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

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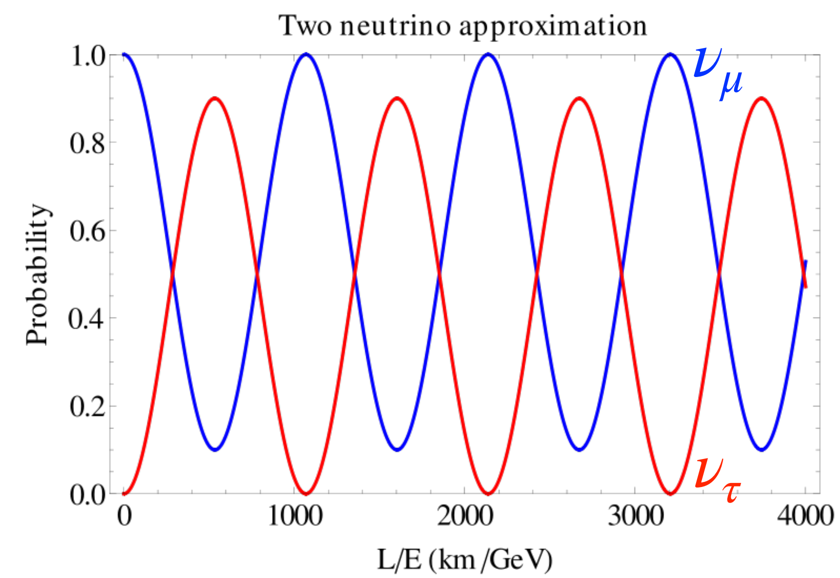
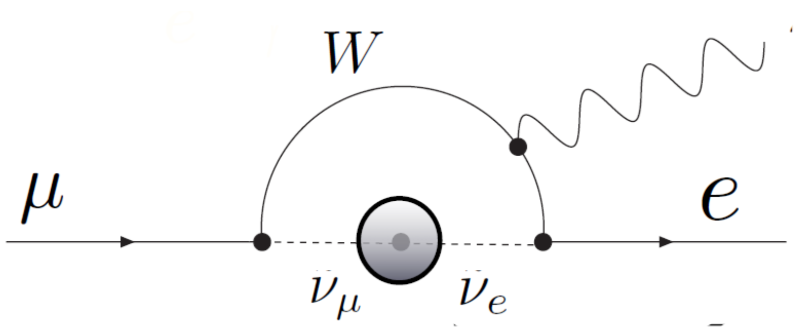
RHIC&AGS Users' Meeting 2022

Charged Lepton Flavor Violation

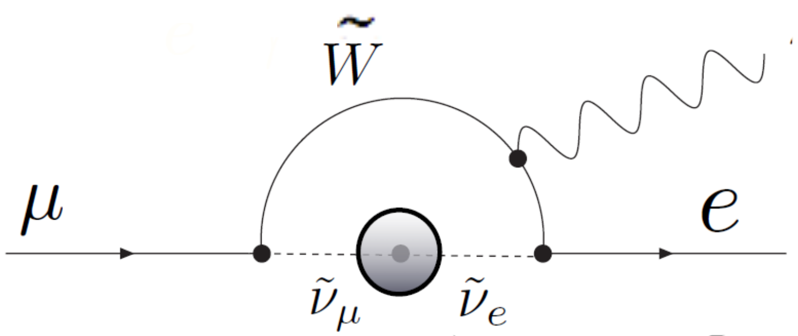
- Lepton Flavor (generation) is not conserved, neutrino oscillations observed. (2015 Nobel Prize)
- Charged lepton flavor violations (CFLV) should also be allowed within the SM; but extremely low rate, e.g. BR($\mu \to e\gamma$) < 10^{-54}
- Many BSM models predict significantly higher rate of CFLV,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





neutrino oscillations

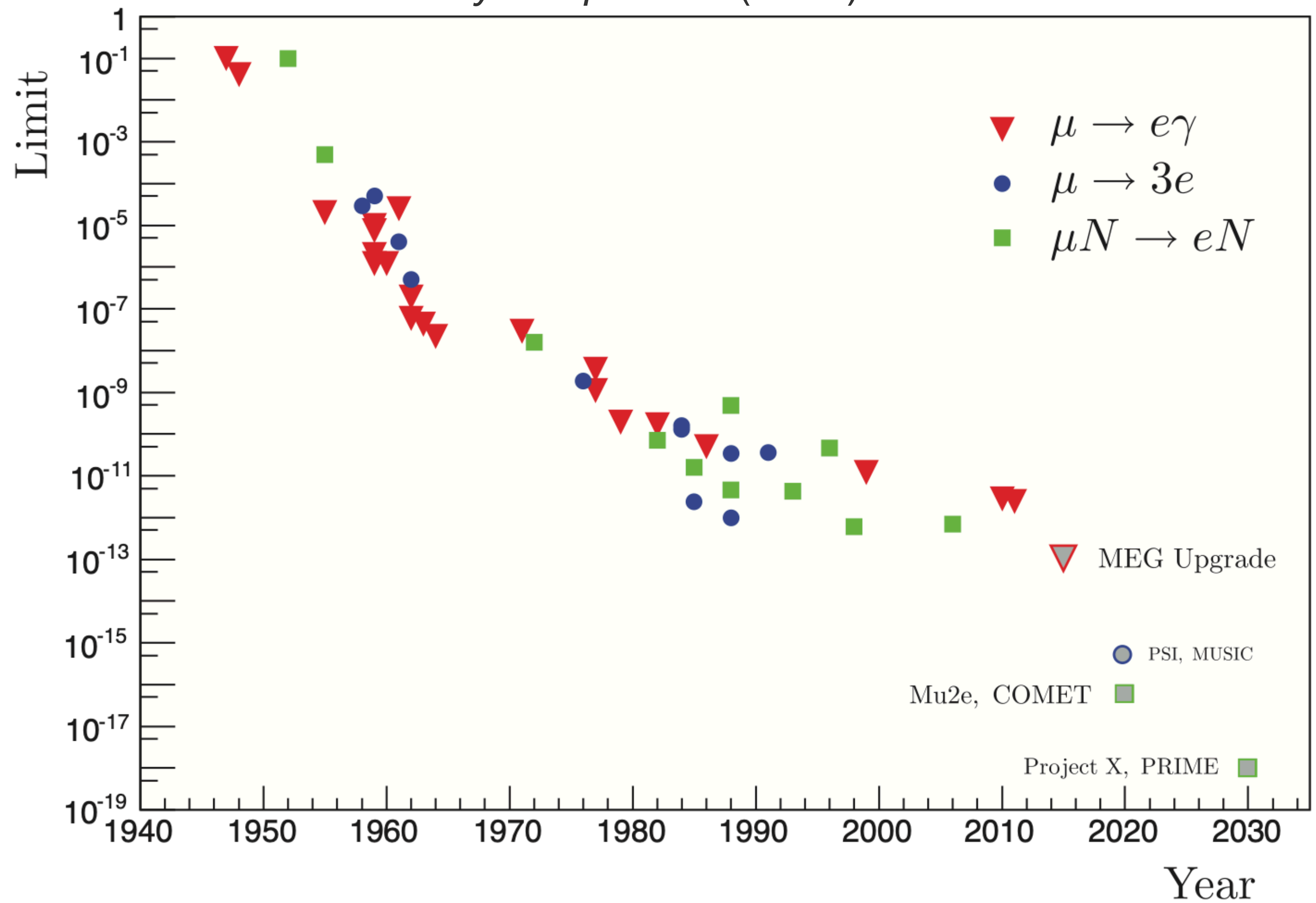
BSM



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)

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

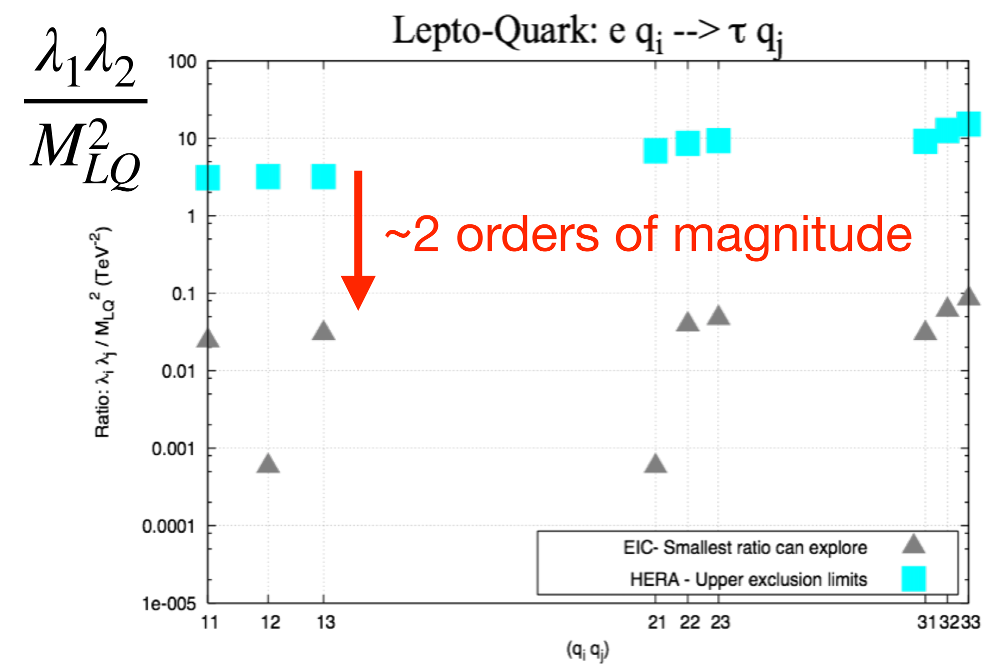
Various models predict enhanced sensitivity for LFV(1,3) while suppressing LFV(1,2)

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

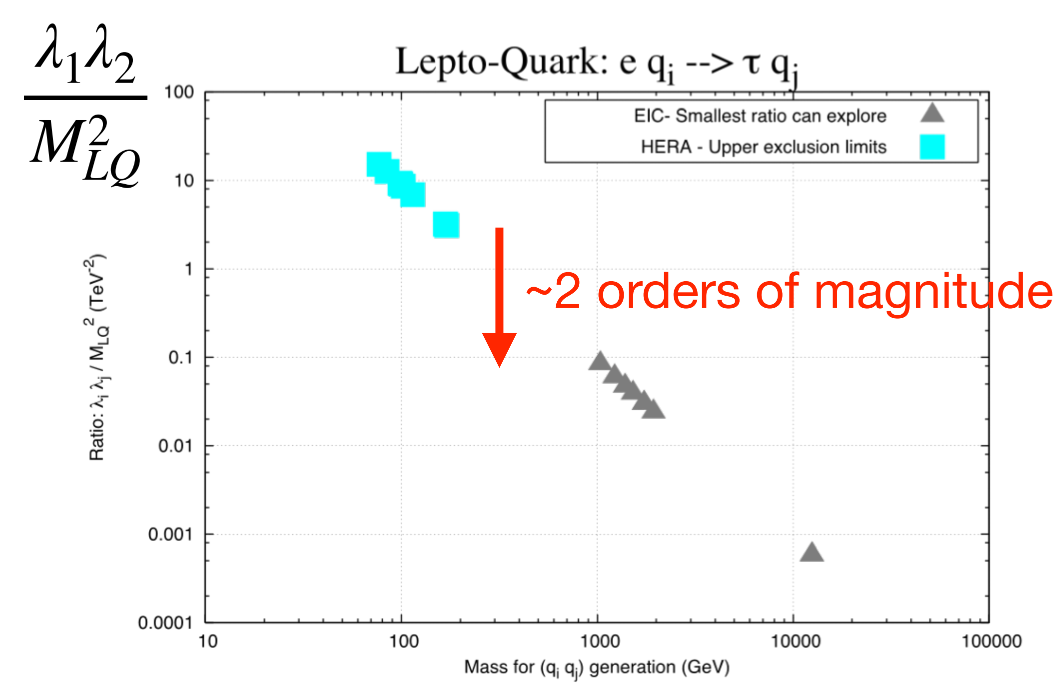
- HERA set limits in coupling-mass space for LQ production in e-p scatterings

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

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



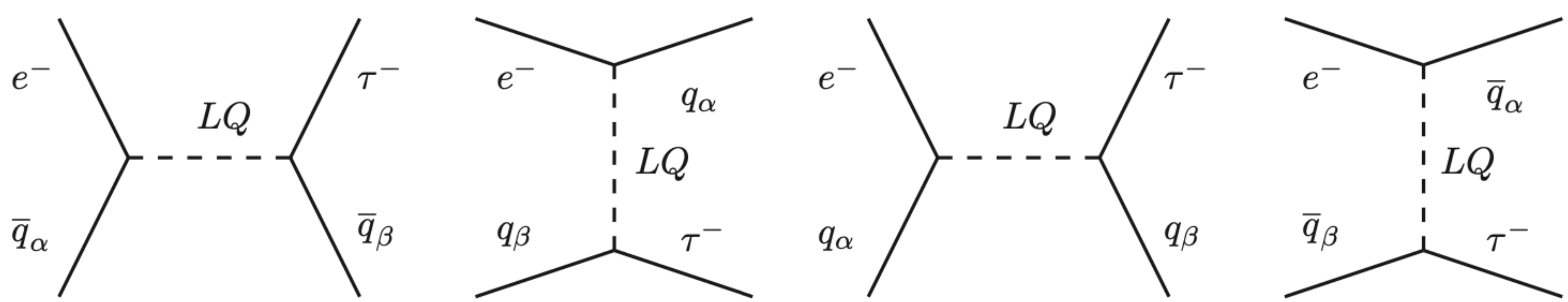
Assume 0.1 fb cross-section sensitivity



Leptoquark

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

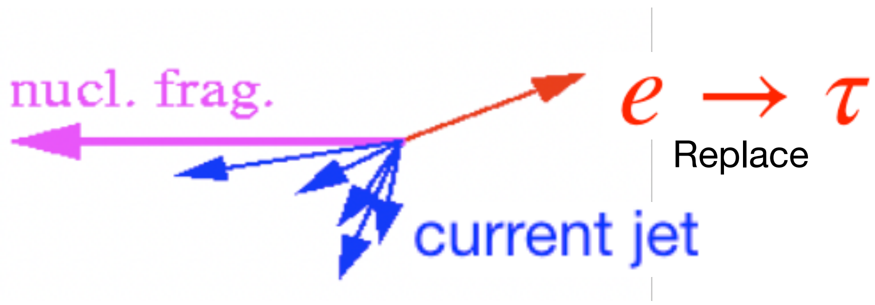
- Symmetry between lepton sector and quark sector
- Flavor violating but fermion number (F = 3B+L) conserving
- Buchmüller-Rückl-Wyler (BRW) framework: 14 different LQ types (7 scalars, 7 vectors)
- CLFV at tree level processes; allow coupling between same and different generations of quarks and leptons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



s-channel u-channel s-channel u-channel

$F = 0$ $|F| = 2$

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

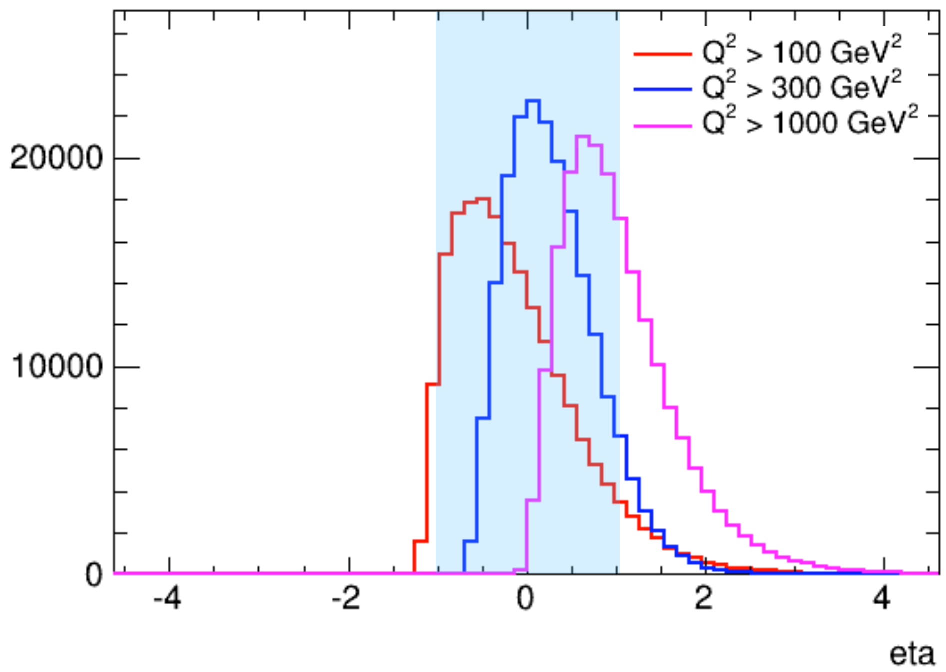
- **3-prong** **15.21 (0.06)%**
  - $\pi^-\pi^+\pi^-\nu_\tau$ 9.31 (0.05)%
  - $\pi^-\pi^+\pi^-\pi^0\nu_\tau$ 4.62 (0.05)%
  - others (kaon, etc) 1.28%
- **1-prong** **84.58 (0.06)%**
  - $\mu^-\bar{\nu}_\mu\nu_\tau$ 17.39 (0.04)%
  - $e^-\bar{\nu}_e\nu_\tau$ 17.82 (0.04)%
  - $\pi^-\nu_\tau$ 10.82 (0.05)%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

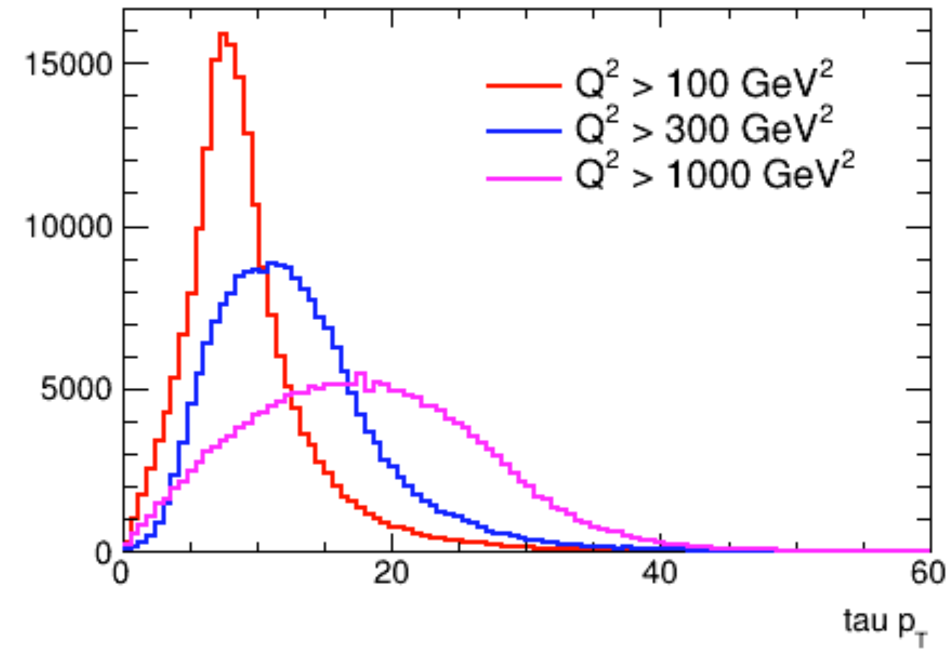
At EIC, benefit from improved vertex and jet detection, aim to greater than 10% efficiency with negligible background in a 100 fb^{-1} data sample

How LQ Tau looks like in ep

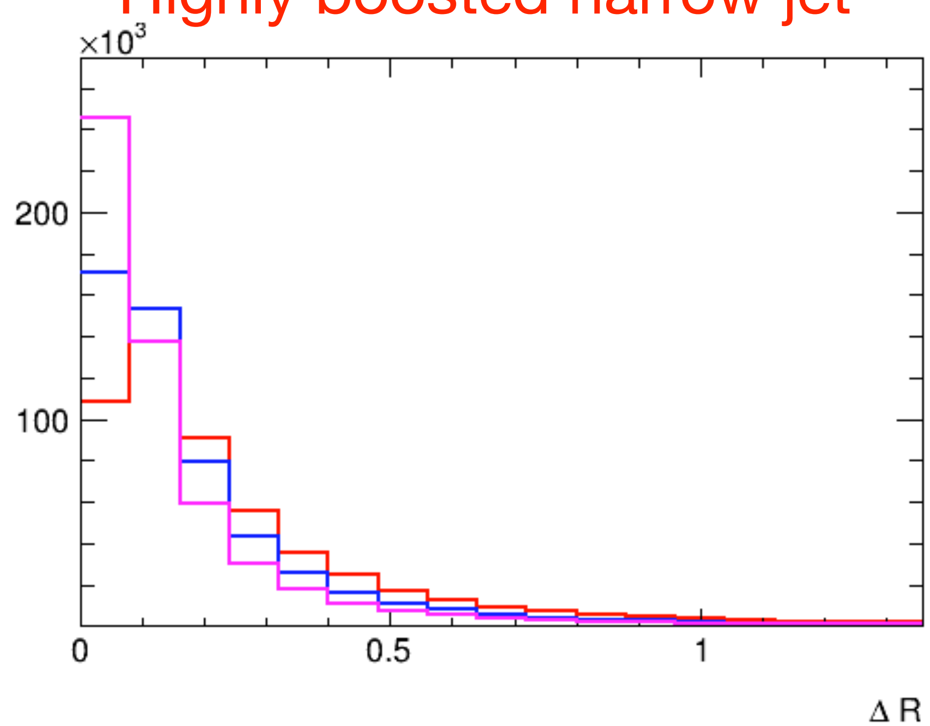
Mostly at Barrel (best detector performance)



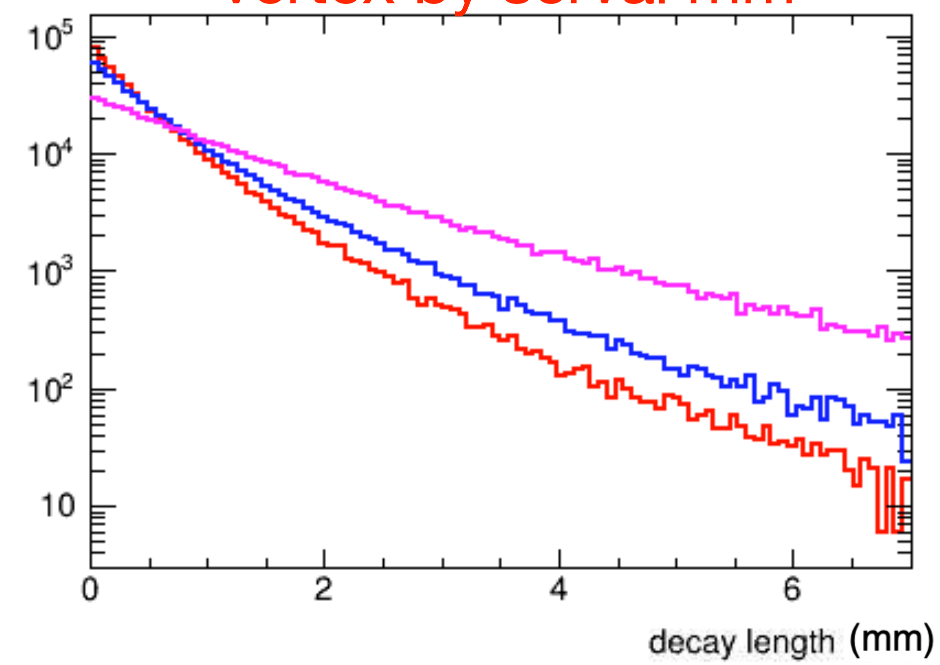
high pT



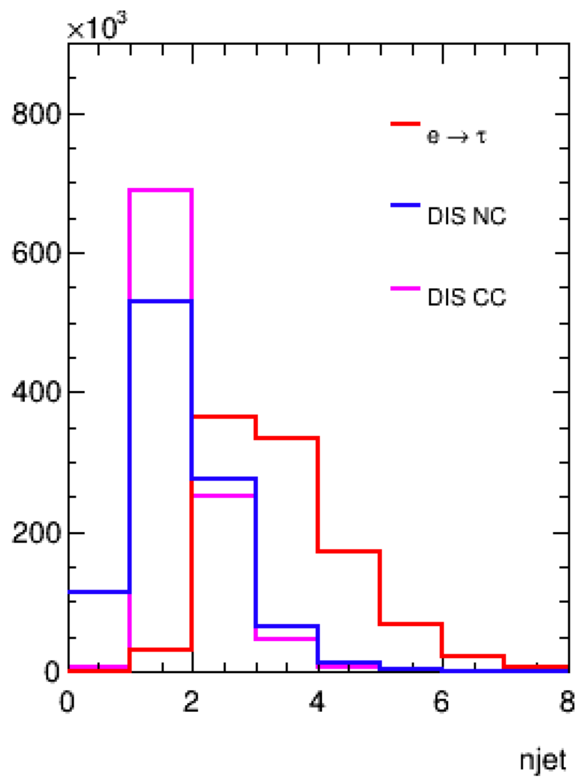
Highly boosted narrow jet

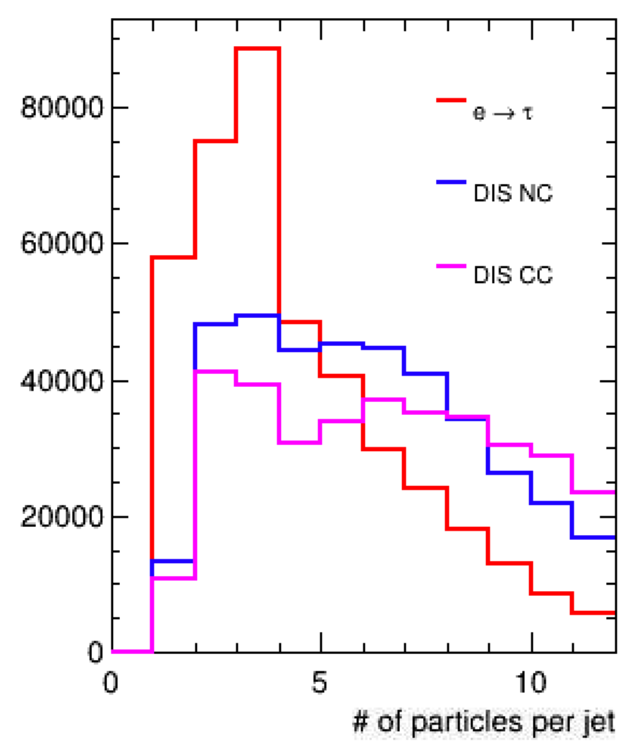


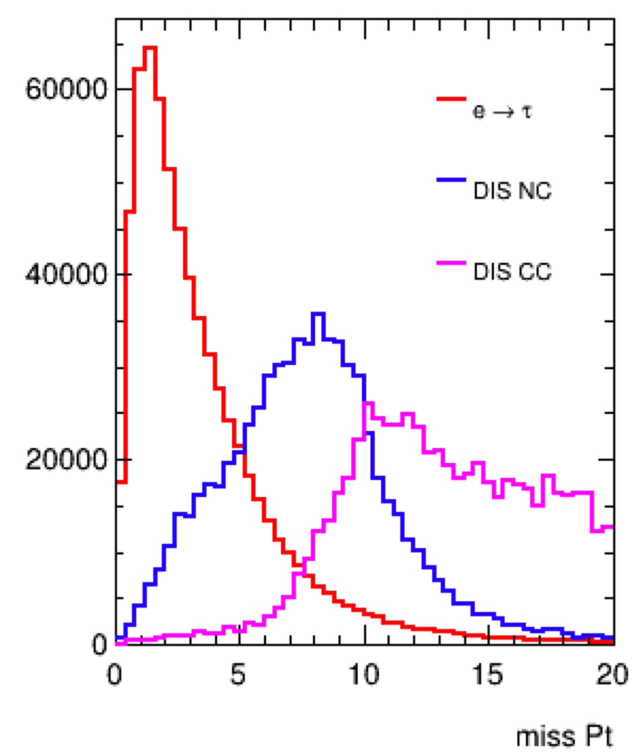
Away from primary vertex by serval mm



Features of LQ $e \rightarrow \tau$ event







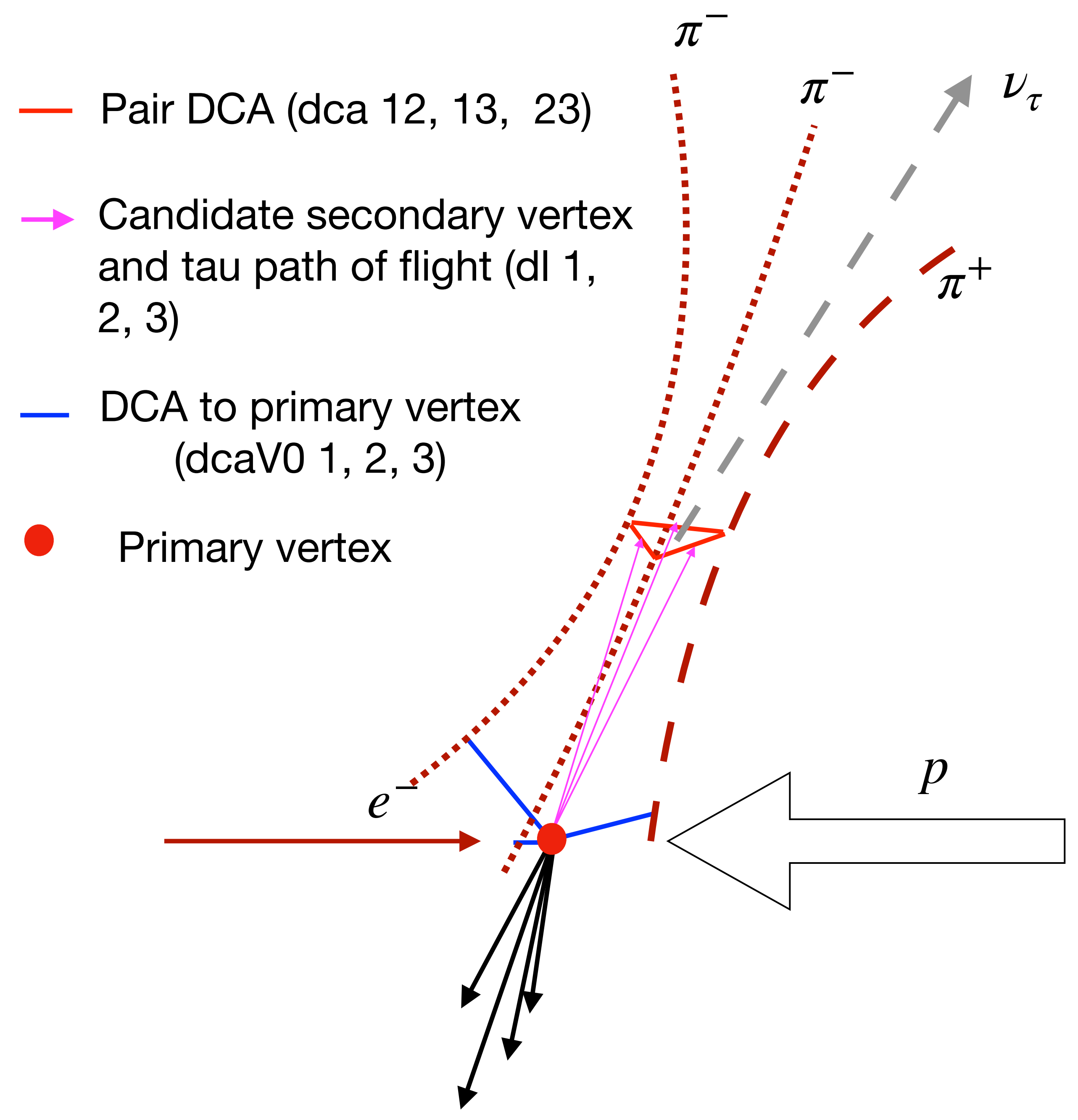
Note: electron in DIS NC is masked; Fastjet, Anti-k_T, R = 1.0; jet pt > 2 GeV; Q^2>100 GeV^2

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

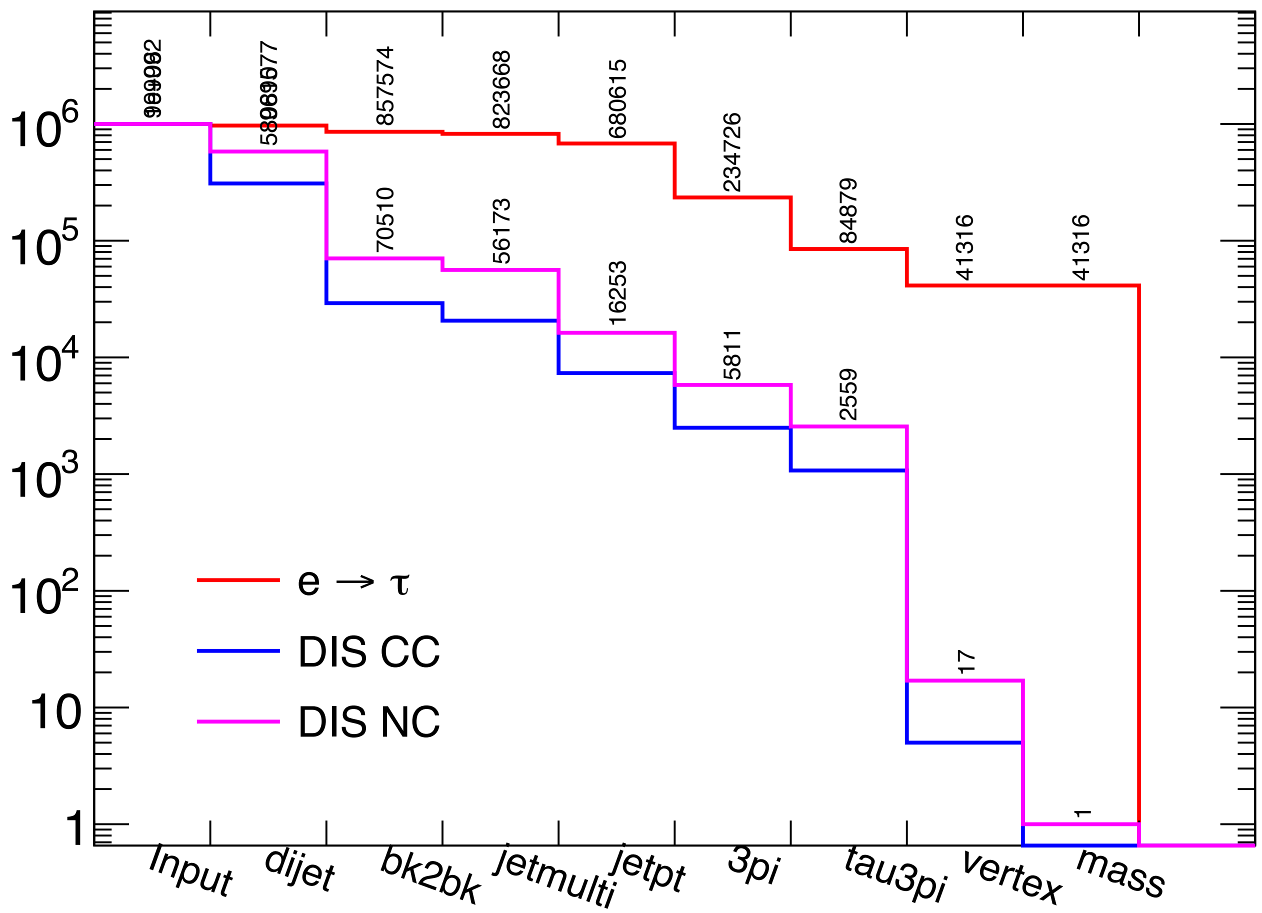
- DIS event
  - 1 jets dominating
  - Higher particle multiplicity
  - Missing pT ~ lepton pT

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:

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

Length matching:

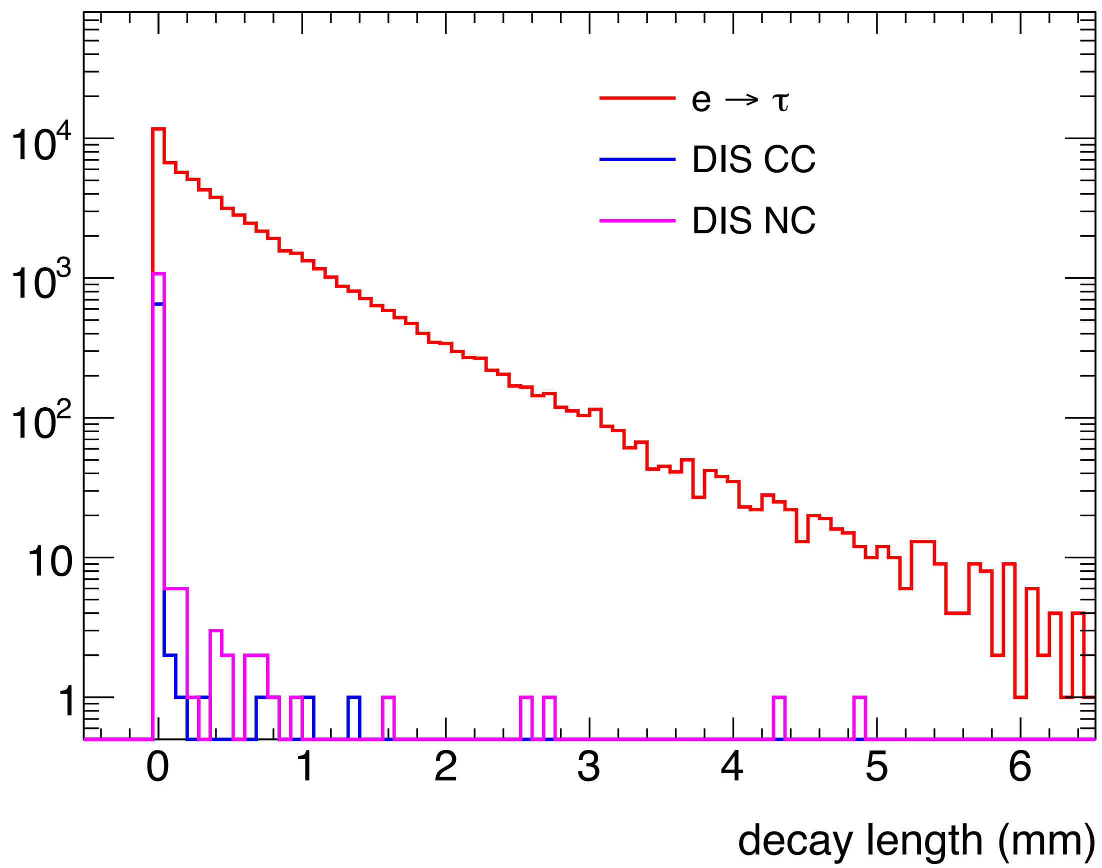
$$dl\_asy = |dl_1 - dl_2| + |dl_1 - dl_3| + |dl_2 - dl_3|$$

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

Last Two Cuts

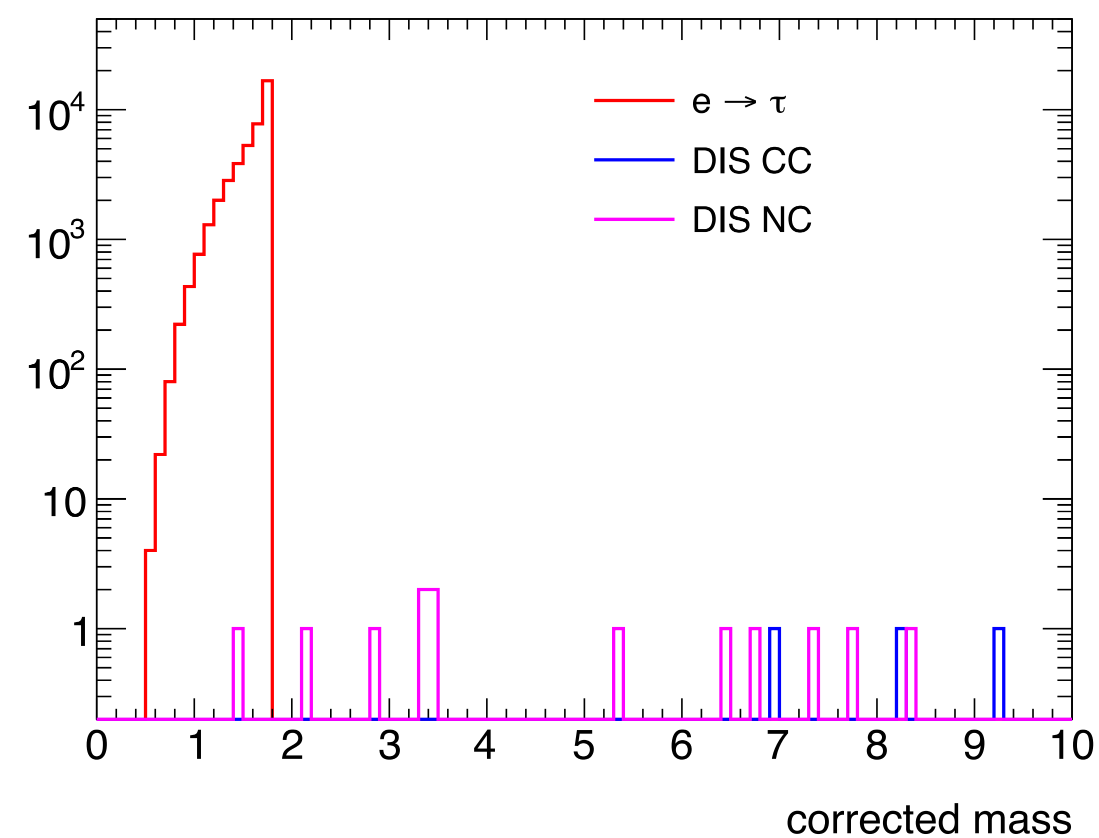


- Secondary vertex and corresponding decay length reconstructed from paired pion tracks

- Corrected mass from 3 pions

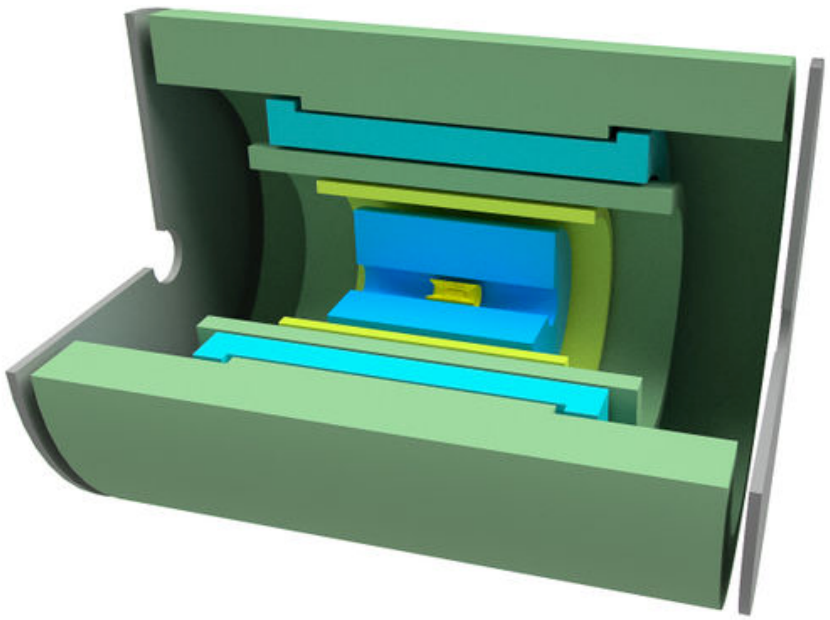
$$\sqrt{M_{3\pi}^2 + p_{3\pi}^2 sin^2\theta} + p_{3\pi} sin\theta$$

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



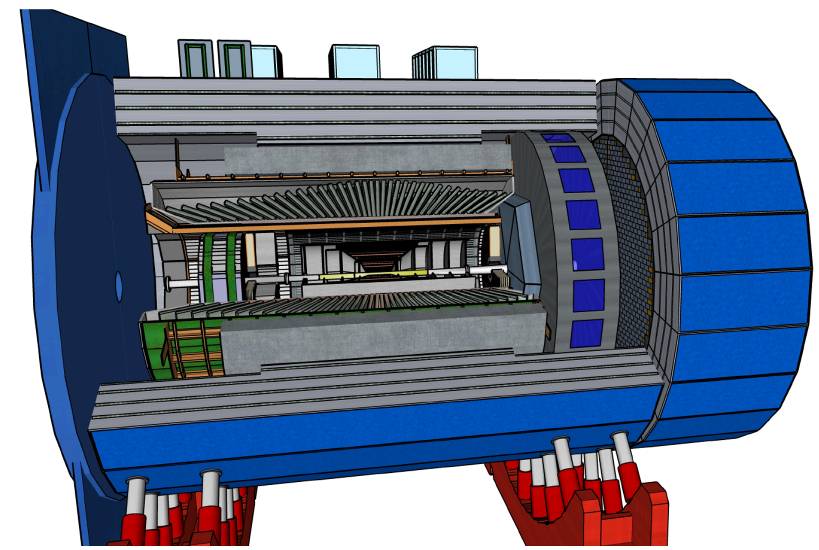
Detector Simulation: sPhenix and ECCE

sPHENIX



$-1.1 < \eta < 1.1$

sPHENIX-EIC -> ECCE



$-3.5 < \eta < 3.5$

Solenoid
Flux return
Central tracking
Electromagnetic calorimeter
Forward tracking
Hadron calorimeter
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

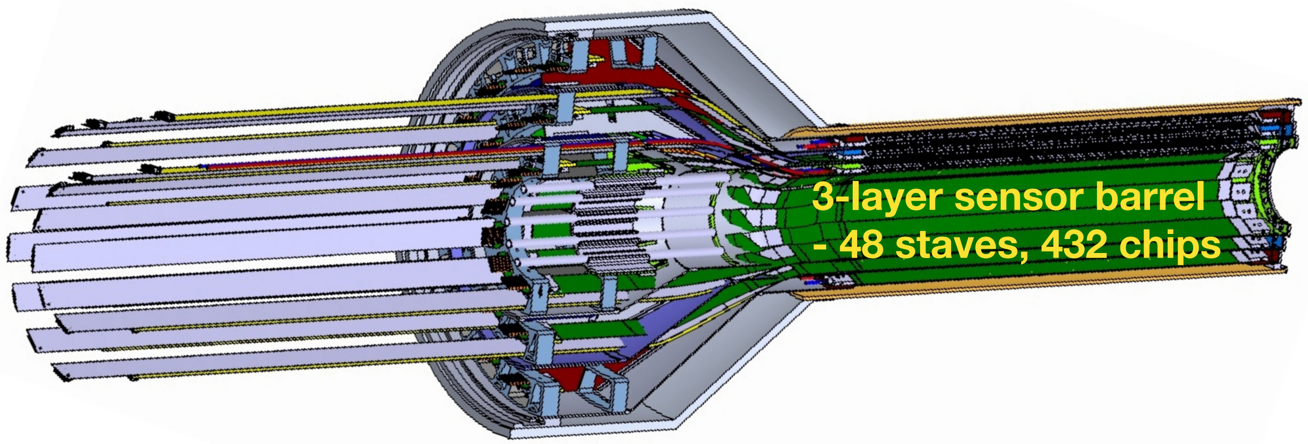
- GEANT4 Simulation framework, well developed.
- Analyses including vertexing and tracking have been implemented in heavy flavor studies.

Vertex Detector: MAPS-based silicon

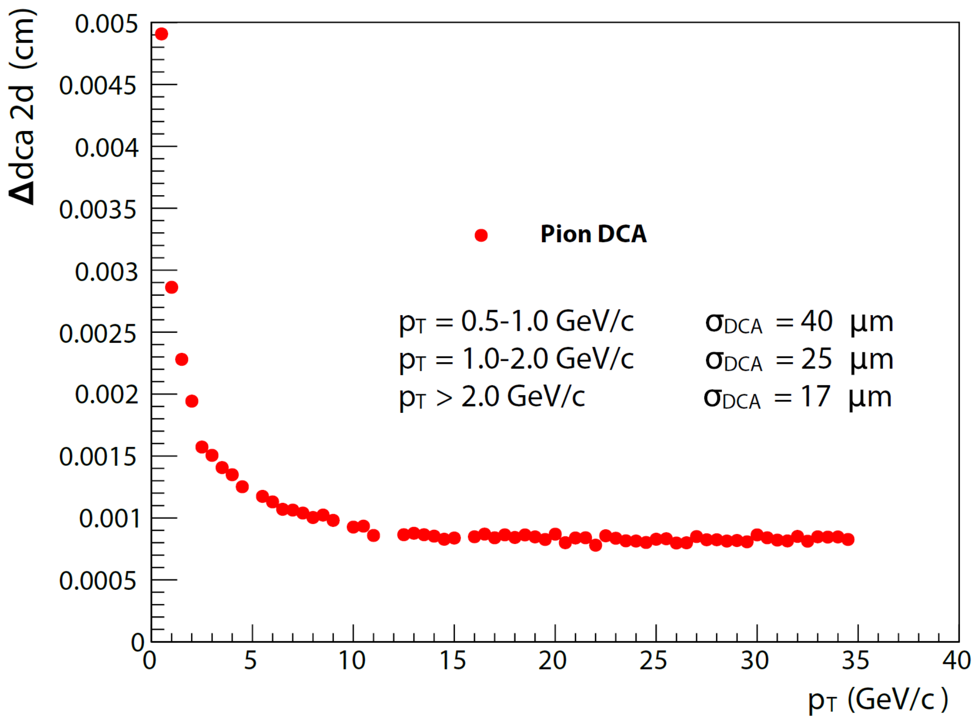
- For initial τ-reco evaluation: sPHENIX vertex tracker
  - 30 μm ALICE Pixel MAPS pixel in three layers, total 200 M pixel channels
  - 5 μm hit position resolution
  - 0.3% X_0 thickness per layer
  - R ~2cm.

state-of-the-art vertex detector

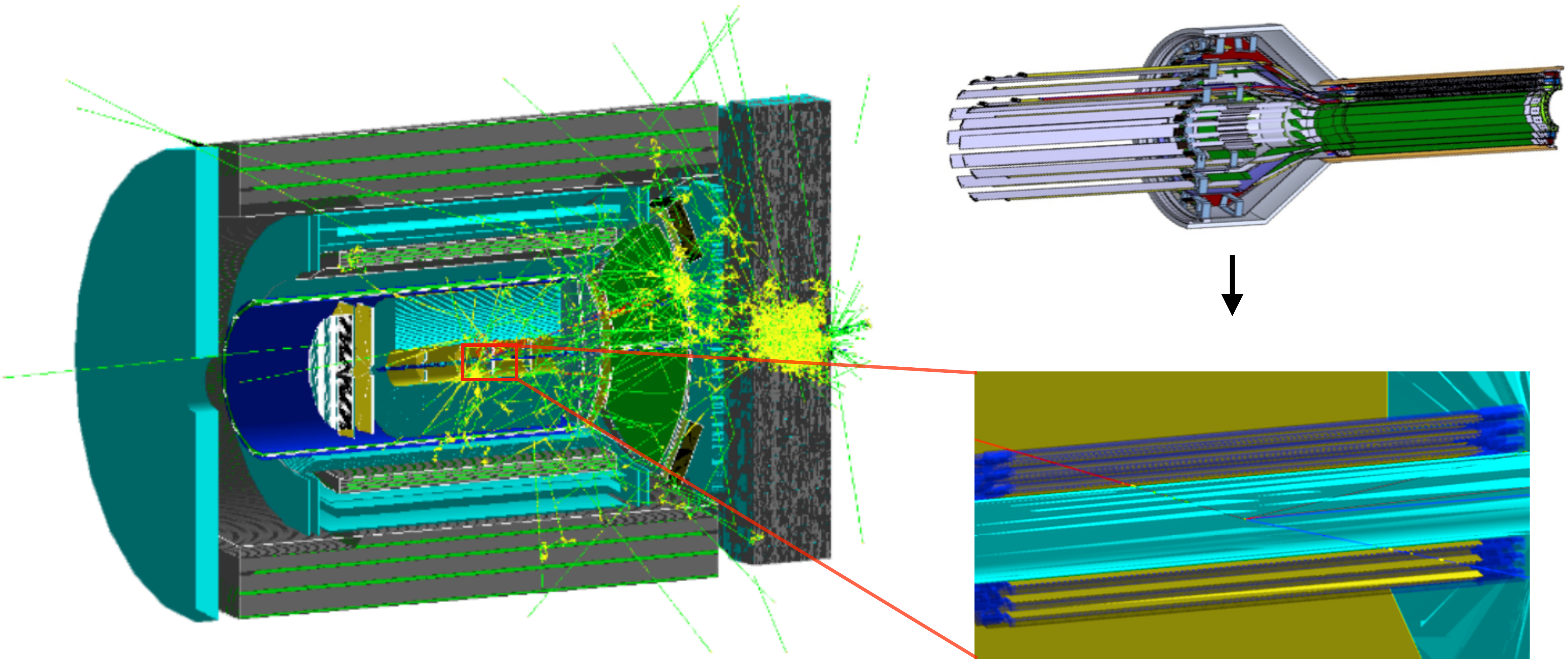
MVTX — Monolithic-Active-Pixel-Sensor-based Vertex Detector



Service cone: signal, power, cooling
and mechanical support



LQ event at sPhenix-EIC detector

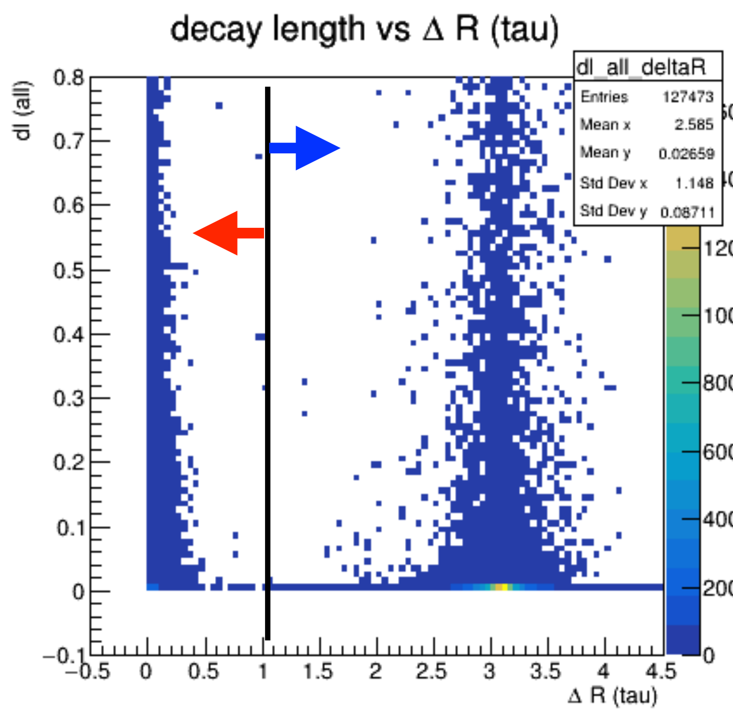


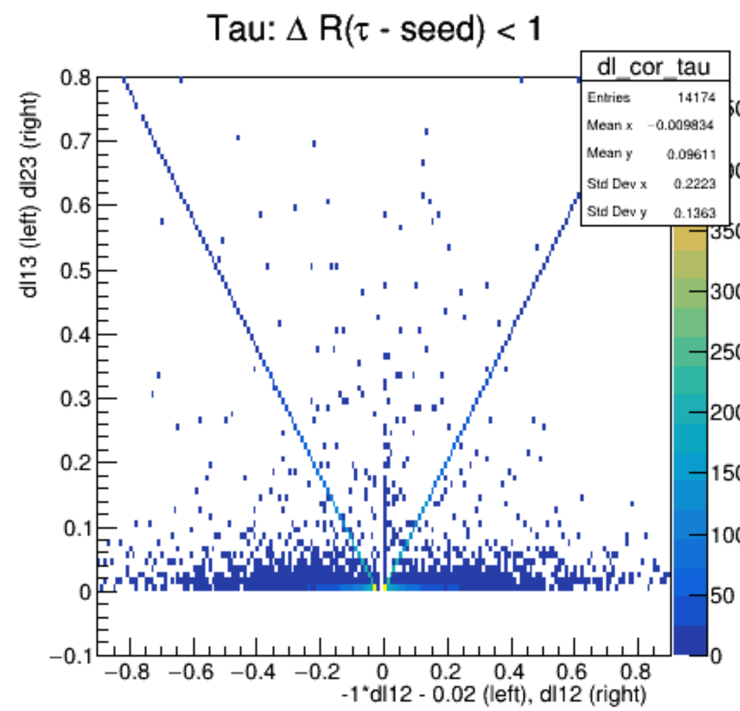
- LQGENEP 1.0 Leptoquark event e+p 18x275 GeV/c + sPHENIX-EIC sim
- For initial τ-reco evaluation: sPHENIX vertex tracker

Simplified secondary vertex reconstruction

Generator level

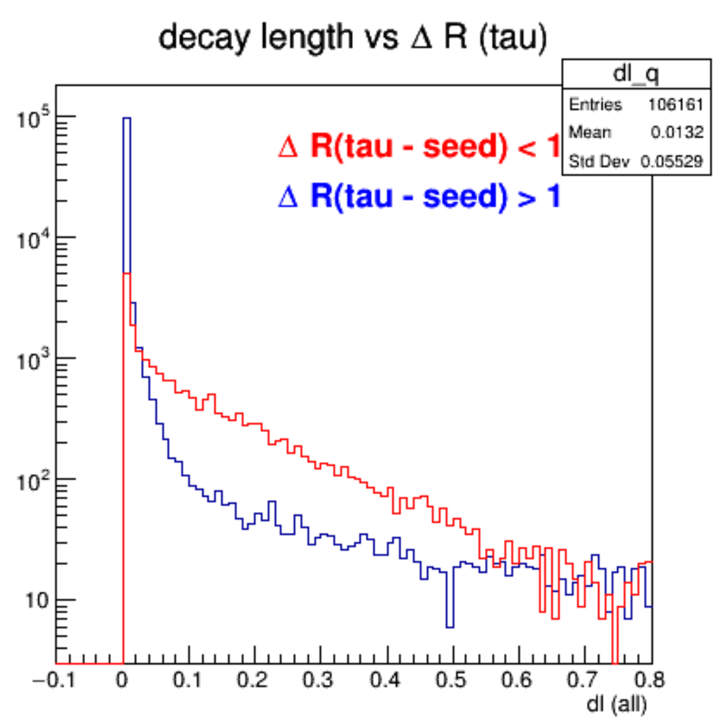
Tag 3-prong candidate with truth tau direction

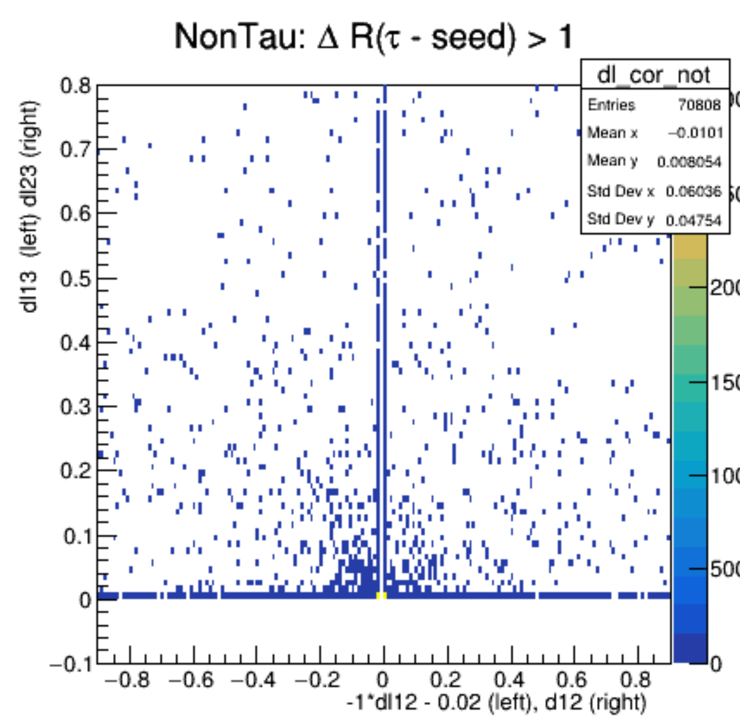




Tau side:
Clear correlations between 3 reconstructed decay length

Significantly long reconstructed decay length at Tau side



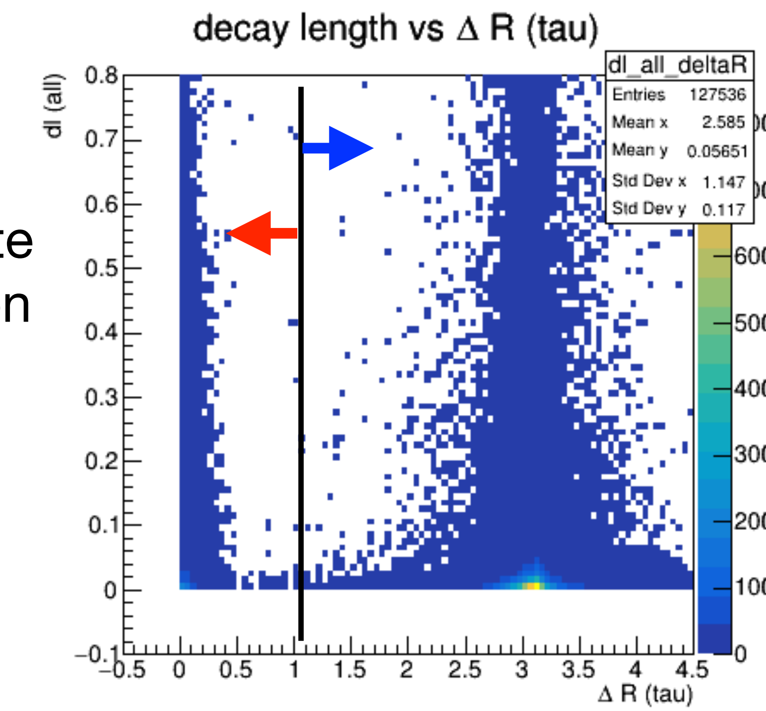


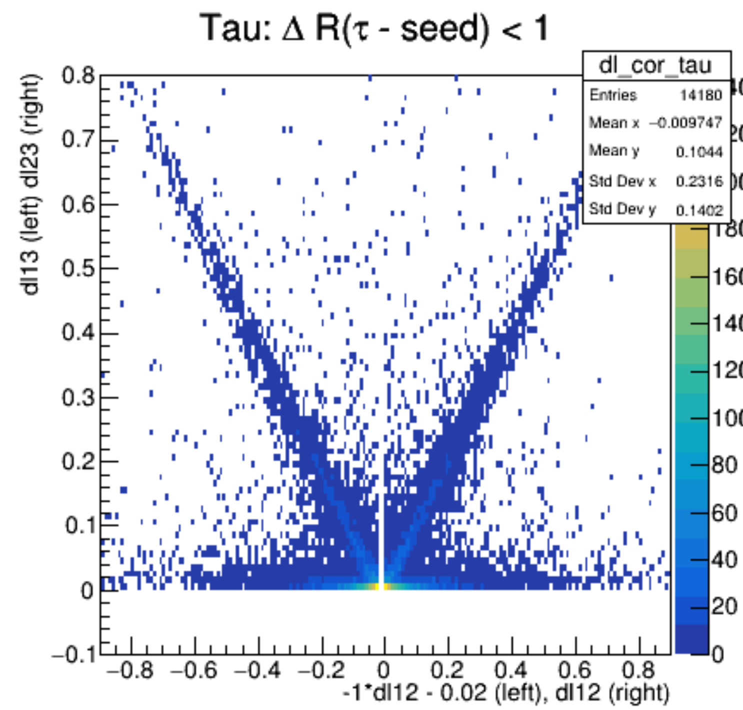
Away side:
No correlations between 3 pair combination

Simplified secondary vertex reconstruction

Full Geant4 of sPHENIX

Tag 3-prong candidate with truth tau direction





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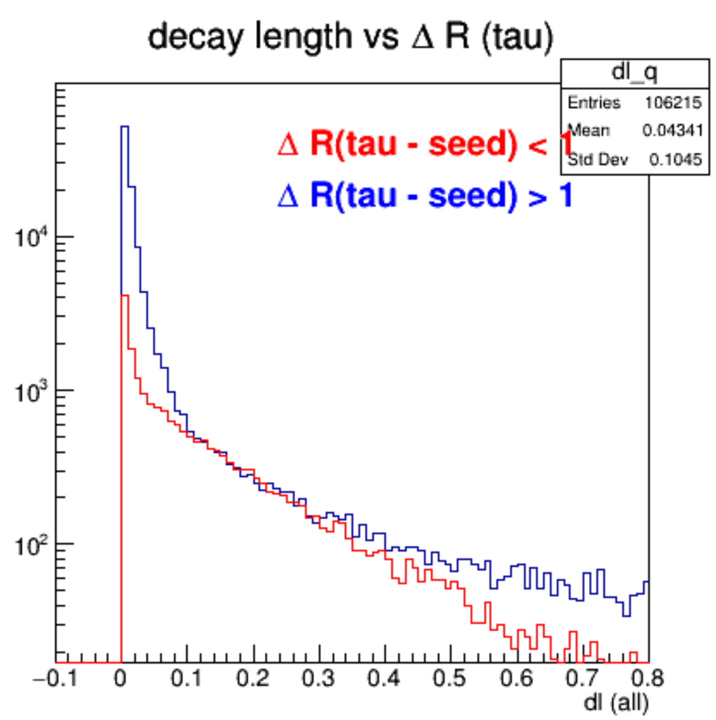
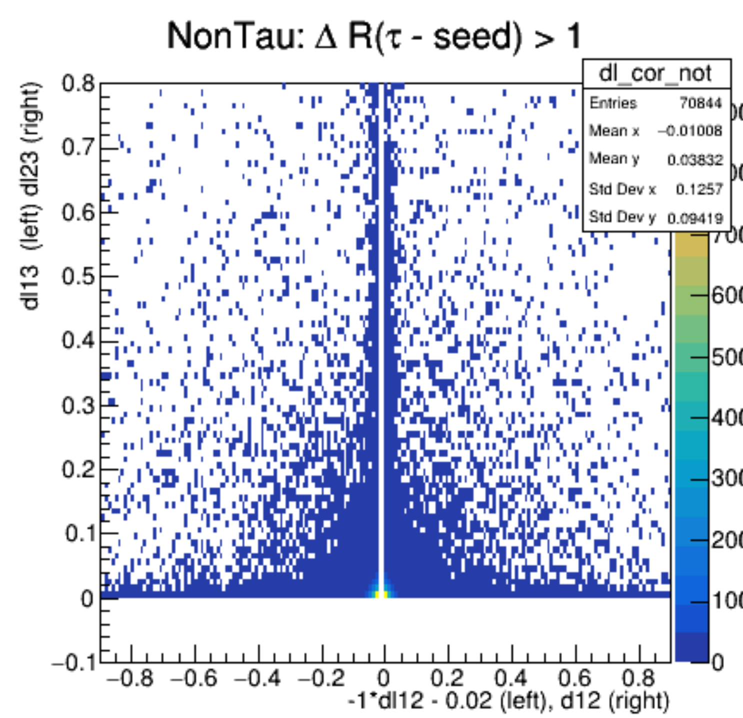
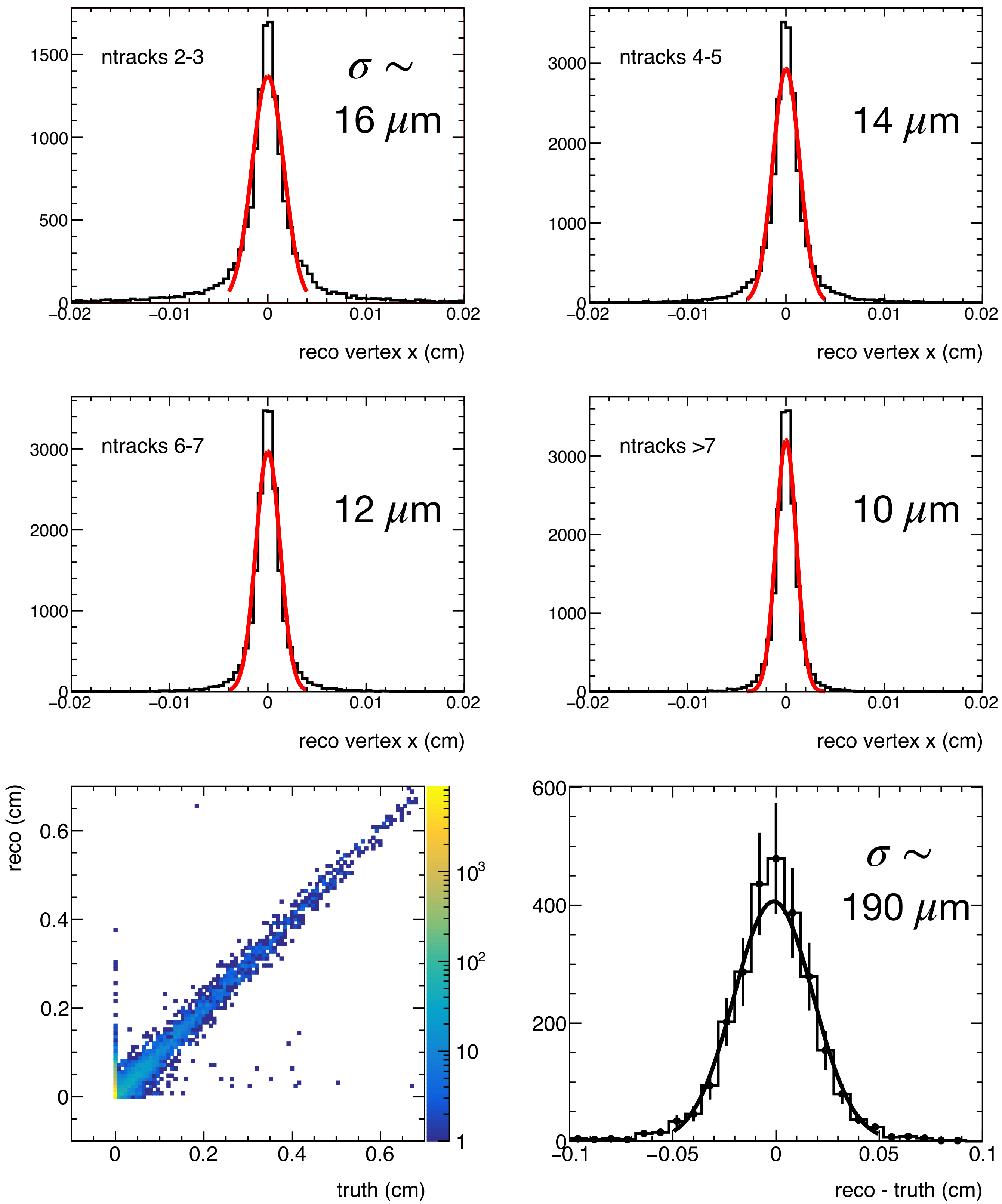




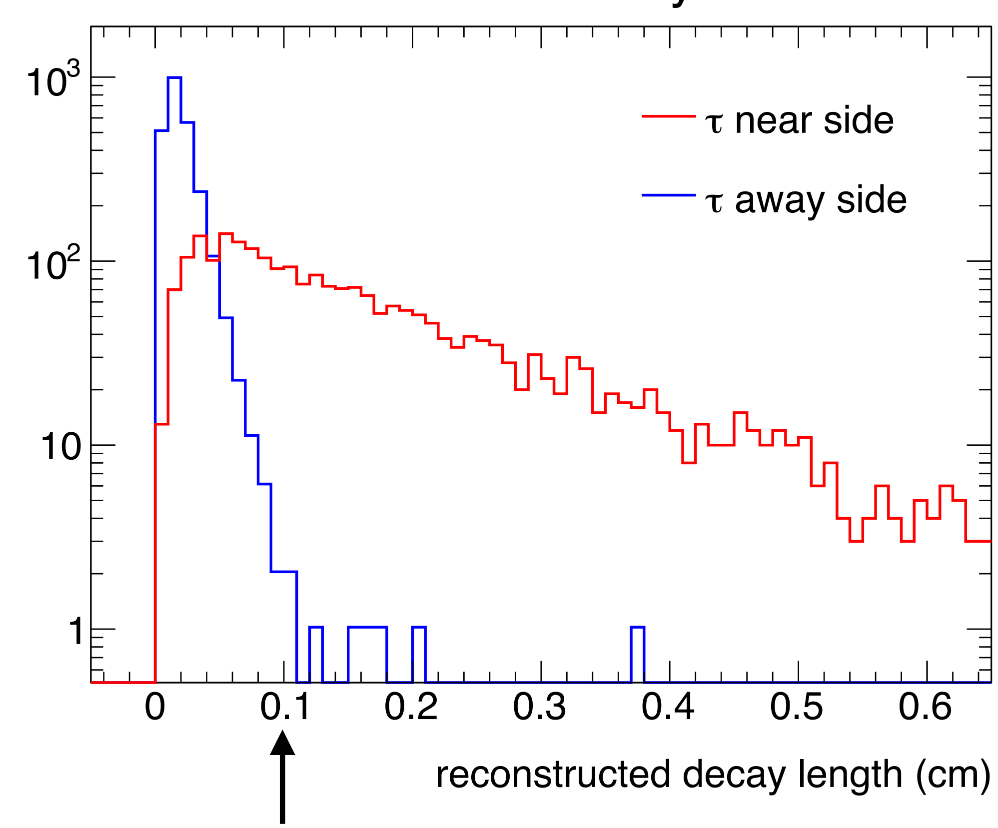
Away side:
No correlations between 3 pair combination

Effect of resolution

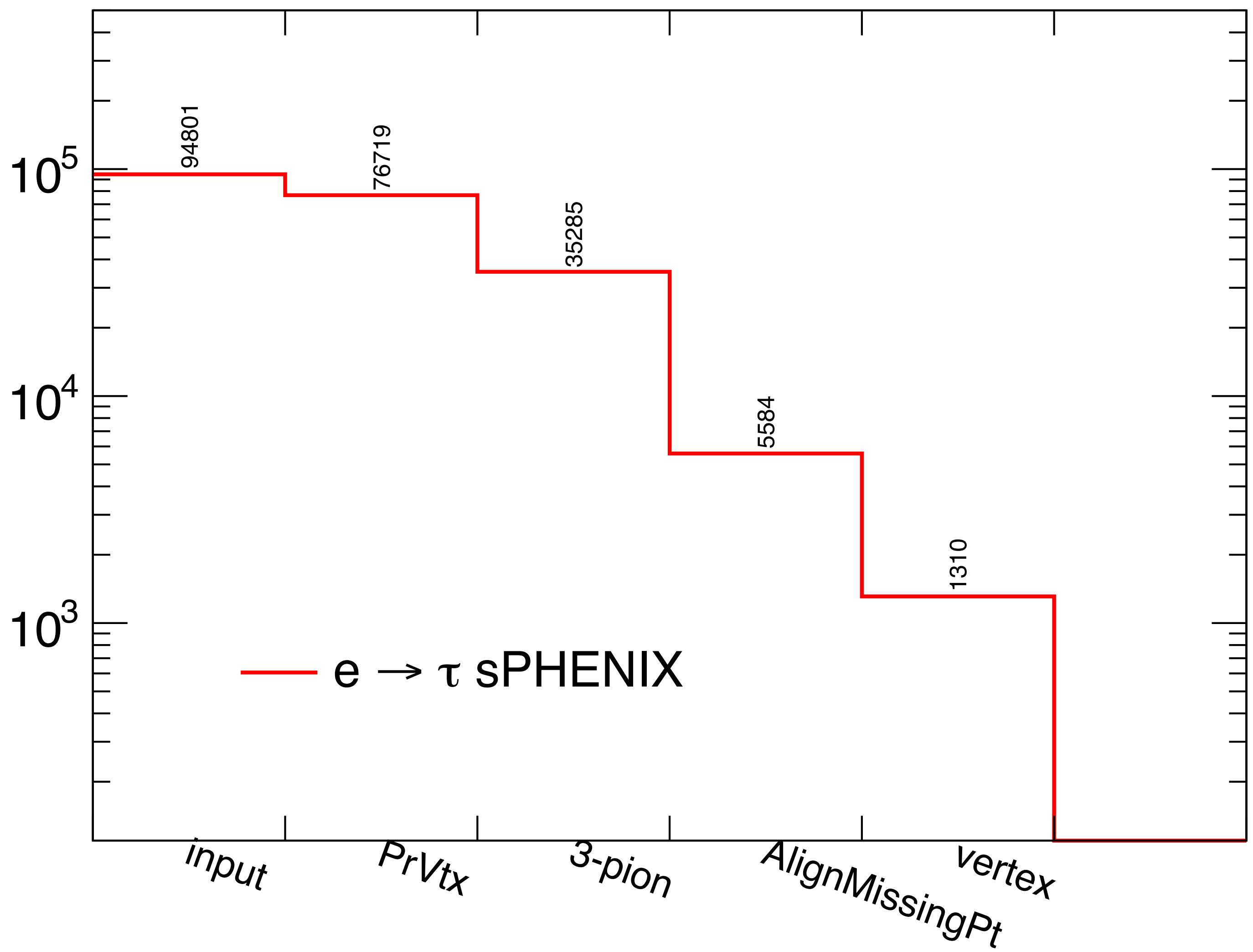


- Vertex resolution at x component **~10** μm
- Similar for y and z components at middle rapidity
- Decay length resolution ~ 190 μm

- Similar algorithm applied as for Generator level analysis



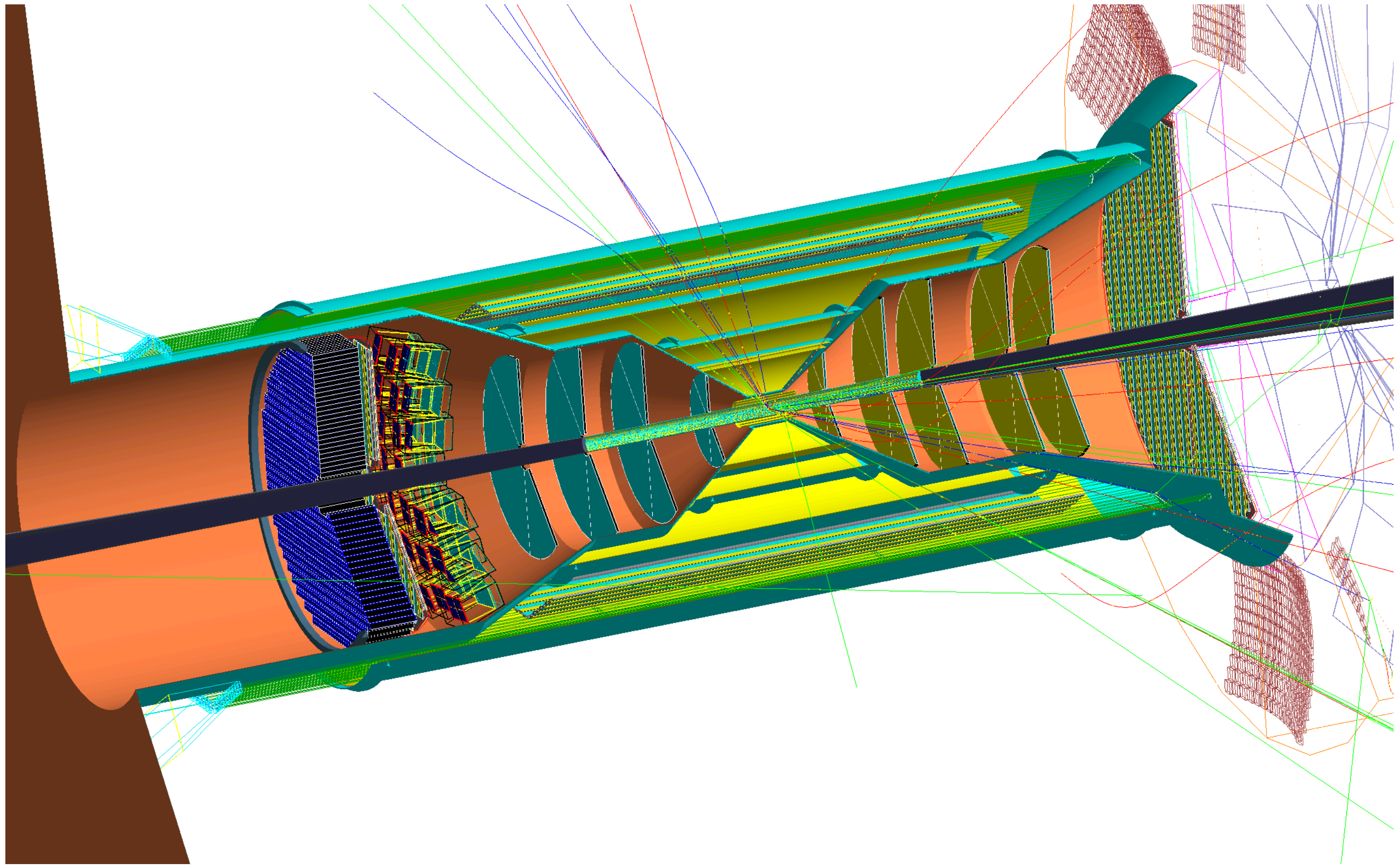
Efficiency with Detector Effects



- 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

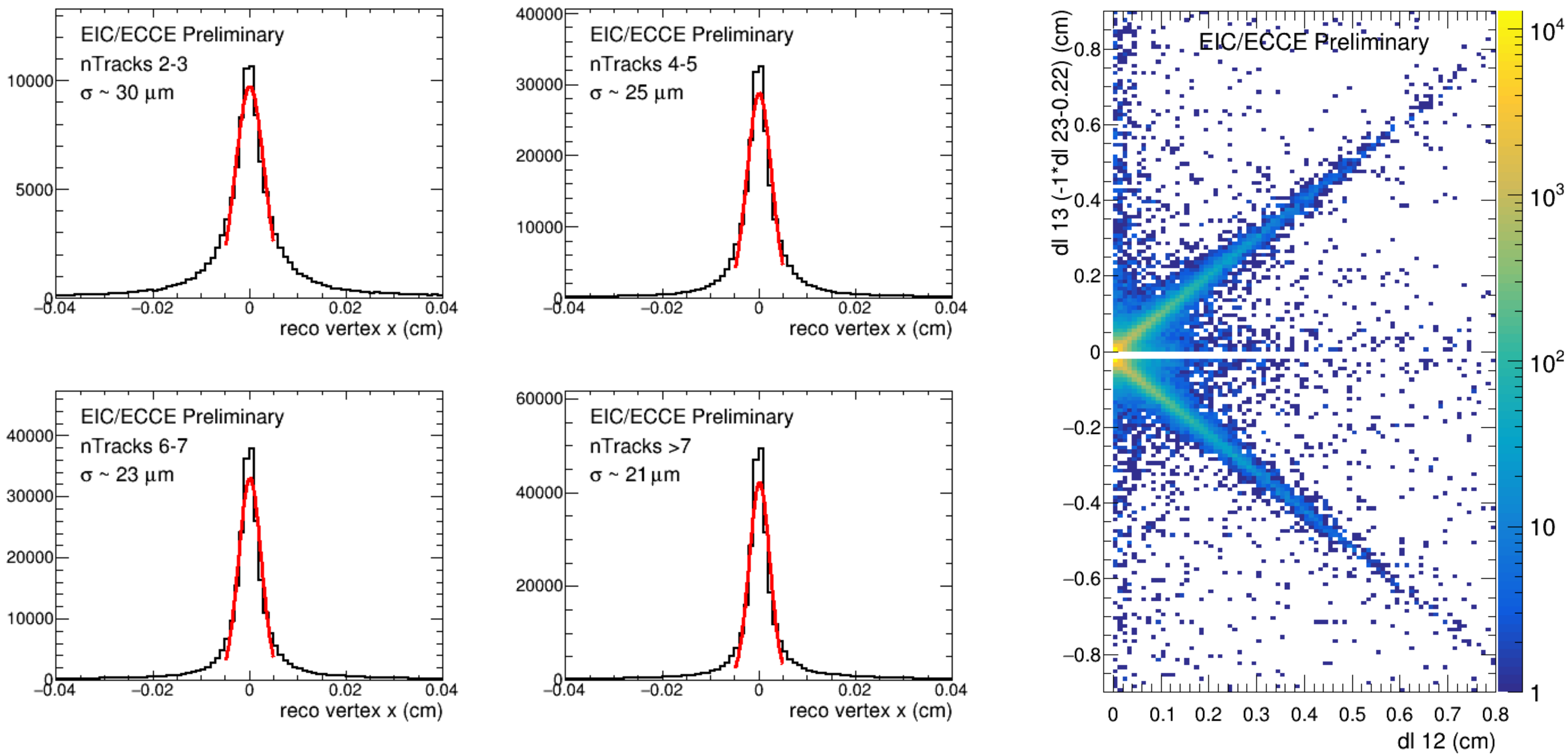


- ECCE hybrid tracking detector design
  - **MAPS based silicon vertex/tracking**
  - mRWELL tracking subsystem
  - AC-LGAD outer tracker

Thanks to ECCE
Software working group!

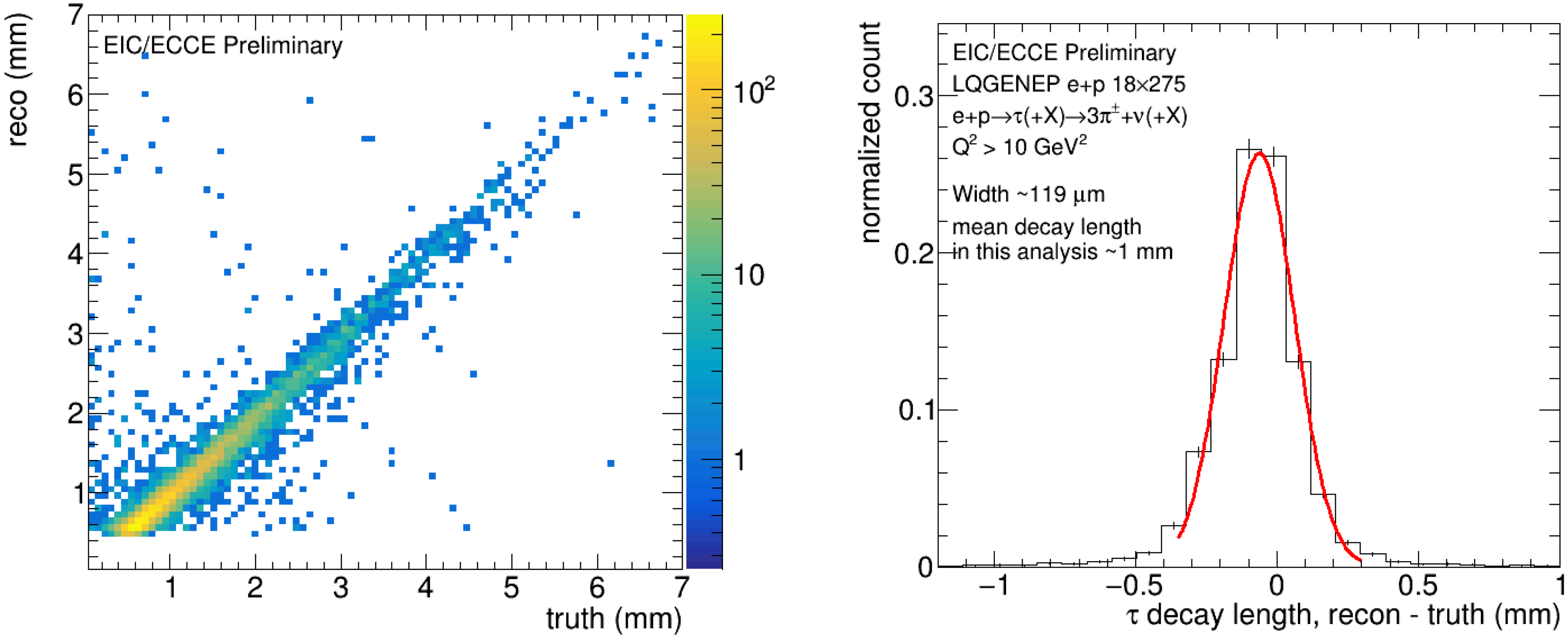
ECCE tracking, arXiv: 2205.09185

Vertex reconstruction



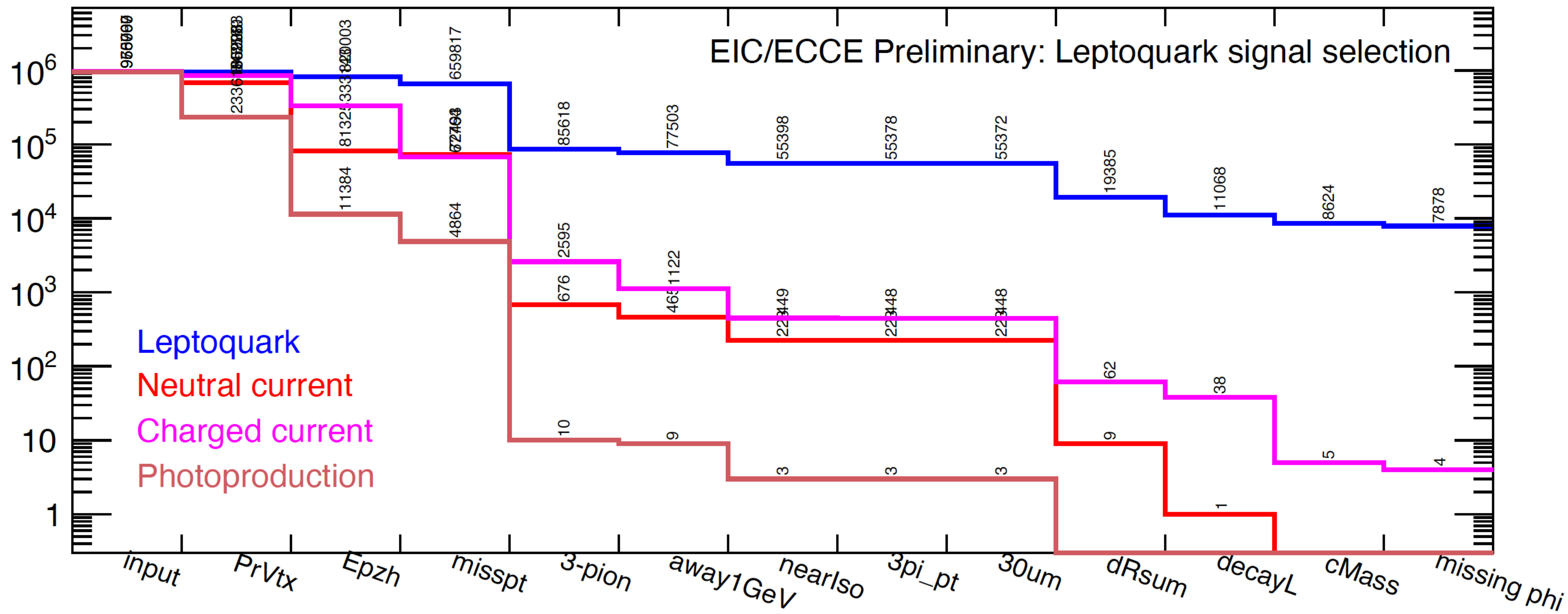
- With ECCE hybrid tracking detector design
  - Primary vertex x-component 20~30 microns
  - Secondary vertex reconstructed for tau candidates

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 ($10^{34}/cm^2/s$) 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

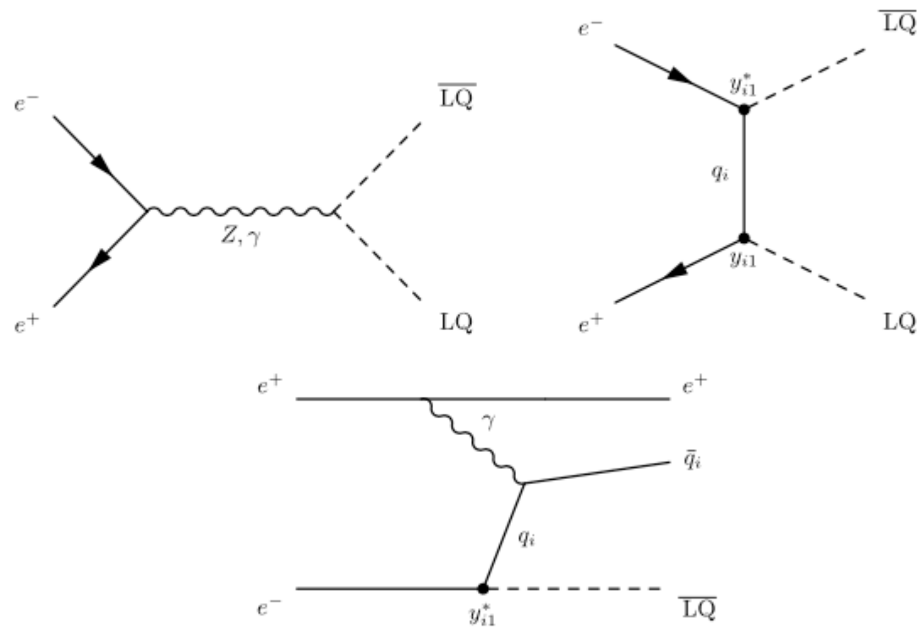
Next step

- 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

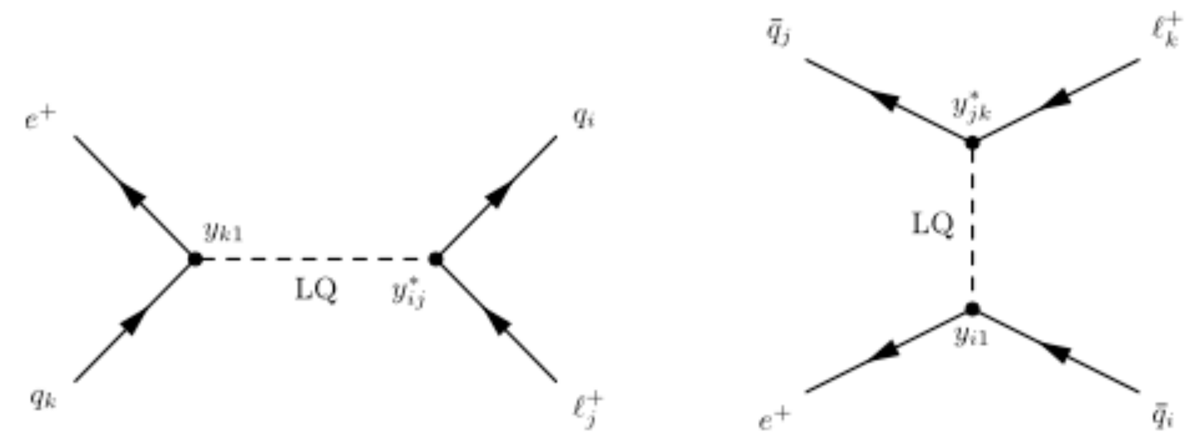
Backup

Experimental Searches of Leptoquarks

e^+e^-



ep



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