Charged Lepton Flavor Violation Study at EIC

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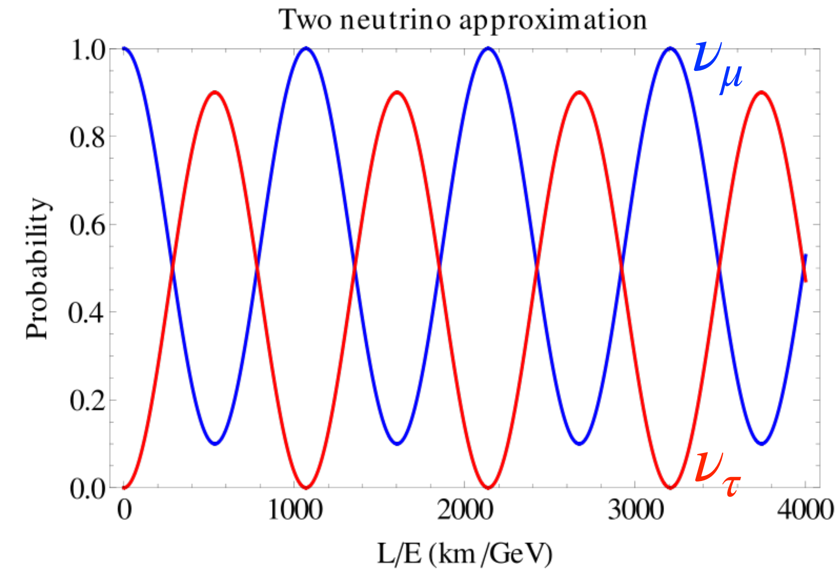
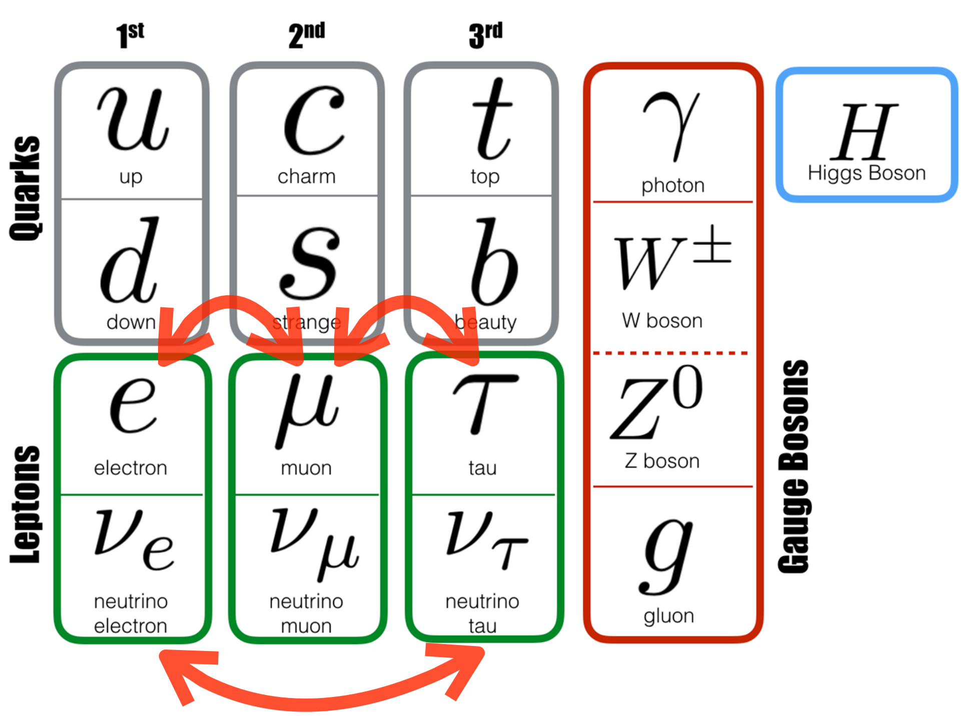
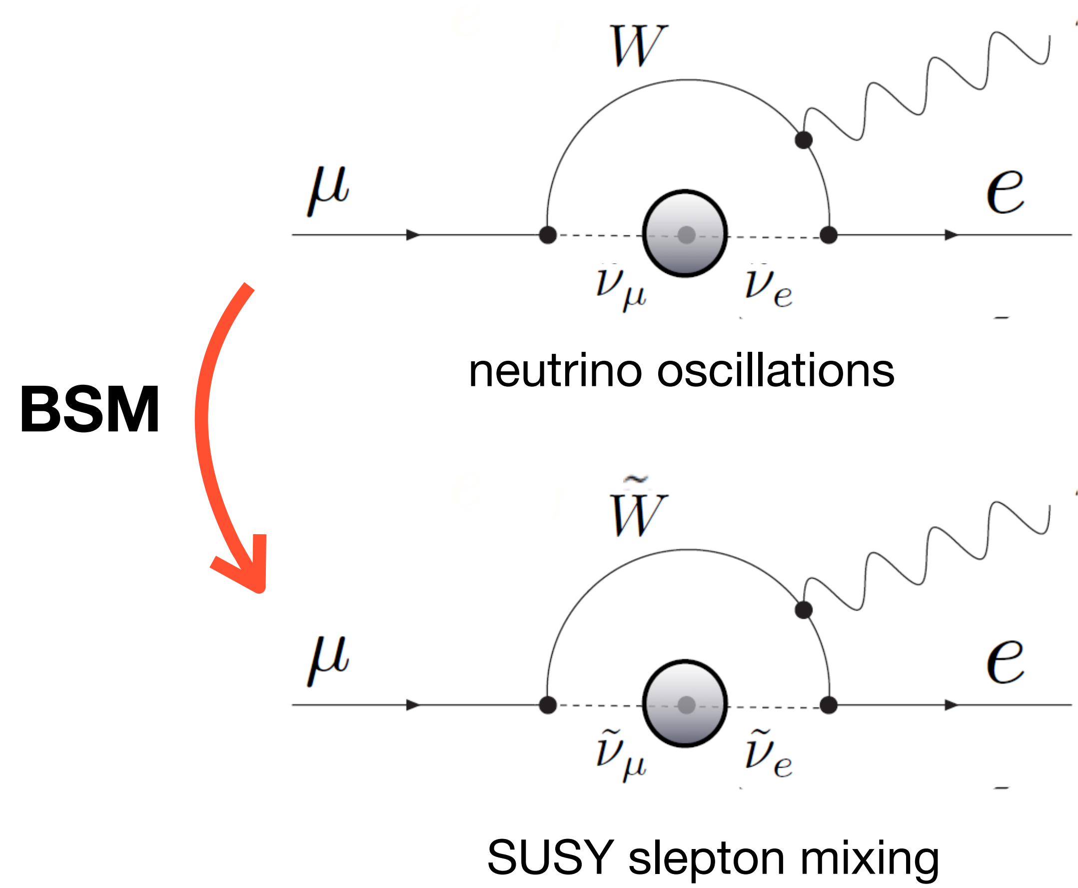
Charged Lepton Flavor Violation

- 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}



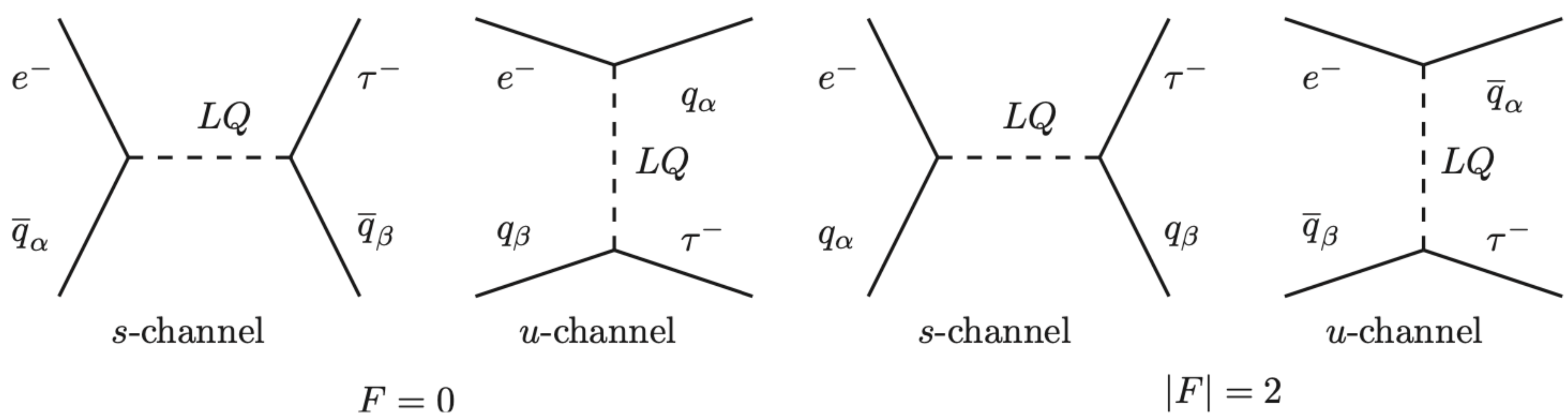




Leptoquark

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

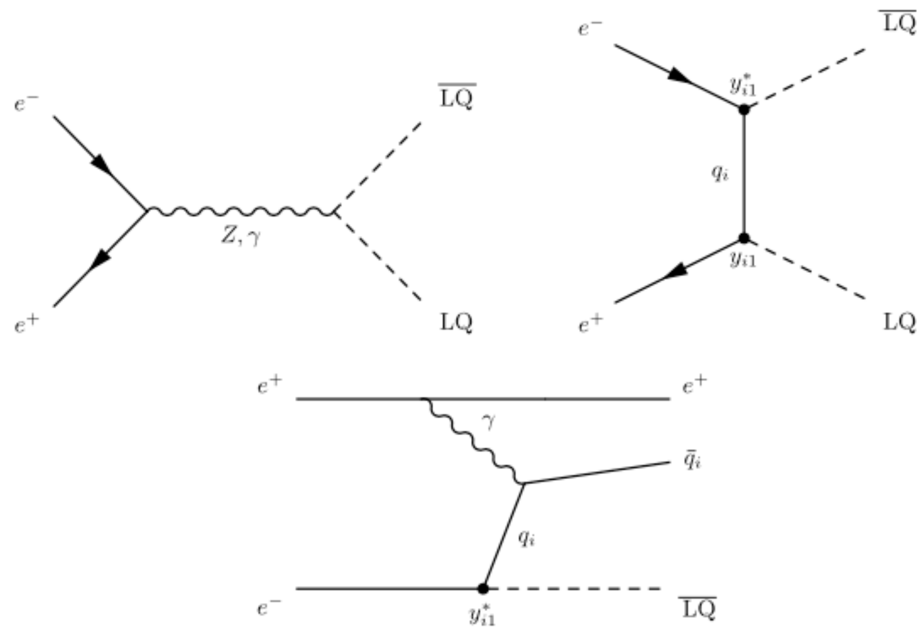
- Symmetry between lepton sector and quark sector
- Flavor violating but fermion number (F = 3B+L) conserving
- Buchmüller-Rückl-Wyler (BRW) framework: 14 different LQ types (7 scalars, 7 vectors)
- CLFV at tree level processes; allow coupling between same and different generations of quarks and leptons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



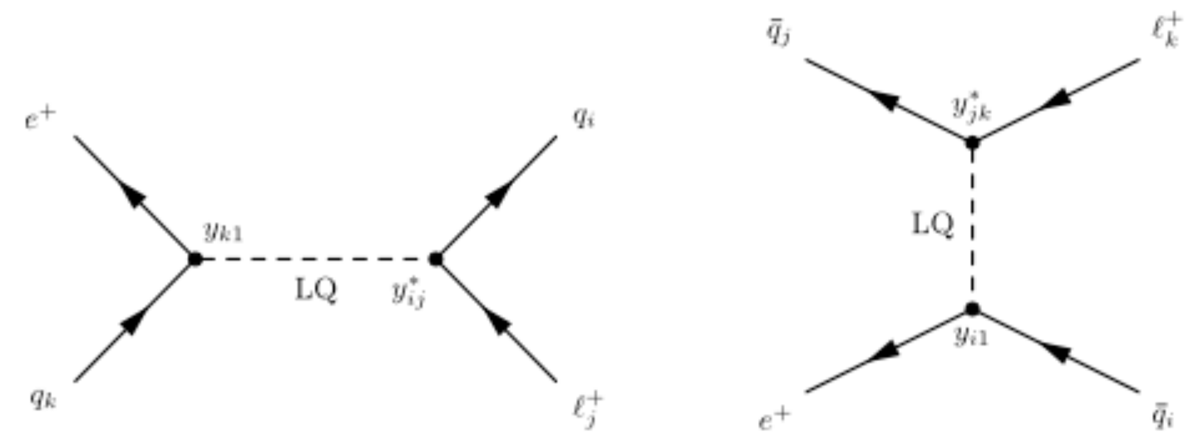
Good benchmark for EIC CLFV searches

Experimental Searches of Leptoquarks

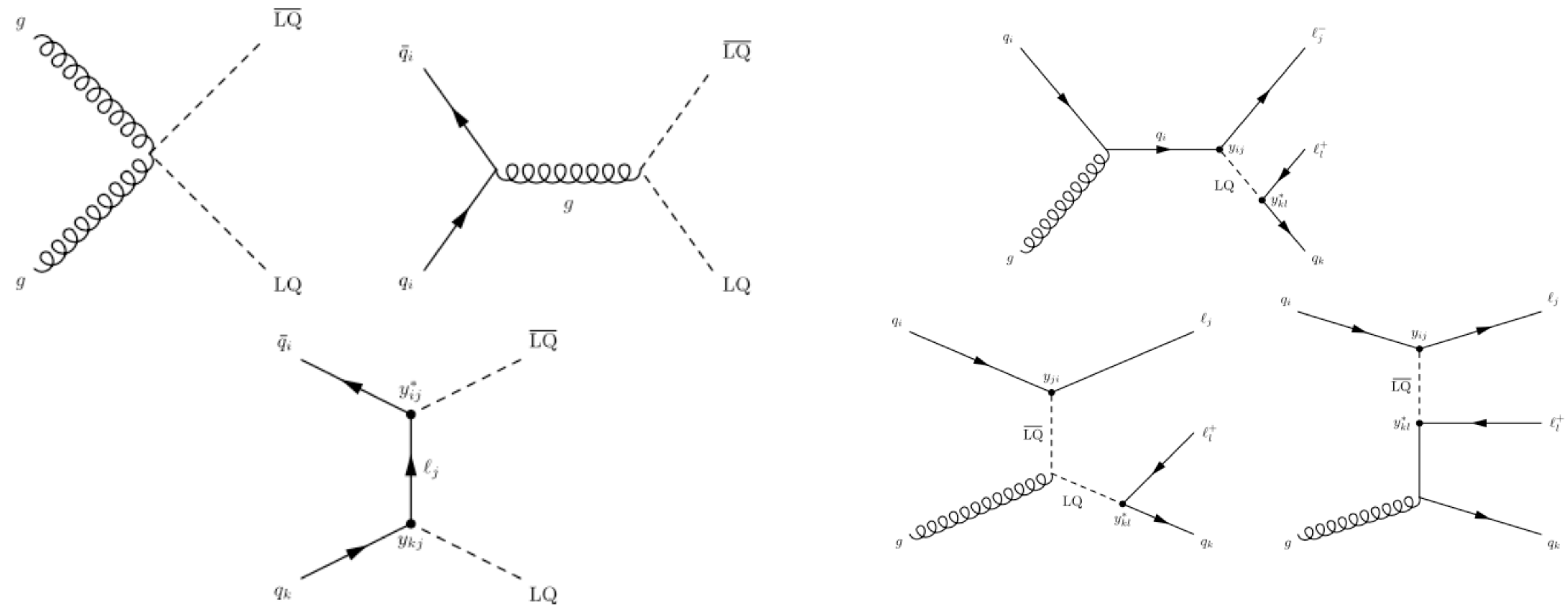
e^+e^-



ep



pp / $p\bar{p}$



$e \rightarrow \tau$ Conversion at EIC

$e \leftrightarrow \mu$ conversion upper limits < 10^{-13}

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

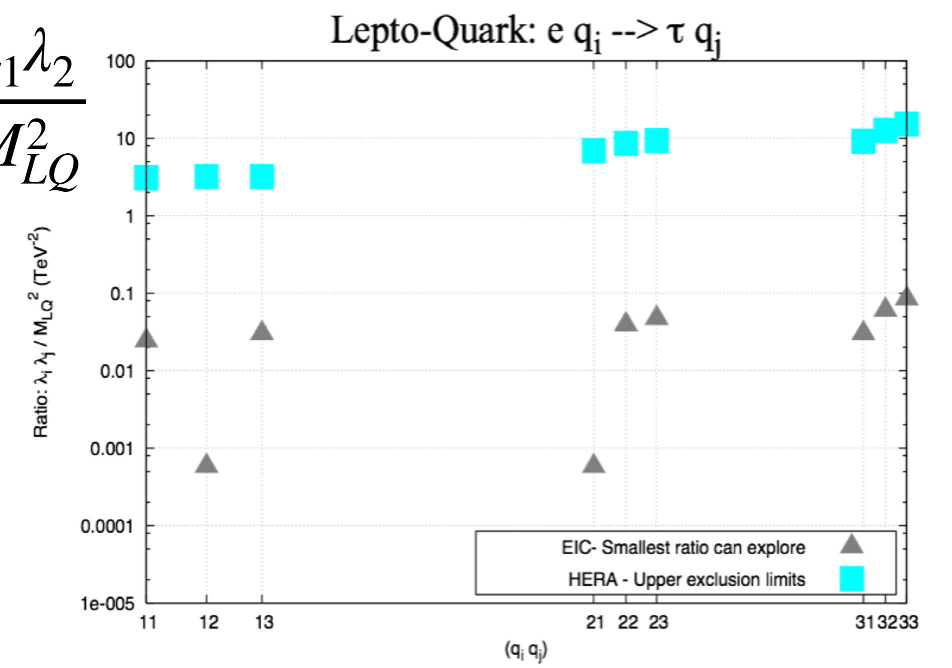
New discovery space: $e \rightarrow \tau$ Conversion

- Leptoquark models provide a good benchmark to study sensitivity

Gonderinger, Ramsey-Musolf, JHEP (2010) 2010: 45

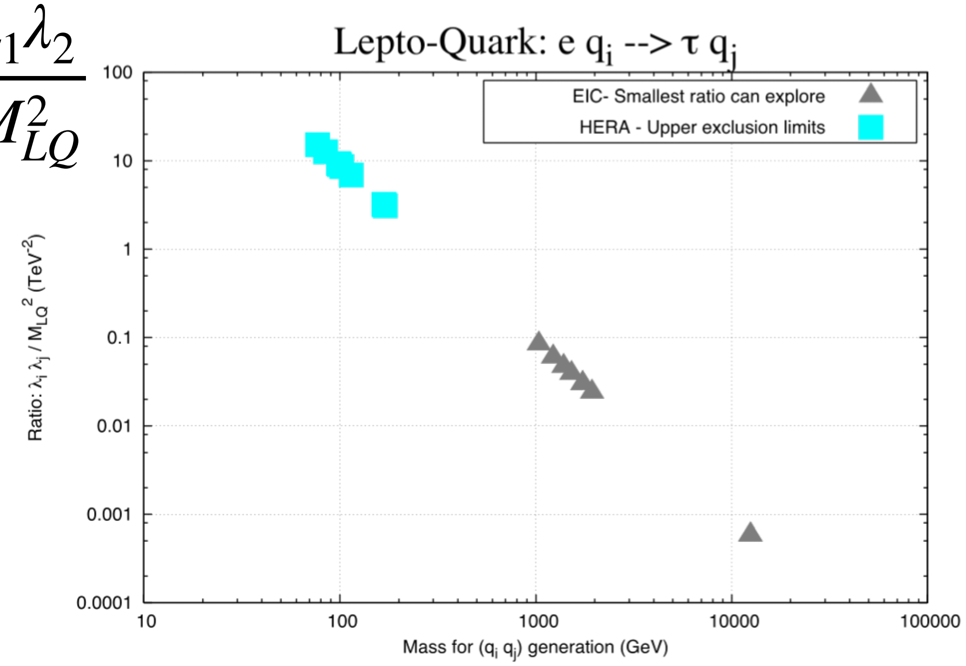
- Current limits set by HERA in coupling-mass space
- With much higher luminosity, $10^{30-31} \rightarrow 10^{33-34}$ cm^{-2}s^{-1}, ~2 orders of magnitude improvement of the sensitivity is expected at EIC

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

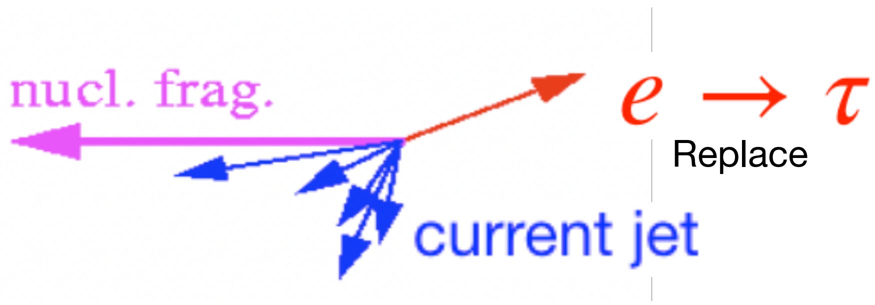


Assume 0.1 fb cross-section sensitivity

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



Goal of this Study



- Replace electron with tau
- Tau back-to-back with current jet
- Primary vertex reconstructed from tracks of current jets
- **Tau vertex displaced at cm 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

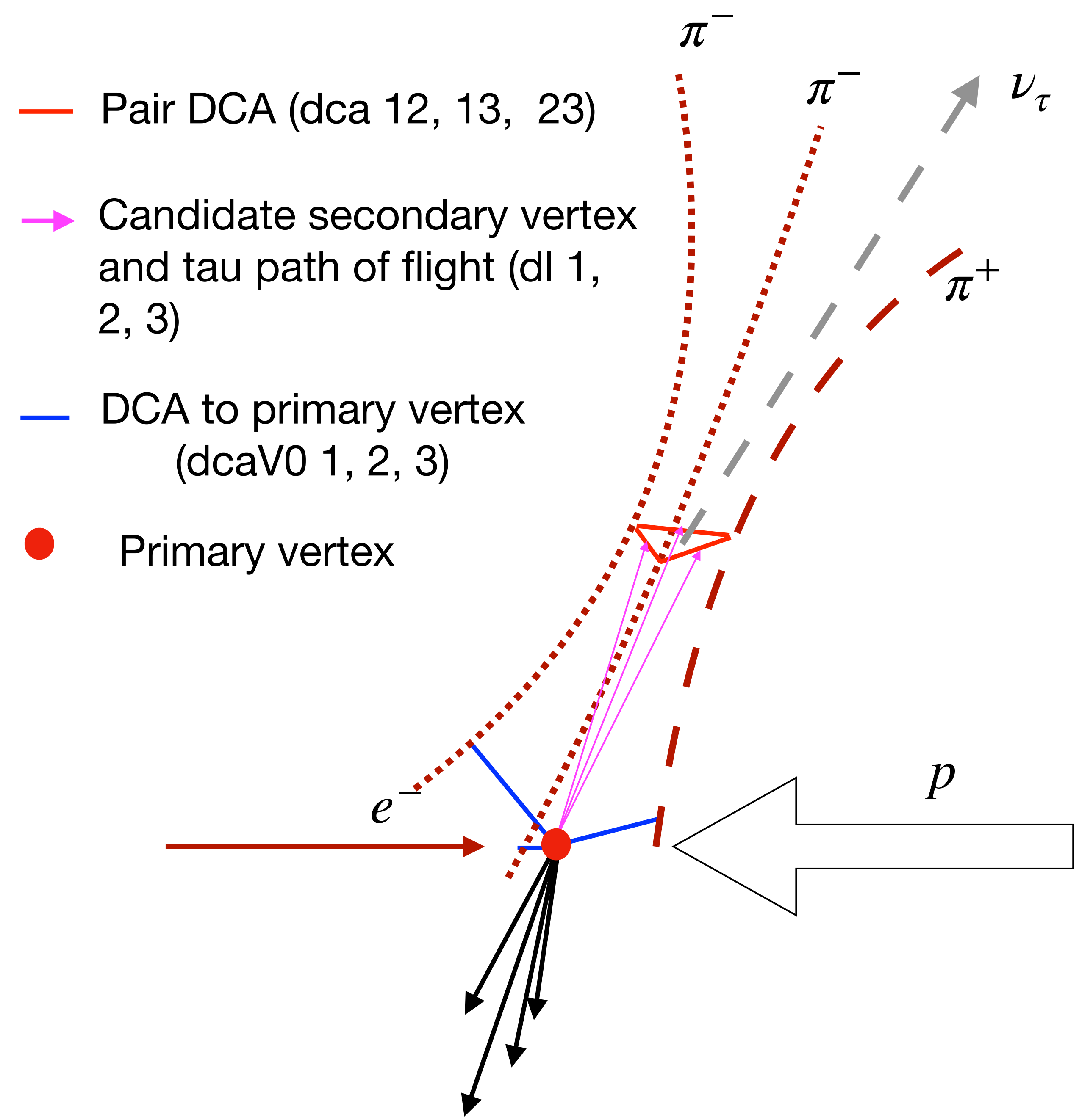
- **3-prong** **15.21 (0.06)%**
  - $\pi^-\pi^+\pi^-\nu_\tau$ 9.31 (0.05)%
  - $\pi^-\pi^+\pi^-\pi^0\nu_\tau$ 4.62 (0.05)%
  - others (kaon, etc) 1.28%
- **1-prong** **84.58 (0.06)%**
  - $\mu^-\bar{\nu}_\mu\nu_\tau$ 17.39 (0.04)%
  - $e^-\bar{\nu}_e\nu_\tau$ 17.82 (0.04)%
  - $\pi^-\nu_\tau$ 10.82 (0.05)%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

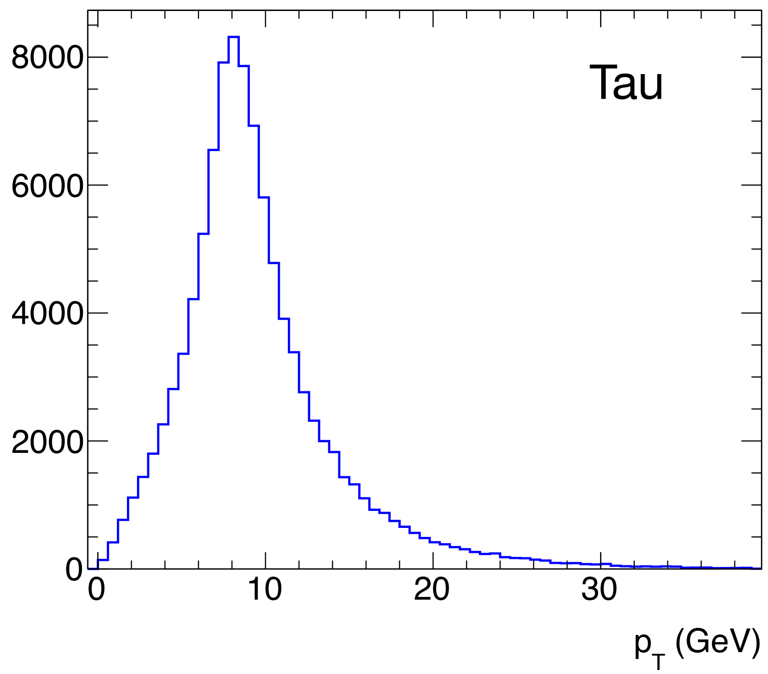
EIC, benefit from improved vertex and jet detection, aim to greater than 10% efficiency with negligible background in a 100 fb^{-1} data sample

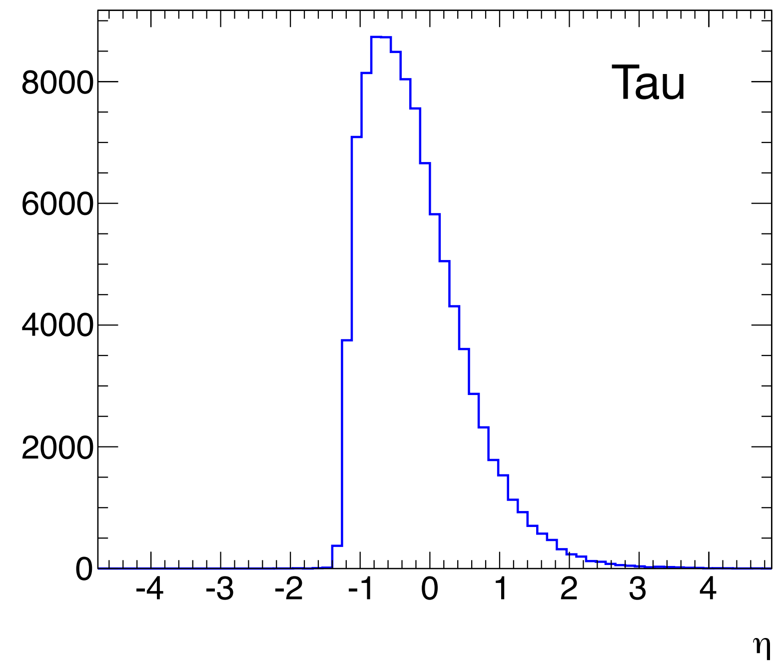
Search strategy for 3-prong decays

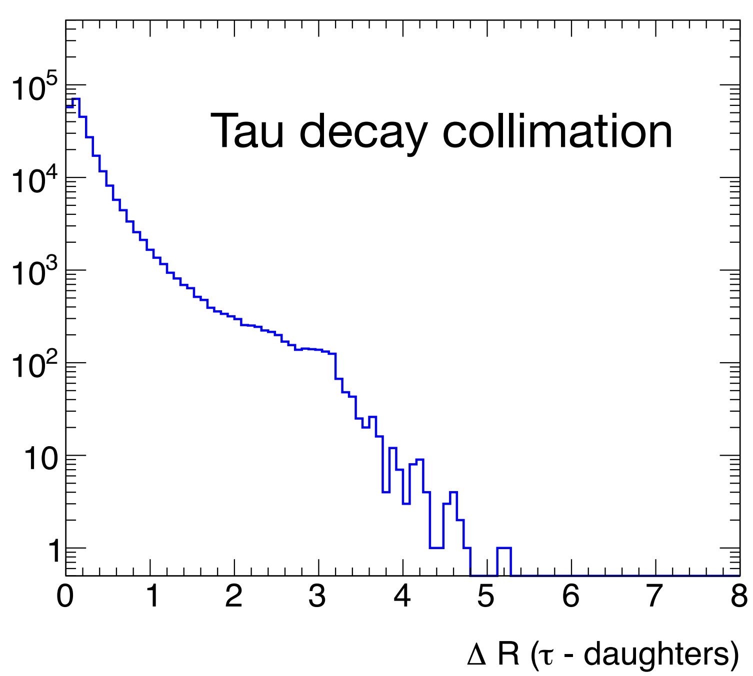
- Event generators:
    - LQGENEP 1.0 for Leptoquark events (L. Bellagamba, 2001)
    - DJANGOH 4.6.8 for DIS (NC + CC) events (H. Spiesberger 2005)
- Jets reconstructed from MC events
    - Anti-k_T, R = 1.0
    - Scattered electron for SM DIS and neutrinos **excluded**
- Secondary vertex finding from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

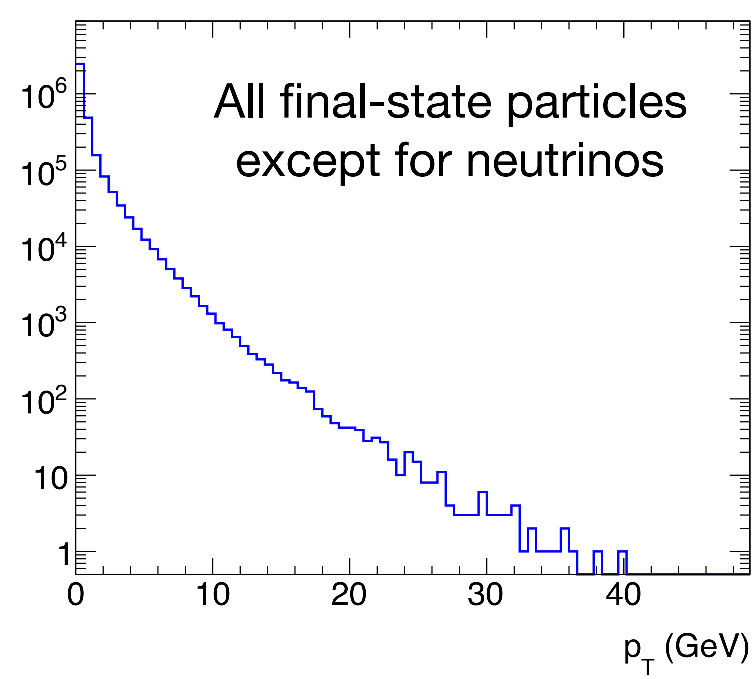


Event kinematics





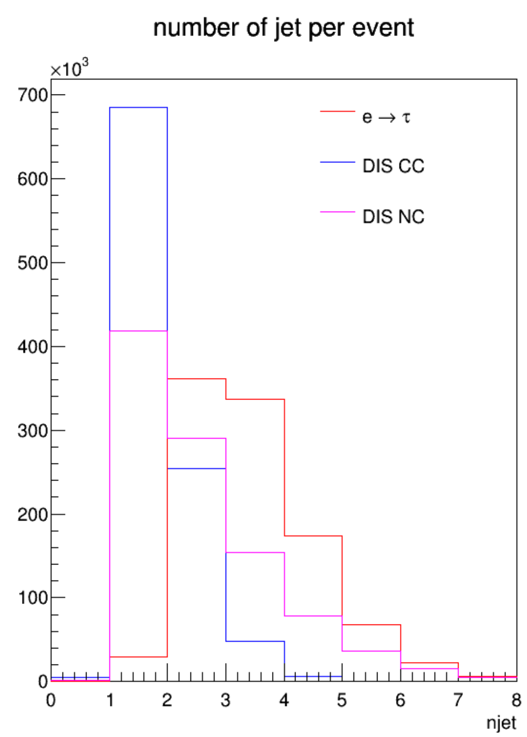


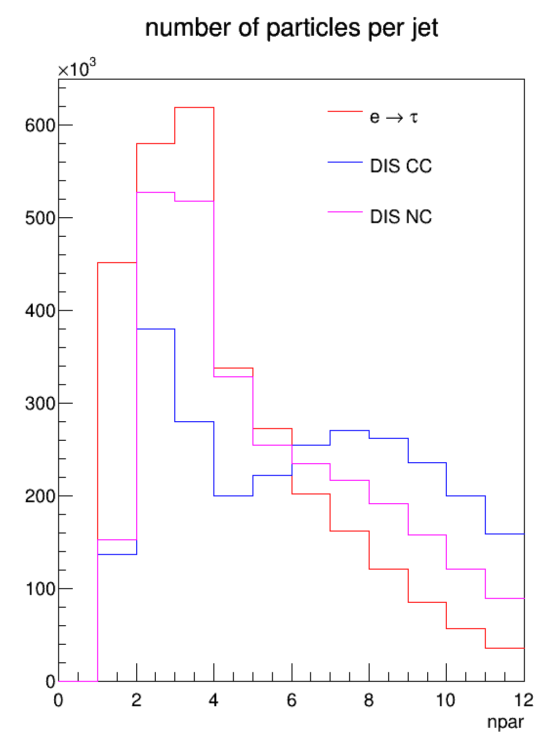


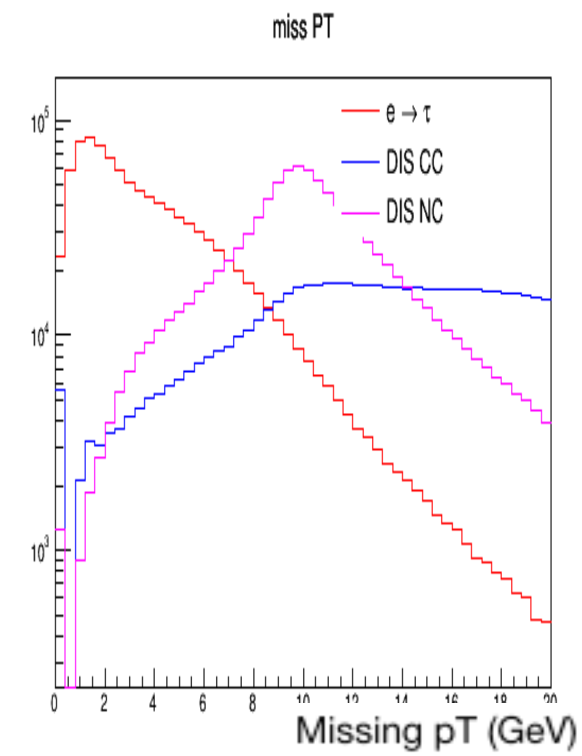
Generator level:

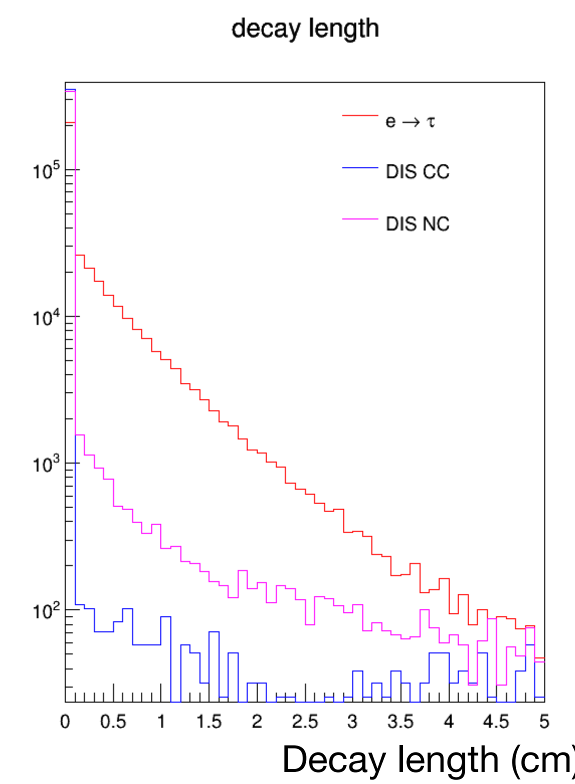
- e+p 20x250 GeV^2
- $Q^2 > 100\ GeV^2$

LQ vs SM DIS







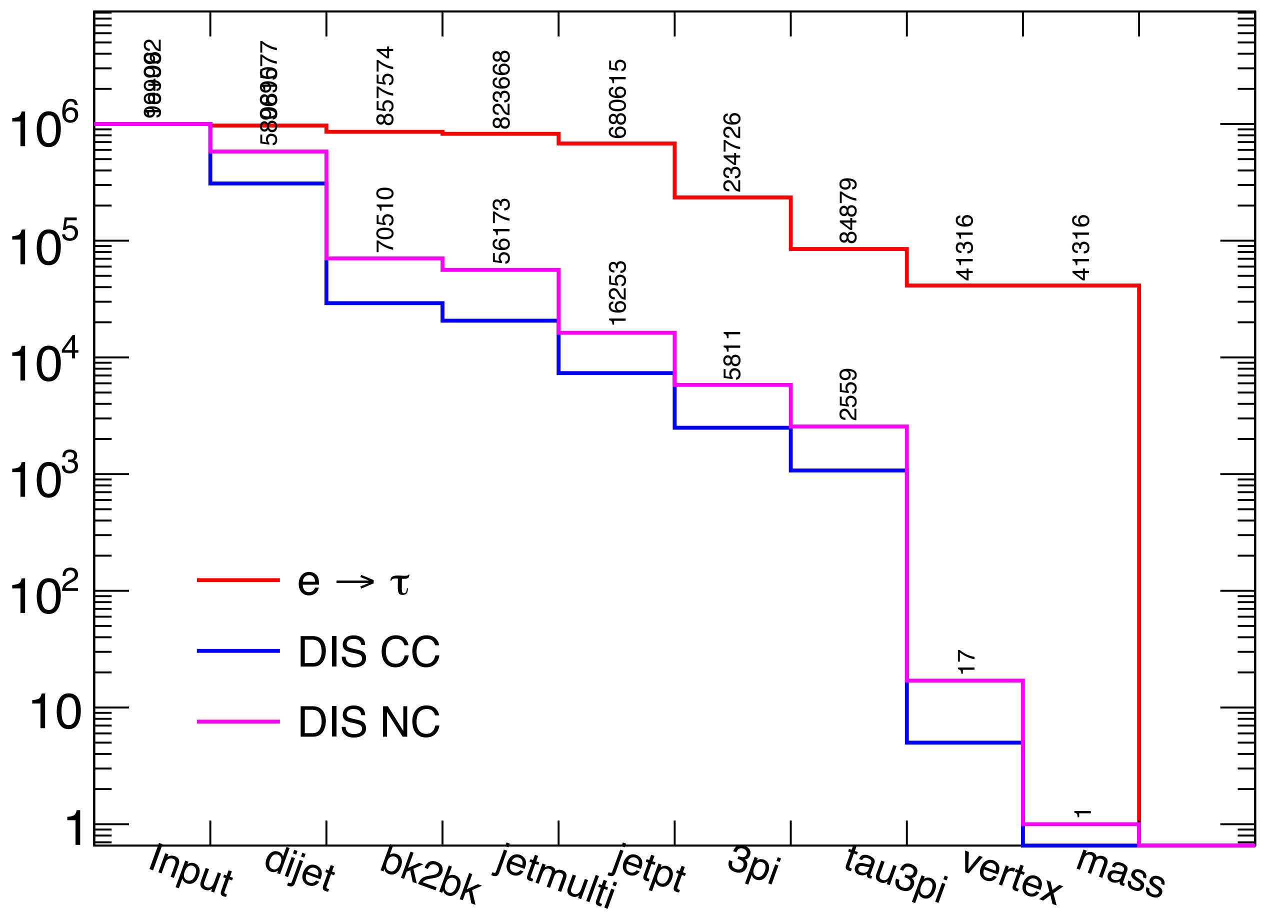


Note: electron in DIS NC is masked

- $e \rightarrow \tau$ event
  - 2+ jets
  - Low particle multiplicity
  - Modest missing pT (partial of tau pT)
  - decay length in order of *cm*

- DIS event
  - 1 jets dominating
  - Higher particle multiplicity
  - Missing pT = lepton pT
  - “zero” decay length

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: dRsum < 0.2 && dl_asy < 0.2 mm && dl_ave > 0.2 mm

Collimation in (η, ϕ) space:

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

Length matching:

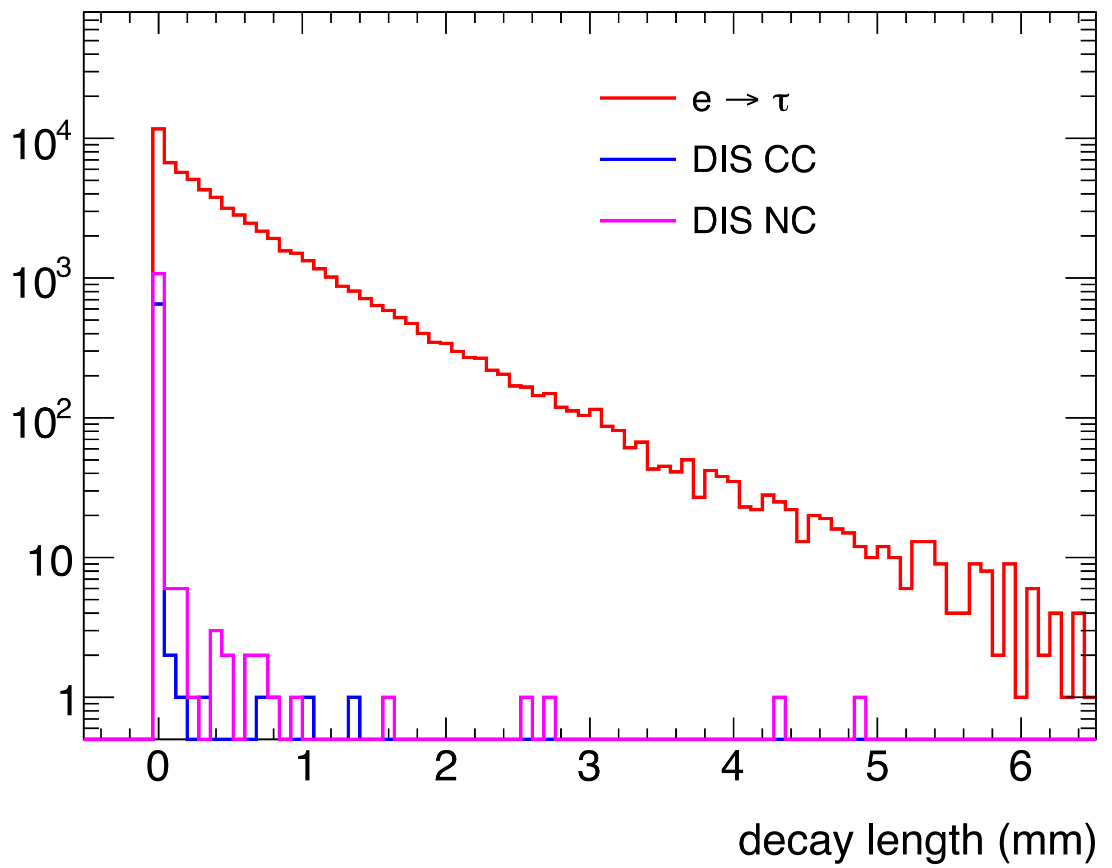
$$dl\_asy = |dl_1 - dl_2| + |dl_1 - dl_3| + |dl_2 - dl_3|$$

- 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

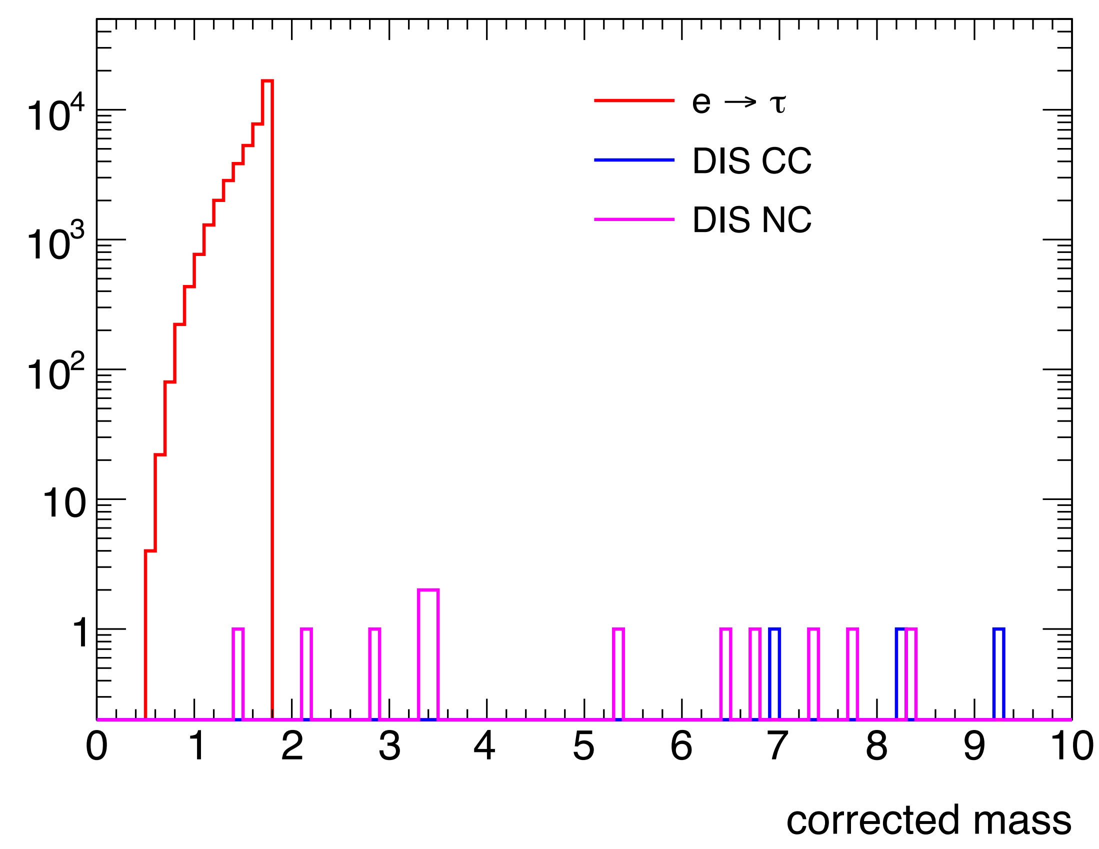


- Secondary vertex and corresponding decay length reconstructed from paired pion tracks

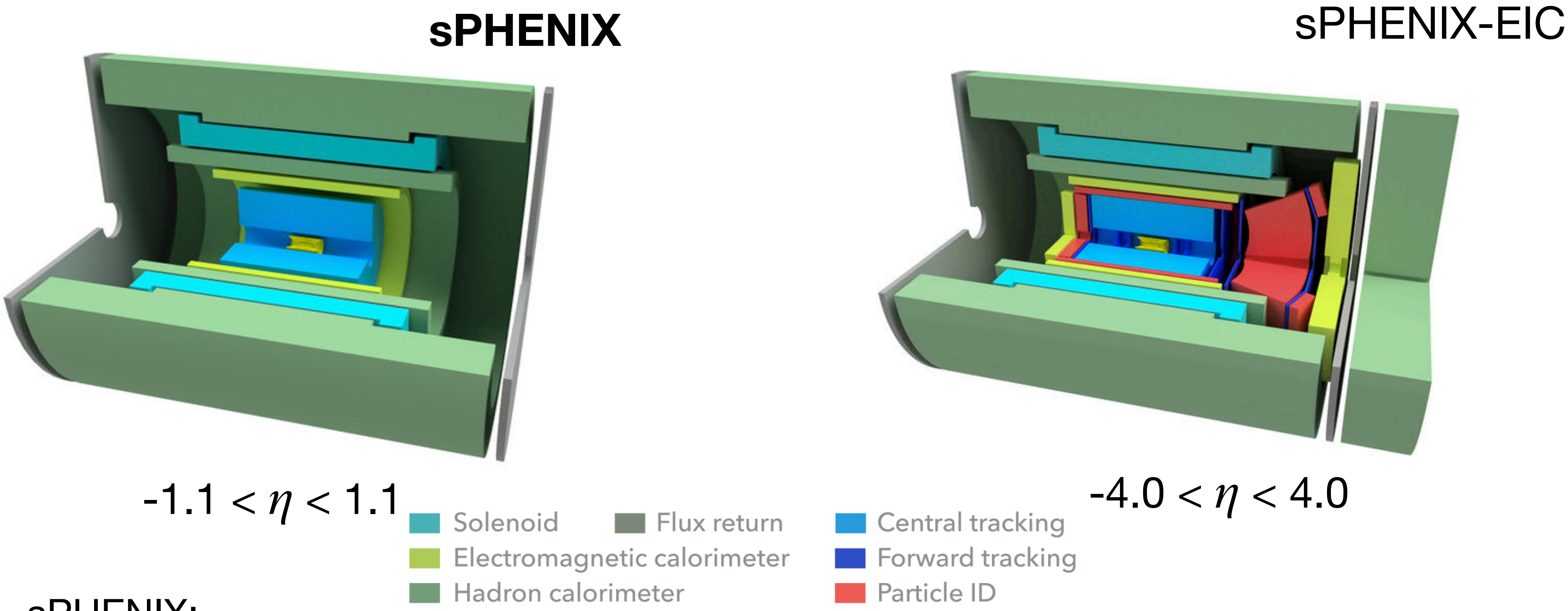
- Corrected mass from 3 pions

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

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



Detector Simulation: sPhenix and further



sPHENIX:

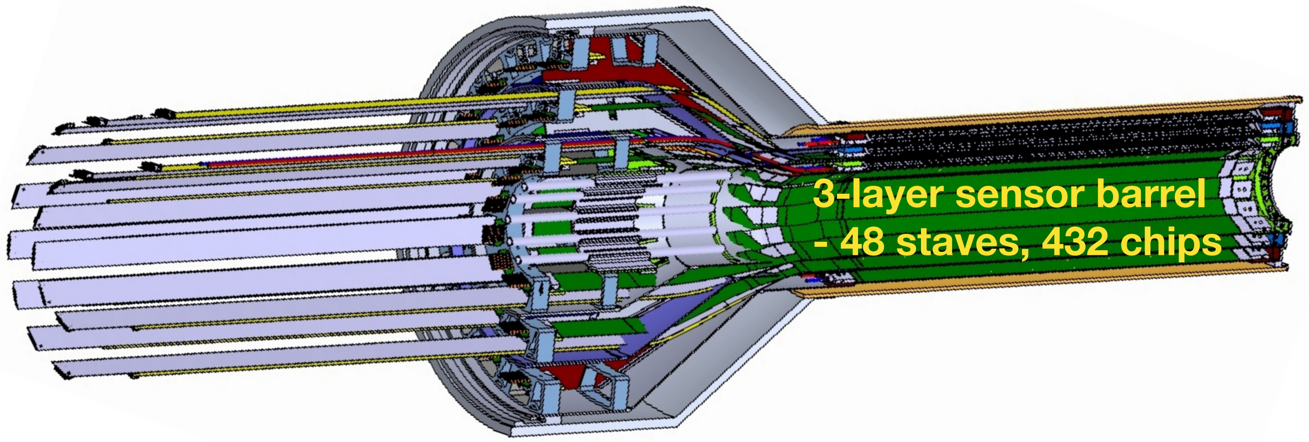
- Next generation RHIC detector, Approved of construction
- Foundation for an EIC detector concept [arXiv:1402.1209, sPH-cQCD-2018-001]

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

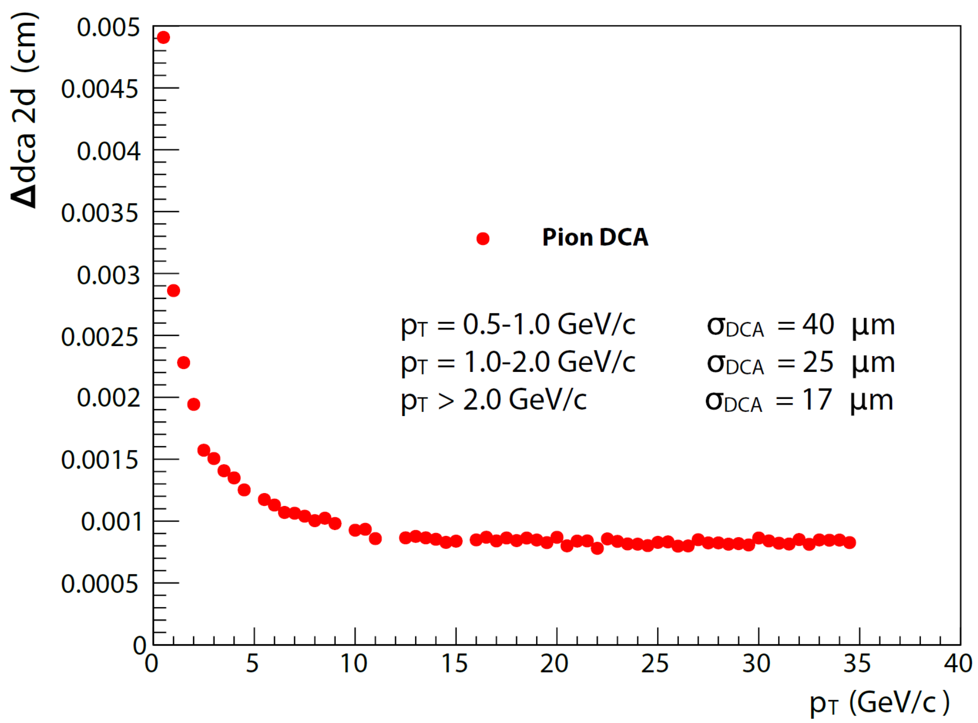
- GEANT4 Simulation framework, well developed.
- Analyses including vertexing and tracking have been implemented in heavy flavor studies.

Vertex Detector: MAPS-based silicon

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



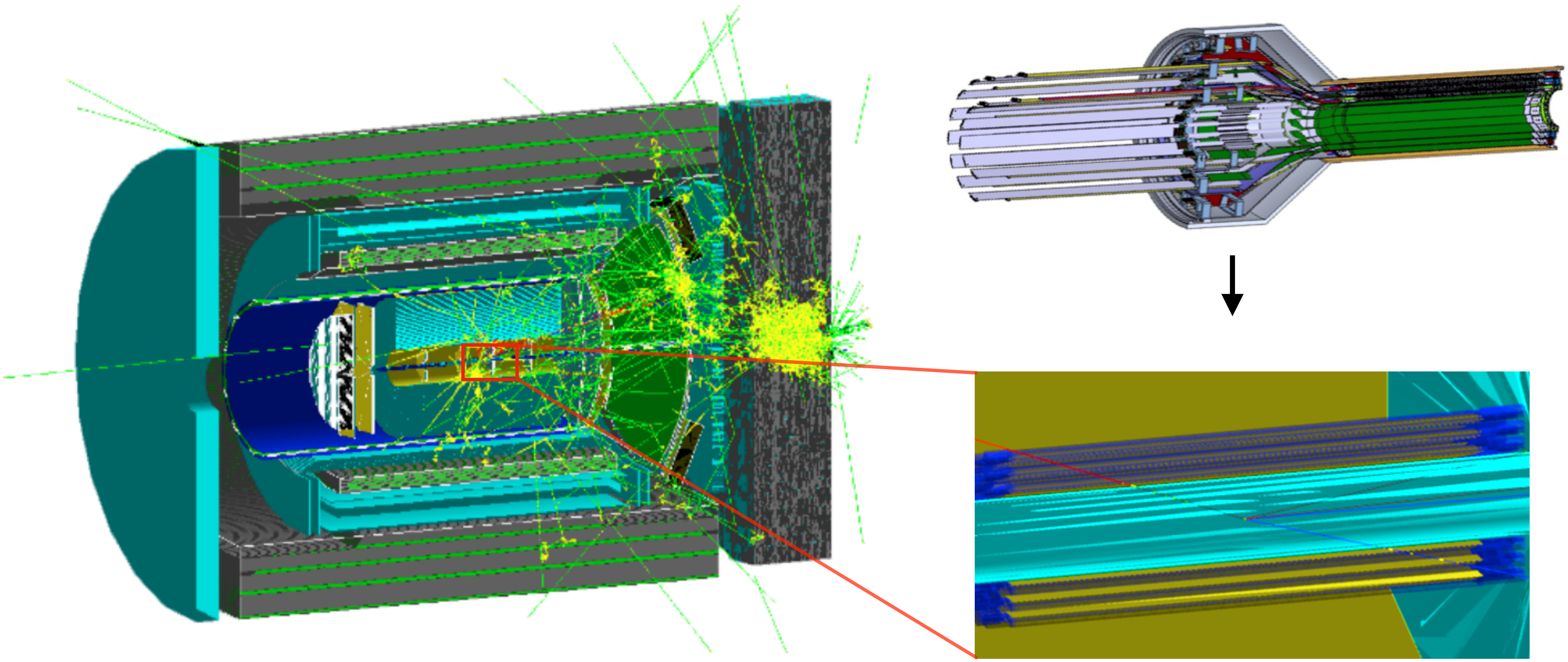
Service cone: signal, power, cooling and mechanical support



- 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. Note: EIC R likely ~3cm

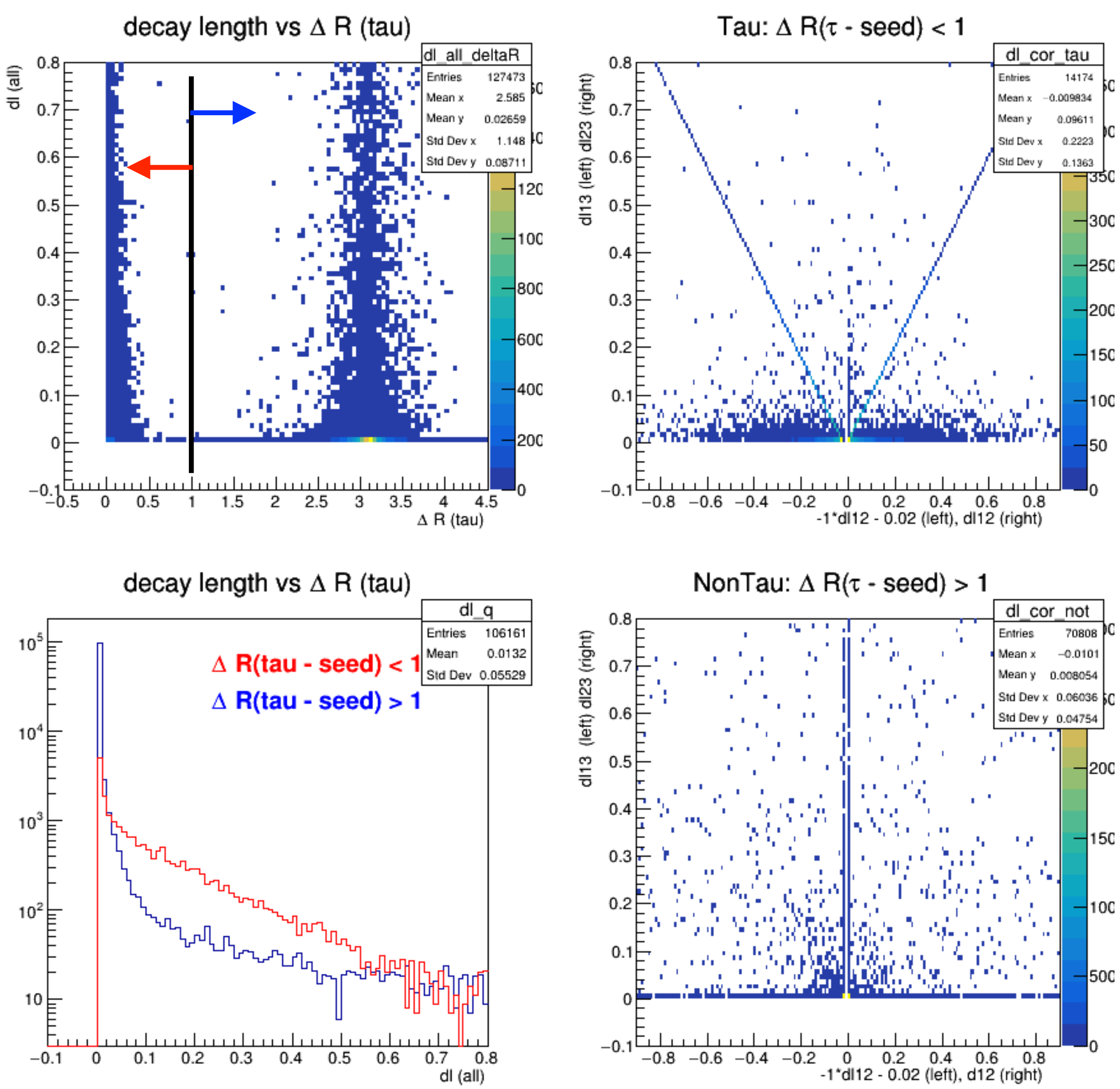
state-of-the-art vertex detector

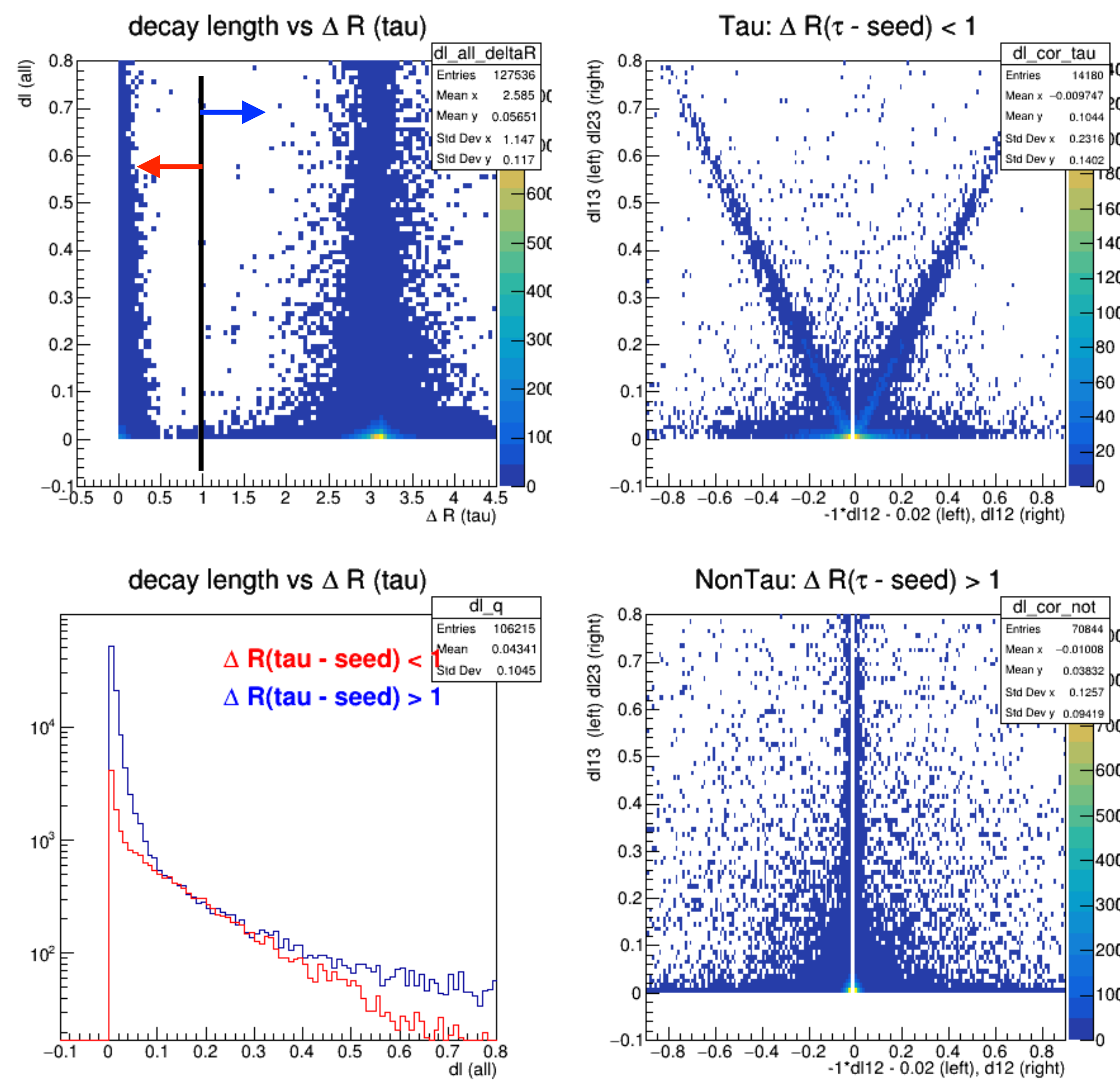
LQ event at sPhenix-EIC detector



- LQGENEP 1.0 Leptoquark event e+p 20x250 GeV/c + sPHENIX-EIC sim
- For initial τ-reco evaluation: sPHENIX vertex tracker

Reconstruction

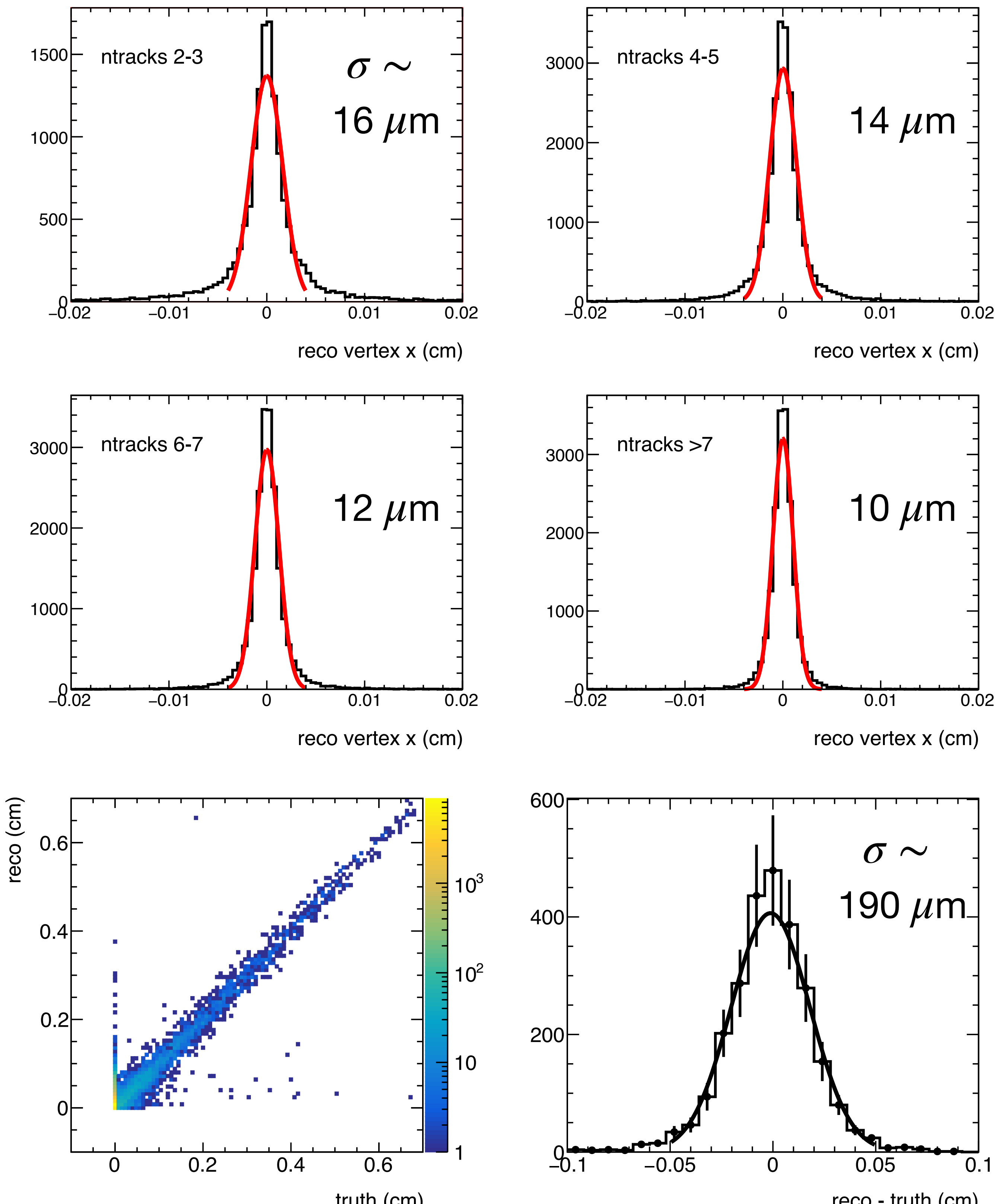




Generator

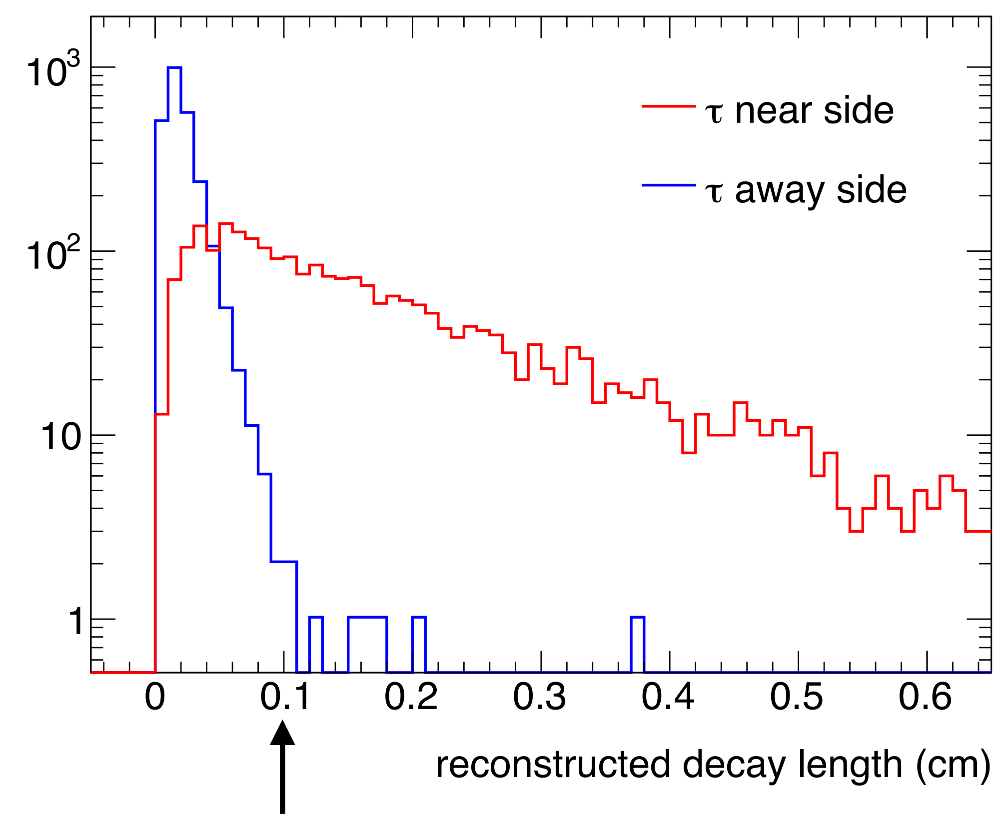
Full detector simulation

Effect of resolution

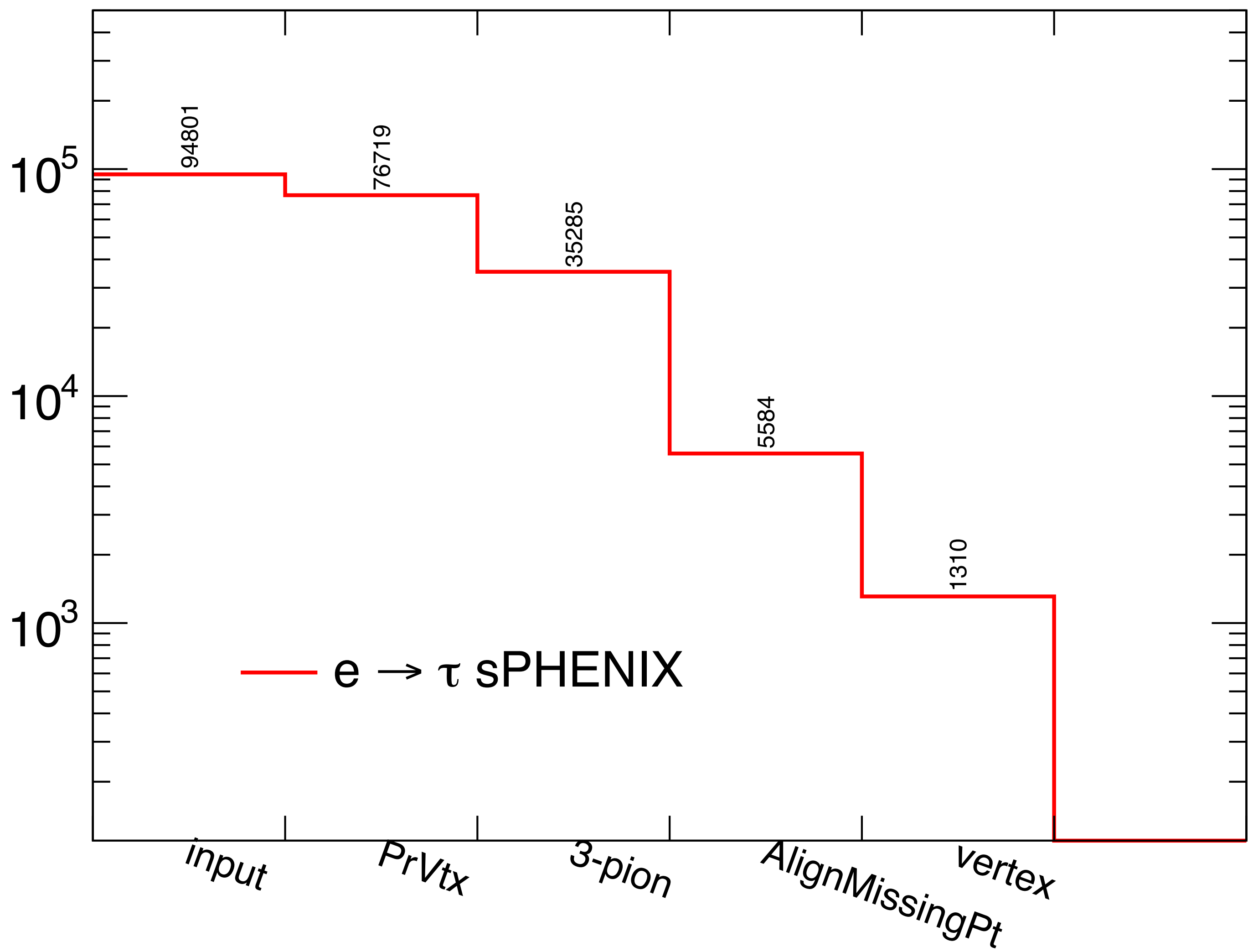


- Vertex resolution at x component **~10** μm
- Similar for y and z components at middle rapidity
- Decay length resolution ~ 190 μm

- 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

Next step

- Move to EIC configuration for the full detecter simulation
- Completing 3-prong decays
  - Optimize selection cuts; apply Multi-Variable Analysis (MVA)
  - Investigate lower Q2 (10-100 GeV2) data
  - Make the sensitivity projection
- Explore the 1-prong decays
  - Devise independent cuts for single muon and single pion modes
  - Vertex detector

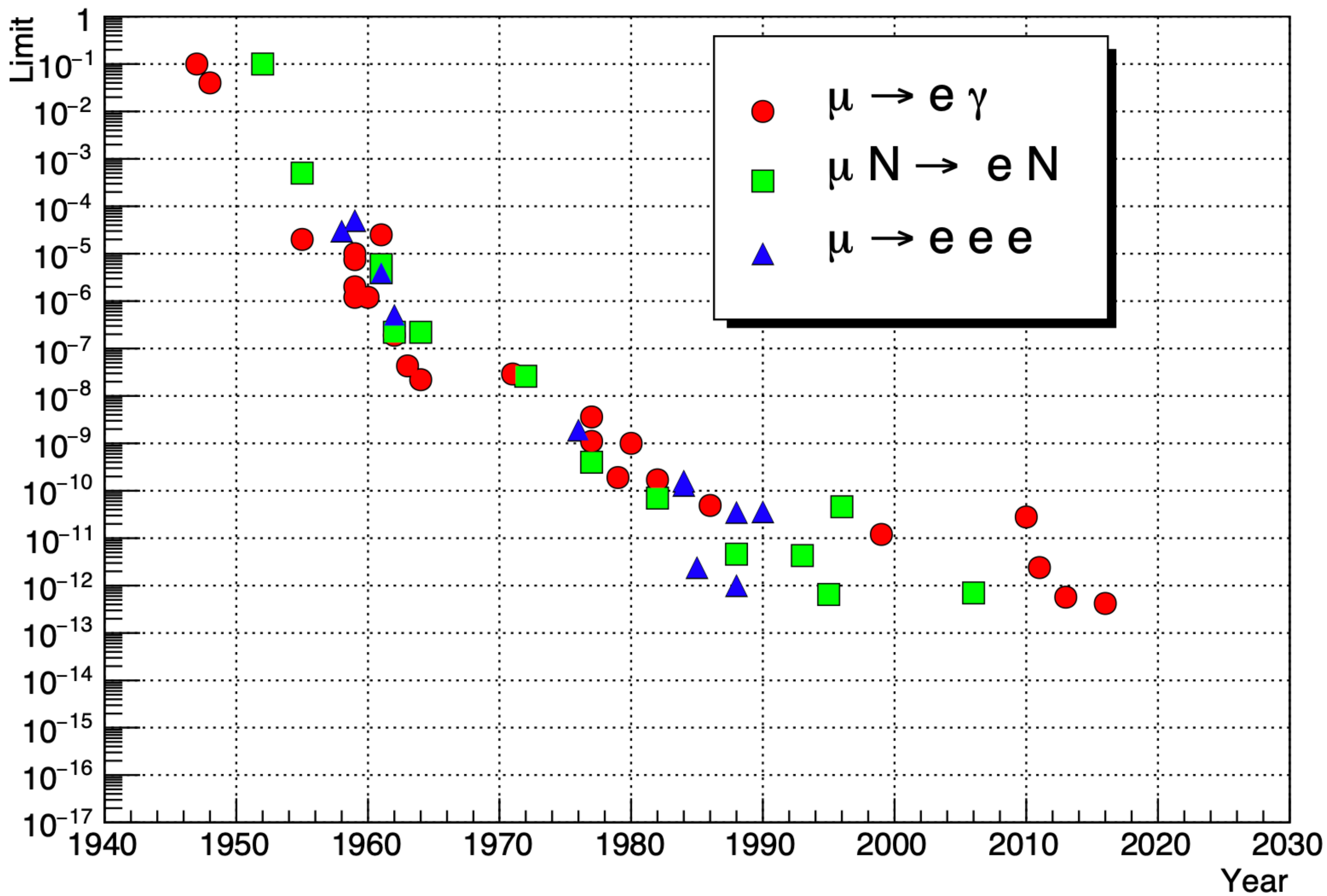
Summary

- 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
- Starting an effort re-examining the potential of CLFV search with decay topological using modern precision vertex tracker and event shape analysis
  - Aiming for 0.1 fb cross-section sensitivity
  - Synergies with other high luminosity topics e.g. heavy flavors
- LQGENEP generator + Full detector simulations and reconstruction via sPHENIX- EIC concept

This is only the beginning; significant remains to be done.

Backup

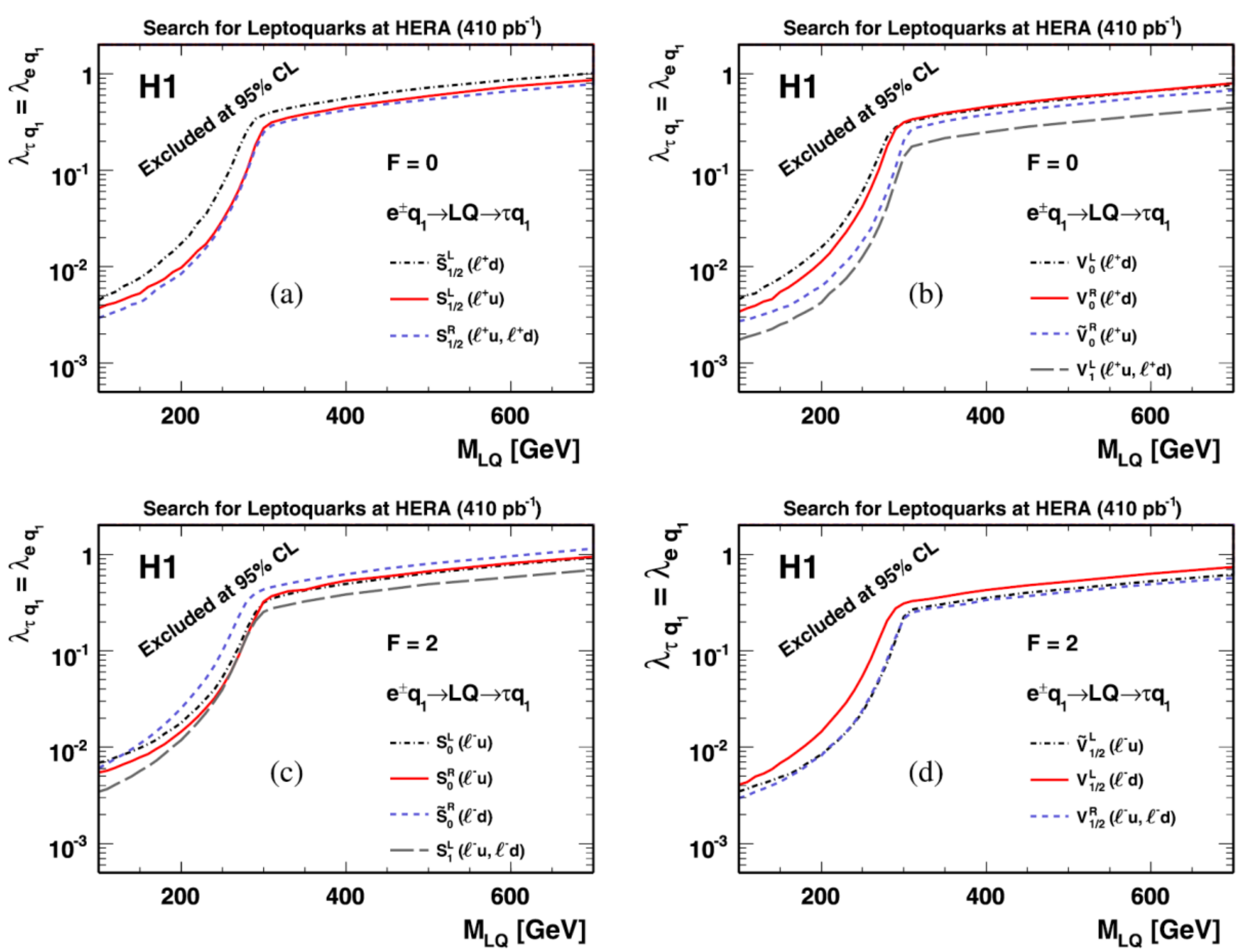
Experimental Searches of LFV(1,2)



- 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)

HERA

H1, PLB 701, 20-30 (2011)



ZEUS, PRD 99, 092006 (2019)