In collaboration with:
Jinlong Zhang (SBU), Jin Huang (BNL), Yuxiang Zhao (INFN Trieste)
and Abhay Deshpande (SBU)

Searching for Tau Lepton Appearance at the EIC

Is the EIC sensitive to charged lepton flavor violation at an interesting level?

Krishna Kumar
University of Massachusetts, Amherst
and
Amherst Center for Fundamental Interactions

EICUG Meeting 2019
Paris, France

Outline

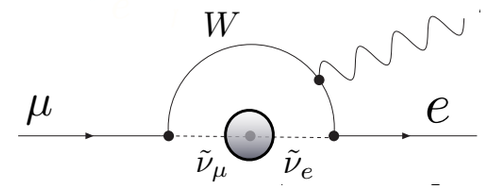
- ✦ **Physics Motivation**
- ✦ **First attempt at event selection and background rejection**
- ✦ **Next steps**
- ✦ **Conclusion and Outlook**

Charged Lepton Flavor Conservation

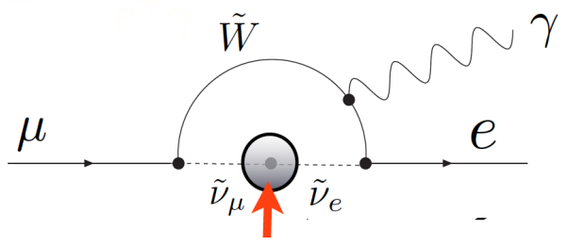
Is it exact? No! **Neutrino Oscillations!**

- **ν's have mass!** ***individual lepton flavors are not conserved***
- **Therefore Flavor Violation occurs for charged Leptons too**

$\mu \to e\gamma$



Slepton mixing in SUSY



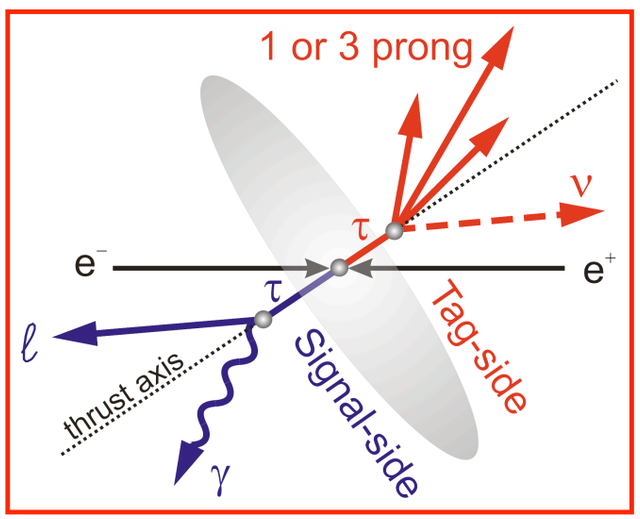
$\mathrm{BR}(\mu \to e\gamma) \sim 10^{-15}$

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

tiny standard model branching fraction

Major experimental searches are ongoing; mass reach depends on flux and sensitivity of technique

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \frac{C_{\mu e}}{\Lambda^2}\bar{e}_L\sigma^{\alpha\beta}\mu_R\Phi F_{\alpha\beta}$$



Tau Decays at e+e- colliders

μ or $\tau \longrightarrow e\gamma$, e^+e^-e, $K_L \to \mu e$, ...

Need very high fluxes for required statistical reach

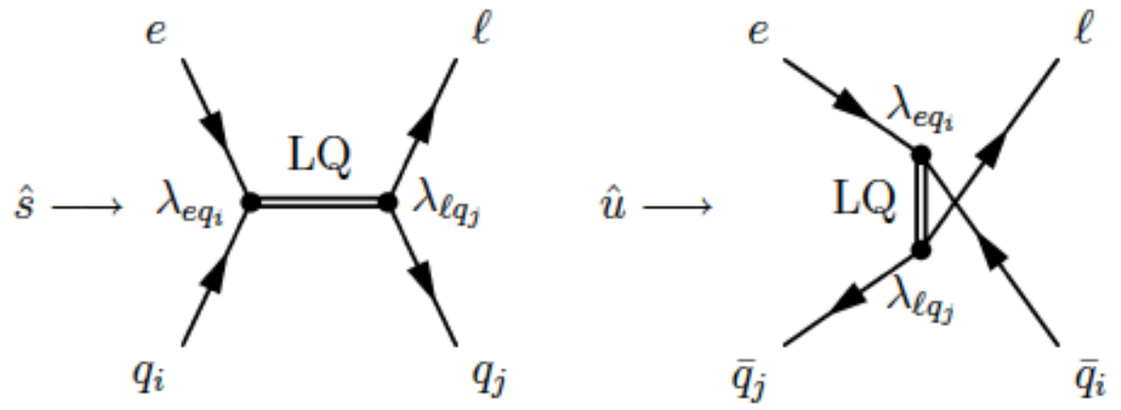
New high intensity kaon & muon beams and high luminosity e+e- colliders all over the world

First to Third Generation CLFV

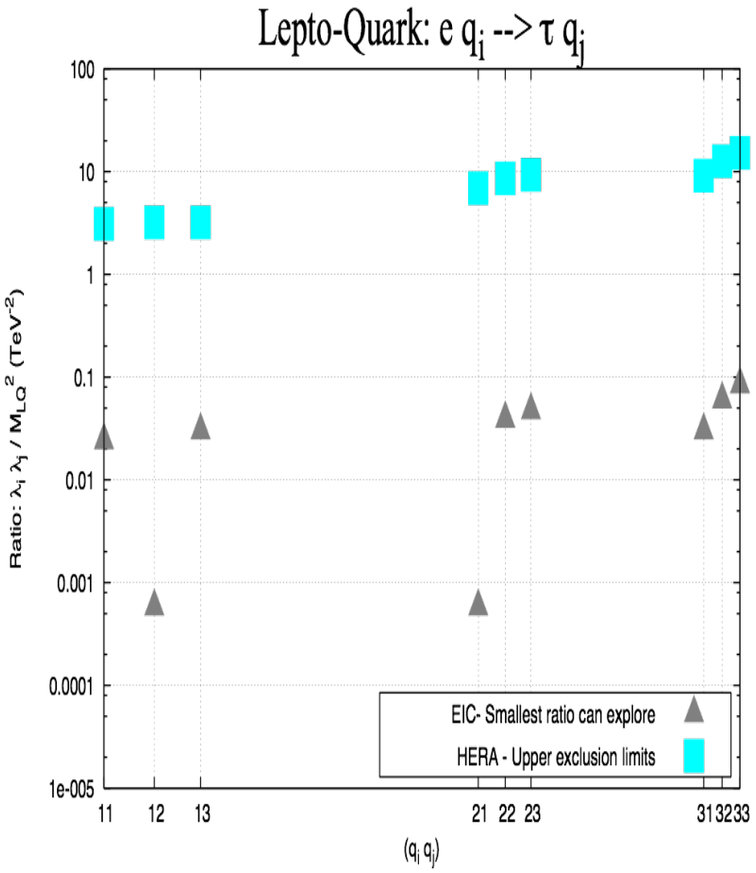
$\tau \rightarrow e$ or $e \rightarrow \tau$

- **Various models predict enhanced sensitivity for 1-3 transitions while suppressing 1-2 transitions**
  - ★ specific parameter space of MSSM see-saw model
  - ★ SU(5) GUT with leptoquarks
- **Leptoquark models provide a good benchmark to study sensitivity**

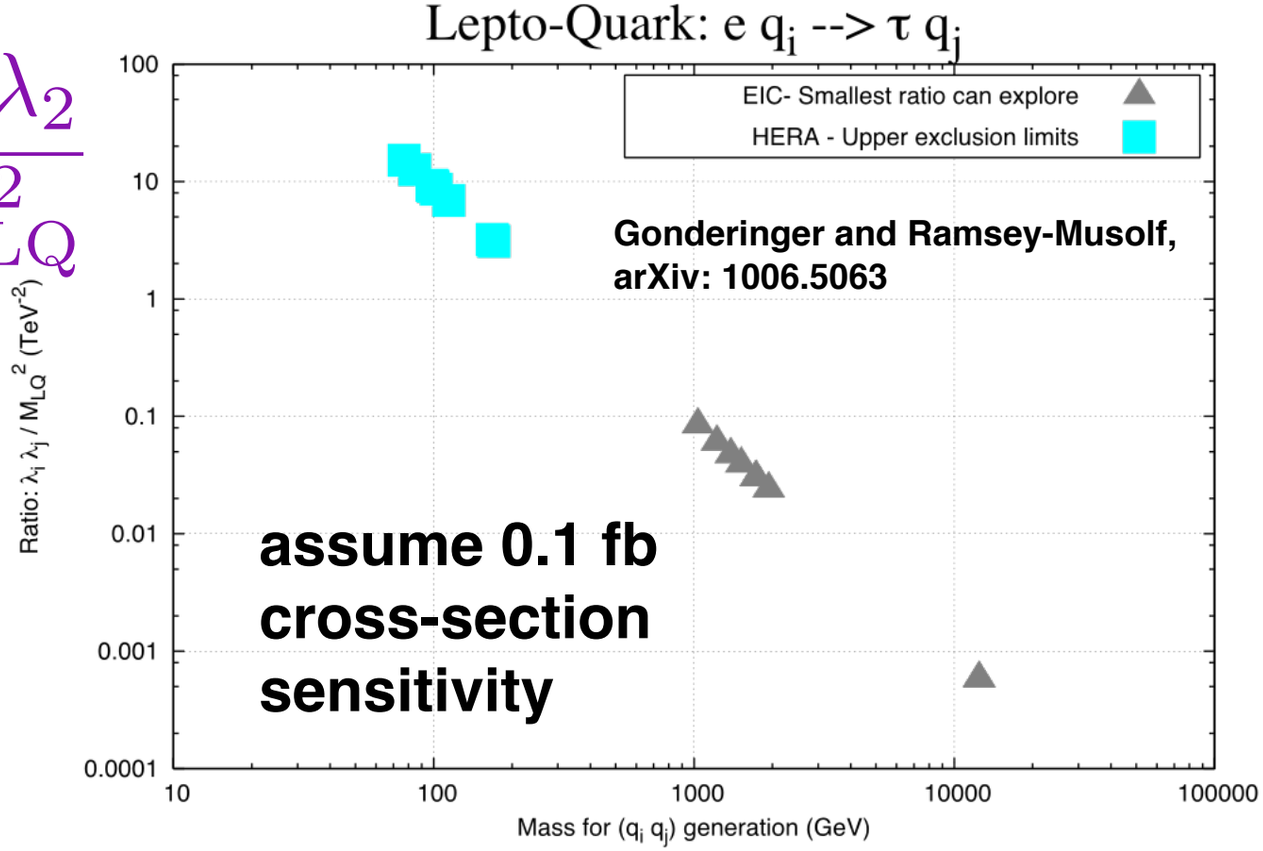
Gonderinger and Ramsey-Musolf, arXiv: 1006.5063



Main Message: New discovery space if one can achieve 0.1 fb cross-section sensitivity



$$\frac{\lambda_1 \lambda_2}{M_{\mathrm{LQ}}^2}$$



Even a decade from now, the EIC can compete in the first-to-third generation searches

e-τ Conversion Search

$$e^- + p \rightarrow \tau^- + X$$

Topology: neutral current DIS event; except that the electron is replaced by tau lepton

Tau Decay Modes and Branching Ratios

- **1-prong** **85.24 (0.06)%**
  - $\mu^-\bar{\nu}_\mu\nu_\tau$ 17.39 (0.04)%
  - $e^-\bar{\nu}_e\nu_\tau$ 17.82 (0.04)%
  - $\pi^-\nu_\tau$ 10.82 (0.05)%
  - $\pi^-\pi^0\nu_\tau$ 25.49 (0.09)%
  - $\pi^-2\pi^0\nu_\tau$ 9.26 (0.10)%
  - $\pi^-3\pi^0\nu_\tau$ 1.04 (0.07)%
  - others (kaon, etc) 3.24%
- **3-prong** **14.55 (0.06)%**
  - $\pi^-\pi^+\pi^-\nu_\tau$ 9.31 (0.05)%
  - $\pi^-\pi^+\pi^-\pi^0\nu_\tau$ 4.62 (0.05)%
  - others (kaon, etc) 1.28%
- others 0.21%

- If mixed in with hadron remnants, tau is boosted
- If forward along incident electron, the tau is isolated
- Potential for clean identification with high efficiency:
  - look for single pion, three pions in a narrow cone, single muon: should be able to devise good triggers
  - tau vertex displaced 200 to 3000 microns: would greatly help background rejection and maintain high efficiency with the use of a vertex detector, which is included in EIC detector design

Is it possible to have greater than 10% efficiency with negligible background in a 100 fb^{-1} data sample?

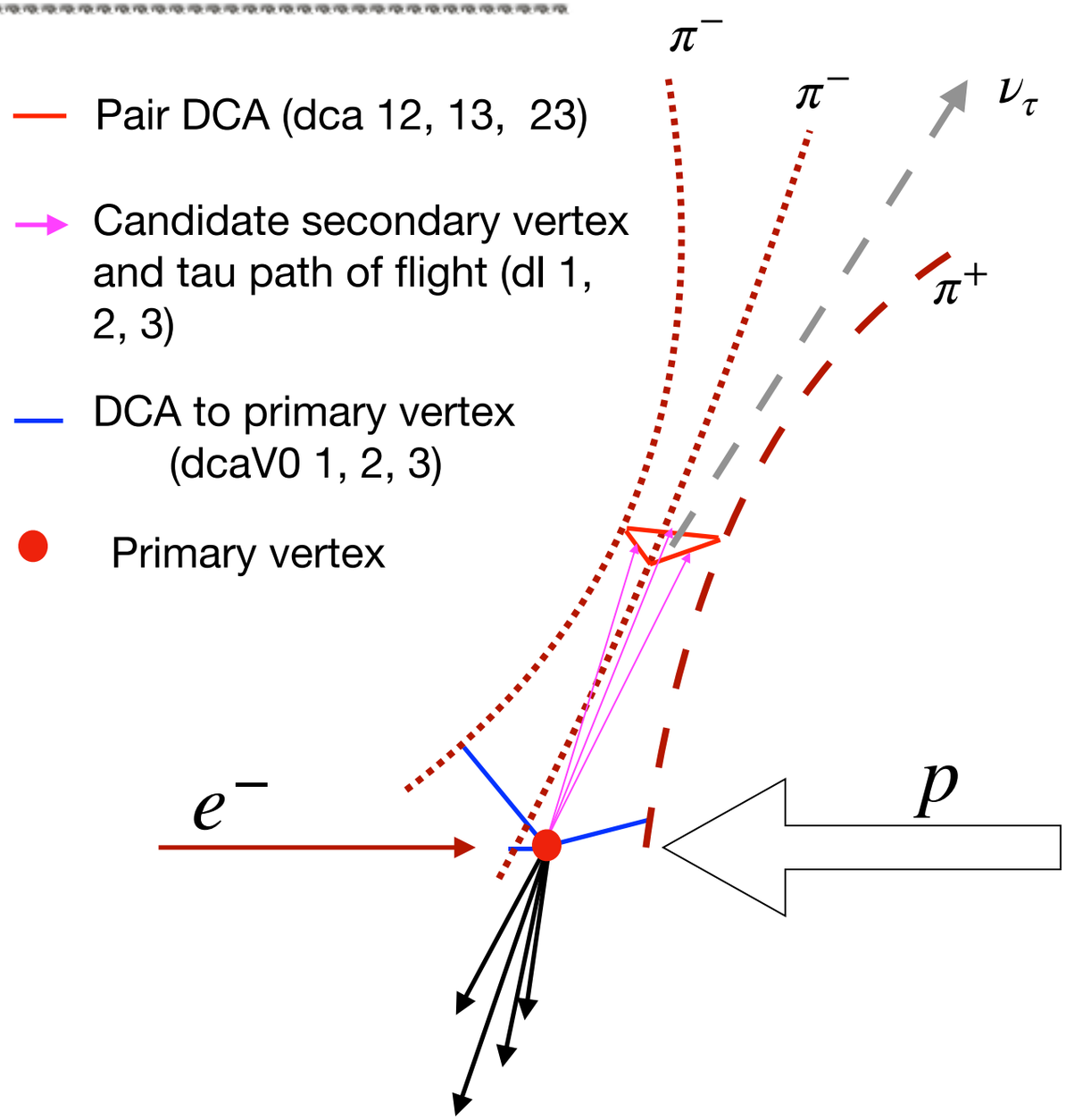
HERA searches had ~ 2.5% efficiency but EIC detector capabilities and improved understanding of jet shapes should allow for significant improvement

Zeroth Order Strategy

work of Jinlong Zhang

Generator Level Study, tau 3-prong decays

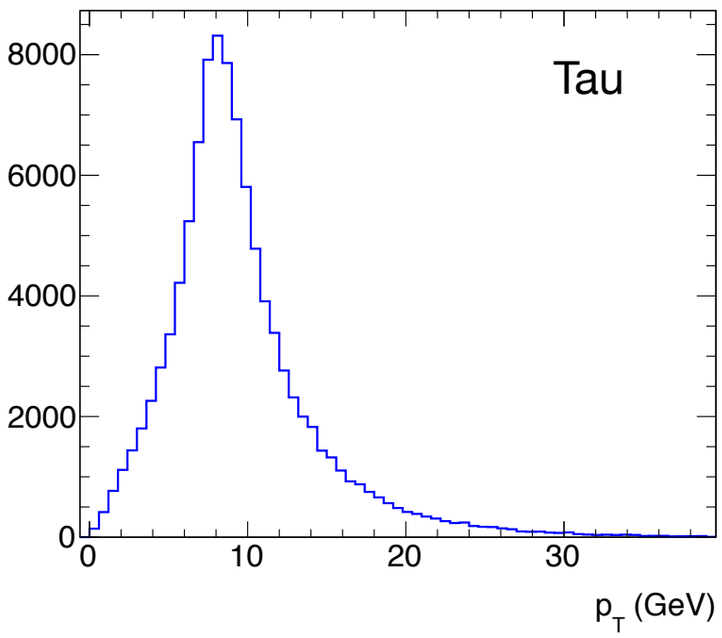
- Event generators:
  - LQGENEP 1.0 for Leptoquark events (L. Bellagamba, 2001)
  - DJANGOH 4.6.8 for DIS (NC + CC) events (H. Spiesberger 2005)
- Jets reconstructed from MC events
  - Anti-k_T, R = 1.0
  - Scattered electron for SM DIS and neutrinos **excluded**
- Secondary vertex finding from $\pi^-\pi^+\pi^-$

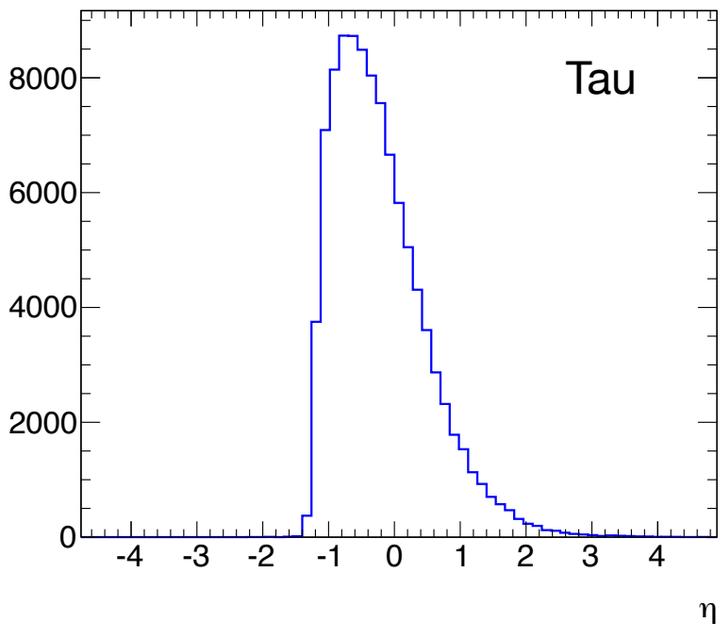


fast simulation investigations will then be validated with full detector simulation and reconstruction

Generator-level Distributions

Tau Event Kinematics





Generator level:

- e+p 20x250 GeV^2
- $Q^2 > 100$ GeV^2

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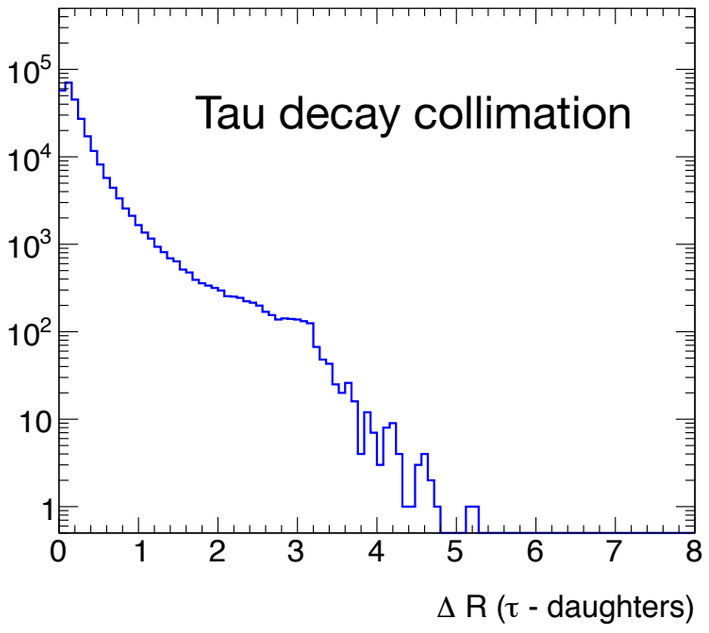

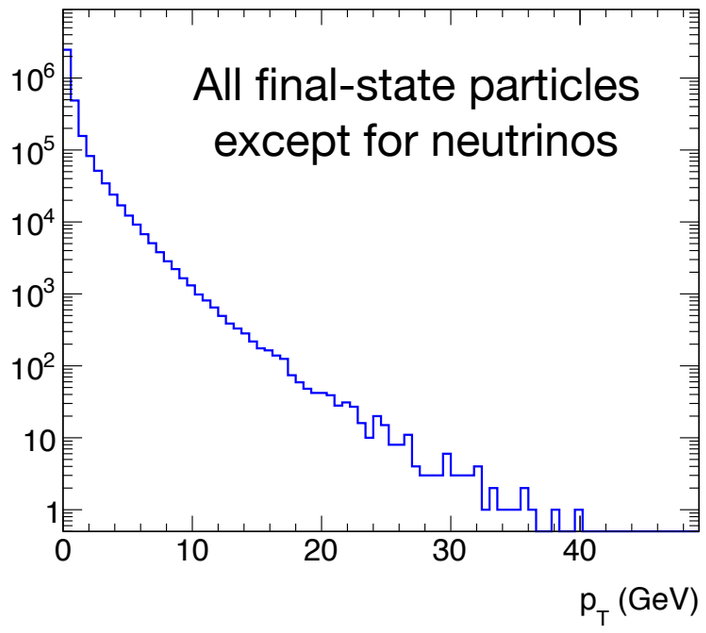

Generator-level Fast Simulation

Event Selection

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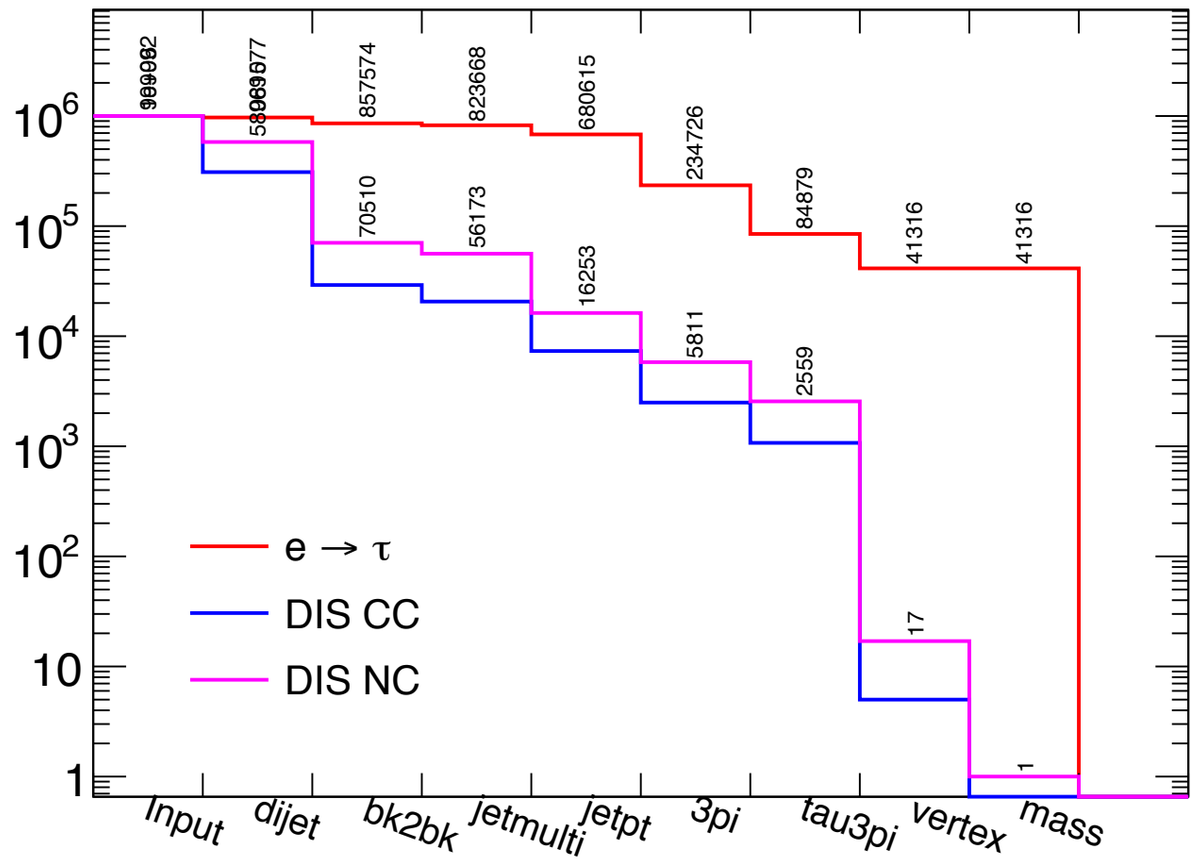
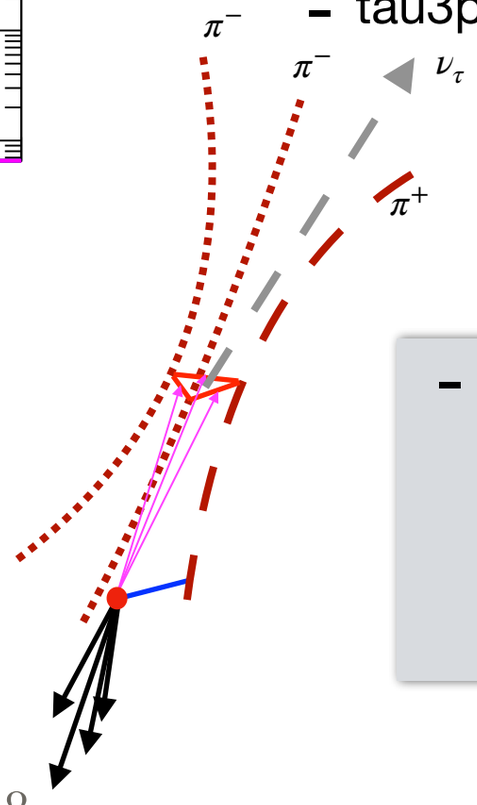


- di-jet: number of jets >= 2
- bk2bk: $cos\Delta\phi_{jet1-jet2}$ < -0.7
- jetmulti: number of particles < 5 for at least one of the jets
- jetpt: p_T (jet1) > 4.0 and p_T (jet2) > 2.5
- 3pi: jet contain 3pi
- tau3pi: 3pi jet aligns with missing p_T



- vertex: dRsum < 0.2 && dl_asy < 0.2 mm && dl_ave < 0.2 mm

Collimation in (η, ϕ) space:

$$dRsum = \Delta R(\vec{1}, \vec{2}) + \Delta R(\vec{2}, \vec{3}) + \Delta R(\vec{1}, \vec{3})$$

Length matching:

$$dl\_asy = |dl_1 - dl_2| + |dl_1 - dl_3| + |dl_2 - dl_3|$$

- mass: corrected mass < 1.8 GeV

$$\sqrt{M_{3\pi}^2 + p_{3\pi}^2 sin^2\theta} + p_{3\pi} sin\theta$$

θ: angle between $\overrightarrow{V_{2nd}}$ and $\overrightarrow{p_{3\pi}}$

Generator-level Fast Simulation

Last Two Cuts

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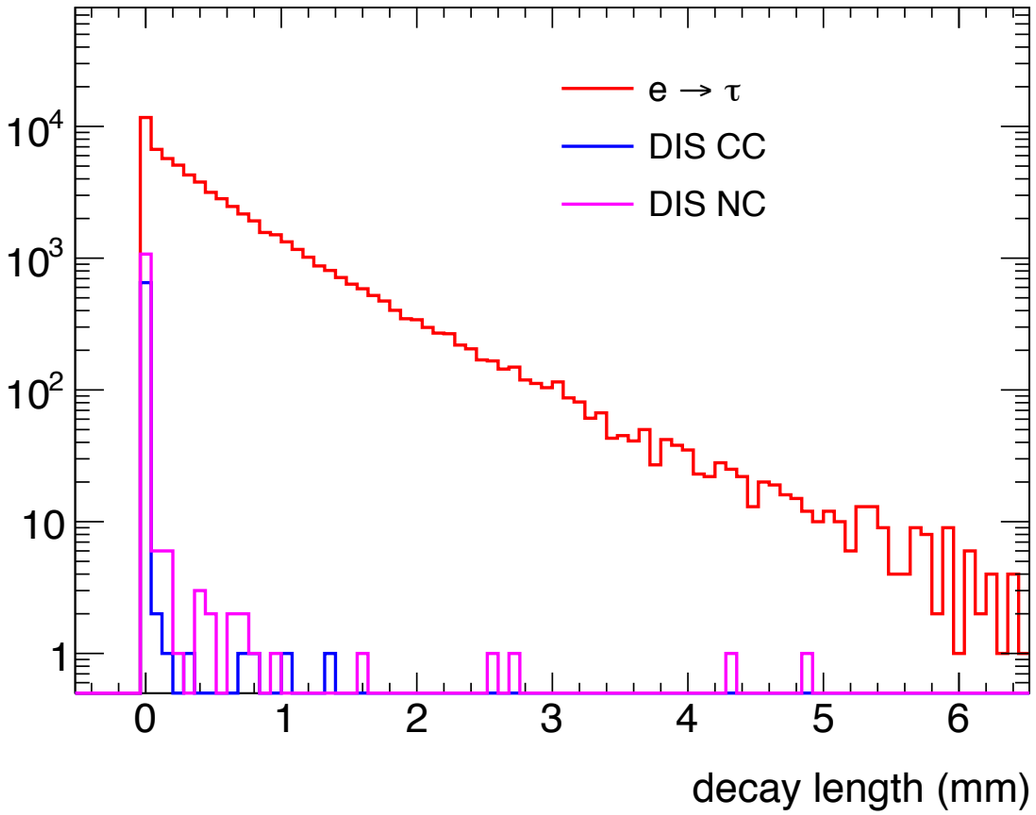
- Secondary vertex and corresponding decay length reconstructed from paired pion tracks

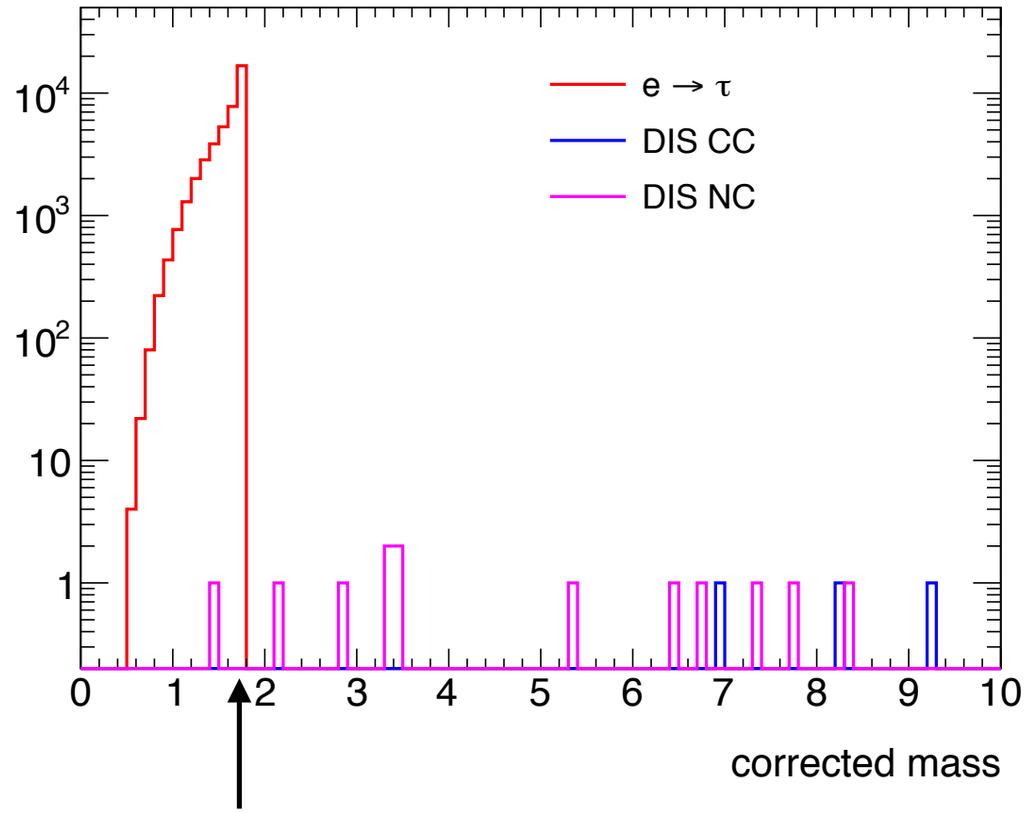


Neutral current cross-section: 3.6 nb
Charged current cross-section: 2.0 pb

- Corrected mass from 3 pions

$$\sqrt{M_{3\pi}^2 + p_{3\pi}^2 sin^2\theta} + p_{3\pi} sin\theta$$

θ: angle between $\overrightarrow{V_{2nd}}$ and $\overrightarrow{p_{3\pi}}$



1M events in all 3 processes: need to run 50 to 100 times more neutral current events

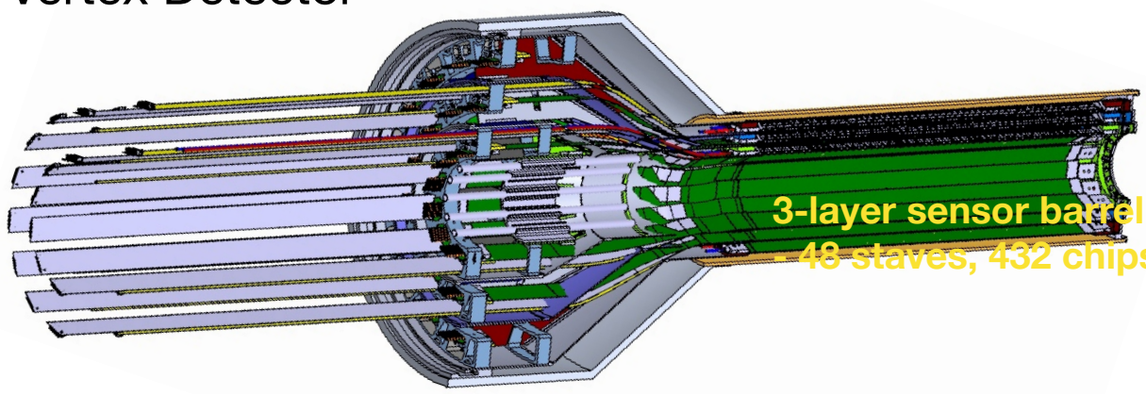
Note: we have not yet rejected events with an isolated stiff electron

Towards Detector Simulation and Full Reconstruction

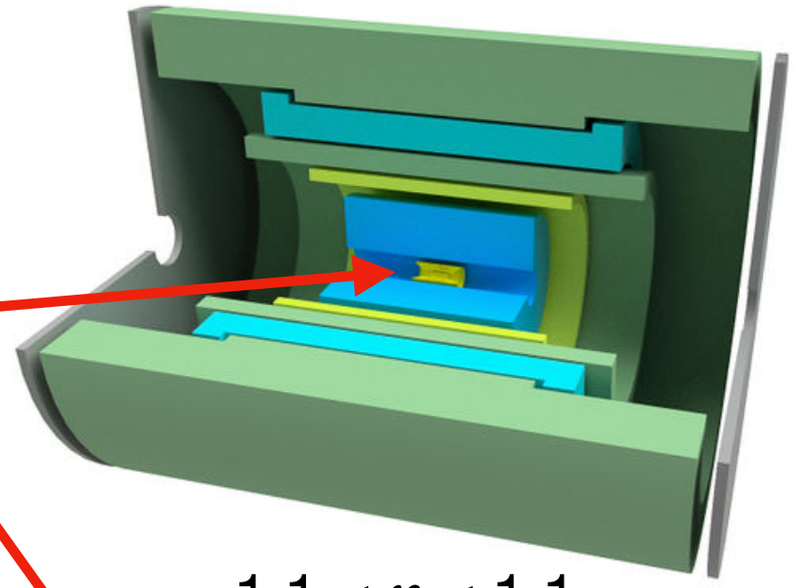
see talk by C. Pinkenburg on Thursday

sPHENIX

MVTX — Monolithic-Active-Pixel-Sensor-based Vertex Detector

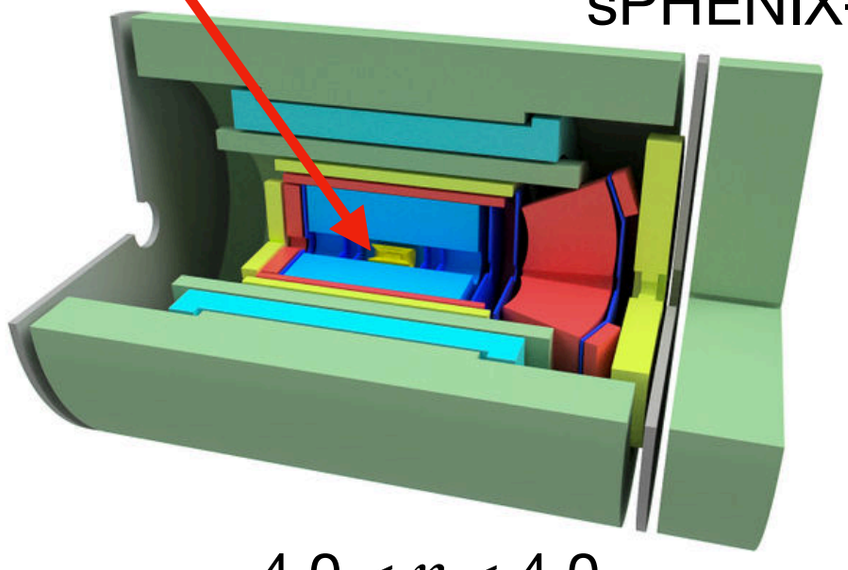


Service cone: signal, power, cooling and mechanical support



$-1.1 < \eta < 1.1$

sPHENIX-EIC



$-4.0 < \eta < 4.0$

MVTX parameters

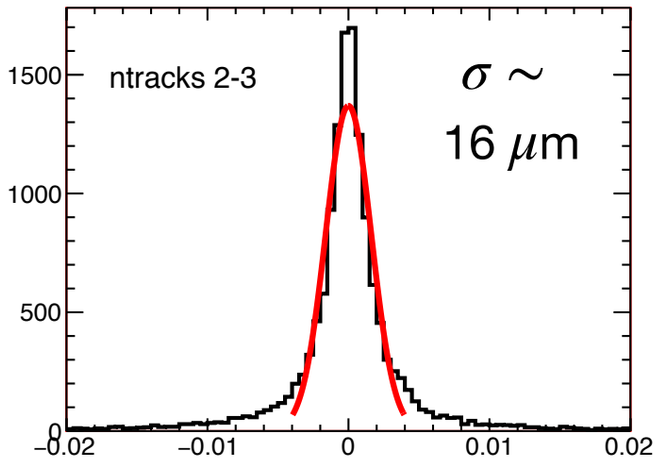
- 30um ALPIDE MAPS pixel in three layers, total 200 M pixel channels
- 5us hit position resolution, 0.3% X0 thickness per layer
- < 50 um DCA for track pT > 1 GeV

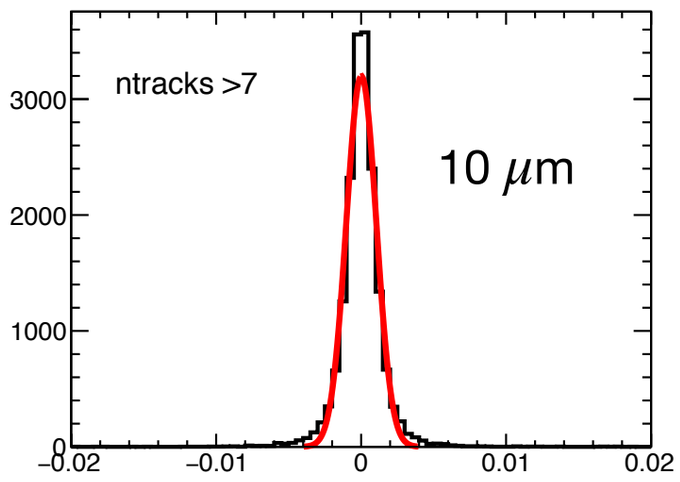
caveat: the EIC beam pipe likely larger… configuration likely won't directly translate

Full Detector Simulation and Reconstruction

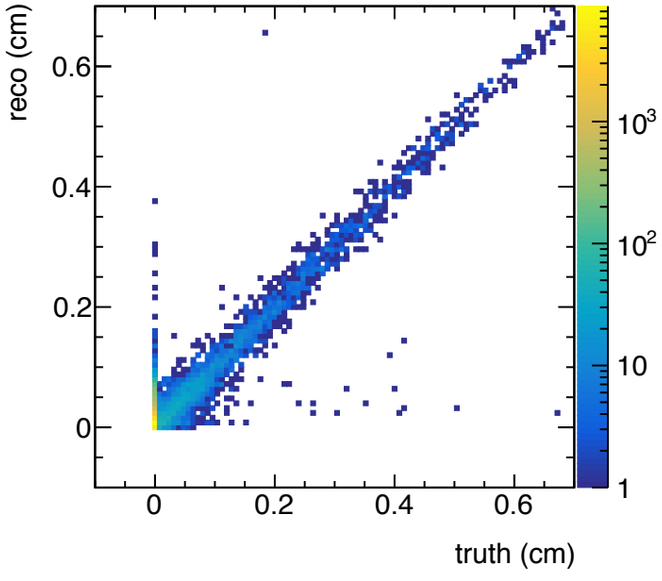
work of Jinlong Zhang

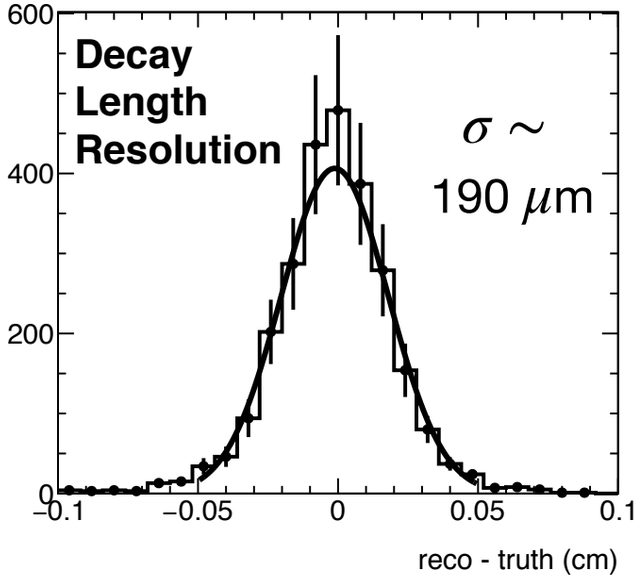
Vertex Resolution



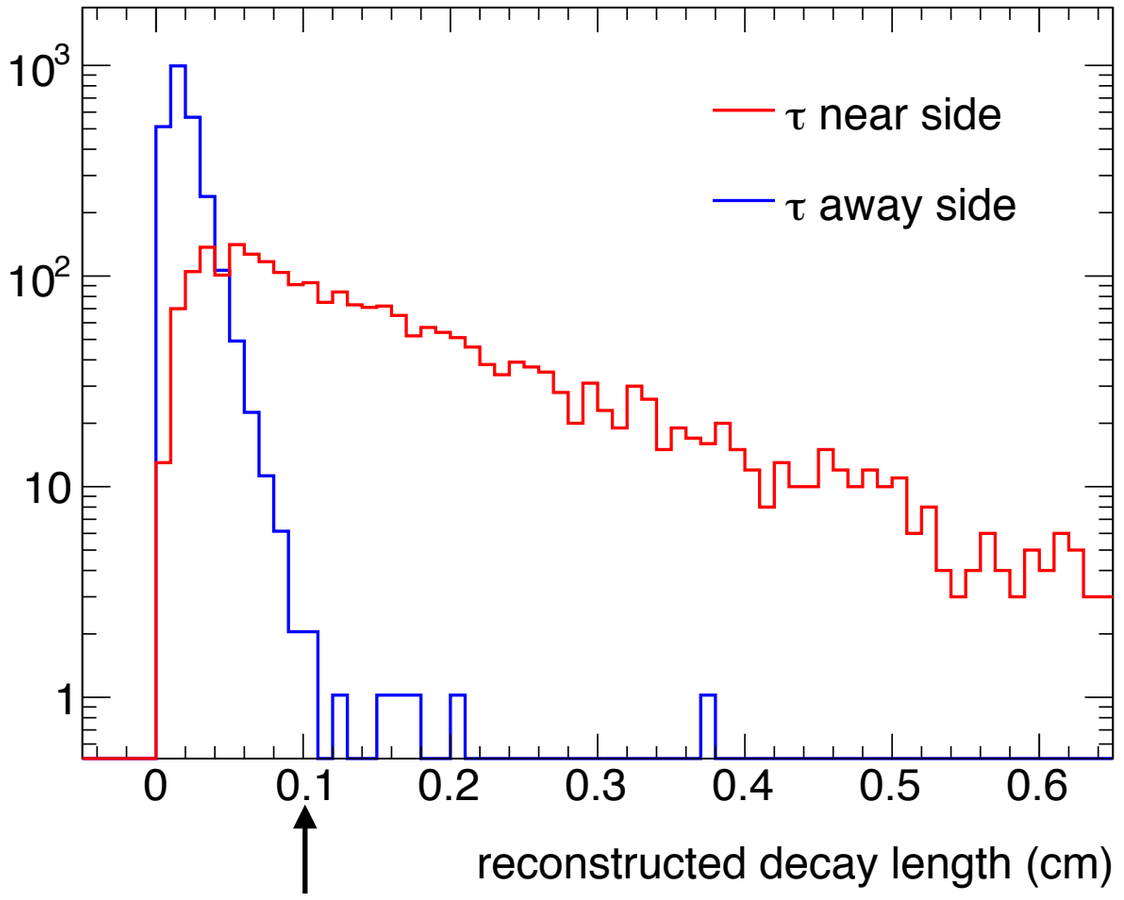


- Vertex resolution at x component **~10** μm
- Similar for y and z components at middle rapidity





- Similar algorithm applied as for Generator level analysis



- Decay length resolution ~ 190 μm

Efficiency with Detector Effects

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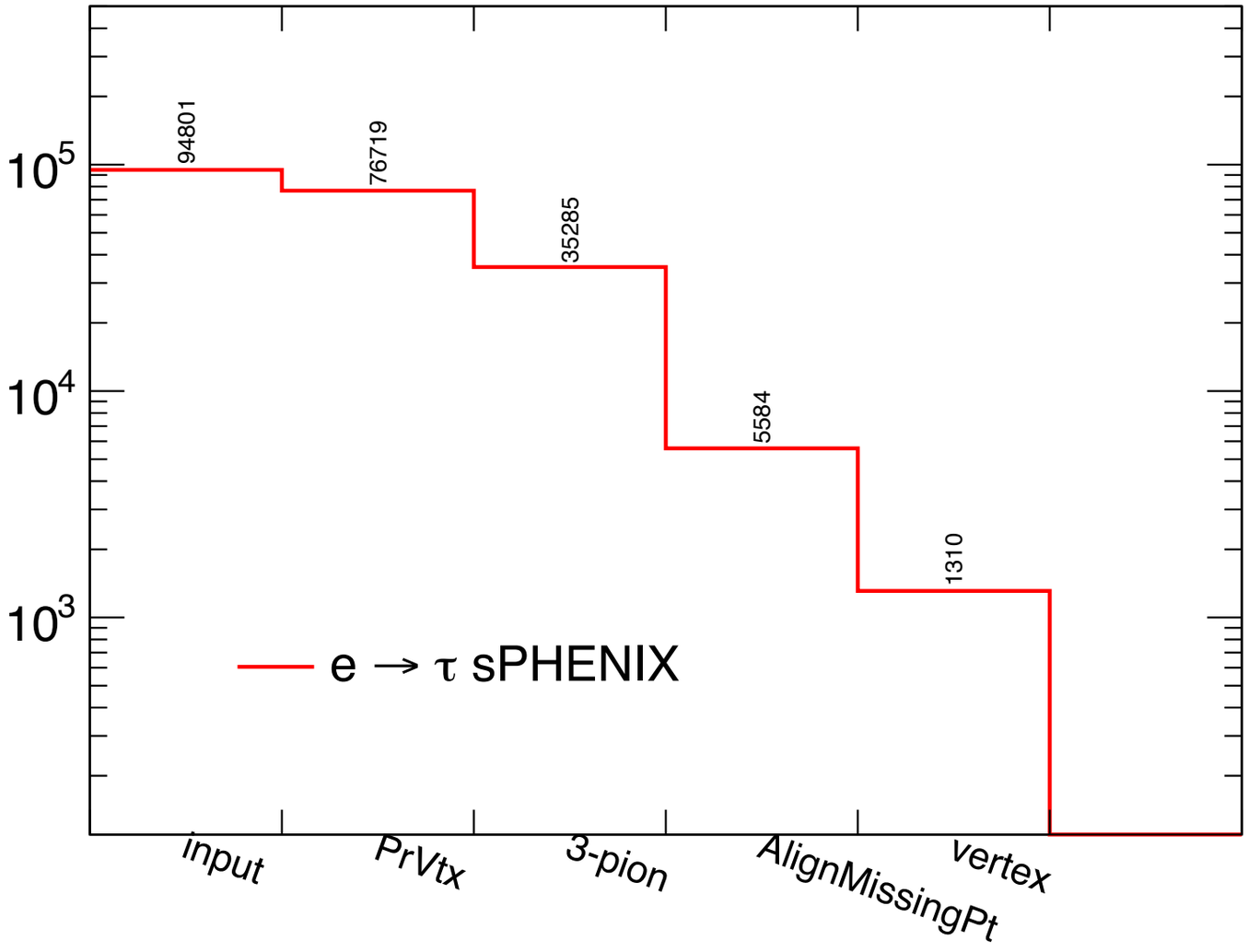

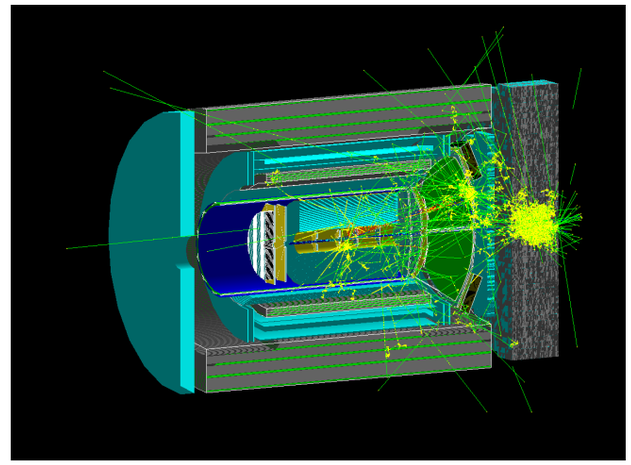

- PrVtx: good primary vertex
- 3-pion: only accept for 3-pion events (assuming 100% PID)
- AlignMissingPt: 3-pion should be at the “missing-pT” side azimuthally
- Vertex: match reconstructed secondary vertexes, decay length > 1 mm

- **Similar algorithm applied as for Generator level analysis**
- **First pass: 15% of 3-prong signal efficiency from sPHENIX detector simulation: should be able to do better with further optimization of selection criteria**

Next Steps

- **Generate a much larger sample of neutral current events**
- **Tau 3-Prong Decays:**
  - ★ Review generator level cuts to improve signal selection efficiency
    - *redundant cuts? Of course, background suppression should not be compromised*
  - ★ Investigate if we can also use $10 < Q^2 < 100\ GeV^2$ events
- **Tau 1-Prong decays:**
  - ★ Devise independent cuts for single muon and single pion modes
  - ★ Possible to use $\pi^+\pi^0$ mode while rejecting background?
  - ★ does vertex detector impact parameter help significantly?

Conclusion and Outlook

- **EIC machine designs now aiming aggressively for high luminosity (> $10^{34}/cm^2/s$)**
  - new ideas on vertex trackers and improved understanding of jet shapes and structures merits a re-examination of potential reach and background rejection
- **A sensitivity reach of ~ 0.1 fb cross-section while suppressing backgrounds looks promising**
  - this study is only the beginning; significant work remains to be done
- **The reconstruction tools and background suppression techniques likely has synergies with other high luminosity topics e.g. heavy flavors...**

Backup

Reconstructed DCA Resolution