Characterizing *Geant4 + GENIE* ν-DIS kinematics

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Outline

(a) Selecting some nice DIS kinematic variables
(b) Comparing Genie and Geant4 ν-DIS kinematics
(c) Addressing (more) bugs in G4
(d) Discussing energy limitations of G4
(e) Conclusions

Kinematic variable selection

Question: *Which kinematic variables best characterize neutrino DIS interactions?*

PDG reference document "Structure Functions" [1] (rev. 2023) details a set of *Lorentz-invariant* lepton–nucleon scattering kinematic quantities including:

Symbol	Name	Significance
Q^2	squared four-momentum transfer	**Resolution of the scattering probe** into the nucleon.
W	invariant hadronic mass	**Final-state mass** of target nucleon. Relates to the process' scattering regime (elastic, resonant, DIS).
x	Bjorken scaling variable	The **fraction of nucleon momentum** carried by the particular struck parton.
y	inelasticity	**Fraction of the scattering lepton's energy** given to the hadronic system.

These quantities are lepton–nucleus invariants, and suit the characterization of general DIS interactions.

Usefulness to generator comparison

Imagine comparing DIS kinematics for GENIE and Geant4. Disagreement between the two generators could tell us:

- (Q^2) whether generators predict different amounts of momentum transfer for the same lepton energy,
- (W) whether generators disagree on which scattering regime (elastic, resonance, DIS) an event belongs to,
- (x) whether generators assume different parton distribution functions,
- (y) whether generators disagree on how much of the lepton's energy transfers to the hadronic system.

Dataset generation

Both runs generated with `GDMLTargetPractice` [1].

Beam and target parameters

Beam: *muon neutrino* (ν_μ)

900 GeV | oriented along $+\hat{z}$

Target: *graphite block*

$A = 12$, $Z = 6$ | $10 \times 10 \times 60$ cm

GENIE

Tune: `G18_10a_02_11a` (valid to ~1 TeV),

☞ setting valid processes with `--event-generator-list DIS`

Geant4

Bias: `/gdmltp/neutrinoBias 5e+12 5e+12 5e+12` (CC, NC, ν–e).

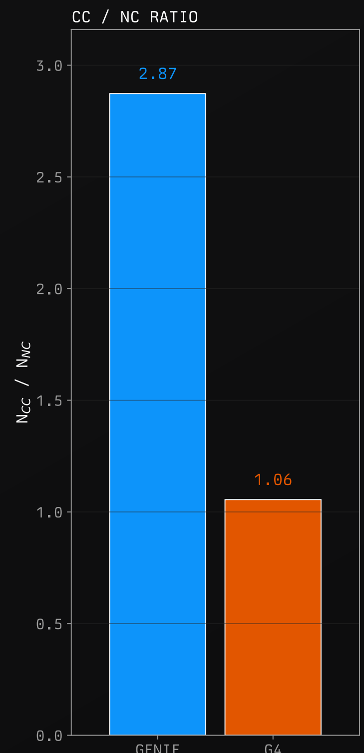
☞ NOT using Jon's (improved) biasing method via `G4VBiasingManager`.

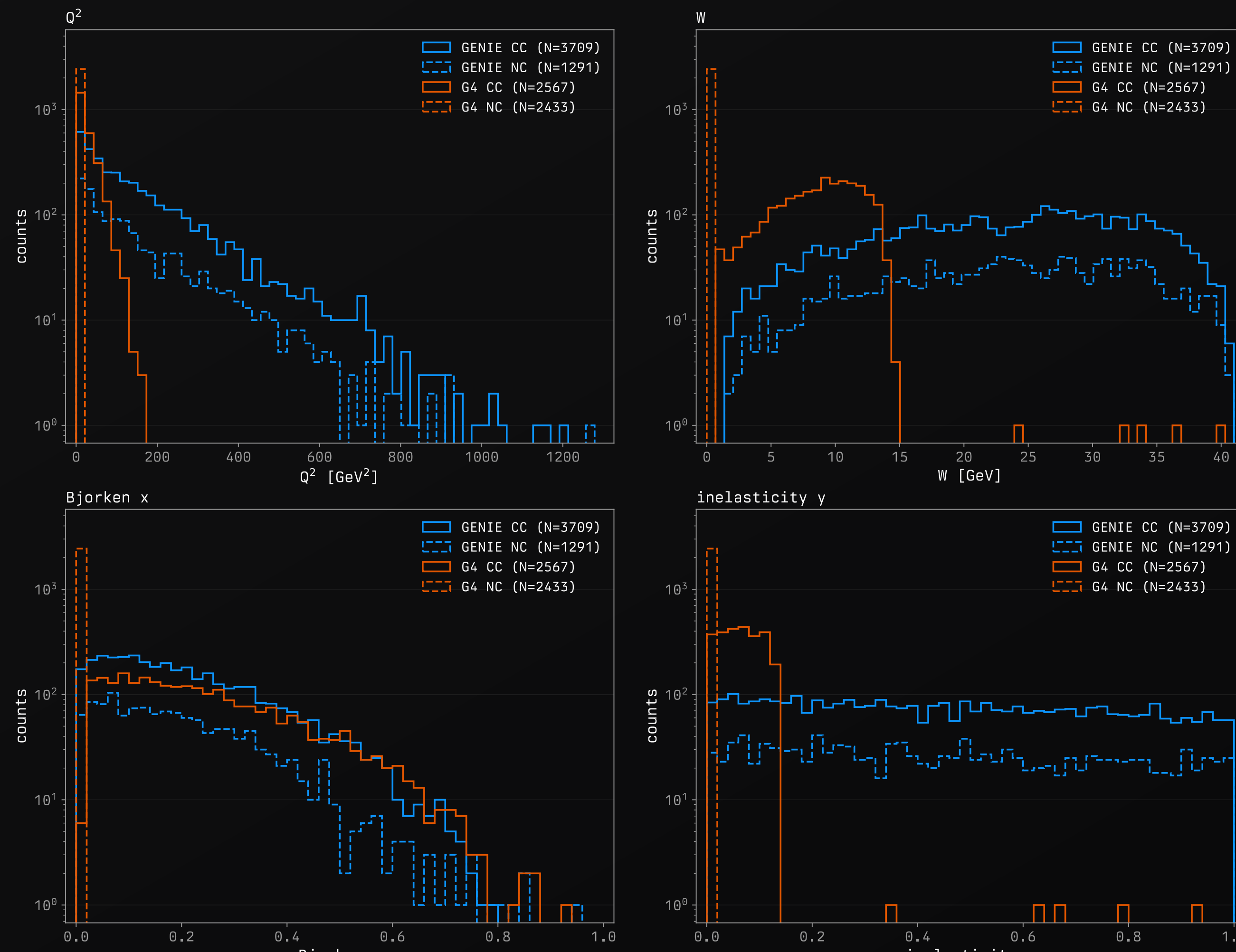
[1] starting from GDMLTP *commit* `07fbb85` and Geant4 *commit* `f3d5293`

Baseline kinematics

GENIE vs. GEANT4 (07fbb85)

BEAM	nu_mu, 900 GeV
TARGET	graphite (A=12,Z=6)
GENIE N	5000 (CC3709/NC1291)
G4 N	5000 (CC2567/NC2433)





F1 | Unmodified GDMLTP *commit 07fbb85* + Geant4 *commit f3d5293*.

Bug | Classifier chain

`GDMLTargetPractice/g4sim/SteppingAction.cc`

initial
`07fbb85`
(local)

```cpp
if (track->GetParentID() == 0) {
```

In Geant4's stepping, a neutrino can re-appear as its own “daughter” partway through a shower, so a parent-ID check confuses **primary** tracks with **later steps of the same neutrino**.

Patch checks the PDG code directly (`GetPDGEncoding`) against the primary ID stored on the event, so continuation of the same neutrino is recognized as part of the same chain rather than miscounted.

The fix allows `g4sim` to fill the NC kinematics branches, but it should be **scrutinized**.

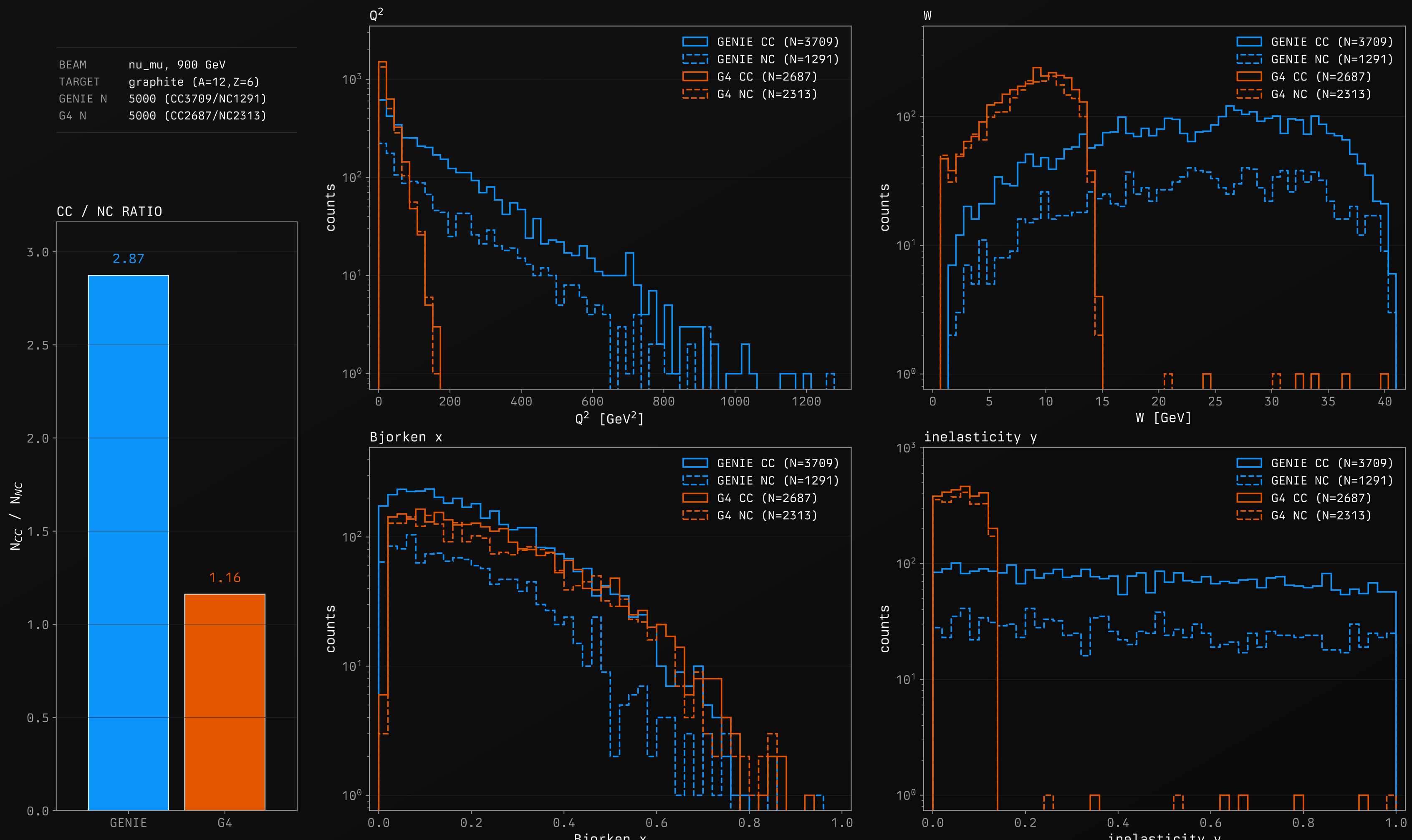
fix
`57607a1`
(local)

```cpp
int pdg = particle->GetPDGEncoding();
bool isPrimaryNeutrino =
    std::abs(pdg) == 12 || std::abs(pdg) == 14 || std::abs(pdg) == 16;
bool isNeutrinoChainLink = isPrimaryNeutrino && pdg == fEventAction->primaryPDG;
```

Bug | Classifier chain

GENIE vs. GEANT4 (stock)

BEAM	nu_mu, 900 GeV
TARGET	graphite (A=12,Z=6)
GENIE N	5000 (CC3709/NC1291)
G4 N	5000 (CC2687/NC2313)



F2 | Geant4 patch 1/4 (`stock`).

Bug | Shared static KR tables

`geant4/ … /G4NeutrinoNucleusModel.hh`

initial
f3d5293

```cpp
static G4double fNuMuXarrayKR[50][51];
static G4double fNuMuXdistrKR[50][50];
static G4double fNuMuQarrayKR[50][51][51];
static G4double fNuMuQdistrKR[50][51][50];
```

`static` on a class member ensures a **shared copy across all class instances**. Geant4 constructs a separate `G4NeutrinoNucleusModel` instance for all interaction channels (CC, NC, different flavors). Each is meant to fill in its own kinematic tables; however, since the arrays are `static`, every instance points at the same four arrays in memory.

Whichever instance builds its tables **last** destroys whatever the others had already written, so models sometimes sampled kinematics from the wrong channel's distribution entirely. The fix just removes `static`.

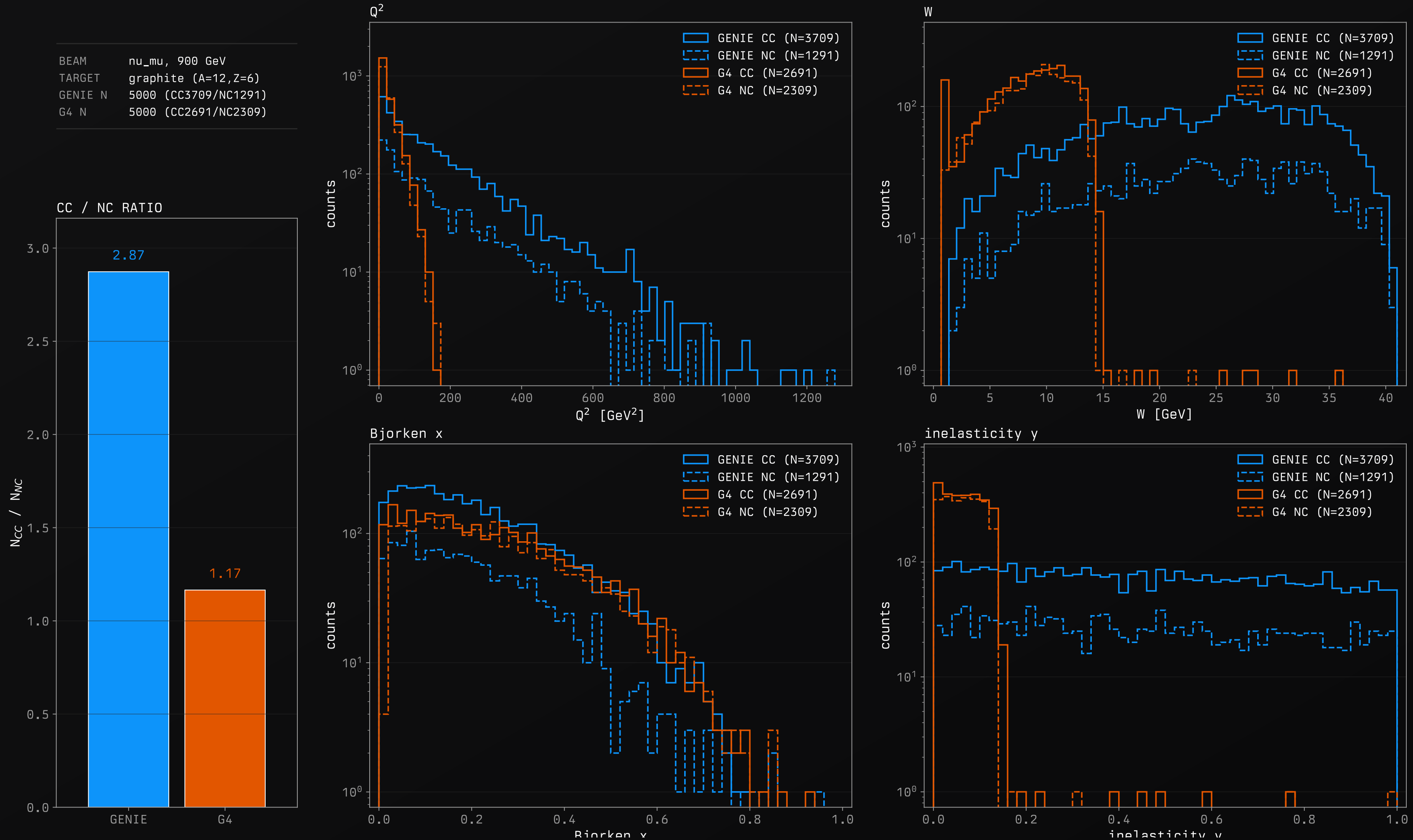
fix
e6f5337

```cpp
G4double fNuMuXarrayKR[50][51] = {{1.0}};
G4double fNuMuXdistrKR[50][50] = {{1.0}};
G4double fNuMuQarrayKR[50][51][51] = {{{1.0}}};
G4double fNuMuQdistrKR[50][51][50] = {{{1.0}}};
```

Post-fix

GENIE vs. GEANT4 (table fix)

BEAM	nu_mu, 900 GeV
TARGET	graphite (A=12,Z=6)
GENIE N	5000 (CC3709/NC1291)
G4 N	5000 (CC2691/NC2309)



F3 | Geant4 patch 3/4 (`table fix`).

Bug | NC/CC coupling coefficient

`geant4/ ... /G4MuNeutrinoNucleusTotXsc.cc`

initial
f3d5293

```cpp
fCofS = 5. * fSin2tW * fSin2tW / 9.;
fCofL = 1. - fSin2tW + fCofS;
```

$$g_L^2 = \underbrace{\frac{1}{2} - \sin^2\theta_W}_{\texttt{0.5 - fSin2tW}} + \underbrace{\frac{5}{9}\sin^4\theta_W}_{\texttt{fCofS}} \qquad \text{(Llewellyn–Smith formula)} \tag{10}$$

This coefficient contributes to Geant4′s NC cross-section formula, so it **affects how often NC events are generated relative to CC**.

The initial implementation was off by a factor of two.

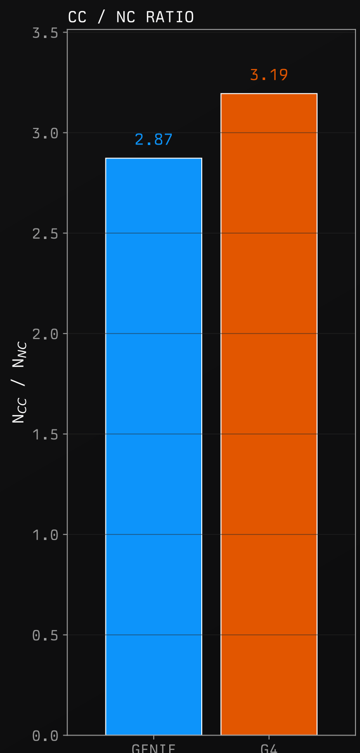
fix
ca6751d

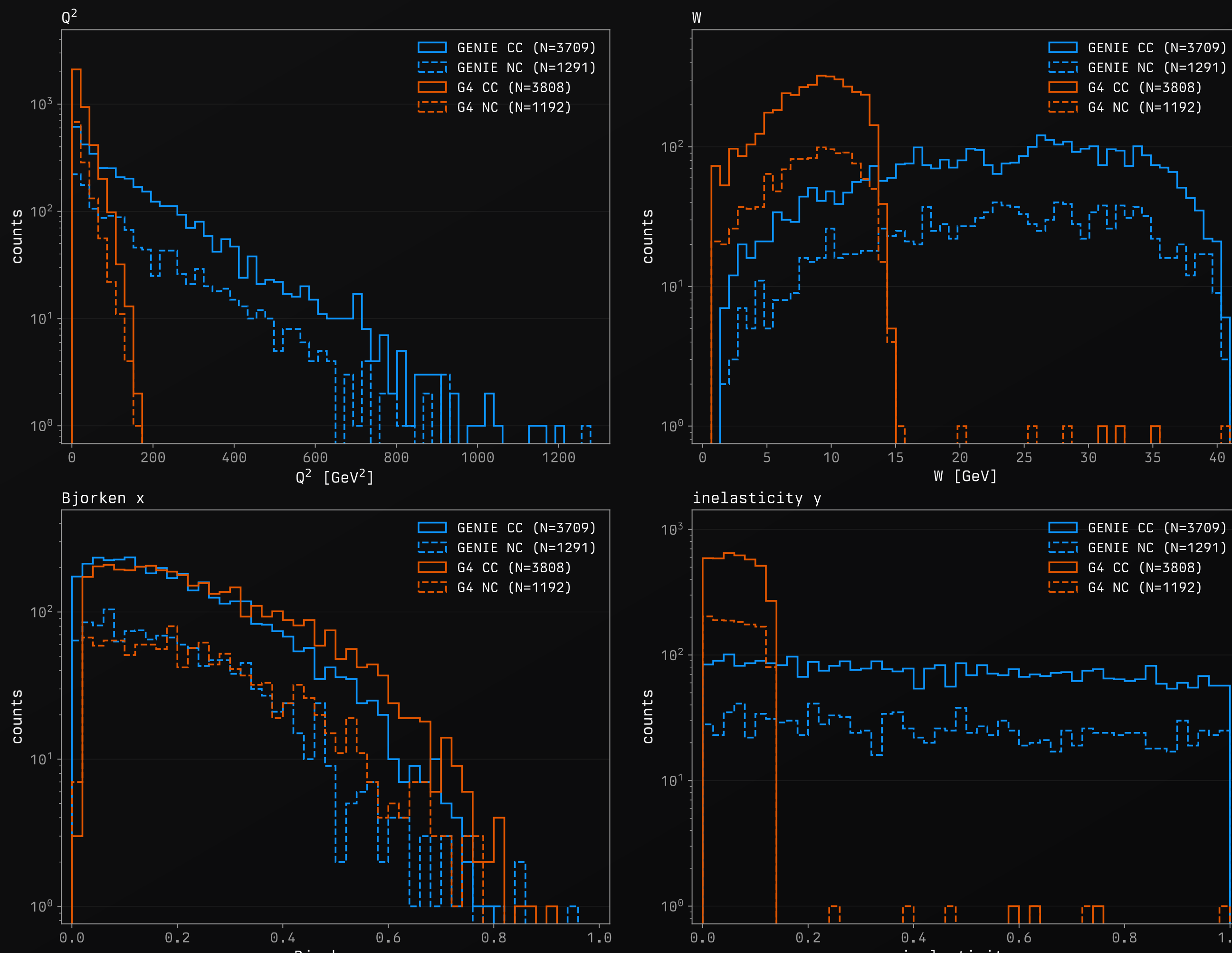
```cpp
fCofS = 5. * fSin2tW * fSin2tW / 9.;
fCofL = 0.5 - fSin2tW + fCofS;
```

Bug | NC/CC coupling coefficient

GENIE vs. GEANT4 (fCofL fix)

BEAM	nu_mu, 900 GeV
TARGET	graphite (A=12,Z=6)
GENIE N	5000 (CC3709/NC1291)
G4 N	5000 (CC3808/NC1192)



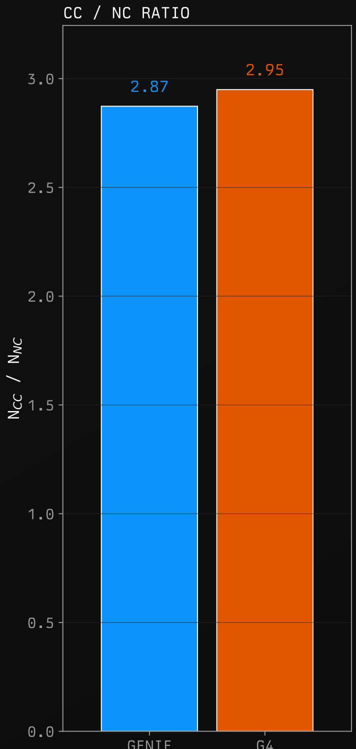


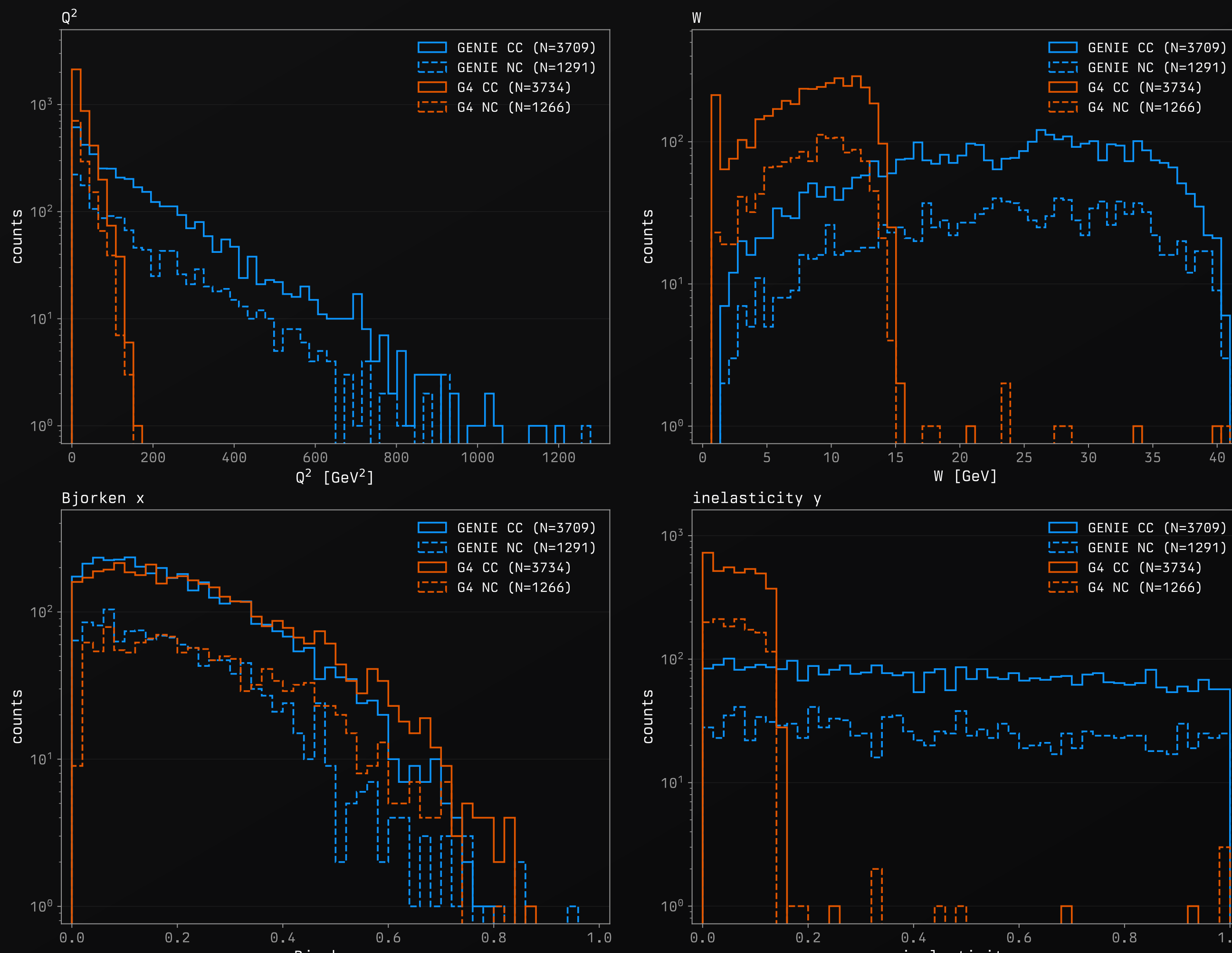
F4 | Geant4 patch 2/4 (`fCofL fix`).

Both fixes combined

GENIE vs. GEANT4 (both fixes)

BEAM	nu_mu, 900 GeV
TARGET	graphite (A=12,Z=6)
GENIE N	5000 (CC3709/NC1291)
G4 N	5000 (CC3734/NC1266)





F5 | Geant4 patch 4/4 (`both fixes`).

Energy limitations?

DIS is too demanding to compute in real time. GENIE and Geant4 both pre-compute tables to interpolate kinematic sampling distributions from.

`geant4/source/processes/hadronic/models/lepto_nuclear/src/G4NeutrinoNucleusModel.cc:95`

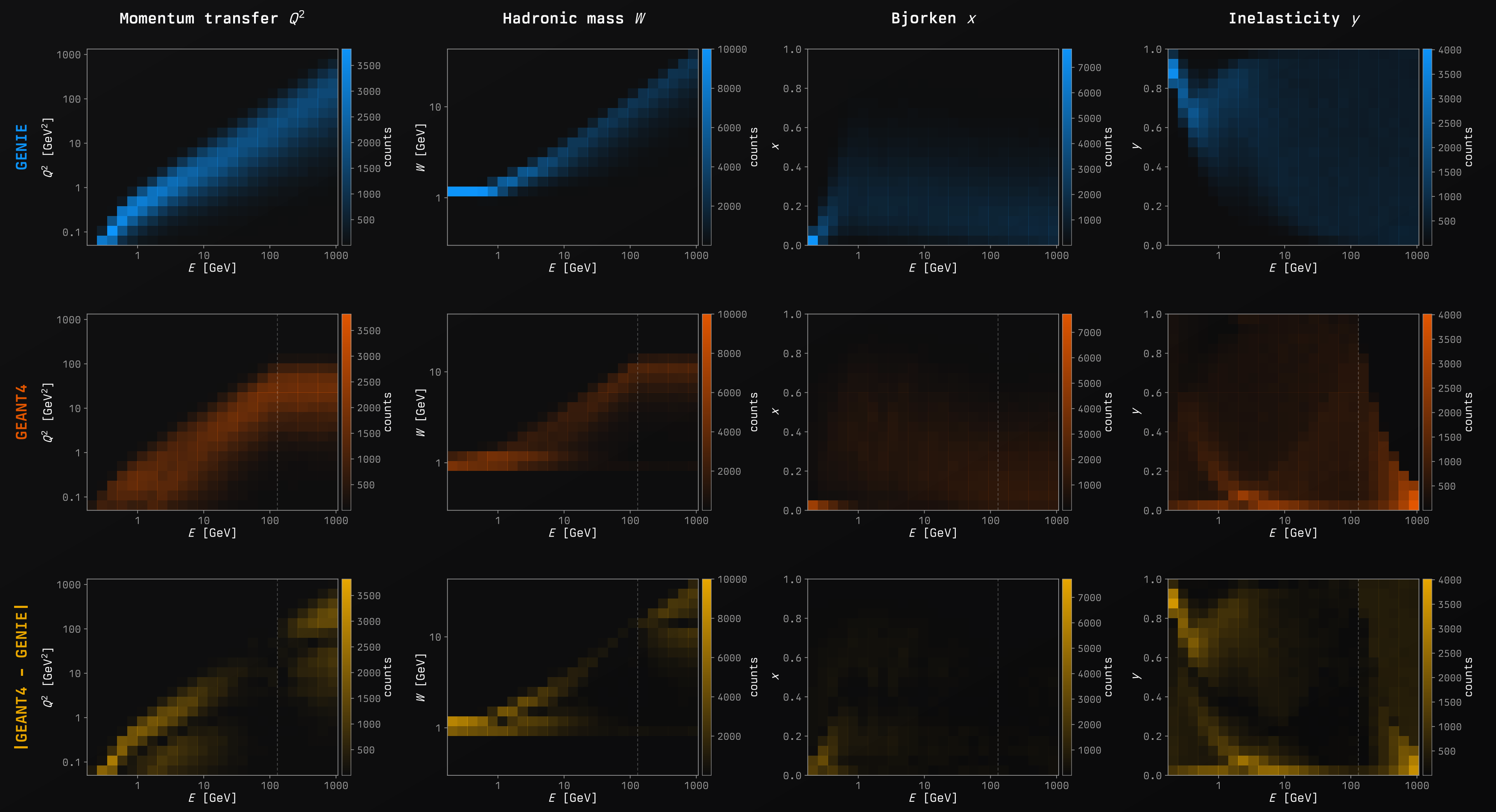
cpp

```cpp
95 const G4double G4NeutrinoNucleusModel::fNuMuEnergyLogVector[50] = {
96 115.603, 133.424, 153.991, 177.729, 205.126, 236.746, 273.24, 315.361, 363.973, 420.08, 484.836, 559.573, 645.832,
97 745.387, 860.289, 992.903, 1145.96, 1322.61, 1526.49, 1761.8, 2033.38, 2346.83, 2708.59, 3126.12, 3608.02, 4164.19,
98 4806.1, 5546.97, 6402.04, 7388.91, 8527.92, 9842.5, 11359.7, 13110.8, 15131.9, 17464.5, 20156.6, 23263.8, 26849.9,
99 30988.8, 35765.7, 41279, 47642.2, 54986.3, 63462.4, 73245.2, 84536, 97567.2, 112607, 129966 };
```

The ν_μ “knot” table above tops out at 129.966 GeV. What does this affect?

MAIA | ν-studies

GENIE vs. GEANT4 DIS KINEMATICS: ENERGY SWEEP (0.205-900 GeV)



F6 | Energy sweep as 2D heatmaps (energy vs. kinematic variable, color = counts).

Conclusions

Geant4

Constraints on performance:

- ☞ Just *so* many bugs: many are fixable in principle—but we should have concerns about effort required.
- ☞ Energy knots are limited to an energy range well below our needs, and are ***not*** *reasonably extensible*.

Geant4

Currently comes with limitations, but it's extensible to higher energy.

Also dummy-proof in that it won't allow you to generate data that it's not confident it can handle (an impression).

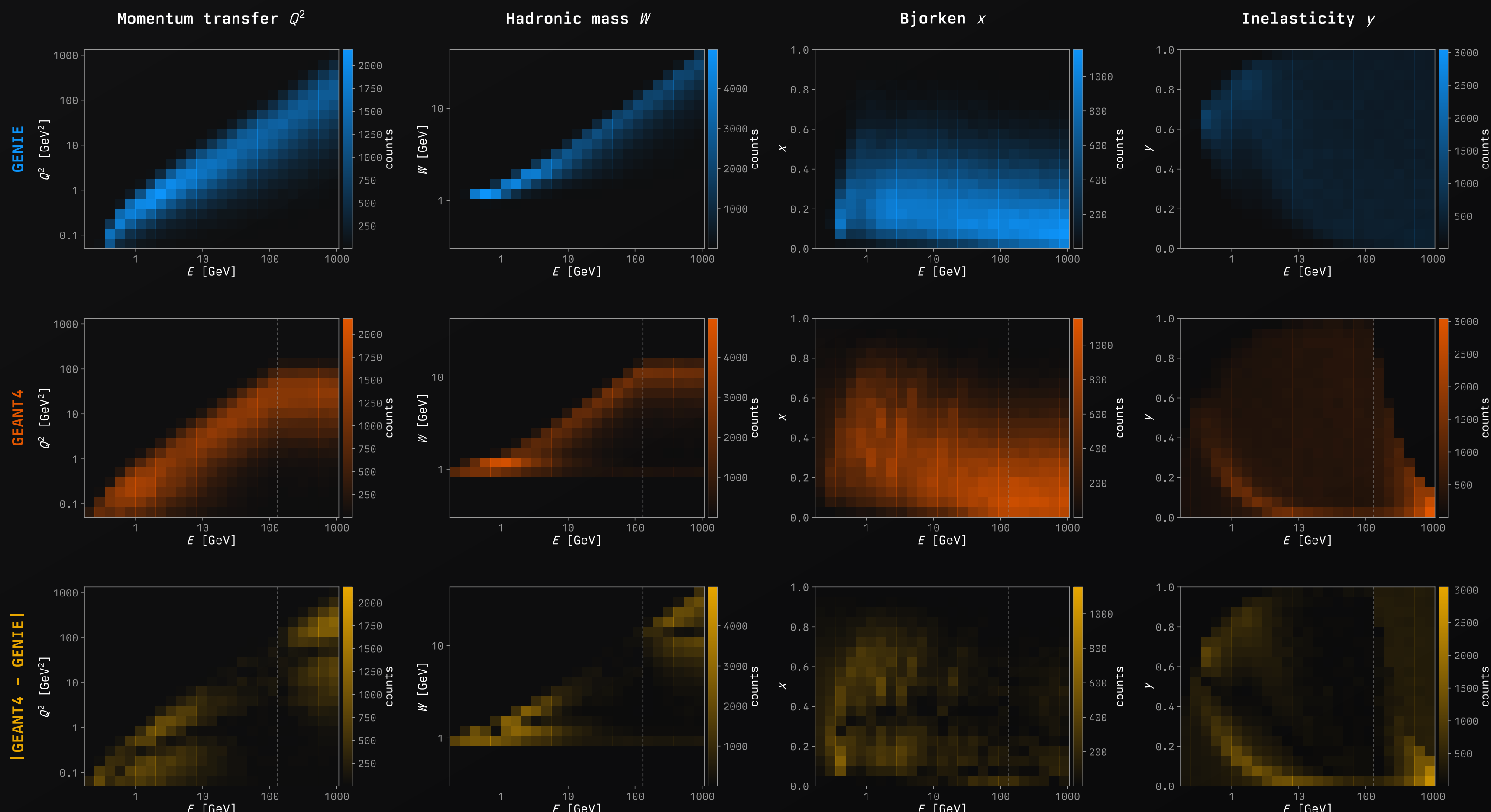
- ☞ Did not generate trials with antiparticles or consider ν–e scattering.
- ☞ Have not yet submitted PRs for these changes.

References

[1] R. L. Workman and Others, “Review of Particle Physics,” *PTEP*, vol. 2022, p. 083C01, 2022, doi: *10.1093/ptep/ptac097*.

Backup

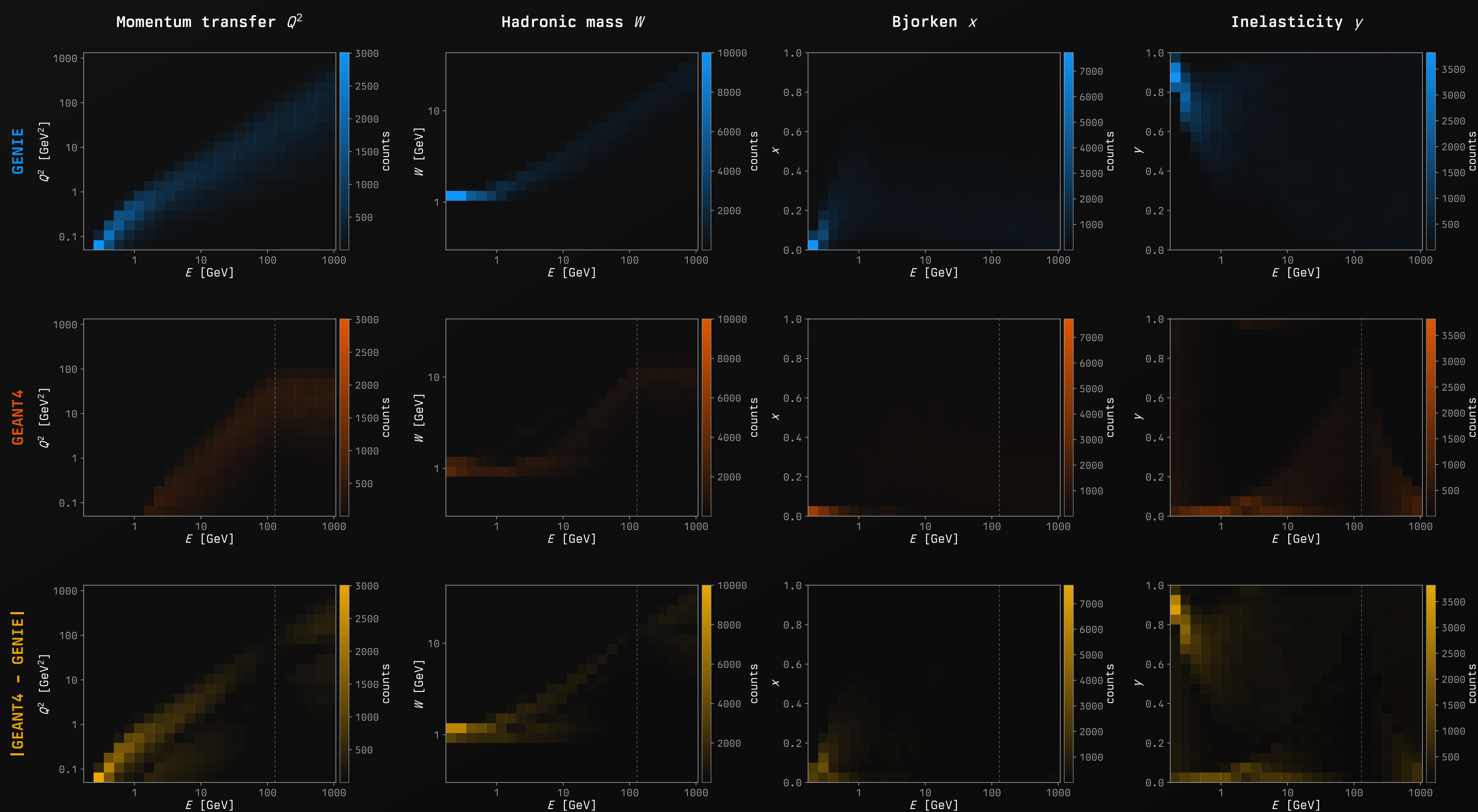
GENIE vs. GEANT4 DIS KINEMATICS: ENERGY SWEEP (0.205-900 GeV) (CC)



F7 | Energy sweep heatmap, CC events only.

Backup

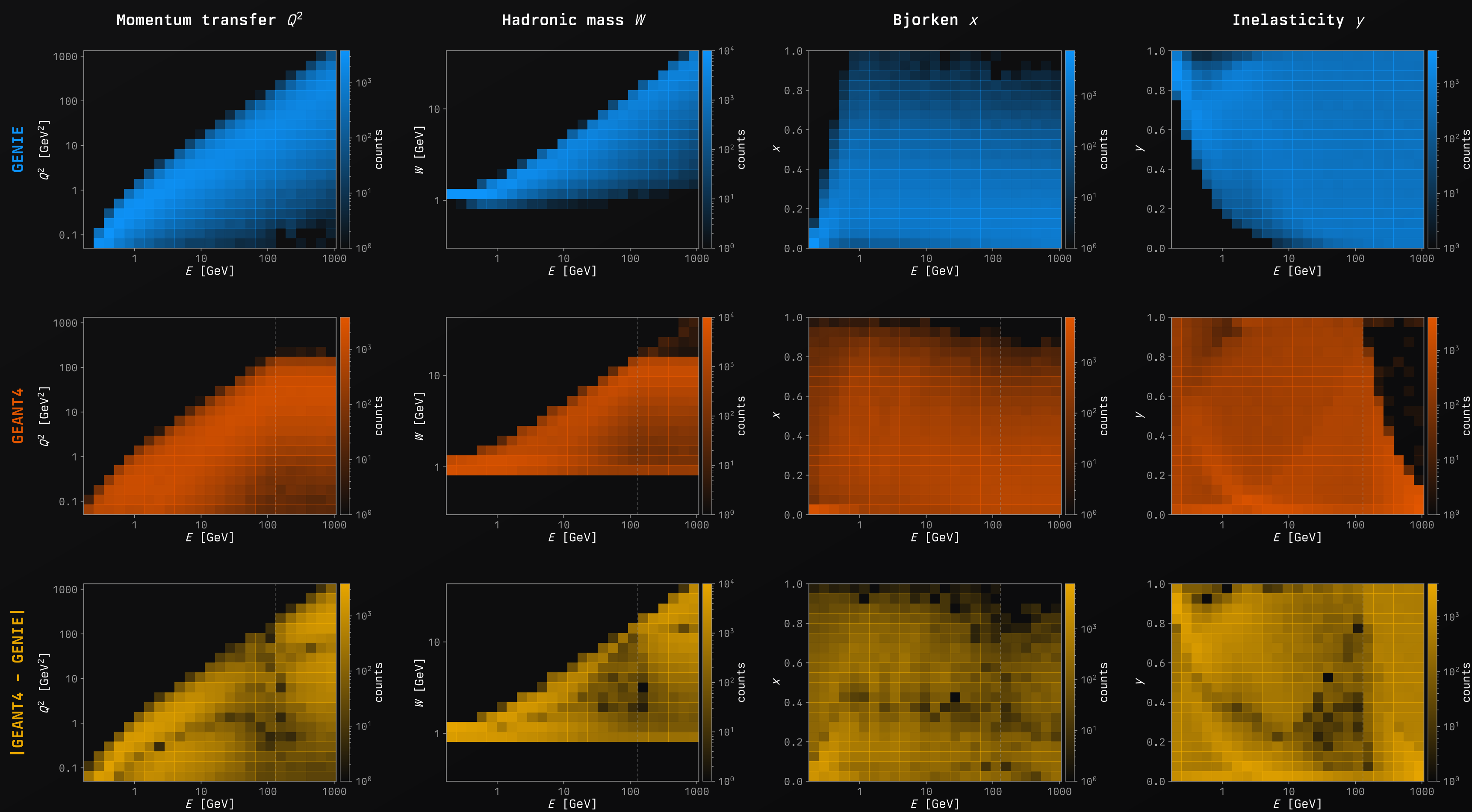
GENIE vs. GEANT4 DIS KINEMATICS: ENERGY SWEEP (0.205-900 GeV) (NC)



F8 | Energy sweep heatmap, NC events only.

Backup

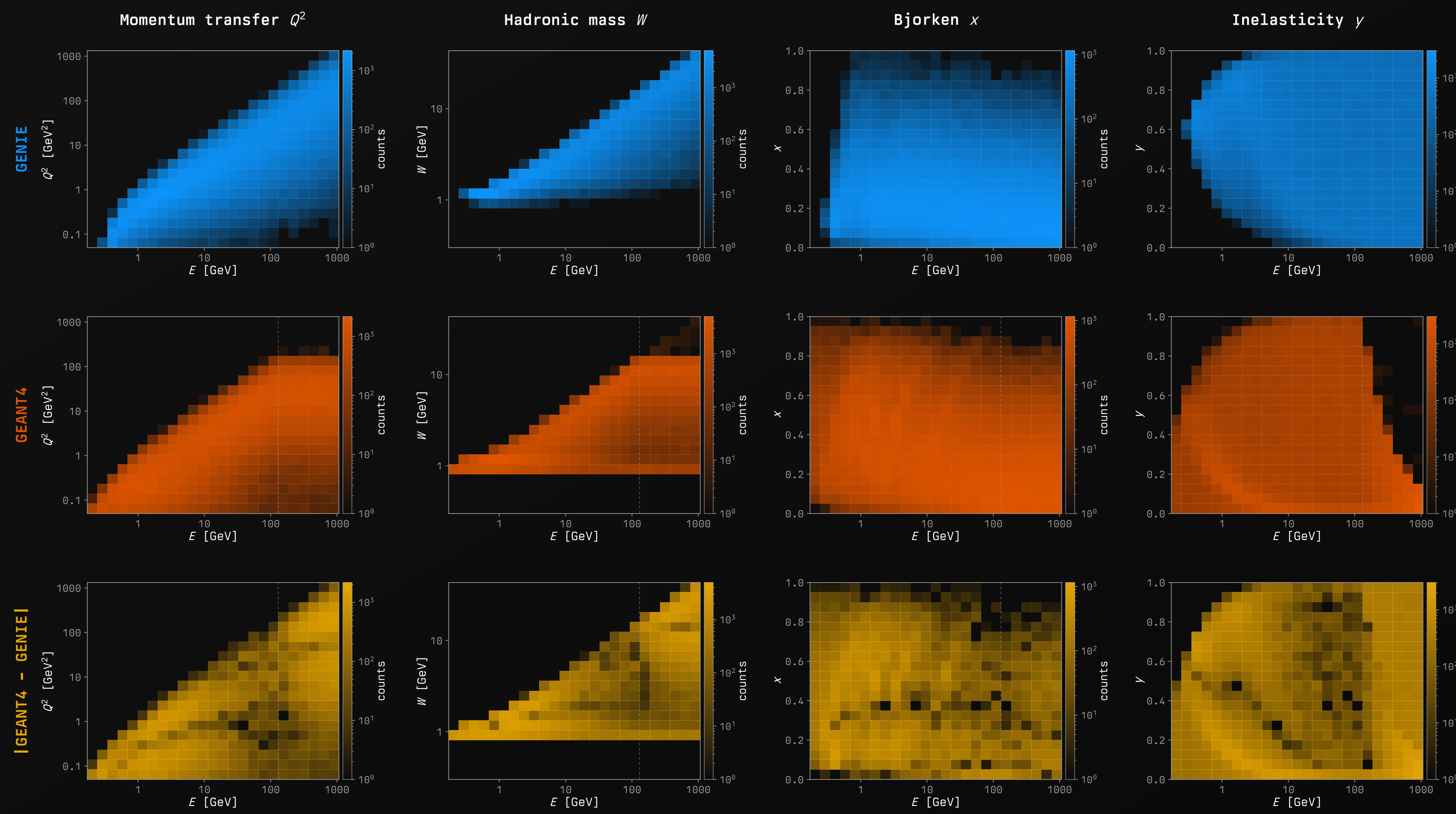
GENIE vs. GEANT4 DIS KINEMATICS: ENERGY SWEEP (0.205-900 GeV)



F9 | The same energy sweep heatmap, log color axis.

Backup

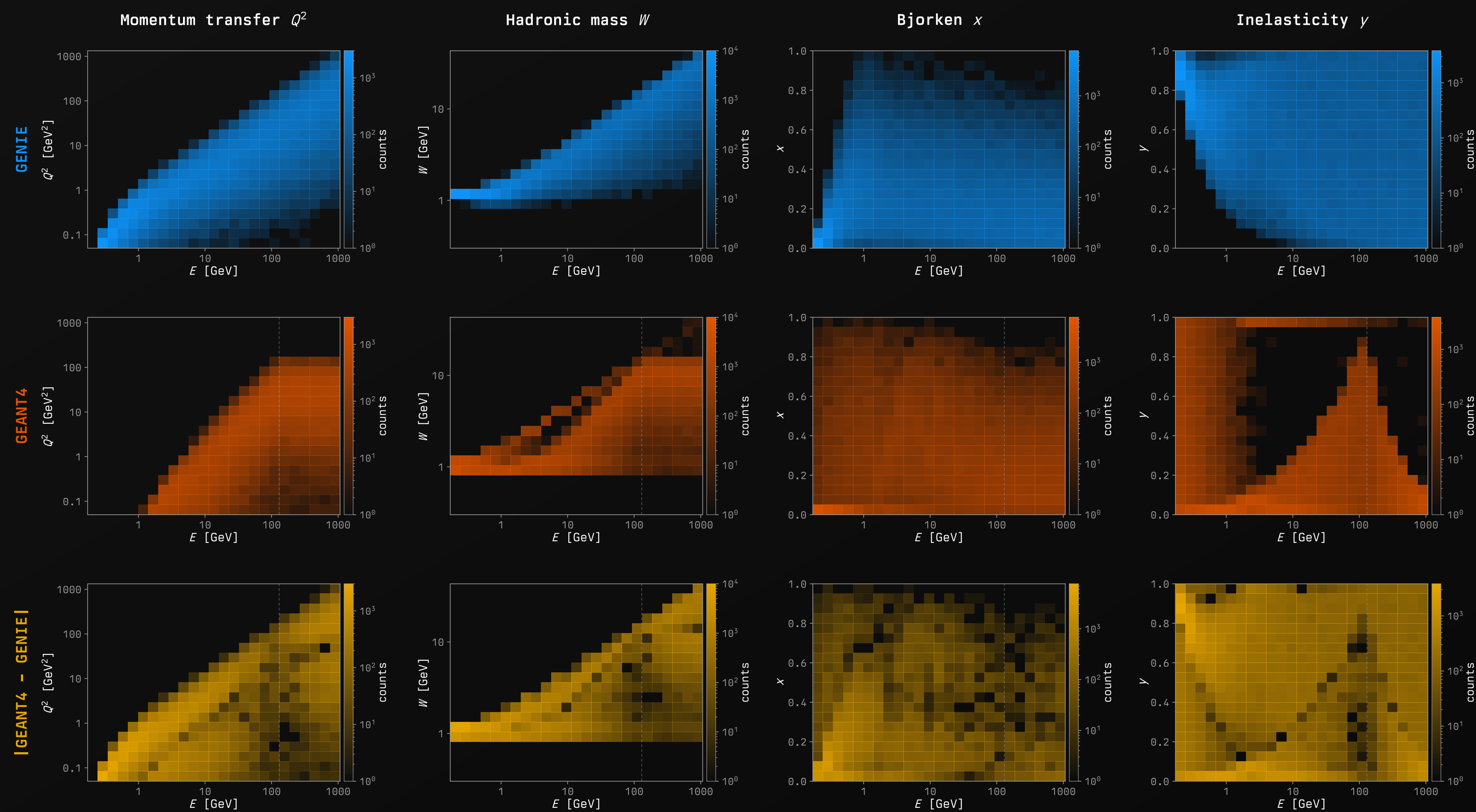
GENIE vs. GEANT4 DIS KINEMATICS: ENERGY SWEEP (0.205-900 GeV) (CC)



F10 | Energy sweep heatmap (log color axis), CC events only.

Backup

GENIE vs. GEANT4 DIS KINEMATICS: ENERGY SWEEP (0.205-900 GeV) (NC)



F11 | Energy sweep heatmap (log color axis), NC events only.