# Tau leptons at FCC-ee: Decay identification and polarization measurements

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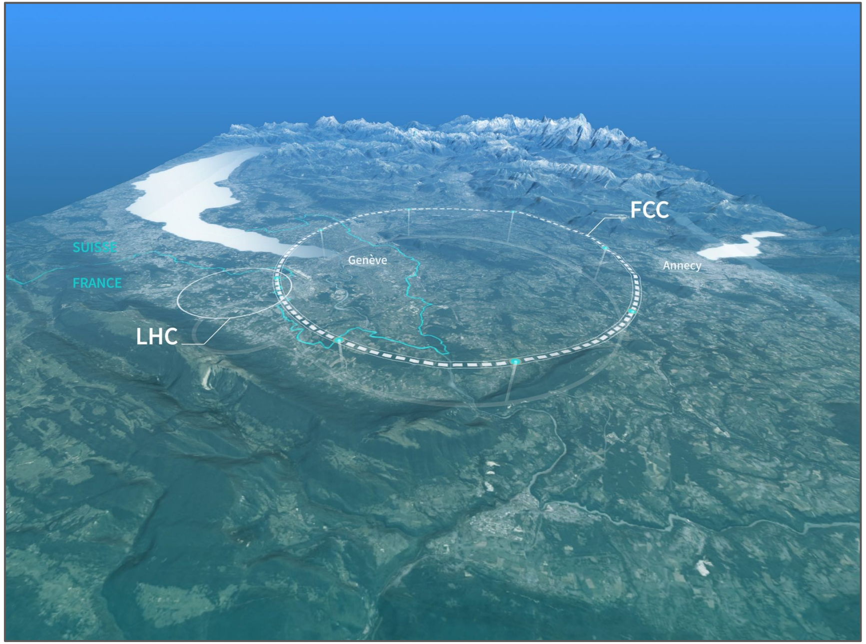
# Outline

1. FCC-ee overview
2. Why tau leptons?
3. Decay channel ID (BDTs)
4. Polarization measurements
5. Conclusions

# FCC-ee: Proposed high-energy lepton collider




**$e^+/e^-$ collider, 100 km circumference**
Electroweak physics at Z pole

- New measurements
  - find SM inconsistencies
- Project finer uncertainties
  - SM parameters

- **Ideally**: Systematic < statistical uncertainties (acceptance, background)

# FCC-ee Luminosity

$$\mathcal{L} = \frac{N}{A \cdot \Delta t}$$

$\uparrow L \Rightarrow \uparrow$ Rate of collisions

★ $\uparrow$ P(boson production)
★ $\uparrow$ data points for precision measurements

- Heavy bosons (Z, W, H) ✓ (1 LEP/2 min)
- FCC-ee vs LEP: *L* x 10^5 (Z pole)
- Statistical uncertainty up to 300x smaller than LEP*

- Ambitious Z $\rightarrow \tau+\tau-$ polarization study — achieve precision target*:

$$< 5 \cdot 10^{-6} \text{ (30x better vs present, } 1.8 \cdot 10^{-4}\text{)}$$


*EPJ Special Topics, Vol. 228, Issue 2: https://link.springer.com/journal/11734/volumes-and-issues/228-2

# Tau polarization

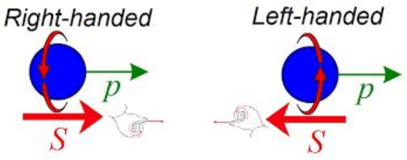
1. FCC-ee overview
2. Why tau leptons?
3. Decay channel ID (BDTs)
4. Polarization measurements
5. Conclusions

# What is tau polarization?

- Describes orientation of spin angular momentum w.r.t. momentum direction

- Helicity: projection of spin onto momentum

- Tau lepton: spin ±½
  - RH: dir(spin) = dir(motion)



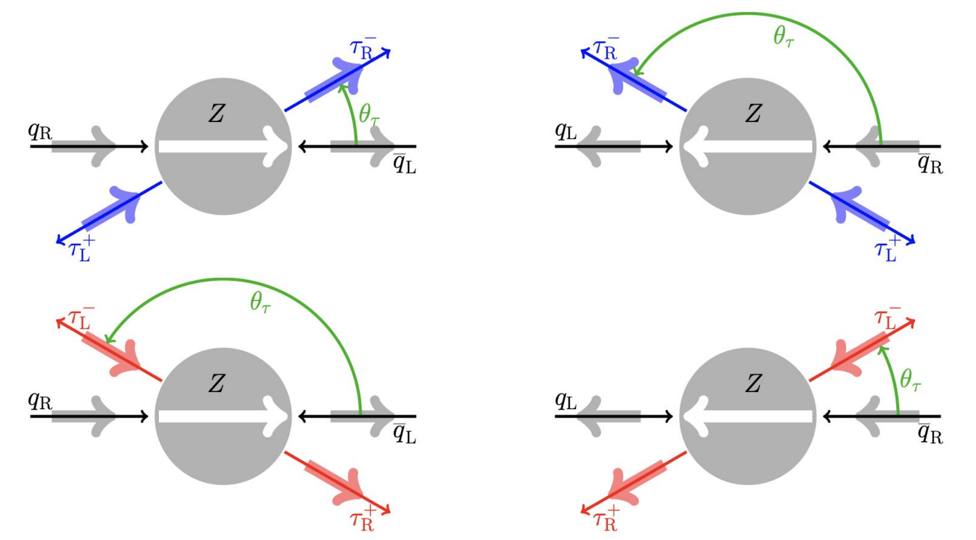




Figure 1: The four possible helicity states of incoming quarks and outgoing $\tau$ leptons. Thin arrows depict the direction of movement and the thick arrows show the spin of the particles. The angle $\theta_\tau$ is the scattering angle of the $\tau^-$ lepton with respect to the quark momentum in the rest frame of the Z boson.

# Obtaining the weak mixing angle (SM param)

$$P_\tau \approx -2\frac{g_V^\tau}{g_A^\tau} = -2(1 - 4\sin^2(\theta_w))$$

coupling ratio x 8 → measurement error reduction

**Weak mixing angle:**

- describes weak **interaction strength**, w.r.t. electromagnetic interactions
- vector and Axial **coupling constants** (describes lepton - Z0 boson, same/opposite chirality)
- mass ratio, Z and W bosons: $\cos(\theta_w) = \frac{m_w}{m_z}$

# How do we measure polarization?

$$P_\tau \approx -2\frac{g_V^\tau}{g_A^\tau} = -2(1 - 4\sin^2(\theta_w))$$

$$\frac{1}{N}\frac{dN}{dx} \approx 1 + P_\tau(2x - 1)$$

energy distribution

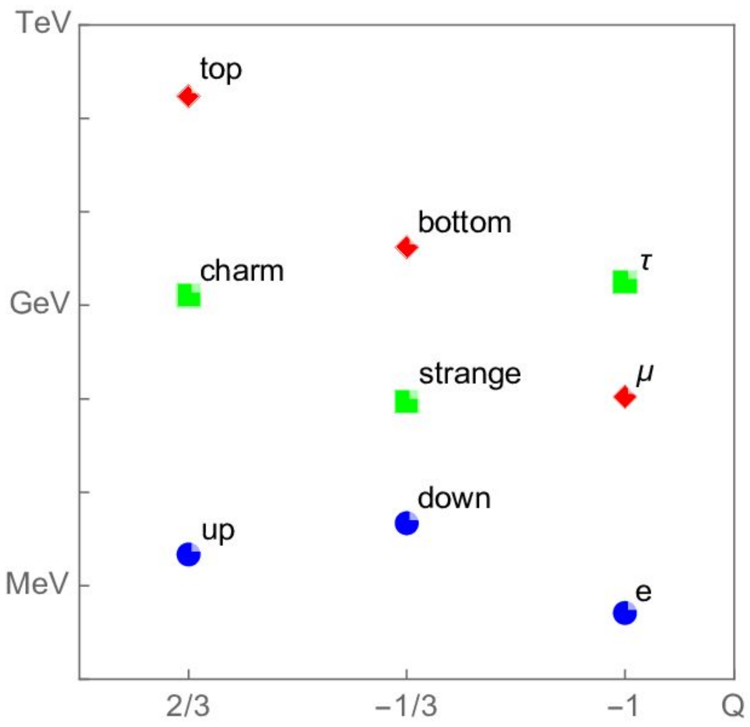
normalized energy/momentum

** diff E distributions for diff decay channels*

# Tau tagging ✓

- Unstable particle ⟶ will decay ✓

- Heavier, sizeable decay length:
  - $c\tau = 87\ \mu m$
  - vs μ
  - ⟶ measure final state E



# Tau tagging ✓

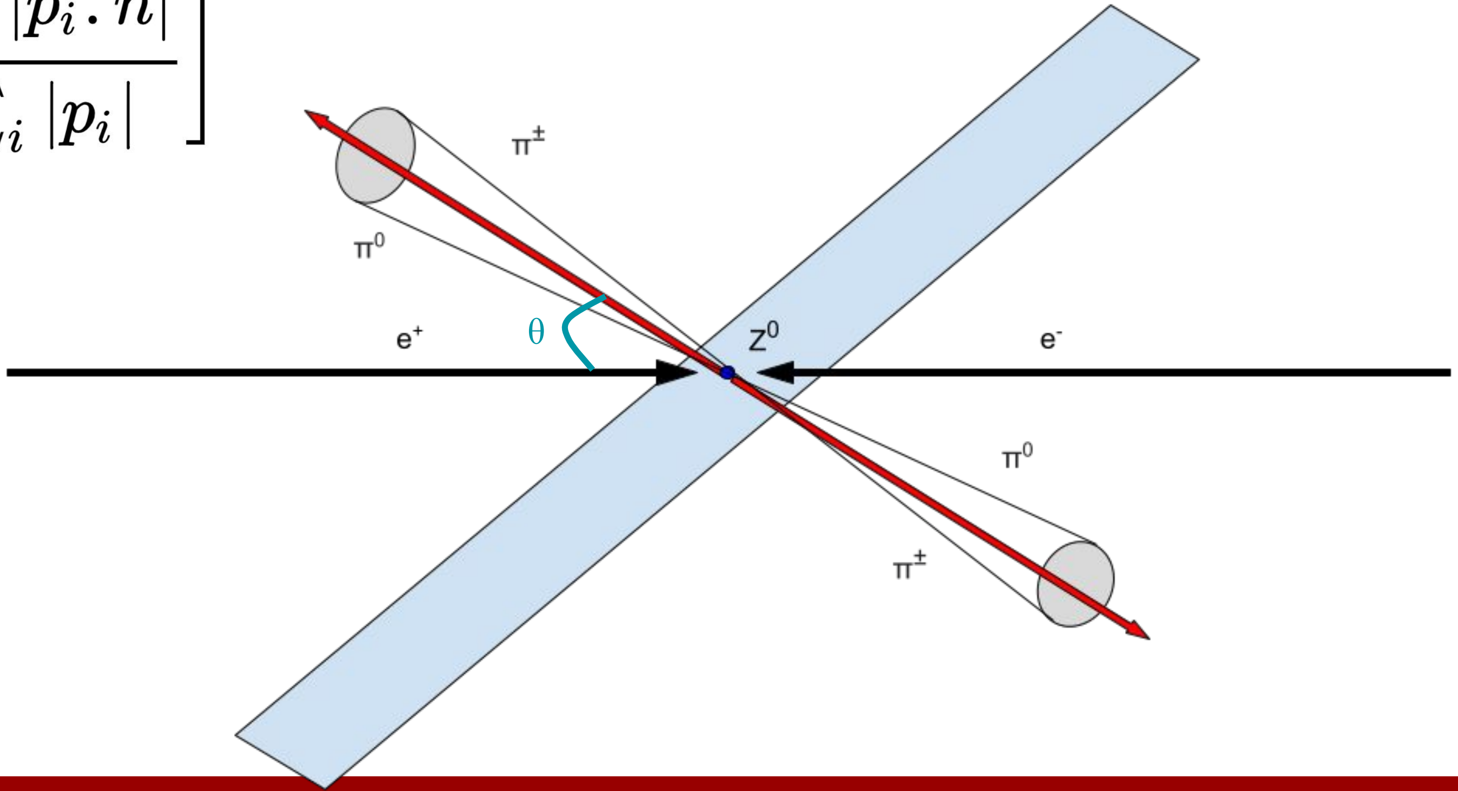
- Unstable particle → will decay
- Heavier, sizeable decay length:
  - $c\tau$ = 87 μm
- Hadronic tau decay criteria
  - 1 charged particle (49.5%)
  - 3 charged particles (15.2%)
  - 5 charged particles (0.1%)
  - Otherwise, 3-body decay w/neutrinos or irrelevant

| | |
|---|---|
| $\tau \to e\nu_e\ \nu_\tau$,<br>$\tau \to \mu\nu_\mu\ \nu_\tau$ | 17.8 %<br>17.4 % |
| $\tau \to \pi^\pm\nu_\tau$ | 11.1 % |
| $\tau \to \pi^0\pi^\pm\nu_\tau$ | 25.4 % |
| $\tau \to \pi^0\pi^0\pi^\pm\nu_\tau$ | 9.19 % |
| $\tau \to \pi^0\pi^0\pi^0\pi^\pm\nu_\tau$ | 1.08 % |
| $\tau \to \pi^\pm\pi^\pm\pi^\pm\nu_\tau$ | 8.98 % |
| $\tau \to \pi^0\pi^\pm\pi^\pm\pi^\pm\nu_\tau$ | 4.30 % |
| $\tau \to \pi^0\pi^0\pi^\pm\pi^\pm\pi^\pm\nu_\tau$ | 0.50 % |
| $\tau \to \pi^0\pi^0\pi^0\pi^\pm\pi^\pm\pi^\pm\nu_\tau$ | 0.11 % |
| $\tau \to K^\pm X\nu_\tau$ | 3.74 % |
| $\tau \to (\pi^0)\pi^\pm\pi^\pm\pi^\pm\pi^\pm\pi^\pm\nu_\tau$ | 0.10 % |
| others | 0.03 % |

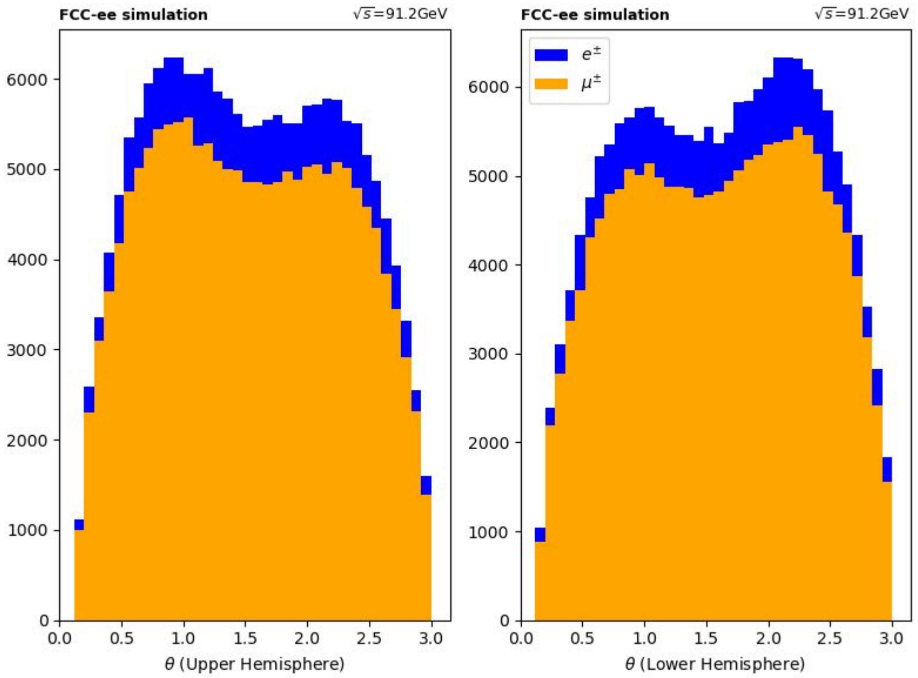
*Table 1 Most relevant τ decay branching ratios*

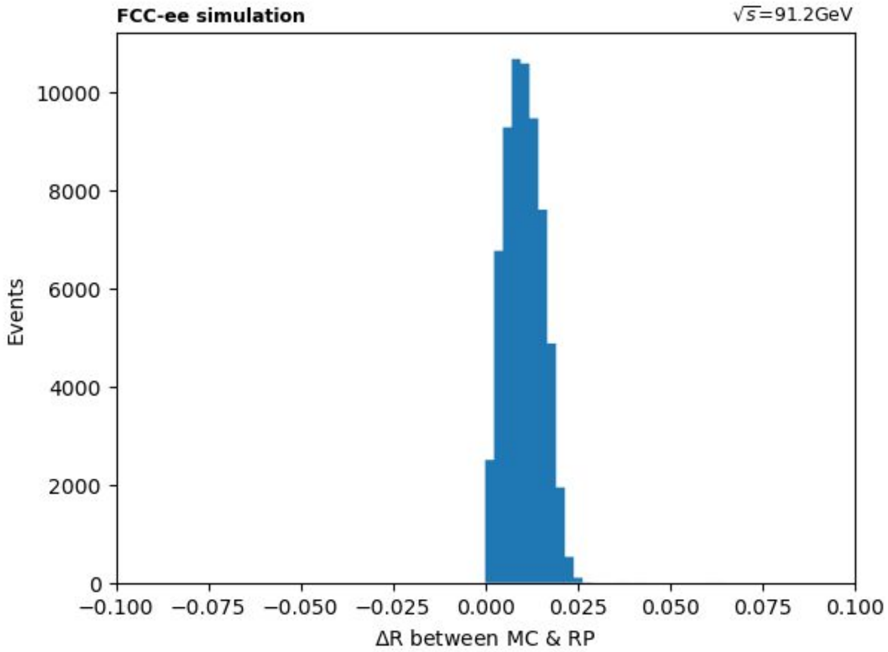
# Thrust Axis Determination

$$T = \max_{|n|=1}\left[\frac{\sum_i |p_i \, . \, n|}{\sum_i |p_i|}\right]$$



# Thrust Axis Validation



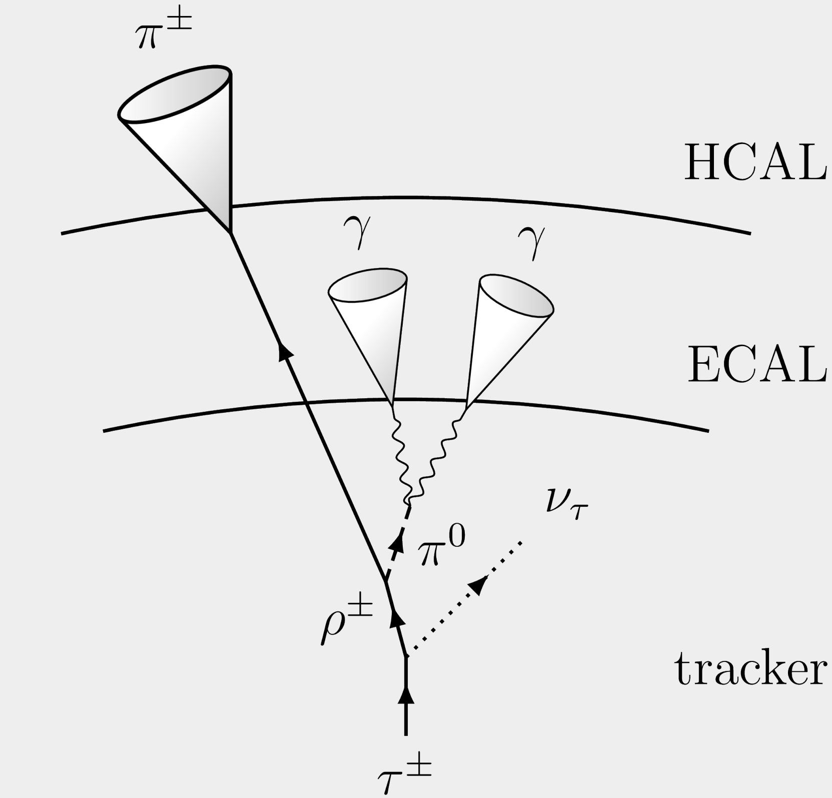



# Decay channel identification

*applying Boosted Decision Trees (BDTs)*

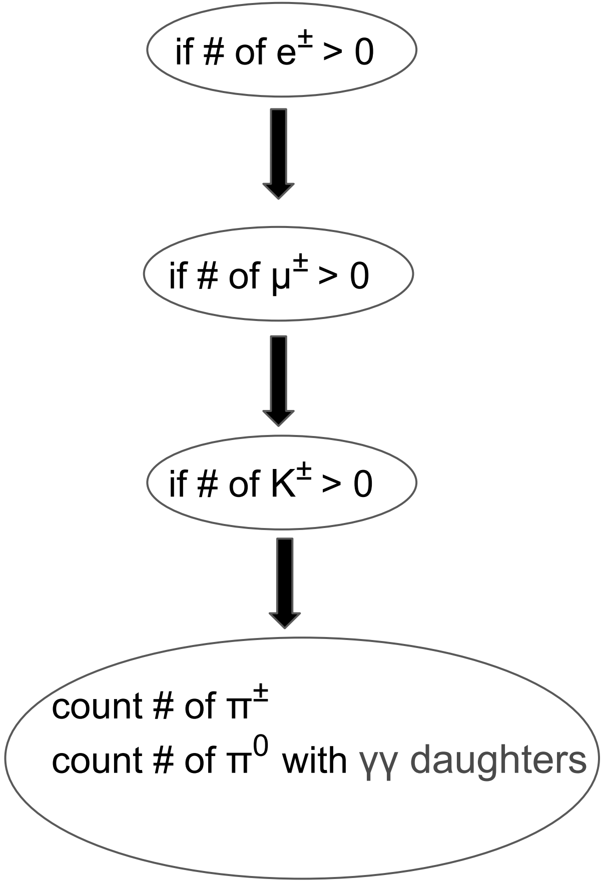
# Decay Selection Process

- First use a naive selection process using particle counts and detector information
- Then use boosted decision tree for optimized classification

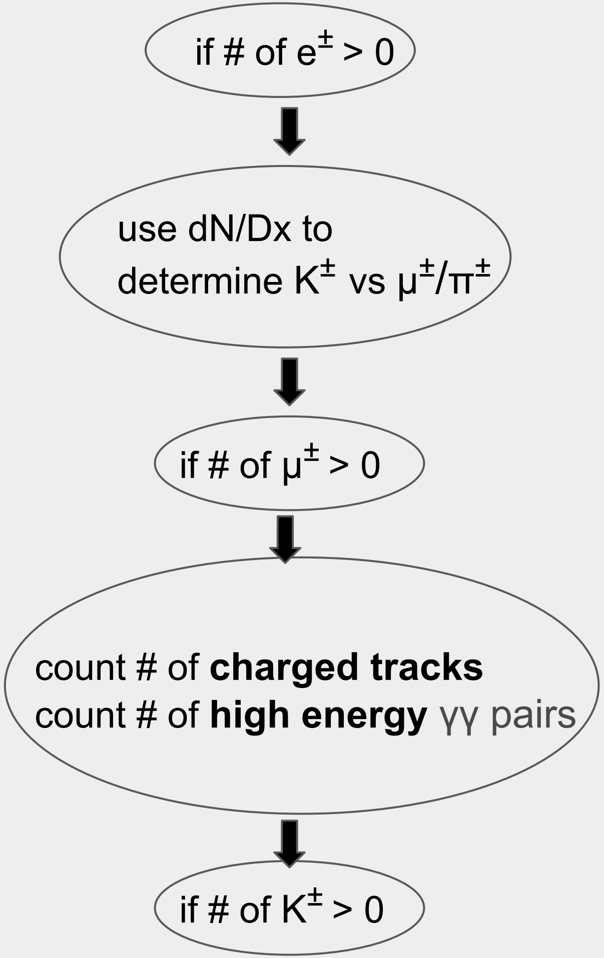



$$\tau^{\pm} \rightarrow \rho^{\pm}\nu_\tau \rightarrow \pi^{\pm}\pi^0\nu_\tau$$

## Monte Carlo Decay Selection Process

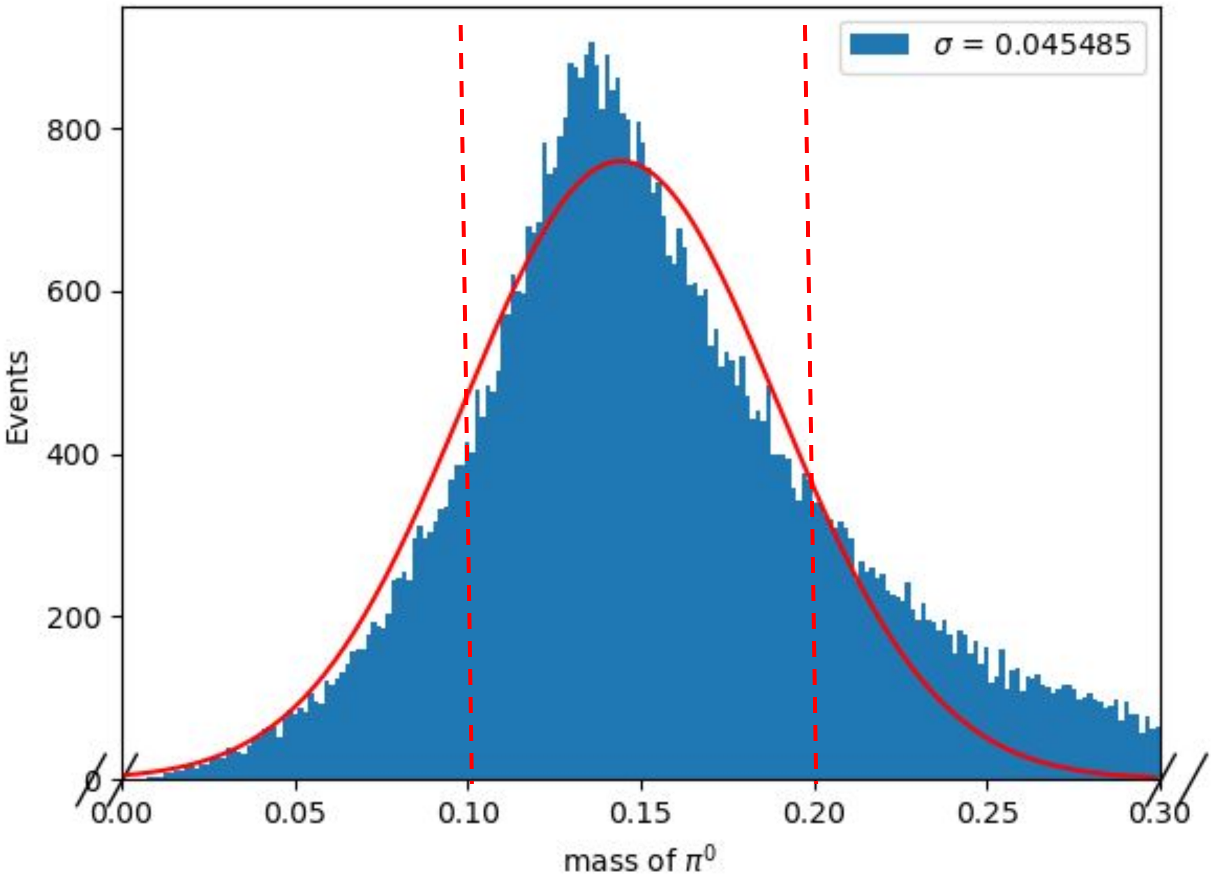



## Reconstructed Particle Decay Selection Process



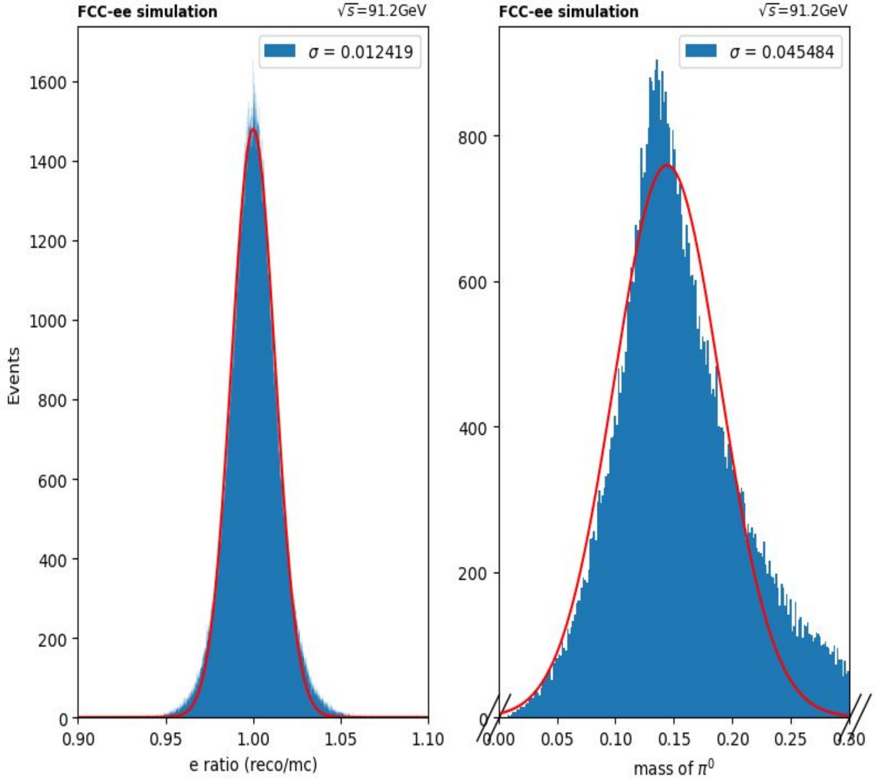
# $\pi^0$ mass reconstruction

- Cuts at 0.1 and 0.2 GeV for $\pi^0$ identification
- Exhaust all combinations of $\gamma$'s energy deposits $\rightarrow$ if within mass range, label as $\pi^0$ (accounts for very collinear $\gamma$'s )
- Potential for training BDT explicitly for $\pi^0$ identification

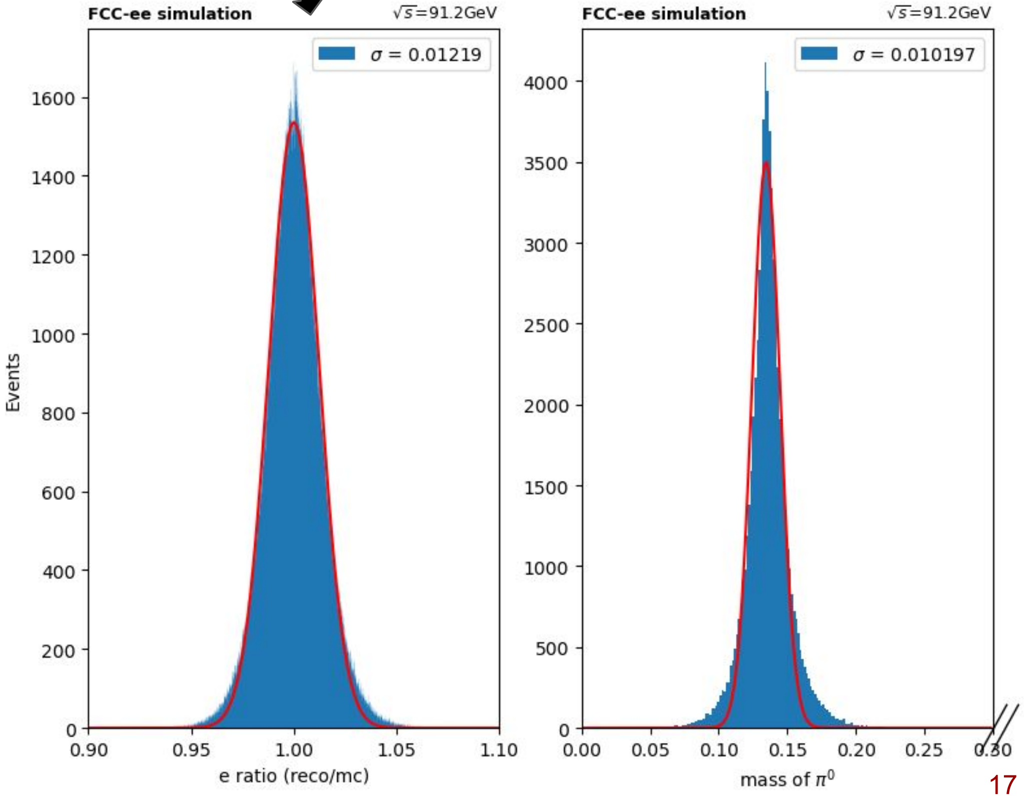


# $\pi^0$ mass reconstruction

current CMS granularity




w/ 4x better granularity

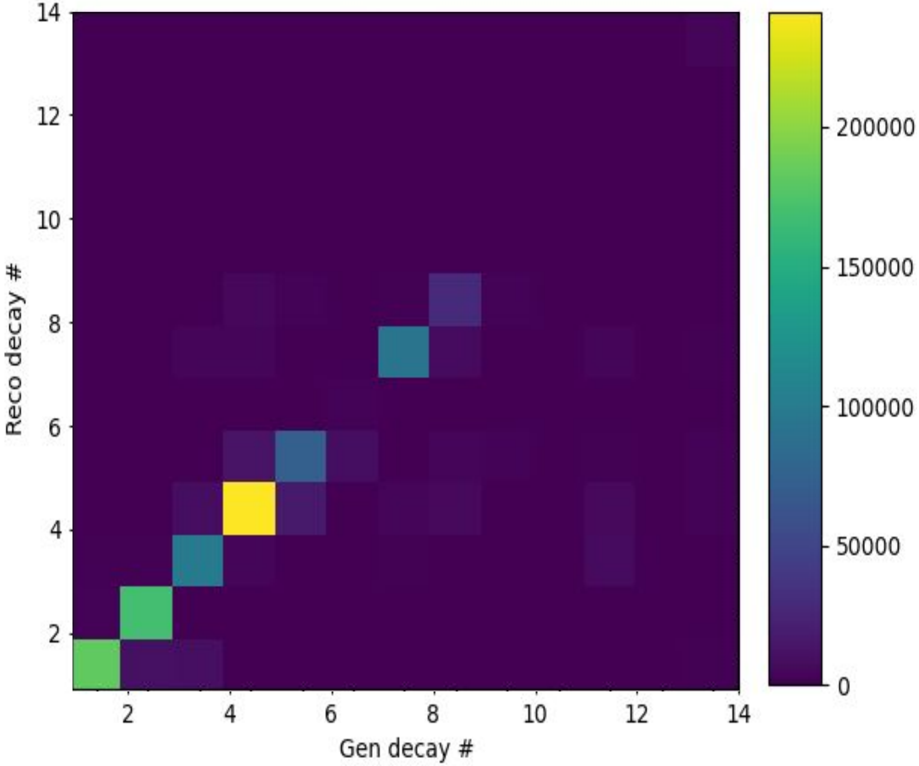


# BDT Classification Input Variables

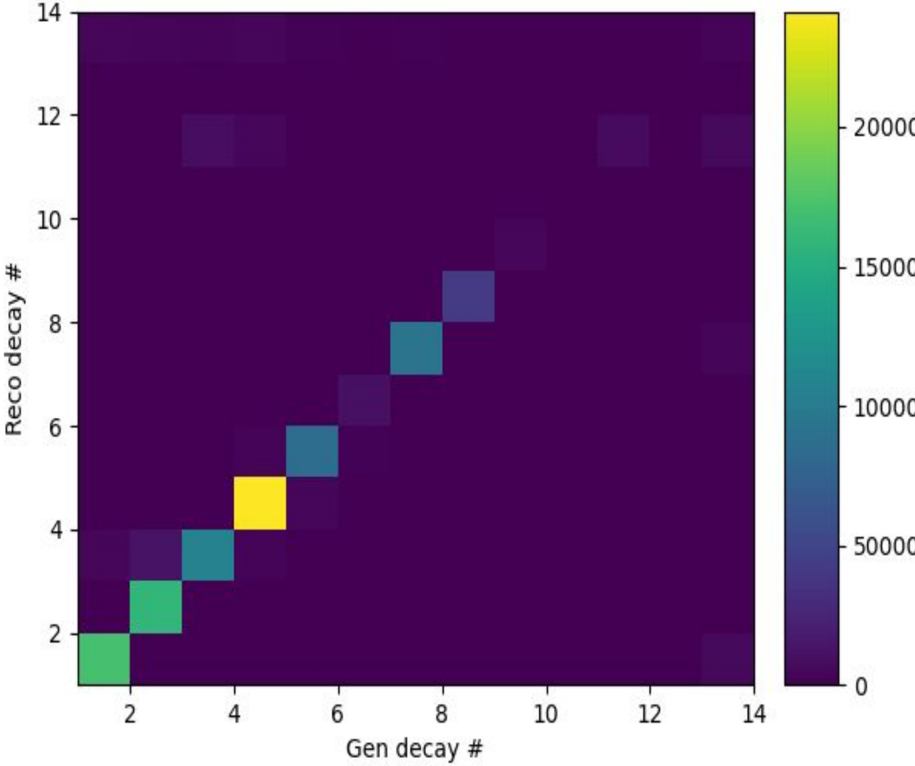
- Invariant Mass
- $\pi^0$ count
- Free $\gamma$ count
- Charged particle momentum
- Charged particle $\phi$
- Charged particle $\eta$
- # of muons
- # of electrons

# Confusion Matrix

Naive Classification




BDT Classification



# Performance Statistics

## BDT Performance

| Decay Mode | Precision | Recall |
|---|---|---|
| 1 | 0.99 | 0.96 |
| 2 | 0.97 | 0.93 |
| 3 | 0.81 | 0.96 |
| 4 | 0.95 | 0.95 |
| 5 | 0.92 | 0.95 |
| 6 | 0.88 | 0.85 |
| 7 | 0.91 | 0.97 |
| 8 | 0.83 | 0.91 |
| 9 | 0.67 | 0.50 |
| 10 | 0.84 | 0.67 |
| 11 | 0.17 | 0.08 |
| 12 | 0.85 | 0.94 |
| 13 | 0.95 | 0.79 |

## Naive Performance

| Decay Mode | Precision | Recall |
|---|---|---|
| 1 | 0.98 | 0.92 |
| 2 | 0.90 | 0.85 |
| 3 | 0.61 | 0.88 |
| 4 | 0.77 | 0.89 |
| 5 | 0.33 | 0.22 |
| 6 | 0.29 | 0.85 |
| 7 | 0.66 | 0.74 |
| 8 | 0.82 | 0.77 |
| 9 | 0.45 | 0.48 |
| 10 | 0.83 | 0.57 |
| 11 | 0.00 | 0.00 |
| 12 | 0.67 | 0.50 |
| 13 | 0.51 | 0.43 |

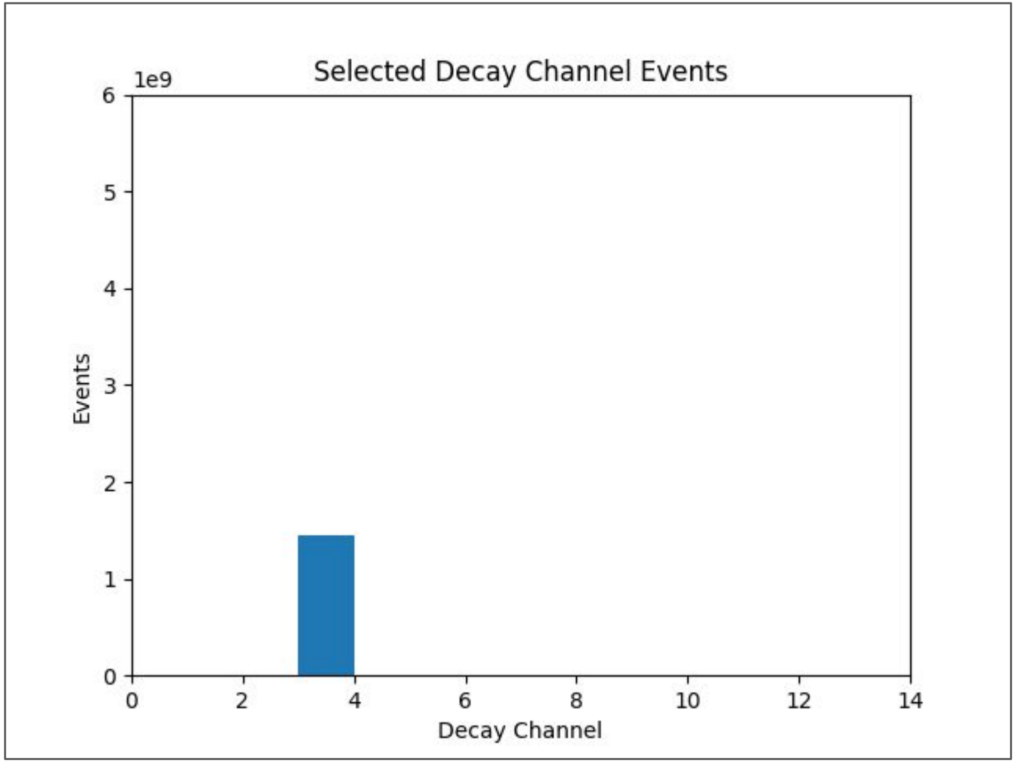
*Given a decay channel:*

# Measure tau polarization

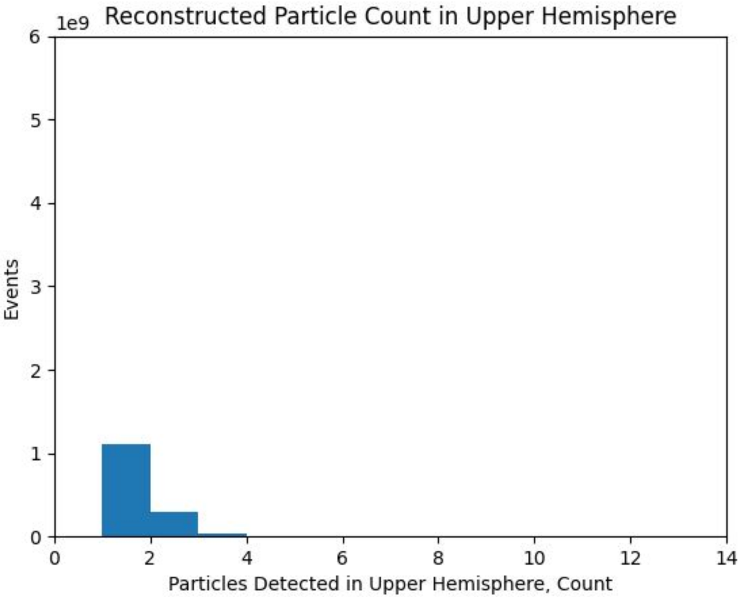
$$\tau \rightarrow \pi^{\pm} \nu_\tau$$ (3, simplest channel)

| | |
|---|---|
| $\tau \rightarrow e\nu_e \ \nu_\tau,$<br>$\tau \rightarrow \mu\nu_\mu \ \nu_\tau$ | 17.8 %<br>17.4 % |
| $\tau \rightarrow \pi^{\pm}\nu_\tau$ | 11.1 % |
| $\tau \rightarrow \pi^0\pi^{\pm}\nu_\tau$<br>$\tau \rightarrow \pi^0\pi^0\pi^{\pm}\nu_\tau$<br>$\tau \rightarrow \pi^0\pi^0\pi^0\pi^{\pm}\nu_\tau$ | 25.4 %<br>9.19 %<br>1.08 % |
| $\tau \rightarrow \pi^{\pm}\pi^{\pm}\pi^{\pm}\nu_\tau$<br>$\tau \rightarrow \pi^0\pi^{\pm}\pi^{\pm}\pi^{\pm}\nu_\tau$<br>$\tau \rightarrow \pi^0\pi^0\pi^{\pm}\pi^{\pm}\pi^{\pm}\nu_\tau$<br>$\tau \rightarrow \pi^0\pi^0\pi^0\pi^{\pm}\pi^{\pm}\pi^{\pm}\nu_\tau$ | 8.98 %<br>4.30 %<br>0.50 %<br>0.11 % |
| $\tau \rightarrow K^{\pm}X\nu_\tau$ | 3.74 % |
| $\tau \rightarrow (\pi^0)\pi^{\pm}\pi^{\pm}\pi^{\pm}\pi^{\pm}\pi^{\pm}\nu_\tau$ | 0.10 % |
| others | 0.03 % |

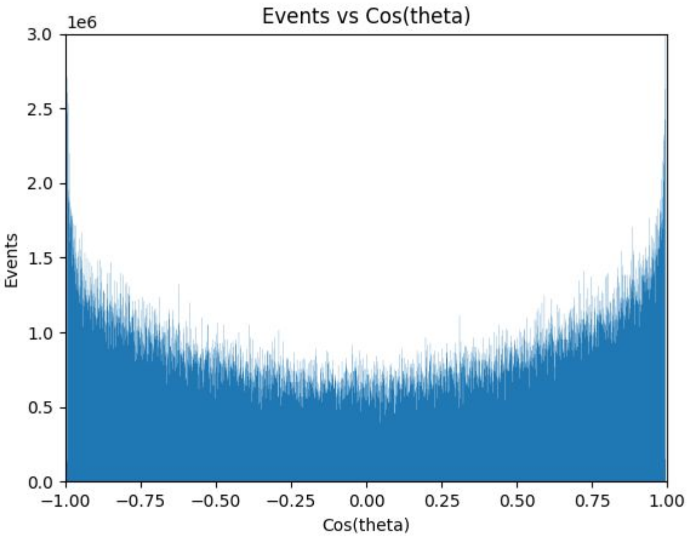
***Table 1 Most relevant τ decay branching ratios***

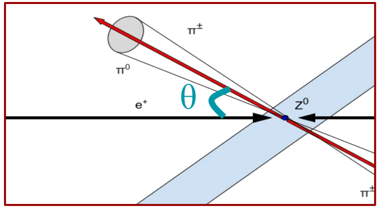


# Reconstructed particle data (upper hem)

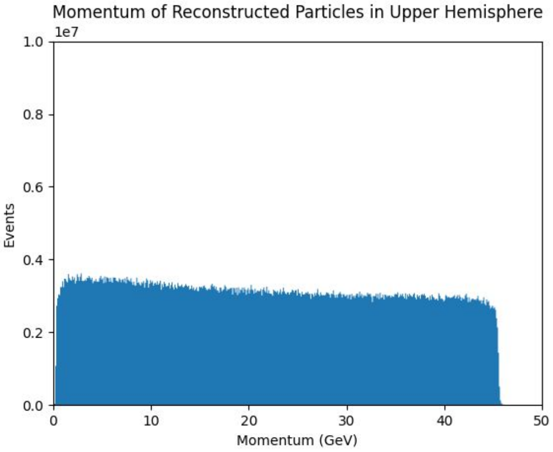


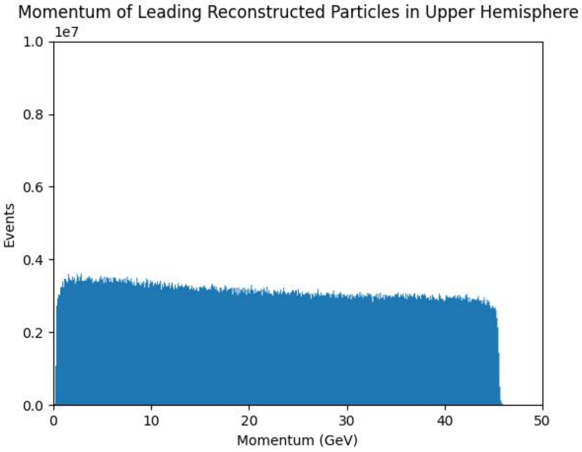

$$\tau \rightarrow \pi^{\pm} \nu_{\tau}$$

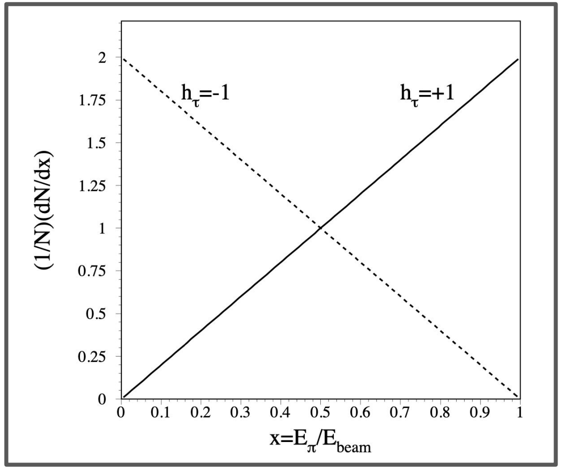


# Reconstructed particle data (upper hem)



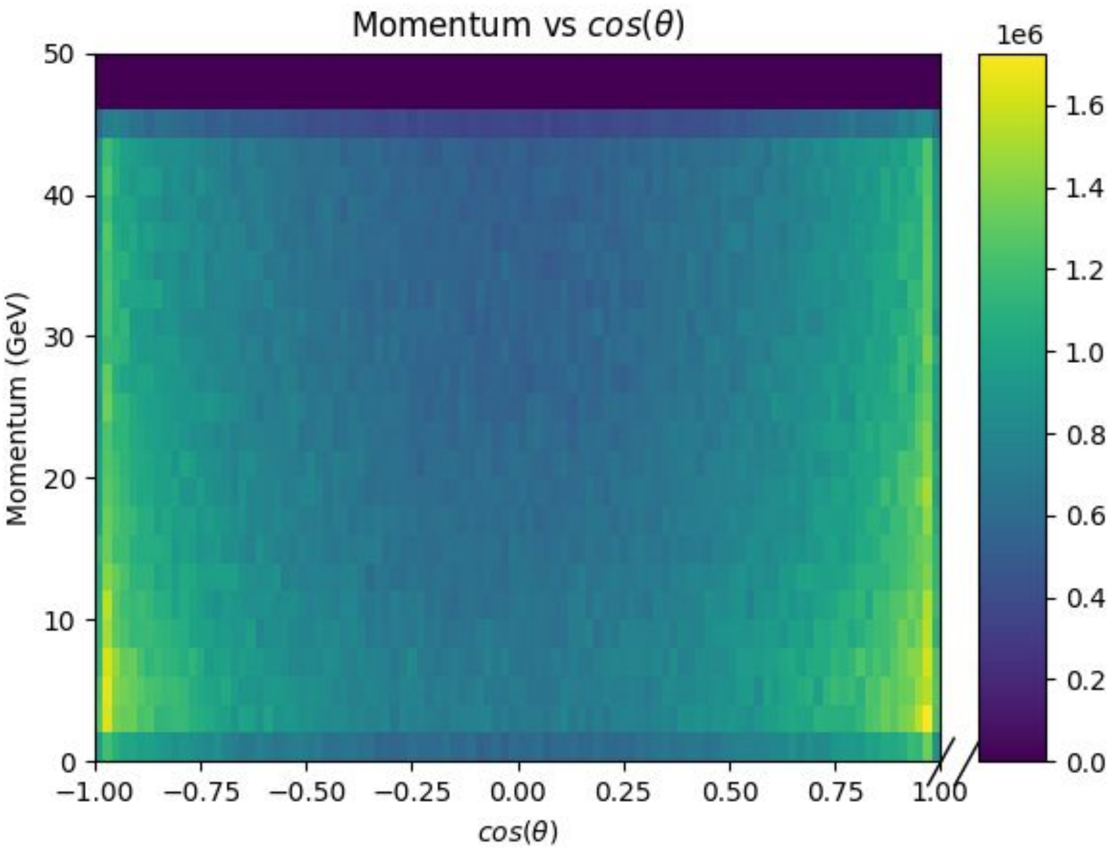



# Method

Goal:

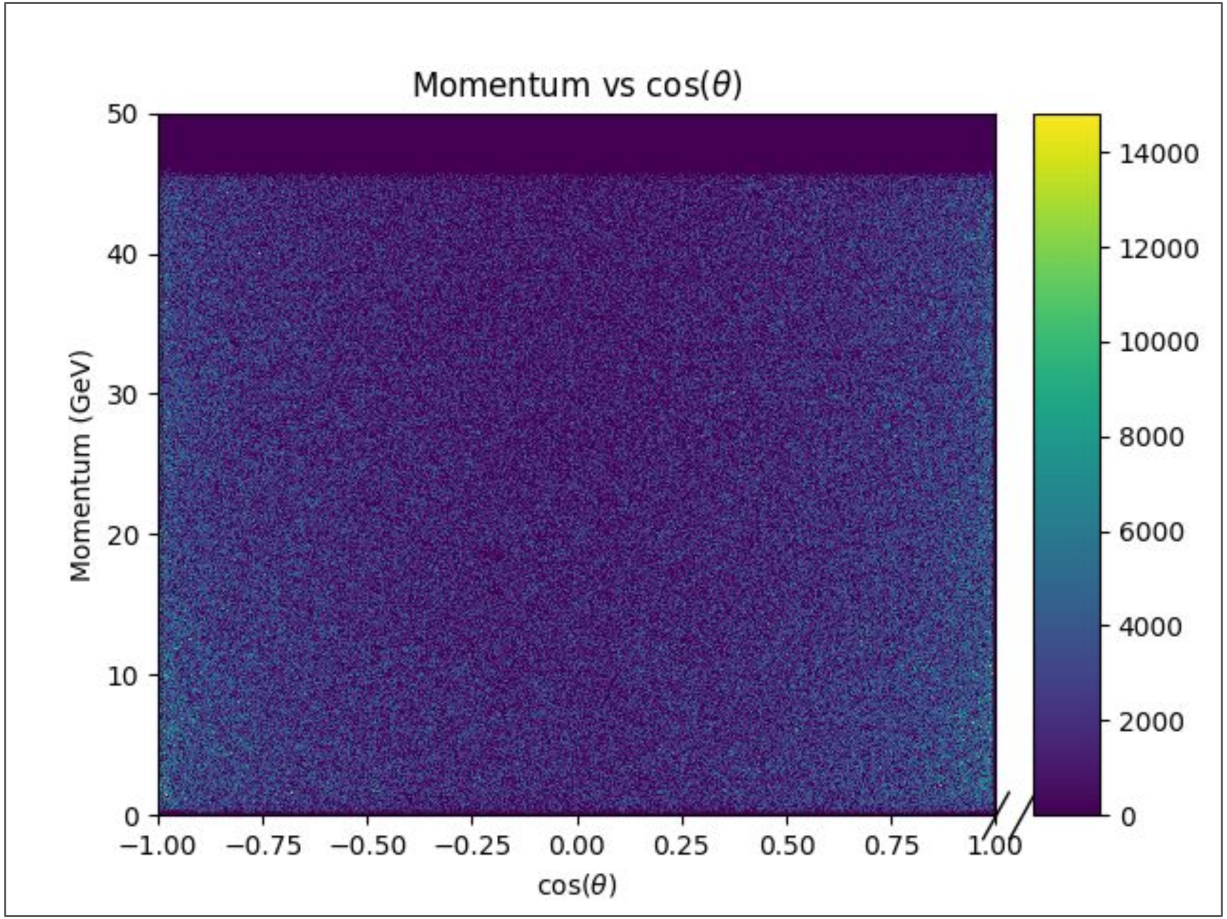
$P_\tau(\cos(\theta))$ distribution

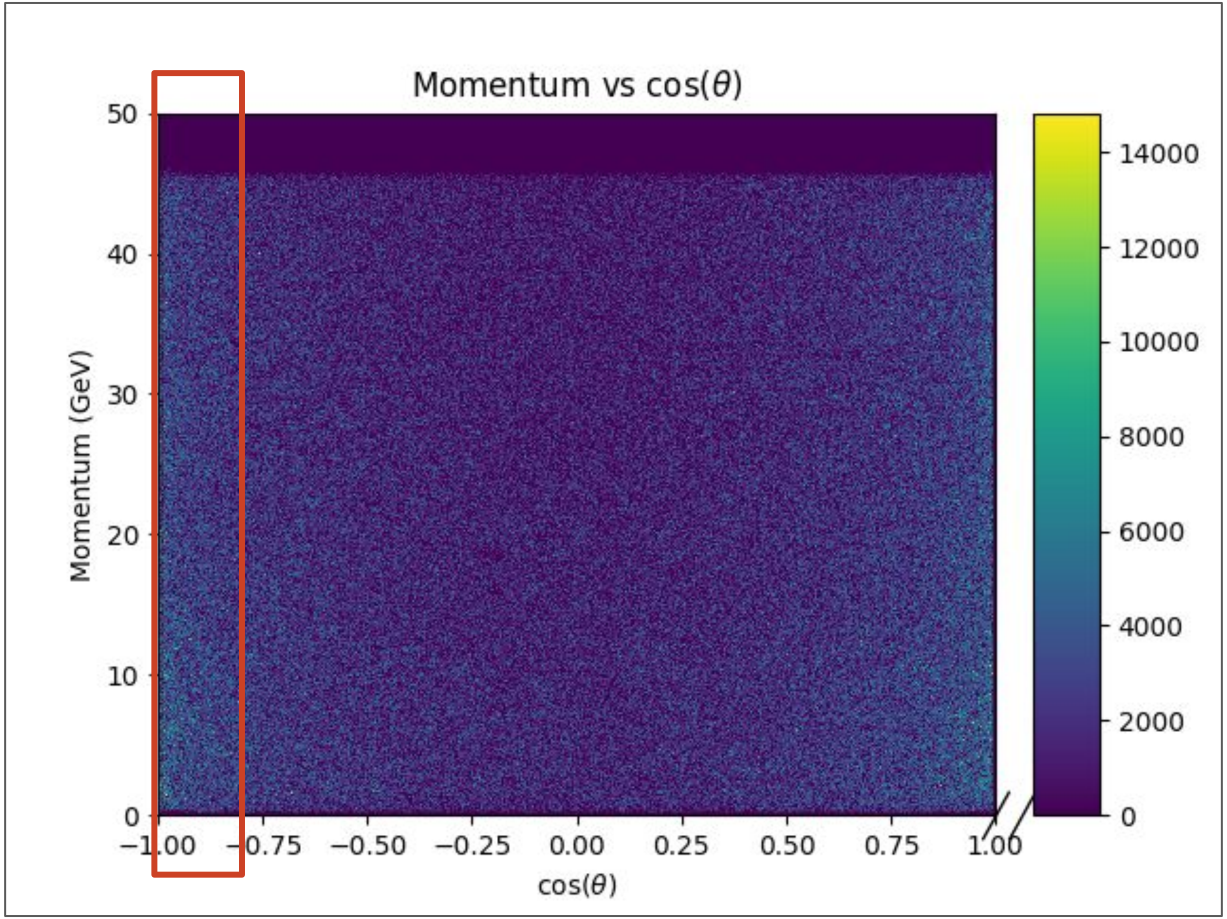


# Method

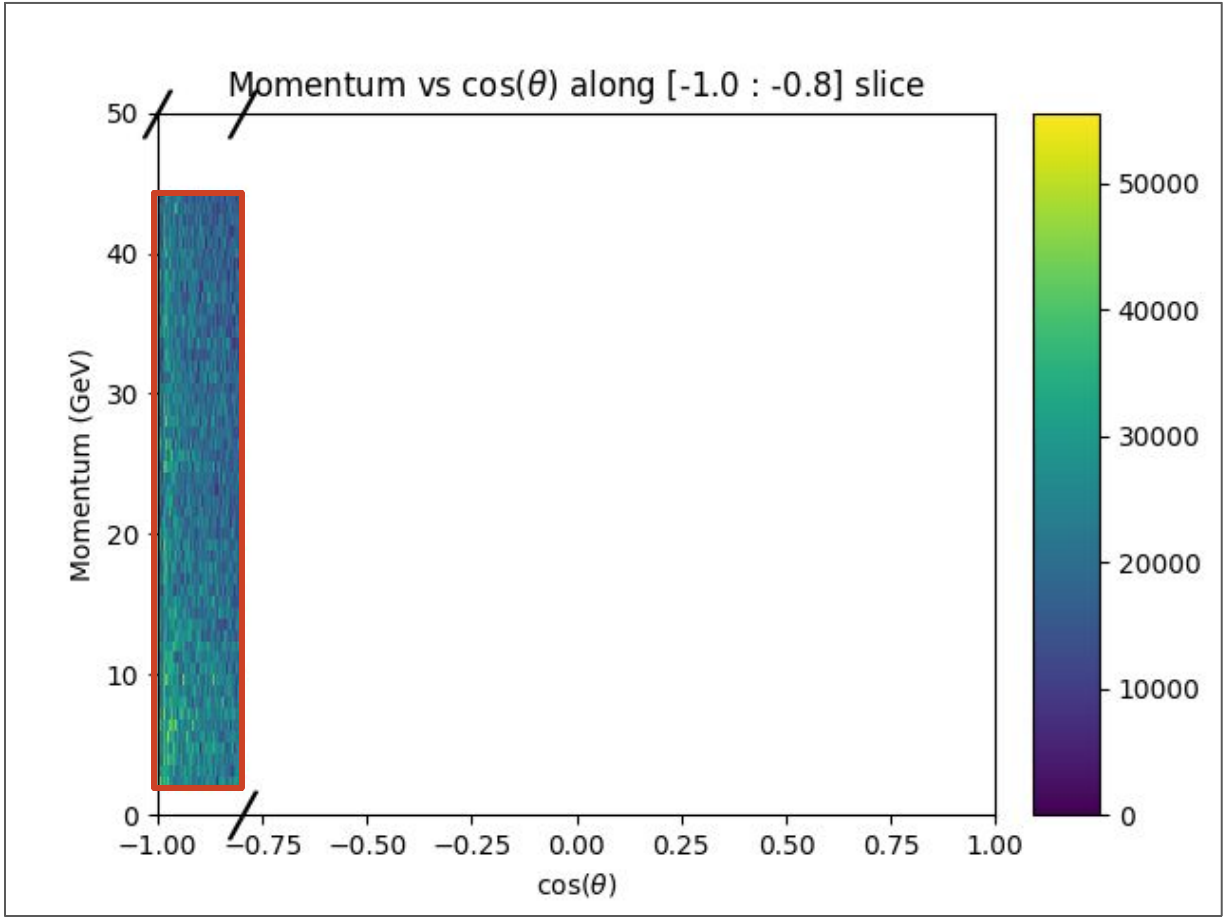
Goal:
$P_\tau(\cos(\theta))$ distribution

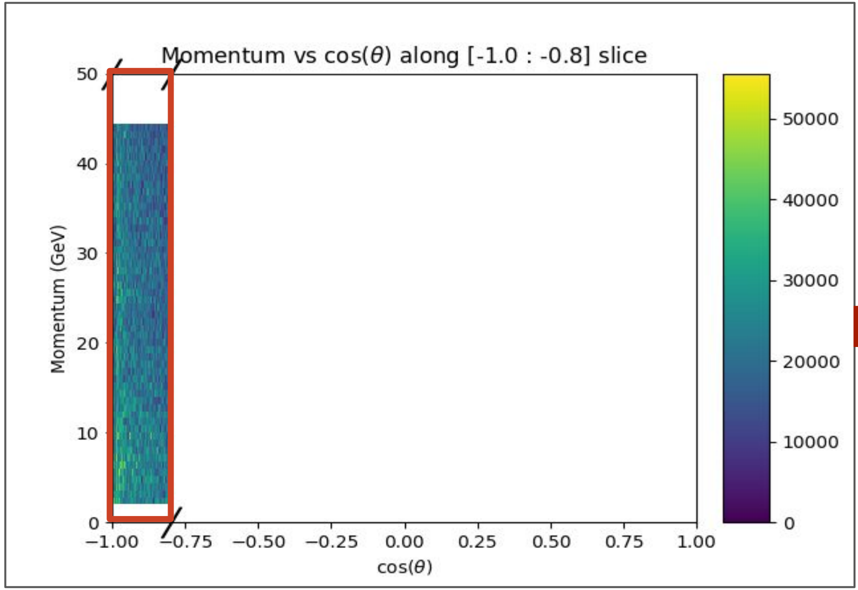
Smaller bins, used in pipeline

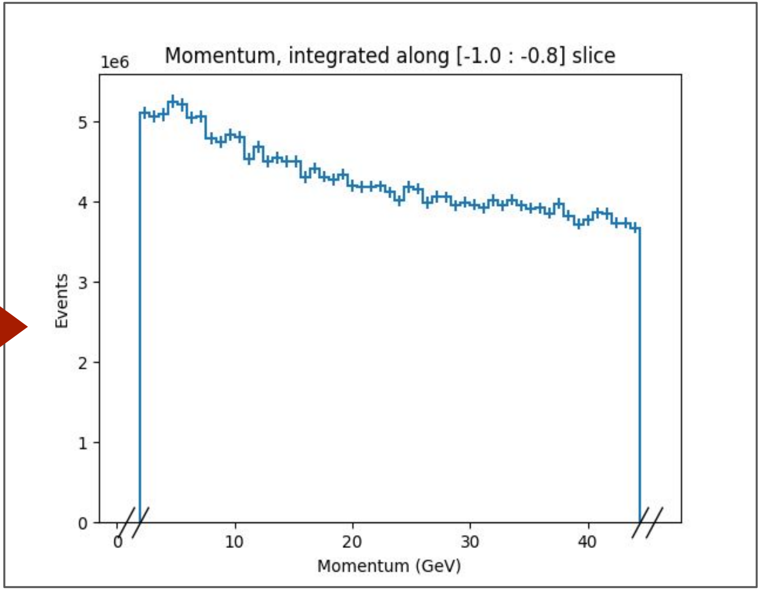




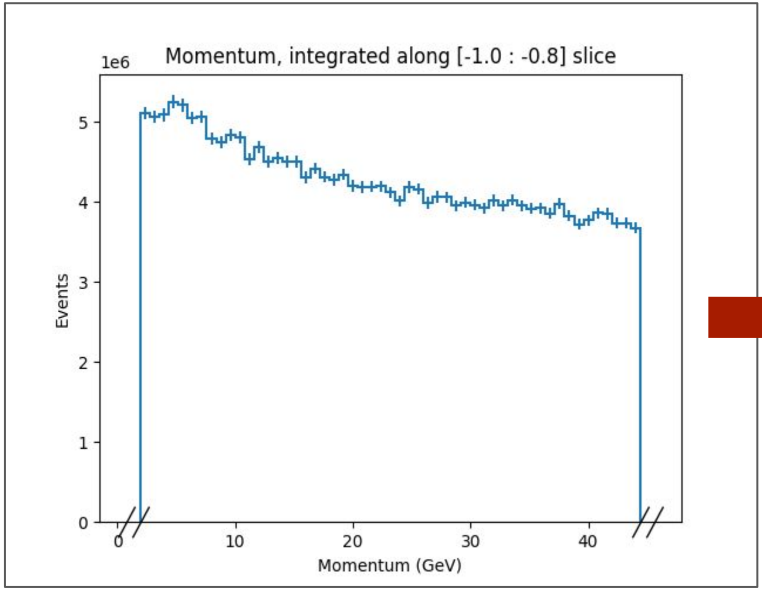
Momentum vs cos(θ)
Momentum (GeV)
50
40
30
20
10
0
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
cos(θ)
14000
12000
10000
8000
6000
4000
2000
0

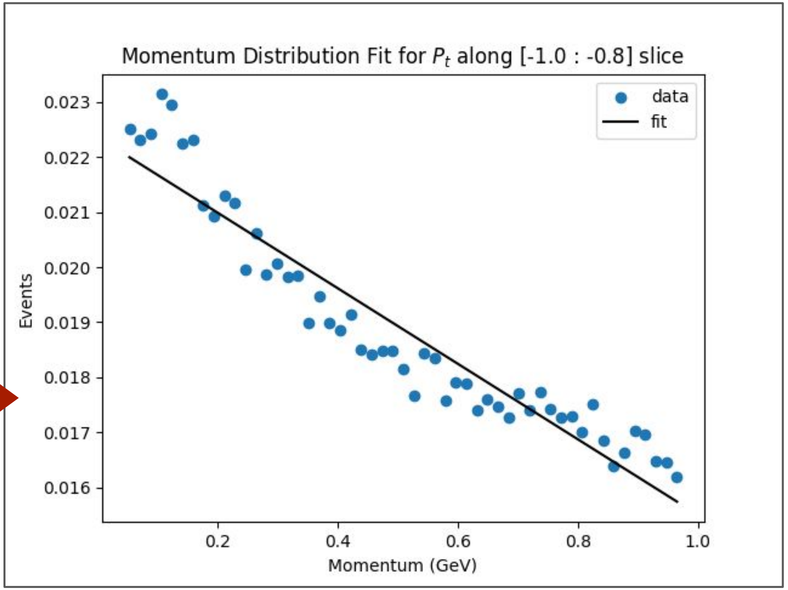

Momentum vs cos(θ) along [-1.0 : -0.8] slice
Momentum (GeV)
50
40
30
20
10
0
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
cos(θ)
50000
40000
30000
20000
10000
0


Momentum vs cos(θ) along [-1.0 : -0.8] slice
Momentum (GeV)
cos(θ)
0
10
20
30
40
50
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
0
10000
20000
30000
40000
50000


Momentum, integrated along [-1.0 : -0.8] slice
1e6
Events
Momentum (GeV)
0
1
2
3
4
5
0
10
20
30
40

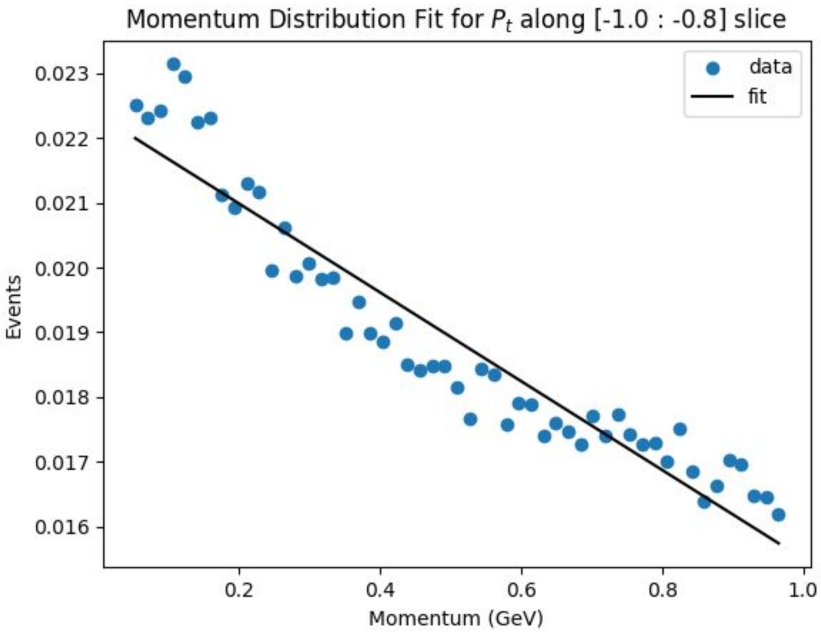
# Decay Energy/Momentum Distribution → find $P_\tau$




$$\frac{1}{N}\frac{dN}{dx} \approx 1 + P_\tau(2x-1)$$

# Decay Energy/Momentum Distribution → find $P_\tau$



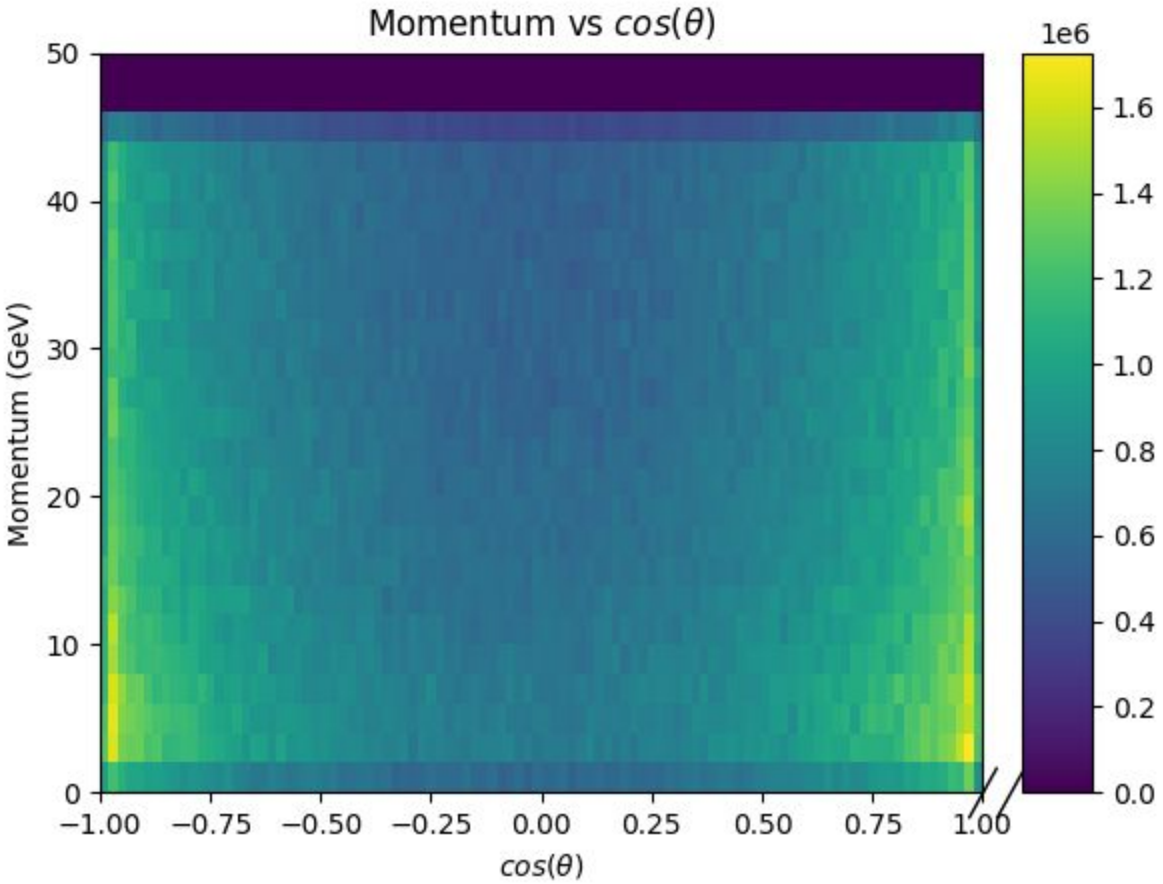

$$\frac{1}{N}\frac{dN}{dx} \approx 1 + P_\tau(2x - 1)$$

$P_\tau$ = -0.18117835

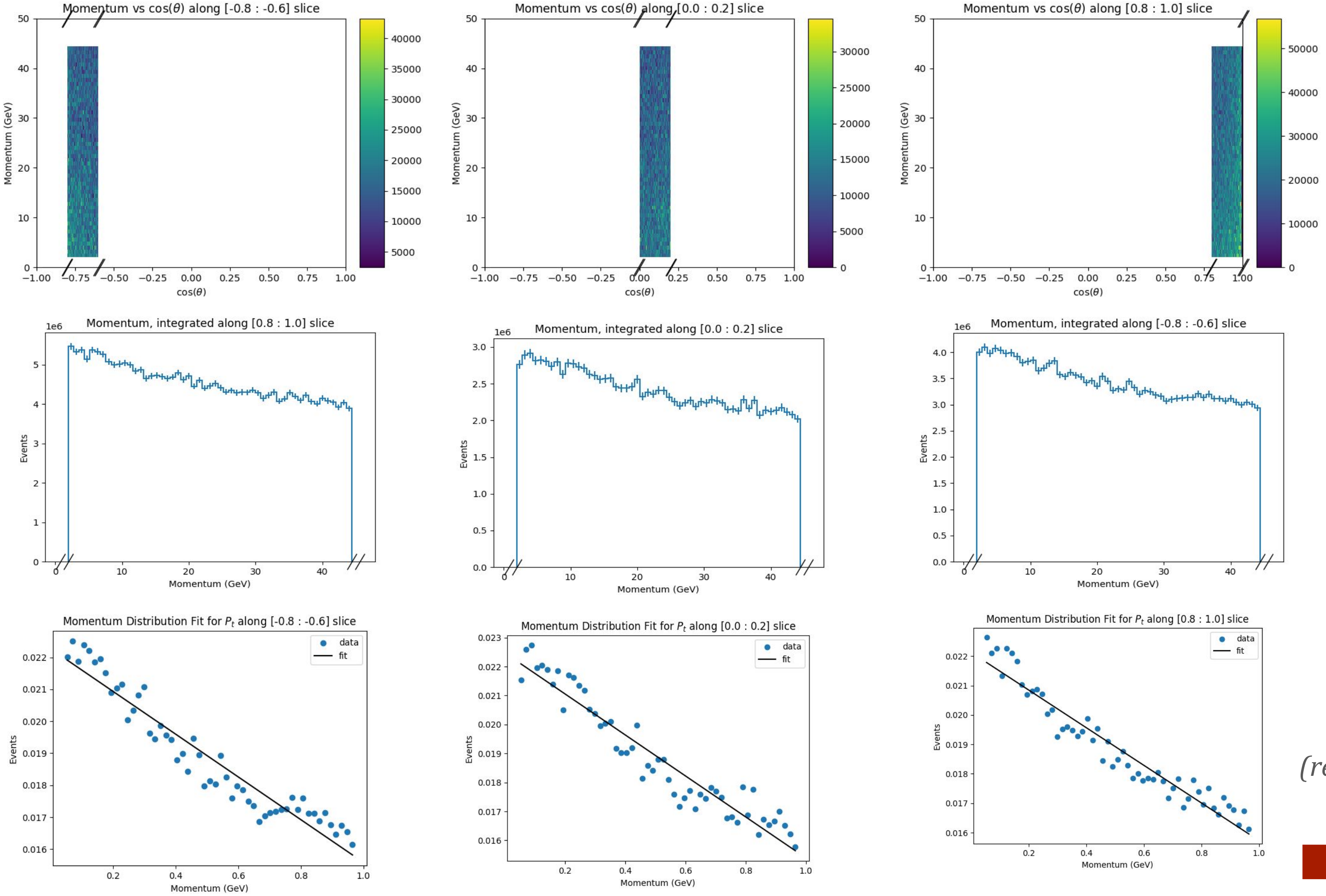
±0.00838 using cov

*But, not our final value…*

# Repeat



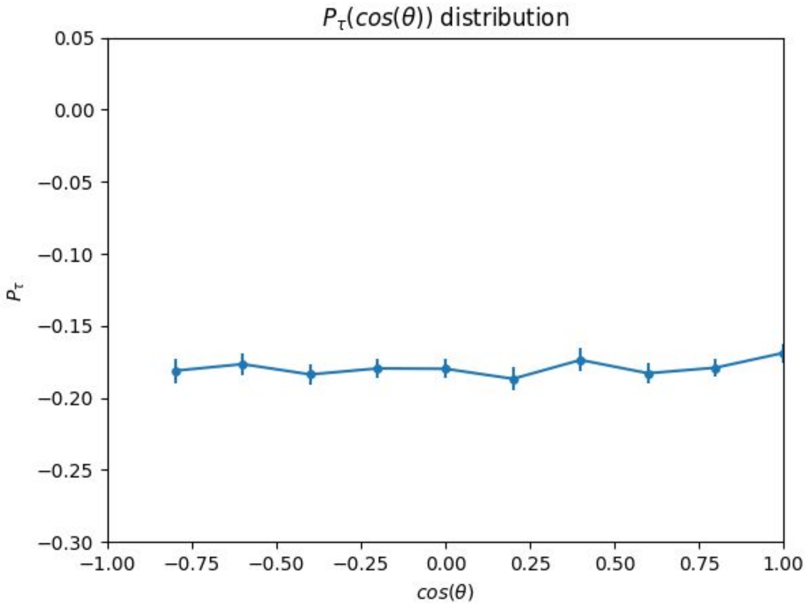
Momentum vs $cos(\theta)$
Momentum (GeV)
50
40
30
20
10
0
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
$cos(\theta)$
1e6
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0

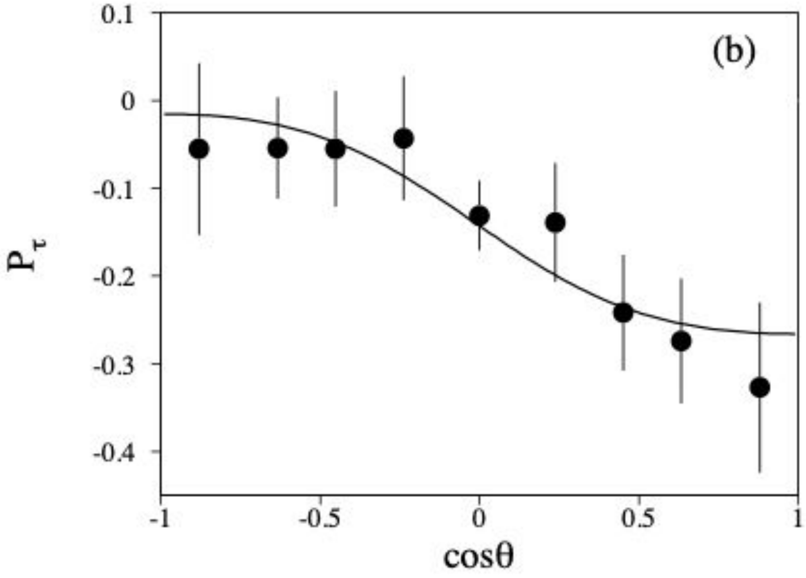



*(repeat for each slice)*

→ $P_\tau$ ✓

# The errors will be revisited.



# Next Steps

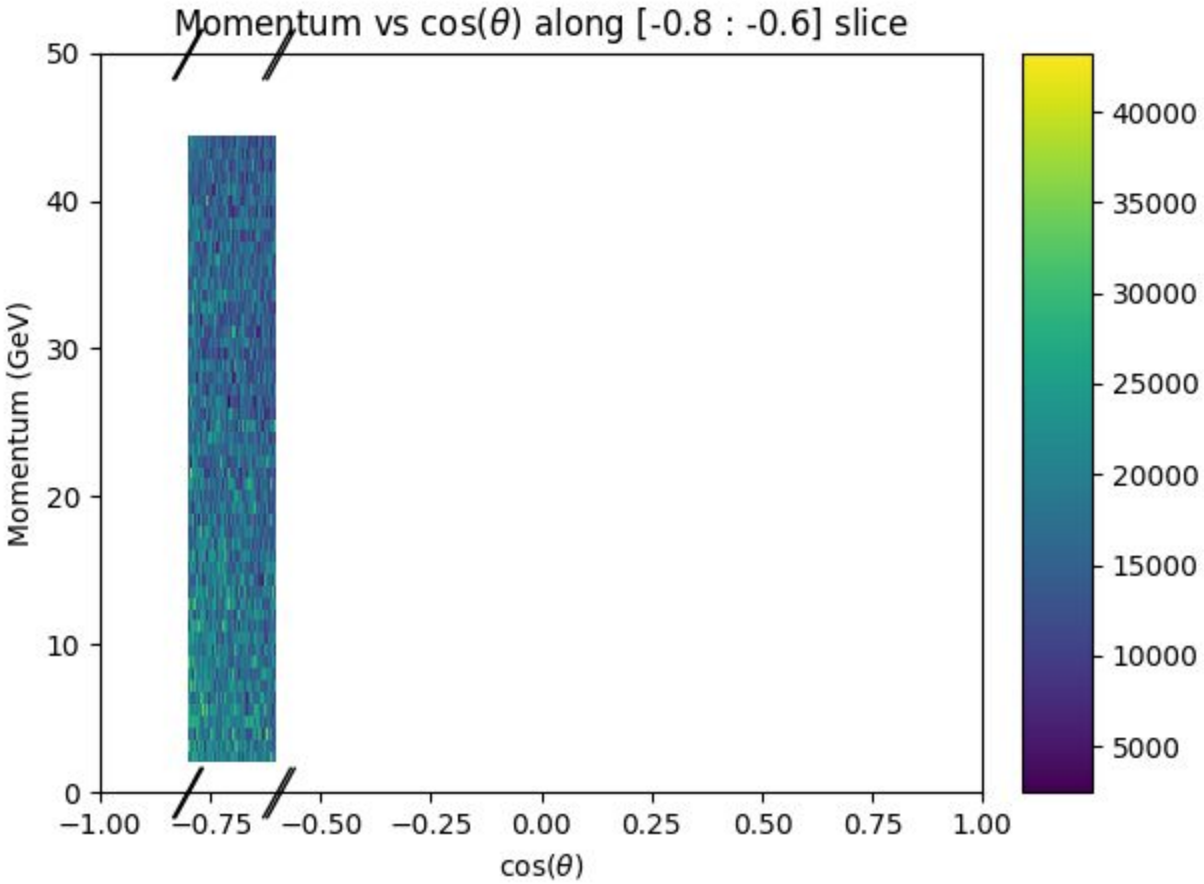
# Next Steps

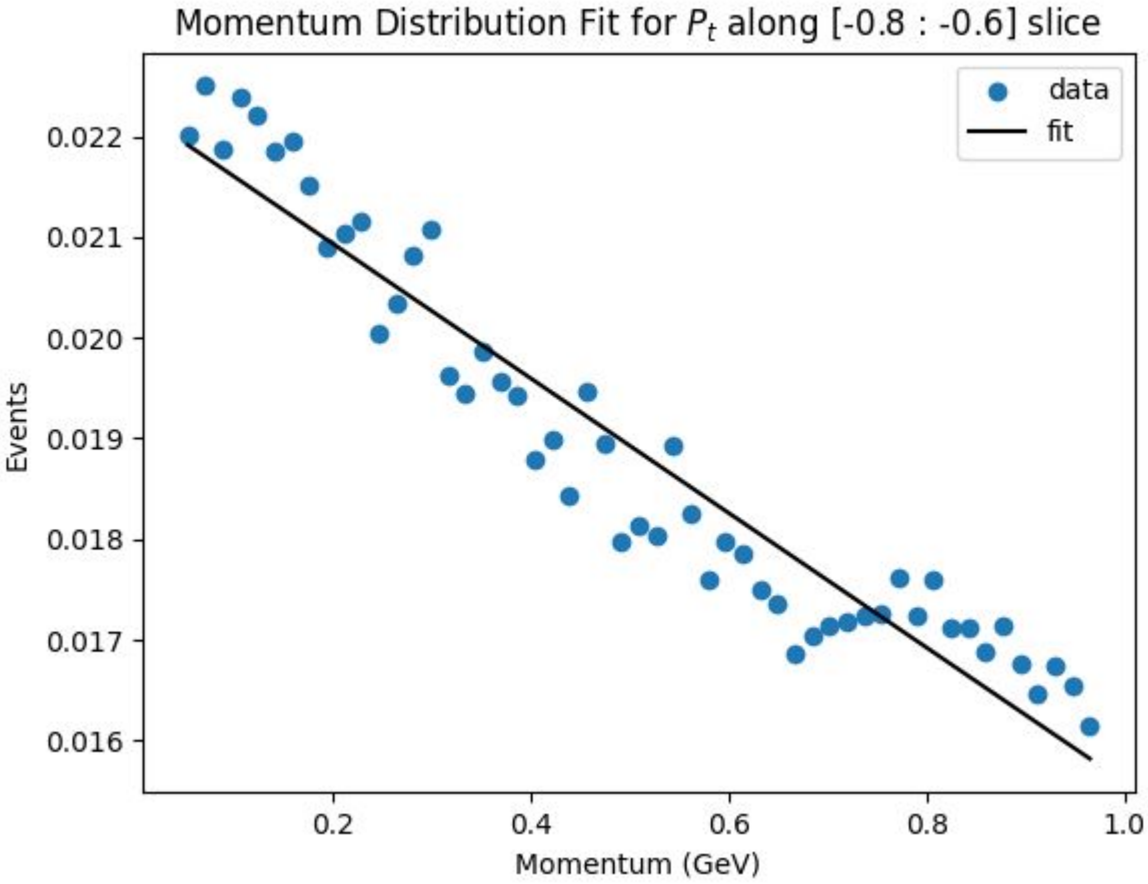
- Refine BDT performance
    - optimize for 1, 3, leptonic decay channels for complete polarization measurement
    - train BDT on samples w/FS
- Polarization measurement
    - in-depth error verification: only negative tau, Whizard/KKMC generator
    - acquire polarization factors (A_e, A_tau), thanks to angle dependence on P_t asym

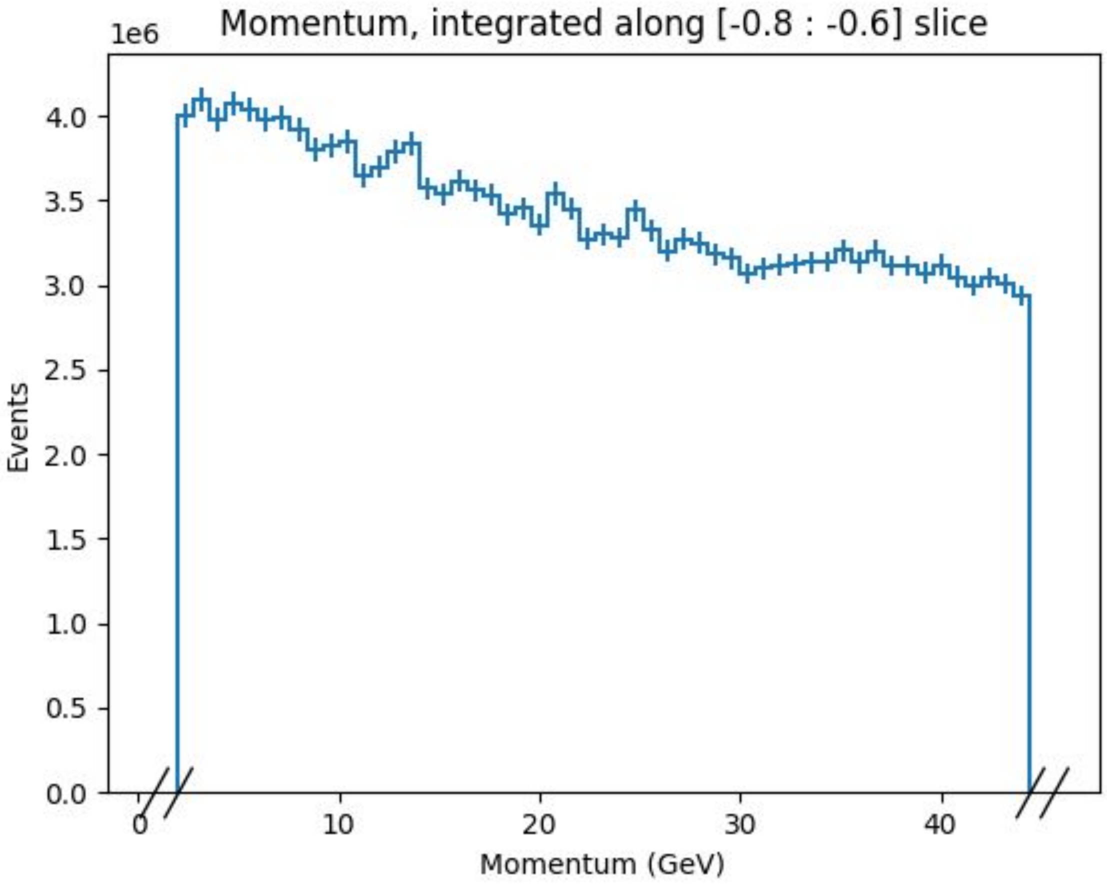
- Integrate the two components → complete, single pipeline

**Thank you!**

# Backup Slides


Momentum vs cos(θ) along [-0.8 : -0.6] slice
Momentum (GeV)
cos(θ)
0
10
20
30
40
50
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
5000
10000
15000
20000
25000
30000
35000
40000


Momentum Distribution Fit for $P_t$ along [-0.8 : -0.6] slice
data
fit
Events
0.022
0.021
0.020
0.019
0.018
0.017
0.016
0.2
0.4
0.6
0.8
1.0
Momentum (GeV)



Momentum, integrated along [-0.8 : -0.6] slice
1e6
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Events
0
10
20
30
40
Momentum (GeV)