CUTTING DATA FOR ANALYSIS | THE INTERNAL STRUCTURE OF THE NUCLEUS

SENIOR SEMINAR 2
AMELIA KARLE

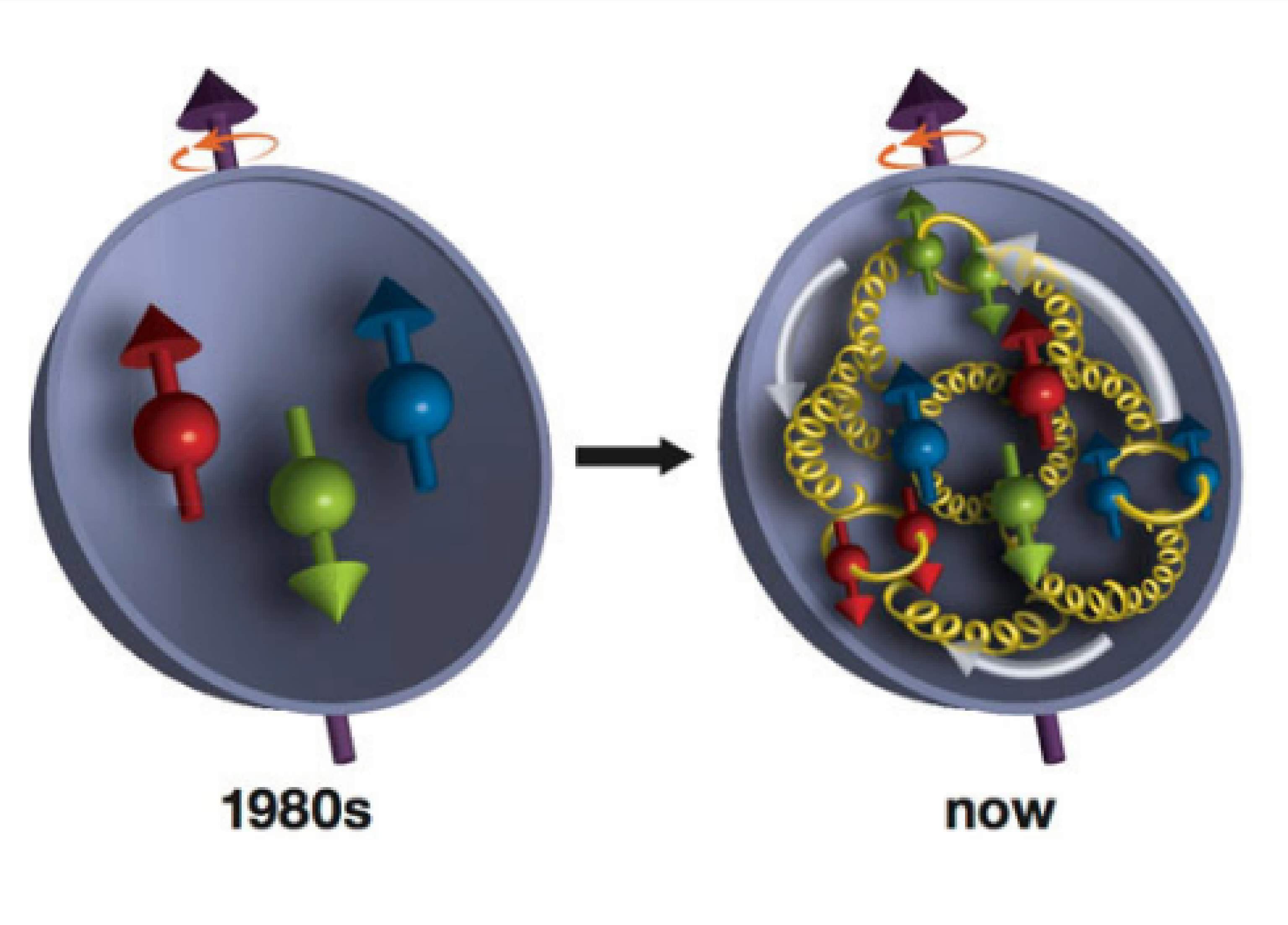
CONTENT

The problem

We want to study what the internal structure of the neutron "looks" like but we can't see something that small

Thought to be fairly simple:

- Spin up and spin down quarks



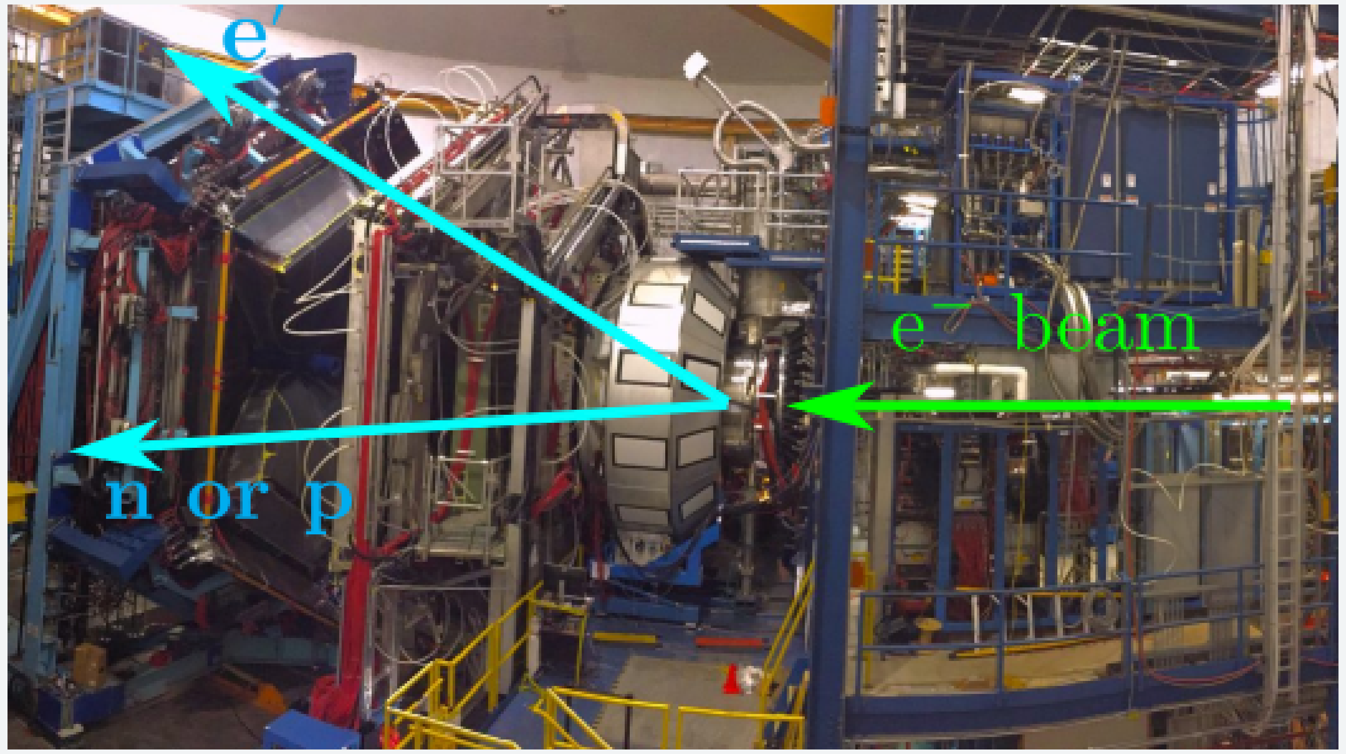
More complex structure:

- Quark, antiquark pairs
- Gluon force carrier particles
- Dynamic nature

The problem

We want to study what the internal structure of the neutron "looks" like but we can't see something that small

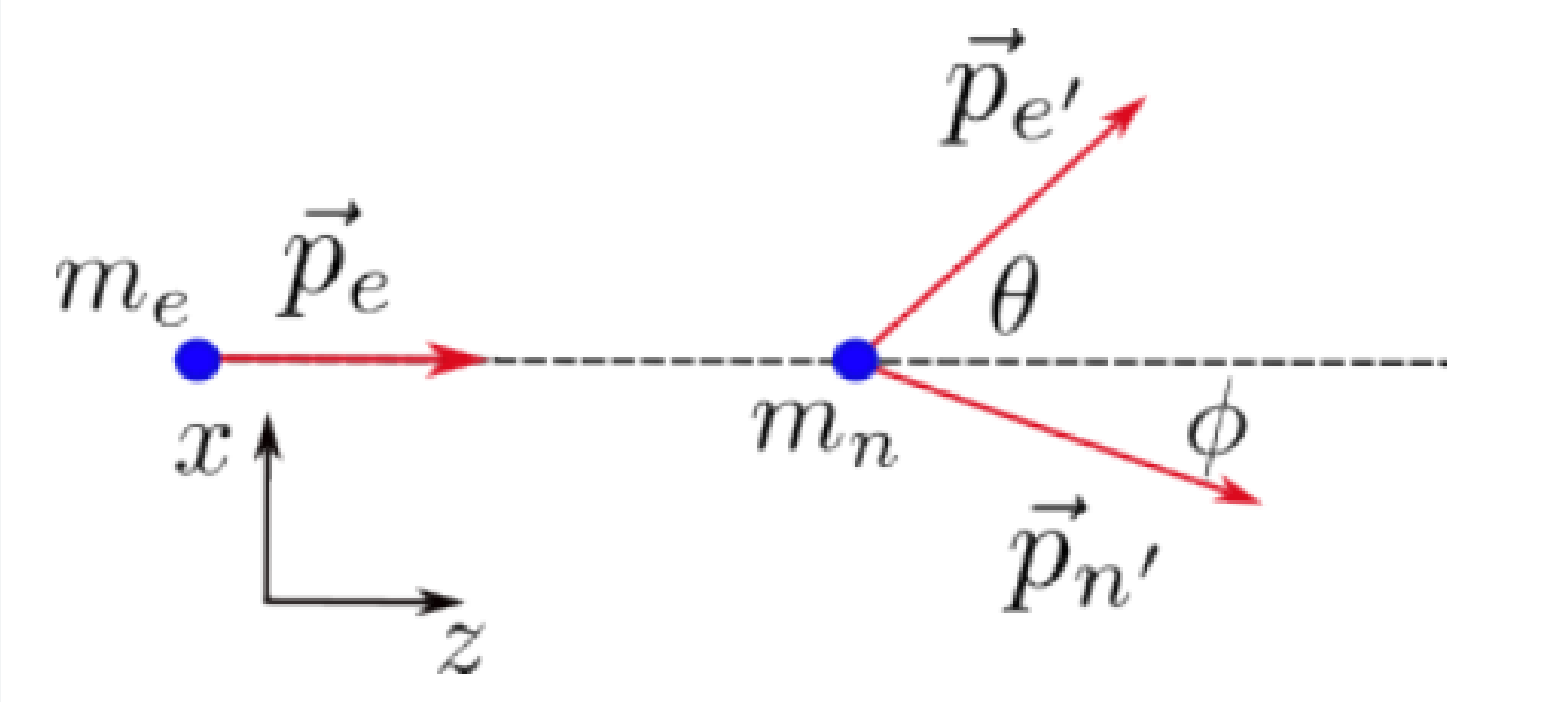
By firing high-energy electrons at nucleons, and observing how they scatter, we can make inferences about the internal structure



CLAS 12 detector at CEBAF

The problem

We want to study what the internal structure of the neutron "looks" like but we can't see something that small

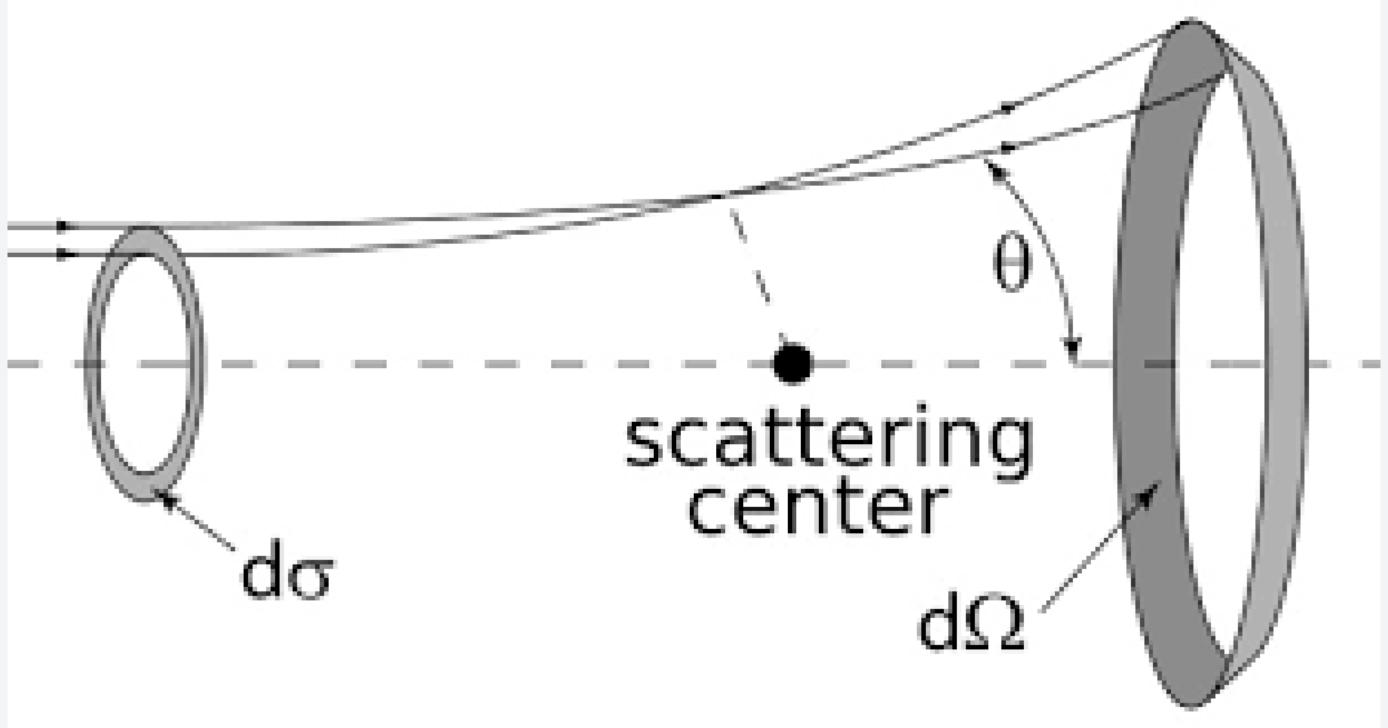


- Physics 131/132 collision problem
    - Energy and momentum are conserved
- Differs in part due to relativistic effects
    - Four-momentum (discussed last semester)

Differential cross-section

- Differential cross-section: measures the probability of scattering at a particular angle given initial parameters
- Diff. cross-section can tell us information about the **scattering amplitude** according to:

$$\frac{d\sigma}{d\Omega} = |f(\theta, \phi)|^2$$



- In elastic scattering events, the **scattering amplitude** can be factorized into a part that depends on
    1. Momentum transfer (q)
    2. The internal structure of the target --> Form Factors

Elastic Electromagnetic Form Factors

$$G_M^n,\ G_E^n,\ G_M^p, \text{ and } G_E^p$$

- Help us understand the **shape**, **size**, and **internal composition** of the atomic nucleus.
- Used to help challenge nuclear structure models and understand the charge and magnetization distribution.
- We measure the **momentum dependence** (q^2) of the form factors and use the Fourier transform to convert this into a **space variable.**

At **low momentum transfers**, the Fourier transform of form factors can be used to find these magnetic and electric densities.

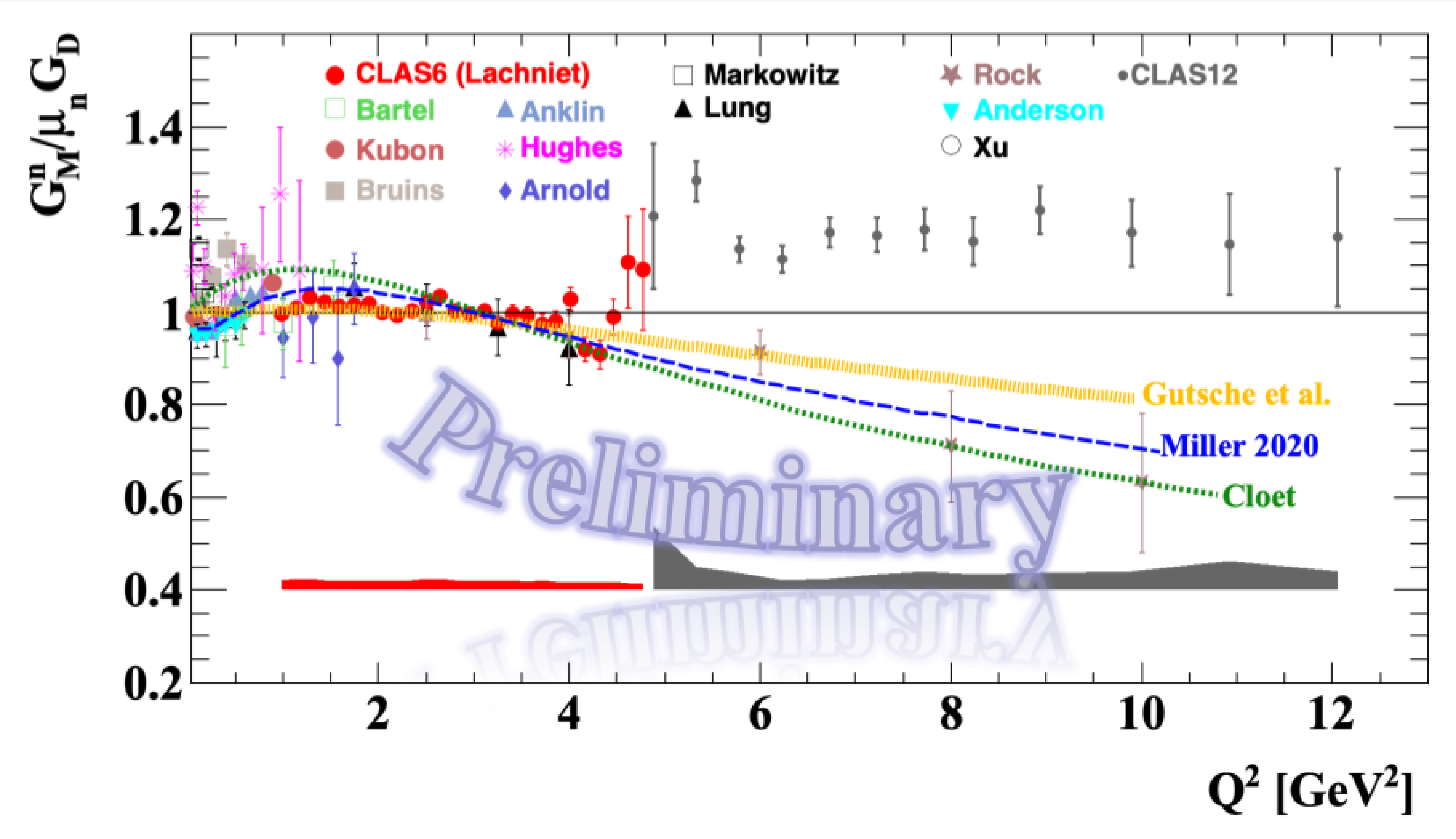
Squared Momentum Transfer (q^2)

- Calculated using the final and initial four-momentum of the electron beam:

$$q^2 = -(k - k')^2$$

- Form factors are functions of q^2 derived from fitting the scattering amplitude to experimental data

Not for distribution



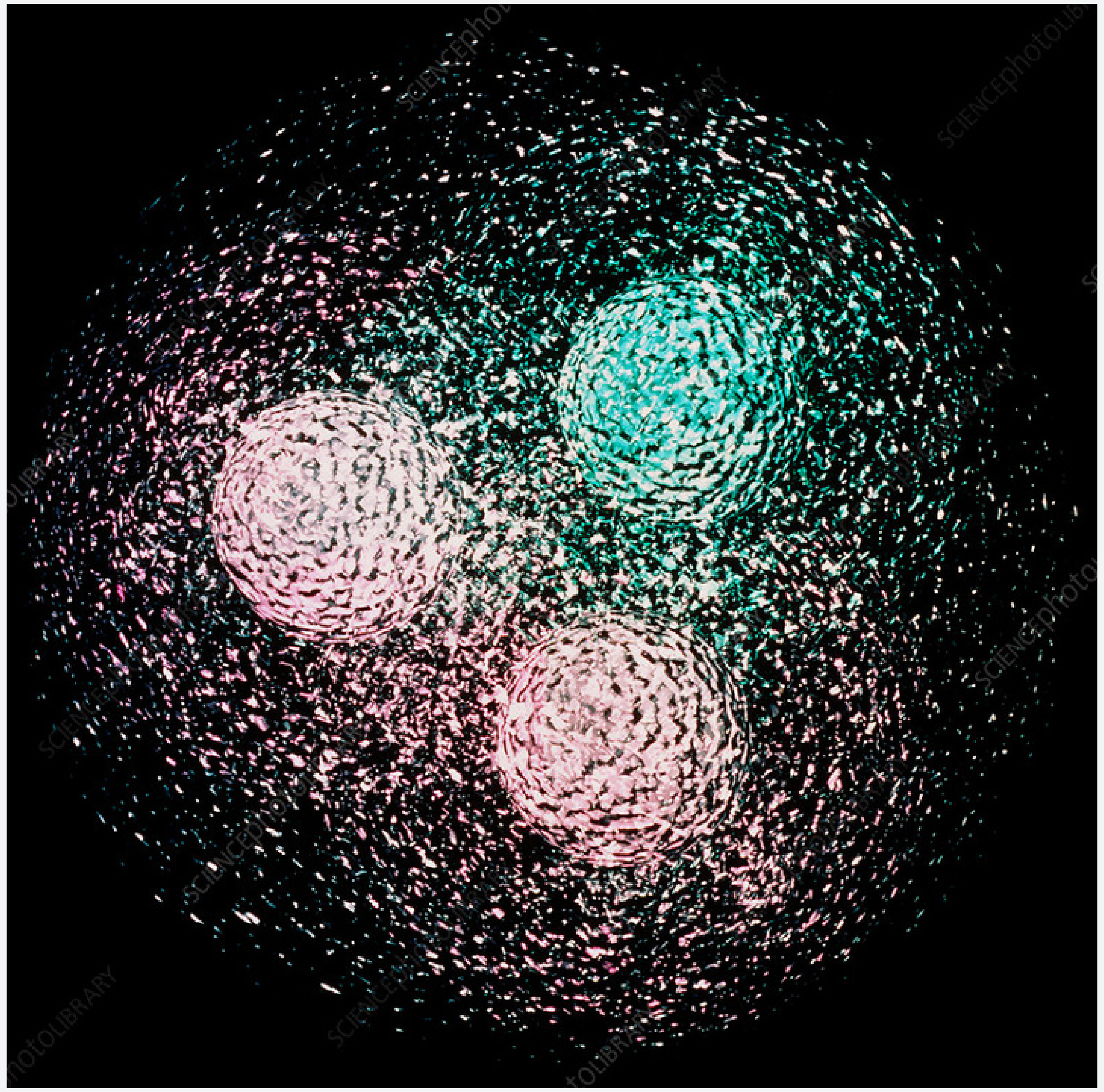
$G_M^n \longrightarrow$ Magnetic form factor of the neutron

- Proton FFs are already precisely known
- Proton FFs are easier to measure than neutrons'
  - Charge --> Neutrals are harder to measure
  - Final state interactions
  - Fermi motion
- We can determine the properties of the neutron based on data about the proton
- Measure the ratio, R, of e-n/e-p events
- Turn the ratio into the neutron magnetic form factor

$$R \approx \frac{e - n}{e - p}$$

Selecting for elastic events

- Assuming the target particle is elastically scattered by the electron: both **kinetic energy and internal structure are preserved** post-collision
  - Gives us tools to select quasi-elastic events
  - Higher precision regarding q measurements



Selecting for quasi-elastic events

Energy of the scattered electron

Energy of the electron beam

$$E_e = \frac{E_e{}'}{1 - \frac{2E_e{}'}{m_n}\sin^2\left(\frac{\theta}{2}\right)}$$

Angle of the scattered electron

$$E_e{}' = \sqrt{p_x{}^2 + p_y{}^2 + p_z{}^2}$$

$$\theta = cos^{-1}\left(\frac{pz}{\sqrt{px^2 + py^2 + pz^2}}\right)$$

*Ultrarelativistic so we can leave out the mass term

Selecting for quasi-elastic events

1.634436	0.193994	6.326643	-1.021685	-0.213937	2.714751
1.331283	0.050550	8.721537	-0.708558	0.074410	1.570567
-1.259352	-0.211419	7.865813	1.060560	0.179980	2.120686
-1.259352	-0.211419	7.865813	1.060560	0.179980	2.120686
0.730718	-1.105812	8.145447	-0.253450	0.713766	1.760155
0.730718	-1.105812	8.145447	-0.253450	0.713766	1.760155
0.730718	-1.105812	8.145447	-0.253450	0.713766	1.760155
-1.494071	0.131742	7.946397	0.902485	-0.141173	2.505114
-1.494071	0.131742	7.946397	0.902485	-0.141173	2.505114
-1.494071	0.131742	7.946397	0.902485	-0.141173	2.505114
-1.335934	0.018648	7.496870	0.379169	-0.224226	1.176343
-1.335934	0.018648	7.496870	0.379169	-0.224226	1.176343
-1.335934	0.018648	7.496870	0.379169	-0.224226	1.176343
0.798161	-1.190946	7.901173	-0.519460	0.839315	2.042446
0.798161	-1.190946	7.901173	-0.519460	0.839315	2.042446
0.798161	-1.190946	7.901173	-0.519460	0.839315	2.042446
1.785968	-0.247135	6.081645	-1.145481	0.152035	2.369555

Pe (first three columns) Pp (last three columns)

Using Mathematica to Analyze CLAS 12 Data

1. Define functions to calculate Ee’ and θ using their momentum components
2. Define a function to calculate beam energy using Ee’ and θ

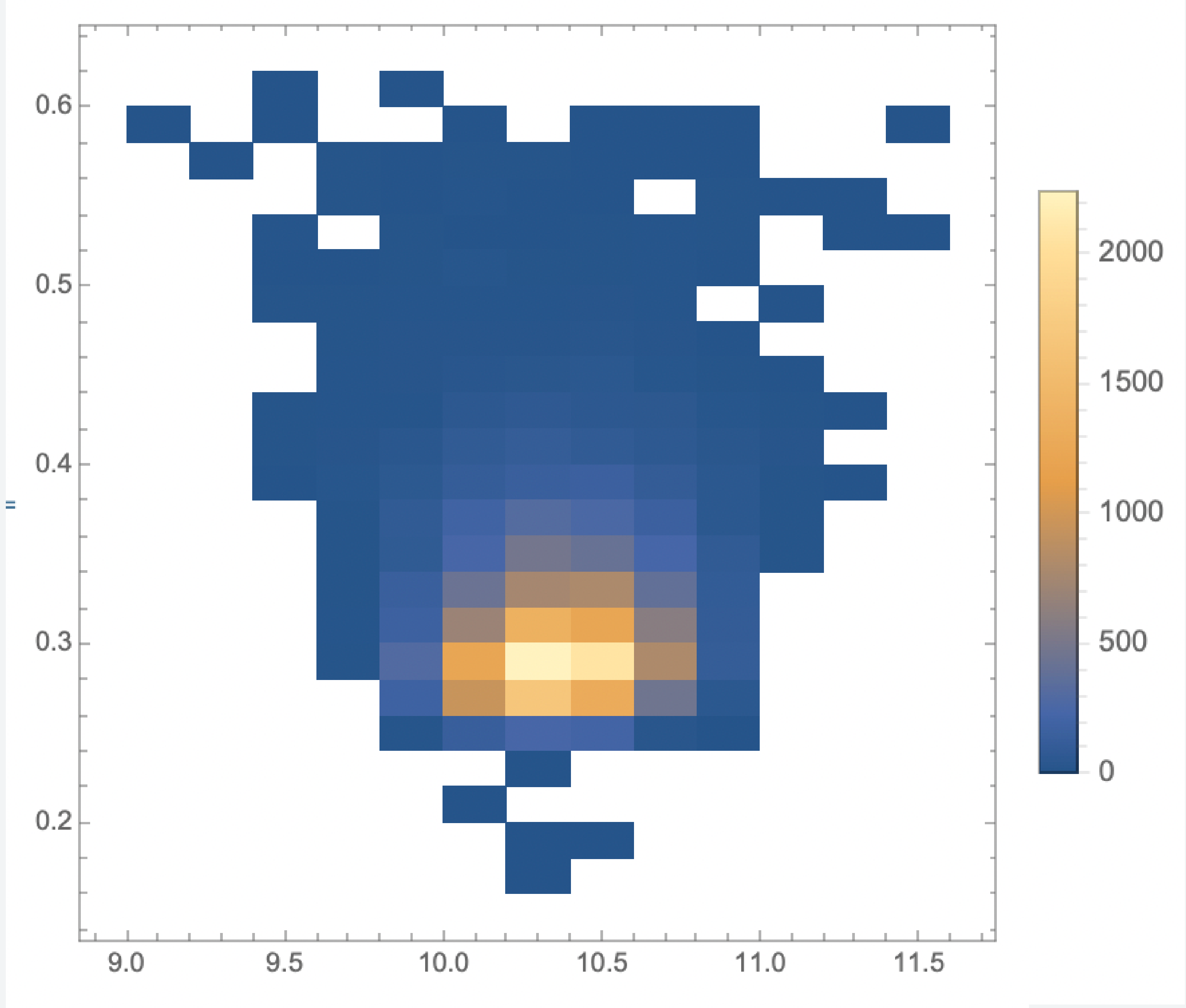
```
(*calculate E_e' from momentum*)
calculateEePrime[px_, py_, pz_] := Sqrt[px^2 + py^2 + pz^2];

(*calculate deflection angle*)
calculateTheta[px_, py_, pz_] := ArcCos[pz/Sqrt[px^2 + py^2 + pz^2]];

(*calculate beam energy E_e*)
calculateEe[EePrime_, theta_] := EePrime/(1 - (2*EePrime)/mp*Sin[theta/2]^2);
```

3. Create an array to store the processed data
4. Assign each component of the data (pex, pey pez, ppx, ppy, ppz)
5. Calculate beam energy in a loop over the length of the data
6. Add in the cut for elastic scattering
7. Store desired data to the array

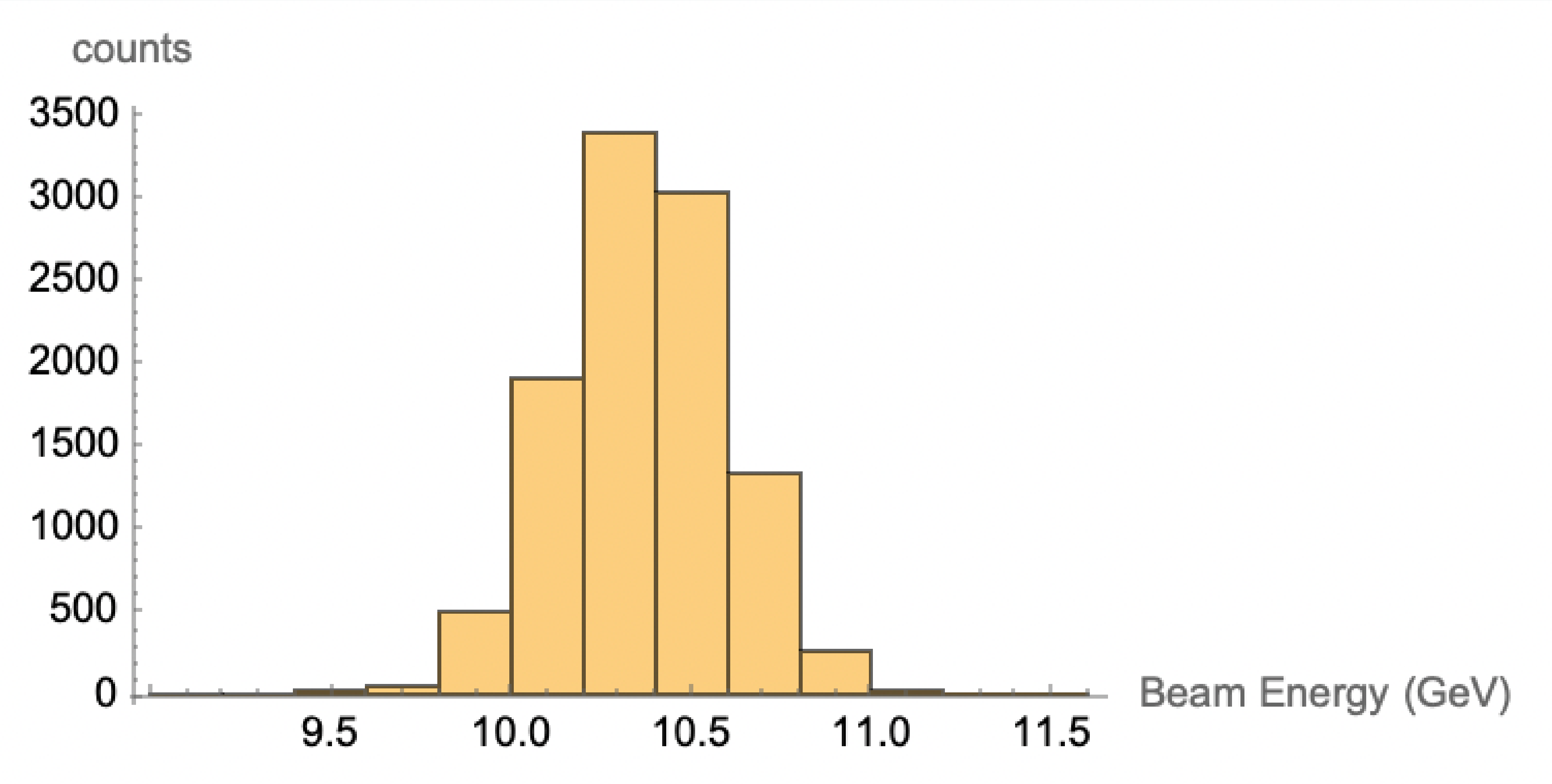
Results (10.4 GeV Beam)



Scattering angle (radians)

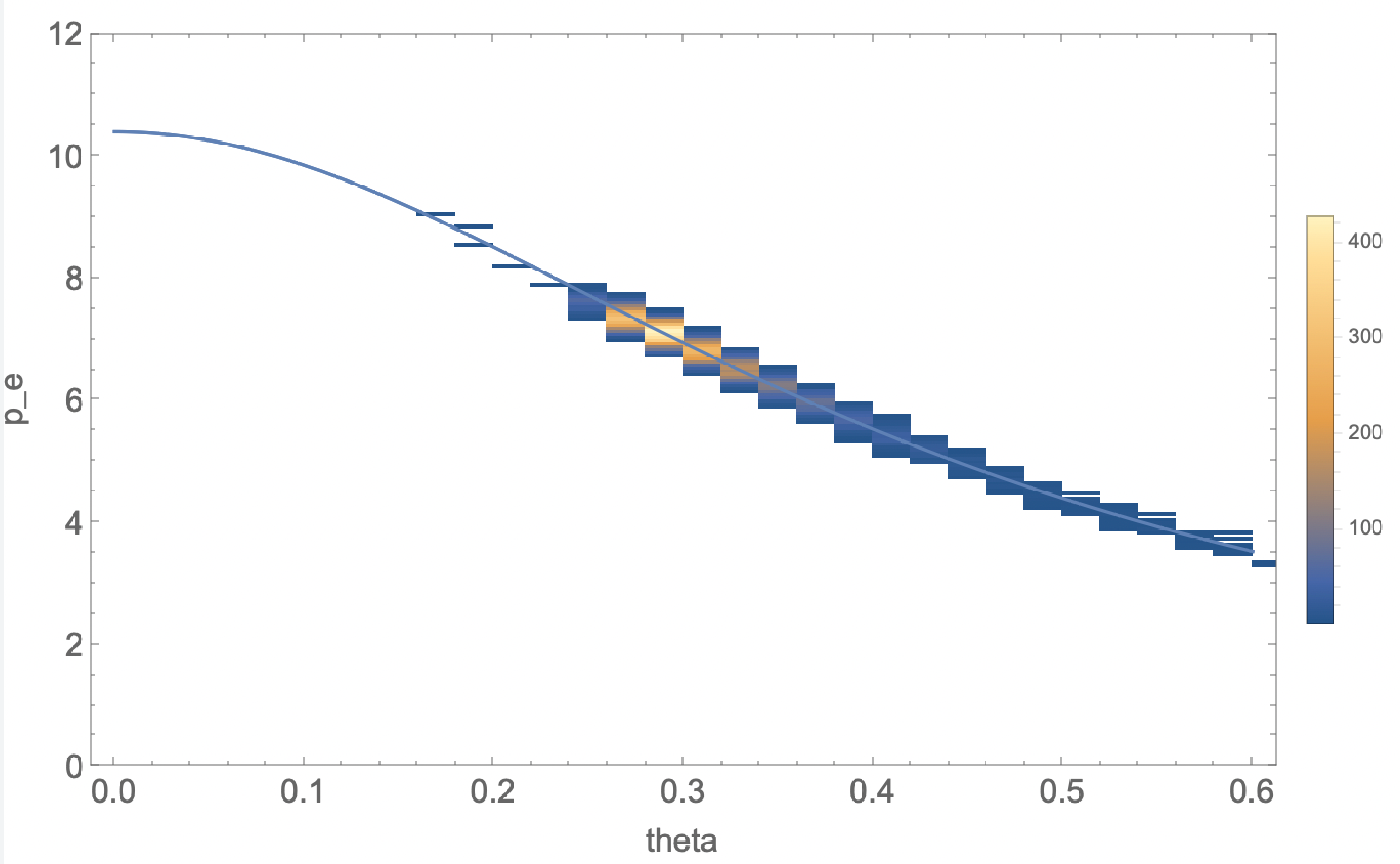
Beam energy (GeV)

Counts: 10482



3D histogram of the calculated beam energy using theta and Ee'

Results (10.4 GeV Beam)



Counts: 10482

Fit line according to:

```
g[x_] := Ebeam / (1 + ((2*Ebeam/Mn) * (Sin[x/2])^2))
```

$$g[x\_] := \frac{Ebeam}{1 + \left(\frac{2*Ebeam}{Mn} * \left(\sin\left[\frac{x}{2}\right]\right)^2\right)}$$

Resolution effects make scattering angles more precise than momenta:

Scattering angle of the electron

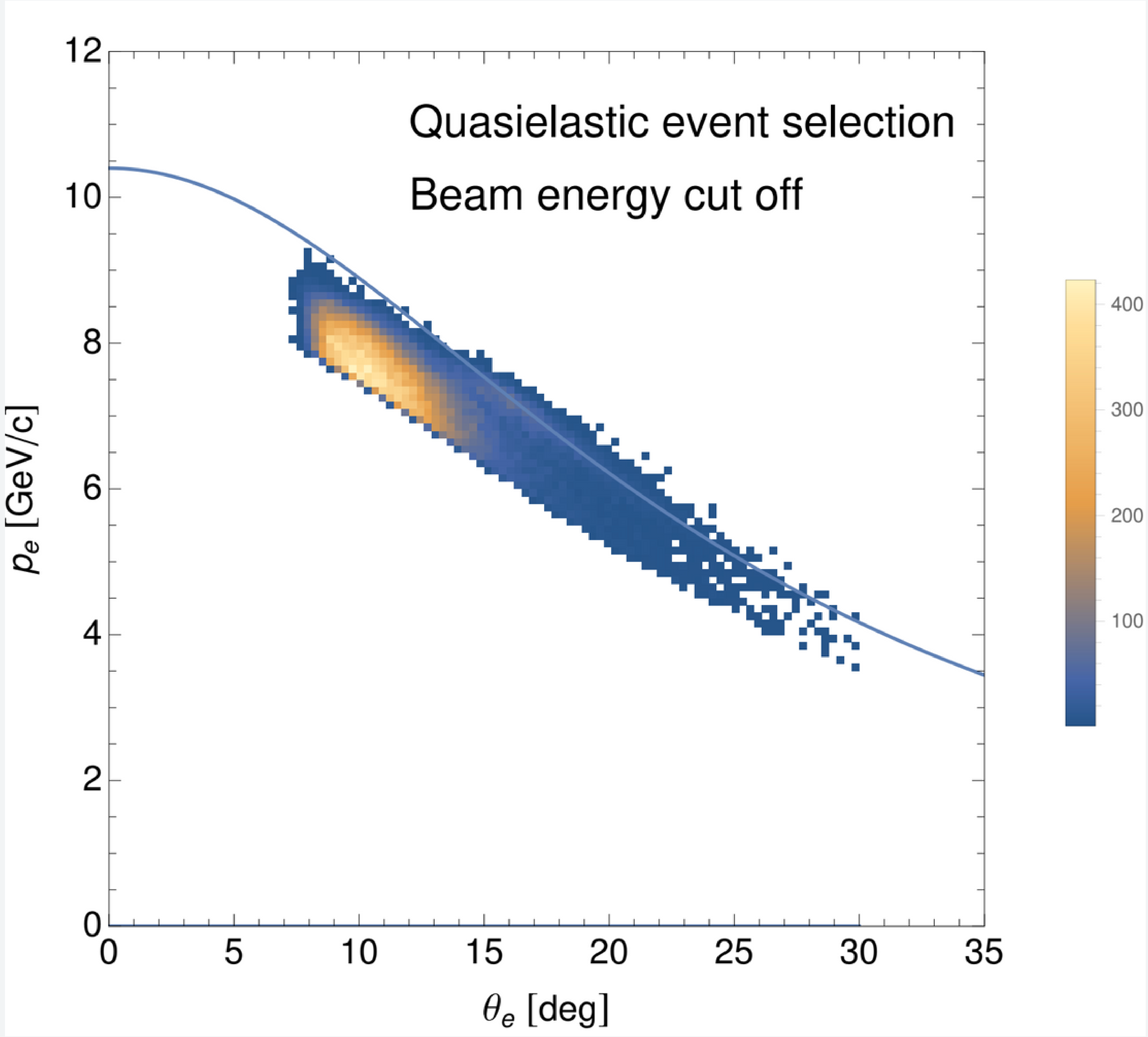
$$E_e = \frac{m_N}{1 - \cos\theta_e}\left(cos\theta_e + cos\theta_p \frac{sin\theta_e}{\sin\theta_p} - 1\right)$$

CLAS-NOTE 2002-008

Scattering angle of the proton

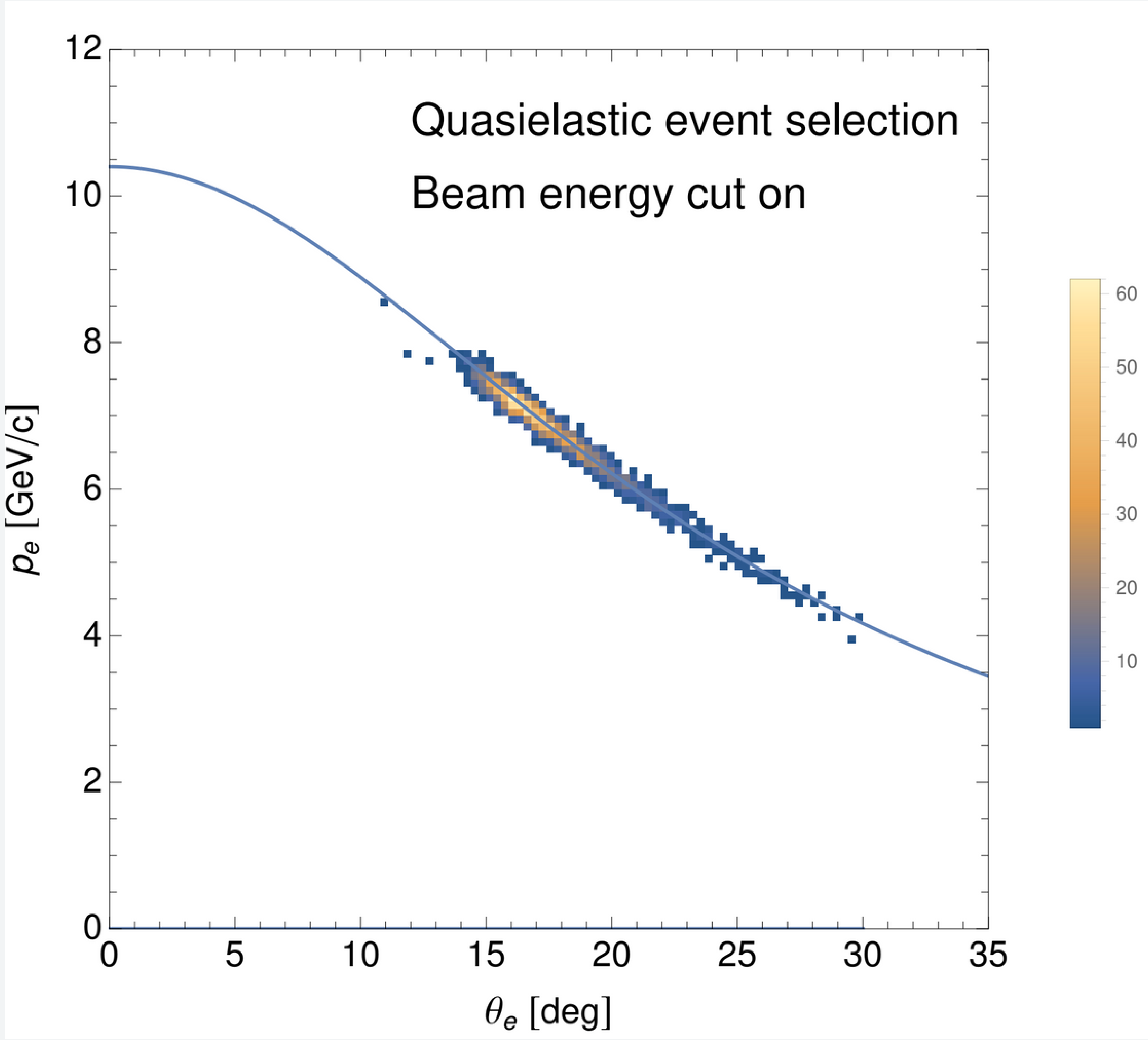
$$\theta = cos^{-1}\left(\frac{p_z}{\sqrt{{p_x}^2 + {p_y}^2 + {p_z}^2}}\right)$$

Results (10.4 GeV Beam)



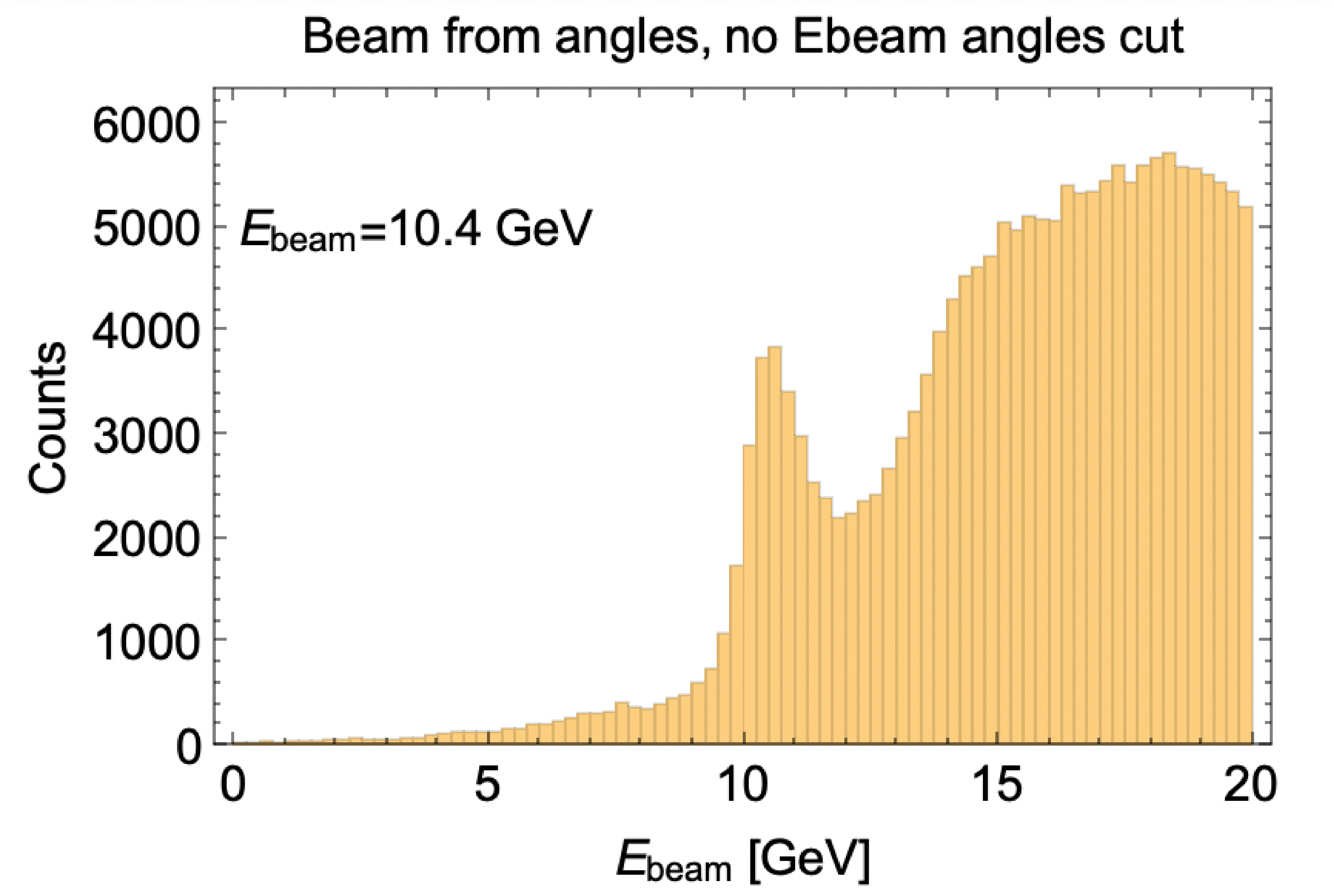
Counts = 264959

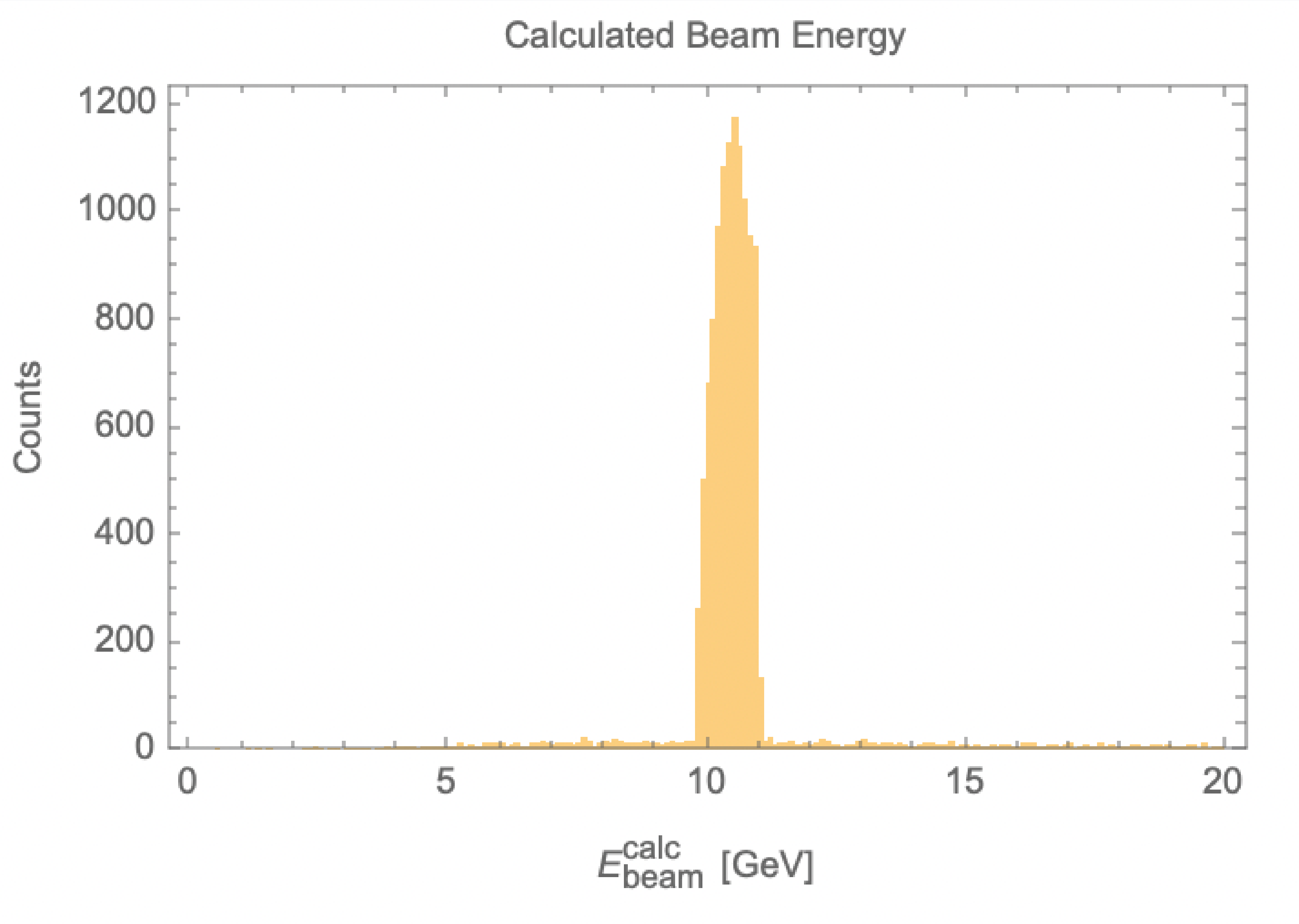
Results (10.4 GeV Beam)



Counts = 2313

Results (10.4 GeV Beam)

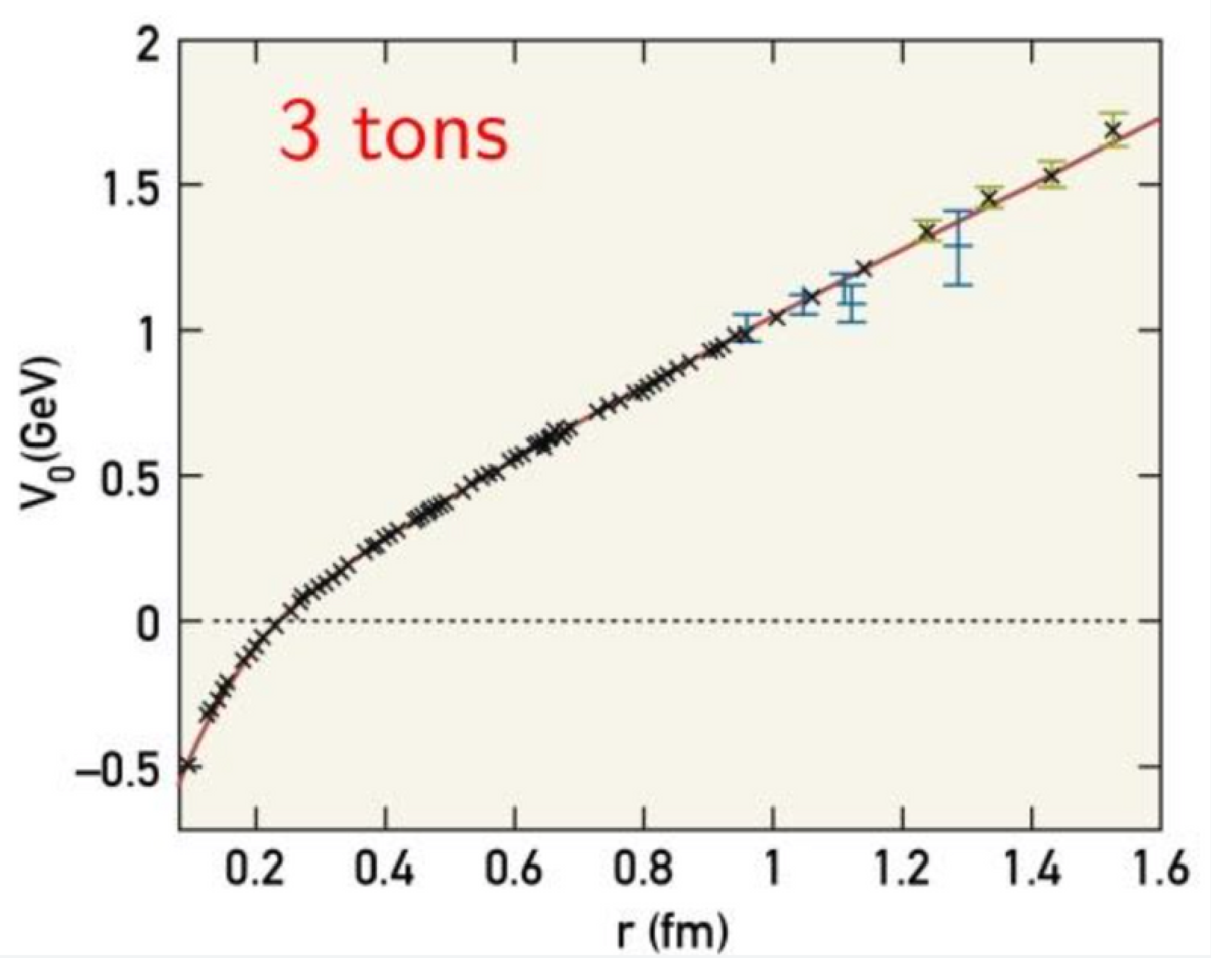




Events outside the cut

Non-elastic events are not meaningless. They are evidence of another interesting area of study in particle physics.

- **Color**: analog of charge for the strong force, new property specific to quantum color chromodynamics (QCD)
- Color is the property that responds to the QCD field (strong force, color force)
- Describes energy density
- Unique property: force is constant in relation to distance (r)

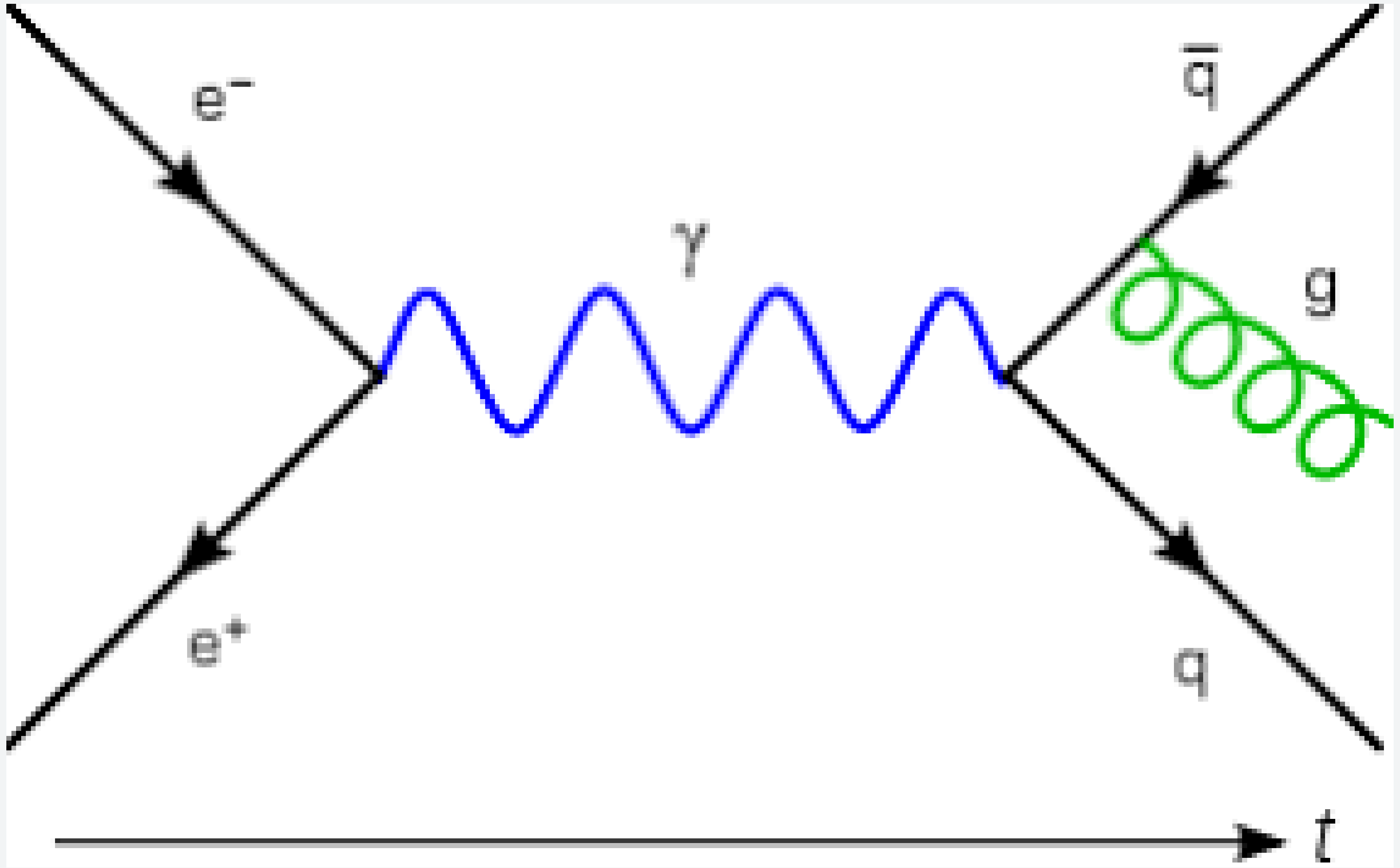


$$\Delta U = \int F dx.$$

Events outside the cut

Non-elastic events are not meaningless. They are evidence of another interesting area of study in particle physics.

$$E=mc^2$$



Feynman Diagram

The Importance of data selection

Send us a Tip! | Shop | Subscribe

GIZMODO

The Future Is Here

Search

HOME LATEST NEWS REVIEWS SCIENCE EARTHER IO9 AI SPACE ESPAÑOL VIDEO

PHYSICS

Physicists Just Learned Something Major About the Proton

The research has "changed the way we think about the structure of the proton," one scientist said.

By **Isaac Schultz** Published January 24, 2024 | Comments (22)

Hall A at Thomas Jefferson National Accelerator Facility. Photo: Wikimedia Commons

Thank you Professor Gilfoyle!!

Sources:

1. https://www.bnl.gov/newsroom/news.php?a=26123
2. https://www.sciencephoto.com/media/2098/view/visualisation-of-quark-structure-of-neutron
3. https://facultystaff.richmond.edu/~ggilfoyl/research/researchIntroS23.pdf
4. https://facultystaff.richmond.edu/~ggilfoyl/research/GnmtalkforCLAS12LB-23-jul-12.pdf
5. https://facultystaff.richmond.edu/~ggilfoyl/research/researchIntroS23.pdf
6. https://facultystaff.richmond.edu/~ggilfoyl/research/agnm_Thesis_finalversion.pdf
7. https://www.newworldencyclopedia.org/entry/Particle_physics
8. https://www.quantamagazine.org/inside-the-proton-the-most-complicated-thing-imaginable-20221019/
9. https://en.wikipedia.org/wiki/Feynman_diagram