Search for Charged Lepton Flavor Violation at the Electron-Ion Collider

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

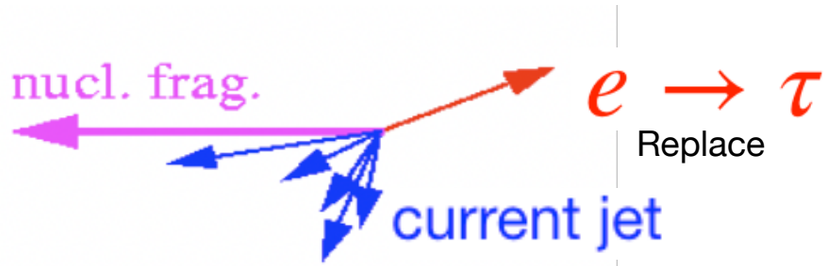
CFNS workshop: EIC opportunities for Snowmass2021

Jan 25, 2021

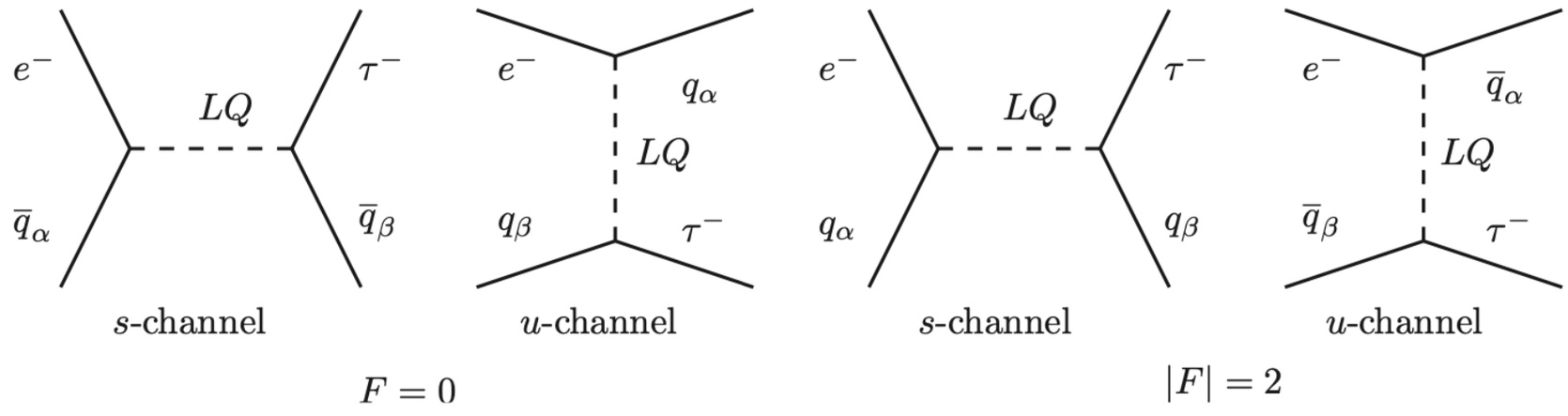
CLFV in EIC: $e \rightarrow \tau$ Transition

- While CLFV(1,2) is stringently constrained, limits on CLFV(1,3) are weaker by several orders of magnitude.
- Various models predict enhanced sensitivity for CLFV(1,3) while suppressing CLFV(1,2)
- CFLV in DIS:

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

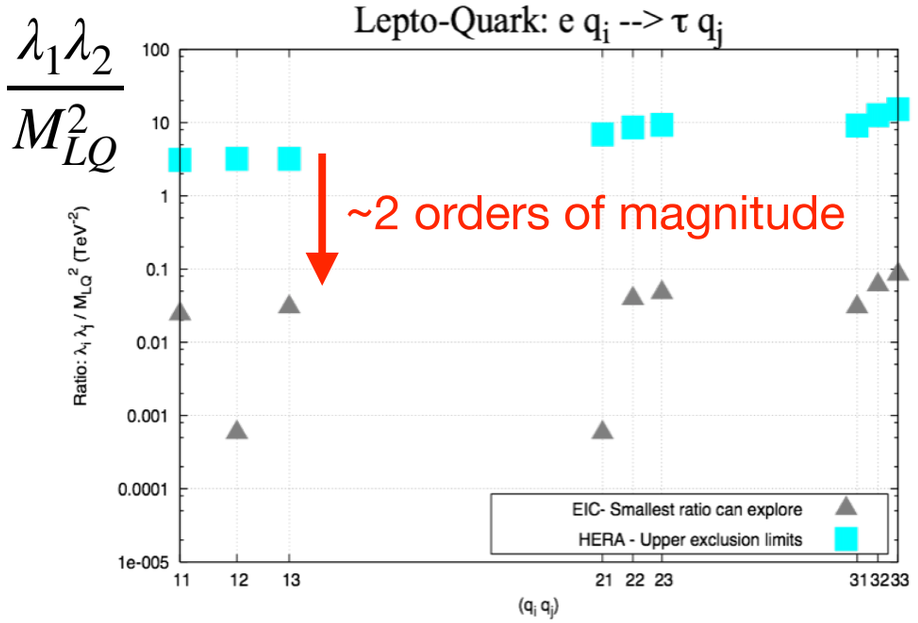


- **Leptoquark** models provide a good benchmark to study sensitivity
  - CLFV at tree level processes; allow coupling between same and different generations of quarks and leptons at initial state and final state



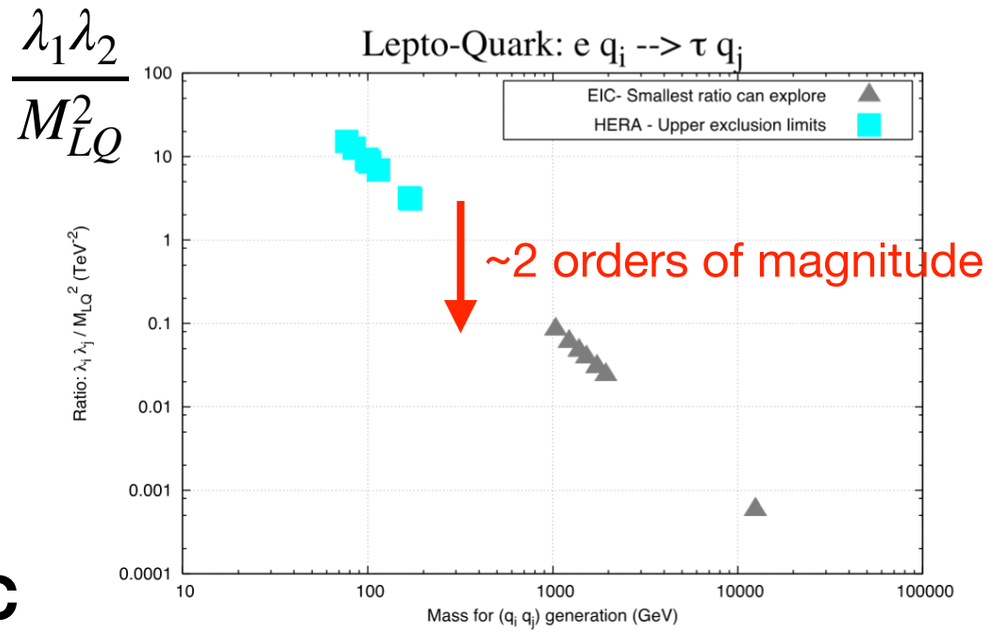
$e \rightarrow \tau$ meditated by LQs in DIS

- At HERA, the first electron-proton collider, H1 and ZEUS have searched for Leptoquarks (CLFV) and set limits
  - $\sqrt{s}$ ~ 320 GeV
  - Luminosity ~ $10^{30\text{-}31}$ $cm^{-2}s^{-1}$
  - Dataset: ~ 0.5 fb^{-1}



- First phenomenological study for CLFV mediated by LQs at EIC done by Gonderinger, Ramsey-Musolf, JHEP (2010) 2010: 45
- 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 comparing to HERA is expected

Assume 0.1 fb cross-section sensitivity

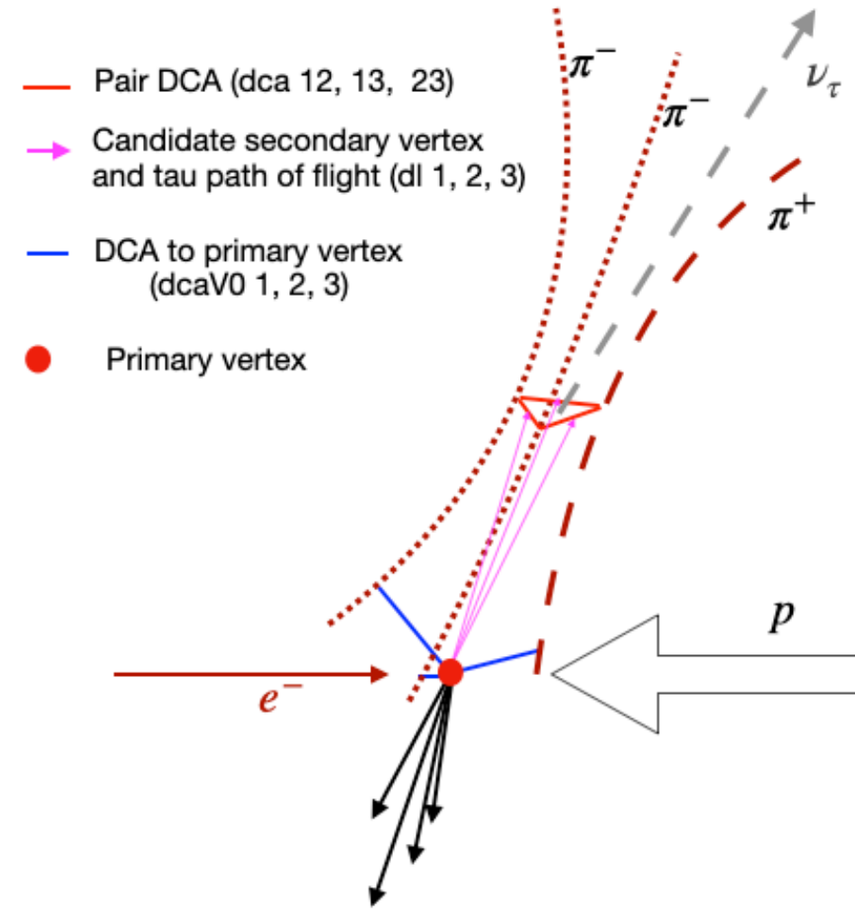


New discovery space: $e \rightarrow \tau$ transition at EIC

Goal and strategy of this Study

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

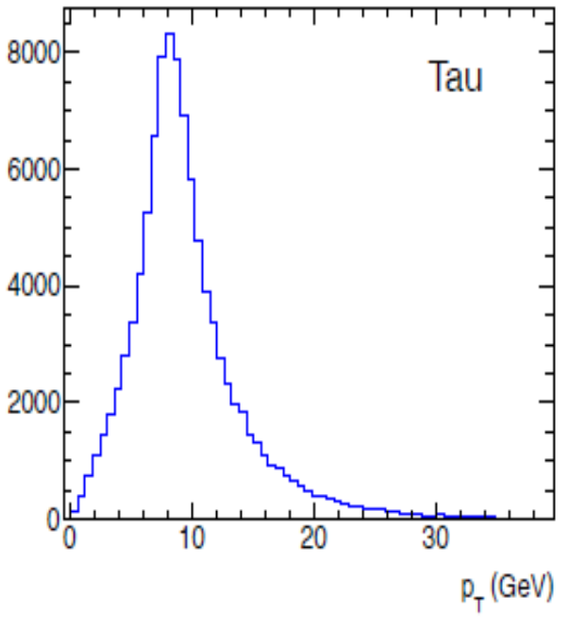
- Event generators:
  - LQGENEP 1.0 for Leptoquark events (L. Bellagamba, 2001)
  - DJANGOH 4.6.8 for DIS (NC + CC) events (H. Spiesberger 2005)
- Jets reconstructed from MC events
  - Fastjet, Anti-k_T, R = 1.0
  - Scattered electron for SM DIS and neutrinos **excluded**
- Primary vertex reconstructed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

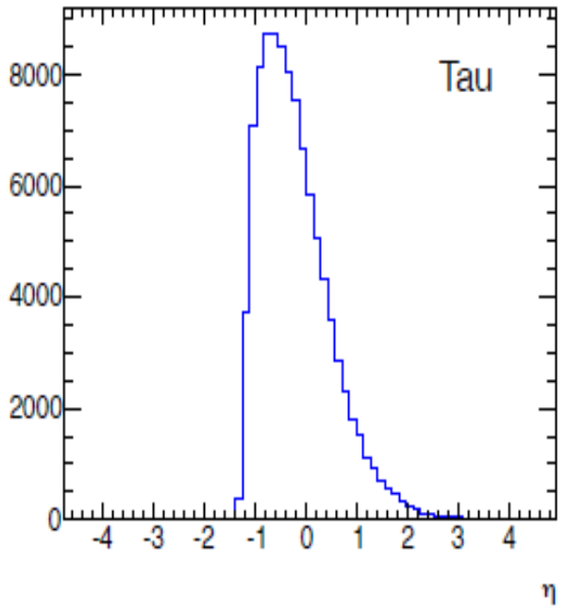


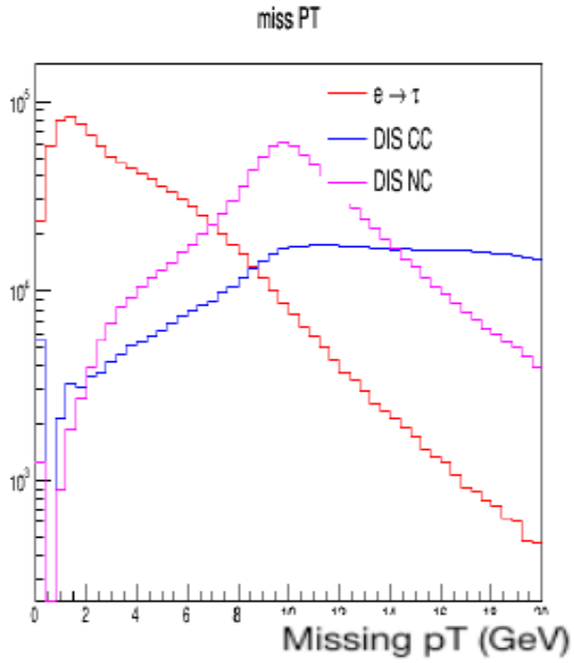
3-prong: ***secondary vertex*** *finding from* $\pi^-\pi^+\pi^-$

Features of LQ $e \rightarrow \tau$ event

18x275 GeV^2



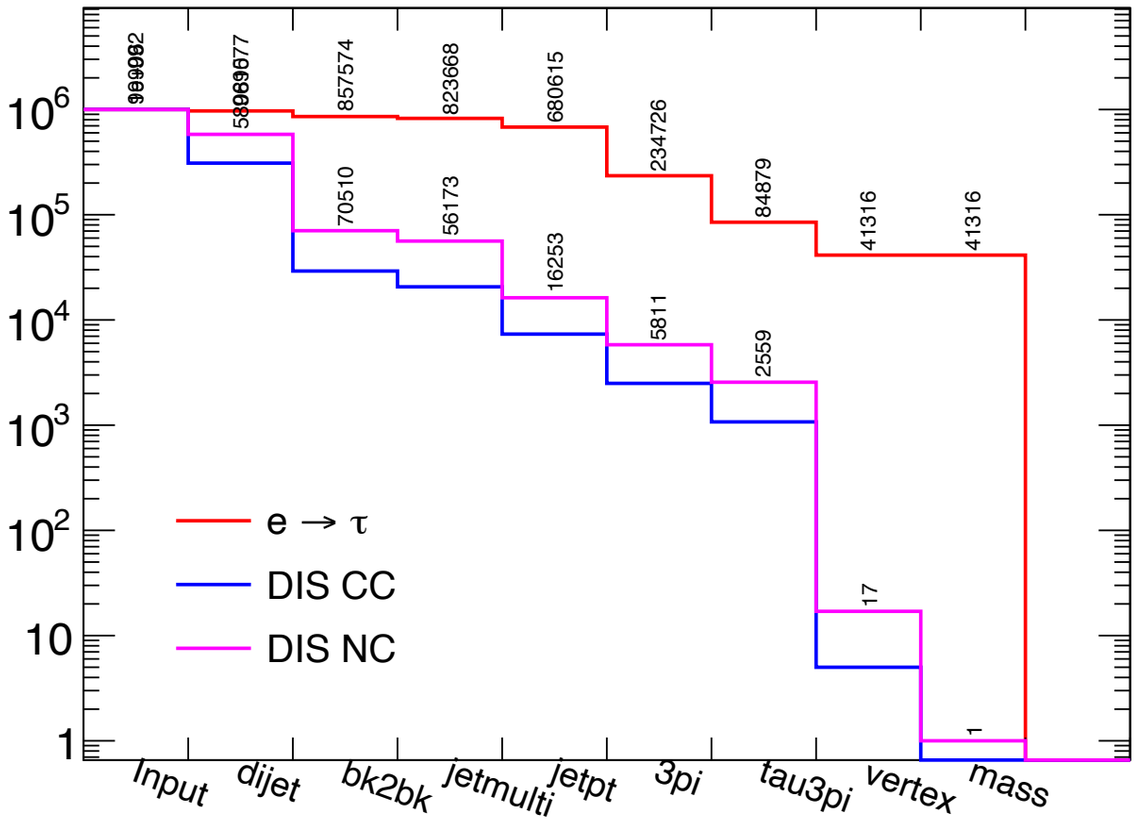




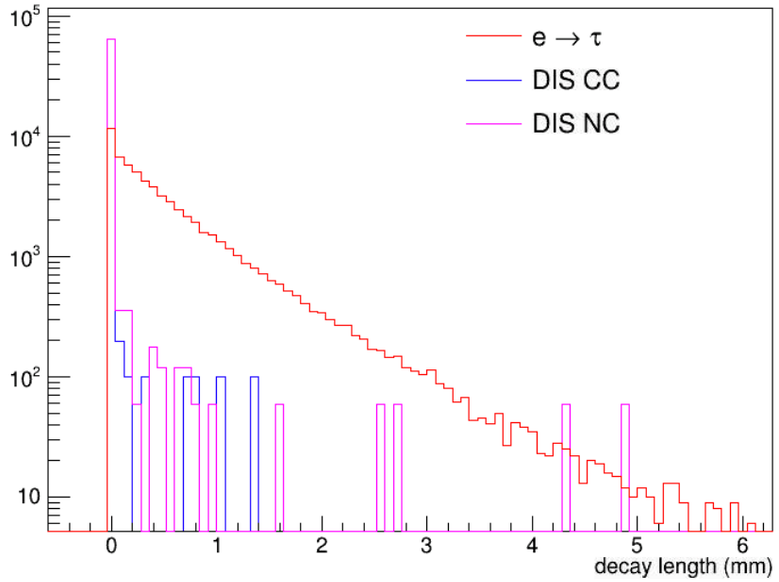
Note: electron in DIS NC is masked; Fastjet, Anti-k_T, R = 1.0; jet pt > 2 GeV; Q^2>100 GeV^2

- $e \rightarrow \tau$ event
  - 2+ jets: High pT tau decay into collimating and low multiplicity jet
  - Signal mainly located at central region
  - Modest missing pT (partial of tau pT)
- DIS event
  - 1 jets dominating
  - Higher particle multiplicity
  - Missing pT ~ lepton pT

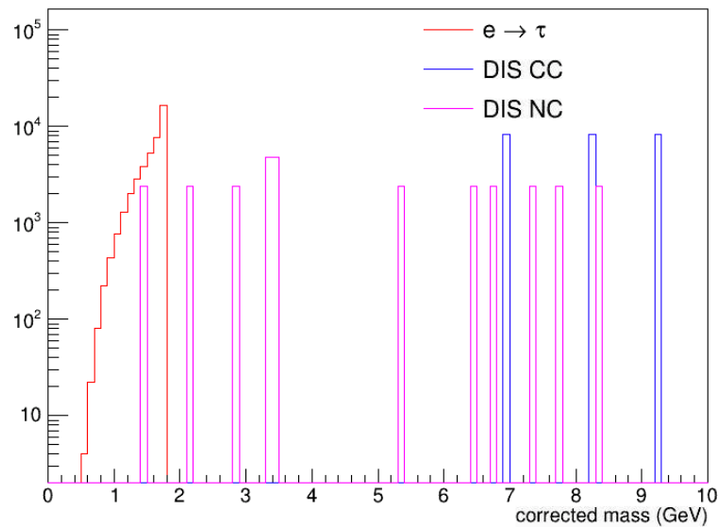
Progressive Selection



Search for 3 charged tracks aligning to missing pT and back-to-back with a high pT jet



Secondary vertex and corresponding decay length reconstructed from paired pion tracks

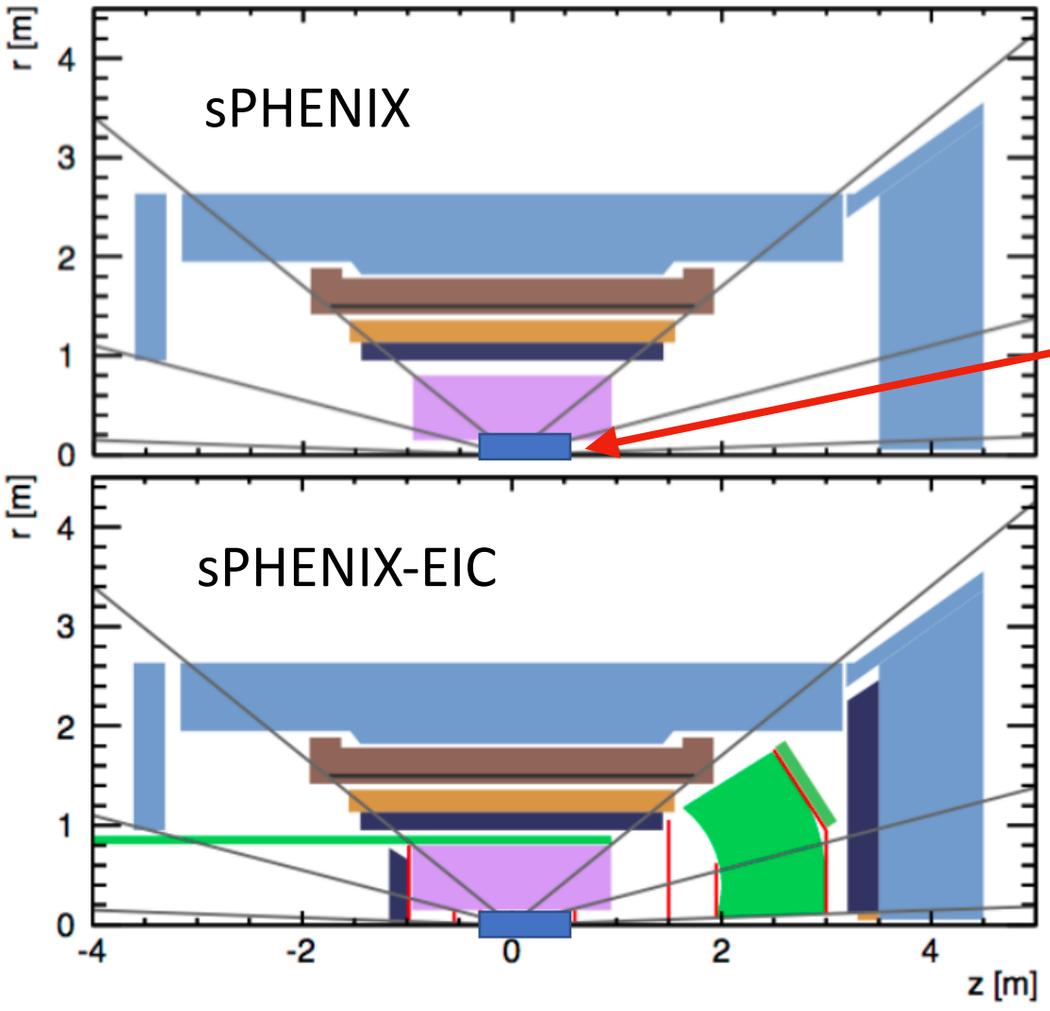


mass: corrected mass < 1.8 GeV

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

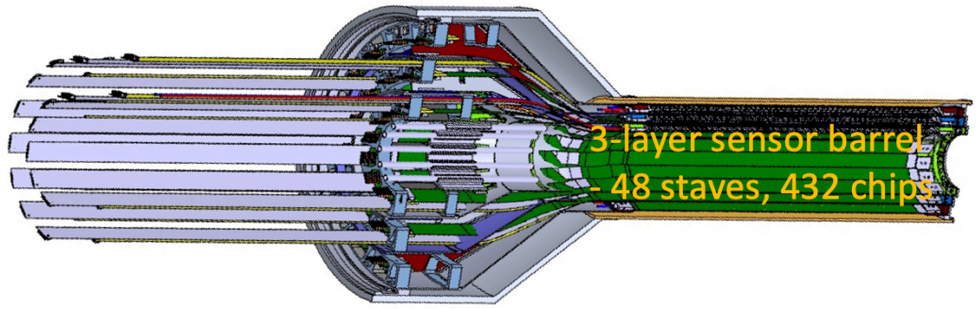
θ: angle between $\overrightarrow{V_{2nd}}$ and $\overrightarrow{p_{3\pi}}$

Detector Simulation: sPHENIX-EIC



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

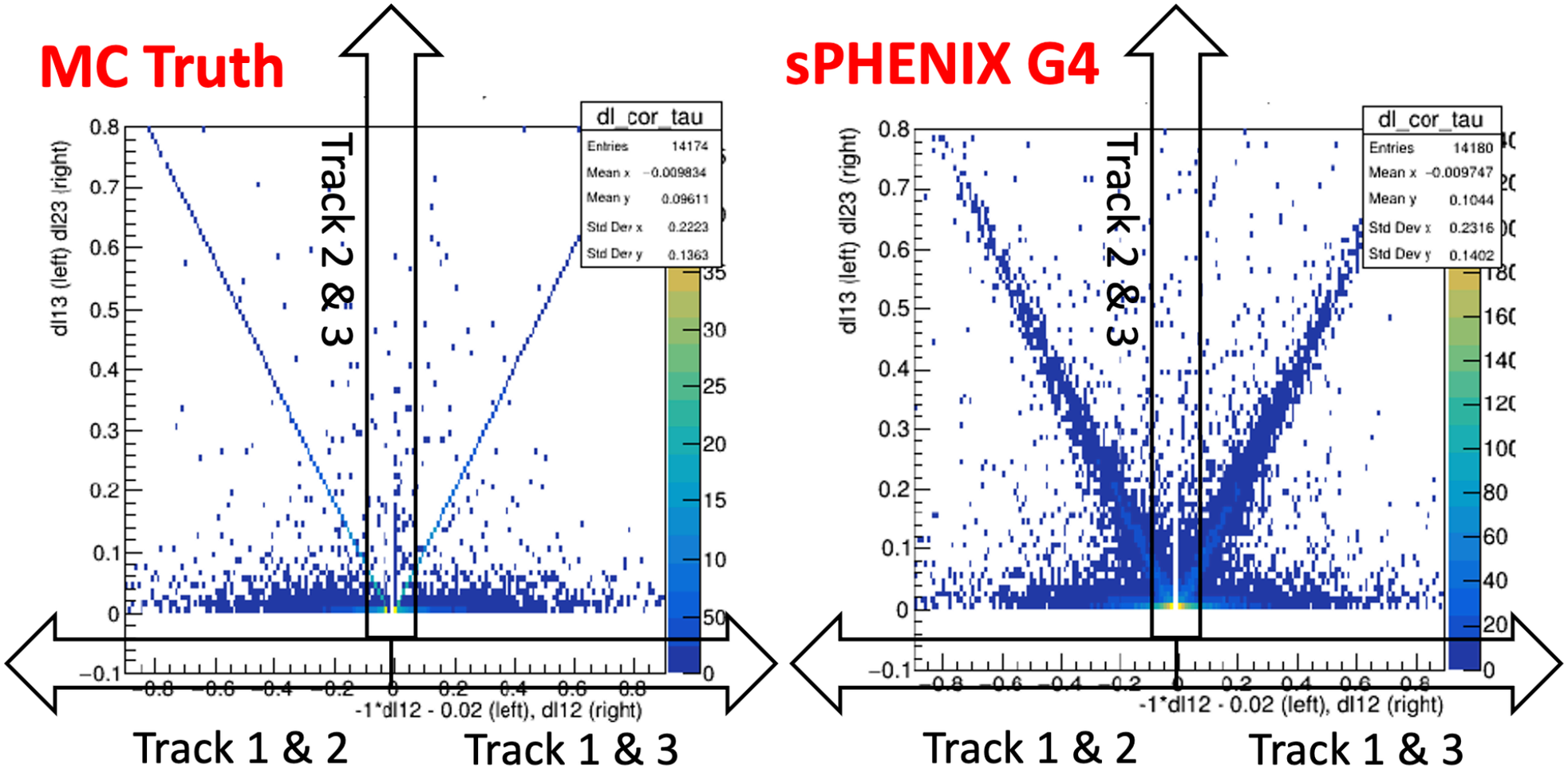
sPHENIX-MVTX



Service cone: signal, power, cooling and mechanical support

- Full detector Geant4 simulation: https://github.com/sPHENIX-Collaboration/coresoftware
- Analyses including vertexing and tracking have been also implemented in heavy flavor studies.

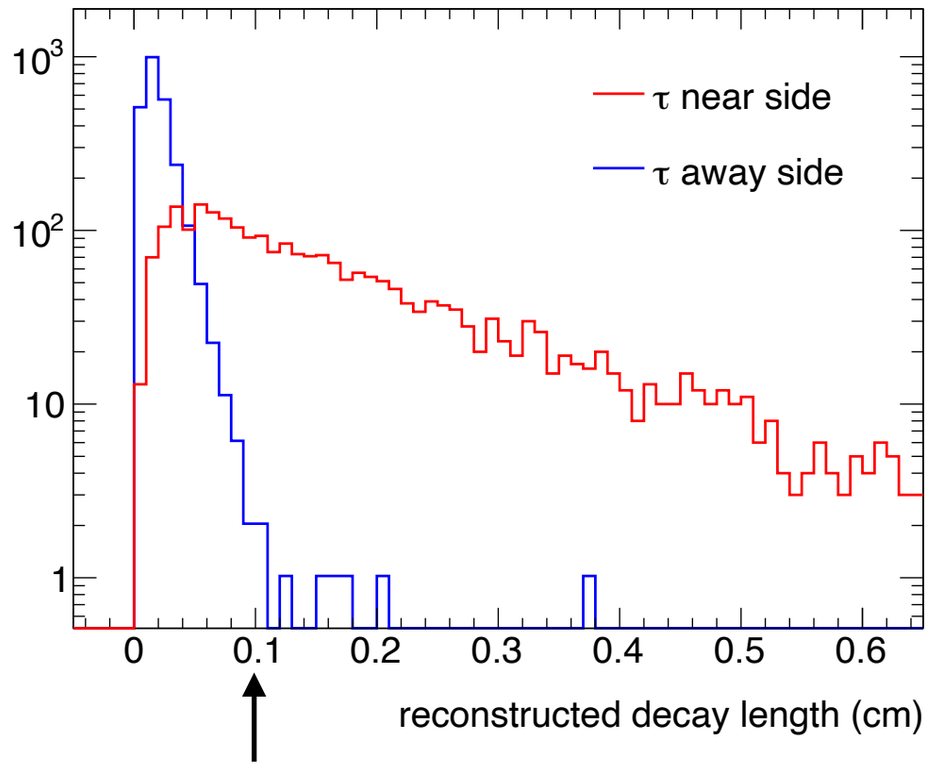
Secondary vertex reconstruction



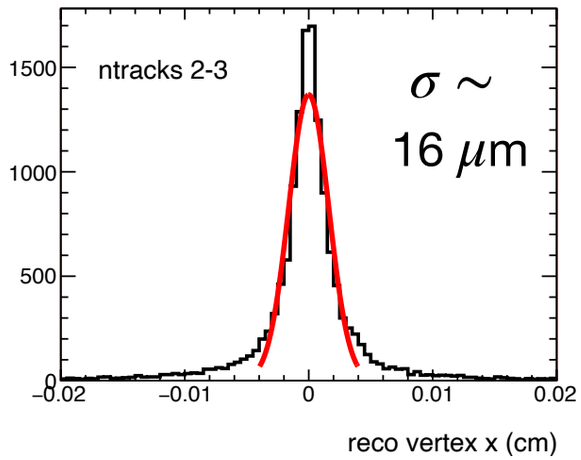
- Secondary vertex from track pairs (3 pairs from 3 tracks)
- Smeared but still well consistent 3-prong secondary vertex

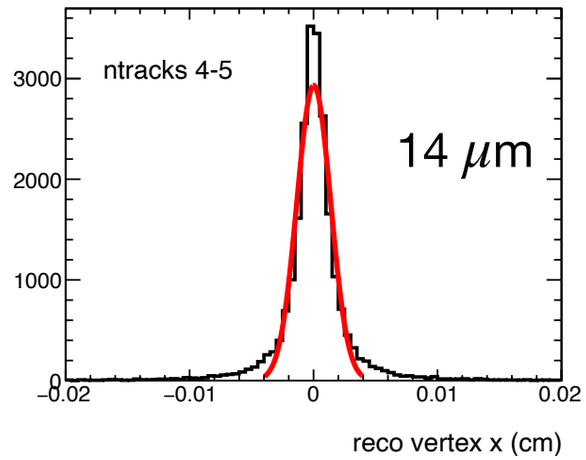
Effect of resolution

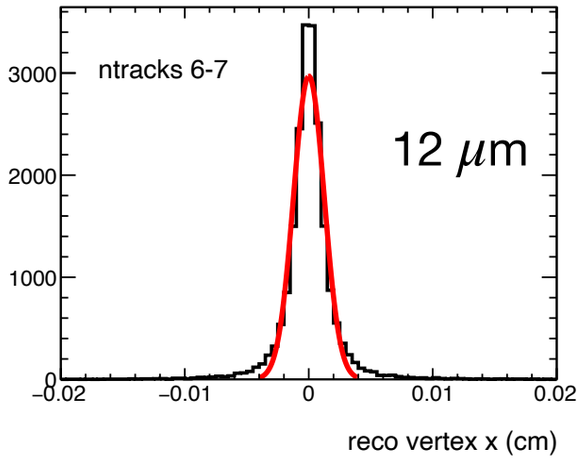
Capable separation of τ jet from QCD jet

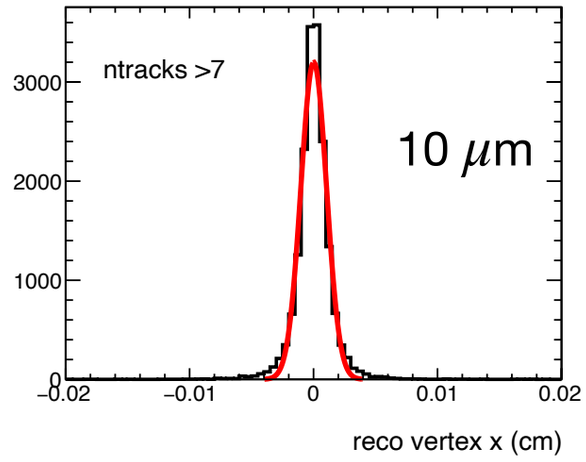


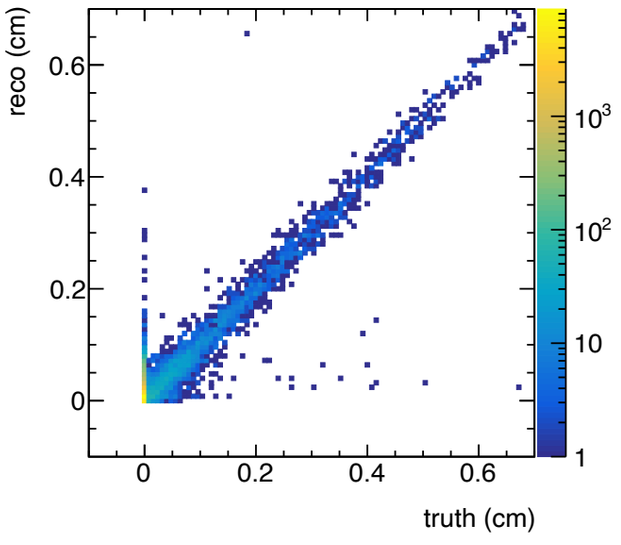
- Vertex resolution at x component **~10** μm
- Similar for y and z components at middle rapidity
- Decay length resolution ~ 190 μm

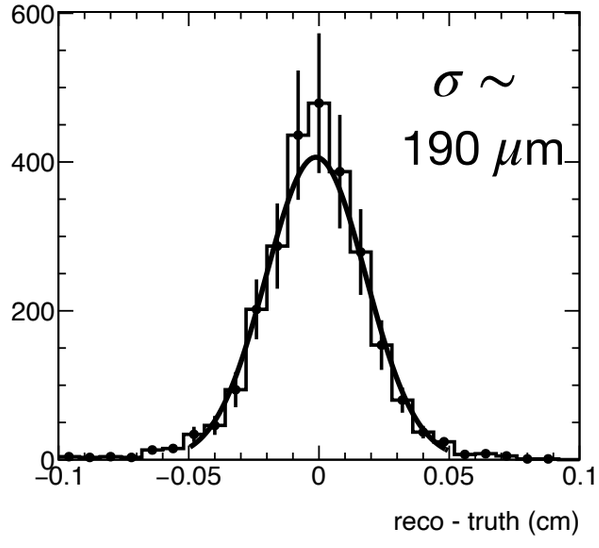




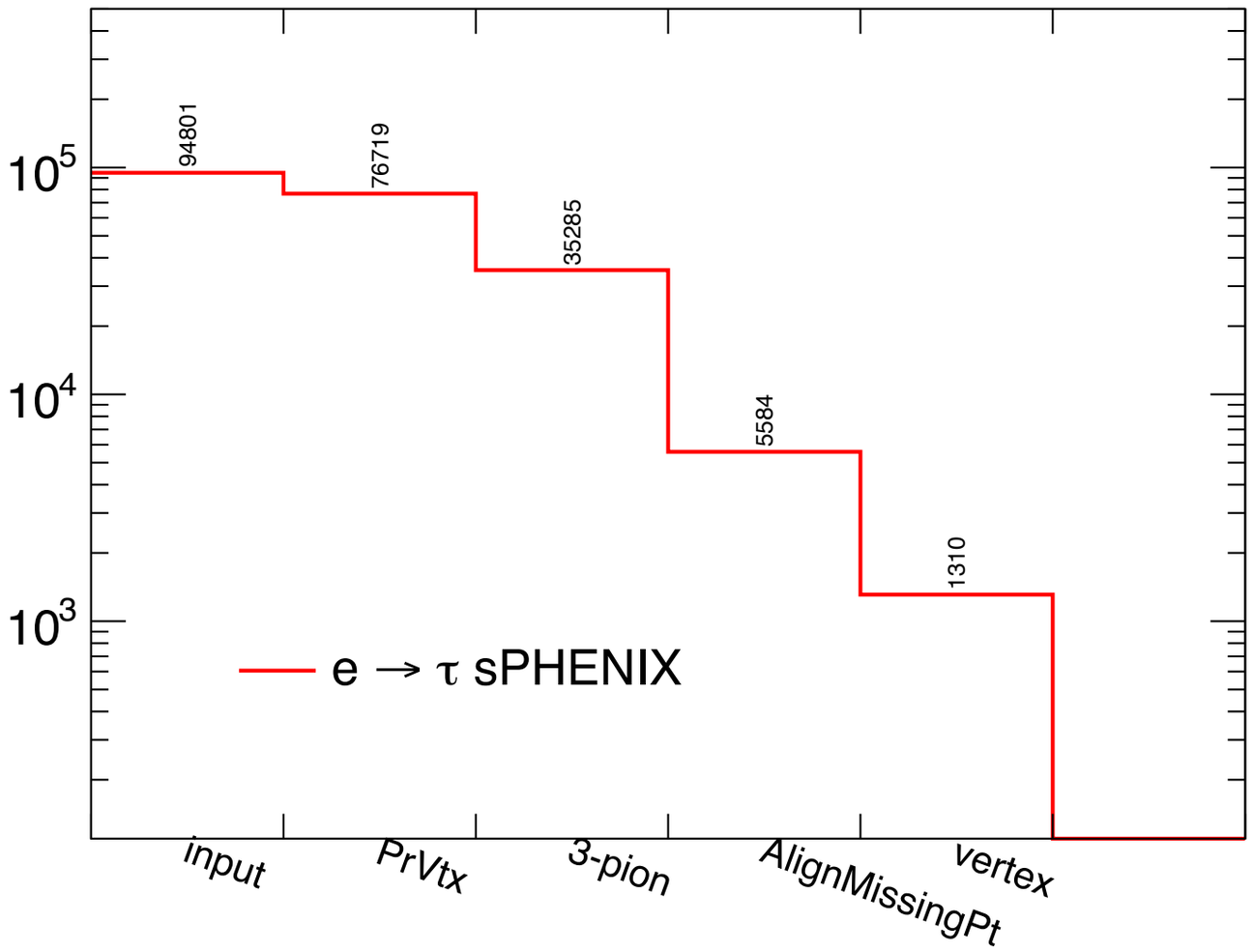








Efficiency with Detector Effects



- 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

Current activities and To-do

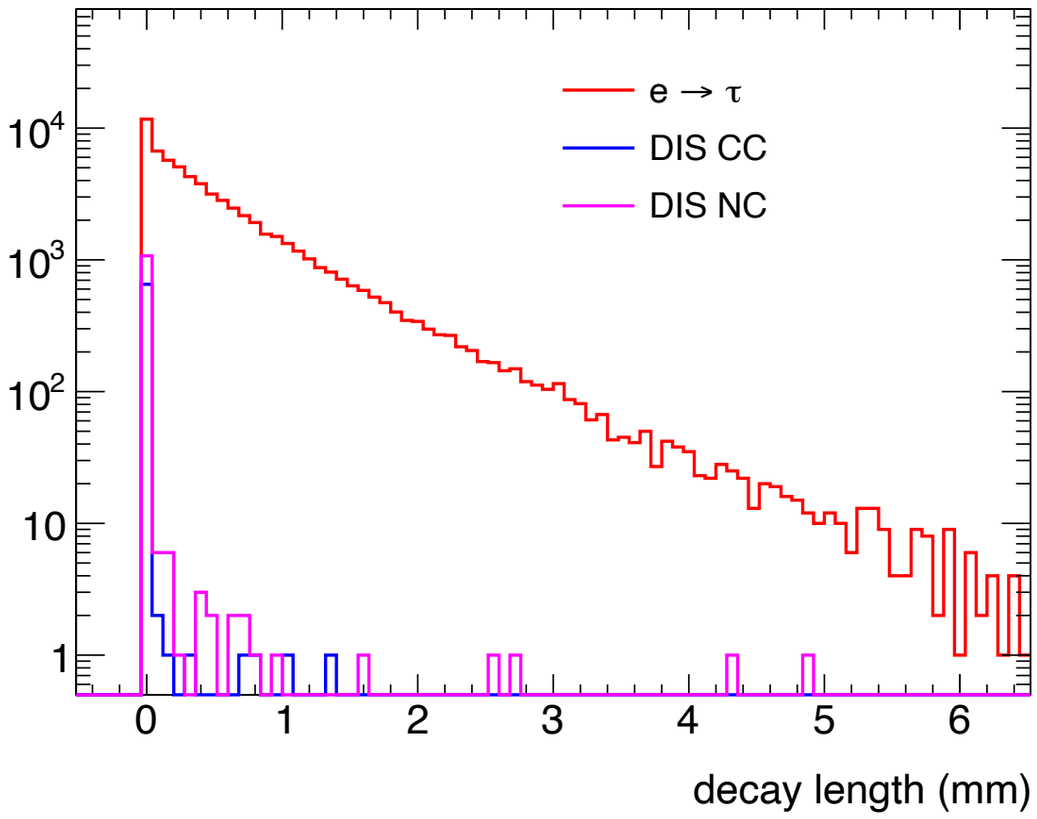
- One-prong analysis from sPHENIX-EIC Geant4 simulation
  - Muon identification based on particle flow analysis
  - MVTX detector based DCA analysis for muon and charged pion channel
    - Neutral pion reconstruction for pho- channel identification
- Overall projection for 100 pb^{-1} dataset
  - 3 charged pion, isolated 1 charged pion, and isolated muon

Summary

- EIC with high ($10^{34}cm^{-2}s^{-1}$) 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-EIC concept
- Studied 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

Backup

Last Two Cuts

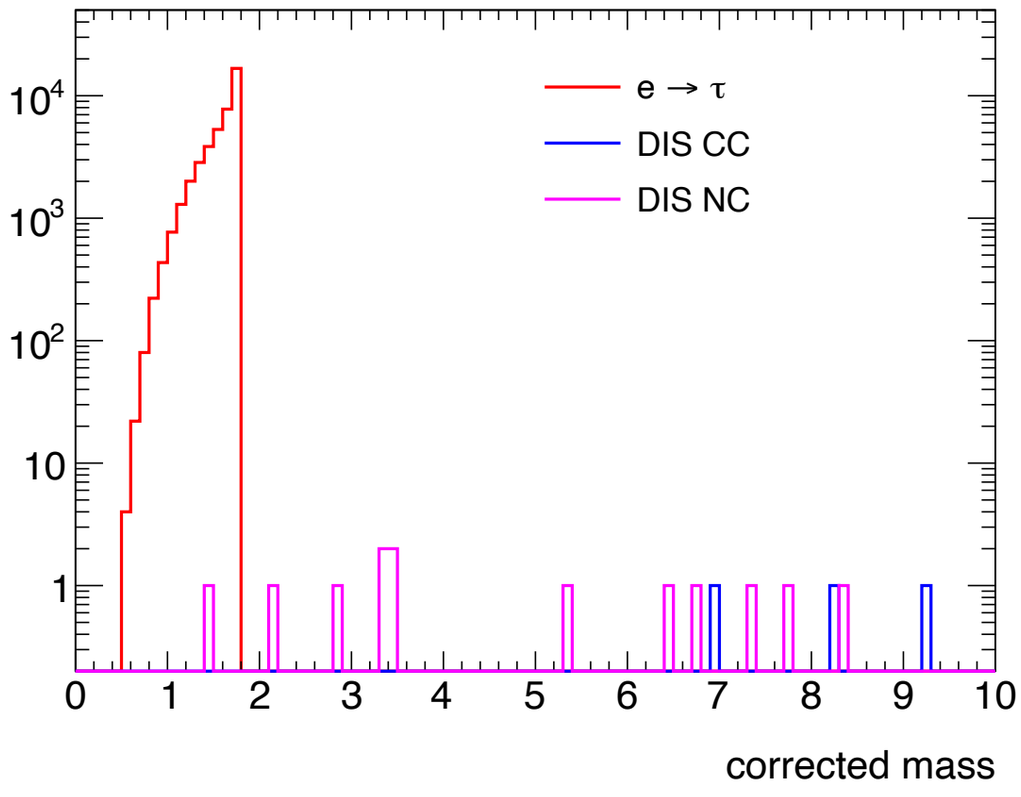


- Secondary vertex and corresponding decay length reconstructed from paired pion tracks

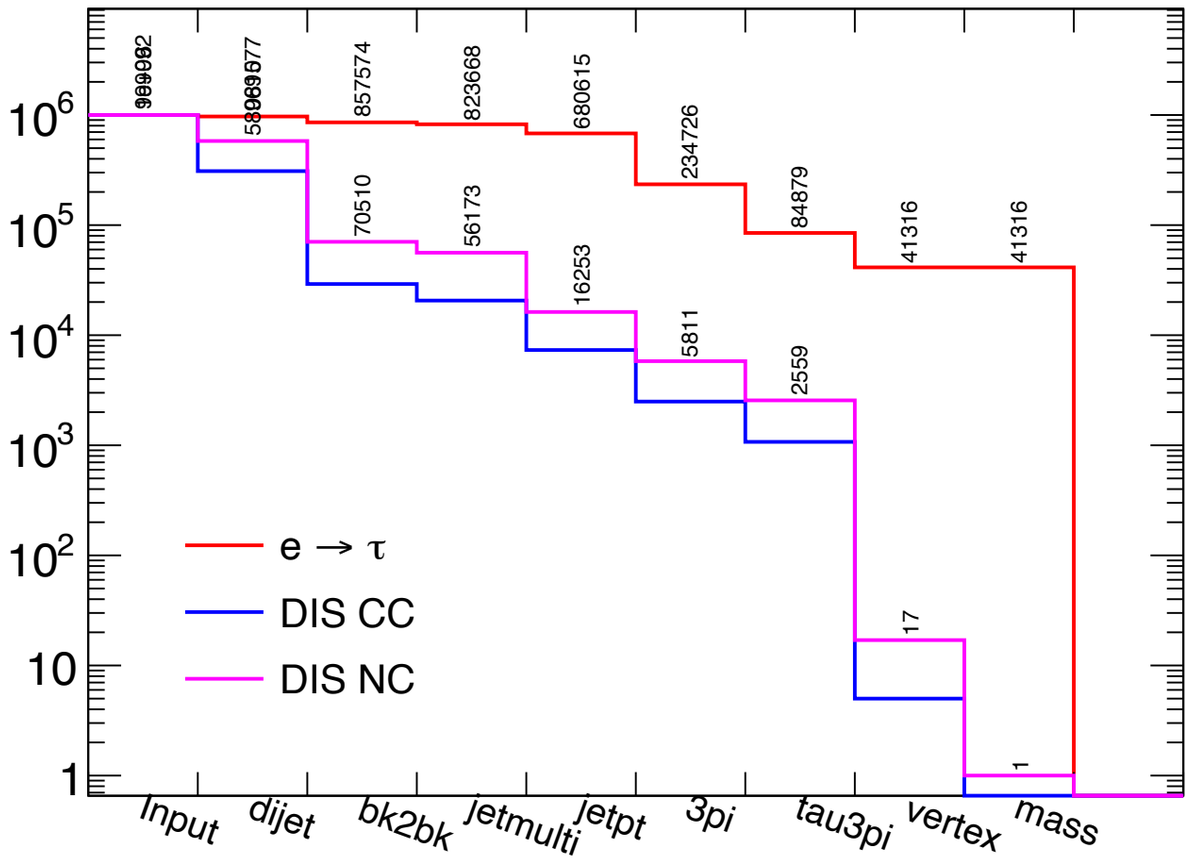
- Corrected mass from 3 pions

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

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



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

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)
- Decades search at different facilities worldwide.

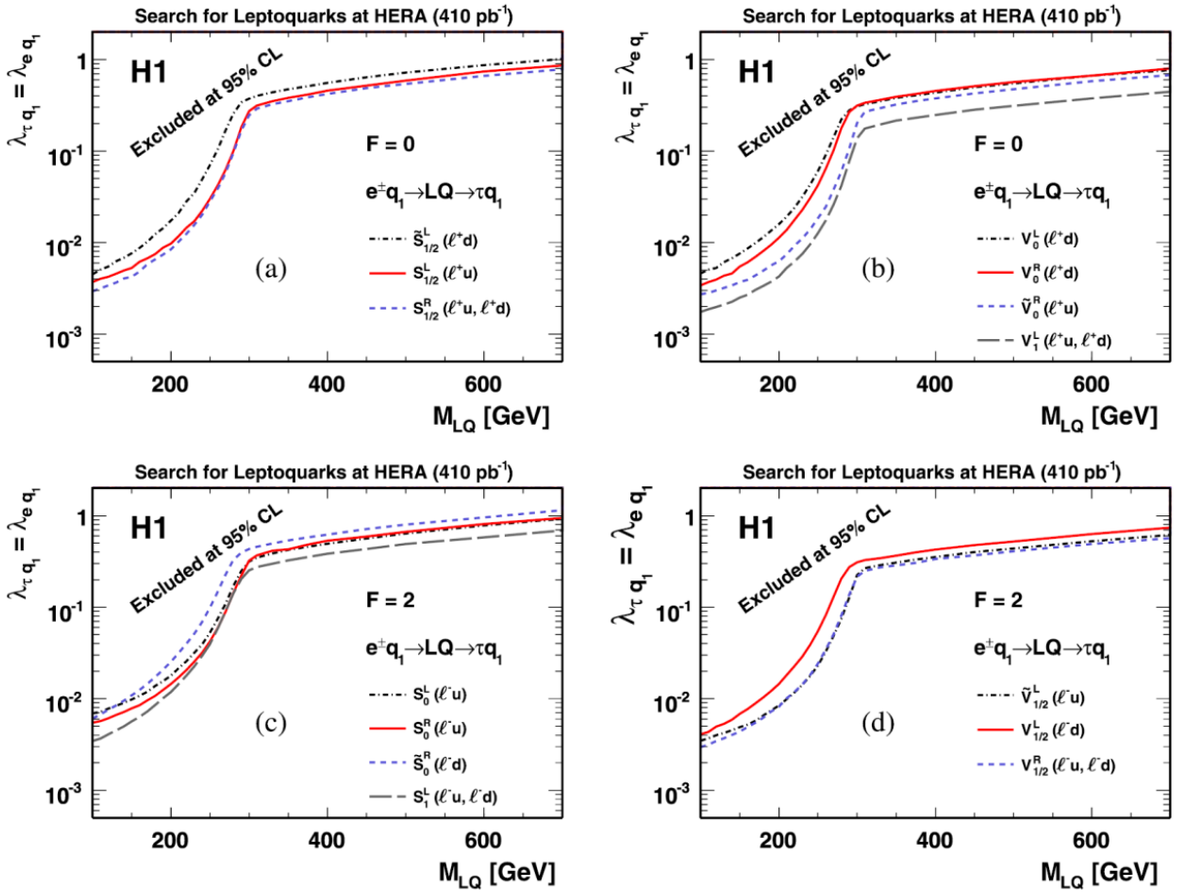
Buchmüller-Rückl-Wyler (BRW)

Type	J	F	Q	ep dominant process	Coupling	Branching ratio β_ℓ
S_0^L	0	2	$-1/3$	$e_L^- u_L \to \ell^- u$	λ_L	1/2
				$\nu_\ell d$	$-\lambda_L$	1/2
S_0^R	0	2	$-1/3$	$e_R^- u_R \to \ell^- u$	λ_R	1
$\tilde{S}_0^R$	0	2	$-4/3$	$e_R^- d_R \to \ell^- d$	λ_R	1
S_1^L	0	2	$-1/3$	$e_L^- u_L \to \ell^- u$	$-\lambda_L$	1/2
				$\nu_\ell d$	$-\lambda_L$	1/2
			$-4/3$	$e_L^- d_L \to \ell^- d$	$-\sqrt{2}\lambda_L$	1
$V_{1/2}^L$	1	2	$-4/3$	$e_L^- d_R \to \ell^- d$	λ_L	1
$V_{1/2}^R$	1	2	$-1/3$	$e_R^- u_L \to \ell^- u$	λ_R	1
			$-4/3$	$e_R^- d_L \to \ell^- d$	λ_R	1
$\tilde{V}_{1/2}^L$	1	2	$-1/3$	$e_L^- u_R \to \ell^- u$	λ_L	1

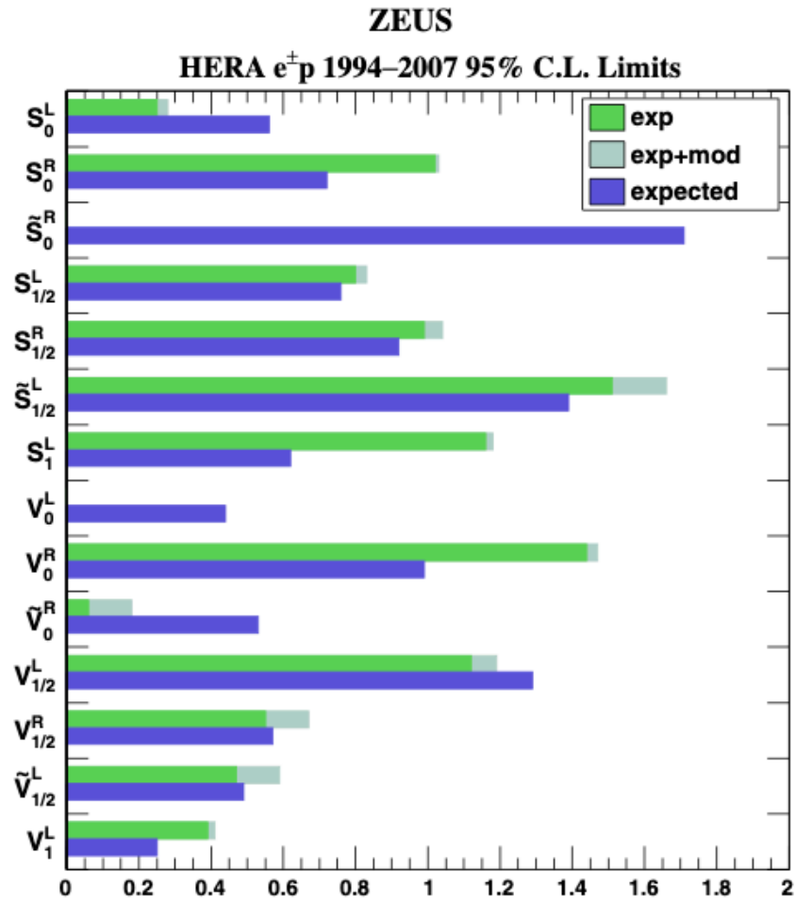
Type	J	F	Q	ep dominant process	Coupling	Branching ratio β_ℓ
V_0^L	1	0	$+2/3$	$e_R^+ d_L \to \ell^+ d$	λ_L	1/2
				$\bar{\nu}_\ell u$	λ_L	1/2
V_0^R	1	0	$+2/3$	$e_L^+ d_R \to \ell^+ d$	λ_R	1
$\tilde{V}_0^R$	1	0	$+5/3$	$e_L^+ u_R \to \ell^+ u$	λ_R	1
V_1^L	1	0	$+2/3$	$e_R^+ d_L \to \ell^+ d$	$-\lambda_L$	1/2
				$\bar{\nu}_\ell u$	λ_L	1/2
			$+5/3$	$e_R^+ u_L \to \ell^+ u$	$\sqrt{2}\lambda_L$	1
$S_{1/2}^L$	0	0	$+5/3$	$e_R^+ u_R \to \ell^+ u$	λ_L	1
$S_{1/2}^R$	0	0	$+2/3$	$e_L^+ d_L \to \ell^+ d$	$-\lambda_R$	1
			$+5/3$	$e_L^+ u_L \to \ell^+ u$	λ_R	1
$\tilde{S}_{1/2}^L$	0	0	$+2/3$	$e_R^+ d_R \to \ell^+ d$	λ_L	1

HERA

H1, PLB 701, 20-30 (2011)



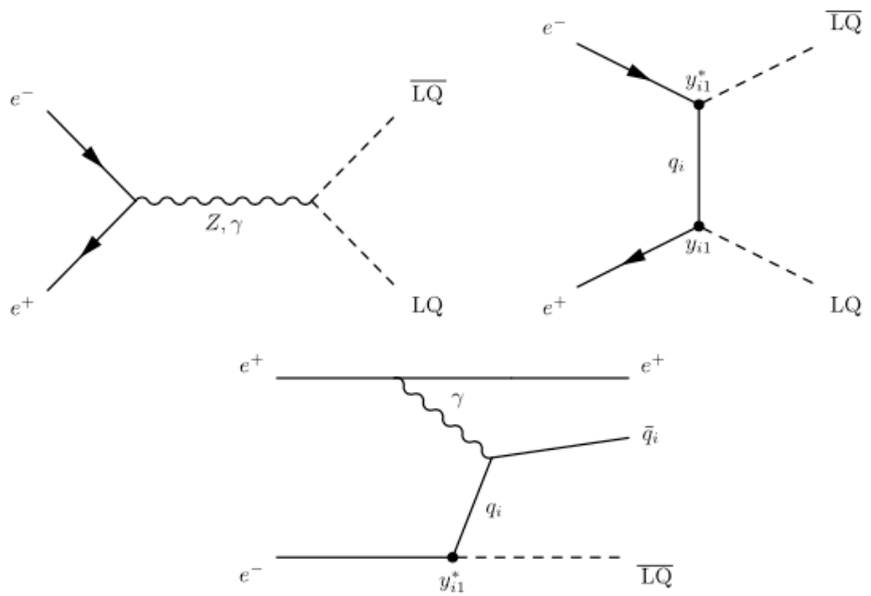
ZEUS, PRD 99, 092006 (2019)



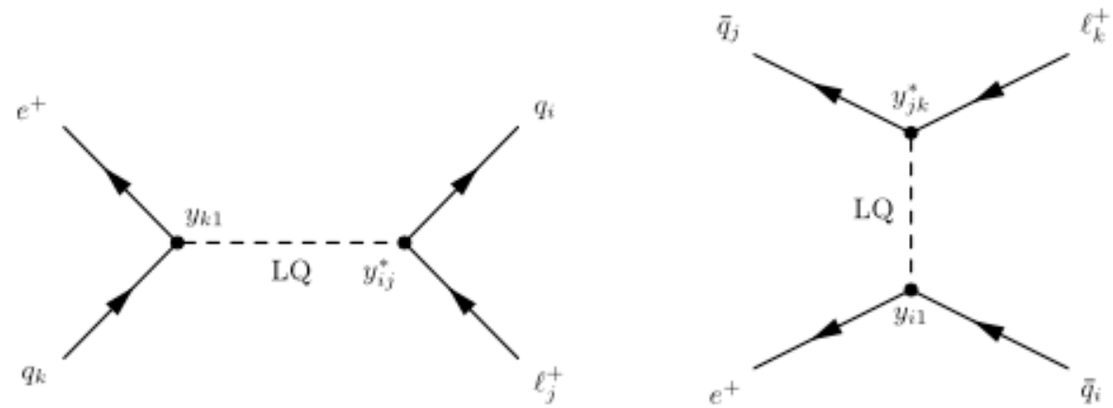
$$\eta_{LQ} = \frac{\lambda^2_{LQ}}{M^2_{LQ}}\ (\mathrm{TeV}^{-2})$$

Experimental Searches of Leptoquarks

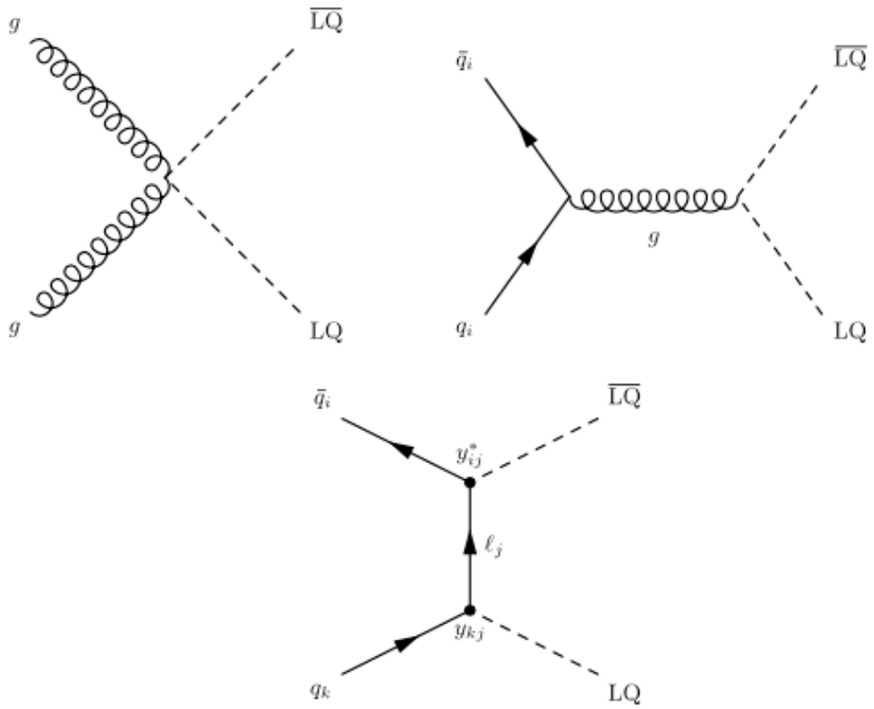
e^+e^-

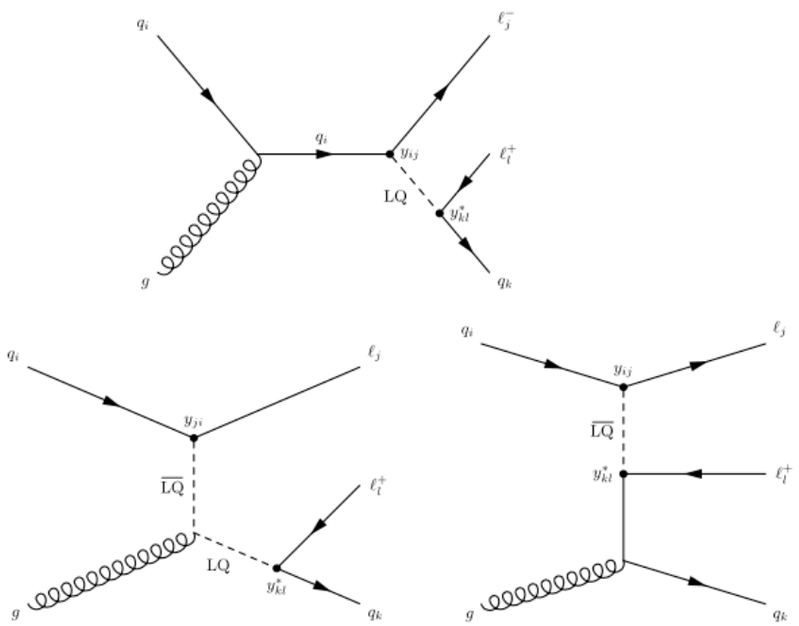


ep

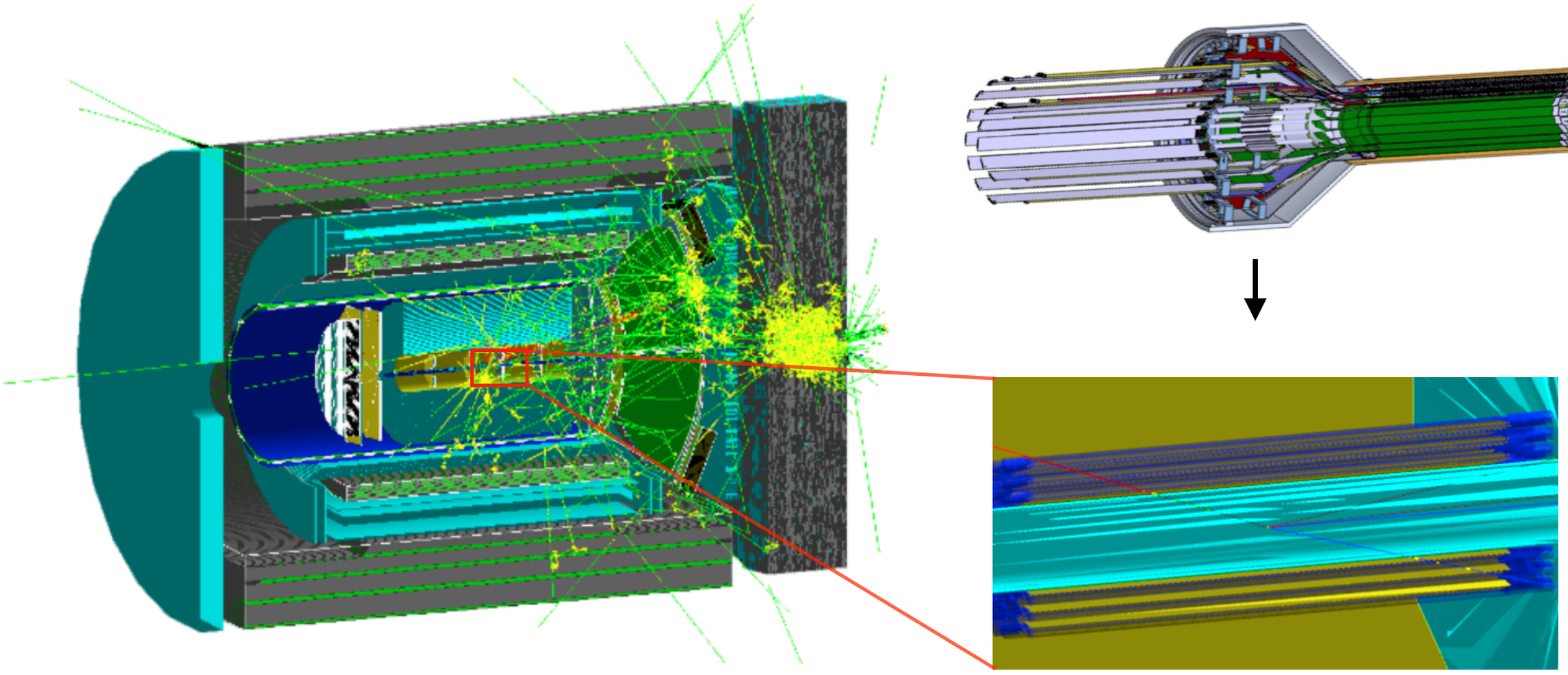


pp / $p\bar{p}$



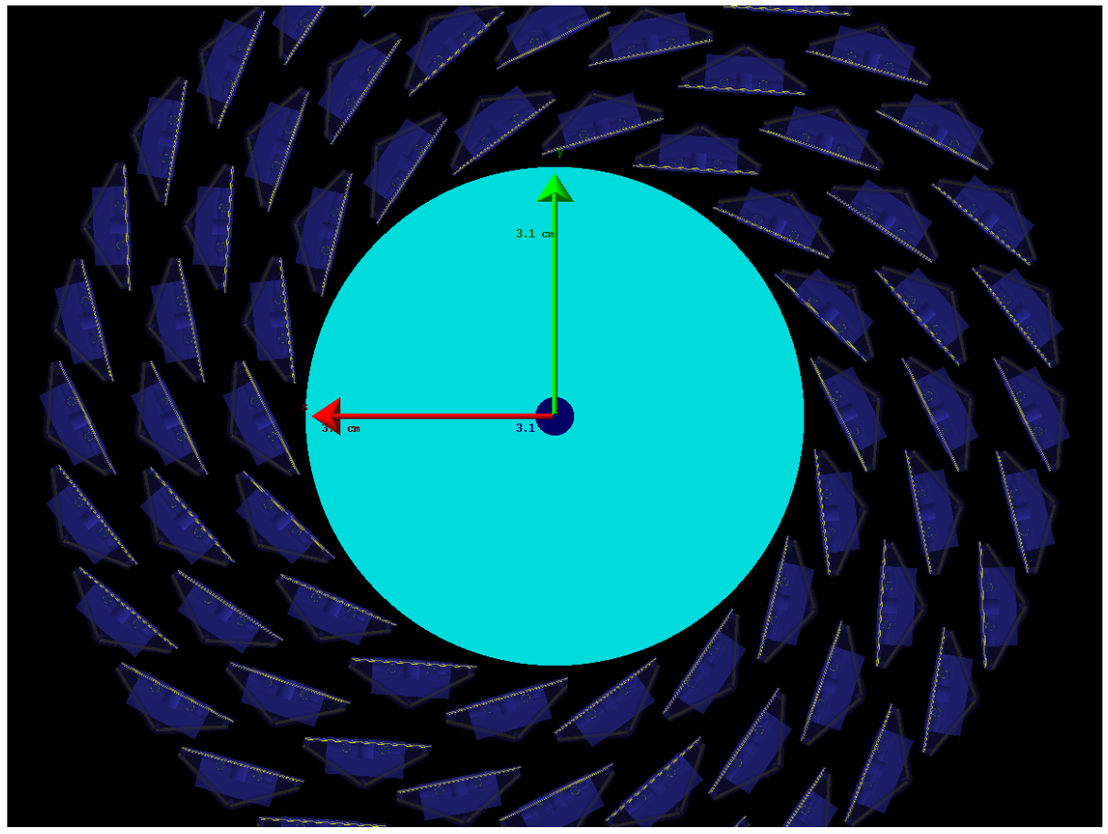


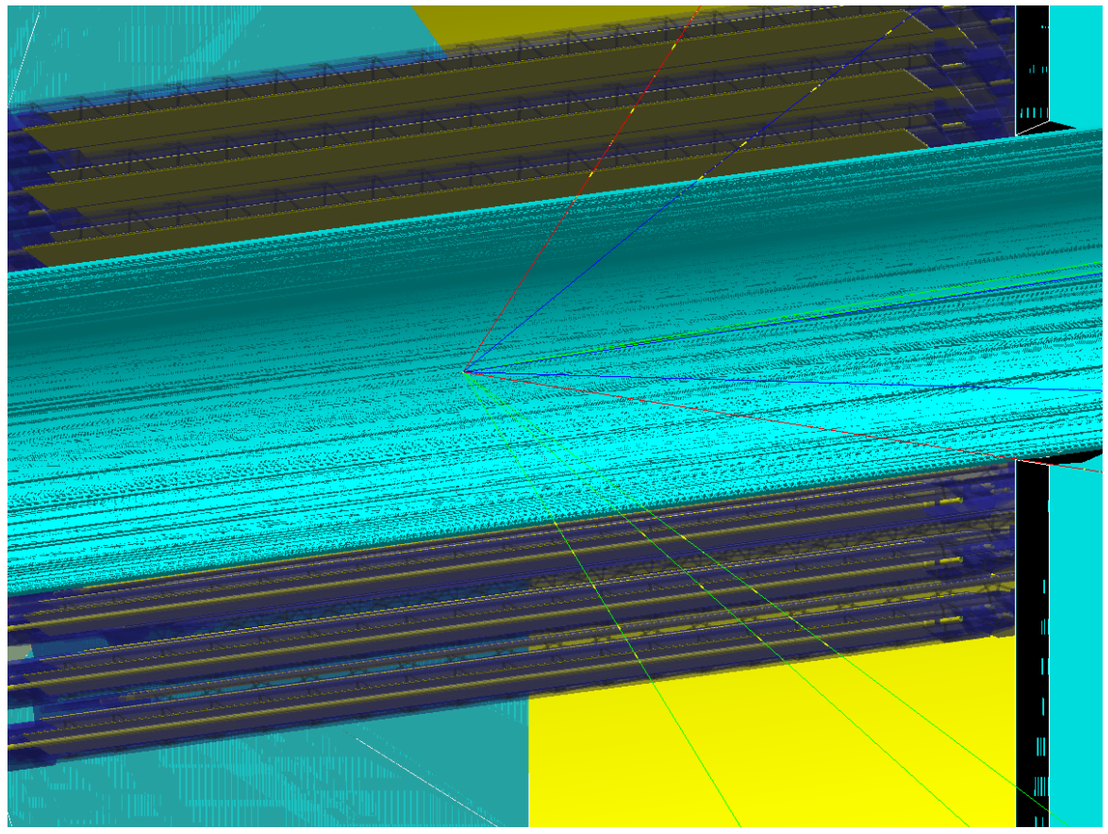
LQ event at sPhenix-EIC detector



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

Silicon Vertex Tracker Layout



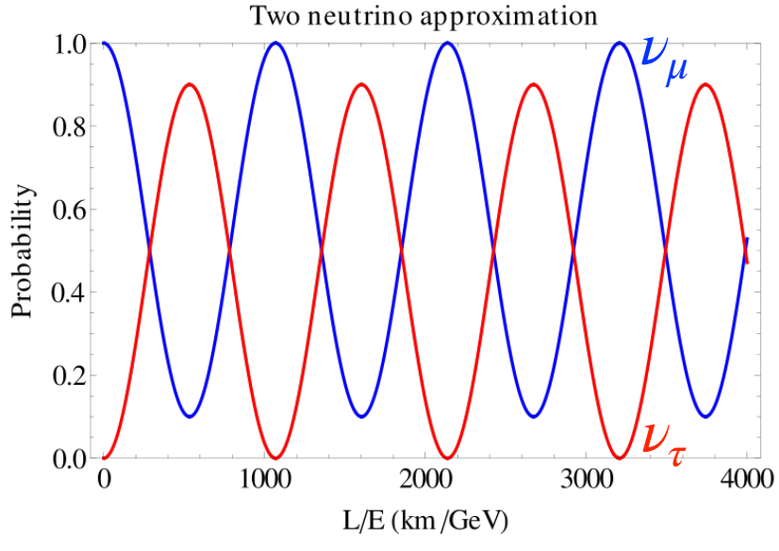


The EIC beam pipe is ~50% larger than the RHIC beam pipe. The MVTX geometry is adjusted to accommodate this pipe. The layout is based on the inner tracker from eRD16/18 from Håkan Wennlöf hwennlof@kth.se.

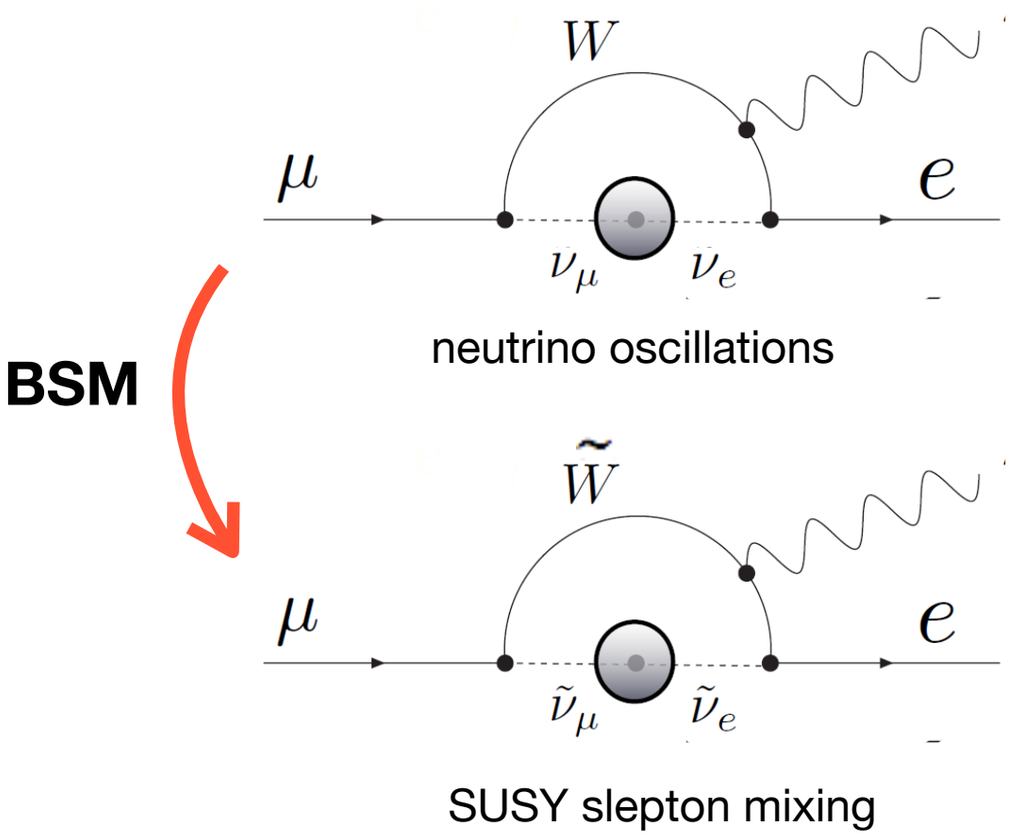
Charged Lepton Flavor Violation

- 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}



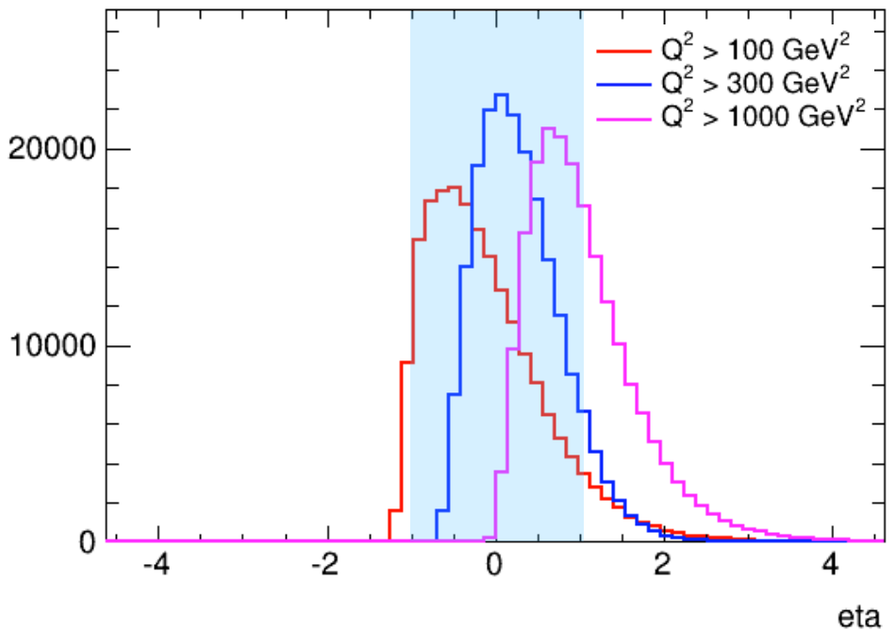
- Many BSM models predict significantly higher rate of CFLV, e.g. SUSY slepton mixing BR($\mu \rightarrow e\gamma$) < 10^{-15}



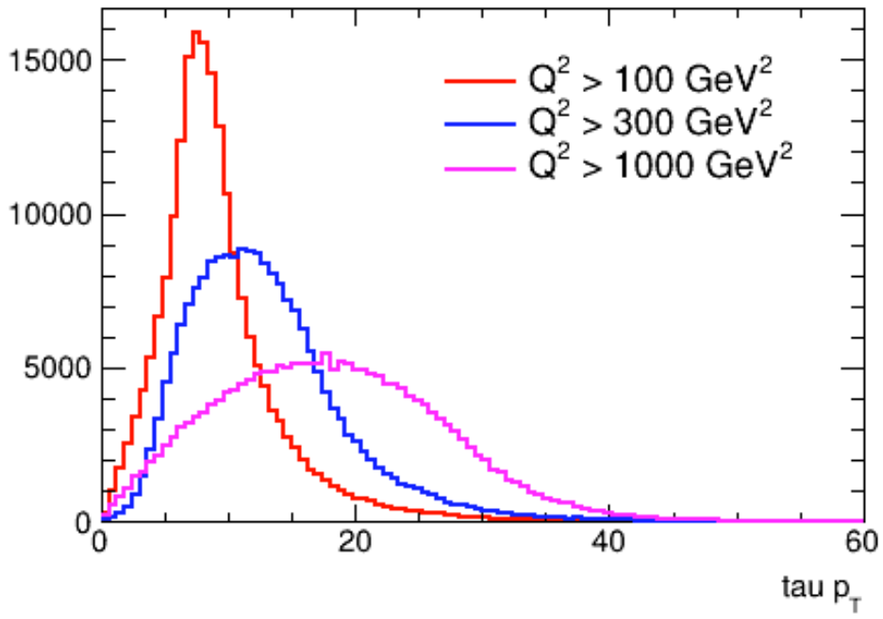
How LQ Tau looks like at e+p

18x275 GeV²

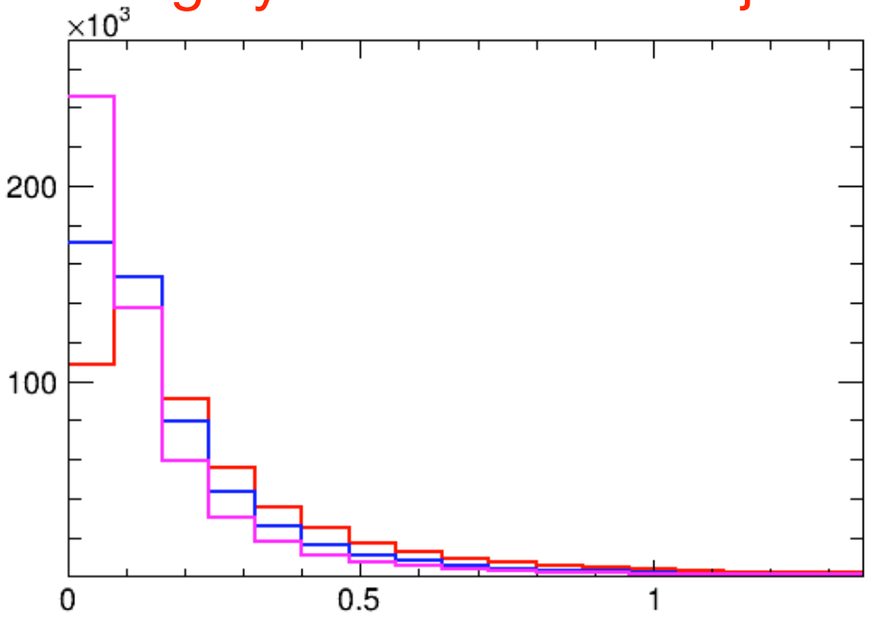
Mostly at Barrel (best detector performance)



high pT



Highly boosted narrow jet



Away from primary vertex by serval cm