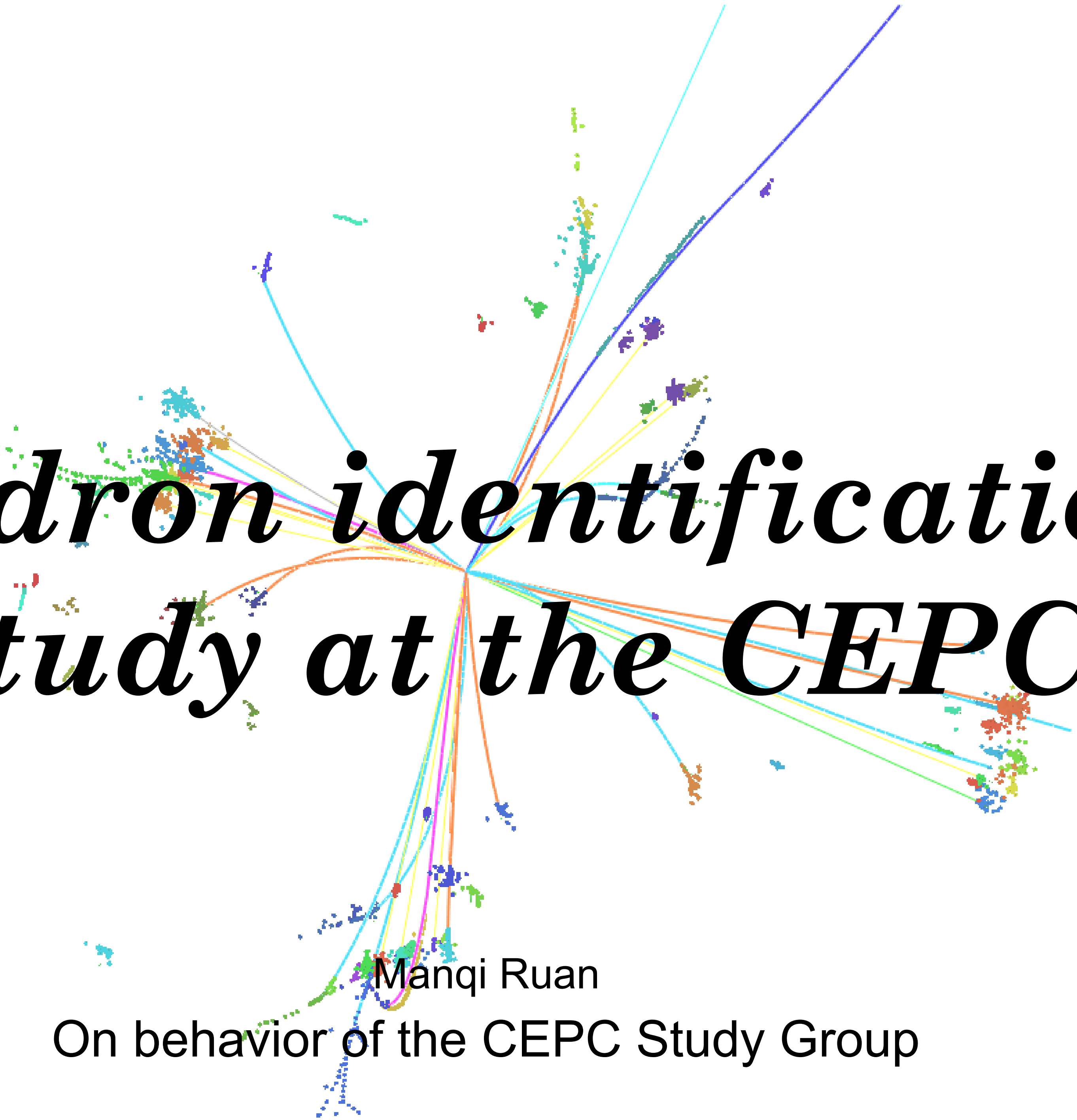
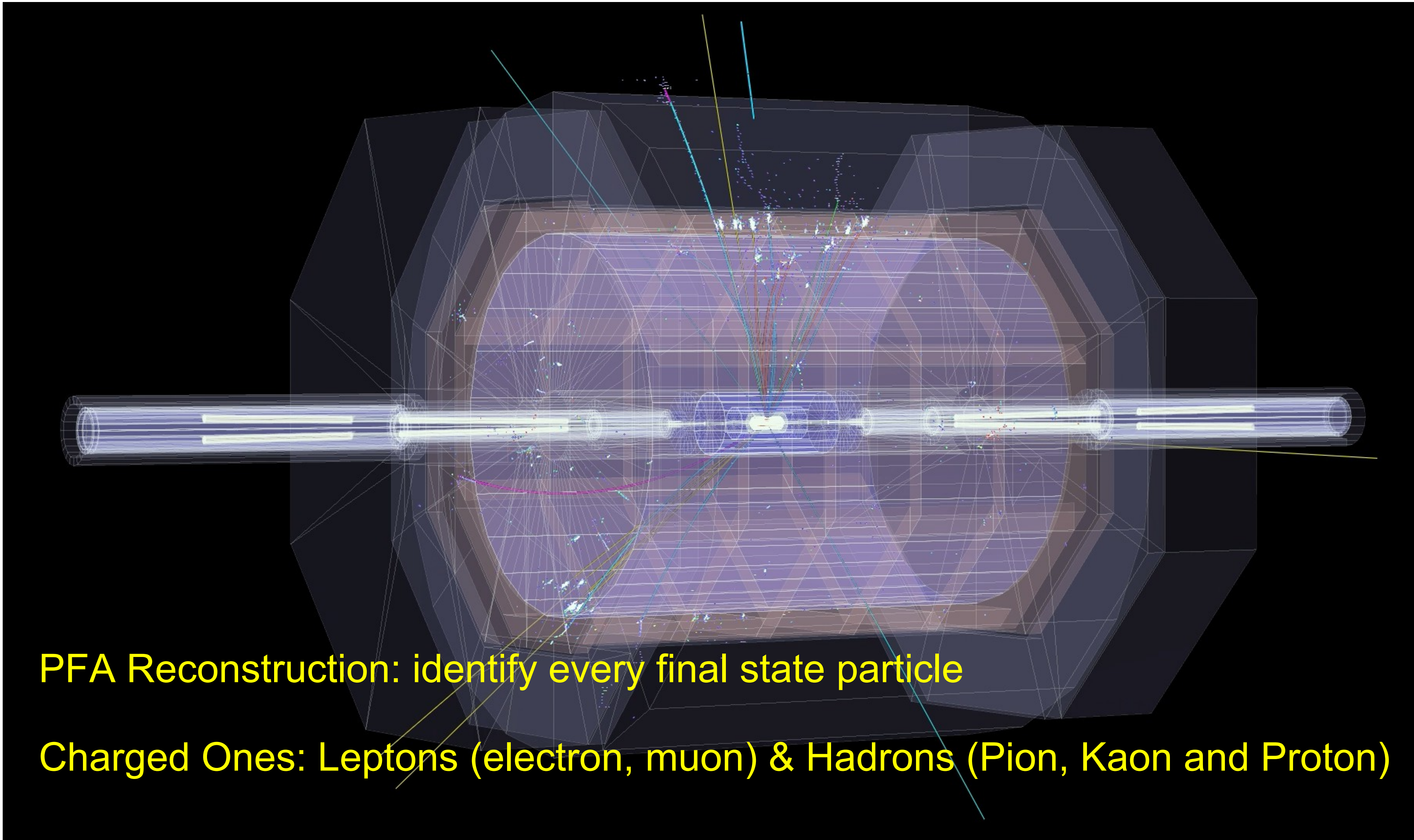


Hadron identification study at the CEPC

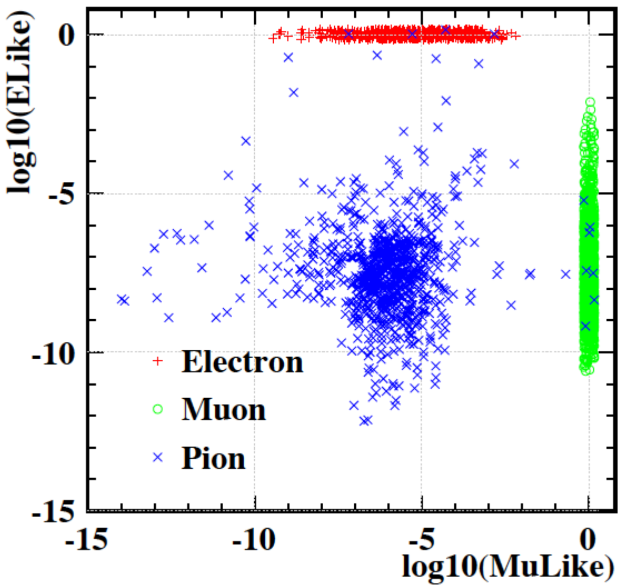
Manqi Ruan
On behavior of the CEPC Study Group

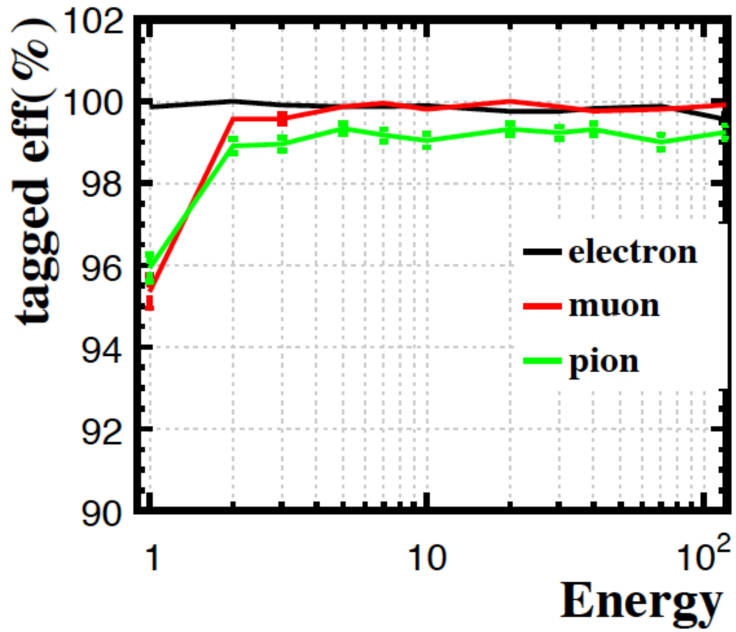


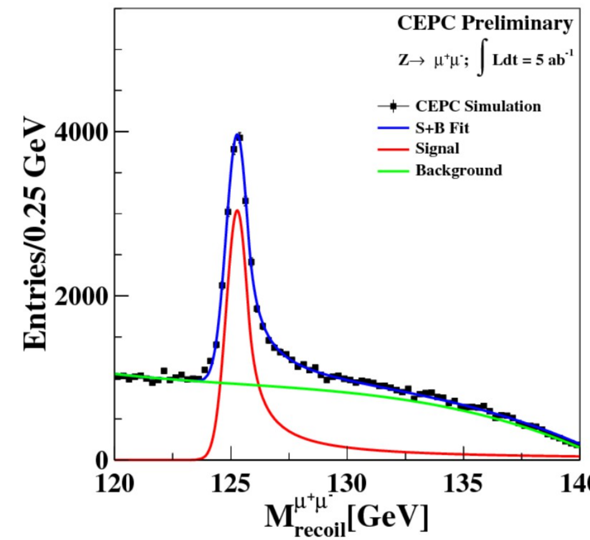
PFA Reconstruction: identify every final state particle

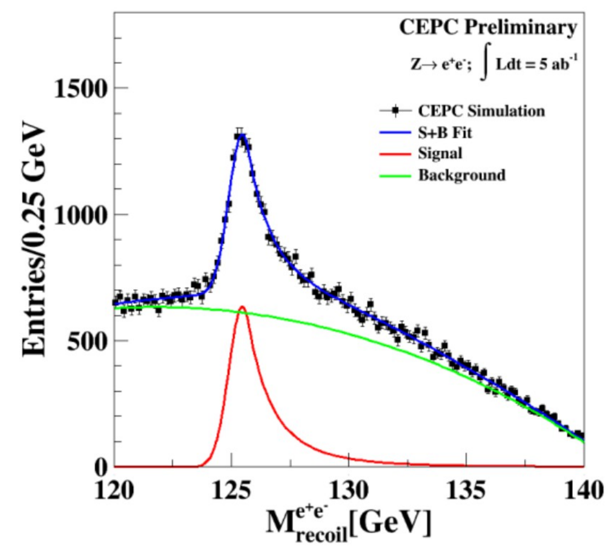
Charged Ones: Leptons (electron, muon) & Hadrons (Pion, Kaon and Proton)

Lepton









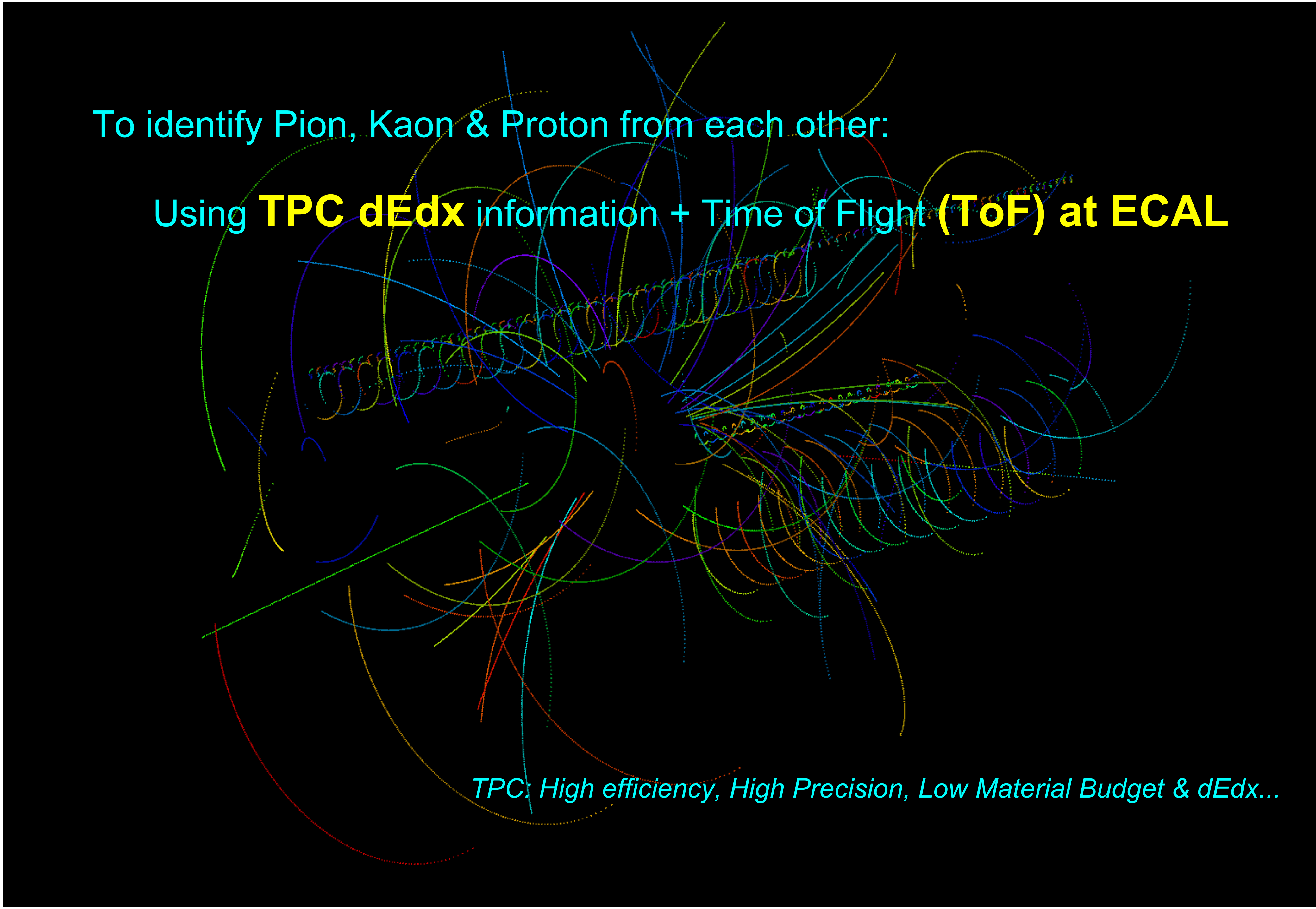
BDT method using 4 classes of 24 input discrimination variables.

Test performance at: Electron = E_likeness > 0.5 ;
Muon = Mu_likeness > 0.5
Single charged reconstructed particle, for E > 2 GeV:
lepton efficiency > 99.5% && Pion mis id rate ~ 1%

https://link.springer.com/article/10.1140/epjc/s10052-017-5146-5

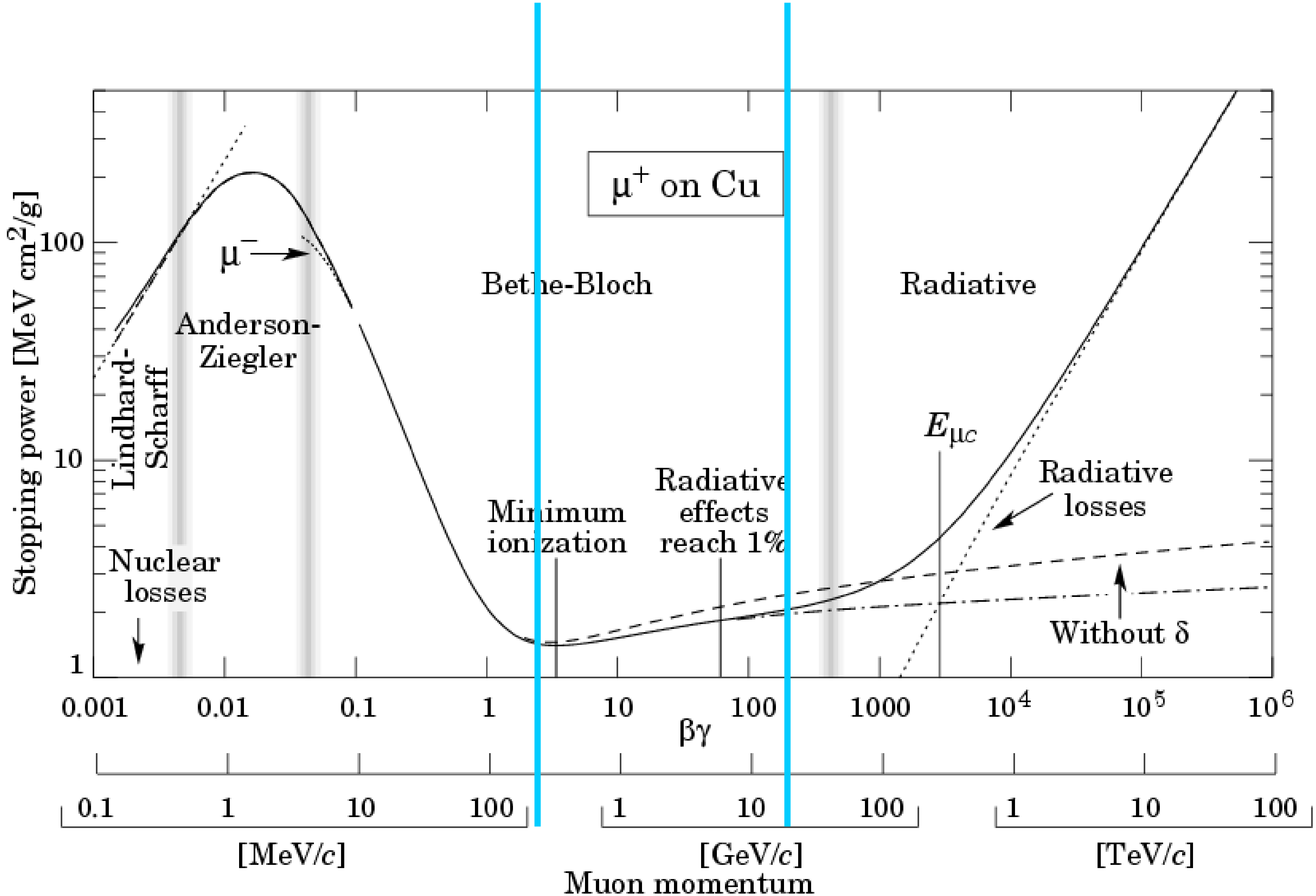
To identify Pion, Kaon & Proton from each other:

Using **TPC dEdx** information + Time of Flight **(ToF) at ECAL**

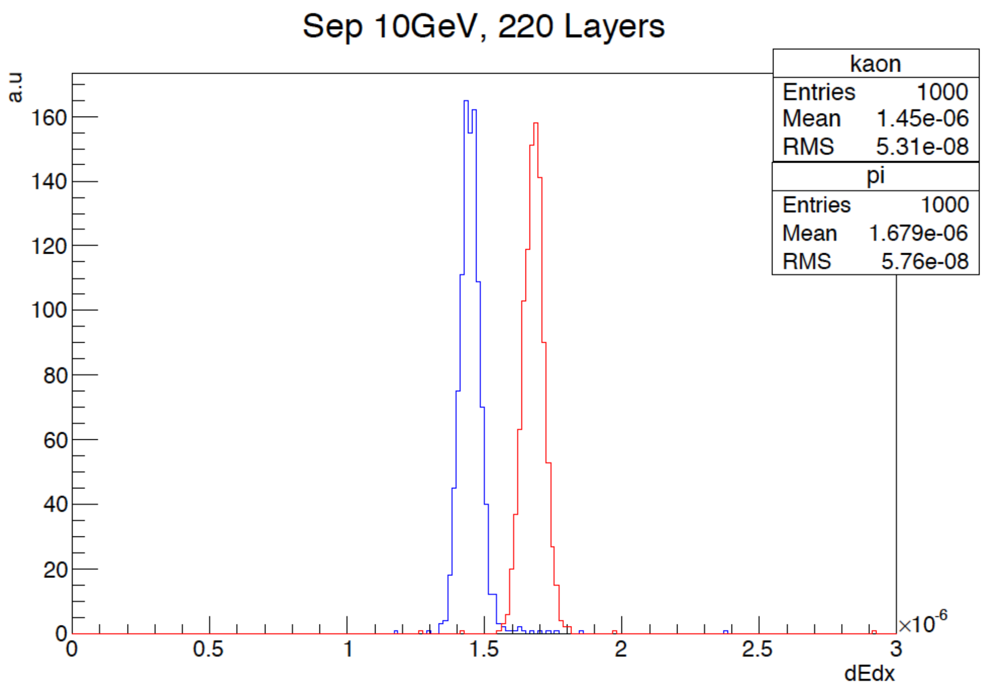


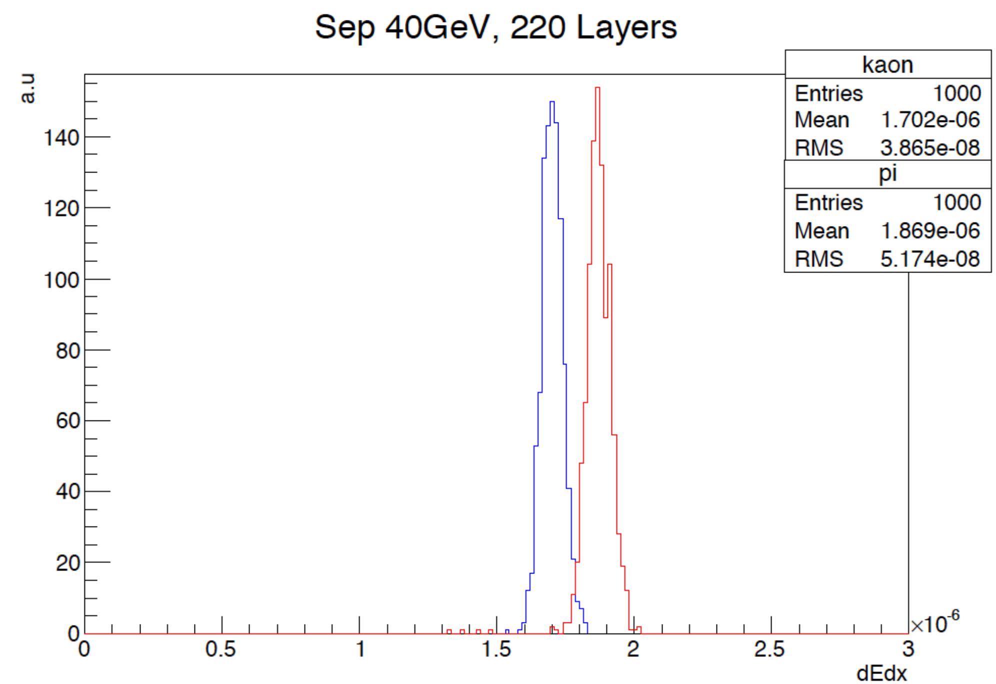
TPC: High efficiency, High Precision, Low Material Budget & dEdx...

dEdx: Prediction of Bethe-Bloch...



Pi-K separation with dE/dx at TPC





An efficient Pi-Kaon separation is highly appreciated for CEPC Z pole program

dE/dx seems to be a promising tool for pi-K separation even at E > 10 GeV...

Key question:

How, differentially & statistically, is the performance?
How well is the dEdx information preserved at Sensor/DAQ level?

Validation of Geant 4 Simulation...

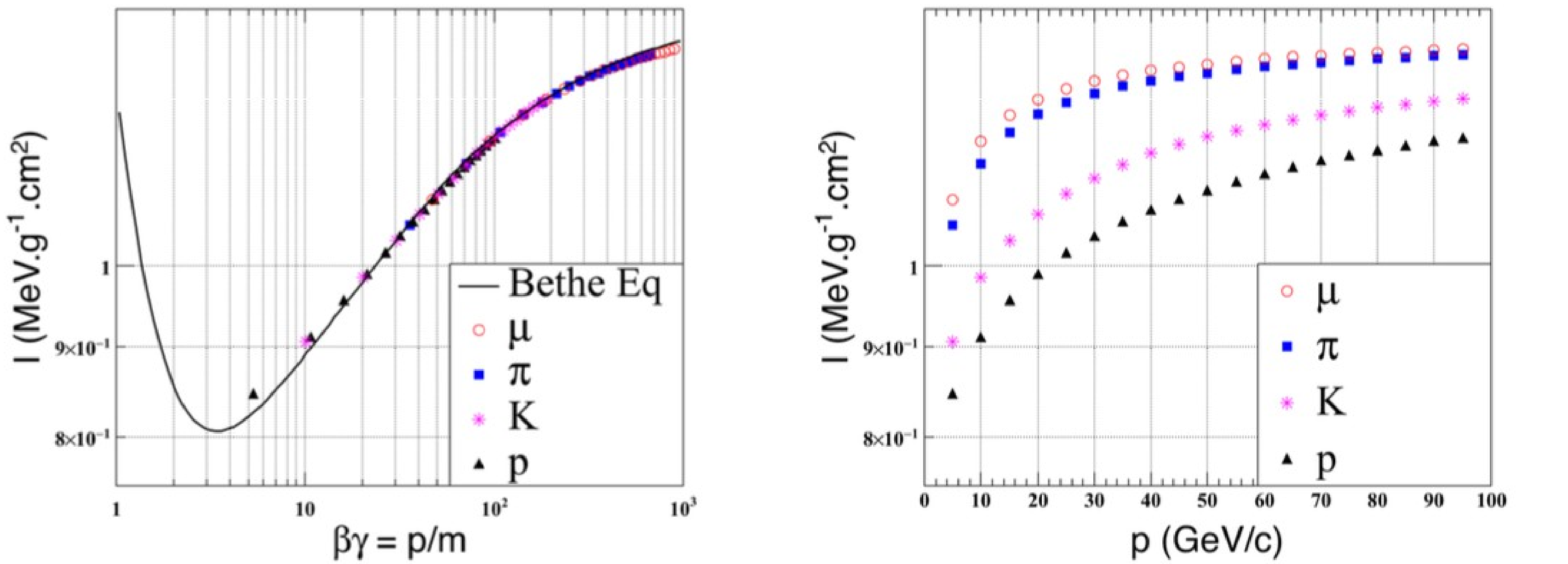
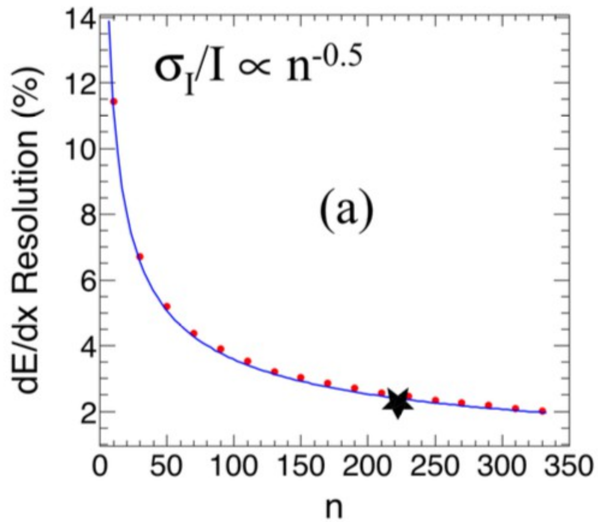
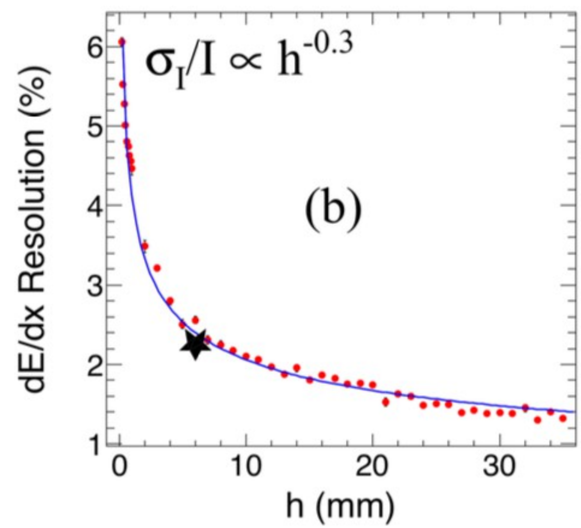


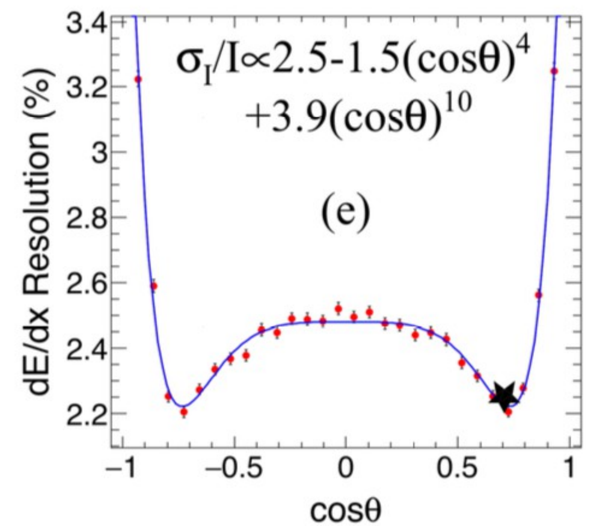
Fig. 1 Variation of the ionizing energy I versus (left) $\beta\gamma$ and (right) p of particles in argon-based gas (93% Ar+5% CH_4+2% CO_2) in simulation.

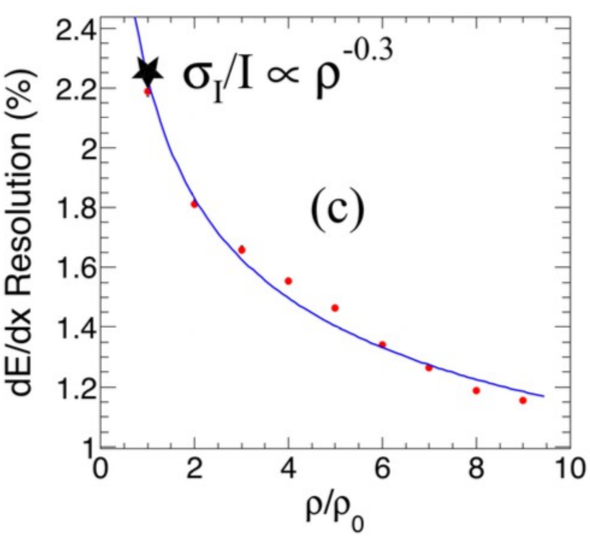
The Geant 4 Simulation agrees with Bethe-Bloch Prediction

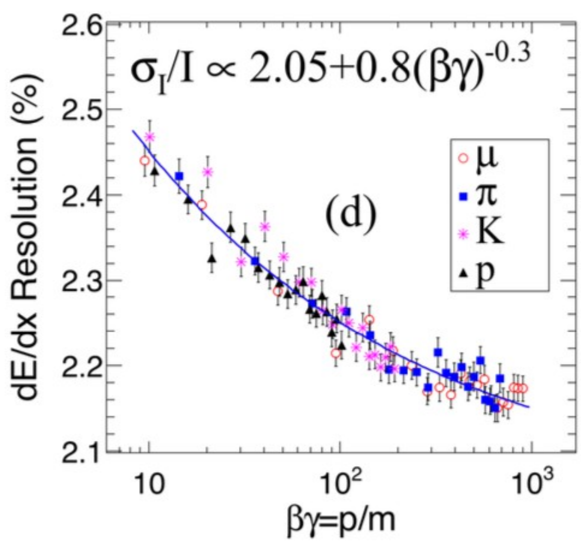
Resolution at different conditions











$$\frac{\sigma_I}{I} = \frac{13.5}{n^{0.5}\cdot(h\rho)^{0.3}}\left[2.05+0.8(\beta\gamma)^{-0.3}\right]$$
$$\times\left[2.5-1.5(\cos\theta)^4+3.9(\cos\theta)^{10}\right].$$

Reference to existing experiments

Table 1 Properties of TPCs in previous experiments. Comparison of the relative dE/dx resolution between MC and experimental measurements.

Experiment	PEP-4 [21–23]	TOPAZ [24]	DELPHI [25, 26]	ALEPH [27, 28]	STAR [29, 30]	ALICE [4, 31]	CEPC
Year	1982	1987	1989	1989	2000	2009	-
Particle Collide	e^-/e^+	e^-/e^+	e^-/e^+	e^-/e^+	Au/Au	p/p	e^-/e^+
E_{beam} (GeV)	14	26	45.6	45.6	100	1380	125
Gas	Ar: 0.8 CH4: 0.2	Ar: 0.9 CH4: 0.1	Ar: 0.8 CH4: 0.2	Ar: 0.91 CH4: 0.09	Ar: 0.9 CH4: 0.1	Ne: 0.857 CO2: 0.095 N2: 0.048	Ar: 0.93 CH4: 0.05 CO2: 0.02
Pressure (atm)	8.5	3.5	1	1	1	1	1
ρ (mg/ml)	12.43	5.47	1.46	1.57	1.56	0.95	1.73
n	183	175	192	344	13, 32[2]	63,64,32	222
h (mm)	4	4	4	4	12, 20	7.5,10,15	6
L (mm)	2000	3000	2680	4400	4200	4994	4700
Control Sample	e	π	π	e	π	π	π
(GeV/c)	14	0.4-0.6	0.4-0.6	45.6	0.4-0.6	6.0	5.0
Truncation	0-65%	0-65%	8-80%	8-60%	0-70%	0-60%	0-90%
N_{eff}	n	0.7n[3]	0.6n[4]	338	44	149	0.9n
$(\sigma_I/I)_{MC}$	2.6%	3.8%	5.4%	3.0%	5.3%	3.3%	3.1%
$(\sigma_I/I)_{exp}$	3.5%	4.6%	6.2%	4.4%	6.8%[5]	5.0%	4.6%
$\lvert\frac{(\sigma_I/I)_{exp}}{(\sigma_I/I)_{MC}}-1\rvert$	0.35	0.21	0.15	0.47	0.28	0.52	0.50

To the worst case: the REAL dEdx accuracy is 50% worse than the MC Truth

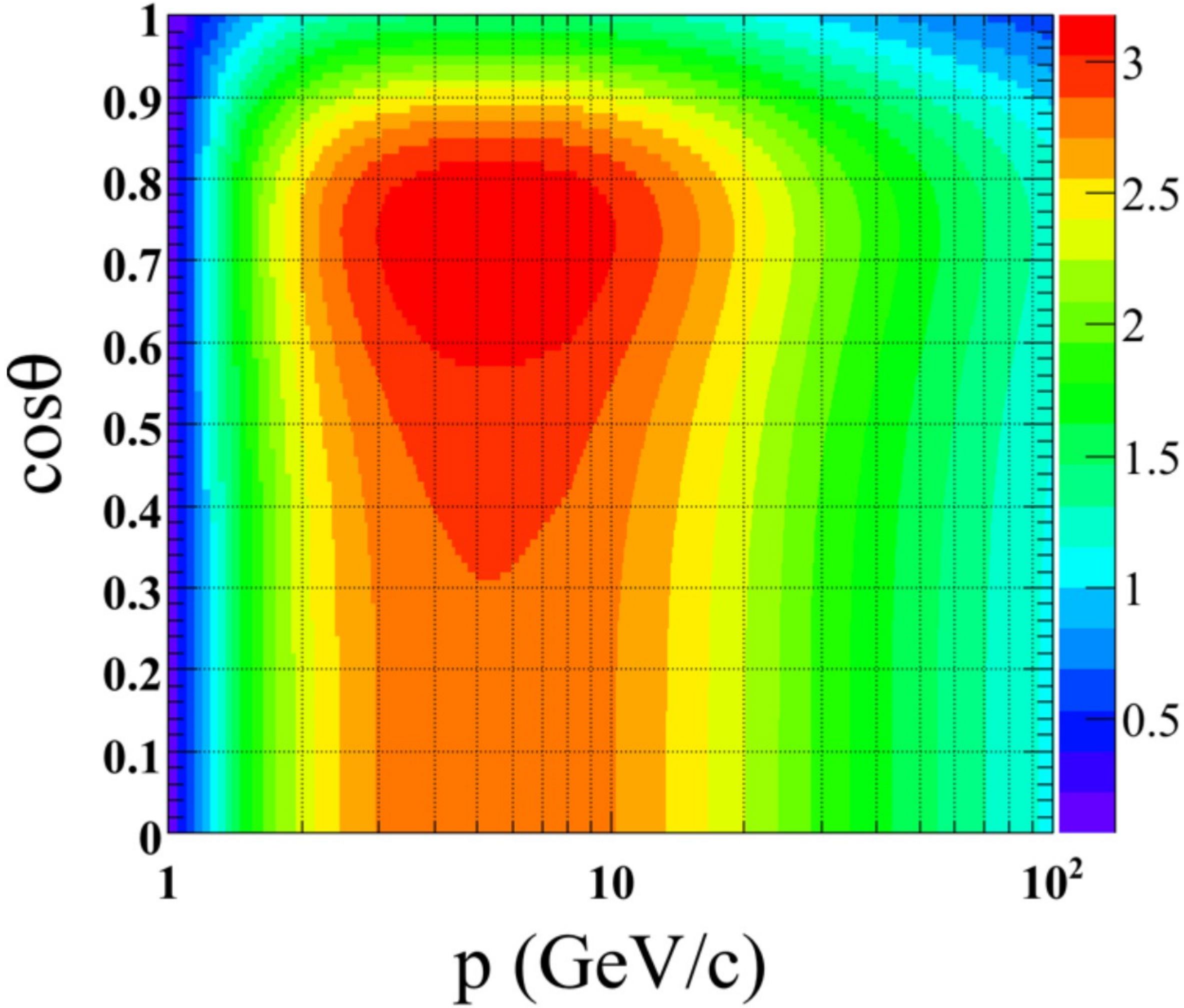
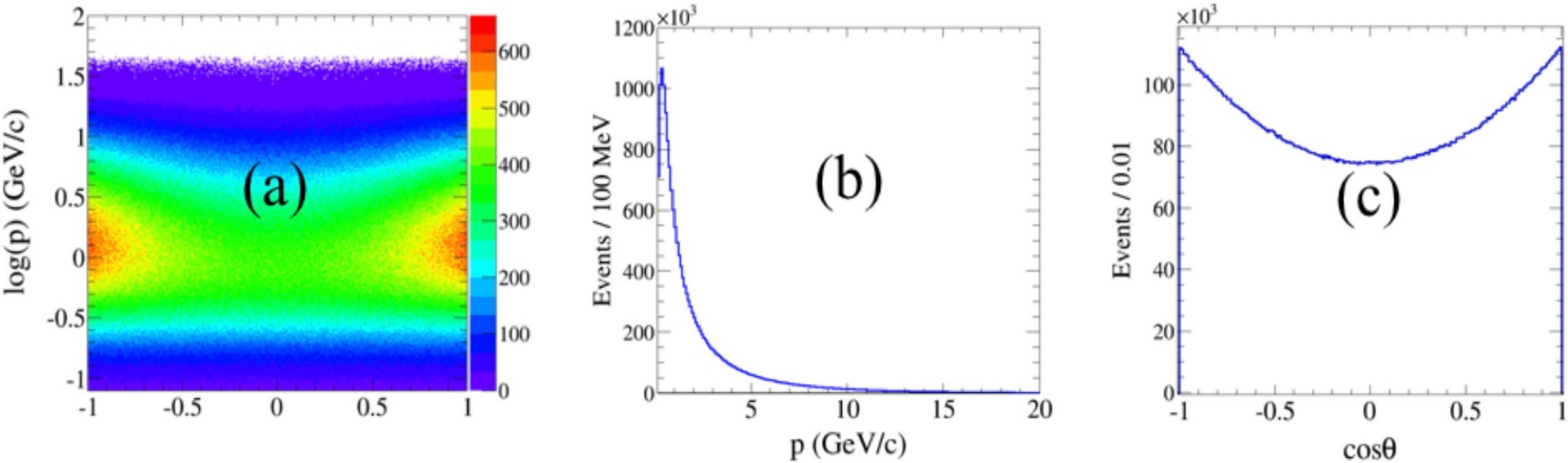


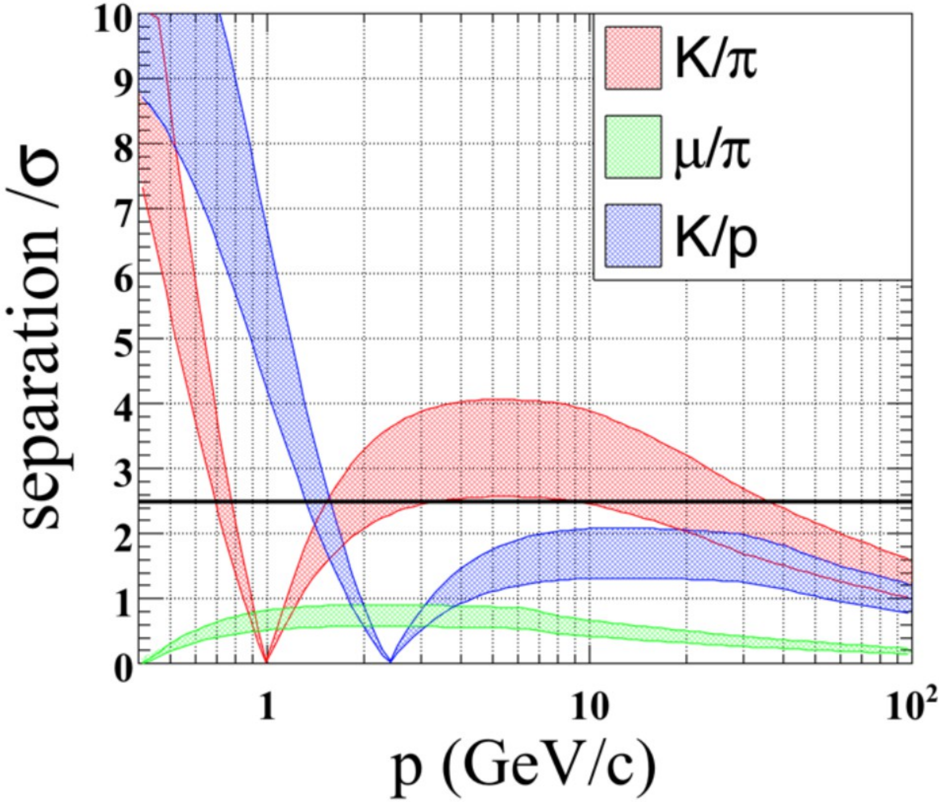
Fig. 4 Separation power between kaon and pion in 2-D (p, $\cos\theta$) space assuming 90% effective hits and deterioration of 0.5 arising in experimental measurements.

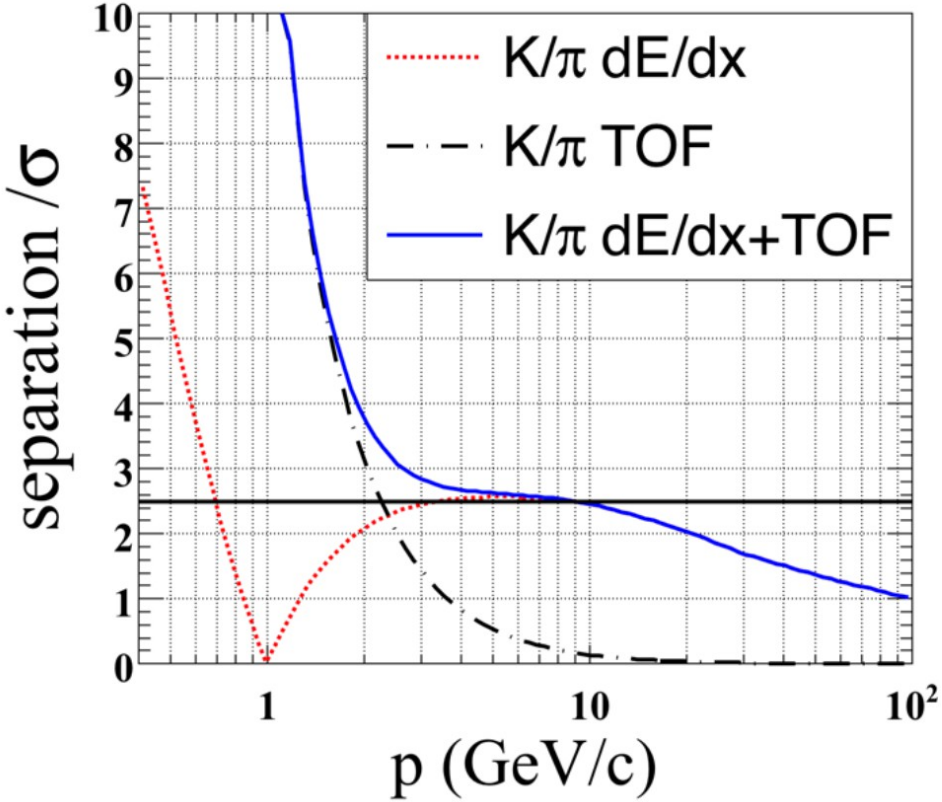
Z->qq differential distribution of Track Momenta



Overall performance: Integrated the separation over the differential distribution along The differential parameters(polar angle/momenta)

Performance: K/pi

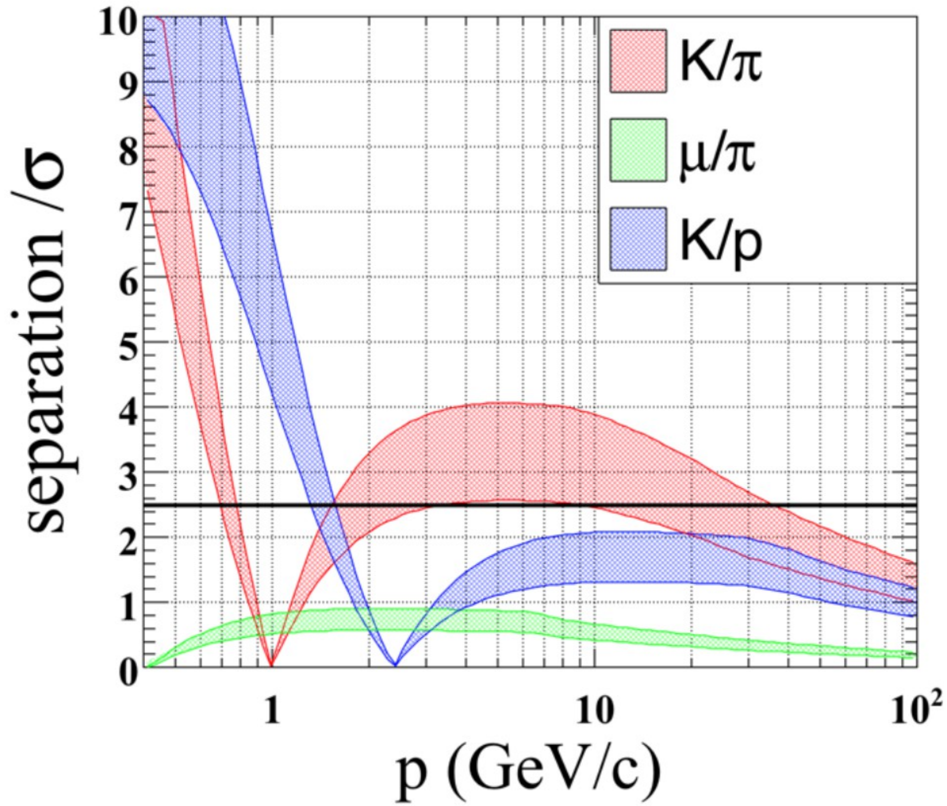


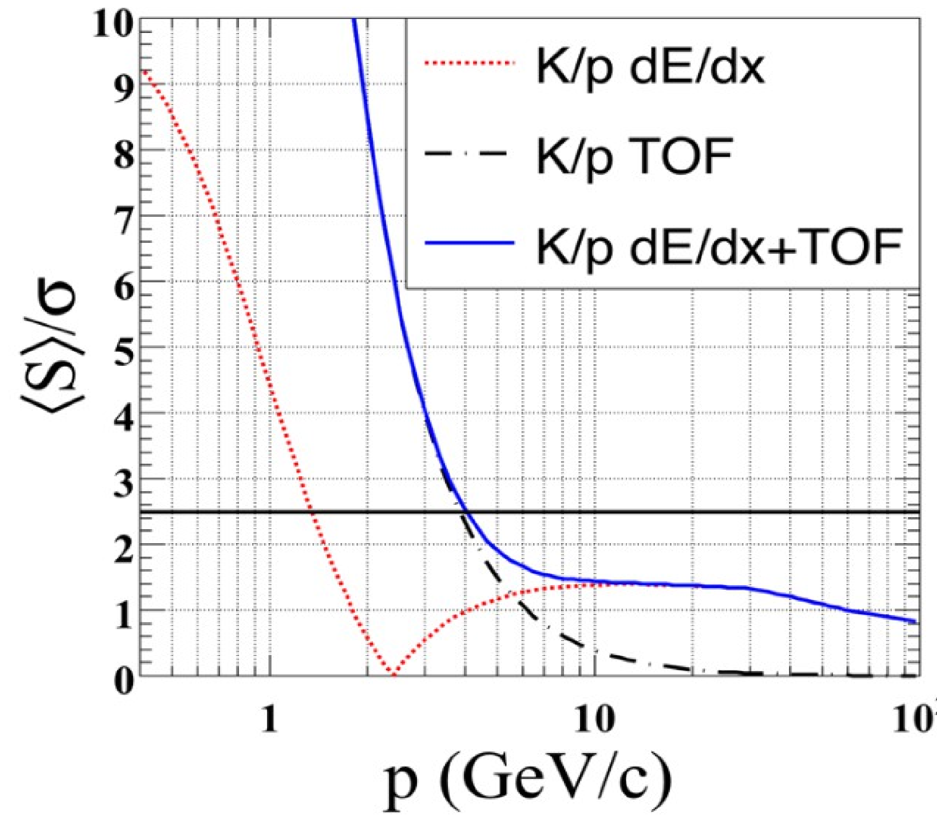


Left: Separation wi/wo 50% degrading

Right: Degraded Performance + 50ps ToF information (measured from the ECAL)

Performance: K/proton





Left: Separation wi/wo 50% degrading

Right: Degraded Performance + 50ps ToF information (measured from the ECAL)

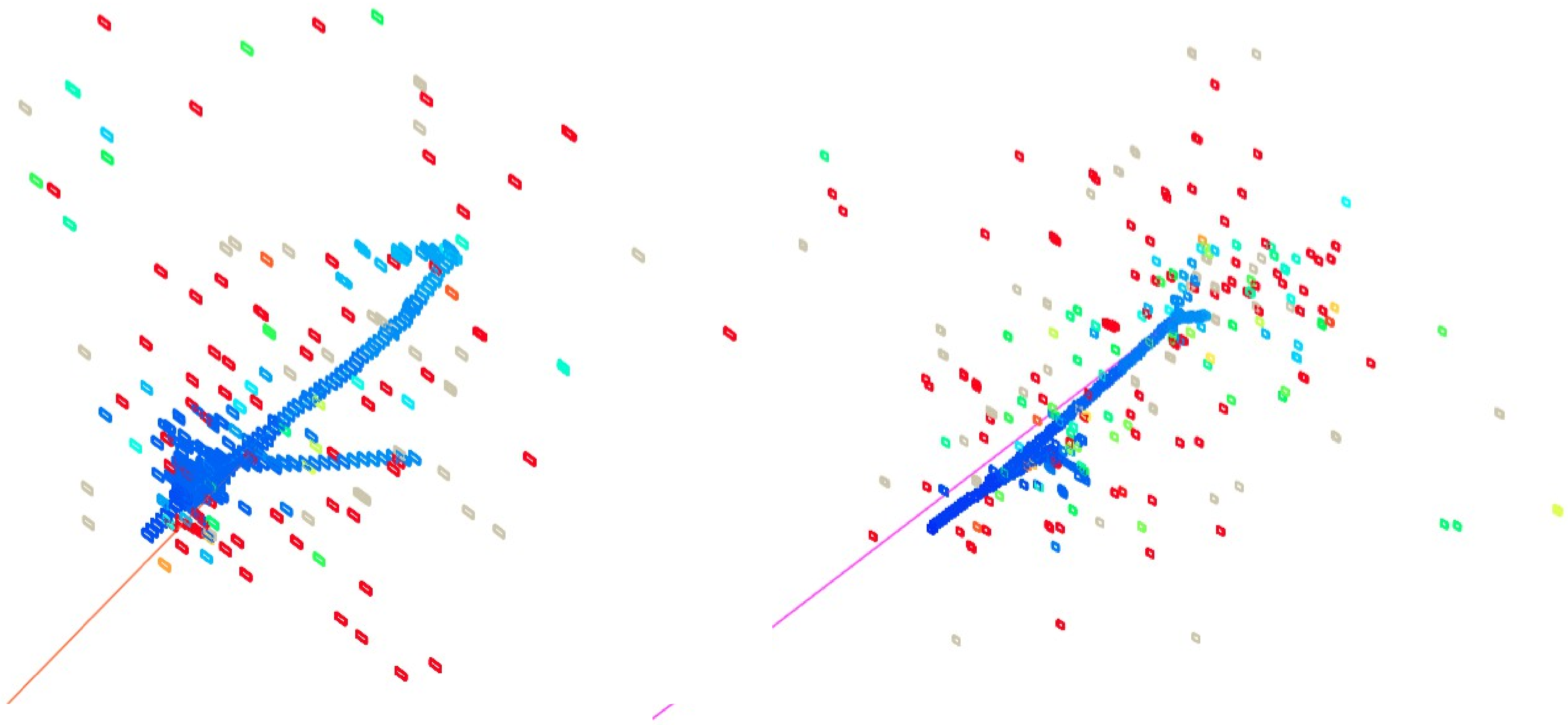
Over all Performance

- Efficiency & Purity at Z pole
  - Statistically: Pion is roughly 8 times w.r.t Kaon, which is 1.4 times more than Protons
  - integrated over 2 – 20 GeV momenta range and the fiducial polar angles

Condition		#σ(π-K/K-p)	Efficiency	Purity
MCTruth	dEdx only	3.9/1.5	88%	86%
	+ TOF	4.0/3.2	98%	98%
20% degraded	dEdx only	3.1/1.2	81%	79%
	+ TOF	3.3/3.0	96%	96%
50% degraded	dEdx only	2.4/0.9	68%	68%
	+ TOF	2.8/2.9	91%	94%

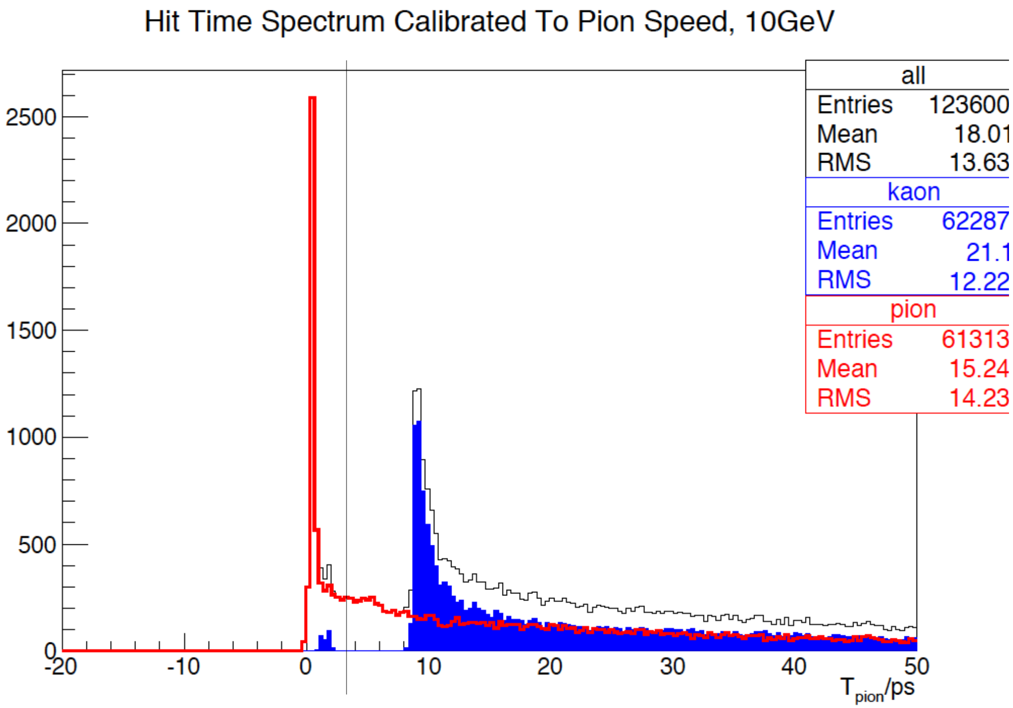
Hand waving objective:
To understand the source of degrading, and control it to be less than 20%.

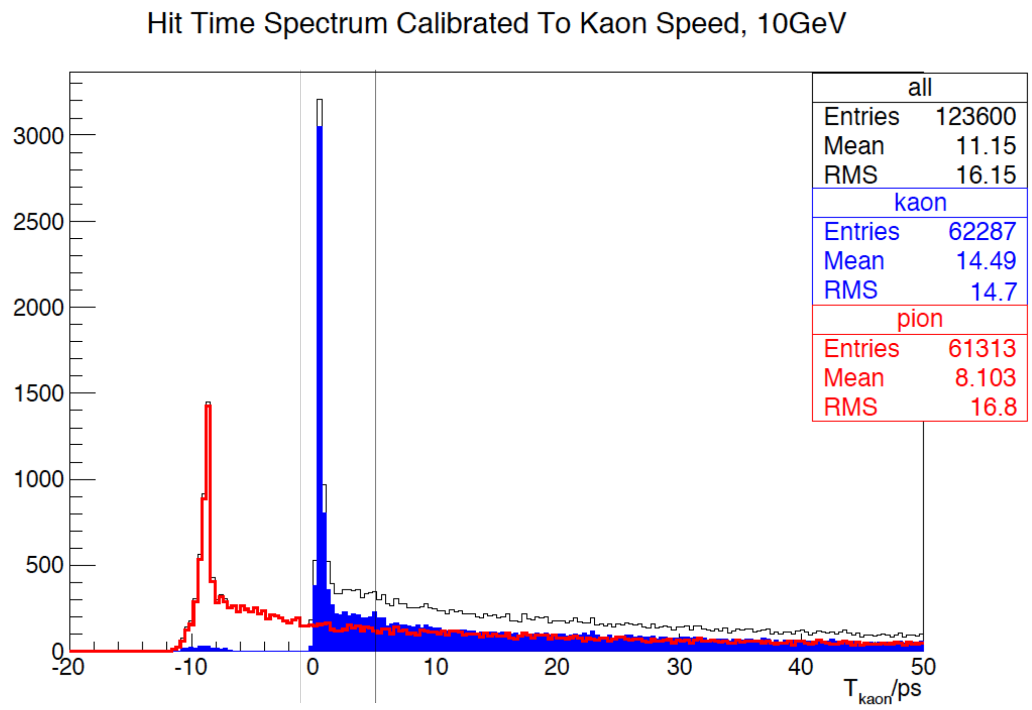
Pion(Left) – Kaon(Right) @ 10 GeV



For hadronic Shower: Hits have wide time distribution...

100 events

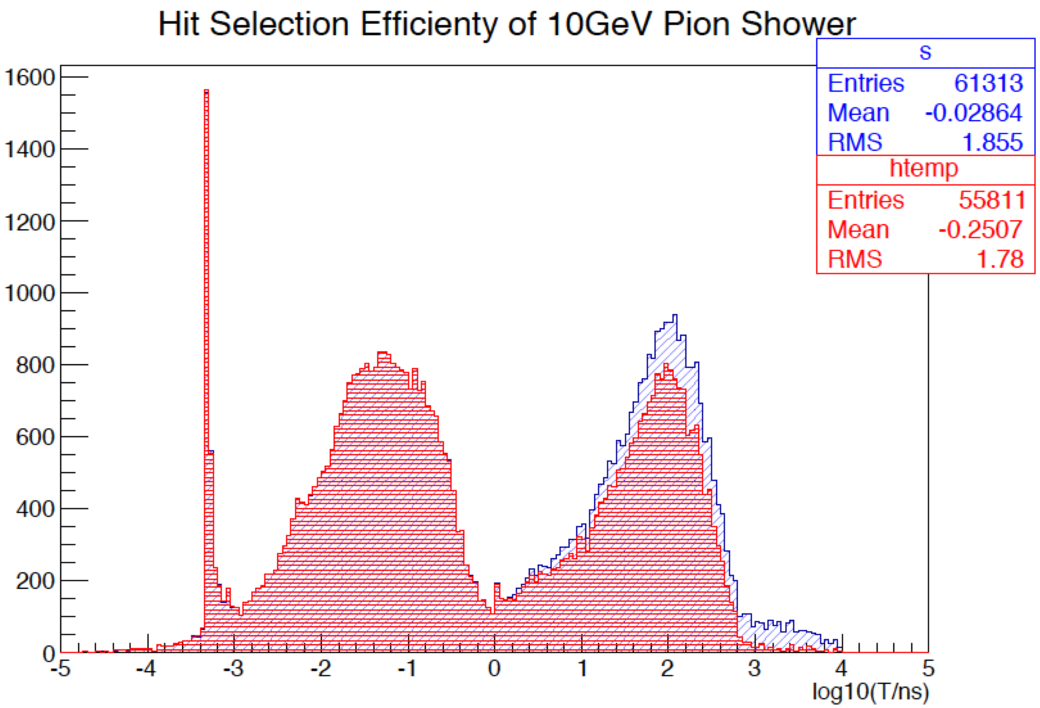


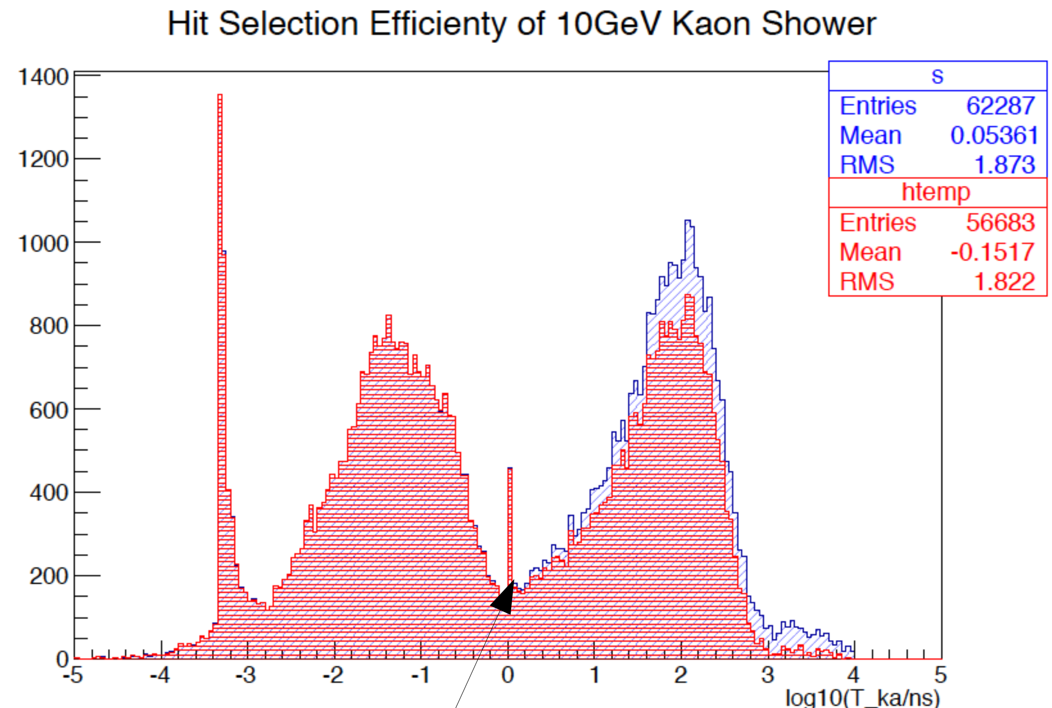


Average #Hits Per event	T < 5 ps	T < 5ps && Nlayer < 30	T < 2ps	T < 2ps && Nlayer < 30
Pion	64.6	38.3	43.6	27.3
Kaon	68.3	34.8	50.2	26.3

If every channel can measure the time: ~ 25 hits can be used to determine the time.

Clustering: Hit Collection Efficiency





Most of the fast hits can be collected by the Clustering algorithm

Arbor Core Parameter dependent.

Kaon decay...

- 50 ps time resolution at cluster level:

#layer equipped with TDC	Needed Time resolution per channel
25	250 ps
4-5	100 ps

dEdx, ToF and particle id

- dEdx(at LCPTC setup) + ToF(at 50ps resolution) leads to decent Pi-Kaon separation for CEPC Z pole Runs – which is appreciated for the flavor physics
- Modeling of Gain/DAQ/Readouts:
  - Experimental data exhibit degrading of 15-50% w.r.t the MCTruth
  - Induced by Hit Energy Resolution, Gain Homogeneity, Stability, etc...
- ToF is required
  - Fulfill the gap at 1 GeV,
  - Makes a significant impact for the conservative case of (Degrading ~ 50%)
- Would be great if the degrading is controlled to 20%
  - **Is it feasible? & HOW? & Test & Roadmap?**
- *Remark:*
  - *Depends on the Bethe-Bloch prediction – How is it validated on experimental data at hadrons with E ~ 10 GeV?*
  - *Geometry optimizations may lead to improvements on dEdx measurements*

Backup

Summary

- **TPC is Promising for the CEPC** (e+e- collider with High event rate Z pole operation)
  - Both for the Z/Higgs operation
  - No show stopper from occupancy and distortion (based on Z->qq events)
- dEdx + ToF: leads decent particle id
  - Based on the control of performance degrading w.r.t the MCTruth
- Goal: a globally optimized & realistic design of the TPC system: **To protect these important performances from other effects**
  - Forward region, X-ray flux estimation & Detector protection designs
  - A validation of Bethe-Bloch equation
  - Neutron/Gamma Flux
  - Methodology developments and validation for Homogeneity/Stability Control
    - Proper digitization that models these effects (GAIN/DAQ, etc)
    - Calculate the margin w.r.t the spatial & dEdx accuracy
    - Gas, power, cooling, calibration, alignments, in-situ monitoring...

Key questions

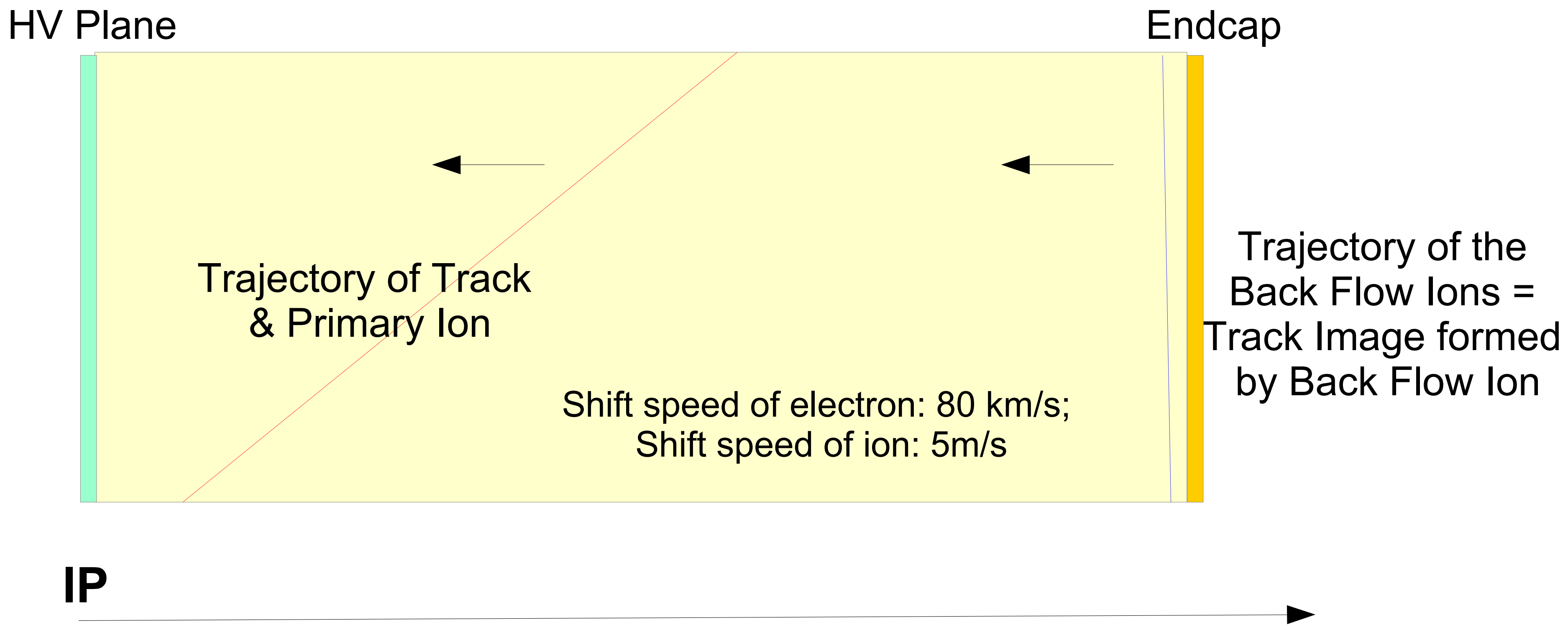
- Can we use TPC at CEPC?
  - Occupancy
  - Distortion

ArXiv: 1704.04001, 2017 JINST 12 P07005

- **dEdx measurements**
  - **Performance & K-Pi separation?**
- Requirement for Stability, Alignment, etc
- *Study done at CEPC-v1, which uses ILD TPC Geometry*
  - *R_{in}/R_{out} = 330/1800 mm, Segmented into 220 radical layers (with 6*1 mm^2 cells) between R = 390 – 1710 mm*

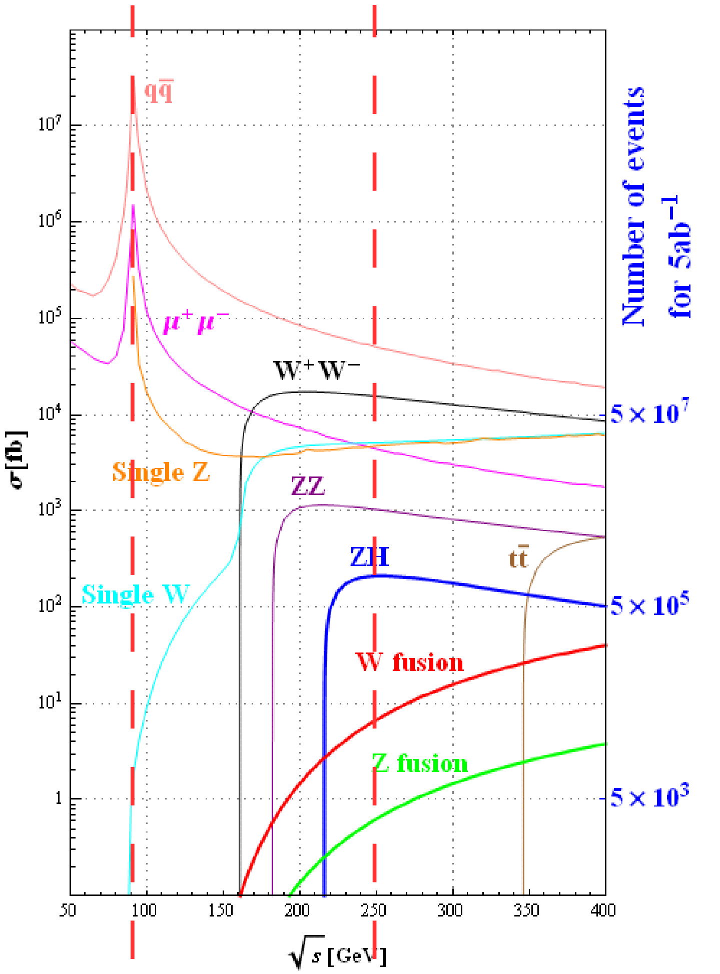
Feasibility of TPC

- Question: Would it be Limited by
  - Voxel occupancy
  - Charge Distortion Induced by ions: Mainly from Ion back flow



- Ion Charge ~ Primary + Back flow ion ~ (1 + k), k = Gain*IBF

Sources of Hits



CEPC Design –Higgs Parameters

Parameter	Design Goal
Particles	e+, e-
Center of mass energy	2*120 GeV
Luminosity (peak)	2*10^34/cm^2s
No. of IPs	2

⇒ one million Higgs from 2 IPs in 10 years

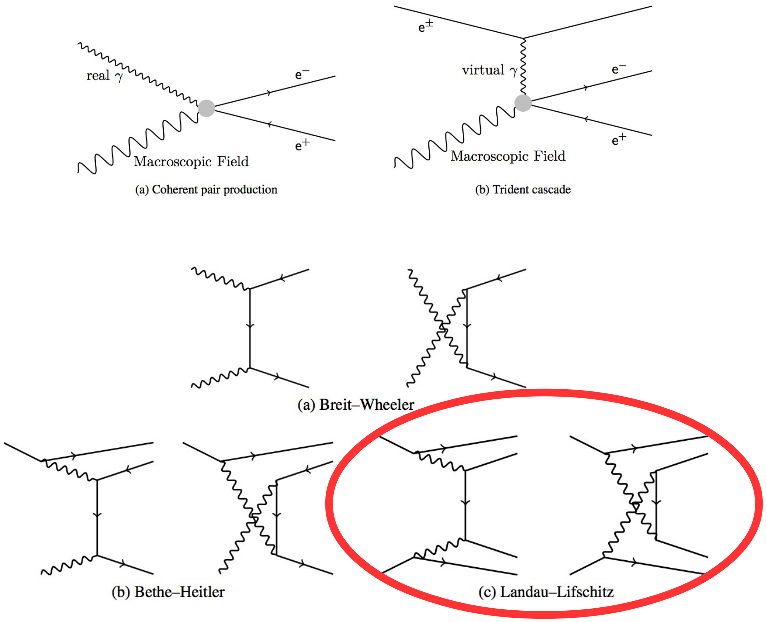
CEPC Design – Z-pole Parameters

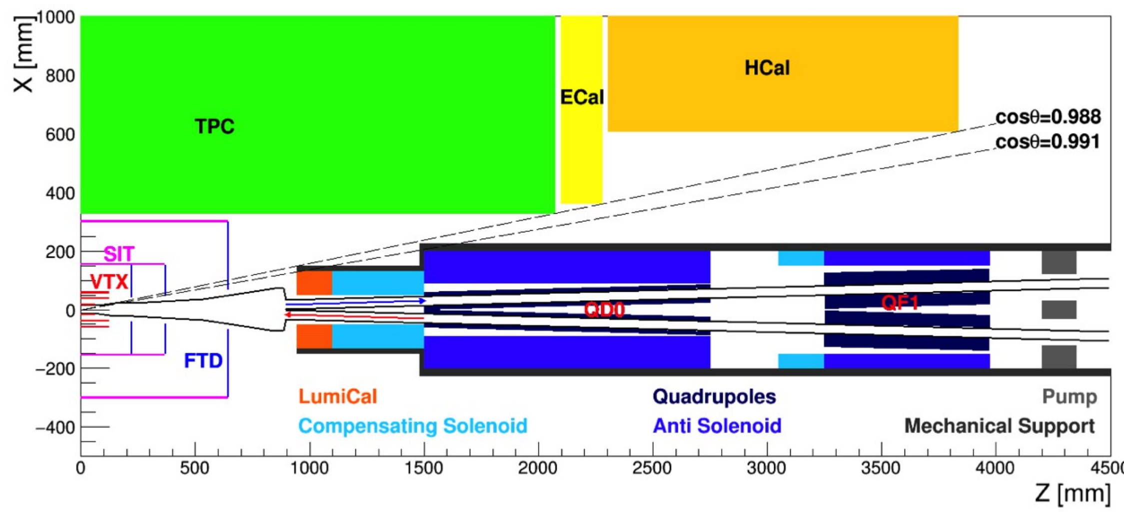
Parameter	Design Goal
Particles	e+, e-
Center of mass energy	2*45.5 GeV
Integrated luminosity (peak)	>1*10^34/cm^2s ~1*10^35/cm^2s (if needed as Super Z-factory)
No. of IPs	2
Polarization	Consider in the second round

10^{10} Z in 1 year

- Benchmark luminosity: $2*10^{34}$ cm^{-2} s^{-1} for both Higgs/Z pole runs
- Physics Event: Event Rate at Z pole >> at Higgs Runs

Sources of Hits

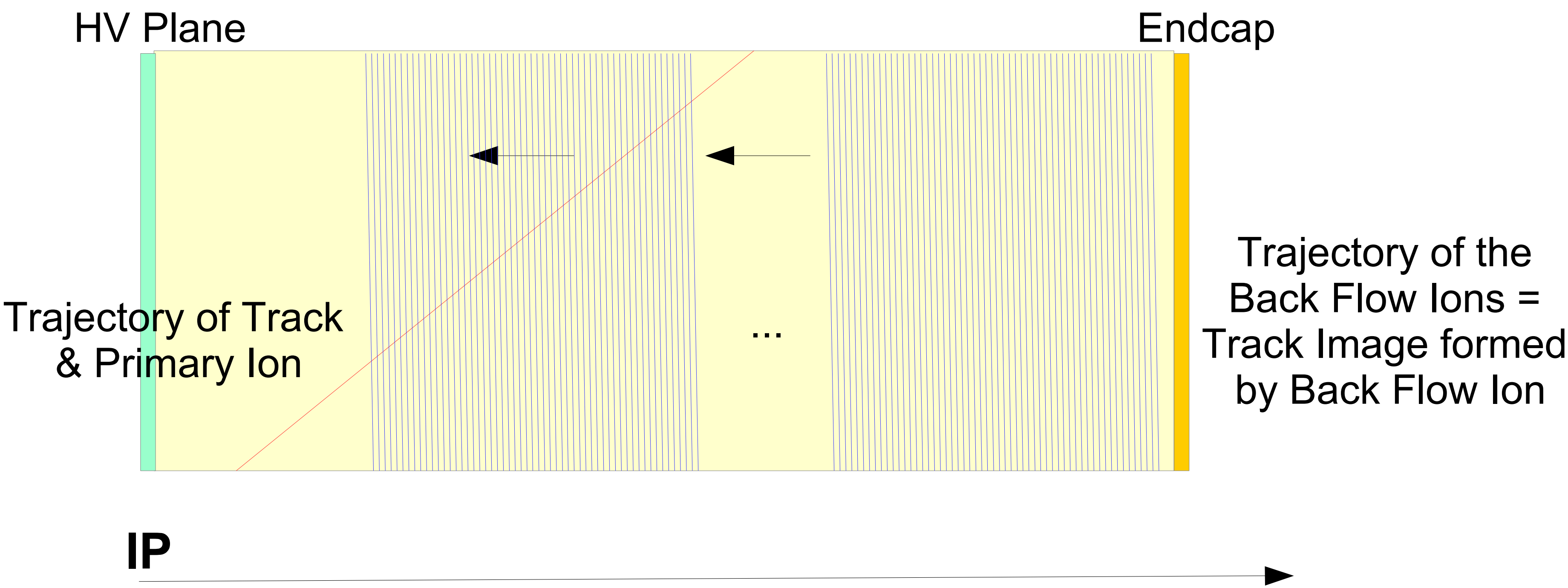




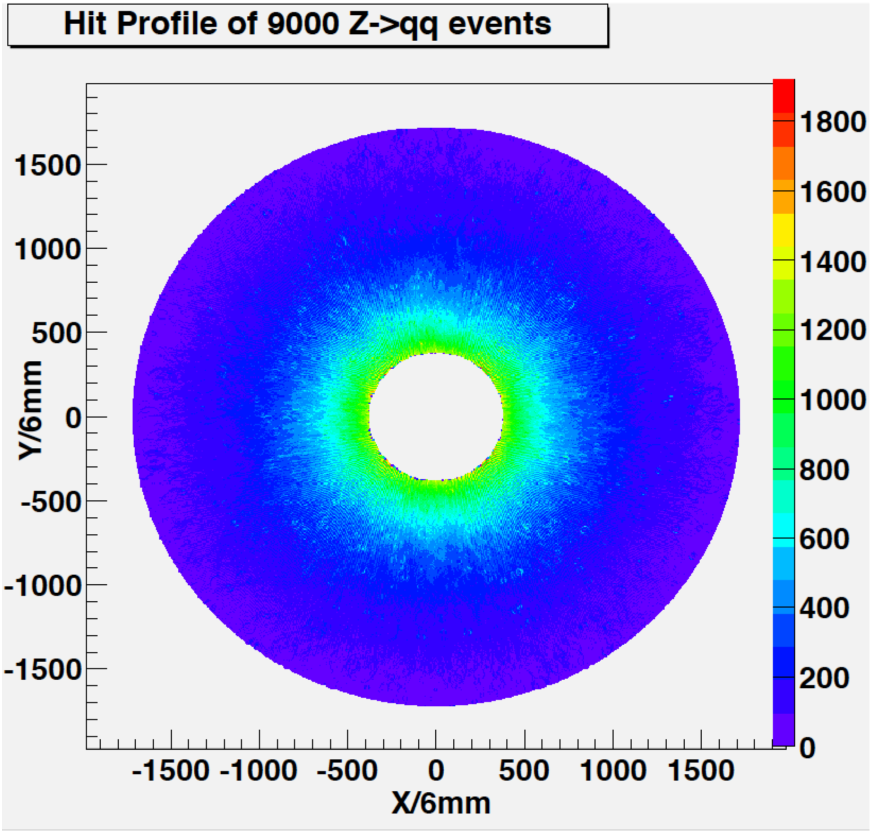
- Beam background (Preliminary): Mini-jets << Incoherent pairs (L-L) << Z->qq
  - Electron-Positron Pairs: Landau-Lifschitz Processes>> all others, with X-section is 1-2 orders of magnitude smaller than physics events at TPC fiducial volume
  - Mini-jets, muons, etc: << Electron-Positron Pairs
  - Synchrotron radiation, especially scattered/back scattered X rays: Need careful designed Shielding/detector protection

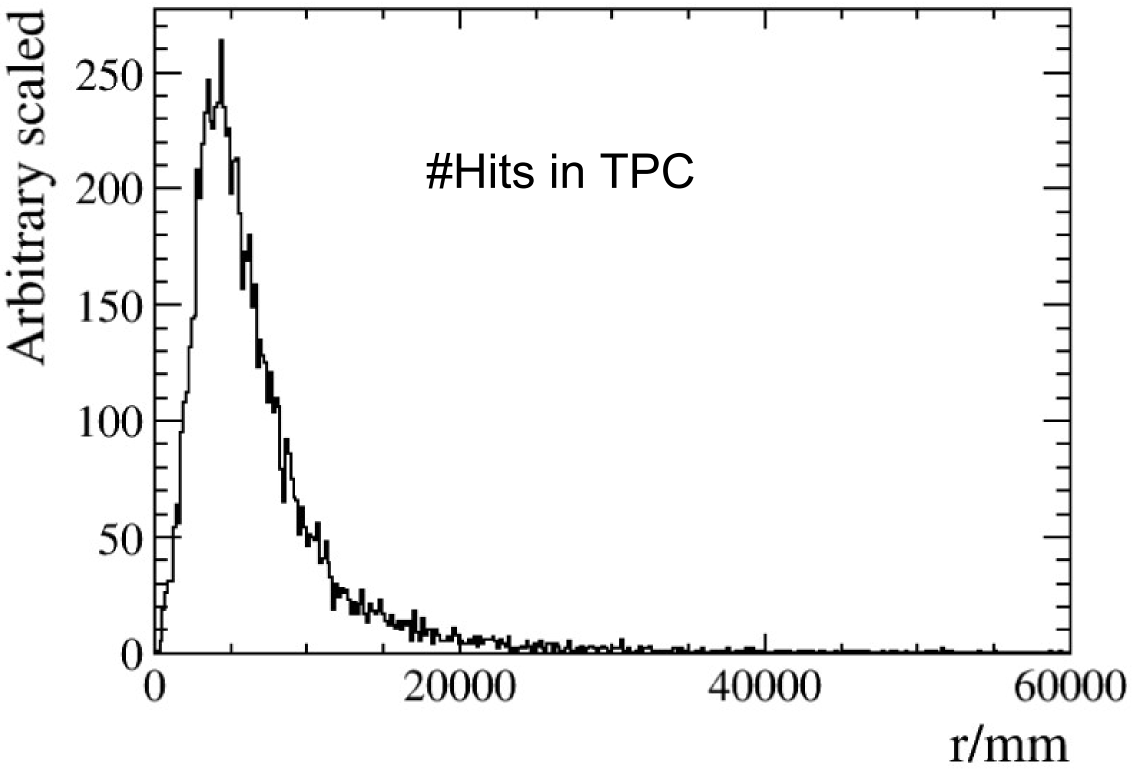
Feasibility of TPC at Z pole

- Need ~ 0.5 second for the ion to travel from the Endcap to the HV plane
- 600 Ion Disks induced from Z->qq events at 2E34$cm^{-2}s^{-1}$



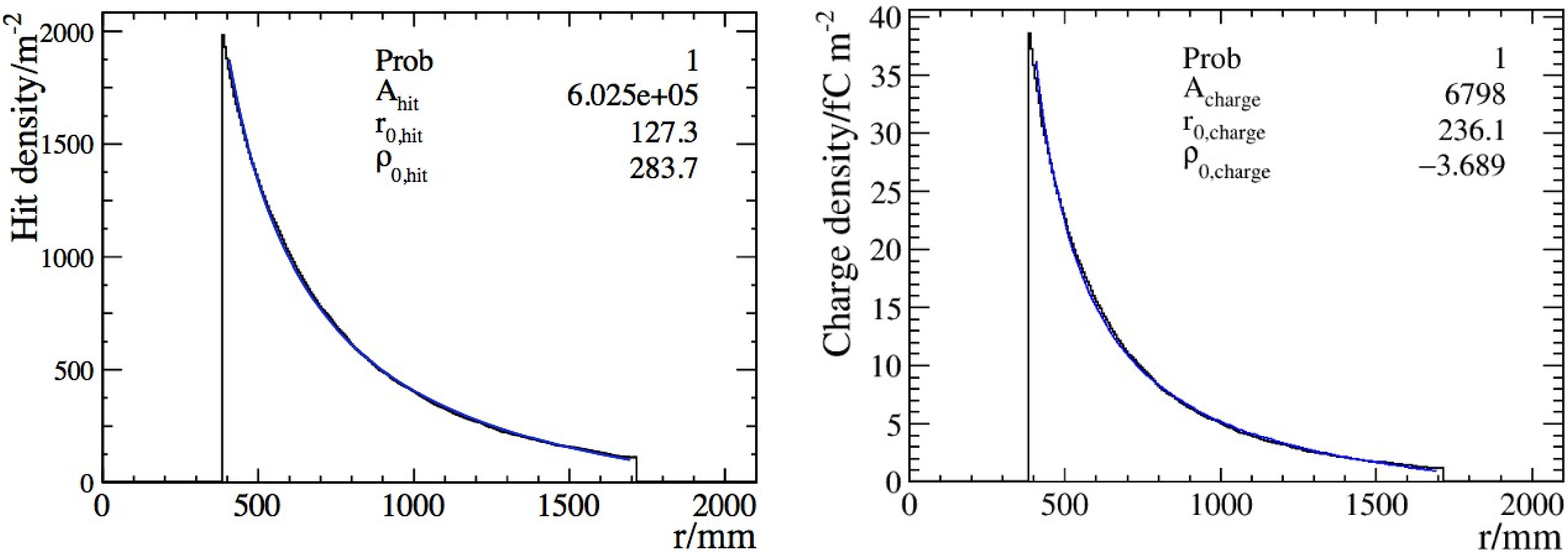
TPC Feasibility (Preliminary)





- On average: 1 physics event induces ~ 7k TPC Hits (MPV: 4k Hits, with long tail)
- 4 Million TPC hits in 1 second, induced from Z->qq events

Hit & Charge Radical Profile

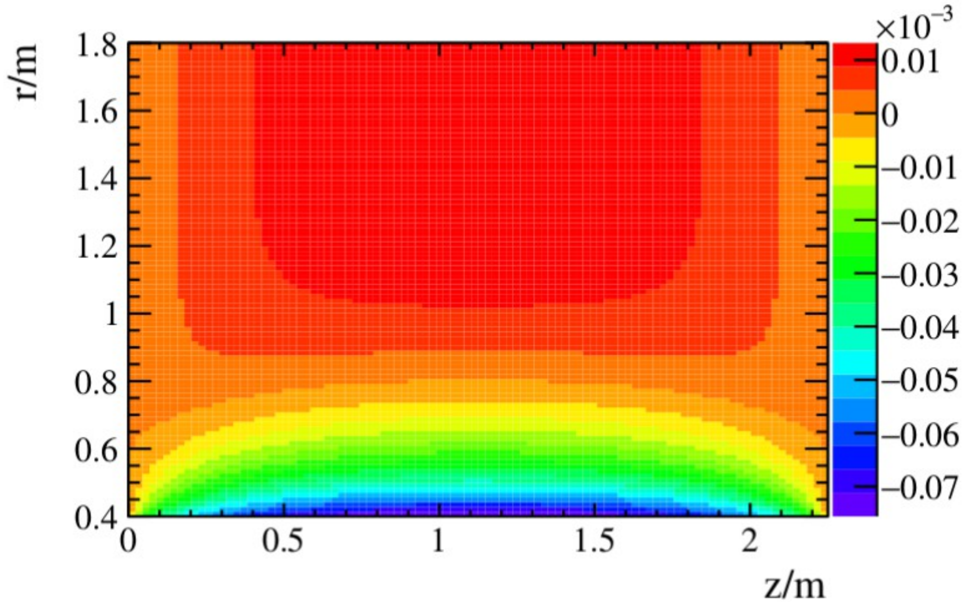


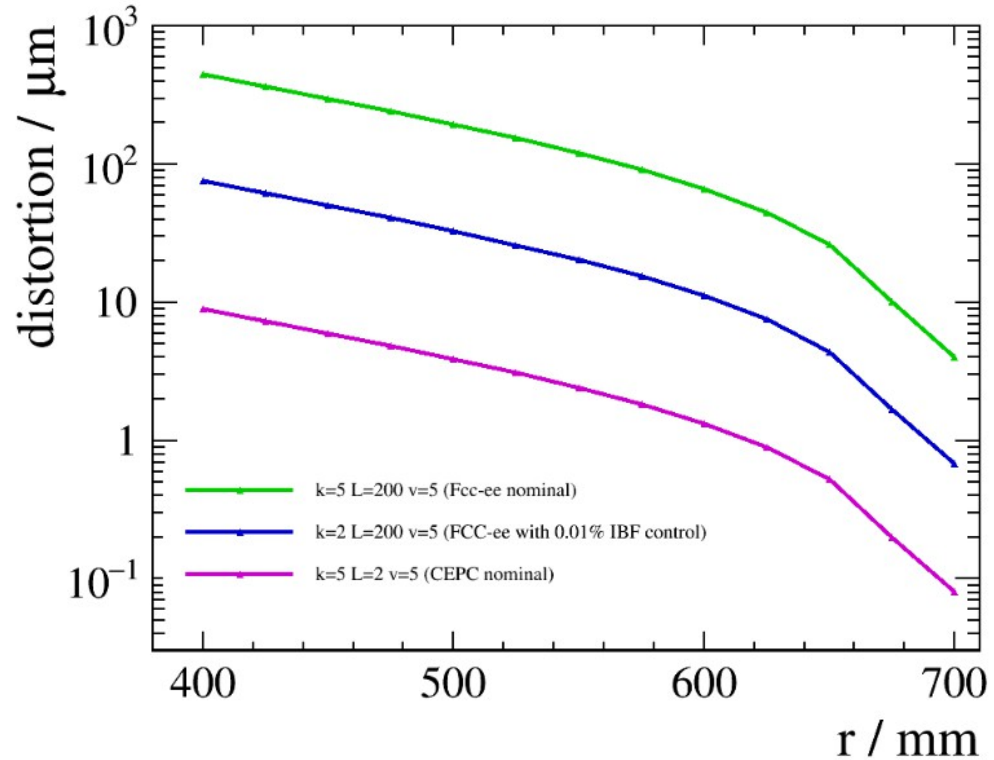
Occupancy:

- TPC Provides $1.3*10^{14}$ Voxels per second (DAQ at 40 Mhz)
- Each Hit occupies ~ 10 Voxels along the time direction (250 ns)
- Hits are much denser in the forward region
- Maximal Occupancy: ~o(10^{-5}) level at CEPC Nominal

Charge distortion

$$\Delta l = \frac{\omega\tau}{1+(\omega\tau)^2} \times \frac{E_r}{E_z}\Delta z,$$



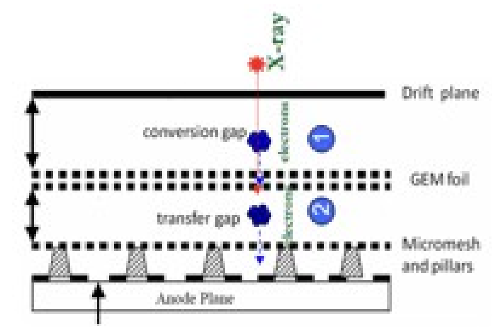


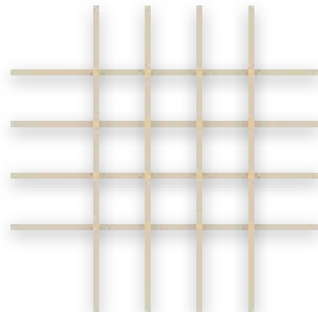
Er/Ez at L=2*10^{34}, IBF*Gain = 5 & Ion velocity = 5m/s

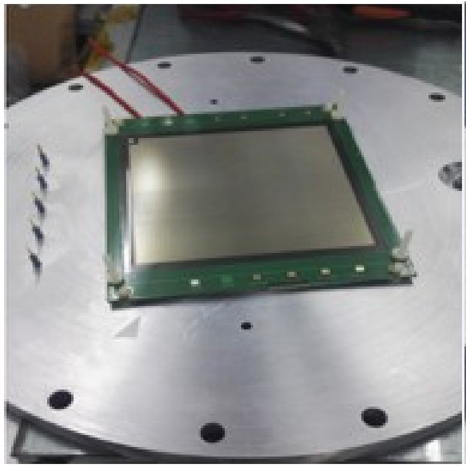
- Electric fields calculated using Fujii-San's code (Many Thanks!)
- Once the IBF controlled to 10^{-3} (IBF*Gain ~ 5), the spatial distortion (induced by Z->qq events) is 1 order of magnitude smaller than the intrinsic TPC Hits resolution

ArXiv: 1704.04001, 2017 JINST 12 P07005

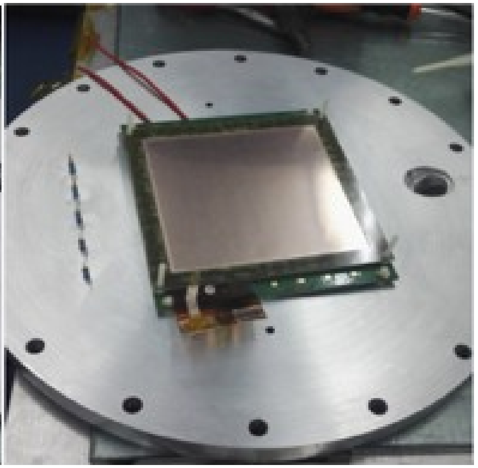
R&D on the IBF control



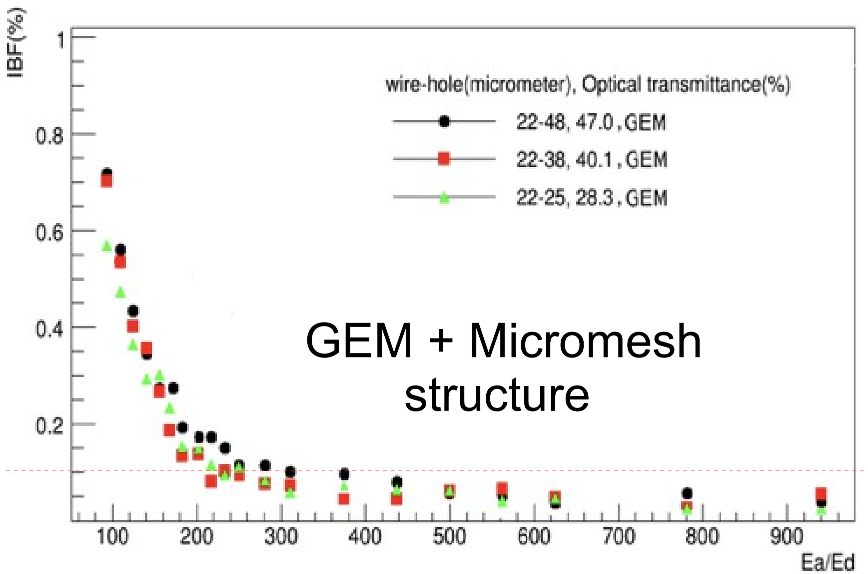


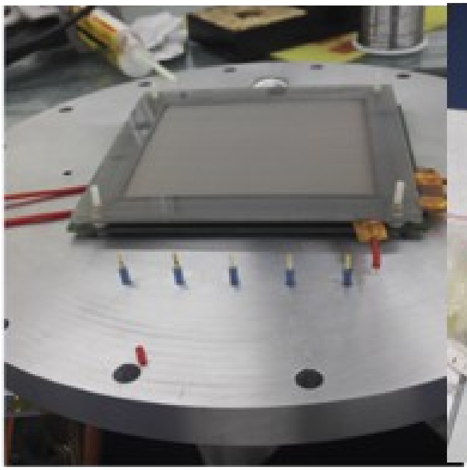


Micromegas(Saclay)

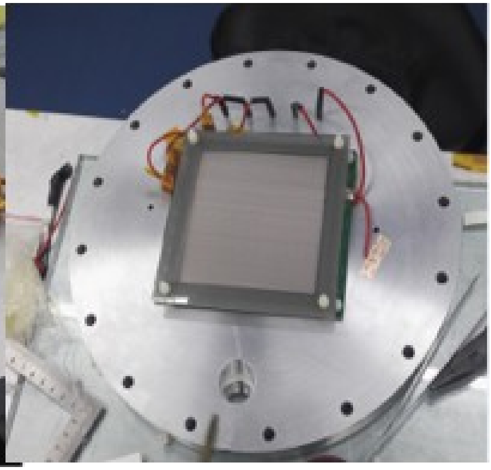


GEM(CERN)



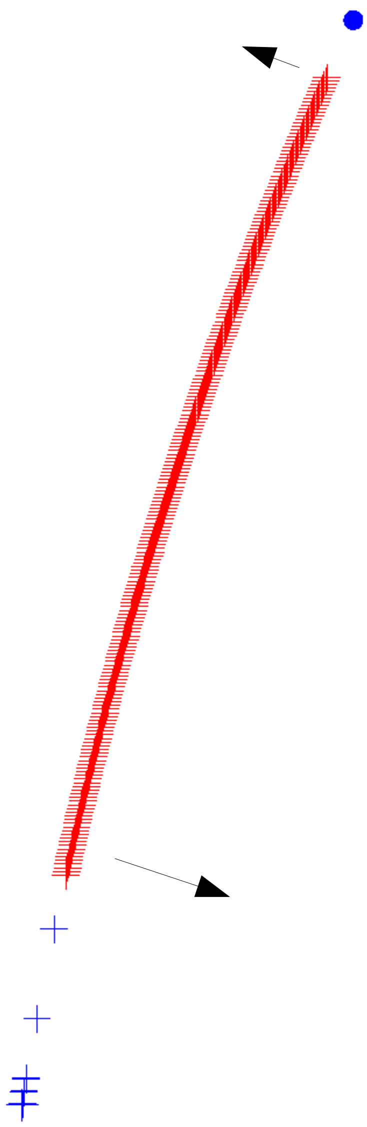


Cathode with mesh



GEM-MM Detector

For even higher luminosity: FCC-ee



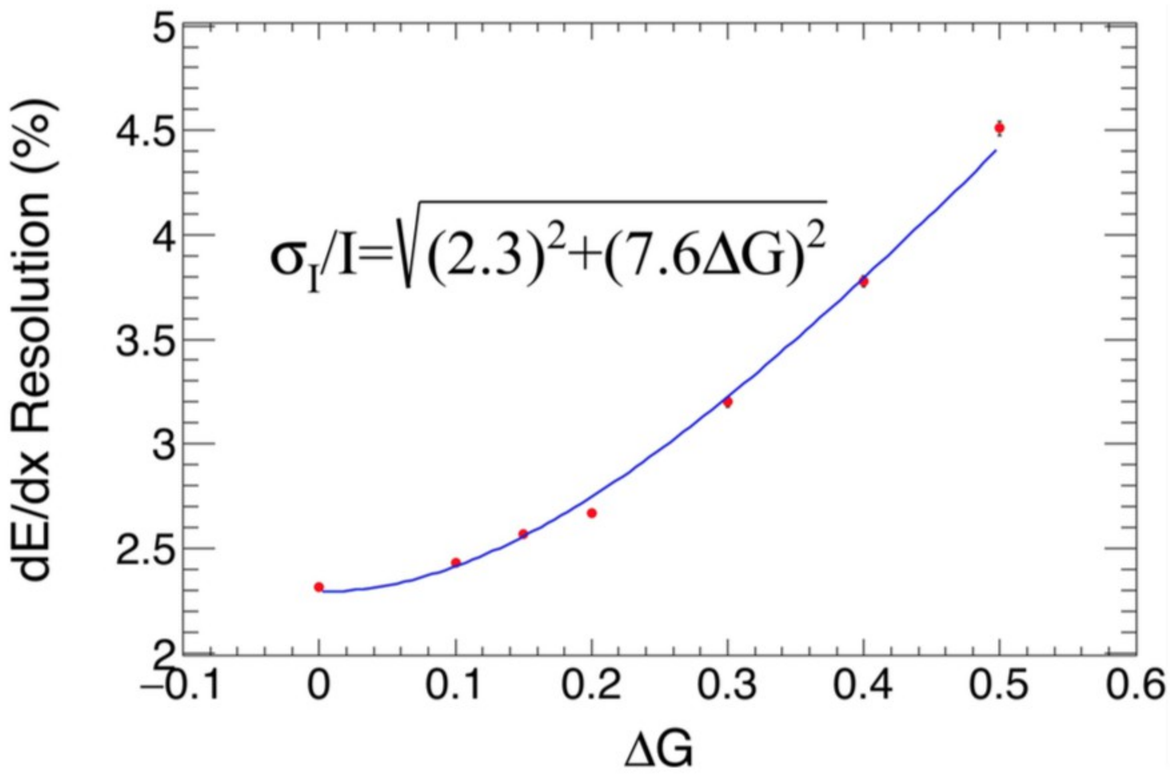
- The same TPC geometry, giving 2 orders of magnitude higher luminosity, leads to a maximal distortion of 0.5 mm
- **Mitigating options** | **Reduction factor**

Mitigating options	Reduction factor
– Large HV (20 kV -> 40 kV ?)	4
– Large Ion Mobility (5m/s -> 10m/s)	2 - 3
– Shorter TPC Length (2.3 -> 2.0)	1.5
– Larger TPC inner Radius (400 -> 600)	~5
– Increasing B Field	1.2

  - Combination of these options reduces the distortions up to 2 orders of magnitude
- **Distortion is predictable, what matters is only its fluctuation**
- **TPC is mainly used for Track finding (with Silicon devices)**

Feasibility of TPC at CEPC

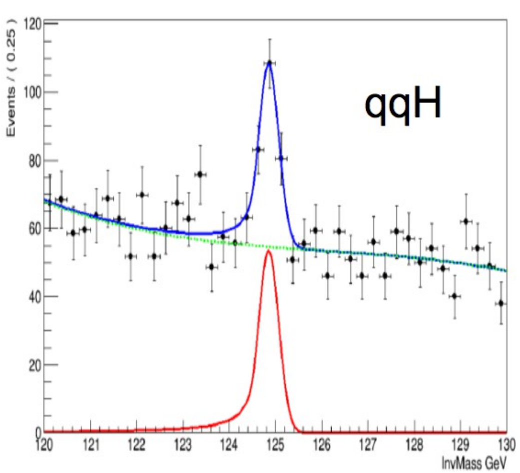
- **Z pole**
  - Most of the hits is induced by physics events (Z->qq) **if** the synchrotron radiations (X-ray fluxs, backscattered fluxs) can be reduced by careful Forward/Detector Protection design
- ILD TPC, at nominal luminosity ($2*10^{34}$) on Z->qq events
  - Maximal Occupancy: o(10^{-5}): safe
  - Maximal Distortion: o(10 μm), 1 order of magnitude smaller than intrinsic resolution **as** the IBF can be controlled to per mille level
- TPC might also be an option for FCC-ee, with much higher luminosity
  - Multiple mitigation methods may significant reduce of the distortion
  - Physics requirement, with smart reconstruction/correction algorithms, could be much less demanding
- To be understand: Detector Protection Performance & Integrated Performance

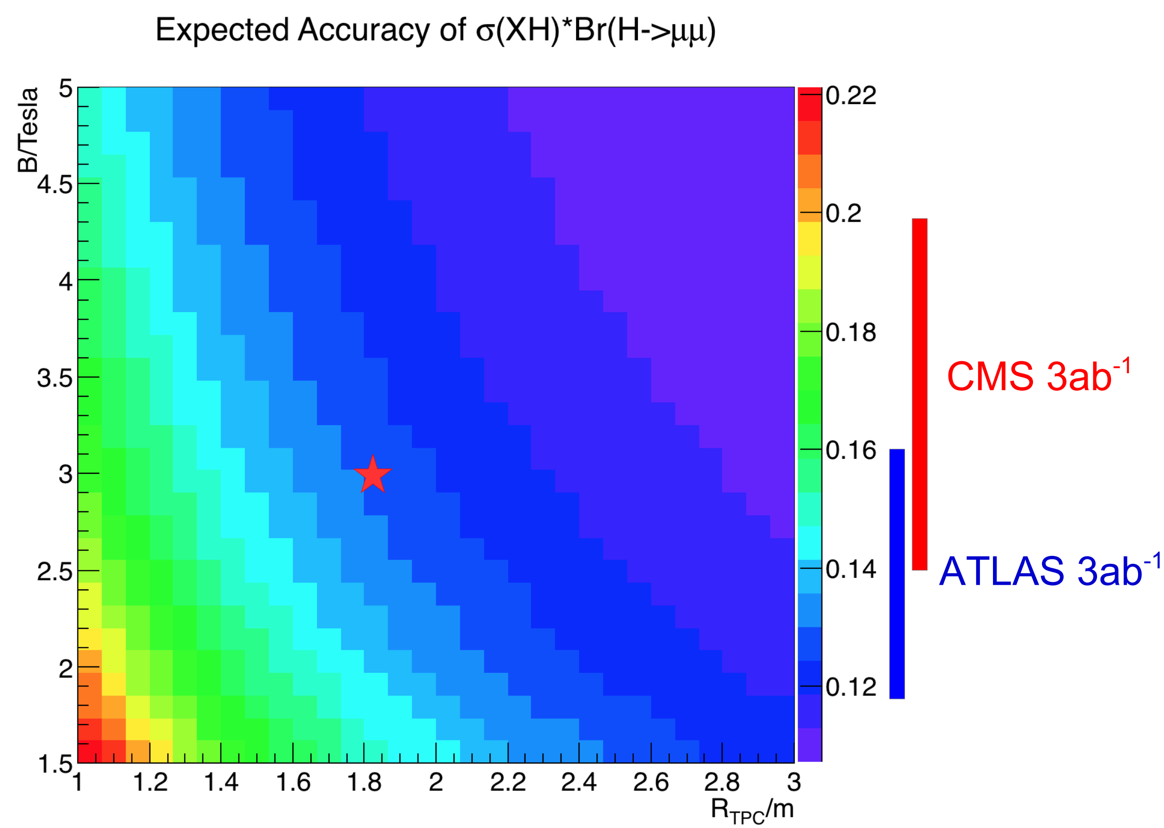


Delta(G): Relative Accuracy of Energy Resolution at individual cell,
Can be measured from radiation source tests. Cri. Value at 30%

Tracker Radius: the optimized value

- Detector cost is sensitive to tracker radius, however, I recommend TPC radius >= 1.8m:
  - Better separation & JER
  - Better dEdx
  - **Better (H->di muon) measurement**





★ *Default TPC Setting: B = 3 T & R_{out} = 1.8*