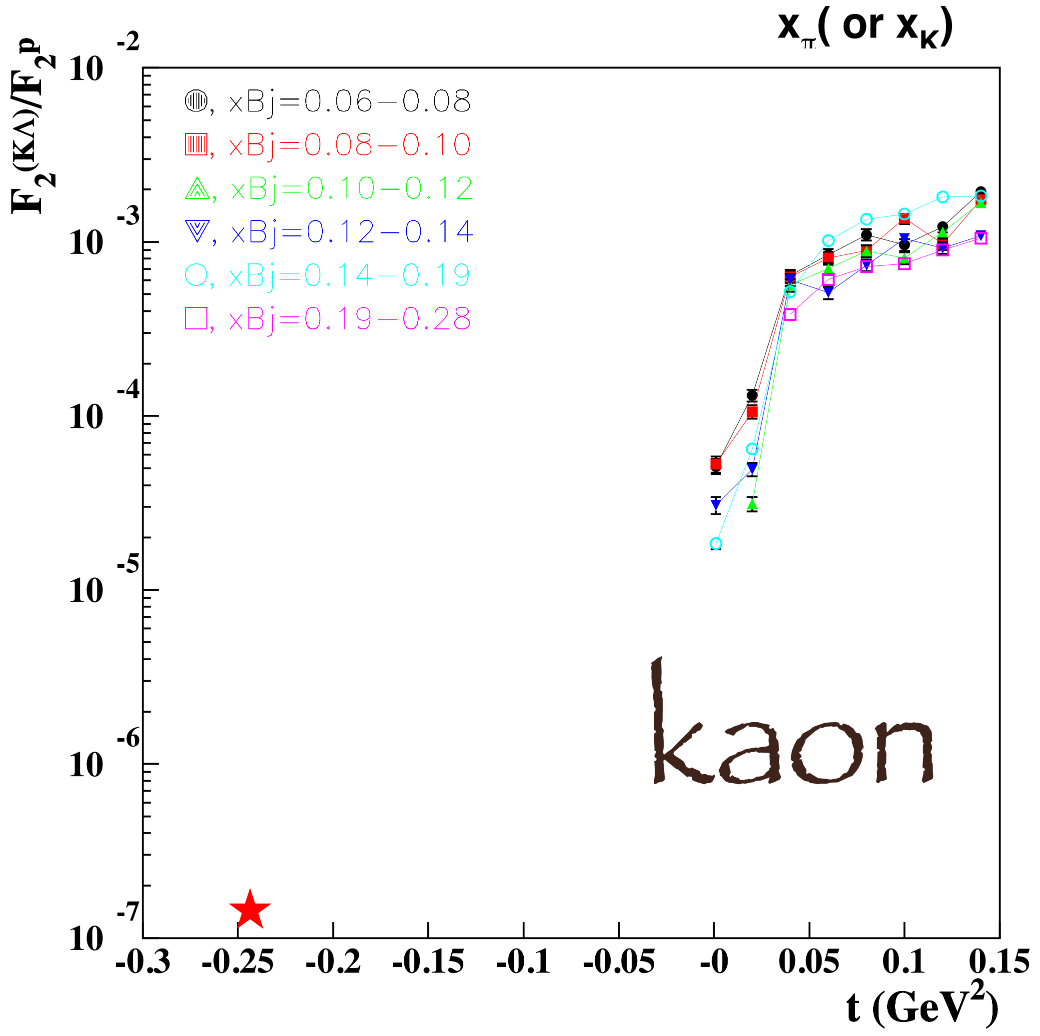
27days of PAC

$k/\pi - TDIS$

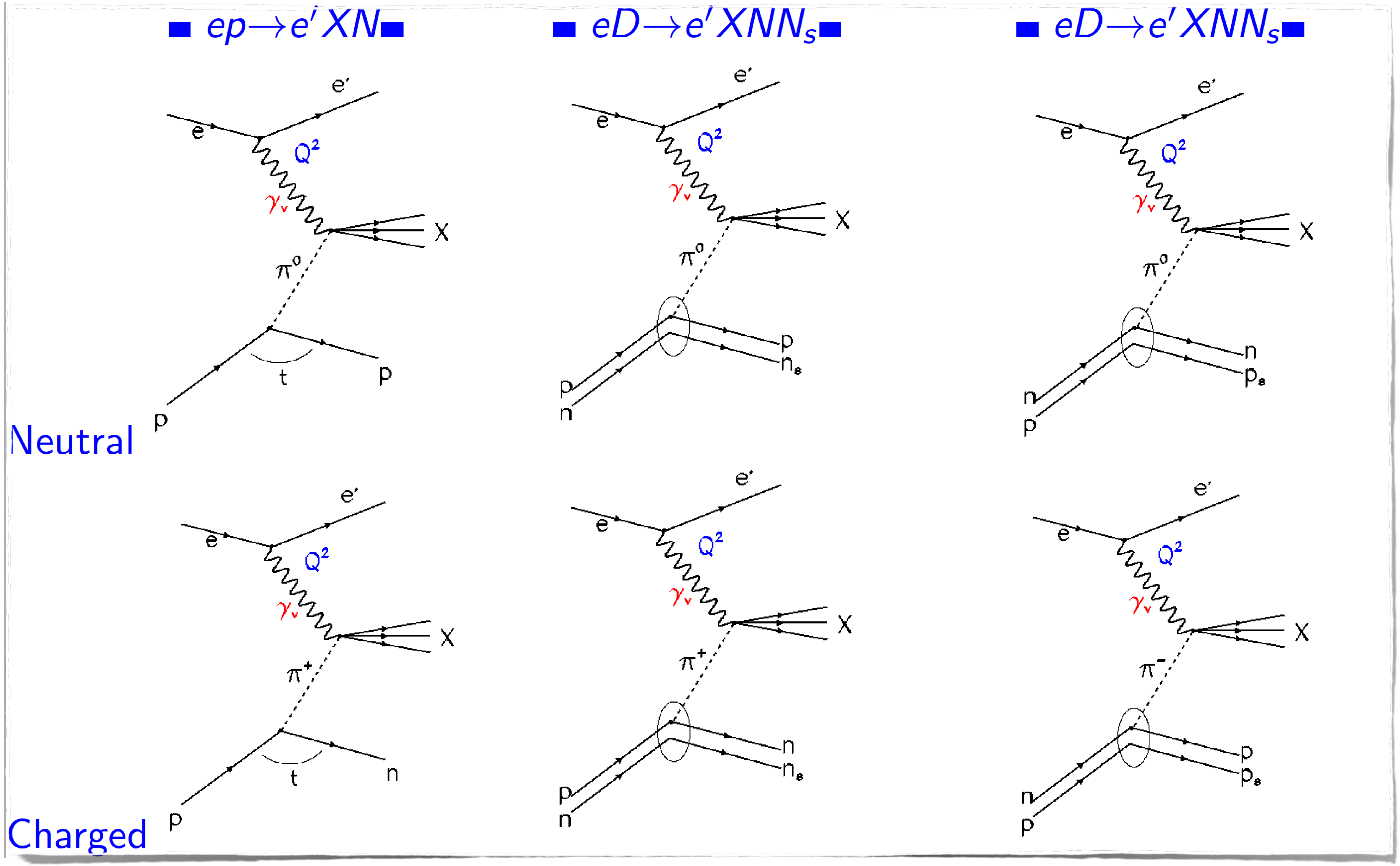




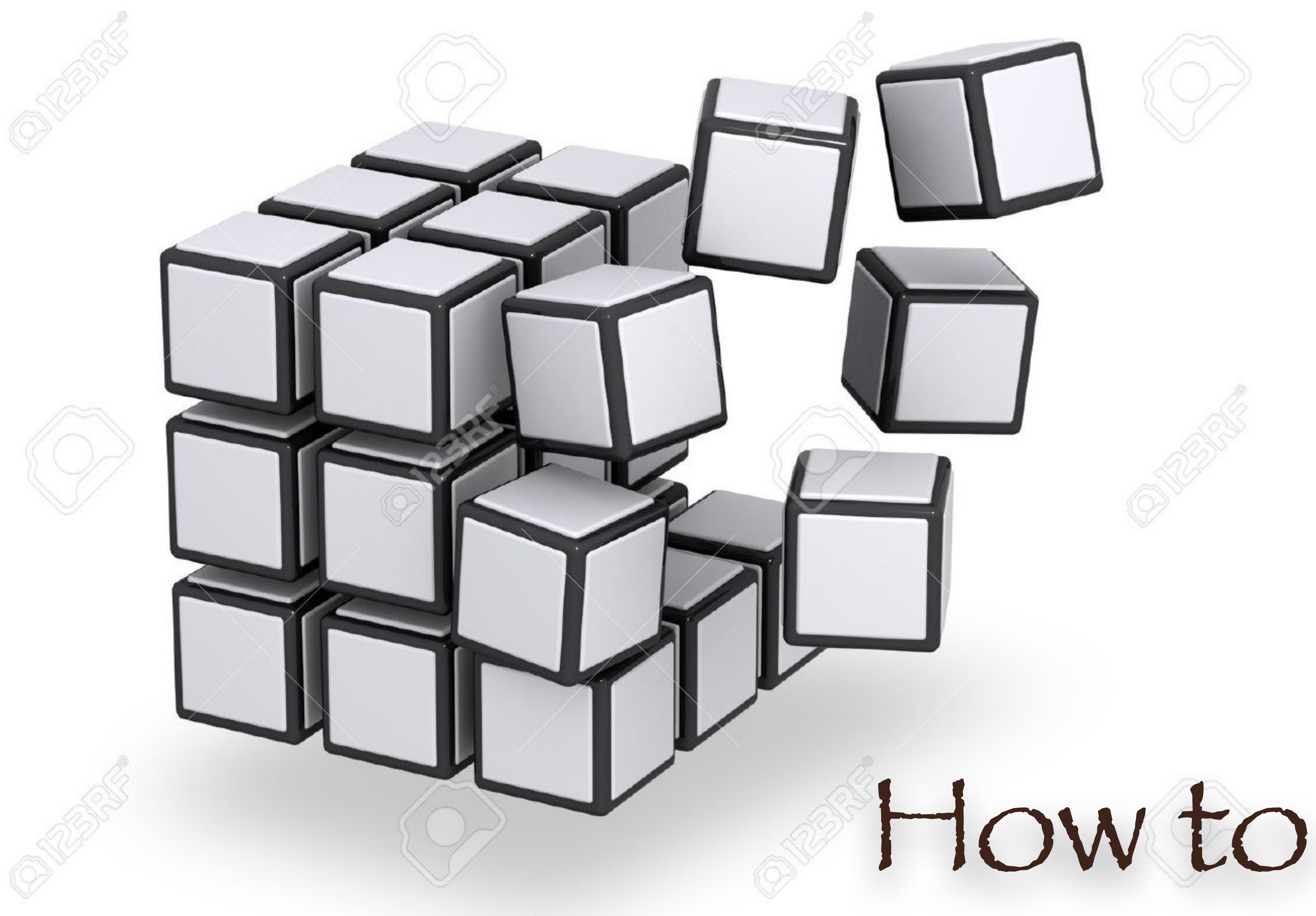




Dissociation Mode



MC GEATN4 Simulation



How to Implement Model into Event Generator

Present Preliminary Simulation Results

-> help to guide a baseline far-forward detector

Event Generator (EG)

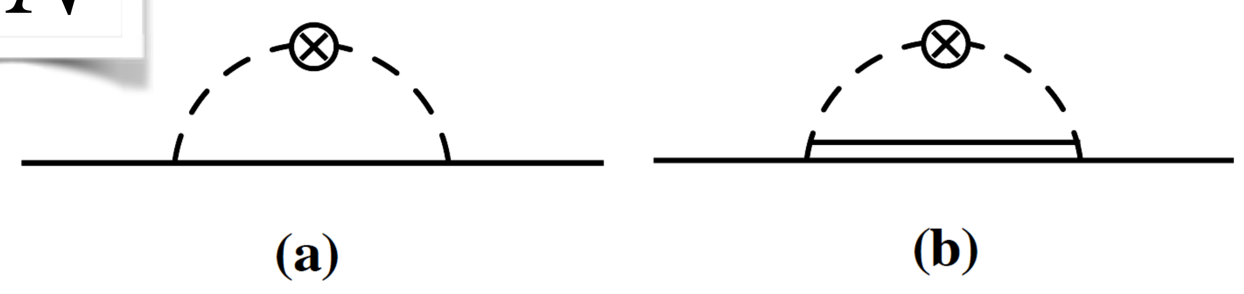
- Implementing accelerator info
  - Beam emittances($\epsilon^{n}_{e,i}$, $\beta^{*}_{e,i}$) IP, Cross-angle: 50 mrad, $[E_e x E_D] = [5\text{x}100]$ GeV^2, $p_R < 300$ MeV
  - Longitudinal p and angular spread of the beam: $dp/p = 3 \times 10^{-4}$, $d\theta = 2 \times 10^{-4}$
- User inputs:
  - cross-section model/ nucleon Struc.Func./ deuteron Wav.Func./
    pi/k single meson exchange models / various regularization forms
- Resolution and Uncertainty
  - Initial State Smearing (ISS) is $\ll \pm 1\%$
  - Intrinsic MC Statistical Uncertainty is $\leq 1\%$
  - Sufficient t' resolution for the onshell-extrapolation
  - FSI (D, on-going work, developement of theorety code)

FSI: see Wim's Talk

- Codes are built with C^{++} (phase-space) and ROOT v5.34.34 → **v6.10.02**
- Very compact and stand alone code**(running MacOS/CentOS6.5) → **CentOS7.2**
  - TDISMC_EIC.cpp, TDISMC_EIC.h for proton tagged
  - TDISMC_EICn.cpp, TDISMC_EICn.h for neutron tagged
  - Theory Inputs:
  - moment_ld2b.dat
  - cteq/cteqpdf.h
  - cteq-tbls/ctq66m/ctq66.00.pds
- Produce outputs: (various output formats)
  - TDIS-MC05x100.root (Ntuple/Histograms) **evio/ROOT for GEANT4**
  - TDIS_lund.txt (ASCII/GEMC Input)

Feynman diagrams

πN



(a) a nucleon (solid lines)

(b) a Δ isobar (double solid line)

P. Kroll and S. Goloskov, Eur. Phys. J **A47** 112 (2011).

Model dependence: coupling constant

$g_{\pi NN} = 13.1$	$g_{K^+ p\Lambda} = -13.3$	$g_{K^+ p\Sigma} = -3.5$

Model dependence: various regularization form

$F = \left(\frac{\Lambda_t^2 - m_K^2}{\Lambda_t^2 - t}\right)$	t-dependent monopole	In Code
$F = exp[(M^2 - s)/\Lambda_s^2]$	s-dependent exponential	In Code

Splitting functions

$$f_N^{(\mathrm{on})}(y) = \frac{g_A^2 M^2}{(4\pi f_\pi)^2} \int dk_\perp^2 \frac{y\,(k_\perp^2 + y^2 M^2)}{(1-y)^2 D_{\pi N}^2}$$

arXiv.org > hep-ph > arXiv:1512.04459

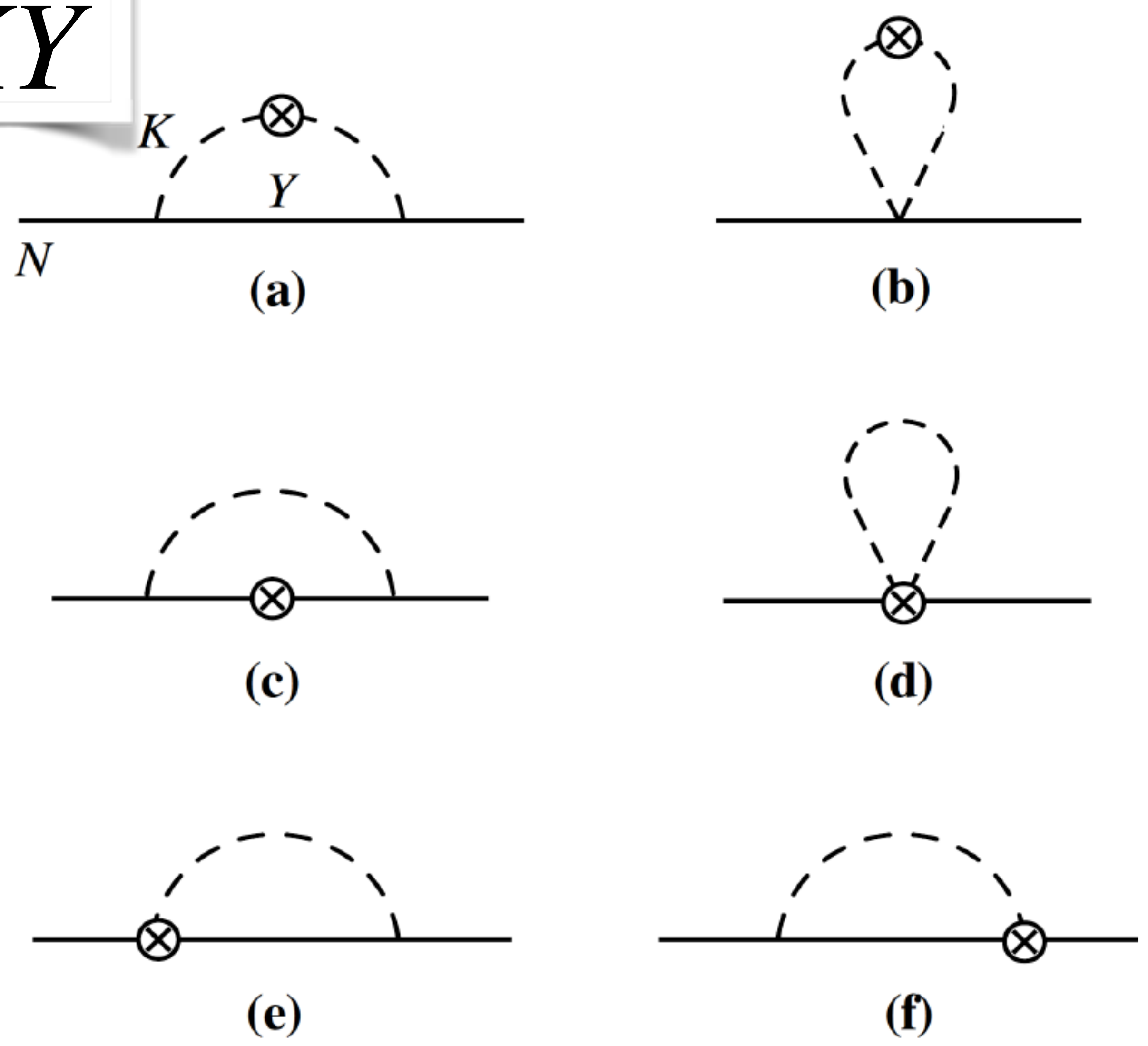
High Energy Physics – Phenomenology

Pion structure function from leading neutron electroproduction and SU(2) flavor asymmetry

J. R. McKenney, Nobuo Sato, W. Melnitchouk, Chueng-Ryong Ji

(Submitted on 14 Dec 2015)

KY



- (a) kaon rainbow
  $f_{KY}^{(rbw)}(y) = \kappa \left[f_Y^{(on)}(y) + f_K^{(\delta)}(y) \right]$
- (b) kaon buble diagram ($\bar{s}$ PDFs)
  $= f_K^{(bub)}(y)$
- (c) Hyperon rainbow
  $= f_{YK}^{(rbw)}(y)$
- (d) kaon tadpole (s PDFs)
  $= f_K^{(tad)}(y)$
- (e), (f) Kroll-Ruderman diagrams
  $= f_{YK}^{(KR)}(y)$

$$f_Y^{(on)}(y) = y \int dk_\perp^2 \frac{k_\perp^2 + (My + \Delta)^2}{(1-y)^2 D_{KY}^2} F$$

arXiv.org > hep-ph > arXiv:1610.03333

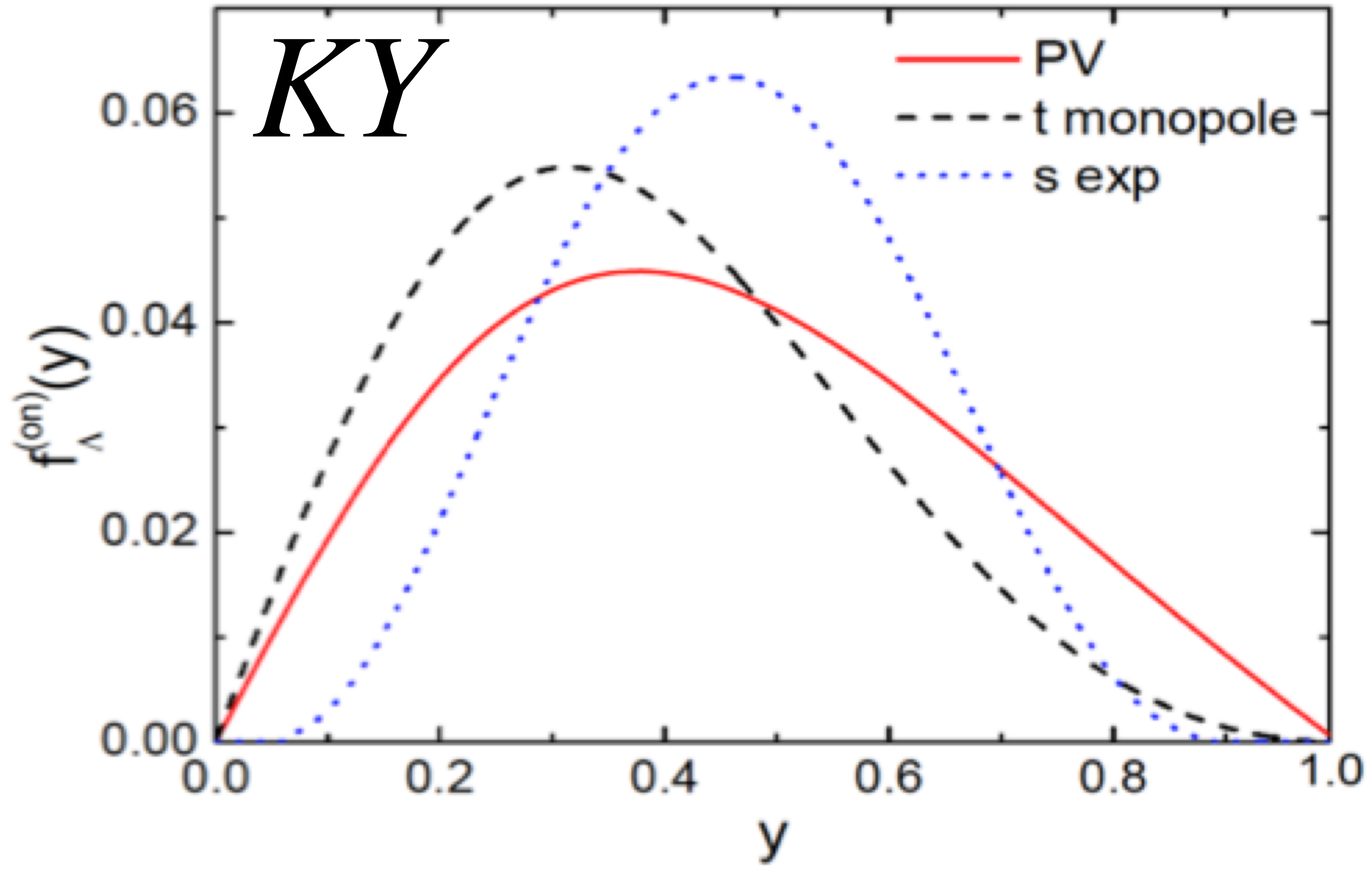
High Energy Physics – Phenomenology

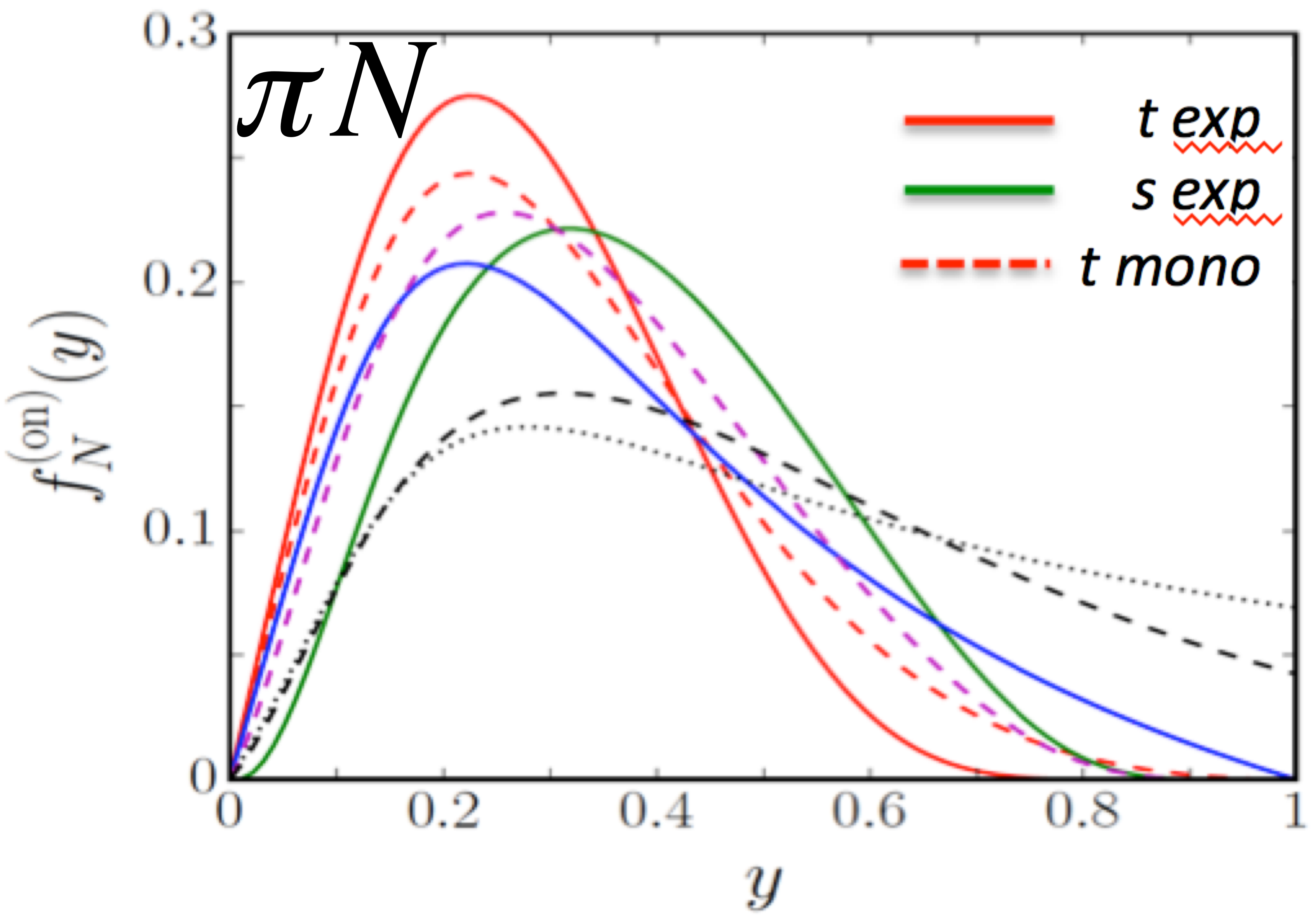
Strange quark asymmetry in the proton in chiral effective theory

X.G. Wang, Chueng-Ryong Ji, W. Melnitchouk, Y. Salamu, A.W. Thomas, P. Wang

(Submitted on 11 Oct 2016)

On-shell Splitting Functions





Meson exchange model

$F = \exp\left[(t - m_\pi^2)/\Lambda^2\right]$ [t-dependent exponential],

$F = \exp\left[(M^2 - s)/\Lambda^2\right]$ [s-dependent exponential],

$F = \left[1 - \frac{(t - m_\pi^2)^2}{(t - \Lambda^2)^2}\right]^{1/2}$ [Pauli-Villars].

$F = y^{-\alpha_\pi(t)} \exp\left[(t - m_\pi^2)/\Lambda^2\right]$ [Regge exponential],

$F = \left(\frac{\Lambda^2 - m_\pi^2}{\Lambda^2 - t}\right)$ [t-dependent monopole].

This F.F. is also in the code

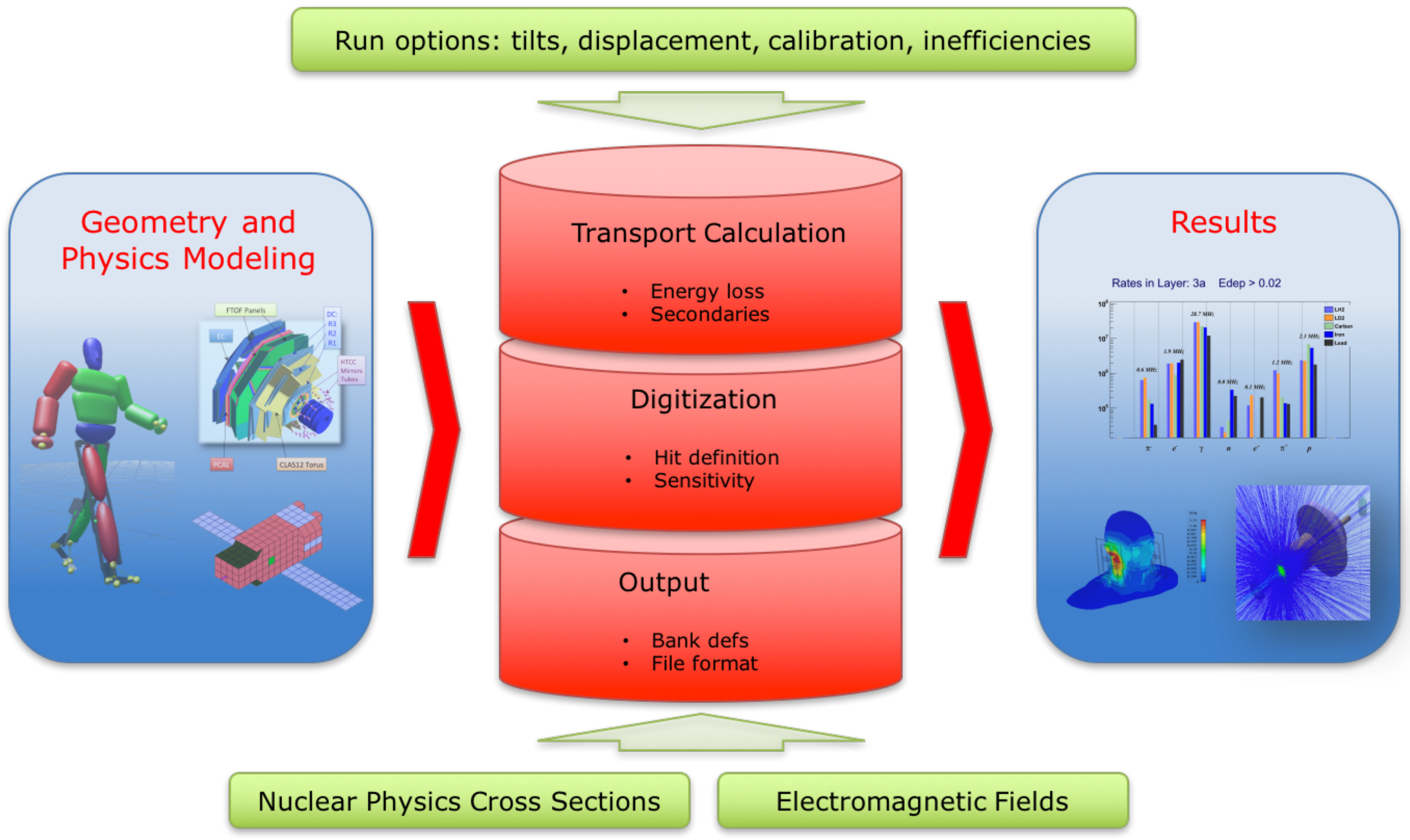
$F = y^{-\alpha_\pi(t)}$ [Bishari],

Model Dependent Regularization Form

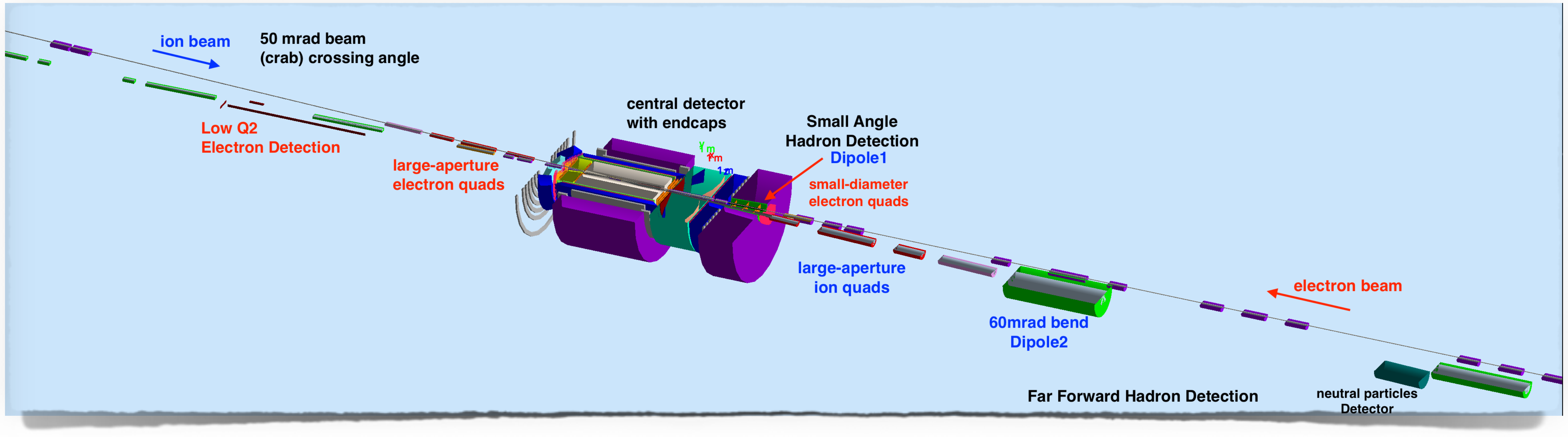
Detector Simulation for Acceptance

Plug event into GEMC: 5x100 GeV2, e/p beams

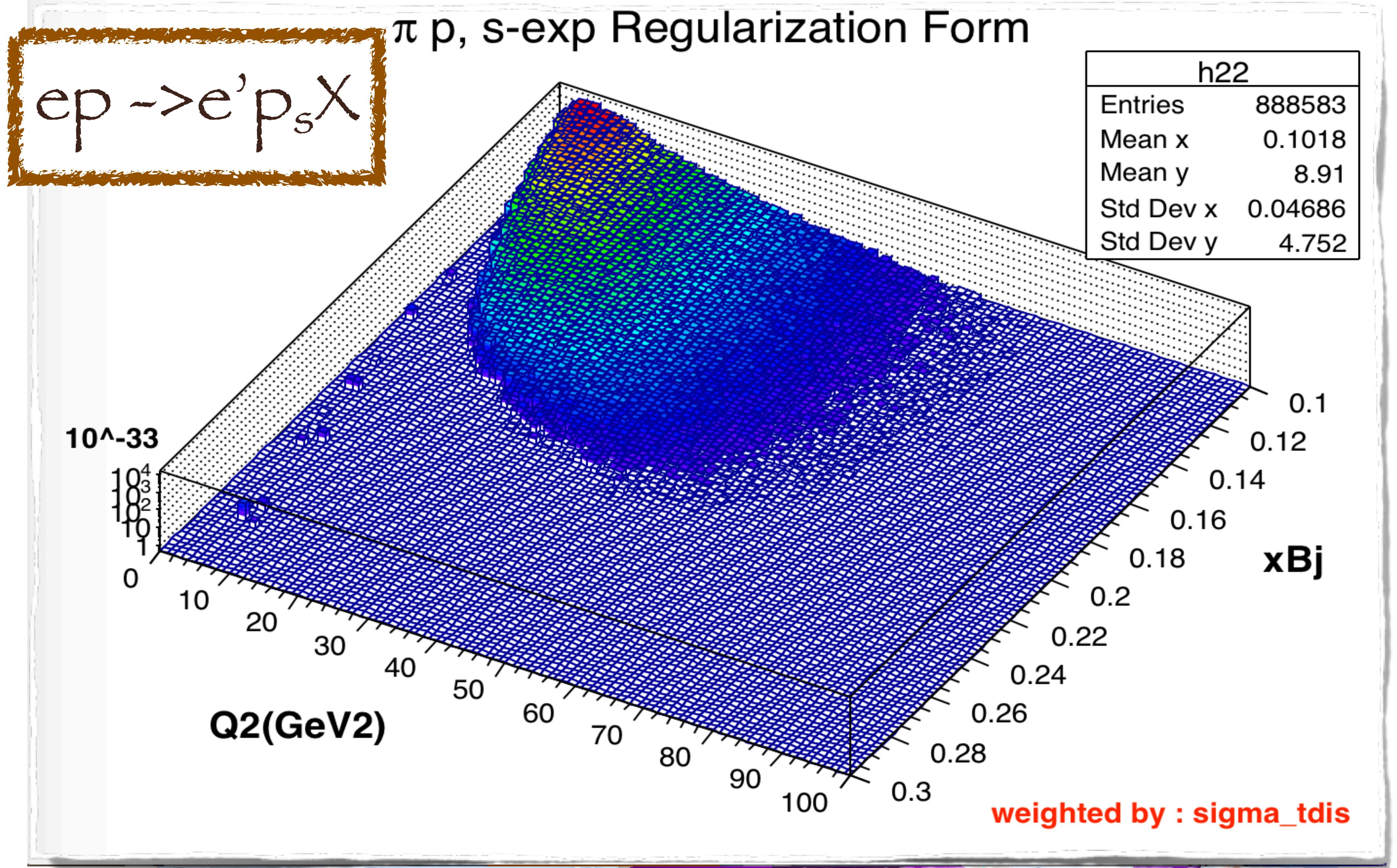
GEANT4MC



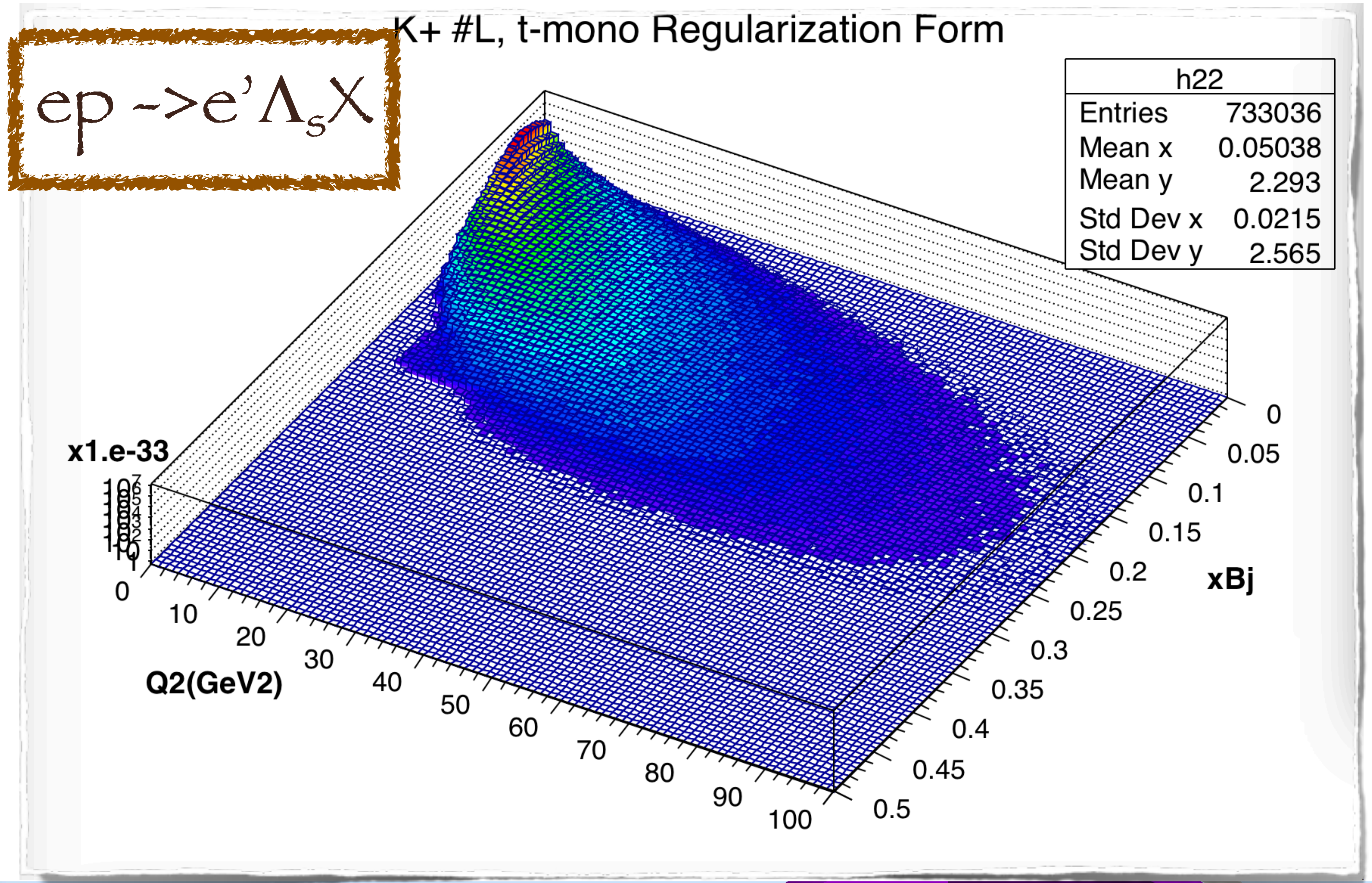
The architecture of gemc



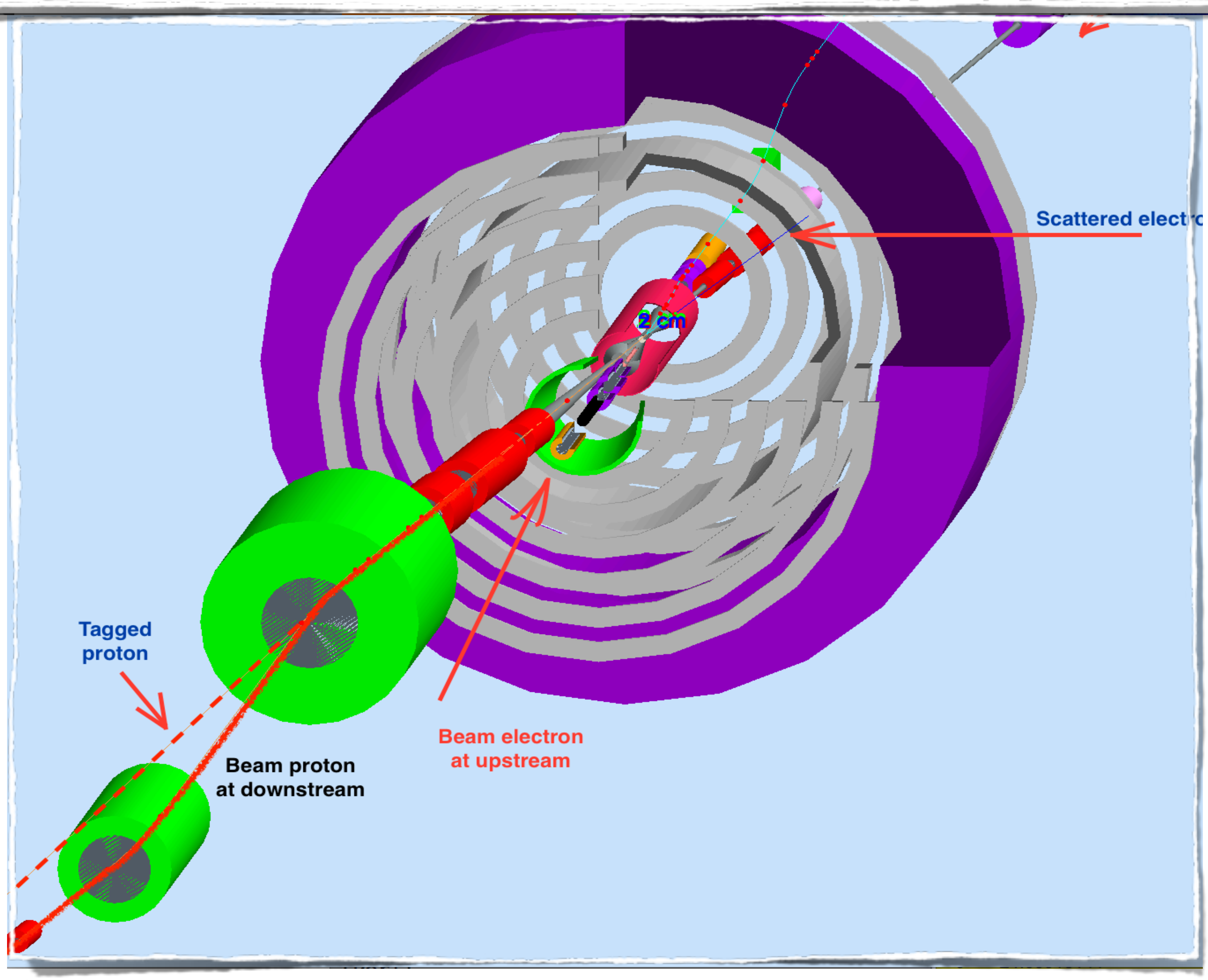
JLEIC Design Overview: see Vasiliy's Talk



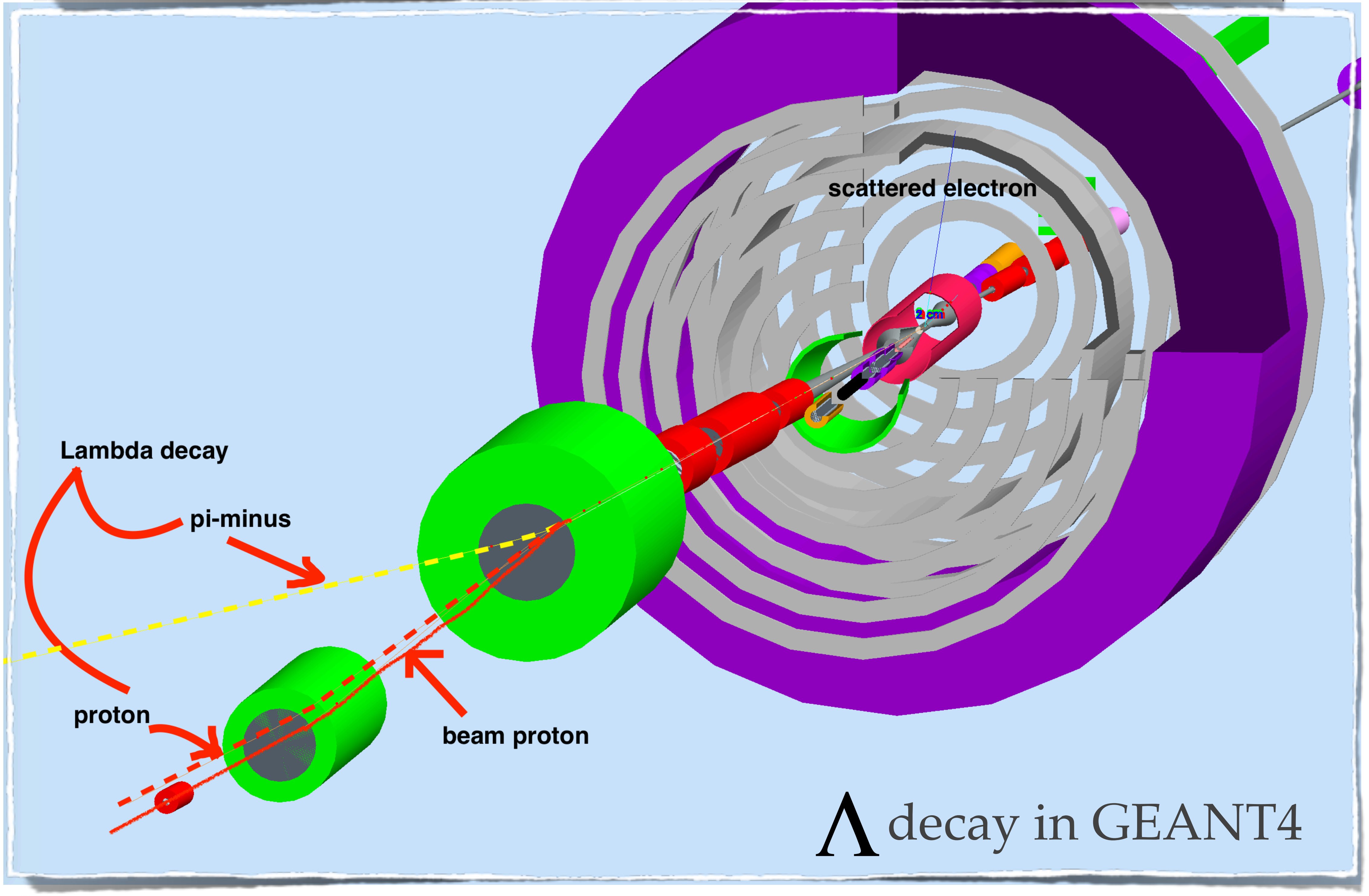
ep ->e'p$_s$X
π p, s-exp Regularization Form
h22
Entries 888583
Mean x 0.1018
Mean y 8.91
Std Dev x 0.04686
Std Dev y 4.752
10^-33
Q2(GeV2)
xBj
weighted by : sigma_tdis



ep ->e'Λ$_s$X
K+ #L, t-mono Regularization Form
h22
Entries 733036
Mean x 0.05038
Mean y 2.293
Std Dev x 0.0215
Std Dev y 2.565
x1.e-33
Q2(GeV2)
xBj



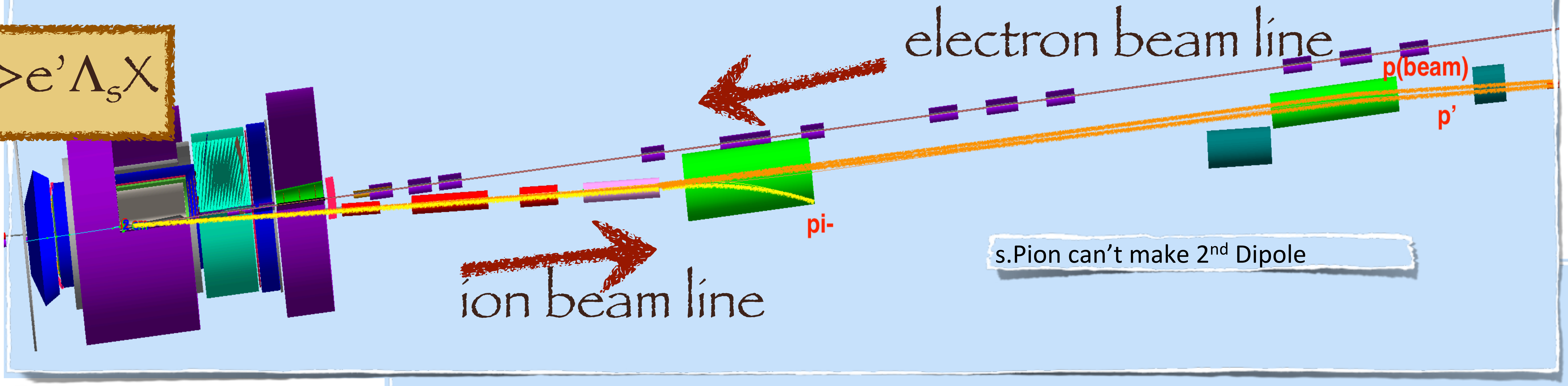
Scattered electr
Tagged proton
Beam proton at downstream
Beam electron at upstream

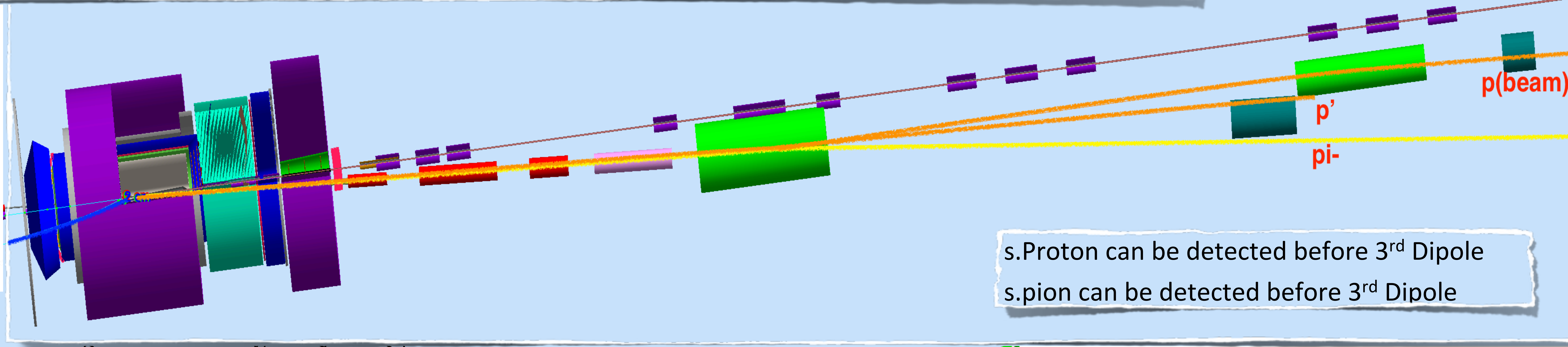


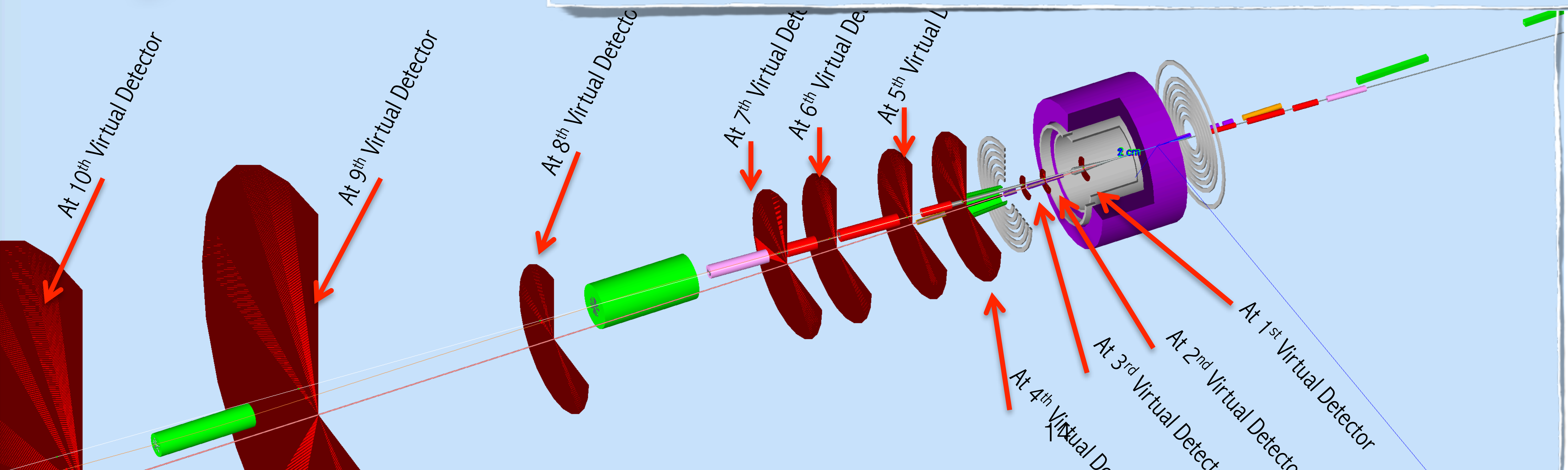
scattered electron
Lambda decay
pi-minus
proton
beam proton
Λ decay in GEANT4

$ep \to e'\Lambda_s X$

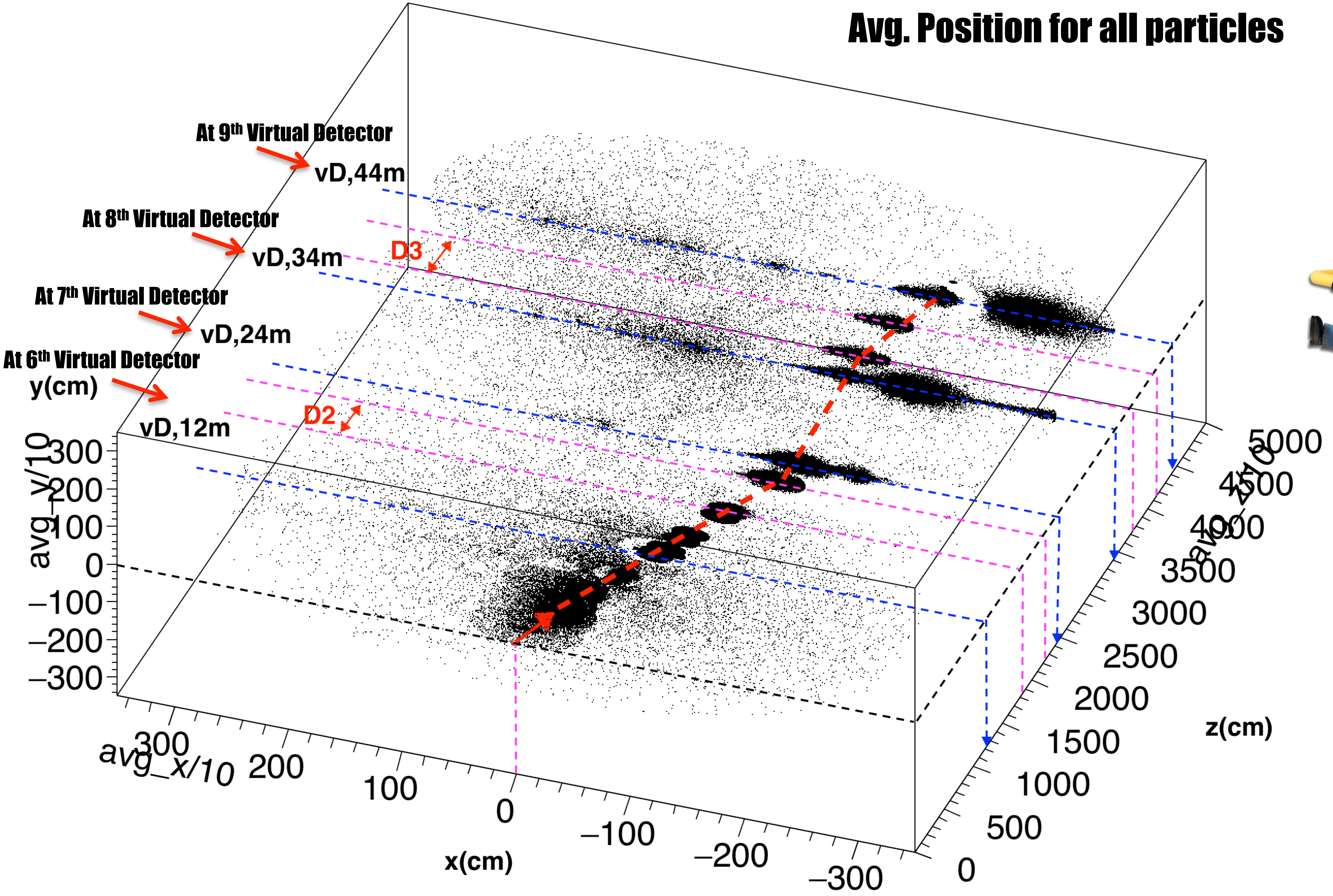
Particle Trajectory



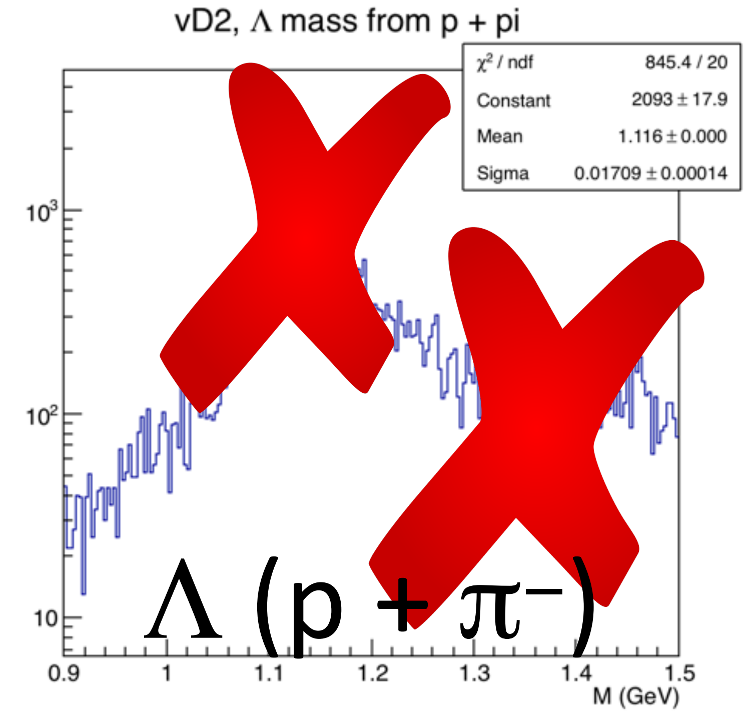


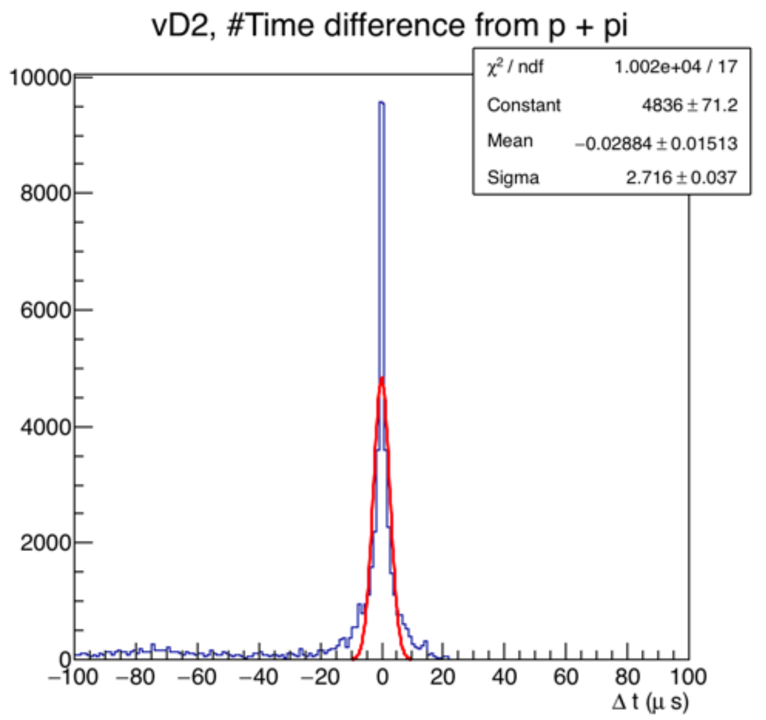


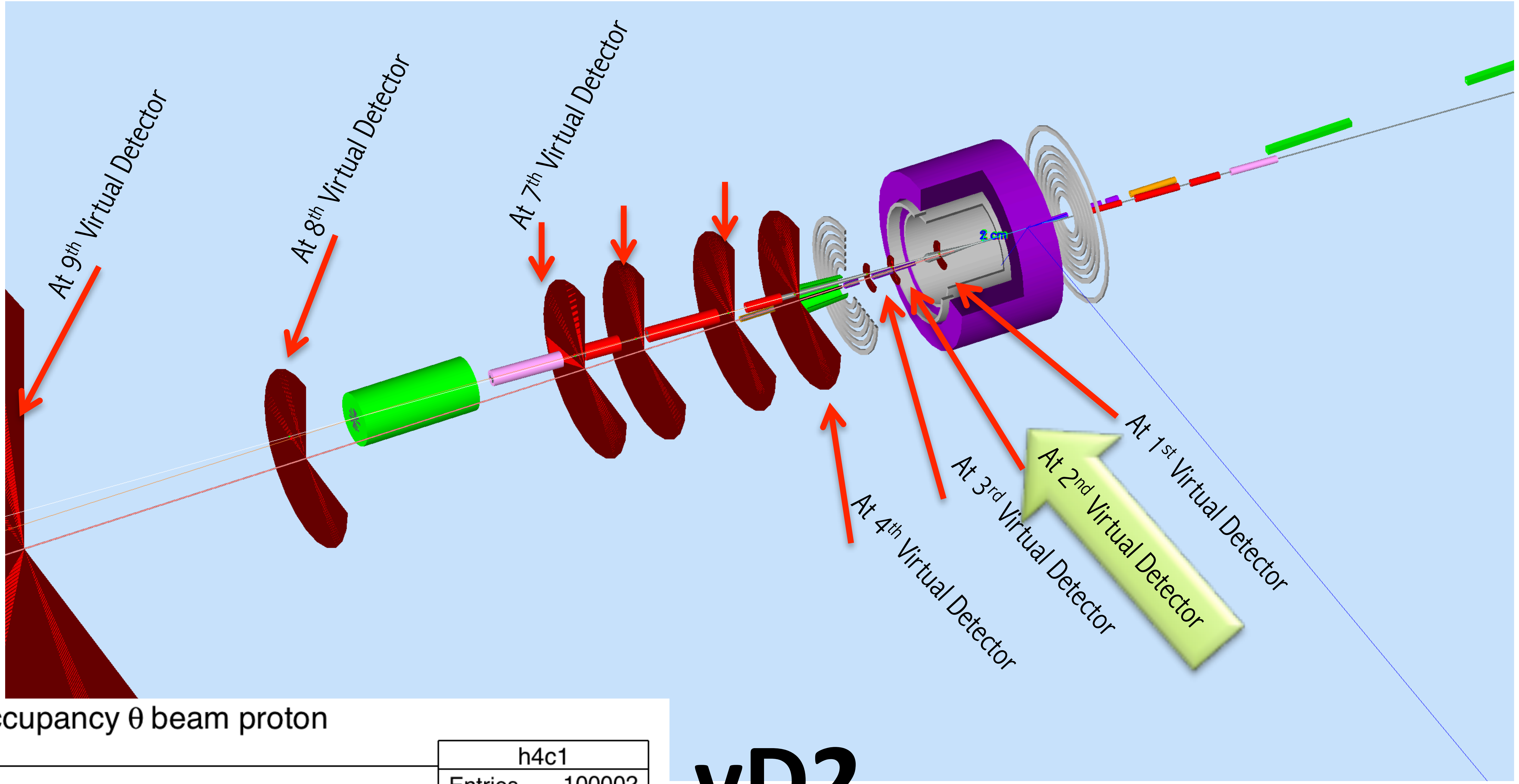
Avg. Position for all particles



Before 1st Dipole

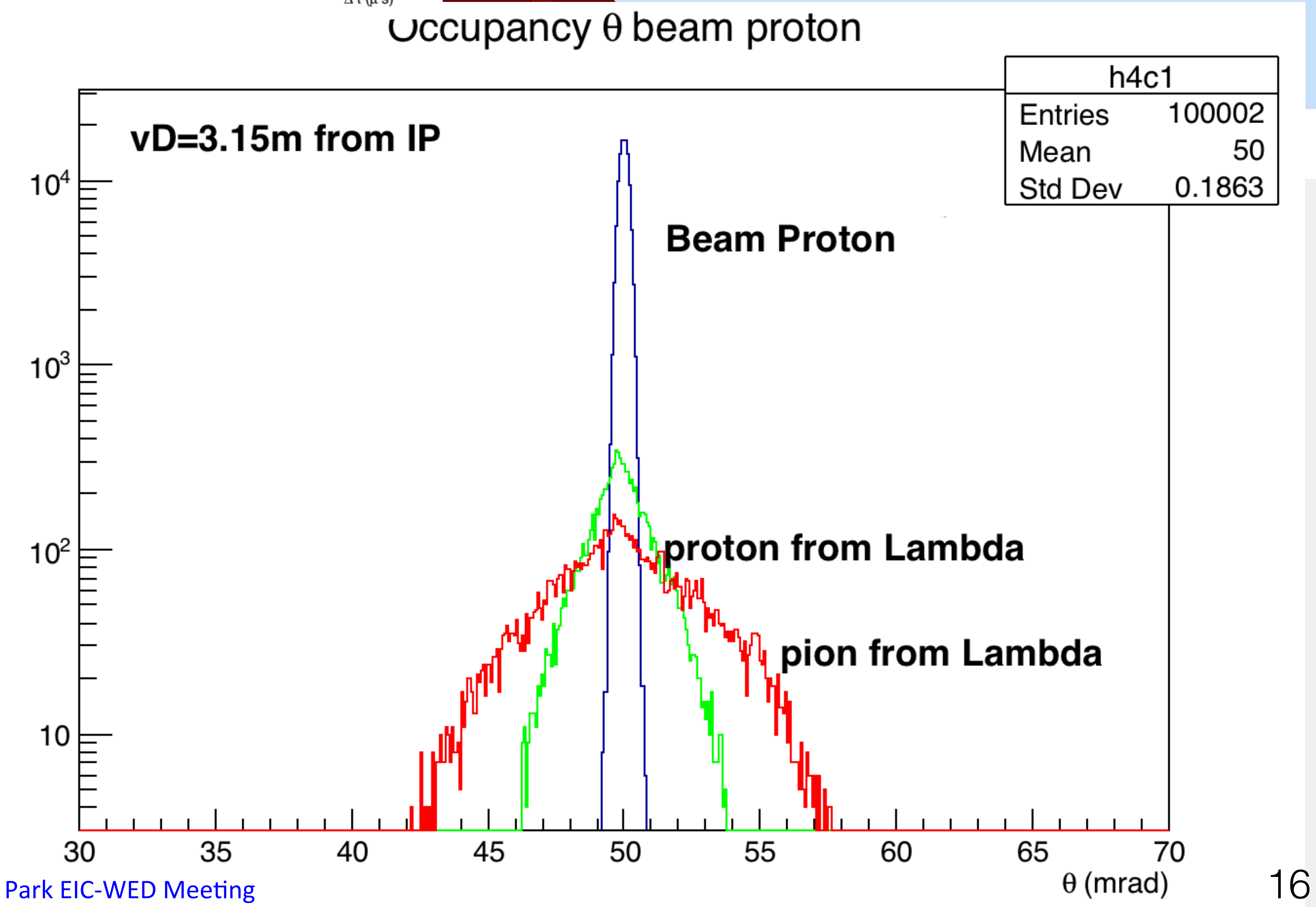


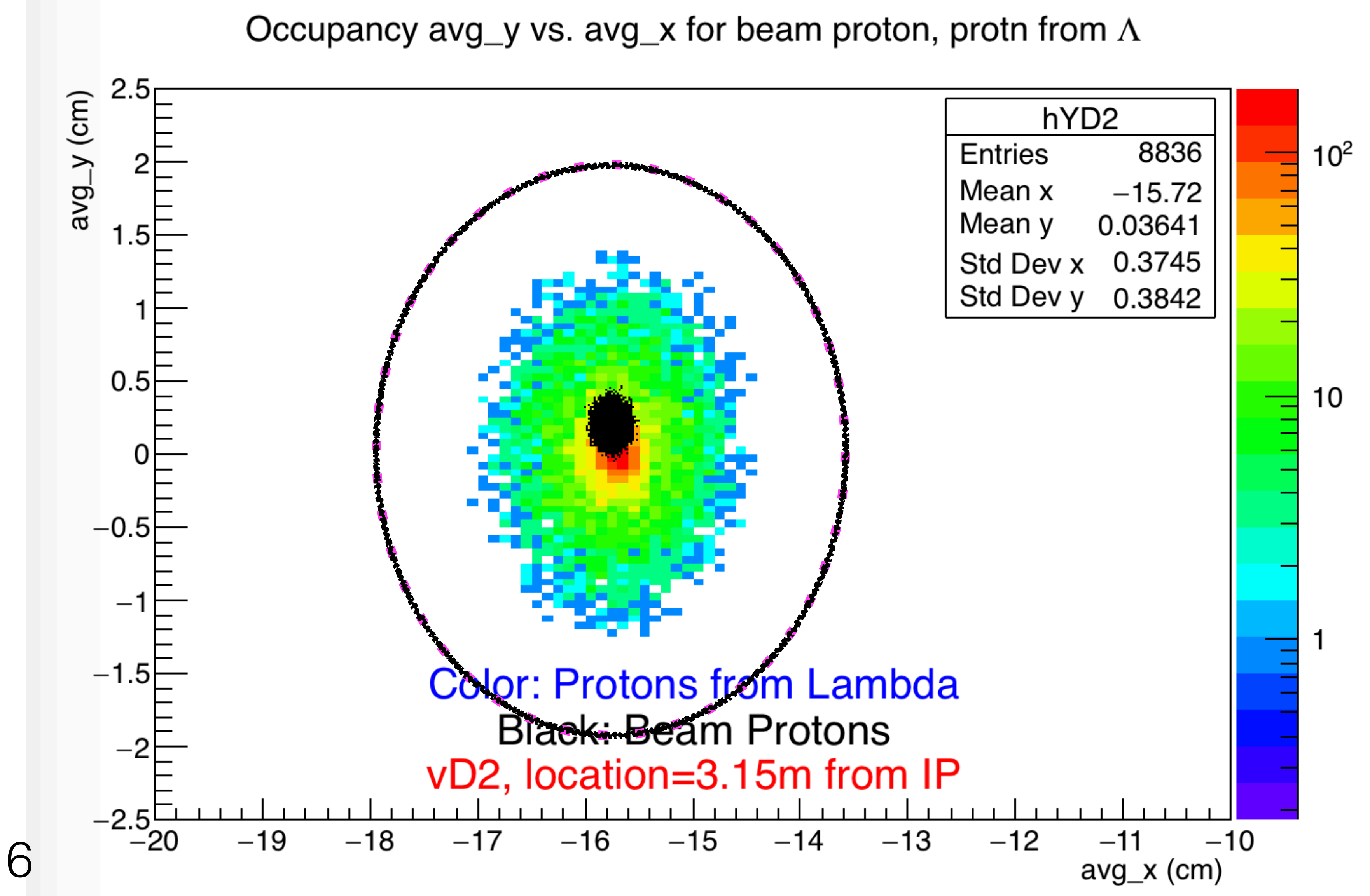


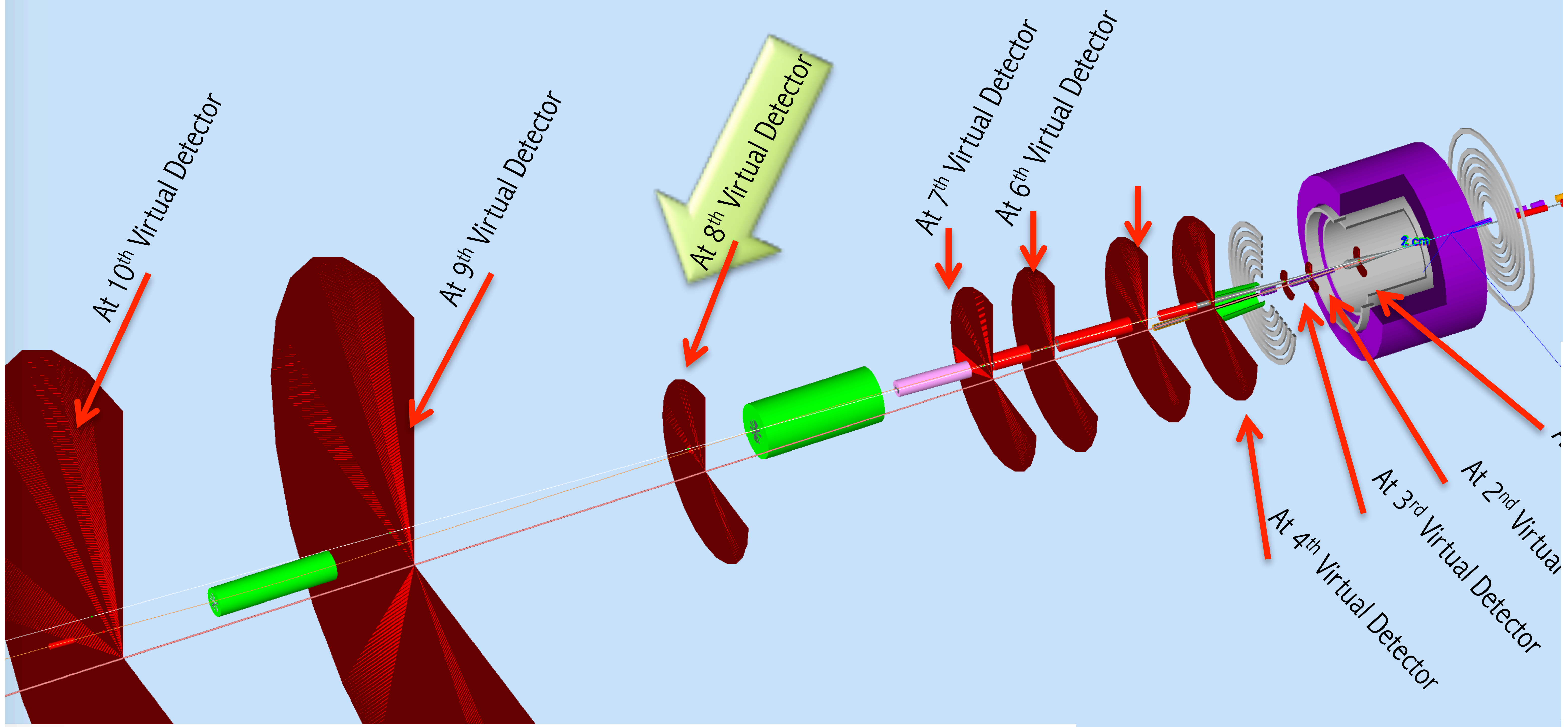


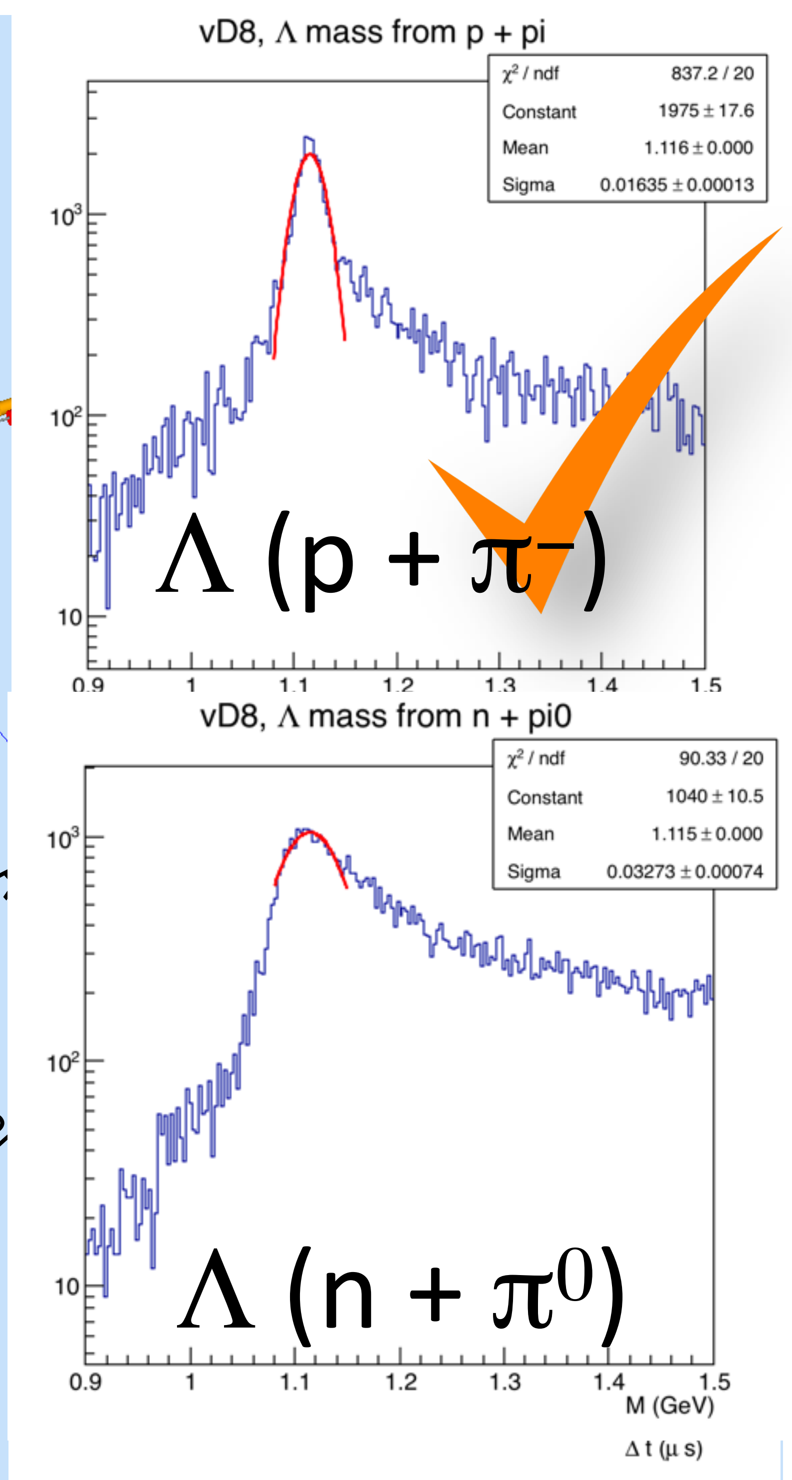
Dark red-disks are virtual detectors

vD2

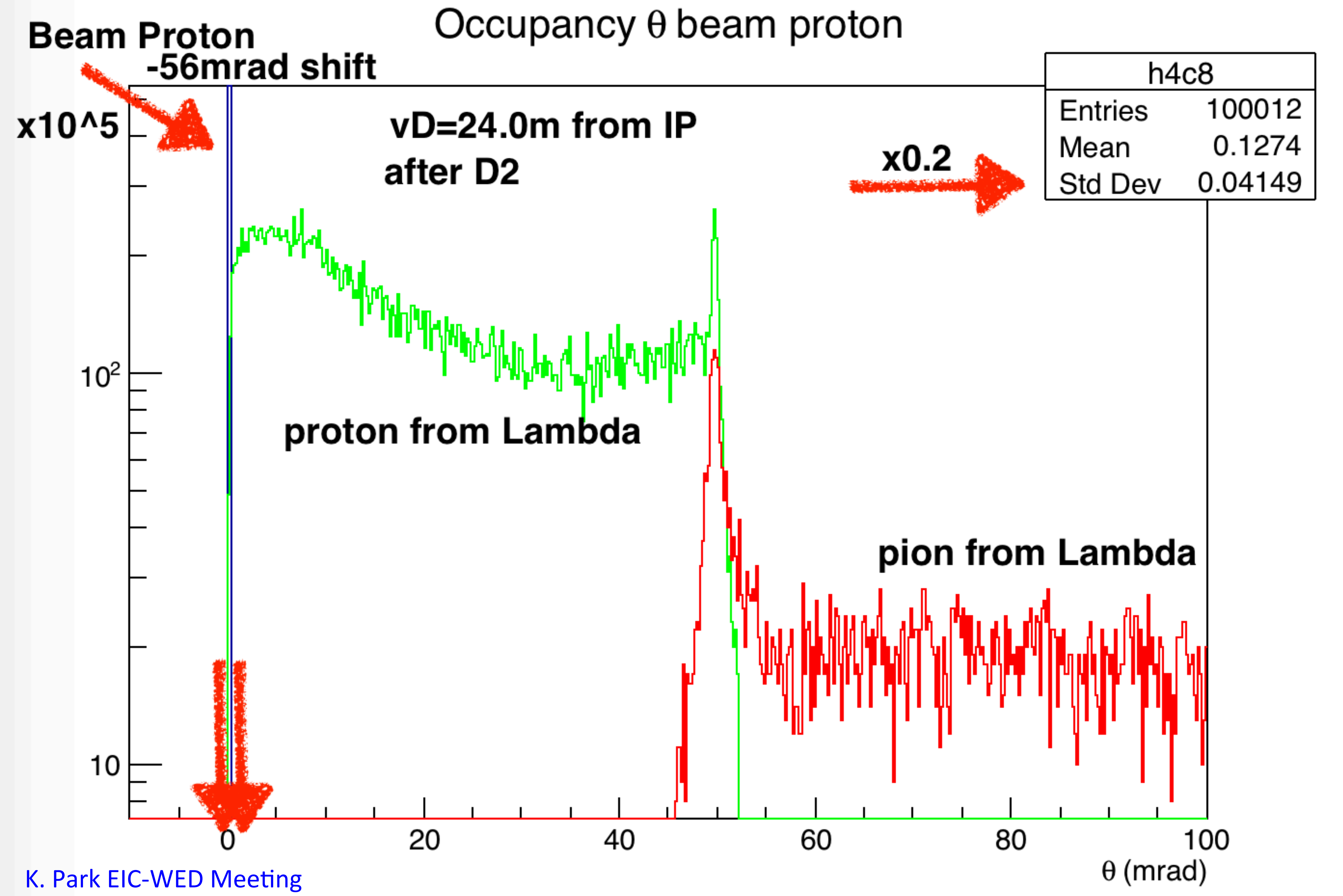




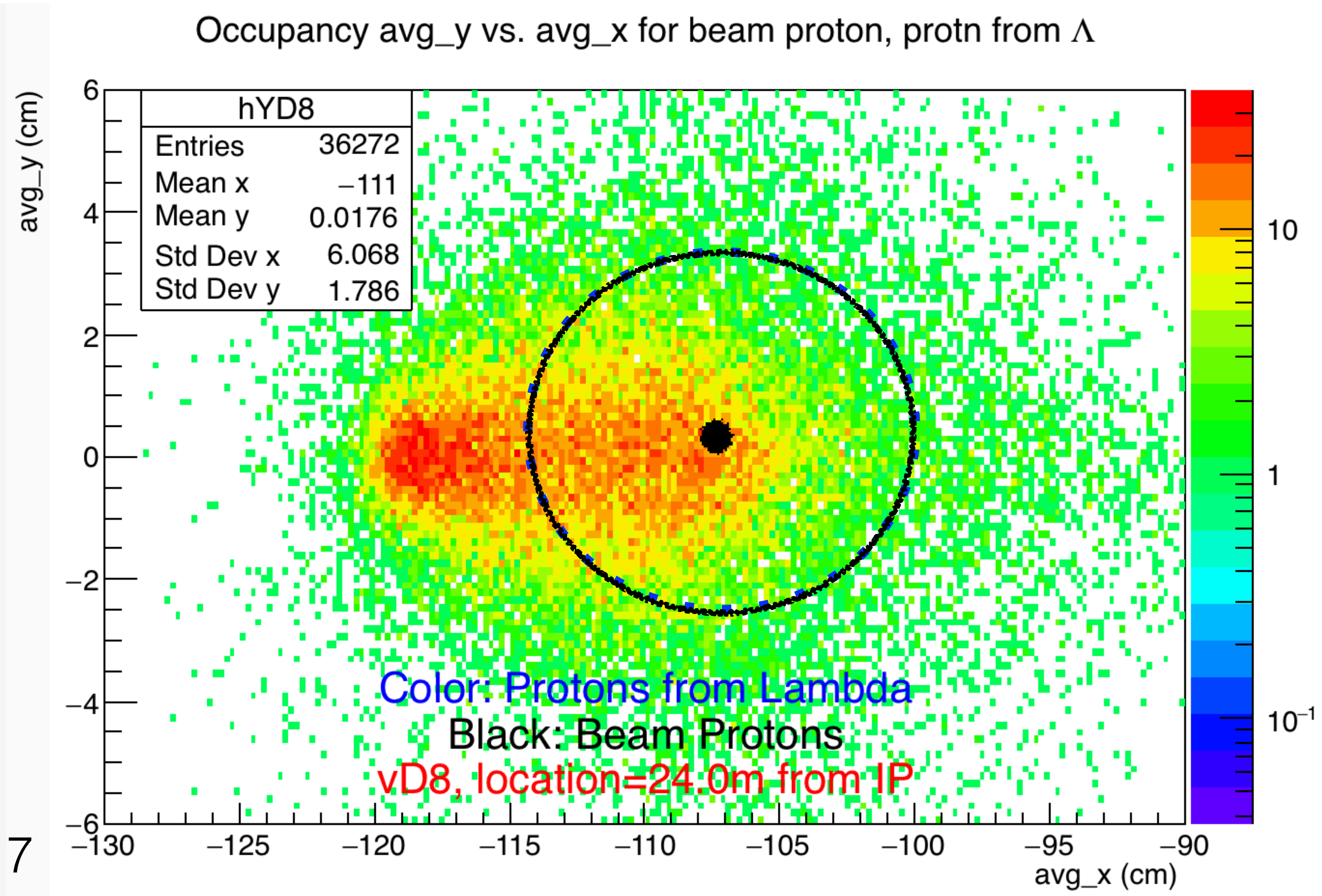




Between 2nd and 3rd Dipoles

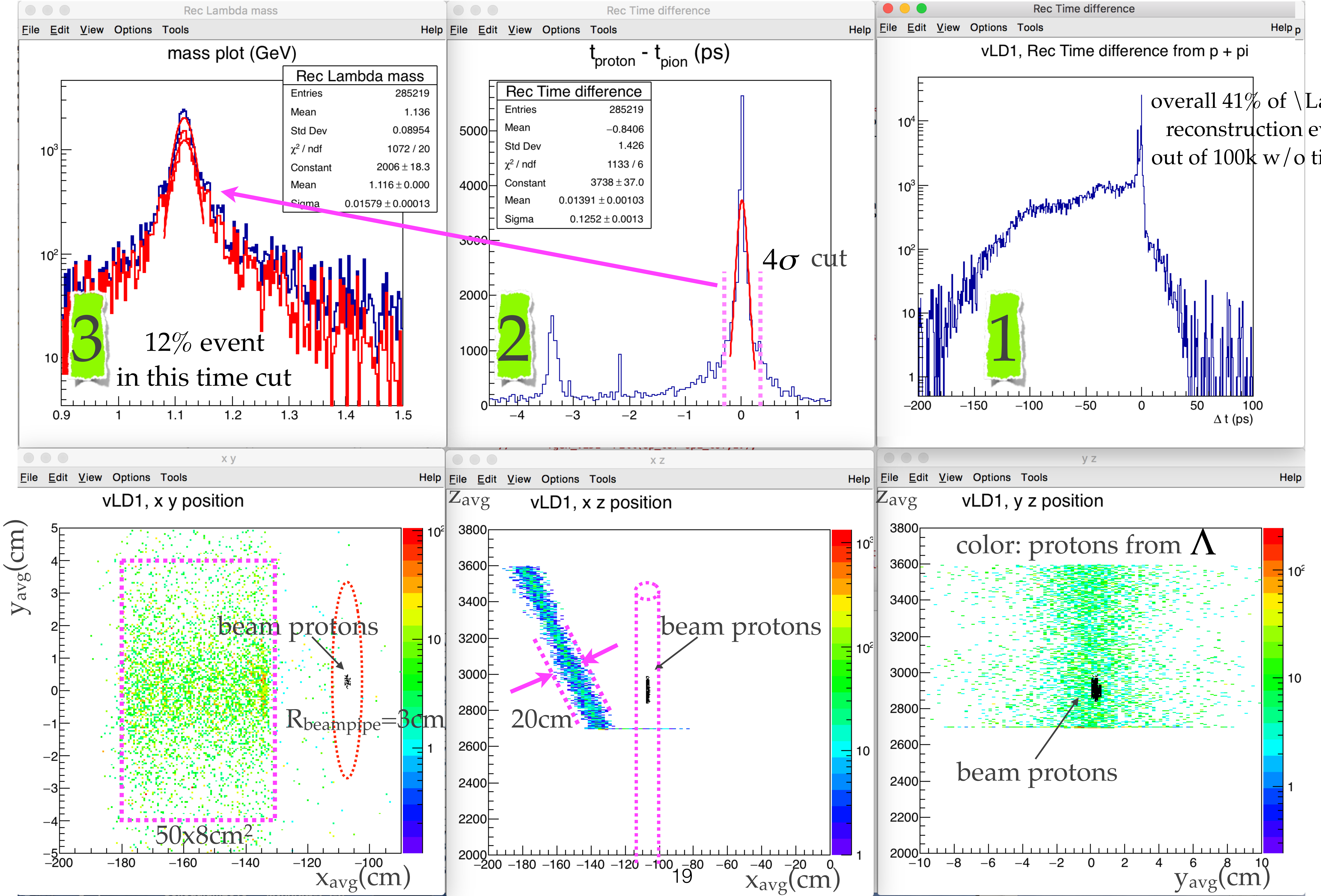


vD8



let's build giant virtual detector cover this region

angle between 2nd and 3rd Dipoles:
= 7.697701e-03 rad

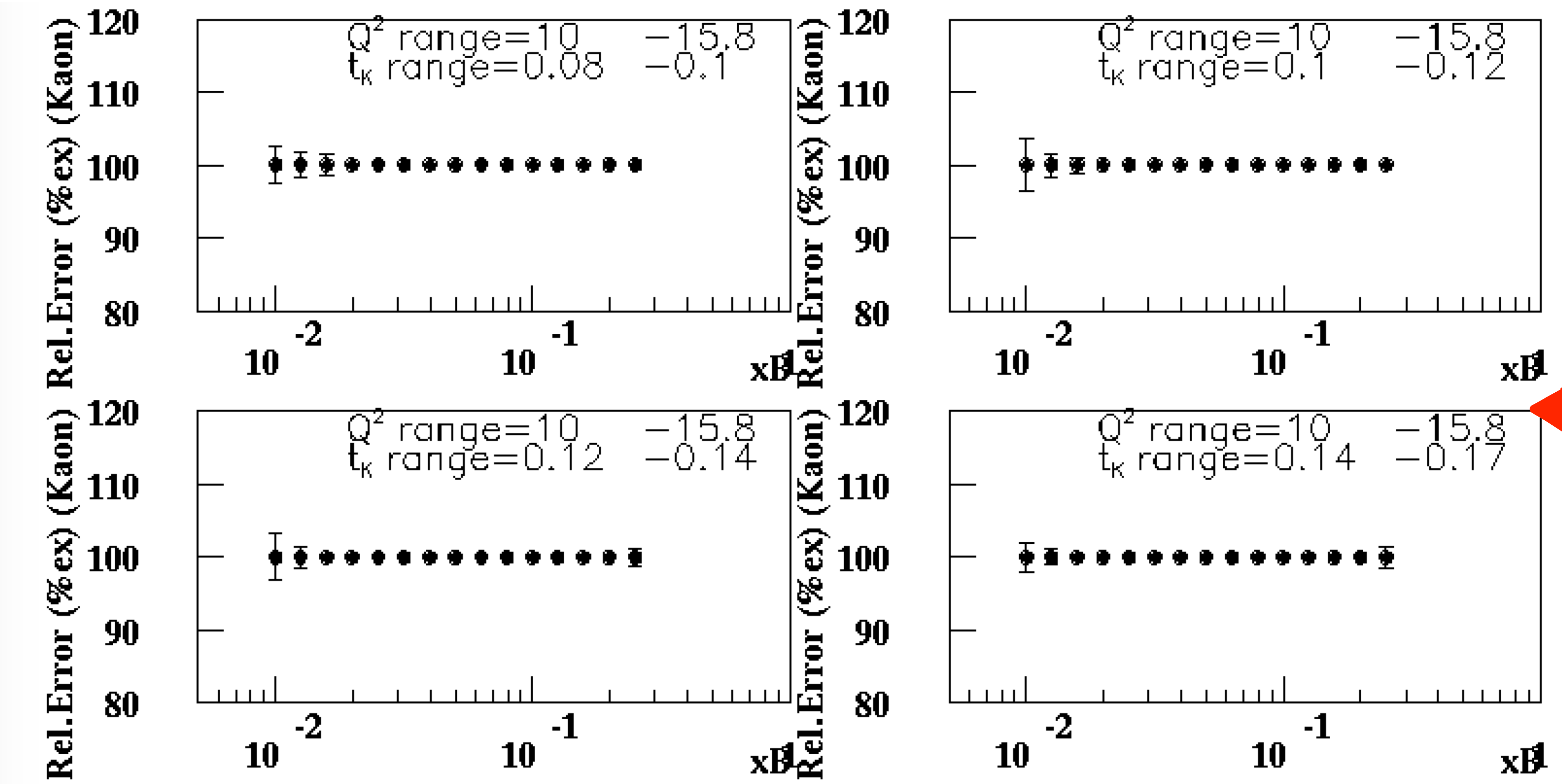


Reconstructed Mass , Time

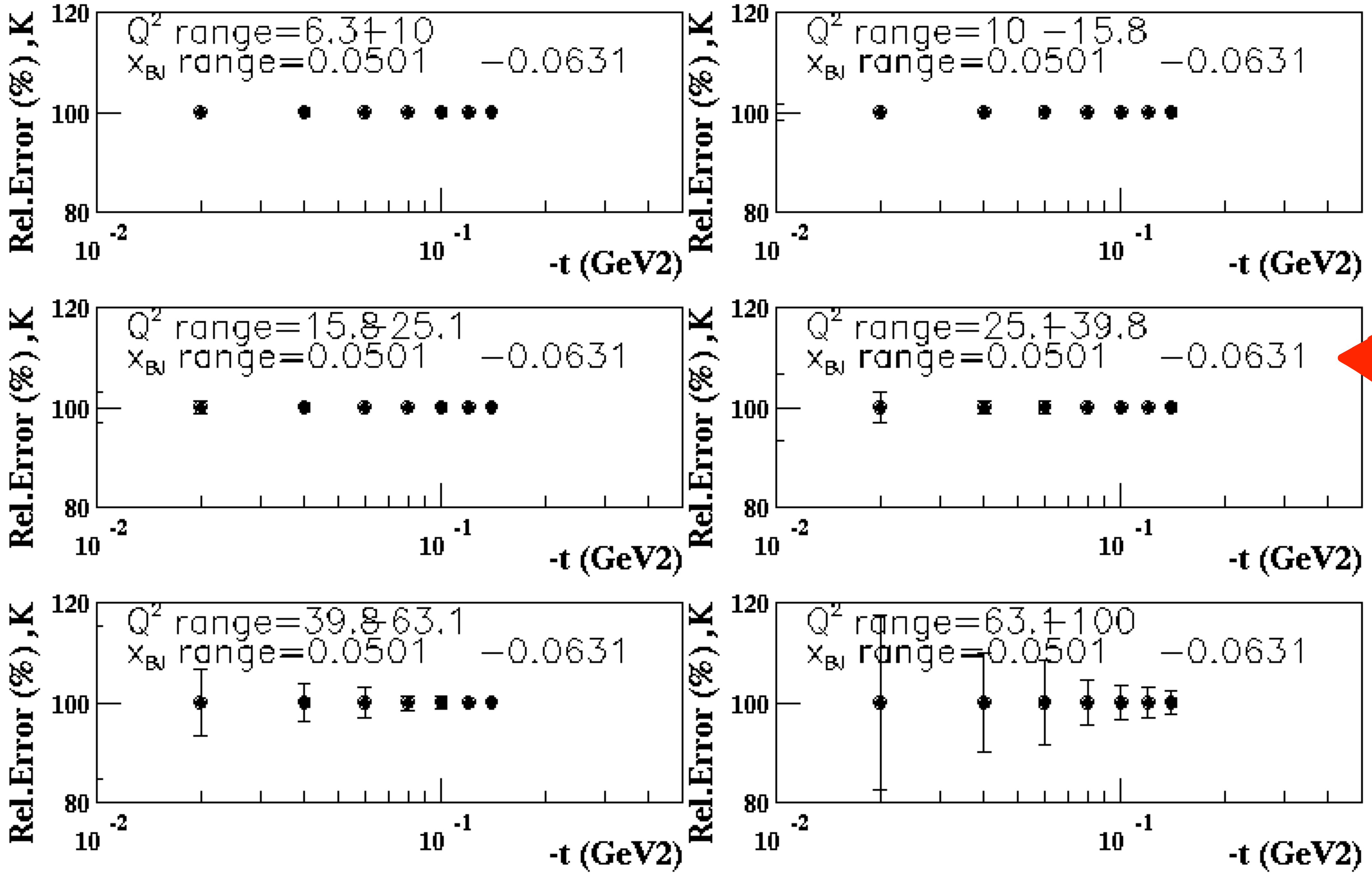
Global coordinate

Estimation of Errors

kaon TDIS



x_B dependence
middle Q^2



Q^2 dependence
small x_B

$\mathcal{L}_{int} \approx 100 fb^{-1}$

$Br_{Decay} \approx 0.64 (p, pi-)$

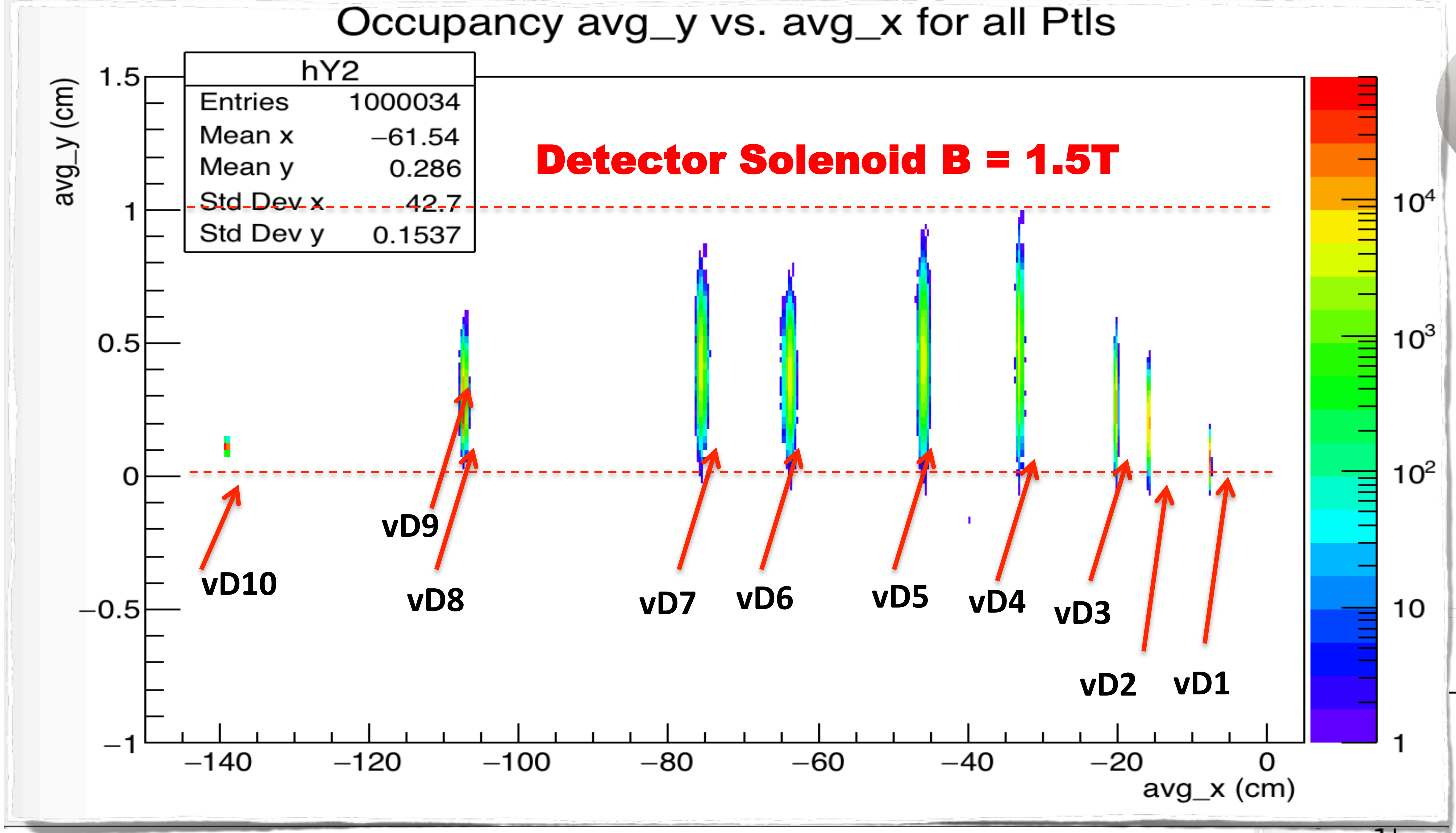
Statistics Error≈ $1/\sqrt{N}$

Summary

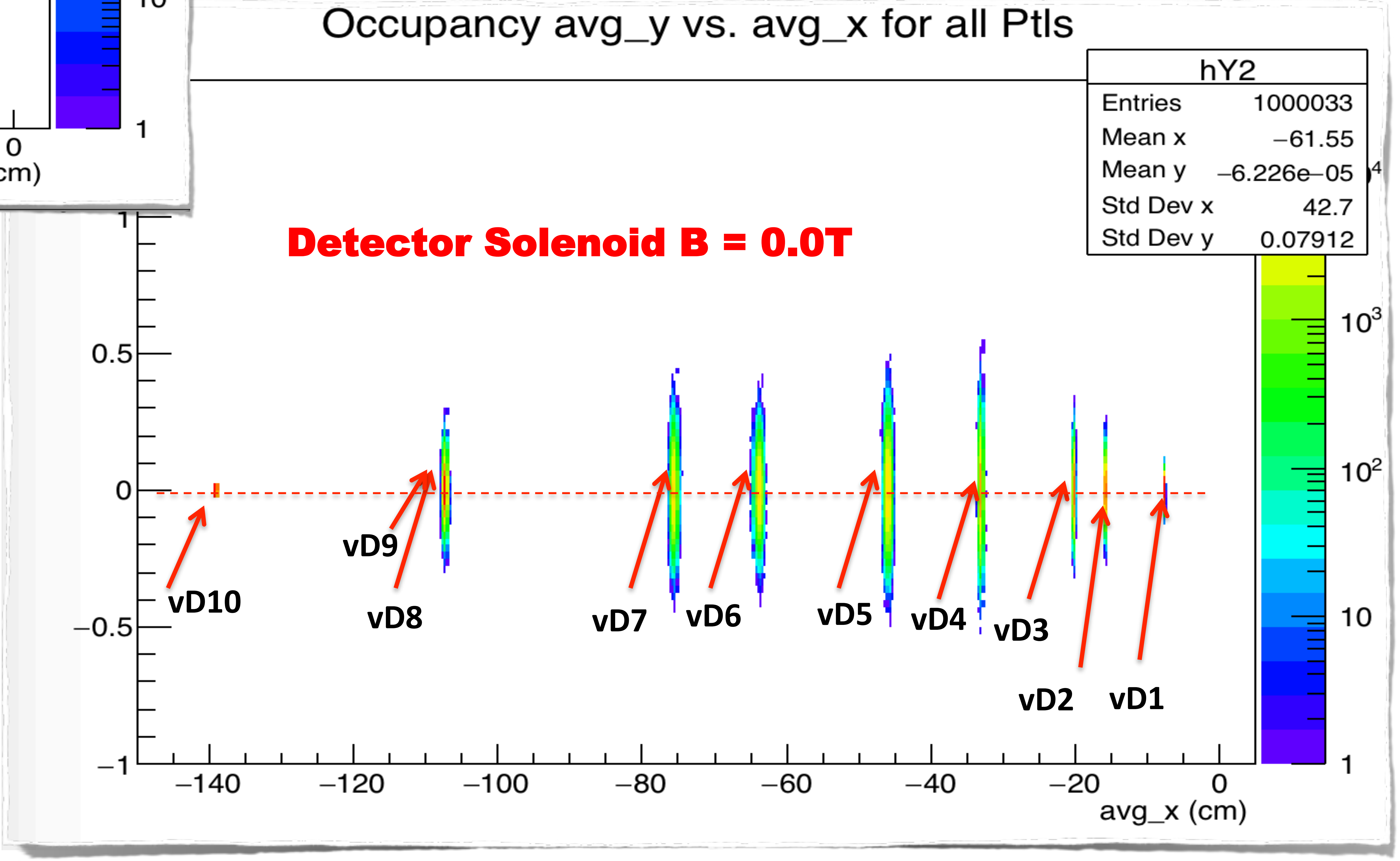
TDIS technique allows to probe the partonic components of the meson cloud of the nucleon

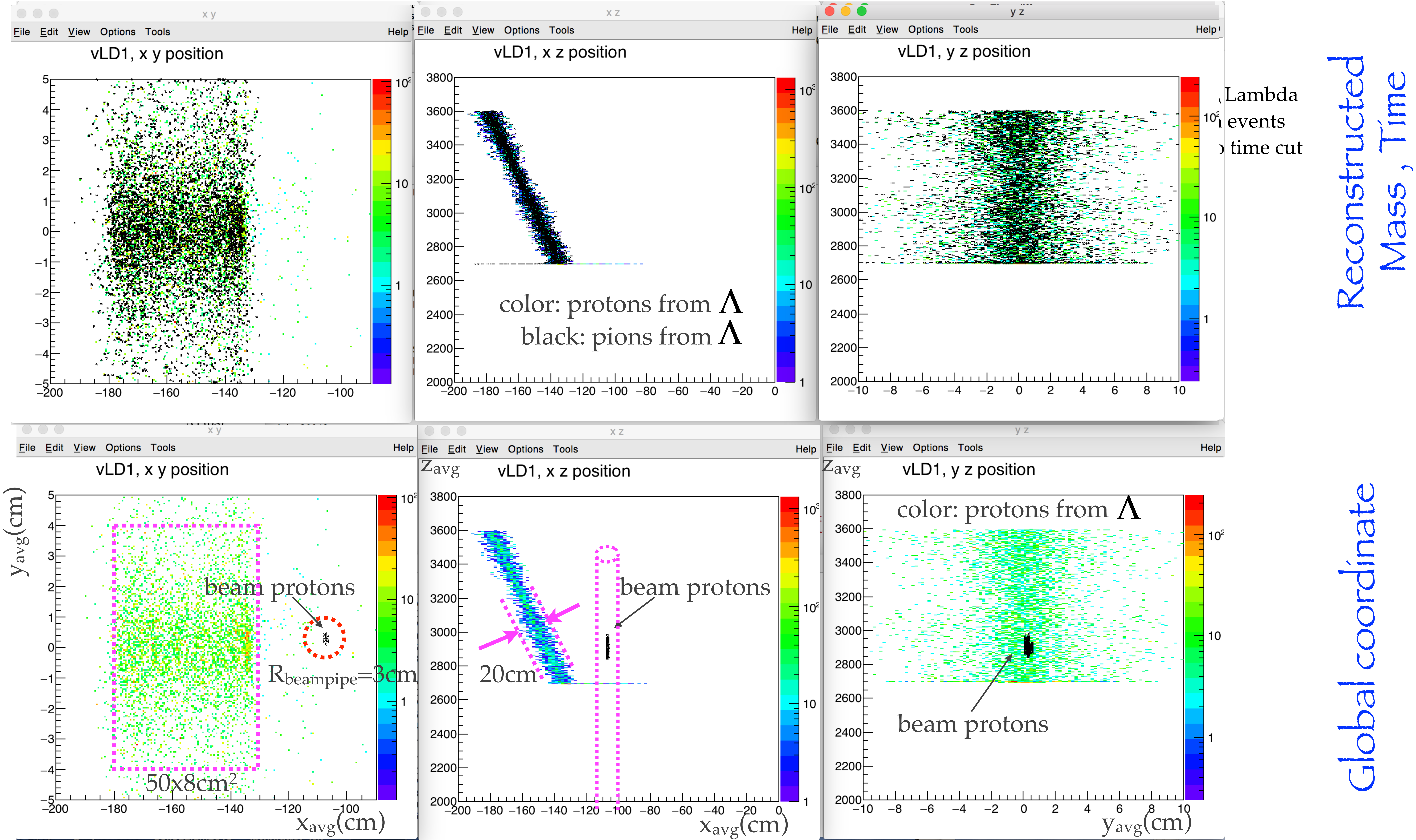
- Limited (pion) / no (kaon) experiment at all
- Address what part of the nucleon pdf comes from the mesonic component
- Help to understand flavor asymmetry of the nucleon sea
- Extraction of the pion and kaon structure functions
  - ➡ Fundamental QCD
  - ➡ The result of the studies is that one can use the Sullivan process to probe pion/kaon structure.

Thank you
for your attention!



Detail simulation provides a useful feedback !

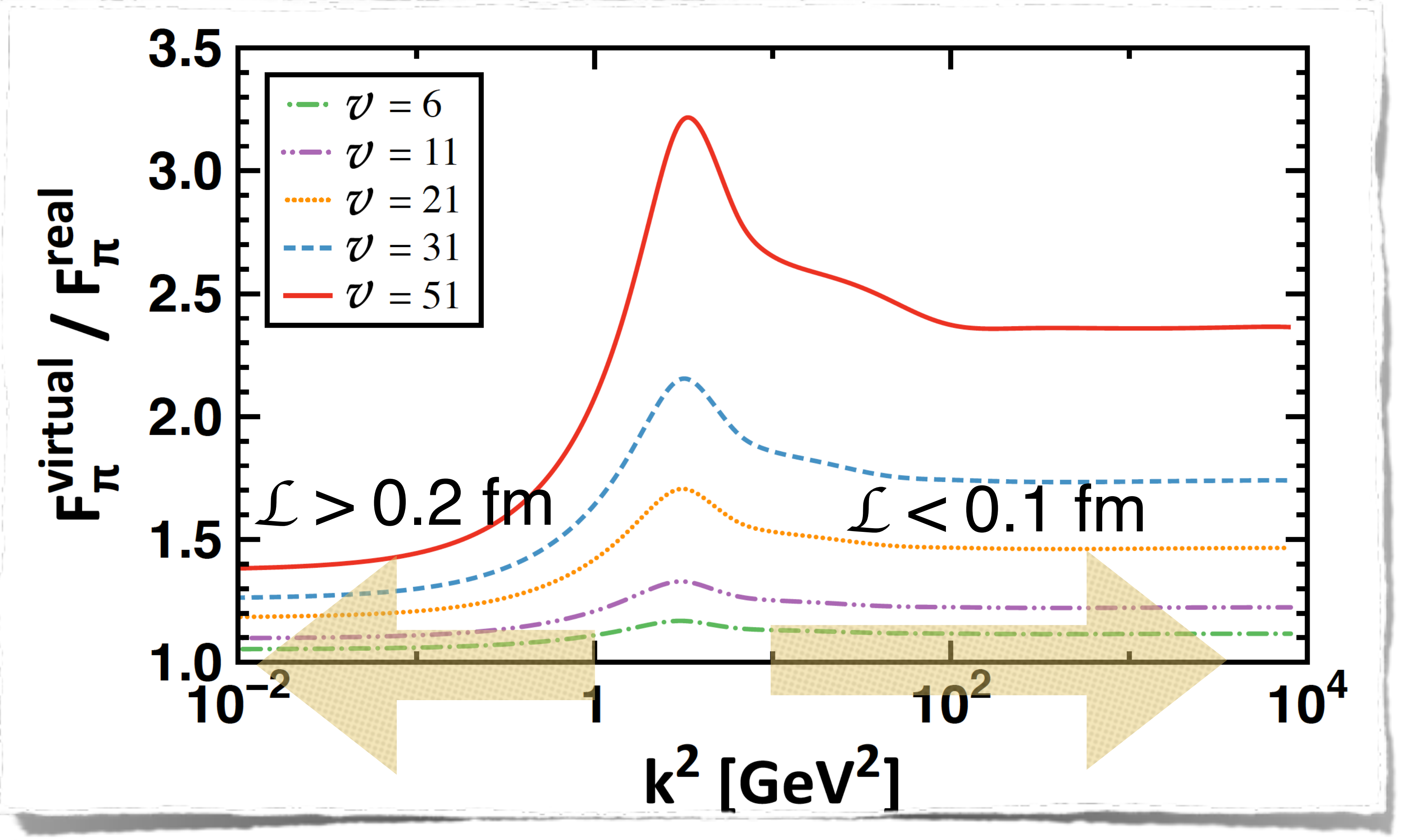




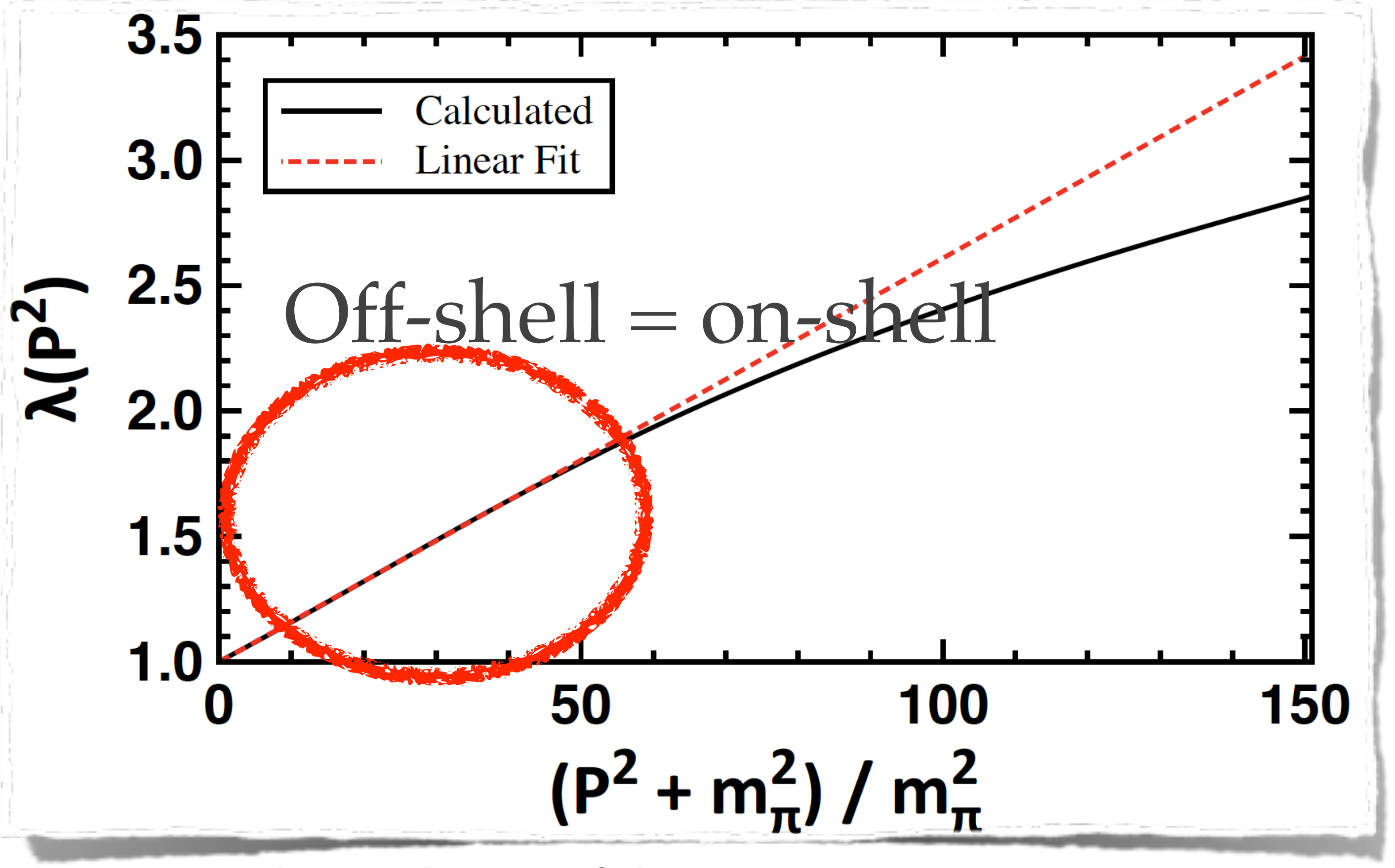
vLD1, x y position
vLD1, x z position
vLD1, y z position
Lambda
events
time cut
color: protons from Λ
black: pions from Λ
Reconstructed Mass, Time
beam protons
$R_{beampipe}$=3cm
50x8cm²
20cm
y_{avg}(cm)
x_{avg}(cm)
z_{avg}
y_{avg}(cm)
Global coordinate

off-shellness

Cite: arXiv:1702.06100v1, S. Qin, C. Roberts (2017)



The virtuality-dependence exhibited by one of the UV-dominant terms in the pion's Bethe-Salpeter amplitude



v-dependence of the virtuality eigenvalue

To check for pole-dominance, range of low t.

Q1) In calculation, up to what values of t one may expect meson pole dominance ?

1/ Intro. a virtuality ($\mathcal{V}$, off-shell) eigenvalue for the bound-states in the Bethe-Salpeter Eq.
-> explore the off-shellness.

2/ Virtuality < 31, all changes in pion internal structure are linear, modest.

3/ Well-constrained extrapolation as used in experimental analysis should be reliable.

Q2) How the internal structure of the pion is modified ?

1/ Possible rearrangements of the pion's internal structure from studying the impact of $\mathcal{V}$ scalar functions

2/ k^2-dependence of the $F_{virtual}/F_{real}$ of the leading ***Chebyshev moment*** for the UV dominant amplitudes

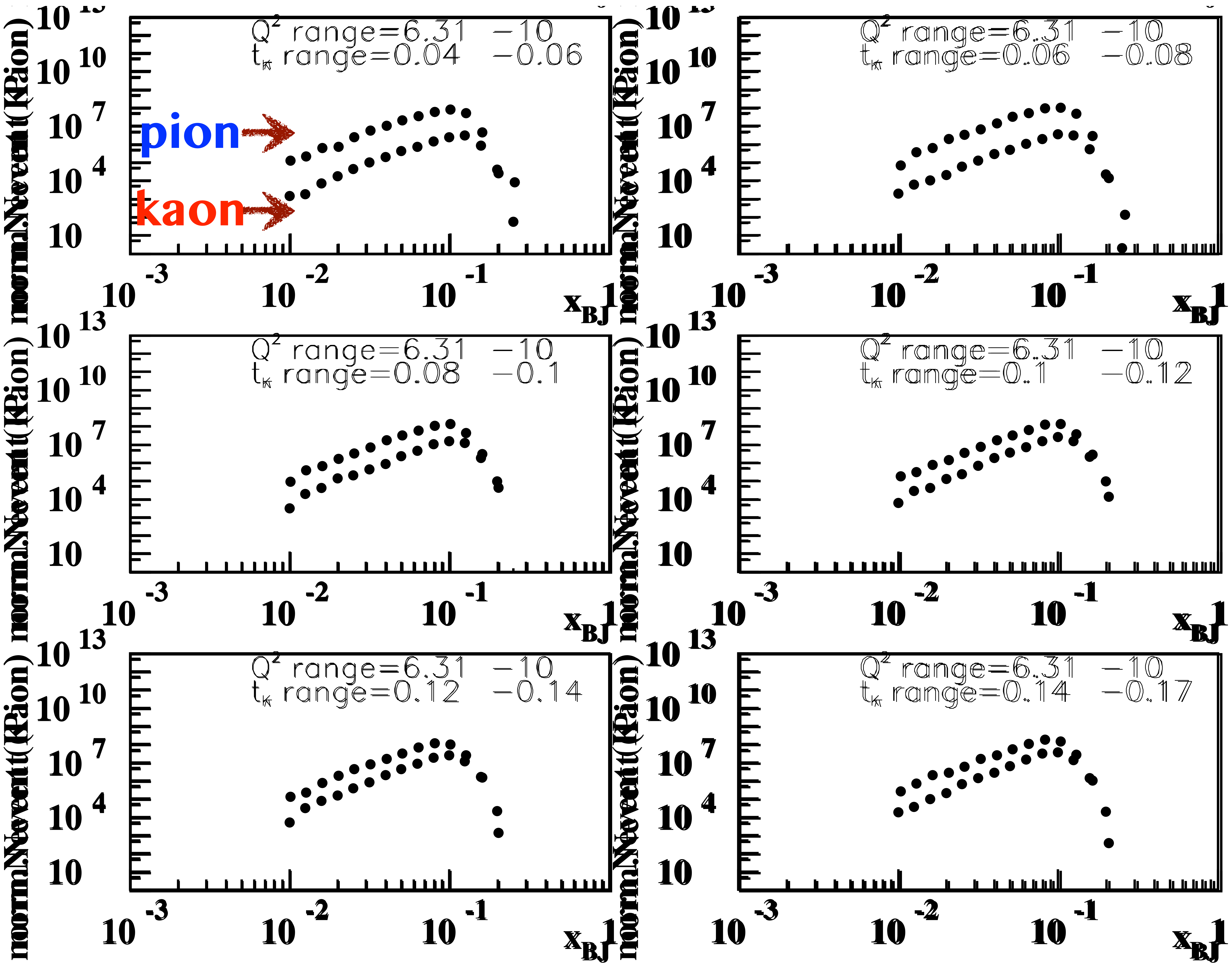
3/ Shows an impact of nonzero $\mathcal{V}$ on the pion's internal structure is modest at $\mathcal{V} = 31$ (corresponds to -t ~ 0.6 GeV^2) for length scales ($\mathcal{L}$) > 0.2 fm.

4/ By repeating this analysis and expanding to kaon, $s + \bar{s}$ pseudo-scalar bound-state

5/ Interpolating to the pion & kaon, the off-shell correlation serves
pions: $-t < 0.6$ GeV^2, kaons: $-t < 0.9$ GeV^2

kinematic variables

- x $(= x_{BJ})$: scaling variable, Bjorken x
- Q^2: virtuality of the exchanged photon $= -(k_i - k_f)^2$
- $y_e = \frac{Q^2}{x \cdot s}$: scaling variable, electron fractional energy loss in the target rest frame
- p^+: proton momentum in light cone frame
- k^+: meson momentum in light cone frame
- y**(or** z**)** $= \frac{k^+}{p^+}$**: light-cone momentum fraction of the initial nucleon carried by the interacting meson**
- $x_F = 1 - y$: light-cone momentum fraction of the initial nucleon carried by the neutron
  $\rightarrow$ leading neutron production at HERA
- $x_\pi = \frac{x}{x_F} = \frac{x}{1-y}$: pion momentum fraction (x$_k$= kaon momentum fraction)


pion
kaon
Q² range=6.31 −10
t range=0.04 −0.06
Q² range=6.31 −10
t range=0.06 −0.08
Q² range=6.31 −10
t range=0.08 −0.1
Q² range=6.31 −10
t range=0.1 −0.12
Q² range=6.31 −10
t range=0.12 −0.14
Q² range=6.31 −10
t range=0.14 −0.17
x_BJ


Rec Time difference
t_proton - t_pion (ps)
x y
vLD1, x y position
x z
vLD1, x z position
y z
vLD1, y z position
Rec Lambda mass
vD1, Λ mass from n + pi0
x y
vLD1, x y momentum
x z
vLD1, x z momentum
color = protons
black = pions
y z
vLD1, y z momentum