Charged Lepton Flavor Violation Study at EIC

Jinlong Zhang (SBU/CFNS)

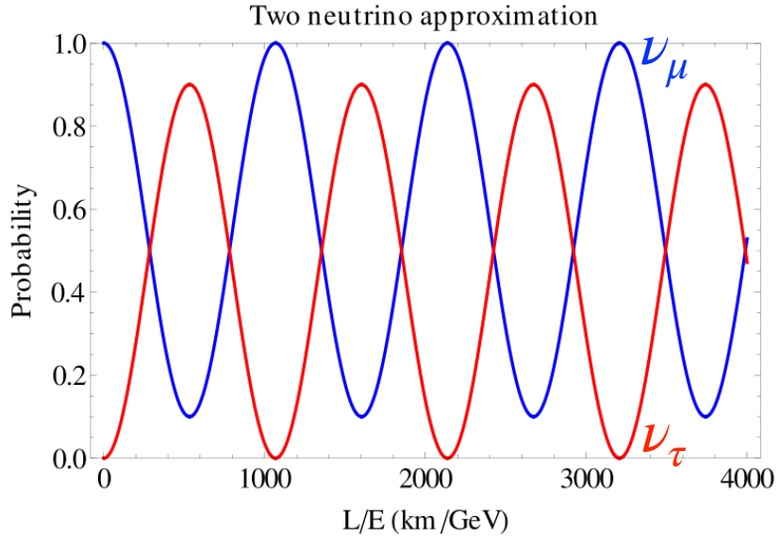
Based on work with Abhay Deshpande (SBU/BNL/CFNS), Jin Huang (BNL), Krishna Kumar (UMass, Amherst), Yuxiang Zhao (IMP,CAS)

EW/BSM Physics at the EIC
May 6-7, 2020

Charged Lepton Flavor Violation

- Lepton Flavor (generation) is not conserved, neutrino oscillations observed. (2015 Nobel Prize)

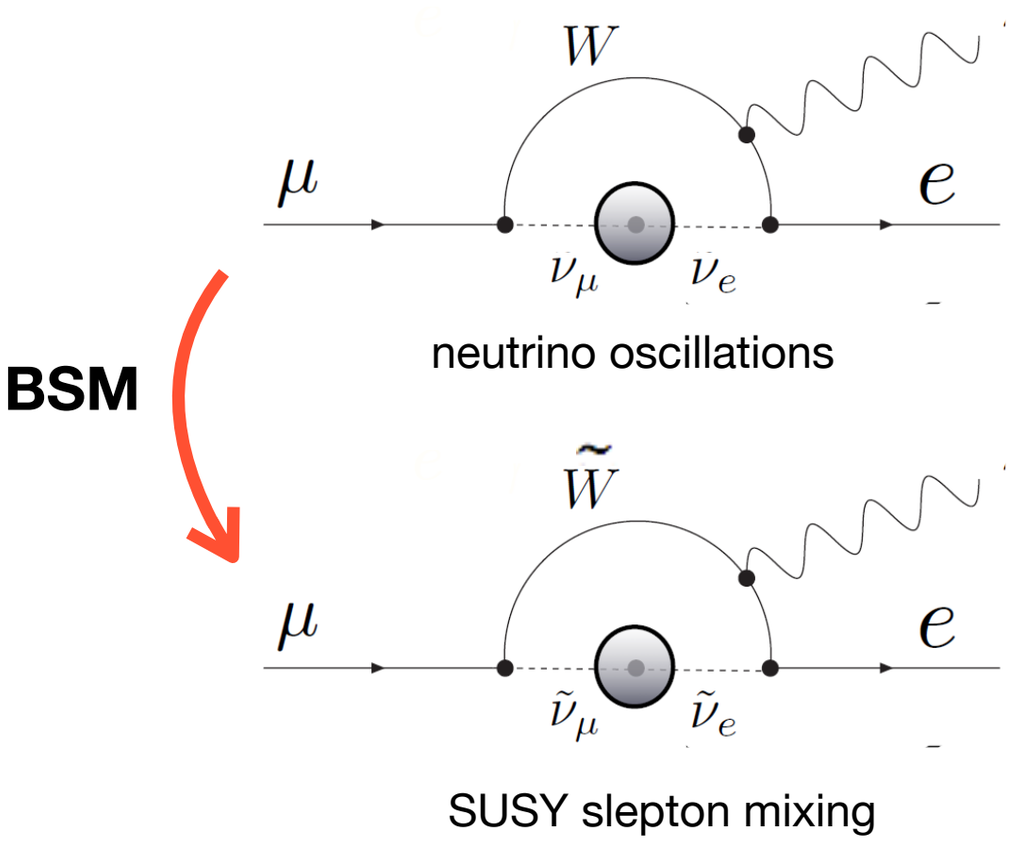
- Charged lepton flavor violations (CFLV) should also be allowed within the SM; but extremely low rate, e.g. BR($\mu \rightarrow e\gamma$) < 10^{-54}



- Many BSM models predict significantly higher rate of CFLV, e.g. SUSY slepton mixing BR($\mu \rightarrow e\gamma$) < 10^{-15}

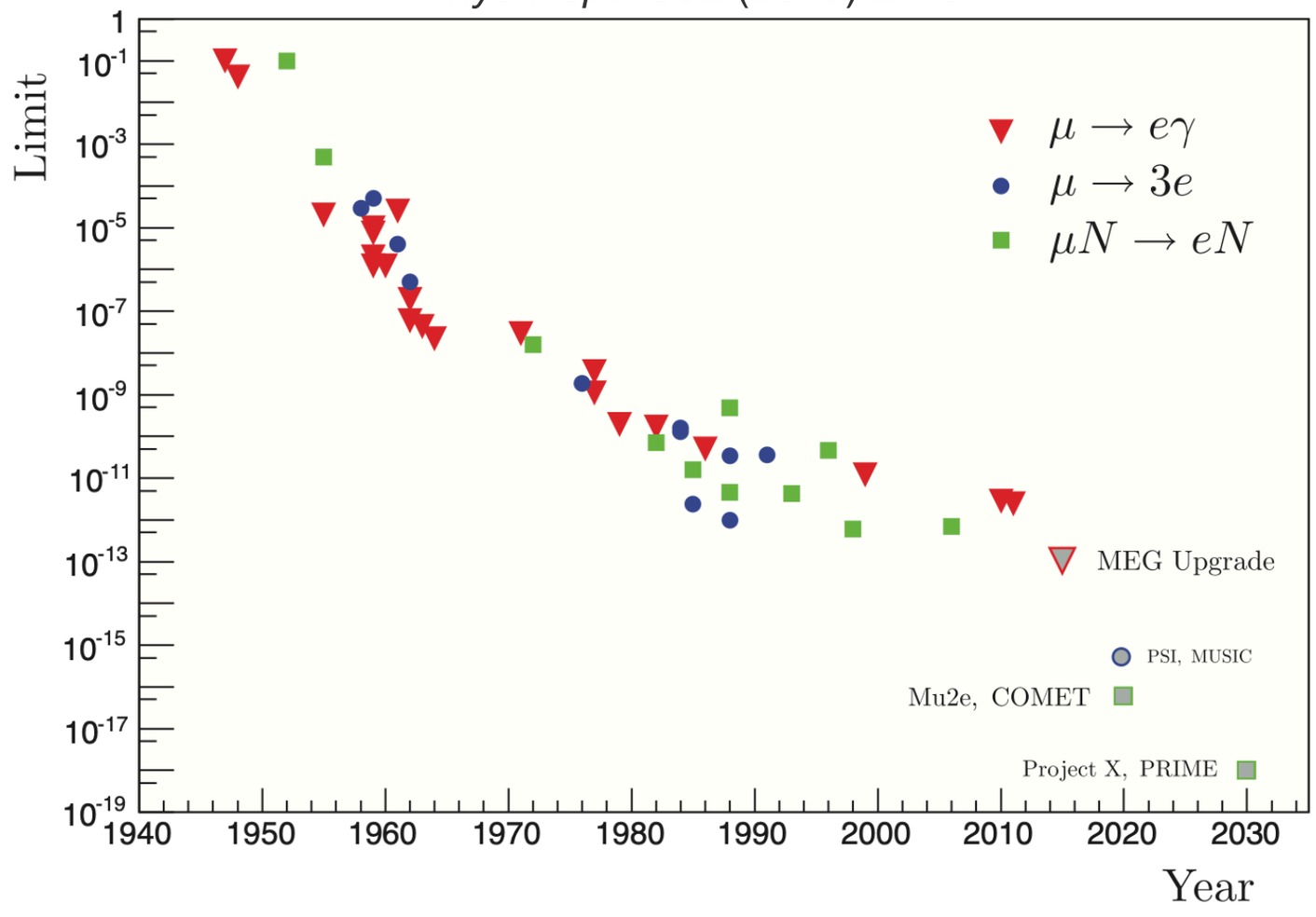
See Sonny Mantry's talk

(Thanks Sonny)



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

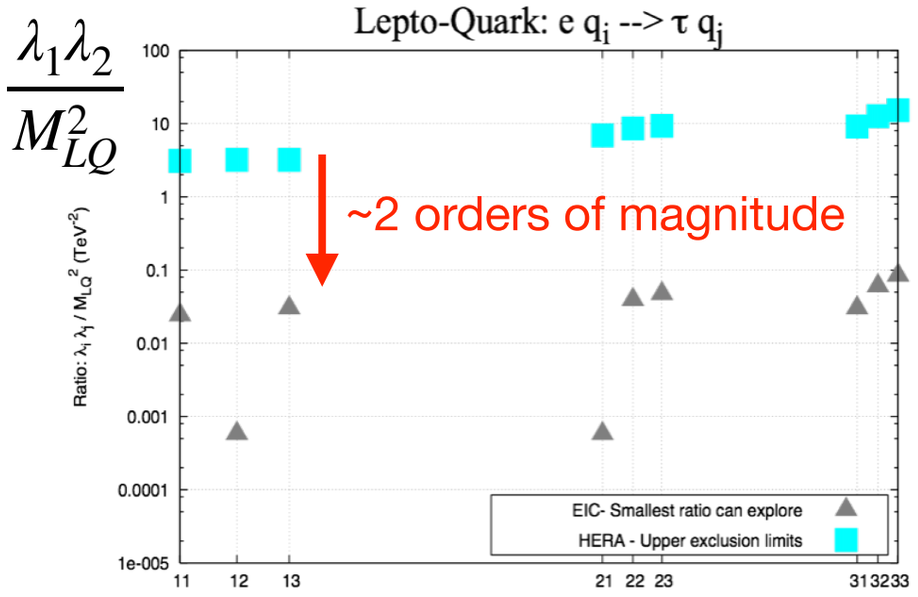
Various models predict enhanced sensitivity for LFV(1,3) while suppressing LFV(1,2)

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

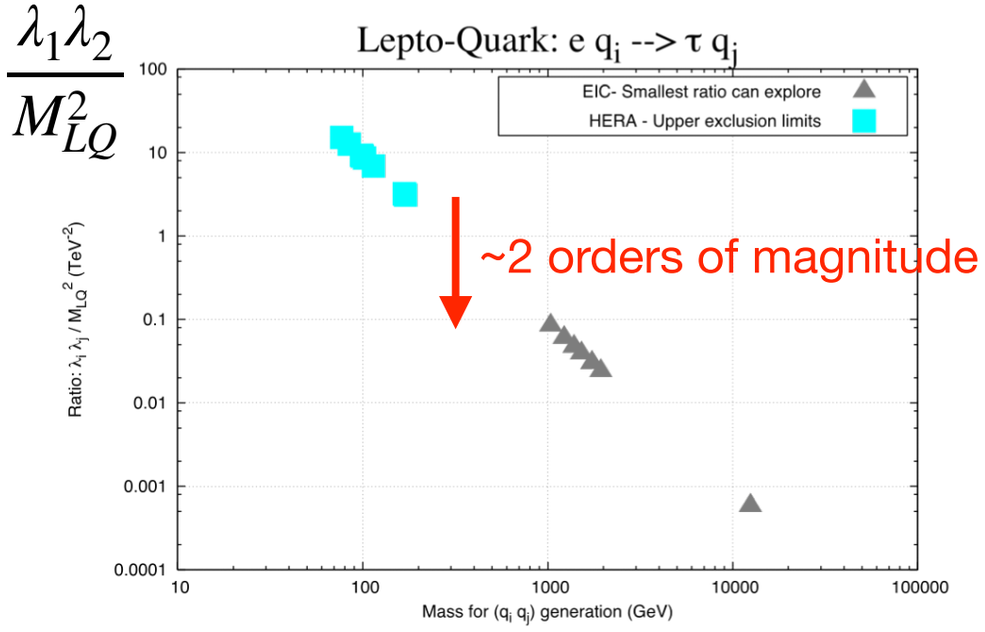
- HERA set limits in coupling-mass space (See *Elisabetta Gallo*'s talk)

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

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



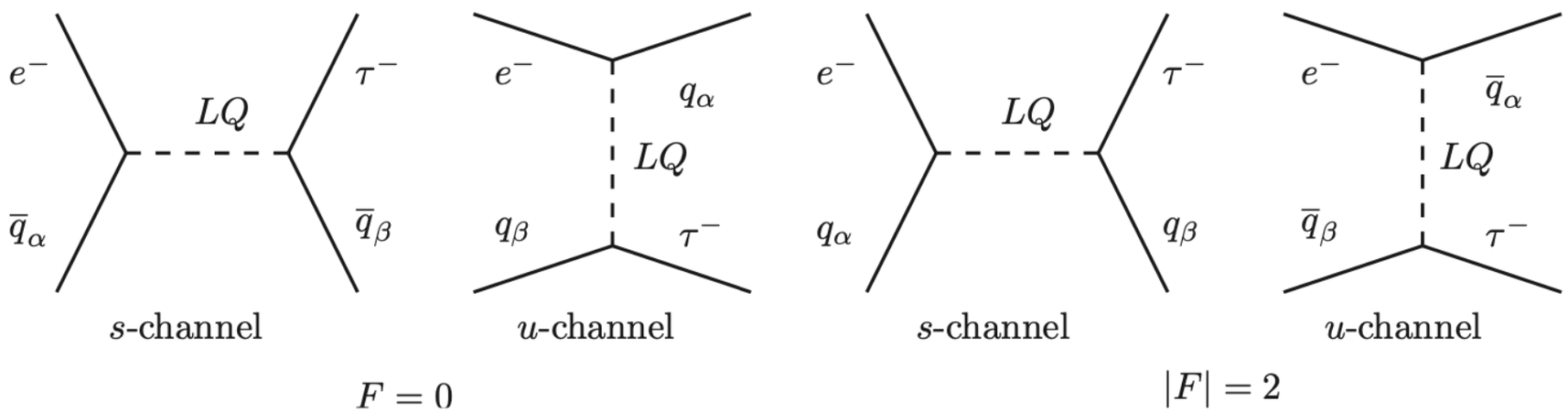
Assume 0.1 fb cross-section sensitivity



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 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

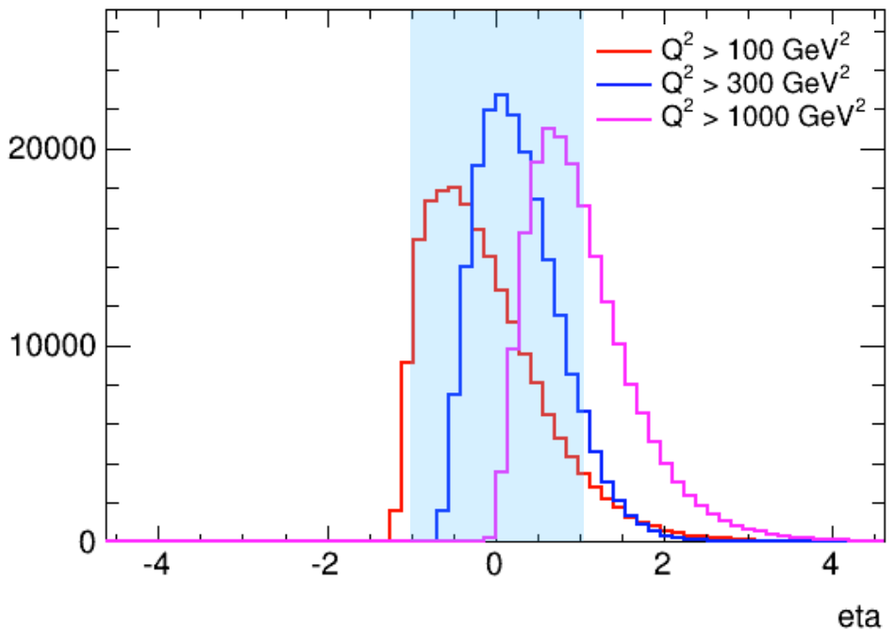
- **3-prong** **15.21 (0.06)%**
  - $\pi^-\pi^+\pi^-\nu_\tau$ 9.31 (0.05)%
  - $\pi^-\pi^+\pi^-\pi^0\nu_\tau$ 4.62 (0.05)%
  - others (kaon, etc) 1.28%
- **1-prong** **84.58 (0.06)%**
  - $\mu^-\bar{\nu}_\mu\nu_\tau$ 17.39 (0.04)%
  - $e^-\bar{\nu}_e\nu_\tau$ 17.82 (0.04)%
  - $\pi^-\nu_\tau$ 10.82 (0.05)%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

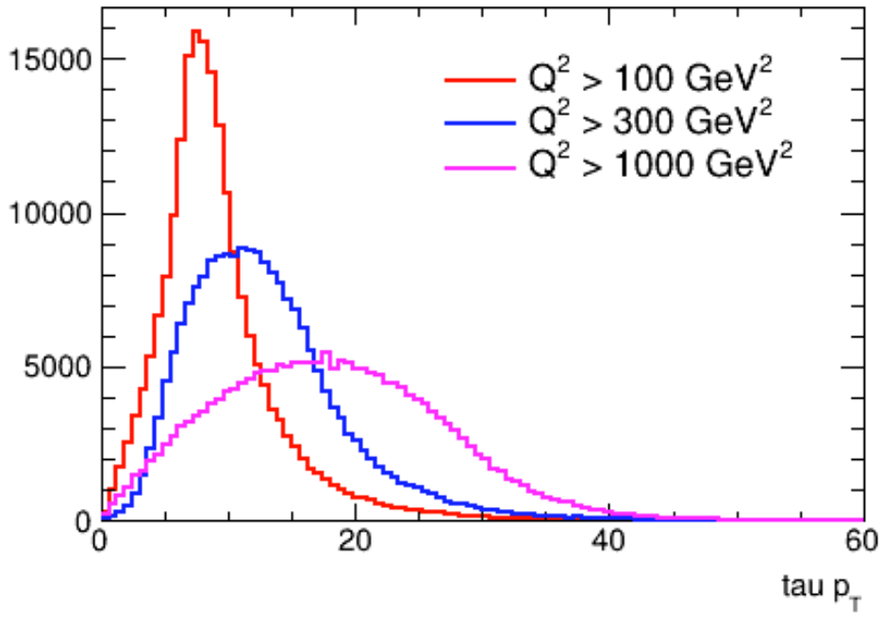
At EIC, benefit from improved vertex and jet detection, aim to greater than 10% efficiency with negligible background in a 100 fb^{-1} data sample

How LQ Tau looks like in ep

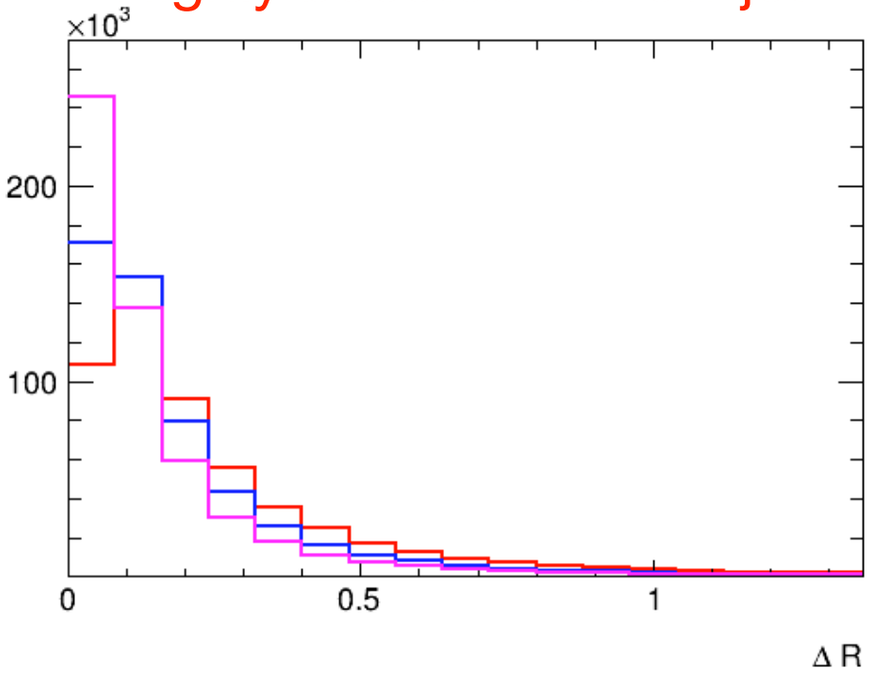
Mostly at Barrel (best detector performance)



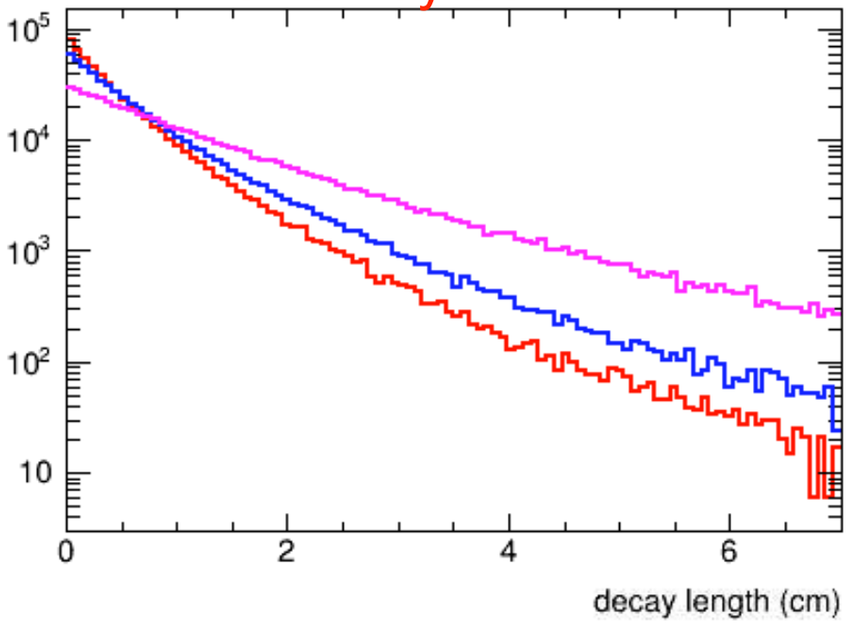
high pT



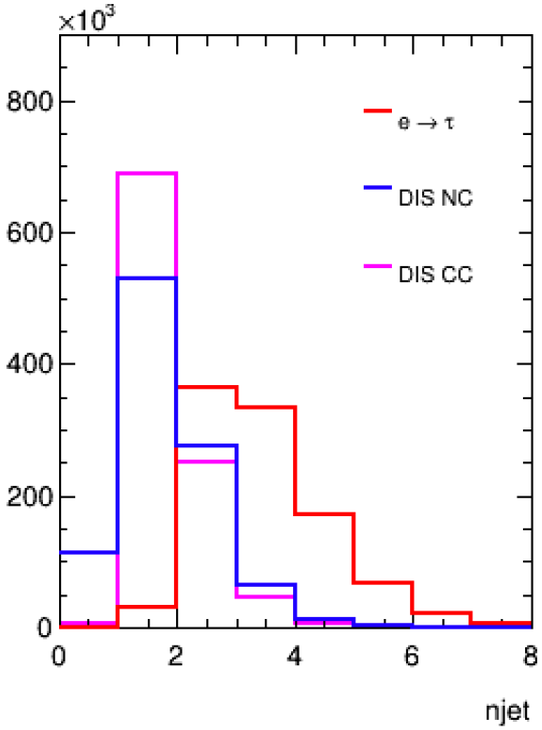
Highly boosted narrow jet

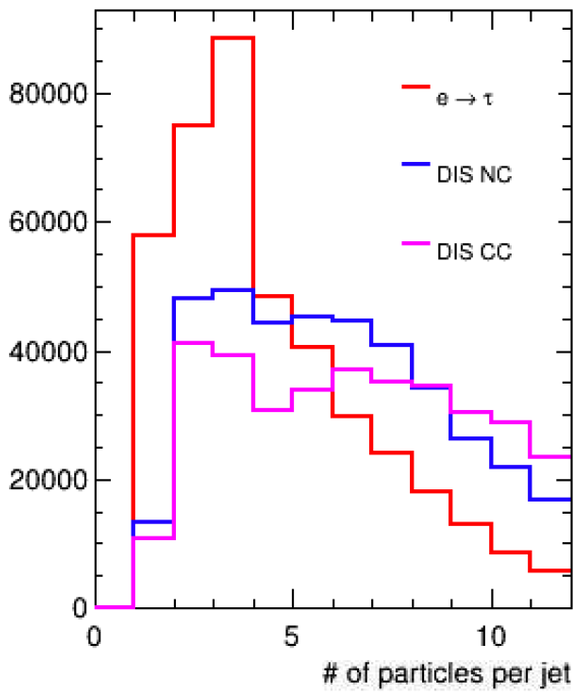


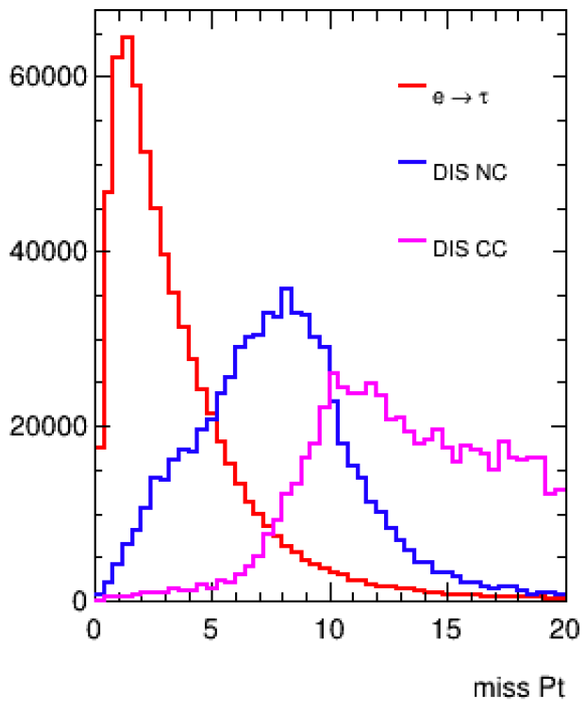
Away from primary vertex by serval cm



Features of LQ $e \rightarrow \tau$ event





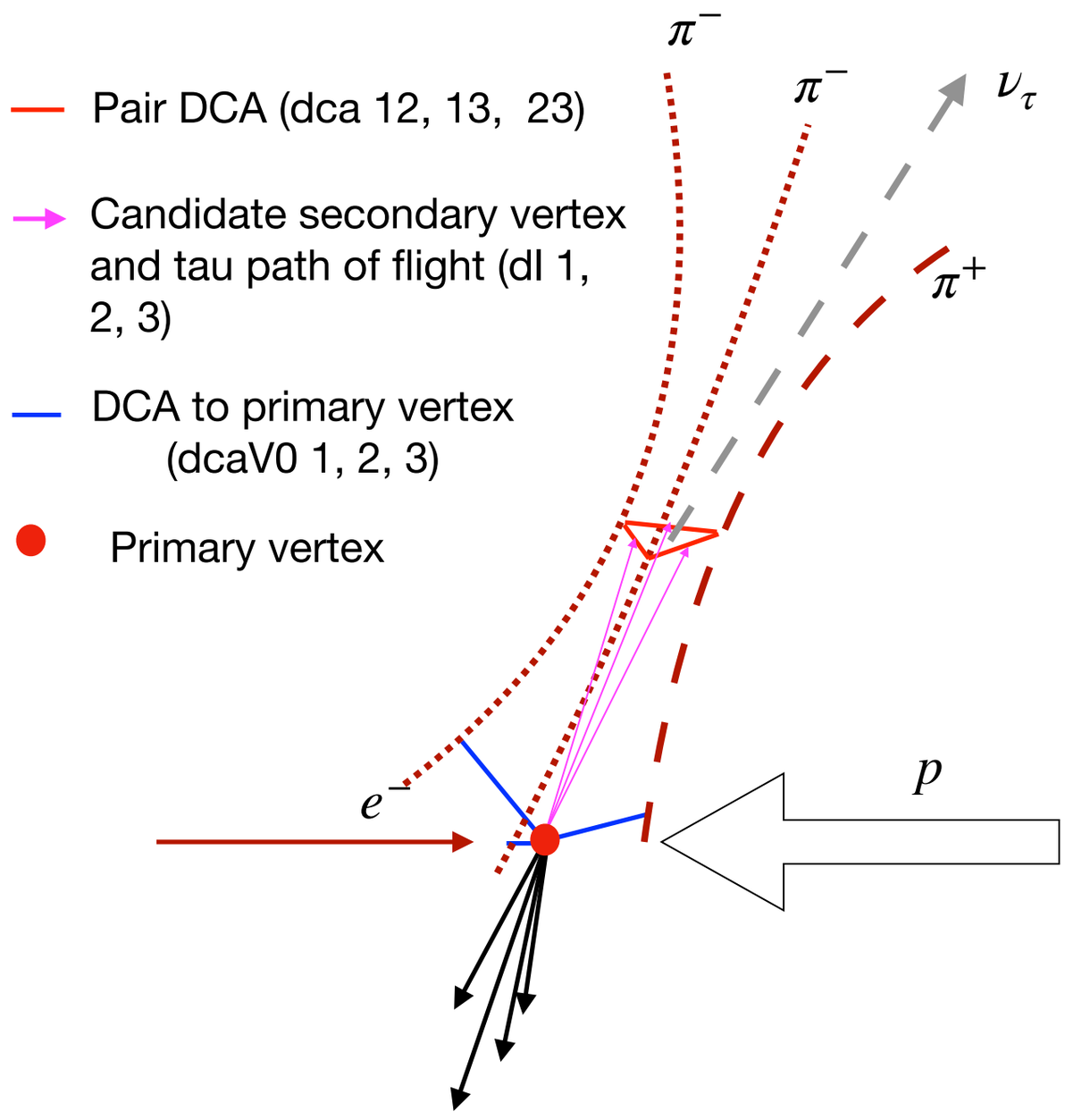


Note: electron in DIS NC is masked; Fastjet, Anti-k_T, R = 1.0; jet pt > 2 GeV; Q^2>100 GeV^2

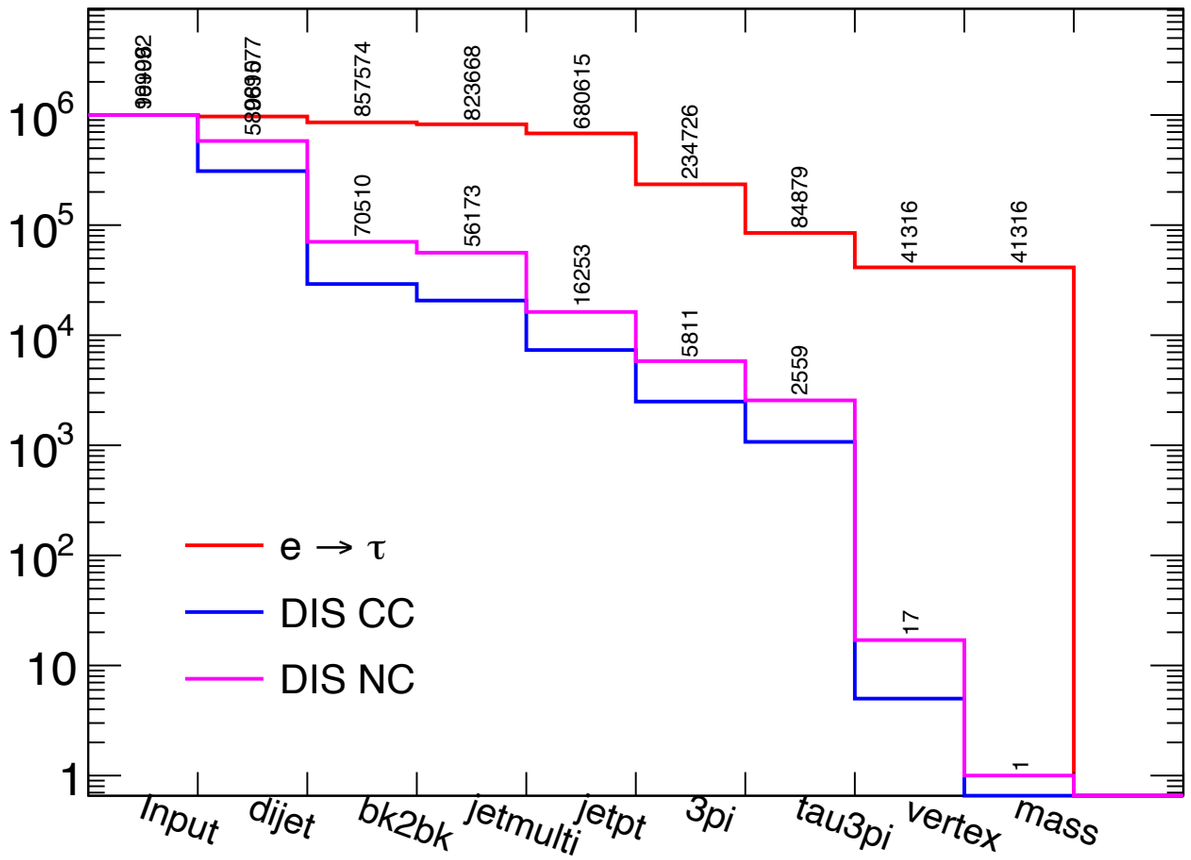
- $e \rightarrow \tau$ event
  - 2+ jets
  - Low particle multiplicity
  - Modest missing pT (partial of tau pT)
- DIS event
  - 1 jets dominating
  - Higher particle multiplicity
  - Missing pT ~ lepton pT

Search strategy for 3-prong decays

- Event generators:
  - LQGENEP 1.0 for Leptoquark events (L. Bellagamba, 2001)
  - DJANGOH 4.6.8 for DIS (NC + CC) events (H. Spiesberger 2005)
- 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:

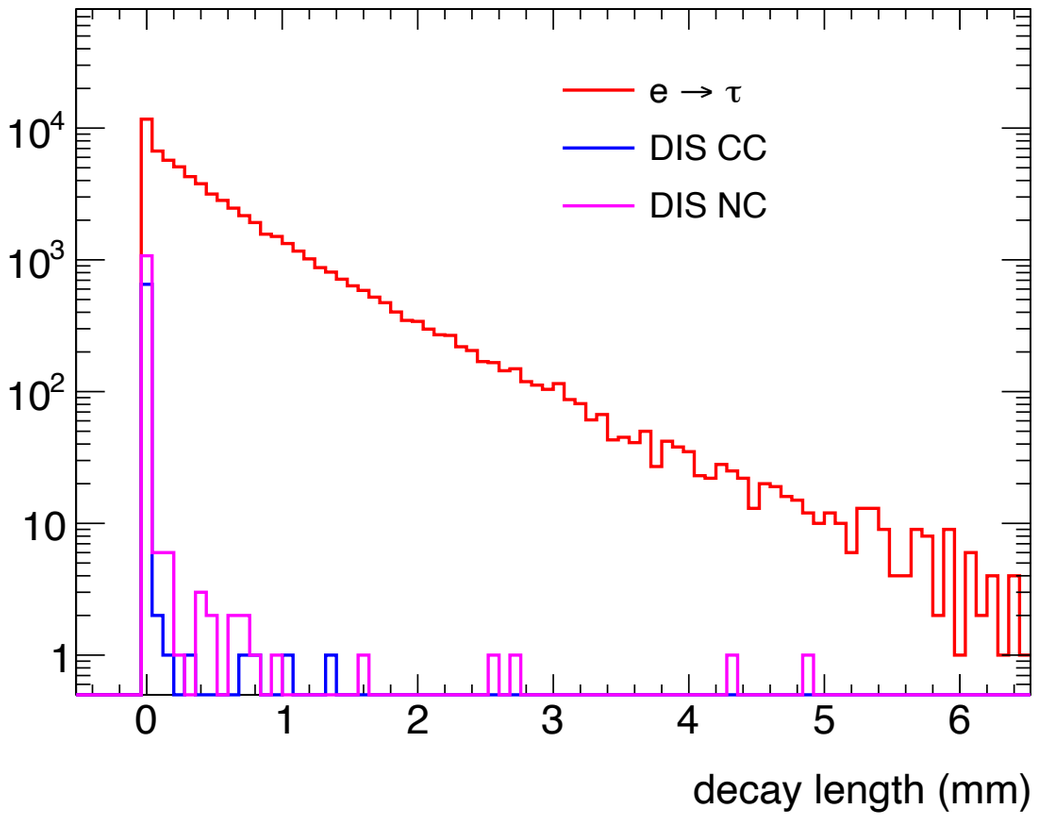
  $$dl\_asy = |dl_1 - dl_2| + |dl_1 - dl_3| + |dl_2 - dl_3|$$

- 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

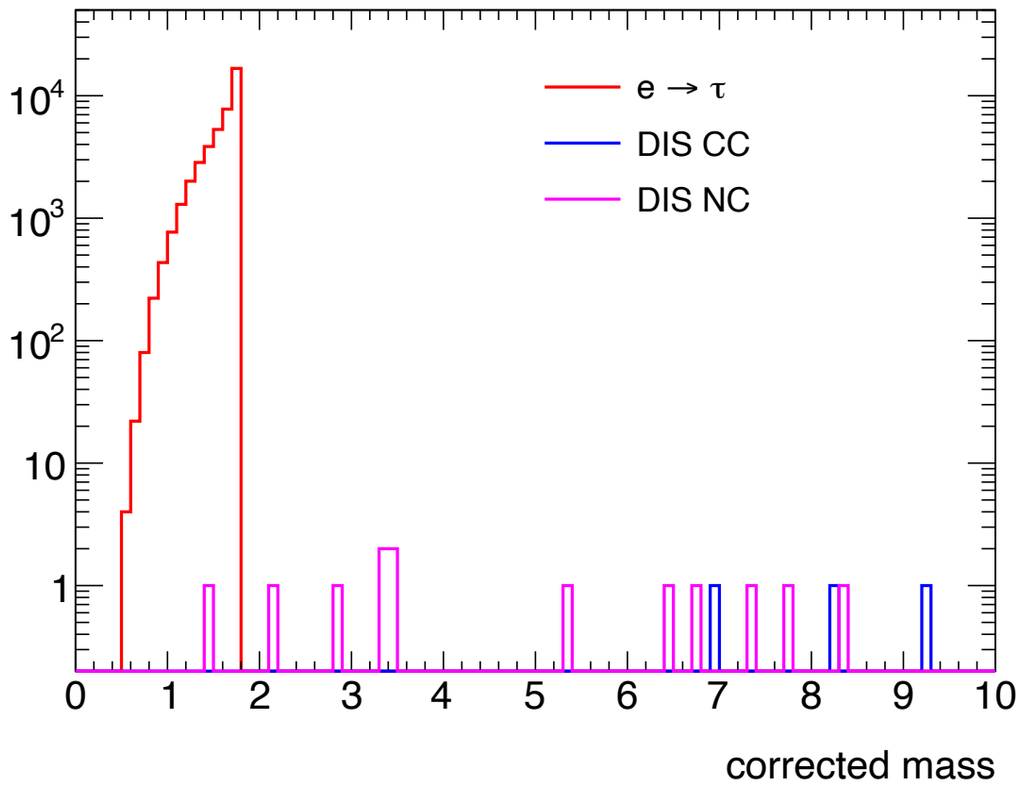


- Secondary vertex and corresponding decay length reconstructed from paired pion tracks

- Corrected mass from 3 pions

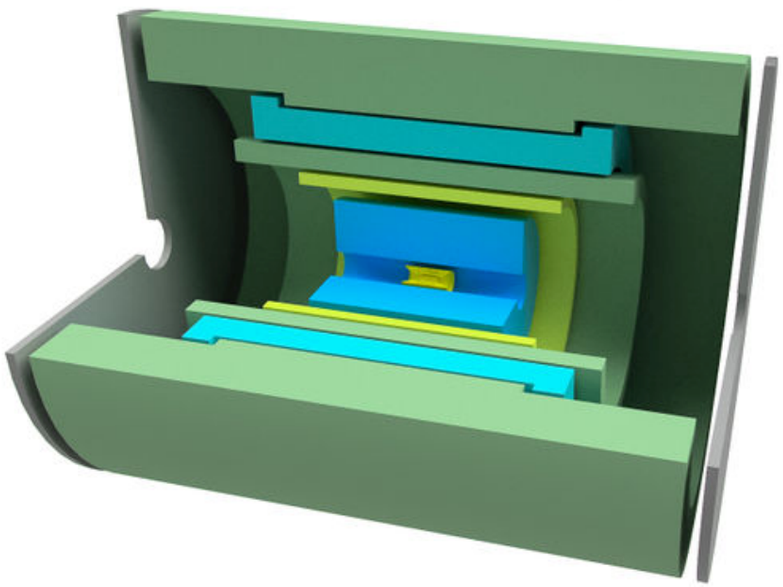
$$\sqrt{M_{3\pi}^2 + p_{3\pi}^2 sin^2\theta} + p_{3\pi} sin\theta$$

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



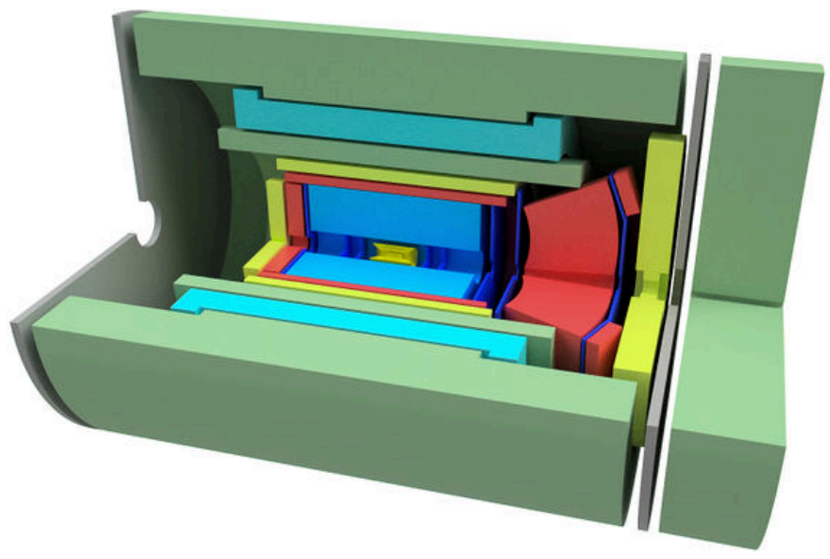
Detector Simulation: sPhenix and further

sPHENIX



$-1.1 < \eta < 1.1$

sPHENIX-EIC (ePHENIX)



$-4.0 < \eta < 4.0$

sPHENIX:

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

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

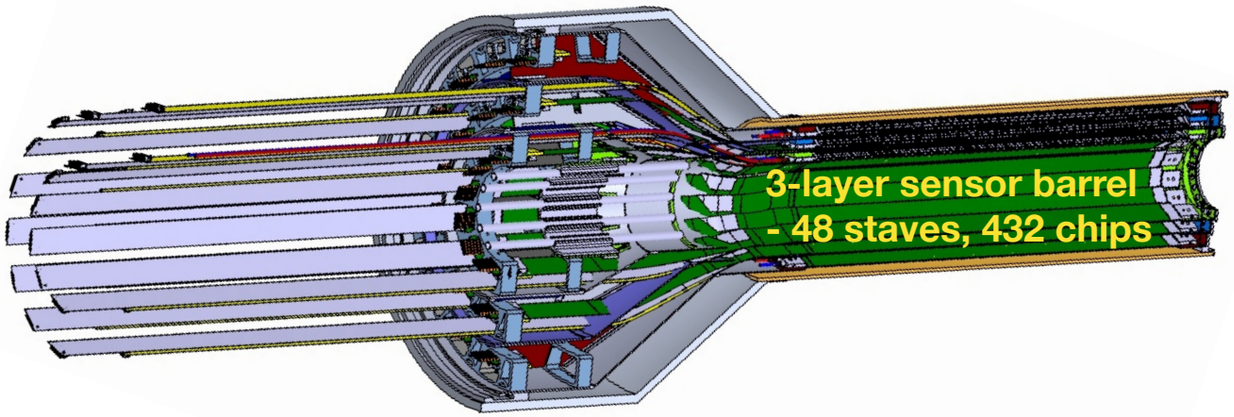
- GEANT4 Simulation framework, well developed.
- Analyses including vertexing and tracking have been implemented in heavy flavor studies.

Vertex Detector: MAPS-based silicon

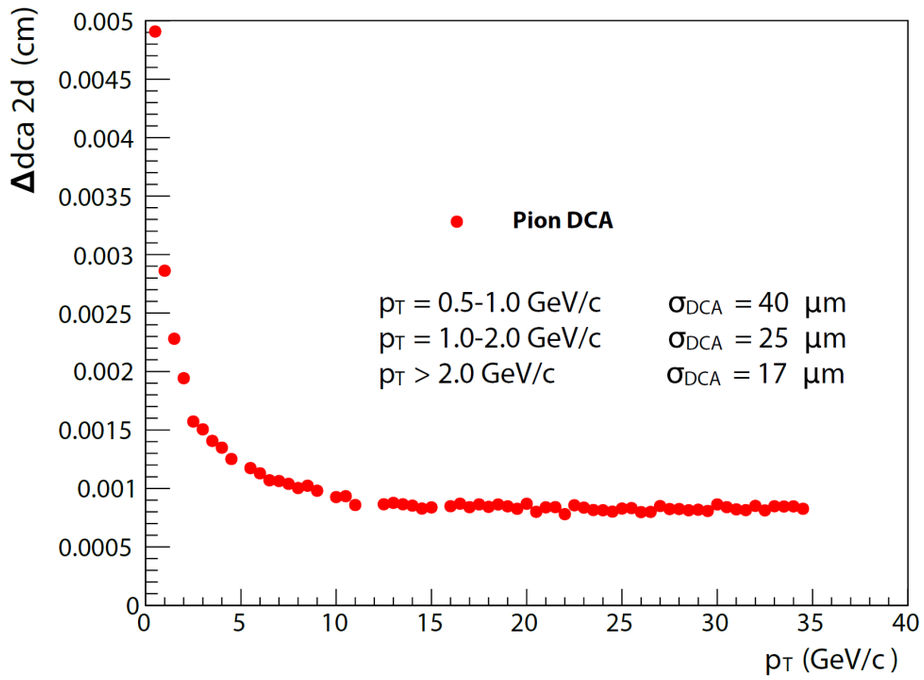
- For initial τ-reco evaluation: sPHENIX vertex tracker
  - 30 μm ALICE Pixel MAPS pixel in three layers, total 200 M pixel channels
  - 5 μm hit position resolution
  - 0.3% X_0 thickness per layer
  - R ~2cm. Note: EIC R ~ 3cm

state-of-the-art vertex detector

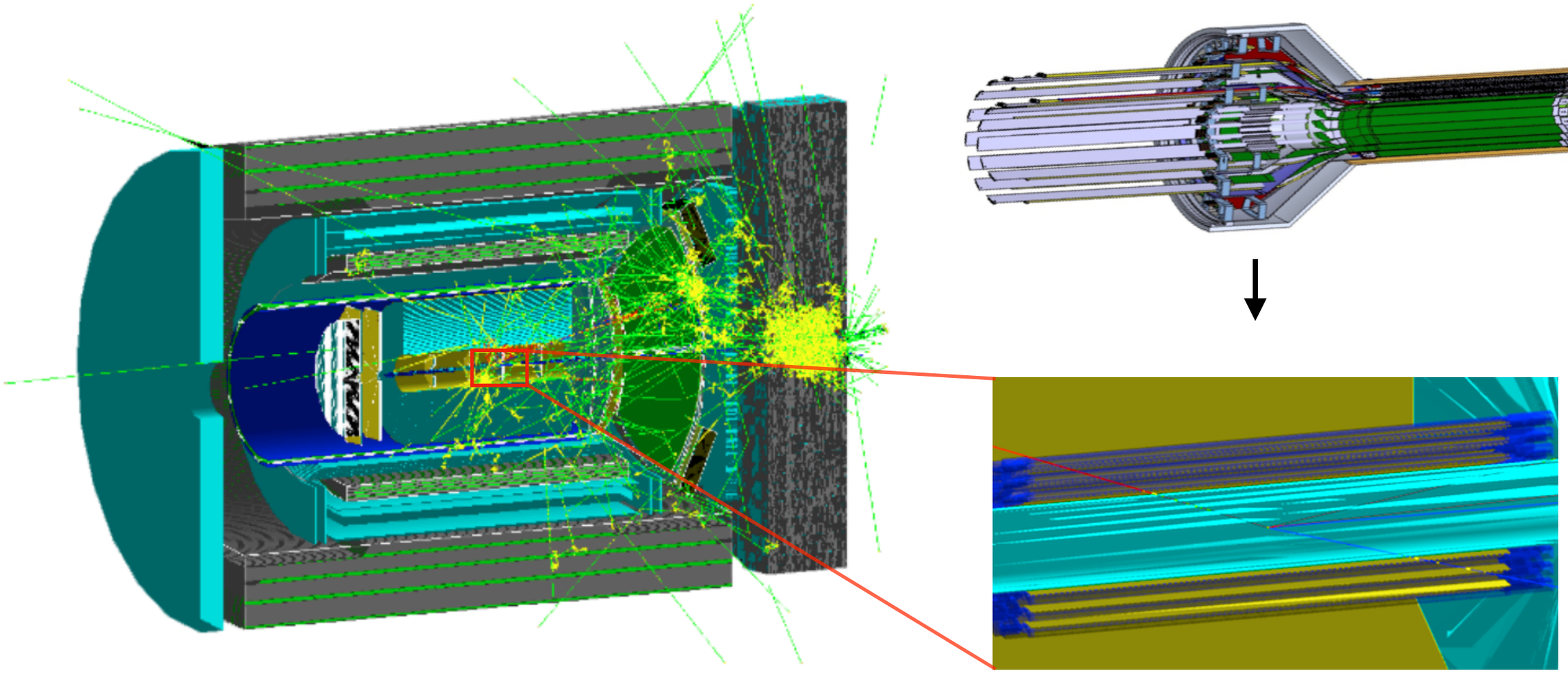
MVTX — Monolithic-Active-Pixel-Sensor-based Vertex Detector



Service cone: signal, power, cooling and mechanical support



LQ event at sPhenix-EIC detector

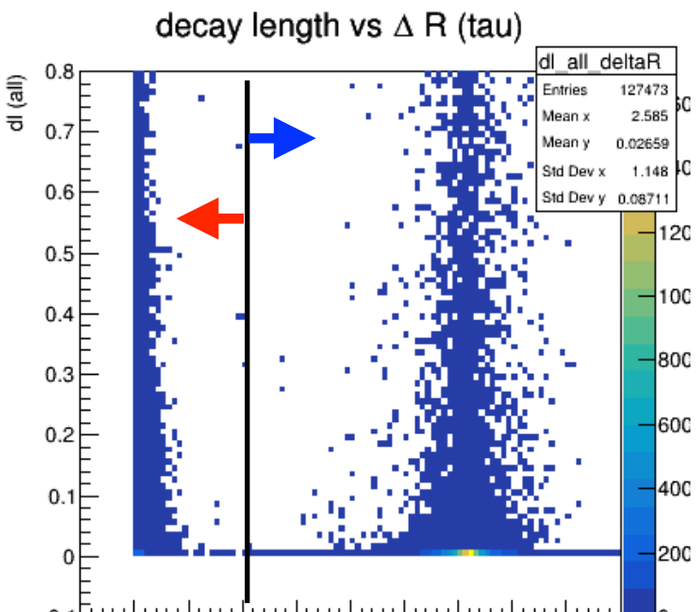


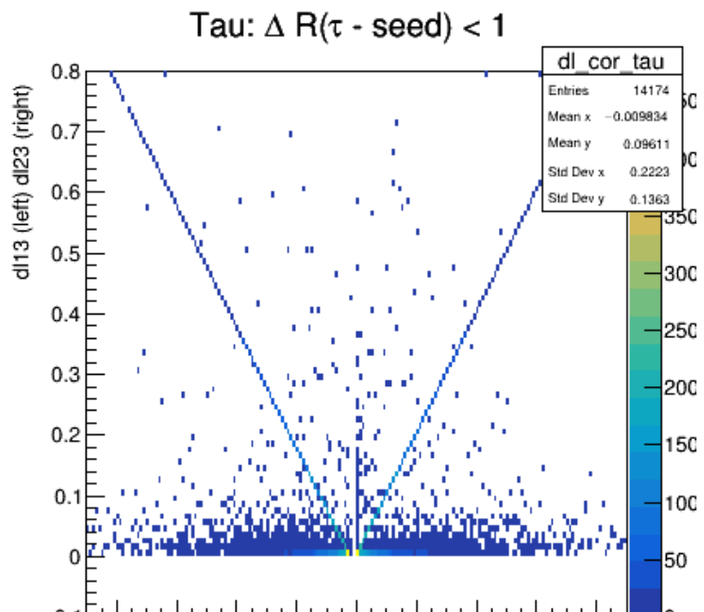
- LQGENEP 1.0 Leptoquark event e+p 18x275 GeV/c + sPHENIX-EIC sim
- For initial τ-reco evaluation: sPHENIX vertex tracker

Simplified secondary vertex reconstruction

Generator level

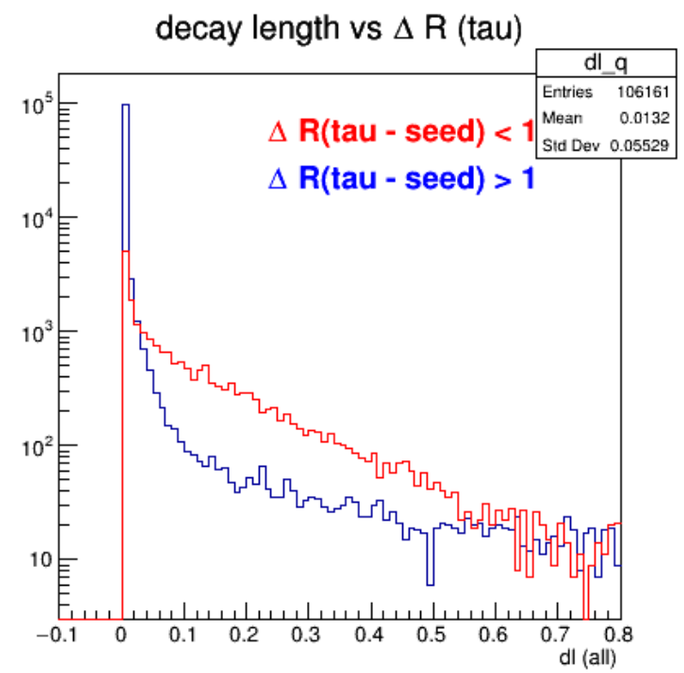
Tag 3-prong candidate with truth tau direction

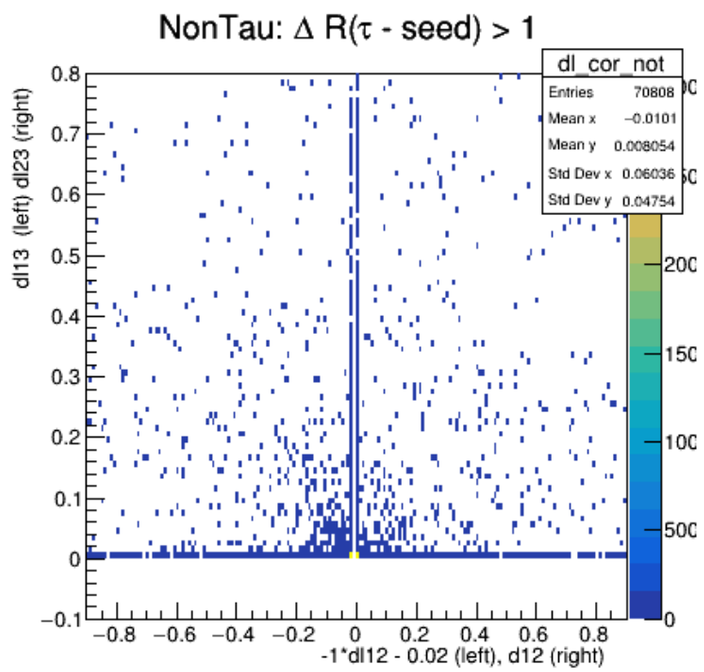




Tau side:
Clear correlations between 3 reconstructed decay length

Significantly long reconstructed decay length at Tau side



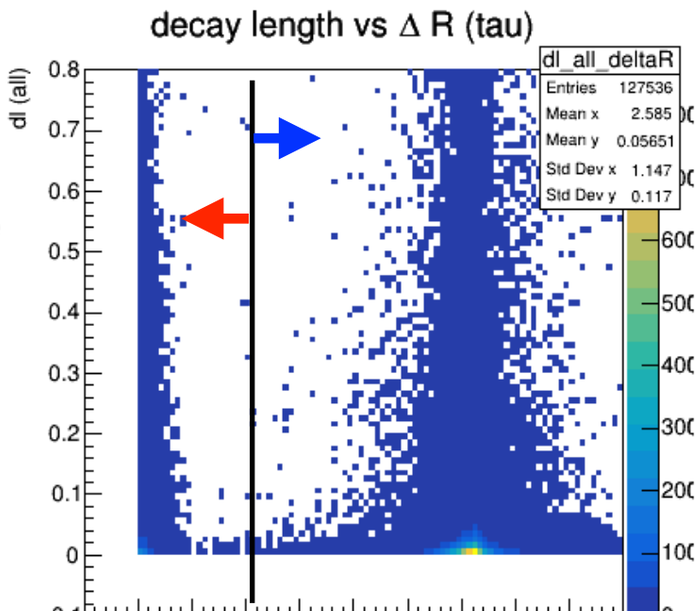


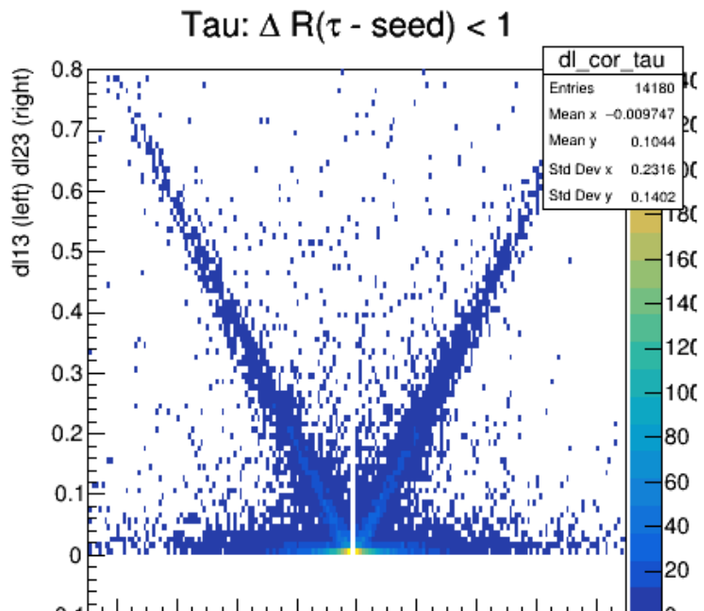
Away side:
No correlations between 3 pair combination

Simplified secondary vertex reconstruction

Full Geant4 of sPHENIX

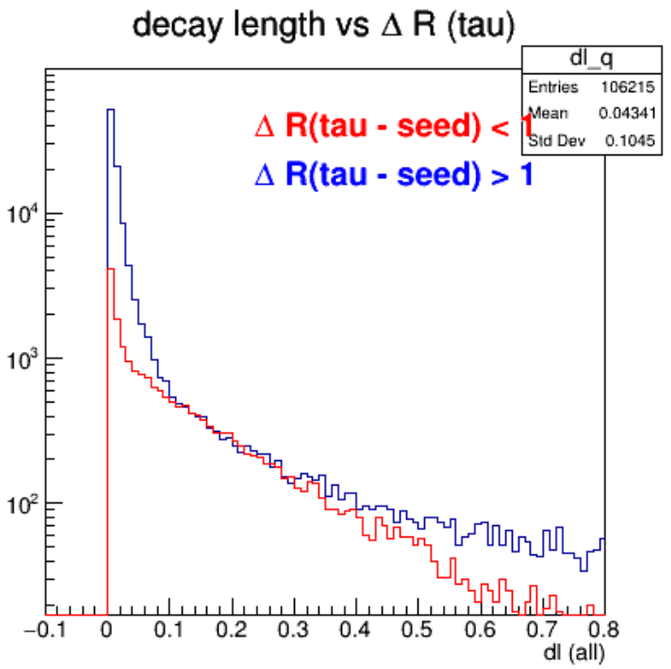
Tag 3-prong candidate with truth tau direction

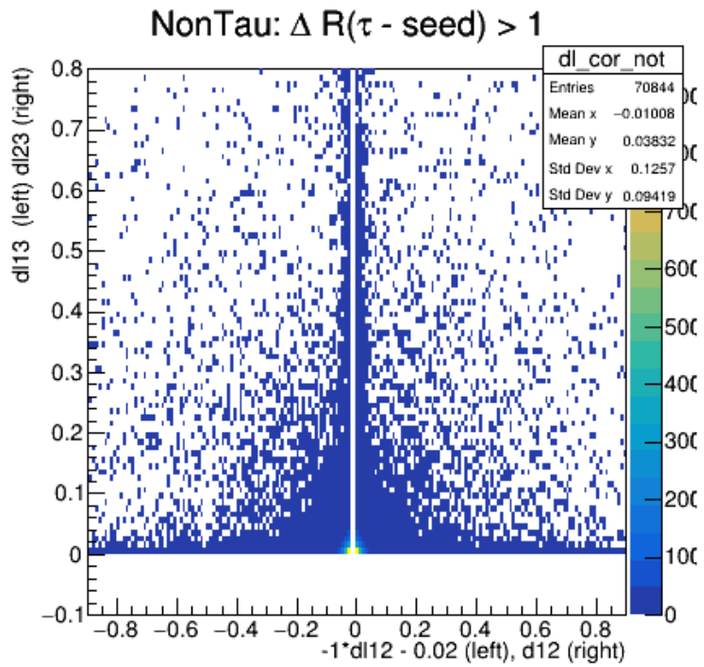




Tau side:
Clear correlations between 3 pair combination

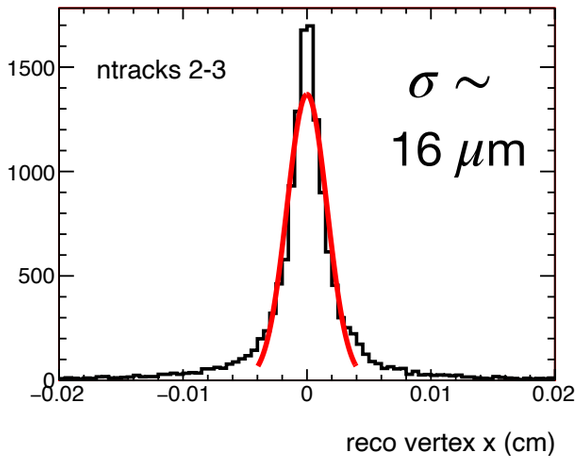
Significantly long reconstructed decay length at Tau side

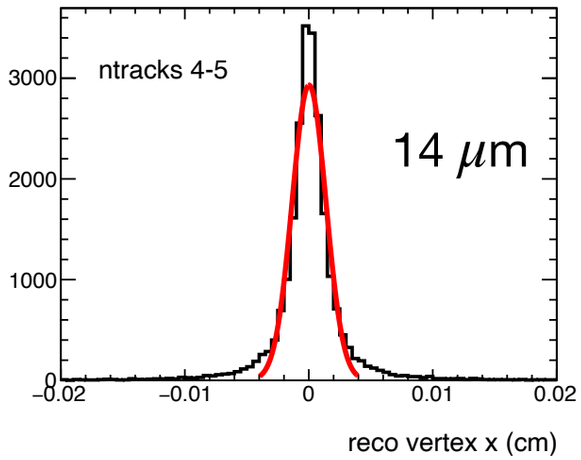


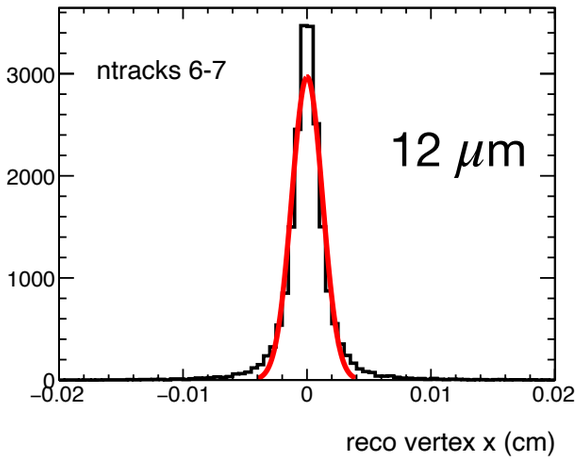


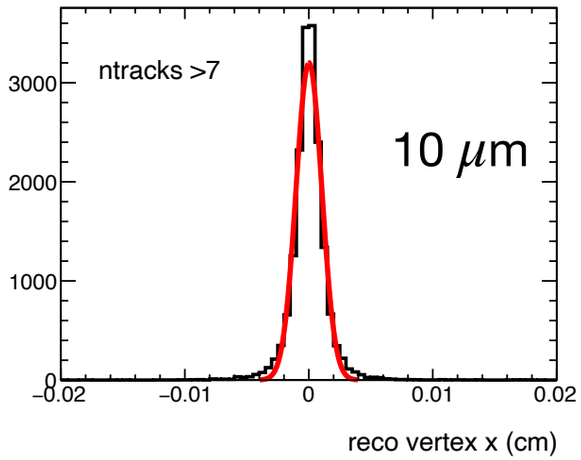
Away side:
No correlations between 3 pair combination

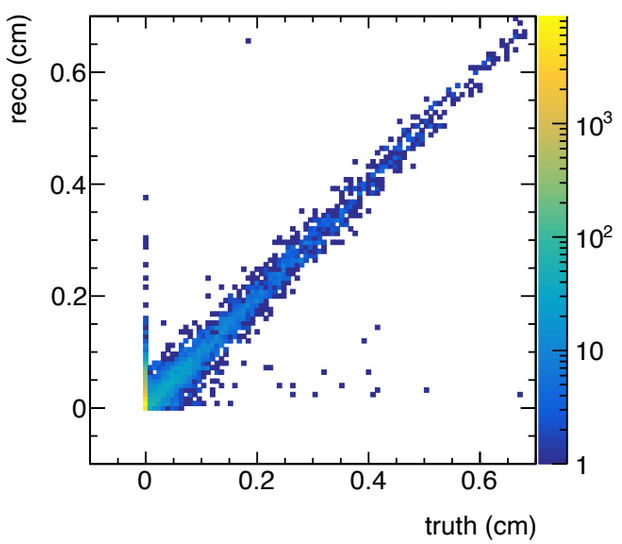
Effect of resolution

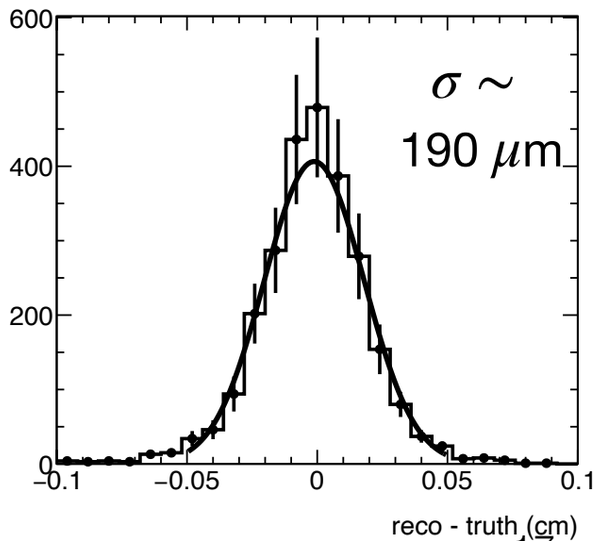






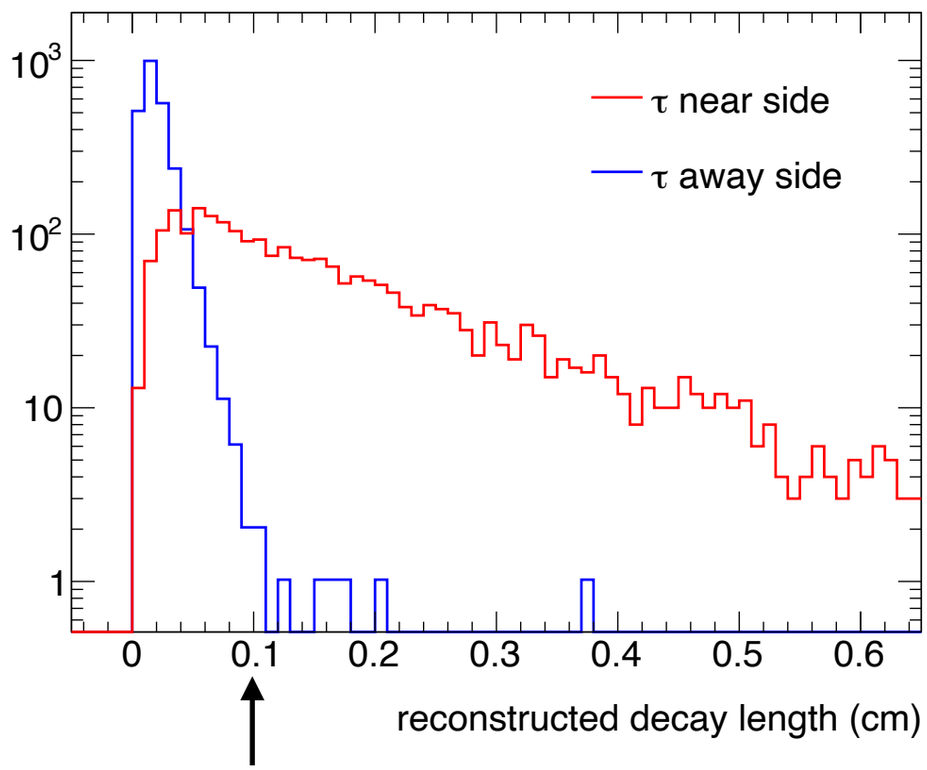




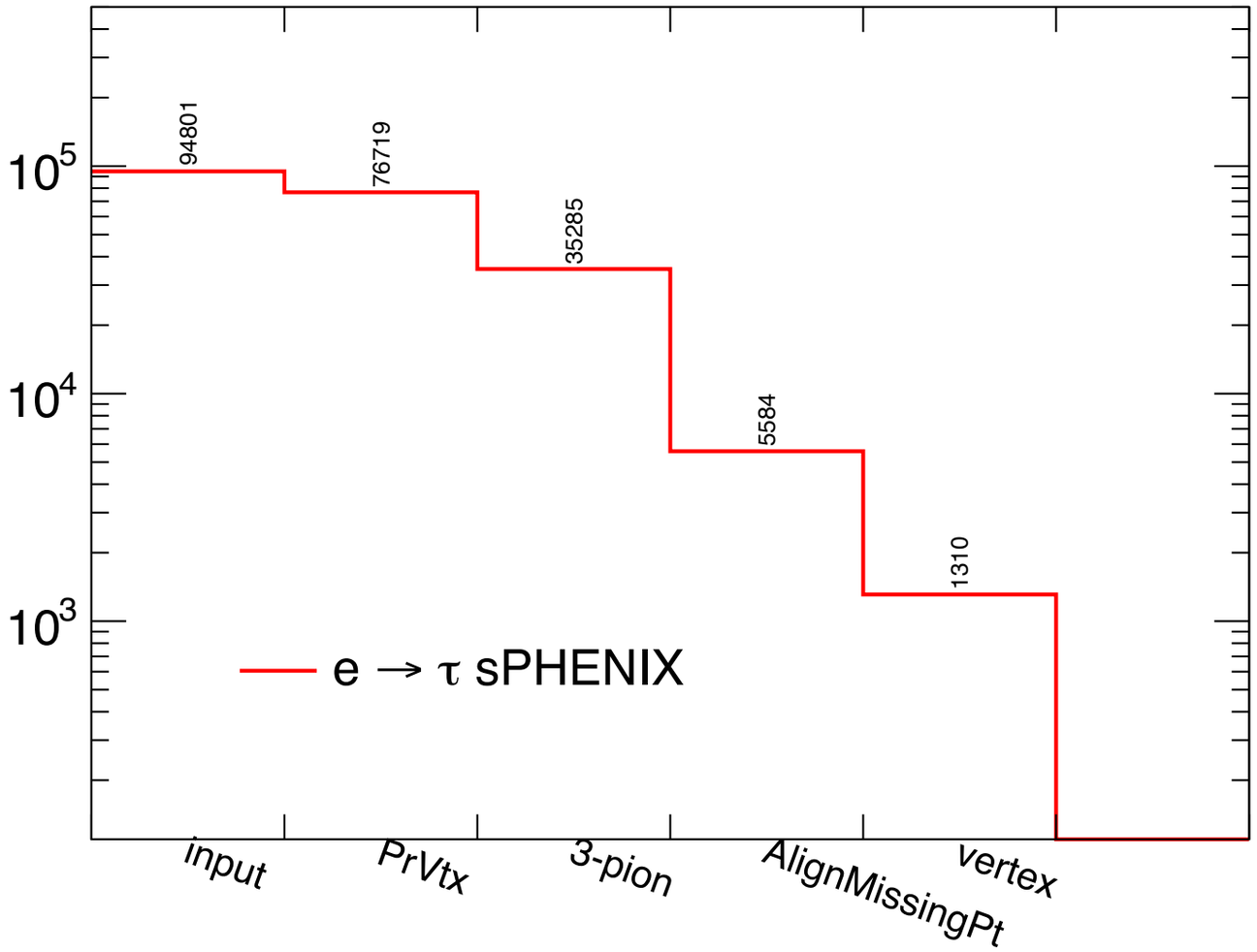


- Vertex resolution at x component ~**10** μm
- Similar for y and z components at middle rapidity
- Decay length resolution ~ 190 μm

- Similar algorithm applied as for Generator level analysis



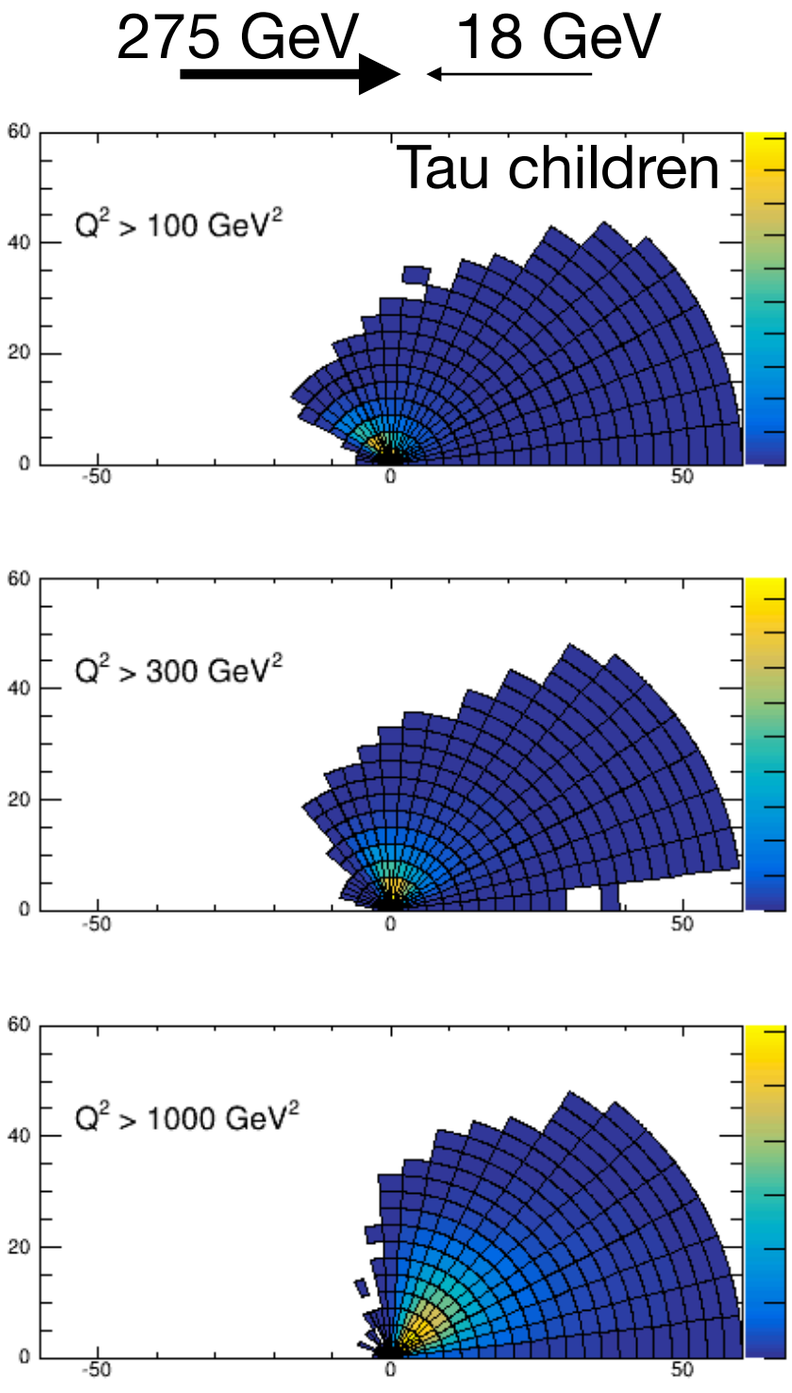
Efficiency with Detector Effects



- 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

Detector requirement summary



Angle for theta, radius for momentum

3-prong

- Missing energy reconstruction for tau jet tagging
- Veto scattering electron at middle/forward rapidity (high Q2)
- Tracking and jet detection at central detectors
- Vertex detector for precise secondary vertex reconstruction

1-prong (not studied yet)

- π^0 reconstruction
- Muon identification

Next step

- Move to EIC configuration for the full detecter simulation
- Completing 3-prong
  - 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

For yellow report

- Kinematic map for different final status
- PID requirement: high momentum charged pion
- Electromagnetic calorimeter: neutron pion reconstruction
- Muon identification

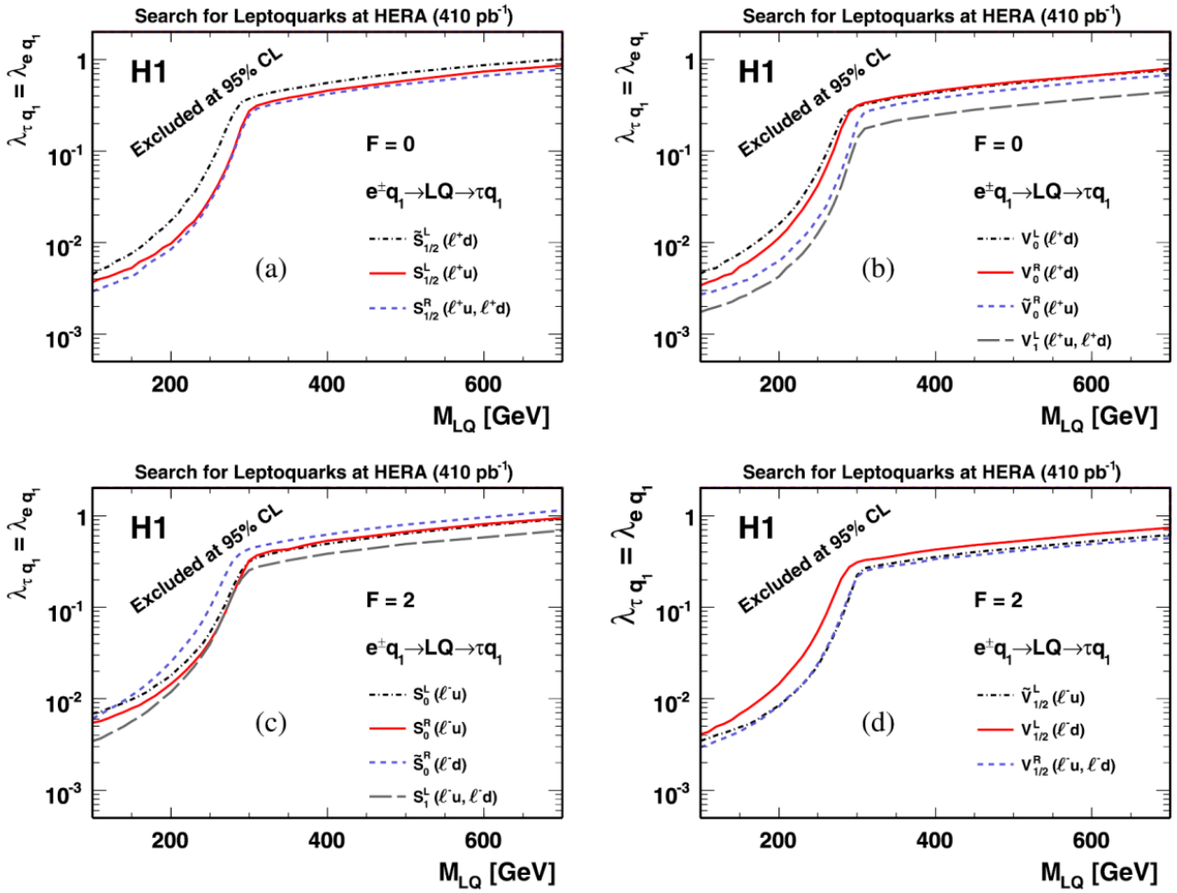
Summary

- 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 ePHENIX (sPHENIX-EIC) concept
- for EIC yellow report: quantify detector requirements

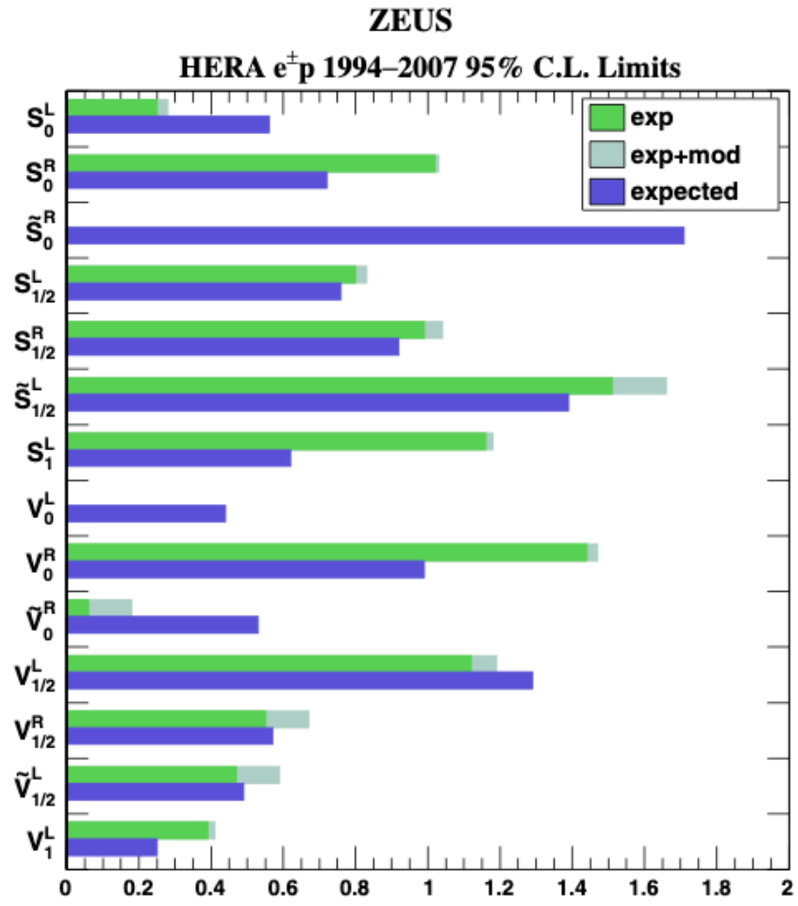
Backup

HERA

H1, PLB 701, 20-30 (2011)



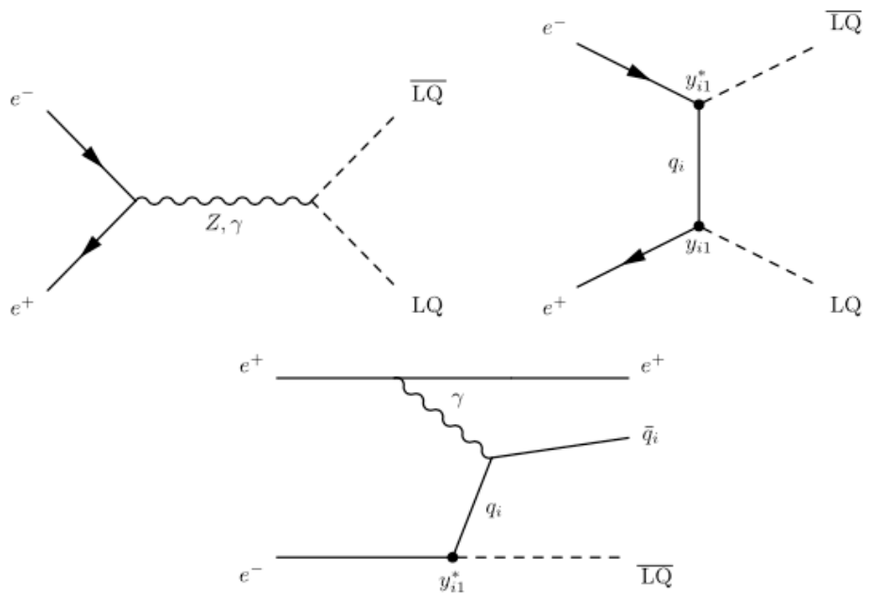
ZEUS, PRD 99, 092006 (2019)



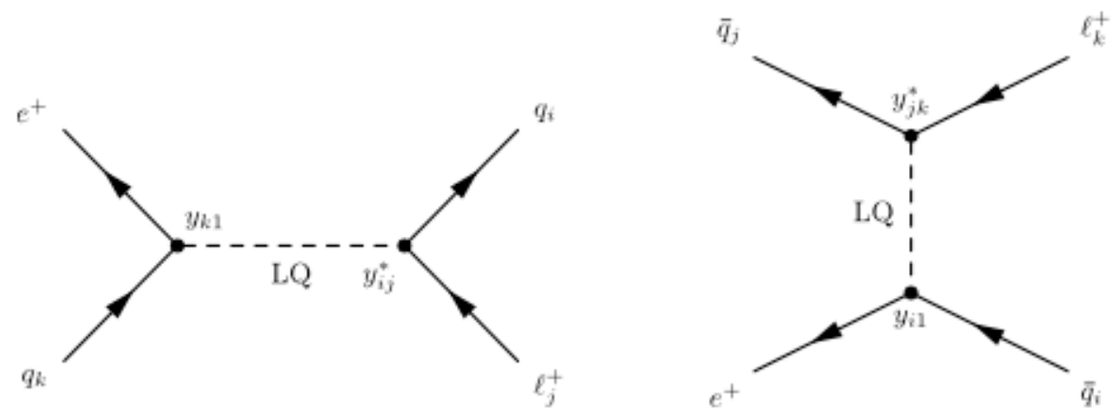
$$\eta_{LQ} = \frac{\lambda^2_{LQ}}{M^2_{LQ}}\ (\mathrm{TeV}^{-2})$$

Experimental Searches of Leptoquarks

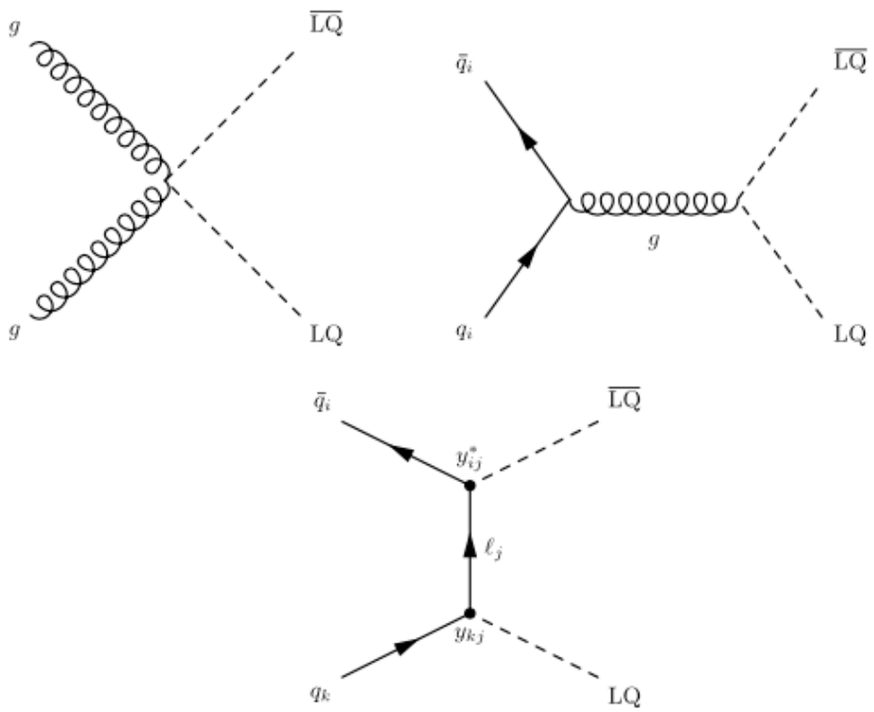
e^+e^-

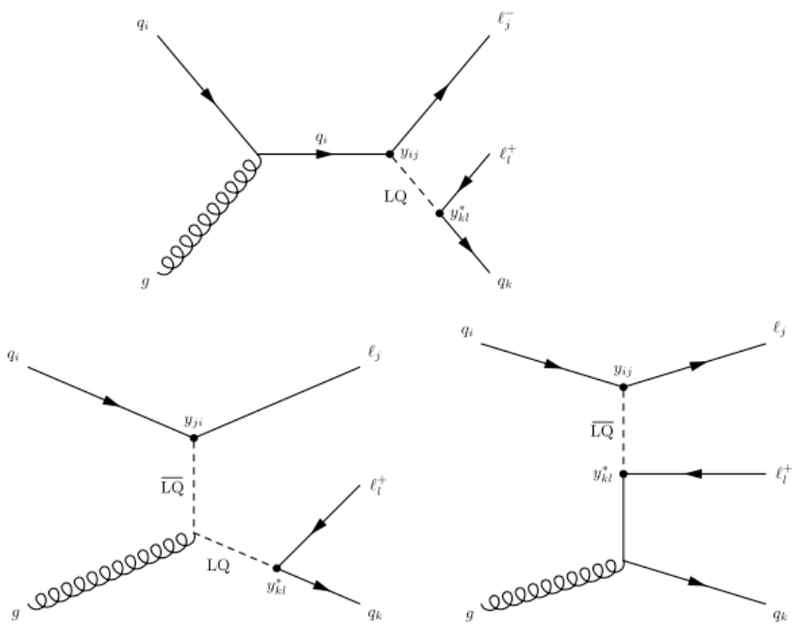


ep

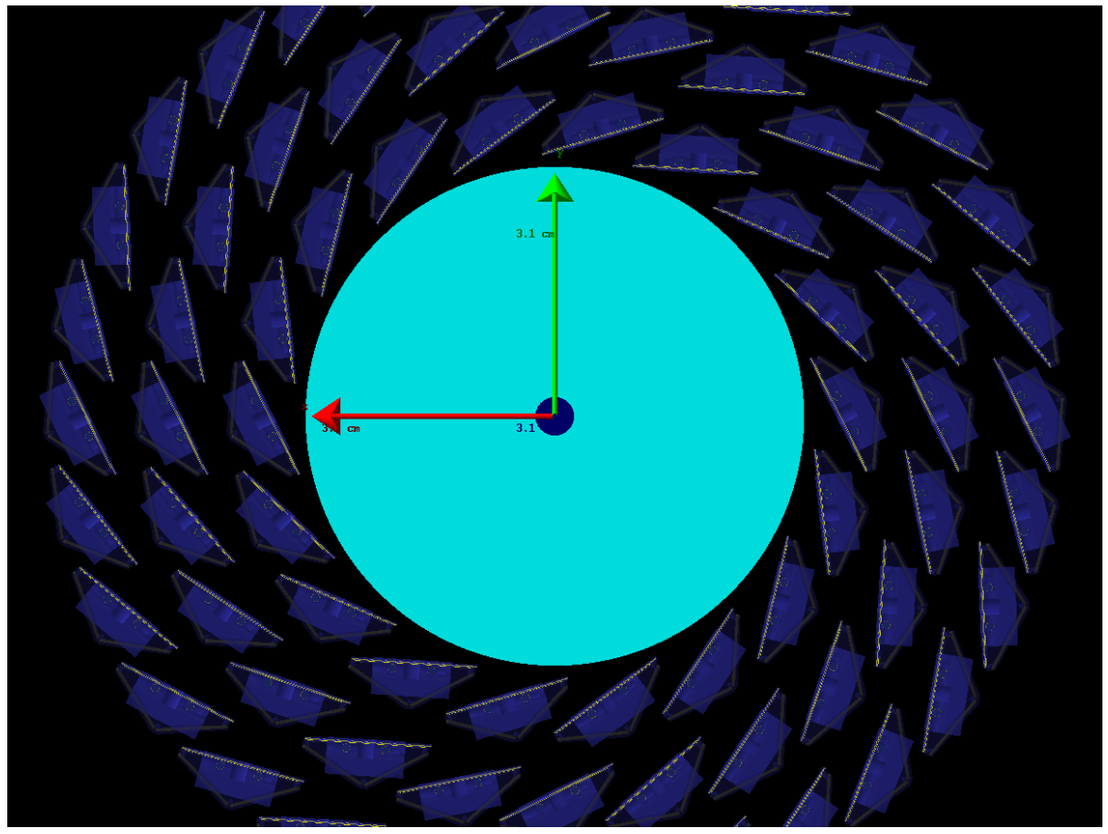


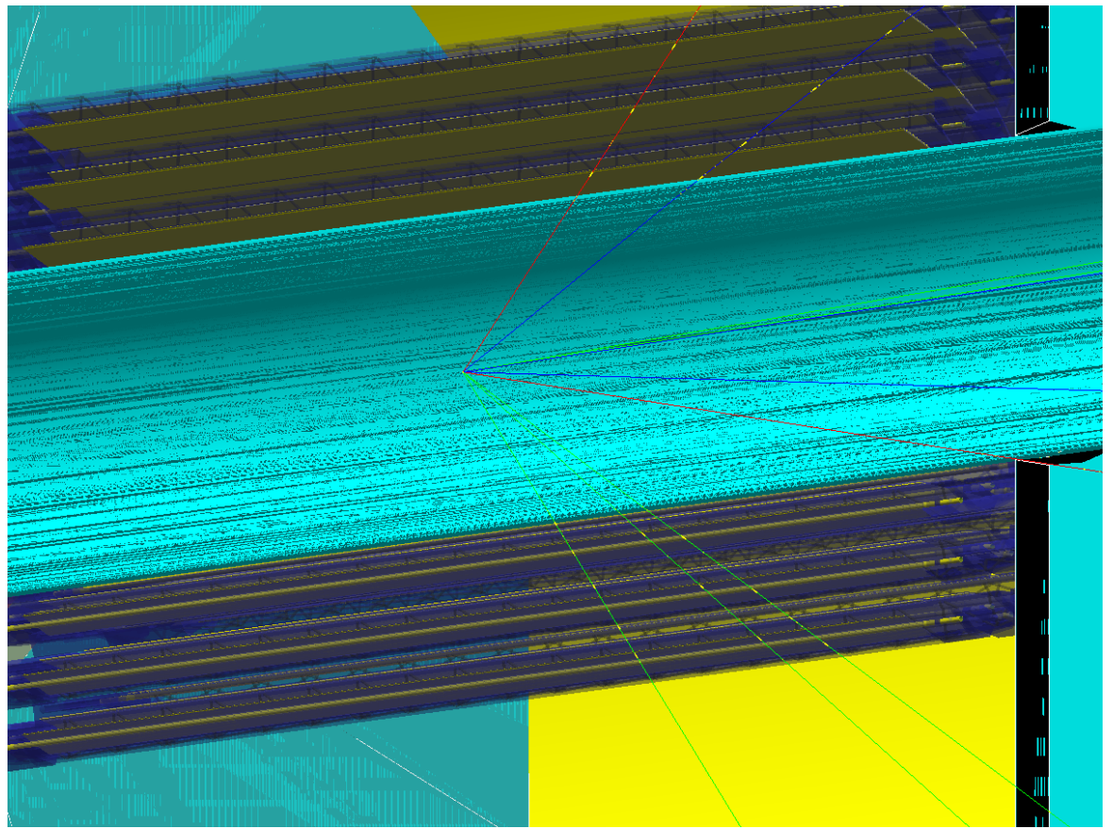
pp / $p\bar{p}$





Silicon Vertex Tracker Layout





The EIC beam pipe is ~50% larger than the RHIC beam pipe. The MVTX geometry is adjusted to accommodate this pipe. The layout is based on the inner tracker from eRD16/18 from Håkan Wennlöf hwennlof@kth.se.