Machine Learning for particle identification

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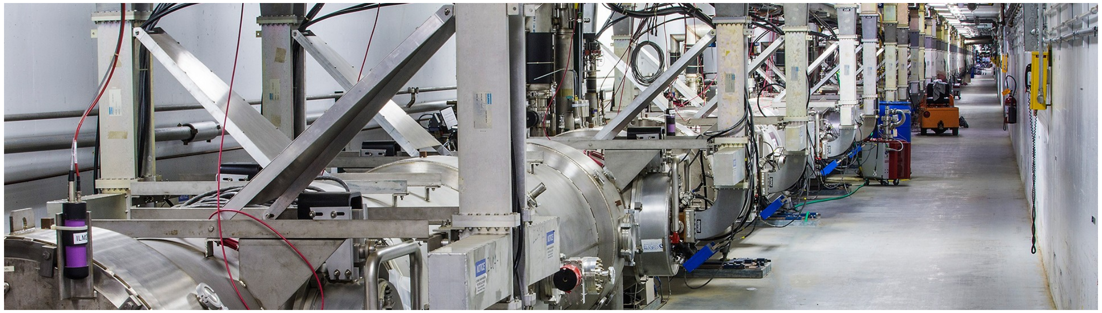
U.S. DEPARTMENT OF ENERGY · JSA · Jefferson Lab

Outline

- Introduction or global strategy for next generation of particle experiments
- Application of Machine Learning algorithms for particle identification
- Current implementation of ML algorithms for transition radiation detectors/trackers (as example)
- Conclusions

Third millennium accelerator/detector technologies for "Femto-world"



High luminosity accelerator facilities
(need for precision measurements and rear physics)

High granularity detectors
(high rate and precision measurements)

=> New requirements for **data processing** => especially for **online data processing**

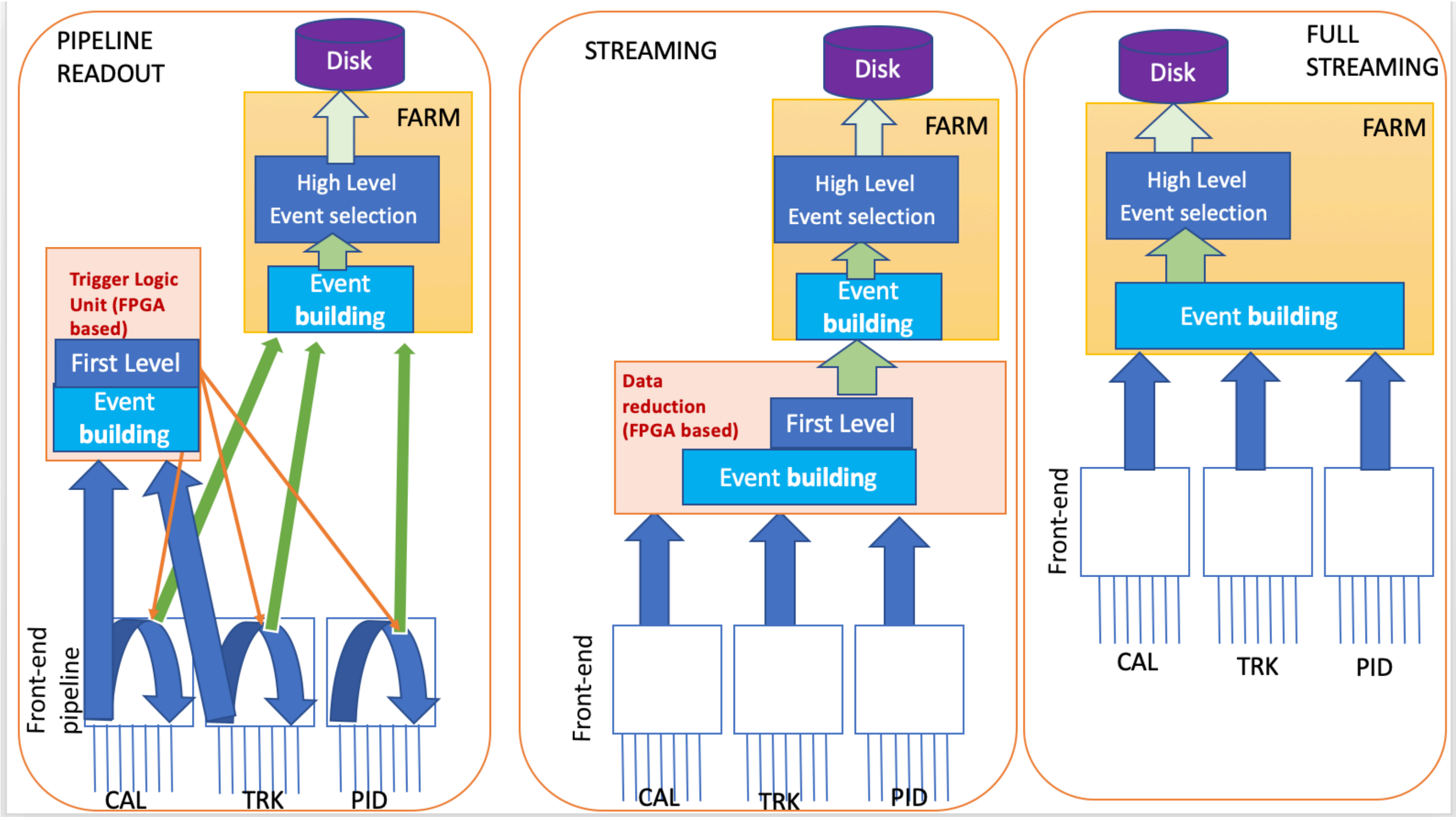
FPGA based

Computer Farm based

Online reconstruction of physics quantities

Readout system capable to handle high rate environments would allow to run at higher luminosity.

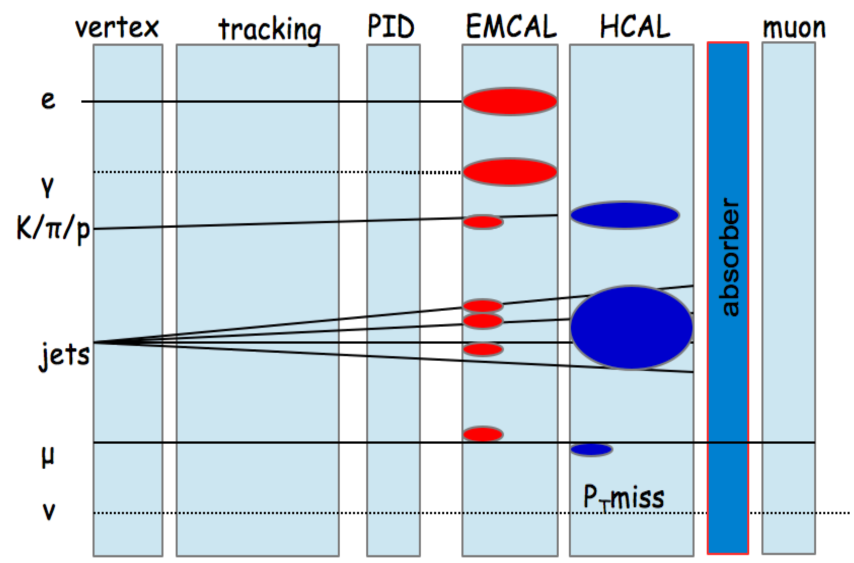
=> Having a possibility to reconstruct physics properties (p, E, vtx, pid) would allow to perform physics event selections (or online data reduction) more efficiently (before storage).



Particle identification

Limited number of "stable" final state particles:

- Scattered and secondary electrons
- Gammas
- Individual hadrons ($\pi^{\pm}$, $K^{\pm}$,p)
- Jet/Jets
- Muons (absorber and muon chamber)
- Neutrinos (missing PT in EM+HCAL)
- Neutral hadrons (n,K^0_L) (HCAL)



Looking at topology

- Electrons: EMCAL cluster + track pointing to cluster
- Gammas (γ): EMCAL cluster, no track pointing to cluster
- Neutrinos (ν): missing P_T
- Muons: track, min. energy in EMCAL, min. energy in HCAL, track in muon det.

Other Methods for PID (mass difference):

-dE/dx: (p<1GeV)

-Time-of-Flight: (p<3-6GeV)

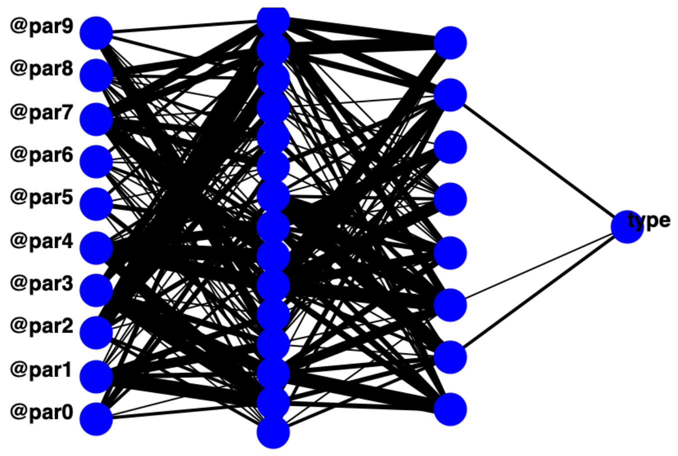
-Cherenkov radiation: p < 5 (50) GeV)

-Transition radiation: (e/h separation) 1 < p < 100GeV

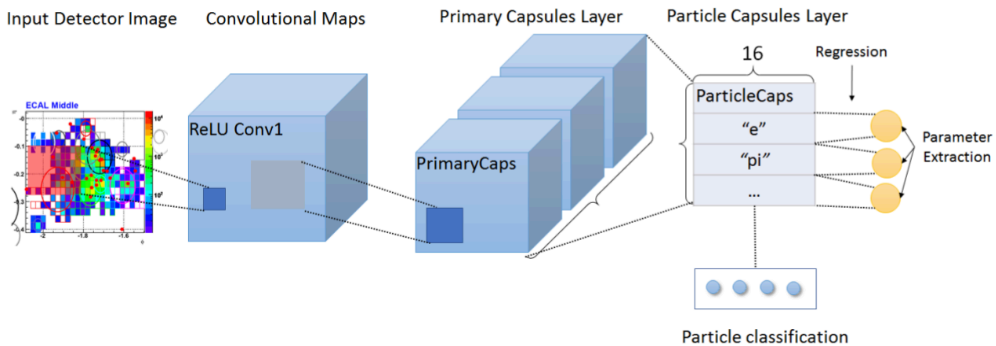
Machine Learning tools

Multivariate classification:

- **JETNET** (Fortran based Artificial Neural Network)
- **ROOT-based Toolkit** for Multivariate Data Analysis (TMVA) https://root.cern.ch/tmva:
  - -> Deep networks (DN)
  - -> Multilayer perception (MP)
  - -> Boosted decision trees



Capsule Networks (pixelated)
(first introduced by Geoffrey Hinton in 2017): joint proposal of ODU and Jefferson Lab to study application of capsule networks

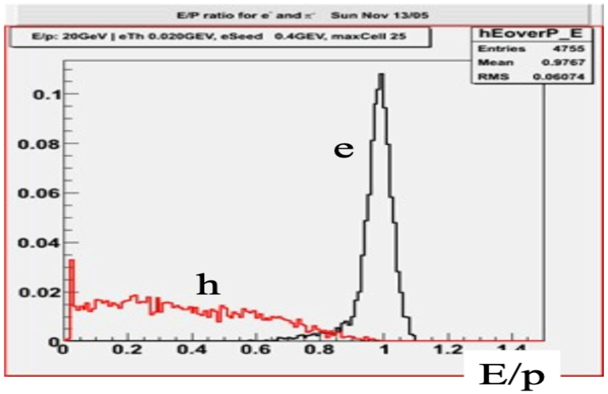


(Khan M. Iftekharuddin (ODU), D.Romanov (JLAB))

ML for PID with Calorimeter

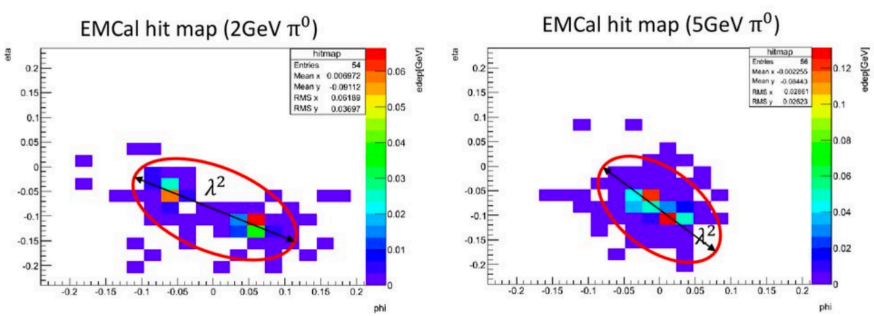
- <u>EMCAL Calorimeter:</u>
    - electron/hadron identification (shower profile, E/p)

      Multivariate classification



- gamma vs $\pi^0 \to \gamma\gamma$ (cluster profile)

  Capsule (pixelated) ML algorithms

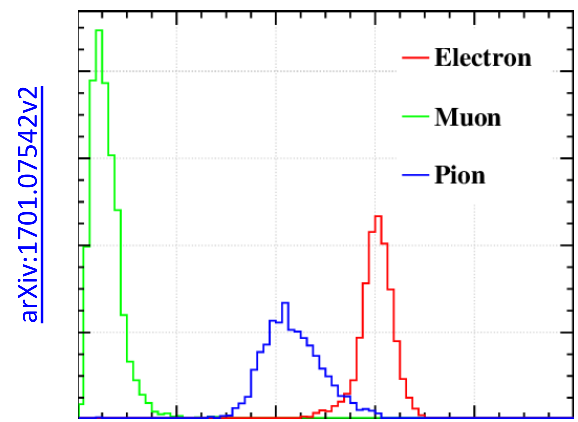


Pictures: Phenix collab.

- <u>Hadronic Calorimeter :</u>
    - electron/hadron identification (shower profile, EMCAL/HCAL)
    - Muons (EMCAL/HCAL)

  Multivariate classification

Fractal dimension using both ECAL and HCAL for e − , μ − and π + at 40 GeV



- Jets

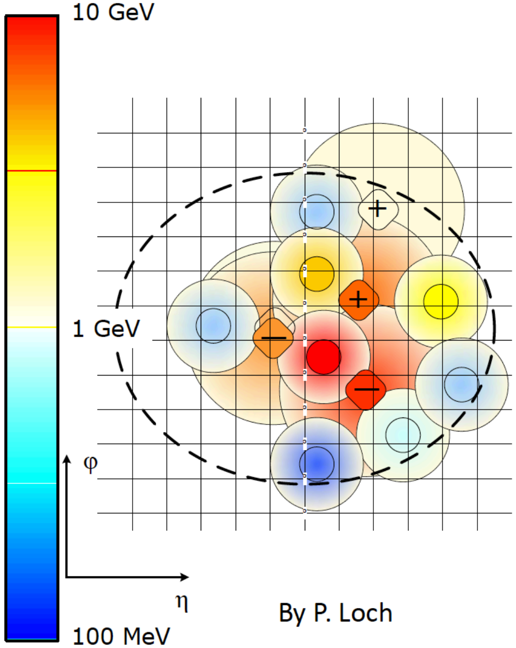
  Capsule (pixelated) ML algorithms

ML for Jets

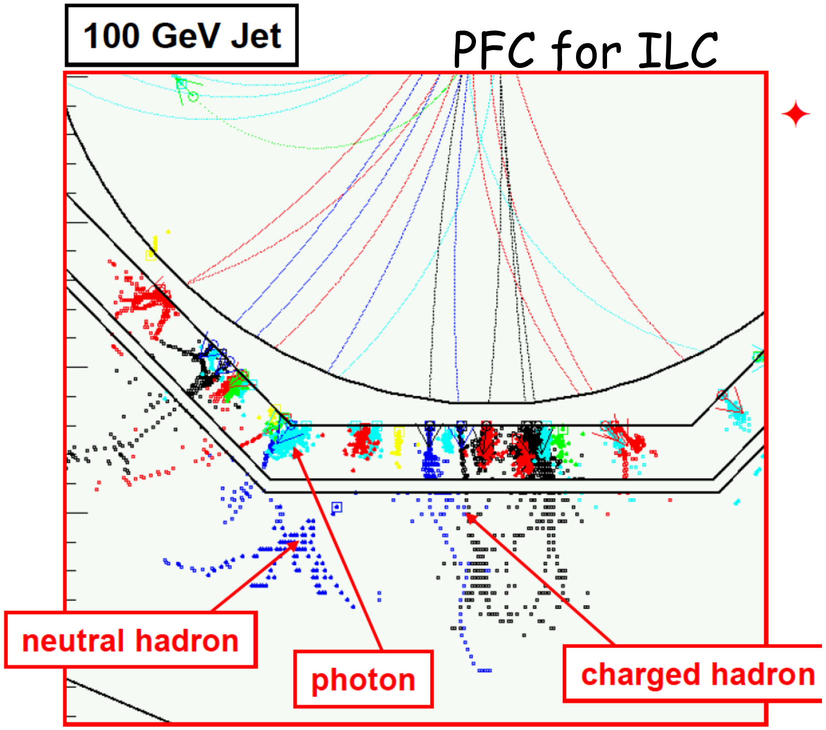
Particle-flow calorimeter

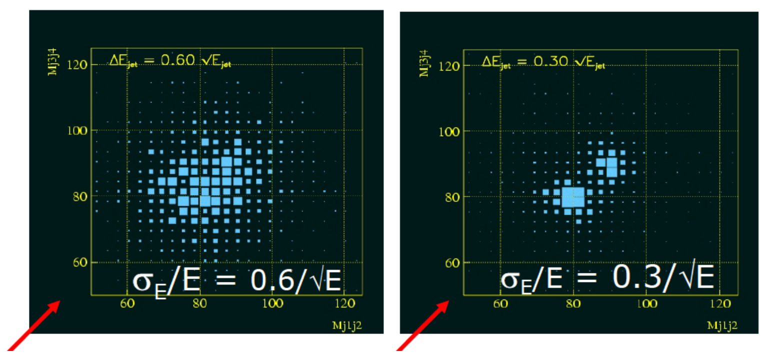
Capsule (pixelated) ML algorithms

- Jet-finding algorithms (shape of jet cone)
- Overlapping jets
- Sub-structure of jets



By P. Loch





Mark Thomson

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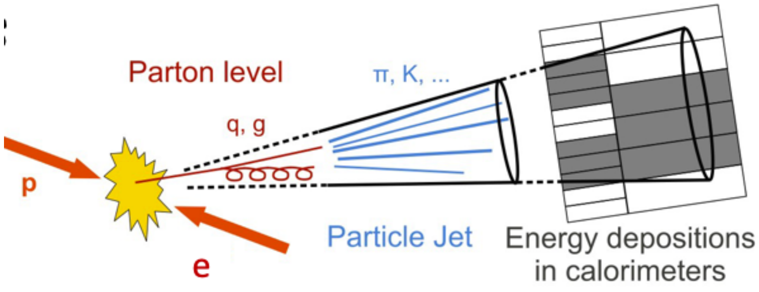
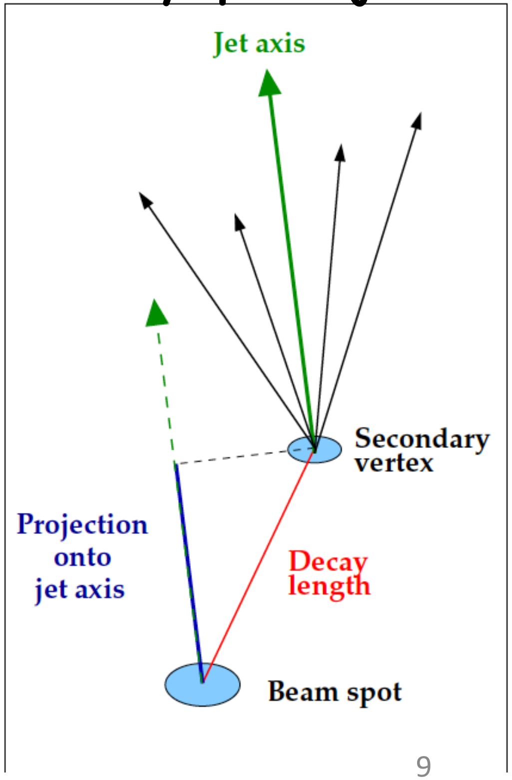
JET identification at parton level

Multivariate classification

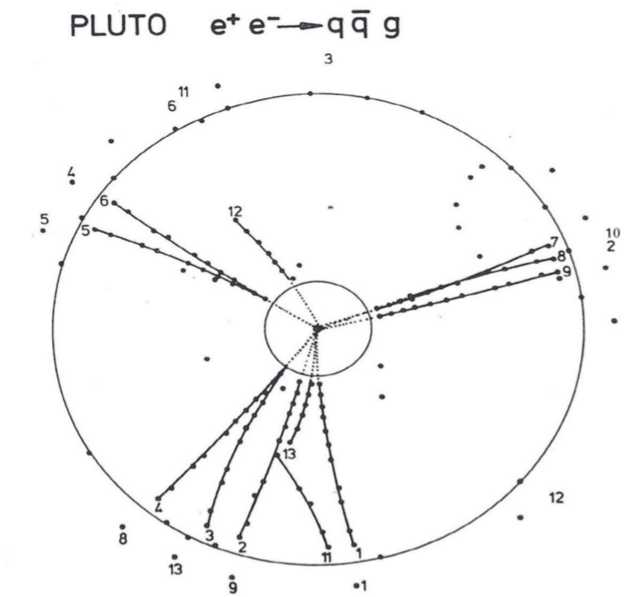


Use such properties as number of particles in jet, particle id, energy, shape, displaced vertex, etc..

Heavy quark jets

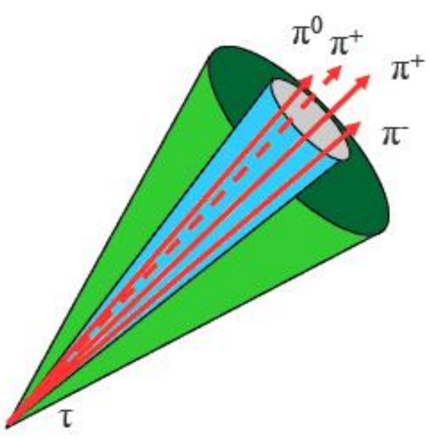


light-quark vs gluon-jet



DORIS e+e- storage ring (DESY)

Tau-Jets



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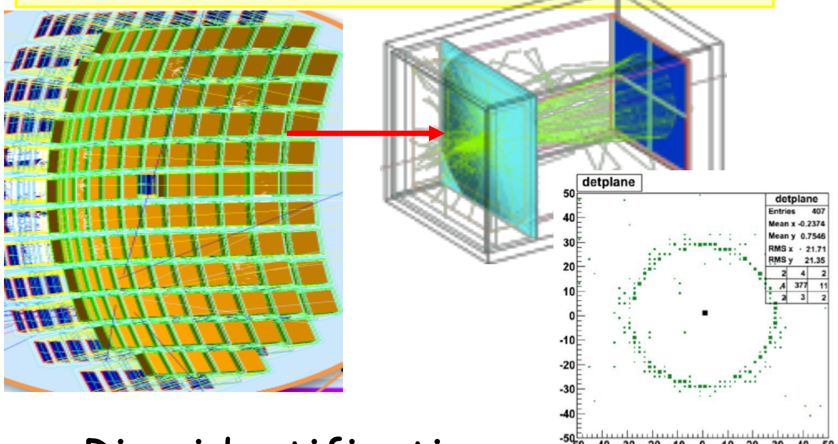
ML for Cherenkov, TOF, tracking detectors

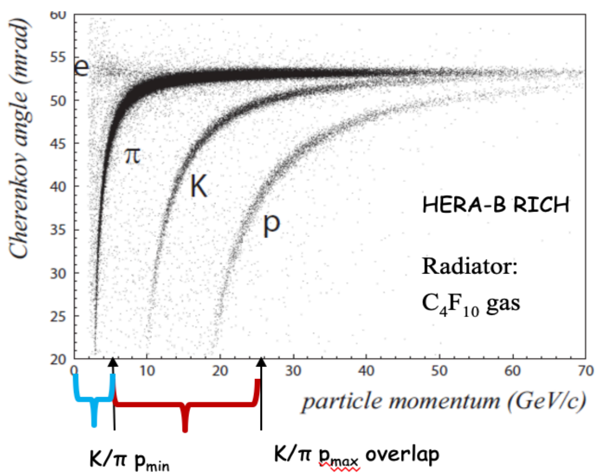
Example, Modular RICH for EIC



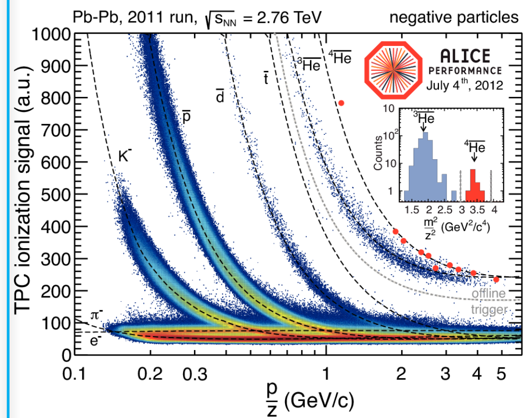
- Ring identification

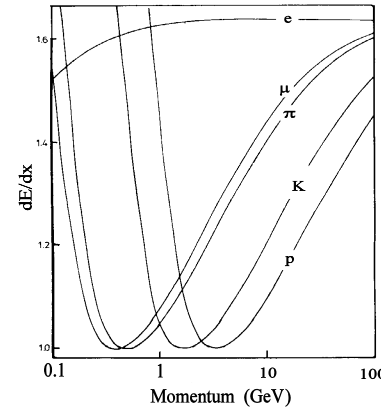
  Capsule (pixelated) ML algorithms
- Particle IDs

  Multivariate classification

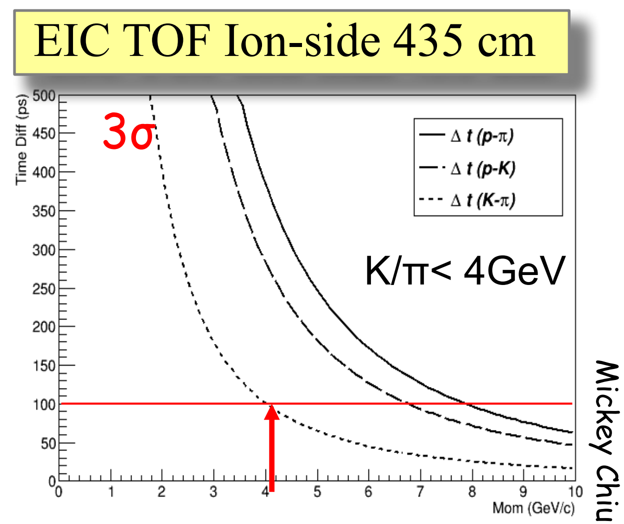


dE/dx in tracking detectors





TOF



ML for Transition radiation detector

(ongoing EIC detector R&D eRD22 project)

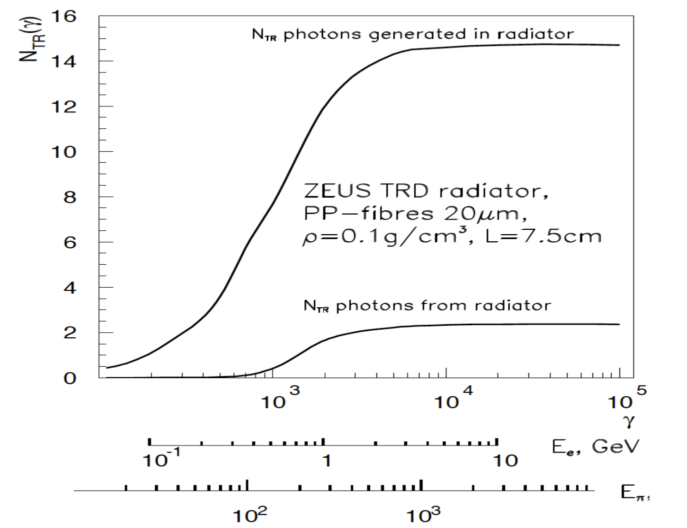
- Jefferson Lab:
  - ✓ Howard Fenker
  - ✓ Yulia Furletova
  - ✓ Sergey Furletov
  - ✓ Lubomir Pentchev
  - ✓ Beni Zihlmann
  - ✓ Chris Stanislav
  - ✓ Fernando Barbosa
  - ✓ Cody Dickover

- University of Virginia
  - ✓ Kondo Gnanvo
  - ✓ Nilanga K. Liyanage

- Temple University
  - ✓ Matt Posik
  - ✓ Bernd Surrow

ML for Transition radiation detector

(ongoing EIC detector R&D eRD22 project)



Transition radiation is produced by a charged particles when they cross the interface of two media of different dielectric constants

Use TRD for electron identification, electron/hadron separation (for particle γ>1000)

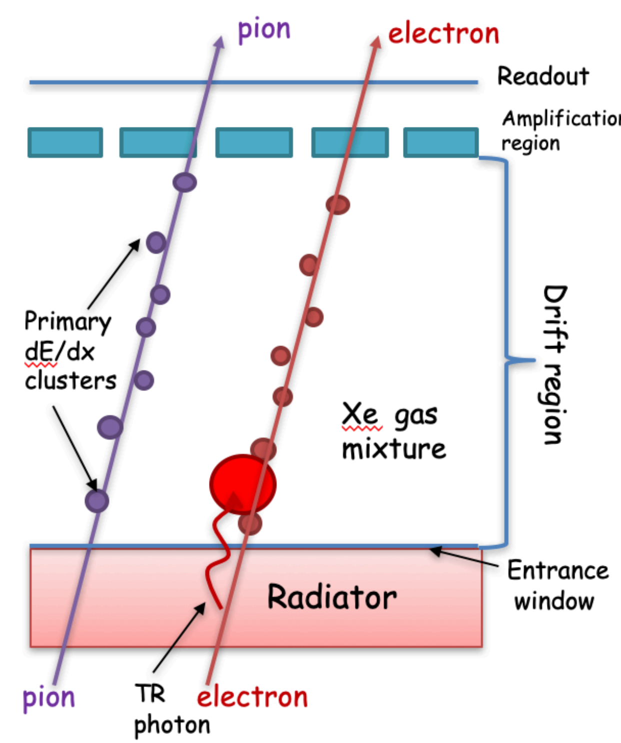
TR in X-ray region is extremely forward peaked within an angle of 1/γ

Energy of TR photons are in X-ray region (2 - 40 keV)

Total TR Energy ETR is proportional to the γ factor of the charged particle

TRD combined with GEM tracker: high granularity (high rate capabilities).

Overlapping clasters TR and dE/dx measurements



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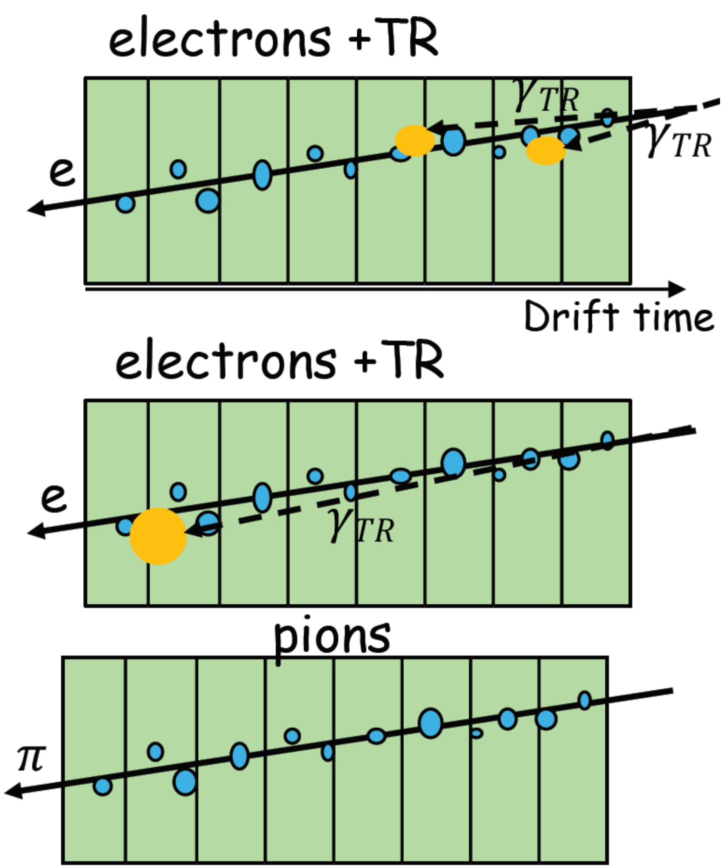
Electron and pion identification (TR photons)



Separation/ Identification of TR-clusters and dE/dx clusters

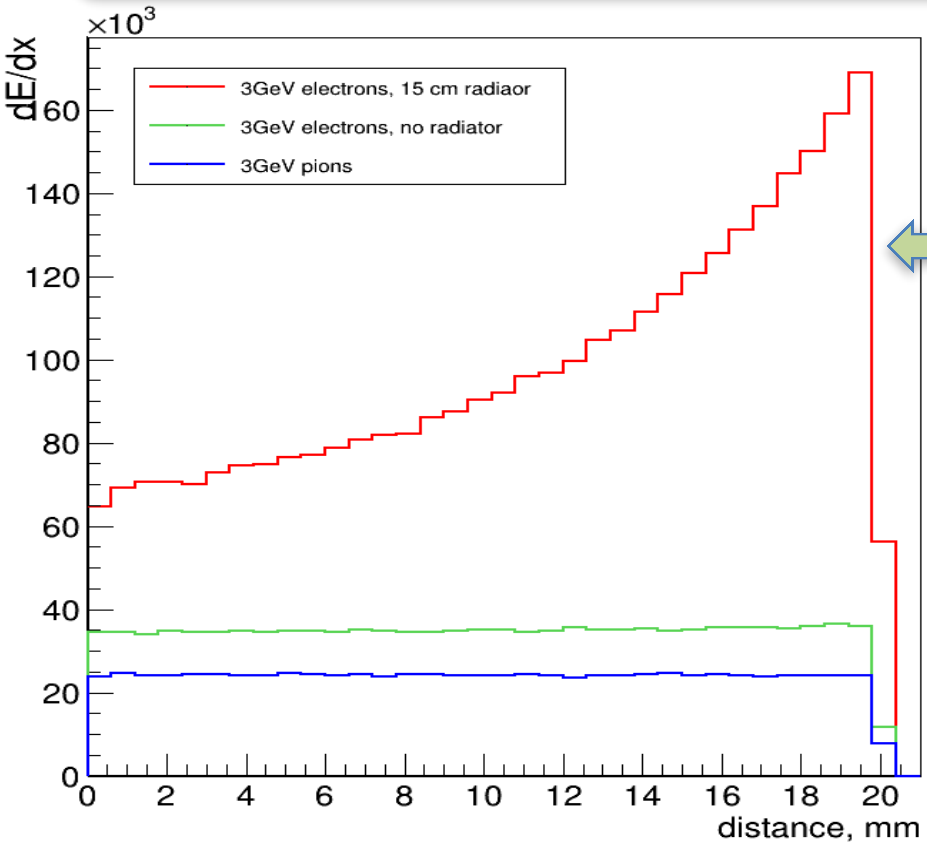
Electrons (dE/dx + TR photons)

- Soft TR-photons:
  - absorbs near entrance window, therefore have large drift time
  - sensitive to dead volumes, like Xe-gap, cathode material.
  - Increase of radiator thickness does not lead to increase of number of soft-photons (radiator self-absorption)
- Hard TR-photons:
  - Depending on energy of TR-photons, could escape detection (depends on detection length)
  - Increase of radiator leads to increase of hard TR-spectra.

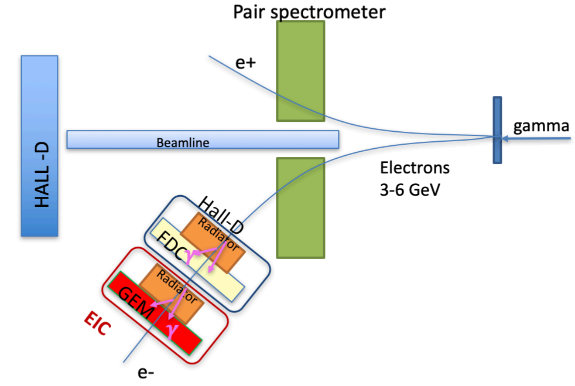
- Pions: dE/dx only

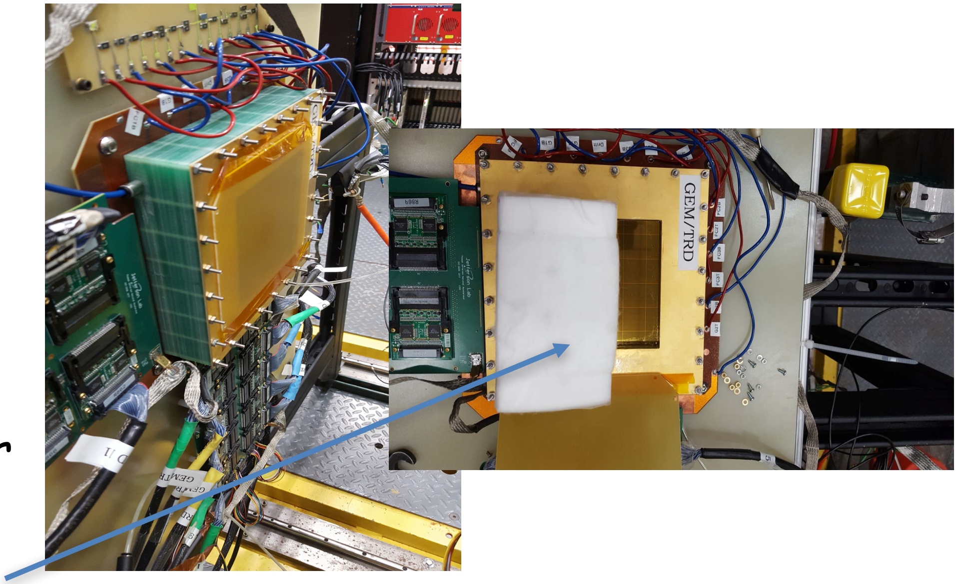
GEANT4: electron and pion comparison

Energy deposition (dE/dx + TR) vs drift distance



e,π ~3 GeV





- 3-6 GeV electrons in Hall-D from pair spectrometer
- covered ½ of the sensitive area with radiator (to mimic pion beam)

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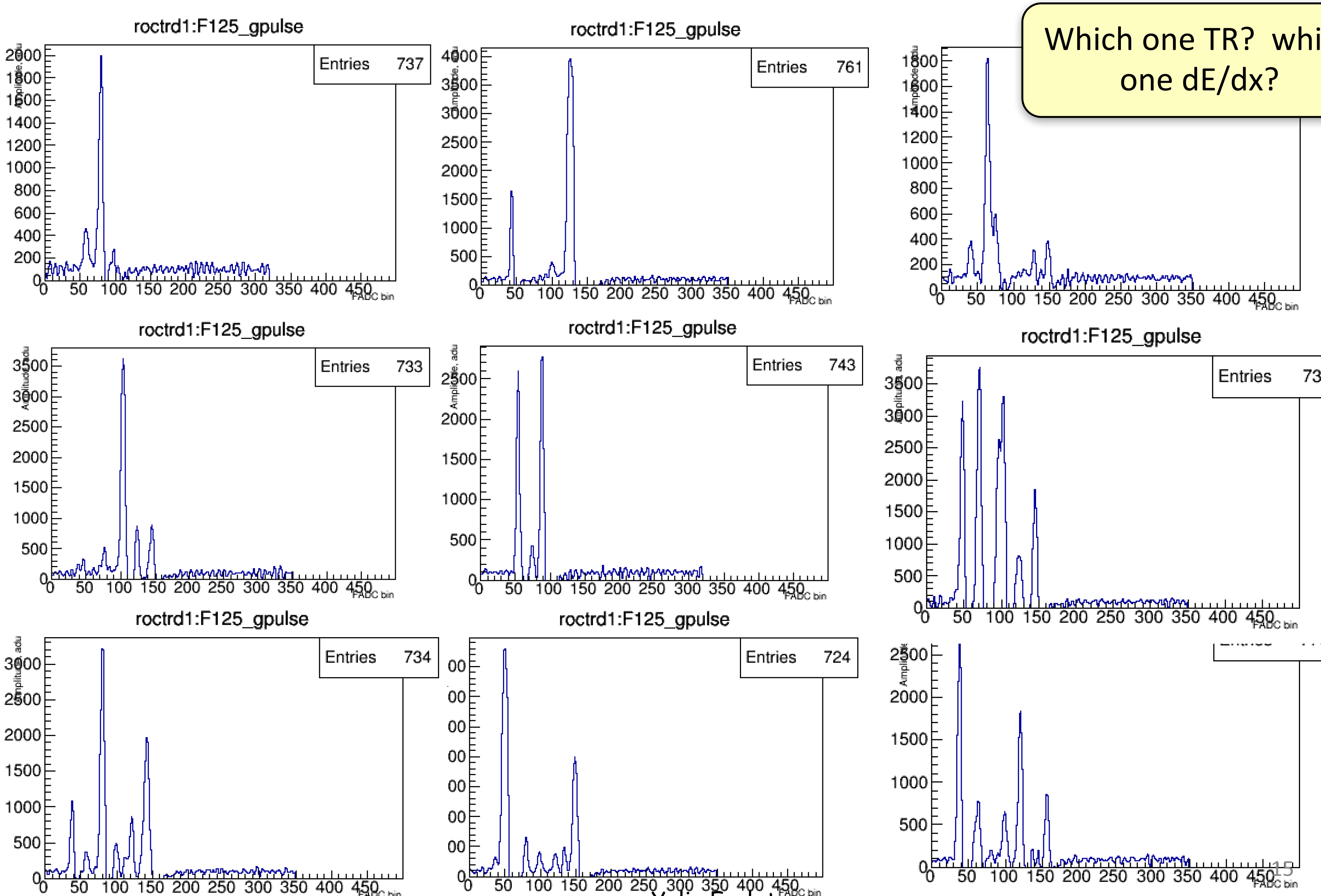
Signals from GEMTRD using FlashADC125



Which one TR? which one dE/dx?

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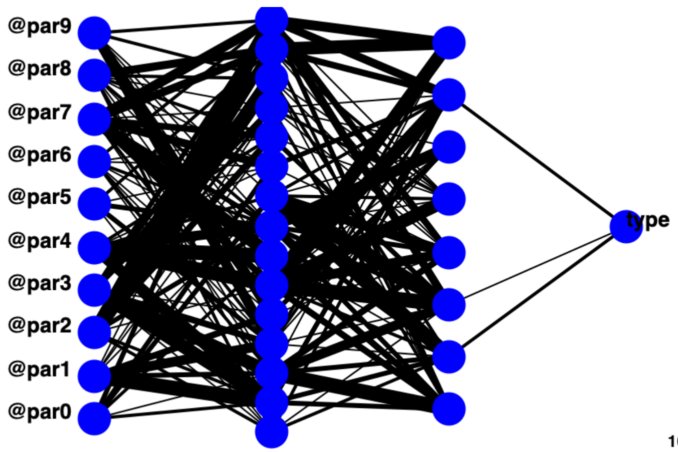
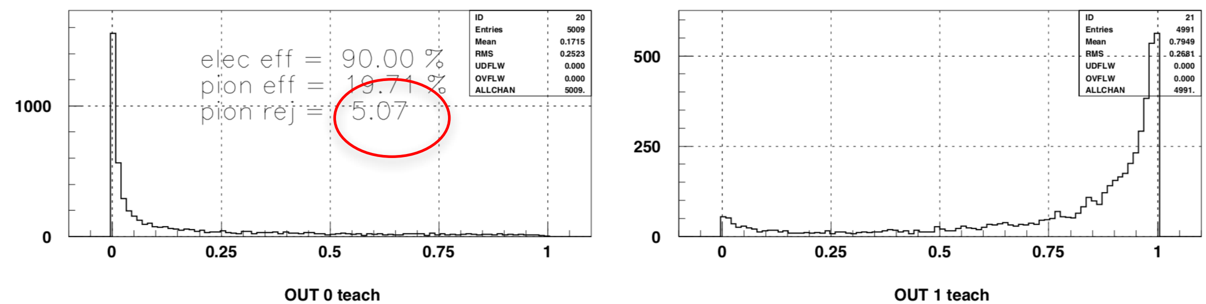
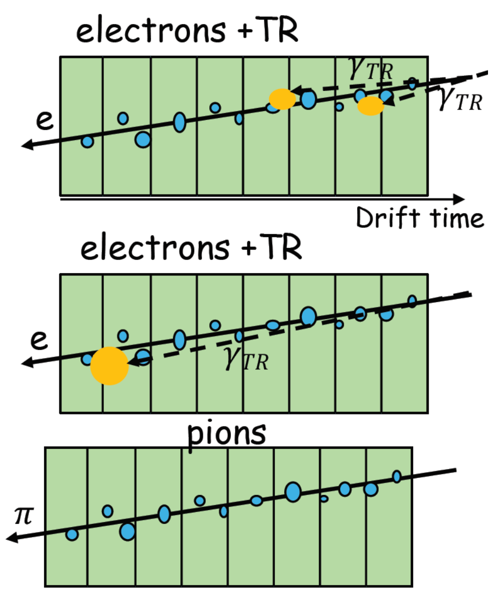
Machine learning technique



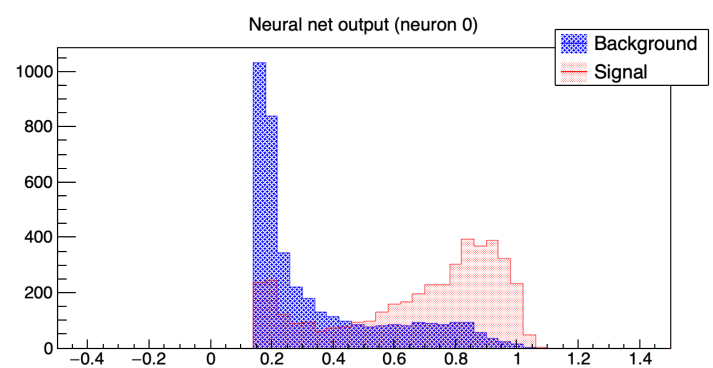
Used different methods/programs (JETNET, Root based-TMVA, etc) for cross-check.
Ca. 23 input variables (<E> per slice along drift distance, timing, etc)

Neural network output for e/π identification





Multilayer perceptron output for a single module (DATA sample)



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ML in FPGA

10x10cm module (GEM based tracking device), high granularity!

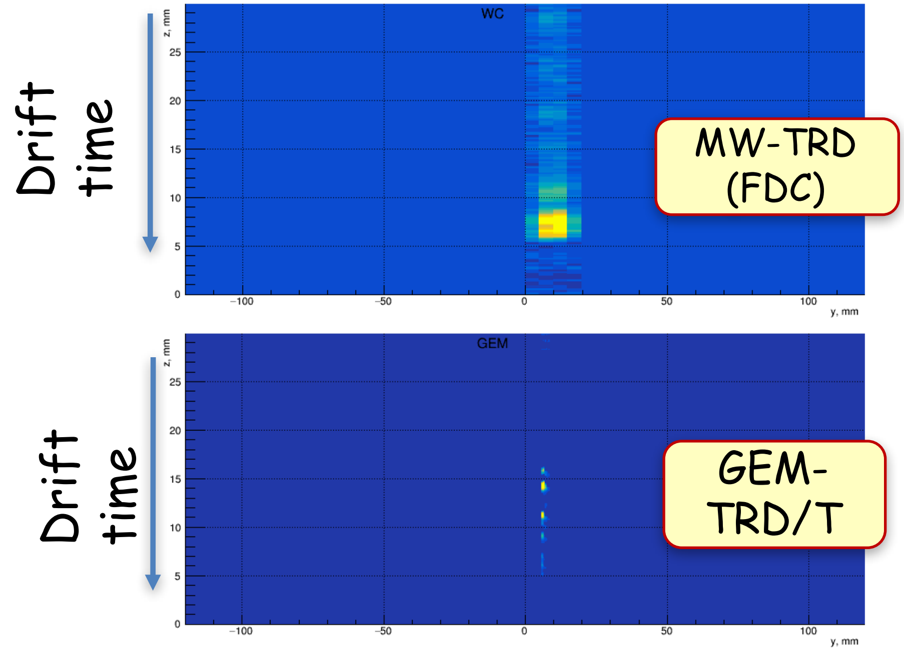
Raw-mode (trigger-less): 125MHz x 2 bytes x 1024 channels ~ **250 GBytes/s** (99.9 % is just noise/pedestals)

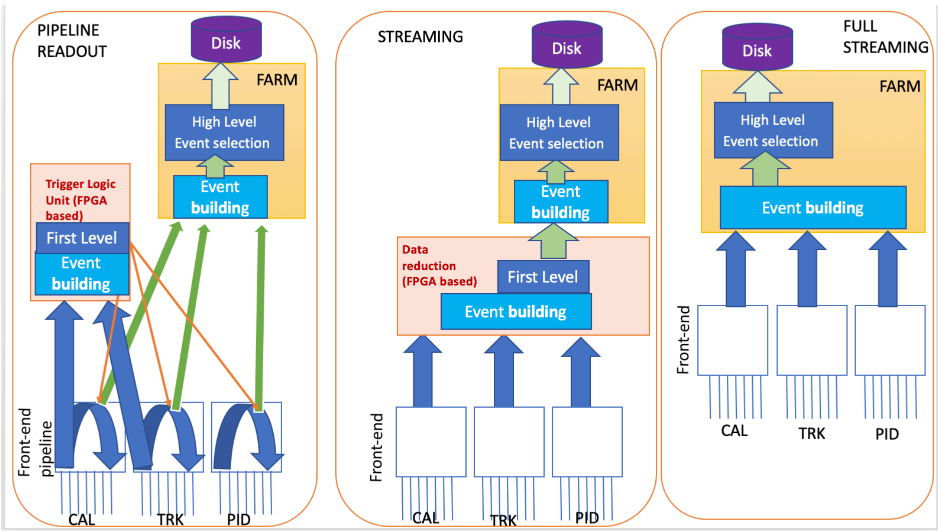
Difficult for streaming directly to farm, need data reduction at early stage (during online processing on FPGA)

Move data processing into FPGA
-> Zero-suppression and Cluster finding
-> particle identification

That would allow to include such types of detectors into a high-level event selection.

Ongoing development for GEMTRD EIC detector R&D eRD22 (GEMTRD) project!





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Summary

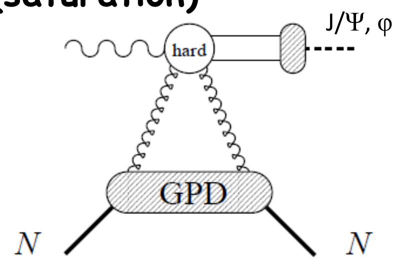
- Particle identification is very important for EIC physics. That's directly related to a physics event selection efficiency and precision measurements at the femto-scale level.
- With high luminosity and high data rate environment we should have a FAST decision (data reduction) along data transfer => ML in FPGA are naturally suited for that type of applications (online data reduction or high level physics event selection/trigger)
- Offline (on farm) ML particle identification algorithms could be used for GLOBAL Particle identification (combined information from different sub-detectors CAL, TOF, Cherenkov, dE/dx, TRD, etc), after individual sub-detectors FPGA ML decisions.

Thank you!

Backup

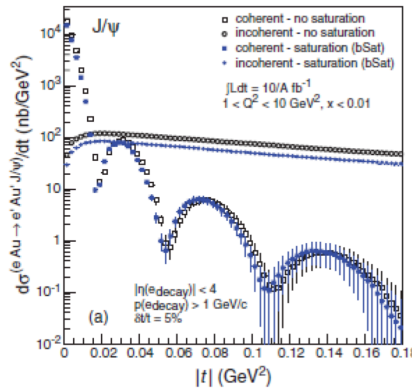
Electron identification (e/hadron separation)

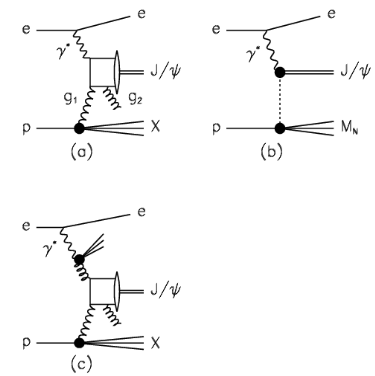
- **GPD and Coherent Exclusive Diffraction (saturation)**



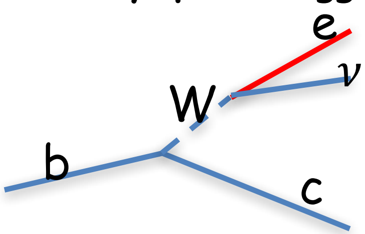
Br ($J/\psi \to e^+e^-$) ~6%

Br ($J/\psi \to \mu^+\mu^-$) ~6%



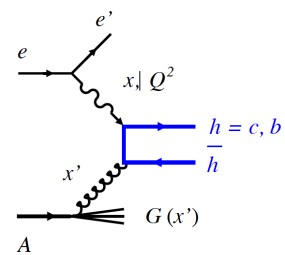


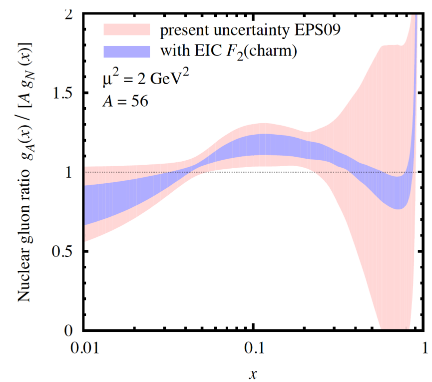
- **Heavy quark tagging**



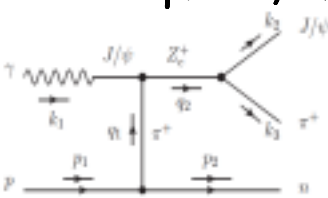
Br ($D^{\pm} \to e+X$) ~16%

Br ($B^{\pm} \to e+\nu+X_C$) ~10%





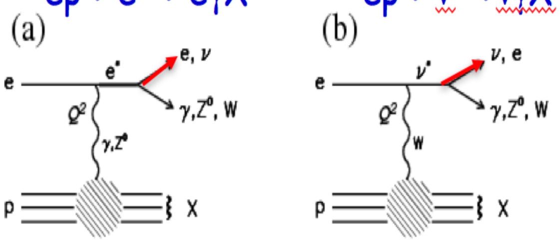
- **Exotic spectroscopy (pentaquarks, tetraquarks, XYZ)**

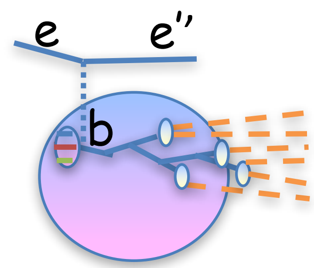


- **Other BSM physics**

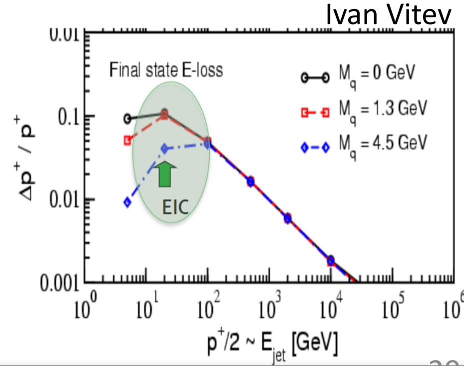
ep-> e*-> eγX

ep-> ν*->νγX





Ivan Vitev

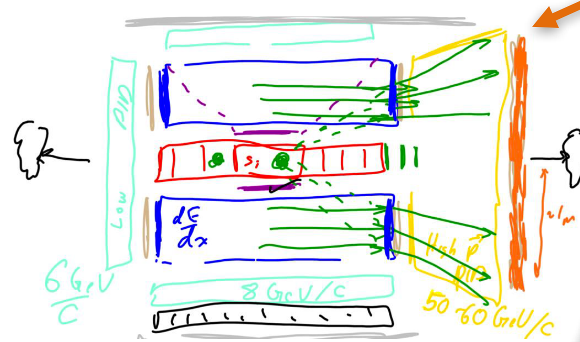


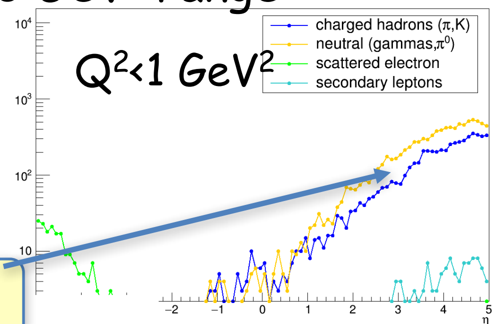
Electron/hadron separation

- The main detector for e/hadron separation is a Calorimeter. Also dE/dx in tracking detectors, as well as Cherenkov detectors could be used in the limited momentum range.
- TRD offers high e/h rejection for electrons in 1-100 GeV range

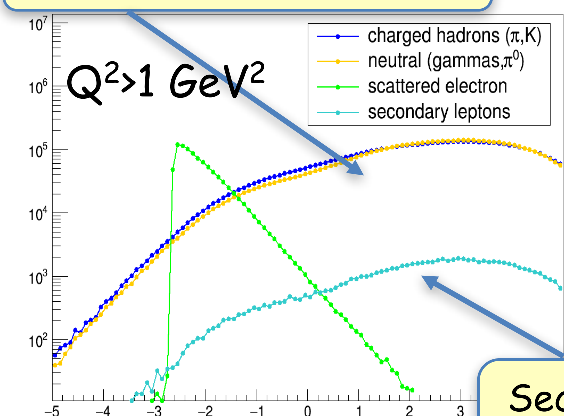
- Hadron end-cap
- between dRICH and EMCAL (extra tracking point)

GEM-TRD/T

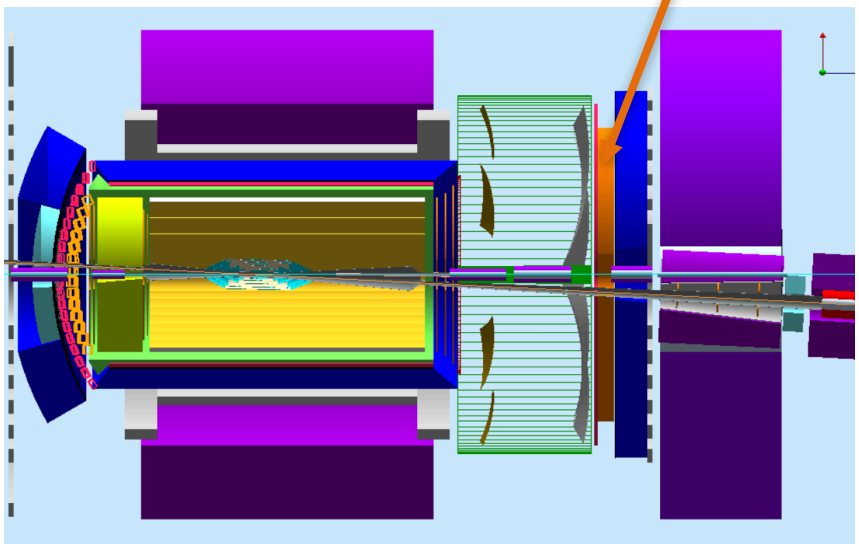




High hadron background



Secondary electrons, pt>100MeV



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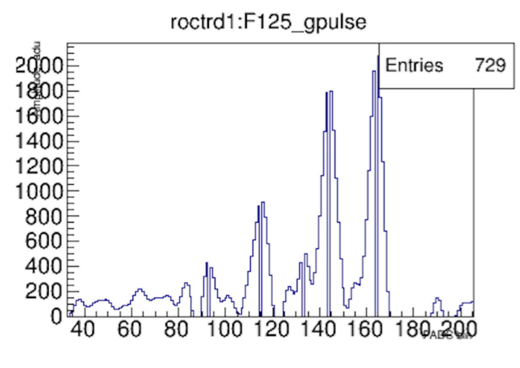
Electronics:



	MHz	ns/bin	Peaking time	Range	Channels/chip cost	ADC bits	Shaper
FlashADC125	125	8	30ns	$1\mu s$ or stream	\$50/channel	14bit	-Undershooting -No baseline restorer
APV25	40	25	50ns	625ns	128 chan/chip		Analog output (no digitalization)
DREAM (CLAS12)	40	25	50ns		64chan/chip		Analog output (no digitalization)
VMM3 (ATLAS)	4	250	25-200ns		64chan/chip	10bit	L0 or continuous
SAMPA (ALICE)	10-20	100-50	160ns	Stream 3.2Gbit/s	32chan/chip 30\$/chip 1\$/channel	10bit	500ns- return to baseline Baseline restorer, DSP (zero-suppression, thr)