Measurement of meson Structure Functions through Tagged DIS at SBS

SBS Collaboration Meeting

July 13th, 2017

Kijun Park

General Overview

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
– correlated with the Equation of State and astrophysical observations
4) Mass is enigma – cannibalistic gluons vs. massless Goldstone bosons

- T. Horn

- **Evolution of PDFs, it <u>must</u> include both <u>valence quarks</u> and <u>sea quark & glue</u> at hadronic scale**
- **Flavor dependence of DCSB modulates the strength of SU(3) flavor symmetry breaking in meson PDFs.**

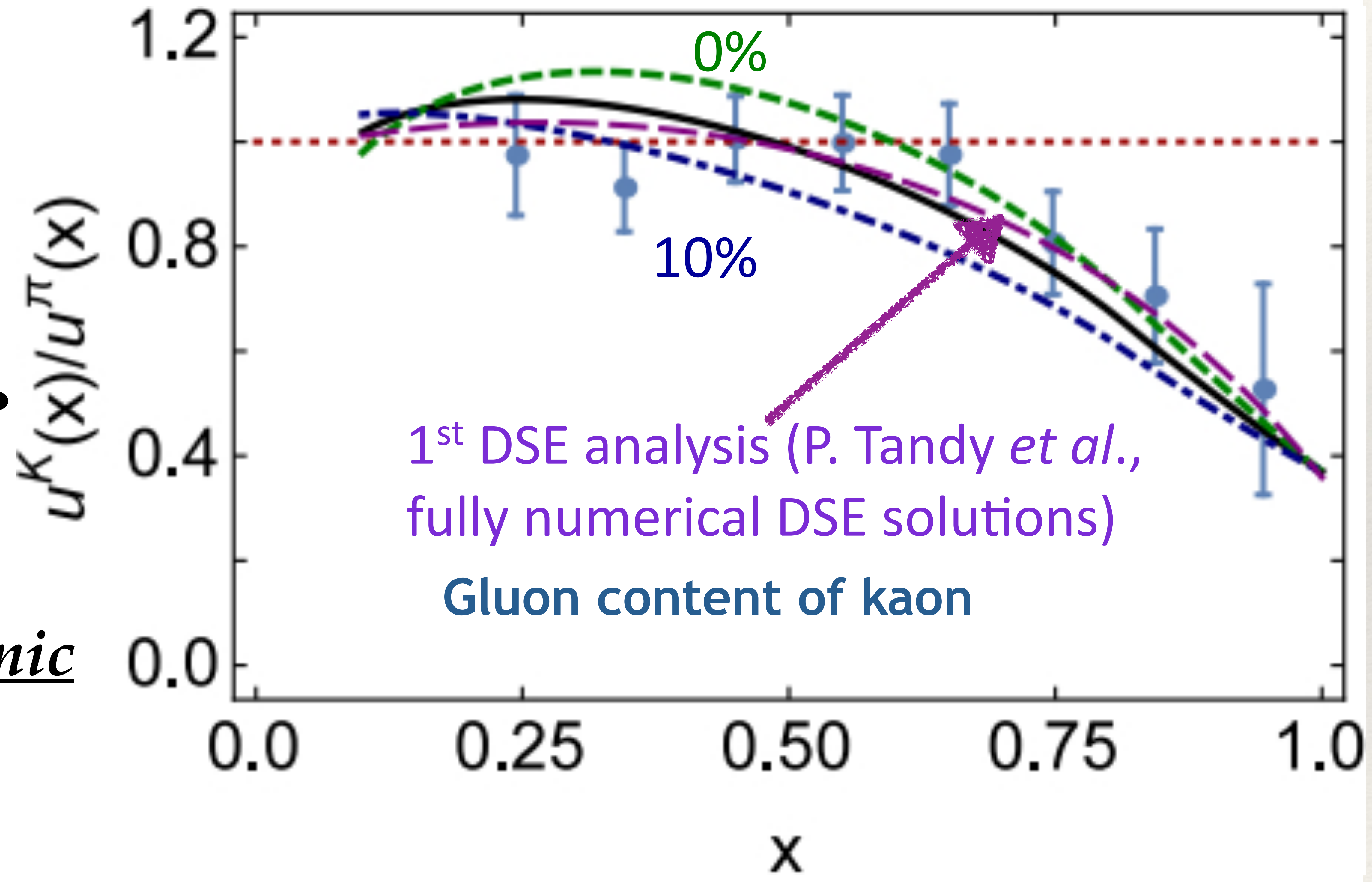
- C. Roberts

Why pi/k structure function is interesting ?

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)



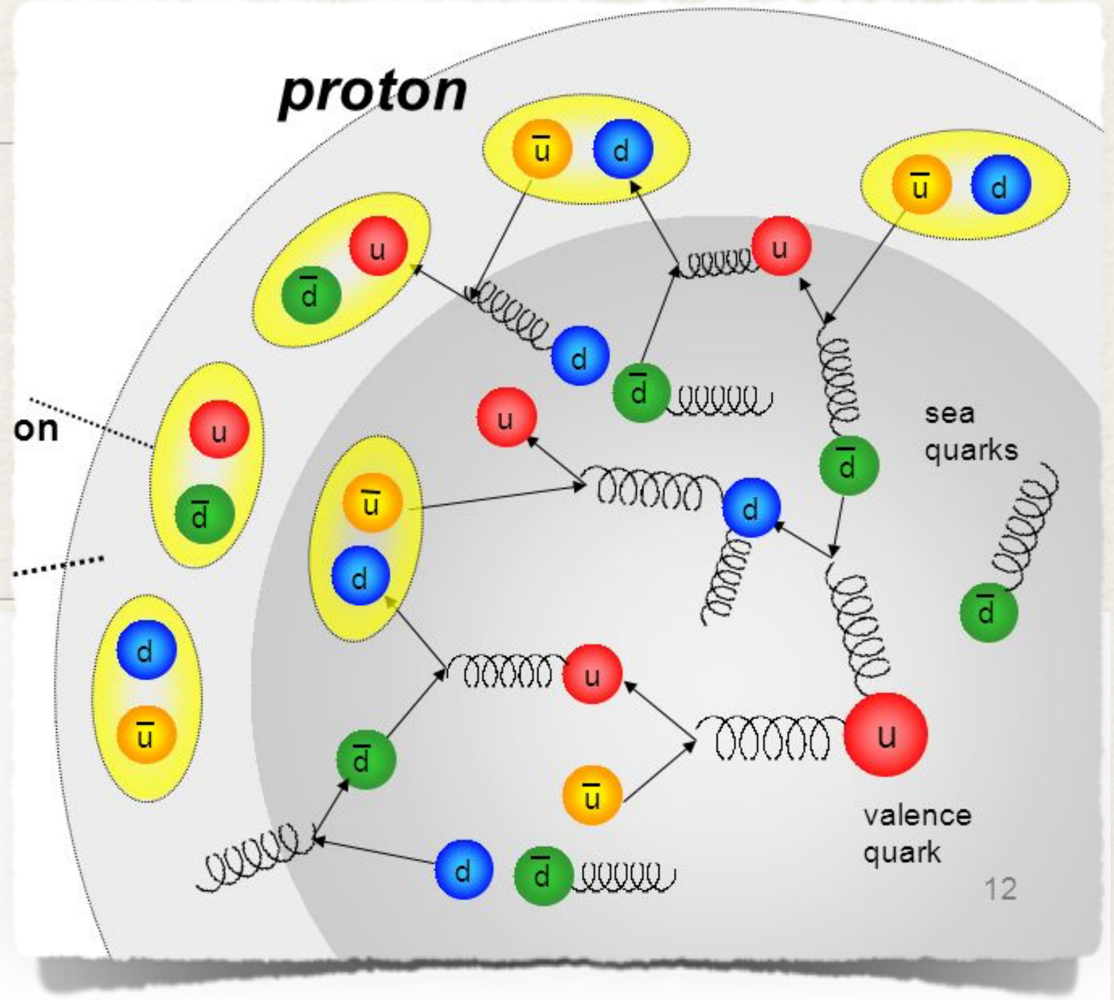
DSE prediction for the ratio of u-quark distributions in the kaon and pion

only Drell-Yan data !!!

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

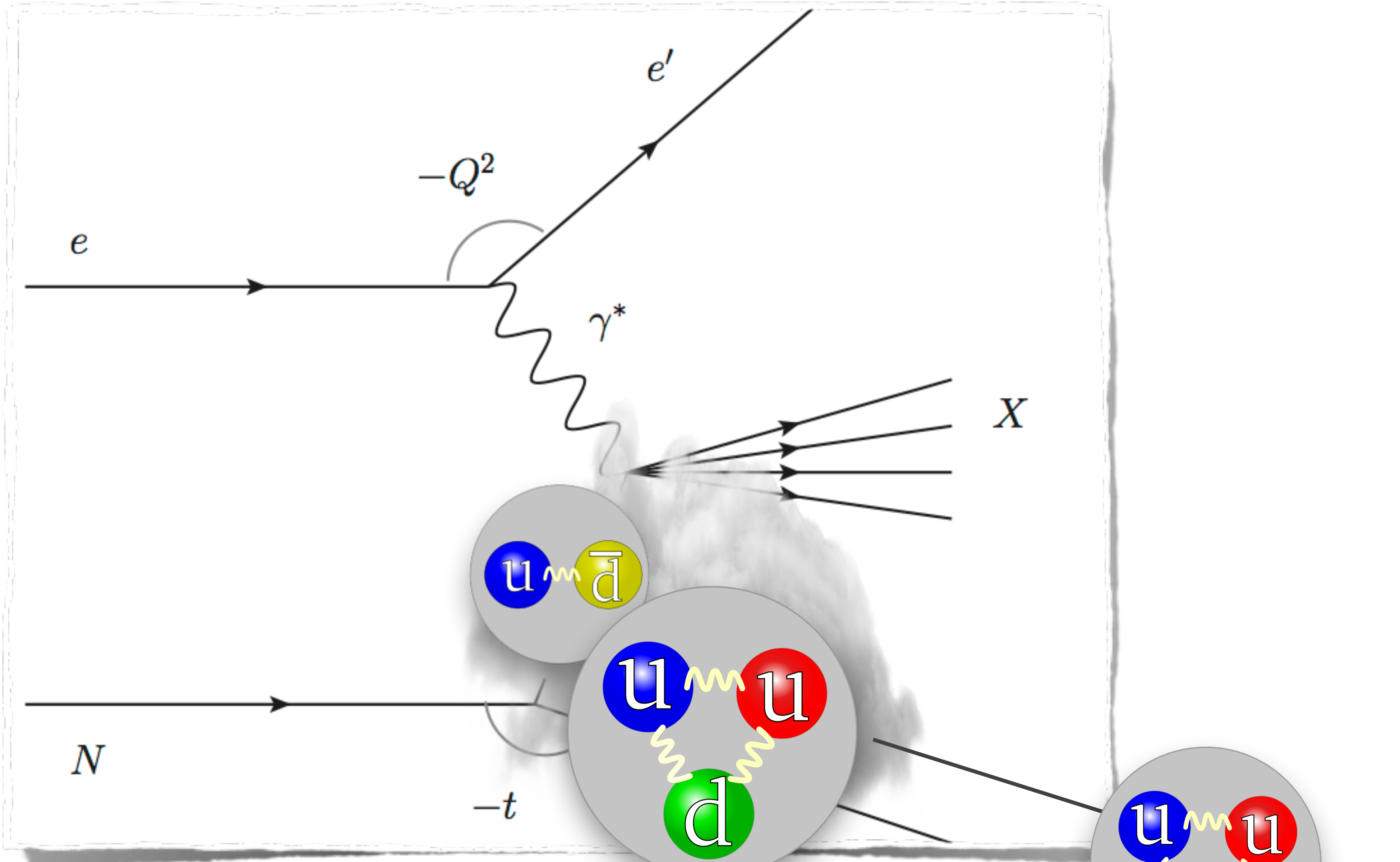
- ✦ Extraction of the pi/k structure function
- ✦ Testing of fundamental QCD
- ✦ Worldly first data ever !! (kaon)
- ✦ Crucial to understand an important background in pion-TDIS (kaon)

How do we want to measure ?

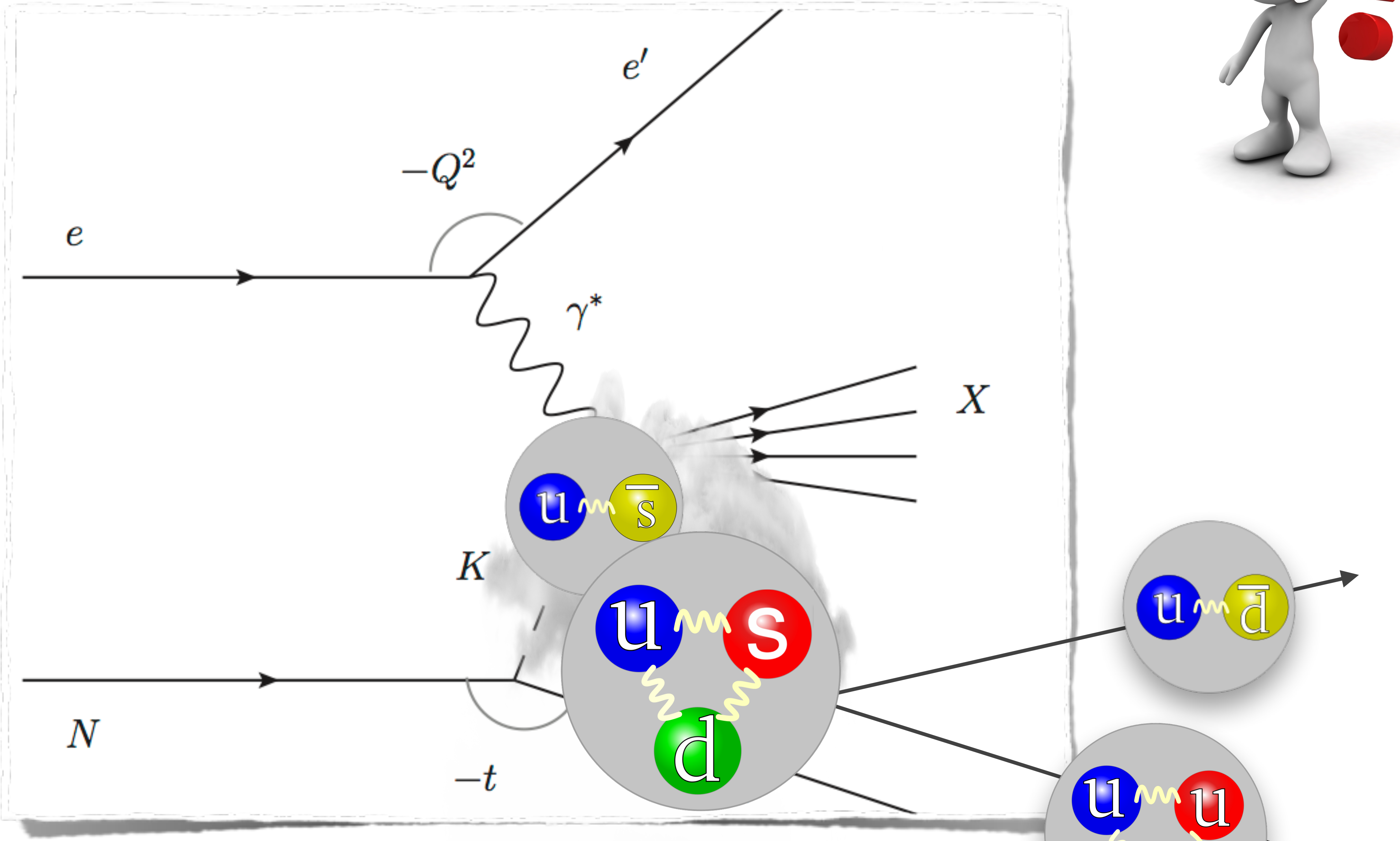


Tagged Deep Inelastic Scattering (TDIS)

- 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



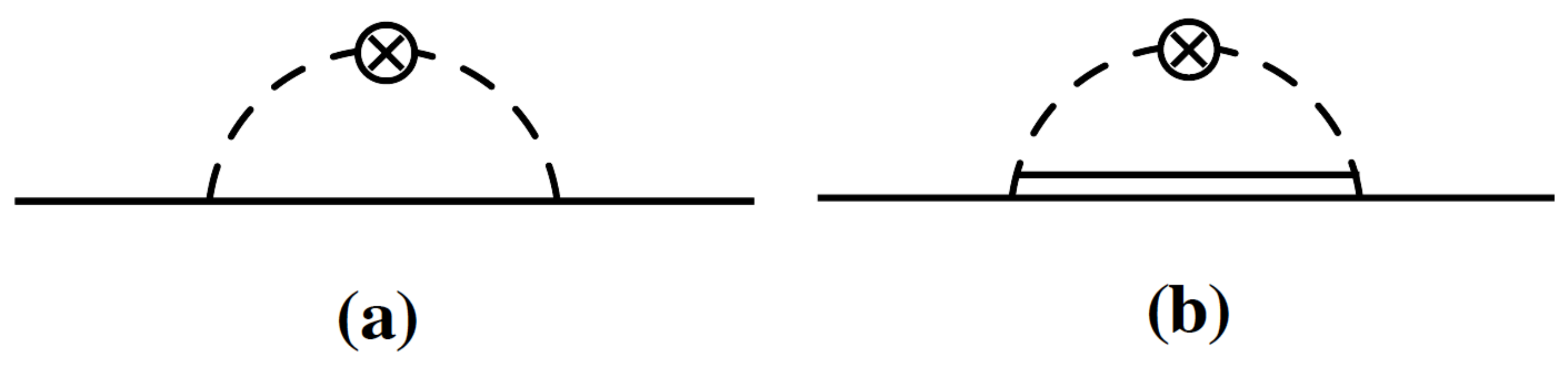
πTDIS



kTDIS

Feynman Diagrams for πN

chiral effective theory w/ meson exchange model



(a) a nucleon (solid lines)

(b) a Δ isobar (double solid line)

arXiv.org > hep-ph > arXiv:1512.04459

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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)

Splitting functions

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

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

Model dependence: coupling constant

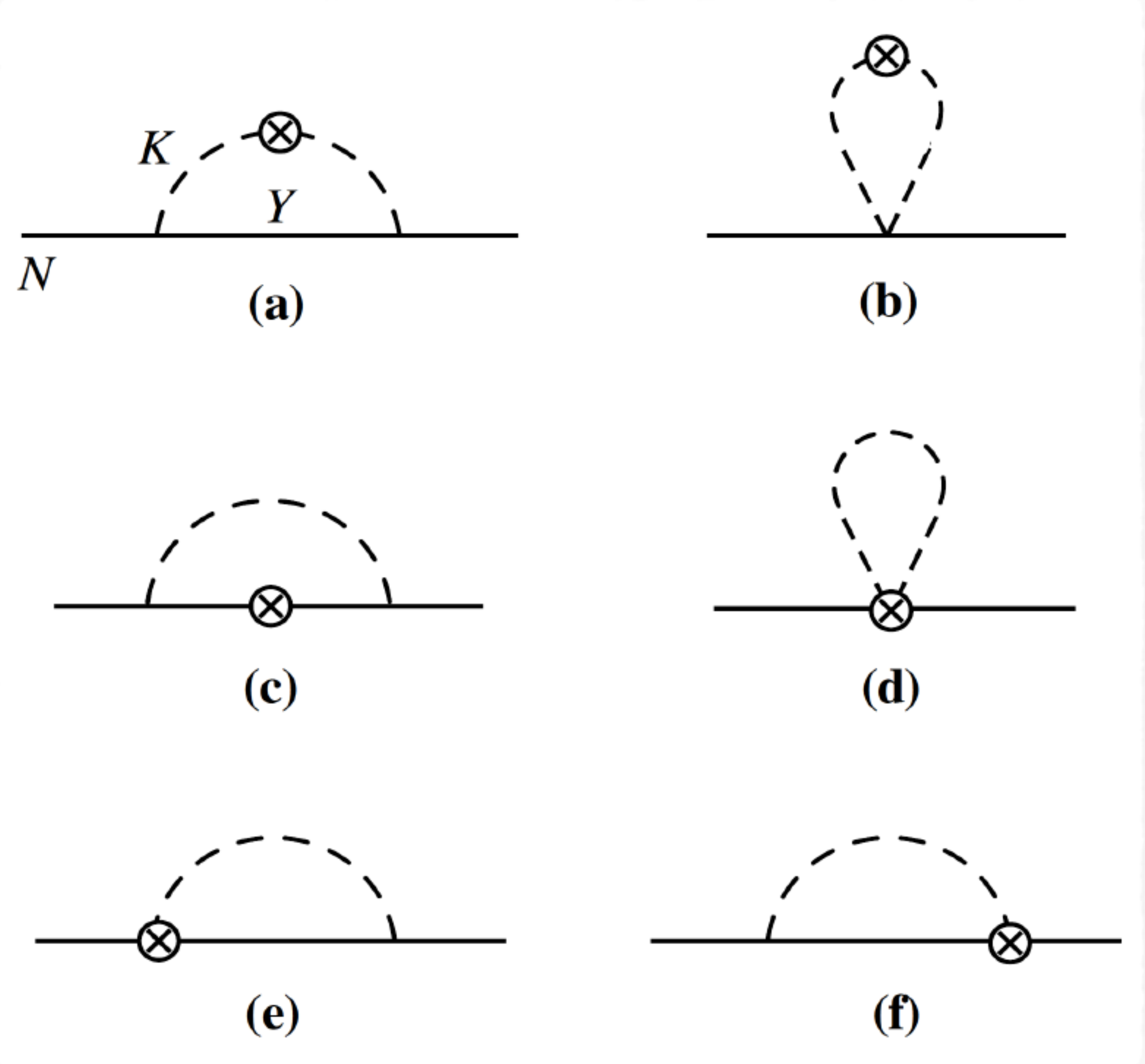
$g_{\pi NN} = 13.1$	$g_{K^+p\Lambda} = -13.3$	$g_{K^+p\Sigma} = -3.5$

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

Feynman Diagrams for KY

chiral effective theory w/ meson exchange model



- (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
  $= f_{YK}^{(KR)}(y)$

Splitting functions

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

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

Model dependence: coupling constant

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arXiv.org > hep-ph > arXiv:1610.03333

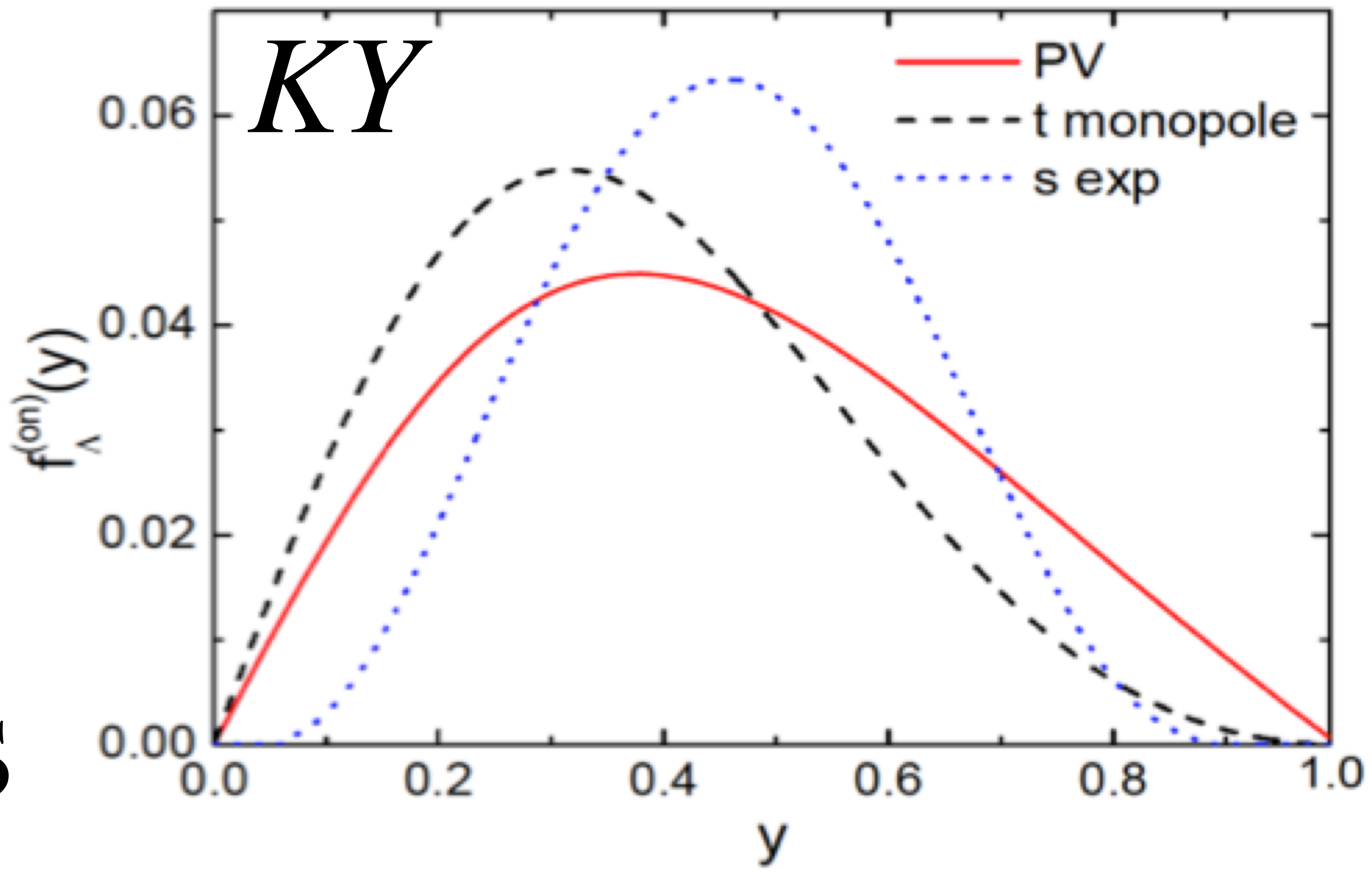
High Energy Physics – Phenomenology

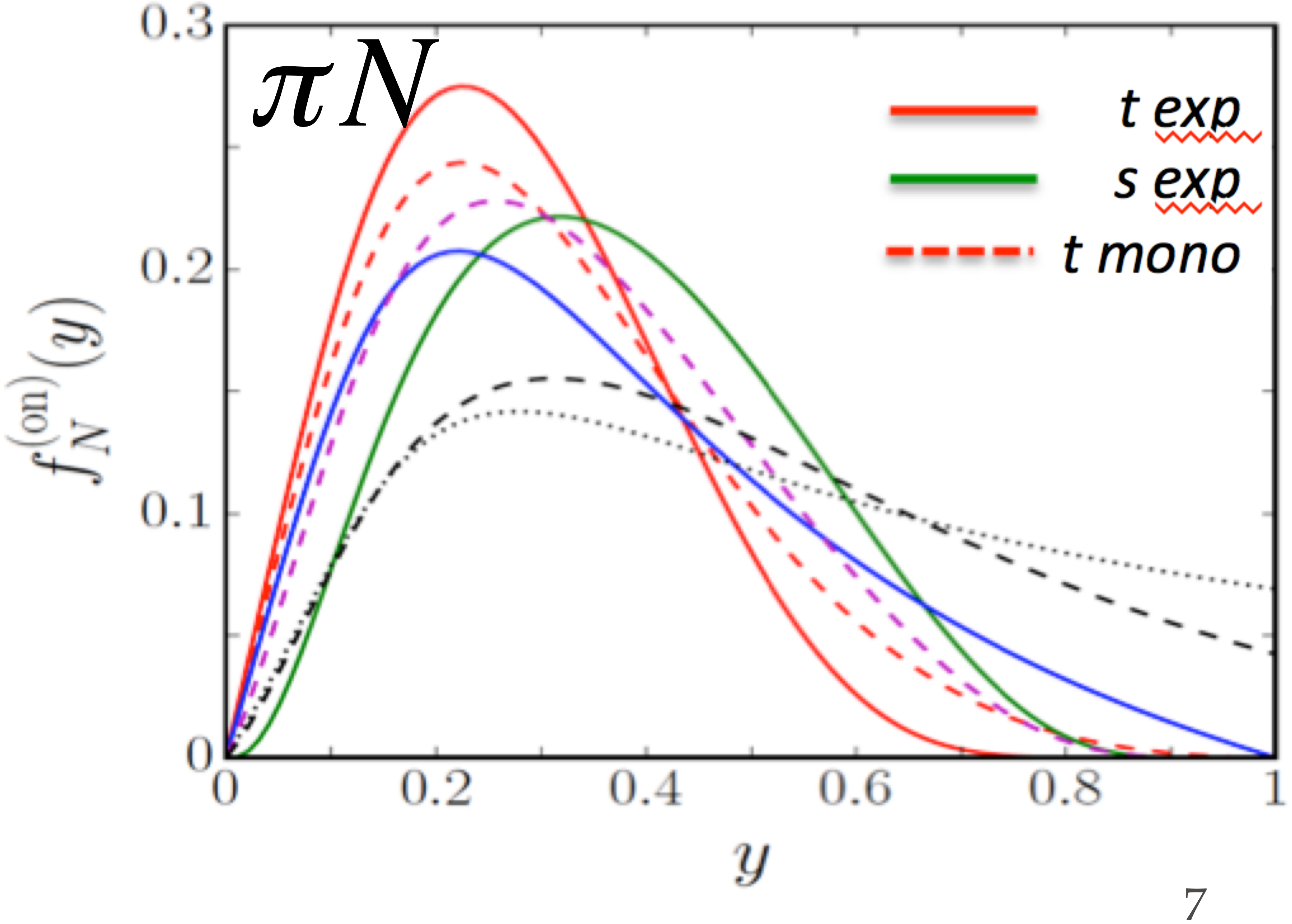
Strange quark asymmetry in the proton in chiral effective theory

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

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

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

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

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

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

This F.F. is also in the code

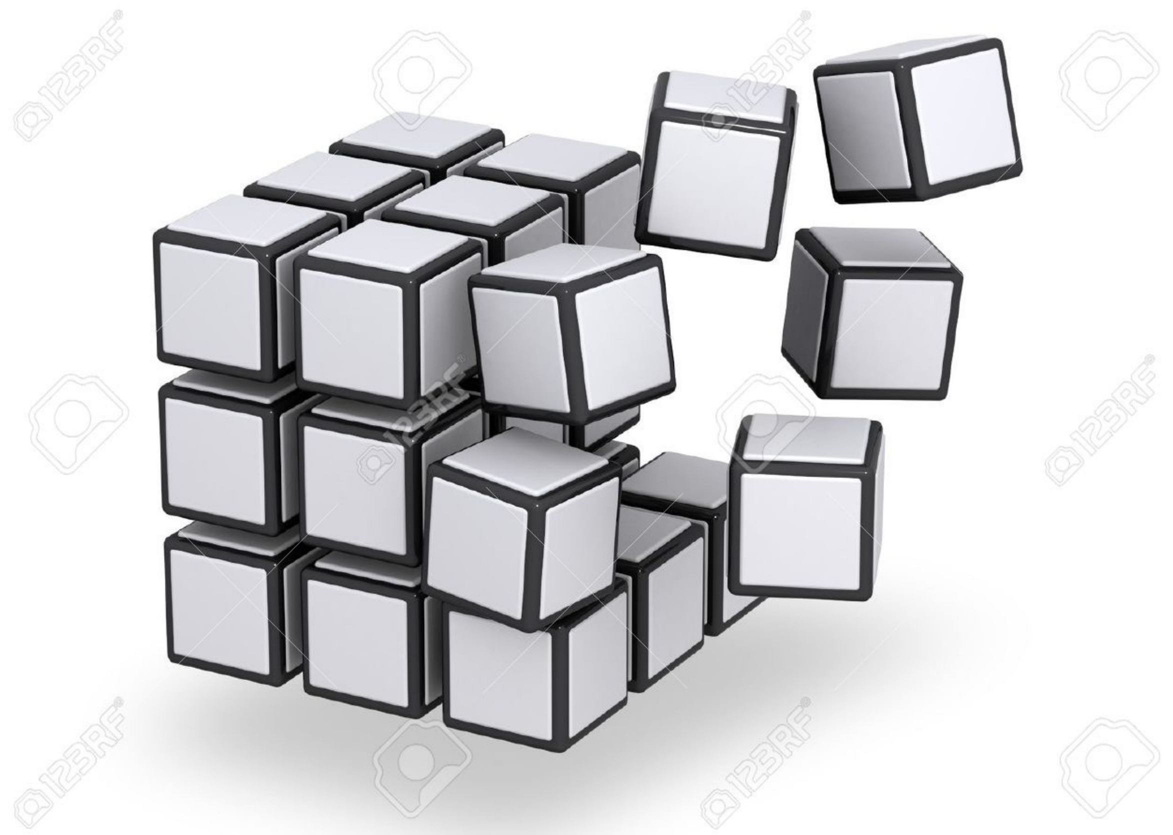
$$F = y^{-\alpha_\pi(t)} \quad \text{[Bishari],}$$

Model Dependent Regularization Form

Event Generator

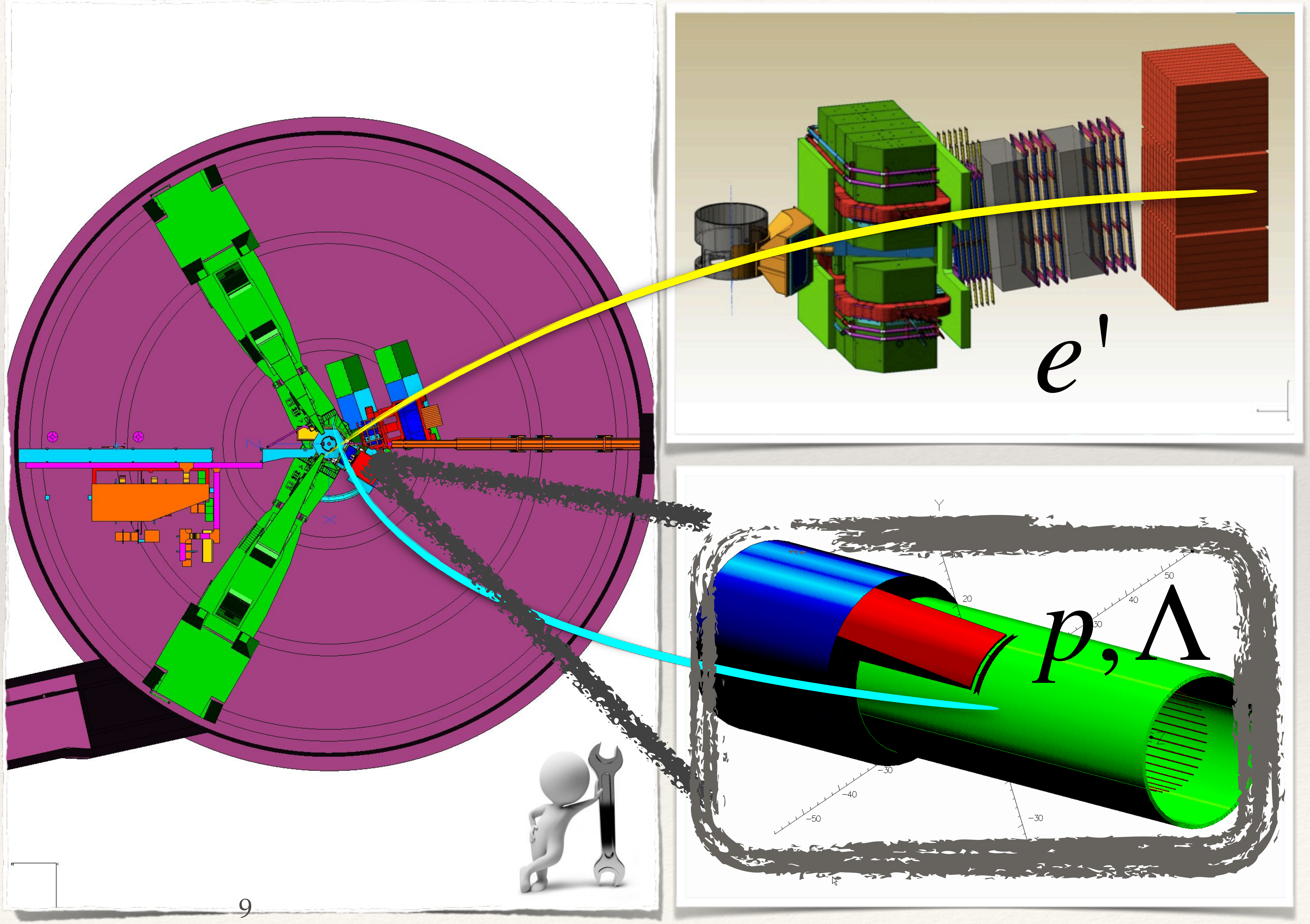
- User inputs:
  pi/k single meson exchange models
  various regularization forms

$$ep \rightarrow e'p'X \qquad ep \rightarrow e'\Lambda^0 X$$



- Codes are built with C^{++} (phase-space)
- Very compact
  subroutine in g4SBS MC package
  - cteq/cteqpdf.h
  - cteq-tbls/ctq66m/ctq66.00.pds
- Produce outputs:
  ROOTfile for GEANT4

Experimental Apparatus for TDIS

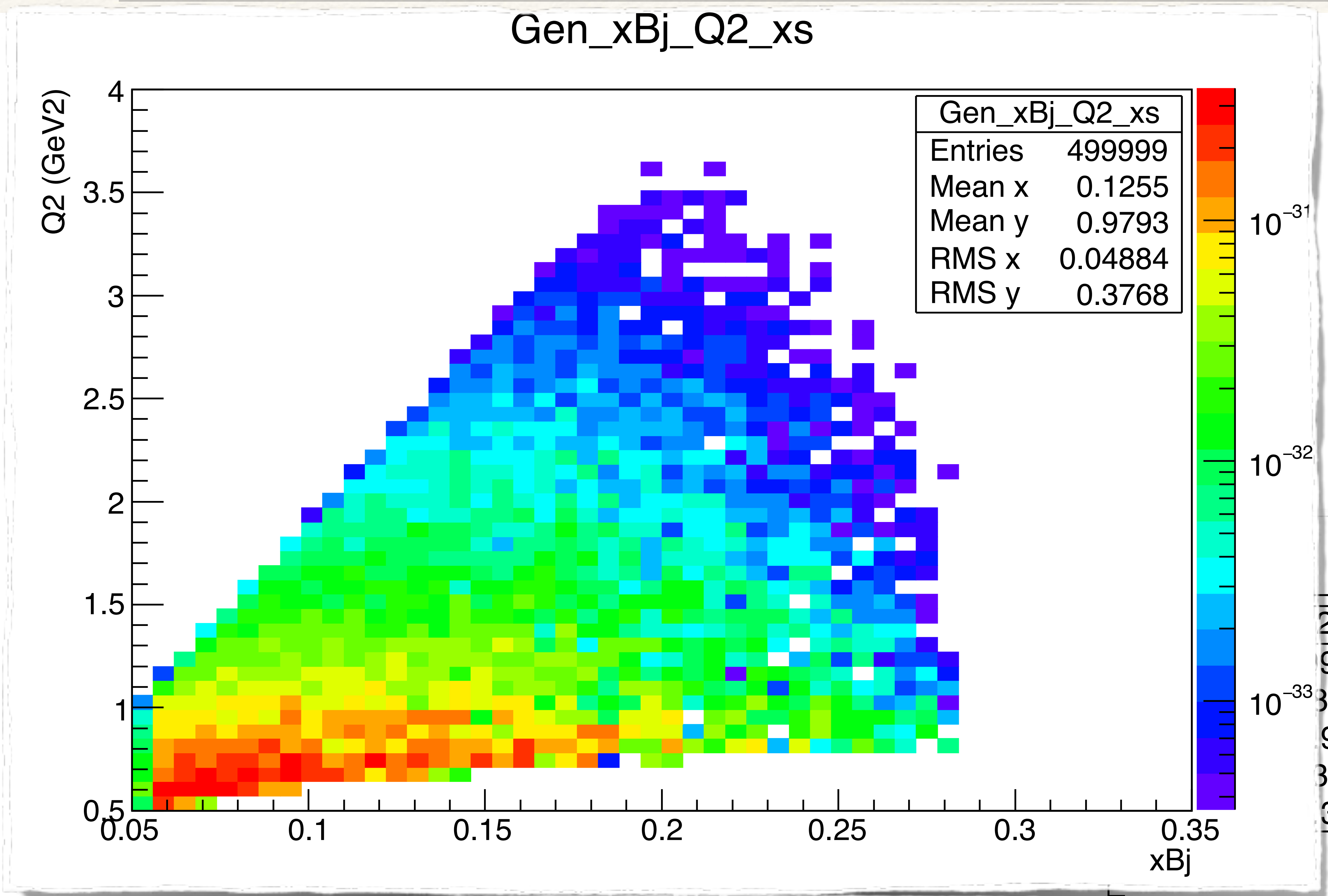


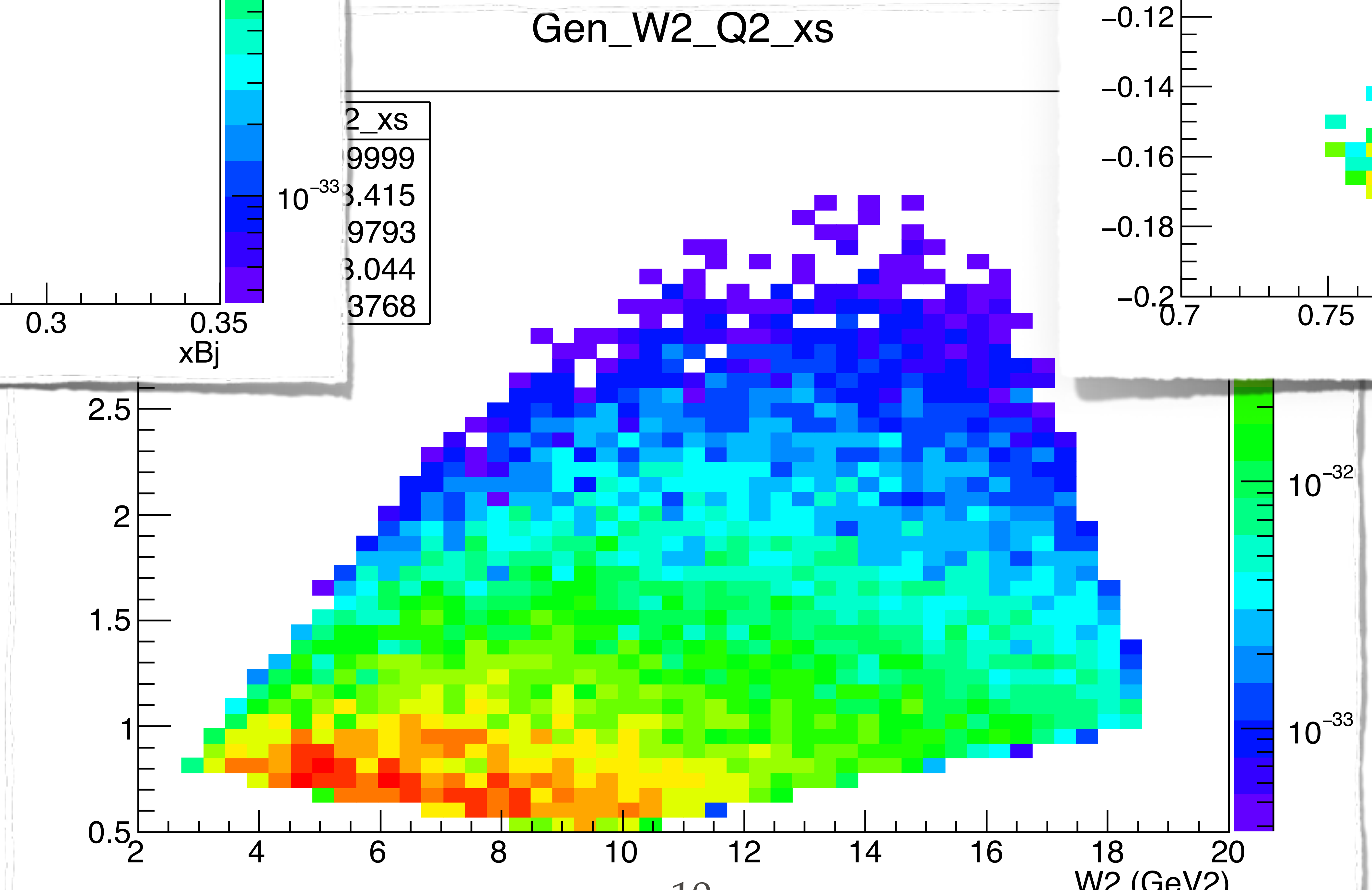
Hall A with Super Bigbite:

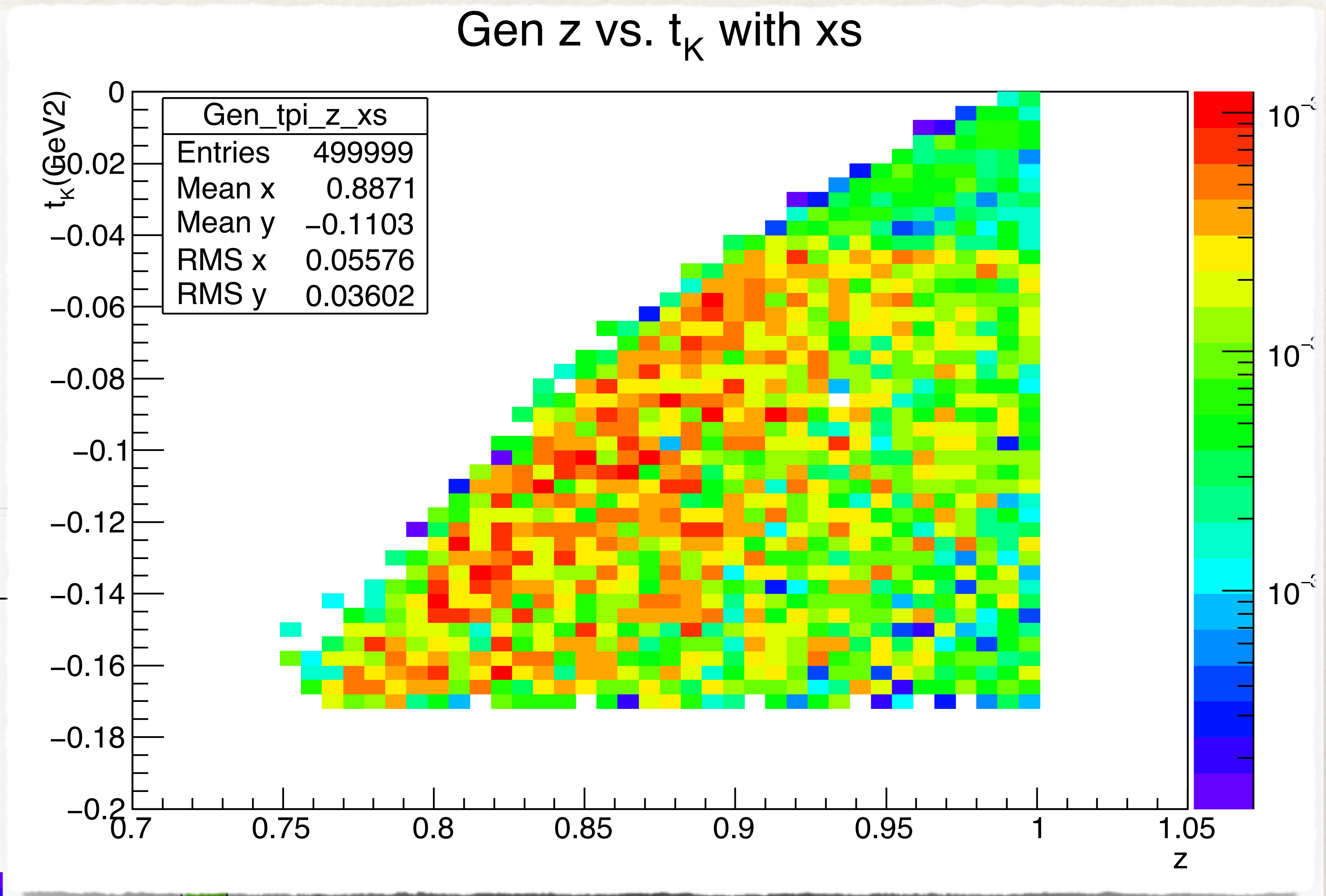
✓High luminosity,
    50 μAmp, $\mathcal{L}$ = 3 x $10^{36}/cm^2$ s
✓Large acceptance
    Super Bigbite ~70 msr, hadron spectrometer
✓HCAL will be used in RTPC calibration
✓ **BONUS-type RTPC, requires Solenoid B-field**
✓ **SBS for electron detection**

SBS Overview

MC Simulation with Cross-section Weighted





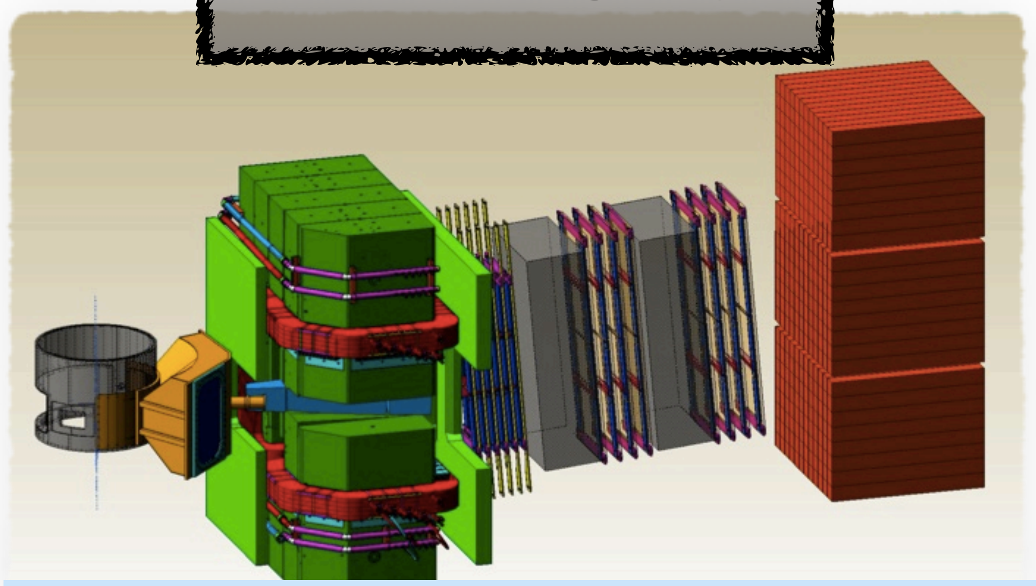


g4SBS simulation package
+ TDIS (pion/Kaon)

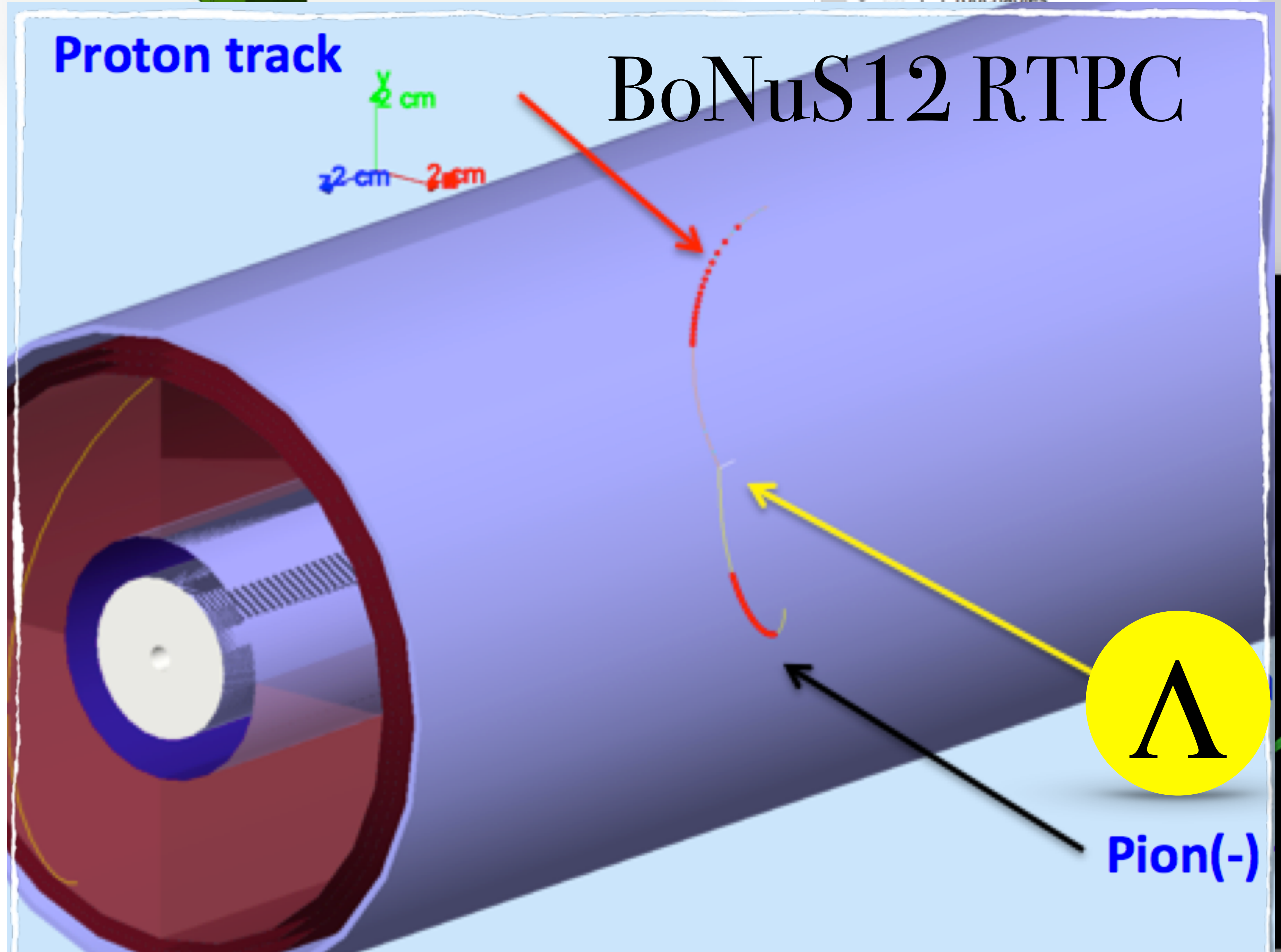
Beam Current	50.0 muA	BB angle	30.0°
Target	H2	BB dist	1.55 m
Target Pressure	1.0) atmosphere	BB field	1 T
Target length	40.0 cm	HCAL angle	14.0°
rasterx	2.0 mm	HCAL dist	6.5 m
rastery	2.0 mm	48d48 field	1
kine	tdis	48D48 dist	2.5 m
Run Time	480.0 hour	SBS Mag field	1.4 T
Beam E	11.0 GeV	RICH dist	5.0 m

MC GEANT4 Simulation

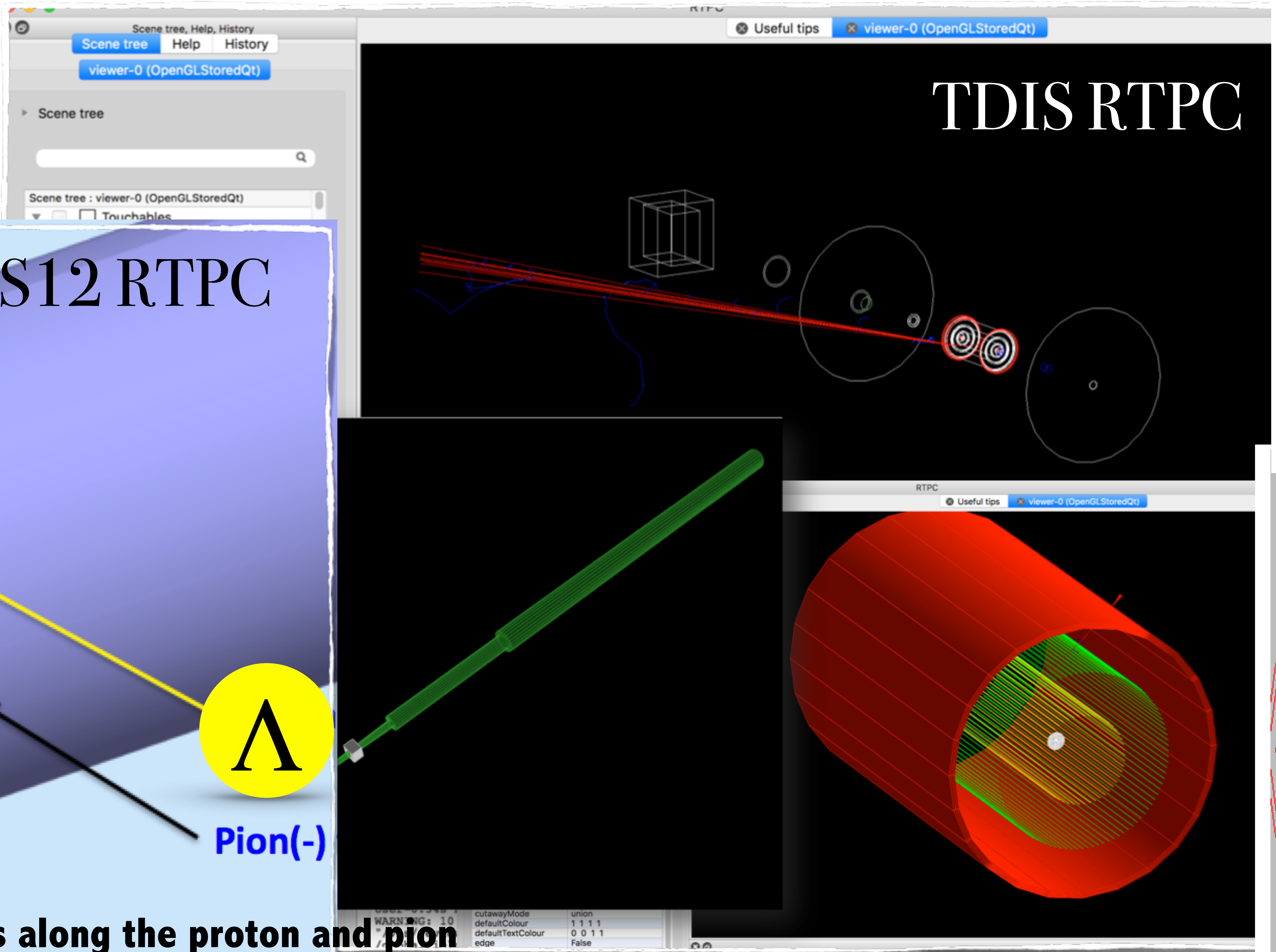
electrons



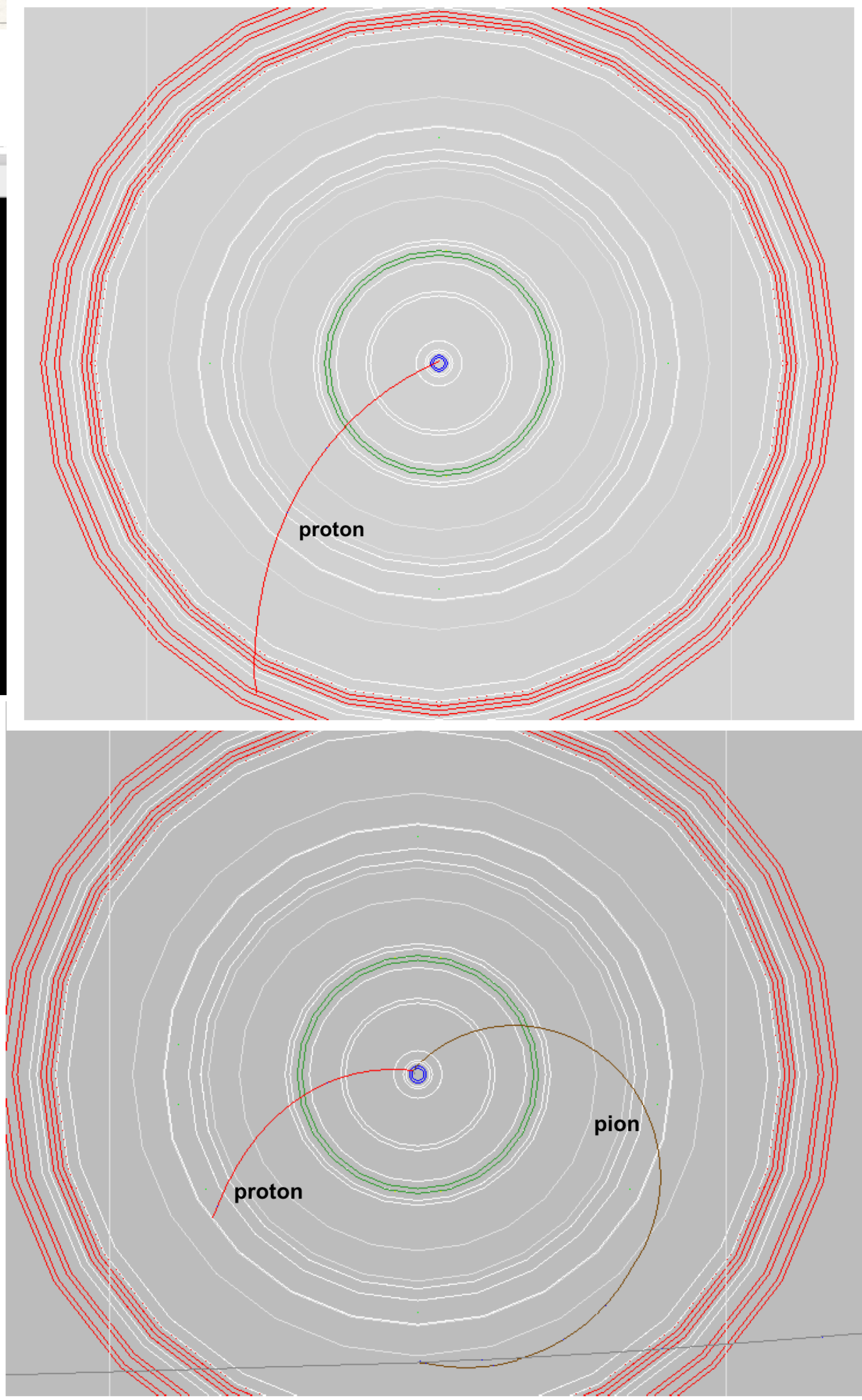
recoiled nucleons



* The red dots are hits along the proton and pion tracks in the active region of the RTPC



TDIS Event Generator Input for Pion TDIS



MC Simulation(current status)

Update for Geant4 Geometry:

- Exit beam pipe / Beamline material / Extra casing around RTPC
- Curved exit window for target / curved spherical Al exit wall
- Mechanical integrity of RTPC – will allow for studies of any different pressure set ups
- Improvement to chord finding for TOSCA magnetic field map in Geant4

Event Generator Input:

- Studies performed using input pi/K event generator (ROOT)
- Studying efficiency as a function of magnetic field position (H,D)

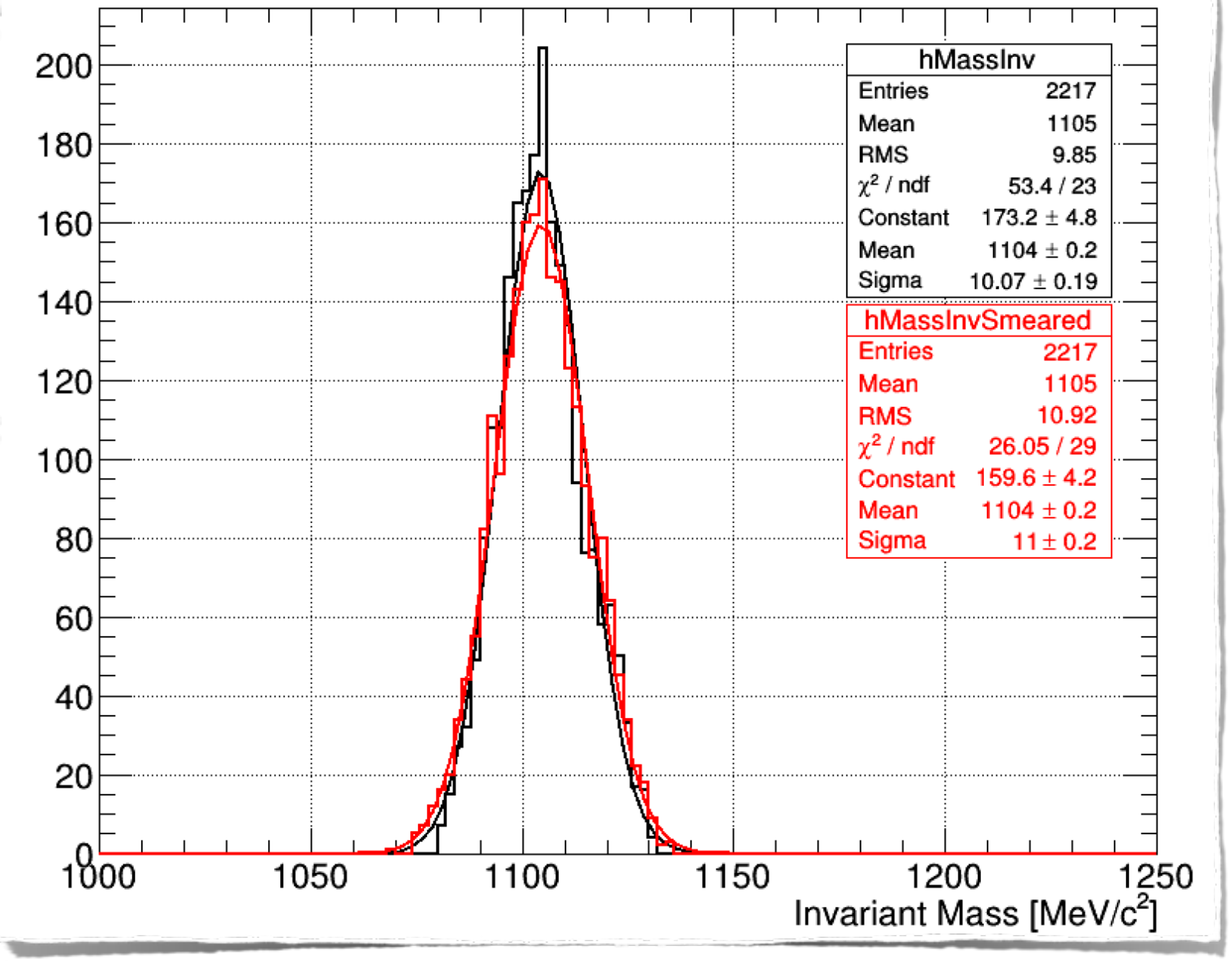
Improving Electron Drift Studies in RTPC:

- Electron parametrisation using Magboltz simulation for electron drift velocity (different gas settings)
- Updated to include 1/r dependence of E field in magboltz simulations
- Study of alternative method using Garfield++ for drift electrons (low energy protons)
- Geant4/Garfield++ interface

MC GEANT4 Simulation for RTPC

Λ reconstructed mass

3% of Gaussian smearing in RTPC resolution



Probability of creating a track of particle in RTCP gas volume (%)

Offset(mm) \ Reaction	$H(e, e'\Lambda)X$	$H(e, e'p)X$
tracked particle type	$(p{:}\pi^-{:}p\pi^-)$	(p)
0	(40:50:33)	74.4%
100	(40:50:33)	74.6%
200 (nominal)	(40:52:35)	74.6%
500	(40:54:36)	75.7%
600	(40:54:37)	75.9%
1000	(41:55:38)	75.8%

proton is driving particle !

Performing for optimizations will benefit both measurements !!

DAQ

- Monthly meeting
- People: Paul/Kondo/Graham/Chris/Thia/Kijun…
- Lots of discussion:

- ❑ How to handle pile-up ?
- ❑ DREAMS(BoNus) vs. APV25(CMS) vs. SAMPA(ALICE)
- ❑ Integration:
  how many chips we'll need, how many channels (560), how many can we fit on a board ?
- ❑ Shielding ?
- ❑ What about data volume ?
- ❑ How many events/sec ? 25 Mbyte/sec/chip (Paul), 12 bit ADC (Gabriel)
- ❑ How many total channels ? 36,000 pads ?
- ❑ How to route out the cables/traces ?
- ❑ …

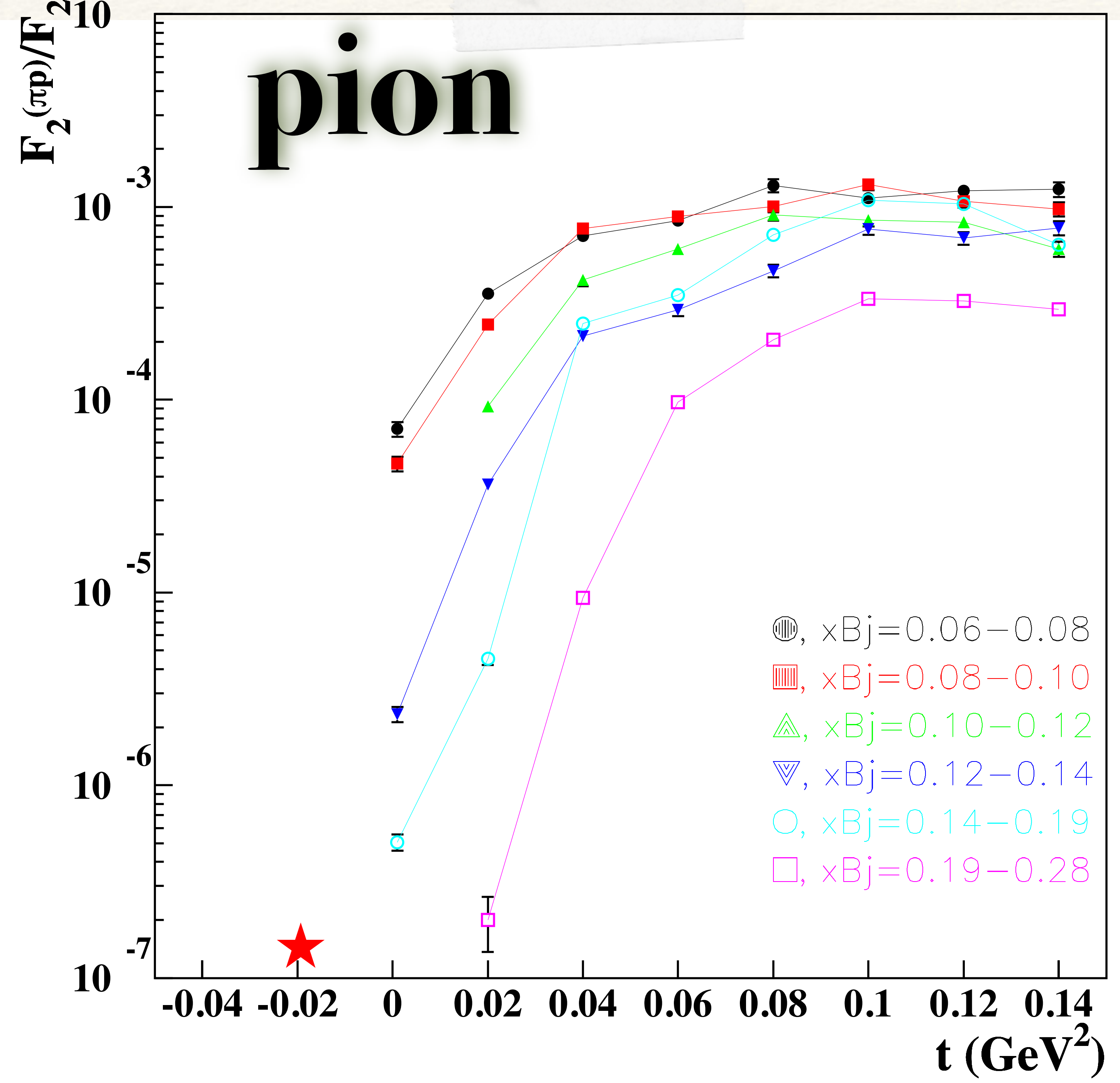
Expected Uncertainty

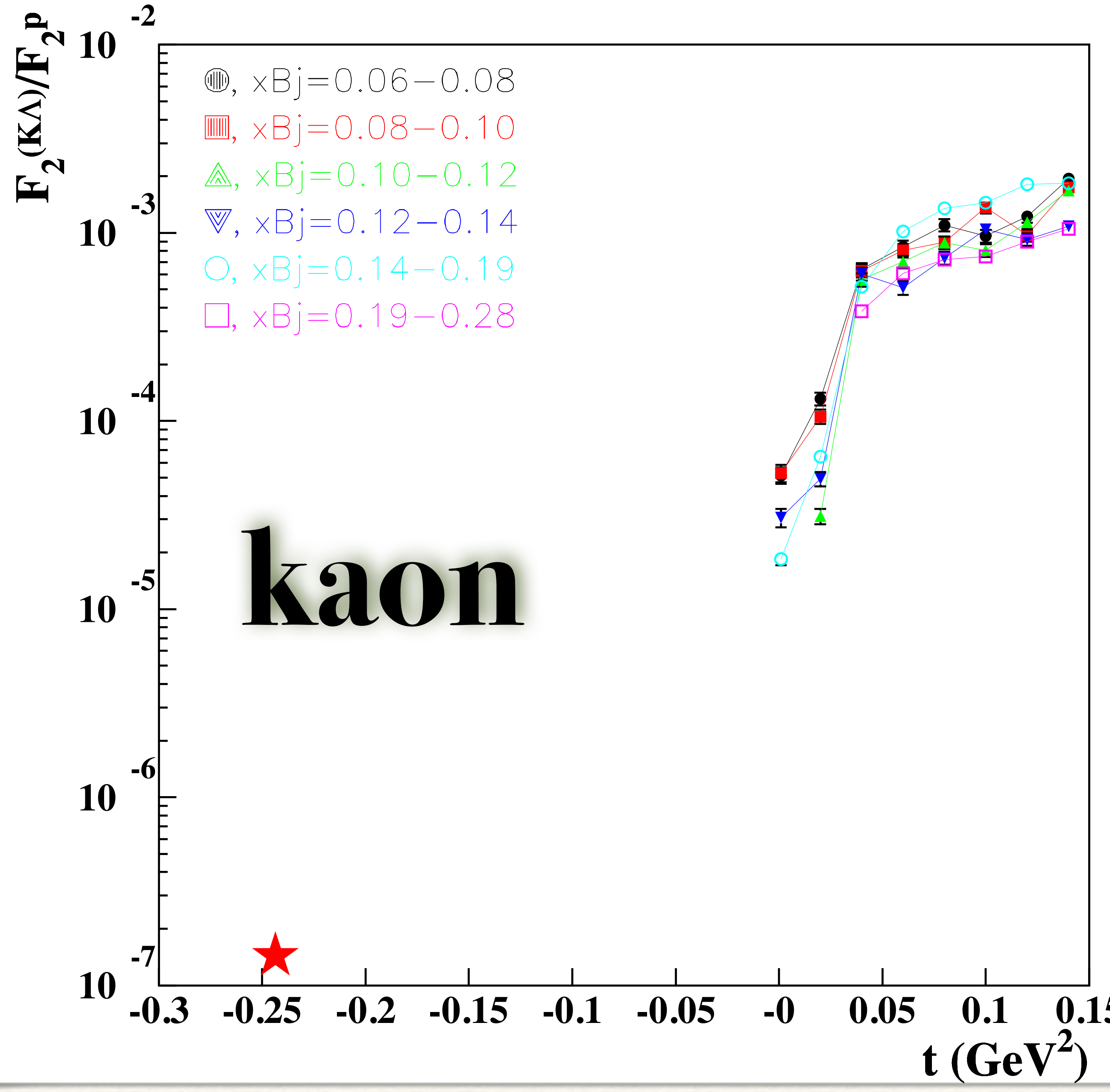
Estimation of systematic uncertainties (%)

source	uncertainty
Accidental background subtraction	5.0
PID by dE/dx and coincidence	1.0
DIS electron cross-section (Target density, Beam charge, Acceptance, Det.eff.)	3.0
RTPC absolute eff.	2.0
RTPC deadtime	1.0
RTPC momentum resol.	<1.0
RTPC angular accept.	1.0
Total	6.5

pi/K similar

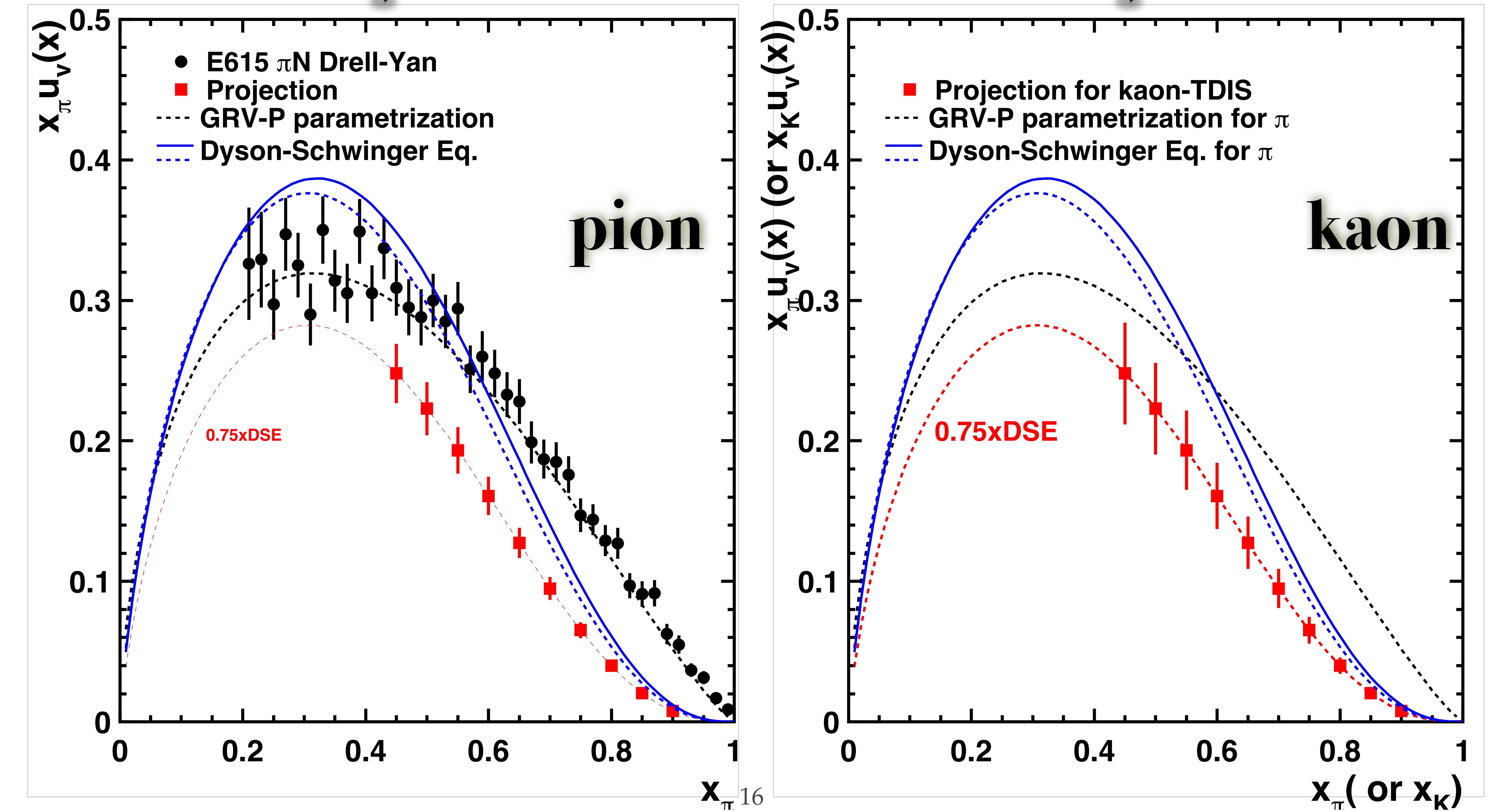
- ✦ The (p,π-) decay angle in CMS is back-to-back.
- ✦ The TIME(correl.) between an e- in the SBS and a proton hit in the RTPC.
- ✦ The VERTEX(correl.) of the electron and proton (in) tracks.
- ✦ The DECAY-VERTEX(correl.) of the spectator (tagging the proton and pion as a target, as in BoNuS).





Projected Results

valence quark distribution



Summary

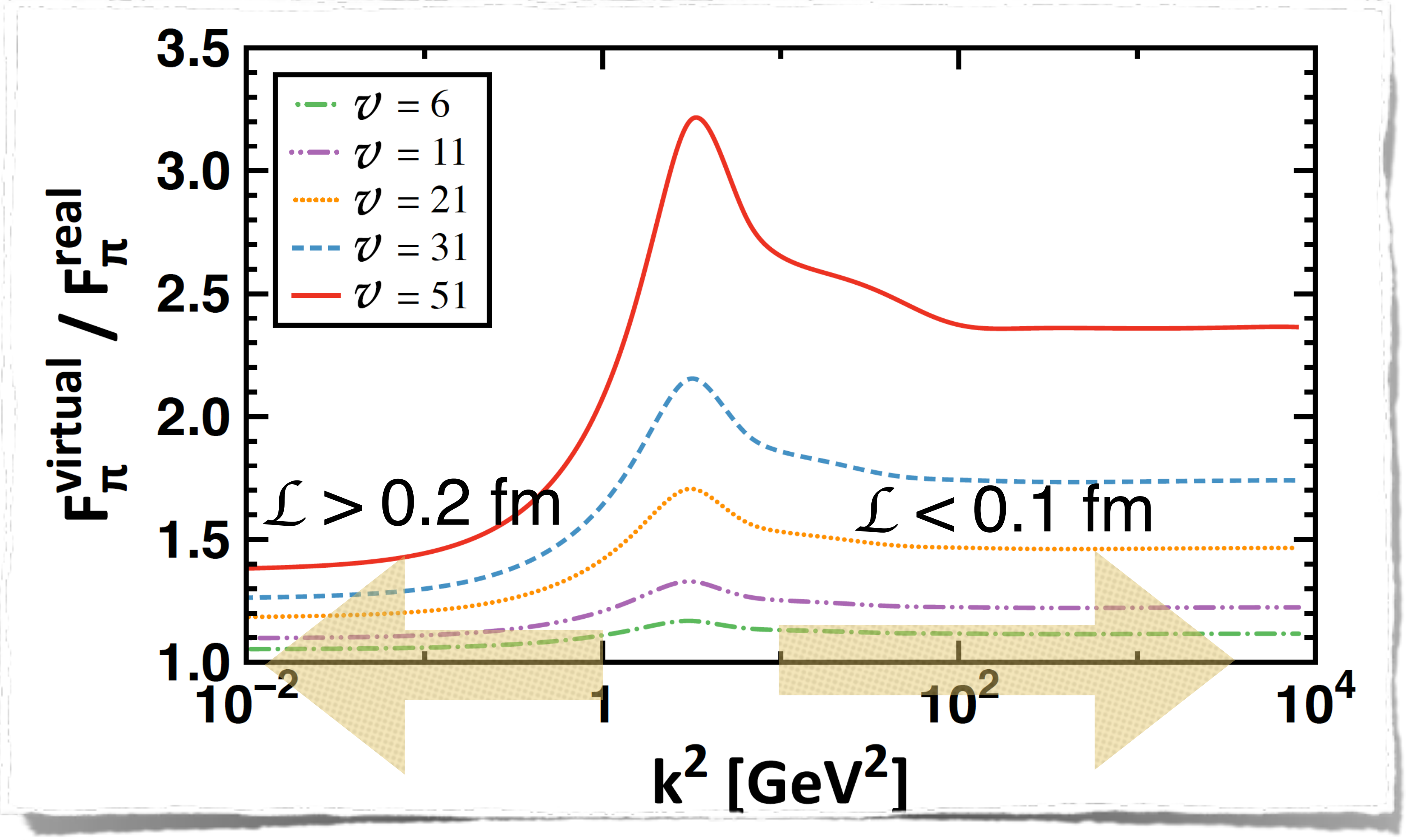
- Pion/Kaon-TDIS has been approved <u>C1 conditionally</u> for full 27 day beam time request
- Pion/KaonTDISs are accessible in terms of statistics and cross-section
  - ➡ <u>Any experimental optimizations would benefit both !!</u>
- Tagged DIS (TDIS) technique to probe the partonic components of the meson cloud of the nucleon
  - ➡ No experiment at all
  - ➡ Help to understand flavor asymmetry of the nucleon sea
- Extraction of the pion/kaon structure functions
  - ➡ Testing of fundamental QCD
  - ➡ Worldly first data ever !!!
  - ➡ Crucial to understand an important background in pion-TDIS

kTDIS, SBS internal report's sent to PAC, 06/23 !!

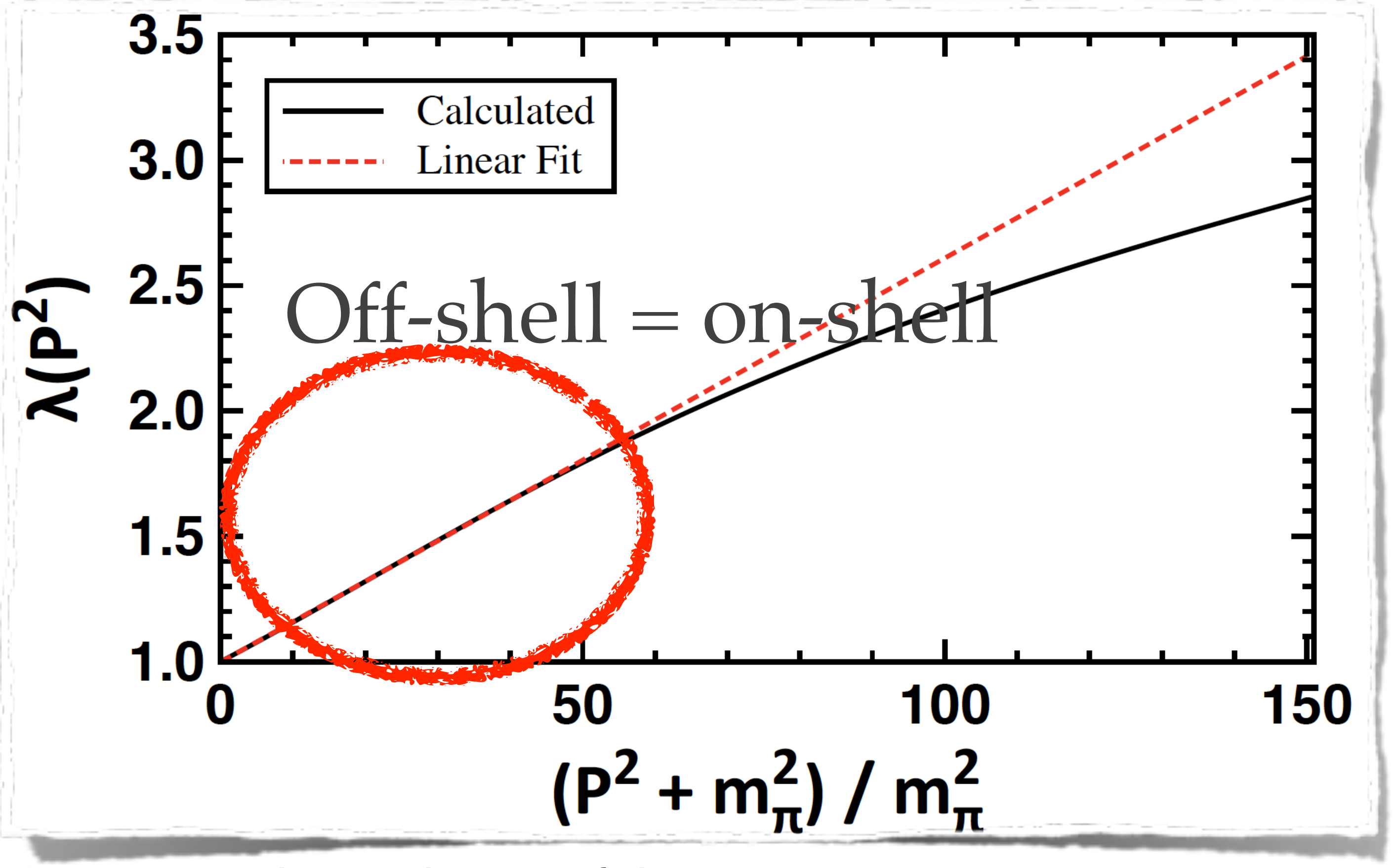
BACKUP SLIDE

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

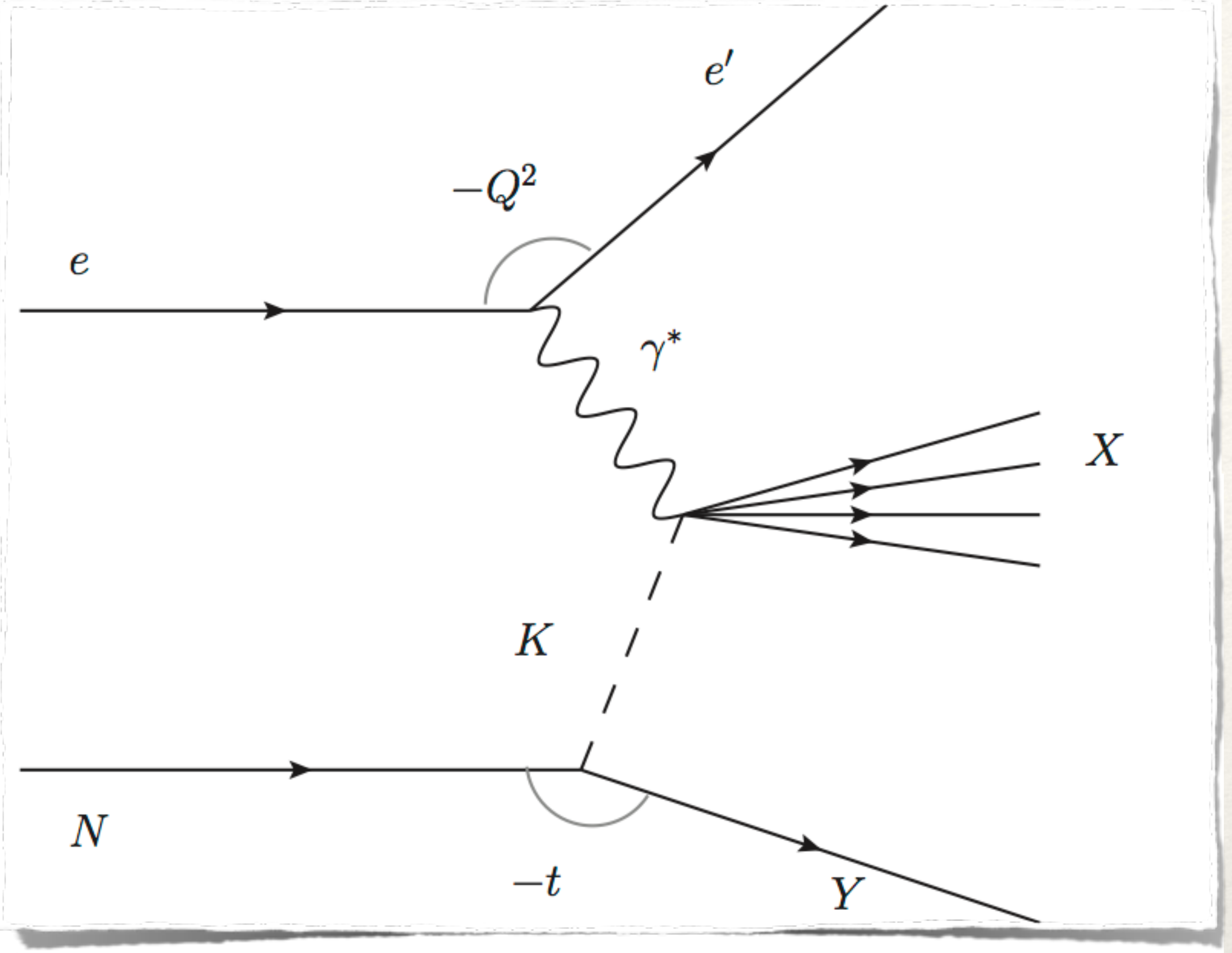
2/ k^2-dependence of the $F_{virtual}/F_{real}$ of the leading ***Chebyshev moment*** for the UV dominant amplitudes

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

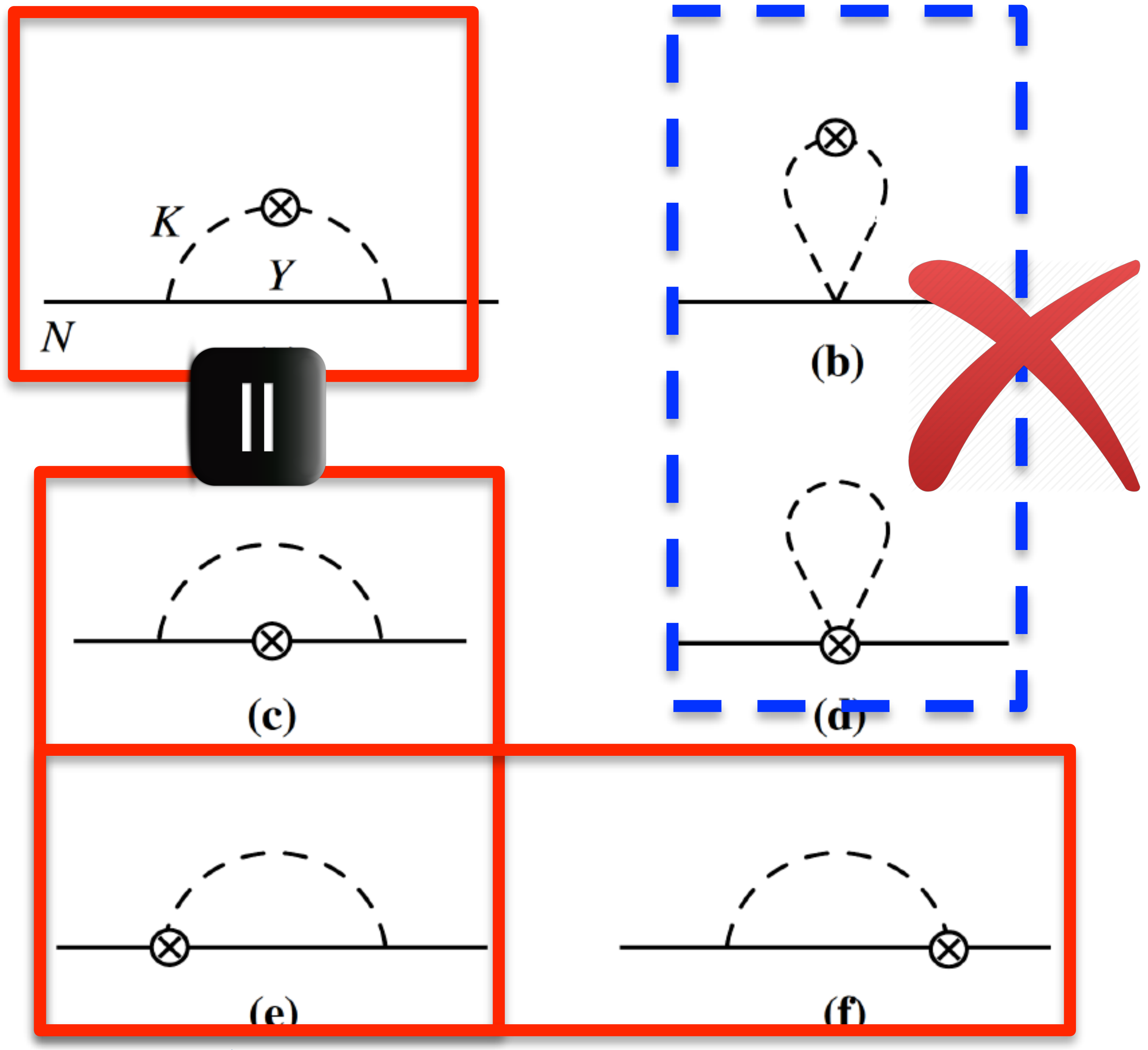
5/ Interpolating to the pion & kaon, the off-shell correlation serves
pions: $-t < 0.6$ GeV^2, kaons: $-t < 0.9$ GeV^2

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 (Lambda)
- k^+: pion momentum in light cone frame (kaon)
- $y(\text{or } z) = \frac{k^+}{p^+}$: **light-cone momentum fraction of the initial nucleon carried by the interacting kaon**
- $x_F = 1 - y$: light-cone momentum fraction of the initial nucleon carried by the neutron
  $\rightarrow$ leading neutron production at HERA
- $x_\pi = \frac{x}{x_F} = \frac{x}{1-y}$: ($x_K$ = kaon momentum fraction)

Feynman Diagrams for 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
  $= f_{YK}^{(KR)}(y)$

Fact:

$$f_K^{(tad)}(y) + f_K^{(bub)}(y) = 0$$

$$f_{YK}^{(rbw)}(y) + f_{YK}^{(KR)}(y) = f_{KY}^{(rbw)}(y)$$

GEM development

Cite: pionTDIS proposal

1/ Reliable GEMs

2/ Channel Cost reduction: 24k IO trips

3/ Improvement of segmentation

- Angular resolution 0.2deg
- Coordinate resolution < 1mm

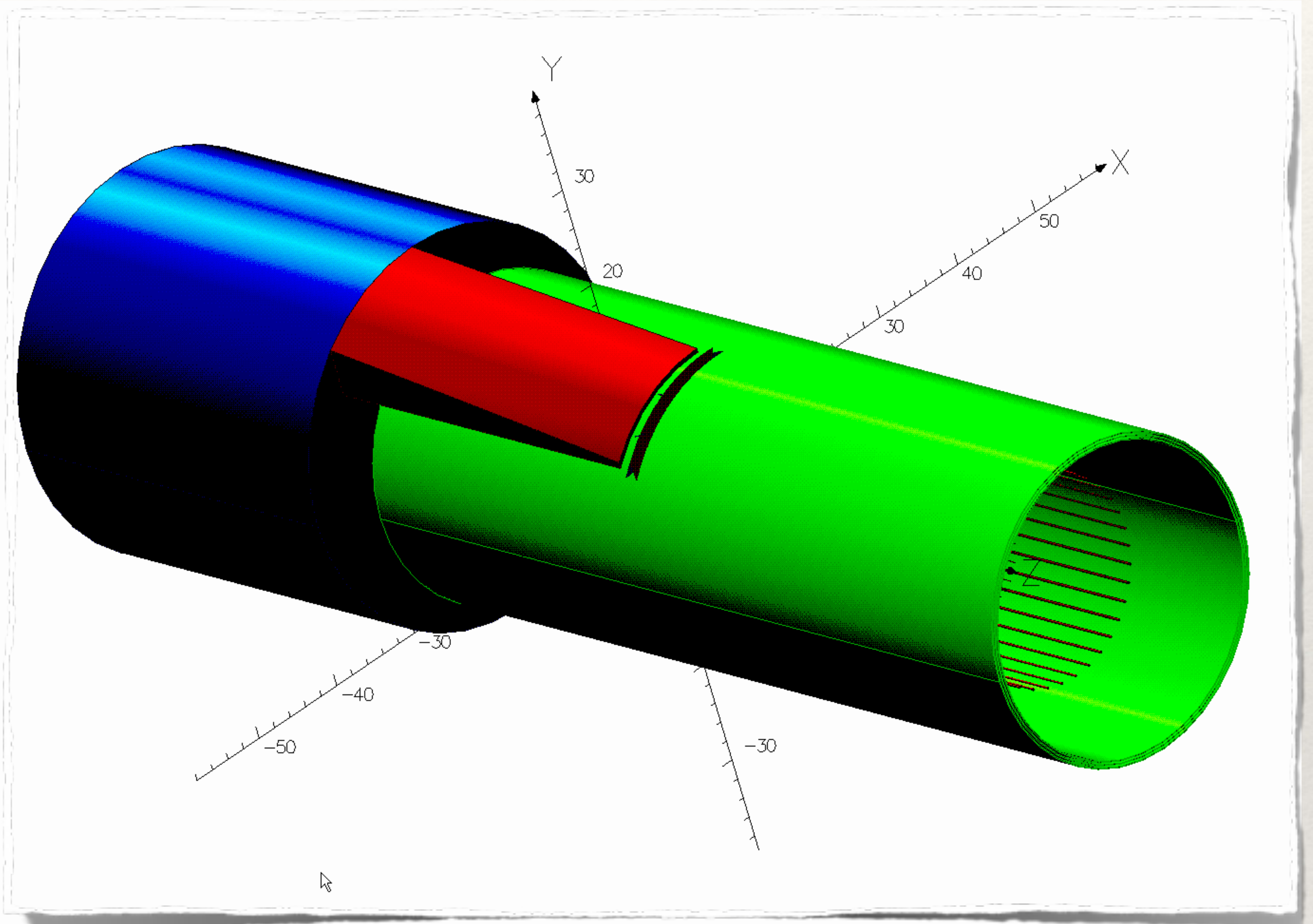
4/ Improvement of time resolution

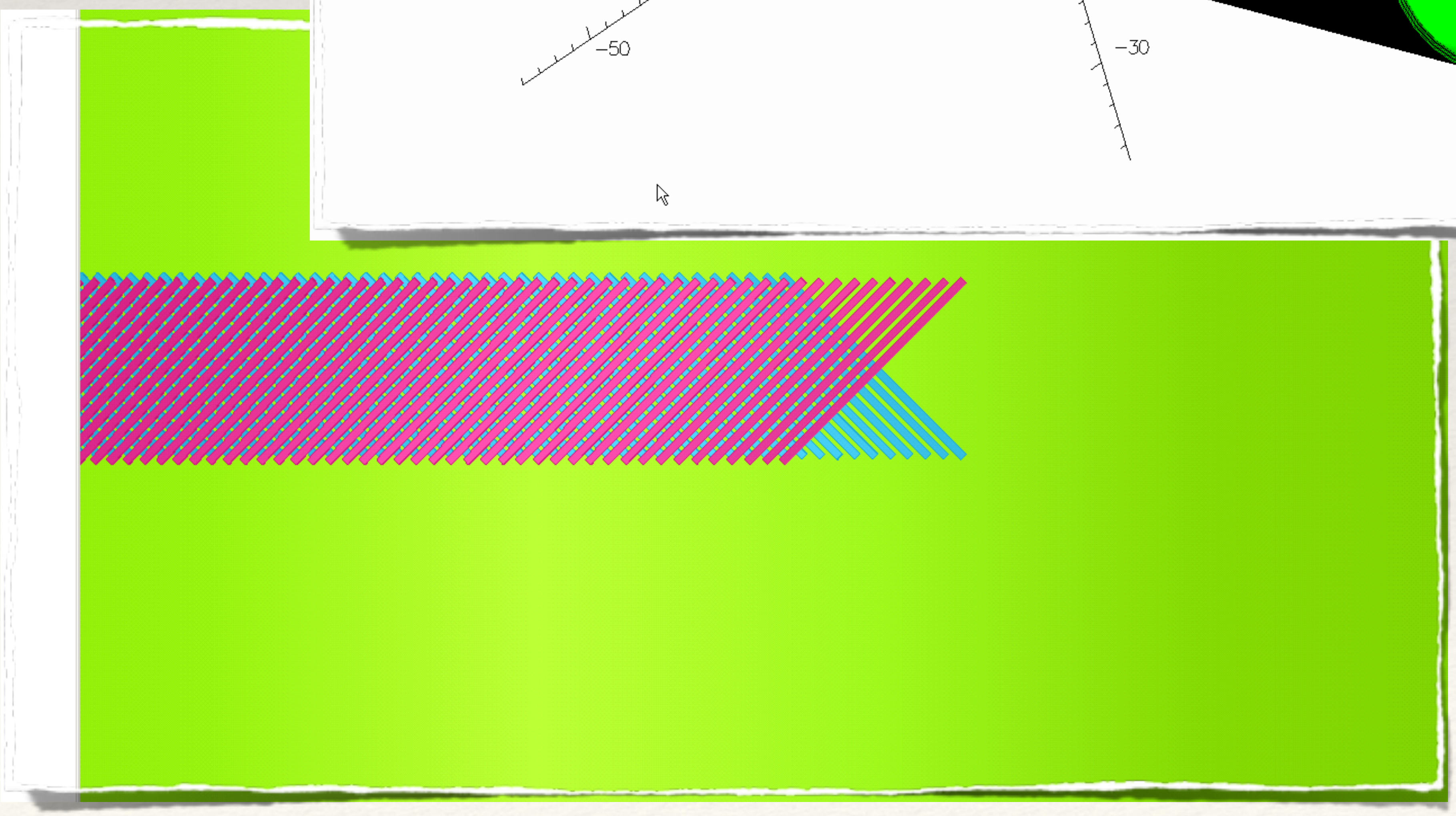
5/ Large bore and high B field

- R=10cm drift region
- Improve momentum resolution
- Max. Momentum < 400MeV/c

6/ Experienced Collaboration

- **Any optimizations would benefit both !!**





1/ simple two body object and LQCD calculation near completely describe all meson sector
2/ complete two different theoretical approaches (LQCD and DSE), bottom up and top down, they ends up same answer for kaon/pion momentum distribution differences…