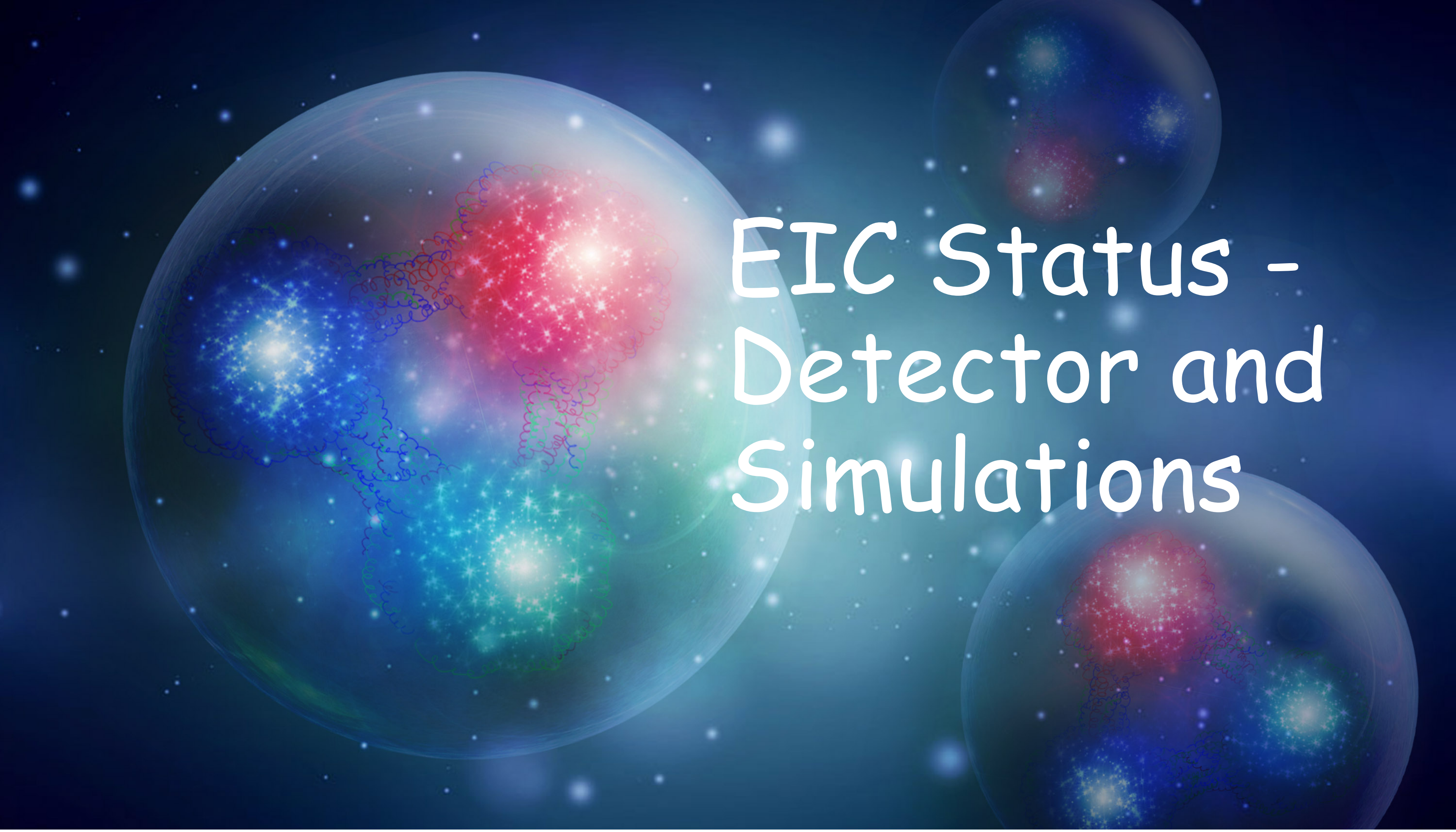
EIC Status - Detector and Simulations



Yulia Furletova

HUGS lectures

Outline

- Introduction to Electron Ion Collider
  - Highlights of EIC physics
  - US based EIC accelerators proposals
- Introduction to Deep Inelastic Scattering
  - DIS kinematic
- EIC detector design
  - Tracking
  - Vertex
  - Calorimeter
  - Muon detectors
  - Particle Identification detectors
    - dE/dx
    - Time of flight
    - Cherenkov
    - Transition radiation
- Detector simulation and reconstruction
- Conclusions

Lecture-1

Lecture-2

Lecture-3

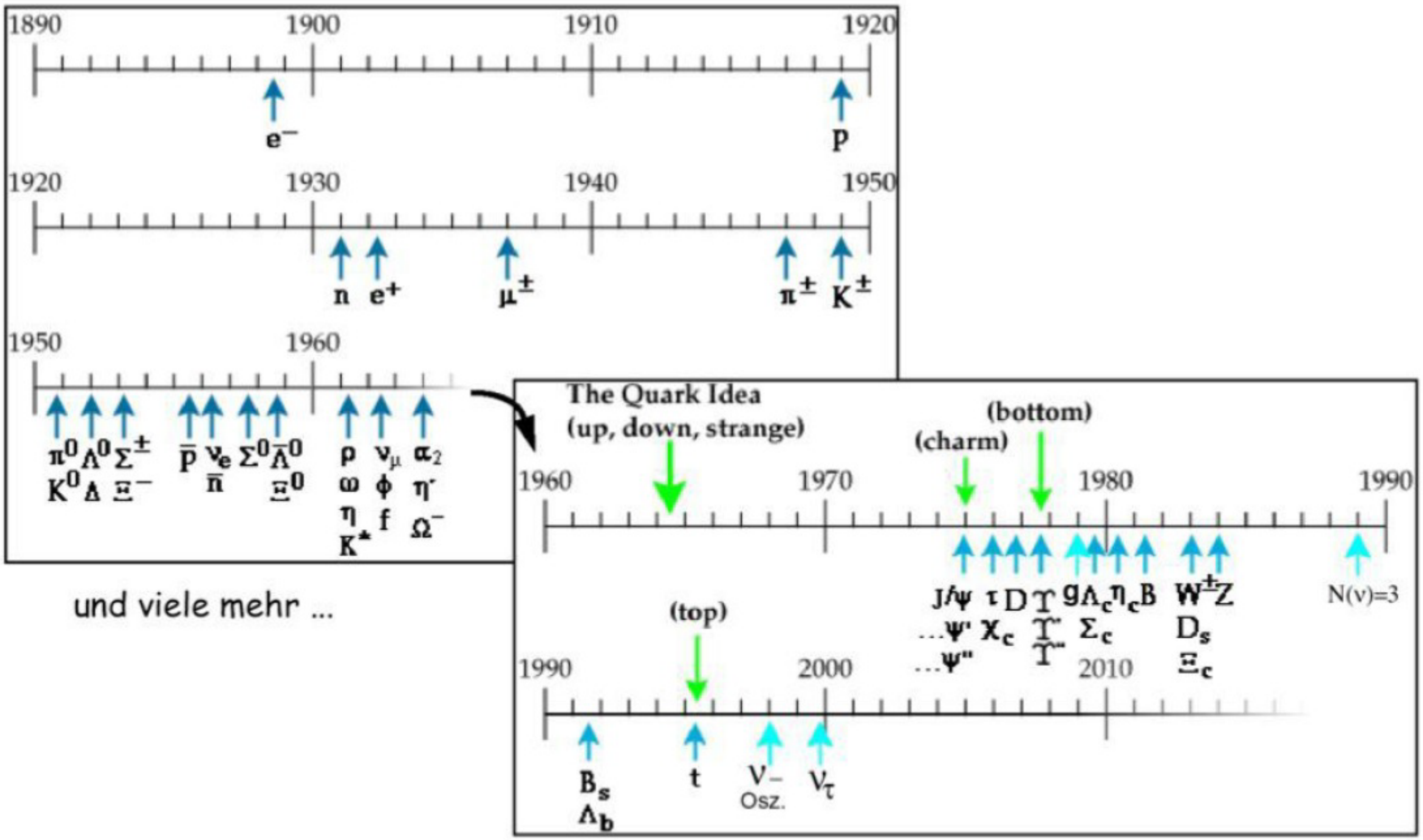
Lecture-4

Lecture-5

Particles

Today more then 200 particles listed in Particle Data Group (PDG)

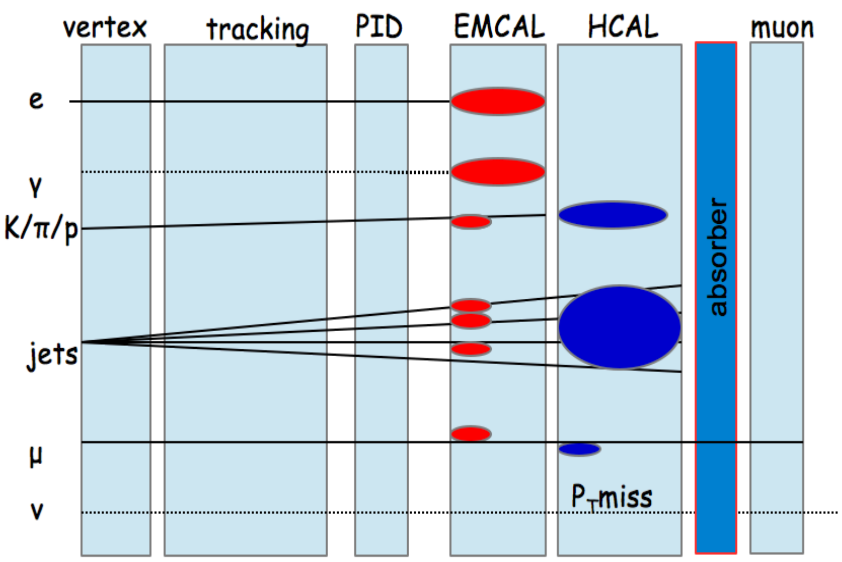
But only 27 have cτ > 1μm
and only 13 have cτ > 500μm



Particles associated with a struck quark

Limited number of "stable" final state particles:

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

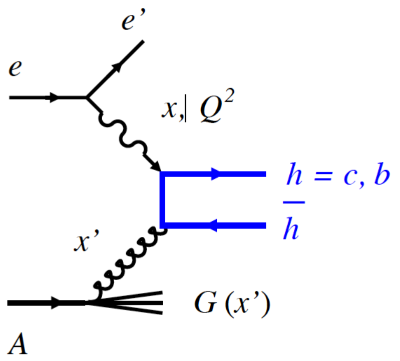


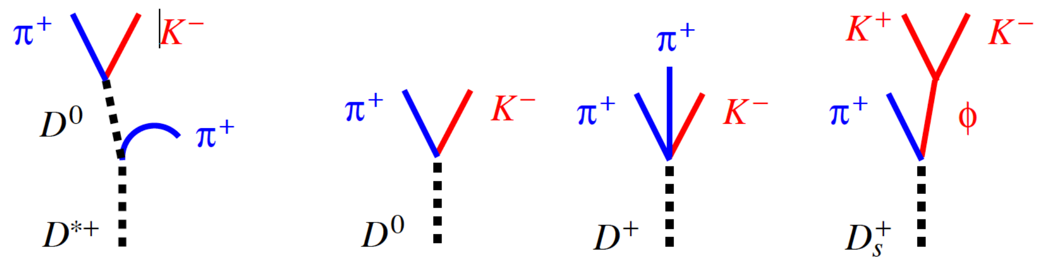
- Electrons: EMCAL cluster + track pointing to cluster
- Gammas (γ): EMCAL cluster, no track pointing to cluster
- Neutrinos (ν): missing P_T
- Muons: track, min. energy in EMCAL, min. energy in HCAL, track in muon det.

Short lived particles: hadron identification

Example: charm -> (fragmentation)-> D-mesons ->(decay) -> hadrons,leptons…
Invariant mass reconstruction

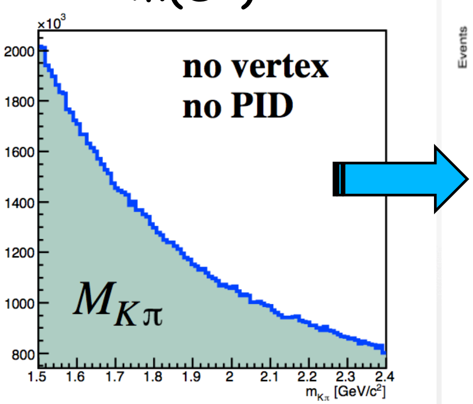
$D^{-*} \rightarrow \pi^{-}_{s} D^{0}$
↳ $\pi^{-}K^{+}$



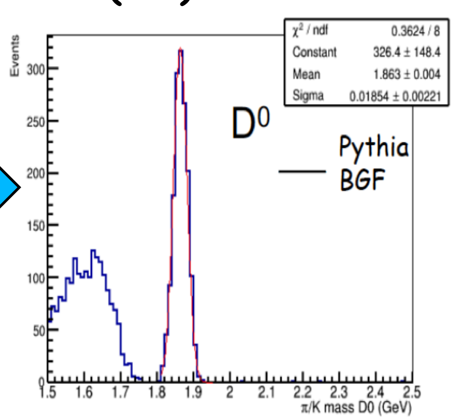


- high combinatorial background without PID

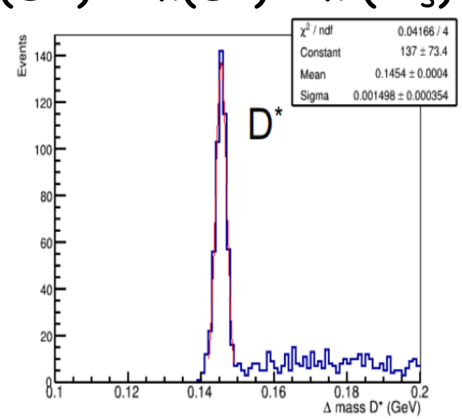
m(D⁰)



m(D⁰)

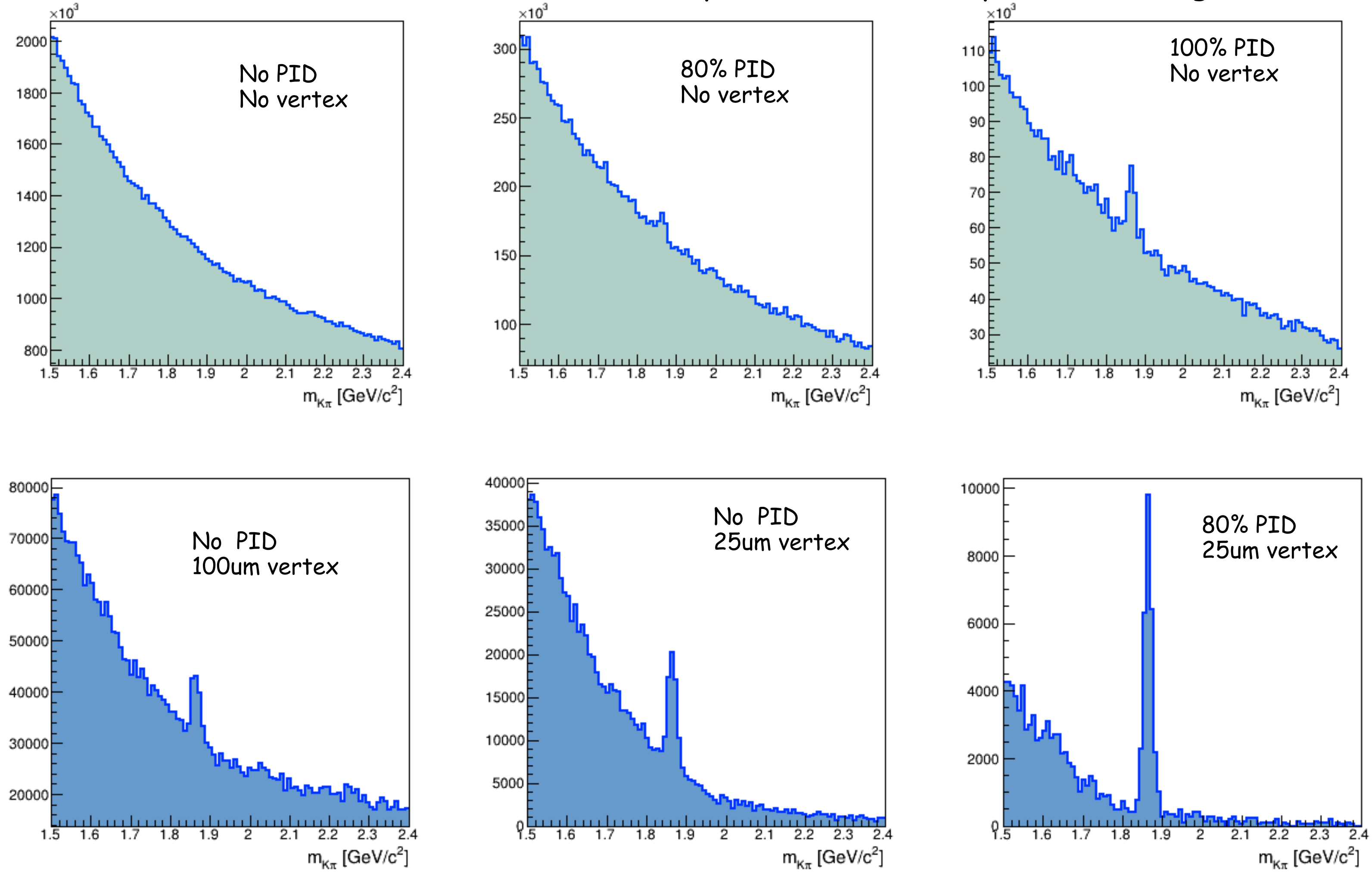


$m(D^{*}) - m(D^{0}) = m(\pi^{-}_{s})$



Individual charged hadrons(π, K, p)

$D^0 \to \pi K$ mass spectrum, on the top of DIS background



Yulia Furletova

Individual charged hadrons(π, K, p)

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

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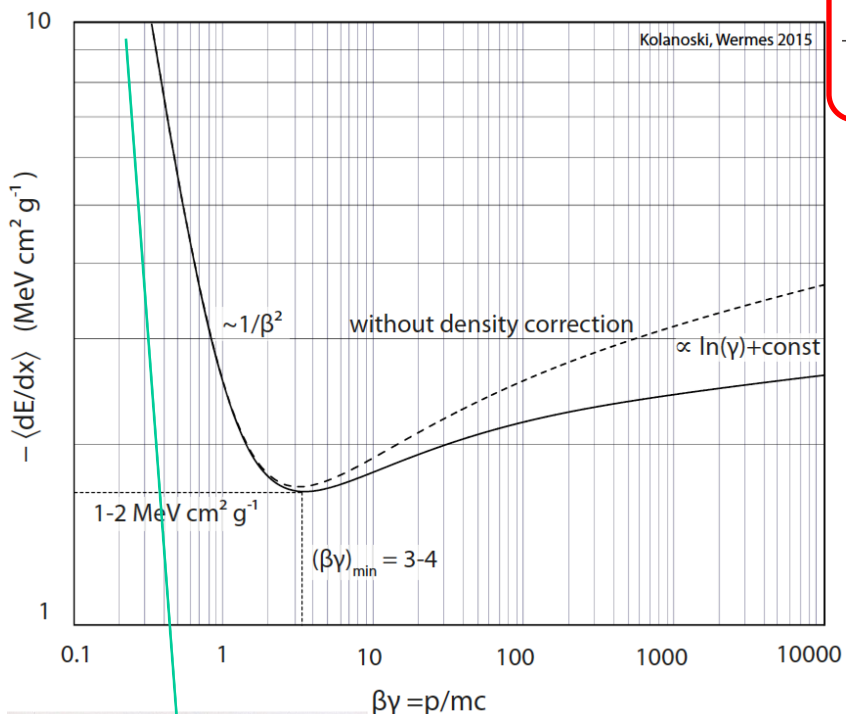
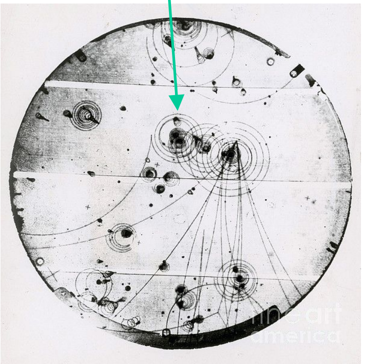
Energy loss dE/dx

Most tracking detectors are ionization detectors





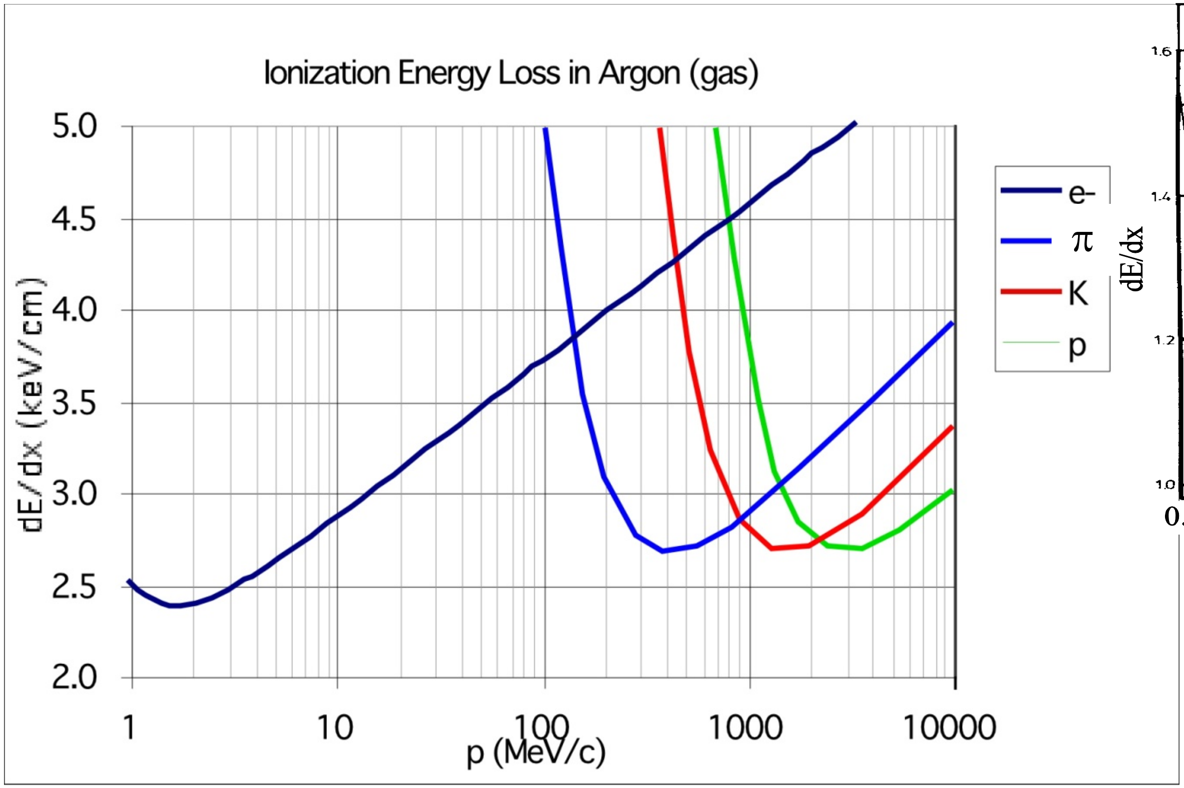
$$-\left\langle \frac{dE}{dx} \right\rangle = K \frac{Z}{A} \rho \frac{z^2}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} - \frac{C(\beta\gamma, I)}{Z} \right]$$

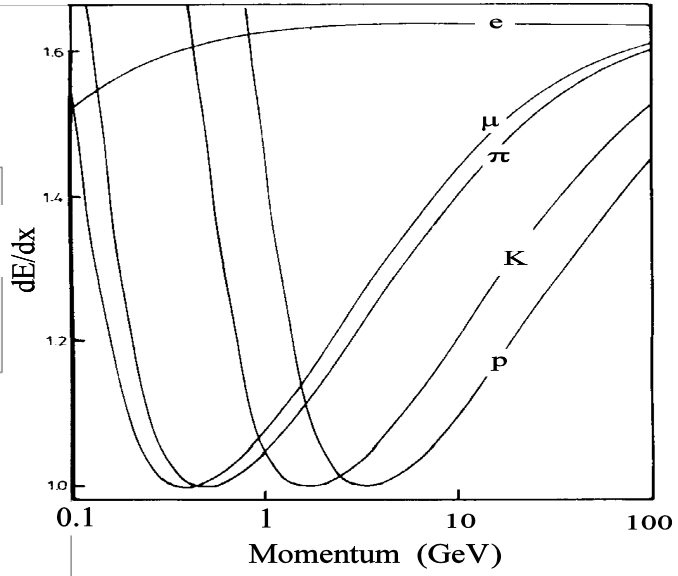
- Almost does NOT depend on material ($Z/A \sim \frac{1}{2}$)
- Proportional to z^2
- Depends on $\beta\gamma$ = p/E *E/m = p/m
- The same curve for all z=1 particles when plotted as a function of $\beta\gamma$)
- Have a minimum at $\beta\gamma$ =3-3.5
- Plateau at high $\beta\gamma$
- But… different curves when plotted as function of p(momentum) -> particle identification

Rolf Ent

Energy loss dE/dx

same curve plotted vs. momentum for different particles.

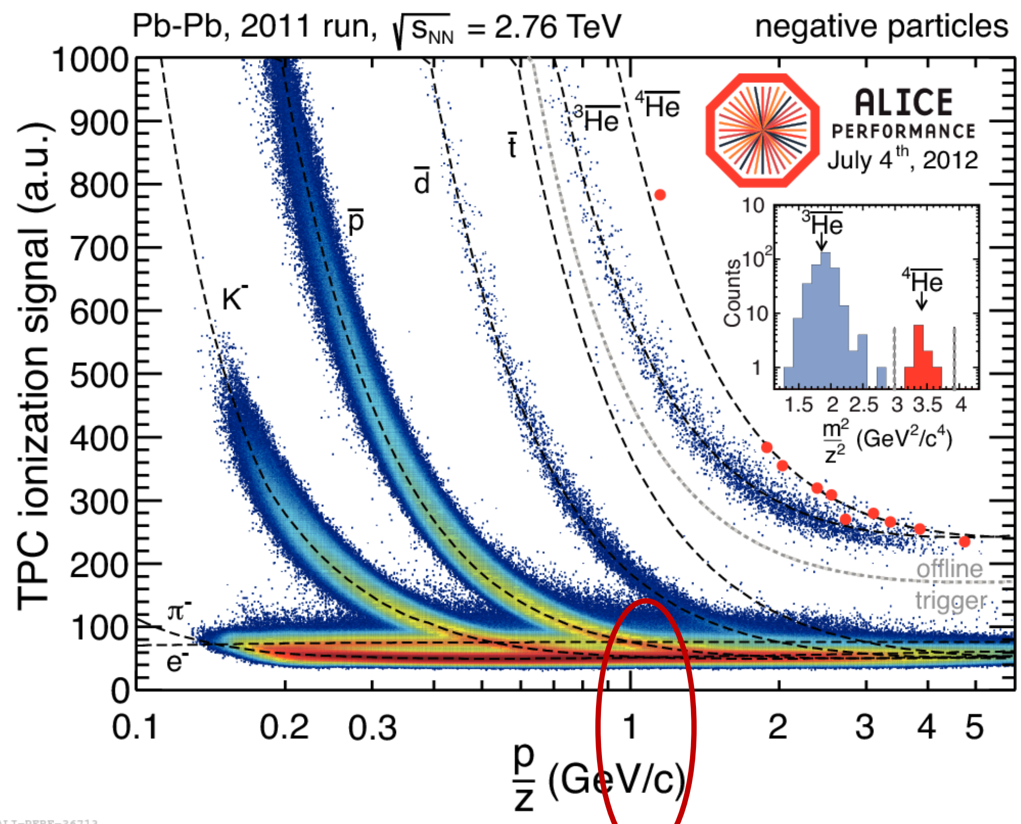




- Limitation : p<1GeV
- Could be used for higher momentum due to he relativistic rise of the Bethe-Bloch curves
- Depending on available electronics a **cluster counting** method could be used to improve momentum coverage

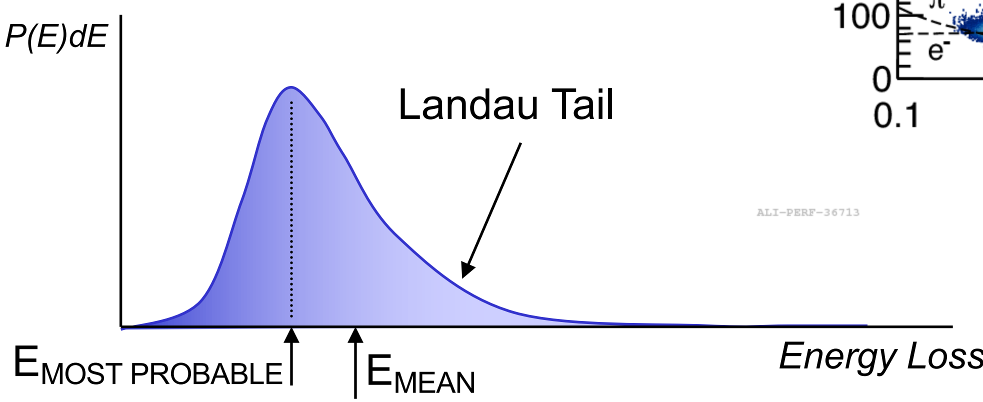
Energy loss dE/dx

same curve plotted vs. momentum for different particles, measured at tracking detectors (TPC, straw,MW, etc)

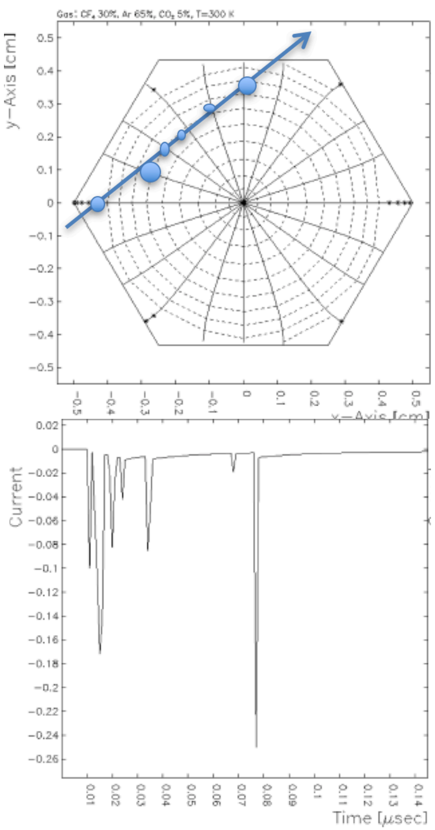


Measurements of energy loss are limited both by detector resolution and by the fundamental statistical nature of the energy loss process…

Energy loss may be skewed towards higher values by low-probability hard-scatters, leading to the *Landau Tail.*

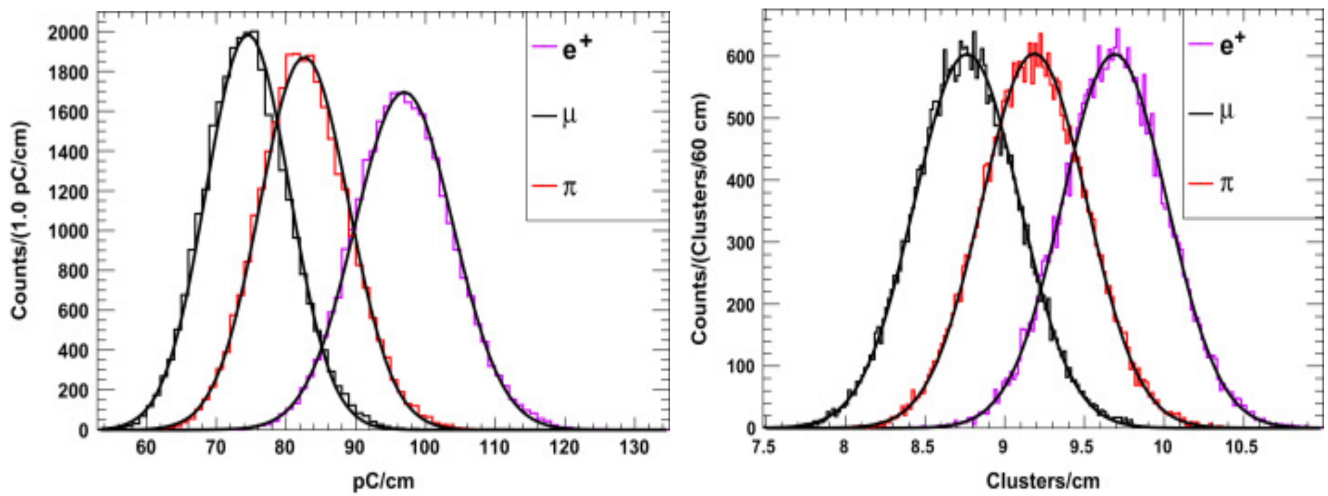


Cluster counting



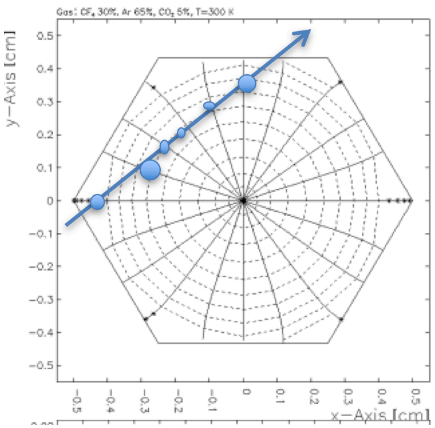
Truncated mean of charges (dE/dx) and number of clusters in composed tracks.

https://doi.org/10.1016/j.nima.2013.09.028



- Could be used for higher momentum due to he relativistic rise of the Bethe-Bloch curves

Cluster counting



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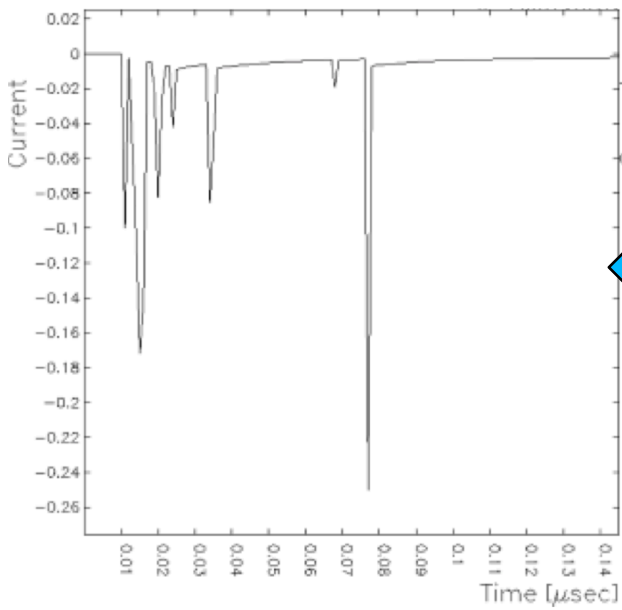

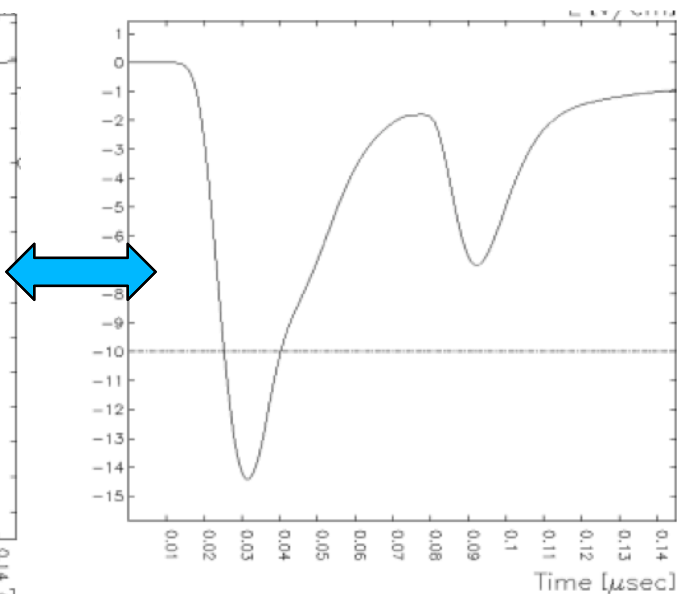

- Depending on available electronics a **cluster counting** method could be used to improve momentum coverage

Individual charged hadrons(π, K, p)

Methods for PID (mass difference):

-dE/dx: (p<1GeV)

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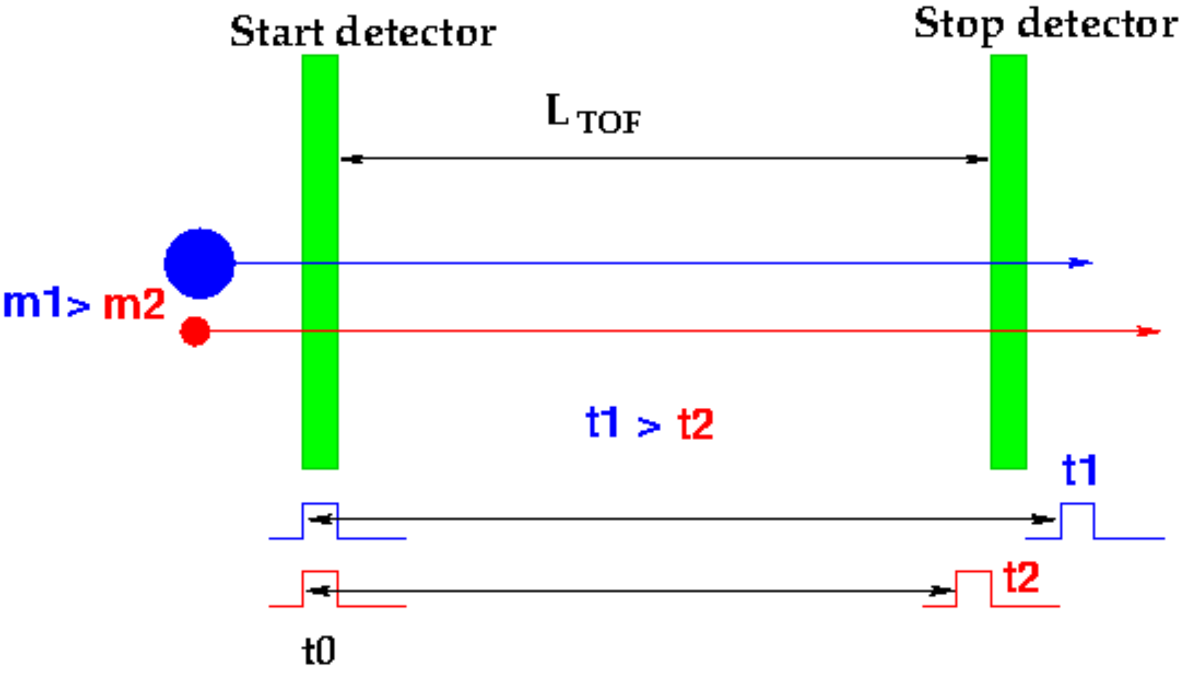
Time of Flight (TOF):

Measure signal time difference between two detectors with good time resolution



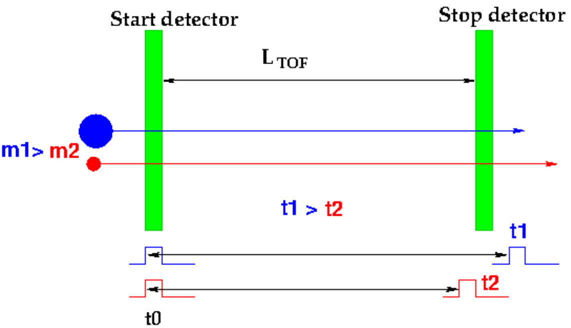
L_{TOF} ~ 2-4 m

$$\Delta t_{TOF} = \frac{c\,LTOF}{2p^2}(m_1^2 - m_2^2)$$

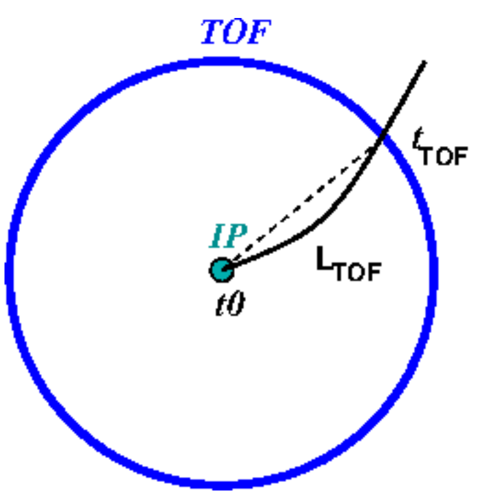
It works for Fixed Target facilities. How does it work in colliders (without "start" detector")?

Time of Flight (TOF):

Measure signal time difference between two detectors with good time resolution



$$\frac{dm}{m} = \frac{dp}{p} + \gamma^2\left(\frac{dt}{t} + \frac{dL}{L}\right).$$



Collider: Barrel

- **Limit in space** (barrel) =>
- Radial space ~10cm for detector placement

➢ L_{TOF} < 1 m => what would be a Δm or Δt ?

$$\Delta t_{TOF} = \frac{c\, LTOF}{2p^2}(m_1^2 - m_2^2)$$

-> need to achieve at least 3σ separation for a given momentum (PID momentum limitation):

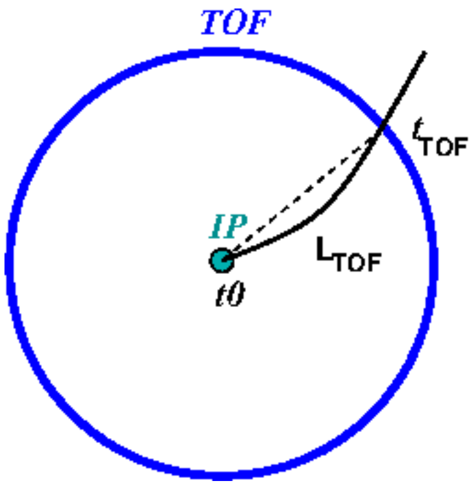
-> depends on resolution of your "stop" detector (for highest momentum, need more precise timing)
-> depends on momentum resolution.

=> could be improved by high precision timing measurements <10psec

Time of Flight (TOF):

Measure signal time difference between two detectors with good time resolution

$$\frac{dm}{m} = \frac{dp}{p} + \gamma^2 \left(\frac{dt}{t} + \frac{dL}{L}\right).$$

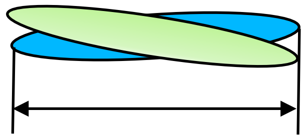


Collider: Barrel

- No space for "Start detector" =>

Start time : t_0=0? But what is Δt_0 then ??

Bunch crossing??

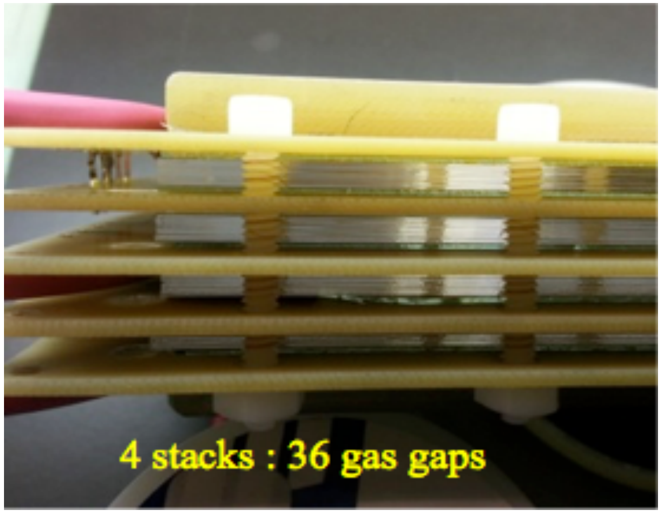


Bunch length 1cm => Δt_0 ~ 60ps =>
Just RF-clock is not enough =>

Need to know **vertex position** more precisely to **measure L_TOF** precise (total particle length/curvature)

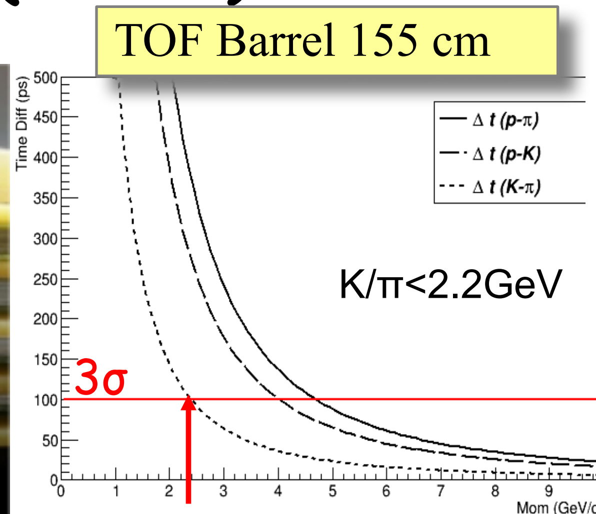
t0 ~ 10ps == dL_{TOF} ~ 3mm

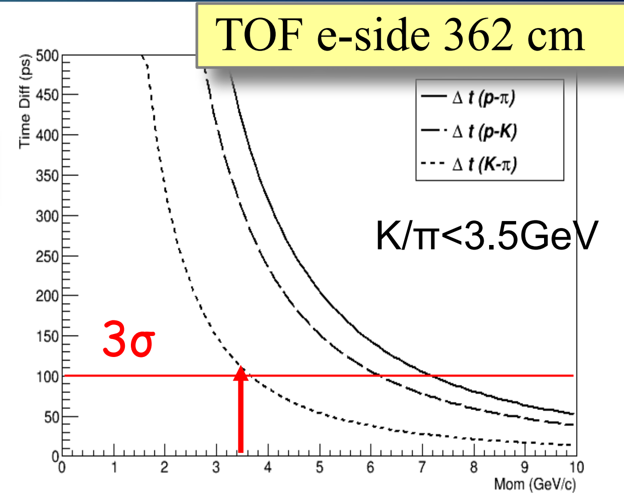
Time of Flight (TOF): MRPC

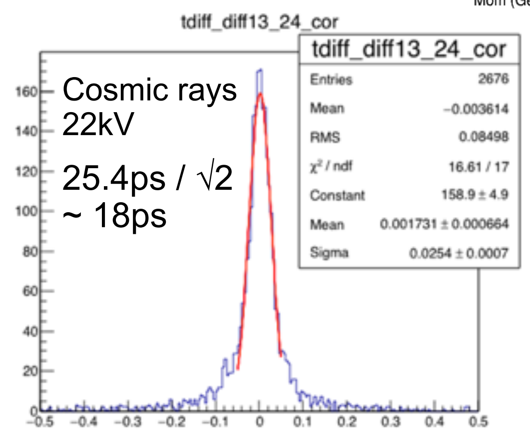


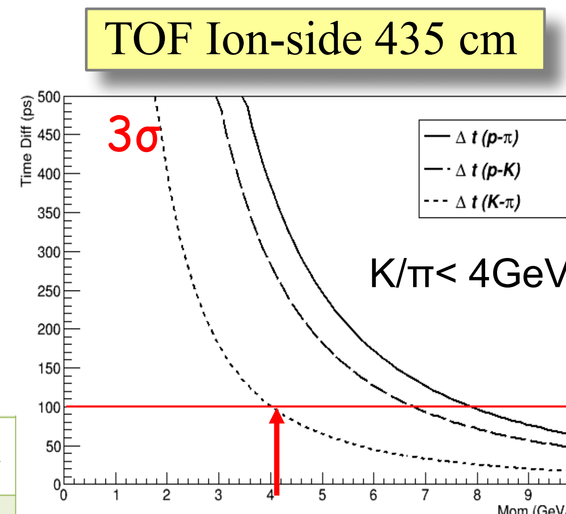
Multi-gap Resistive Plate Chamber (MRPC) R&D: achieved ~18 ps resolution with 36-105 μm gap glass MRPC

Barrel (1m) for 20ps (10ps):
π/K < 2.5 (3.5) GeV,
K/p < 4.2 (6) GeV
End-caps (4m):
π/K < 5 (7.3) GeV,
K/p < 8.5 (12.5) GeV









σ_{tot}=10 ps	1m (Barrel)		
σ_{tot}=10 ps	4m (Hadron)		

Mickey Chiu

Yulia Furletova

Individual charged hadrons(π, K, p)

Methods for PID (mass difference):

-dE/dx: ($p<1$GeV)

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

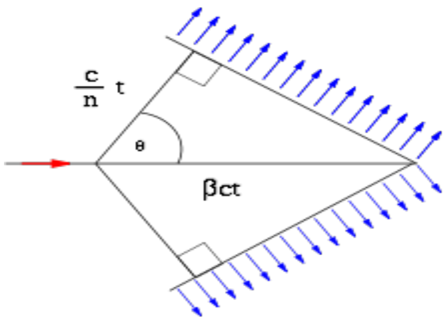
-Cherenkov radiation: $p < 5$ (50) GeV)

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

Peter Križan, Ljubljana

Cherenkov detectors

A charged track with velocity v=βc exceeding the speed of light c/n in a medium with refractive index n emits **polarized light** at a characteristic (Cherenkov) angle, **$\cos\theta = c_0/nv = 1/\beta n$**



Example:
in 1m of air (n=1.00027) a track with β=1 emits N=41 photons in the spectral range of visible light (ΔE ~ 2 eV).
If Čerenkov photons were detected with an average detection efficiency of ε=0.1 over this interval, N=4 photons would be measured.

In general: number of detected photons can be parametrized as $N = N_0 L \sin^2\theta$ where N_0 is the figure of merit,

$$N_0 = \frac{\alpha}{\hbar c}\int Q(E)T(E)R(E)dE$$

and Q T R is the product of photon detection efficiency, transmission of the radiator and windows and reflectivity of mirrors employed.
Typically: N_0 = 50 - 100/cm

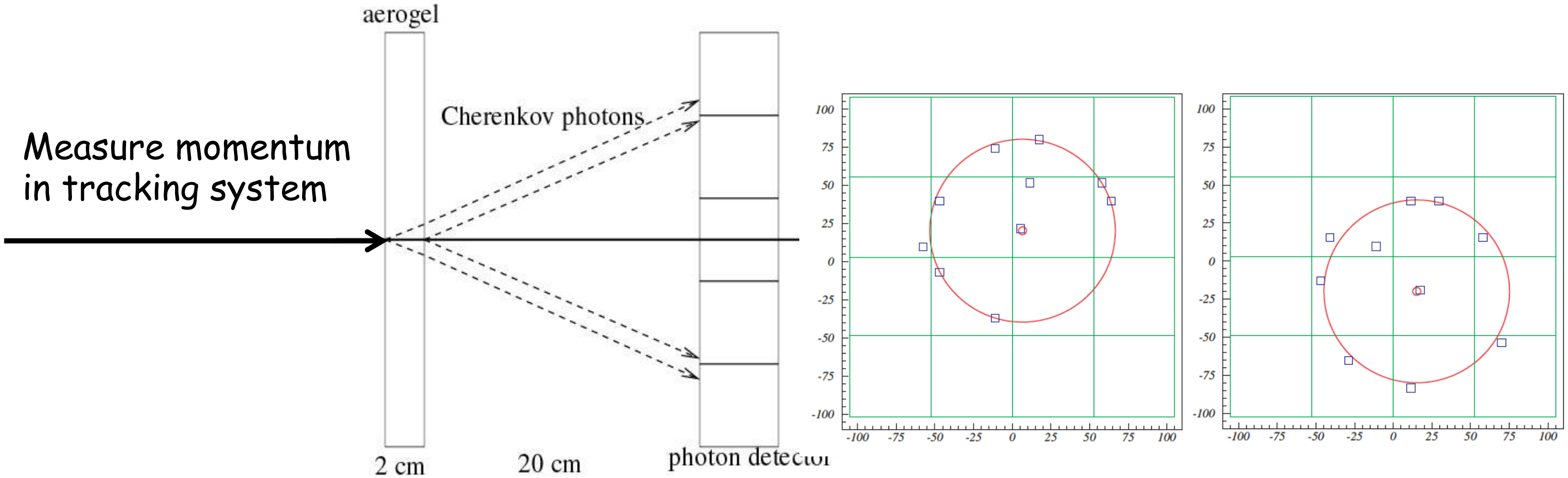
Types of Cherenkov detectors

➢ Threshold counters --> count photons to separate particles below and above threshold; for $\beta < \beta_t = 1/n$ (below threshold) no Čerenkov light is emitted

Choice of n: depends on the momentum range.

At EIC: Hadron blind detector (HBD) for e/π separation

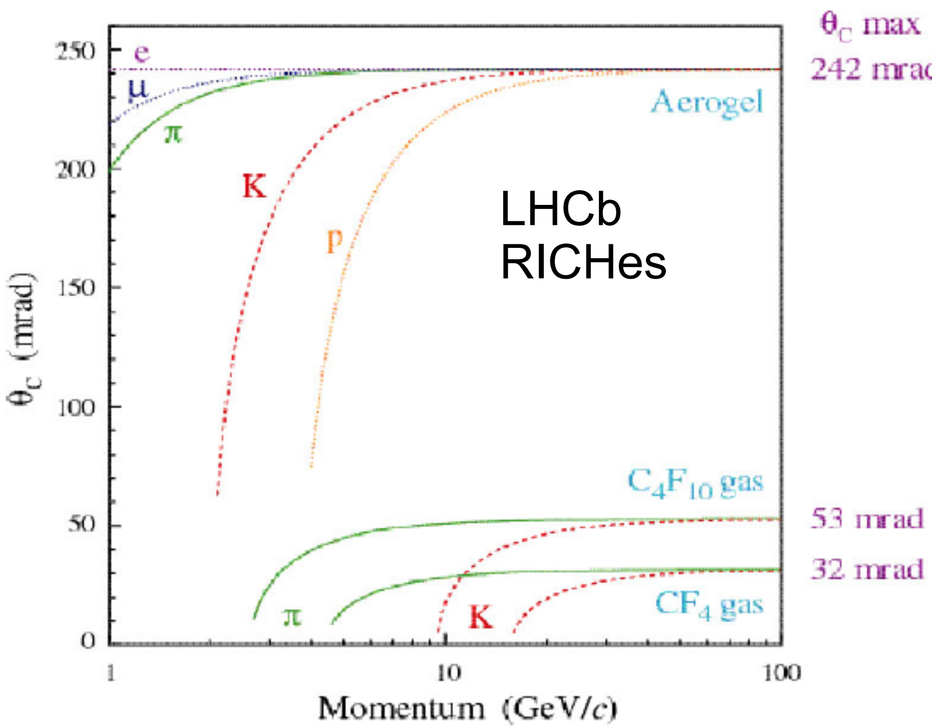
➢ Ring Imaging (RICH) --> measure Čerenkov angle (θ) and count photons

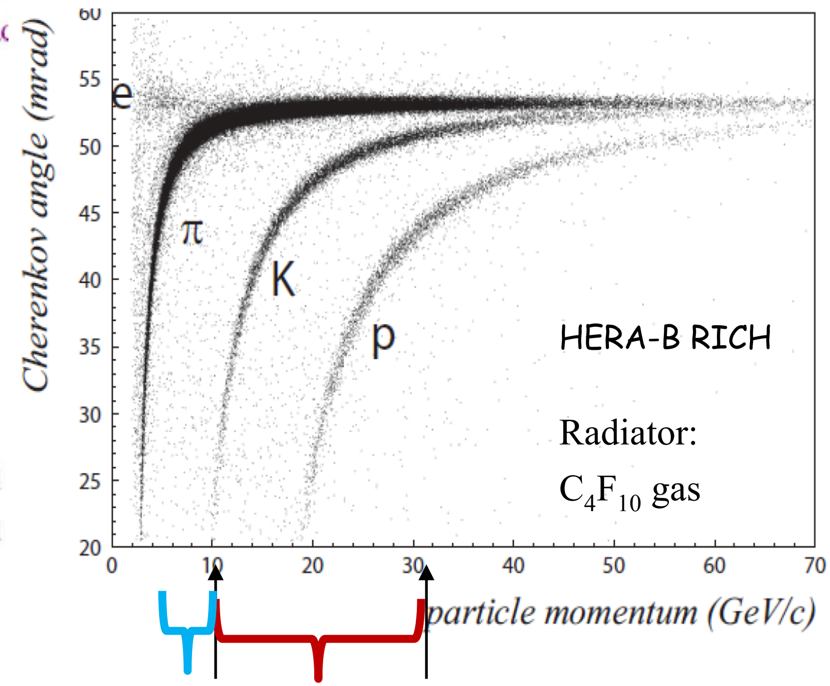


Few photons detected => Important to have a low noise detector

Cherenkov detectors

Limitations:
- p_{min} - p_{max} threshold
- -magnetic field
- -occupancy



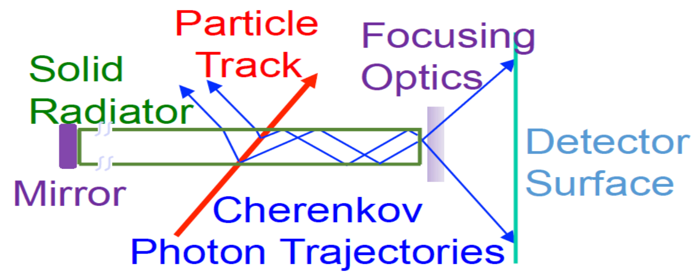


K/π p_{min}

K/π p_{max} overlap

Cherenkov detectors are the main hadron (K/π/p) PID detectors for energies above TOF

DIRC at JLEIC (barrel)

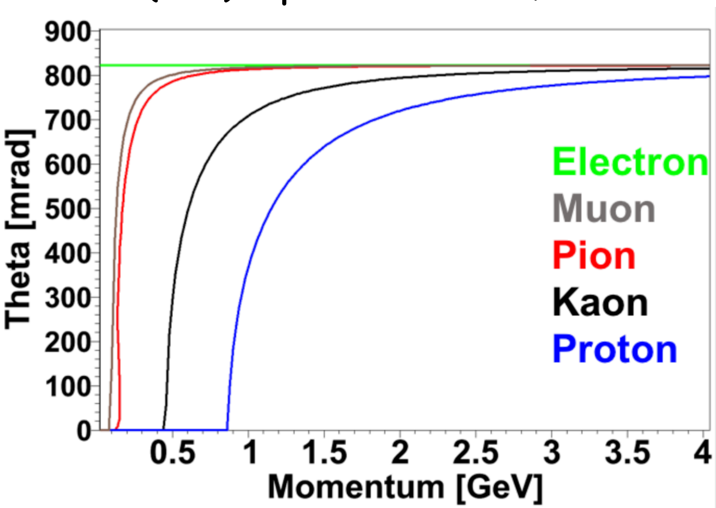


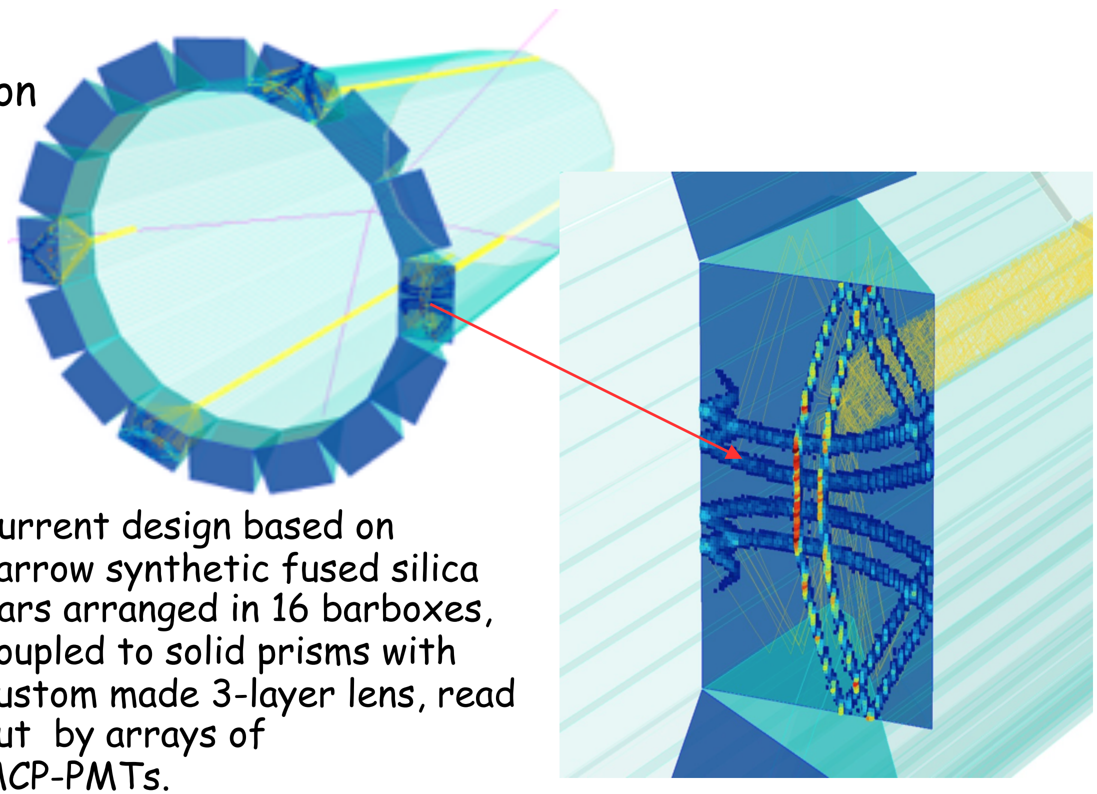
- Radially compact (5 cm) Cherenkov detector (BaBar, Belle II, GlueX)
- eRD14 R&D program: Test beam (together with PANDA), radiation hardness test
- Simulation for particle identification (3σ):

0.15 < e/π < 1.8 GeV

0.15 (0.45) < π/K < 6 GeV,

0.45 (0.8) < p/K < 10 GeV,





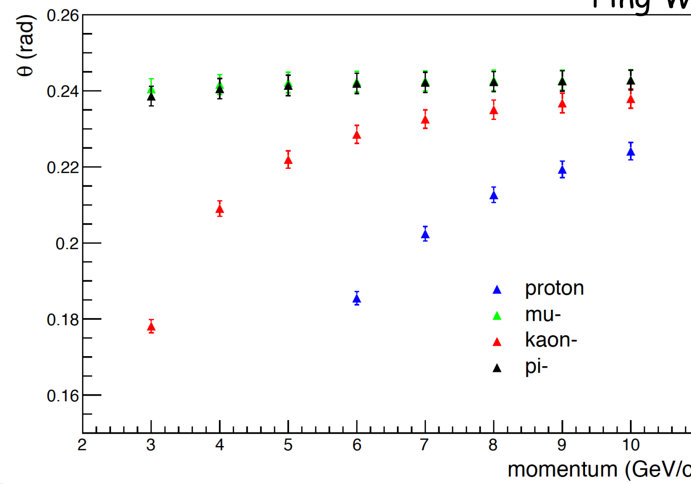
Current design based on narrow synthetic fused silica bars arranged in 16 barboxes, coupled to solid prisms with custom made 3-layer lens, read out by arrays of MCP-PMTs.

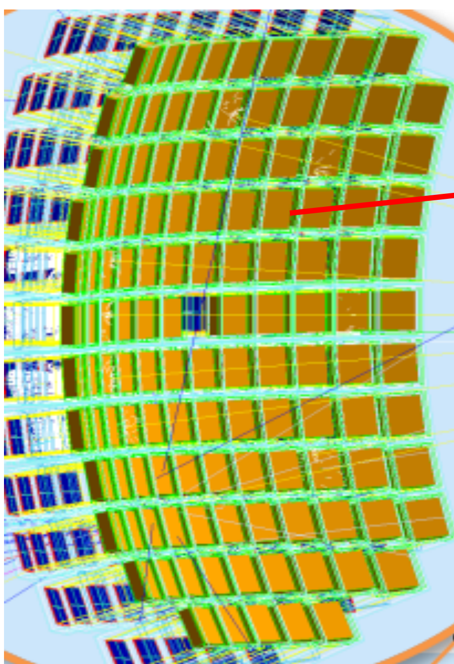
Barrel Cerenkov PID detector
DIRC covers energy for π/K up to 6GeV

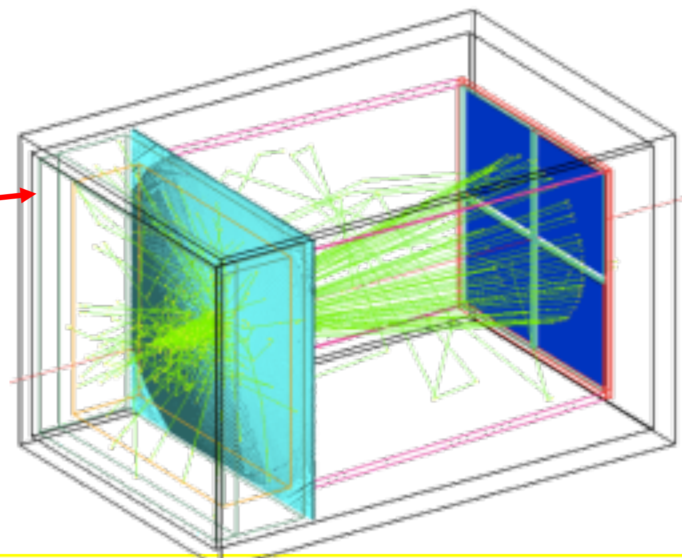
Modular RICH at JLEIC (electron side)

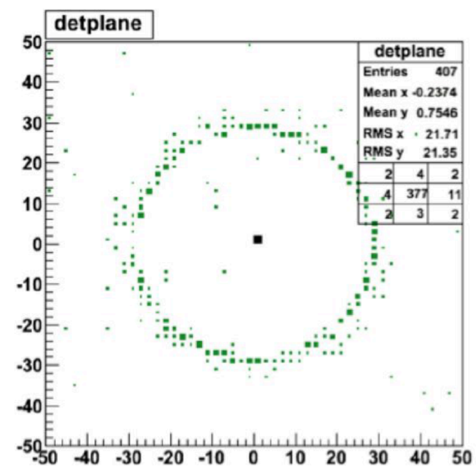
- Modular aerogel RICH: compact, using lens-based design to **reduce ring size and sensor plane area**
- Separation (3σ):
  - 0.56 GeV $<$ e/π $<$ 2 GeV ,
  - 0.56 (2.0) GeV $<$ π/K $<$ 8 (10) GeV,
  - 2.0 (3.8) GeV $<$ K/p $<$ 12 GeV

Ping Wong



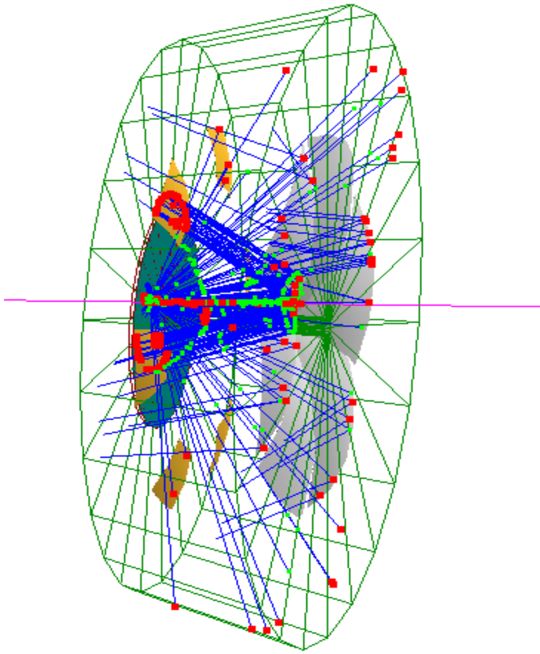






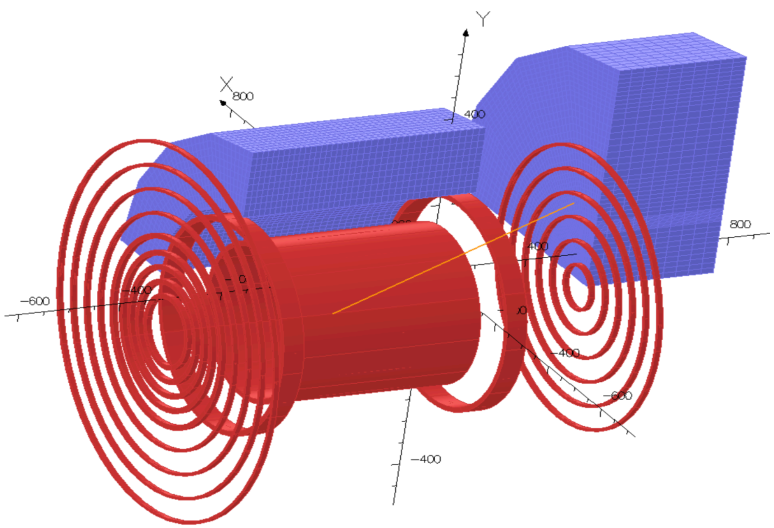
Electron -endcap Cerenkov PID detector
Modular RICH covers energy for π/K up to 10GeV

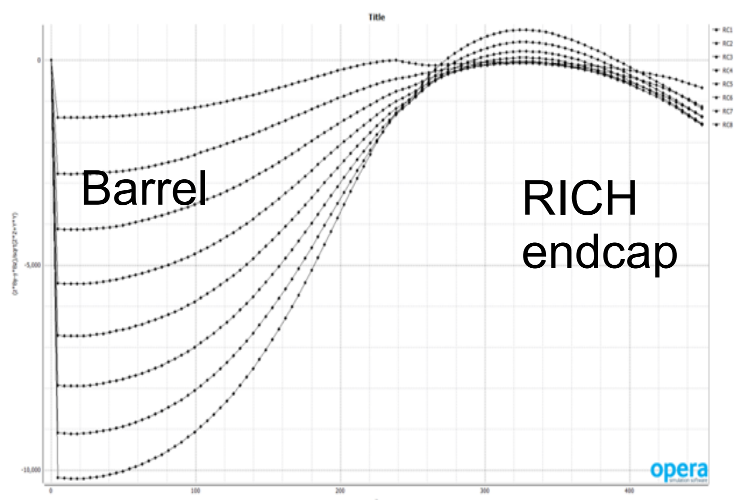
Dual-radiator RICH at JLEIC (forward,hadron side)



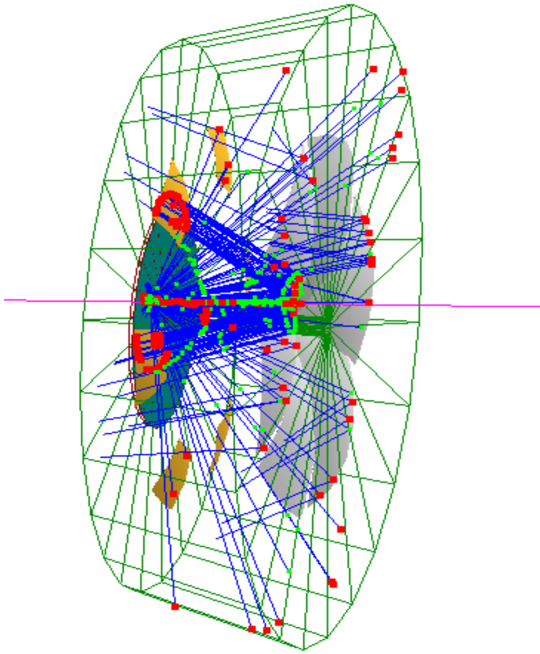
- JLEIC design geometry constraint: ~160 cm length
- Aerogel in front, followed by C_2F_6
- Outward reflecting mirror
- Focal plane away from the beam, reduced background

- Sensitive to magnetic field=> New 3T solenoid minimized a field in RICH region
- Aerogel drives the detector to be solid state (e.g. SiPMs, LAPPDs)



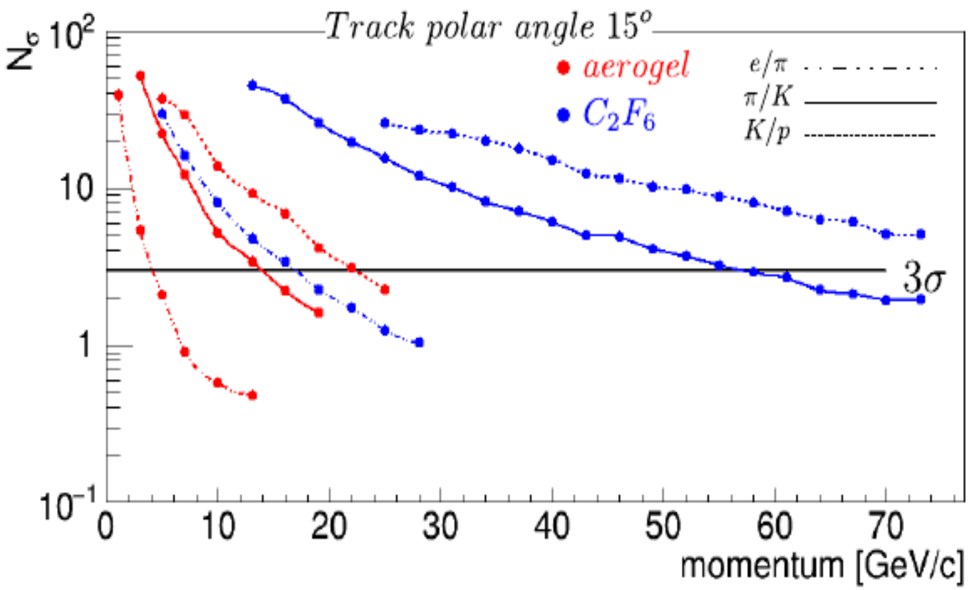


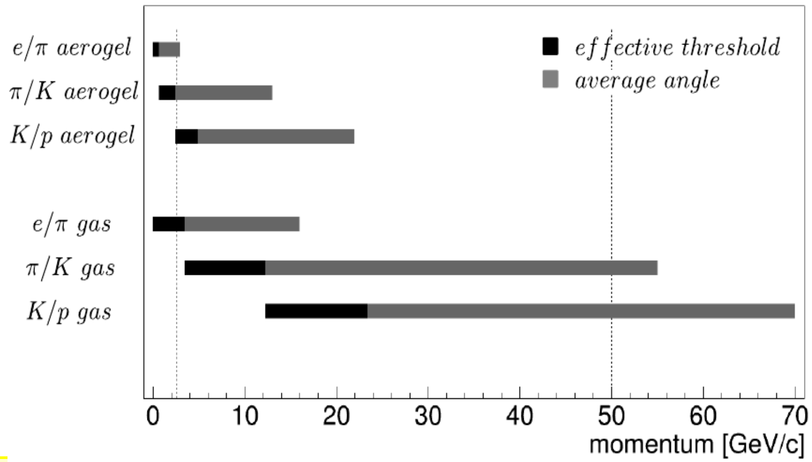
Dual-radiator RICH at JLEIC (forward,hadron side)



- Particle identification:

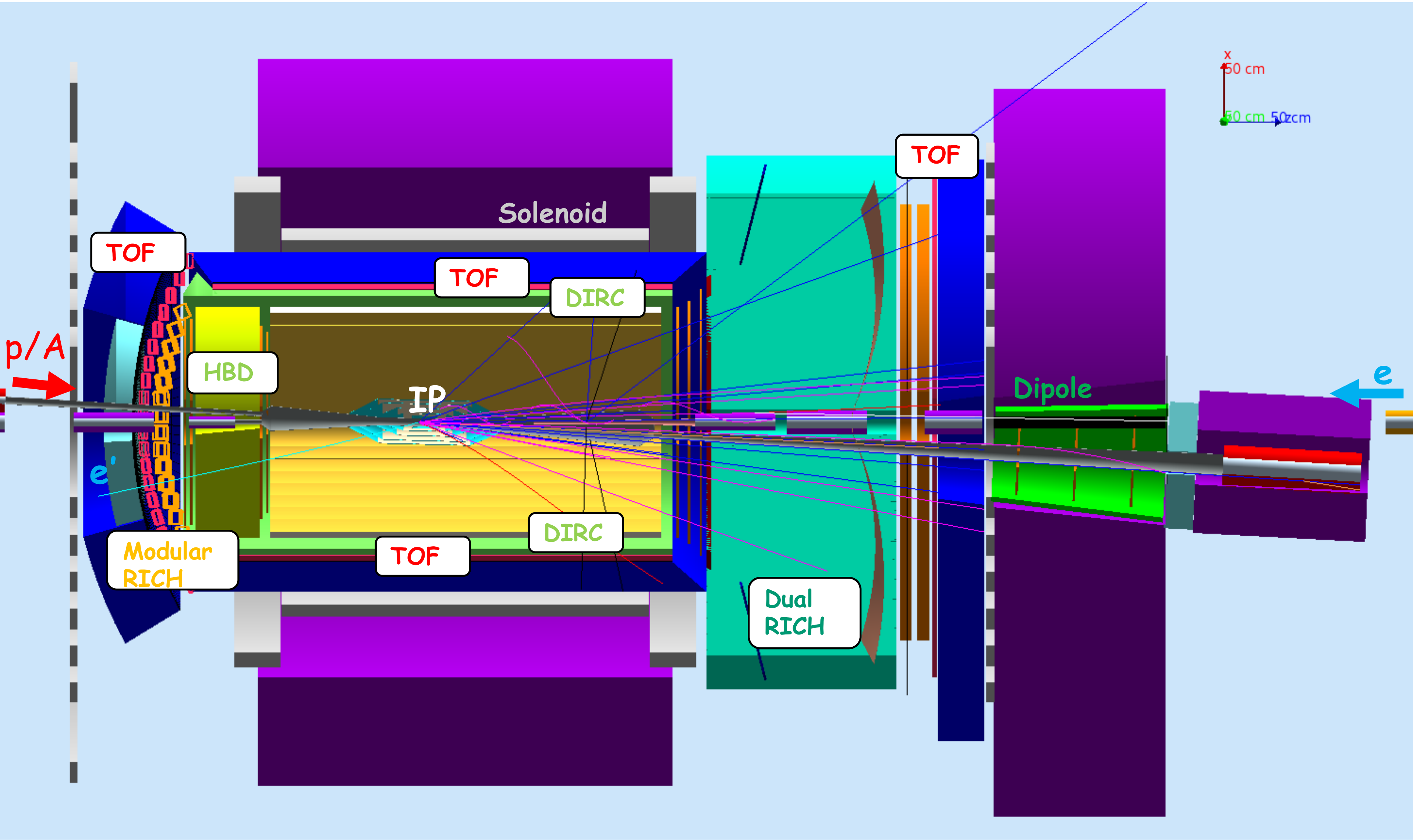
0.003(0.8) < e/π < 4 GeV   0.01 (3.48) < e/π < 18 GeV
0.8 (2.84) < π/K < 14 GeV   3.48(12.3) < π/K < 55 GeV
2.84(5.4) < p/K < 22 GeV   12.3 (23.4) < p/K < 70 GeV



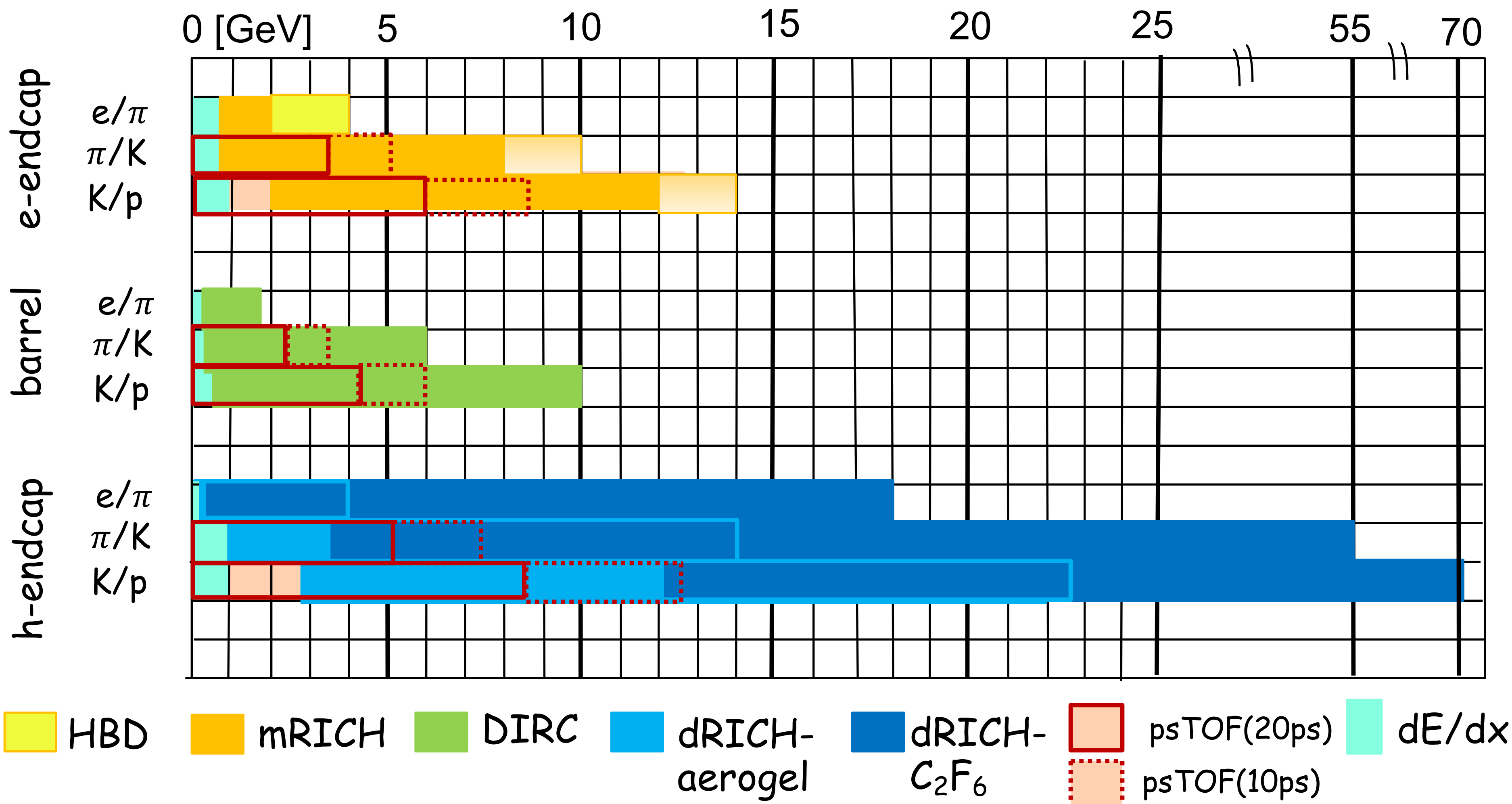


Hadron-endcap Cerenkov PID detector
dual-radiator RICH covers energy for π/K up to 50GeV
Sensitive to magnetic field.

EIC Central detector overview



Individual hadrons (π, K, p): Cherenkov, TOF



** Here, electron/hadron separation only from Cherenkov detectors is shown. Main e/h rejection is done by calorimeters.

Electron/hadron separation

Methods for PID (mass difference):

-dE/dx: (p<1GeV)

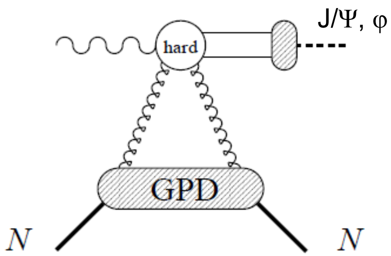
-Time-of-Flight: (p<3-6GeV)

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

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

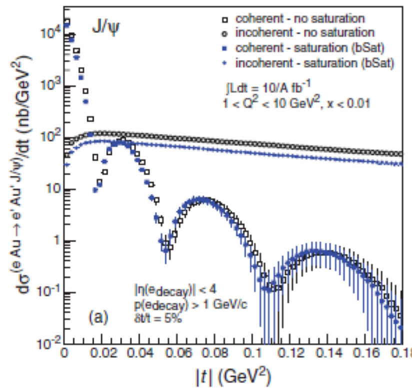
Electron identification (e/hadron separation)

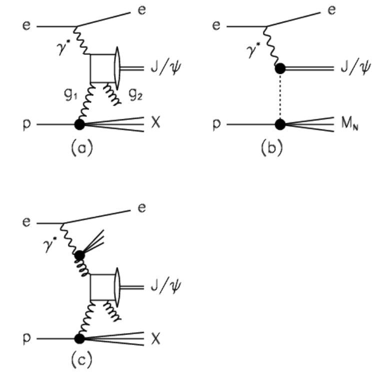
- **GPD and Coherent Exclusive Diffraction (saturation)**



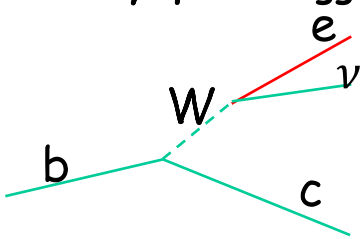
Br (J/ψ->e+e-) ~6%

Br (J/ψ->μ+μ-) ~6%



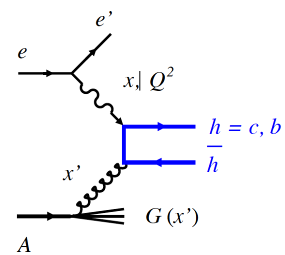


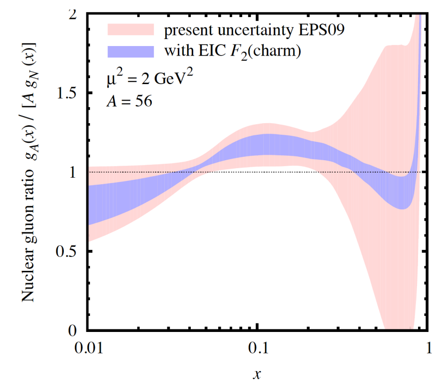
- **Heavy quark tagging**



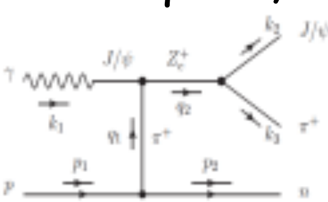
Br ($D^{\pm}$->e+X) ~16%

Br ($B^{\pm}$->e+ν+X_c) ~10%



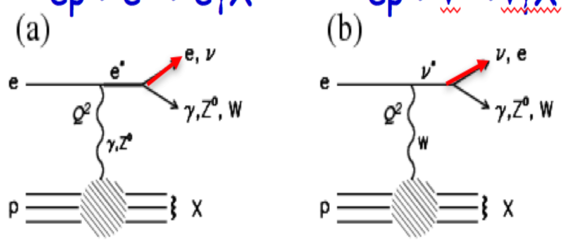


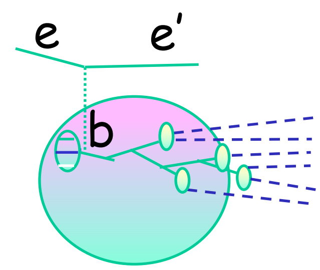
- **Exotic spectroscopy (pentaquarks, tetraquarks, XYZ)**



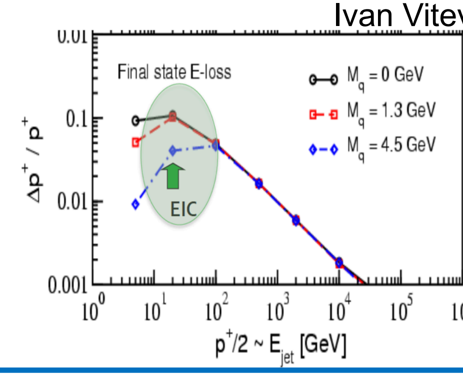
- **Other BSM physics**

ep-> e*-> eγX   ep-> ν*->νγX



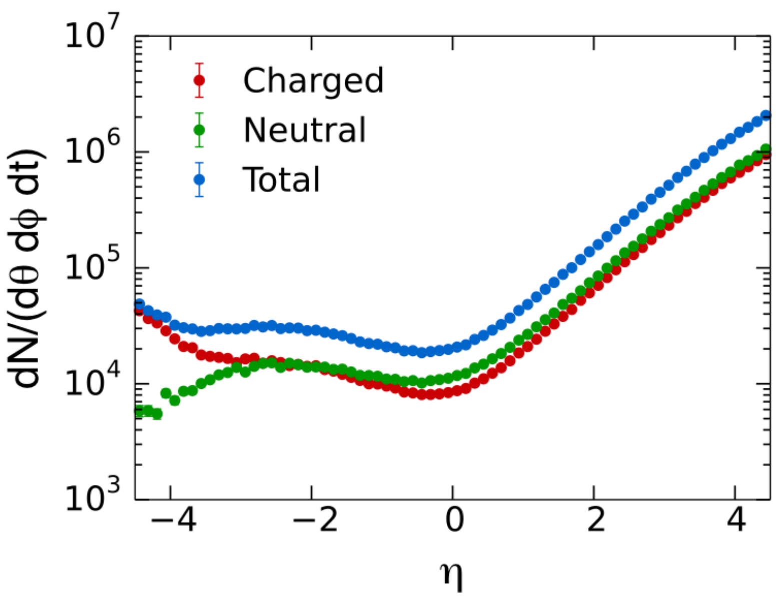


Ivan Vitev



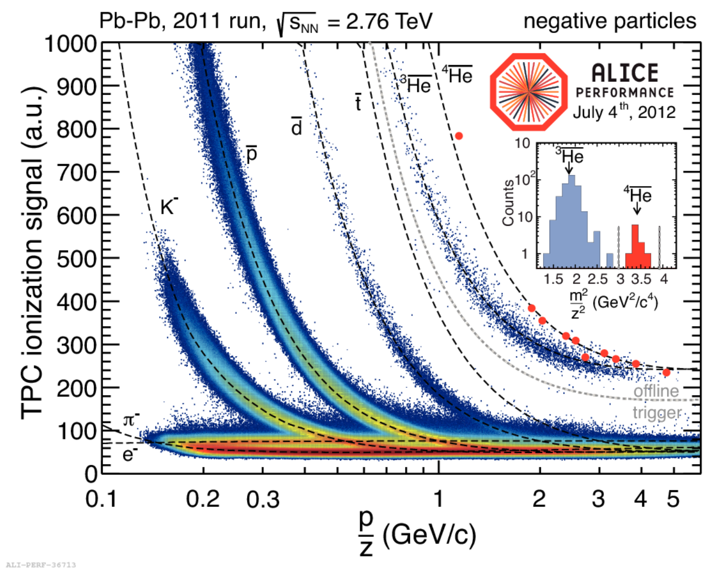
Electron/hadron separation

- The main detector for e/hadron separation is a Calorimeter: EM calorimeter only, or a combination of EM and HCAL
- Typical e/hadron rejection factor for EMCAL only is 50 (300) => (1 out of 50 pions will be identified as an electron (not per event, but per hadron flux !).
- e/hadron rejection from HCAL is 5.

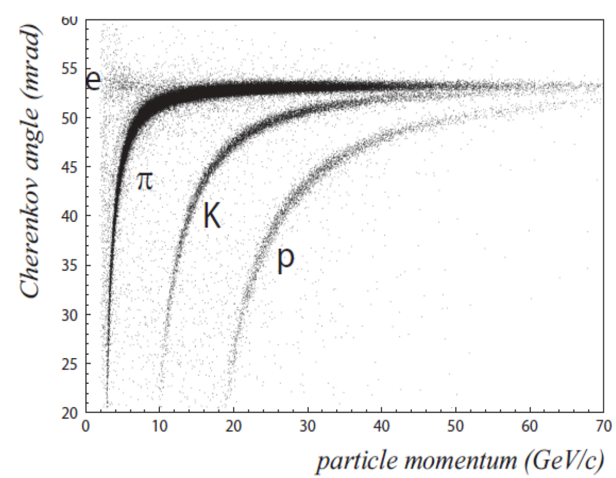


What else?

- dE/dx

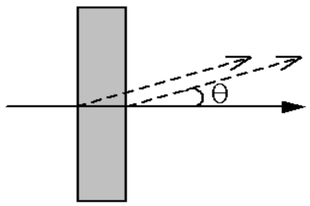


- Cherenkov detectors



Transition Radiation

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



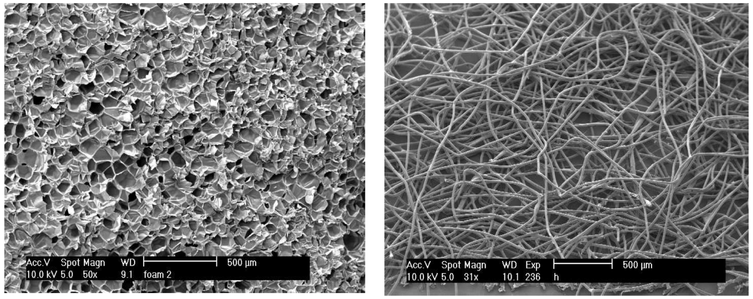
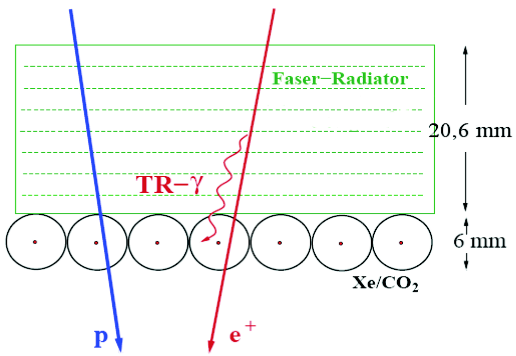
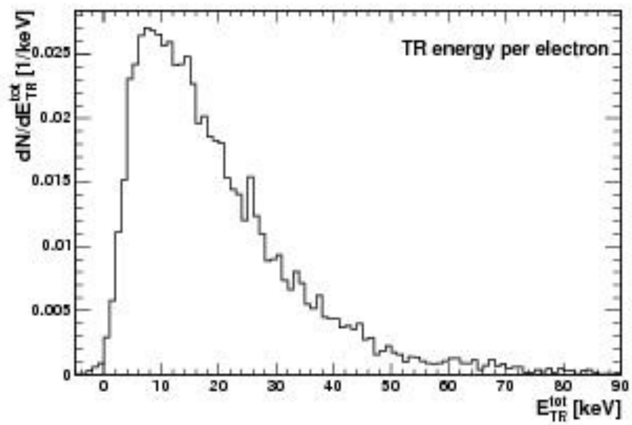


Figure 2: Electron microscope images of a polymethacrylimide foam (Rohacell HF71)(left) and a typical polypropylene fiber radiator (average diameter ≈ 25 μm) (right) [52].



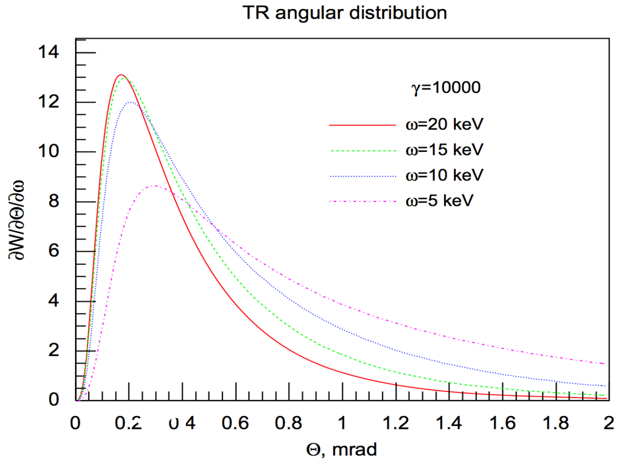


- the probability to emit one TR photon per boundary is of order α~1/137. Therefore multilayer dielectric radiators are used to increase the transition radiation yield, typically few hundreds of mylar foils.

- 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)

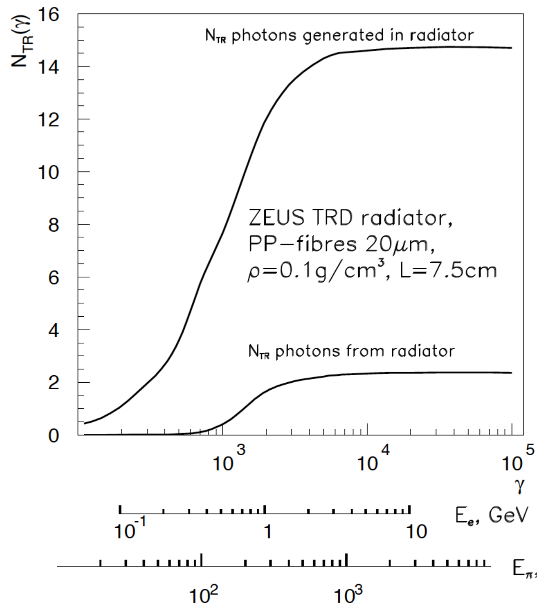
- Total TR Energy ETR is proportional to the γ factor of the charged particle



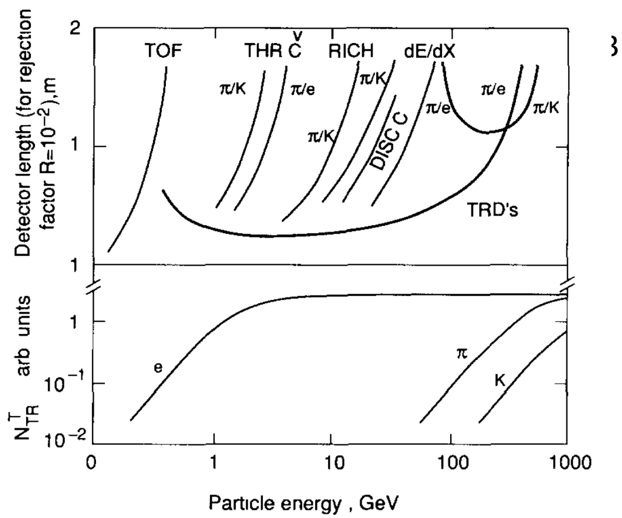
Why transition radiation detector?

- TRD separate particles by their gamma factor
- e/π separation in high $\gamma = E/m$ region (1-100 GeV) where all other methods are not working anymore.
- Provide high rejection factor for a small detector length in a wide range of a particle momentum.
- Identification of the charged particle "on the flight": without scattering, deceleration or absorption.
- Typically TRD is either combined with tracking detector (ATLAS TRT) or provide additional tracking information in the region between RICH and CAL(HERA-B).

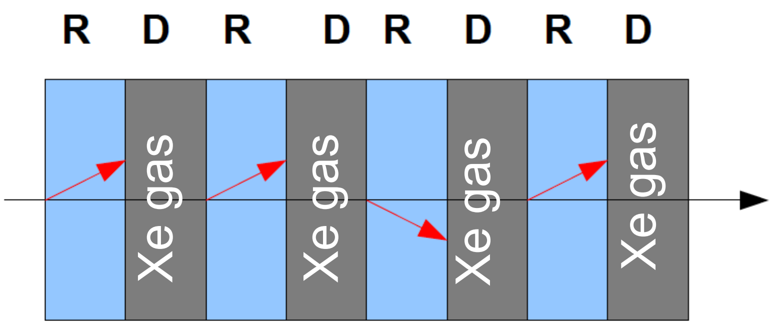
J.Tandler



Length of detector for rejection factor 100.

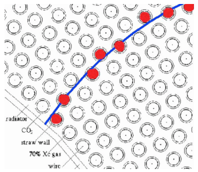


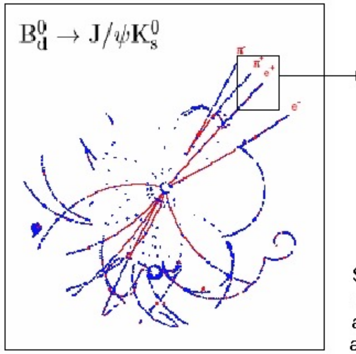
How easy to detect Transition Radiation ?

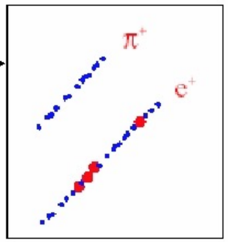


- Stack of radiators and detectors (sandwich)
- For "classical" TRD (straws, MWPC) gas with high Z is required for better absorption of TR photons: Xenon gas (Z=54)
- TRDs are not "hadron-blind" ! charged particles dE/dx, **it is a tracking!**
- Several methods exist to identify TR photons on the top of dE/dx: (TR photons (5-30 keV) over a dE/dX background in Xe gas (2-3 keV)).
  - **Discrimination by threshold**
  - ***Average pulse height along adjacent pads (or along a track)***

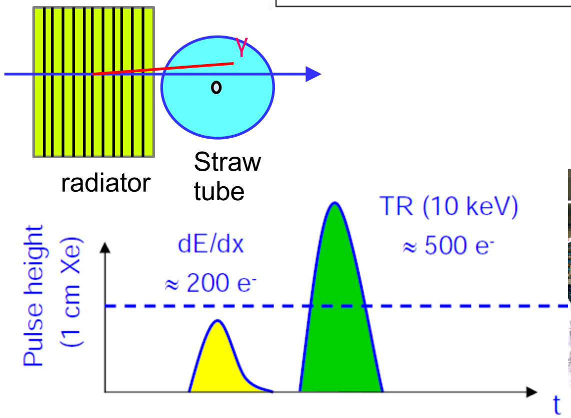
ATLAS

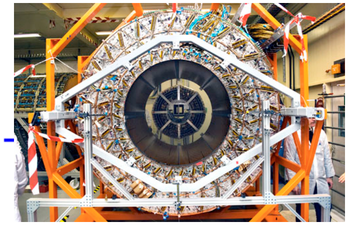






Simulated event, illustration of clusters from eletron/positron and pion hits – small blue dots are ionizing hits, large red dots are TR hits

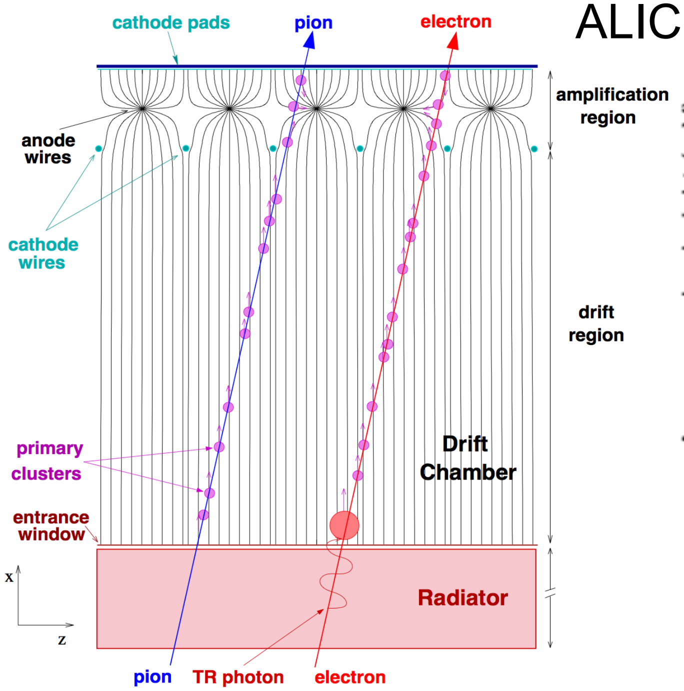




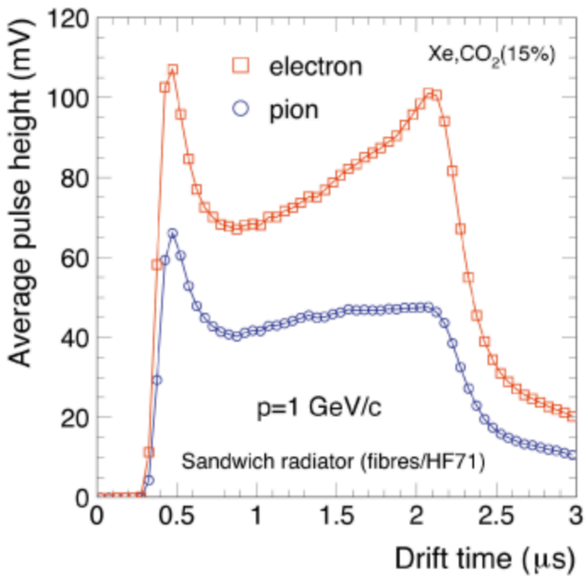
TR detection in MWPC, GEM, Silicon

- With a MWPC or GEM

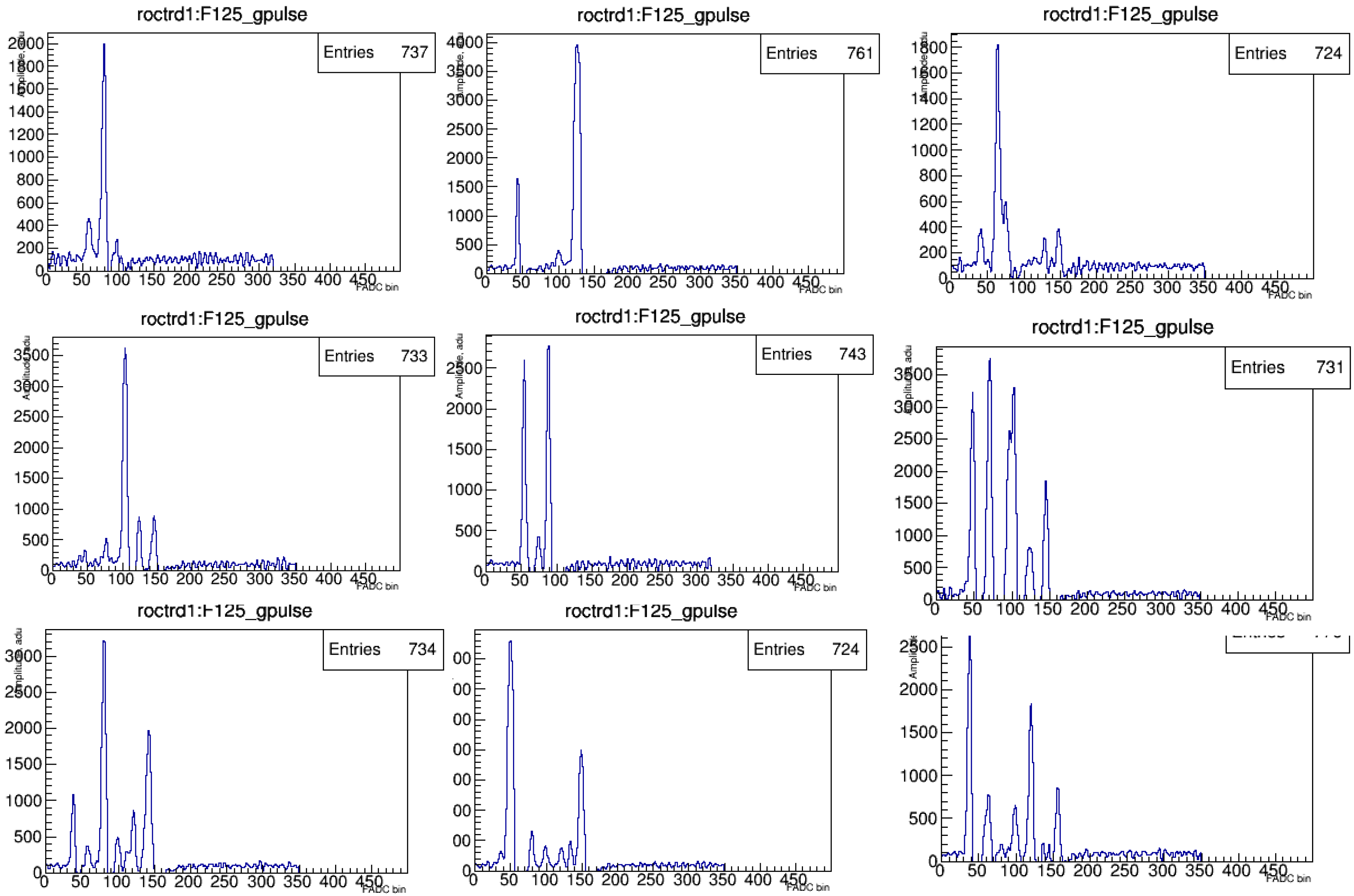
For electrons - significant increase in the average pulse height at later drift times, due to the absorption of the transition radiation near the entrance of the drift chamber.



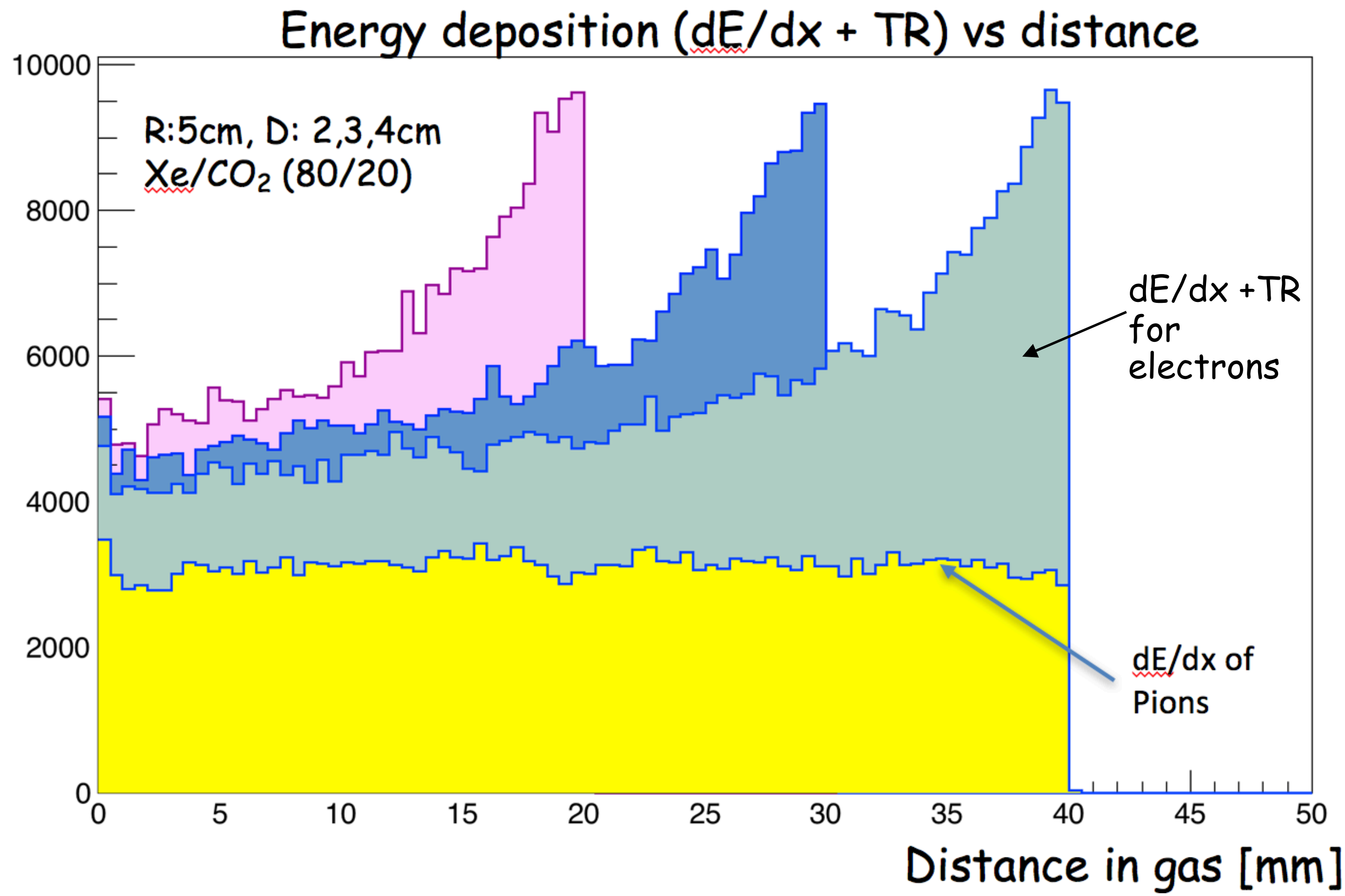
ALICE MWPC - TRD



TR identification: signals

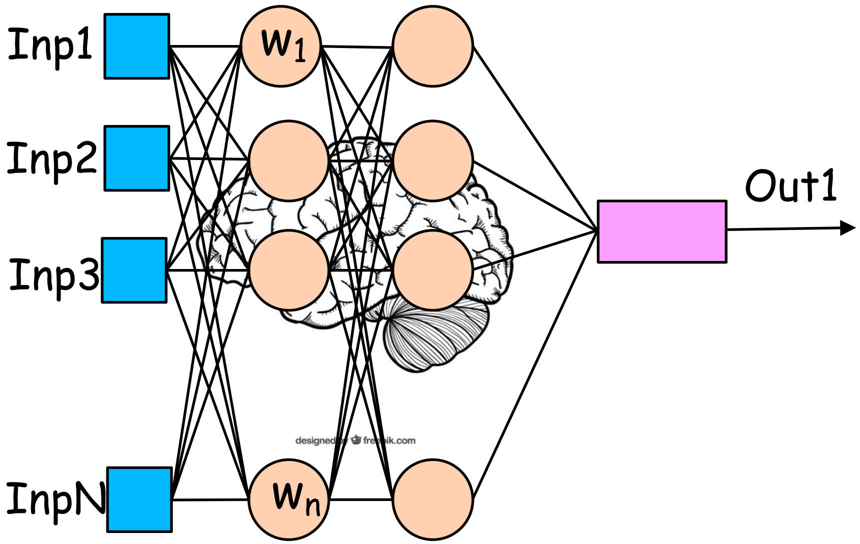


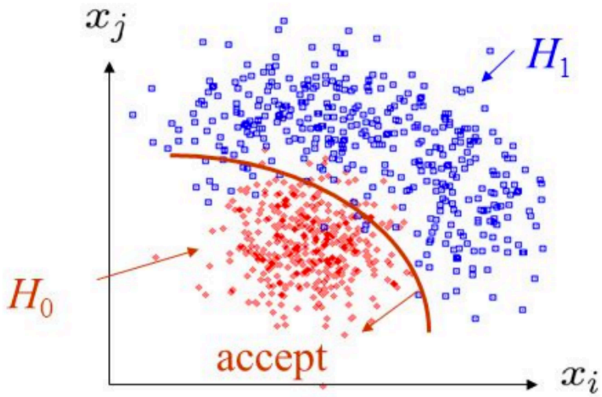
Energy deposition (dE/dx +TR) , e vs pions



e,π ~3 GeV

TR identification: Machine learning technique





Inspired by biological brain models, Artificial Neural Networks are mathematical algorithms which are widely used various applications in particle physics : for example, pattern recognition, selection, forecasting, classification, etc.

Many kinematic variables can be used to disentangle signal and background events.

ANN find the weights (w_i) which solve our classification problem.

ANNs are trained on signal and background using MC event signal and then applied all "knowledge" to the data or an other sample of MC.

The learning rate can be gradually decreased during the training (# epoch)

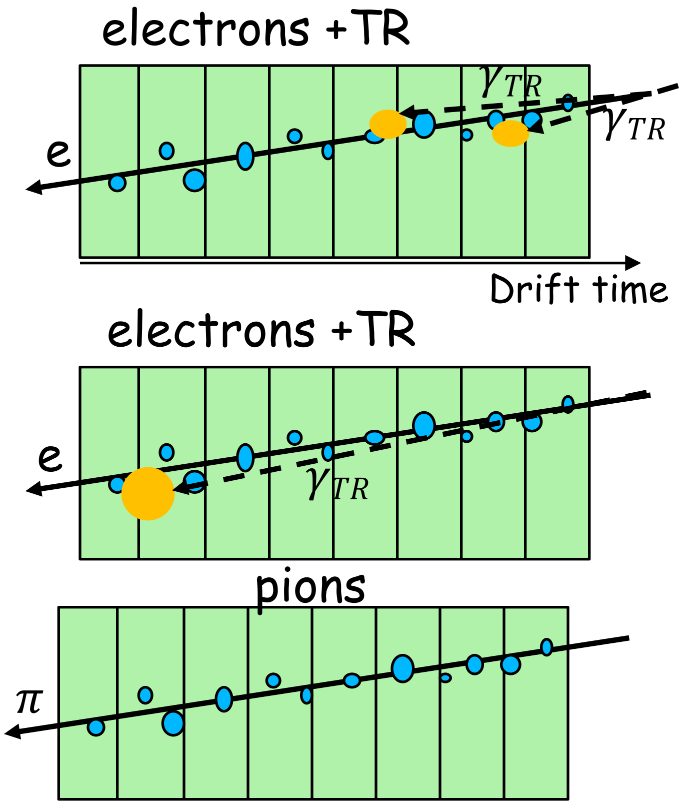
This technique could be applied for everything: track finding, event selection, trigger

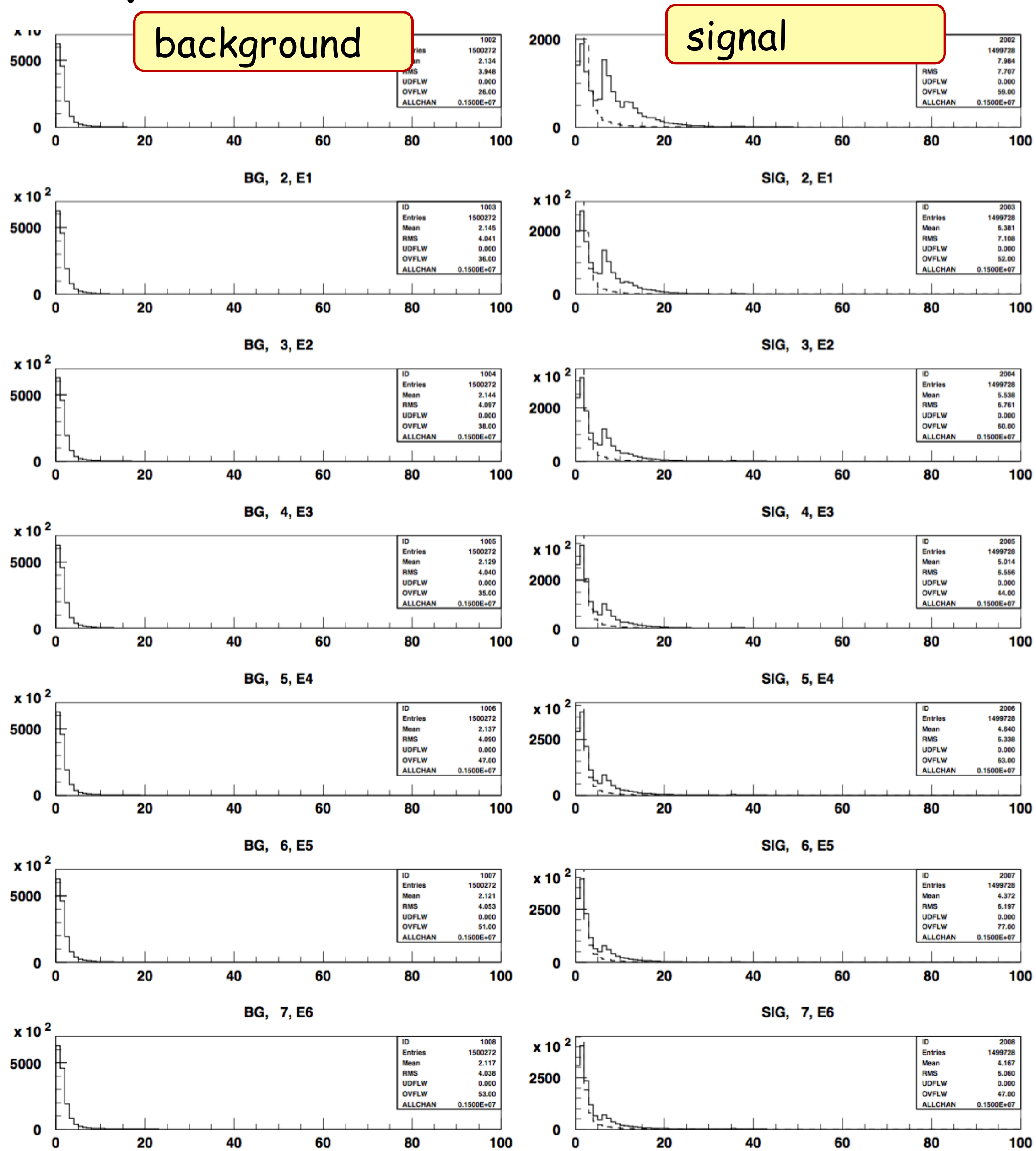
TR identification: Artificial Neural Network

Input variables:

Total or per slice or per cluster (we use 27var)

- <dE/dx>
- Number of clusters
- Timing
- Etc.

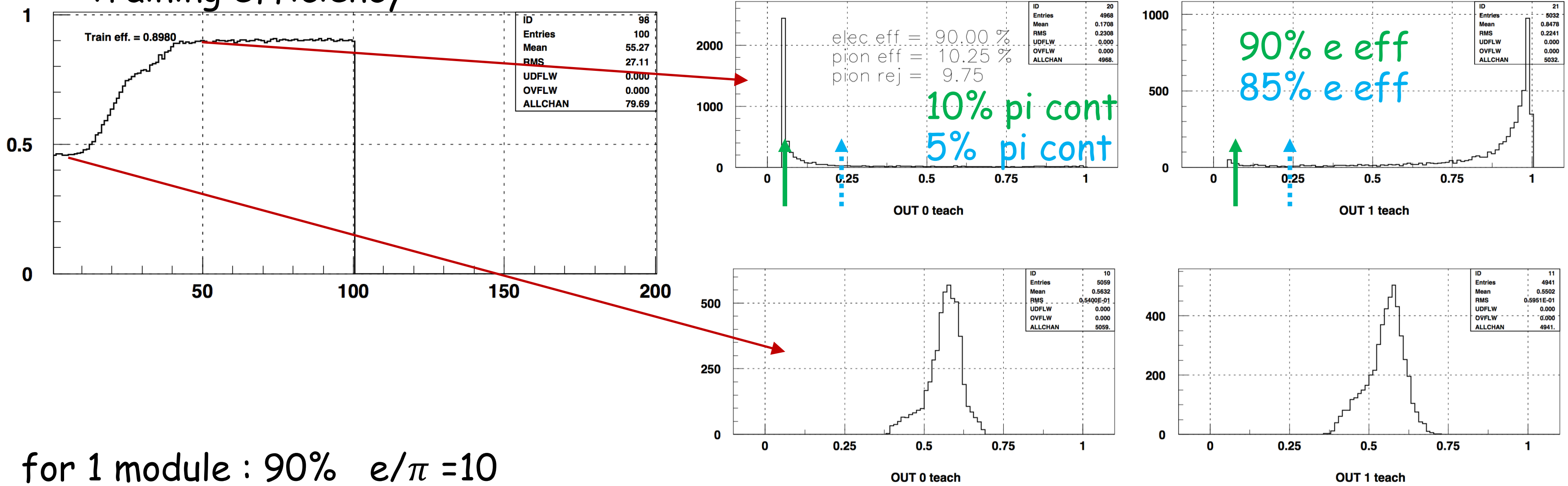




TR identification: Neural Network

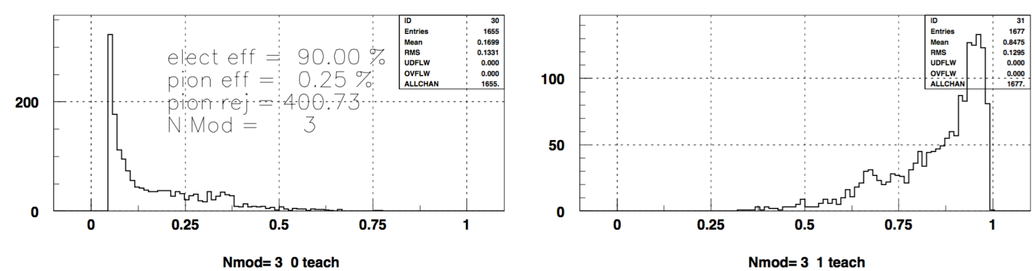
Training efficiency

efficiency for 1 module



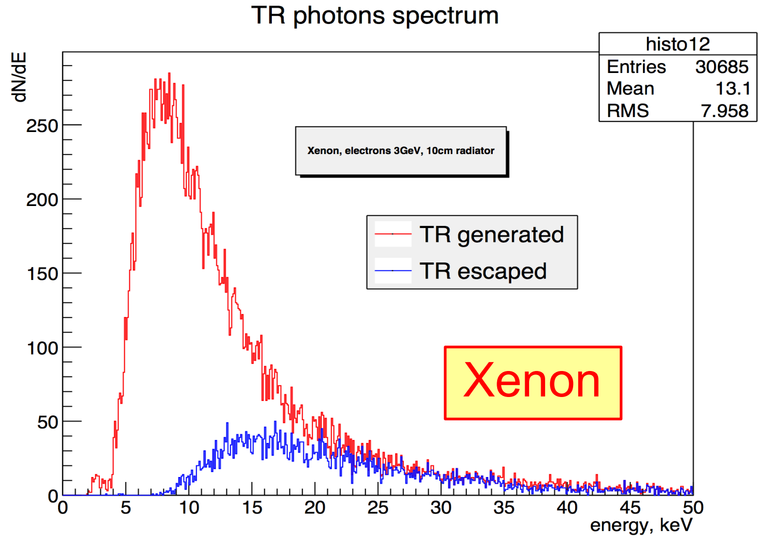
for 1 module : 90% e/π =10
But for 3 modules:
e/pi =10x10x10 = 1000
but e efficiency: 0.9x0.9x0.9=73% (not good!)

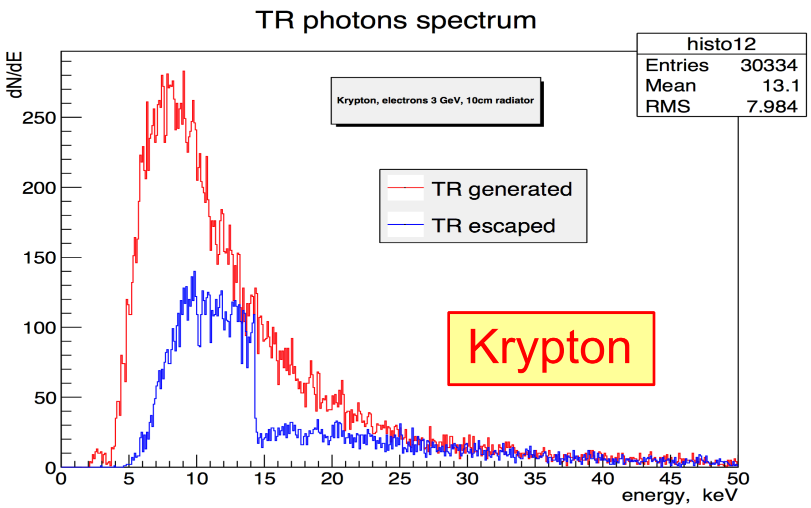
efficiency for 3 (N) modules

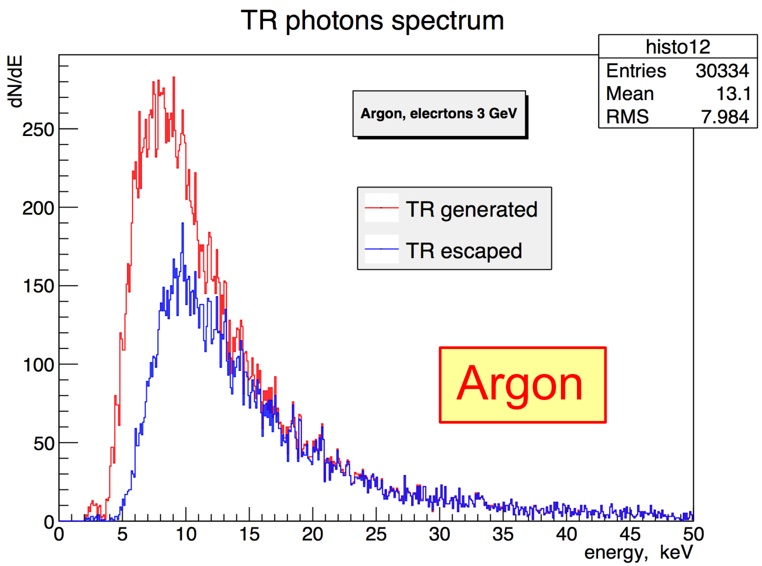


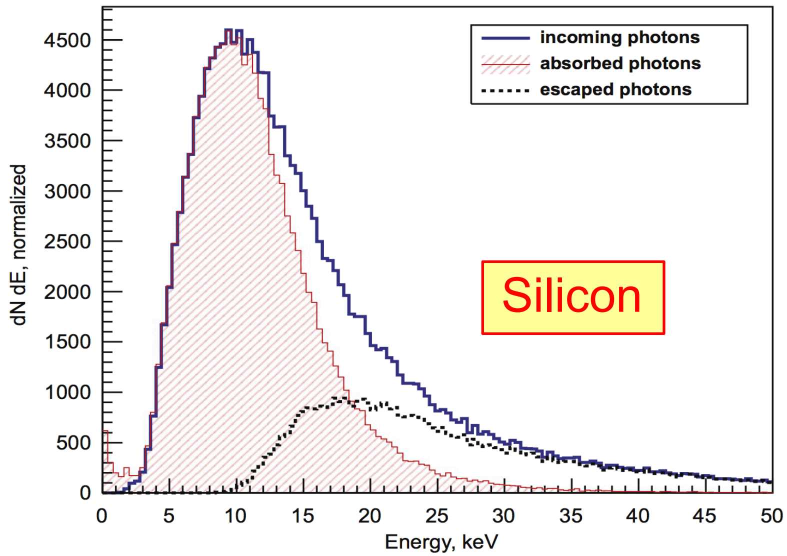
Efficiency for 3 modules:
e efficiency 90%
but e/π ~ 400.

TR- absorption or alternative to gas Xe detectors



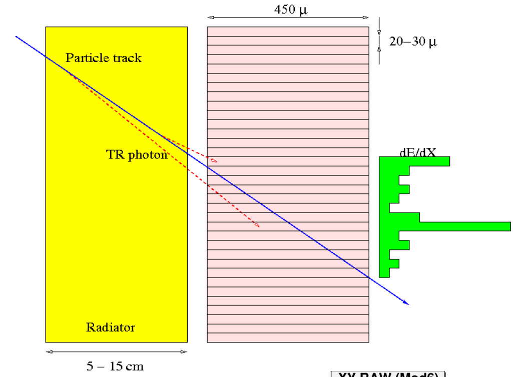


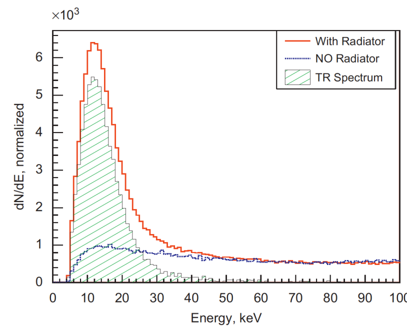




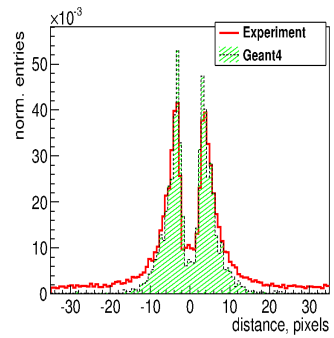
Silicon pixel TRD

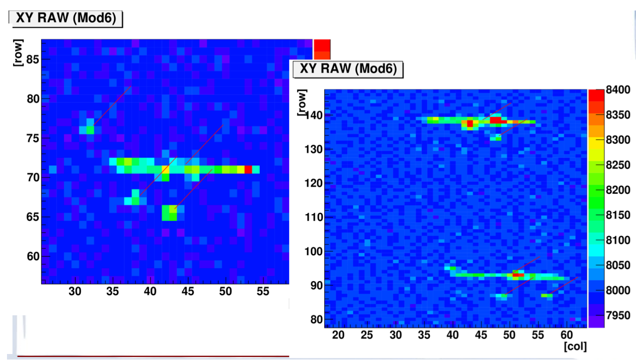
Problem: A huge dE/dX of particles in 300-700μm of silicon - about 100-300keV (TR photons 4-40 keV).





- **DEPFET silicon pixel detector**
  - Low noise, high S/N with 450 µm thick fully depleted bulk(sensitive area), pixel size - 20x20µm^2 .
  - TR photons are clearly visible and separated from track by a few pixels!

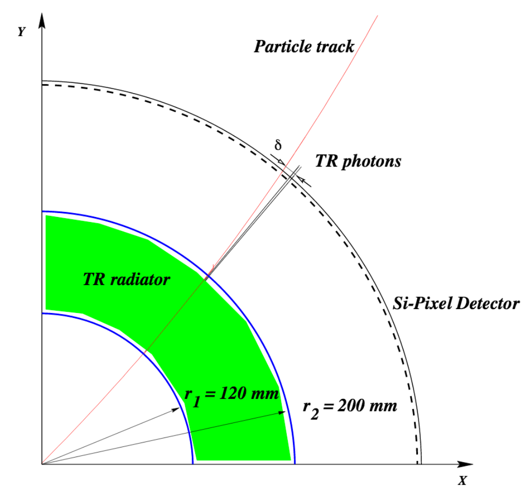




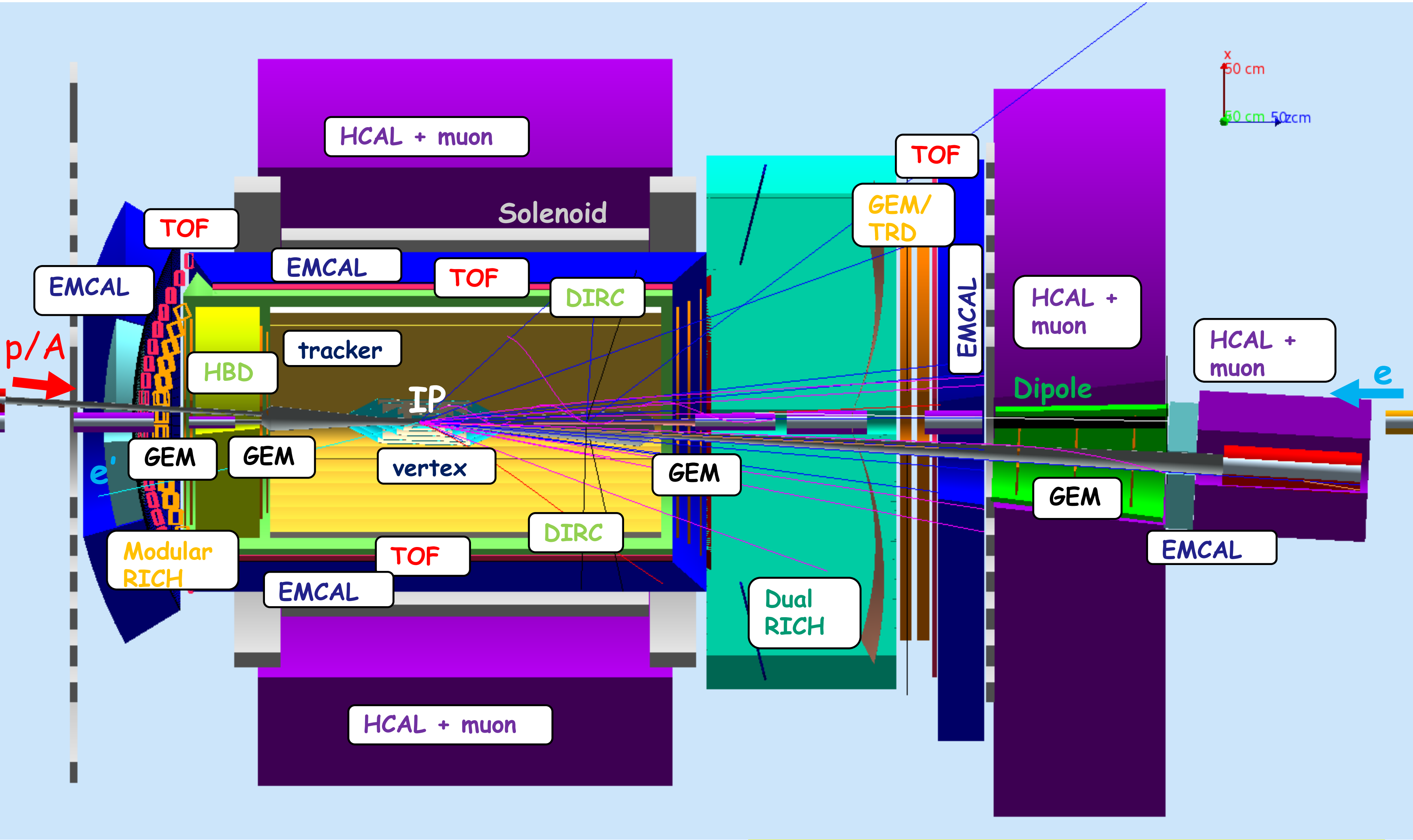
"New transition radiation detection technique based on DEPFET silicon pixel matrices", J.Furletova, S. Furletov, NIM-A 2010, http://dx.doi.org/10.1016/j.nima.2010.06.342
"Geant4 simulation of transition radiation detector based on DEPFET silicon pixel matrices", J. Furletova,S. Furletov, DOI: 10.1016/j.nima.2012.05.009

- **Separation of TR and dE/dX in different pixels in magnetic field**

2000 B. Dolgoshein proposed a design for ILC/TESLA detector (see proposal LC-DET-2000-038)



EIC Central detector overview



Modular design of the central detector

Summary

- Particle identification is one of the key requirement for the EIC detector
- Hadron identification as well as a e/h rejection plays an important role at EIC.
- Combinatorial background could be suppressed by using PID detectors

- Backup