Impact Study on Parity Violating Structure Functions at EIC

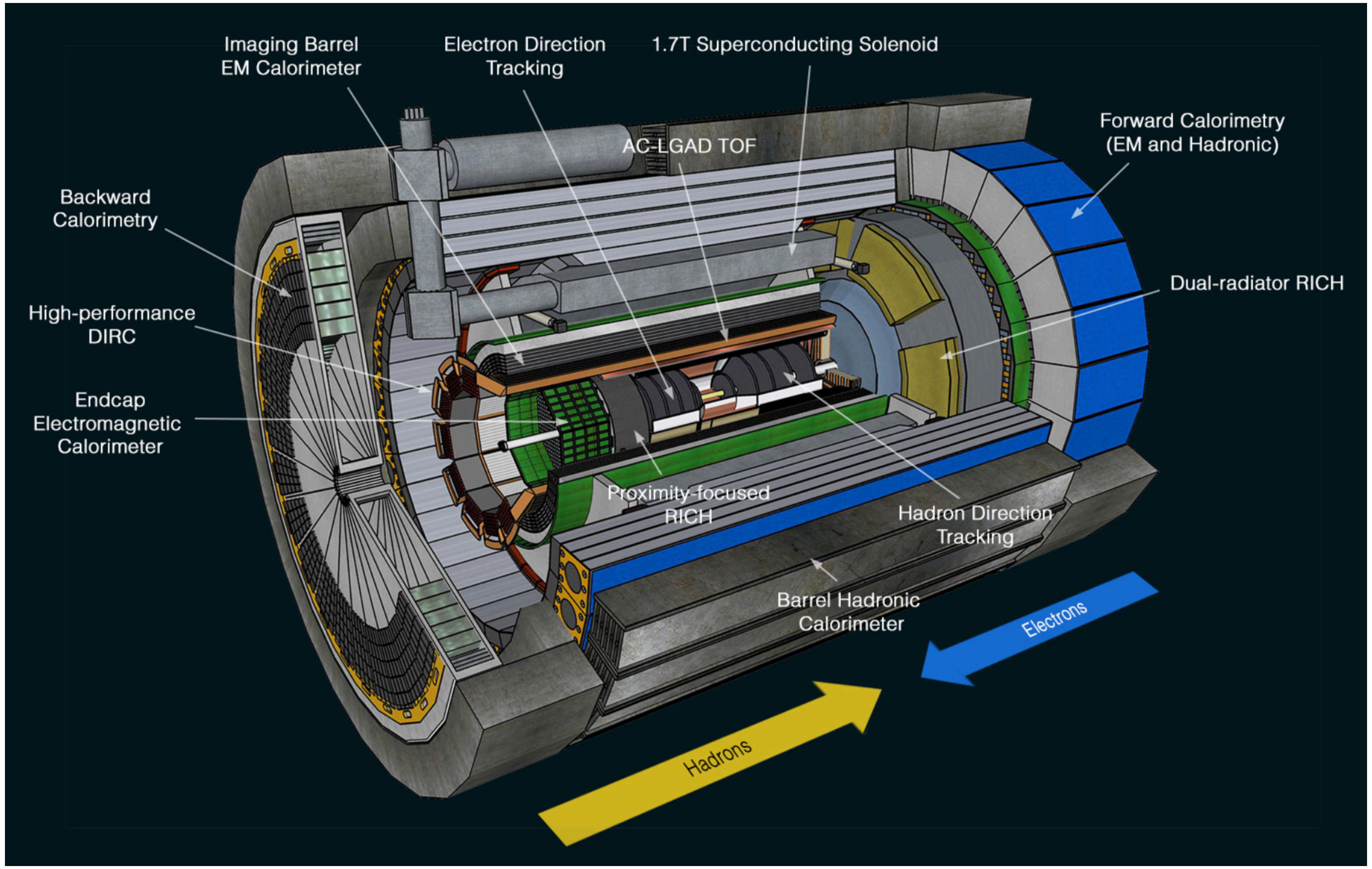
Churamani Paudel

With Prof. David Ruth

New Mexico State University

ePIC detector overview

- Approx 10 m long cylindrical barrel detector (additionaly extends +-45 m on either direction)
- Uses cutting edge technologies to detect the particles from Collisions between high energy electrons and protons (or heavy ions)
- Nearly hermetic, reconstruct scattered electron, hadronic final states, Jets and missing momentum over wider angular range
- Provides wide-acceptance tracking, timing, calorimetry and Particle-Identification



Source : https://www.bnl.gov/eic/epic.php

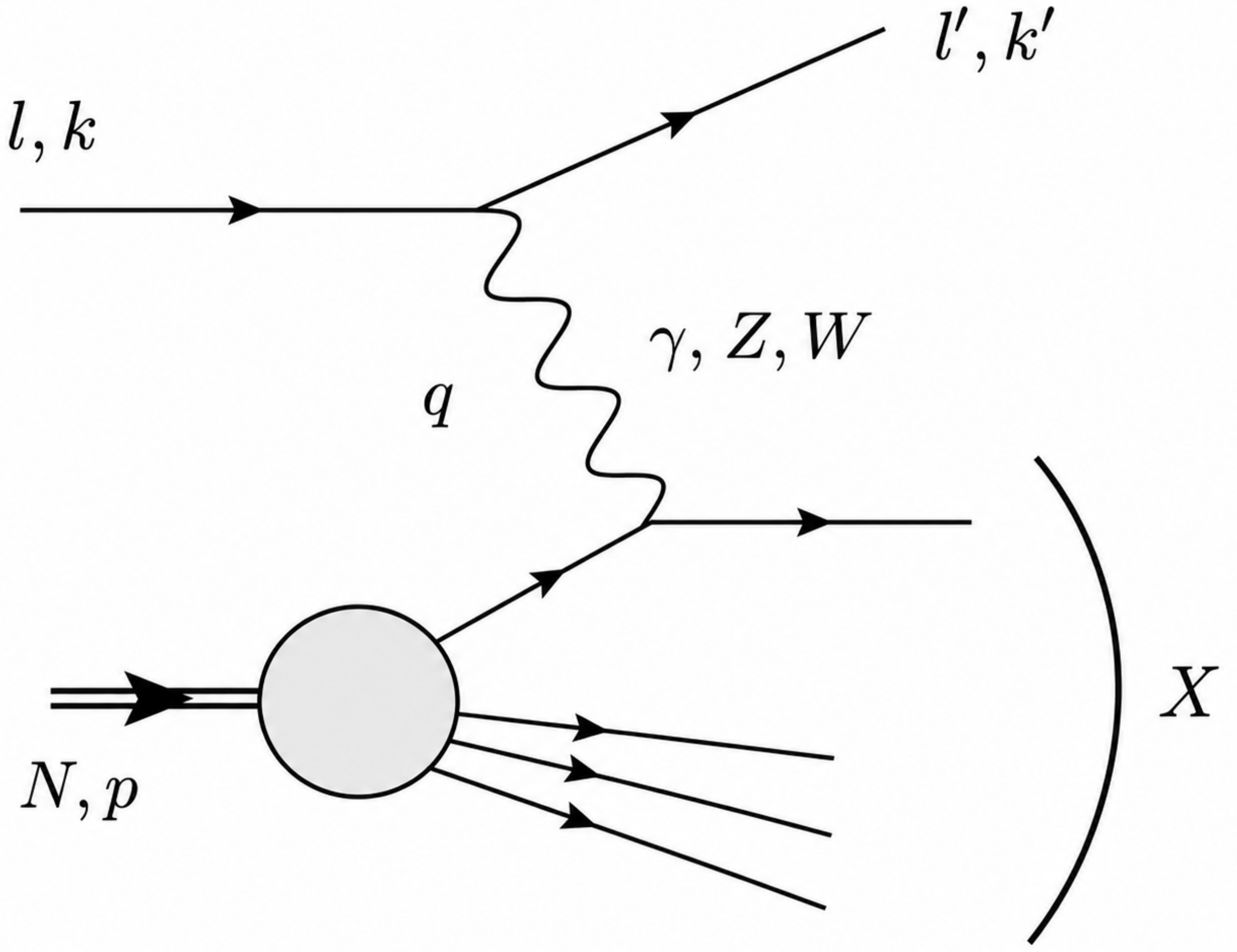
Cutaway view of ePIC detector

DIS Processes and Kinematics

$$\ell(k) + N(p, S) \rightarrow \ell'(k') + X$$

$$e^- + \vec{p} \rightarrow \nu_e + X$$ [for Charged Current]

$$q = k - k'$$



$$Q^2 = -q^2, \quad W^2 = (p+q)^2 = m_N^2 + Q^2\left(\frac{1}{x} - 1\right)$$

$$x = \frac{Q^2}{2p \cdot q} \qquad y = \frac{p \cdot q}{p \cdot k}$$

$$e^- + \vec{p} \rightarrow e'^- + X$$ [For Neutral Current]

General Formalism

$$\ell(k) + N(p, S) \rightarrow \ell'(k') + X$$

$$\frac{d^3\sigma}{dx\,dy\,d\phi} = \frac{y\alpha^2}{2Q^4} \sum_i \eta_i L^i_{\mu\nu} W_i^{\mu\nu} \qquad i = \gamma, \gamma Z, Z, W$$

$$W^i_{\mu\nu} \supset -\frac{p_\mu S_\nu + S_\mu p_\nu}{2p\cdot q} g_3^i + \frac{S\cdot q}{(p\cdot q)^2} p_\mu p_\nu g_4^i + \frac{S\cdot q}{p\cdot q} g_{\mu\nu} g_5^i$$

$F_3^i, \quad g_3^i, \quad g_4^i, \quad g_5^i$ are parity-violating structure functions

$$F_3^\gamma = g_3^\gamma = g_4^\gamma = g_5^\gamma = 0$$

The cross section is built from a leptonic tensor and a hadronic tensor. The hadronic tensor contains the structure functions. The terms g3, g4, g5 appear only when weak interactions are included, so they are parity-violating polarized structure functions.

Charged Current Contraction: How we access g5?

$$e^- + \vec{p} \to \nu_e + X$$

$$g_1^{W^-} = \Delta u + \Delta c + \Delta \bar{d} + \Delta \bar{s}$$

$$g_5^{W^-} = \Delta u + \Delta c - \Delta \bar{d} - \Delta \bar{s}$$

$$g_4^i = 0, \qquad g_3^i = 2x g_5^i$$

$$A_L^{CC} = \frac{1}{P_e P_p} \frac{N^+ - N^-}{N^+ + N^-}$$

$$g_5^{W^-} = \frac{2A_L^{W^-} D - Y_- g_1^{W^-}}{Y_+}$$

$$D = U + (1-y)^2 \bar{D}, \qquad g_3^{W^-} = 2x g_5^{W^-}$$

How to access structure functions?

$$\frac{1}{2m_N}W^i_{\mu\nu} = -\frac{g_{\mu\nu}}{m_N}F^i_1 + \frac{p_\mu p_\nu}{m_N(p\cdot q)}F^i_2 + \frac{i\epsilon_{\mu\nu\alpha\beta}}{2p\cdot q}\left[\frac{p^\alpha q^\beta}{m_N}F^i_3 + 2q^\alpha S^\beta g^i_1 - 4xp^\alpha S^\beta g^i_2\right] - \frac{p_\mu S_\nu + S_\mu p_\nu}{2p\cdot q}g^i_3 + \frac{S\cdot q}{(p\cdot q)^2}p_\mu p_\nu g^i_4 + \frac{S\cdot q}{p\cdot q}g_{\mu\nu}g^i_5$$

F_1, F_2, F_3 : unpolarized structure functions

g_1, g_2, g_3, g_4, g_5 : polarized spin structure functions

The longitudinal spin-difference cross section contains g^i_5.

$$\Delta_L\sigma^{\ell N}(\lambda) = \frac{16\pi m_N E\alpha^2}{Q^4}\sum_i \eta_i C_i \left\{-\lambda xy\left(2 - y - \frac{xym_N}{E}\right)g^i_1 + 2\lambda\frac{x^2ym_N}{E}g^i_2 + x\left[y^2 + (1-y)\left(2 - \frac{xym_N}{E}\right)\right]g^i_5\right\}$$

Charged Current $W^\pm$

$$\Delta_L\sigma^{\ell^\mp N}_{cc} = \frac{64\pi m_N E\alpha^2}{Q^4}\eta_W\left\{\pm xy\left[2 - y + \frac{xm_N}{E}(1-y)\right]g^{W^\mp}_1 + x\left[y^2 + (1-y)\left(2 - \frac{xym_N}{E}\right)\right]g^{W^\mp}_5\right\}$$

For the charged-current DIS, the spin dependent cross-sections contain both $g_1^{W\pm}$ and $g_5^{w\pm}$. The y-dependent coefficients allow sensitivity to g_5.

What parity-violating structure functions tell us?

- g_5 helps to separate spin carried by quarks from spin carried by antiquarks.
  $g_5 \approx \Delta q - \Delta \bar{q}$
- g_3 contains same helicity informations as g_5 for quark and antiquarks because $g_3 \approx 2xg_5$
- At Leading order Quark Parton Model, $g_4^i = 0$
- $g_1^{W^-} = \Delta u + \Delta c + \Delta \bar{d} + \Delta \bar{s}$
- $g_5^{W^-} = \Delta u + \Delta c - \Delta \bar{d} - \Delta \bar{s}$
- $g_3^{W^-} = 2x(\Delta u + \Delta c - \Delta \bar{d} - \Delta \bar{s})$
- $g_4^{W^-} = 0$
- $2xg_5^{W^-} = g_3^{W^-}$

Ordinary polarized DIS mostly give information

About $\Delta q + \Delta \bar{q}$

While parity-violating charged current DIS gives

Access to $\Delta q - \Delta \bar{q}$

Why EIC is good place to study these functions?

- Weak Effects become visible at high Q^2
- $\eta^{\gamma Z} \propto \frac{Q^2}{Q^2 + M_Z^2}$
- $\eta^{W} \propto \left(\frac{Q^2}{Q^2 + M_W^2}\right)^2,$

At low Q^2 photon exchange dominates while

At high Q^2, weak propagator factor increase

Which allows access to parity-violating structure

functions

- High Q^2, Polarized Beams, High Luminosity and broad DIS kinematic coverage
- Small weak asymmetry becomes measurable
- EIC has broad x,Q^2, y coverage
- Charge current DIS give direct access to g_5 structure function

Where does the parity-violation enter?

- The parity violation comes from the axial-vector weak current, the γ_5 term. The photon exchange is parity conserving, so g_3, g_4, g_5 vanish for pure electromagnetic DIS. When Z or W exchange contributes, these parity-violating spin structure functions appear, and g5 becomes sensitive to $\Delta q - \Delta\bar{q}$.

- $J_\mu^\gamma \sim \bar{q}\gamma_\mu q, J_\mu^{Z,W} \sim \bar{q}\gamma_\mu(g_V - g_A\gamma_5)q$, $\gamma_5 \neq 0 \quad \Rightarrow$ Parity Violation ,

- $F_3^\gamma = g_3^\gamma = g_4^\gamma = g_5^\gamma = 0, g_3, \quad g_4, \quad g_5$ are Parity viloating structure functions, and also $g_4^i = 0$.

- $g_3^i = 2xg_5^i, i = \gamma, \gamma Z, Z, W$

DJANGOH what is it?

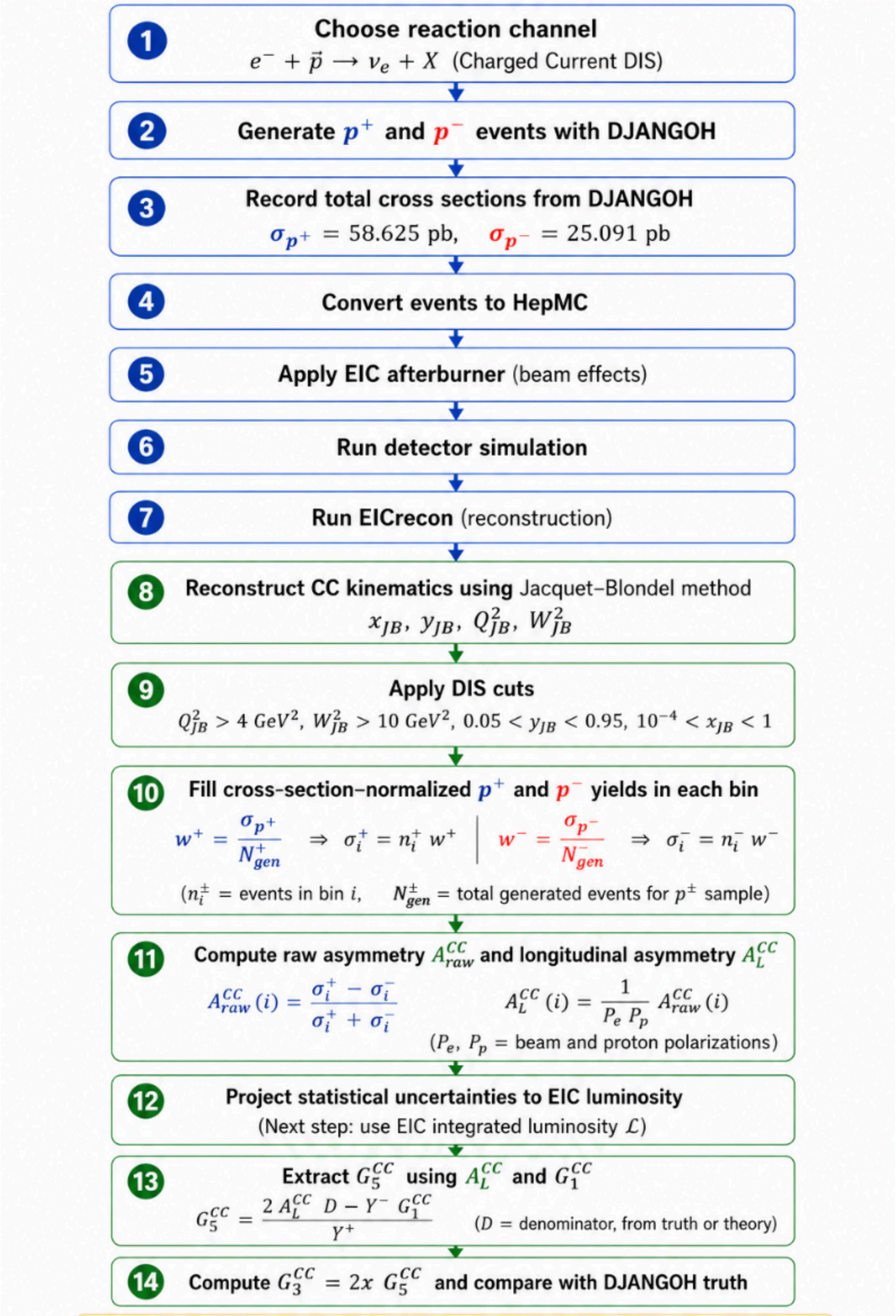
- DIS event egnerator for lepton-nucleon scattering
- Can simulate both neutral currents and Charge current DIS processes
- Allows to extract truth level DIS quantities like $x_{true}, Q^2_{true} and\ y_{true}$
- Allows to form spin asymmetries
- Allows to access truth-level charged current structure functions g1 and g5 which then allow to extract g3
- Thus it facilitates to compare reconstructed EIC pseudo-data can recover these structure functions at truth level.

DJANGOH $\rightarrow\ e^- p^{\pm} \rightarrow \nu X \rightarrow A_L^{CC} \rightarrow\ G_5^{CC}\ \rightarrow\ G_3^{CC}$= 2x G$_5^{CC}$

DJANGOH Charged Current $\frac{G_3^{CC}}{G_5^{CC}}$ Study

- Channel: $e^- + p \rightarrow \nu_e + X$
- Reconstruction: Jacquet-Blondel Method
- Beam Energies, E_e = 18.0 GeV and E_p=275.0 GeV
- DIS cuts: Q^2_{JB}>4.0 GeV^2, W^2_{JB}>10.0 GeV^2 and 0.05<Y_{JB}<0.95
- Cross-Sections: σ_{p+}=58.625 pb, and σ_{p-}=25.091 pb
- G3 and G5 correlated as G3=2xG5
- Extract A_{CC}^{raw} and propagate to G5 and G3

Procedure



Impact Study

DIS event selection

Q²_JB > 4 GeV²

W²_JB > 10 GeV²

0.05 < y_JB < 0.95

10^{-4} < x_JB < 1

Why EIC afterburner?

DJANGOH gives ideal generator level events

The EIC afterburner

applies realistic beam effects

before detector simulation.

1) Beam Crossing angle

2) Beam energy/momentum spread

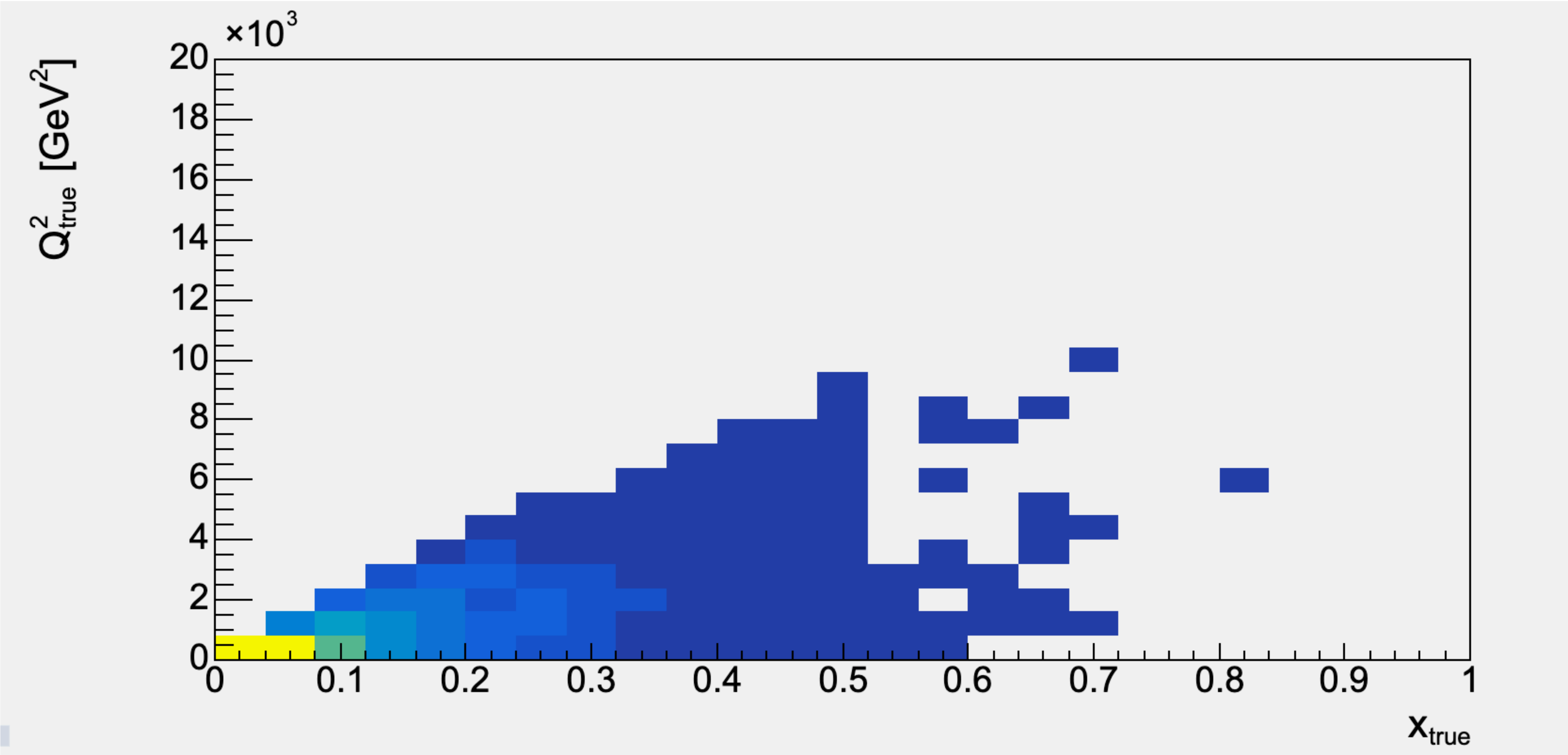
3) Vertex smearing

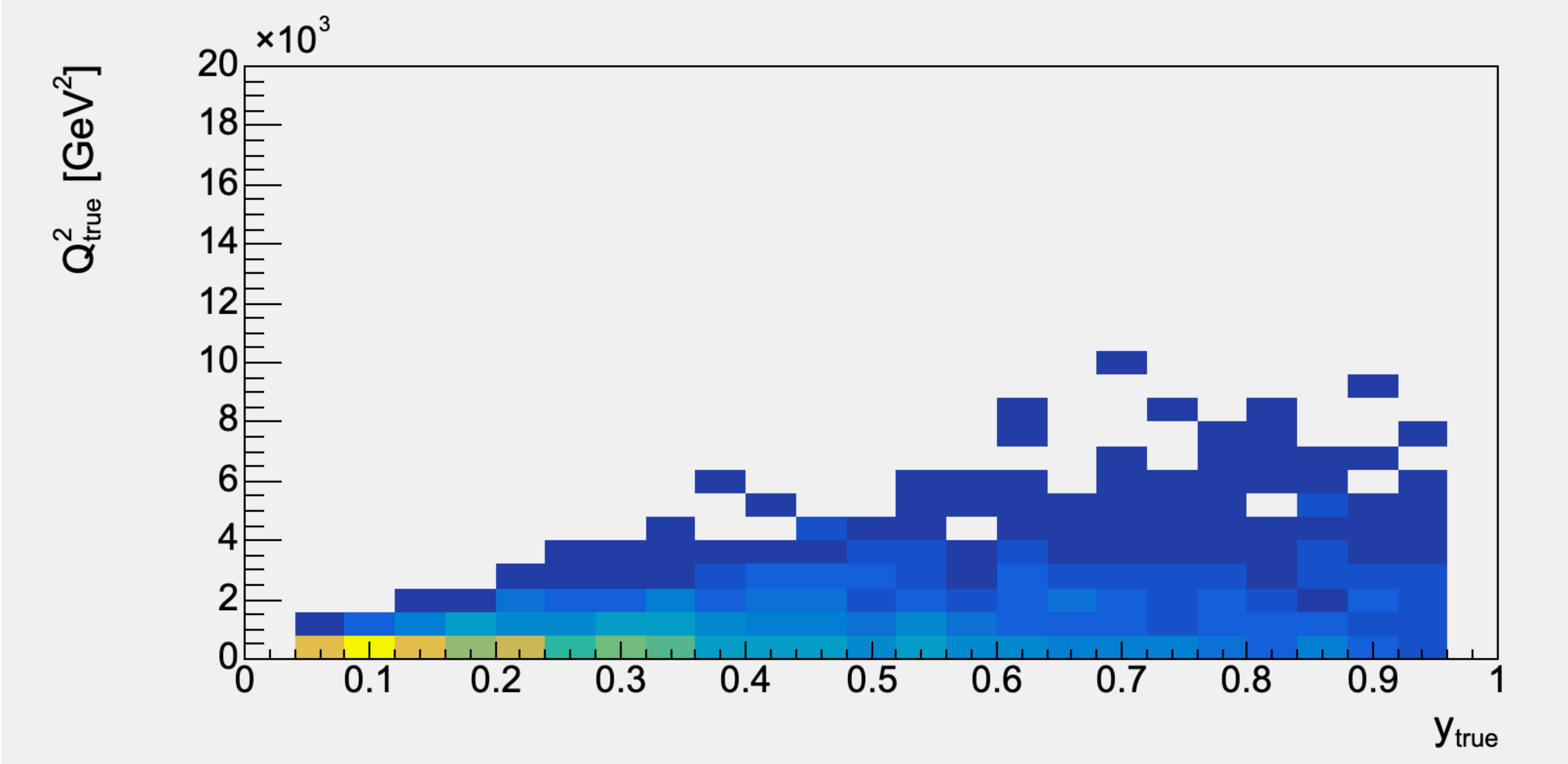
4) Beam Divergence

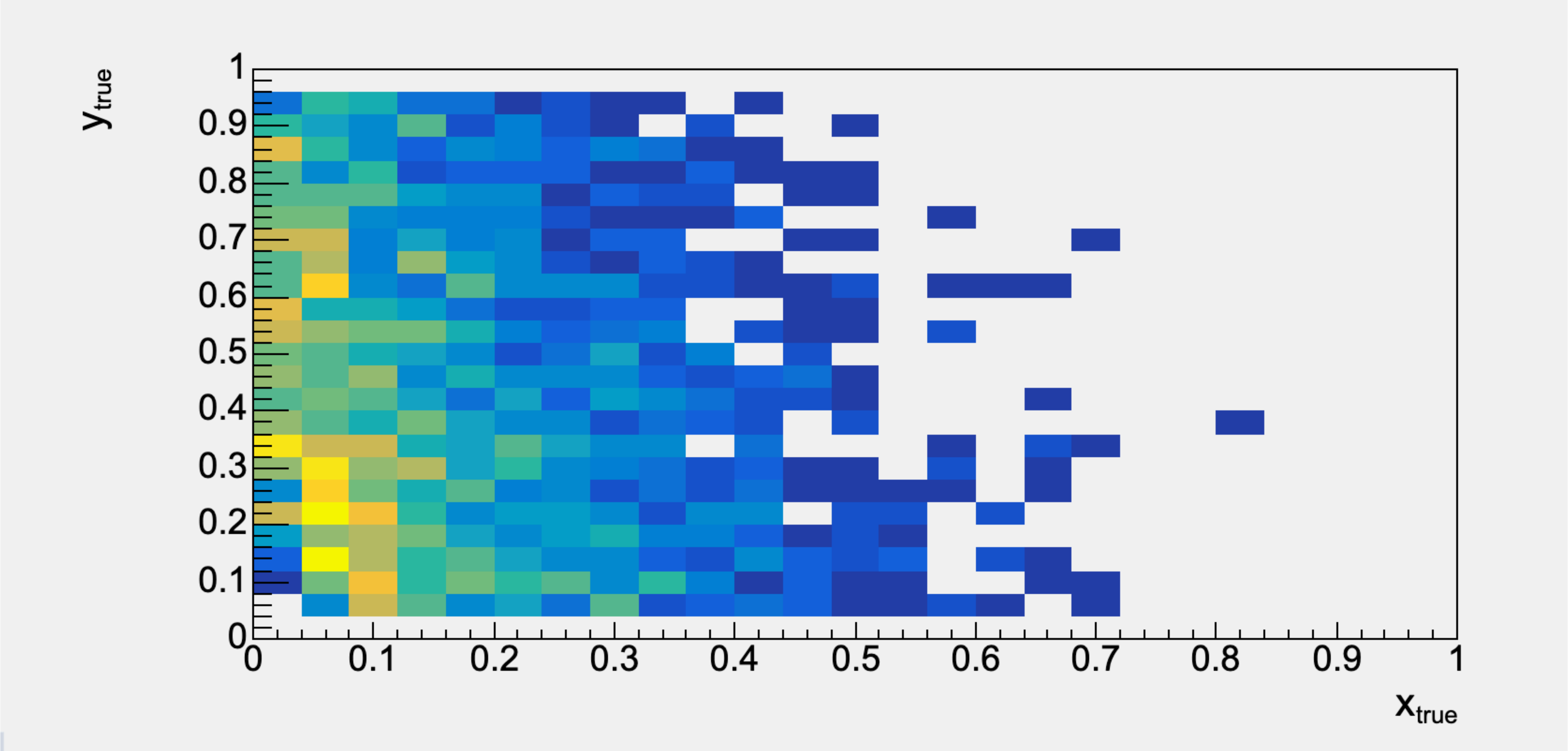
5) Boost to the real lab frame

Since the charged-current final state contains an undetected neutrino, these cuts are applied on the hadronic/Jacquet-Blondel reconstructed variables,

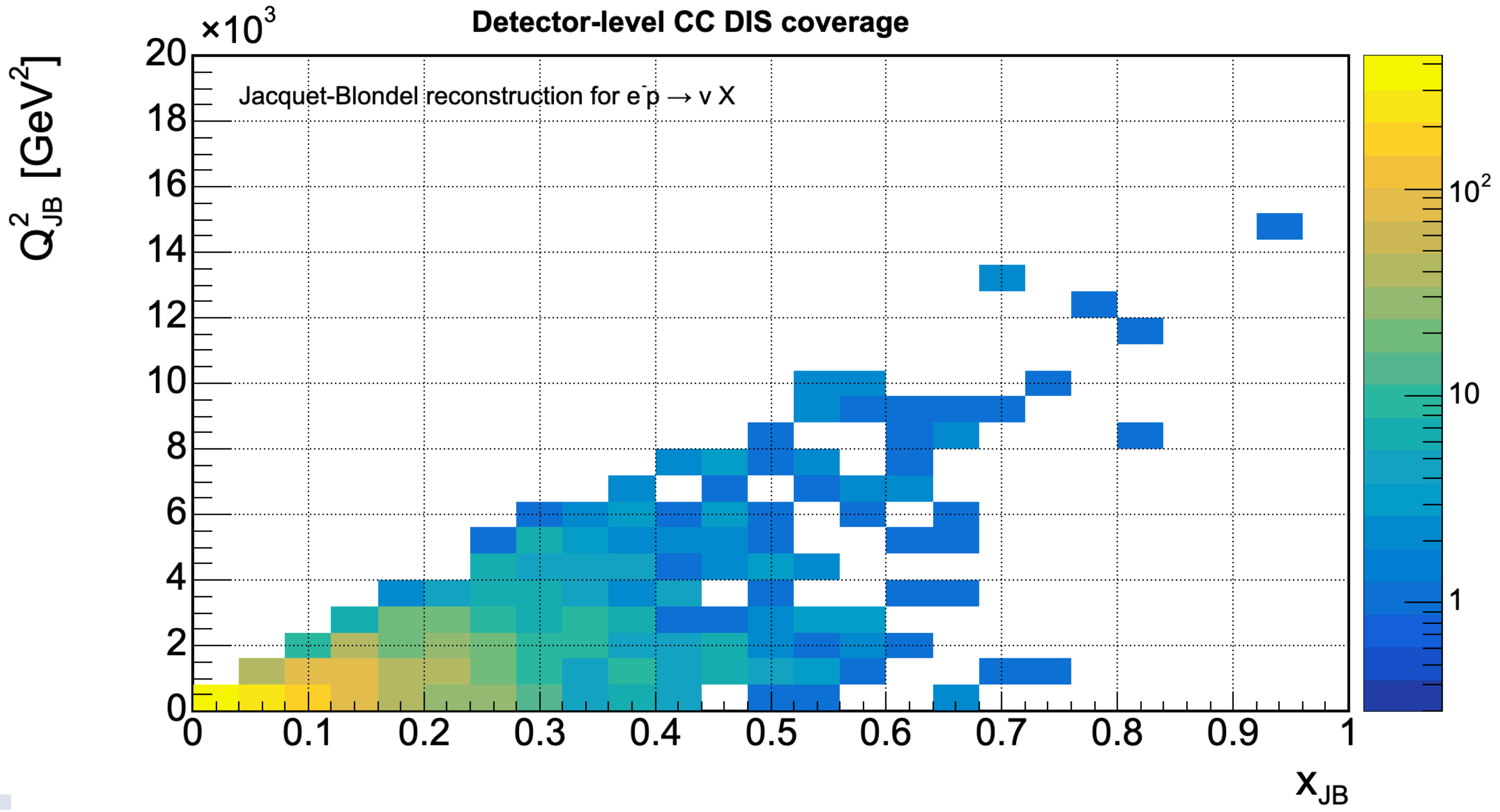
Kinematic coverage at generator/truth level

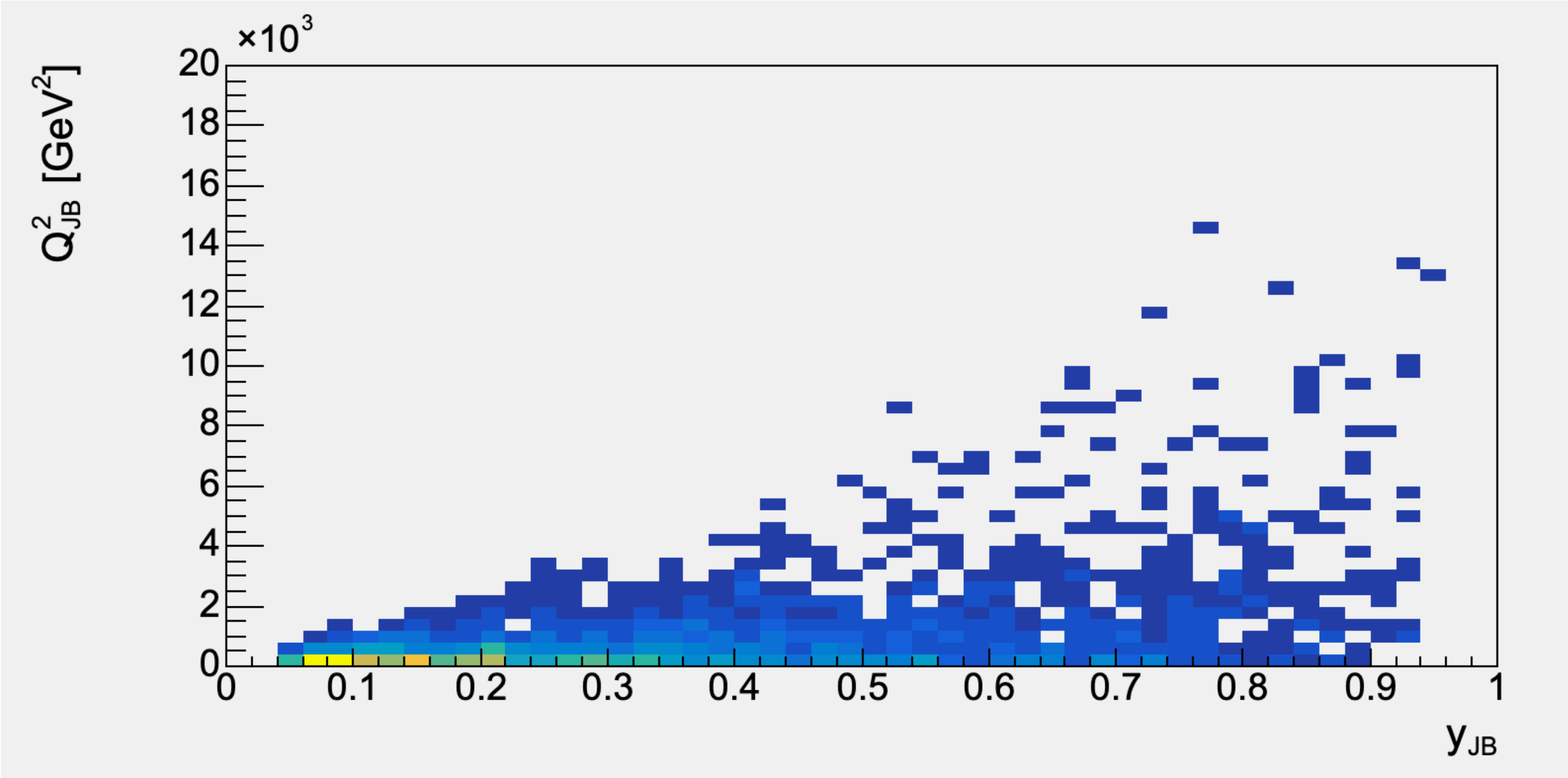


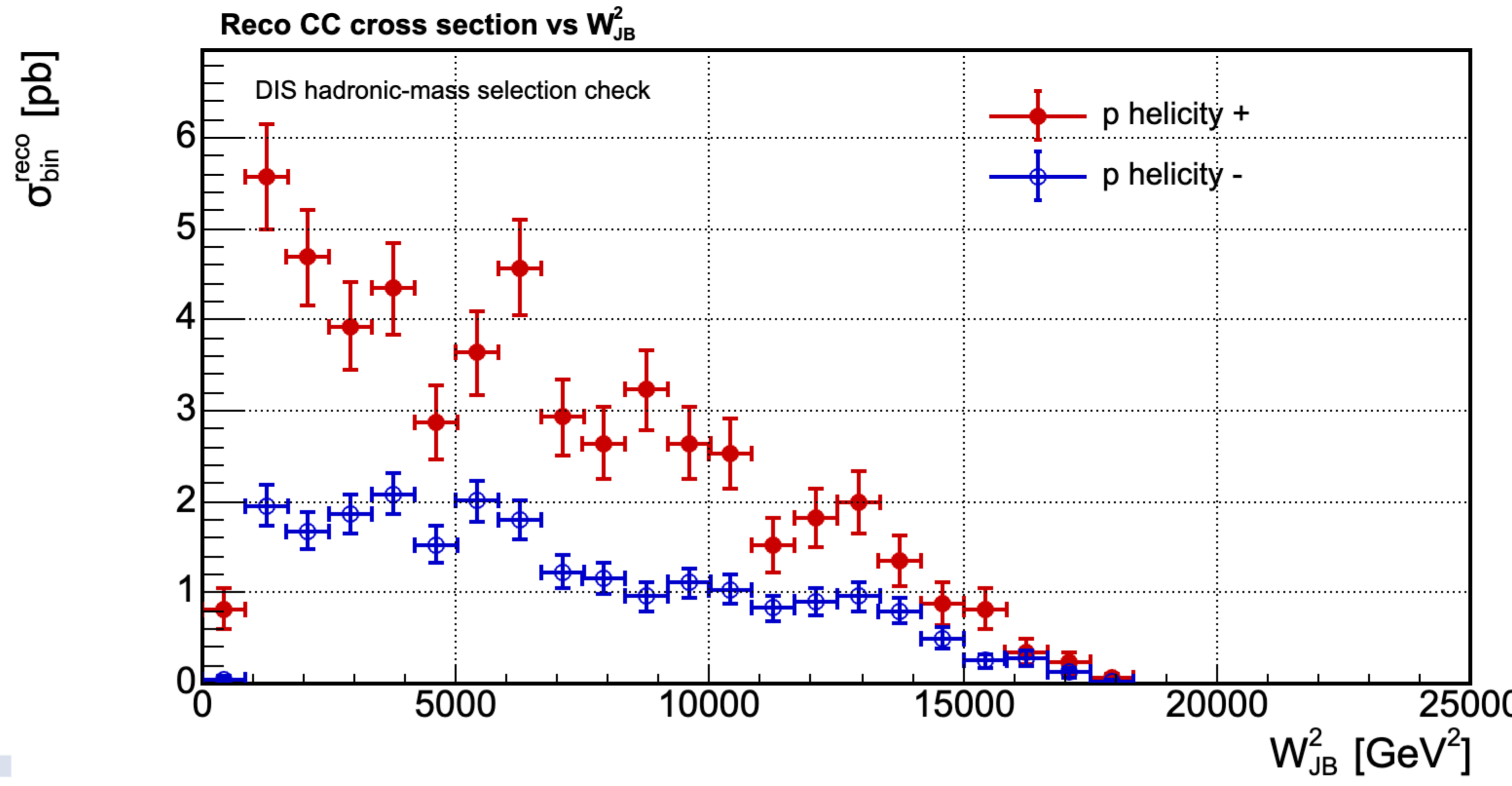


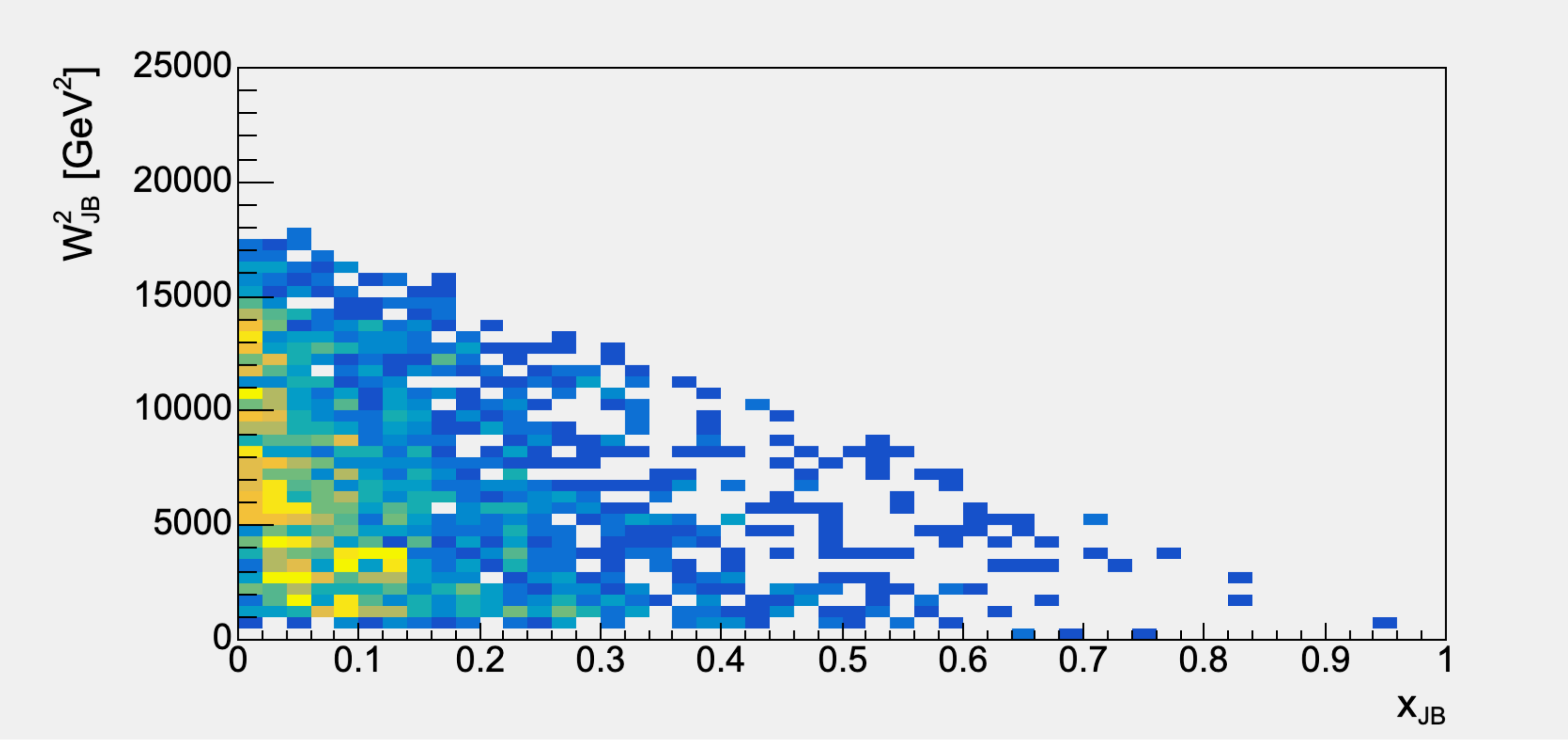


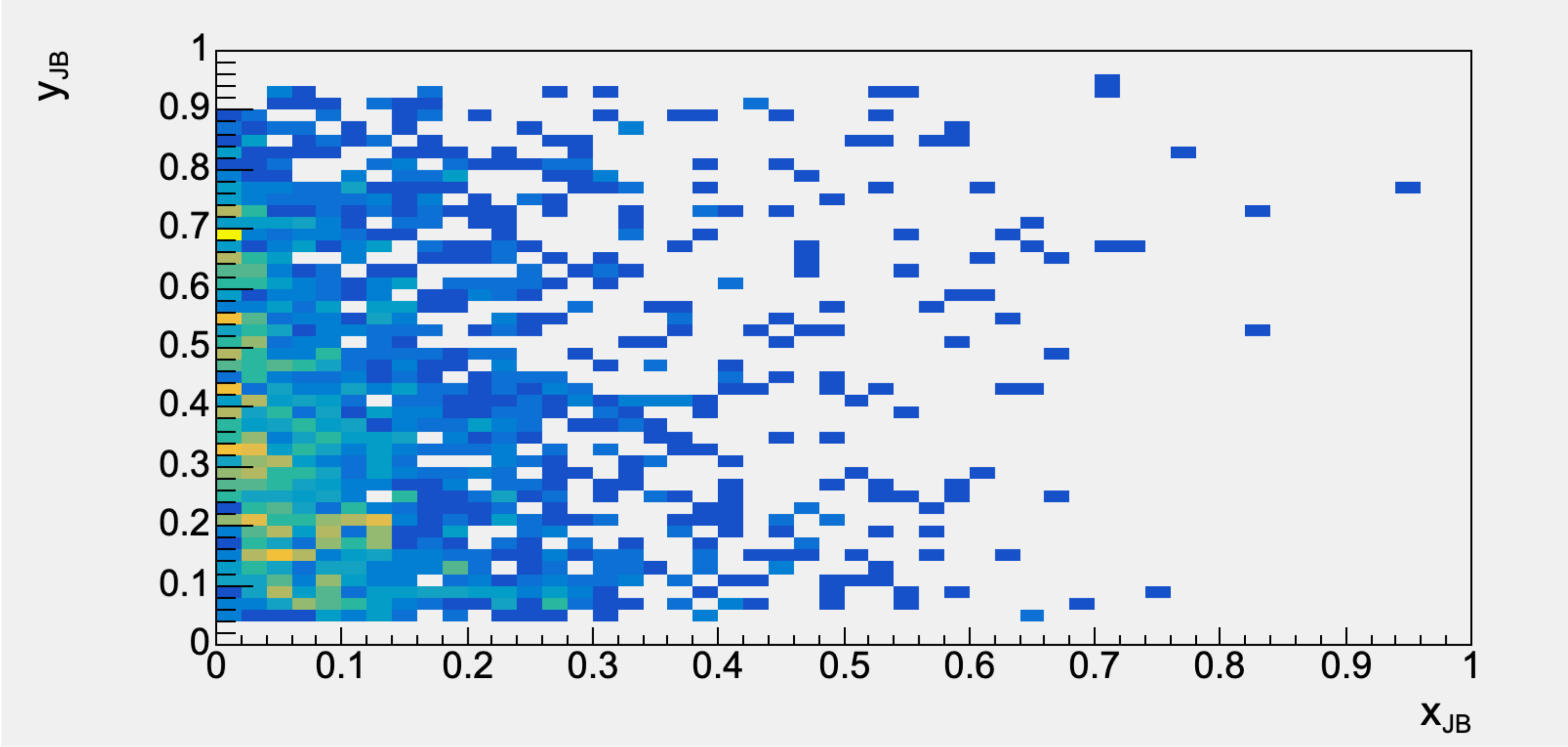
Kinematic coverage at detector level

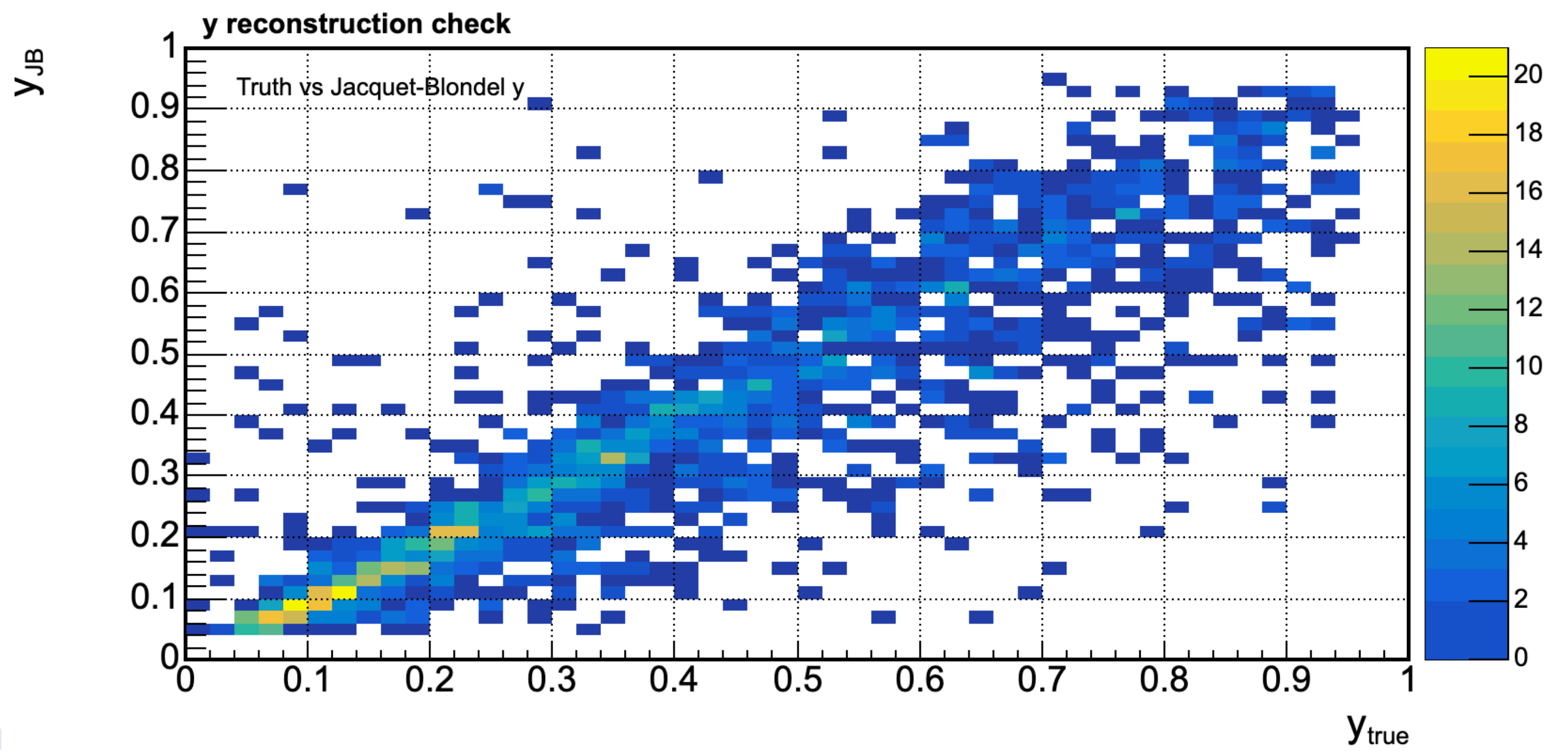




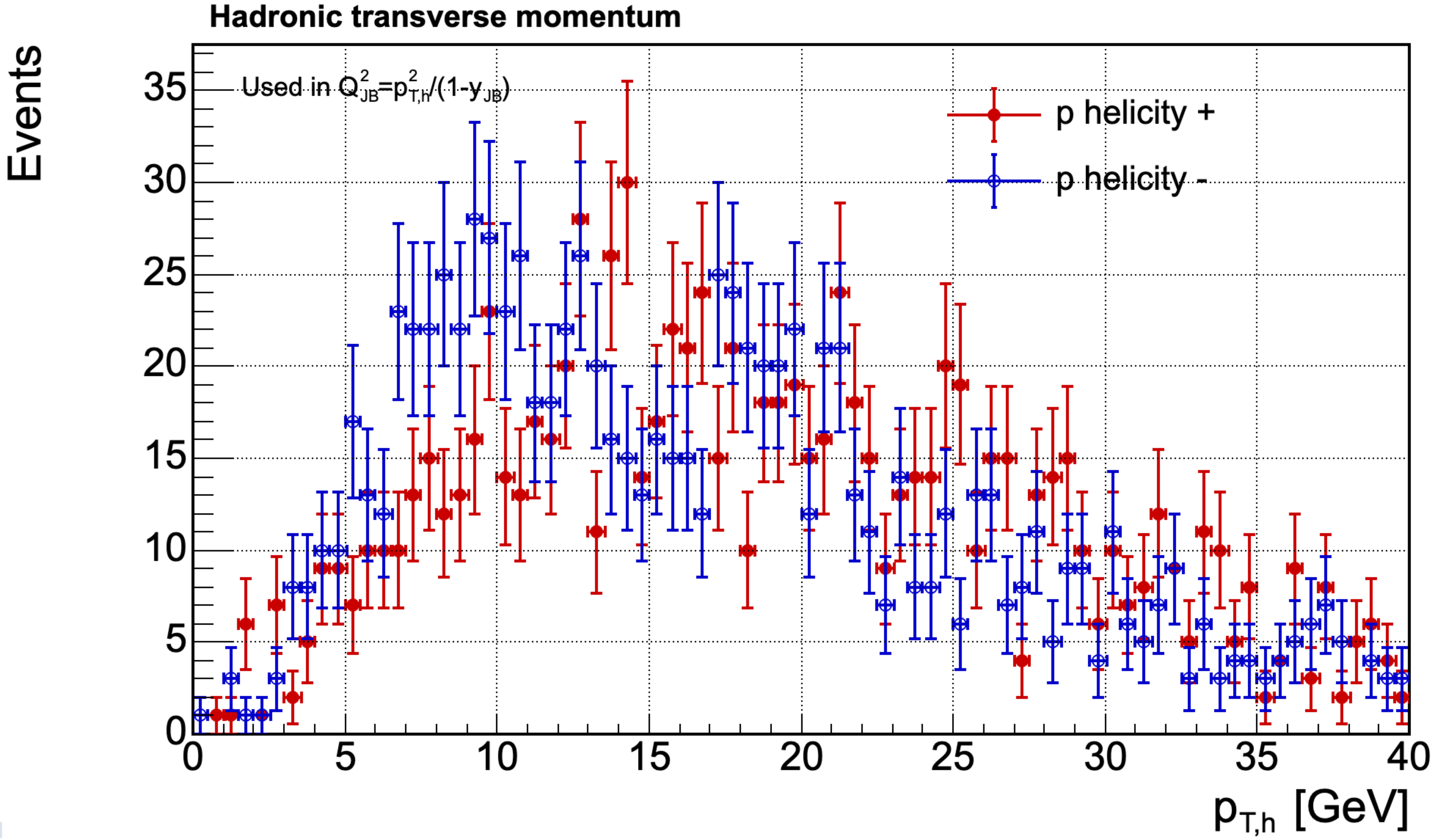




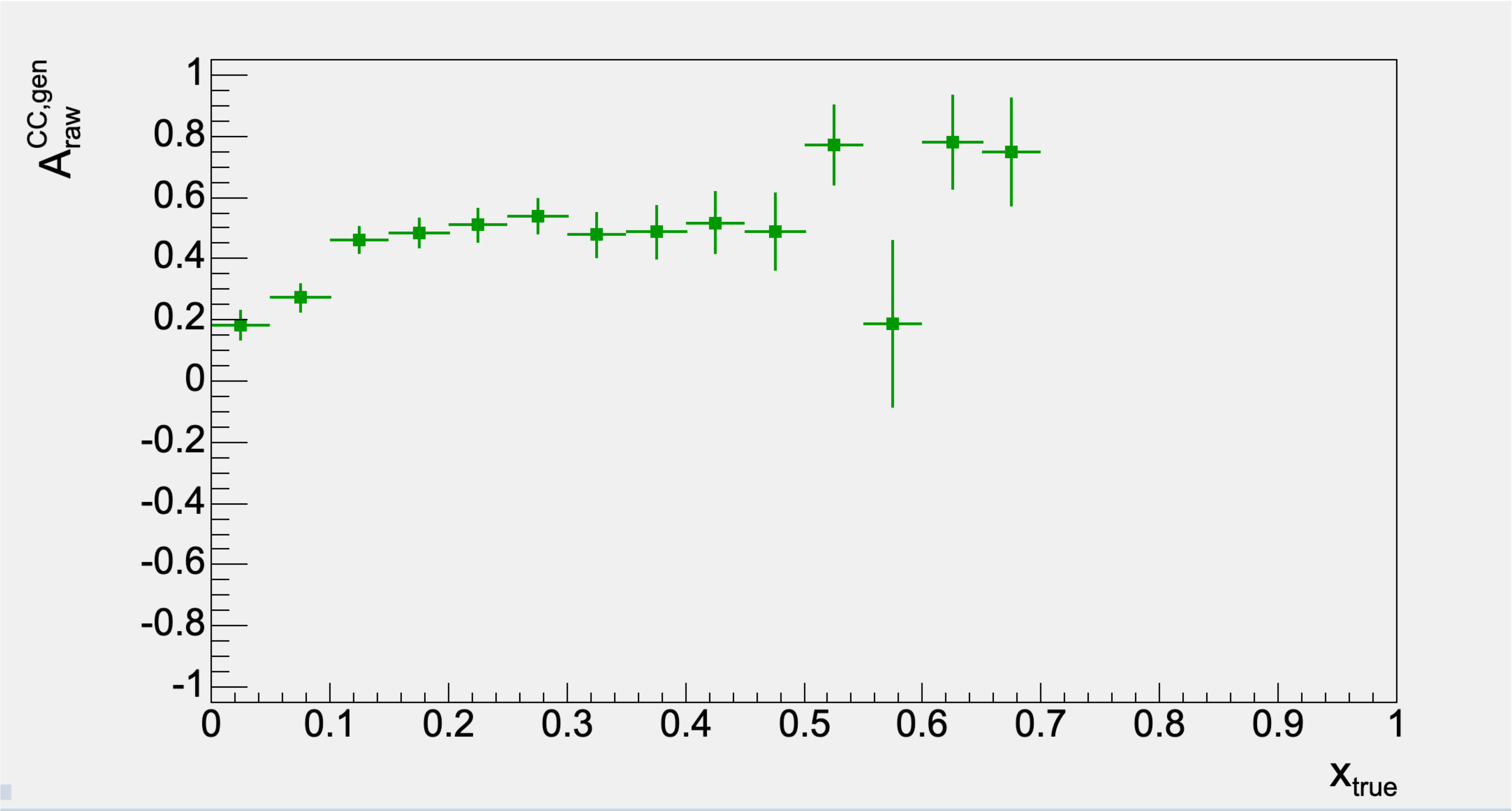


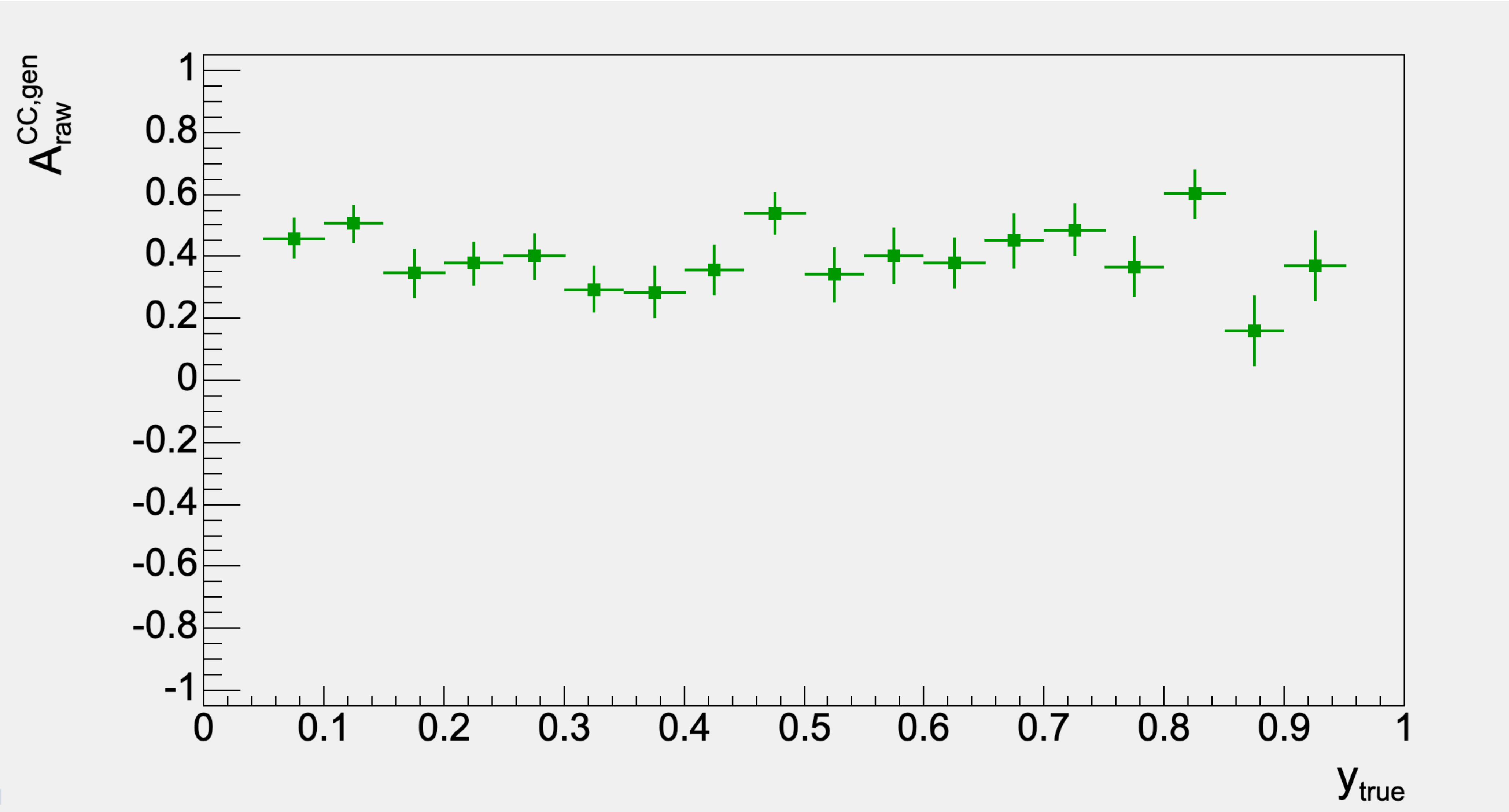


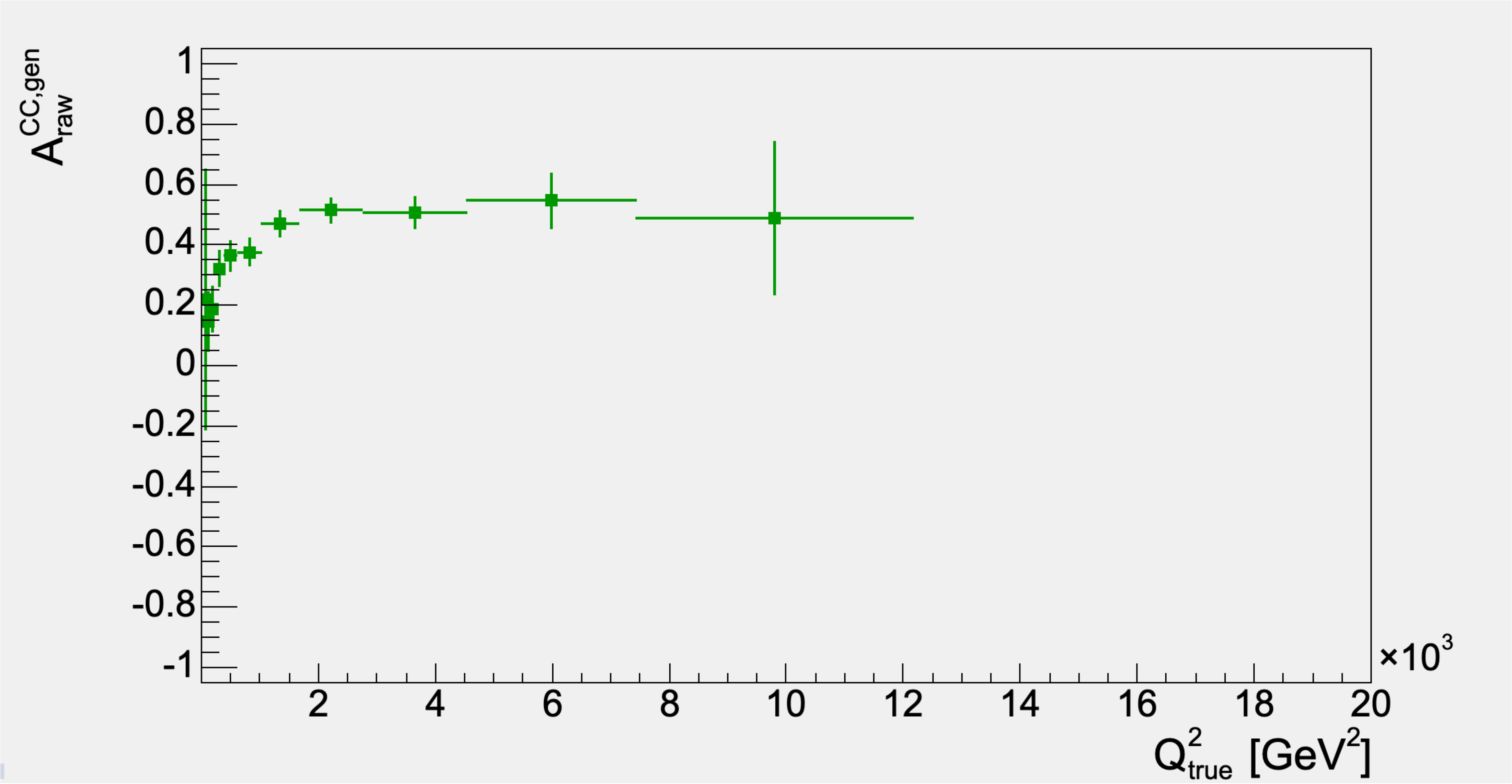
Transverse momentum of hadron



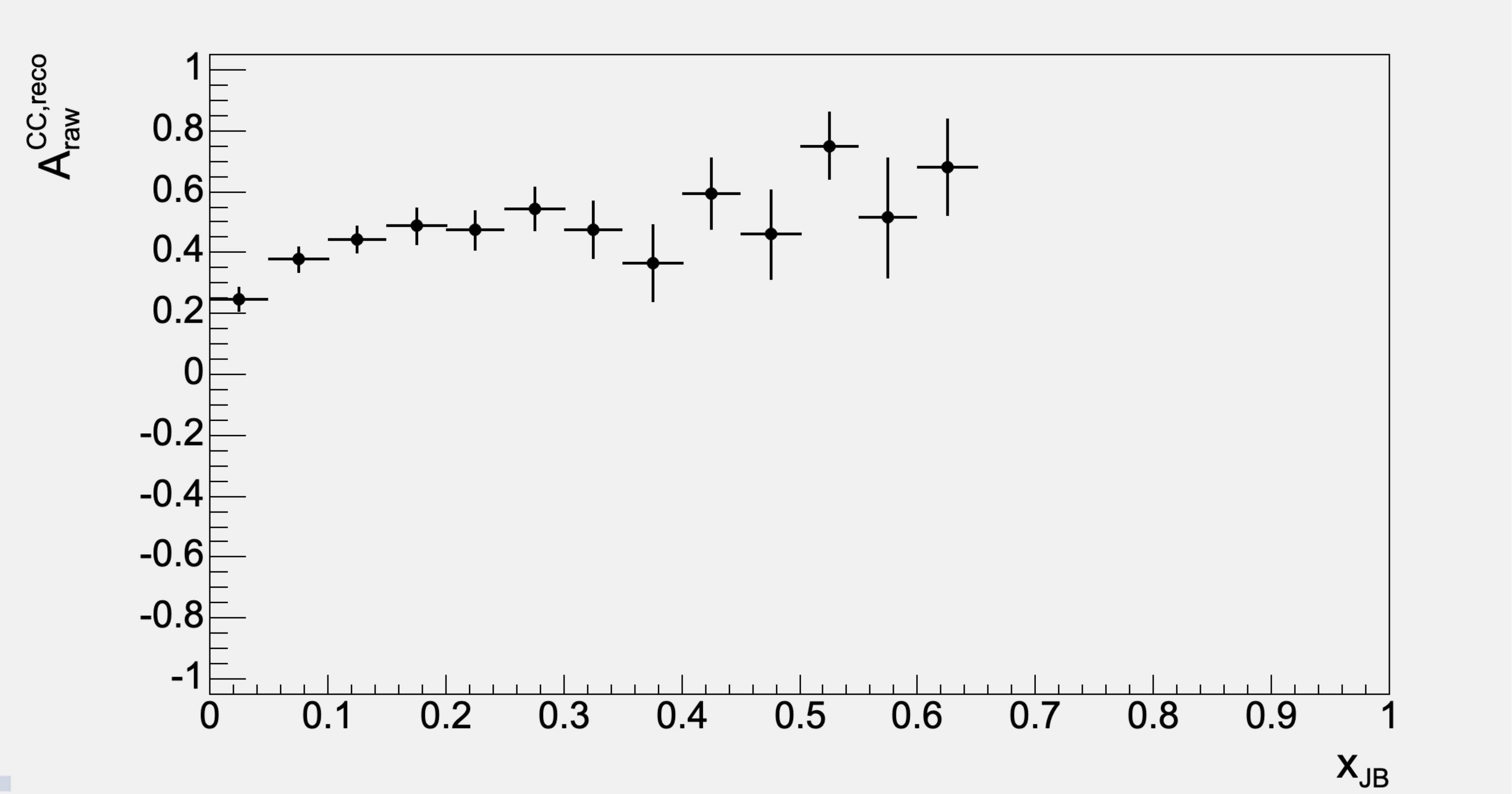
Asymmetries at the generator/truth level

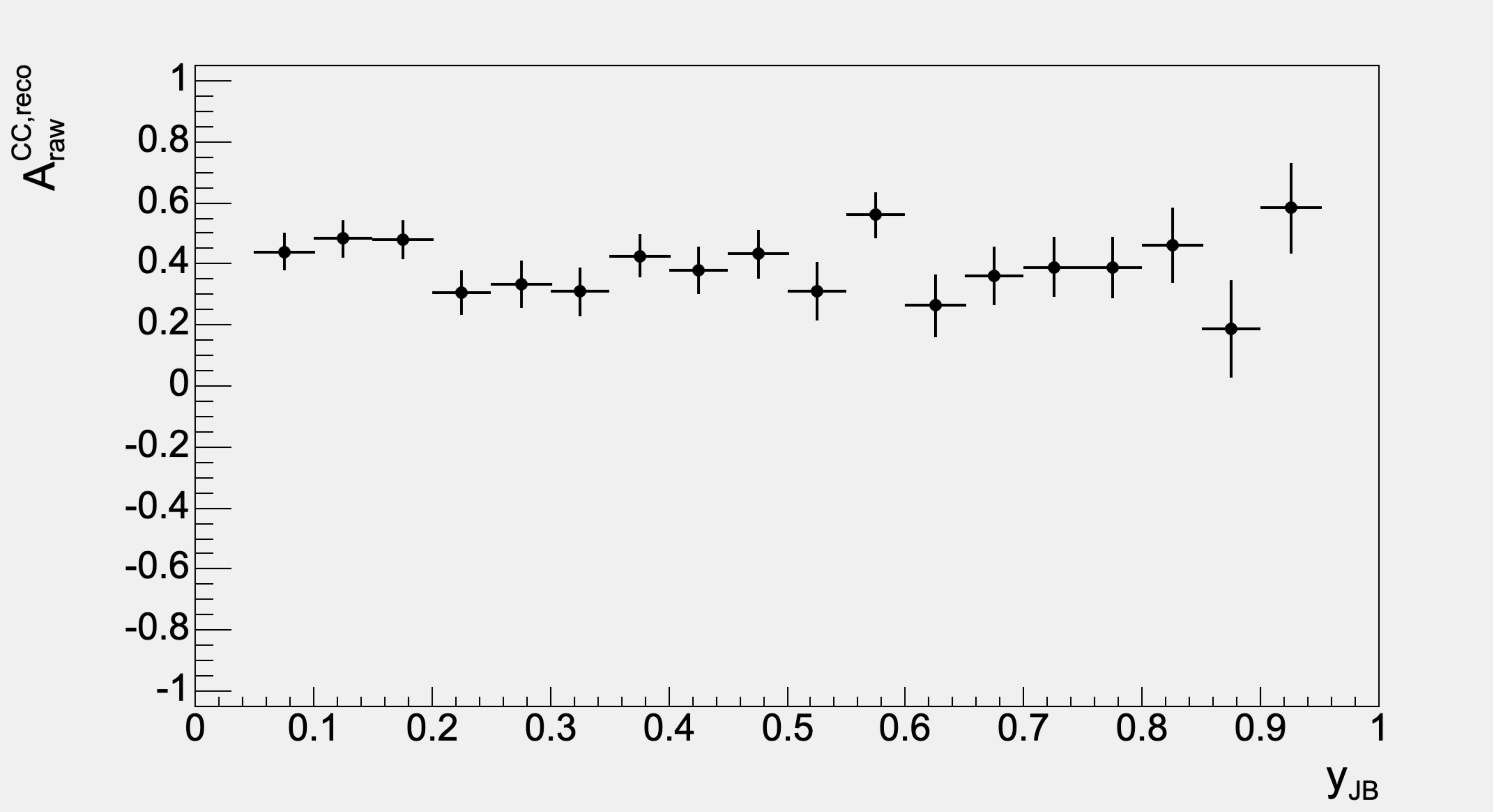


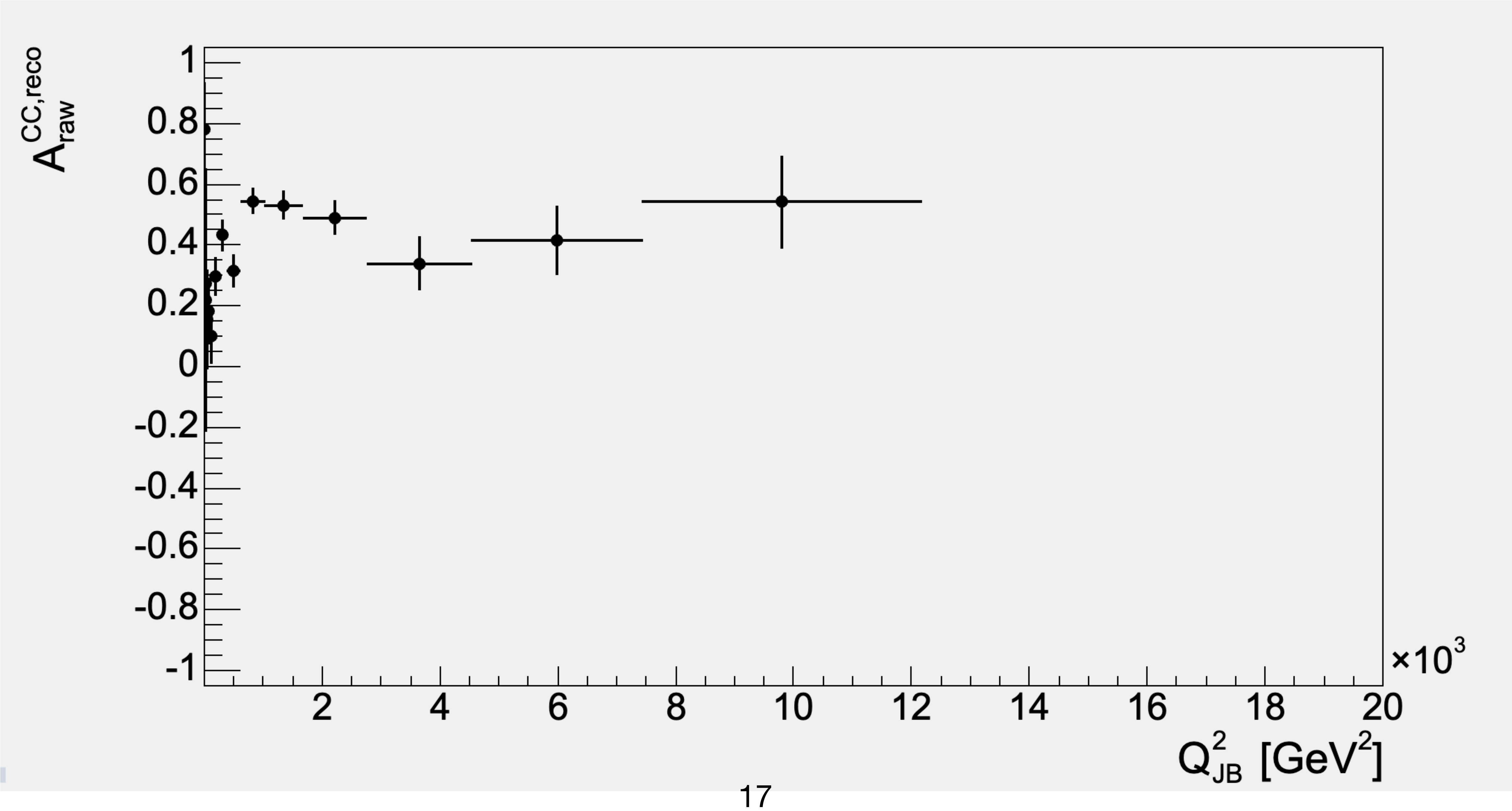




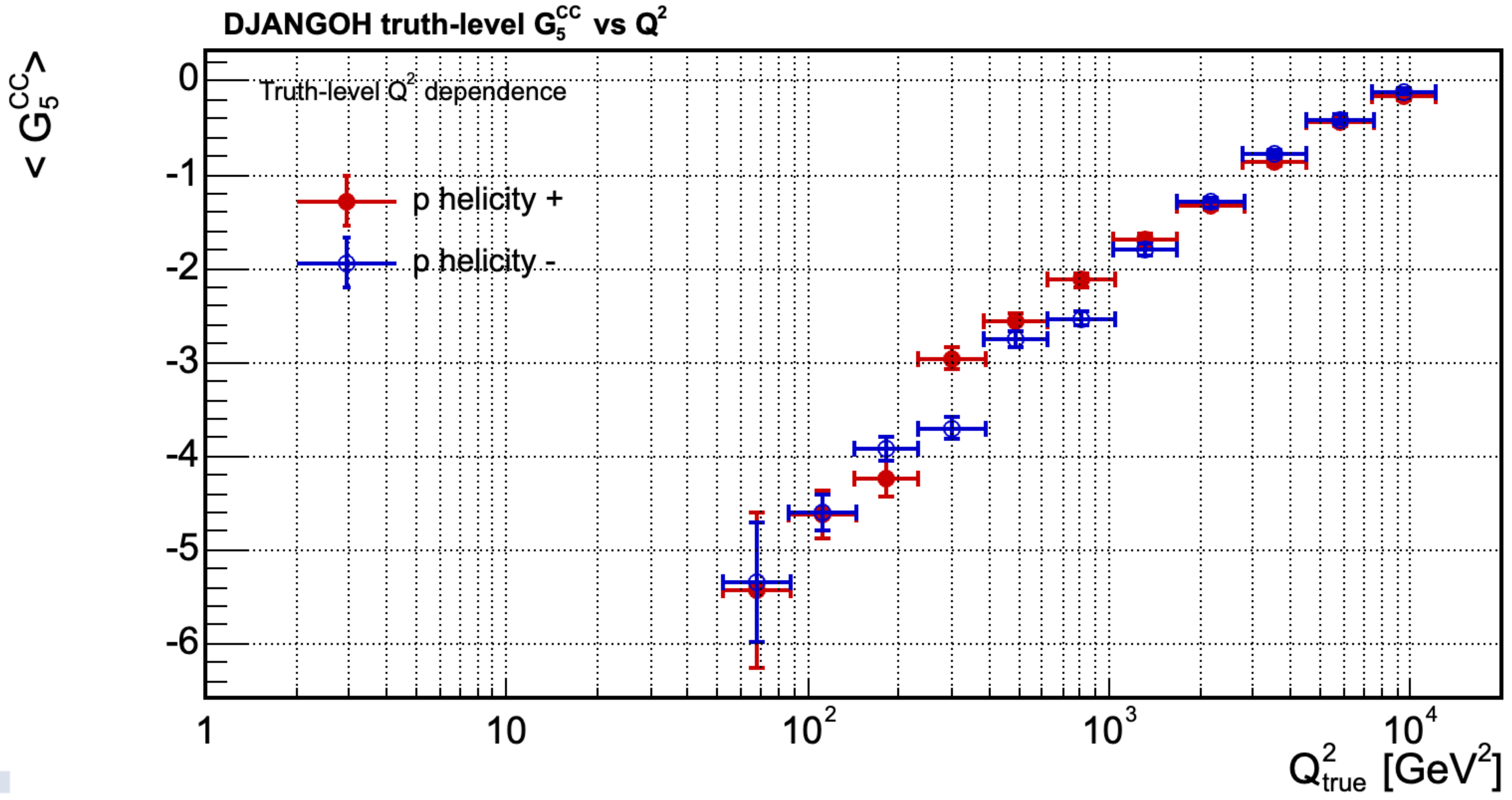
$A_{raw}^{CC,reco}$ at the detector level

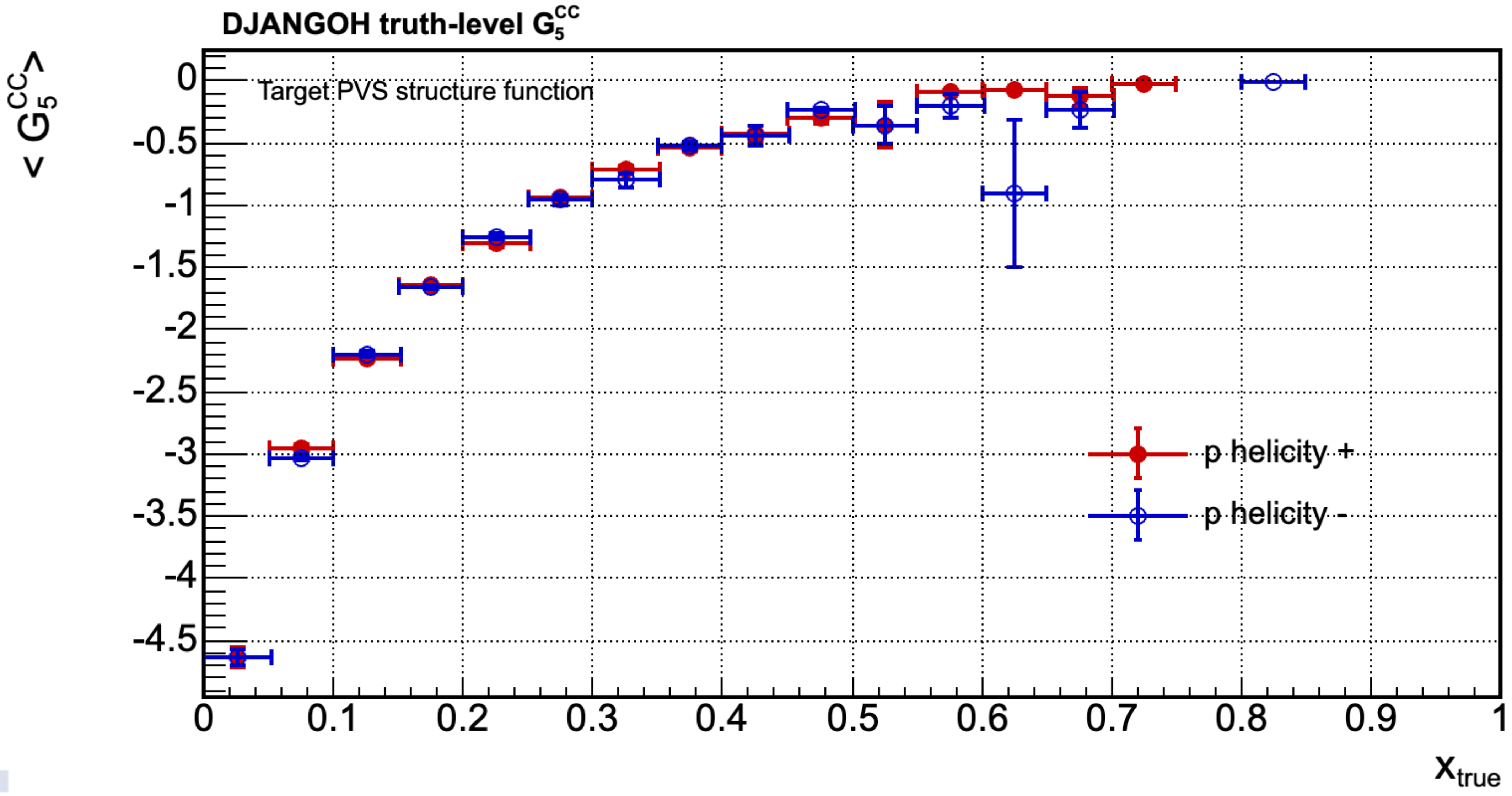


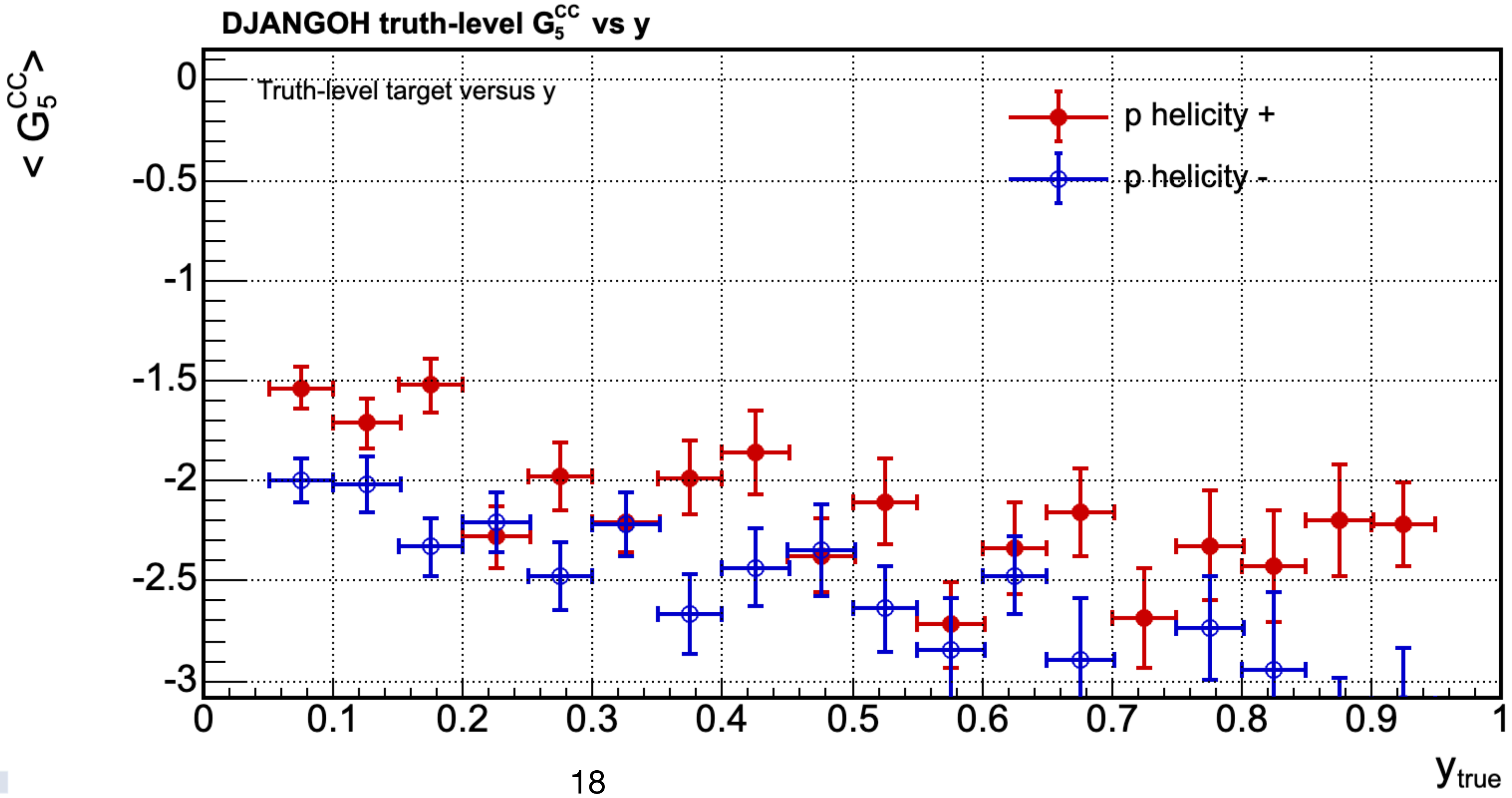




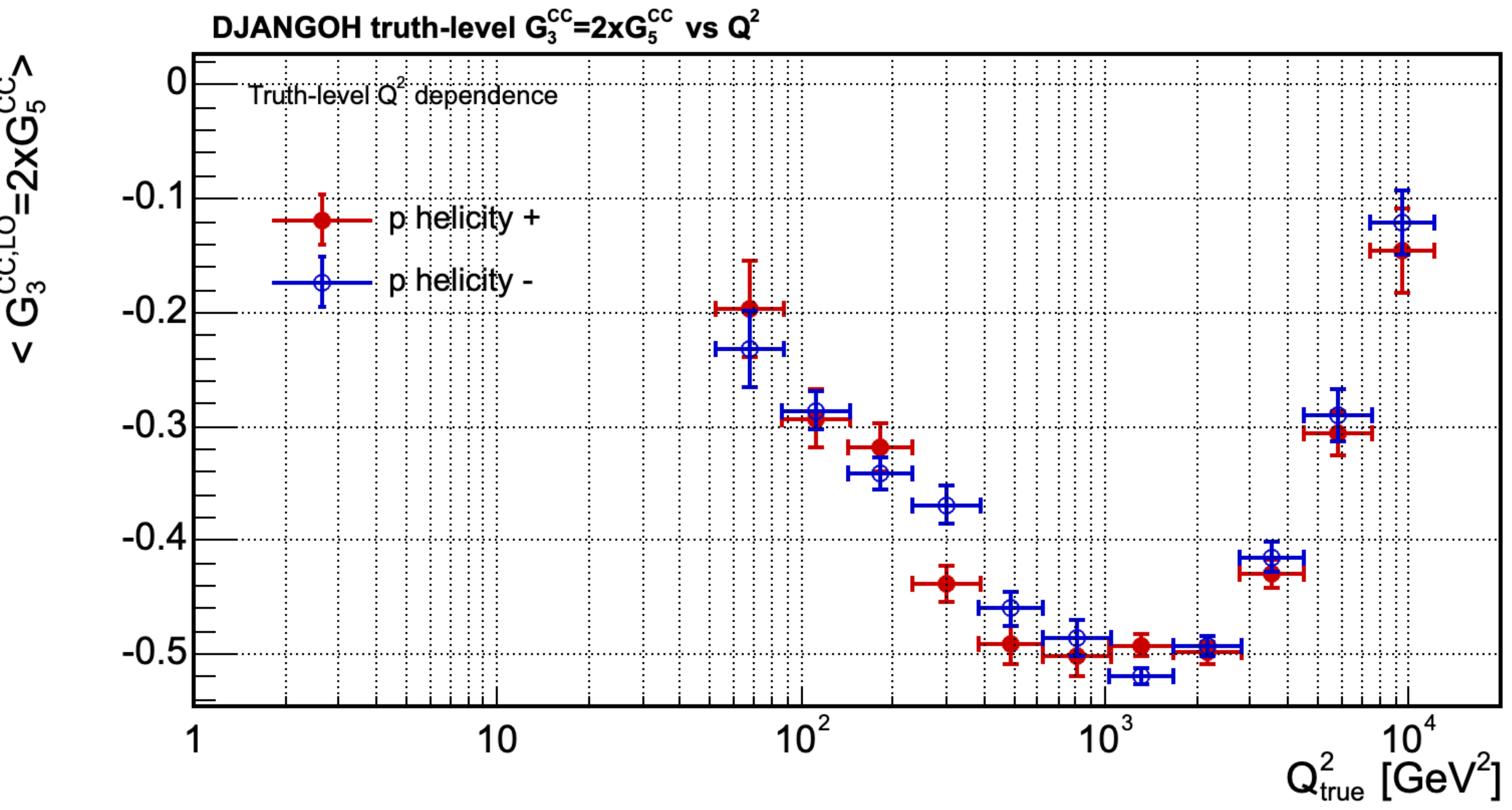
G_5^{CC} at the truth level

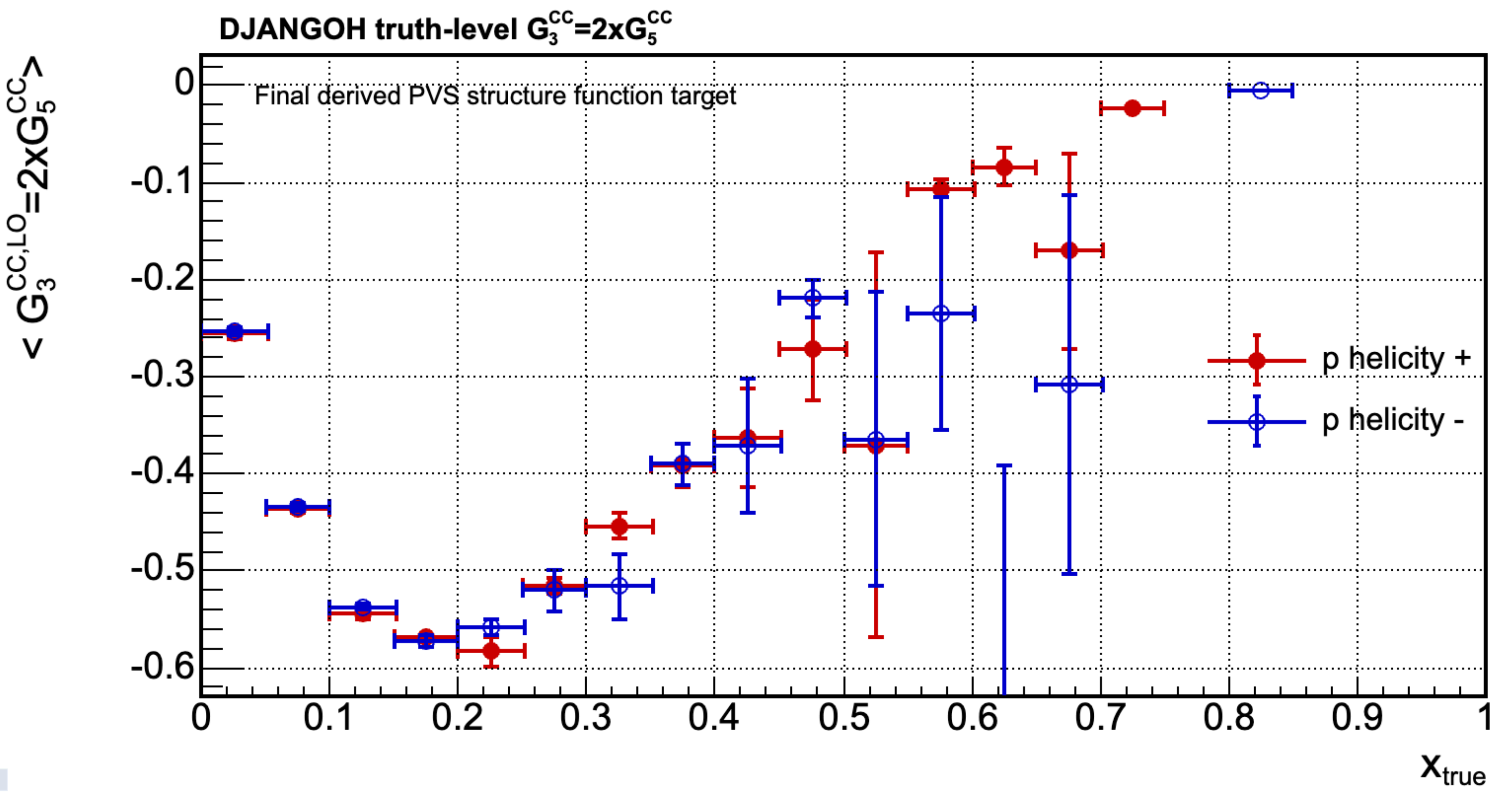


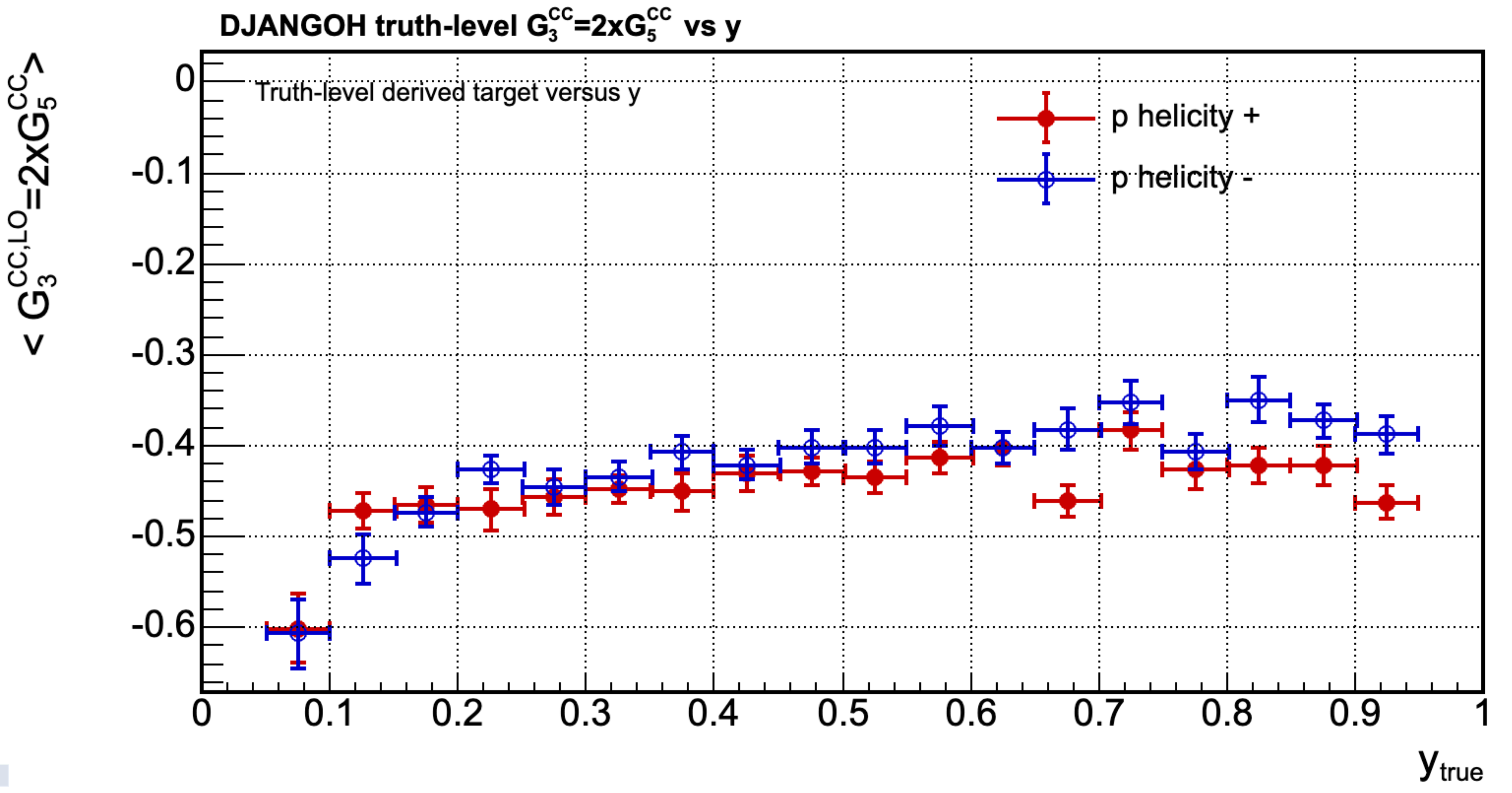




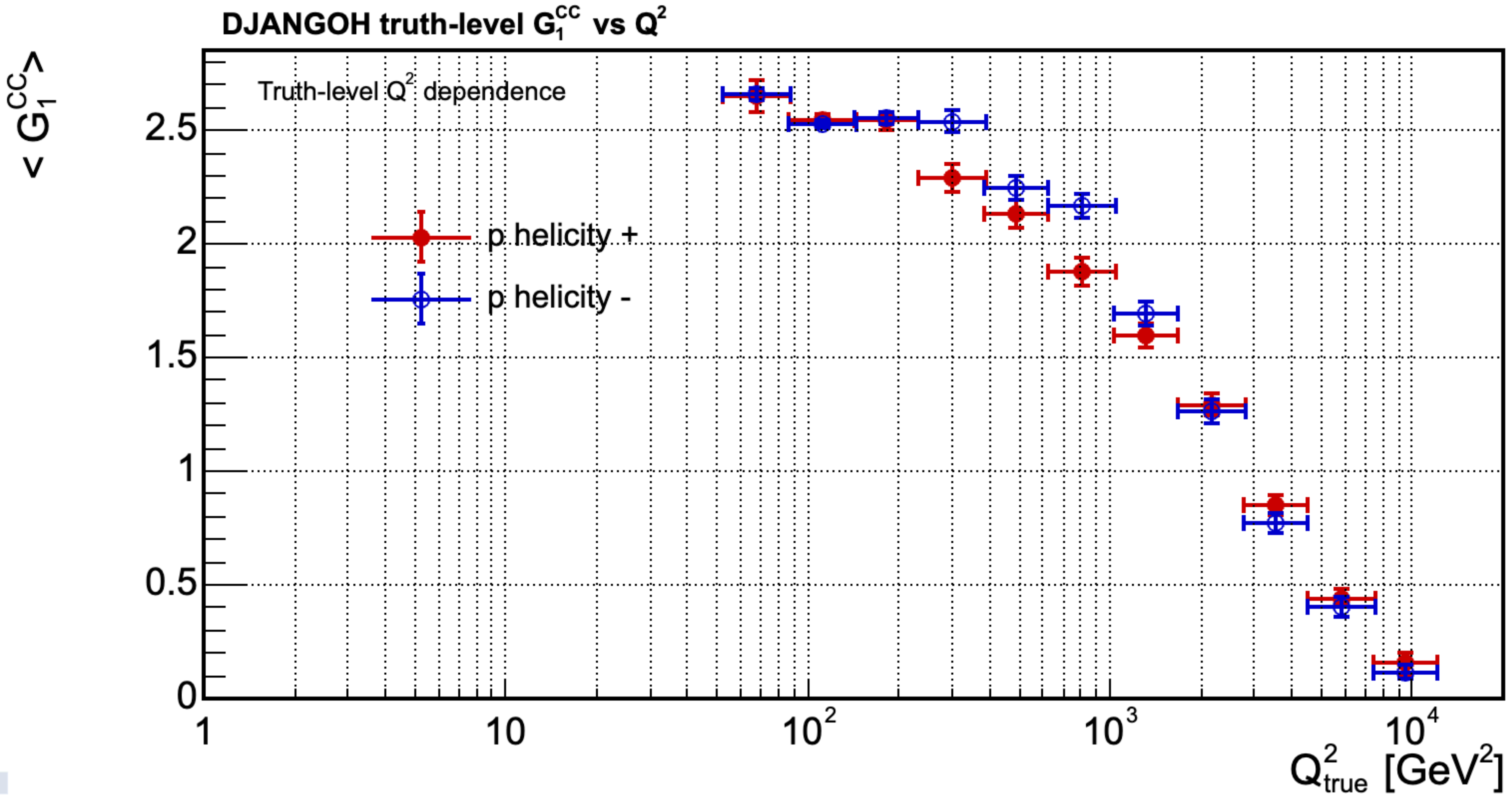
G_3^{CC} at the truth level

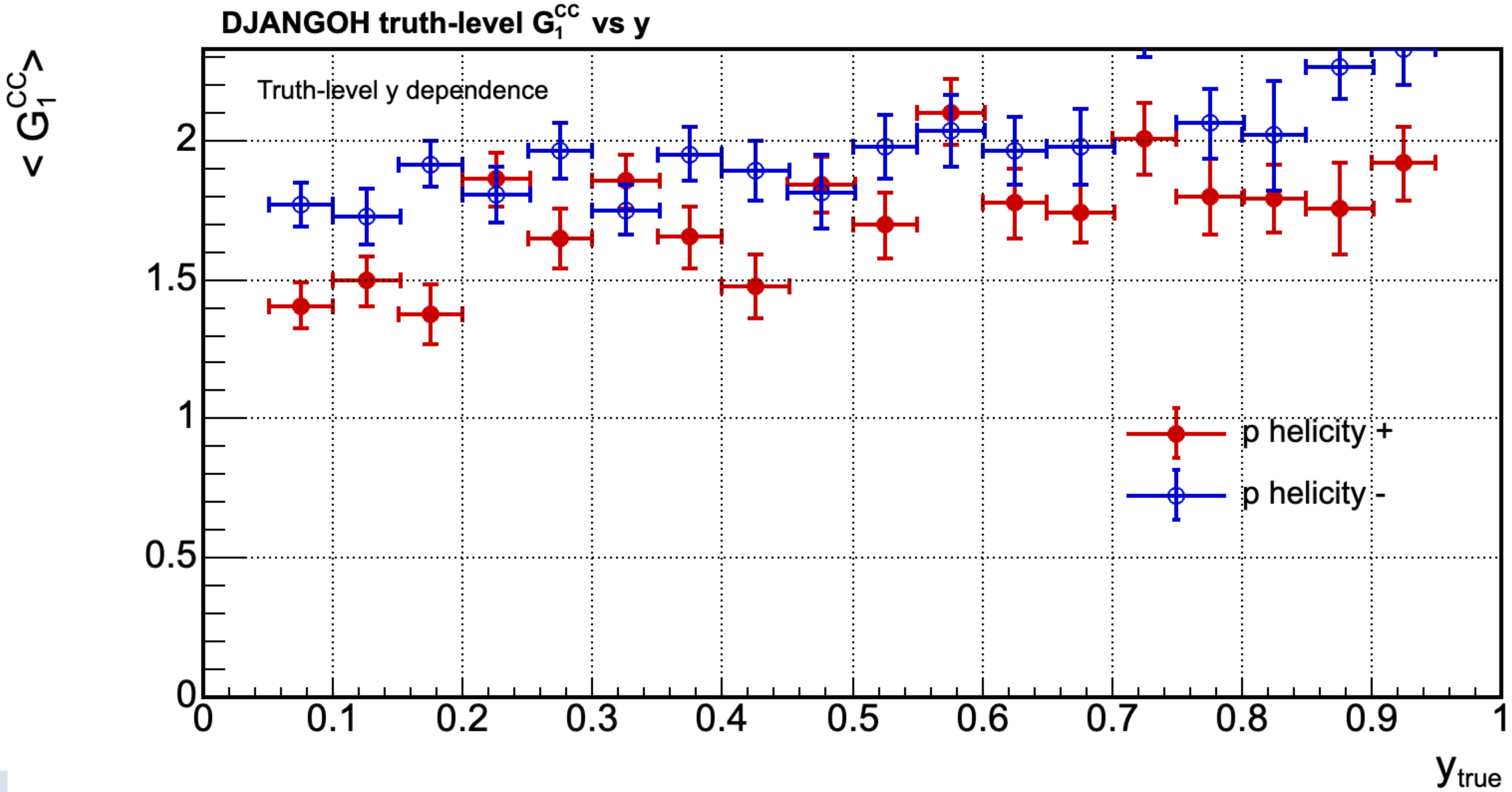


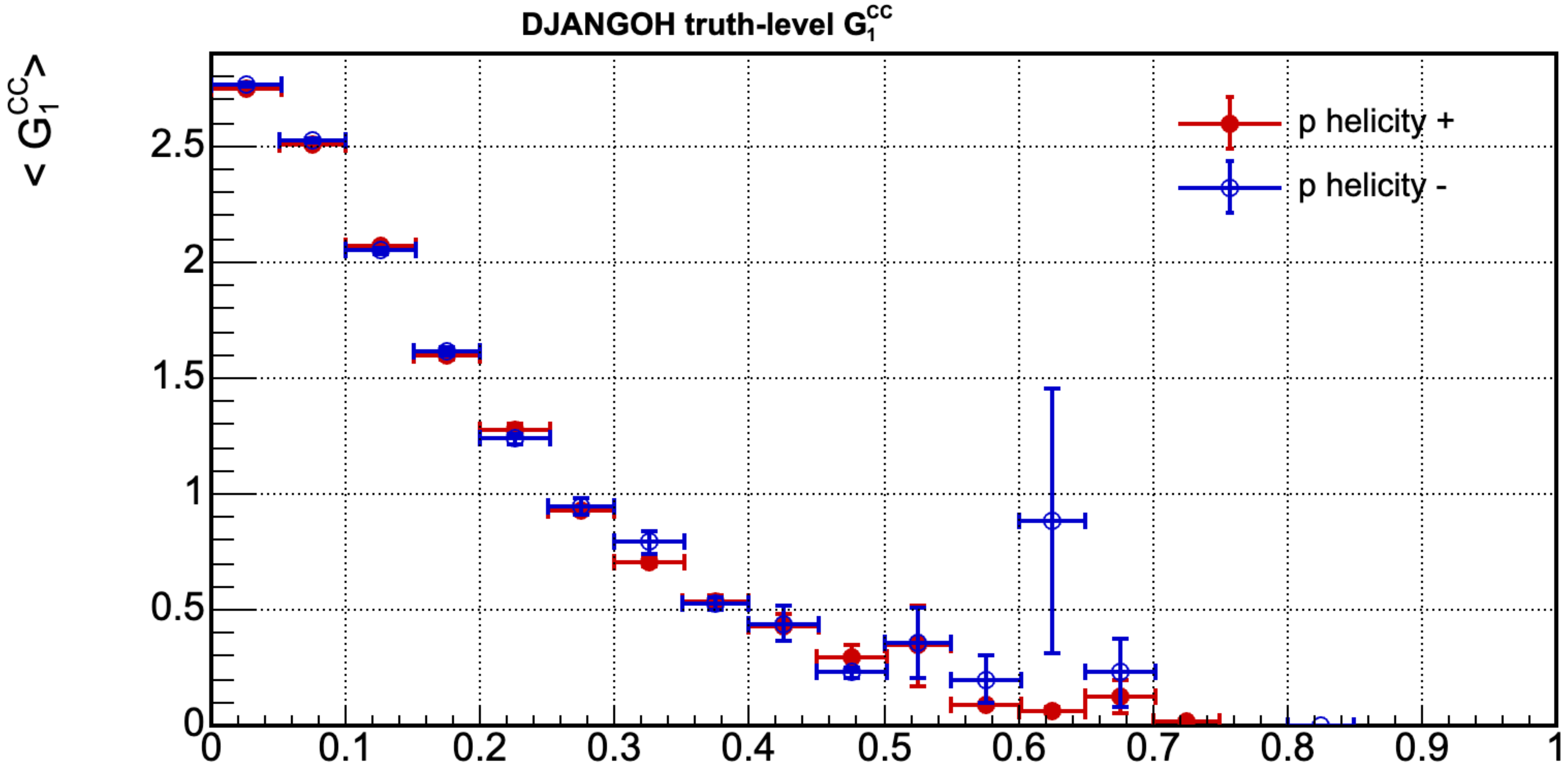




G_1^{CC} at the truth level





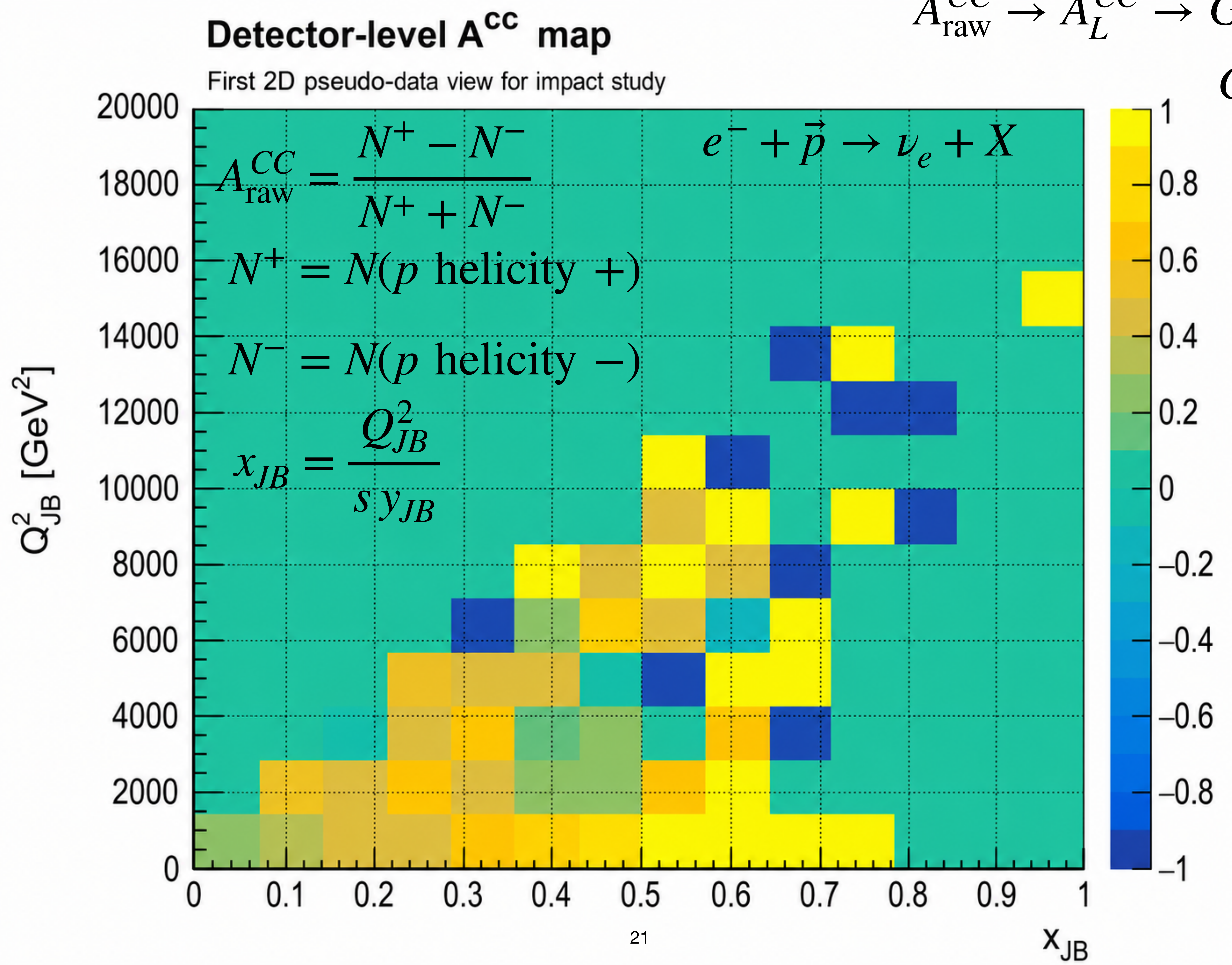


Detector level charged current spin-asymmetry map

$$A_{\text{raw}}^{CC} \to A_L^{CC} \to G_5^{CC} \to G_3^{CC}$$

$$G_3^{CC} = 2xG_5^{CC}$$

$$Q_{JB}^2 = \frac{p_{T,h}^2}{1 - y_{JB}}$$



$$A_{\text{raw}}^{CC} = \frac{N^+ - N^-}{N^+ + N^-}$$

$$e^- + \vec{p} \to \nu_e + X$$

$$N^+ = N(p \text{ helicity } +)$$

$$N^- = N(p \text{ helicity } -)$$

$$x_{JB} = \frac{Q_{JB}^2}{s\, y_{JB}}$$

Summary

- Generated Polarized charged current DIS sample with DJANGOH
- Reconstructed DIS kinematics using Jacquet-Blondel handronic method
- Formed detector level asymmetries for p+ and p- samples
- Need to understand hadnronic final state reconstruction methods
- Need to start looking pseudo-data from simulation campaigns for further study