dE/dx, classical and with cluster counting

A brief review of particle identification in gaseous detectors

- **Outline**
  - some basics and fundamental problems of dE/dx measurements
    - Bethe-Bloch, clusters and all that
    - resolution, particle separation power
  - the classical way: dE/dx by charge measurement
  - the alternative way: dE/dx by cluster counting
    - cluster counting in time
    - cluster counting in 2D with micropattern detectors

Particle ID with dE/dx at e^+e^- colliders and elsewhere

- **QCD**
  - inclusive hadronic particle spectra (pions, kaons, protons)
- **Heavy flavour physics**
  - b-tagging (electrons from semi-leptonic b-decays)
  - c-tagging, D meson spectroscopy (kaon/pion separation)
- **Tau physics**
  - hadronic branching ratios, strange spectral functions
- **Searches**
  - heavy charged long-lived/stable tracks (SUSY)
  - free quarks
  - magnetic monopoles

***Energy Loss Function** (Bethe-Bloch)*

- **“mean” energy loss as function of Q, βγ :**

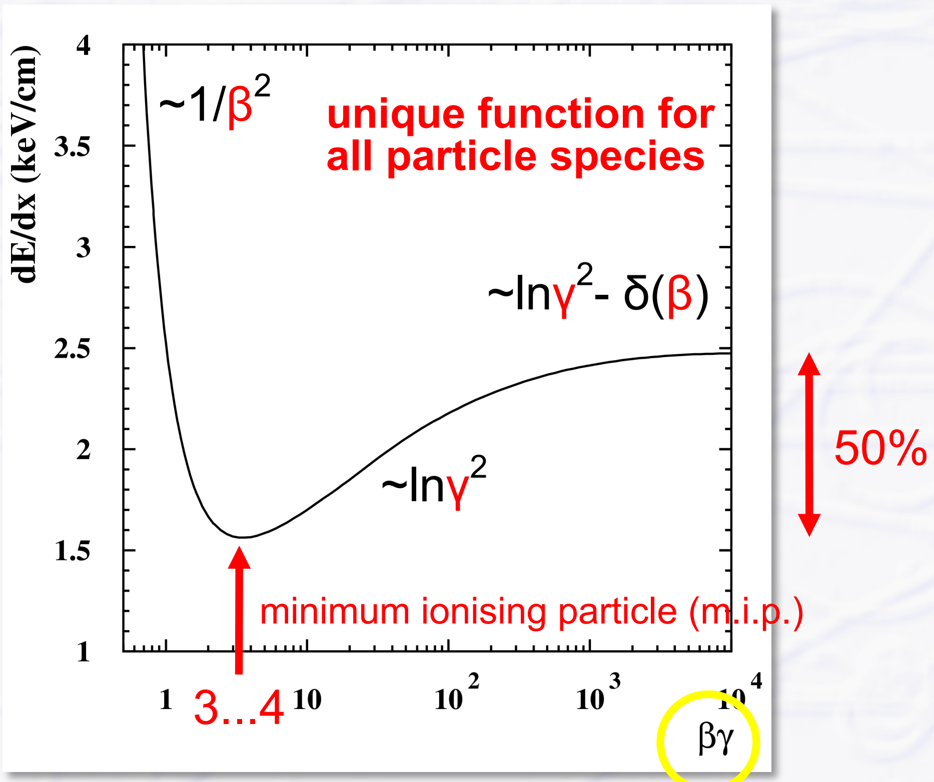
$$\langle dE/dx \rangle = \xi * 1/\beta^2 * Q^2 * [K + \ln Q^2 + \ln\gamma^2 - \beta^2 - \delta(\beta)]$$

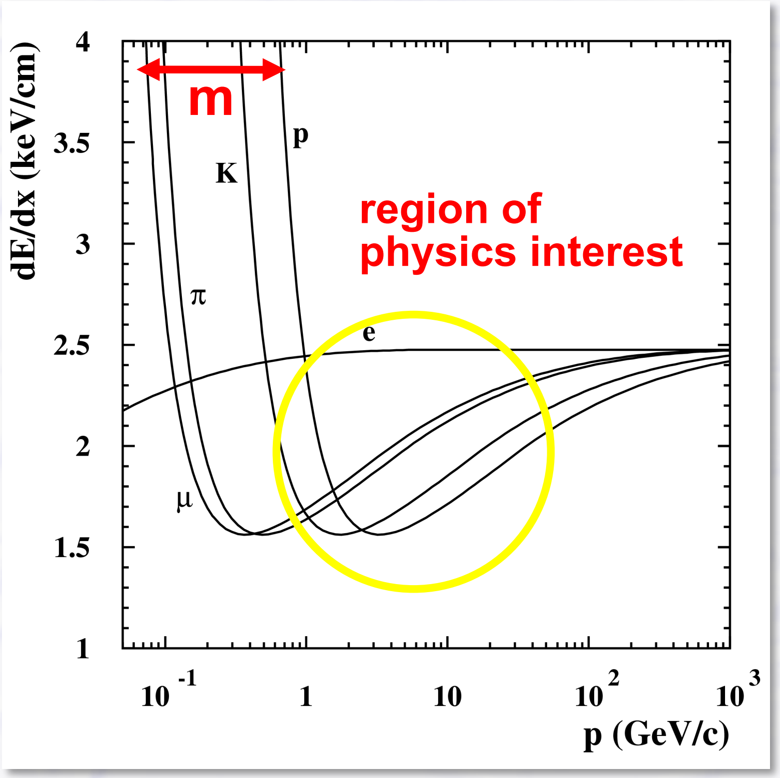
electron density of medium

classical Rutherford scattering (non-relativistic)

relativistic rise - “Lorentz boost” (medium feels higher E-field)

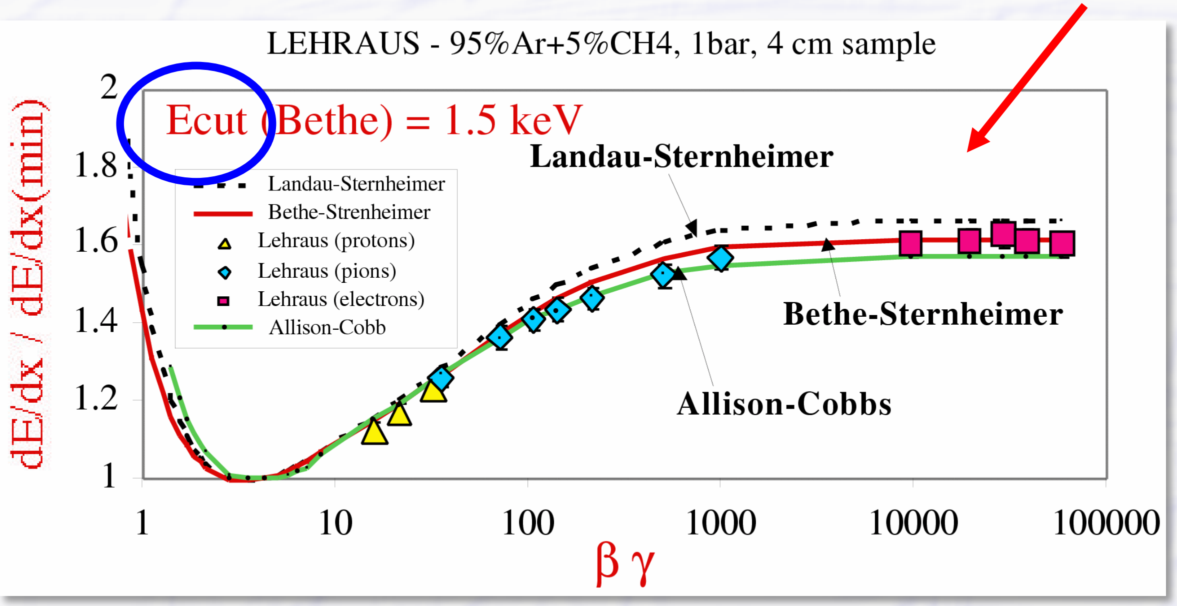
density effect - (Fermi) plateau due to polarization of medium





Bethe-Bloch Calculations...

- ...are difficult, different models exist
  - Landau-Sternheimer calculation
  - Bethe-Sternheimer calculation
  - Allison-Cobb Monte Carlo Ann. Rev. Nucl. Sci., 30 (1980) 253
- Level of (dis)agreement: ~3% in relativistic rise

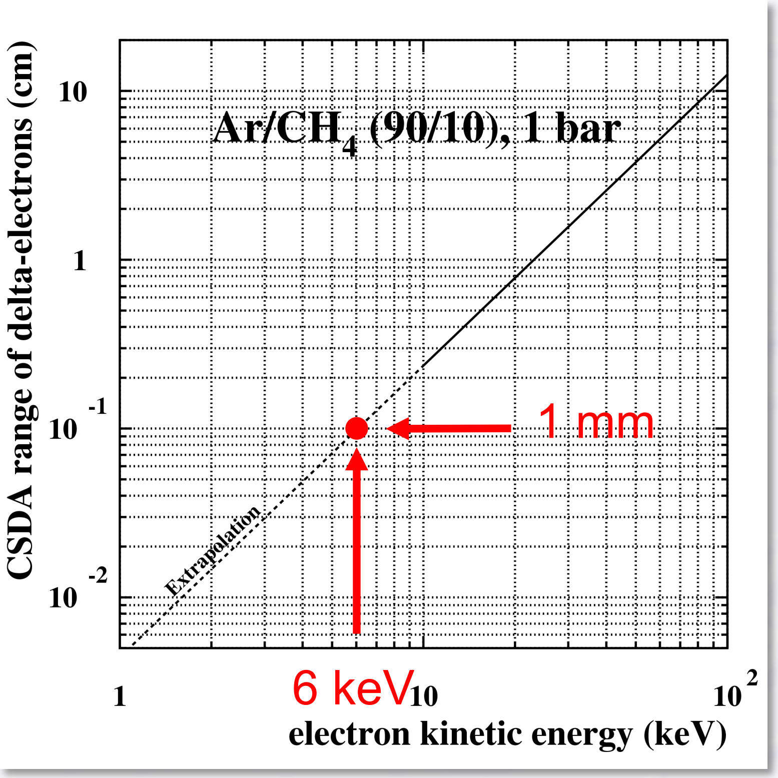


J. Va'vra, NIM A 453 (2000) 262-278

- Common problem
  - what E_{cut} to be used? What's E_{cut} at all?

The cut-off Energy (E_{cut})

- Tracking detectors usually DON'T measure the full energy loss of a particle!
- Secondary electrons with sufficient energy may escape from track, e.g. to adjacent drift cell, pad etc.
  - may be recognized as separate hit, not associated to track
  - detectors measure RESTRICTED energy loss instead of full energy loss
- Cut-off energy E_{cut} defines maximum energy of an electron still associated to a track
  - depends on detector geometry, double hit resolution, magnetic field, diffusion and more
  - typical E_{cut} ~a few keV corresponding to some 100 µm – 1 mm range

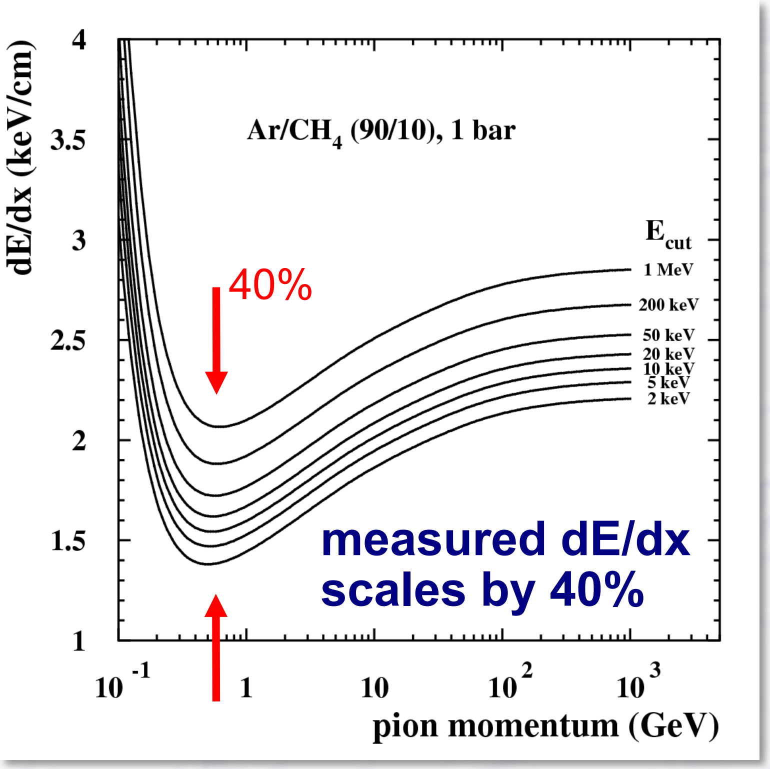


Electron Range
(CSDA = Constant Slowing Down Approximation)

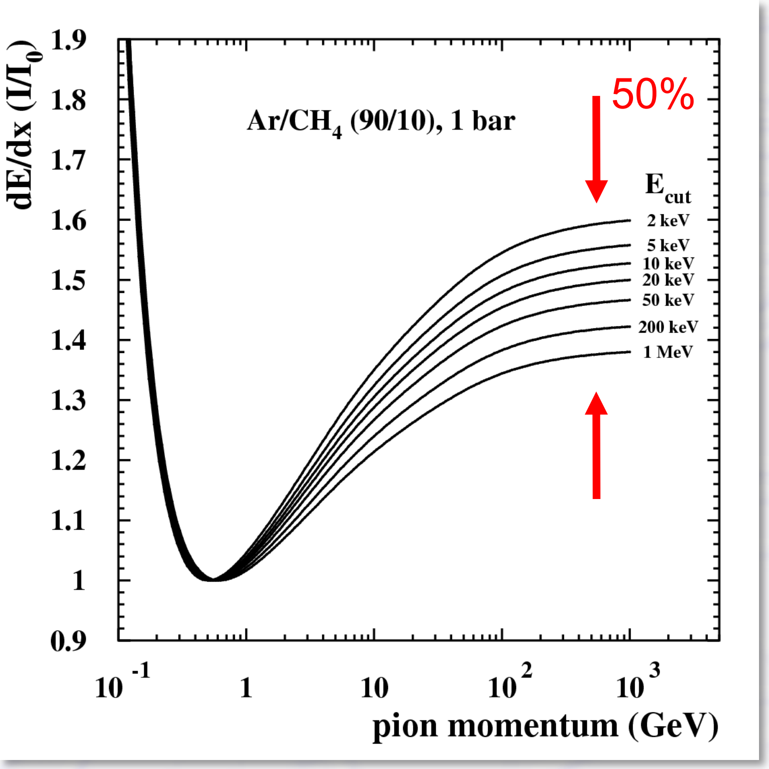
E_{cut} Dependence

- E_{cut} is difficult to determine, basically a free parameter
- Impossible to make calculations of Bethe-Bloch function to percent level or even better
  - results depend on E_{cut} a lot

relativistic rise variation up to 50%



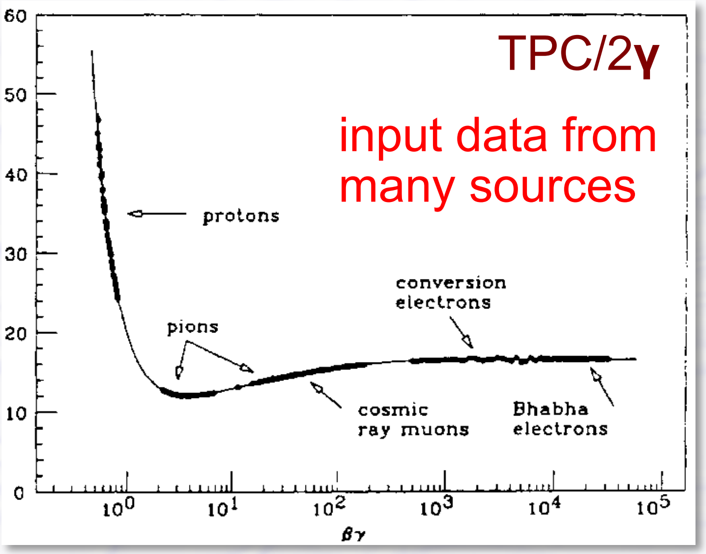
measured dE/dx scales by 40%



- Empirical parameterization used in practice

dE/dx Parameterization

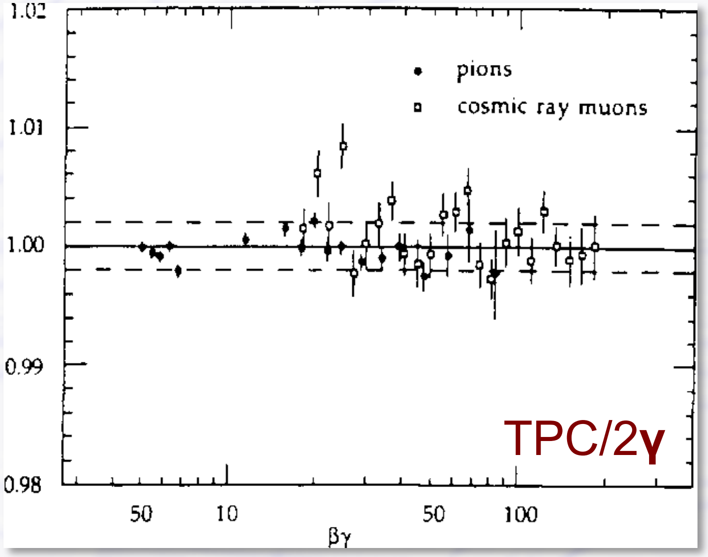
- **Parameterization usually by fit to data (various functional forms)**
  - **fully empirical (any Polynomials), semi-empirical (Bethe-Bloch + parameters)**



TPC/2γ

input data from many sources

G. Cowan, PhD Thesis, LBL (1988), LBL-24715



TPC/2γ

G. Cowan, PhD Thesis, LBL (1988), LBL-24715

< ±0.2%
(< ±0.07σ)

- **Use of dE/dx in physics analysis requires**
  - **good dE/dx parameterization and good estimate of dE/dx resolution**
  - **for any track in question: calculate χ^2 probabilities for each particle species (typically e, μ, π, K, p)**

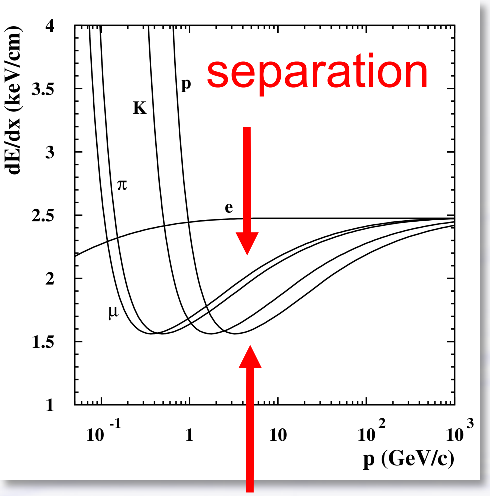
$$\chi^2_{(e,\mu,\pi,K,p)} = \left[\frac{dE/dx_{measured} - dE/dx_{(e,\mu,\pi,K,p)predicted}}{\sigma\ (dE/dx)} \right]^2$$

Particle Separation Power

- **Important for physics**
  - **particle separation power in relativistic rise**

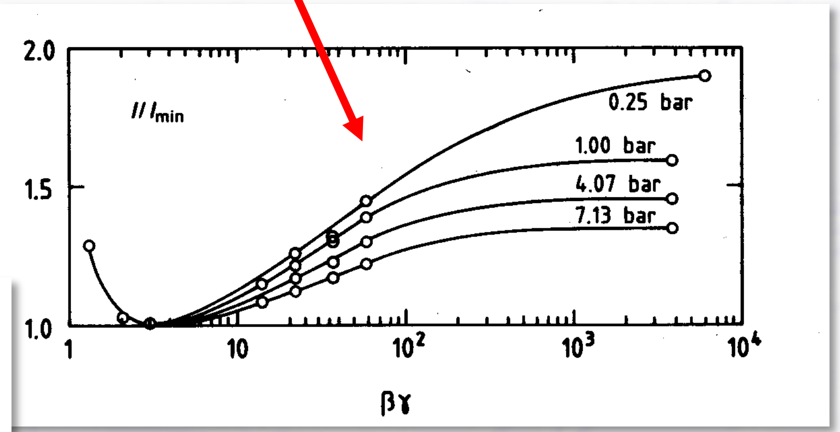
$$\text{separation power} = \frac{\text{separation}}{\text{resolution}}$$

  - **dE/dx resolution is NOT important!**
  - **need to optimize separation power (if possible)**



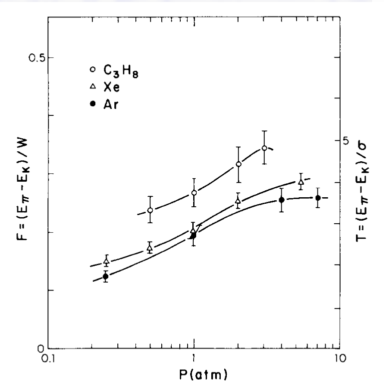
separation

- **Higher pressure reduces separation in relativistic rise**
- **Optimal separation power at 3 - 4 bars**
  - **also less diffusion, but...**
  - **pressure vessel needed...**



A.H. Walenta et al., NIM 161 (1979) 45

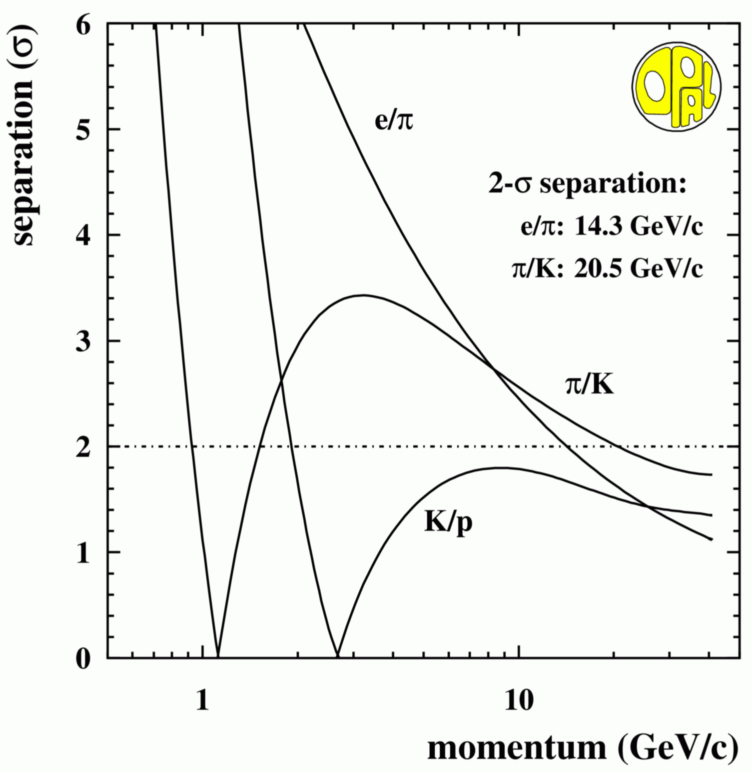
Walenta 1979



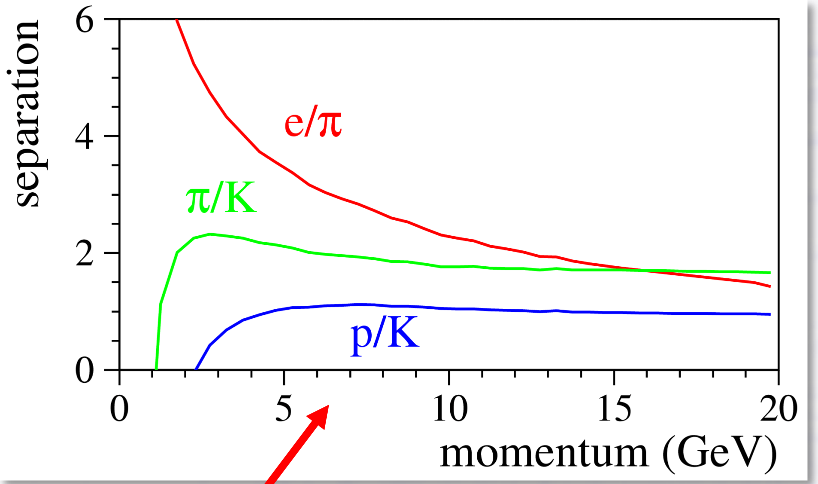
higher pressure doesn't further improve separation power

Particle Separation Power

- Typical (average) particle separation power at LEP
  - e/π > 2σ up to 12...14 GeV
  - π/K > 2σ up to 8...20 GeV (max. 2.5 – 3.5 σ)
  - p/K always below 2σ (max. 1 – 1.7 σ)



similar detector size, different pressure



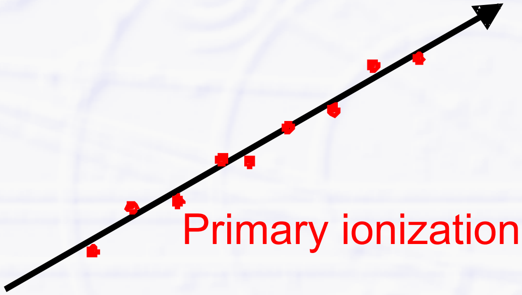
ALEPH TPC, 1 bar

OPAL Jet Chamber, 4 bar

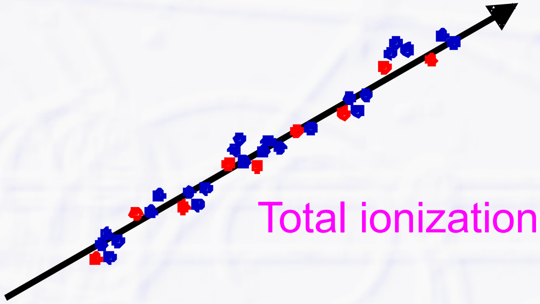
Energy Loss by Ionization

(brief reminder)

- **Primary number of ionizations per unit length is Poisson-distributed**
  - **typically ~30 primary interactions (ionization clusters) / cm in gas at 1 bar**
- **However, primary electrons sometimes get large energies**
  - **can make secondary ionization**
  - **can even create visible secondary track (“delta-electron”)**
  - **large fluctuations of energy loss by ionization**



Primary ionization



Total ionization = primary + secondary ionization

- **Typically: total ionization = 3 x primary ionization**
  - **on average ~ 90 electrons/cm**

Cluster Size Distributions

- **Probabilities (%) to create N_{el} electrons**

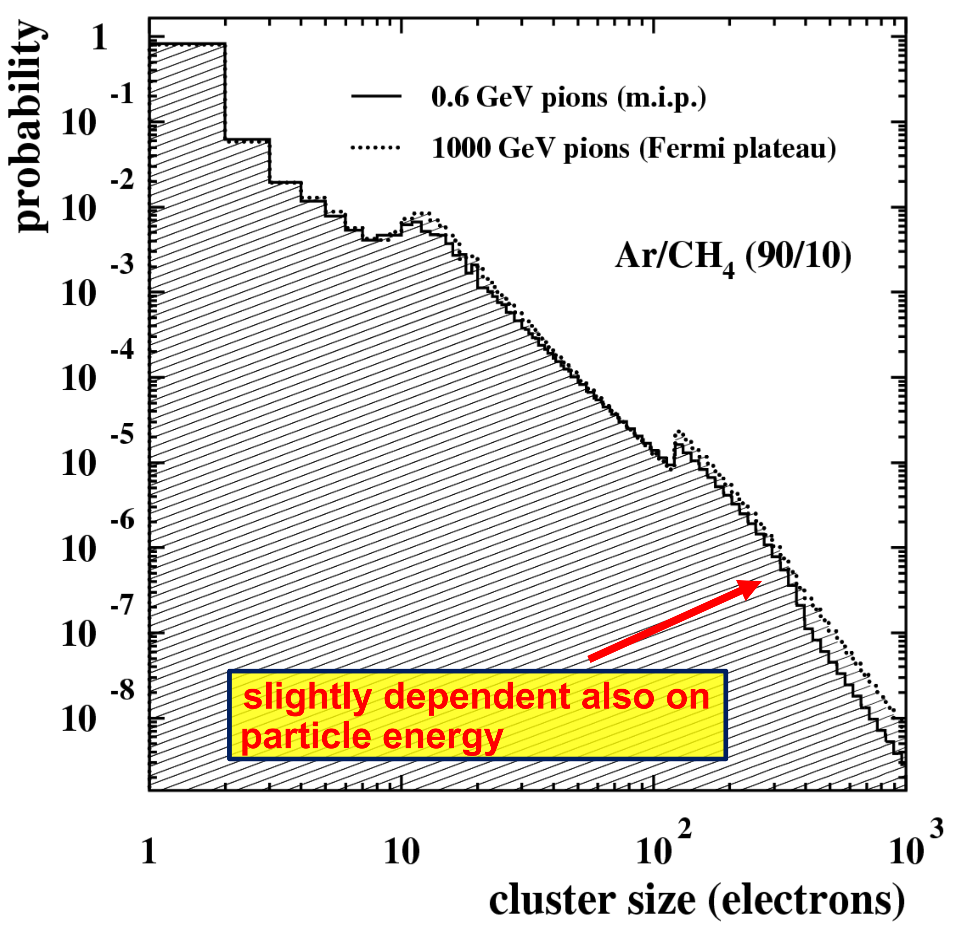
single electron → 1

multi-electron cluster → 2–10

N_{el}	Ar	He
1	65.6	76.6
2	15.0	12.5
3	6.4	4.6
4	3.5	2.0
5	2.25	1.2
6	1.55	0.75
7	1.05	0.50
8	0.81	0.36
9	0.61	0.25
10	0.49	0.19

data from H. Fischle et al., NIM A 301 (1991) 202

less multi-electron clusters in Helium (better!)



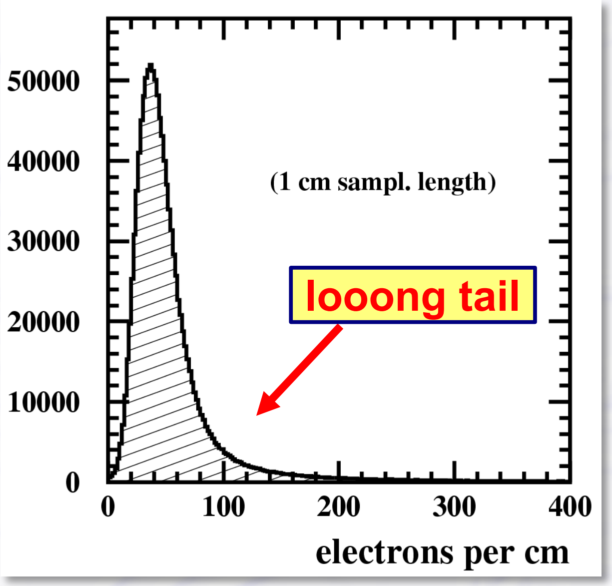
slightly dependent also on particle energy

HEED cluster simulation (HEED written by I. Smirnov)

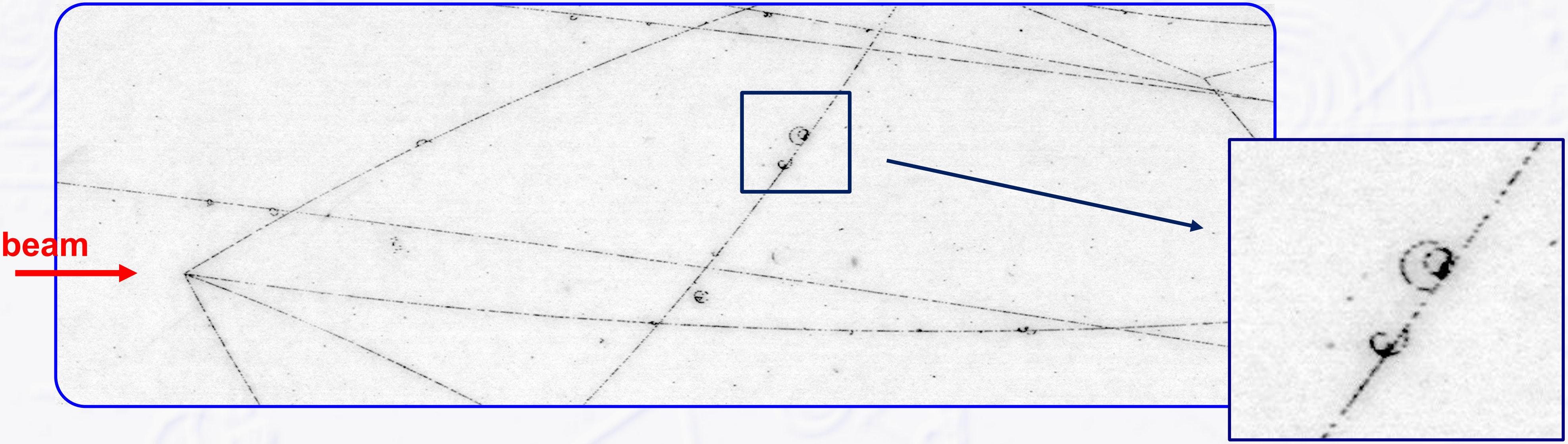
Cluster Size Fluctuations

- **Cluster size fluctuations cause large variations of energy loss from sample to sample**
  - **Landau distribution**
    - **large broad peak (single or few el. clusters)**
      - soft collisions, interaction with whole gas molecule
      - small energy transfer
    - **looong tail (multi el. clusters, δ-electrons)**
      - hard collisions, semi-free shell electrons
      - large energy transfer

1 cm sampling length



tracks in CERN 2m bubble chamber



Ideal dE/dx measurement

- Count number of clusters along track
  - cluster density should be proportional to dE/dx
- Obvious problem
  - how to resolve individual clusters and count them?
    - usually high cluster density (20 - 30 cl./cm in Ar mixtures for m.i.p.) → 1 cluster per 300 – 500 µm
    - at typical drift velocities of 50 µm/ns → 6 – 10 ns in between clusters
  - need device with high time resolution or high granularity to resolve them
    - difficult to achieve
- Most detectors measure CHARGE per sample along a track (charge $\simeq$ number of primary + secondary electrons)
  - sensitive to LARGE fluctuations
    - makes dE/dx resolution by charge measurement much worse than cluster counting
    - this is the fundamental, central problem of all dE/dx measurements by charge

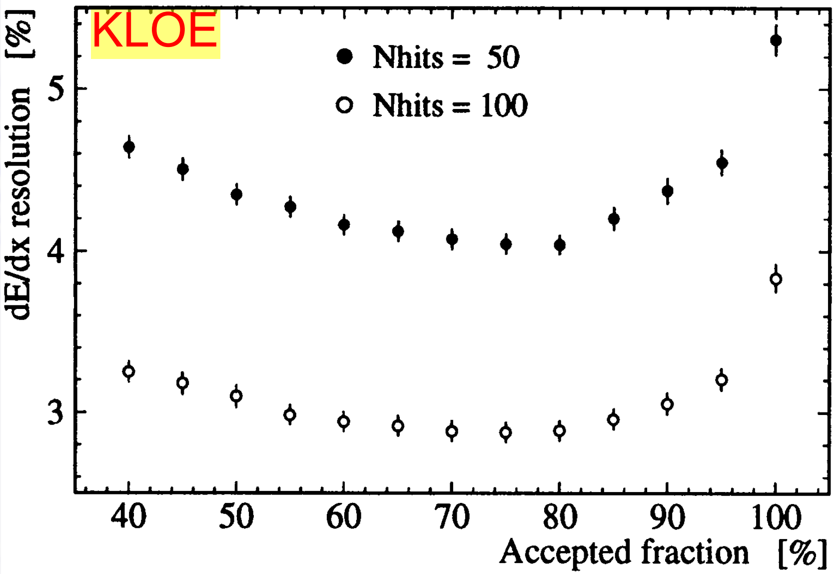
Classical dE/dx Measurement by Charge

- **Widely used (because counting is difficult)**
  - **measure charge of many samples along track**
  - **get ”mean" charge over samples = dE/dx**
- **Problem**
  - **simple “mean” charge subject to large fluctuations due to multi-election clusters**
- **How to get better estimate of “mean” energy loss?**
  - **Most commonly used**
    - **“Truncated Mean” (robust) → reject samples with highest charge**
  - **Other methods (rarely used)**
    - **Max.-Likelihood fit to charge distribution (but more sensitive to changes of Landau shape)**
    - **Inverse transformation: mean of $(1/\mathrm{sqrt}[(dE/dx)_i])^{-1}$**

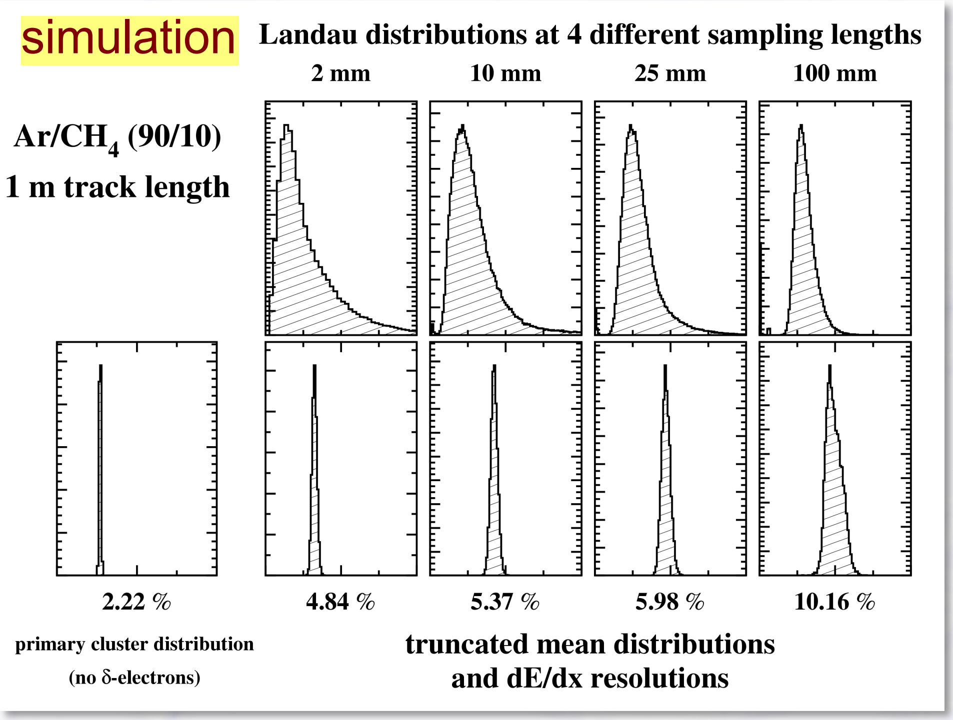
Truncated Mean

- reject (typically) 20-30% of samples with highest charges
  - sometimes also 5...10% of lowest charge samples rejected (noise removal)
- calculate mean (“truncated” mean) of remaining samples
- optimize truncation empirically (→ best dE/dx resolution)
  - Helium mixtures (less multi-electron clusters) need less truncation than Argon mixtures
  - typically accepted fraction
    - He mixtures: 80%
    - Ar mixtures: 65-70%

number of samples / sampling length per track also plays a role



KLOE Collaboration, A. Andryakov et al., NIM A 409 (1998) 390-394



HEED cluster simulation (HEED written by I. Smirnov)

dE/dx resolution

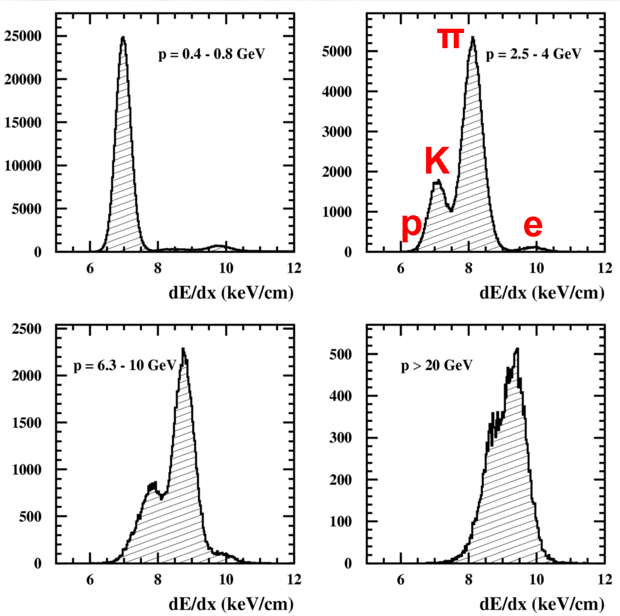
- **For a specific gas, dE/dx resolution depends on**
  - effective detector length L (track length x pressure)

    $\sim L^{-0.32...-0.36}$
  - number of samples N

    $\sim N^{-0.43...-0.47}$

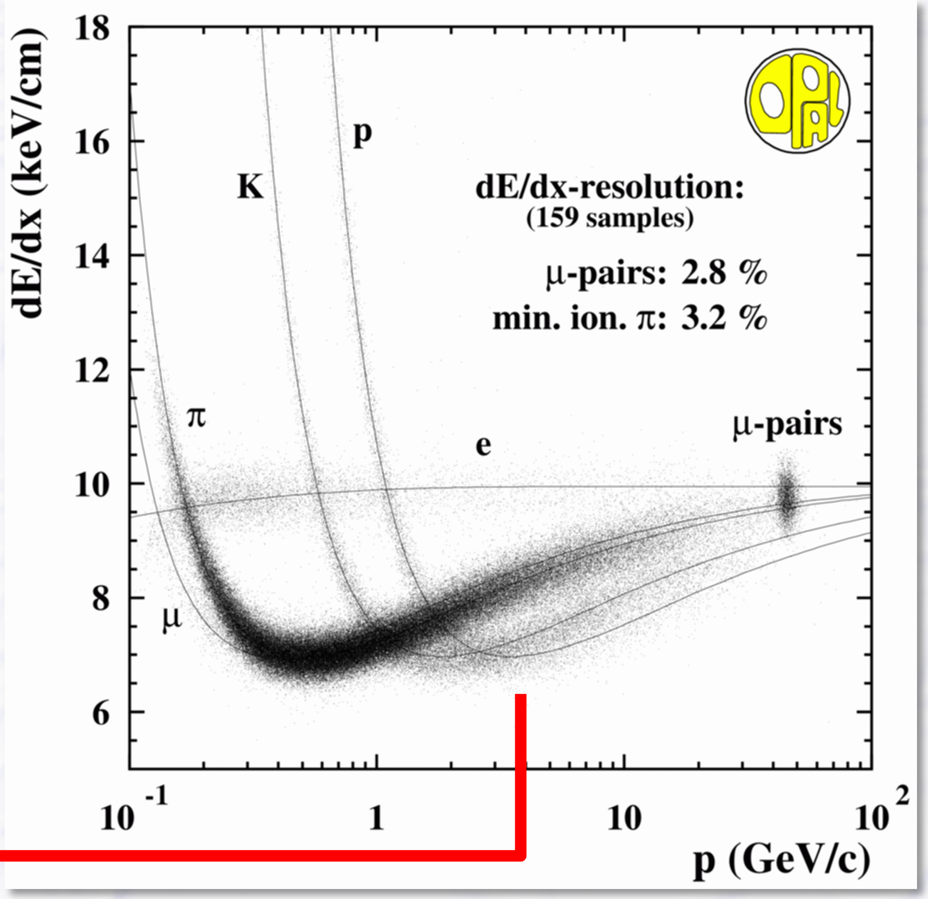
NOT ~ $N^{-0.5}$
due to non-gaussian
Landau distribution

Long tracks and/or high pressure help



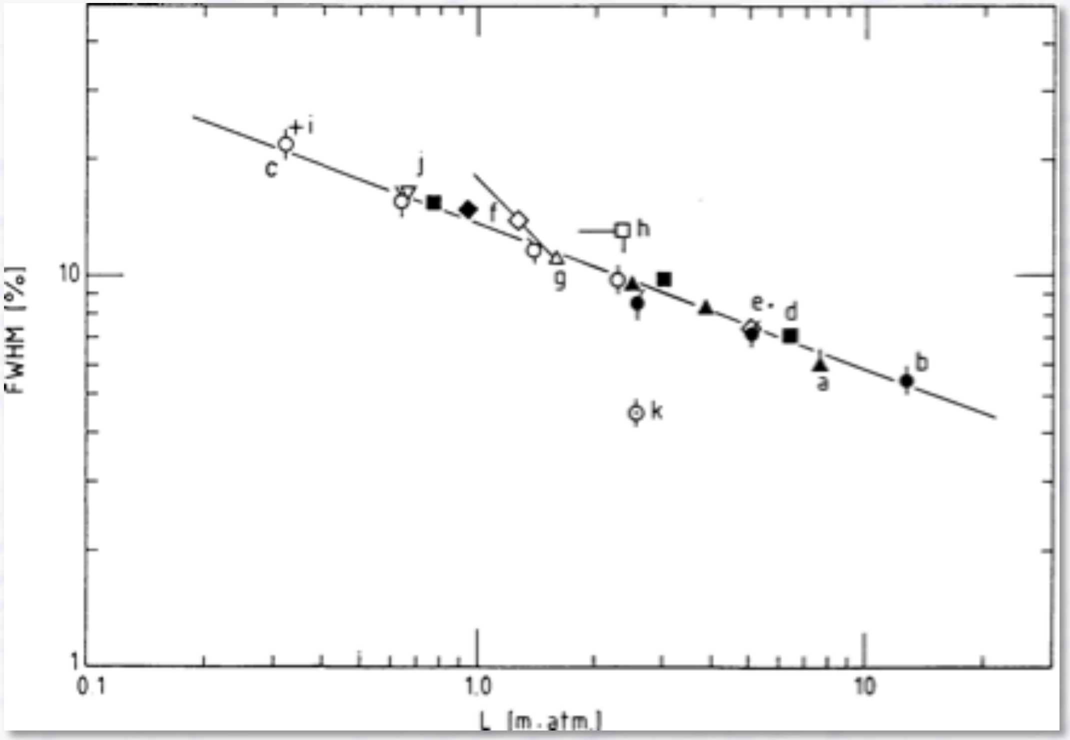
momentum slices

- **OPAL Jet Chamber**
  - 1.6 m track length, 4 bar pressure



“Lehraus” Plot 1983

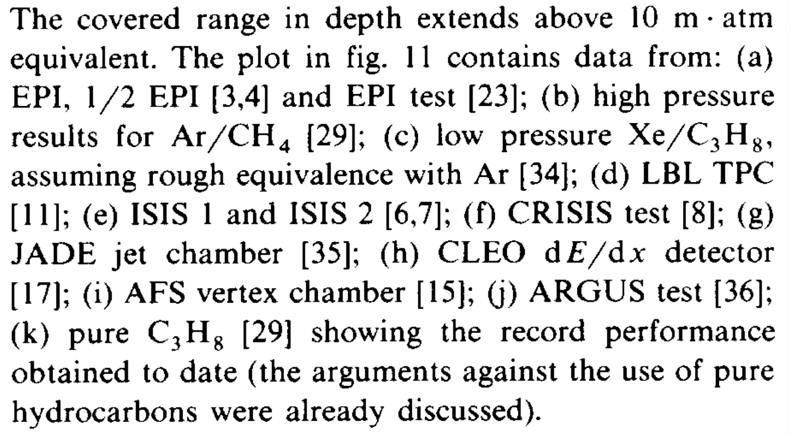
- **First attempt by *Ivan Lehraus* in 1983 to connect dE/dx resolution and detector size** **(effective detector length L = track length * pressure)**



I. Lehraus, NIM 217 (1983) 43-55

dE/dx resolutions achieved in large detectors as a function of the effective detector length.

- **Results from 14 large detectors used**



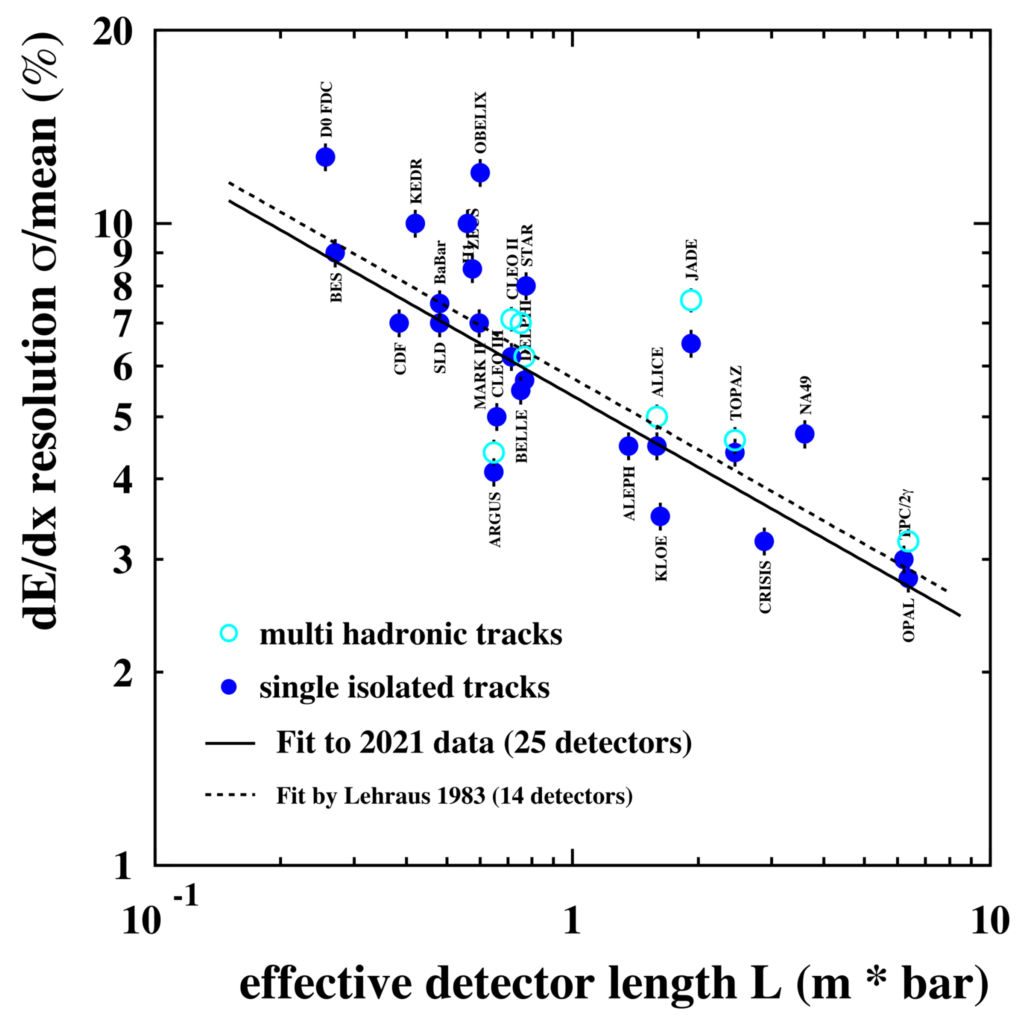
The covered range in depth extends above 10 m · atm equivalent. The plot in fig. 11 contains data from: (a) EPI, 1/2 EPI [3,4] and EPI test [23]; (b) high pressure results for Ar/CH_4 [29]; (c) low pressure Xe/C_3H_8, assuming rough equivalence with Ar [34]; (d) LBL TPC [11]; (e) ISIS 1 and ISIS 2 [6,7]; (f) CRISIS test [8]; (g) JADE jet chamber [35]; (h) CLEO dE/dx detector [17]; (i) AFS vertex chamber [15]; (j) ARGUS test [36]; (k) pure C_3H_8 [29] showing the record performance obtained to date (the arguments against the use of pure hydrocarbons were already discussed).

- **Fit by *Lehraus* :**

dE/dx res. = $5.7 * L^{-0.37}$ (%)

“Lehraus” Plot 2021

- **dE/dx resolution achieved in large detectors, mainly at e^+e^- colliders, at some hadron colliders and fixed target expts.**



- **Fit by *Lehraus* 1983:**

  dE/dx res. = 5.7 * $L^{-0.37}$ (%)

- **Fit in 2021 (25 large detectors):**

  dE/dx res. = 5.4 * $L^{-0.37}$ (%)

  - **5.4% typical dE/dx resolution for 1 m track length**
  - **no significant change to 1983**
  - **performance of present generation of detectors as predicted ~40 years ago**

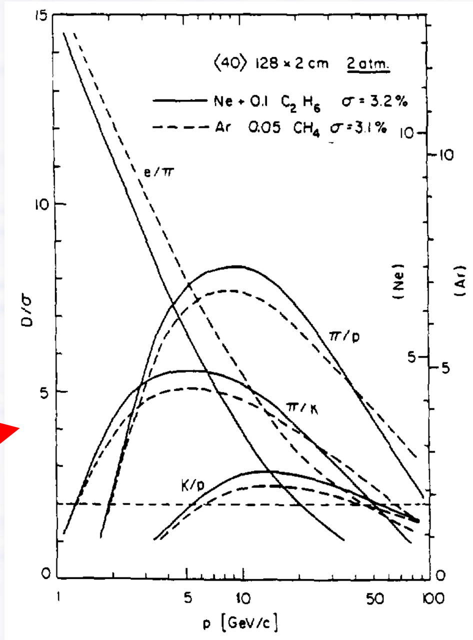
dE/dx Resolutions of major Particle Physics Detectors

- **Input data for the 2021 “Lehraus” plot**

Detector	Accelerator	Type	Size	B (T)	Gas Mixture	Pressure	Number of	Sampling	Effective detector	dE/dx resolution (%)		Truncation	Reference
			(Ø x L)			(bar)	samples	length (mm)	length (bar * m)	isolated tracks	dense tracks	(%)	
ALEPH	LEP	TPC	3.6 m x 4.4 m	1.5	Ar/CH_4 (91/9)	1	338	4	1.35	4.5		8-60	D. Buskulic et al., NIM A 360 (1995) 481
ALICE	LHC	TPC	5.0 m x 5.0 m	0.5	Ne/CO_2 (90/10)	1	159	7.5, 10, 15	1.60	4.5	(5.0)	0-70	W. Yu, NIM A 706 (2013) 55, J. Alme et al., NIM A 622 (2010) 316
ARGUS	DORIS	drift cells	1.7 m x 2 m	0.8	C_3H_8/Methylal	1	36	18	0.65	4.1	(4.4)	10-70	Y. Oku, PhD Thesis, Univ. of Lund (1985), LUNFD6/(NFFL-7024)/
BaBar	PEP-II	drift cells	1.6 m x 2.8 m	1.5	$He/i\text{-}C_4H_{10}$ (80/20)	1	40	12	0.48	7.5		0-80	B. Aubert et al., NIM A 479 (2002) 1-116
BELLE	KEK-B	drift cells	1.9 m x 2.2 m	1.5	He/C_2H_6 (50/50)	1	47	16	0.75	5.5	(7.0)	0-80	E. Nakano, NIM A 494 (2002) 402-408
BES	BEPC	jet cells	2.3 m x 2.1 m	0.4	$Ar/CO_2/CH_4$ (89/10/1)	1	54	5	0.27	9.0		0-70	J.Z. Bai et al., NIM A 344 (1994) 319
CDF	TEVATRON	jet cells	2.6 m x 3.2 m	1.5	$Ar/C_2H_6/C_2H_6O$ (49.6/49.6/0.8)	1	32	12	0.38	7.0		?	D. Stuart, private communications
CLEO II	CESR	drift cells	1.9 m x 1.9 m	1.5	Ar/C_2H_6 (50/50)	1	51	14	0.71	6.2	(7.1)	0-50	Y. Kubota et al., NIM A 320 (1992) 66
CLEO III	CESR	drift cells	1.6 m x 1.9 m	1.5	He/C_3H_8 (60/40)	1	47	14	0.66	5.0		0-70	D. Peterson et al., NIM A 478 (2002) 142-146
CRISIS	TEVATRON	jet cells	1 m x 1 m x 3 m	-	Ar/CO_2 (80/20)	1	192	15	2.88	3.2		0-75	W.S. Toothacker et al., NIM A 273 (1988) 97
DELPHI	LEP	TPC	2.4 m x 2.7 m	1.2	Ar/CH_4 (80/20)	1	192	4	0.77	5.7	(6.2)	0-80	P. Abreu et. al., CERN-PPE/95-194, submitted to NIM
D0 FDC	TEVATRON	jet cells	1.2 m x 0.3 m	-	$Ar/CH_4/CO_2$ (93/4/3)	1	32	8	0.26	12.7		0-70	S. Rajagopalan, PhD Thesis, Northwestern University (1992)
H1	HERA	jet cells	1.7 m x 2.2 m	1.13	Ar/C_2H_6 (50/50)	1	56	10	0.56	10.0		---*	I. Abt et al., NIM A 386 (1997) 348-396
JADE	PETRA	jet cells	1.6 m x 2.4 m	0.48	$Ar/CH_4/i\text{-}C_4H_{10}$ (88.7/8.5/2.8)	4	48	10	1.92	6.5	(7.2)	5-70	K. Ambrus, PhD Thesis, Univ. of Heidelberg (1986)
KEDR	VEPP-4M	jet cells	1.1 m x 1.1 m	2.0	DME (100)	1	42	10	0.42	10.0		5-70	S.E. Baru et al., NIM A 323 (1992) 151
KLOE	DAΦNE	drift cells	4 m x 3.3 m	0.6	$He/i\text{-}C_4H_{10}$ (90/10)	1	58	28	1.62	3.5		0-80	A. Andryakov et al., NIM A 409 (1998) 390-394 (prototype)
MARK II	SLC	drift cells	3 m x 2.3 m	0.475	$Ar/CO_2/CH_4$ (89/10/1)	1	72	8.33	0.60	7.0		5-75	A. Bojarski et al., NIM A 283 (1989) 617
NA49	SPS	TPC	.8 m x 3.8 m x 1.3	-	$Ar/CH_4/CO_2$ (90/5/5)	1	90	40	3.60	4.7		10-65	B. Lasiuk, NIM A 409 (1998) 402-406
OBELIX	LEAR	jet cells	1.6 m x 1.4 m	0.5	Ar/C_2H_6 (50/50)	1	40	15	0.60	12.0		0-70	F. Balestra et al., NIM A 323 (1992) 523
OPAL	LEP	jet cells	3.6 m x 4 m	0.435	$Ar/CH_4/i\text{-}C_4H_{10}$ (88.2/9.8/2)	4	159	10	6.36	2.8	(3.2)	0-70	M. Hauschild, NIM A 379 (1996) 436
SLD	SLC	jet cells	2 m x 2 m	0.6	$CO_2/Ar/i\text{-}C_4H_{10}$ (75/21/4)	1	80	6	0.48	7.0		?	M. Hildreth, private communications
STAR	RHIC	TPC	4 m x 4.2 m	0.5	Ar/CH_4 (90/10)	1	45	17.2	0.77	8.0		0-70	M. Anderson et al., NIM A 499 (2003), 659
TOPAZ	TRISTAN	TPC	2.4 m x 2.2 m	1.0	Ar/CH_4 (90/10)	3.5	175	4	2.45	4.4	(4.6)	0-65	M. Iwasaki et al., NIM A 365 (1995) 143
TPC/2γ	PEP	TPC	2 m x 2 m	1.375	Ar/CH_4 (80/20)	8.5	183	4	6.22	3.0		0-65	G. Cowan, PhD Thesis, Lawrence Berkeley Lab. (1988), LBL-24715
ZEUS	HERA	jet cells	1.7 m x 2.4 m	1.43	$Ar/CO_2/C_2H_6$ (90/8/2)	1	72	8	0.58	8.5		?	W. Zeuner, private communications
												* = inverse gaussian mean 1/sqrt[(dE/dx)i] used	

Cluster Counting

- **Direct cluster counting would avoid any problems with cluster fluctuations, truncated mean etc.**
  - **no charge measurement need, just counting**
- **In theory → ultimate way to measure dE/dx**
  - **30 clusters/cm * 100 cm track length = 3000 clusters**
  - **1.8% dE/dx resolution by cluster counting (statistical error only)**
  - **5.4% dE/dx resolution by charge measurement (Lehraus fit)**
- **Not a brand new idea**
  - **first ideas (1969) by A. Davidenko et al.**
    (JETP, 1969, Vol. 28, No. 2, p. 223)
  - **Detailed studies in mid-1990s by G. Malamud, A. Breskin, B. Chechik**
    - cluster statistics
    - measurements in low pressure drift chamber
    - simulations
    - expected particle separation



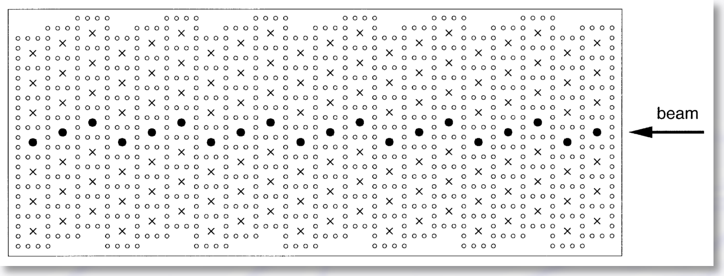
G. Malamud, A. Breskin, B. Chechik, NIM A 372 (1996) 19-30

Cluster Counting How To?

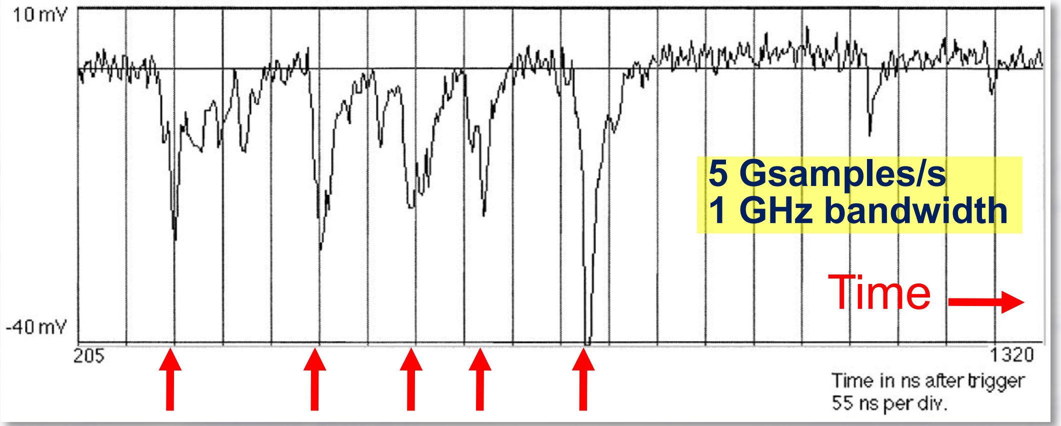
- How to resolve (and count) individual clusters?
  - reminder:
    - typically 30 clusters/cm at 1 bar in Argon mixtures
    - → about 300 μm separated along track on average
    - → time separation in fast gases (~50 μm/ns) about 6 ns
- Most attempts tried to resolve clusters in time
  - however, 6 ns average time separation challenging to resolve them
    - need proper detector geometry/principle
      - clusters need to arrive sequentially at wires/pads, not simultaneously
    - need slow gas with small drift velocity (e.g. CO_2 mixtures, ~10 μm/ns)
      - to stretch arrival time of clusters
    - need gas with lower cluster density (e.g. He mixtures)
      - to further increase time separation between clusters
    - need gas with low diffusion
      - to avoid dissolution of multi-electron clusters
    - gas with good cluster statistics helps too (e.g. He mixtures)
      - more single electron clusters, less multi-electron clusters
    - requires electronics with sufficient time and multi-hit resolution
      - short pulses (proper pulse shaping)

Cluster Counting (by time)

- **Test beam measurements 1998 using $\mathrm{He/CH_4}$ (80/20)**

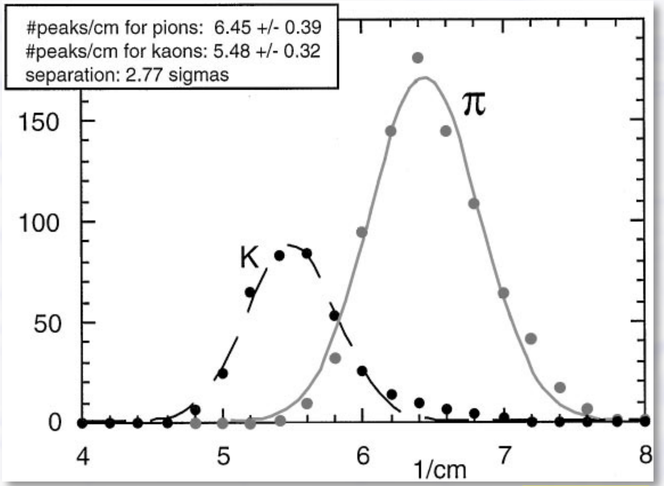


drift cells



Clusters

L. Cerrito et. al, NIM A 436 (1999) 336-340

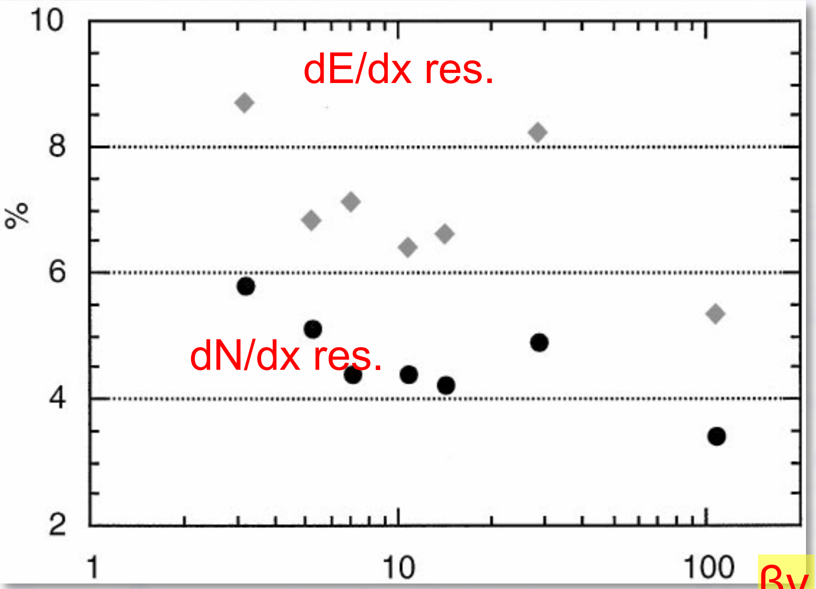


L. Cerrito et. al, NIM A 434 (1999) 261-270

dN/dx

3 GeV/c

120 cm track length



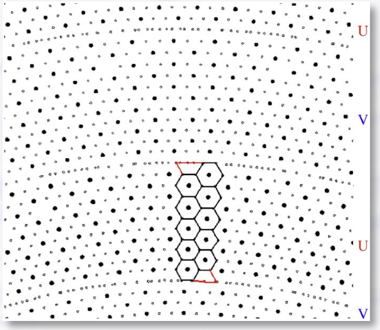
βγ

L. Cerrito et. al, NIM A 434 (1999) 261-270

- **Cluster Counting works in test beam under controlled conditions**
- **but not yet used in large scale particle detectors**

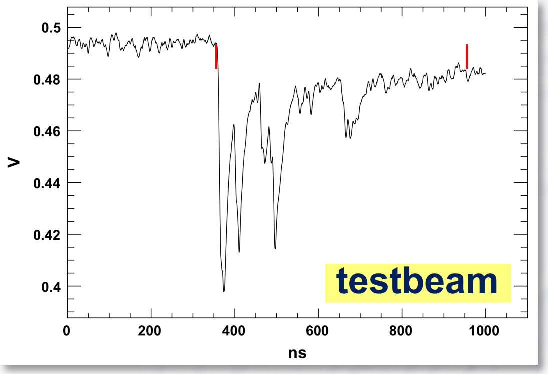
Cluster Counting for Large Detectors

- **New large detector concepts for future e^+e^- colliders consider cluster counting**
  - **4th detector concept for ILC (discontinued)**
    - **CluCou drift chamber with small drift cells**
    - **He/i-Butane (90/10) gas mixture**



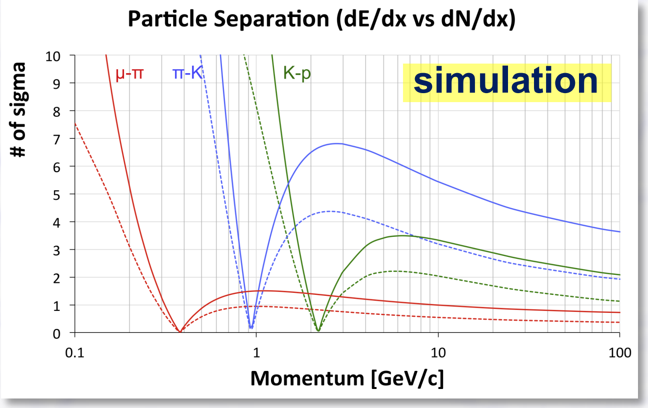
R. Perrino et. al,
NIM A 598 (2009) 98-101

  - **detector for Super-B (discontinued)**
    - **full-length single cell drift chamber prototype**
    - **He/i-Butane (90/10) gas mixture**



J.-F. Caron et al,
NIM A 735 (2014), 169-183

  - **IDEA detector for FFC-ee or CEPC**
    - **follow-up of CluCou, small drift cells**
    - **He/i-Butane (90/10) gas mixture**
    - **simulation shows clear advantage of cluster counting vs. classical dE/dx**
    - **assumes 4.2% dE/dx resolution and 80% cluster counting efficiency**

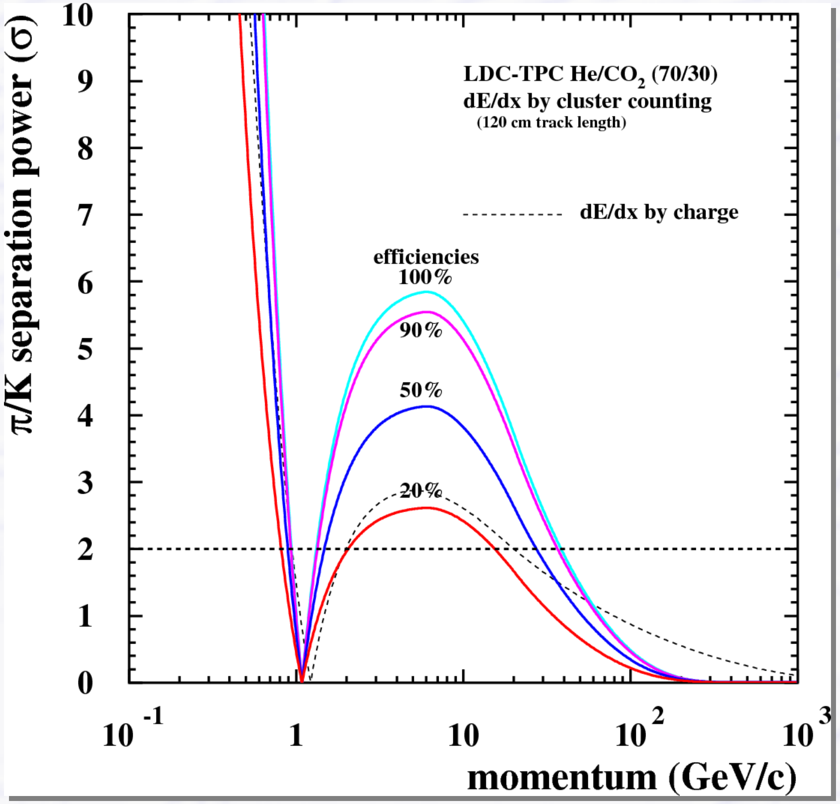


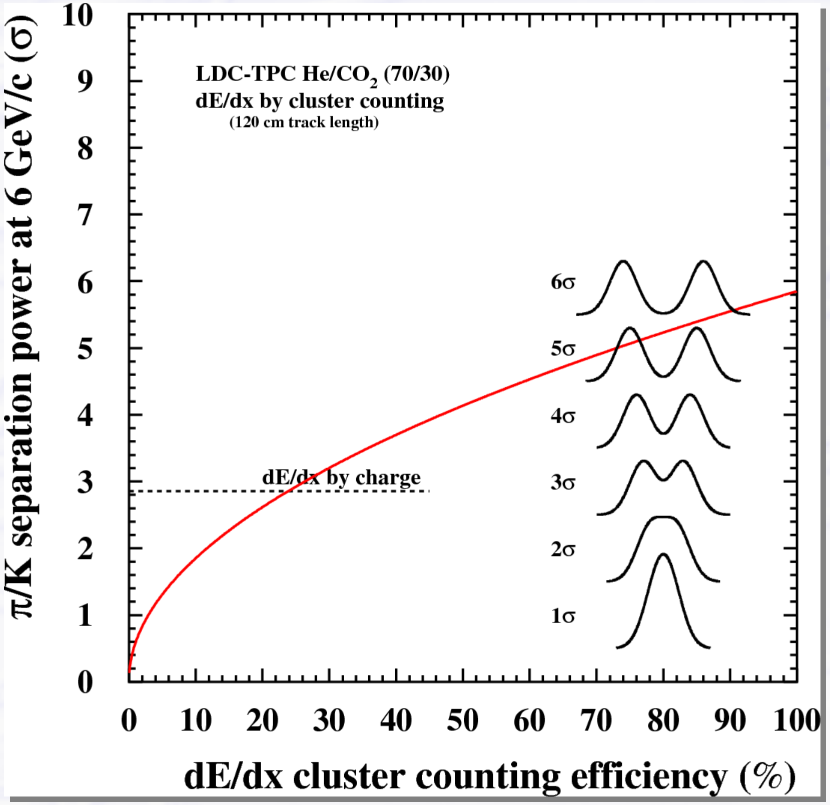
G. Chiarello et. al,
NIM A 936 (2019) 503-504

Cluster Counting Efficiency

- Cluster Counting is not (never) perfect
  - some narrow clusters cannot be resolved
  - but cluster counting efficiency >25% sufficient to beat charge measurement

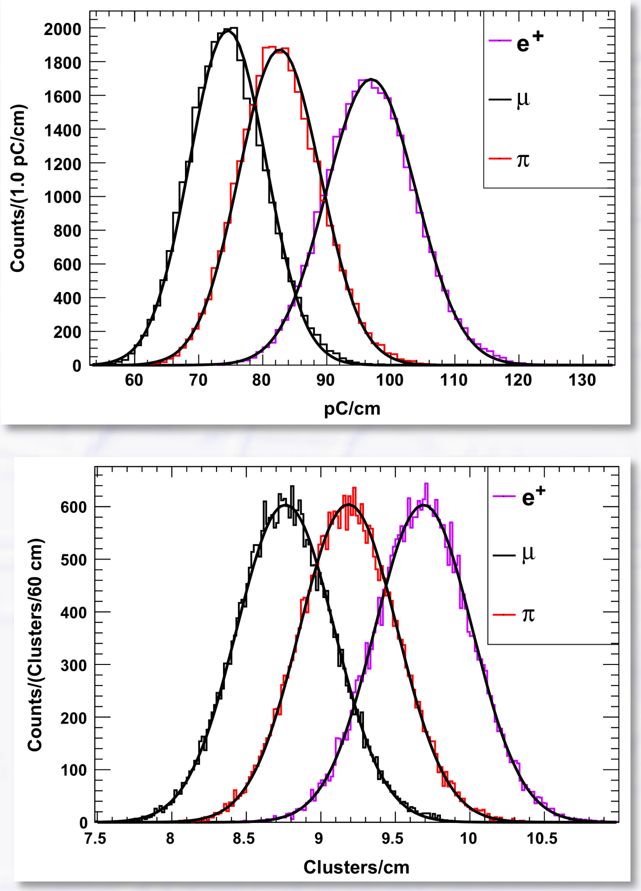
Simulation study for ILD-TPC with He mixture





PID Improvement with Cluster Counting

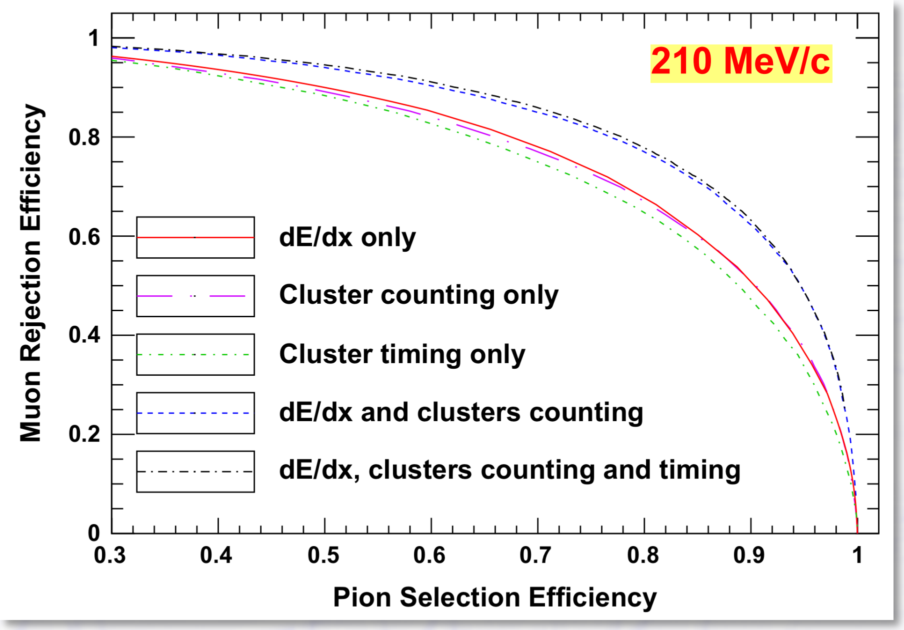
- **PID improvement demonstrated in the full-length single cell drift chamber prototype for Super-B**
  - **simultaneous charge and cluster counting measurement**



dE/dx by charge

cluster counting dN/dx

J.-F. Caron et al, NIM A 735 (2014), 169-183



J.-F. Caron et al, NIM A 735 (2014), 169-183

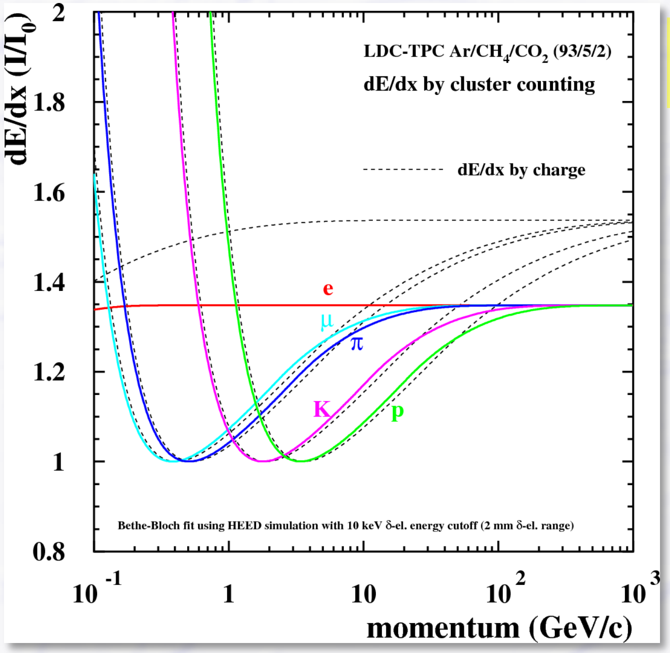
at 210 MeV/c: similar PID capabilities of dE/dx only and of Cluster Counting only

improved PID performance by combination of both

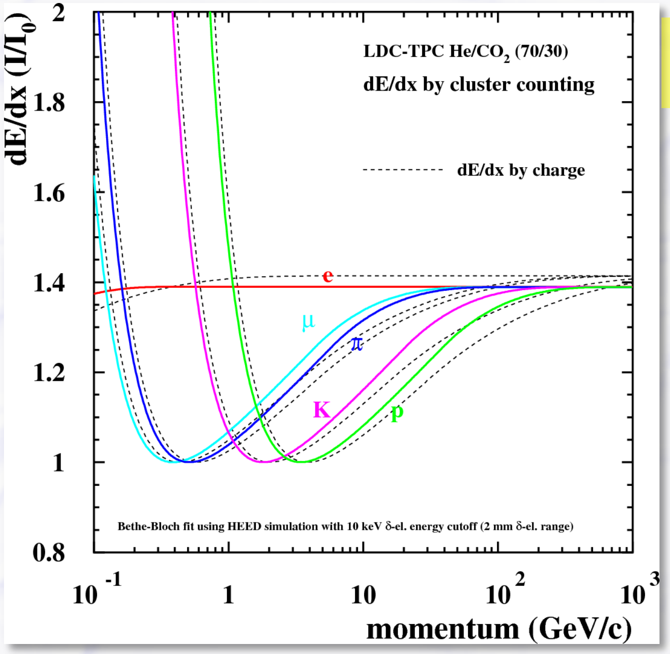
Bethe-Bloch with Cluster Counting

- **Different Bethe-Bloch functions for dE/dx (by charge) and dN/dx (by cluster counting)**
  - **relativistic rise differs (important for particle separation)**
    - charge measurement is highly sensitive to secondary electrons
    - more secondary electrons (deltas) at higher momenta → larger tails in Landau distribution
    - (perfect) cluster counting ignores them → relativistic rise “truncated”
  - **more different at Argon than at Helium (fewer secondary electrons in Helium)**

Simulation study for ILD-TPC



Argon mixture

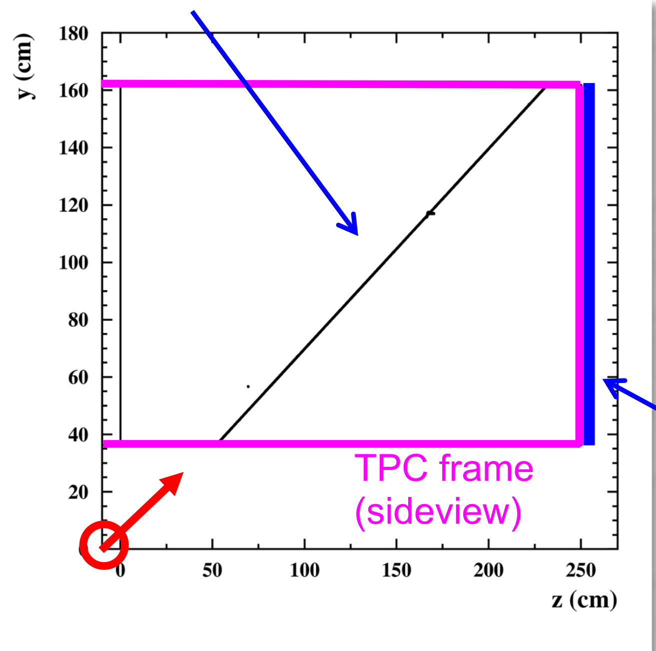


Helium mixture

Cluster Counting in 2D

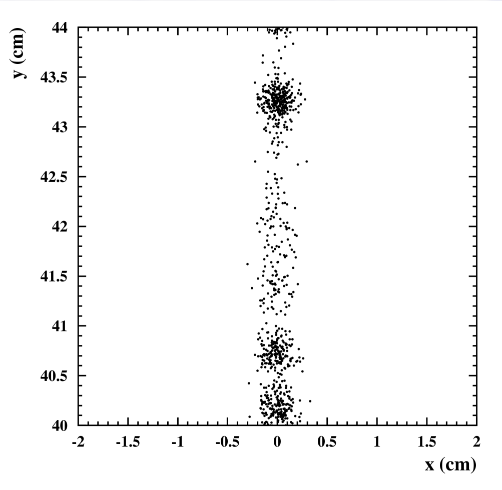
- **Cluster Counting so far based on time measurement in small drift cells**
- **Future TPCs with micro-pattern devices (GEMs/MicroMegas) + small pads/pixels have high granularity**
  - **could make it possible to resolve clusters in space (2D imaging)**
  - **if time could be added → even 3D positions in space**

single track (clusters)

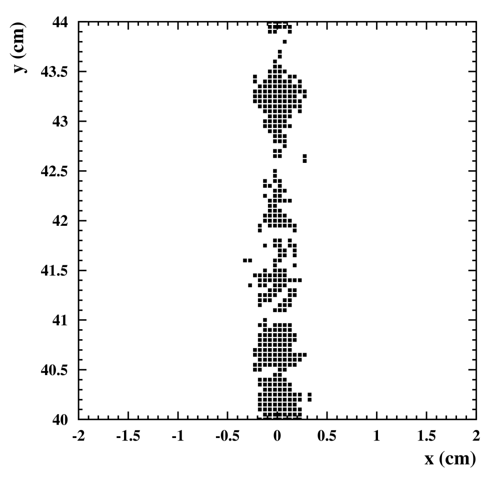


endplate with GEMs or MicroMegas

Simulation study for ILD-TPC with GEMs and small pads



projection of single electrons on endplate

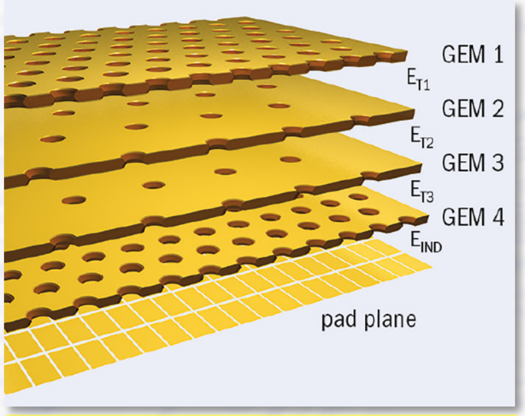


pad response (0.5 x 0.5 mm^2) above threshold (1500 e$^-$)

TPC with Cluster Counting

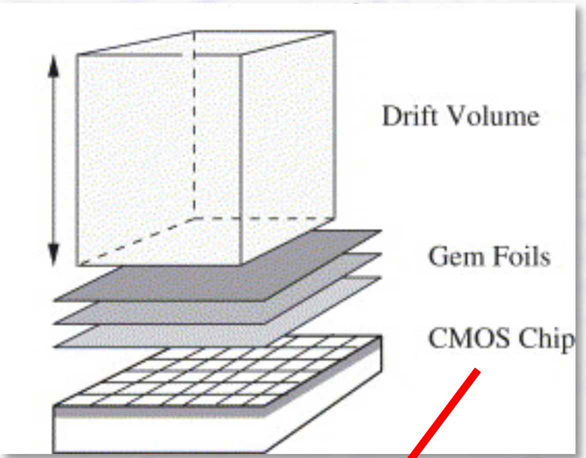
- **Different endplate technologies suitable for Cluster Counting**

Multiple-GEMs with conventional (passive) pads

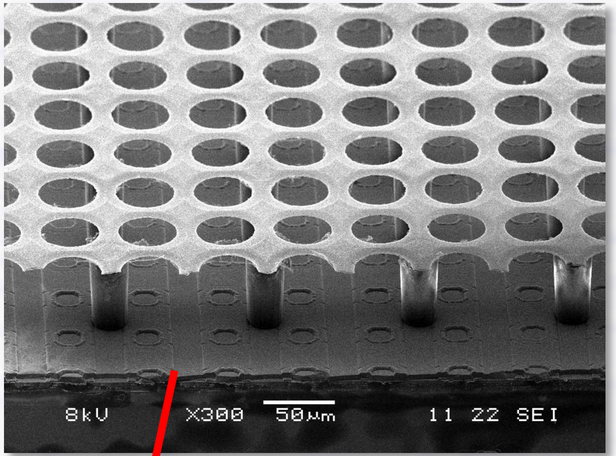


ALICE TPC-upgrade + ILD TPC

Multiple-GEMs with TimePix (active pads, 55 x 55 μm^2)



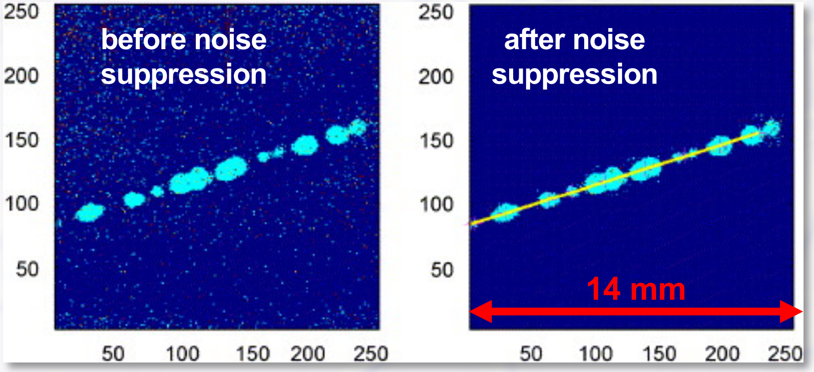
InGrid / GridPix = MicroMegas on top of TimePix (active pads, 55 x 55 μm^2)



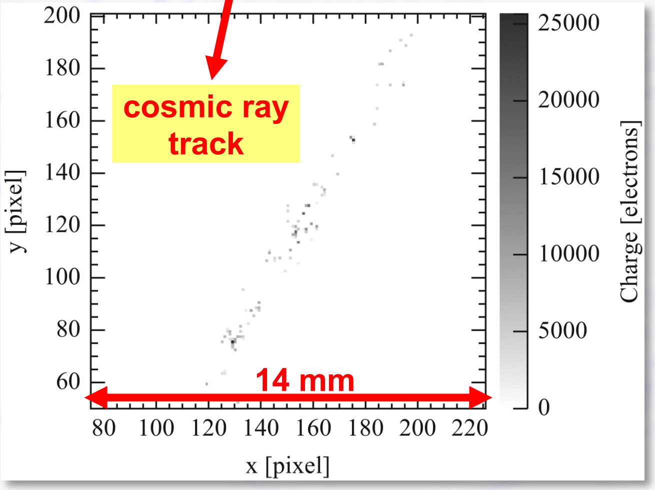
- **Visible individual clusters**

electron track from ^{106}Ru source in Ar/CO$_2$ (70/30)

“blobs” due to diffusion in GEM stack



A. Bamberger et al, NIM A 573 (2007), 361-370

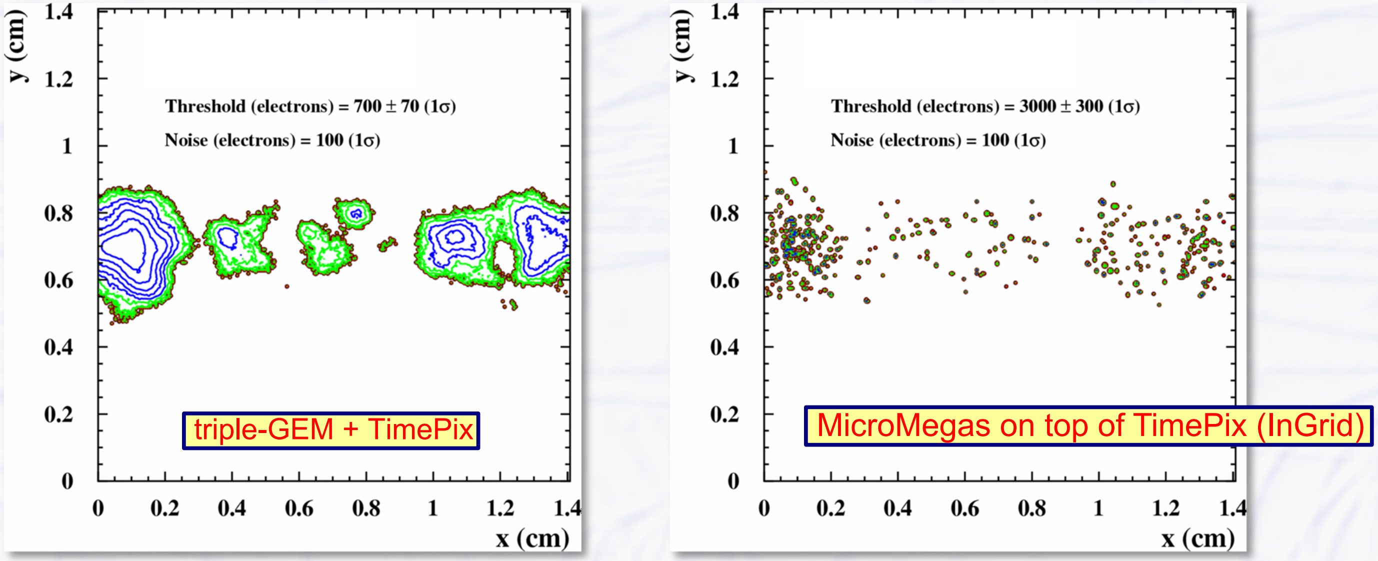


C. Krieger et al, NIM A 729 (2013), 905-909

Counting Clusters

- **How to properly count clusters in space (2D)?**
  - **need cluster finding algorithm**

ILD-TPC simulated 100 GeV muon, 100 cm drift
identical events: same generated primary clusters/electrons



  - **difficult to find clusters dissolved by diffusion**
  - **efficiency also strongly depending on drift length**
  - **+ electronics thresholds + noise**
- **Cluster counting in space sensitive to quite some systematics**

Conclusions

- **Classical PID with dE/dx by charge measurement established since many decades at large detectors**
  - dE/dx resolution depends on track length x pressure
  - ”Lehraus” plot still valid, no miracles to be expected
- **Cluster Counting promises up to ~3x better dE/dx resolution (~2x better separation power)**
  - two ways to count clusters
    - resolve clusters either in time (small drift cells)
      - He mixtures needed, slow gas, fast electronics needed
    - or resolve them in space (TPC with micropattern + pad/pixel endplates)
      - diffusion plays key role, needs good cluster finding algorithm
      - large systematics expected, e.g. depending on drift length
- **Cluster Counting can be complementary to classical dE/dx by charge → but no miracles to be expected for PID**