COHERENT ϕ MESON ELECTRO - PRODUCTION OFF HELIUM-4 NUCLEI

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Goal : Extracting Gluon Density Distributions in Helium-4 nucleus

- **Our Objective:**

Determine how **gluons are spatially distributed** inside the Helium-4 nucleus.

- **Background:**

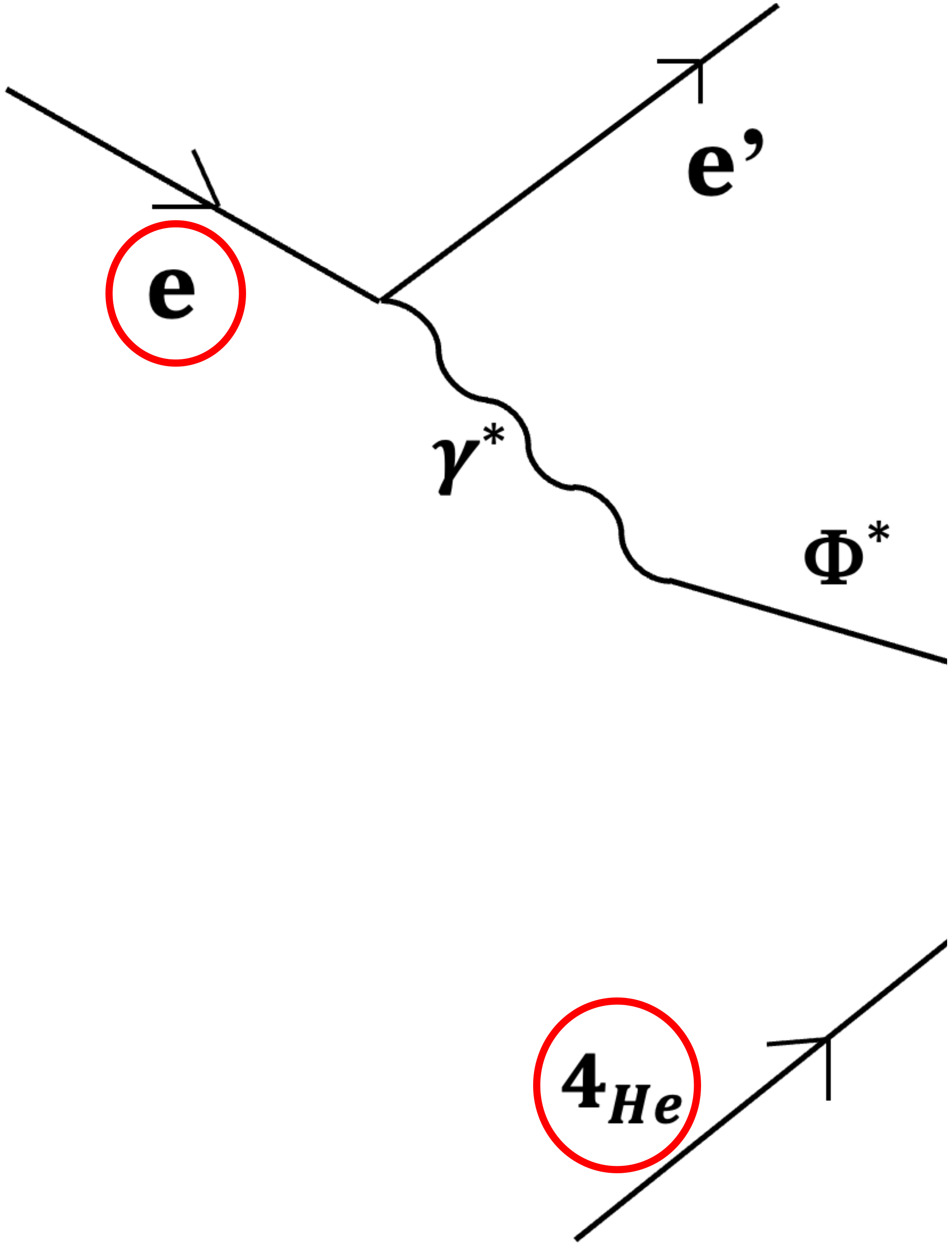
➢ Each **nucleon (proton, neutron)** is made of **quarks and gluons**.
➢ A **Helium-4 nucleus** consists of four nucleons bound together by the **strong (gluon-mediated) force**.

- **Open Questions:**

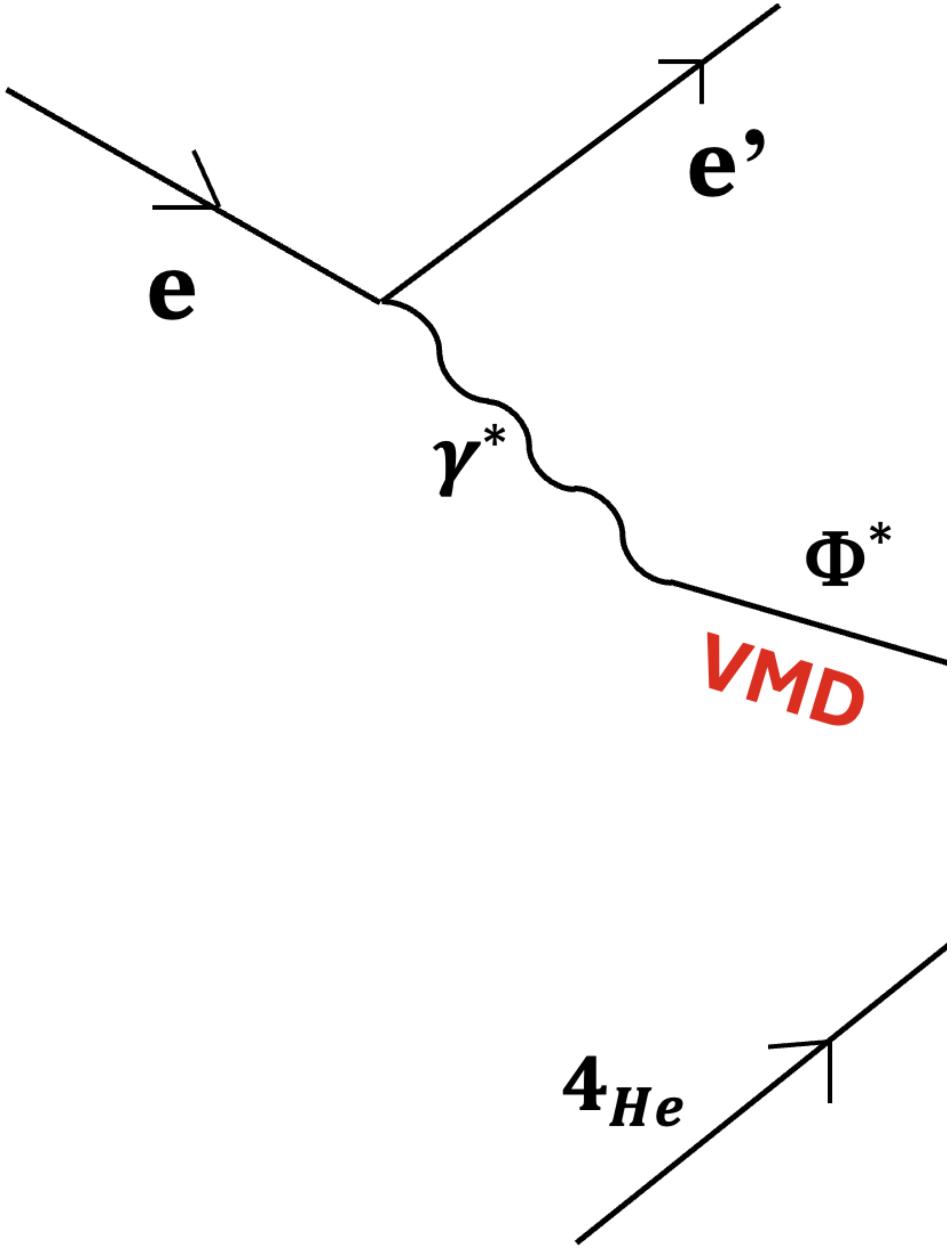
❑ How are the **gluons arranged** within Helium-4?
❑ Are they the densest **at the center** of the nucleus?
❑ More concentrated **within each nucleon**?
❑ Or possibly enhanced **between nucleons** where the binding occurs?

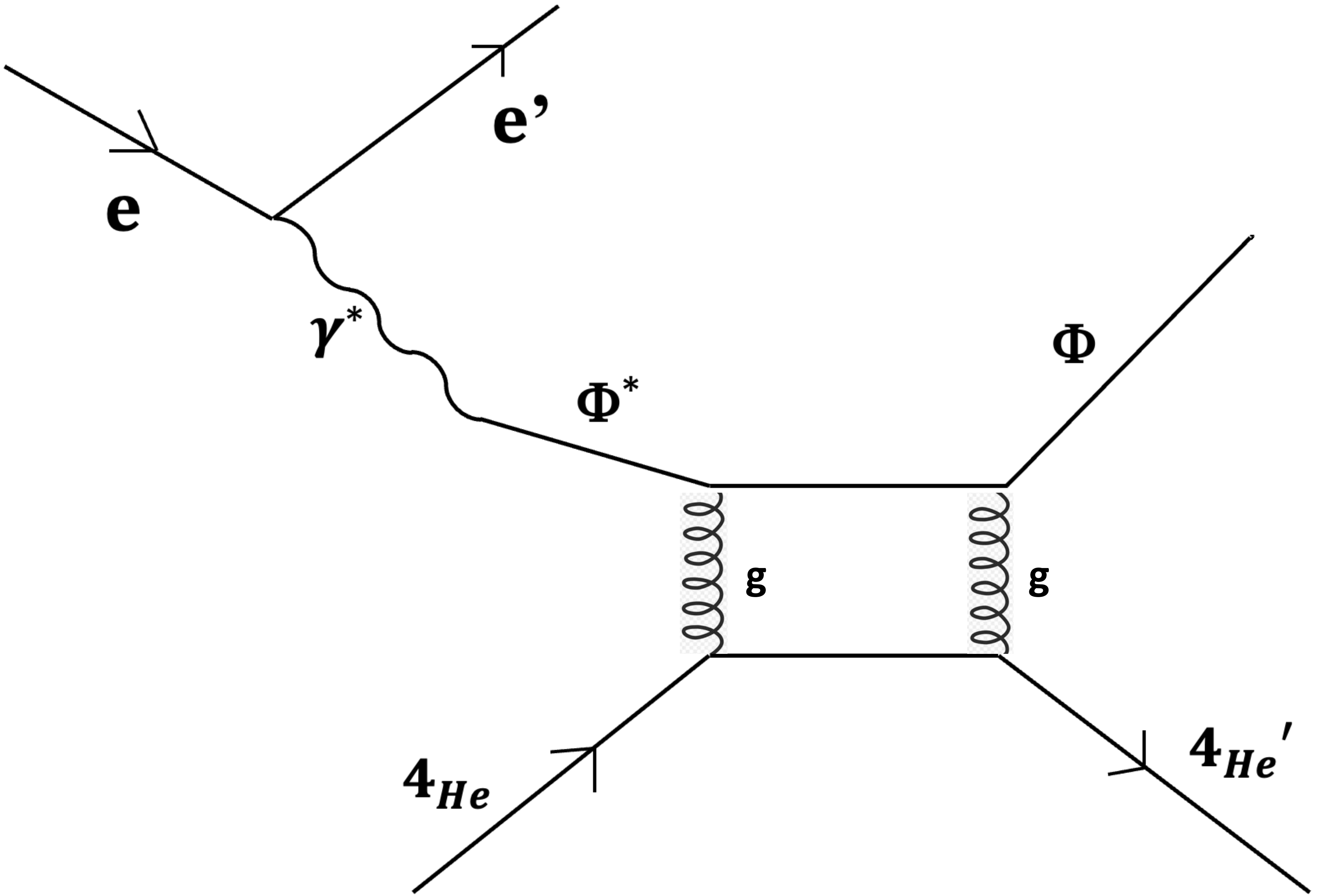
These distributions are **unknown** and measuring them will reveal how gluons bind nuclear matter.

We can measure the cross-section and do a Fourier transform to go from momentum space to cartesian space.

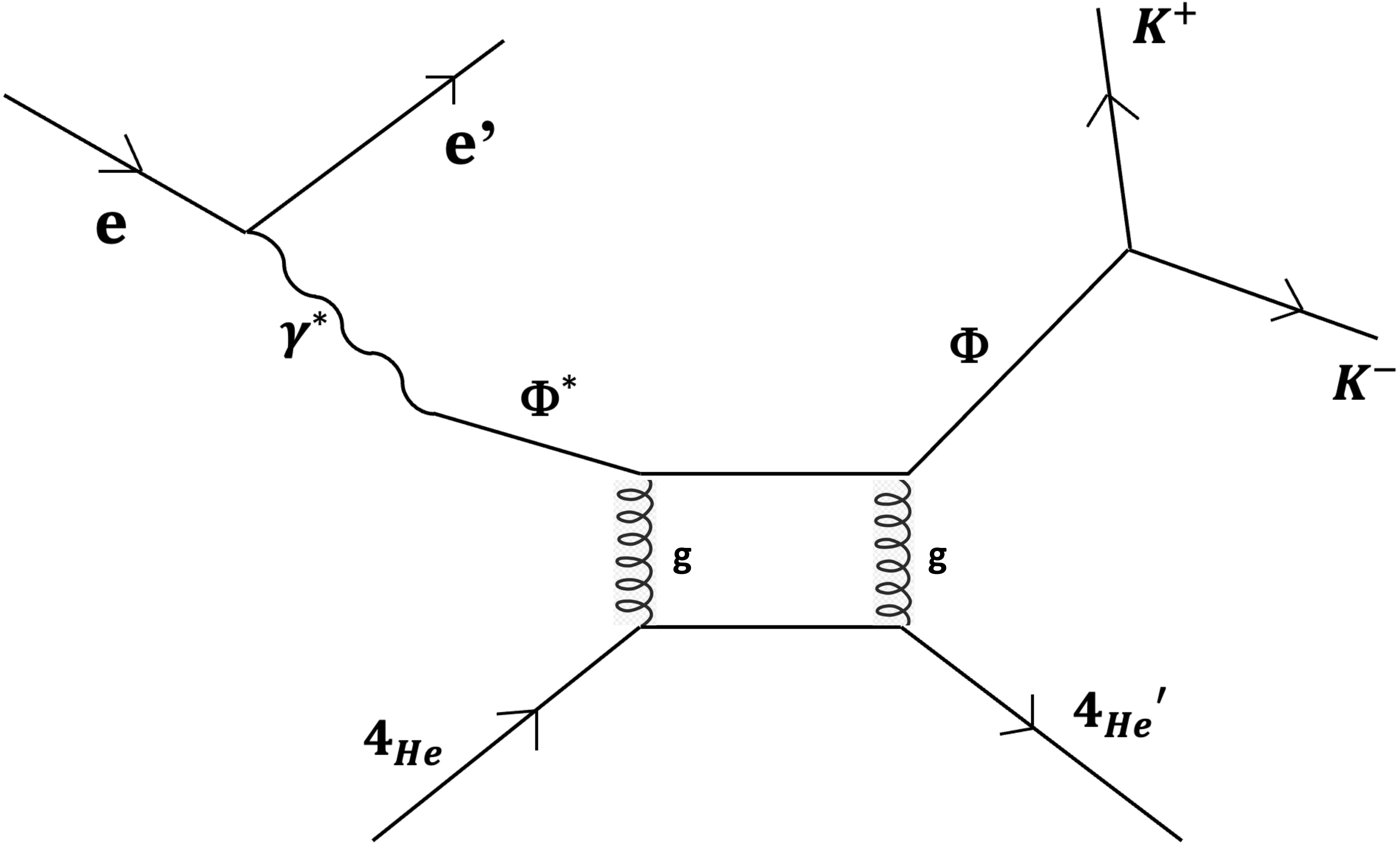


e'
e
γ^*
Φ^*
4_{He}

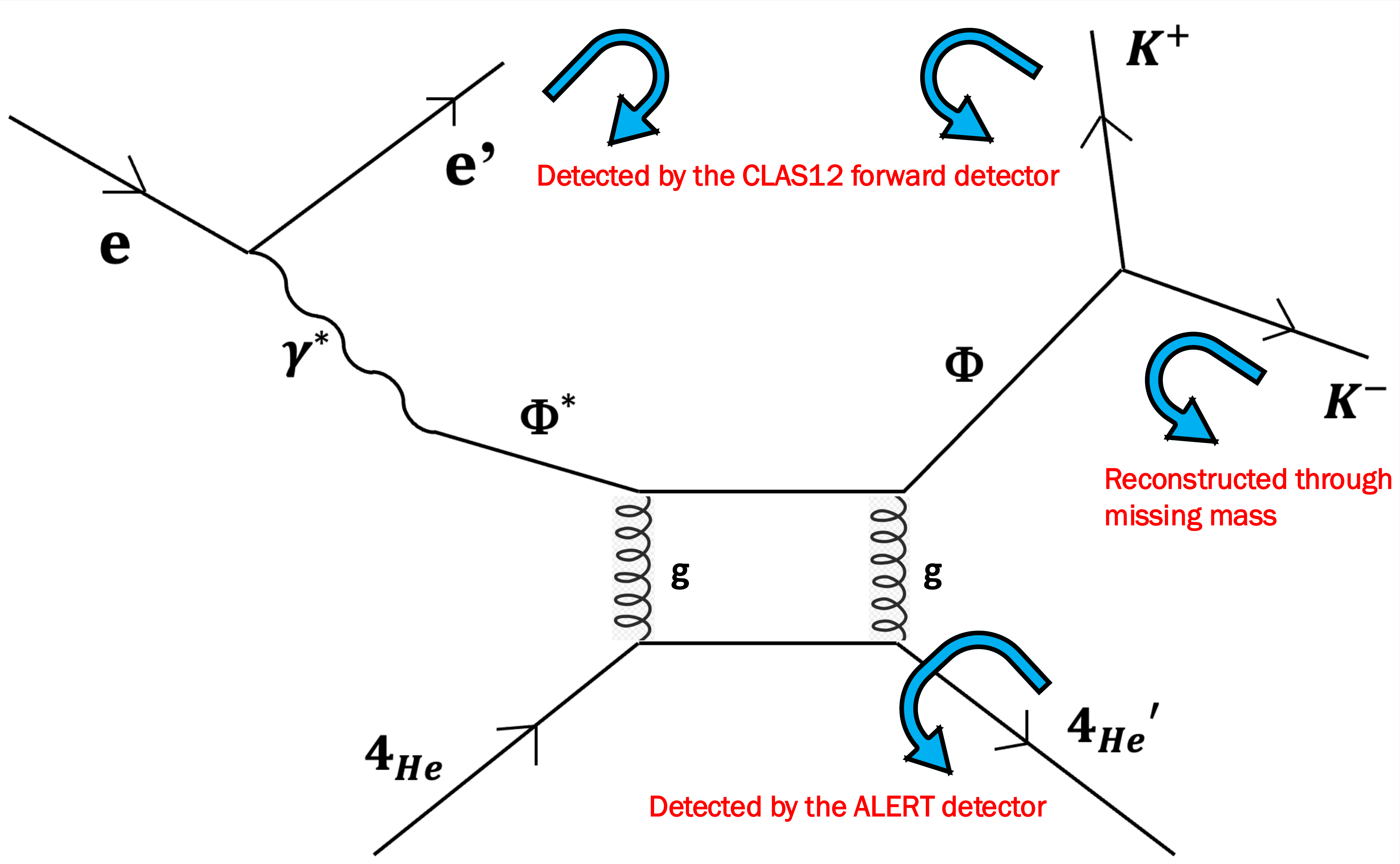

e
e’
γ^*
Φ^*
VMD
4_{He}



e
e'
γ^*
Φ^*
Φ
g
g
4_{He}
$4_{He}'$



e
e’
γ^*
Φ^*
Φ
K^+
K^-
g
g
4_{He}
$4_{He}'$


e
e'
Detected by the CLAS12 forward detector
K^+
γ^*
Φ^*
Φ
K^-
Reconstructed through missing mass
g
g
^4He
$^4He'$
Detected by the ALERT detector

- The cross-section (longitudinal) for this reaction can be expressed in terms of the **General Parton Distribution** or **GPDs** as:

$$\frac{d\sigma_L}{dt} = \frac{1}{Q^6} \left| \int dx\, C_g(x, \xi, Q^2)\, H_g(x, \xi, t) \right|^2$$

where $\boldsymbol{H_g}$ is the **gluon GPD** and $\boldsymbol{C_g}$ is a calculable hard-scattering coefficient.

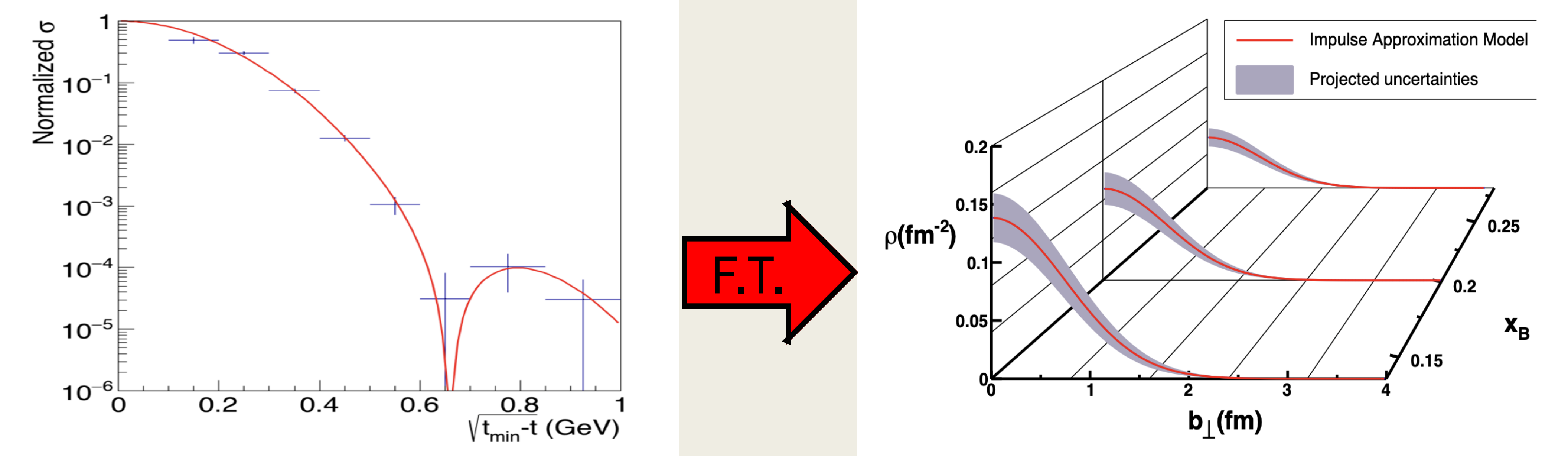
Measuring $d\sigma/dt$ over a range of t, X and Q^2 gives access to the gluon GPD.

Once we have the gluon GPD, we can perform a **Fourier transform** in t to go from momentum space to coordinate space:

$$g(x, b_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2}\, e^{-ib_\perp \cdot \Delta_\perp}\, H_g(x, 0, -\Delta_\perp^2)$$

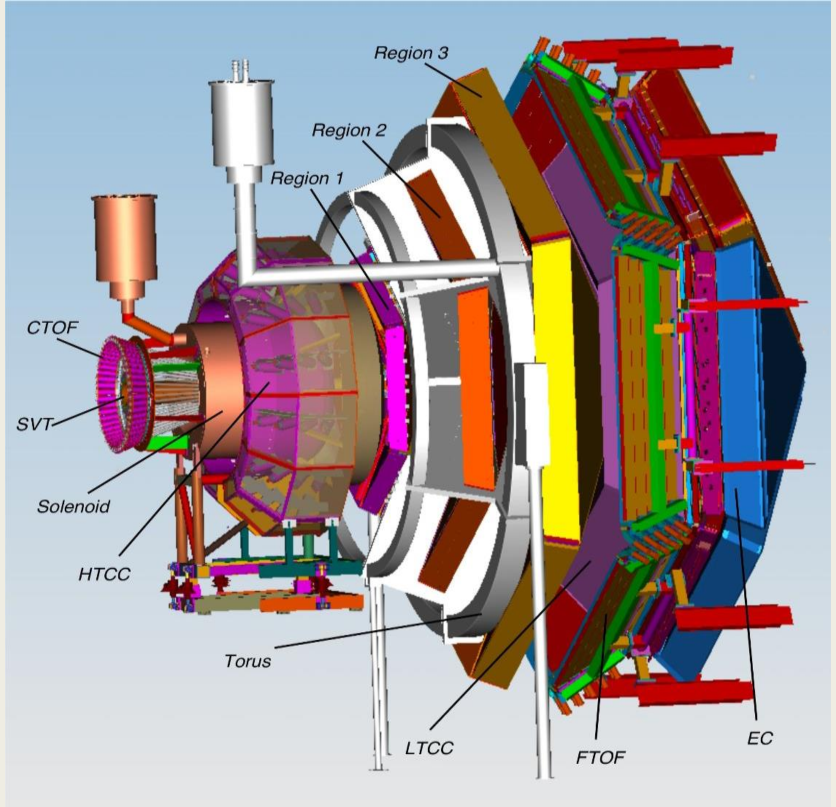
- This gives us $g(x, b_\perp)$, the **spatial gluon density** at a given momentum fraction x.
- In other words, by measuring ϕ electroproduction and its dependence on t we can image where gluons are located inside the Helium-4 nucleus, a technique sometimes called **nuclear gluon tomography**.

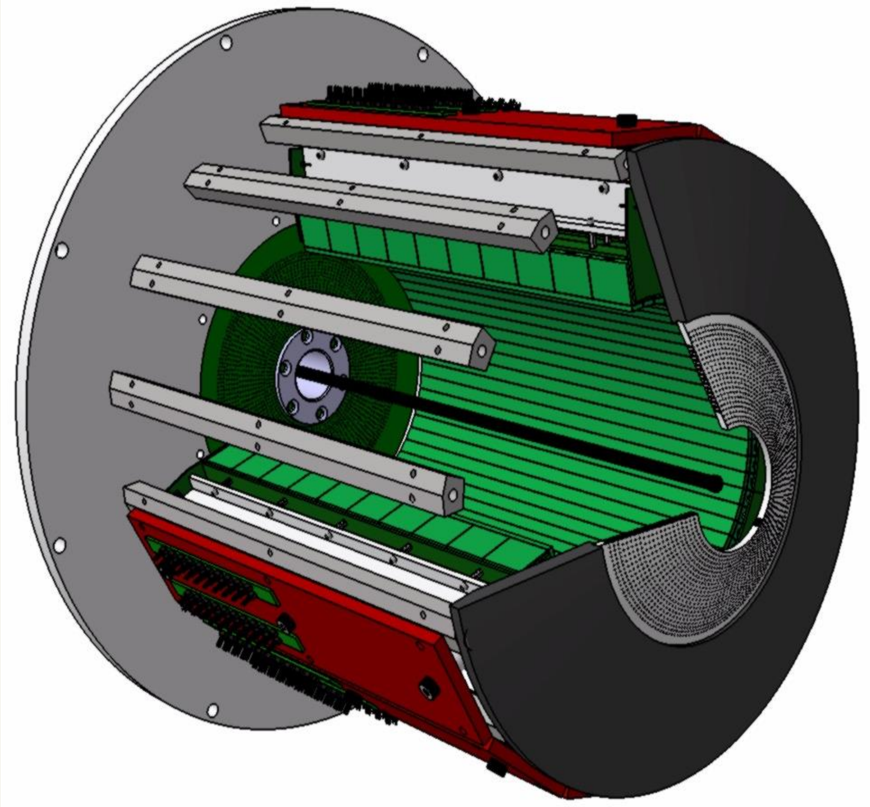
- This integration must be done over t, at a fixed X (and therefore fixed Q^2).



This is the projected result from the experiment.

- In practice, we measure the scattered electron, and the recoil Helium-4 and the produced kaons: only one of them is detected and the other one is reconstructed and that's why it is a **semi exclusive process**. Now, from these particles, we can reconstruct the full kinematics t, X and Q^2 for each event.
- By building up the distribution $d\sigma/dt$ across many events, we can then perform the Fourier transform to obtain the gluon spatial profile.
- The challenge is to measure over a wide range in t, X and Q^2 and that's where the **CLAS12 and ALERT detectors** come in which have a large acceptance in phi (2π). They also have a theta acceptance that is large (but different for each detector).





CLAS12 Detector

- It can detect charged particles like electrons, pions, kaons, but fails to detect low energy recoiling target particles.
- Angular range: **5** degrees to **35** degrees

ALERT Detector

- **Detects lighter nuclei –** protons, deuterons, He-3, He-4 etc.
- Wide angular range, often covering ~ **π/4 to π/2** (i.e., ~ 45° to 90°)

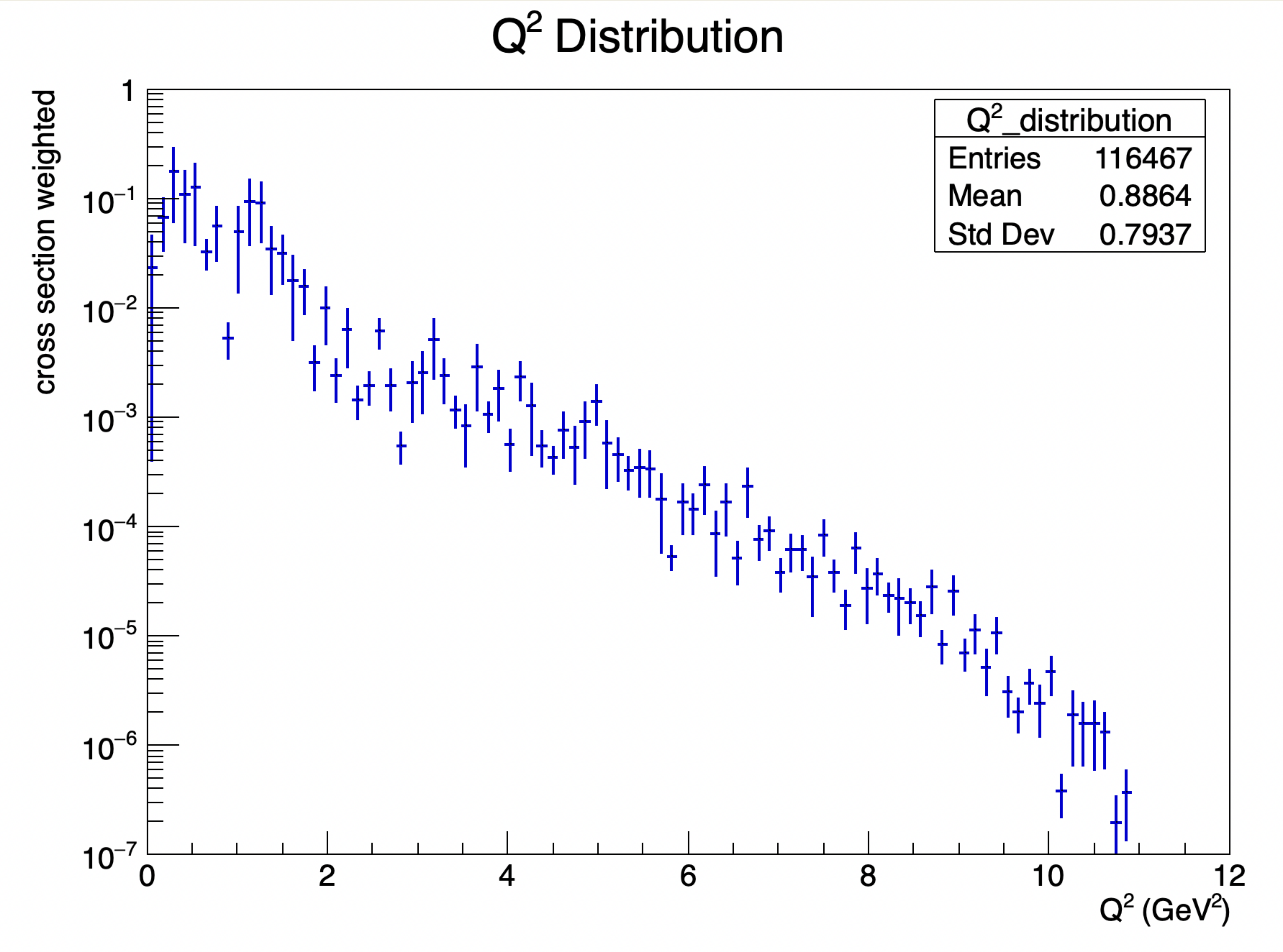
Plots from simulation:

- Forcing it to be fully exclusive:

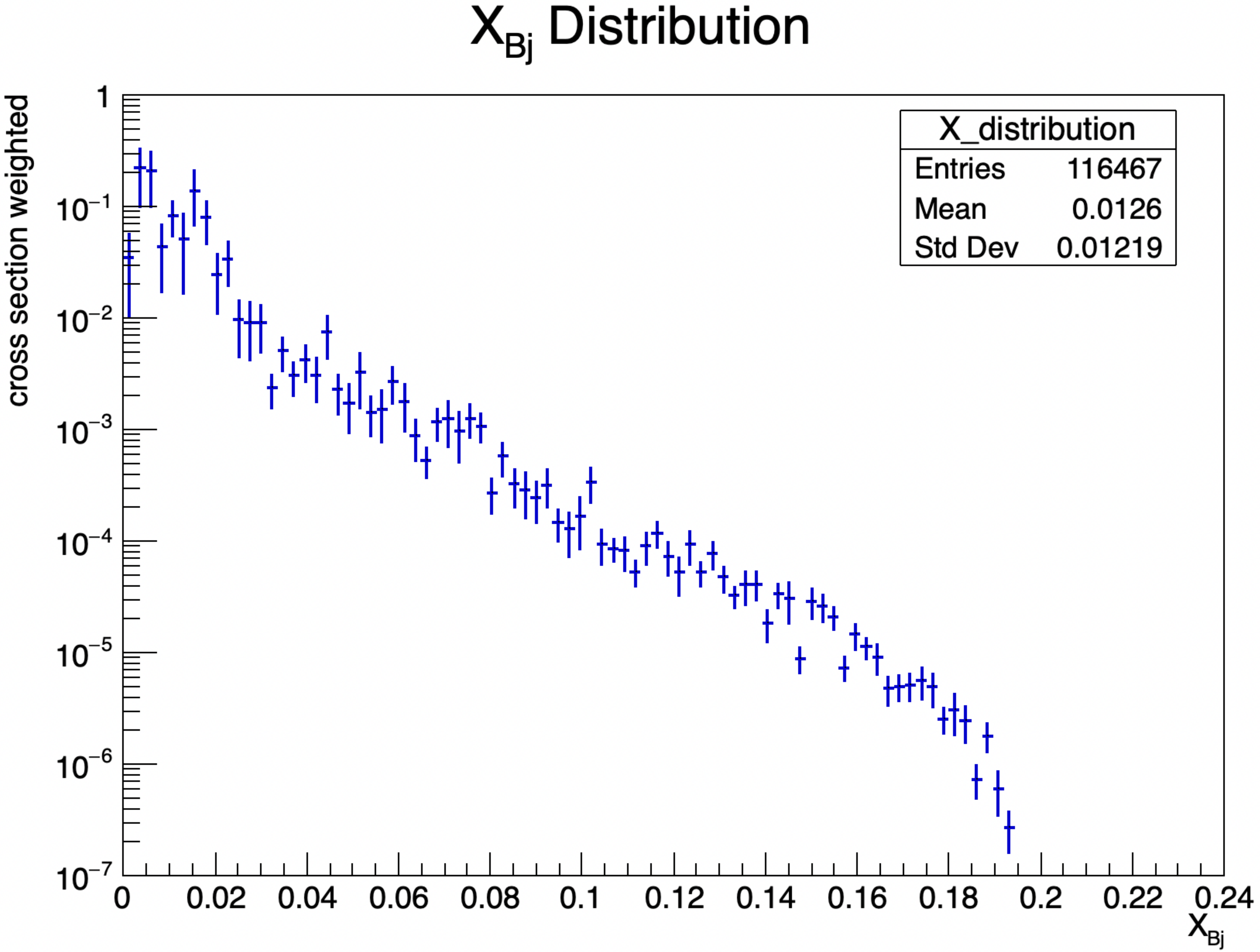
  e + He4 -> e' + He4' + phi

- Coherent Helium - 4 and Phi meson selection.

- Cut on the angle for scattered electron (5 – 45 degrees)

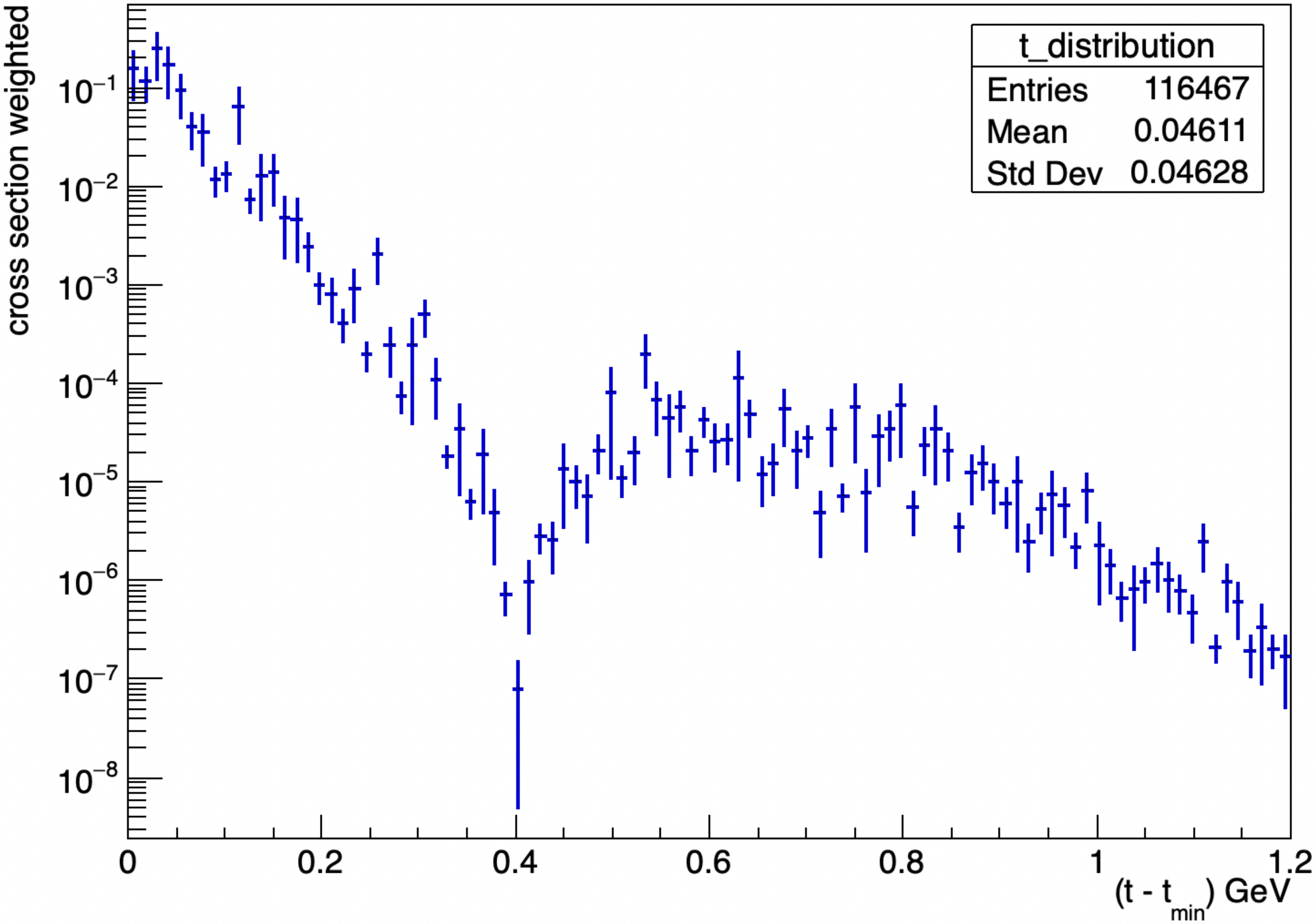


Q2 Distribution
Q2_distribution
Entries 116467
Mean 0.8864
Std Dev 0.7937
cross section weighted
Q2 (GeV2)

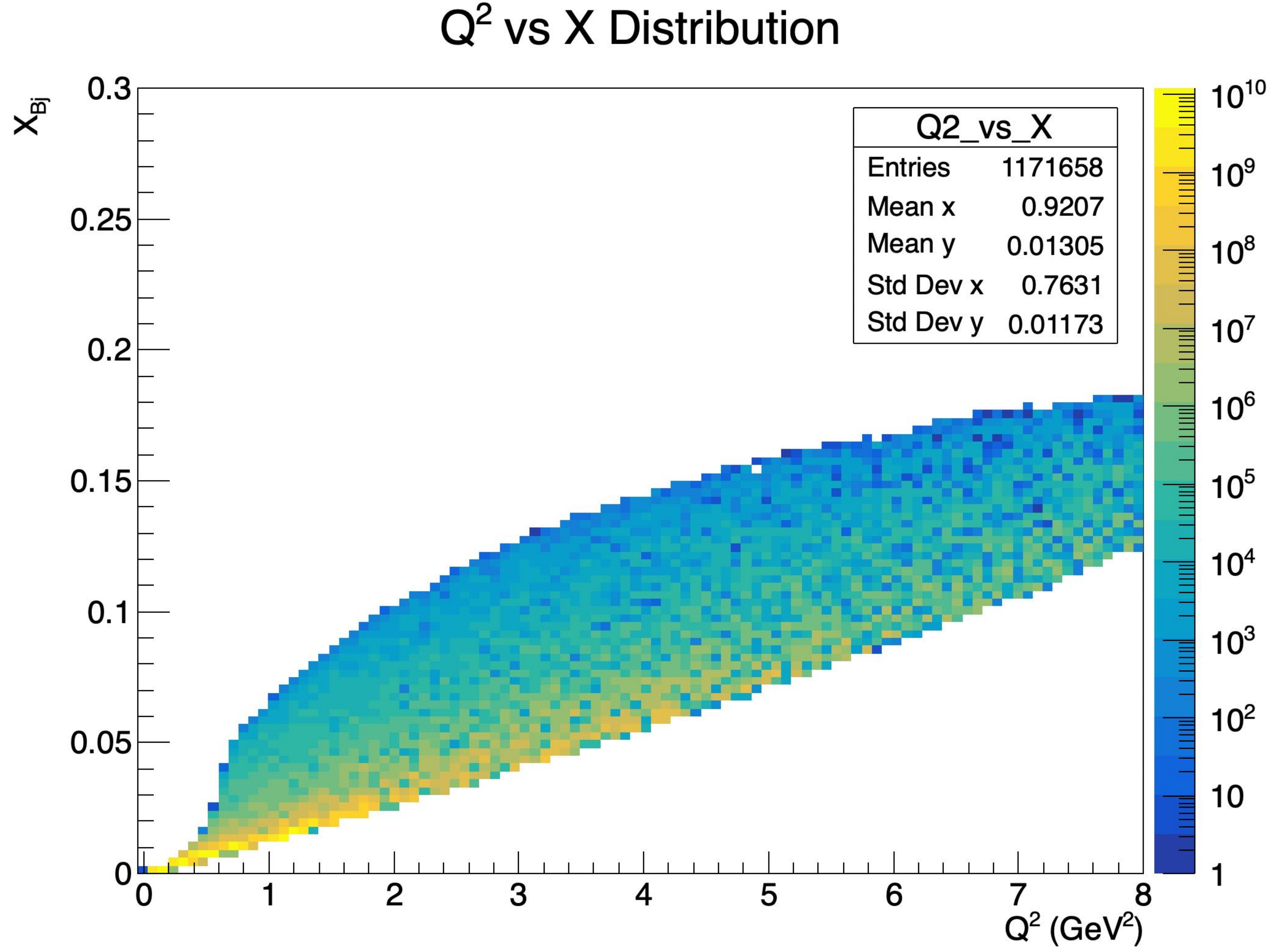


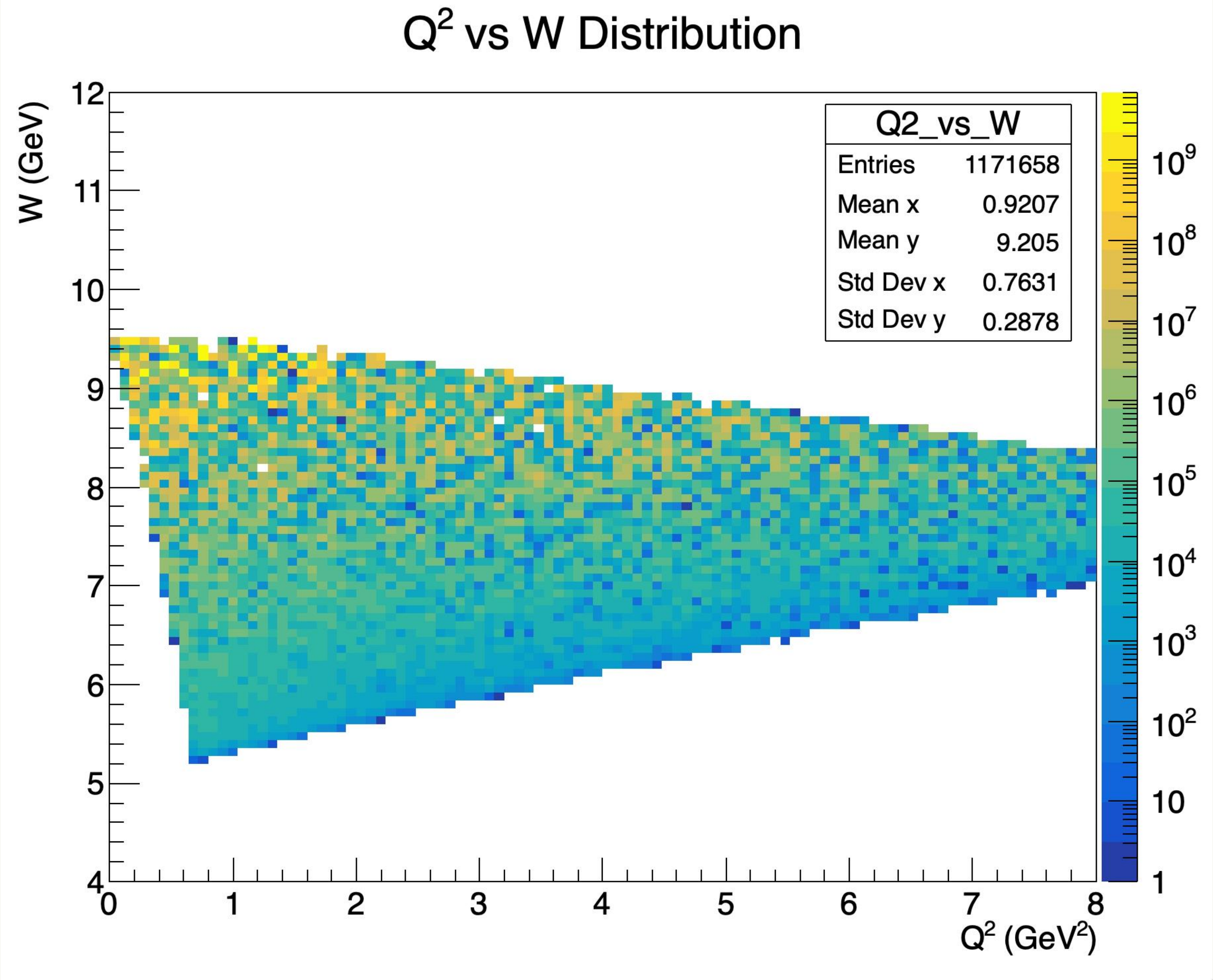
X_{Bj} Distribution
cross section weighted
X_distribution
Entries 116467
Mean 0.0126
Std Dev 0.01219
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2 0.22 0.24
X_{Bj}

$(t - t_{min})$

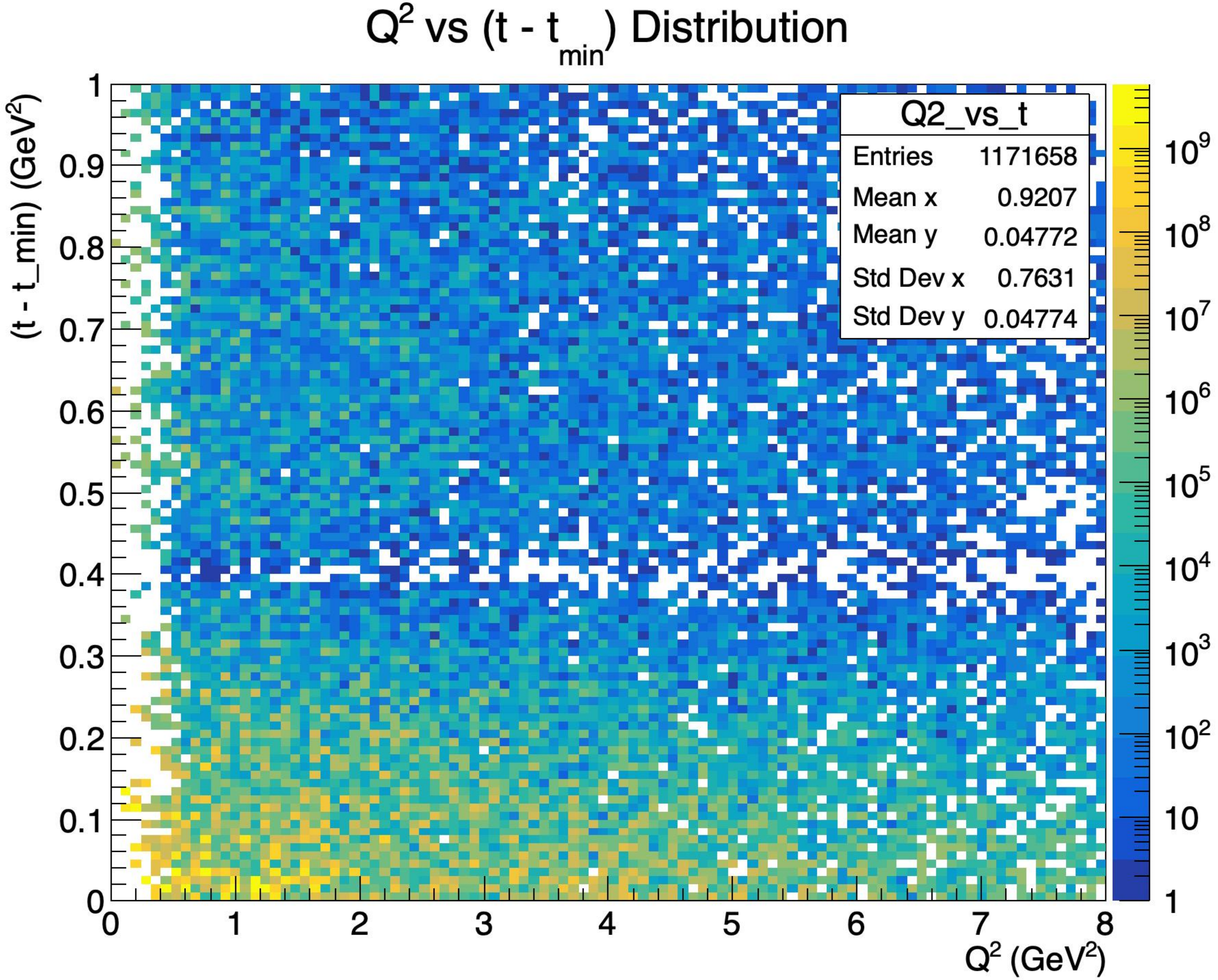


t_distribution
Entries 116467
Mean 0.04611
Std Dev 0.04628
cross section weighted
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
0
0.2
0.4
0.6
0.8
1
1.2
(t - t_min) GeV


Q2 vs X Distribution
X_{Bj}
Q^2 (GeV^2)
Q2_vs_X
Entries 1171658
Mean x 0.9207
Mean y 0.01305
Std Dev x 0.7631
Std Dev y 0.01173



Q^2 vs W Distribution
Q2_vs_W
Entries 1171658
Mean x 0.9207
Mean y 9.205
Std Dev x 0.7631
Std Dev y 0.2878
W (GeV)
Q^2 (GeV^2)

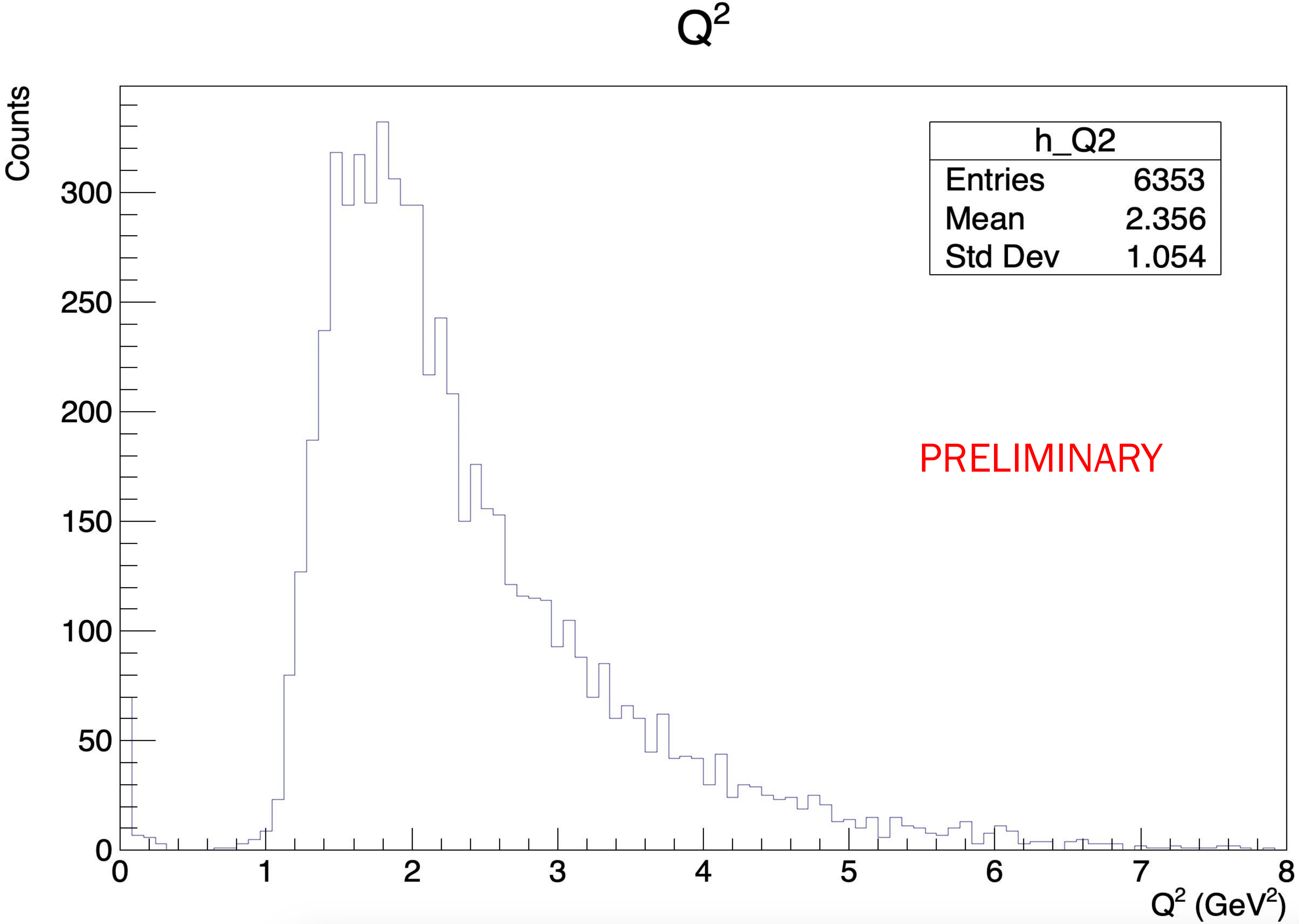

Q2 vs (t - tmin) Distribution
(t - t_min) (GeV2)
Q2 (GeV2)
Q2_vs_t
Entries 1171658
Mean x 0.9207
Mean y 0.04772
Std Dev x 0.7631
Std Dev y 0.04774
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
0 1 2 3 4 5 6 7 8
1 10 102 103 104 105 106 107 108 109

Plots from data:

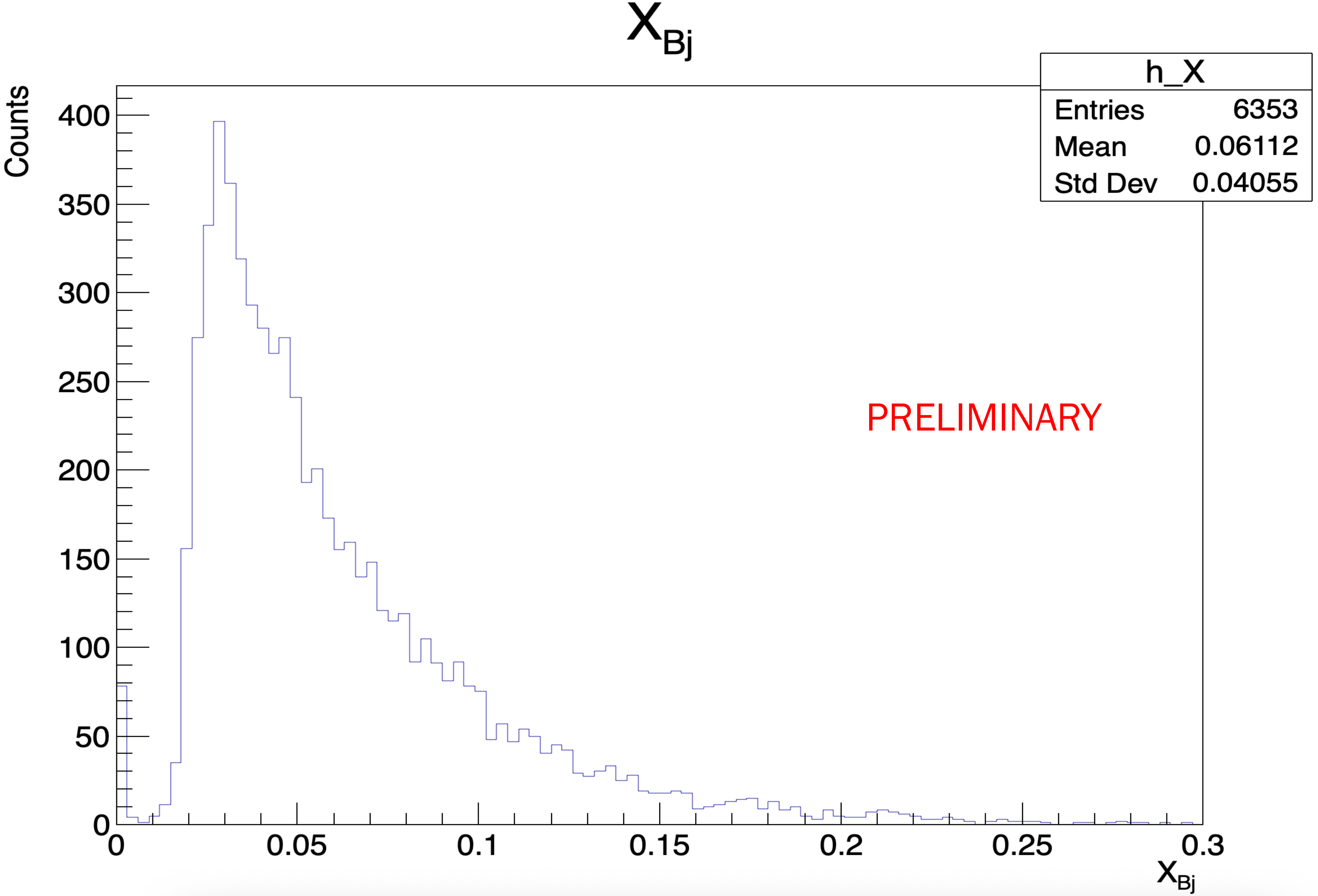
- Have not made any phi-meson or coherent He4 selection, so the plots are of e + He4 -> e' + X.

- We do not expect the simulation and data plots at this stage to match (the semi-exclusive channel will be a subset of this data).

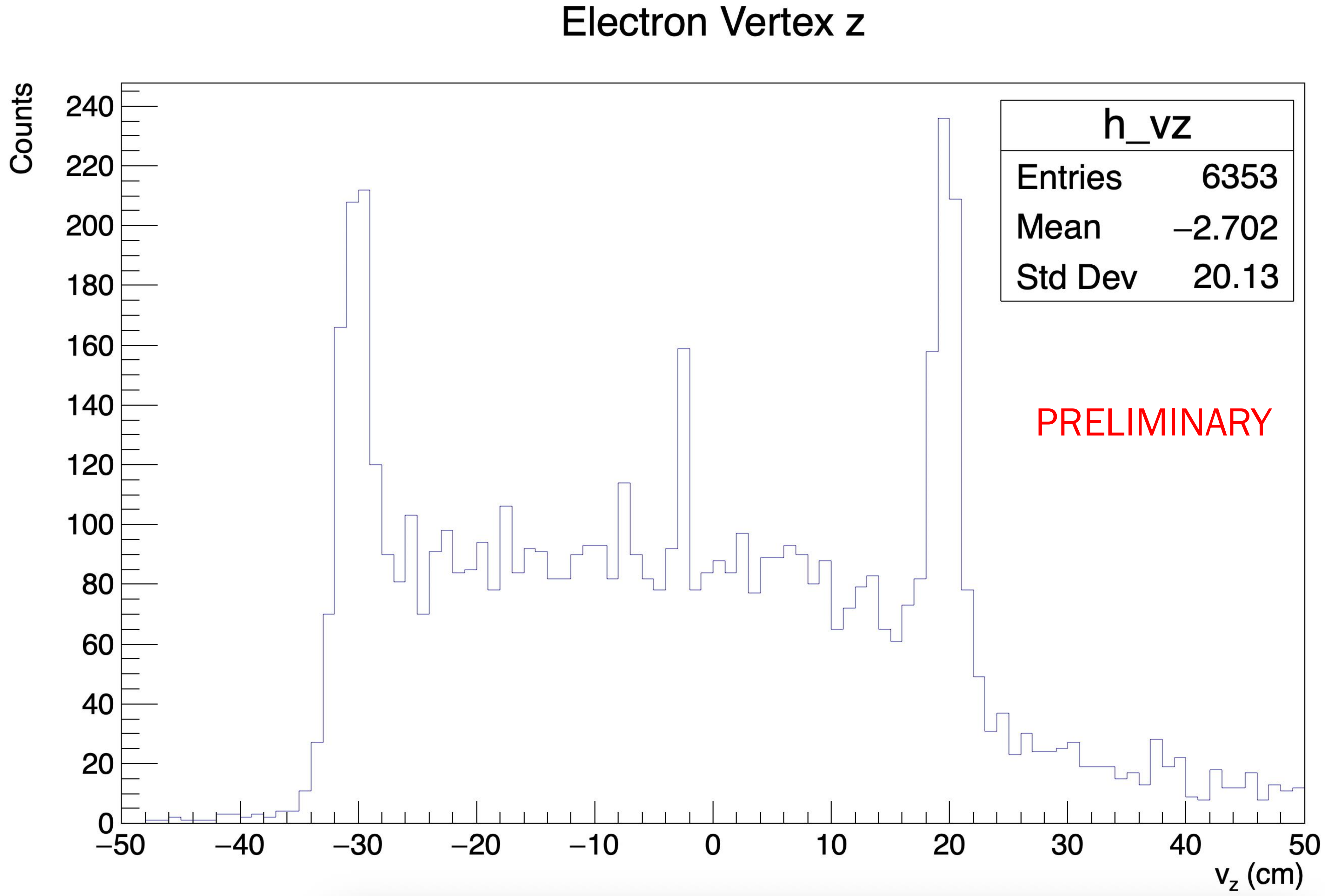
- The plots that are shown for the data are only a very small subset of the entire dataset (much less than 1%).

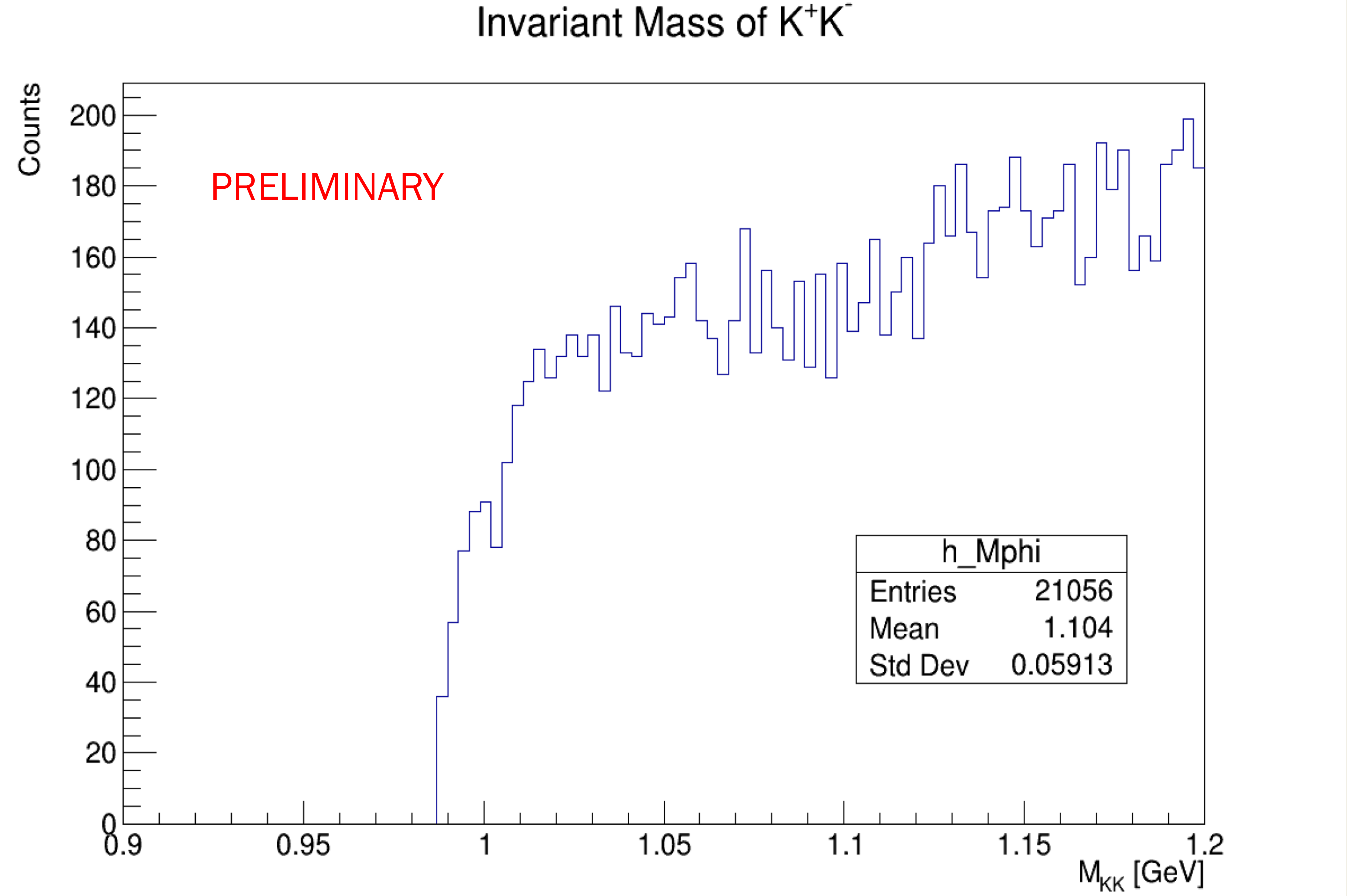


Q^2
Counts
h_Q2
Entries 6353
Mean 2.356
Std Dev 1.054
PRELIMINARY
0
50
100
150
200
250
300
0 1 2 3 4 5 6 7 8
Q^2 (GeV^2)



X_{Bj}
h_X
Entries 6353
Mean 0.06112
Std Dev 0.04055
PRELIMINARY
Counts
0
50
100
150
200
250
300
350
400
0
0.05
0.1
0.15
0.2
0.25
0.3
X_{Bj}


Electron Vertex z
Counts
h_vz
Entries 6353
Mean −2.702
Std Dev 20.13
PRELIMINARY
v_z (cm)
0
20
40
60
80
100
120
140
160
180
200
220
240
−50
−40
−30
−20
−10
0
10
20
30
40
50


Invariant Mass of K+K-
Counts
PRELIMINARY
h_Mphi
Entries 21056
Mean 1.104
Std Dev 0.05913
0
20
40
60
80
100
120
140
160
180
200
0.9
0.95
1
1.05
1.1
1.15
1.2
MKK [GeV]

Summary and future steps:

- The ϕ electroproduction channel provides a clean probe of **gluon dynamics** because it proceeds primarily through two-gluon exchange.

- Measuring $d\sigma/dt$ across a wide kinematic range allows us to access the **gluon GPD** $H_g(x,\xi,t)$.

- Fourier transforming this distribution gives the **spatial gluon density** inside Helium-4.

We are still calibrating ALERT and we don't have any well reconstructed He4 yet in ALERT, which will be crucial to continue the analysis.

Although, a smaller subset of the data could have the K+ and K- minus detected in the CLAS12 detector.

While we are waiting for better calibration and better tracking in ALERT, we can try to reconstruct the phi meson with CLAS12 alone and look for signatures of the He4 in the ALERT detector.

Once that calibration is complete, we will:

- Extract the differential cross section $d\sigma/dt$ for different Q^2 and x.
- Perform the Fourier transform in t to map the gluon spatial density.
- Compare our results with theoretical GPD-based models.

Thank you!