QED radiative corrections on deep inelastic scattering events at the future EIC

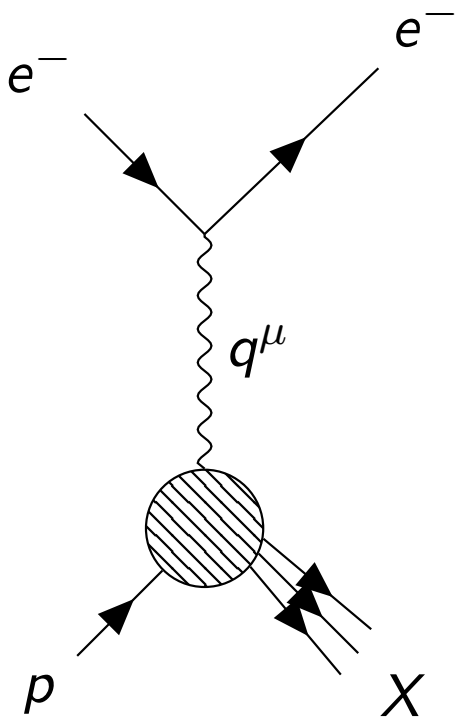
Characterizing radiative photons with simulations

Tucker Hwang

UC Berkeley

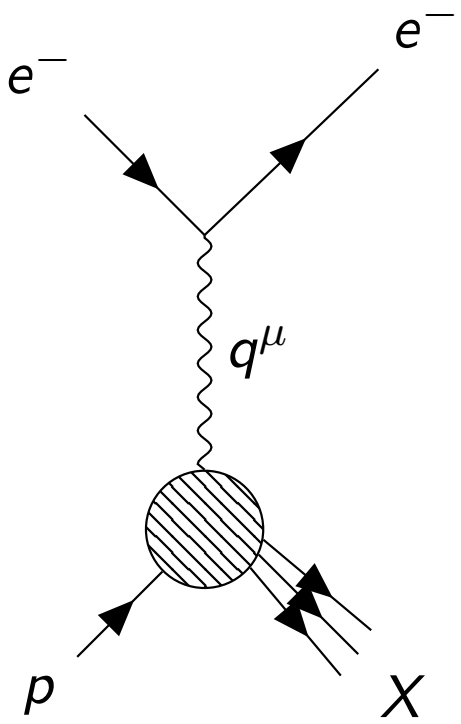
UC EIC Consortium Collaboration Meeting, July 2022

Deep inelastic scattering



- Elucidates p and n partonic structure

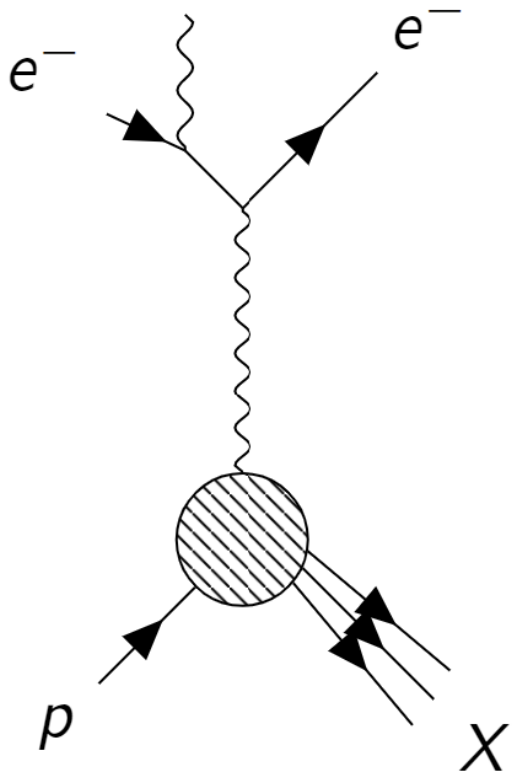
Deep inelastic scattering



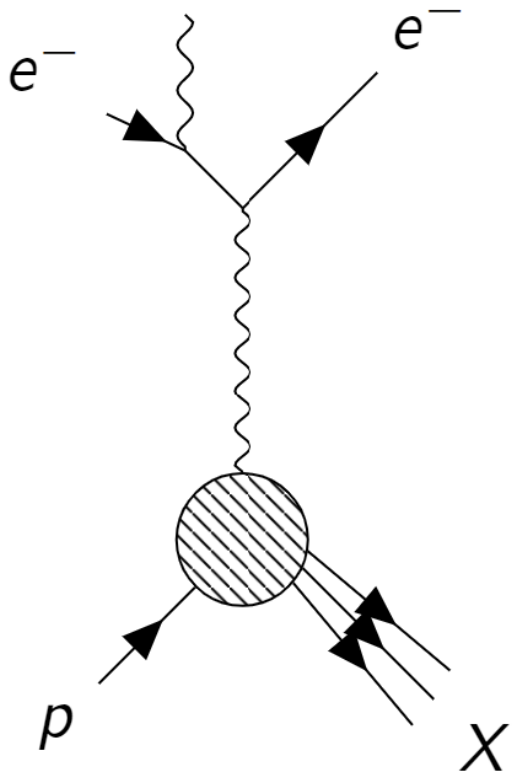
- Elucidates p and n partonic structure
- Momentum fraction x; hadronic momentum transfer $Q^2 \equiv -q^2$
- Scattered electron method: measure final electron state

$$Q^2 = -(e - e')^2, \qquad x = \frac{Q^2}{2p \cdot q}, \qquad y = \frac{p \cdot q}{p \cdot e}$$

QED radiation



QED radiation



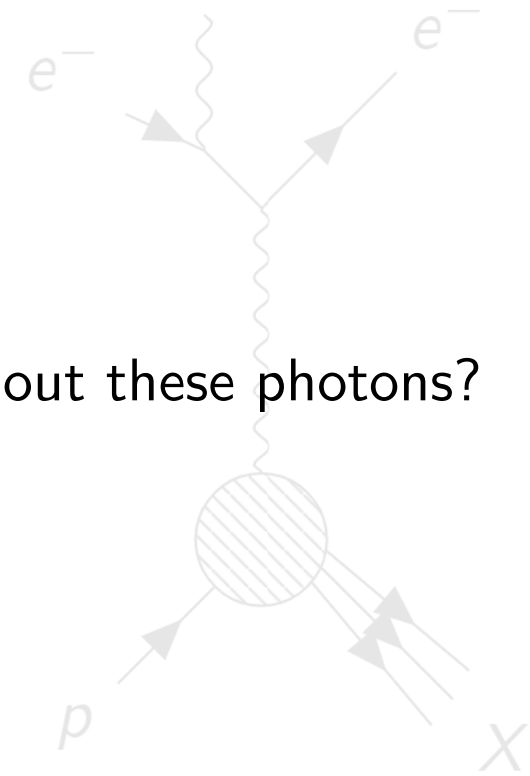
Altered electron momentum $\Longrightarrow$ altered x and Q^2

QED radiation

1. Does it matter?

Altered electron momentum $\Longrightarrow$ altered x and Q^2

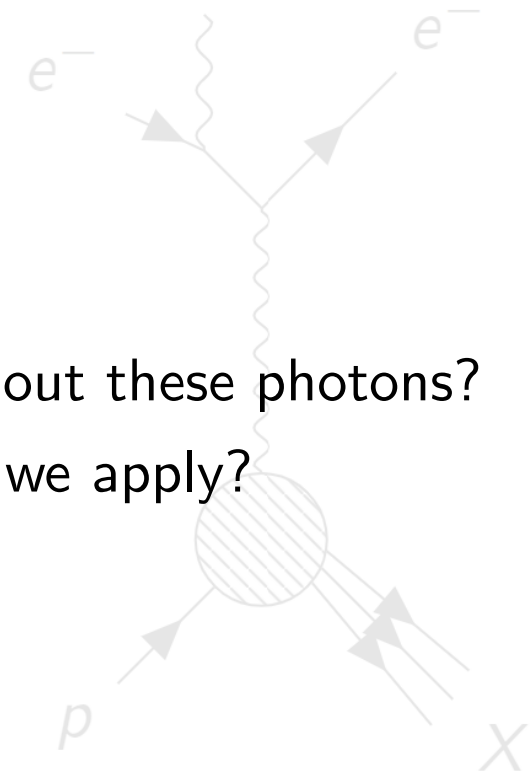
QED radiation



1. Does it matter?
2. What can we learn about these photons?

Altered electron momentum $\Longrightarrow$ altered x and Q^2

QED radiation



1. Does it matter?
2. What can we learn about these photons?
3. What corrections can we apply?

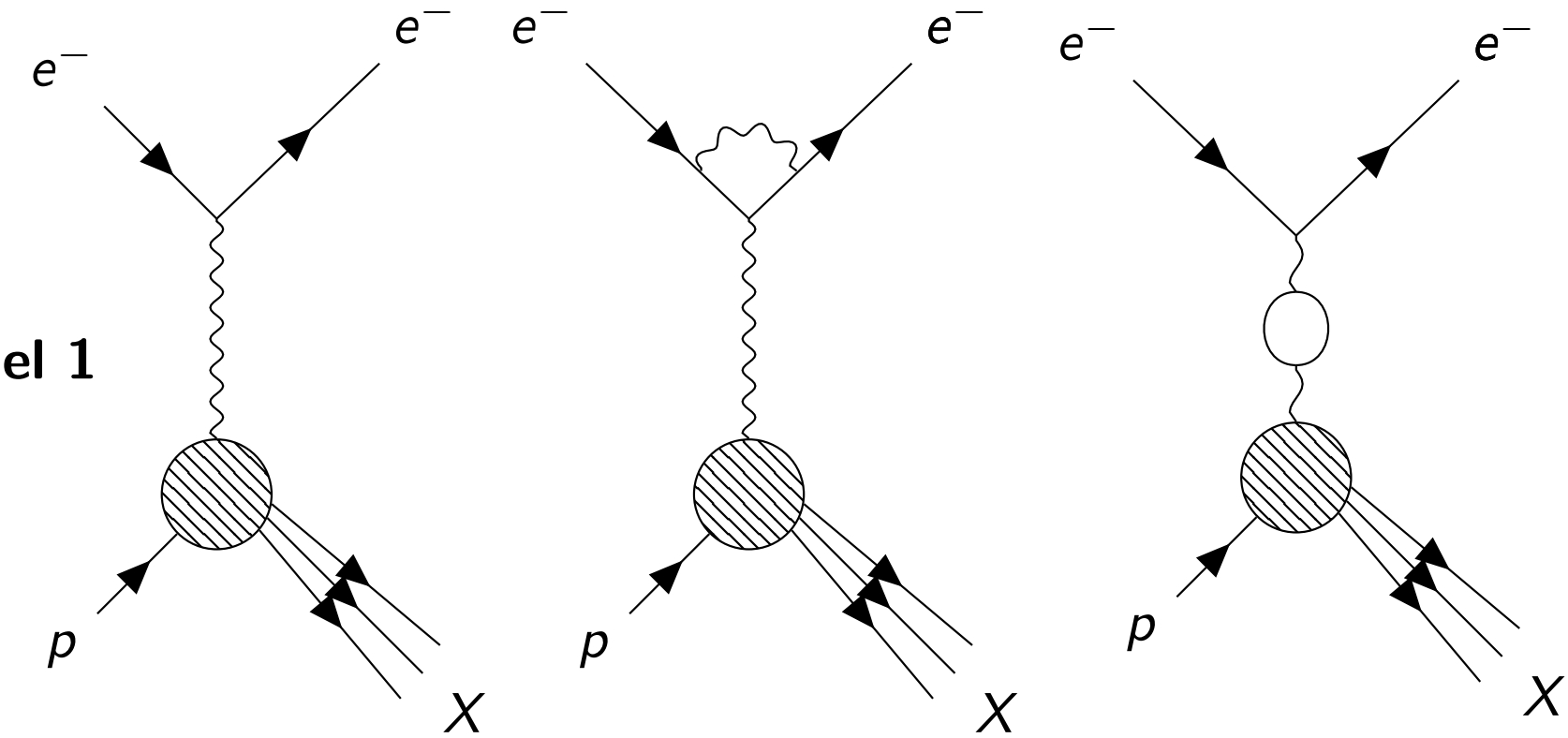
Altered electron momentum $\Longrightarrow$ altered x and Q^2

DJANGOH

- *ep* collision simulation with QED radiation
  - HERACLES: HERA-era NC/CC *ep* interactions; handles electron vertex
  - SOPHIA/LEPTO: fragmentation post-interaction for low and high W, respectively
- Current version on BNL cluster: DJANGOH 4.6.10
- Following plots generated with DJANGOH 4.6.20
- Alternatives: PYTHIAeRHIC: PYTHIA6 with RADGEN interface

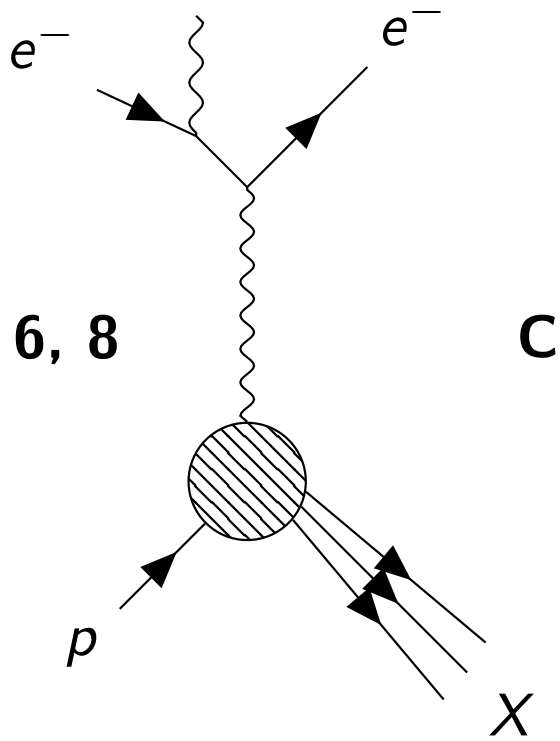
Radiative events in DJANGOH

Channel 1

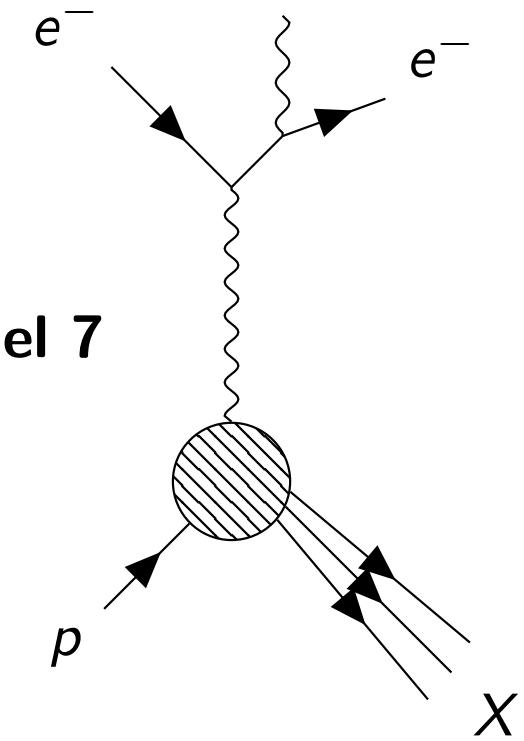


Radiative events in DJANGOH

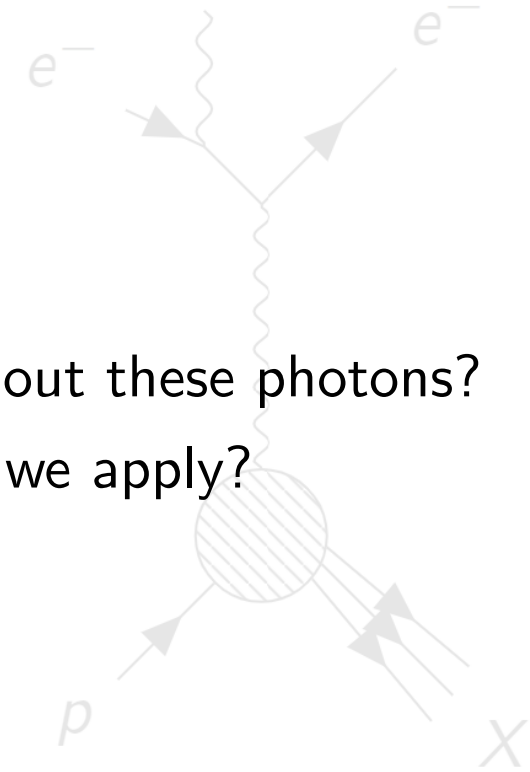
Channels 6, 8



Channel 7



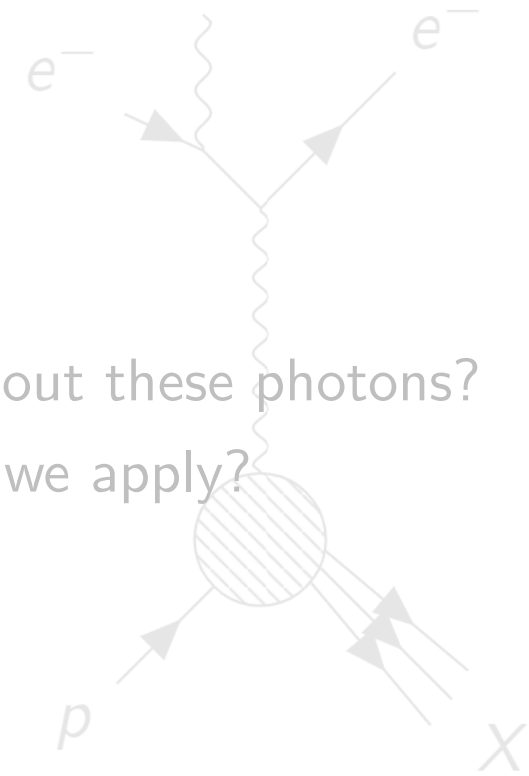
QED radiation



1. Does it matter?
2. What can we learn about these photons?
3. What corrections can we apply?

Altered electron momentum $\Longrightarrow$ altered x and Q^2

QED radiation



1. Does it matter?
2. What can we learn about these photons?
3. What corrections can we apply?

Altered electron momentum $\Longrightarrow$ altered x and Q^2

By the numbers

10 GeV e^- on 100 GeV p; $Q^2_{\text{elec}} > 0.5$ GeV^2:

By the numbers

10 GeV e^- on 100 GeV p; $Q^2_{\text{elec}} > 0.5$ GeV^2:

Non-radiative events: $\approx 44\%$;

By the numbers

10 GeV e^- on 100 GeV p; $Q^2_{\text{elec}} > 0.5$ GeV^2:

Non-radiative events: $\approx 44\%$; **radiative events: $\approx$ 56%**

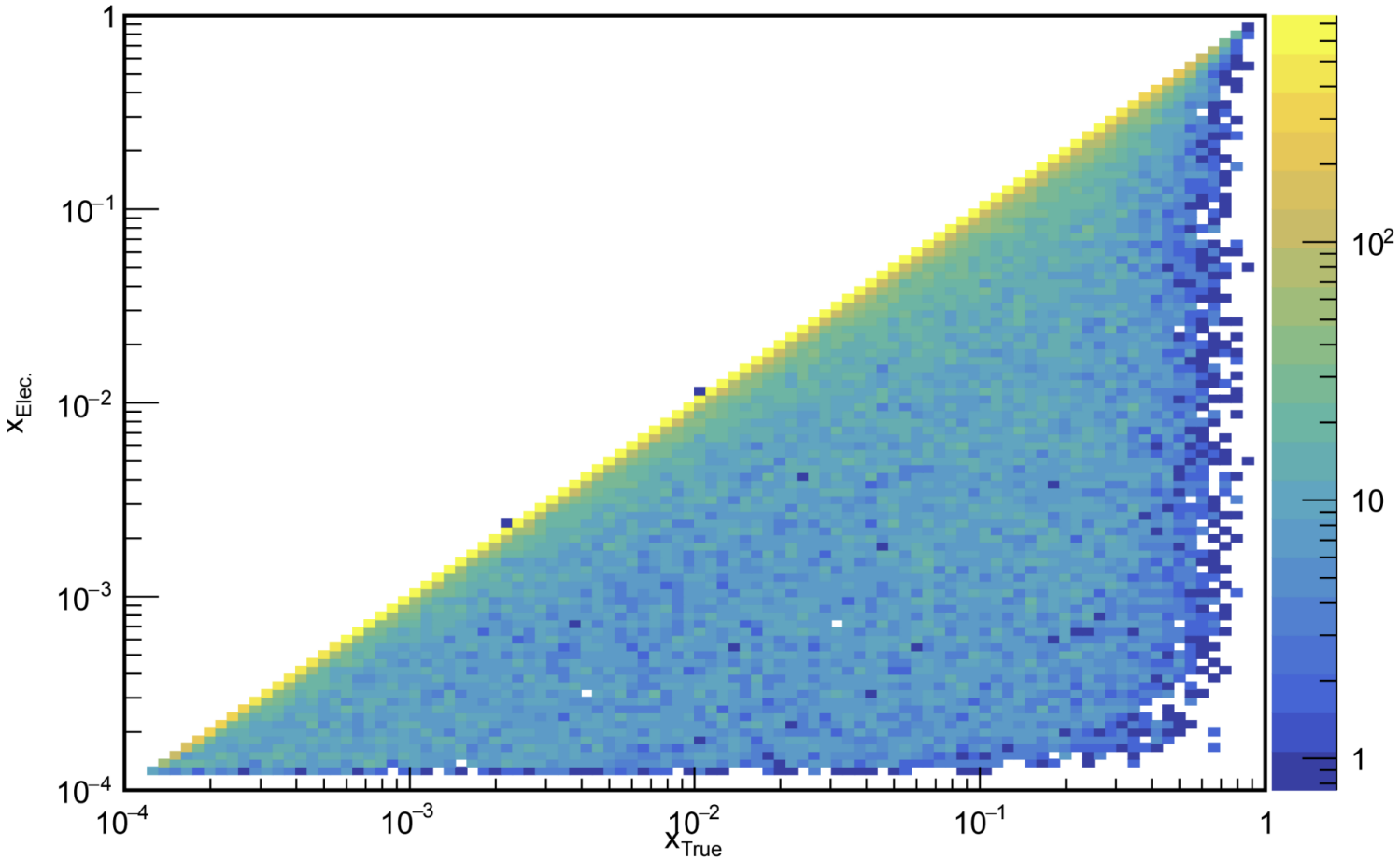
By the numbers

10 GeV e^- on 100 GeV p; $Q^2_{\text{elec}} > 0.5$ GeV^2:

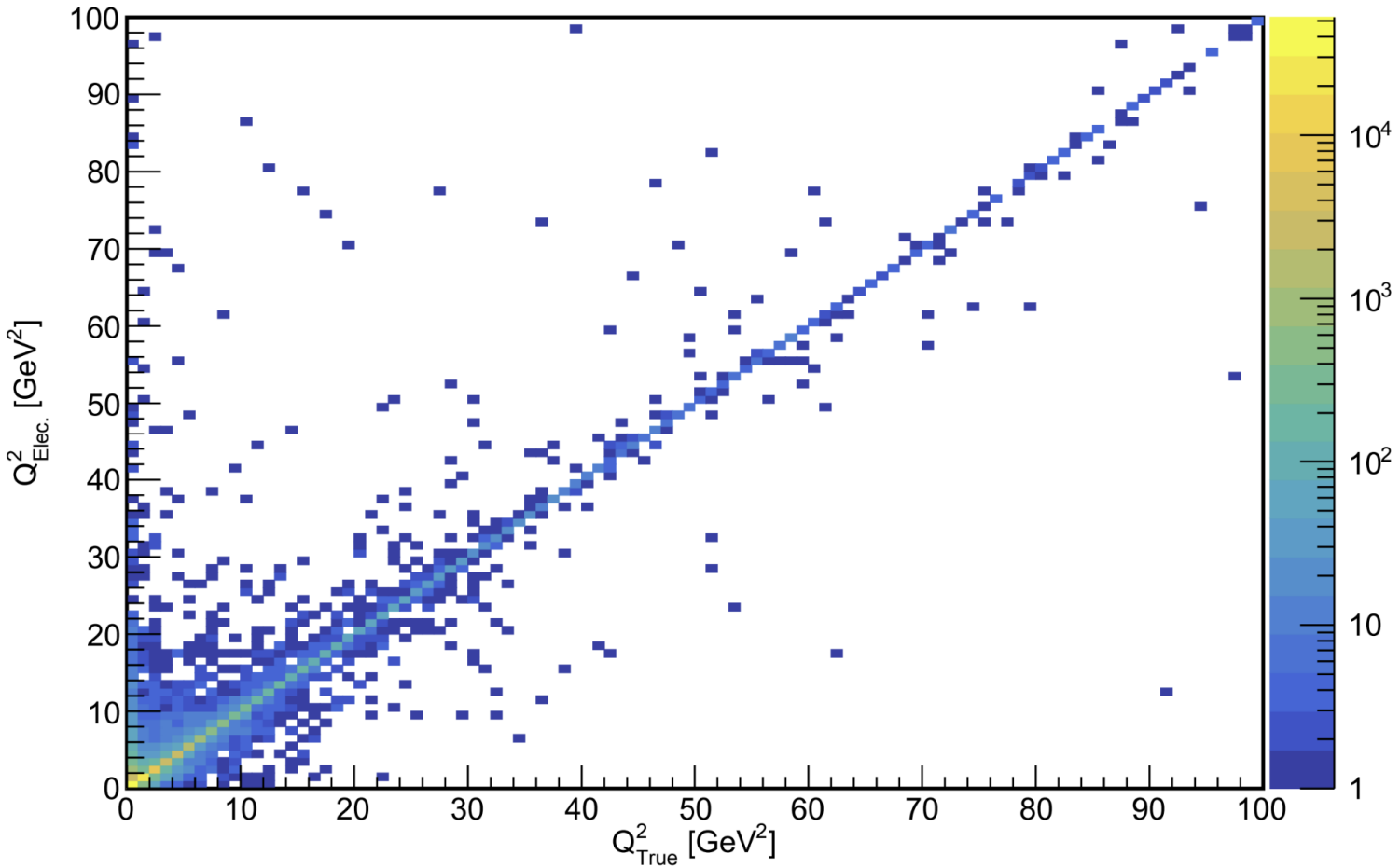
Non-radiative events: $\approx 44\%$; **radiative events: $\approx$ 56%**

- Channel 6: $\approx 53\%$ ($\approx 30\%$ of total)
- Channel 7: $\approx 30\%$ ($\approx 17\%$ of total)
- Channel 8: $\approx 17\%$ ($\approx 9\%$ of total)

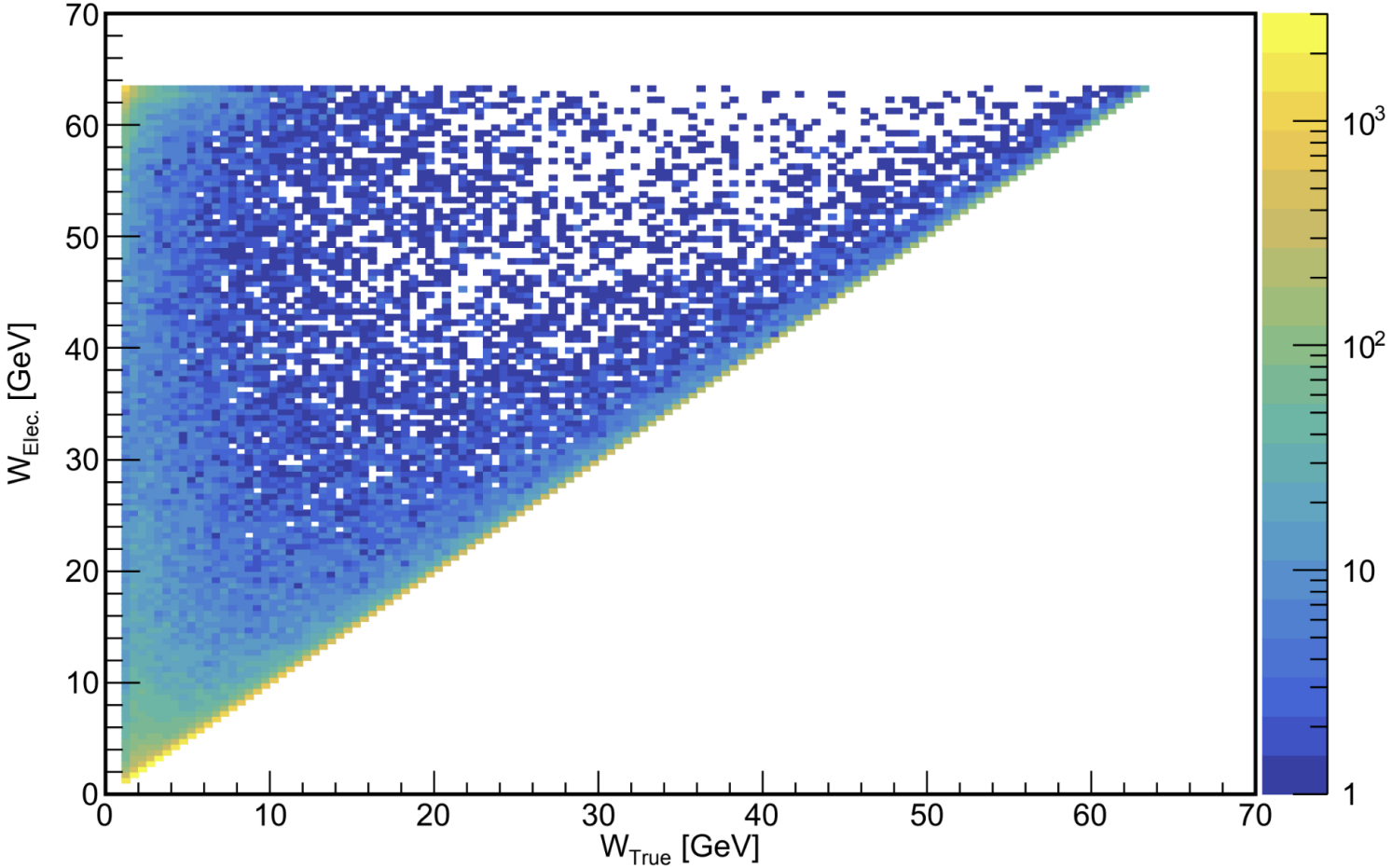
Effects on W, Q^2, x



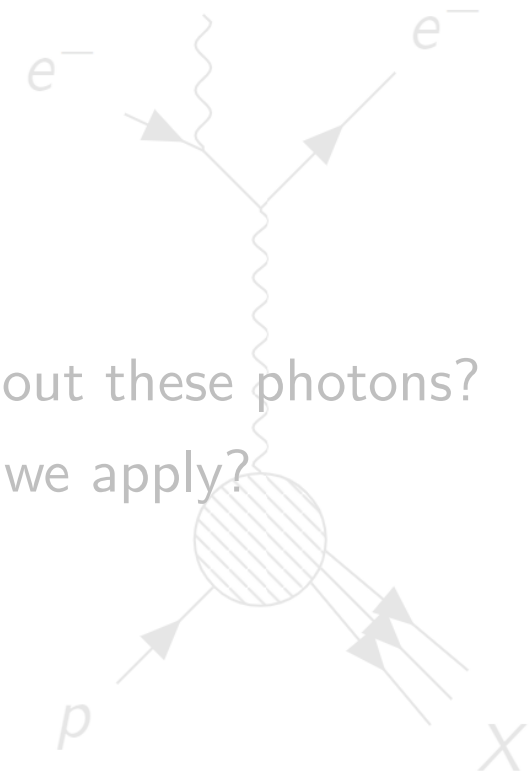
Effects on W, Q^2, x



Effects on W, Q^2, x



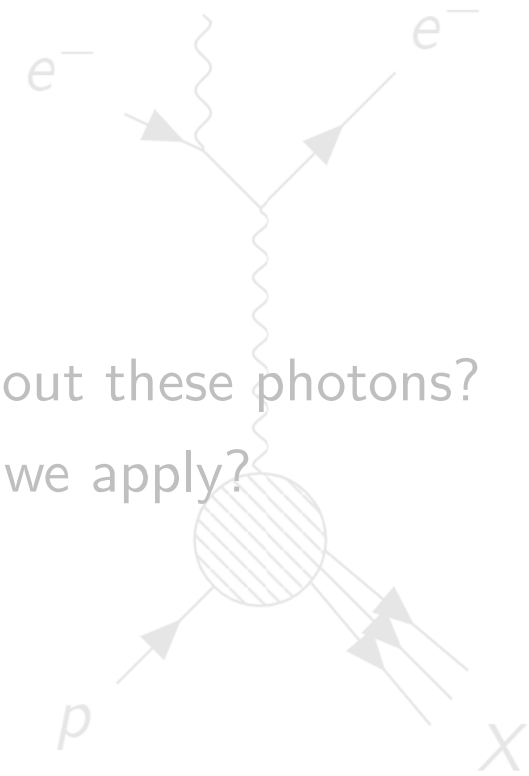
QED radiation



1. Does it matter?
2. What can we learn about these photons?
3. What corrections can we apply?

Altered electron momentum $\Longrightarrow$ altered x and Q^2

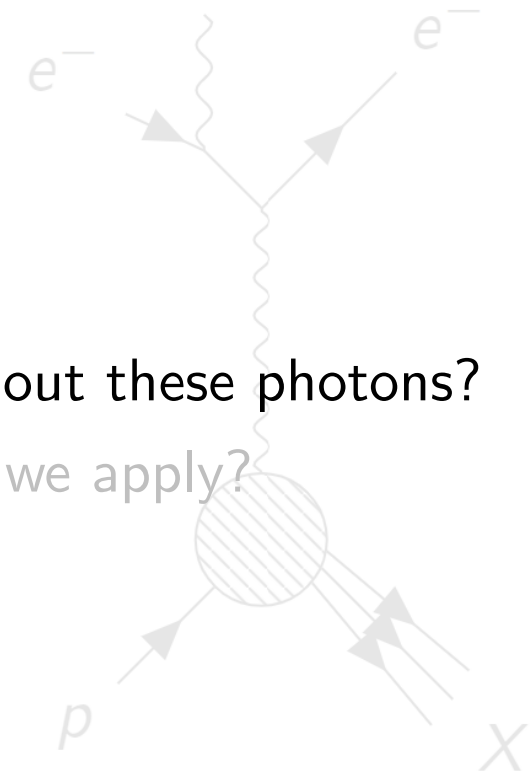
QED radiation



1. Does it matter? Yes!
2. What can we learn about these photons?
3. What corrections can we apply?

Altered electron momentum $\Longrightarrow$ altered x and Q^2

QED radiation



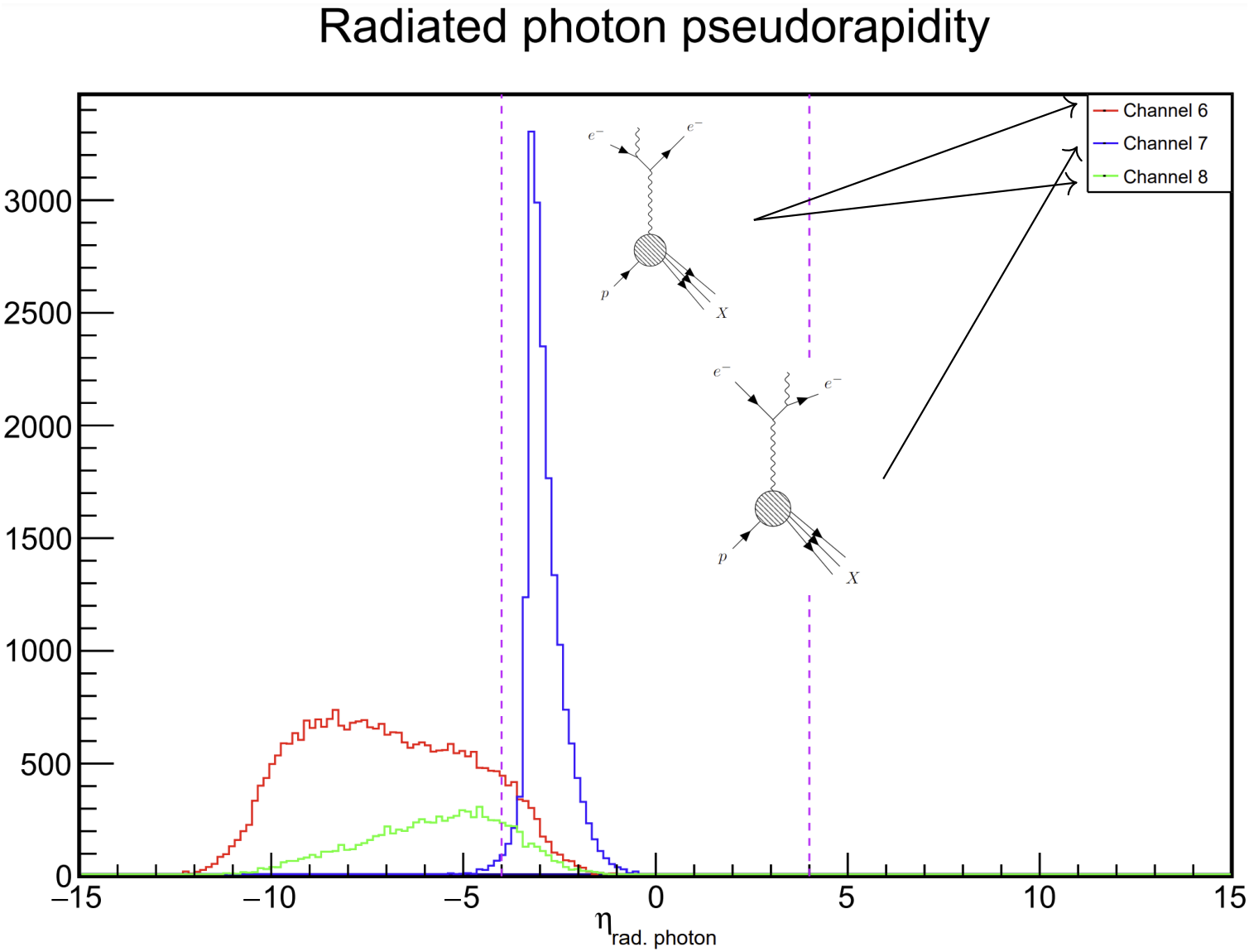
1. Does it matter? Yes!
2. What can we learn about these photons?
3. What corrections can we apply?

Altered electron momentum $\Longrightarrow$ altered x and Q^2

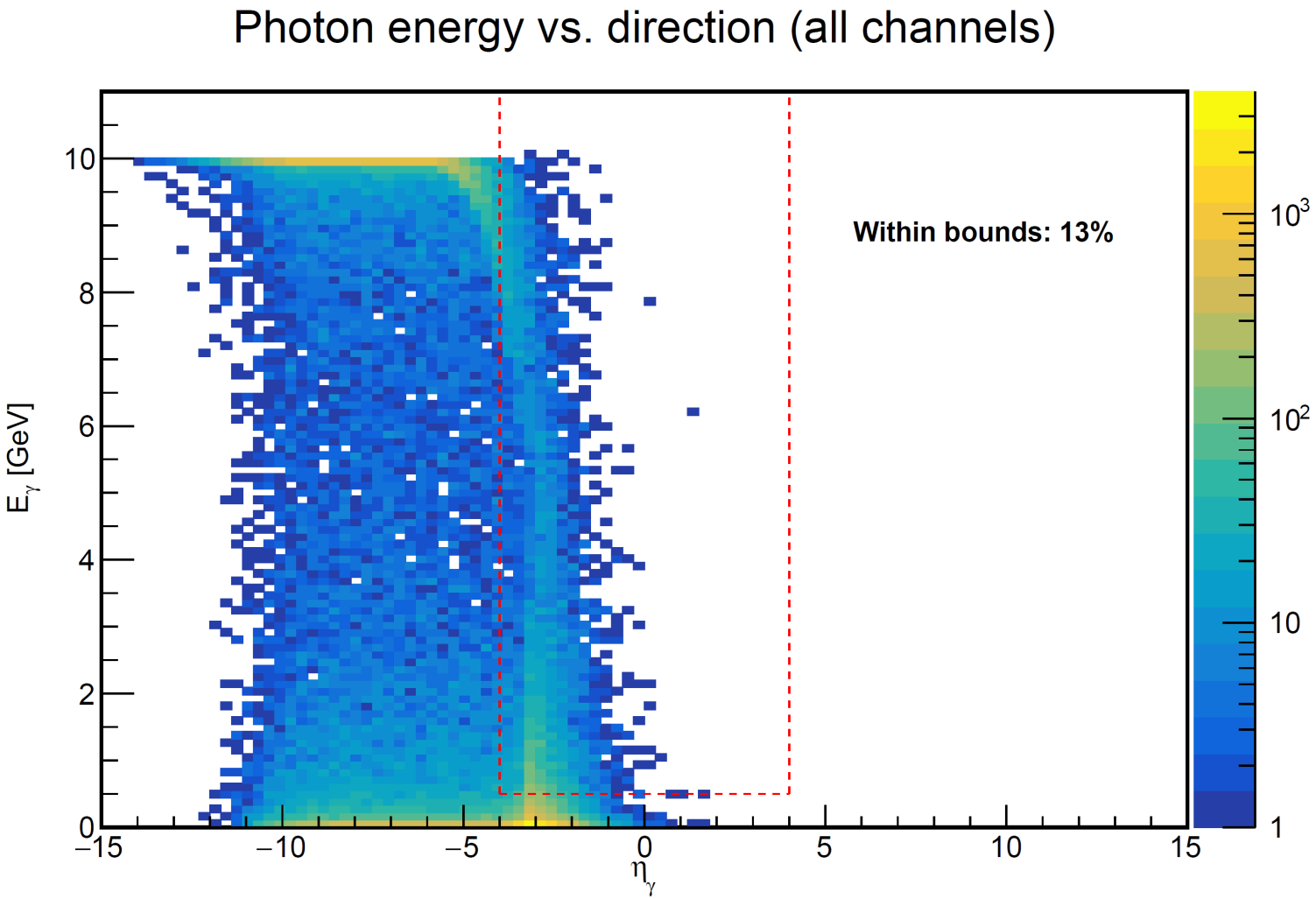
Radiative photon detection: η, $E_{\gamma_{\text{rad}}}$

Estimated photon detection thresholds: $E > 0.5$ GeV, $|\eta| < 4$

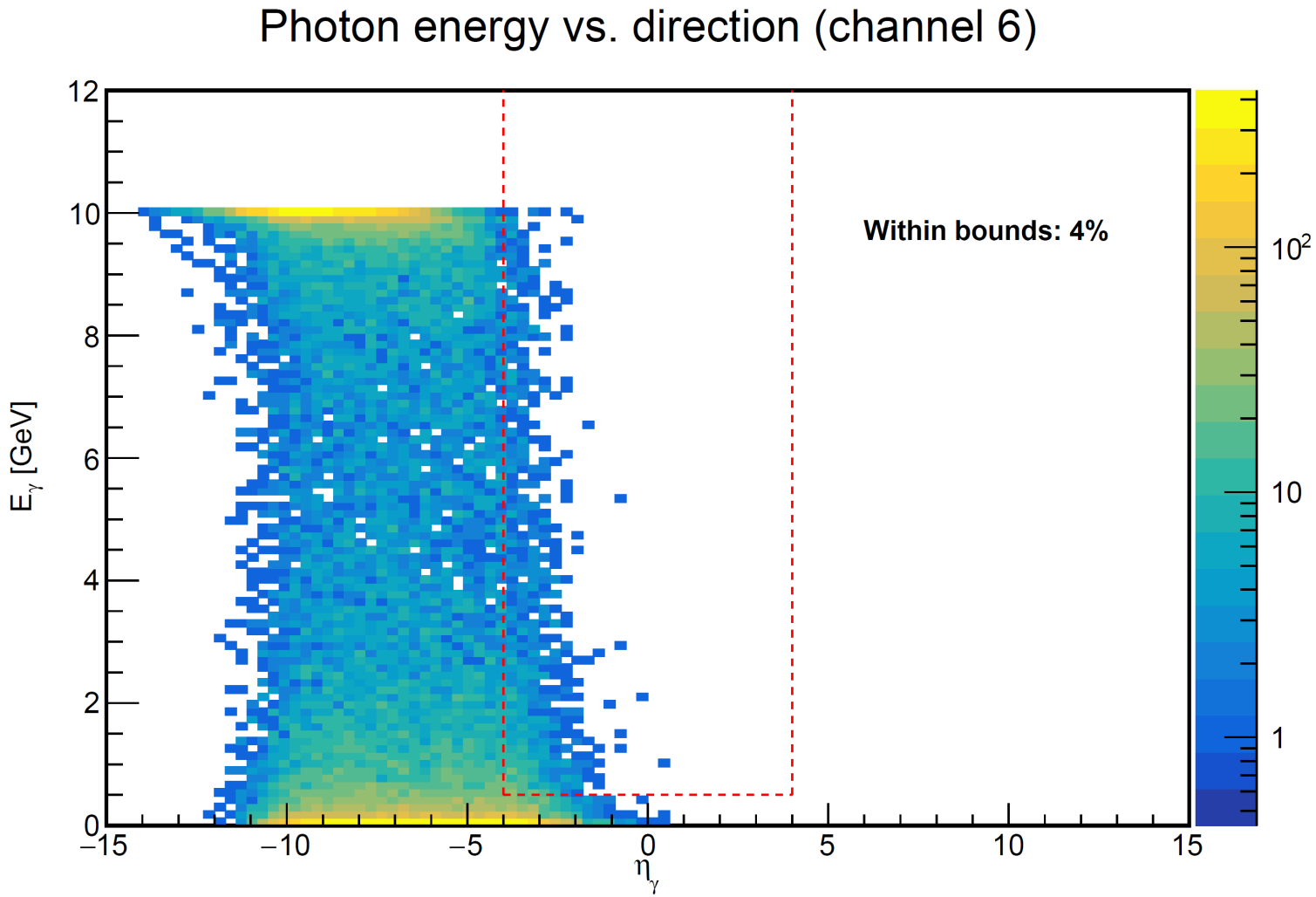
Radiative photon detection: η, $E_{\gamma_{rad}}$



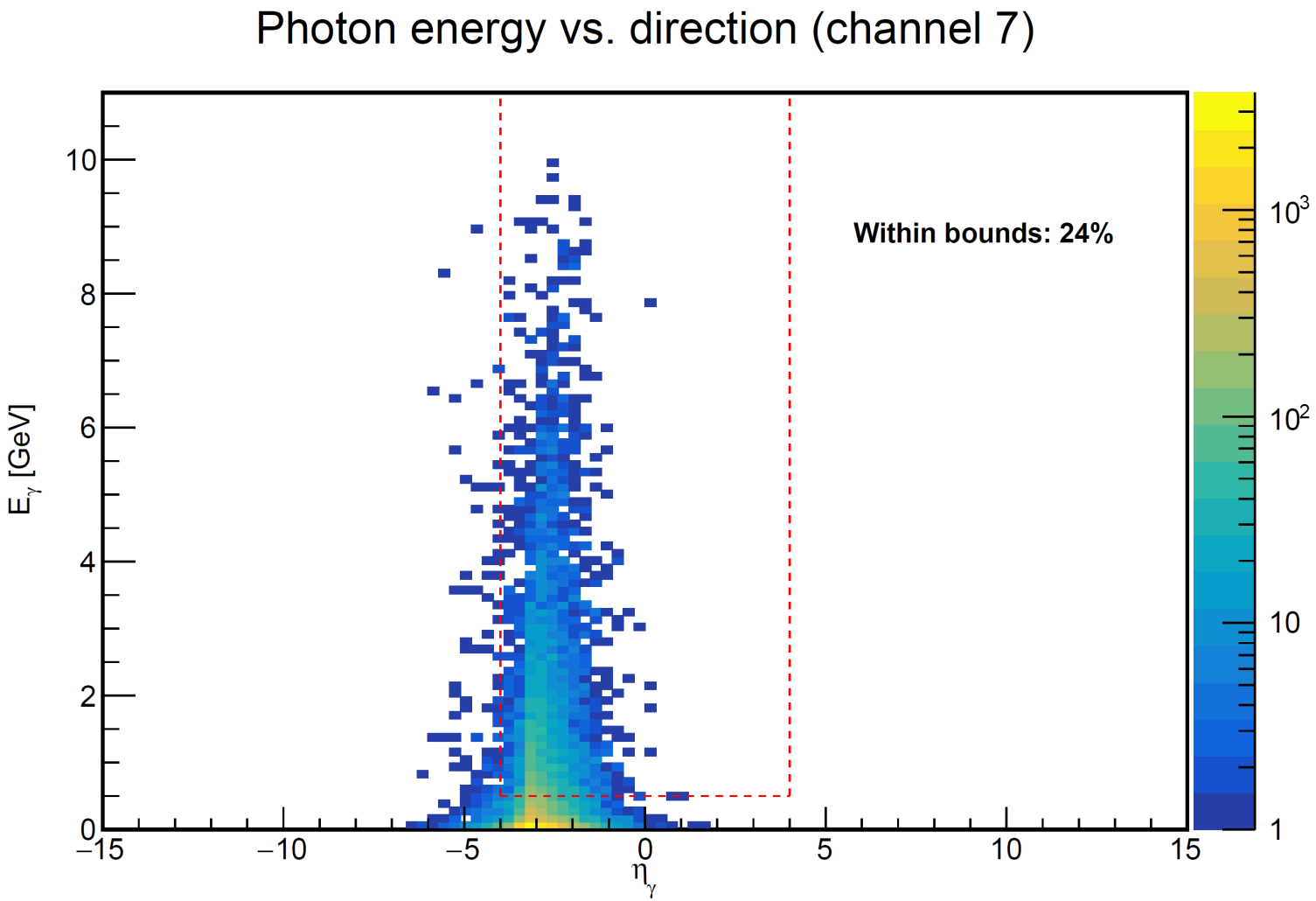
Radiative photon detection: η, $E_{\gamma_{\text{rad}}}$



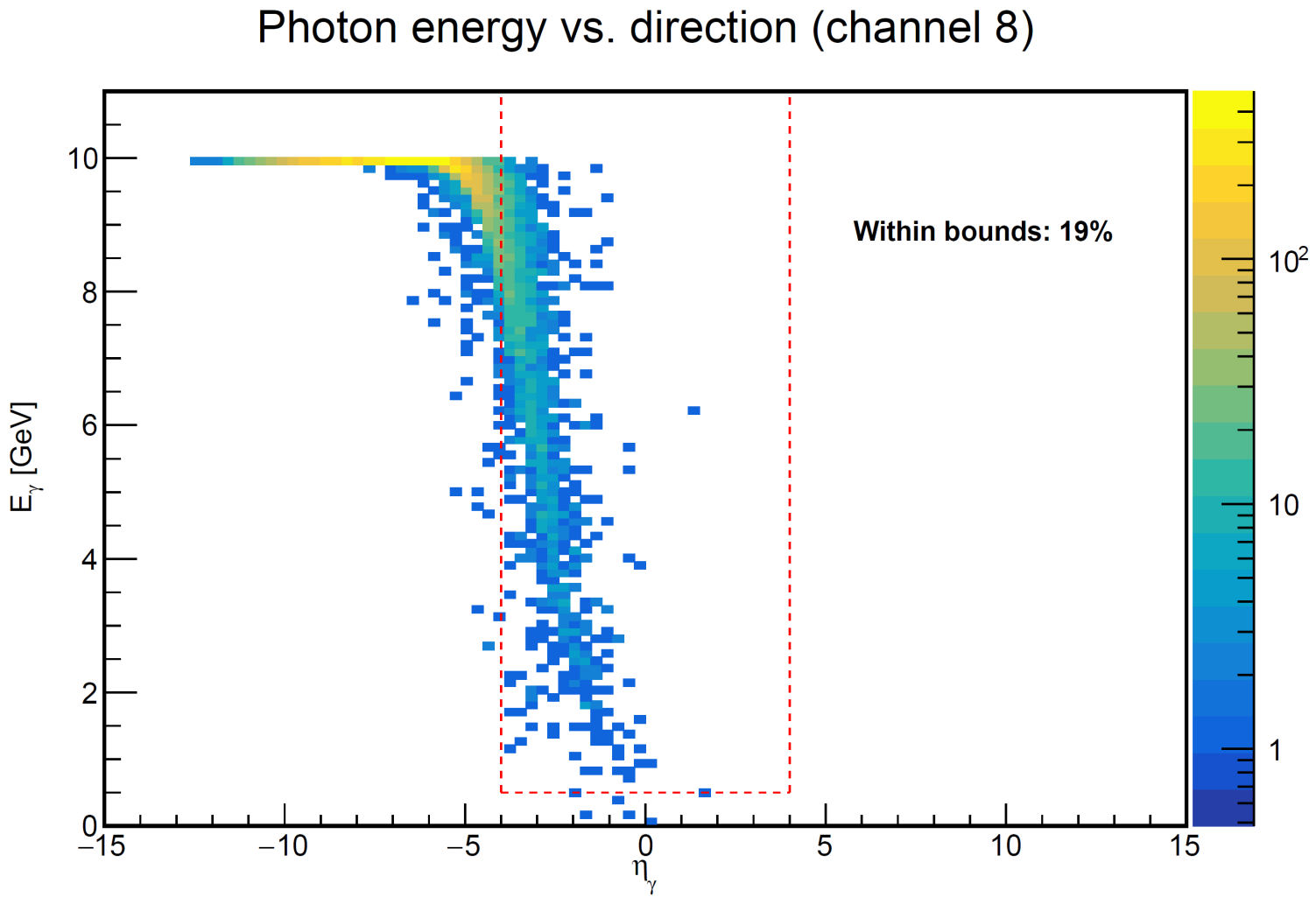
Radiative photon detection: η, $E_{\gamma_{\text{rad}}}$



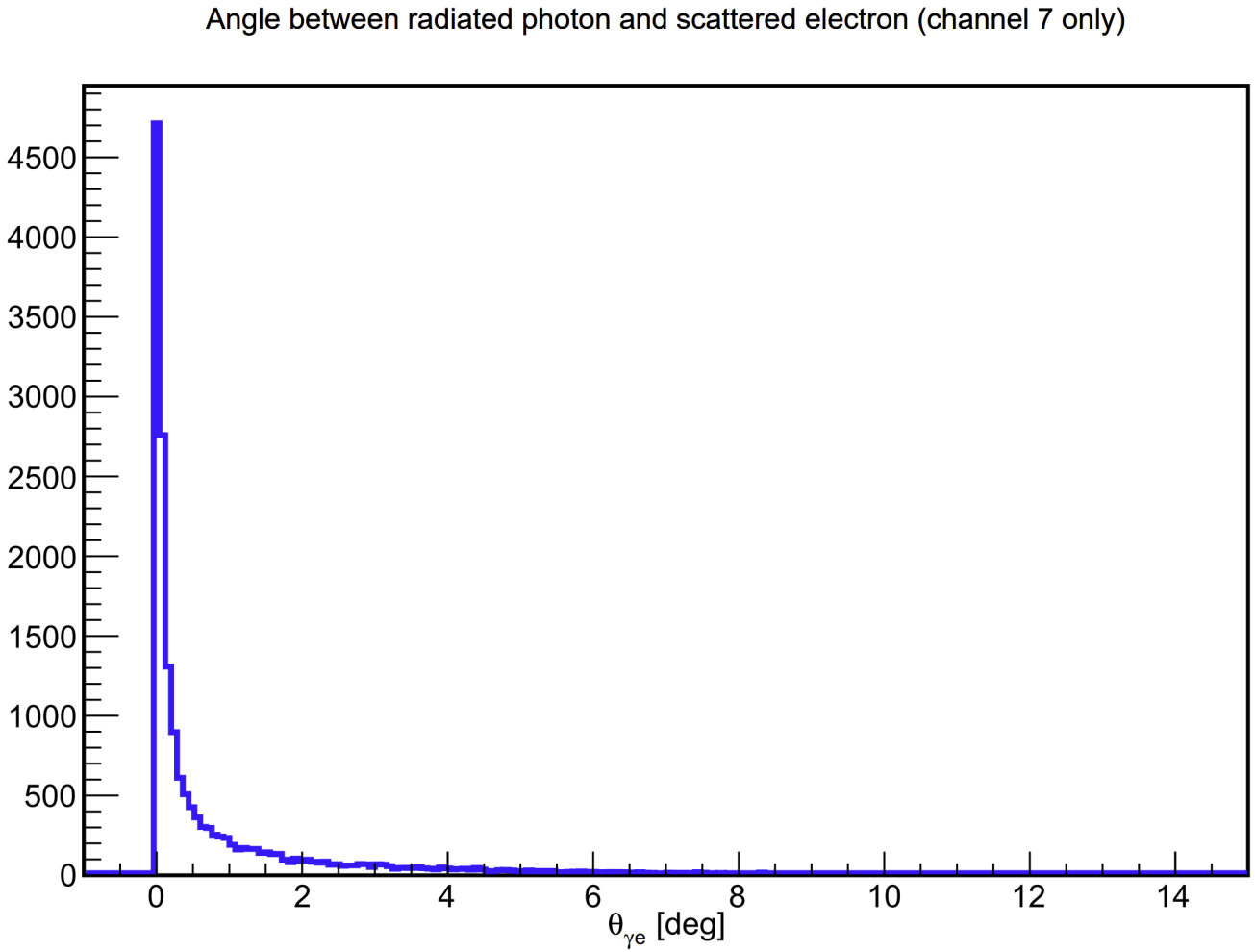
Radiative photon detection: η, $E_{\gamma_{\text{rad}}}$



Radiative photon detection: η, $E_{\gamma_{\text{rad}}}$

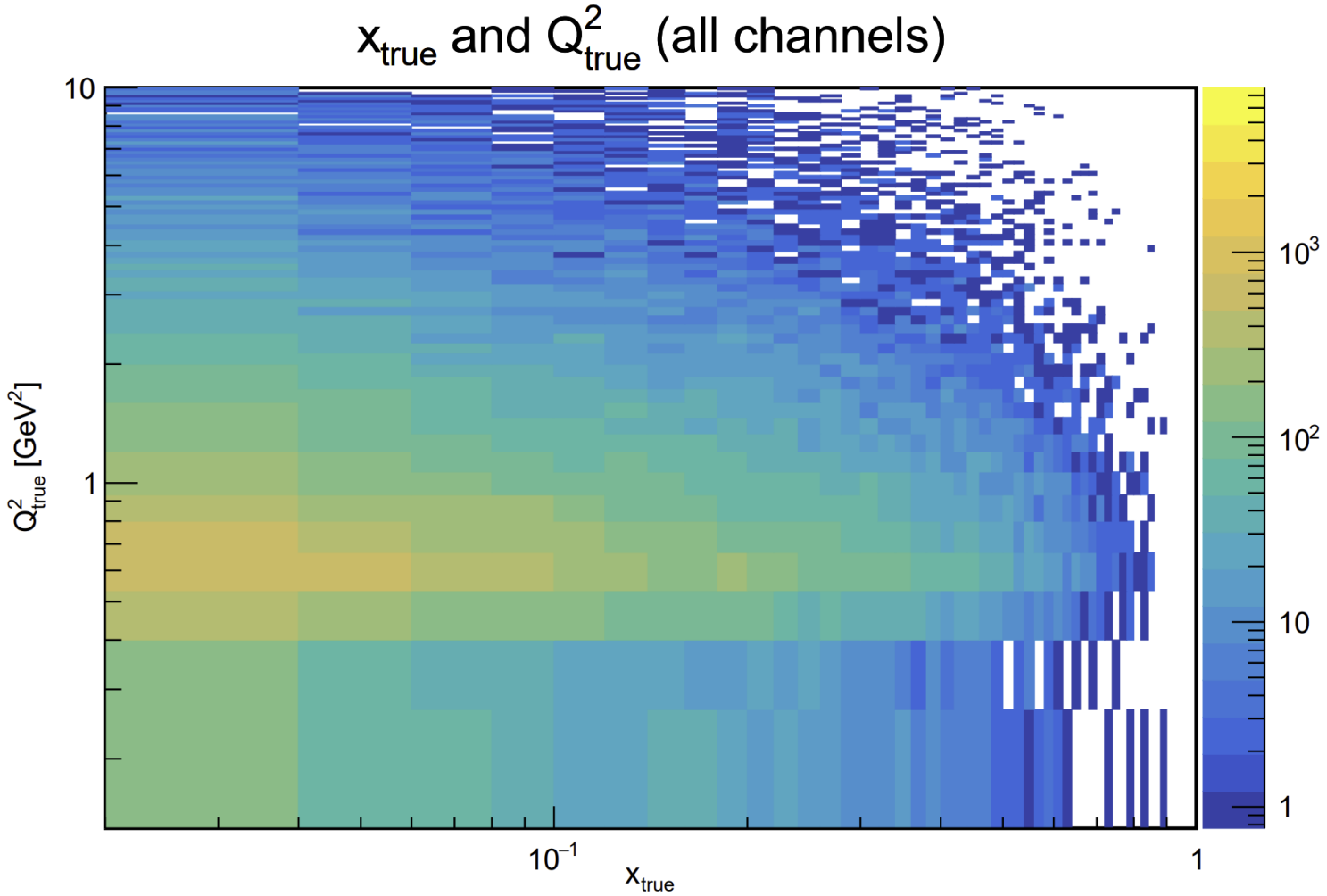


Radiative photon detection: $\theta_{\gamma e}$

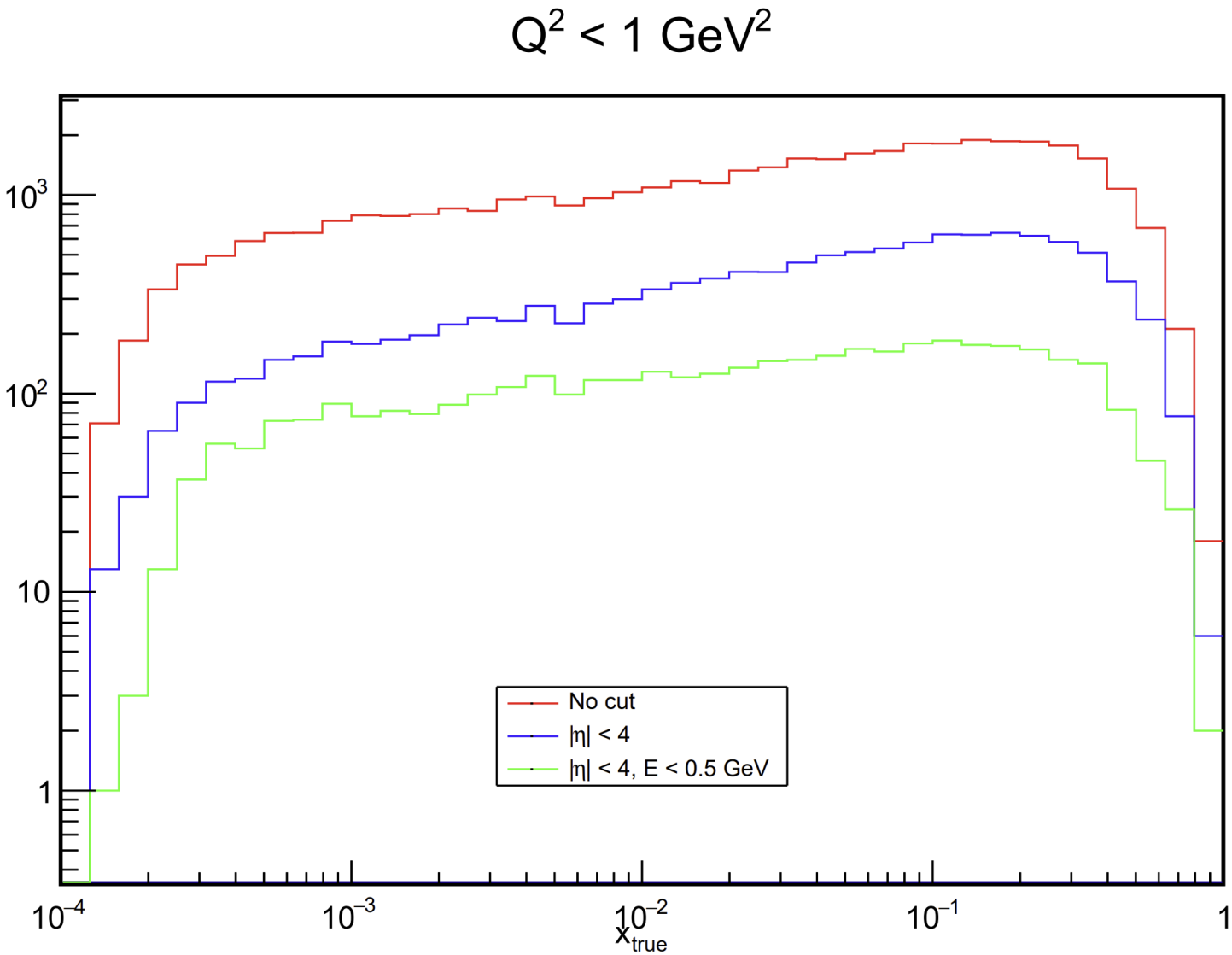


- Implications on (required) calorimeter position resolution

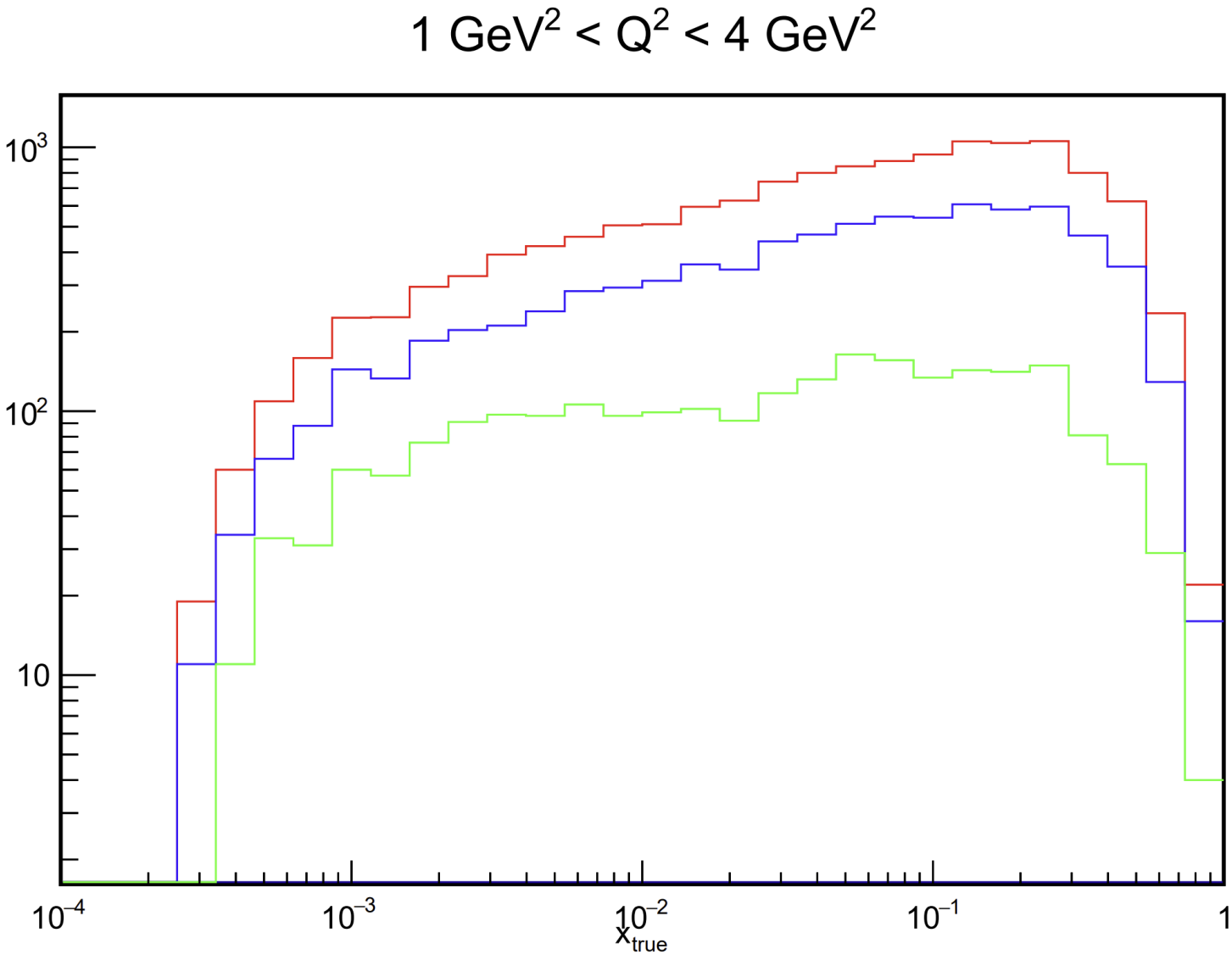
Radiative event characterization: x, Q^2



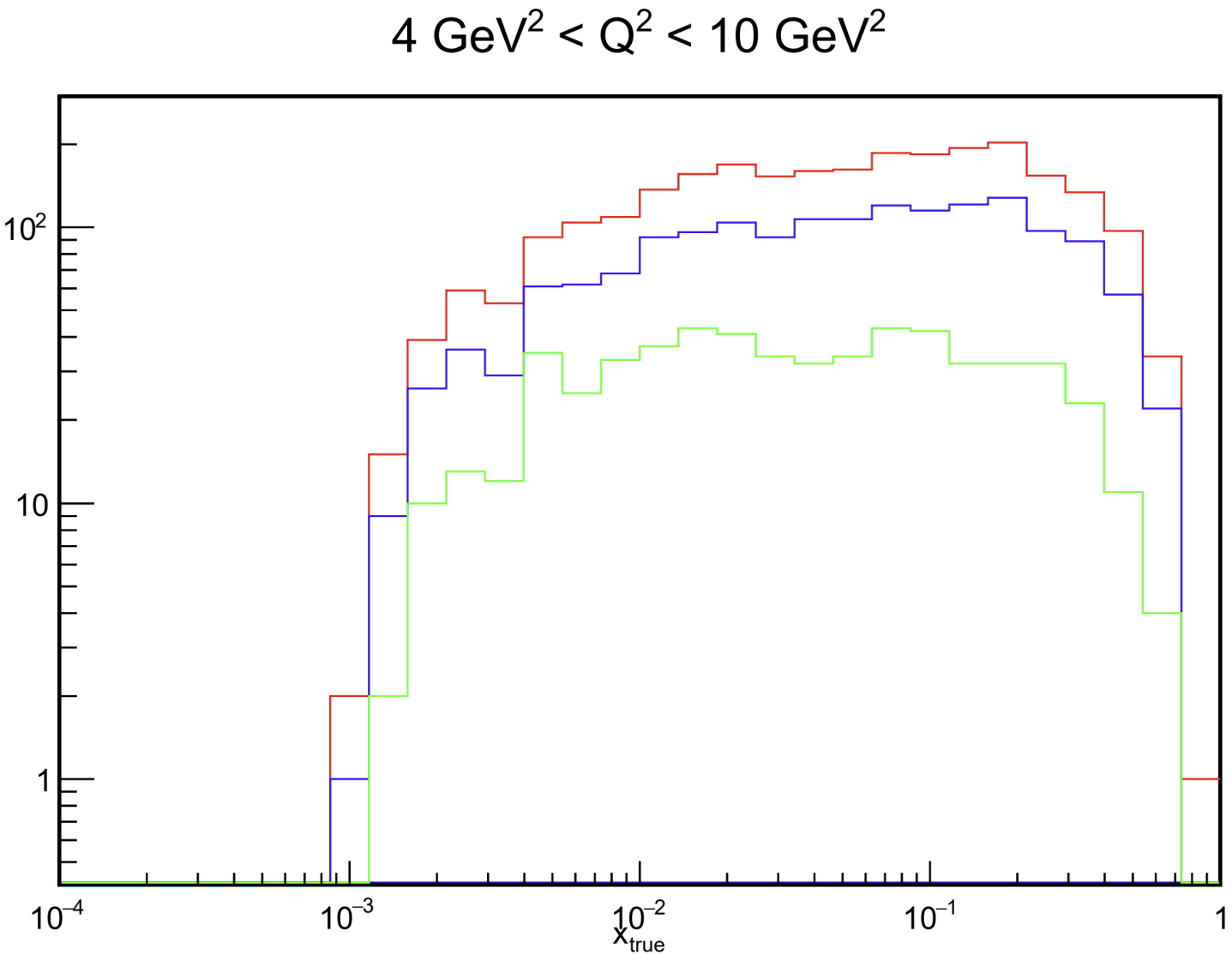
Radiative event characterization: x, Q^2



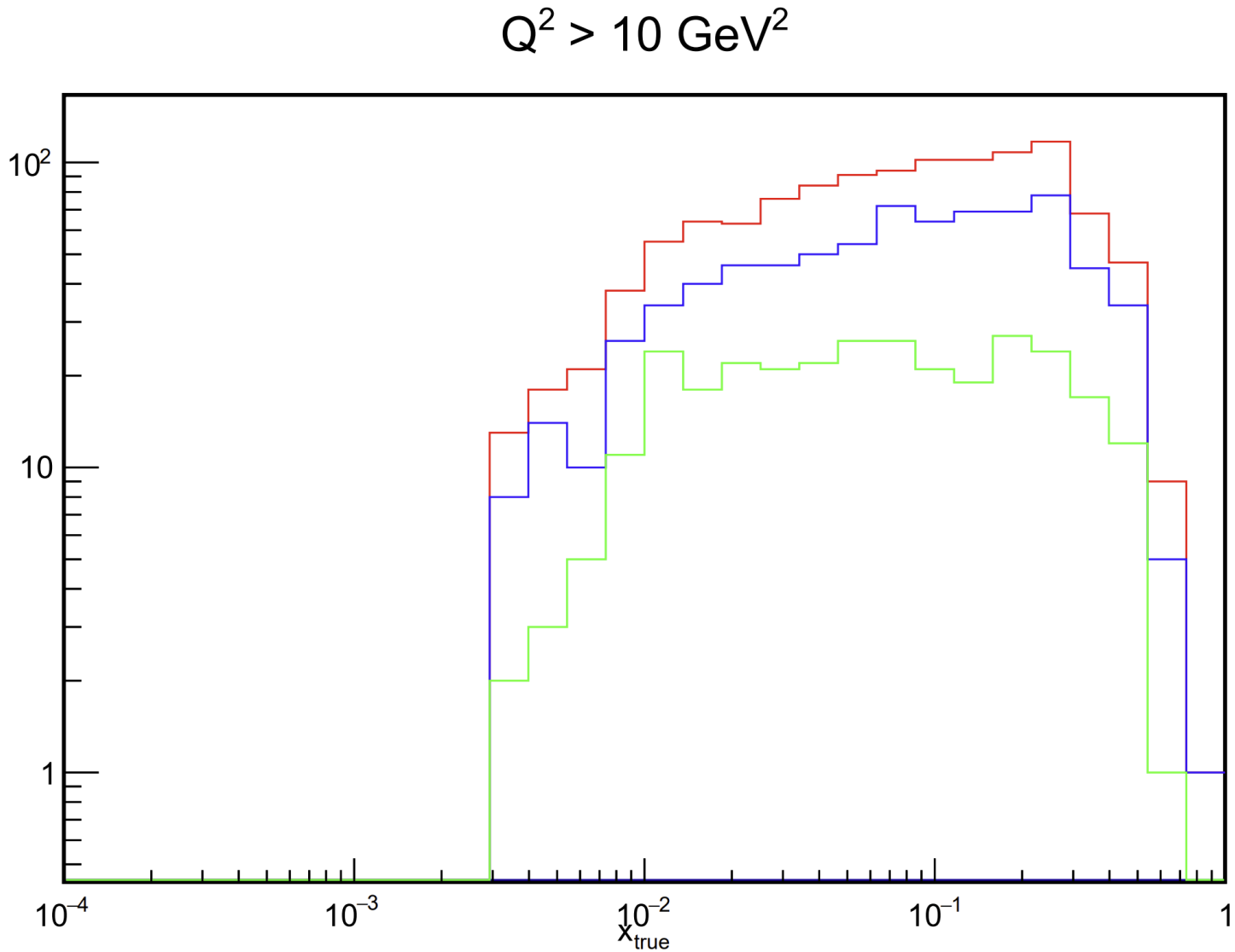
Radiative event characterization: x, Q^2



Radiative event characterization: x, Q^2



Radiative event characterization: x, Q^2



Radiative event characterization: x, Q^2

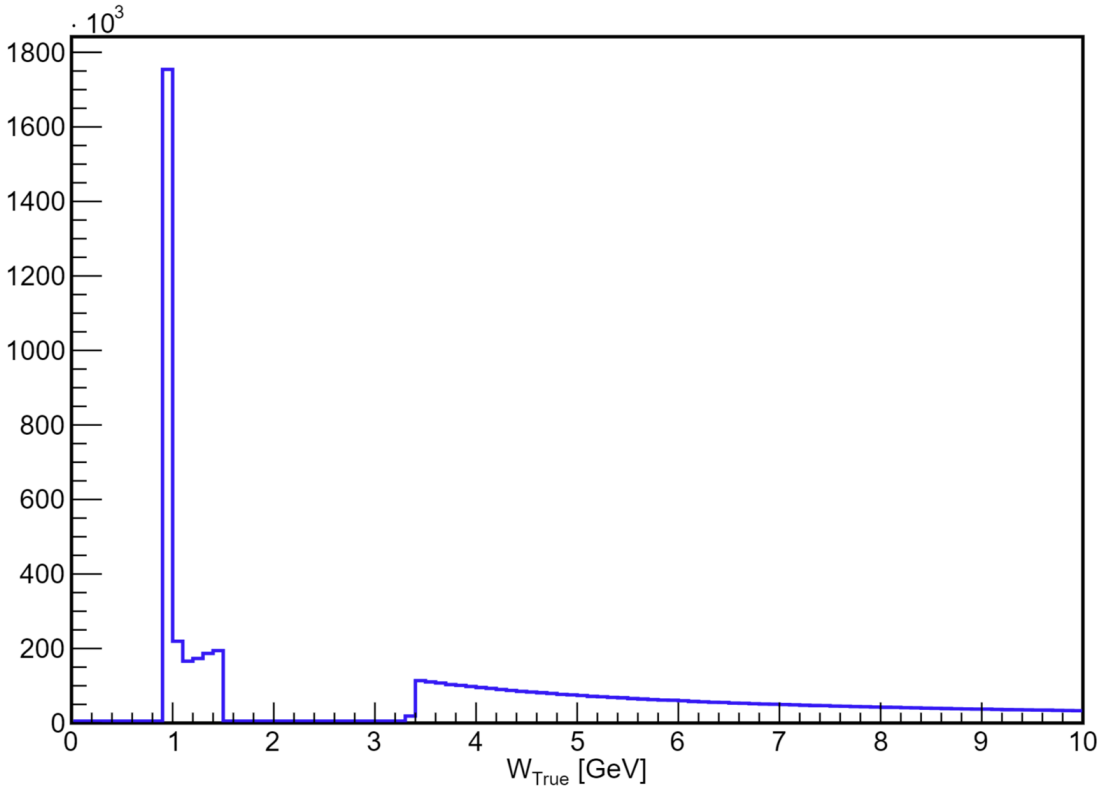
- Mid-low Q^2 (around 0.5$\sim$1 GeV^2), low $x \approx 10^{-2}$ is highest-statistics region

Radiative event characterization: x, Q^2

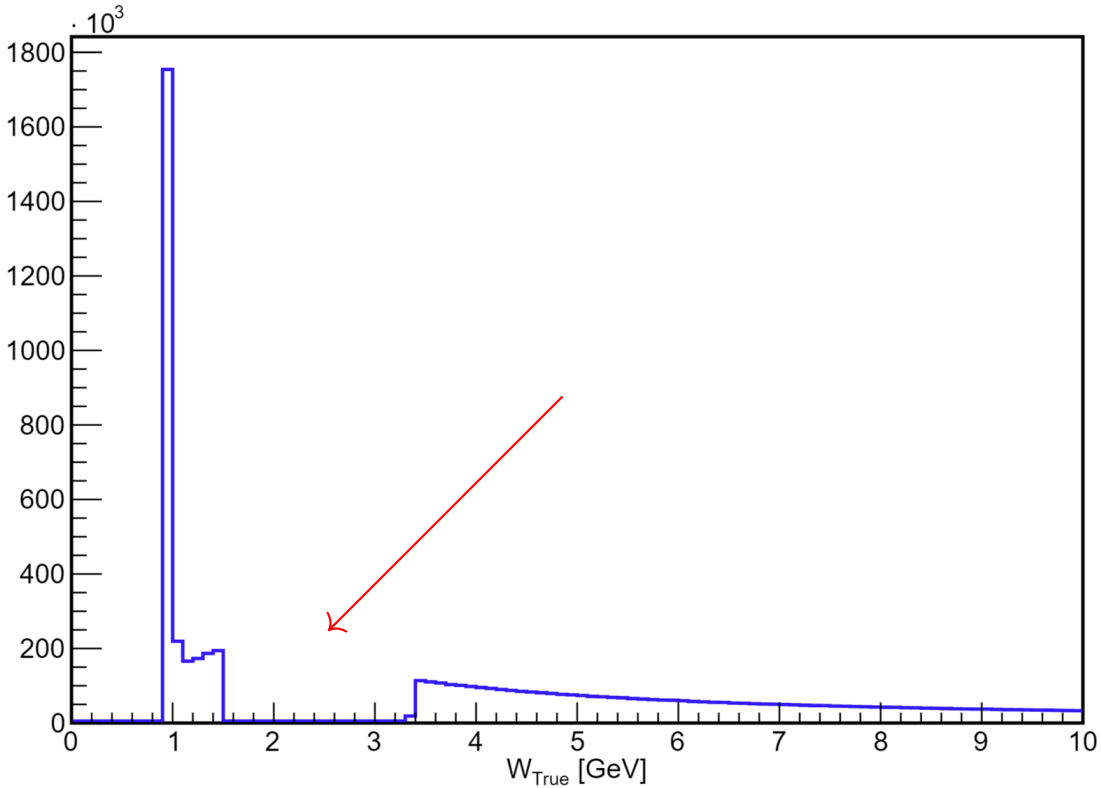
- Mid-low Q^2 (around 0.5$\sim$1 GeV^2), low $x \approx 10^{-2}$ is highest-statistics region
- Higher $Q^2 \implies$ higher accessible x; smaller available regions of x

Technical challenges: W_{true} gap

Technical challenges: W_{true} gap



Technical challenges: W_{true} gap

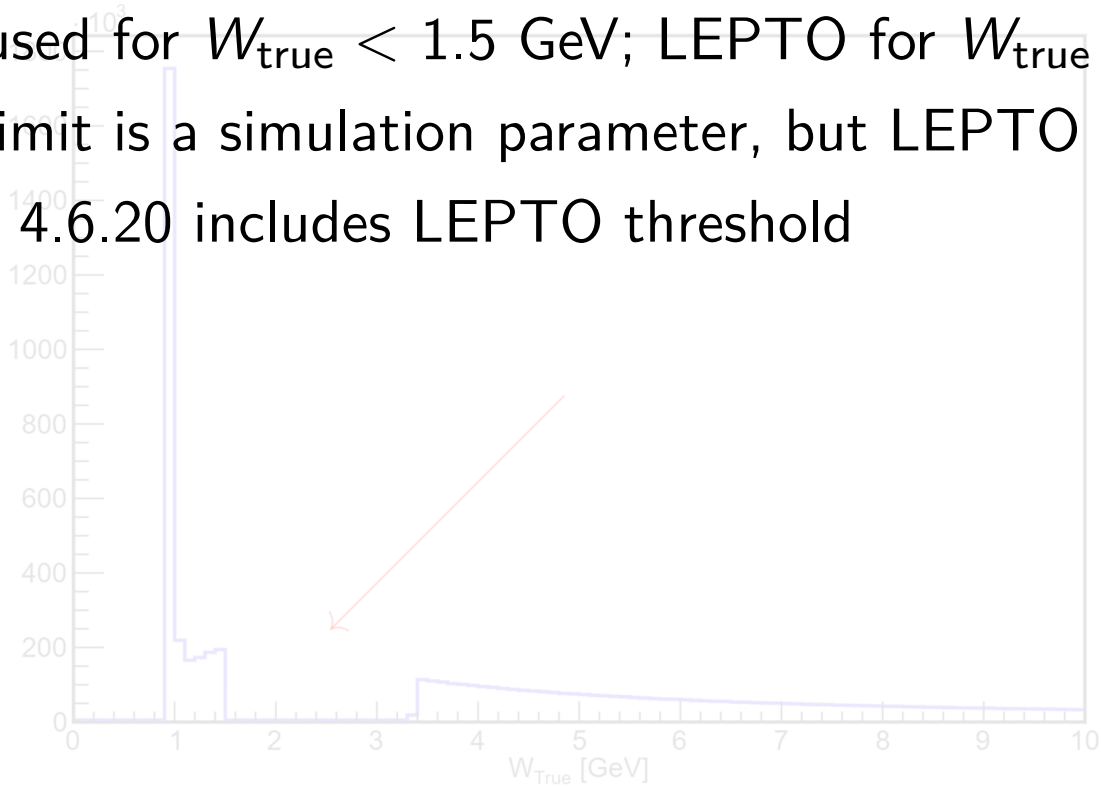


Technical challenges: W_{true} gap

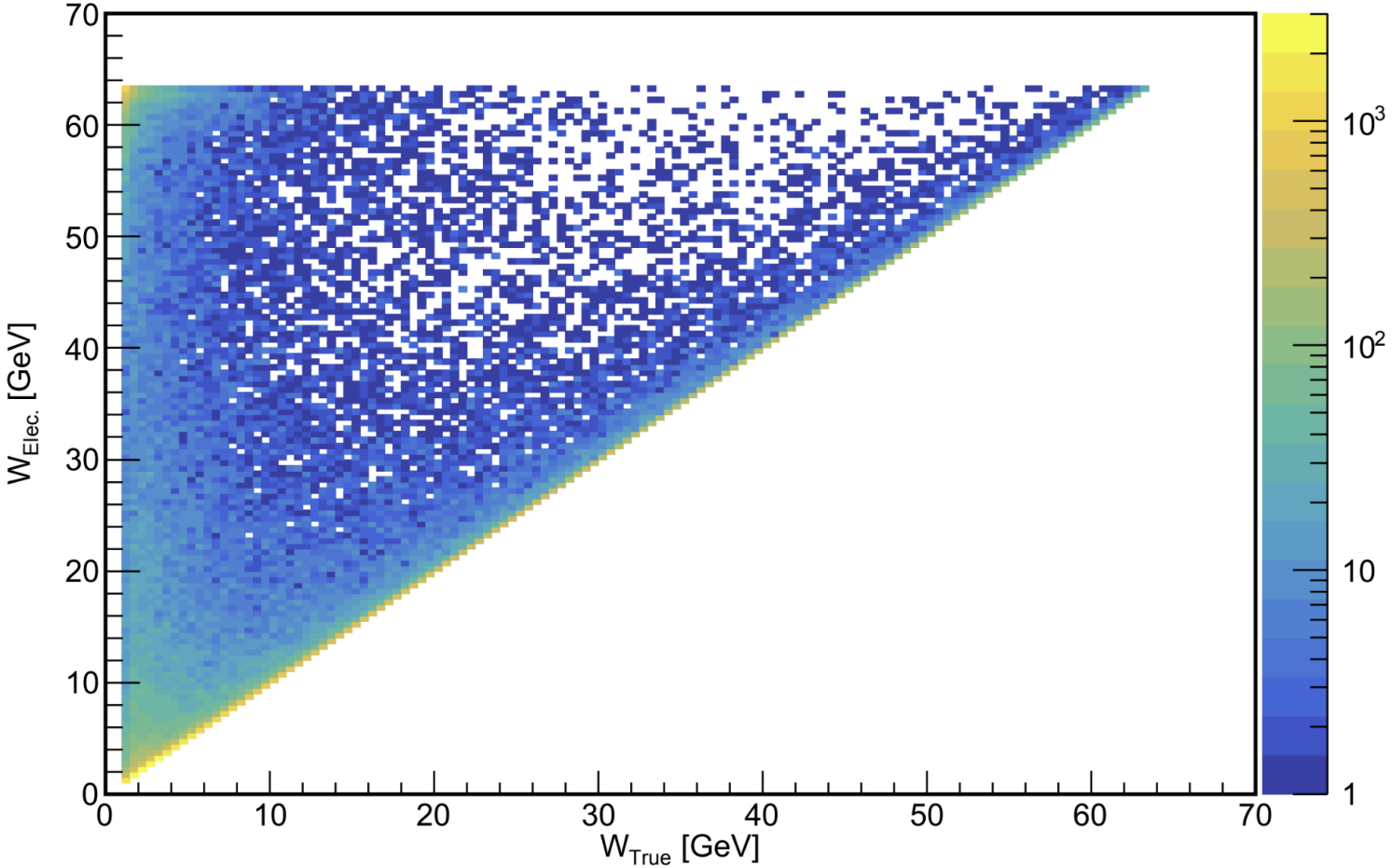
- Gap in events with 1.5 GeV $< W_{\text{true}} <$ 3.4 GeV

Technical challenges: W_{true} gap

- Gap in events with 1.5 GeV $< W_{\text{true}} <$ 3.4 GeV
- SOPHIA used for $W_{\text{true}} <$ 1.5 GeV; LEPTO for $W_{\text{true}} >$ 3.4 GeV
- SOPHIA limit is a simulation parameter, but LEPTO threshold is not
- Update to 4.6.20 includes LEPTO threshold



Technical challenges: W_{true} gap



Technical challenges: hadronization

```
TOTAL EVENT NUMBER      100000
NEUTRAL CURRENT / ELASTIC + SOFT&VIRTUAL          42388       8.5410E-01
NEUTRAL CURRENT / LEPT. INITIAL STATE RADIAT.     30509       3.5575E-01
NEUTRAL CURRENT / LEPT. FINAL STATE RADIAT.       17979       4.8998E-01
NEUTRAL CURRENT / LEPT. COMPTON CONTRIBUTION       9124       4.2735E-01

 ************************************************************************
 Program performance
       100000 Events were accepted by HERACLES
            0 Events do not have min W-remnant in HERACLES
        75019 Events passed fragmentation in LEPTO
            0 Events not accepted for fragmentation in LEPTO
          746 Events failed fragmentation in LEPTO
        11490 Events passed fragmentation in SOPHIA
        12745 Events failed fragmentation in SOPHIA
 Cross section was corrected:
 Total cross section is now    SIGTOT =  0.15047E+04 nb
```

Technical challenges: hadronization

```
TOTAL EVENT NUMBER      100000
NEUTRAL CURRENT / ELASTIC + SOFT&VIRTUAL          42388       8.5410E-01
NEUTRAL CURRENT / LEPT. INITIAL STATE RADIAT.     30509       3.5575E-01
NEUTRAL CURRENT / LEPT. FINAL STATE RADIAT.       17979       4.8998E-01
NEUTRAL CURRENT / LEPT. COMPTON CONTRIBUTION       9124       4.2735E-01

 ************************************************************************
 Program performance
      100000 Events were accepted by HERACLES
           0 Events do not have min W-remnant in HERACLES
       75019 Events passed fragmentation in LEPTO
           0 Events not accepted for fragmentation in LEPTO
         746 Events failed fragmentation in LEPTO
       11490 Events passed fragmentation in SOPHIA
       12745 Events failed fragmentation in SOPHIA
 Cross section was corrected:
 Total cross section is now    SIGTOT =  0.15047E+04 nb
```

Technical challenges: hadronization

```
TOTAL EVENT NUMBER      100000
NEUTRAL CURRENT / ELASTIC + SOFT&VIRTUAL            42388       8.5410E-01
NEUTRAL CURRENT / LEPT. INITIAL STATE RADIAT.       30509       3.5575E-01
NEUTRAL CURRENT / LEPT. FINAL STATE RADIAT.         17979       4.8998E-01
NEUTRAL CURRENT / LEPT. COMPTON CONTRIBUTION         9124       4.2735E-01
```

- Failed, partial, non-accepted hadronizations by LEPTO and SOPHIA (e.g. for looking at X instead e^-)

```
      100000 Events were accepted by HERACLES
           0 Events do not have min W-remnant in HERACLES
       75019 Events passed fragmentation in LEPTO
           0 Events not accepted for fragmentation in LEPTO
         746 Events failed fragmentation in LEPTO
       11490 Events passed fragmentation in SOPHIA
       12745 Events failed fragmentation in SOPHIA
 Cross section was corrected:
 Total cross section is now    SIGTOT =  0.15047E+04 nb
```

Technical challenges: hadronization

```
TOTAL EVENT NUMBER      100000
NEUTRAL CURRENT / ELASTIC + SOFT&VIRTUAL            42388       8.5410E-01
NEUTRAL CURRENT / LEPT. INITIAL STATE RADIAT.       30509       3.5575E-01
NEUTRAL CURRENT / LEPT. FINAL STATE RADIAT.         17979       4.8998E-01
NEUTRAL CURRENT / LEPT. COMPTON CONTRIBUTION         9124       4.2735E-01
 ********** ********** ********** ********** ********** ********** **********
 Program HERACLES
      100000 Events were accepted by HERACLES
 ********** ********** ********** ********** ********** ********** **********
       75019 Events passed fragmentation in LEPTO
           0 Events not accepted for fragmentation in LEPTO
         746 Events failed fragmentation in LEPTO
       11490 Events passed fragmentation in SOPHIA
       12745 Events failed fragmentation in SOPHIA
 Cross section was corrected:
 Total cross section is now    SIGTOT =  0.15047E+04 nb
```

- Failed, partial, non-accepted hadronizations by LEPTO and SOPHIA (e.g. for looking at X instead e^-)
- Issues with conversion to HepMC and passing through `eic-smear`

Technical challenges: hadronization

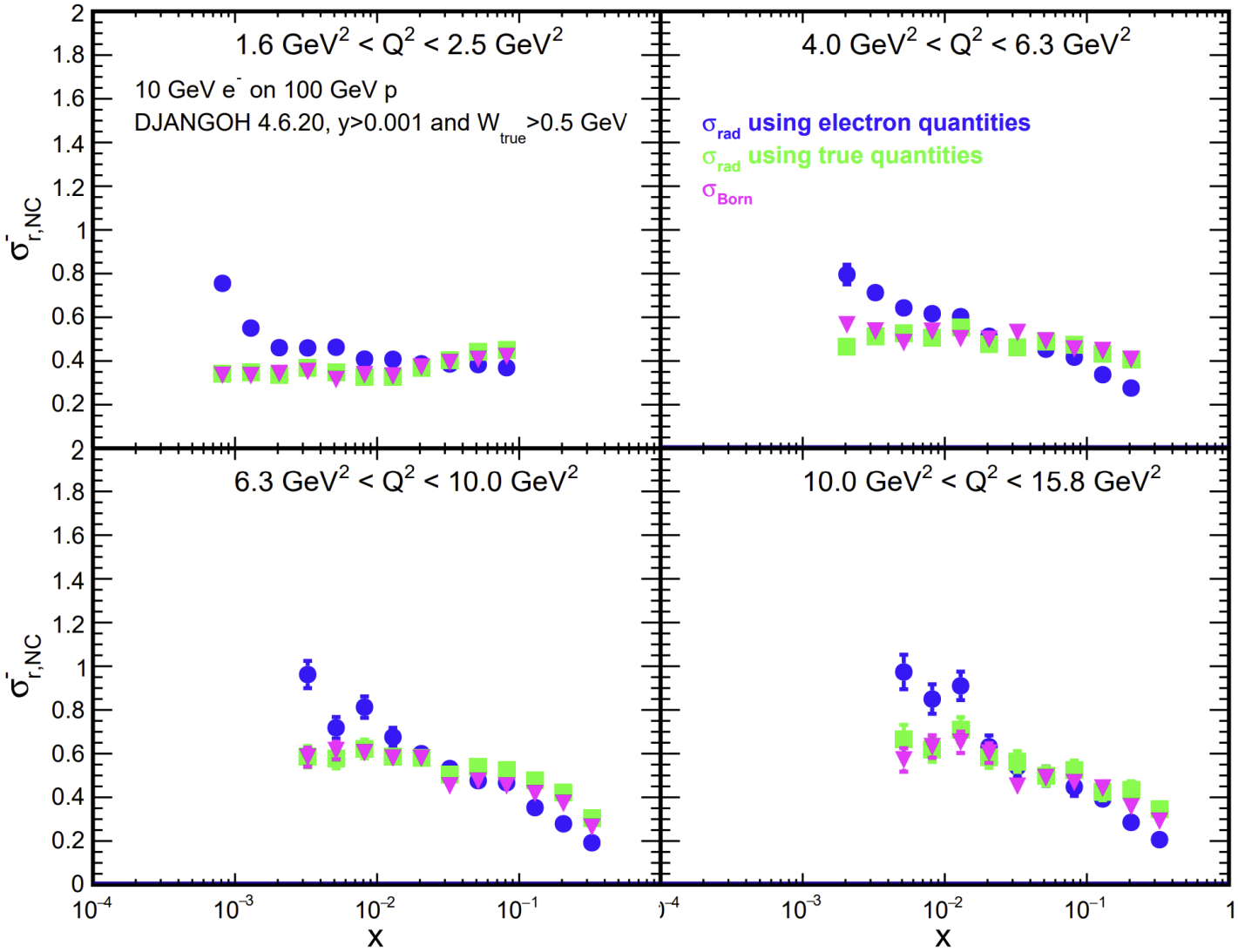
```
TOTAL EVENT NUMBER       100000
NEUTRAL CURRENT / ELASTIC + SOFT&VIRTUAL          42388       8.5410E-01
NEUTRAL CURRENT / LEPT. INITIAL STATE RADIAT.     30509       3.5575E-01
NEUTRAL CURRENT / LEPT. FINAL STATE RADIAT.       17979       4.8998E-01
NEUTRAL CURRENT / LEPT. COMPTON CONTRIBUTION       9124       4.2735E-01

      100000 Events were accepted by HERACLES
        75019 Events passed fragmentation in LEPTO
          746 Events failed fragmentation in LEPTO
        11490 Events passed fragmentation in SOPHIA
        12745 Events failed fragmentation in SOPHIA
 Cross section was corrected:
 Total cross section is now    SIGTOT =  0.15047E+04 nb
```

- Failed, partial, non-accepted hadronizations by LEPTO and SOPHIA (e.g. for looking at X instead e^{-})
- Issues with conversion to `HepMC` and passing through `eic-smear`
- SOPHIA/LEPTO for mid-W events

Optimizing the SOPHIA/LEPTO boundary

- Variation in reduced cross section

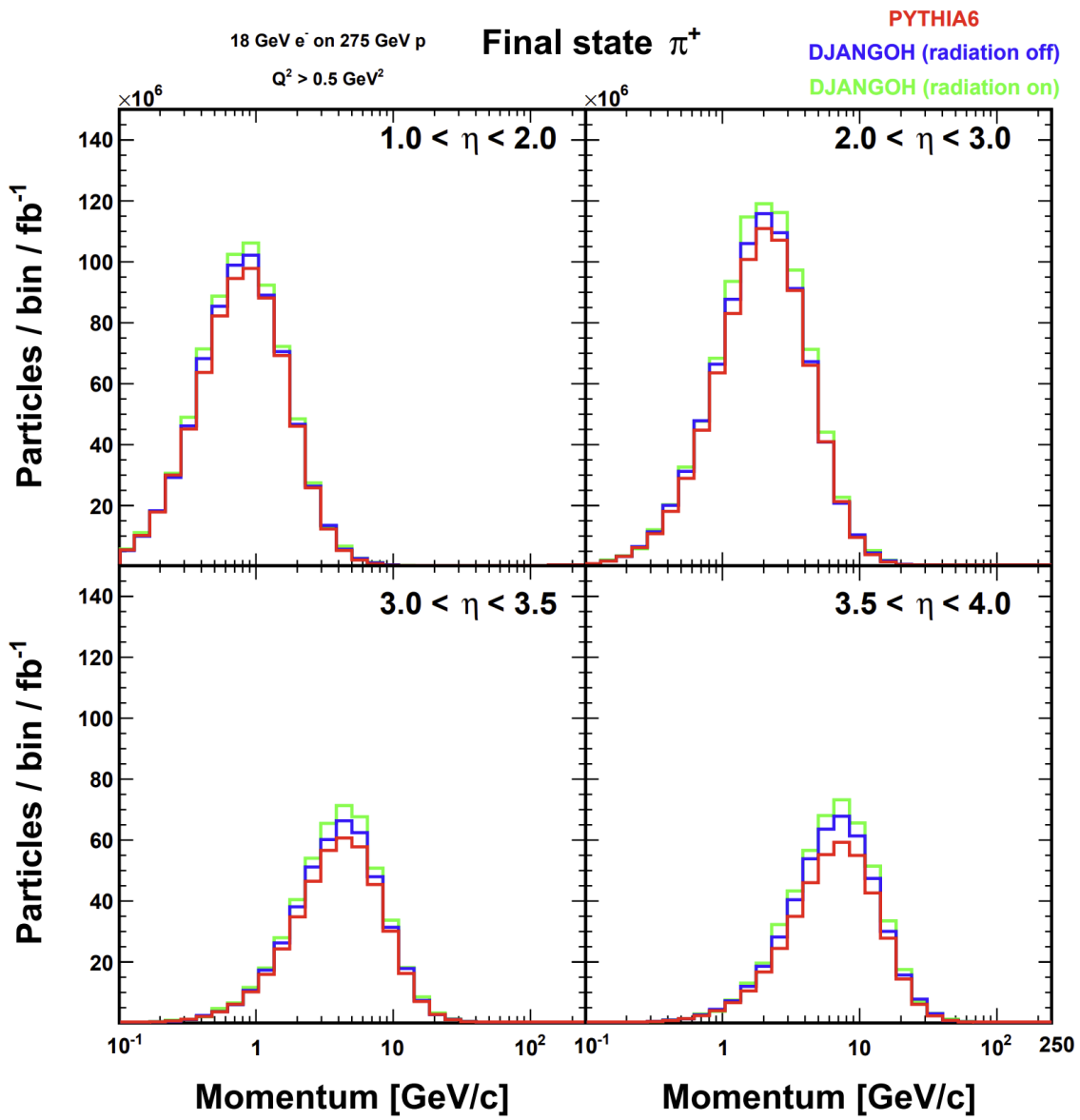
Optimizing the SOPHIA/LEPTO boundary



Optimizing the SOPHIA/LEPTO boundary

- Variation in reduced cross section
- Variation in final particle counts; comparing to `pythiaeRHIC`

Optimizing the SOPHIA/LEPTO boundary



Optimizing the SOPHIA/LEPTO boundary

- Variation in reduced cross section
- Variation in final particle counts; comparing to `pythiaeRHIC`
- Fitting to real data

Current status and future work

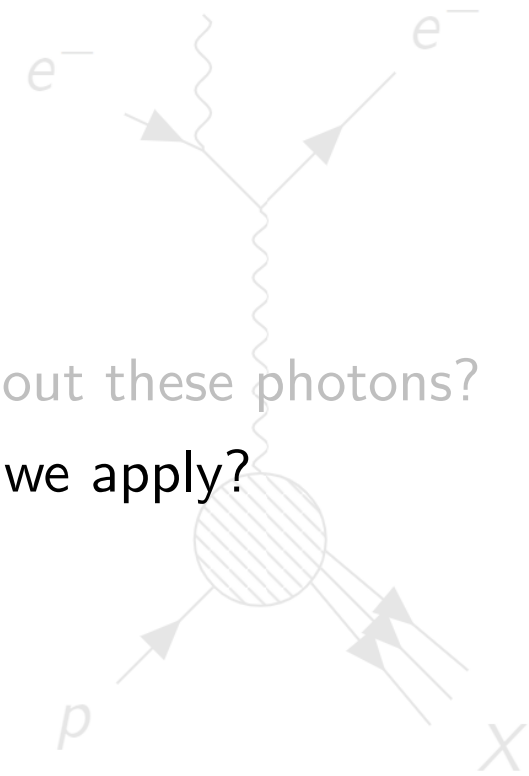
Radiative QED photons confuse our measurements of kinematic variables (x, Q^2) that yield information on parton substructure. Accurate simulations can help us understand and correct for them.

Current status and future work

Radiative QED photons confuse our measurements of kinematic variables (x, Q^2) that yield information on parton substructure. Accurate simulations can help us understand and correct for them.

- Update for DJANGOH on BNL cluster underway
- Technical issues, questions on DJANGOH's approach
- Incorporating detector elements
- Sanity and cross-checks with other simulations (e.g. `pythiaeRHIC`)
- Closer looks at affected areas of phase space

QED radiation

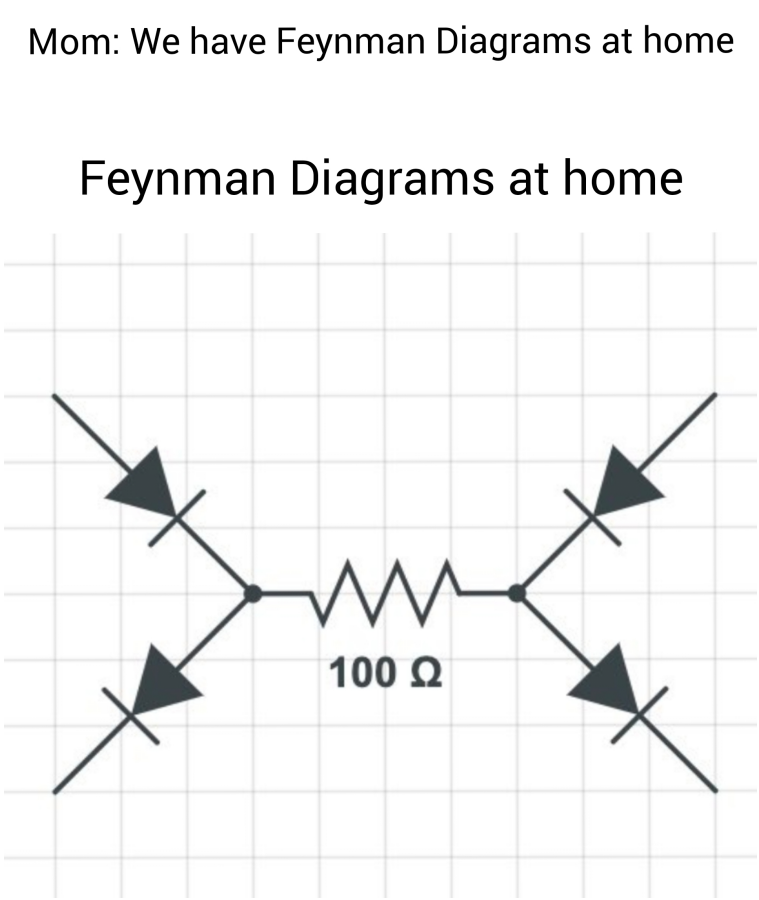


1. Does it matter? Yes!
2. What can we learn about these photons?
3. What corrections can we apply?

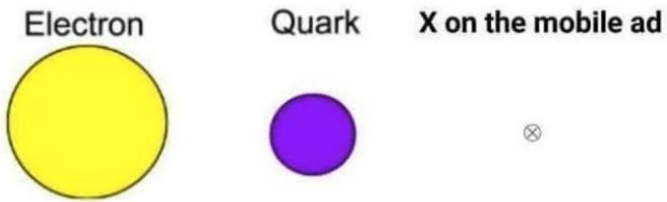
Altered electron momentum $\Longrightarrow$ altered x and Q^2

Any questions?

Mom: We have Feynman Diagrams at home



Smallest things in the Universe



Backup slides

yay

Channel 8 mysteries