SHANDONG UNIVERSITY

Search for leptoquark mediated e-to-tau transit at EIC

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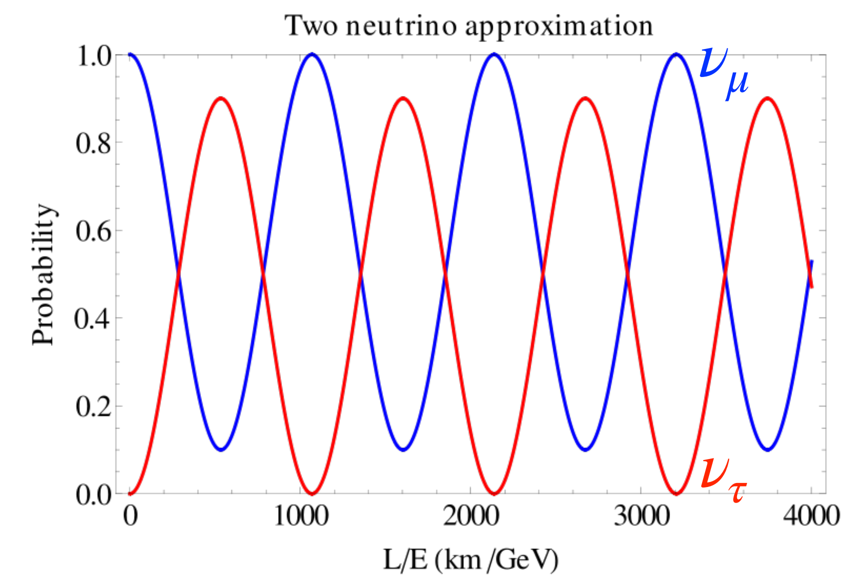
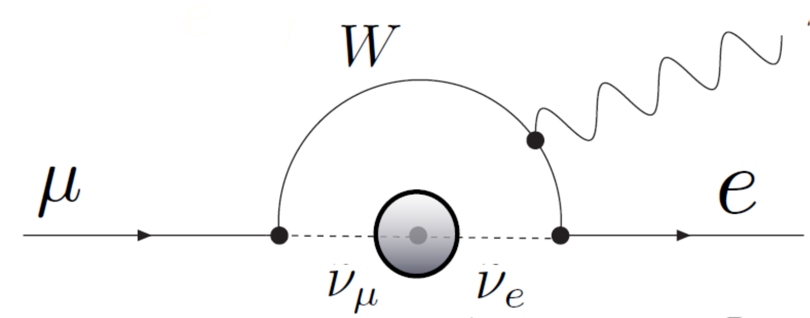
CFNS Workshop: High Luminosity-EIC (EIC-Phase II)
June 22, 2022

Charged Lepton Flavor Violation

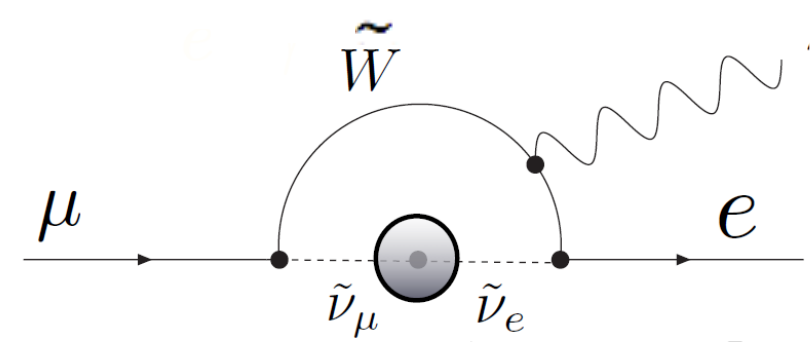
- Lepton Flavor (generation) is not conserved, neutrino oscillations observed. (2015 Nobel Prize)
- Charged lepton flavor violations (CFLV) should also be allowed within the SM; but extremely low rate, e.g. BR($\mu \to e\gamma$) < 10^{-54}
- Many BSM models predict significantly higher rate of CFLV, e.g. SUSY slepton mixing BR($\mu \to e\gamma$) < 10^{-15}





neutrino oscillations

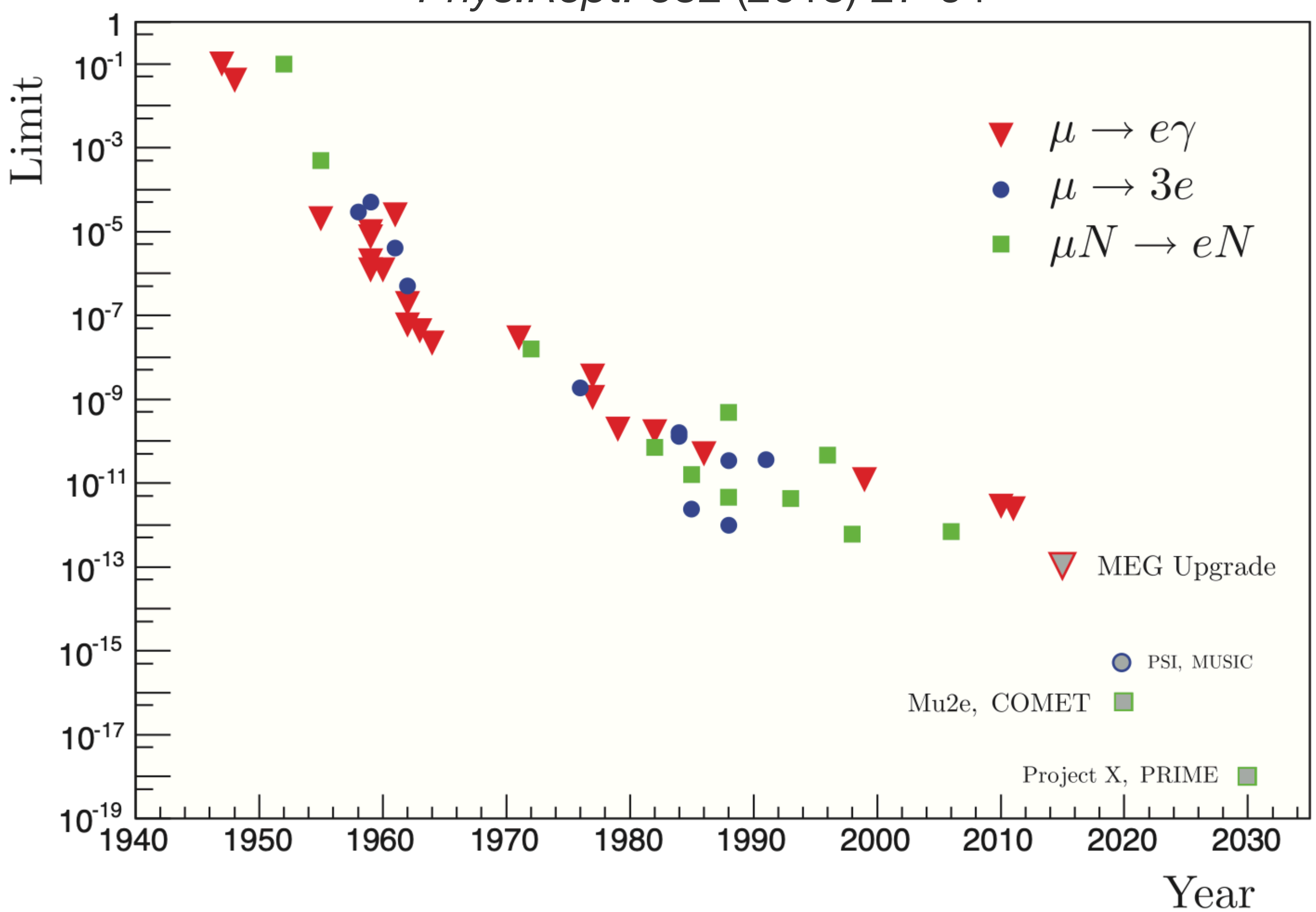
BSM



SUSY slepton mixing

Experimental Searches of CLFV(1,2)

Phys.Rept. 532 (2013) 27-64



- LFV(1,2): Extensive searches for have placed stringent experimental limits.
  - SINDRUM-II, MEGA, SINDRUM Belle, BaBar, *Mu2e,*
- LFV(1,3): Several orders of magnitude **weaker** limits than LFV(1,2)

$e \rightarrow \tau$ conversion at *ep* collision

Various models predict enhanced sensitivity for LFV(1,3) while suppressing LFV(1,2)

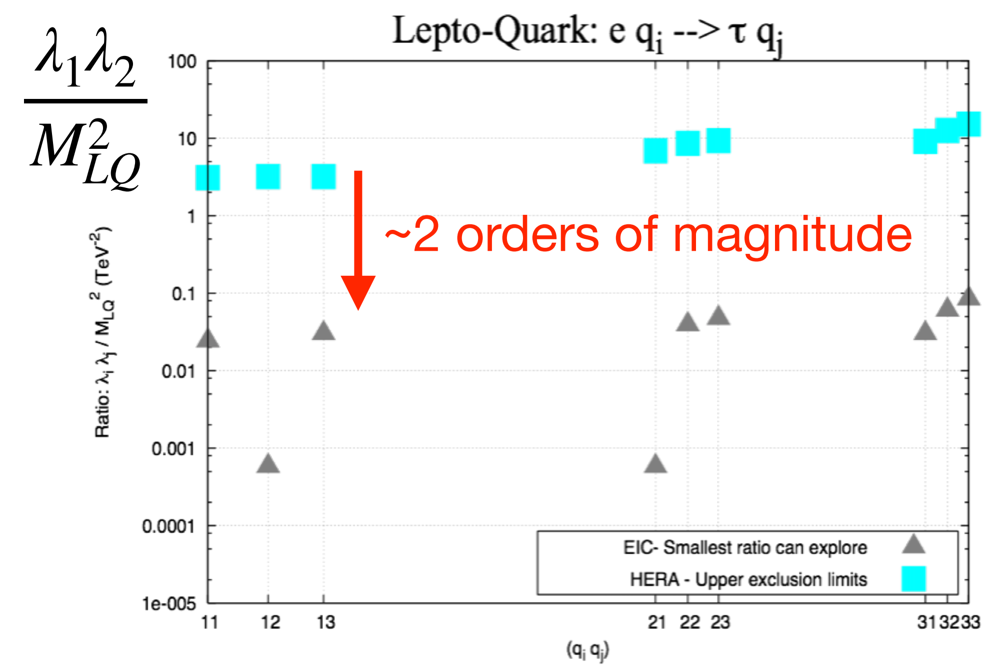
- **Leptoquark** models provide a good benchmark to study sensitivity
  Gonderinger, Ramsey-Musolf, JHEP (2010) 2010: 45

- HERA set limits in coupling-mass space for LQ production in e-p scatterings

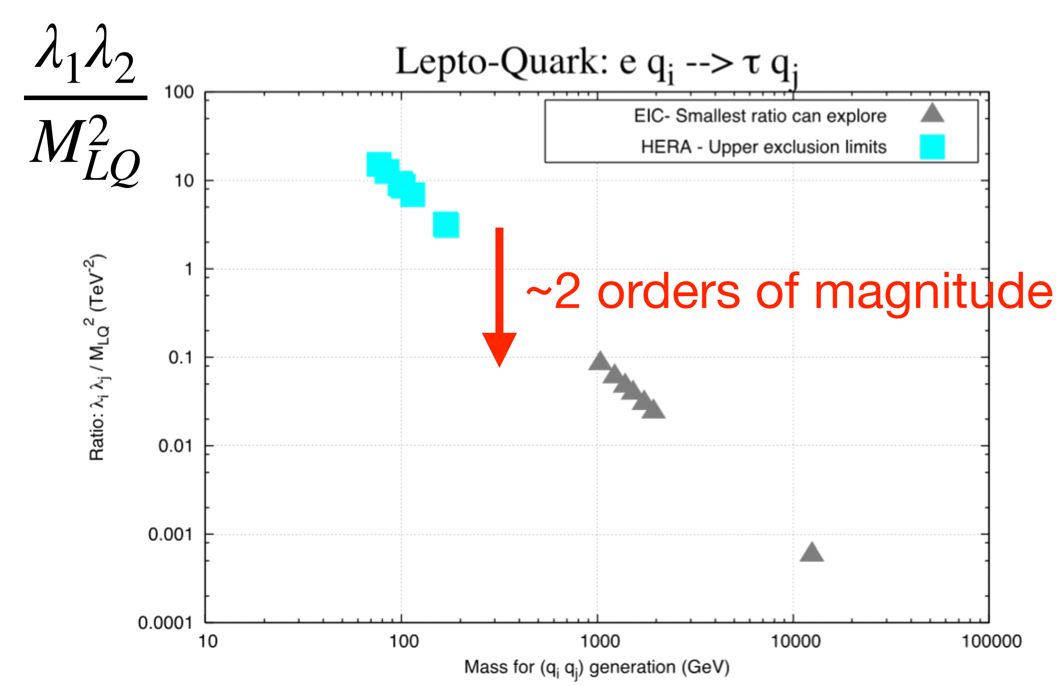
- At the EIC, with much higher luminosity (phase-1) , $10^{30\text{-}31} \rightarrow 10^{33\text{-}34}$ $cm^{-2}s^{-1}$, ~2 orders of magnitude improvement of the sensitivity is expected

New discovery space: $e \rightarrow \tau$ conversion

- will be enlarged with higher luminosity



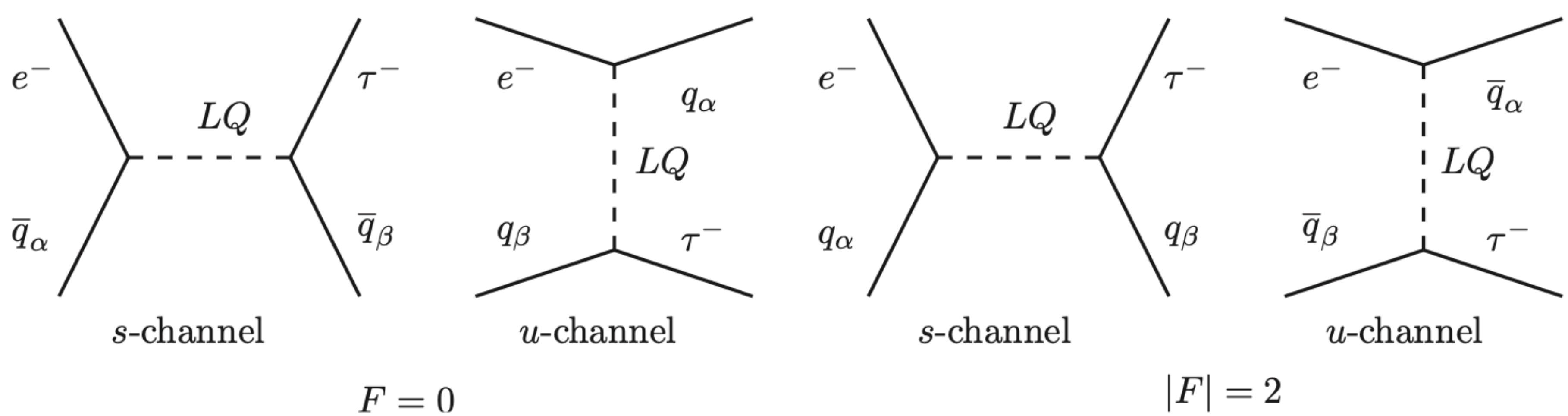
Assume 0.1 fb cross-section sensitivity



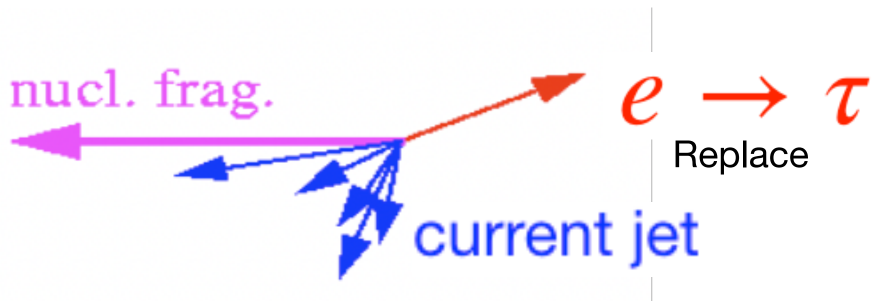
Leptoquark

Leptoquarks (LQs) appear in certain extensions of the SM.

- Symmetry between lepton sector and quark sector
- Flavor violating but fermion number (F = 3B+L) conserving
- Buchmüller-Rückl-Wyler (BRW) framework: 14 different LQ types (7 scalars, 7 vectors)
- CLFV at tree level processes; allow coupling between same and different generations of quarks and leptons at initial state and final state



Goal of this Study at EIC



- Replace electron with tau
- Tau back-to-back with current jet
- Primary vertex reconstructed from tracks of current jets
- **Tau vertex displaced at mm level**
  - 3-prong tau jet; decay topology important for τ jet ID
  - 1-prong: recovering higher branching ratios; but background control is much more demanding

Tau decay mode and branching ratio

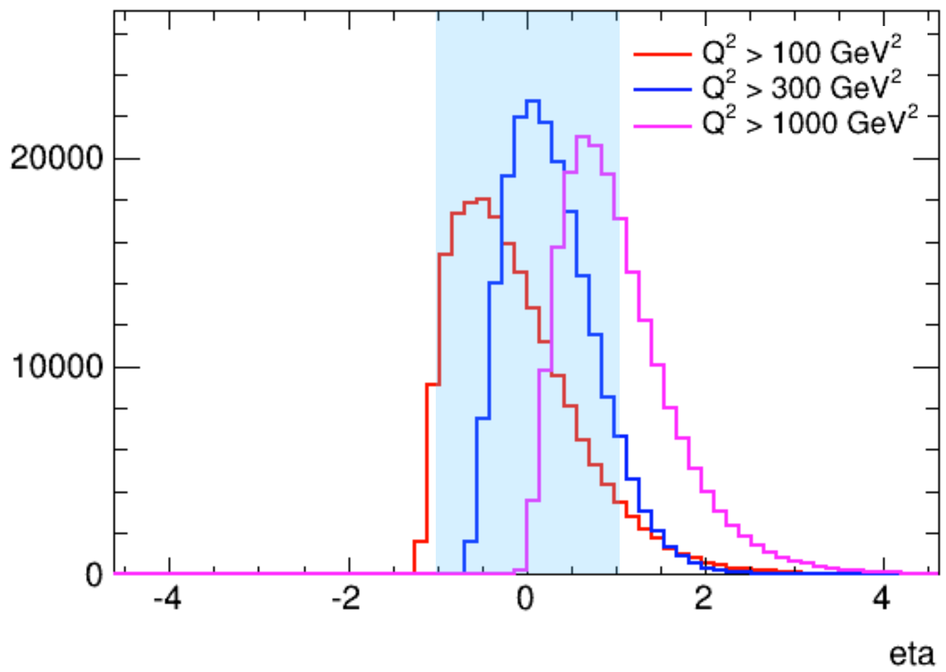
- **3-prong** **15.21 (0.06)%**
  - $\pi^-\pi^+\pi^-\nu_\tau$ 9.31 (0.05)%
  - $\pi^-\pi^+\pi^-\pi^0\nu_\tau$ 4.62 (0.05)%
  - others (kaon, etc) 1.28%
- **1-prong** **84.58 (0.06)%**
  - $\mu^-\bar{\nu}_\mu\nu_\tau$ 17.39 (0.04)%
  - $e^-\bar{\nu}_e\nu_\tau$ 17.82 (0.04)%
  - $\pi^-\nu_\tau$ 10.82 (0.05)%
  - $\pi^-\pi^0\nu_\tau$ 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%
- others 0.21%

HERA Efficiency ~2.5%

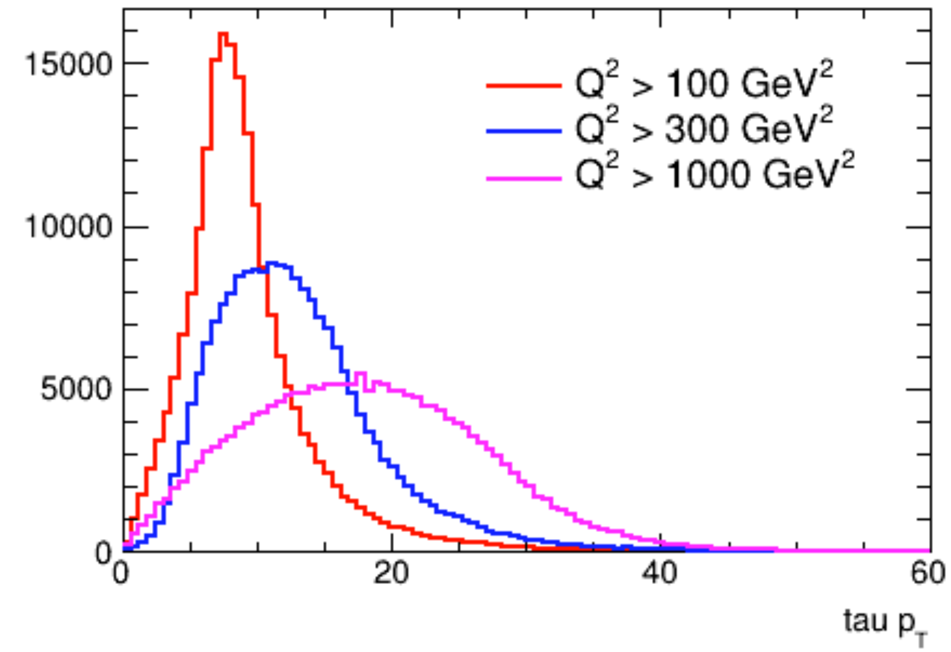
At EIC, benefit from improved vertex and jet detection, aim to greater than 10% efficiency with negligible background in a 100 fb^{-1} data sample

How LQ Tau looks like in ep

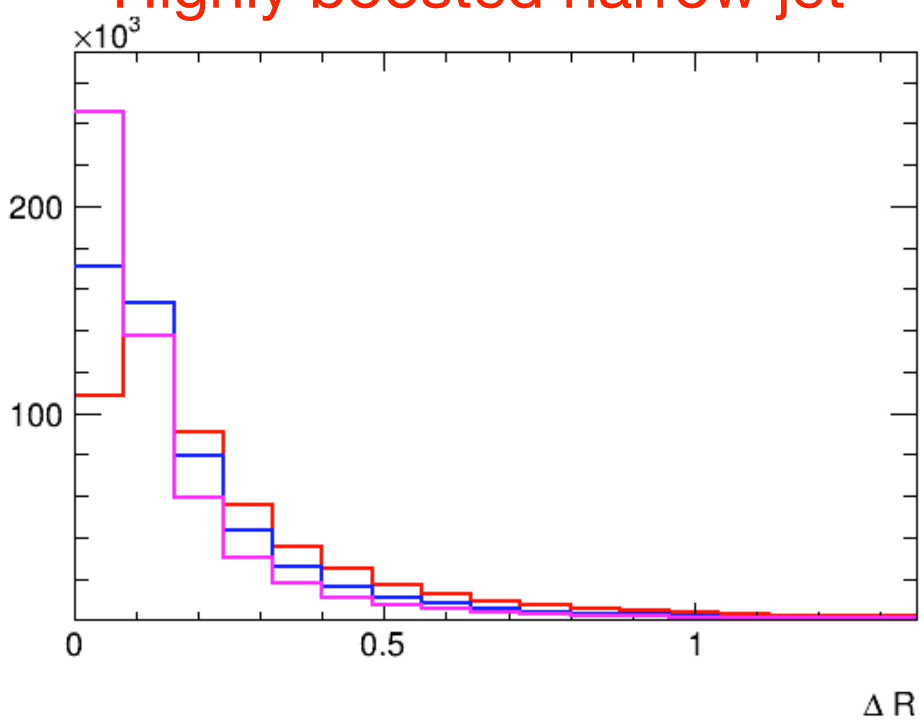
Mostly at Barrel (best detector performance)



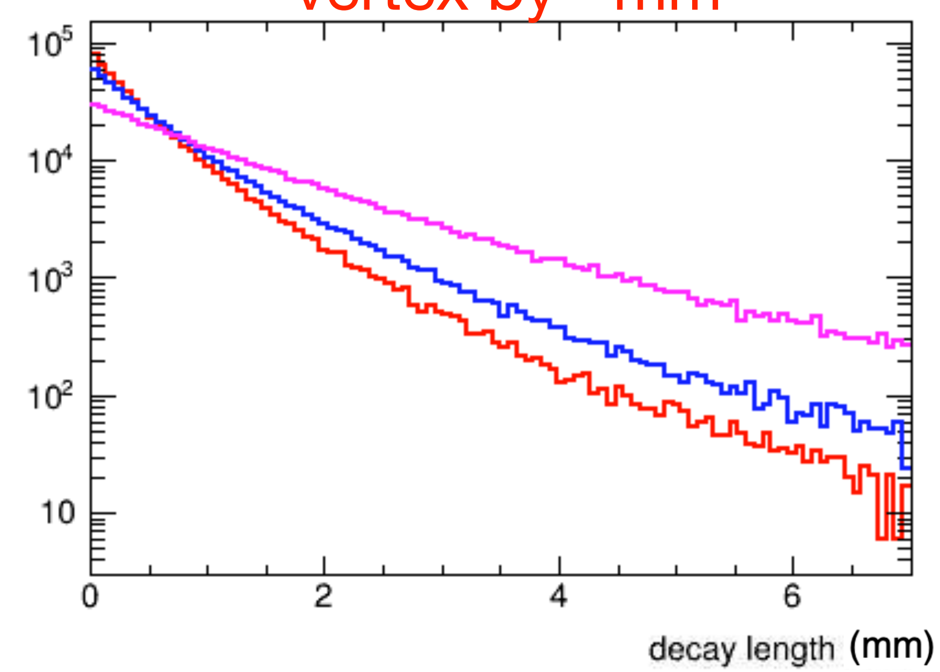
high pT



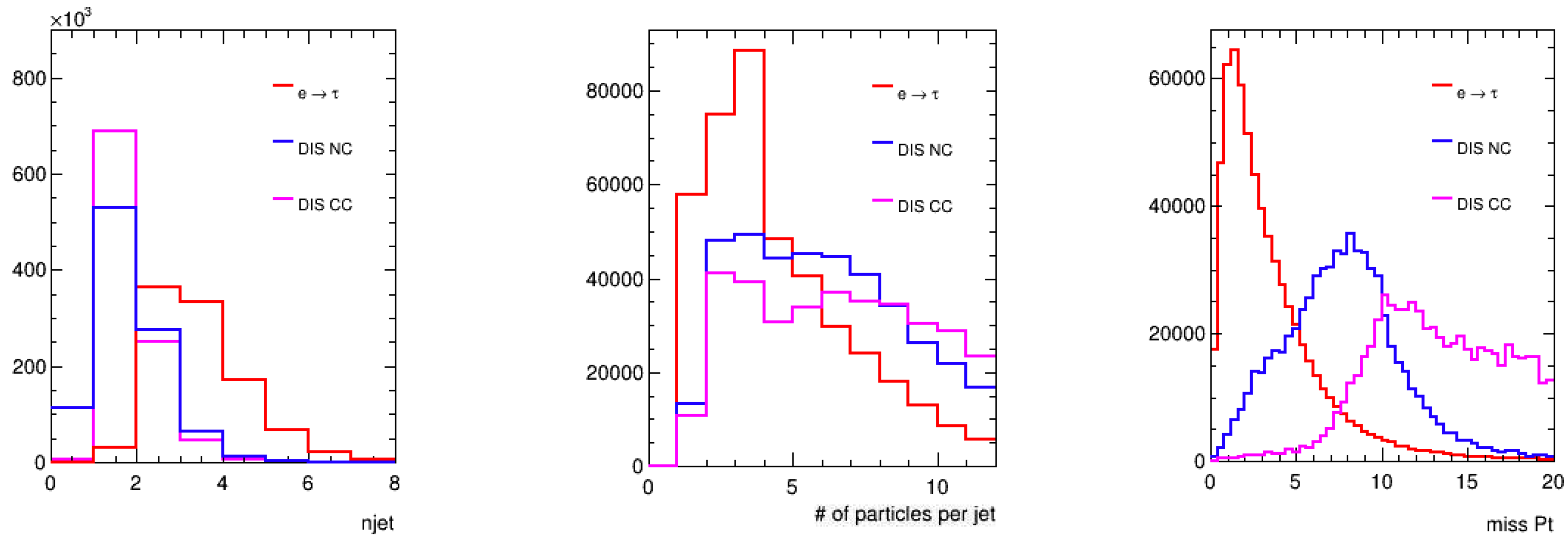
Highly boosted narrow jet



Away from primary vertex by ~mm



Features of LQ $e \to \tau$ event



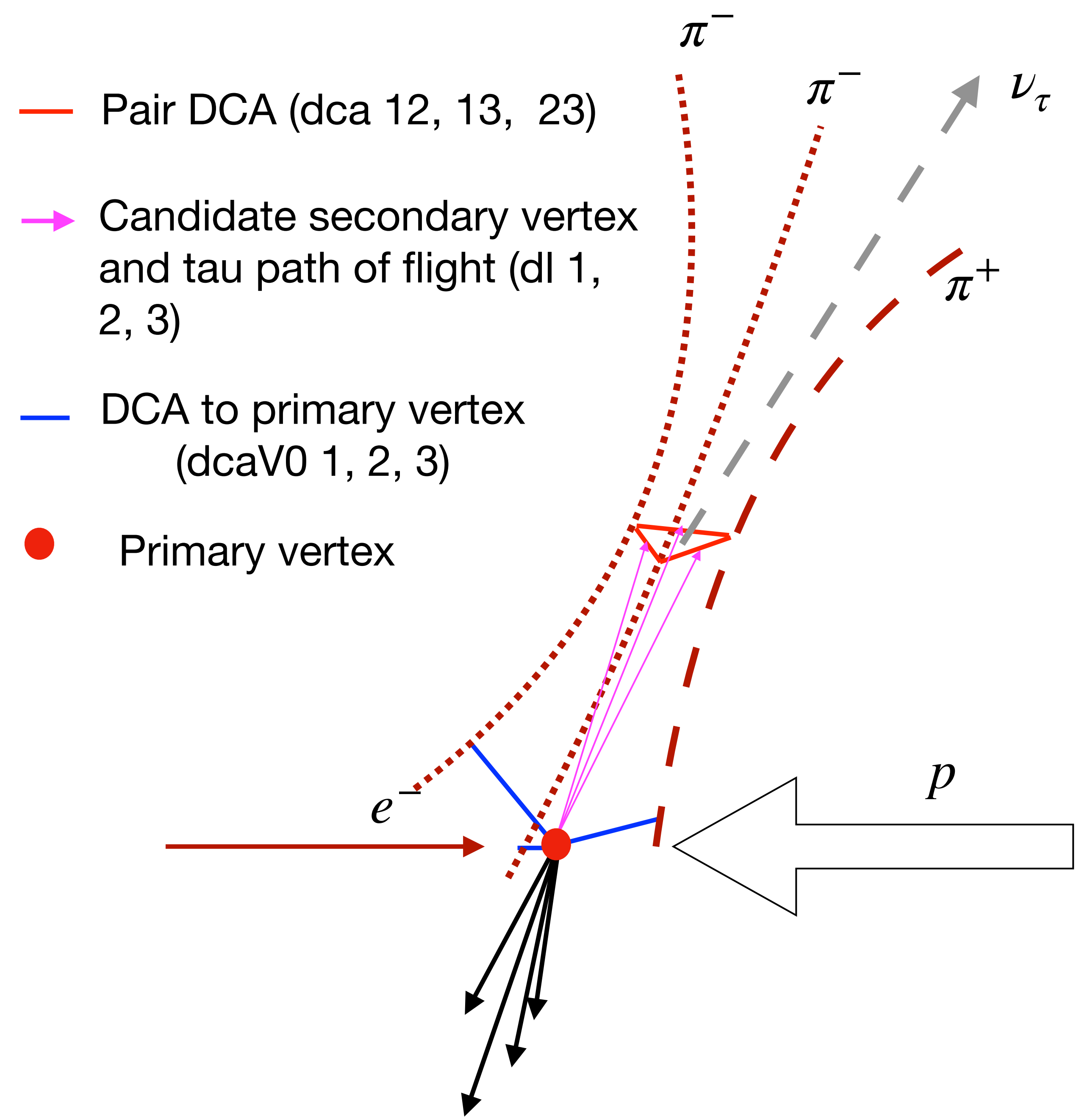
Note: electron in DIS NC is masked; Fastjet, Anti-k_T, R = 1.0; jet pt > 2 GeV; Q^2>100 GeV^2

- $e \to \tau$ event
  - 2+ jets
  - Low particle multiplicity
  - Modest missing pT (partial tau pT)

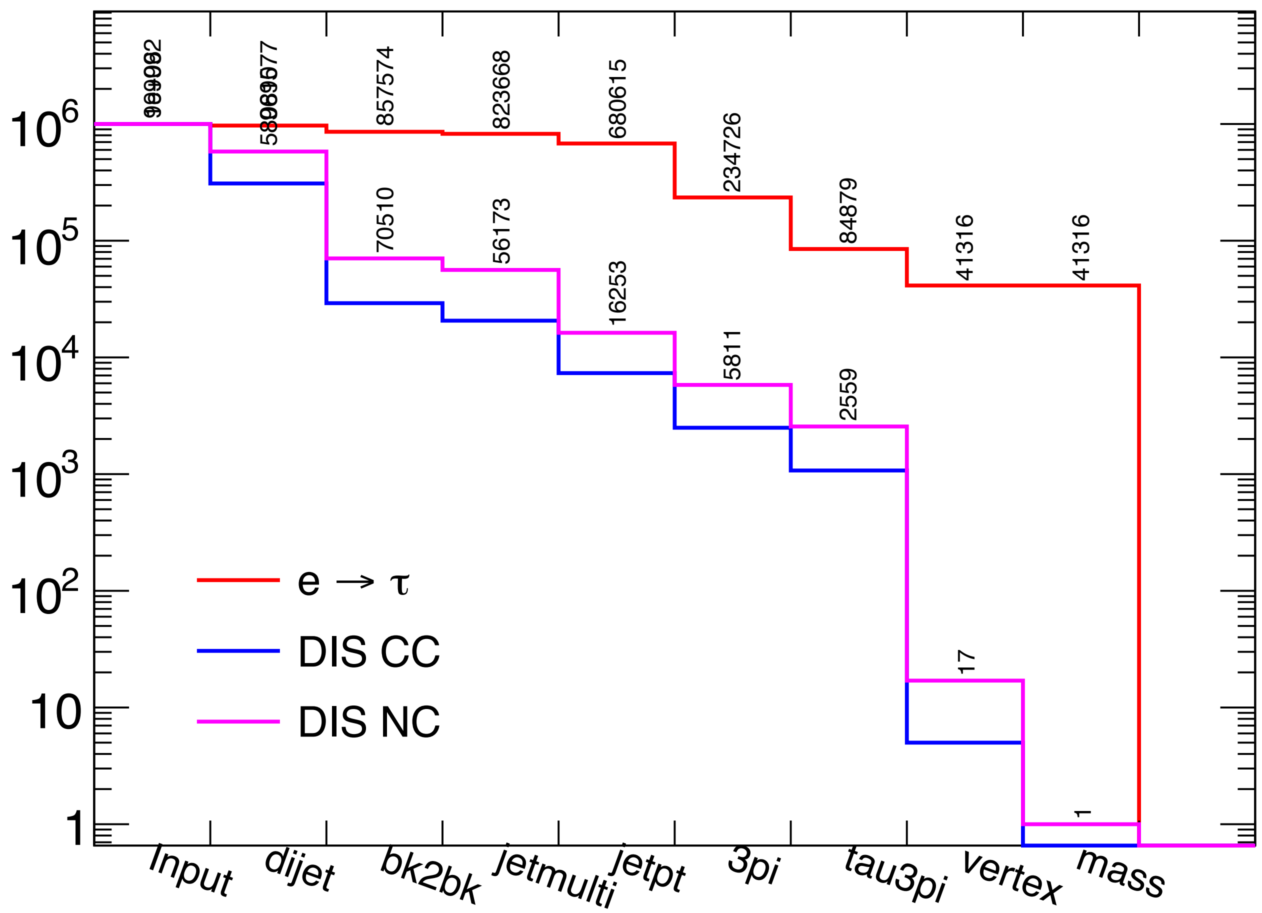
- DIS event
  - 1 jets dominating
  - Higher particle multiplicity
  - Missing pT ~ lepton pT

Search strategy for 3-prong decays

- Event generators:
  - LQGENEP 1.0 for Leptoquark events (L. Bellagamba, 2001)
  - DJANGOH 4.6.8 and pythiaeRHIC (pythia6) for DIS (NC + CC) events
  - Jets reconstructed from MC events
  - Fastjet, Anti-k_T, R = 1.0
  - Scattered electron for SM DIS and neutrinos **excluded**
- **Secondary vertex** finding from $\pi^-\pi^+\pi^-$



Events Selection



- 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: dR_sum < 0.2 && dl_asy < 0.2 mm && dl_average > 0.2 mm

Collimation in (η, ϕ) space:

$$dR\_sum = \Delta R(\overrightarrow{1}, \overrightarrow{2}) + \Delta R(\overrightarrow{2}, \overrightarrow{3}) + \Delta R(\overrightarrow{1}, \overrightarrow{3})$$

Length matching:

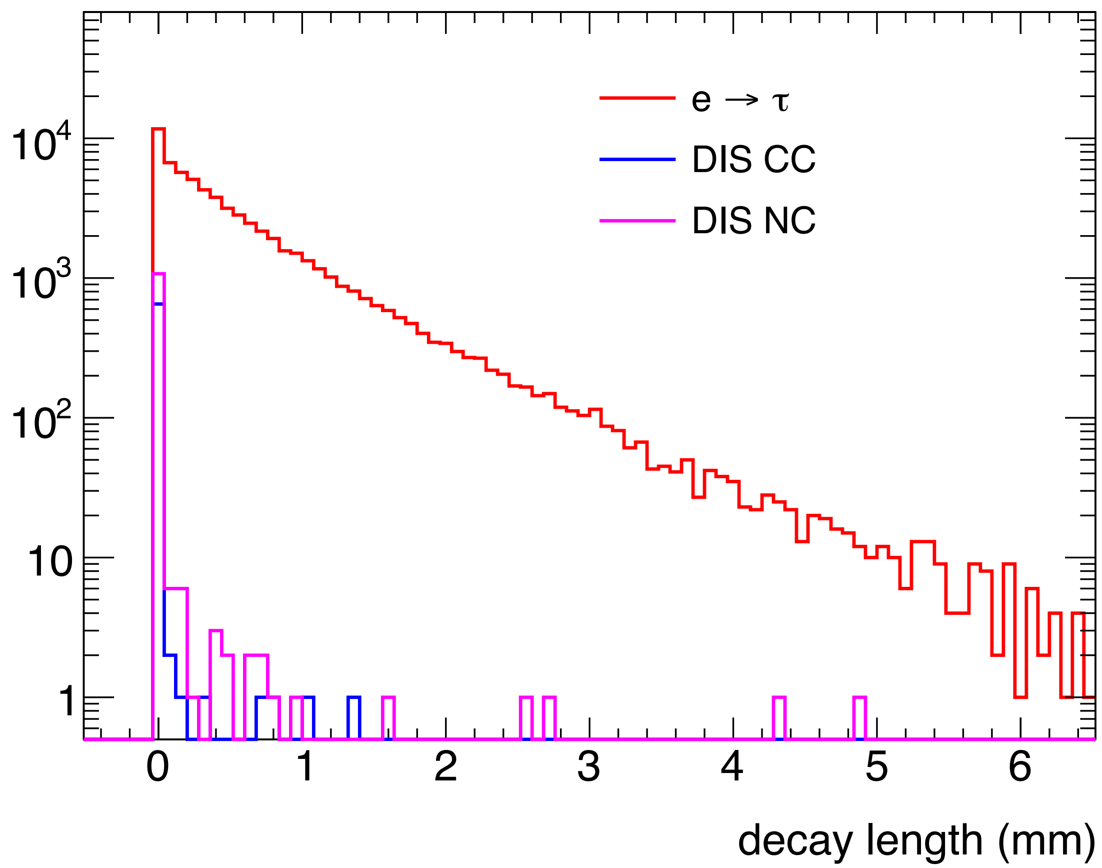
$$dl\_asy = |dl_1 - dl_2| + |dl_1 - dl_3| + |dl_2 - dl_3|$$

- 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 $\overrightarrow{p_{3\pi}}$

Last Two Cuts

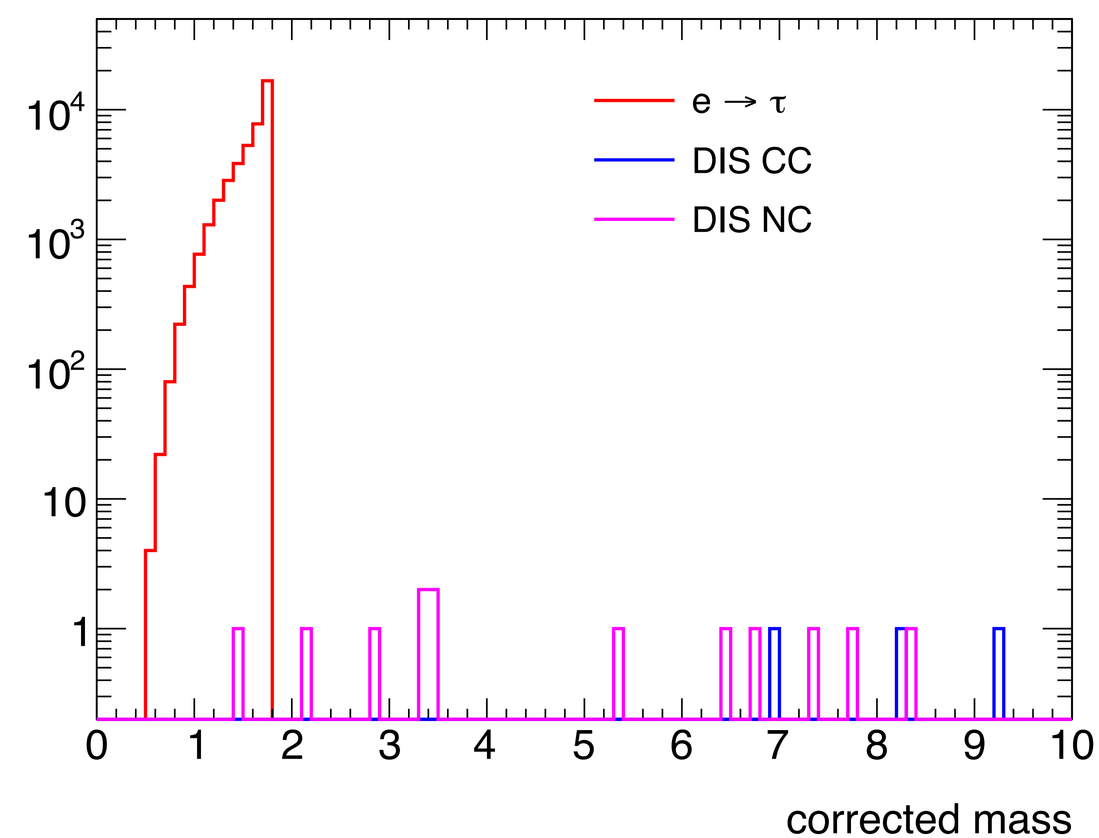


- Secondary vertex and corresponding decay length reconstructed from paired pion tracks

- Corrected mass from 3 pions

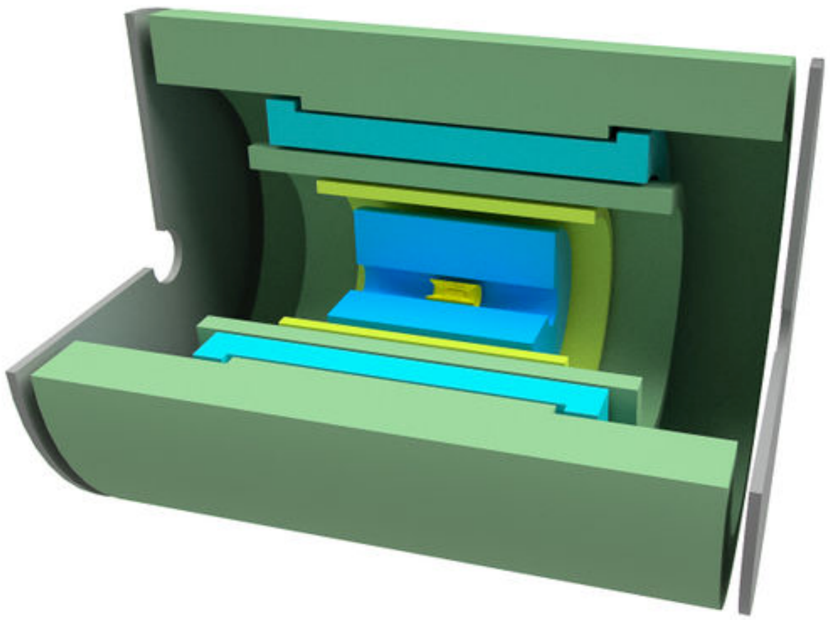
$$\sqrt{M_{3\pi}^2 + p_{3\pi}^2 sin^2\theta} + p_{3\pi} sin\theta$$

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



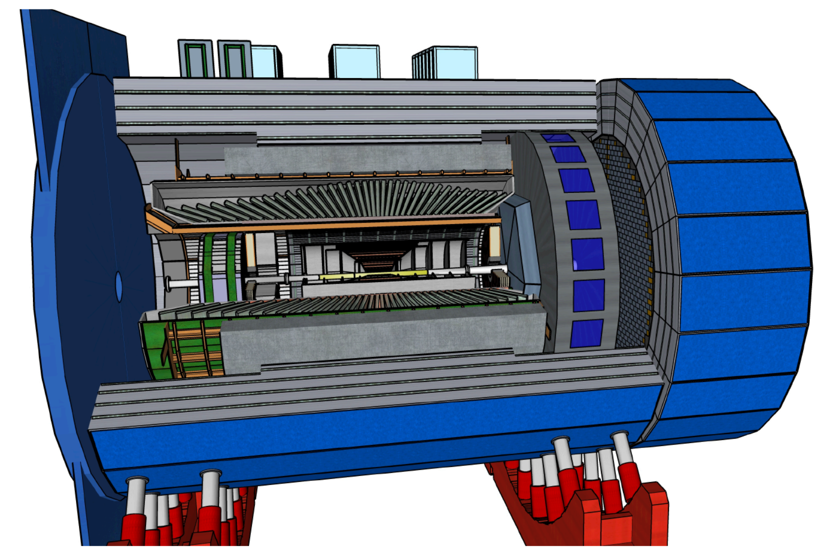
Detector Simulation: sPhenix and ECCE

sPHENIX



-1.1 < η < 1.1

sPHENIX-EIC -> ECCE



-3.5 < η < 3.5

Solenoid
Electromagnetic calorimeter
Hadron calorimeter
Flux return
Central tracking
Forward tracking
Particle ID

sPHENIX:

- Next generation RHIC detector
- Foundation for the selected EIC detector-1 proposal [arXiv:1402.1209]

Full detector simulation: https://github.com/sPHENIX-Collaboration/coresoftware

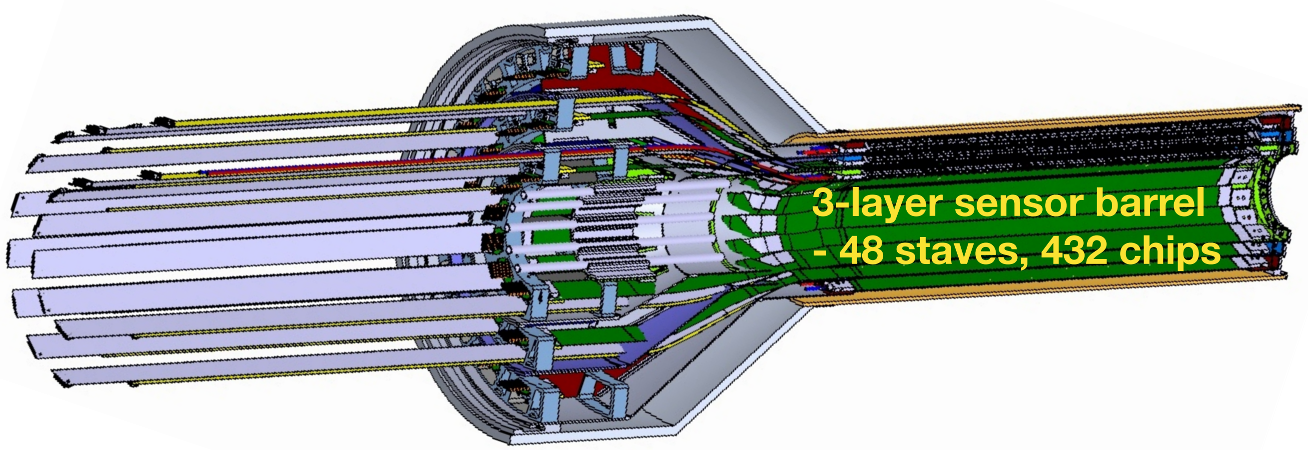
- GEANT4 Simulation framework, well developed.
- Analyses including vertexing and tracking have been implemented in heavy flavor studies.

Vertex Detector: MAPS-based silicon

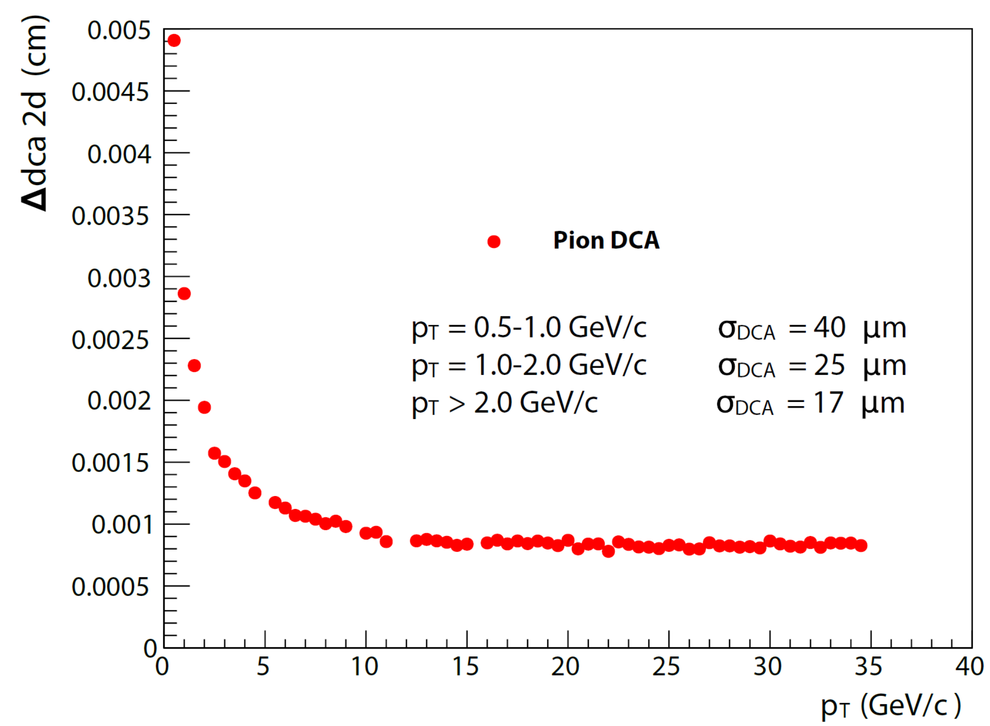
- For initial τ-reco evaluation: sPHENIX vertex tracker
  - 30 μm ALICE Pixel MAPS pixel in three layers, total 200 M pixel channels
  - 5 μm hit position resolution
  - 0.3% X_0 thickness per layer
  - R ~2cm.

state-of-the-art vertex detector

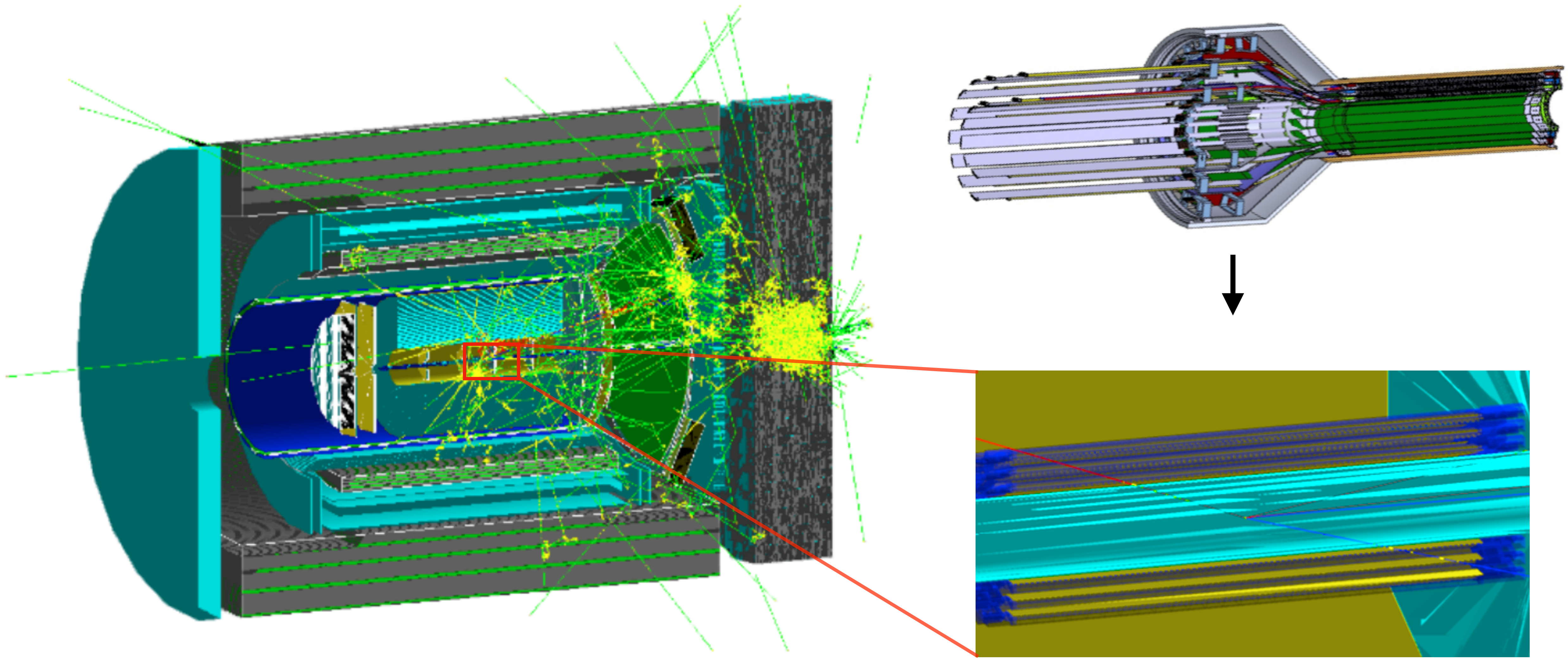
MVTX — Monolithic-Active-Pixel-Sensor-based Vertex Detector



Service cone: signal, power, cooling and mechanical support



LQ event at sPhenix-EIC detector

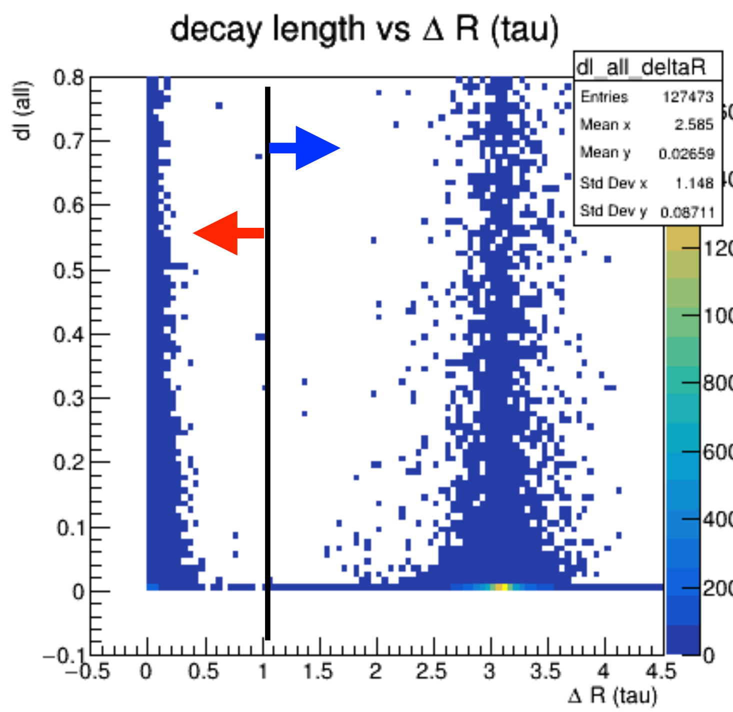


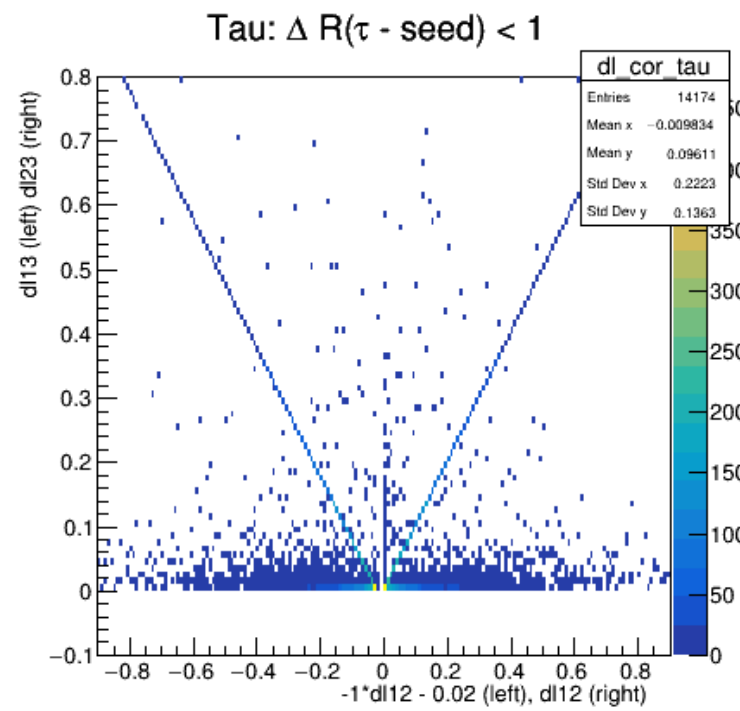
- LQGENEP 1.0 Leptoquark event e+p 18x275 GeV/c + sPHENIX-EIC sim
- For initial τ-reco evaluation: sPHENIX vertex tracker

Simplified secondary vertex reconstruction

Generator level

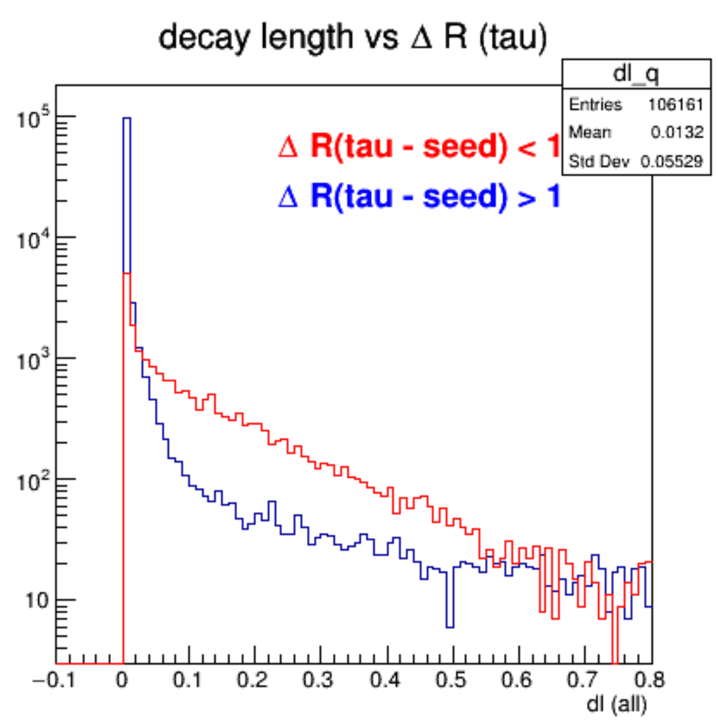
Tag 3-prong candidate with truth tau direction

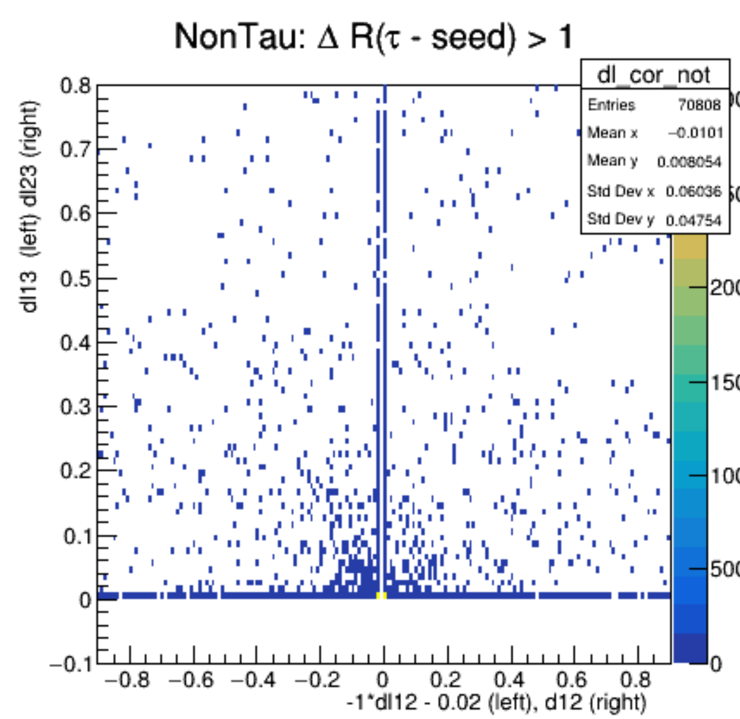




Tau side:
Clear correlations between 3 reconstructed decay length

Significantly long reconstructed decay length at Tau side



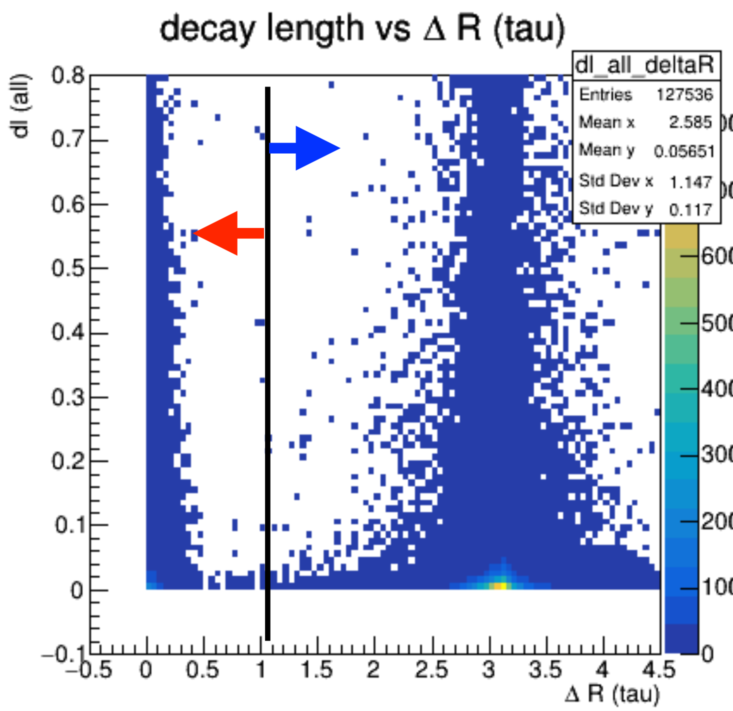


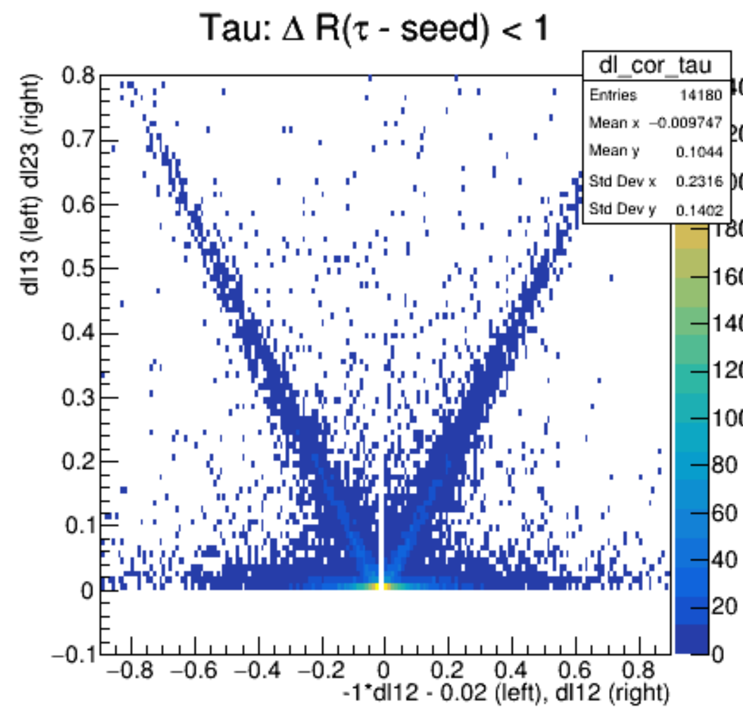
Away side:
No correlations between 3 pair combination

Simplified secondary vertex reconstruction

Full Geant4 of sPHENIX

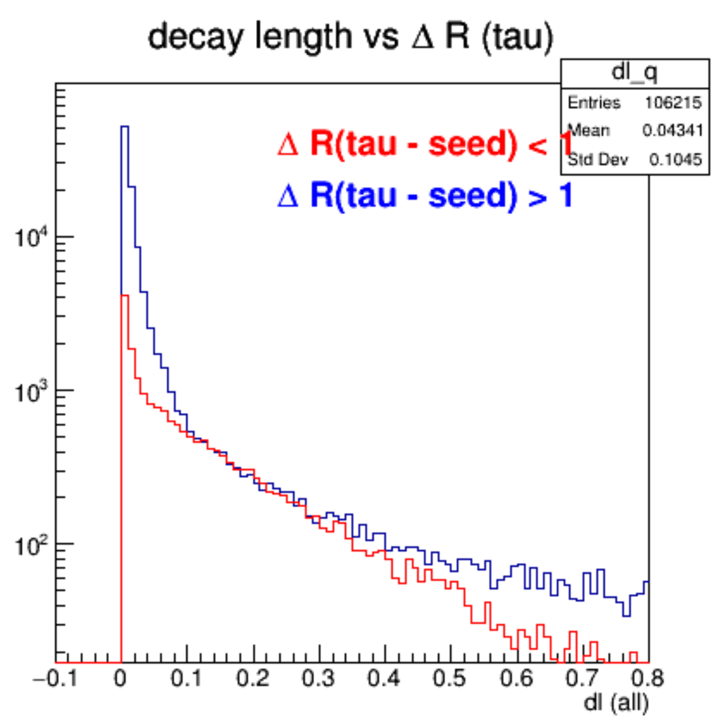
Tag 3-prong candidate with truth tau direction

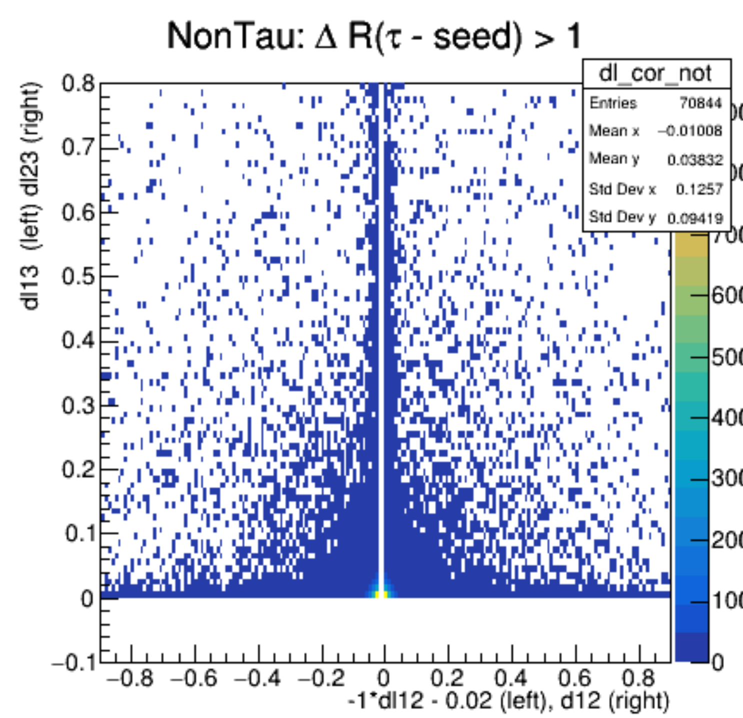




Tau side:
Clear correlations between 3 pair combination

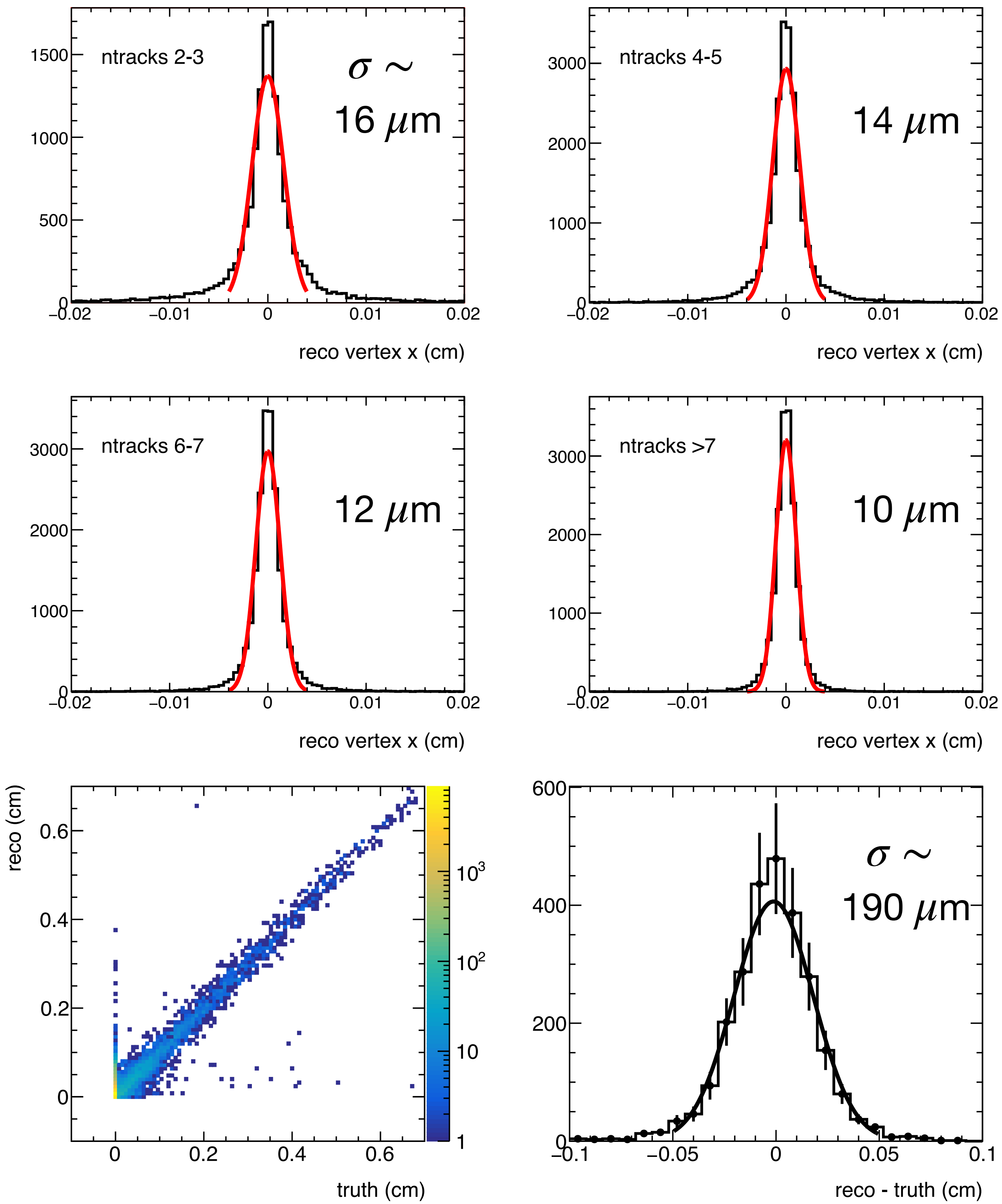
Significantly long reconstructed decay length at Tau side





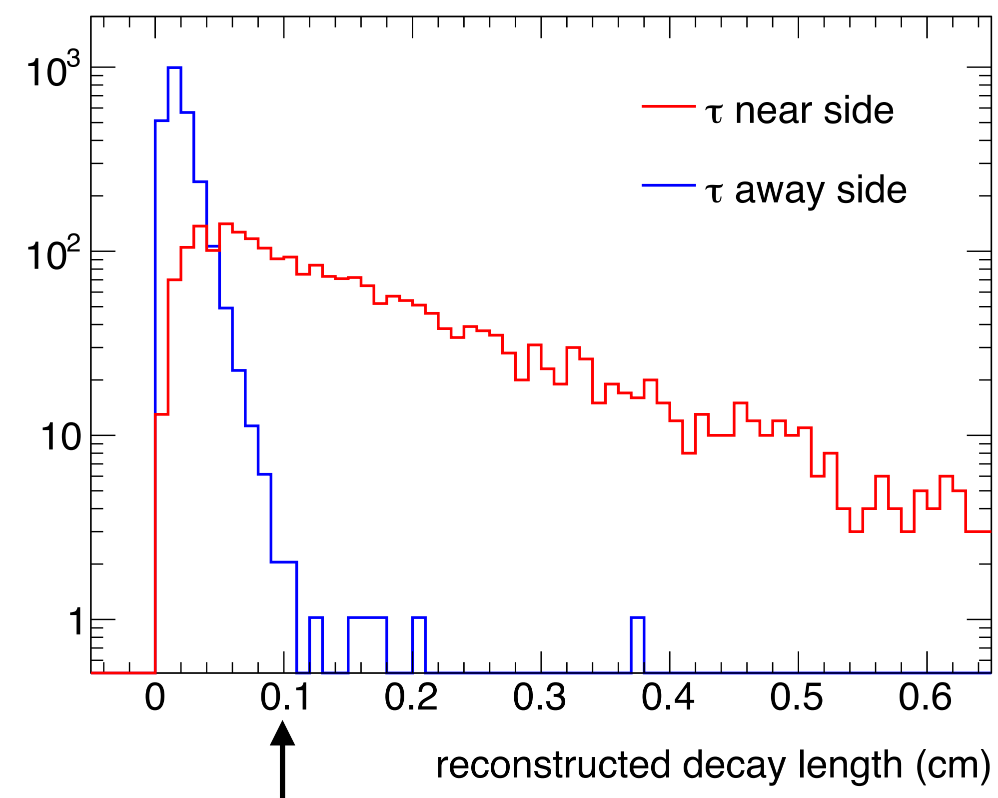
Away side:
No correlations between 3 pair combination

Effect of resolution

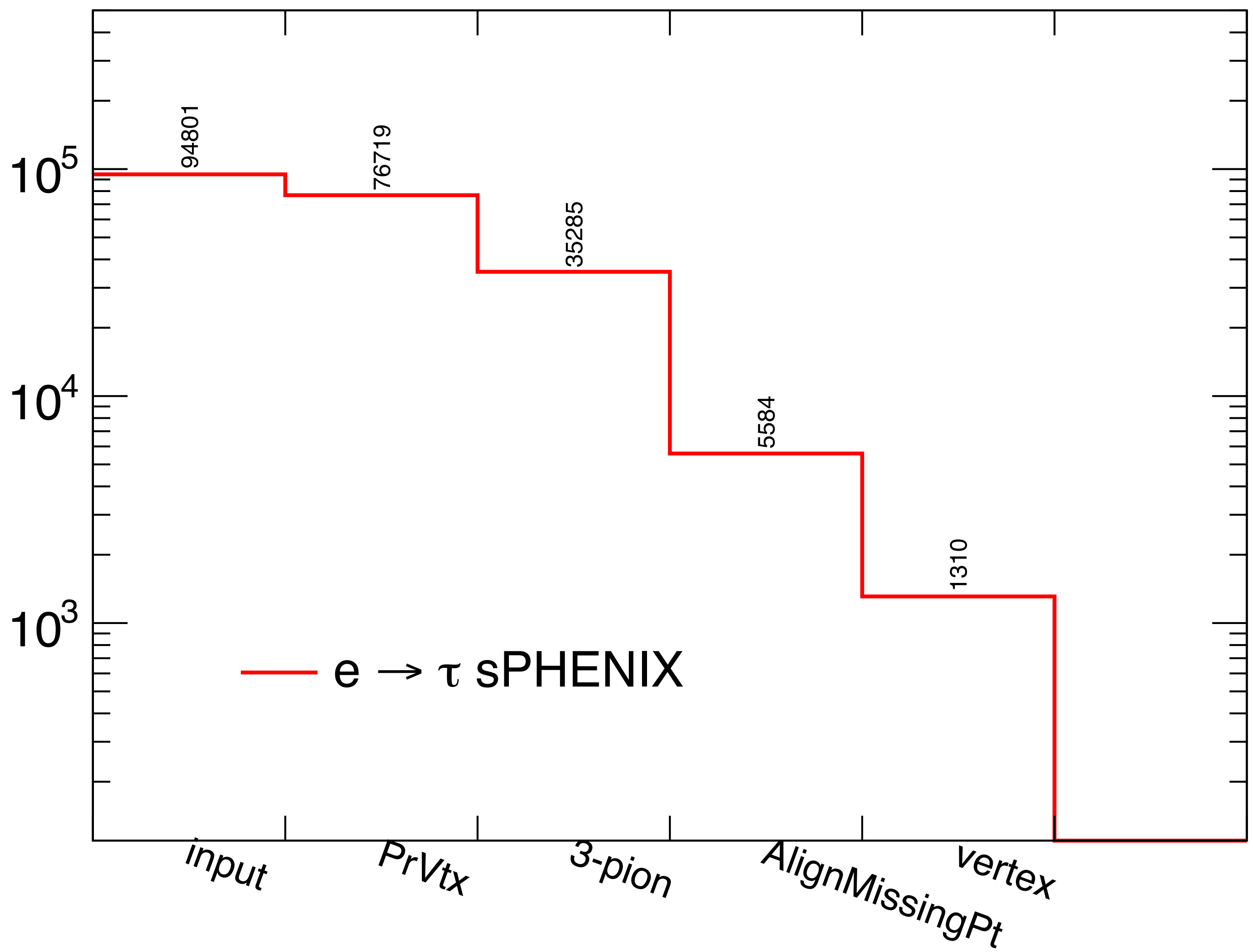


- Vertex resolution at x component **~10** μm
- Similar for y and z components at middle rapidity
- Decay length resolution ~ 190 μm

  - Similar algorithm applied as for Generator level analysis



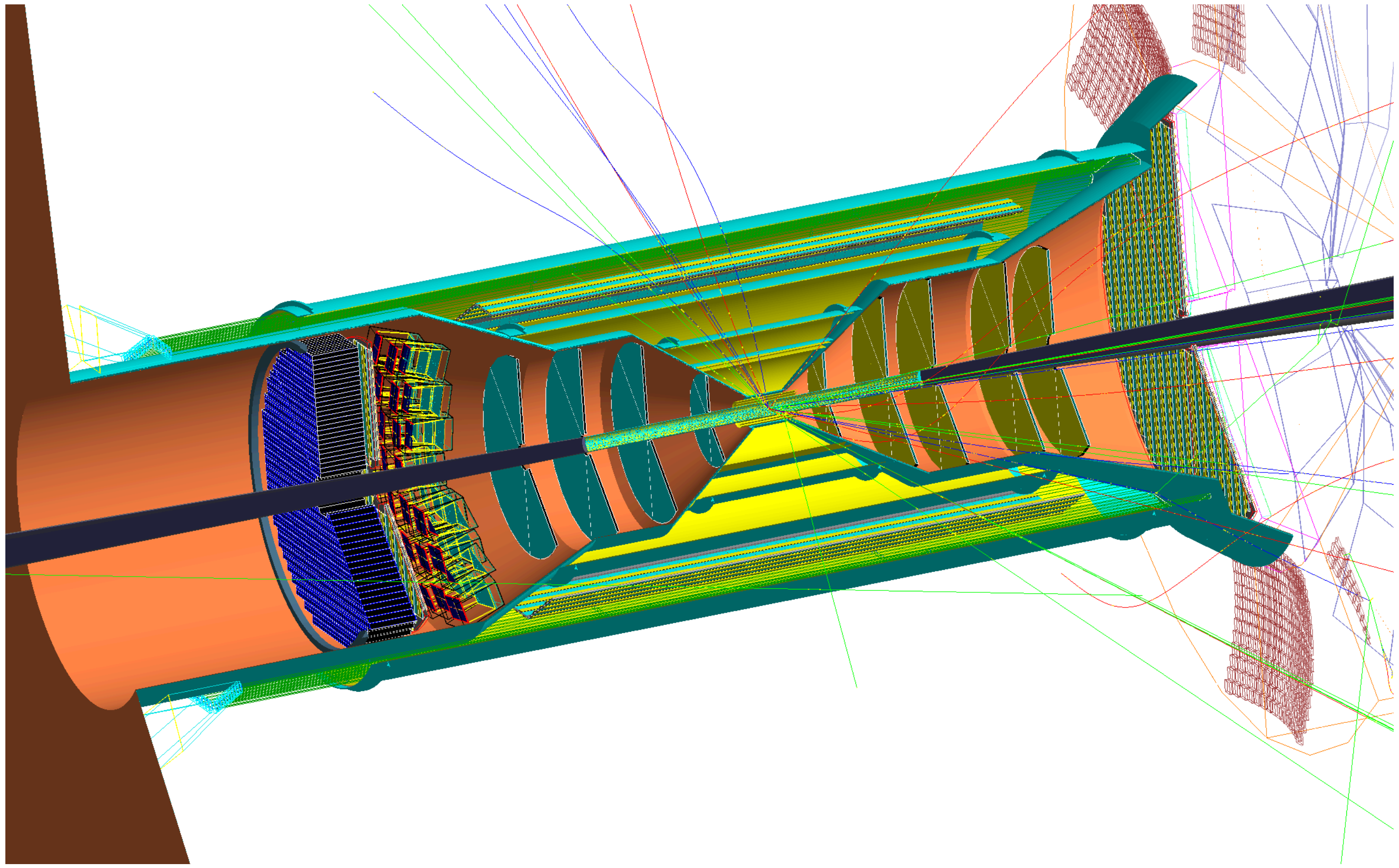
Efficiency with Detector Effects



- 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
- ~1.4% (**~9.3%** out ~15% 3-prong) signal efficiency from sPHENIX detector simulation

Moved to ECCE Vertex/Tracking

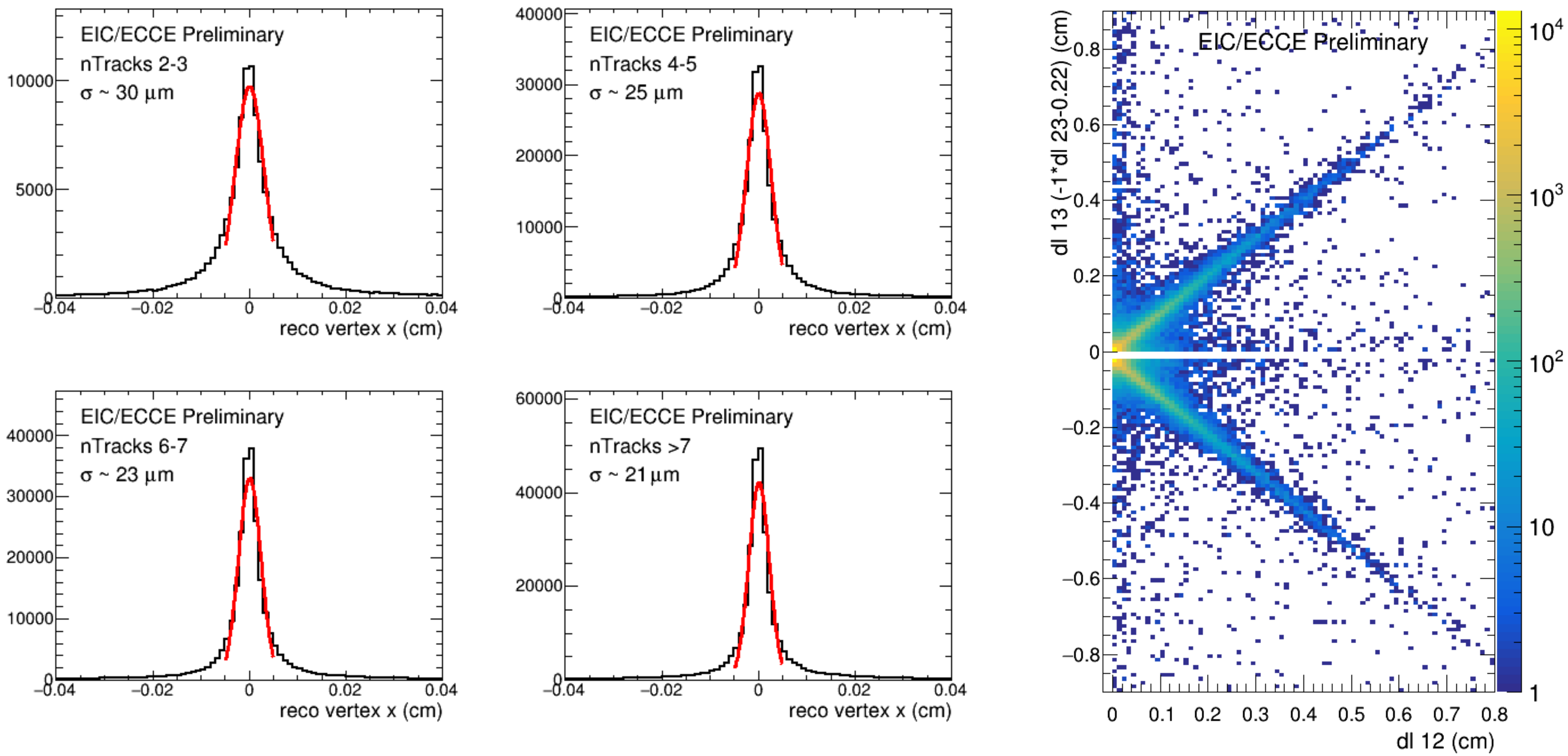


- ECCE hybrid tracking detector design
  - **MAPS based silicon vertex/tracking**
  - mRWELL tracking subsystem
  - AC-LGAD outer tracker

Thanks to ECCE
Software working group!

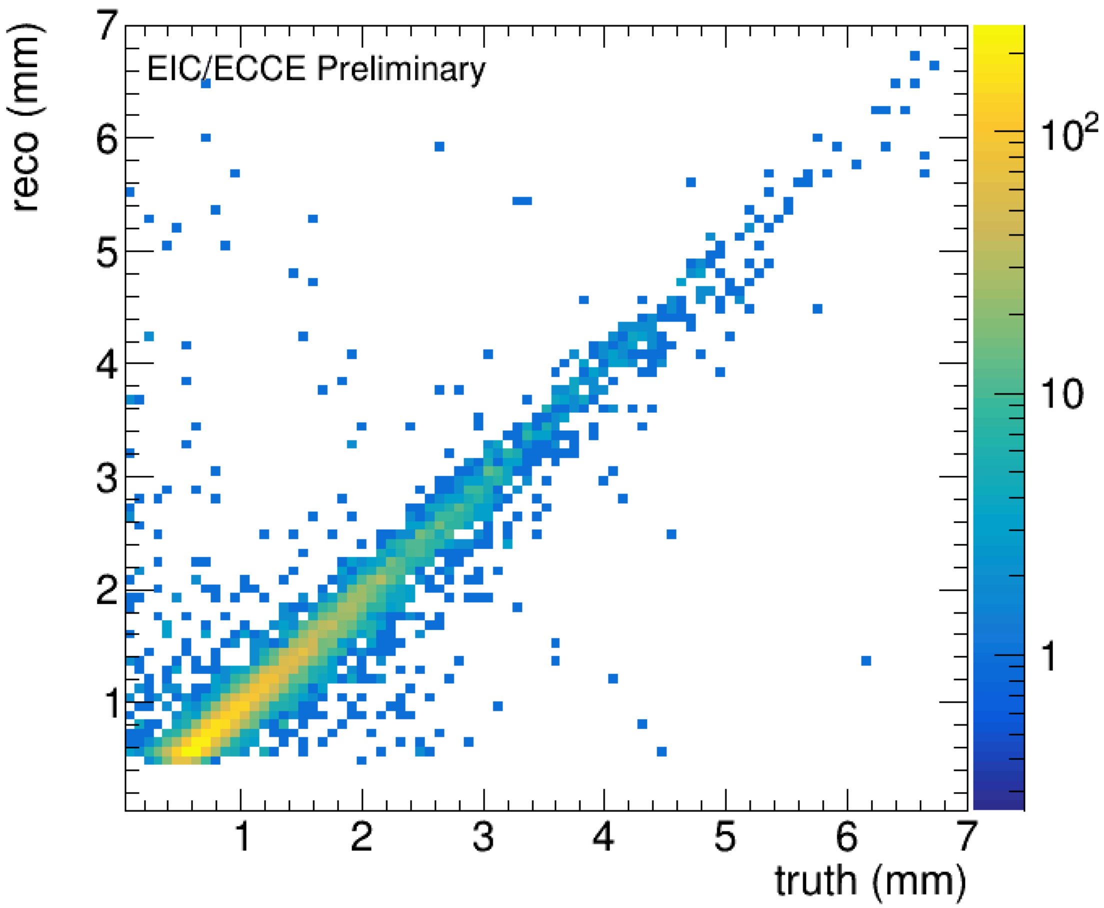
ECCE tracking, arXiv: 2205.09185

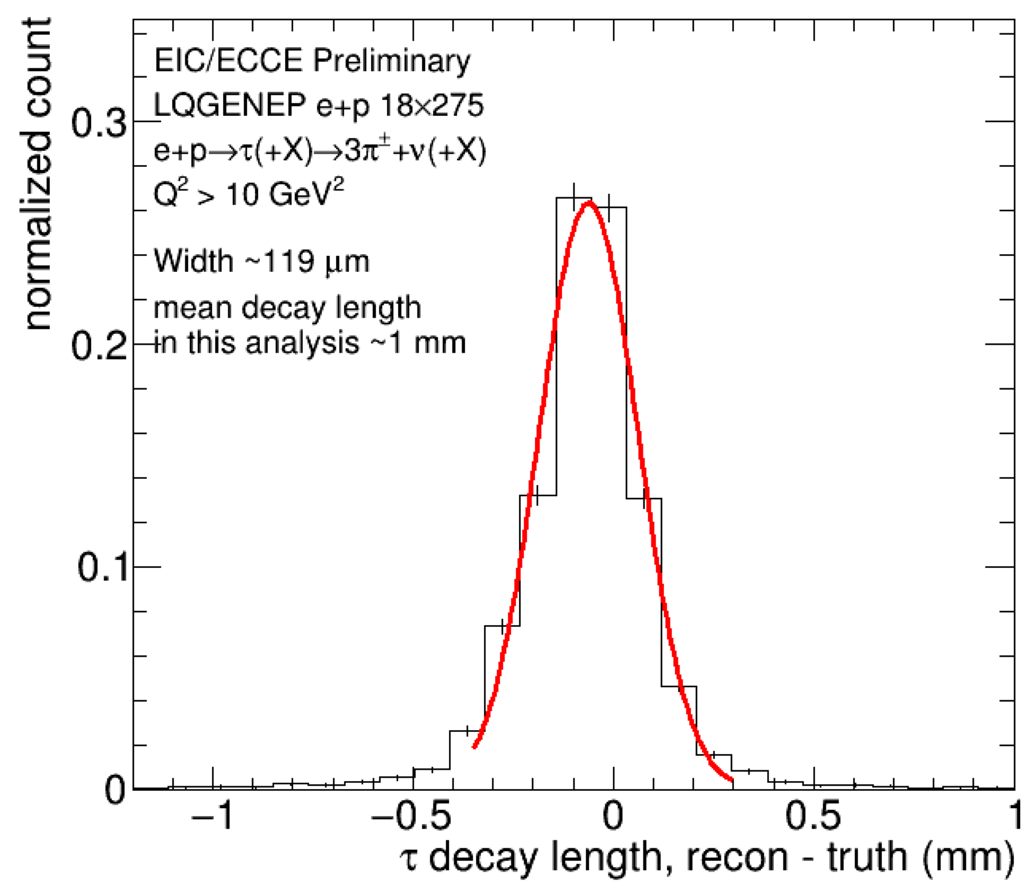
Vertex reconstruction



- With ECCE hybrid tracking detector design
  - Primary vertex x-component 20~30 microns
  - Secondary vertex reconstructed for tau candidates

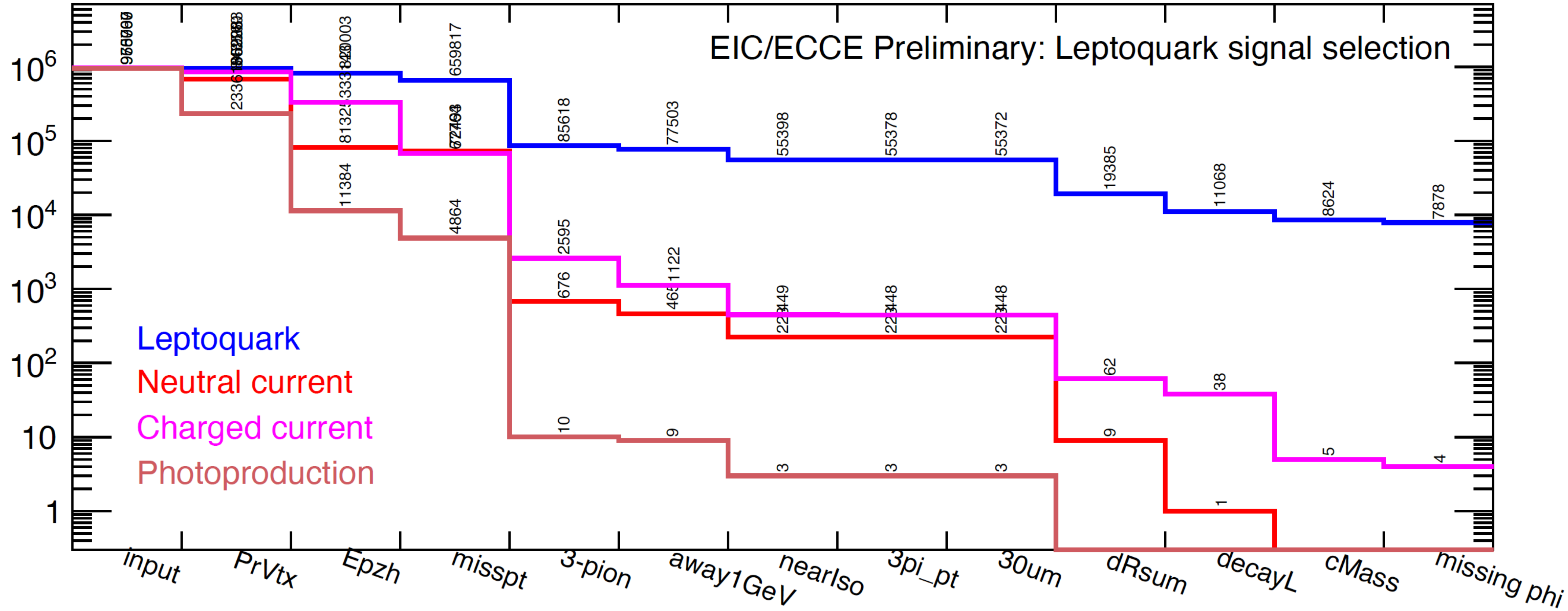
Vertex reconstruction





- Decay length resolution ~ 119 μm

Tau search performance



- Similar selection cuts
- photo-production backgrounds included in addition to NC and CC
- Still lack of statistics for background simulation especially for NC and Photo-production

Summary

- EIC with high ($10^{34\text{-}35}$/cm^2/s) luminosity opens opportunities for Charged Lepton Flavor Violation search
  - Benchmarking $e \rightarrow \tau$ search with Leptoquark models
- LQGENEP generator + Full detector simulations and reconstruction via sPHENIX and ECCE concept
  - Explore the potential of CLFV search with decay topological using modern precision vertex tracker and event shape analysis

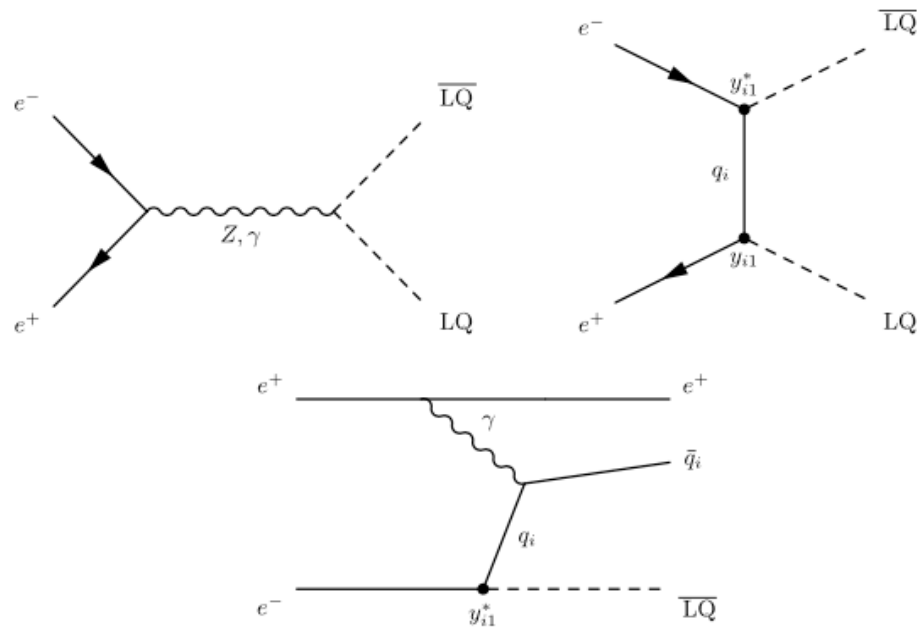
Next step

- 3-prong
  - Optimize selection cuts; apply Multi-Variable Analysis (MVA)
  - Take use of different sub-detector systems: Calorimeters, PID, etc
- Explore the 1-prong decays
  - Devise independent cuts for single muon and single pion modes

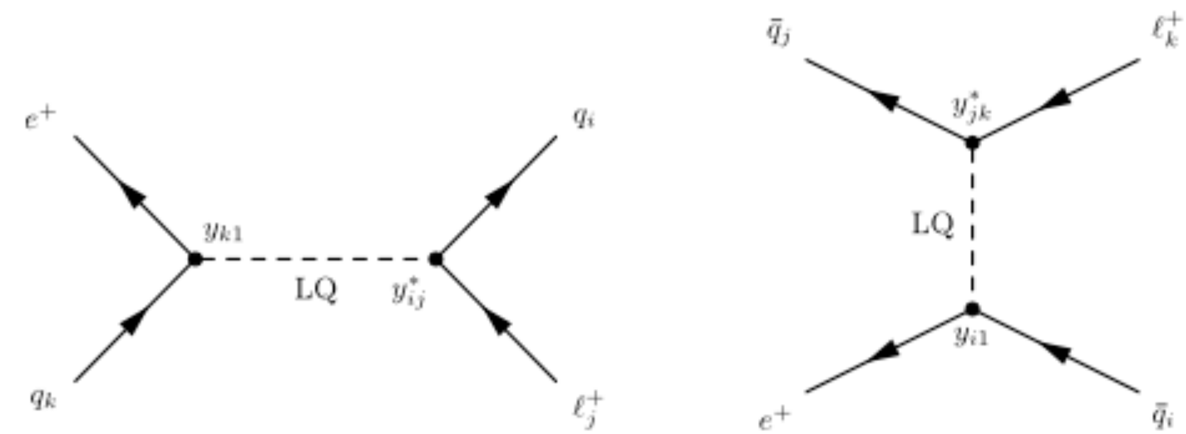
Backup

Experimental Searches of Leptoquarks

e^+e^-



ep



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