J_Psi Analysis Note: Olaiya Olokunboyo

Working with lAger events generator by Joosten Sylvester.
Version 3.6.1 – v3.6.x Tweaked VMD formalism and better examples for DVMP at EIC.

lAger is a flexible MC generator system to simulate electro- and photo-production off nucleons and nuclei.
See the link here for installation instruction https://eicweb.phy.anl.gov/monte_carlo/lager
My work is with the eic 00mrads events, that is events without crossing angle.
The extension for the generator file is .json format with contents allowing for kinematics modifications.

The code to my analysis code can be found
https://github.com/eic/Glouns_DIstribution_From_J_Psi/blob/main/j_Psi_analysis.c

Learning to use the code

This lAger configuration file defines a Monte Carlo (MC) simulation for exclusive J/ψ production via virtual photon (VMP) at an Electron-Ion Collider (EIC)-like setup – hard scattering experiment known as deeply virtual meson production (DVMP). The lAger generator (short for "l/A event generator") is used for simulating lepton-nucleus/nucleon collisions.

Code	Explanations

{
"mc": {
}
}
	Main configuration for the Monte Carlo simulation

"type": "lager-vmp-00mrad", "tag": "disp-jpsi-00-electron", "run": "1", "lumi": "1", "info": "lumi in fb^-1", "output_hepmc": "true",	• **type**: The simulation configuration class; likely for VMP (Vector Meson Production) at 0 mrad (head-on collision). • **tag**: Identifier for this job (J/ψ displaced vertex, 0 mrad, electron beam). • **run**: Simulation run number. • **lumi**: Luminosity = 1 fb^{-1}. • **output_hepmc**: Save events in HepMC format.
"vertex": { "type": "origin" }	All events are generated with the primary vertex at the origin (0,0,0).

"beam": {
"lepton": {
"type": "constant",
	• Electron beam: 10 GeV, traveling in -z direction.

"particle_type": "e-",
"dir": ["0", "0", "-1"],
"energy": "10"
},
"ion": {
"type": "constant",
"particle_type": "proton",
"dir": ["0", "0", "1"],
"energy": "100"
}
}
	• Proton beam: 100 GeV, traveling in +z direction.
	
	• These are head-on beam configurations for EIC

"target": { "type": "primary" }	Interaction occurs with the primary beam particle (the proton).

"photon": {
"type": "vphoton",
"y_range": ["0.001", "1"],
"Q2_range": ["1e-12", "10000"]
}
	• Photon is virtual (from the electron).
	
	• Inelasticity y ranges from 0.001 to 1.
	
	• Virtuality Q^2 from ≈0 (almost photoproduction) to 10^4 GeV^2.

"process_0": {
"type": "oleksii_2vmp",
"info": "Formalism from Phys. Rev. D 94, 074001 (2016)",
"vm_type": "J/psi",
"T0": "0.0",
"R_vm_c": "2.164",
"R_vm_n": "2.131",
"dipole_n": "2.575"
}
	• This simulates exclusive J/ψ production using the "Oleksii 2VMP" model based on:
	
	Phys. Rev. D 94, 074001 (2016) — *Zhalov, Martynov, and Cisek.*
	
	• Parameters control the transverse profile and dipole amplitude used in the amplitude calculation:
	
	• R_vm_c / R_vm_n: Charm/neutron vector meson radii.
	• dipole_n: Dipole model parameter.
	• T0: Minimum momentum transfer.

"detector": { "type": "4pi" }	Idealized full-acceptance (4π) detector — no acceptance loss.

"decay": {
"vm_decay_lepton_type": "11",
"vm_branching_ratio": "0.05971",
"do_radiative_decay_vm": "true"
}
	• Vector meson decay into leptons (type 11 = electron).
	
	• Branching ratio for J/ψ→e+e- is 5.971%**.**
	
	• Radiative decays (like J/ψ→e+e−γ) are enabled.

We can stream event by

xrdfs root://dtn-eic.jlab.org ls /volatile/eic/EPIC/RECO/25.04.1/epic_craterlake/EXCLUSIVE/DIFFRACTIVE_JPSI_ABCONV/lAger3.6.1-1.0/10x100/hiAcc | sed ‘s|^|root://dtn-eic.jlab.org/|g’ > April_2025_1.list

The .list file is the input file into the analysis code - in the .list file, all events to be streamed are automatically written with the prefix root://dtn-eic.jlab.org need for streaming.

10x100 Analysis info

Events are generated with:

- Luminosity: 10 fb^{-1}
- Electron beam energy: 10 GeV
- Proton beam energy: 100 GeV
- Electron moves from the right the left (-z azis)
- Proton moves from the left to the right (+z azis)
- Inelasticity y: 0.001 to 1
- Virtuality Q^2: 1 to 10 GeV^2
- Radiative effect is turned on/

Considering different ranges of the kinematic y and Q^2

Some kinematic expressions

$Q^2 = 4EE' \sin^2(\theta/2)$

$t = (p - p')^2$

See ePIC_DVCS_EvVar.pdf other kinematic expressions. What characterizes DIS is the kinematics.

All MC and RECO must satisfy these conditions first 0.1 < y < 1 and 1< Q^2< 10

The final proton is rotated 25 mrads from the MC and RECO - the crossing angle since EIC events in lab frame are taken at an angle.

Viewing the hepmc file for the generation of the events

```
E 0 4 10
U GEV CM
P 1 0 11 0.0000000000000000e+00 0.0000000000000000e+00 -9.9999999869440011e+00 1.0000000000000000e+01 5.1099900095068825e-04 4
P 2 1 22 7.1333120412188100e-01 4.4987977284199920e-01 -5.6716786731383557e+00 5.5902835836022859e+00 -1.2758924888193302e+00 13
P 3 1 11 -7.1333120412188100e-01 -4.4987977284199920e-01 -4.3283213138056453e+00 4.4097164163977141e+00 5.1060447580408949e-04 1
P 4 0 2212 0.0000000000000000e+00 0.0000000000000000e+00 9.9995598130449537e+01 1.0000000000000000e+02 9.3827209999963668e-01 4
P 5 4 2212 0.0000000000000000e+00 0.0000000000000000e+00 9.9995598130548785e+01 1.0000000000009925e+02 9.3827210000060601e-01 2
V -3 0 [2,5]
P 6 -3 443 1.2926203071155984e+00 4.6861094404528986e-01 -5.1203225407371065e+00 6.1399263809726108e+00 3.0968580153659424e+00 2
P 7 -3 2212 -5.7928910296462122e-01 -1.8731171184941206e-02 9.9444242002121030e+01 9.9450357207159584e+01 9.3827209999963668e-01 1
P 8 6 -11 2.1444125712119213e+00 1.1598531762796790e-01 -2.5314681278311171e+00 3.3196820650209480e+00 5.1099900268880994e-04 1
P 9 6 11 -9.5480715207710576e-01 3.0062532771266198e-01 -2.3727005258228031e+00 2.5752165601517327e+00 5.1099899921256667e-04 1
P 10 6 22 1.0301488798048174e-01 5.2000298704550516e-02 -2.1615388708199074e-01 2.4502775579849659e-01 0.0000000000000000e+00 1
```

Particle pdgpid

Electron : 11

Proton: 2212

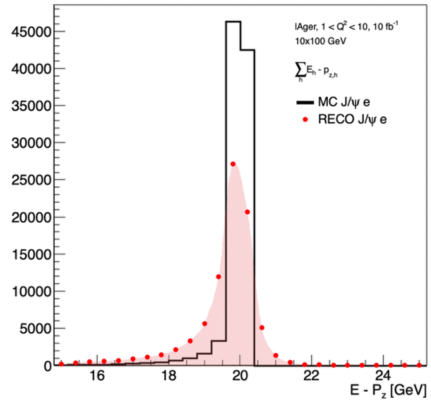
Positron: -11

Photon: 22

$J/\psi(1s)$: 443

See http://pdg.ge.infn.it/2020/reviews/rpp2020-rev-monte-carlo-numbering.pdf for more.

Although not applied as compulsory I considered the Hadronic Final State sum peaking at $2 \times E_{beam}^{incoming}$ as in;



The longitudinal momentum of the scattered electrons must always be less than the longitudinal momentum of scattered electrons. The is the part of the initial conditions together with y and Q^2 .

The Ttree branch for MC data use is `MCParticles`
Events from MC are straight forward to read.

Roman Pot Events Selection Summary in the Far-Forward

The Ttree branch for the RP events taken from `ForwardRomanPotRecParticles`

The pseudorapidity range of RP is from $\eta > 6$. The event selection process here focuses on identifying valid proton candidates in the Roman Pot (RP) detector and computing the four-momentum transfer t using Proton Recoil Method $t = (p - p')^2$.

1. Each iteration processes one RP track, reconstructing its 4-momentum
2. Charge = +1
3. PDG ID = 2212 (proton)
4. Transverse momentum cut: $p_T \geq 0.2$ GeV

For the selected event in RP

- Reconstruct proton with mass (more accurate 4-vector)
- Fill various histogram and map occupancy
- Set flag indicating events section needed for exclusivity

With the selected proton, compute t using:

- Proton Recoil Method $t = (p - p')^2$
- Correct for the acceptance using $correction\ factor, c_f = t_{MC}/t_{acc}$, where acc means acceptance

Scattered Proton Detection in the B0 Detector in the Far-Forward

The Ttree events are taken from `ReconstructedTruthSeededChargedParticle`

These processes reconstructed tracks from the B0 tracker using ACTS. It iterates over all available tracks, extracting their momentum and energy to build a four-momentum vector. The main goal is to identify forward-going proton that scattered into the B0.

The selection process focuses on identifying charged, forward-moving tracks that are also classified as neutral in terms of their PDG code. Only those with pseudorapidity above 4.6 and positive charge are considered. Once a track passes this selection, its four-vector is reconstructed using its mass and rotated slightly by 25 mrads to account for the beam crossing angle.

For each accepted track, various histograms are filled to store kinematic quantities such as pseudorapidity, transverse momentum, momentum components, and energy. These are useful for analyzing the B0 detector performance and tracking quality.

- A flag is set to indicate a successful proton identification in the B0 system needed for exclusivity.

I perform calculations to estimate the four-momentum transfer t using the proton recoil method. An acceptance-corrected method is applied first using a reference vector. If this calculation returns a nonzero result, additional methods are used: one combining RP and B0 information. The resulting t values are stored in histograms for further analysis.

Finally, relative differences between the reconstructed and true t values are computed to assess the reconstruction accuracy, and a 2D histogram is populated to compare true versus B0-derived t. This segment of the code plays a key role in evaluating the kinematic reconstruction capability of the B0 tracking system.

NB: There is a gap between the B0 and RP not covered by any detector. Note that the magnetic aperture is about 1.3 GeV which means (1.3 GeV / 100 GeV = 13 mrads) a value greater than the scope of RP requiring the need look inside the B0 detector.

My kinematic reconstructions are compared with that of the inclusive kinematics, which are read directly from the Ttree branches.

For electrons Scattering into the Backward Direction EndCaps

Here I identify and analyze the highest-energy EM calorimeter (ECAL) cluster from a set of reconstructed clusters in an event in the EMEndCaps.

Looping over all ECAL clusters, updating the tracked values whenever a cluster with higher energy is found. Once the highest-energy cluster is identified, I compute its position and angle (polar angle θ) based on its spatial coordinates. From this, we can calculate the pseudorapidity and fills a histogram for later analysis.

After that, I compute the squared momentum transfer Q^2 using the polar angle and the energy of the highest-energy cluster (interpreted as the scattered electron).

Now to Electron Selection Procedure

This selection needs at least 3 tracks, here are procedures adopted. Events are taken from Ttree branch `ReconstructedTruthSeededChargedParticles`

- Track Multiplicity Check**:** Only consider events with exactly three reconstructed tracks**.**
- Charge Identification**:**
  - Identify two negative tracks (charge = -1) – one electron from the J/ψ daughter decay and the other will be the scattered electron.
  - Identify one positive track (charge = +1) – this is the positron from the J/ψ daughter decay.
  - Continue only if the charge configuration is valid (2 negative, 1 positive).
- Lorentz Vector Construction: Create 4-momentum vectors for the two electron tracks and the positron track.
- It is important to distinguish between electrons, Scattered Electron Identification:
  - Among the two electron tracks, the one with lower longitudinal momentum (P_z) is assumed to be the scattered electron e'.
  - The other electron track is considered J/ψ decay daughter electron.
  - If P_z values for both electrons are equal (undetermined case), the event is skipped.
- Inelasticity y Cut replicated as used in MC:
  - Compute inelasticity between the beam and the difference of the beam and scattered electron.
  - Accept the event only if y falls within the range (0.1, 1.0) and the scattered electron has lower P_z than the other electron track.
- Other Kinematics and Histograms Filling:
  - Store the selected scattered electron and decay product vectors.
  - Compute and fill histograms for:
    - Inelasticity of reconstructed electrons.
    - Inelasticity variables (e.g., $y_{JB}, y_{e\Sigma}, x_{JB}$).
    - Pseudorapidity of the scattered electron.
    - Reconstructed J/ψ mass from decay products.
    - Compute the modified Bjorken x variable based on acceptance.

This selection aims to adequately identify the scattered electron in J/ψ events and compute associated physics observables.

Exclusivity Condition

Exclusive condition is applied only on *t-distribution*. That is, we much have 3 tracks from the electron selection procedure and a scattered proton from the Roman Pot or B0 detector. Remember I used flag earlier, here is the reason for the it.
The *t-distribution* is being corrected by acceptance by using c_f defined earlier.

This distribution is in counts, hence we need to have it in differential cross section, this is done using

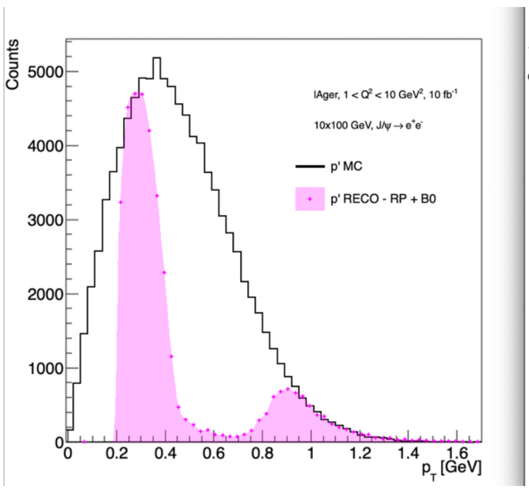
$$\frac{d\sigma}{dt} = \frac{1}{\Delta t \cdot \mathcal{L}} \cdot \frac{N}{E_{ff} \cdot A}$$

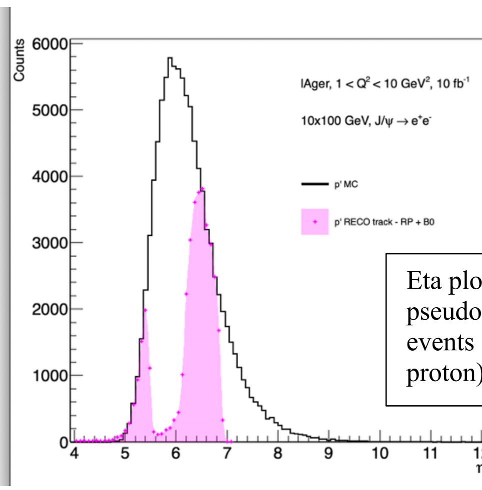
In this, E_{ff} is the efficiency is the detector, taken as 1. A is the acceptance, and N is the number of events, and L is the luminosity.
In my work, I assume Poisson error progression throughout and this is given as

$$\Delta\left(\frac{d\sigma}{dt}\right) = \frac{\sqrt(N)}{\mathcal{L} \cdot \Delta t}$$

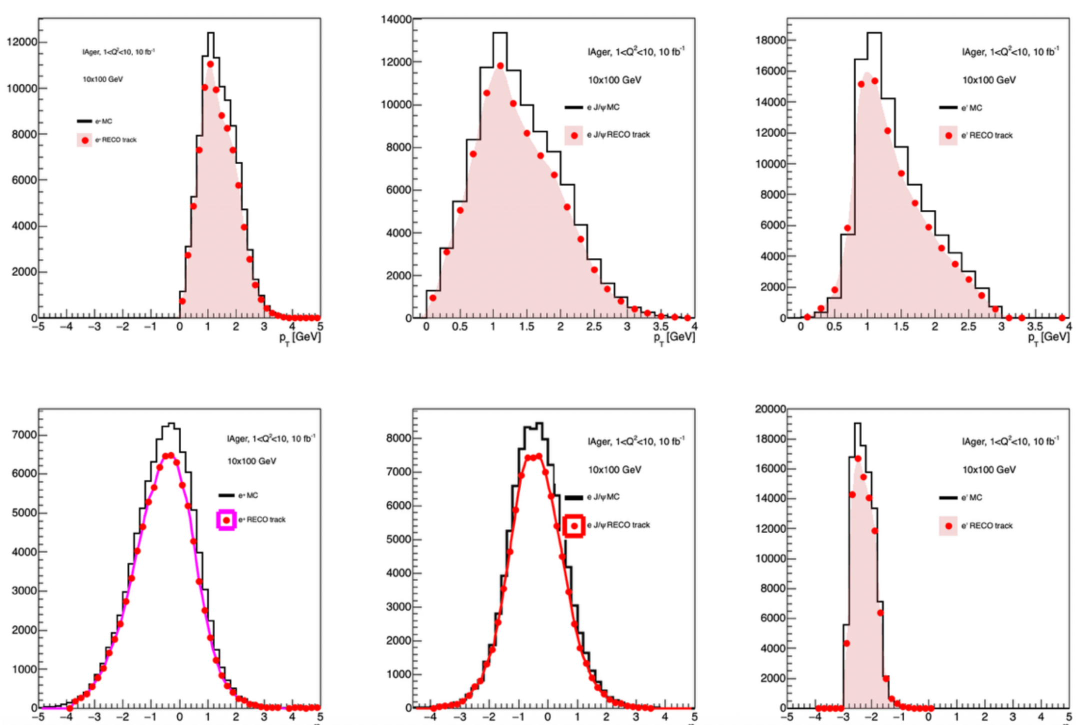
More analysis plots can be found here: Presentation1.pptx

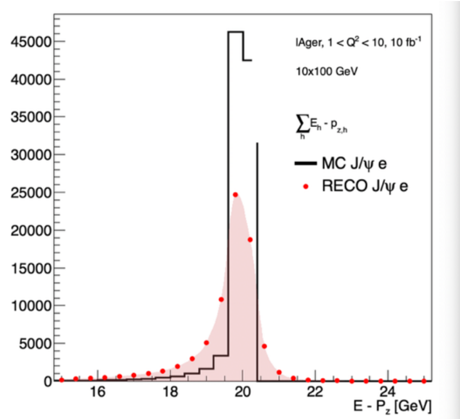
Some Results using Feb_2025_campaign Data for 10x100 energy configuration:

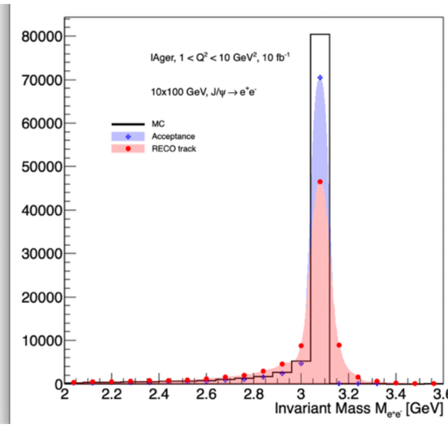


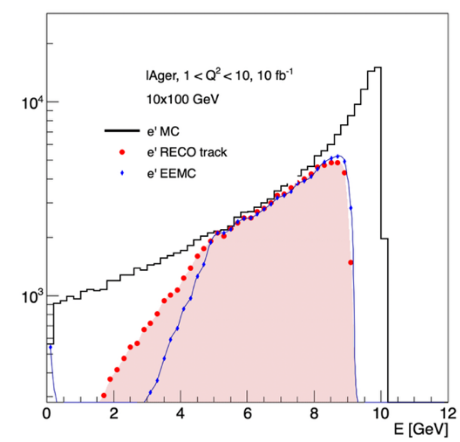


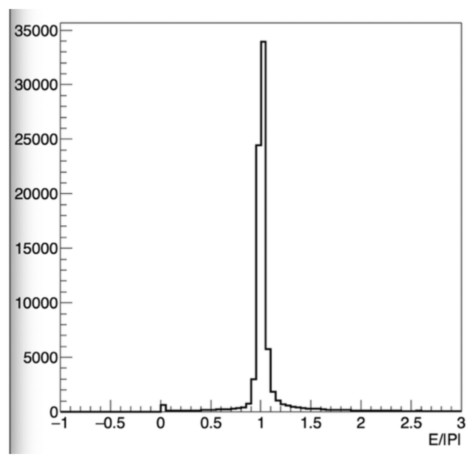
Eta plot to assess the pseudorapidity where events are capture (here the proton)

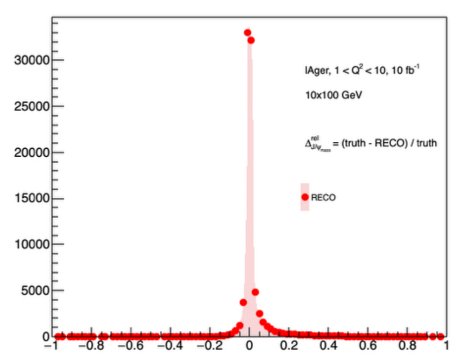


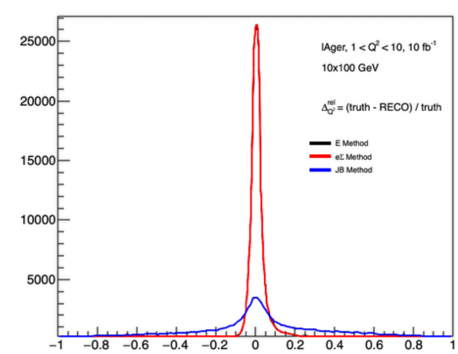

IAger, 1 < Q² < 10, 10 fb⁻¹
10x100 GeV
∑ E_h - p_z,h
MC J/ψ e
RECO J/ψ e
E - P_z [GeV]

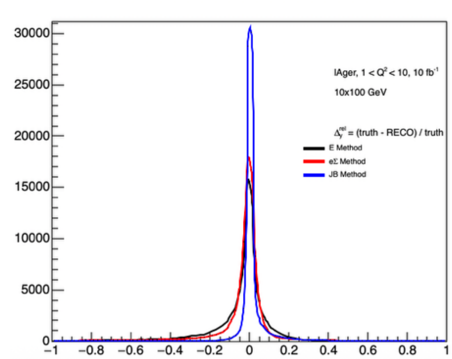

IAger, 1 < Q² < 10 GeV², 10 fb⁻¹
10x100 GeV, J/ψ → e⁺e⁻
MC
Acceptance
RECO track
Invariant Mass M_e⁺e⁻ [GeV]

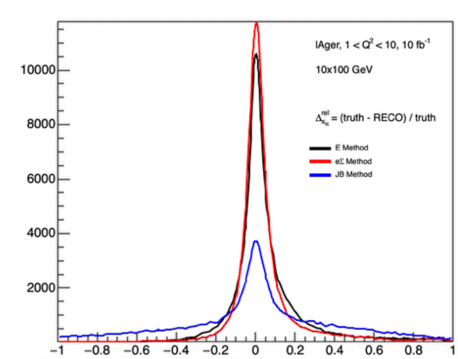

IAger, 1 < Q² < 10, 10 fb⁻¹
10x100 GeV
e' MC
e' RECO track
e' EEMC
E [GeV]

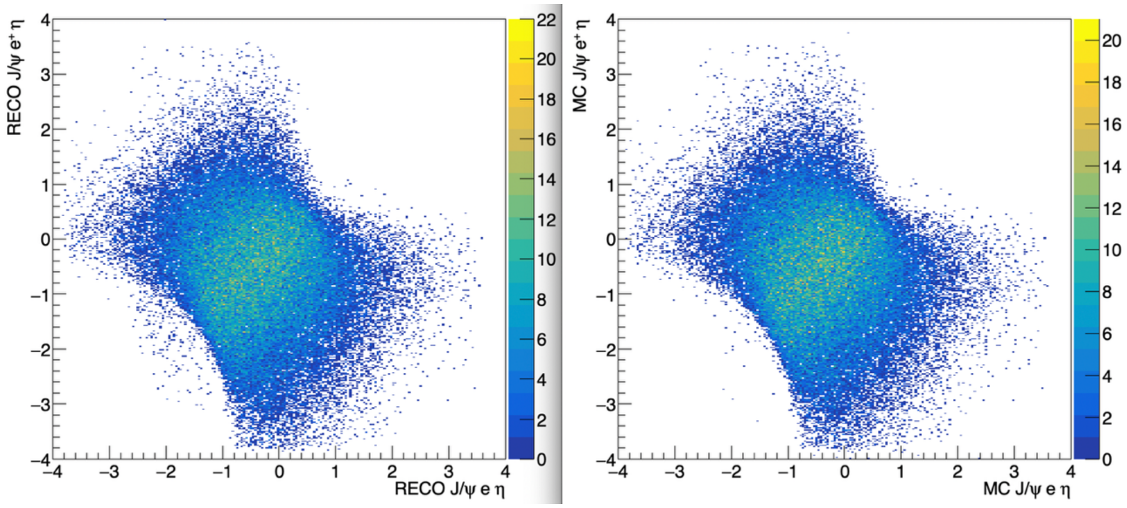

E/|P|

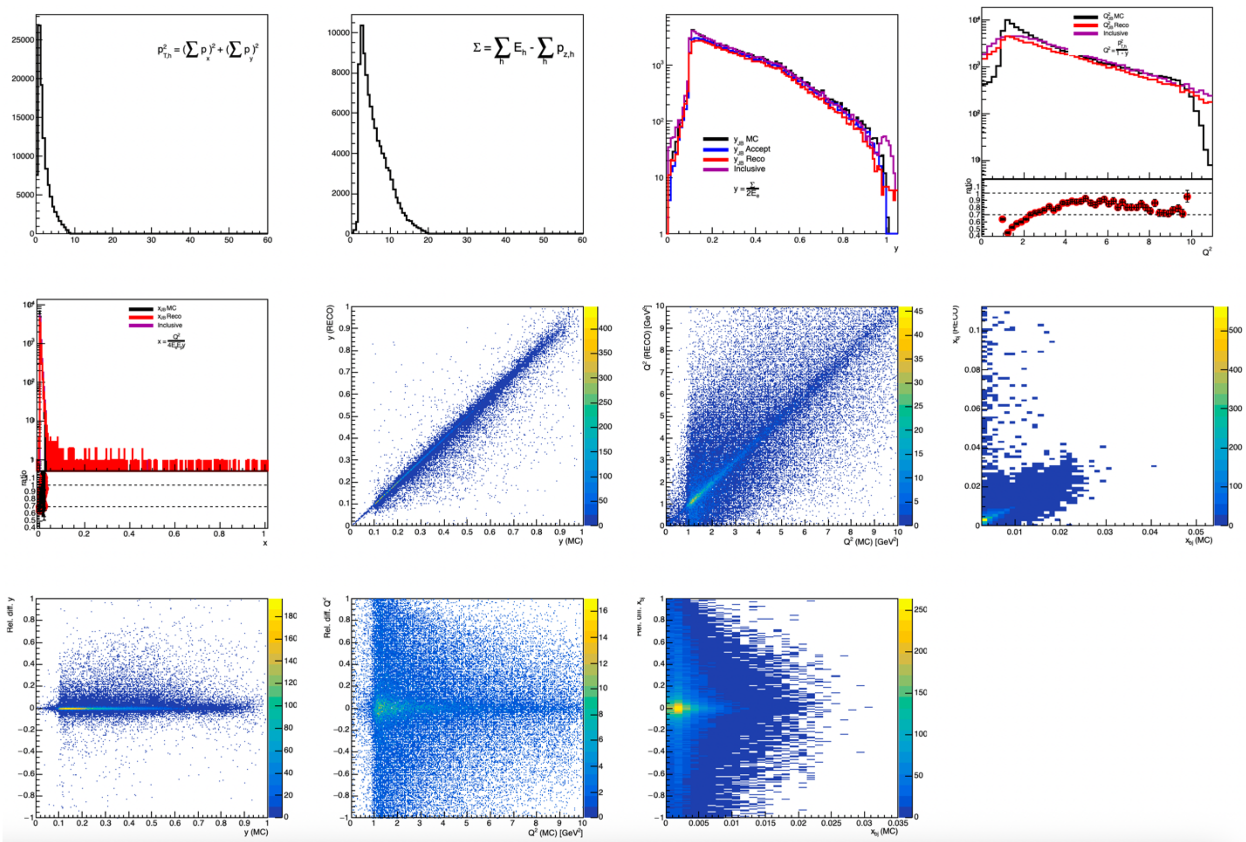

IAger, 1 < Q² < 10, 10 fb⁻¹
10x100 GeV
= (truth - RECO) / truth
RECO

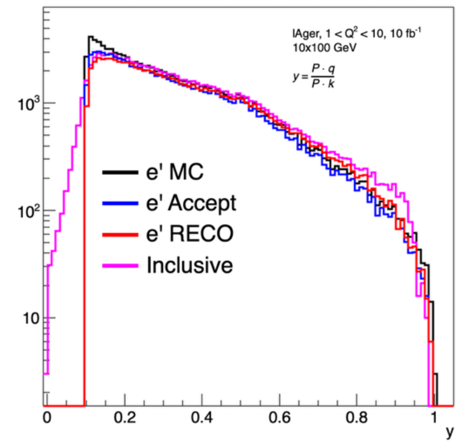

IAger, 1 < Q² < 10, 10 fb⁻¹
10x100 GeV
Δ^rel_Q² = (truth - RECO) / truth
E Method
eΣ Method
JB Method

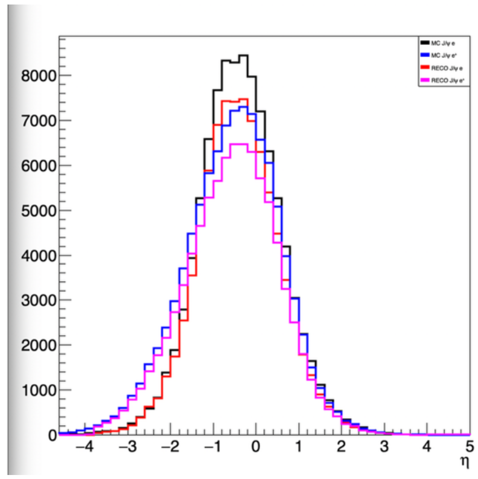

IAger, 1 < Q² < 10, 10 fb⁻¹
10x100 GeV
Δ^rel_y = (truth - RECO) / truth
E Method
eΣ Method
JB Method

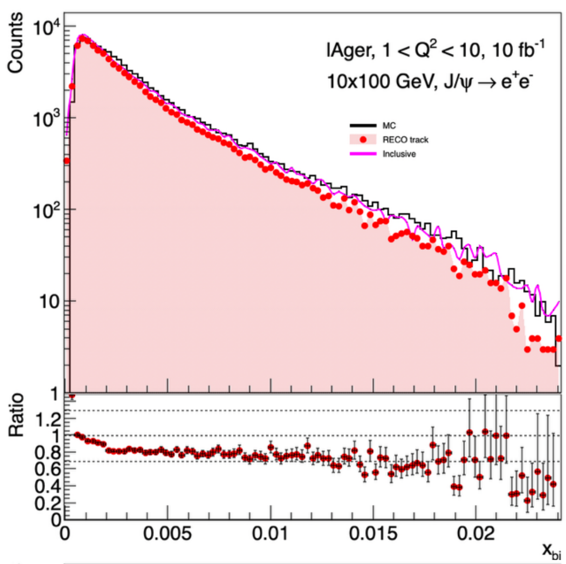

IAger, 1 < Q² < 10, 10 fb⁻¹
10x100 GeV
= (truth - RECO) / truth
E Method
eΣ Method
JB Method

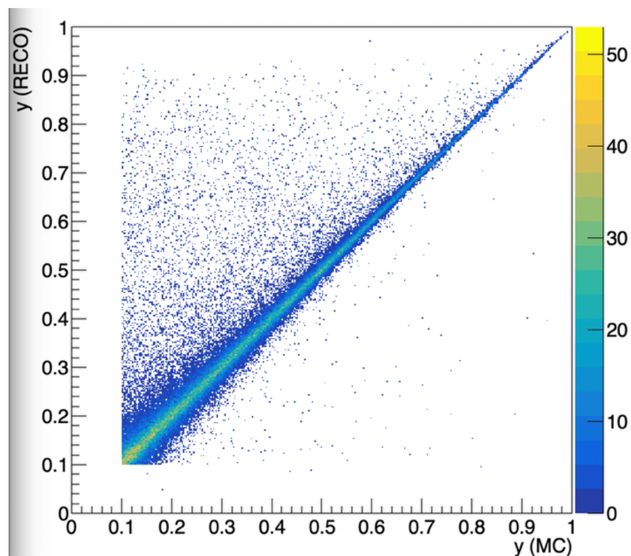

RECO J/ψ e⁺ η
RECO J/ψ e η
MC J/ψ e⁺ η
MC J/ψ e η

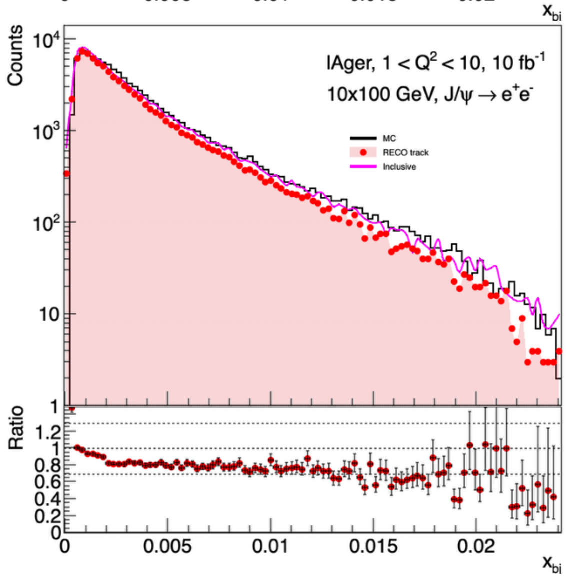

y (RECO)
y (MC)
Q² (RECO) [GeV²]
Q² (MC) [GeV²]
Rel. diff. y
Rel. diff. Q²
Q²

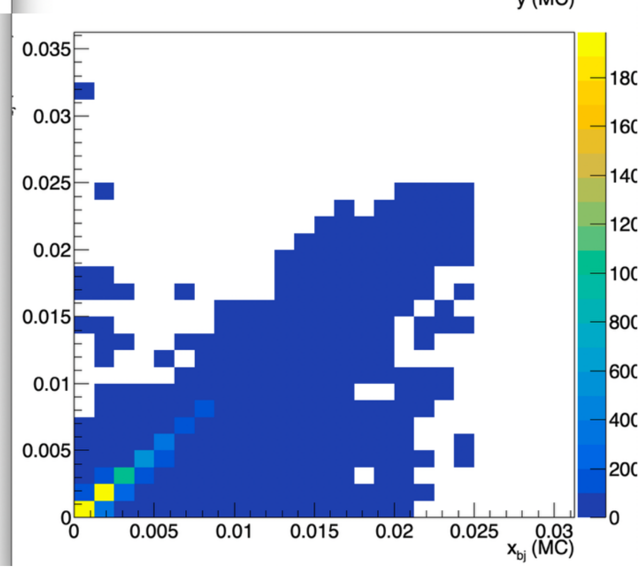

lAger, $1 < Q^2 < 10$, 10 fb^{-1}
10x100 GeV
$y = \frac{P \cdot q}{P \cdot k}$
e' MC
e' Accept
e' RECO
Inclusive
y

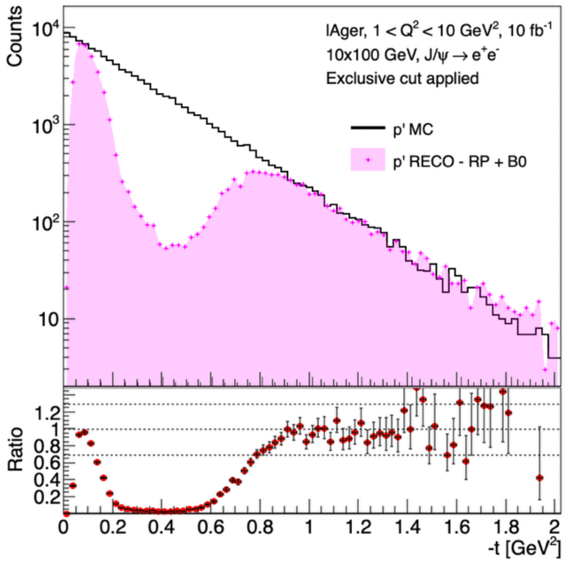
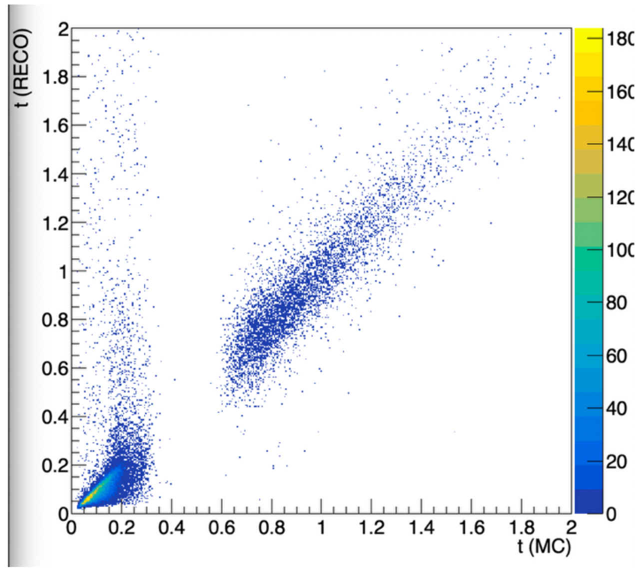
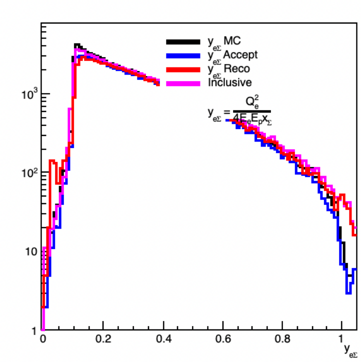
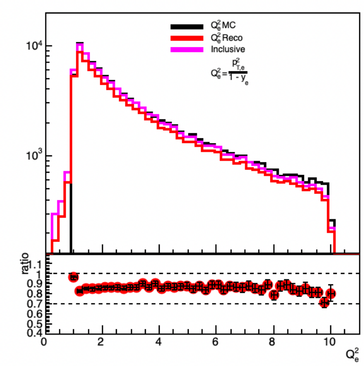
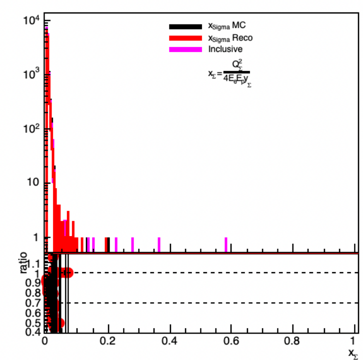
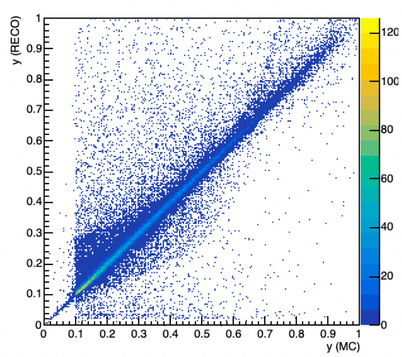
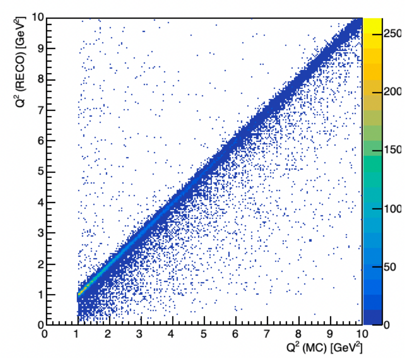
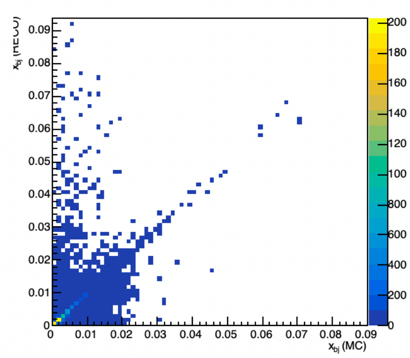
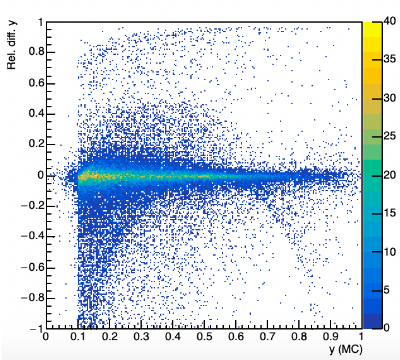
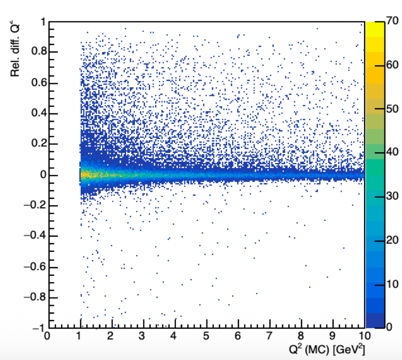
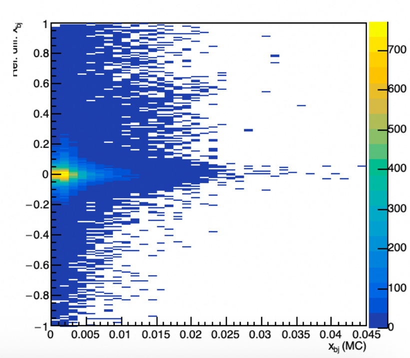

η

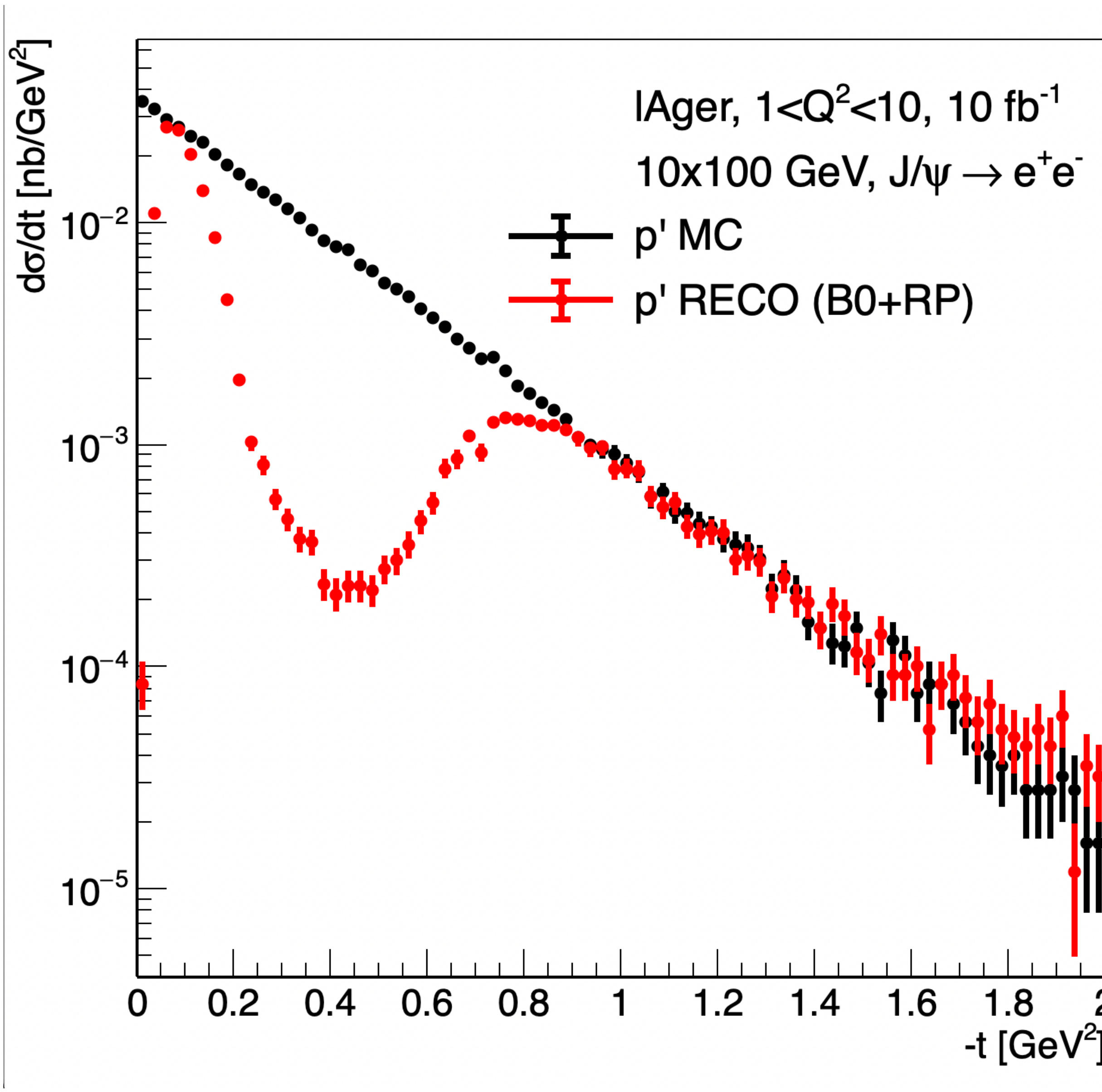

Counts
lAger, $1 < Q^2 < 10$, 10 fb^{-1}
10x100 GeV, $J/\psi \to e^+e^-$
MC
RECO track
Inclusive
Ratio
x_{bj}


y (RECO)
y (MC)


Counts
lAger, $1 < Q^2 < 10$, 10 fb^{-1}
10x100 GeV, $J/\psi \to e^+e^-$
MC
RECO track
Inclusive
Ratio
x_{bj}


x_{bj} (MC)


lAger, $1 < Q^2 < 10$ GeV^2, 10 fb^{-1}
10x100 GeV, $J/\psi \to e^+e^-$
Exclusive cut applied
p' MC
p' RECO - RP + B0
Counts
Ratio
-t [GeV^2]

t (RECO)
t (MC)










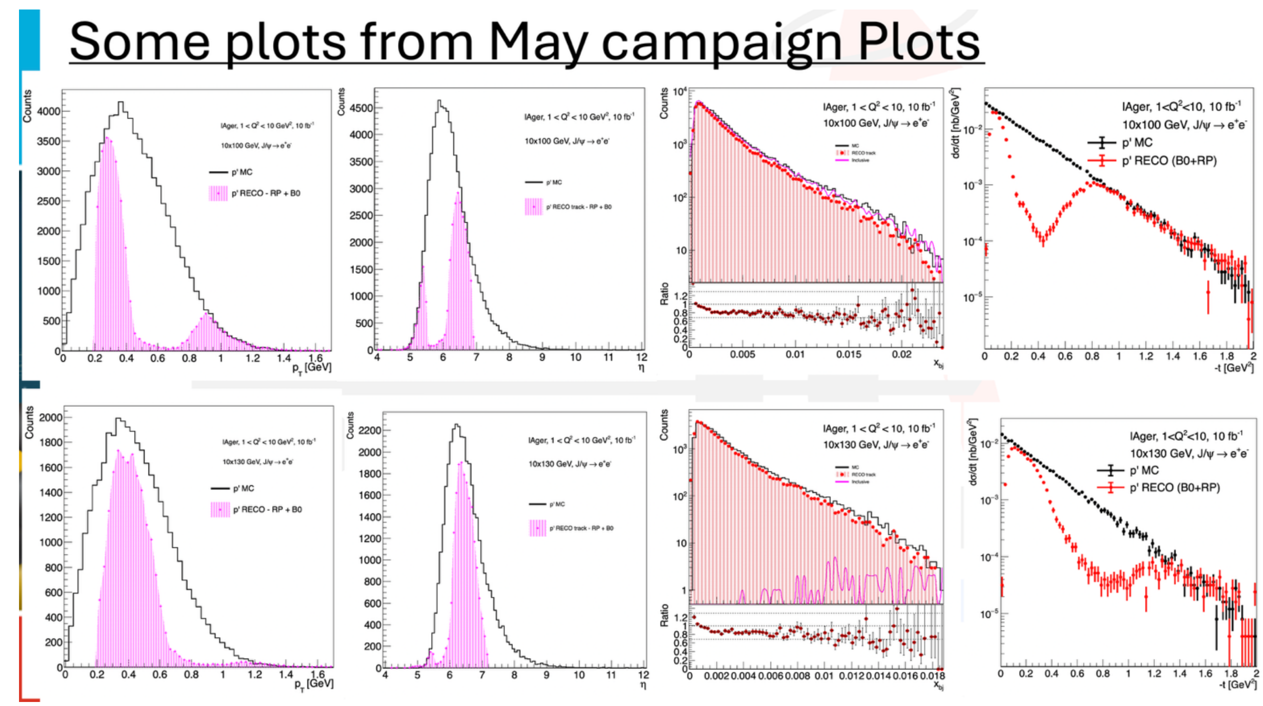


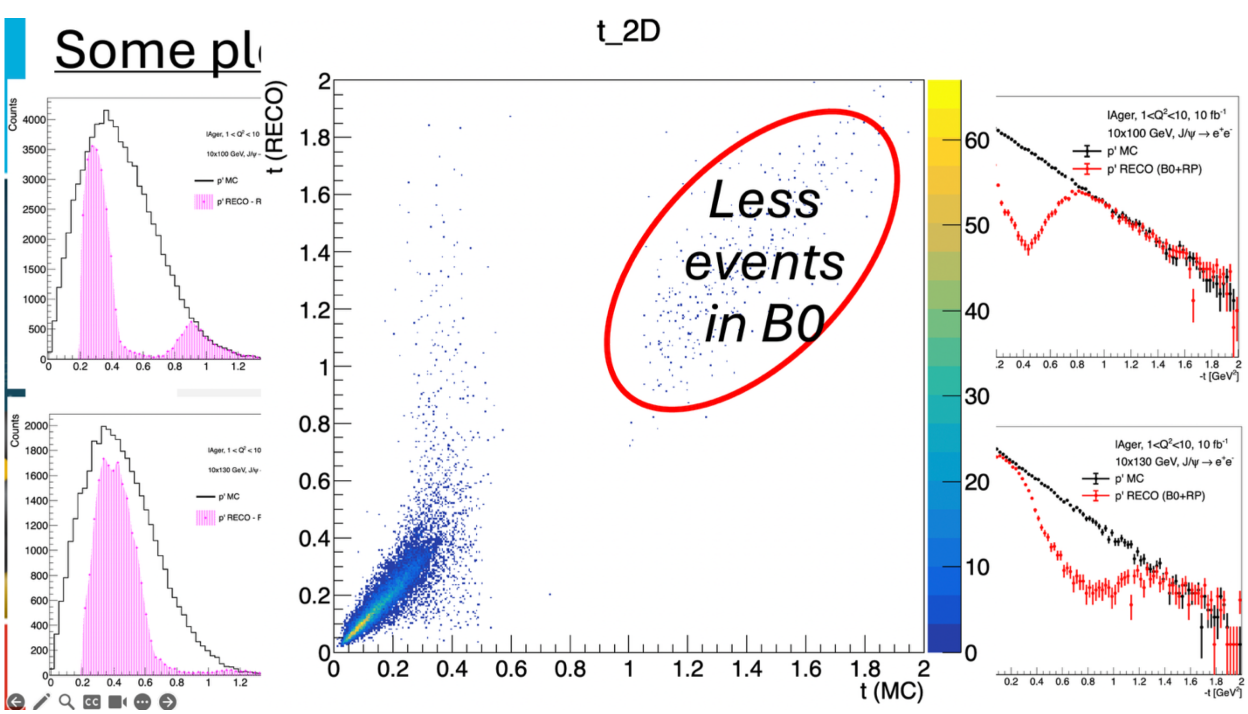
lAger, 1<Q²<10, 10 fb⁻¹
10x100 GeV, J/ψ → e⁺e⁻
p' MC
p' RECO (B0+RP)
dσ/dt [nb/GeV²]
-t [GeV²]
10⁻²
10⁻³
10⁻⁴
10⁻⁵
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

Using this for 10x130 energy configuration on May 2025 campaign

From this campaign 2 distinct properties stand out:

1. the inclusive data for xbj seems off – see the attachment
2. the B0 events captured are small – see the attachment



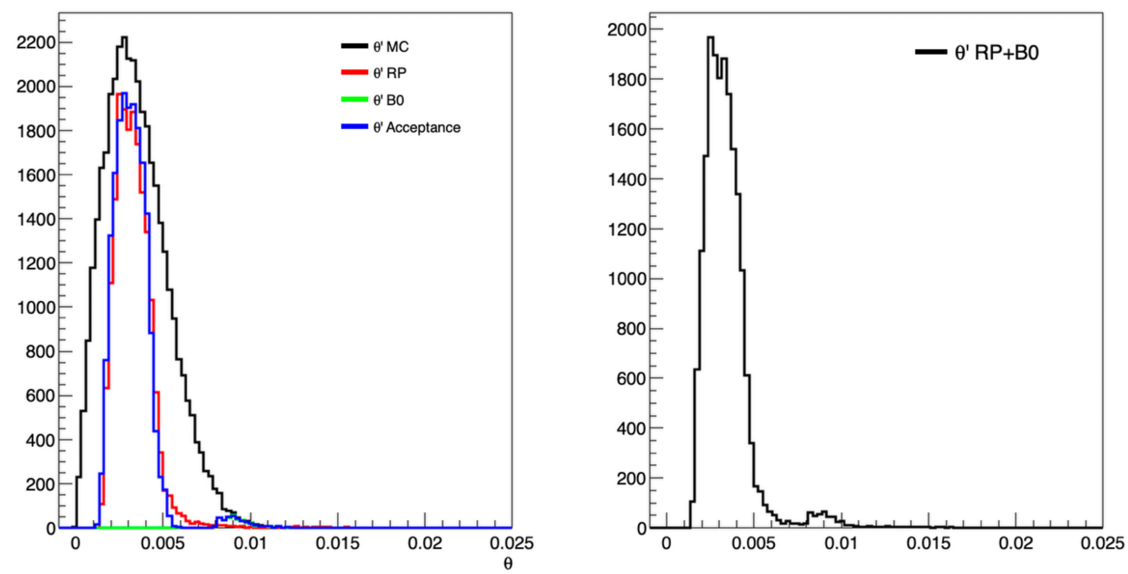


Some explanations of this feature:
For 10x130 it's not too surprising that there are few events in the B0. We shift the B0 protons to higher pT, so some will be outside the B0 acceptance entirely, and the ~130 GeV momentum will further stress the tracking method (worse resolution).

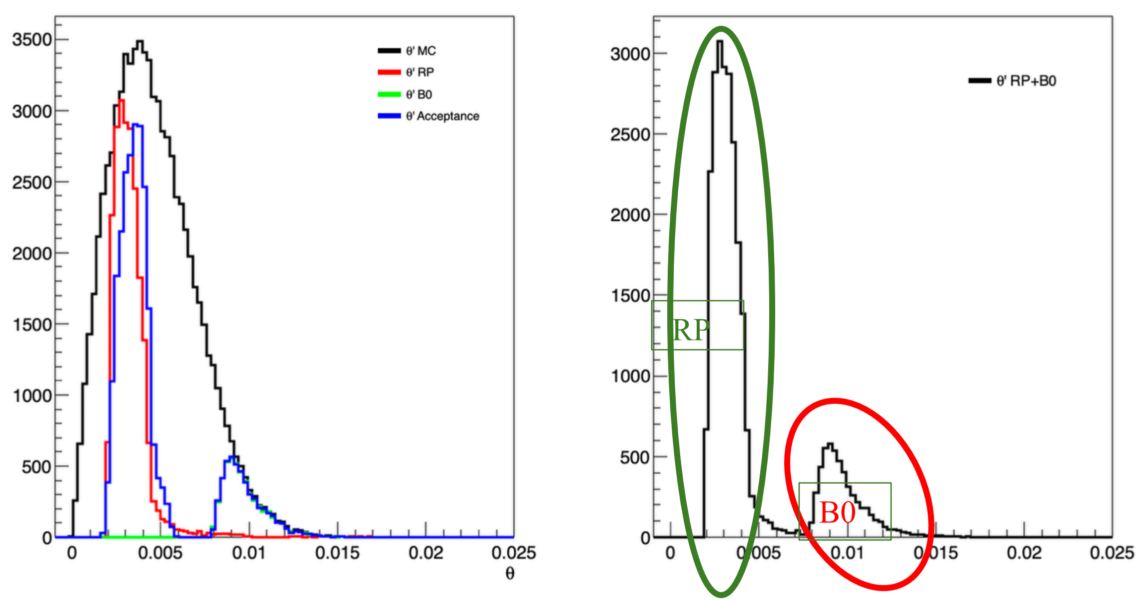
It would be interesting to see the "acceptance only" plots in terms of theta for all protons (RP + B0) to remove the smearing component

Here are the Theta Plots

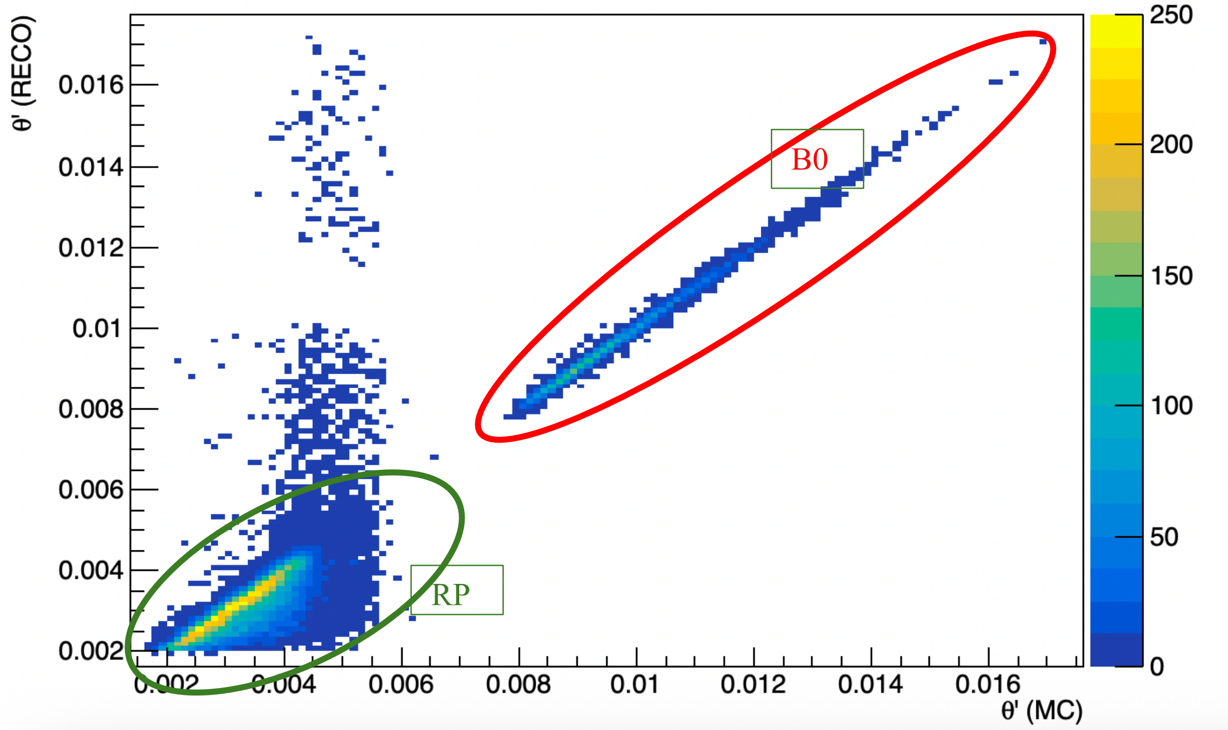
For 10x130



For 10x100



2D plot of RECO theta vs MC theta



Fourier Transform

Performing Fourier transform of a transfer momentum distribution ($d\sigma/dt$), we often transform from momentum space t to impact parameter space b_T(transverse spatial separation).

$$\tilde{f}(b_T) = \frac{1}{(2\pi)^4}\int d^4t\ e^{it\cdot b_T} f(t)$$

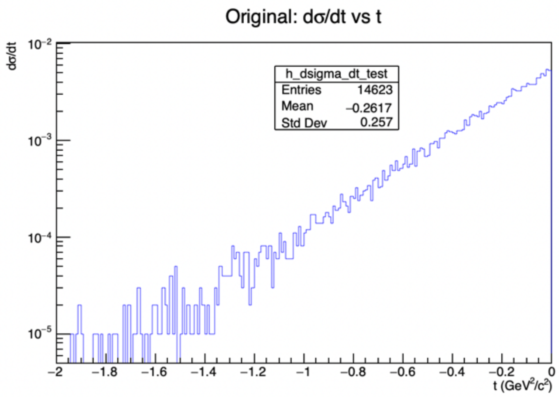
Numerical approach:

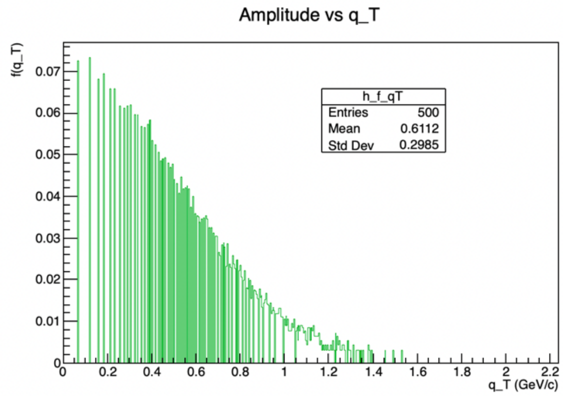
- we have the histogram $f(t)$ – which is the t-distribution
- we assume a 2D transform under radial symmetry with the Zeroth-order Bessel function of the first kind

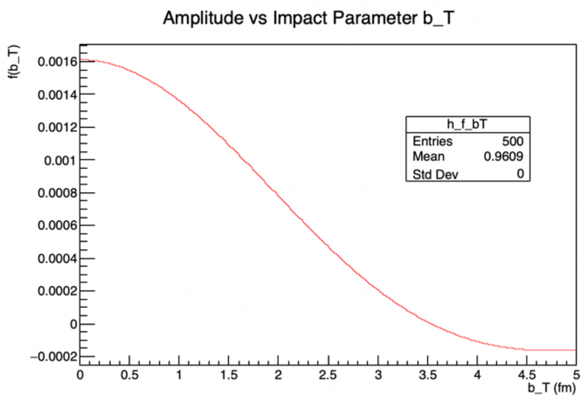
$$\tilde{f}(b_T) = \frac{1}{2\pi}\int_0^\infty t\ d^2t\ J_0(t, b_T) f(t)$$

- choose a range for b_T to evaluate
- using Simpson's rule

Firsthand Fourier transform results for MC







Firsthand Fourier transform results for RECO