UNIVERSITY OF BIRMINGHAM | SCHOOL OF PHYSICS AND ASTRONOMY

QED Radiative Effects

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Overview

- Inclusive Pythia8 simulations ran in campaigns do not include QED radiative effects
  - Measured xsec (with radiative effects) is different to Born xsec → corrected either by calculating and applying post-hoc factors, or by using an event generator which includes QED radiative effects
  - The modelling of these incurs a systematic uncertainty

- The presence of QED ISR can dramatically change event kinematics, leading to incorrectly reconstructed events
  - Different methods of kinematic reconstruction have different sensitivities to QED radiative effects

- Important to understand these → need to generate, simulate, and reconstruct sample containing these effects
  - Djangoh includes QED radiation via HERACLES

Why no (Fully simulated) Djangoh up to this point?

- To get from generated to reconstructed events there are some steps required
- Different stages of the process have caused issues at different points in time
- Steps:
  - Output .dat file to EICTree
  - EICTree to hepmc
  - Hepmc to afterburned hepmc
  - Pass afterburned hepmc through npsim and EICrecon

- Over time we've managed to identify and patch/workaround a multitude of issues. FYI for those wanting to run Djangoh themselves:
  - Use latest Djangoh version 4.6.21
  - Use current EIC-smear version >1.1.11
  - Threshold for W>3 seems to work
  - … and repair the file afterwards

Repairing the file

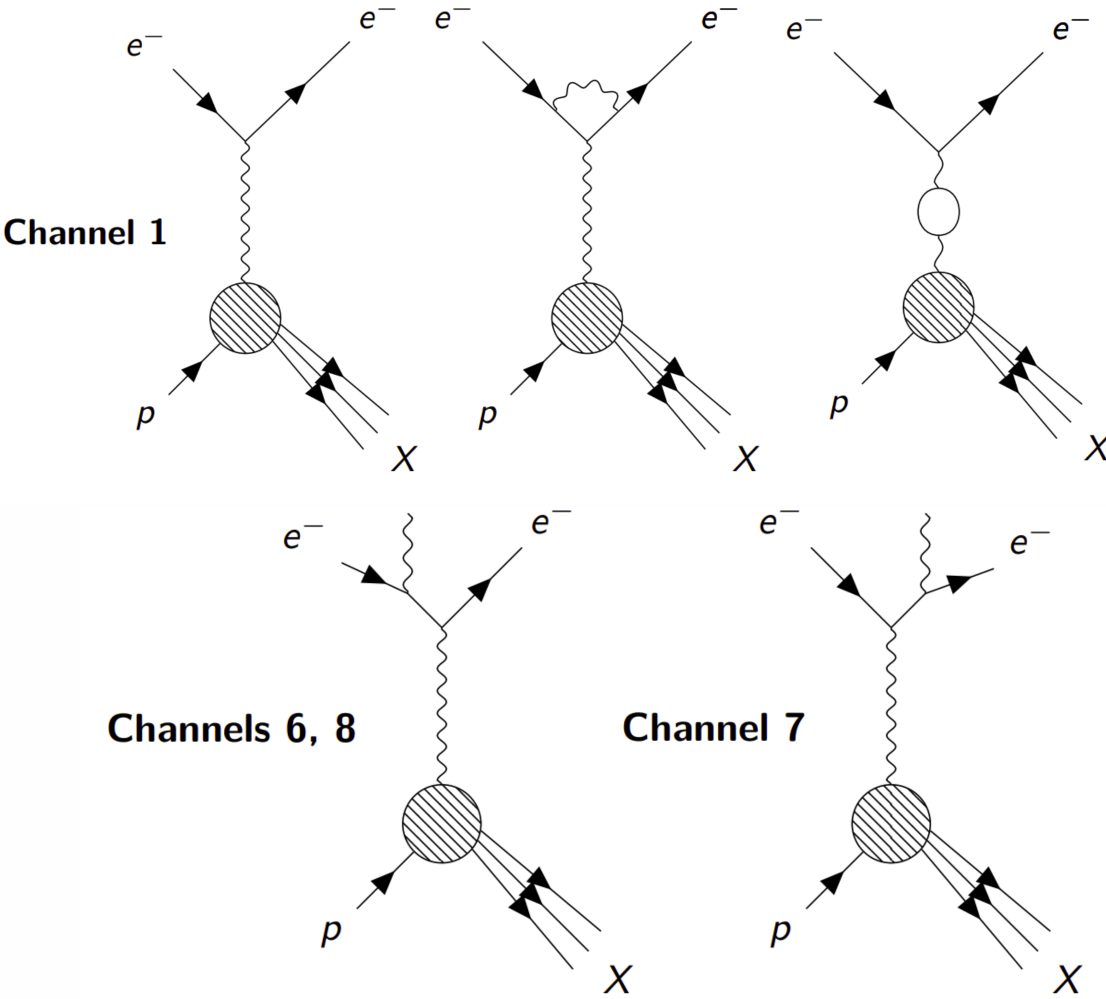
- Even with these updates, the simulation will crash after a few events
- This crash is due to problems with Djangoh's handling of the parent-child relationships of intermediate particles
  - Also sometimes have a crash due to unhadronised partons, but this is largely removed by the W threshold

- Barak kindly put together a script to remove all non beam/final state particles (and unhadronised partons)
  - You can find at /gpfs02/eic/baraks/djangoh/djangoh_local/outfiles/filter

- I also put together a script to try and keep intermediates by setting the parents of particles with looping parent-child relations to 0
  - Found here
  - More optimisation needed – currently get some events with very high number of intermediates which blow up memory usage → will filter these too

Event generation

- Djangoh 4.6.21 used to generate 18x275 GeV^2 e-p events
  - ISR/FSR=ON and OFF
  - Q^2>1,10,100,1000
  - W>3GeV
- Channel 1: Non Radiative NC
- Channel 6: ISR
- Channel 7: FSR
- Channel 8: “Compton event”



Simulation and Reconstruction

- Locally simulated and reconstructed samples in eic-shell version 25.09.0-stable
  - Djangoh sample also ran as part of October campaign (see /volatile/eic/EPIC/RECO/25.10.4/epic_craterlake/DIS/DJANGOH4.6.21-1.0/NC/)
- Calculate reconstructed kinematics manually from ReconstructedParticles branch
- Radiative truth kinematics from InclusiveKinematicsTruth
- Born truth kinematics manually calculated from scattered/beam electron four-vectors (and radiated photon four-vectors where applicable)
- Radiative events identified by looking for final state photons with either the beam or scattered electron as its parent

P ID ParentID PDG

Example of an event containing FSR

```
E 0 17 31 @ -6.5024151476483341e-02 -3.2340523959240464e-03 7.2836286194717754e+00 -1.1102591305812023e+01
U GEV MM
W 1.0000000000000000000000e+00
A 0 GenCrossSection 1.00000000e+00 0.00000000e+00 -1 -1
P 1 0 11 4.2508797487305905e-03 -5.8584259099664689e-03 -1.7998543321755243e+01 1.7998544777182211e+01 5.0999998347833753e-04 4
P 2 1 23 -1.4987102777775796e+00 3.0605648596599666e-01 -8.2423872424536387e-02 1.6787012230887466e-02 -1.5317679643630981e+00 21
P 3 0 2212 -6.9311465581052065e+00 5.4207924557558296e-02 2.7497615832191337e+02 2.7506509088589996e+02 9.3830001354217529e-01 4
P 4 1 11 8.4569052695003066e-01 -1.8006336808800588e-01 -1.0062361416782567e+01 1.0099441918012110e+01 5.1099999109283090e-04 1
P 5 4 22 6.5727062928571922e-01 -1.3185154379459121e-01 -7.8537580325481429e+00 7.8823159503240765e+00 0.0000000000000000e+00 1
P 6 3 2 1.6633901664053902e-02 -9.6425321126547961e-02 1.2190123779769774e+01 1.2190516144475161e+01 -0.0000000000000000e+00 21
P 7 6 2 1.6633901664053902e-02 -9.6425321126547961e-02 1.2190123779769774e+01 1.2190516144475161e+01 -0.0000000000000000e+00 21
```

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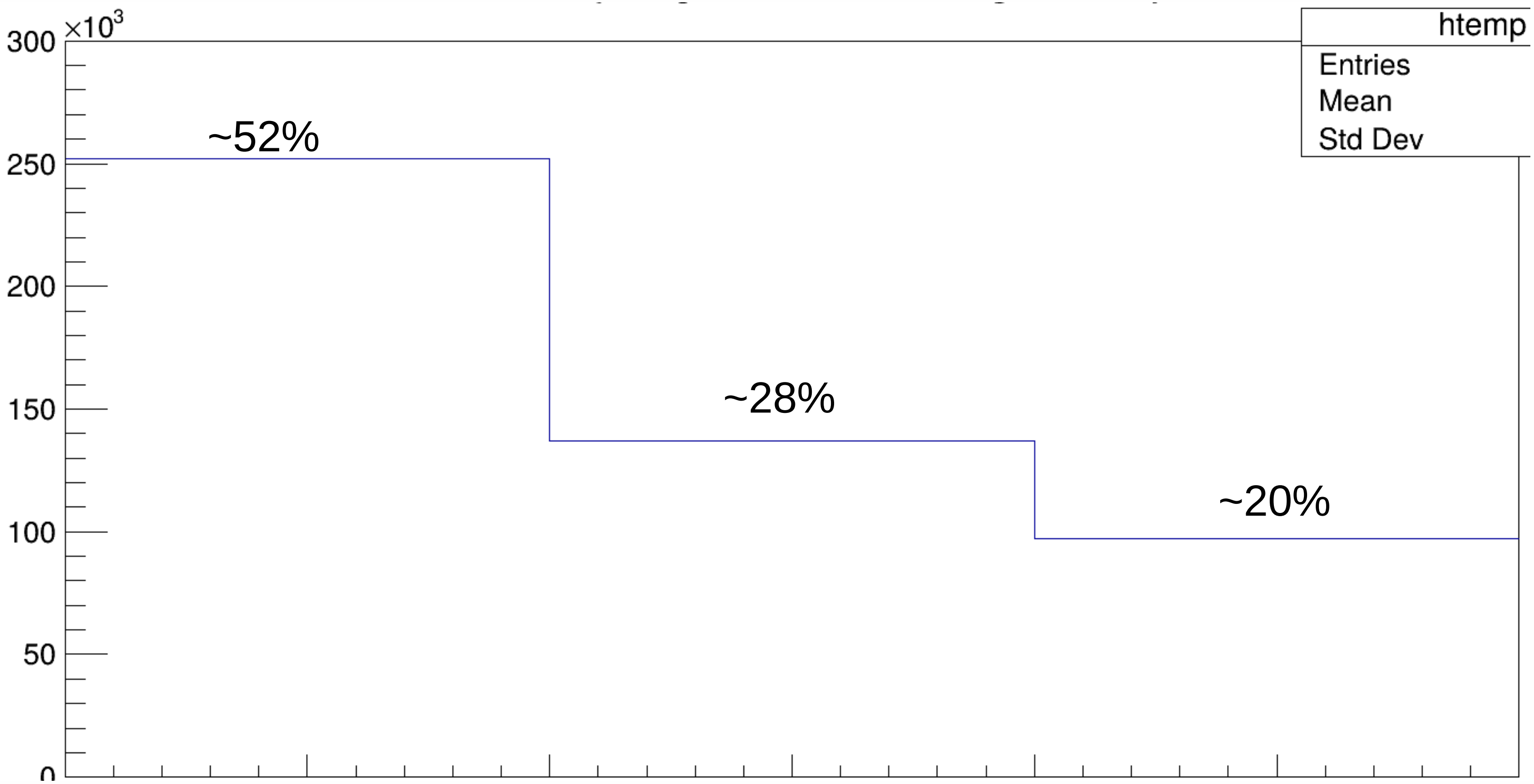
Example of an event containing ISR

```
E 7 64 147 @ 1.6012185733788062e-01 -4.7490747321960415e-03 -2.0748446038297086e+00 1.0020203454212252e+01
U GEV MM
W 1.0000000000000000000000e+00
A 0 GenCrossSection 1.00000000e+00 0.00000000e+00 -1 -1
P 1 0 11 -2.5068112324858061e-03 4.1249875436205254e-03 -1.7998604003829065e+01 1.7998604651091053e+01 5.0999998347833753e-04 4
P 2 1 23 1.3006943859613391e+00 5.3136958329518003e-01 -1.2044042330374824e+01 1.1799994981284147e+01 -2.7916390895843506e+00 21
P 3 0 2212 -6.8885281123426703e+00 8.9282705102835924e-02 2.7497708540380222e+02 2.7506495621145075e+02 9.3830001354217529e-01 4
P 4 1 11 -1.3023291964206973e+00 -5.2736128534009141e-01 -3.9226089551434651e+00 4.1666572915681410e+00 5.1099999109283090e-04 1
P 5 1 22 -8.7200722271252307e-04 1.1668950423773378e-04 -2.0319517183883327e+00 2.0319519015206349e+00 0.0000000000000000e+00 1
P 6 3 21 -5.5575237362920493e+00 2.6065923383987660e-01 2.3122515536748480e+02 2.3129208541825975e+02 -0.0000000000000000e+00 21
P 7 6 21 9.5443660479677683e-01 8.5441304671546270e-01 1.6073344261683296e+00 5.7413160236073968e-01 -1.9735870361328125e+00 21
```

Number of radiative events

Consistent w/ previous work →
Parent ID seems to work well



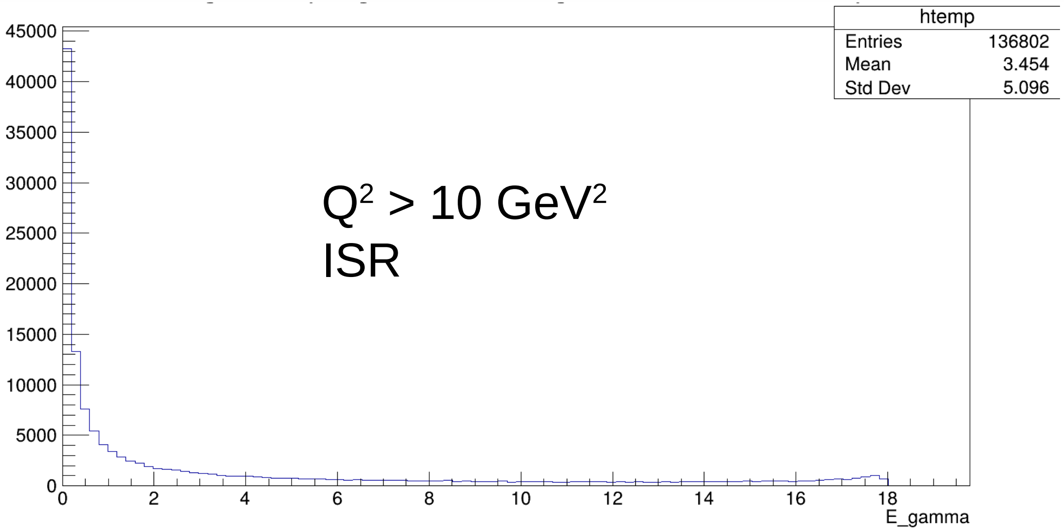
$Q^2 > 10$ GeV^2

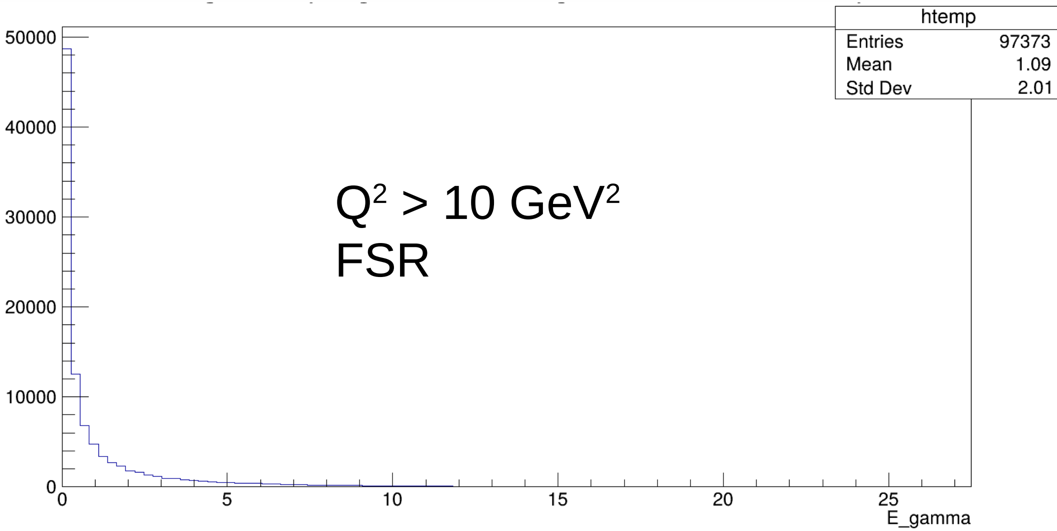
No Rad
(channel 1)

ISR
(channel 6,8)

FSR
(channel 7)

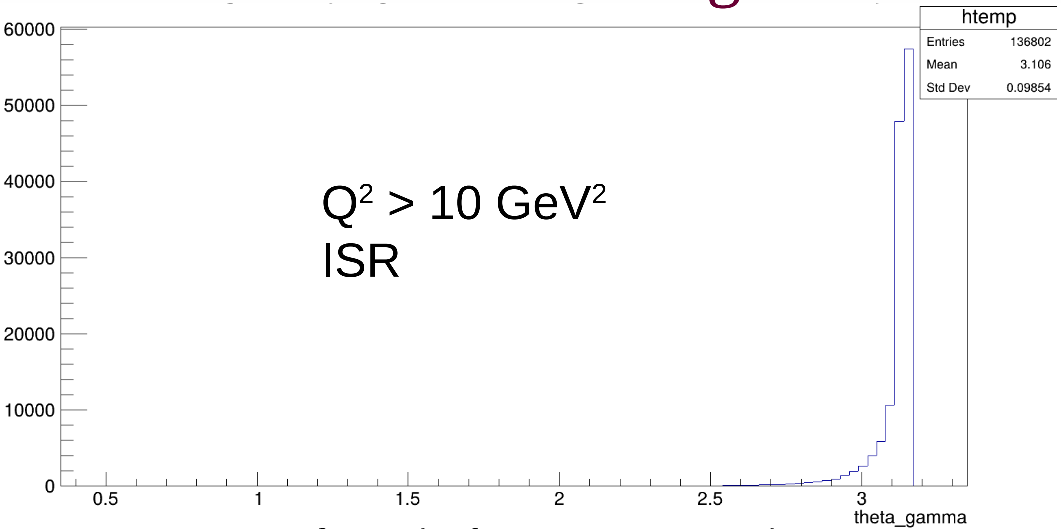
Radiated Photon Energy

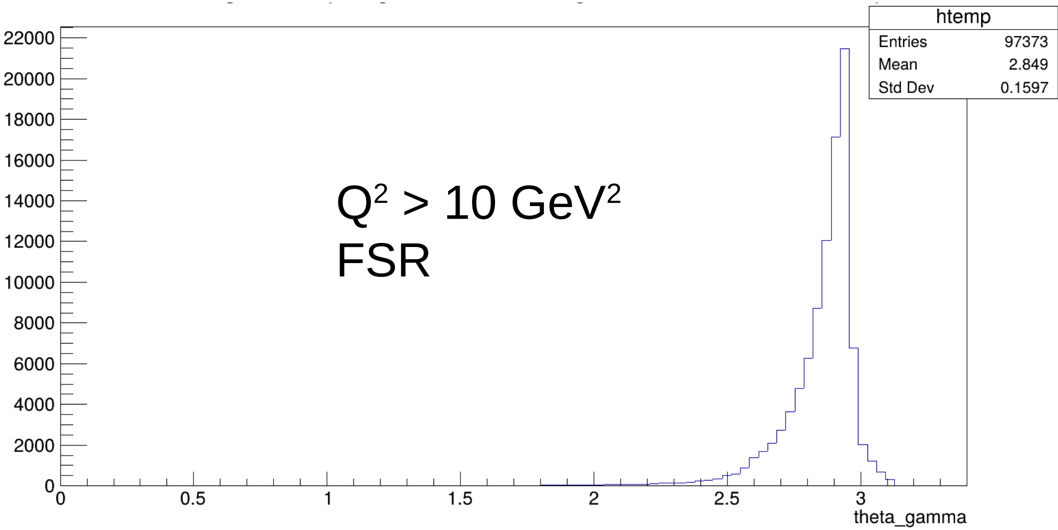


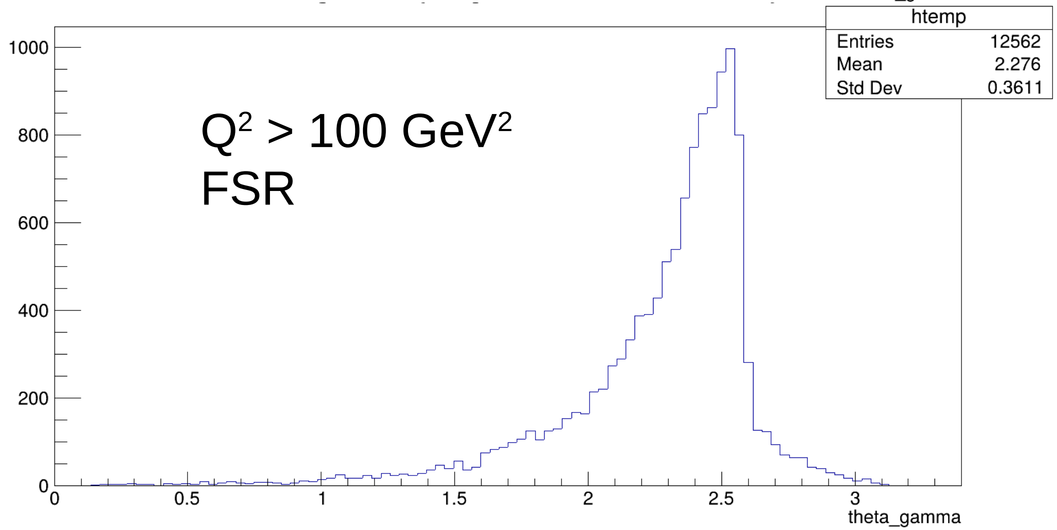


- Number of radiative events sharply decreases with energy
  - No visible difference between different Q^2 ranges

Radiated Photon Angle







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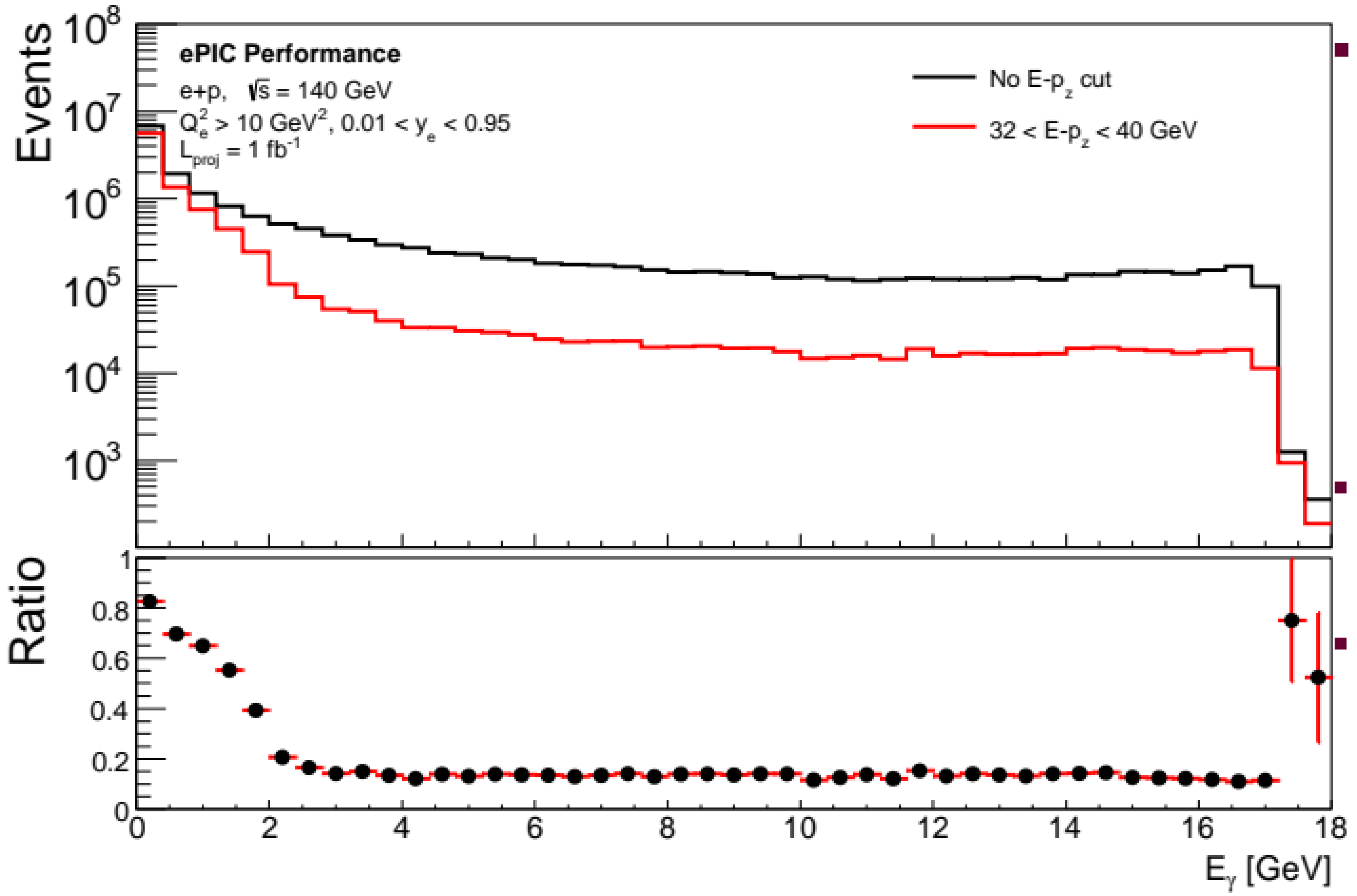
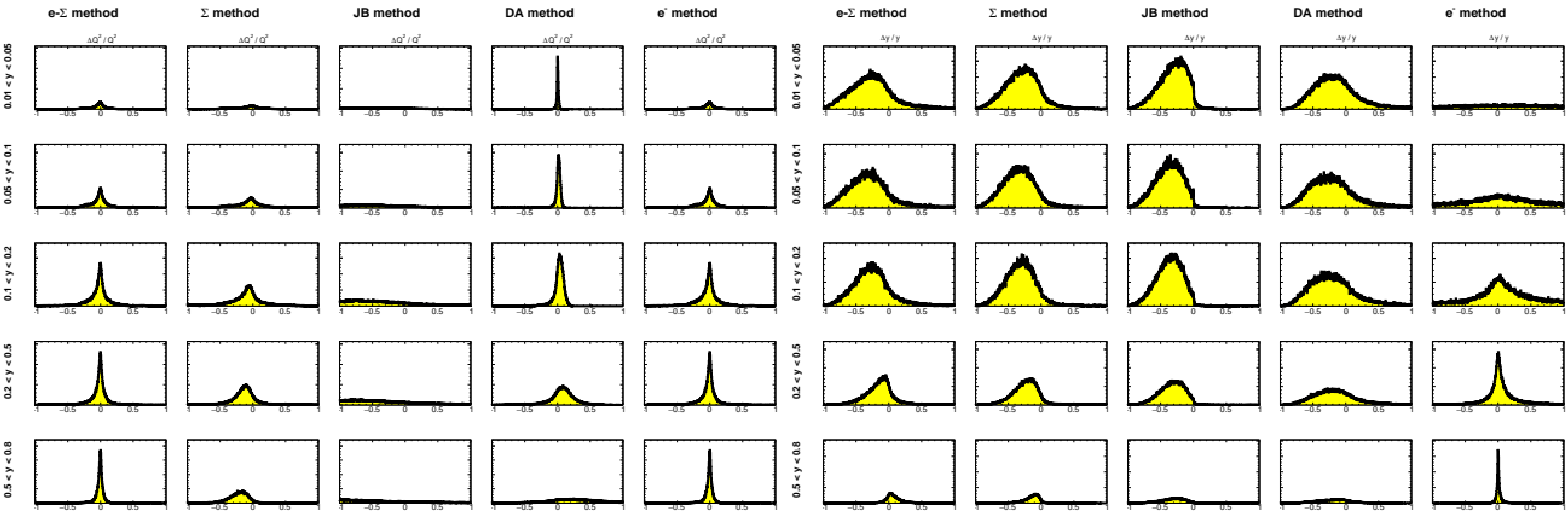
Total E-p_z



- Can veto ISR events either directly (by measuring the photon) or indirectly by measuring both the electron and HFS
  - Total E-p_z ~ $2(E_{e,beam} - E_\gamma)$ with E_γ as E of ISR photon
- E-p_z > 32 GeV removes events with E_γ>2GeV
- Improves kinematic reconstruction and reduces uncertainty from modelling of radiative corrections

Kinematics reconstruction – non radiative events

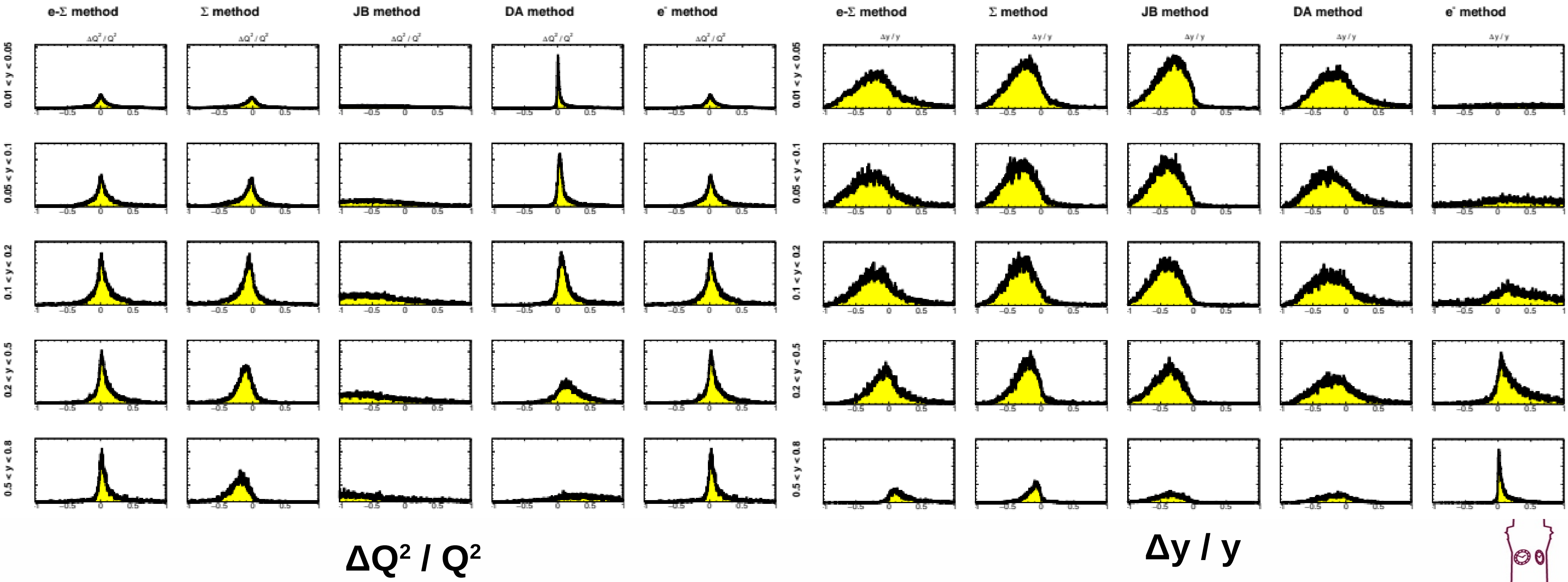


$\Delta Q^2 / Q^2$

$\Delta y / y$

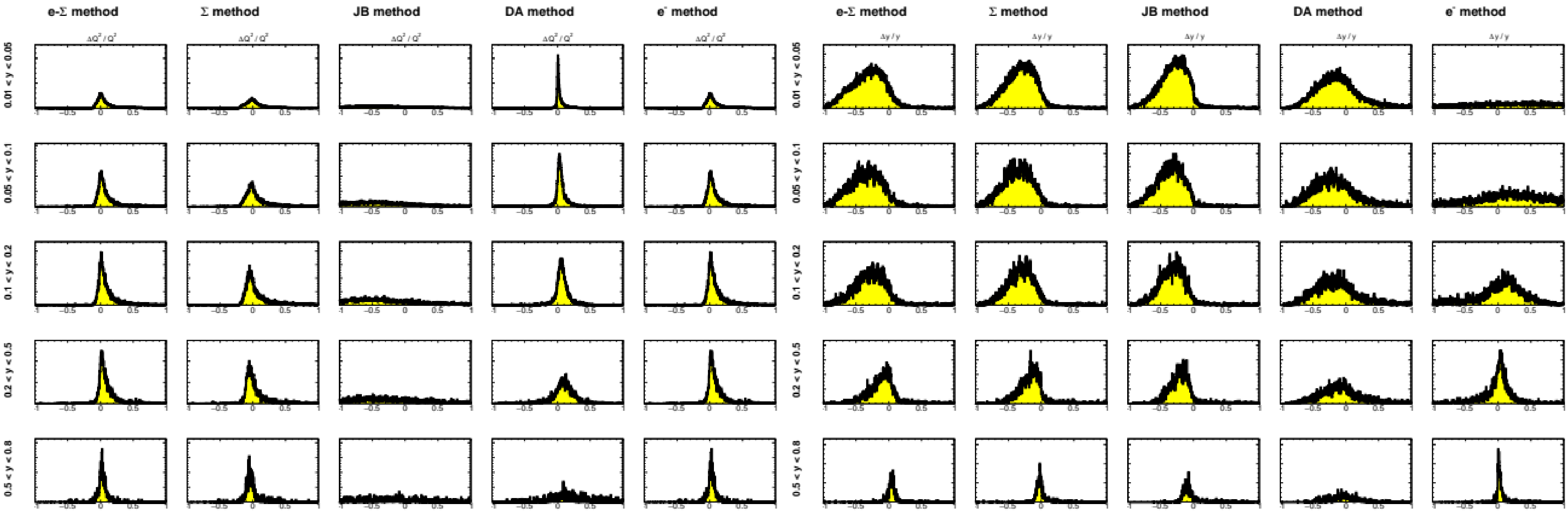
- Note: events scaled to same area – higher peak corresponds to narrower distribution
- Bias in Mixed+JB methods – under reconstruction of HFS (needs correction)

Kinematics reconstruction – All ISR events



- Electron/DA methods skew towards larger values for Q^2 (and for y in case of e-method)
- Relative performance of Σ methods improved

Kinematics reconstruction – All ISR events w/ total $E\text{-}p_z > 32$ GeV

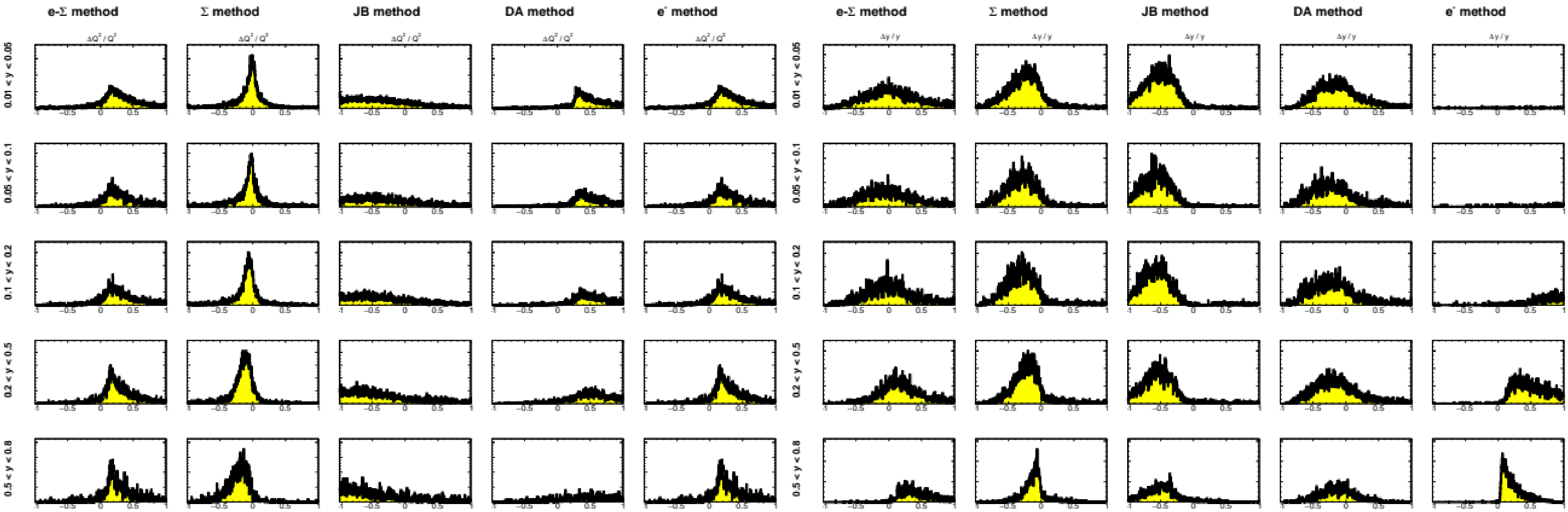


$\Delta Q^2 / Q^2$

$\Delta y / y$

- $E\text{-}p_z$ cut removes events w/ $E_\gamma > \sim 2$ GeV – improves electron+DA methods
- Also improves mixed+JB methods by removing events with poorly reconstructed HFS

Kinematics reconstruction – All ISR events w/ $E_\gamma > 2$ GeV



$\Delta Q^2 / Q^2$

$\Delta y / y$

- For these events which would be removed by $E\text{-}p_z$ cut - e-method degraded in y and Q^2
- DA method Q^2 performance significantly degraded → Σ method performs best

Summary

- Got Djangoh working with full simulations → produced and simulated samples to study
  - Verified that ISR/FSR events are being simulated and identified correctly
- Conventionally use an E-pz cut to remove events with high energy ISR
  - Cut of E-p_z<32 GeV reduces events with ISR photons above 2 GeV significantly
- Kinematics not correctly reconstructed for ISR events → degrades resolutions, but impact limited by E-p_z cut

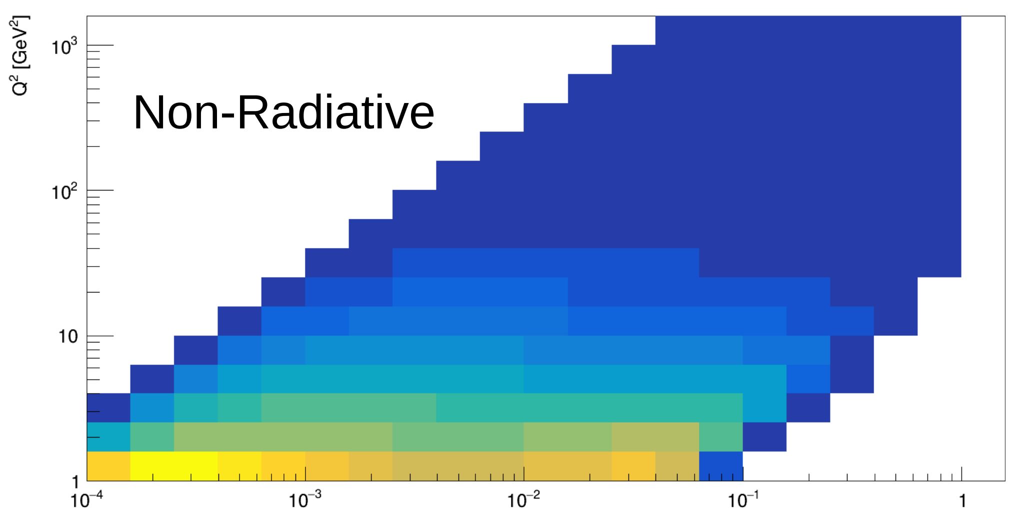
Next Steps

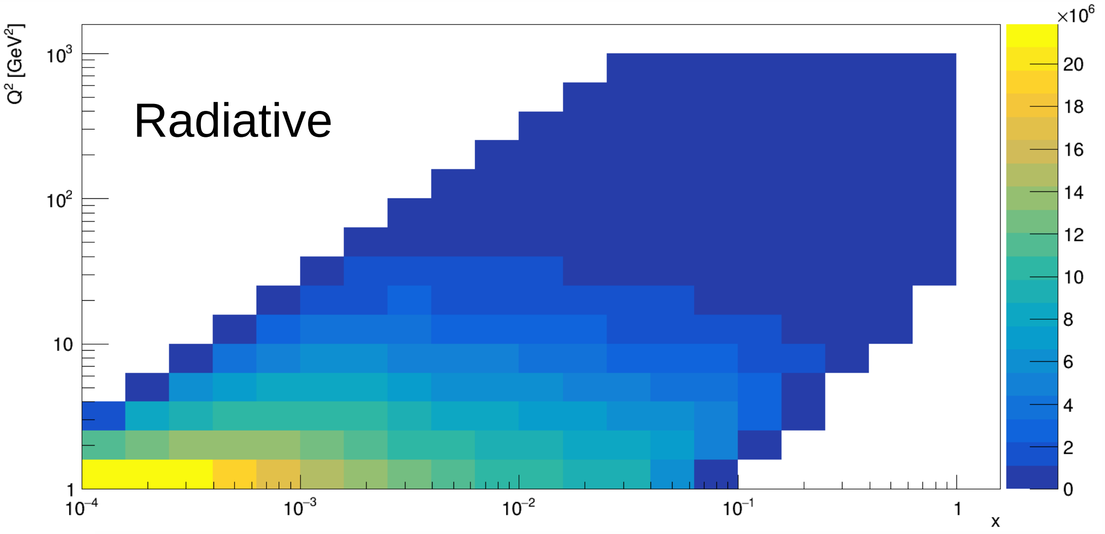
- Perform studies to further limit the impact of ISR/FSR on reconstruction
- Radiative correction factor will have some dependence on DJANGOH settings → generate+simulate more samples with different settings and compare factor → use to estimate systematic uncertainty
- Analysers from other groups are encouraged to look at these samples and see how it impacts their analysis
- Look into potential for modern event generators with QED radiative effects?

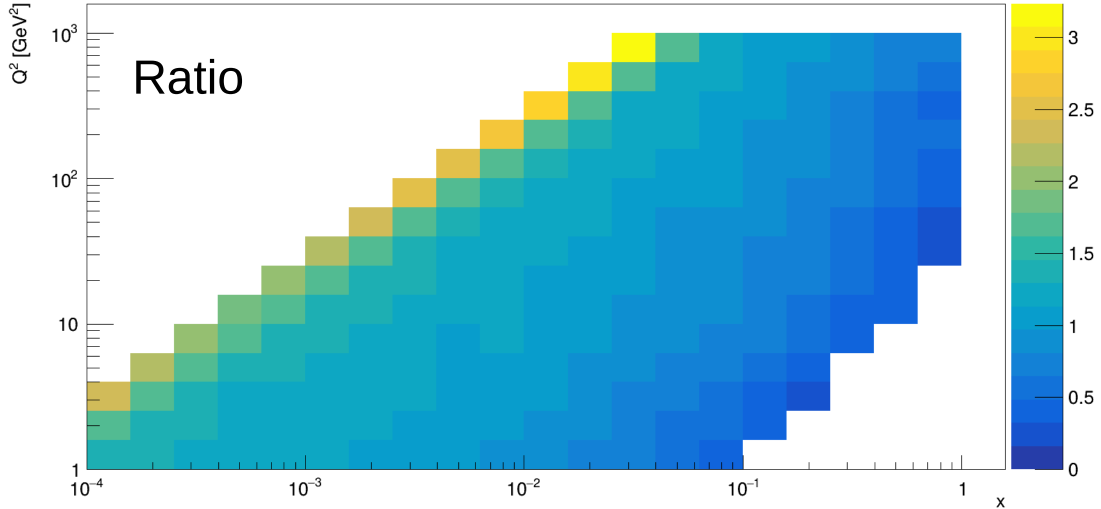
Backup

Non-Radiative vs Radiative Truth (x-Q^2)

Ratio = Num Radiative / Num Non-Radiative in bin

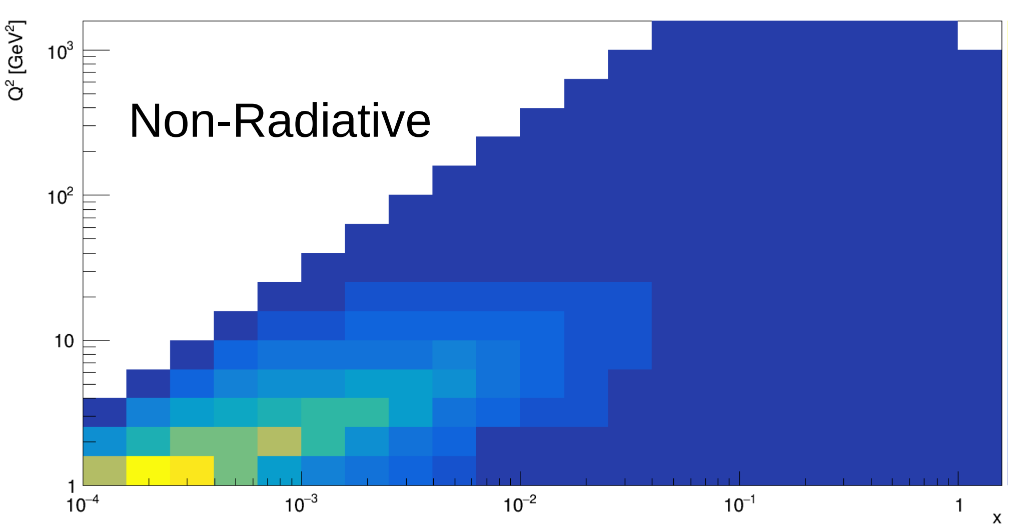


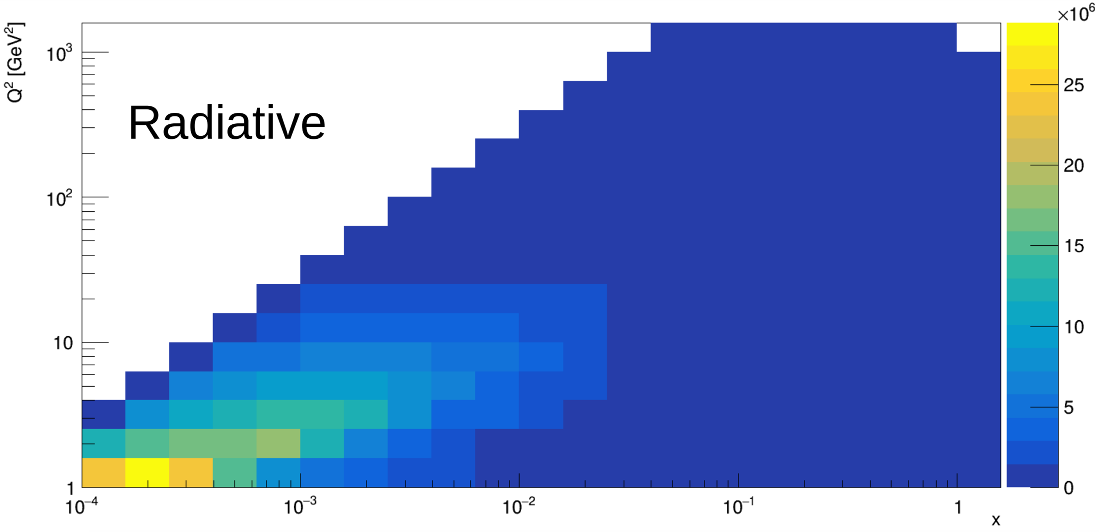


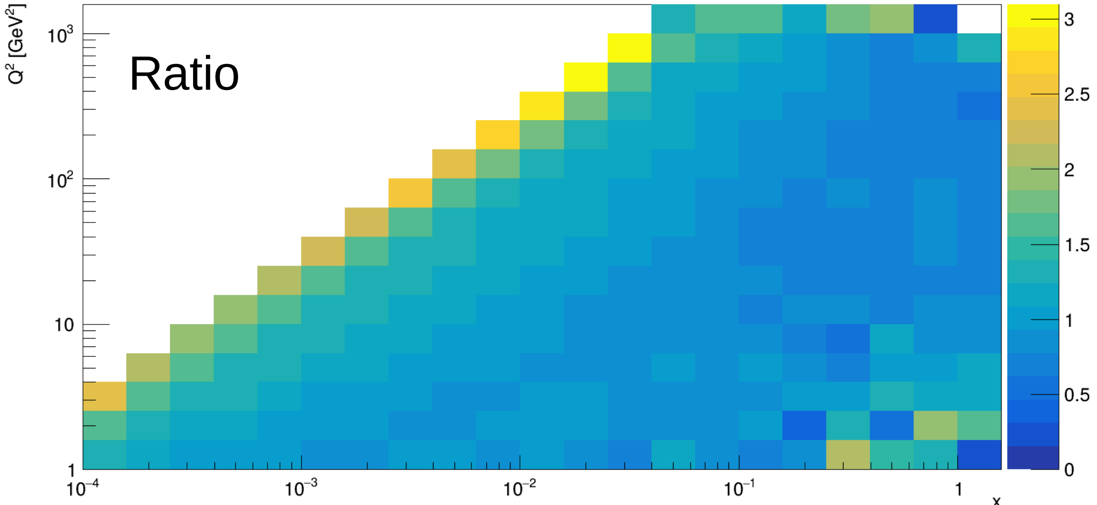


- Radiative events shift kinematics to higher y
- Up to ~3x as many events at high y (and Q2) → highest y bins will be removed by y<0.9-0.95 cut → more like 2x

Non-Radiative vs Radiative: Ele method (x-Q^2)

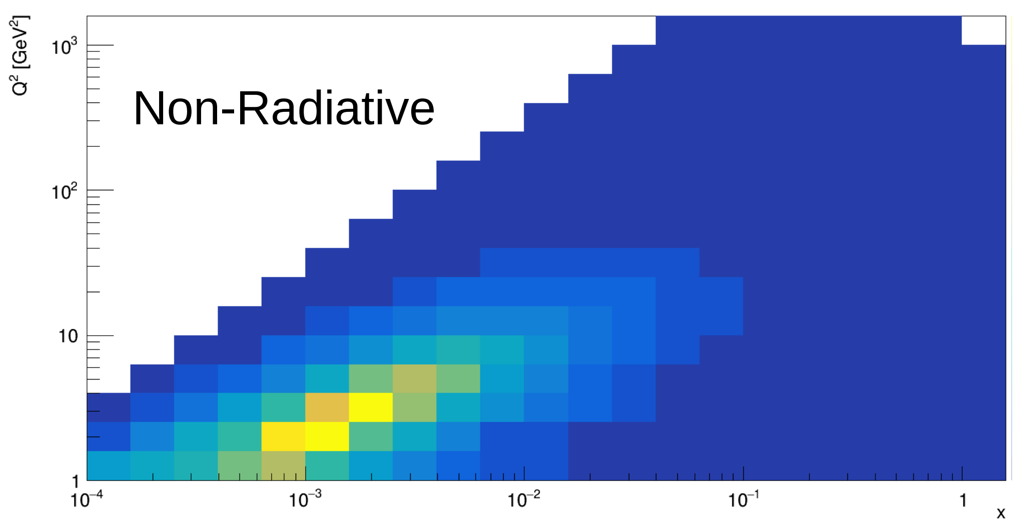


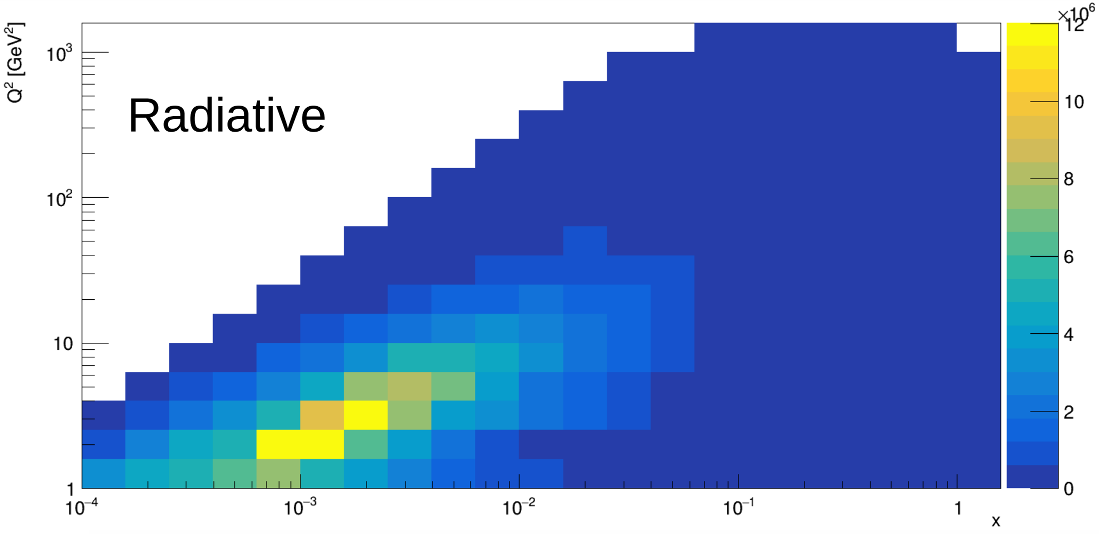


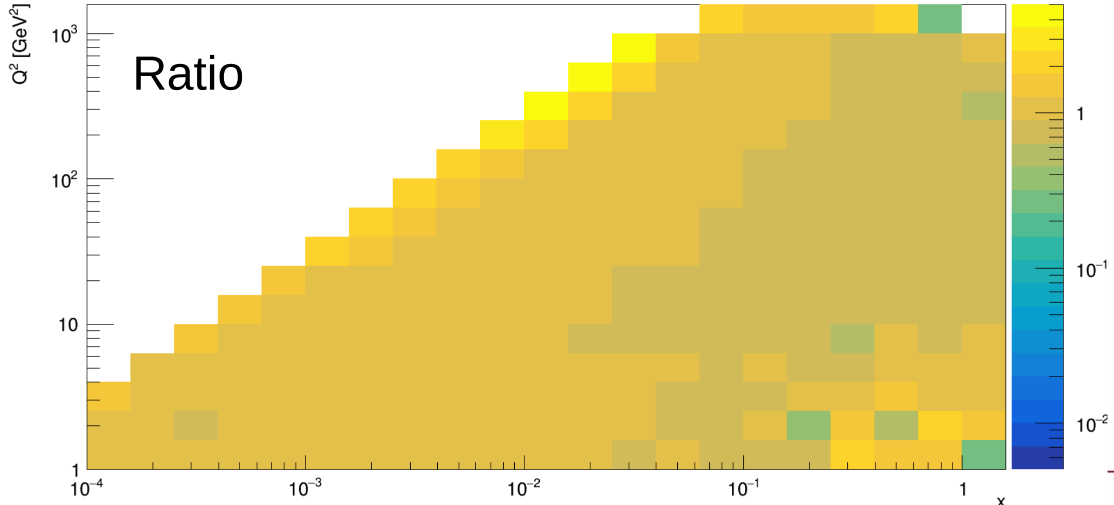


- Ratio mostly ~1
- Some deviation at high y high Q2 and low y

Non-Radiative vs Radiative: Ele method ($E-p_z$ cut) ($x-Q^2$)







- Log scale on ratio for visibility
- Typically ratio is ~1
  - Bins at high y high Q^2 may actually increase with cut
  - Lower y bins comparable with or without the cut