dEdx Options for Linear Colliders

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- Some basics
- Gas-based trackers
- Silicon detectors

The state-of-the-art model: Photo Absorption Ionization (PAI) model (Allison, Cobb, 1980)

- Assume single-photon exchange
  $\rightarrow$ related to photo absorption
- Assume non.rel. recoil electron

Single-collision cross section

(energy loss per collision T)

$$\frac{d\sigma}{dT} = \frac{\alpha}{\beta^2 \pi}\Bigg[\frac{\sigma_\gamma}{TZ} \ln \frac{2m_e\beta^2/T}{\sqrt{(1-\beta^2\epsilon_1)^2 + \beta^4\epsilon_2^2}} + \underbrace{\frac{\Theta}{n_e}\left(\beta^2 - \frac{\epsilon_1}{|\epsilon|^2}\right)}_{\text{Cerenkov}} + \underbrace{\frac{1}{T^2}\int_0^T dT \frac{\sigma_\gamma}{Z}}_{\text{Rutherford}}\Bigg] \quad (*)$$

$\sigma_\gamma(T)$	**photo absorption cross section**
m_e	electron mass
n_e	electron density
α	$1/137$
β	velocity of projectile
Z	atomic number of material
$\epsilon_1 + i\epsilon_2$	$\equiv \epsilon$: **dielectric constant** (fn of σ_γ)
Θ	$= \arg(1 - \epsilon^* \beta^2)$

Logarithmic Rise and Saturation

At **low density** $\epsilon_1 \sim 1$, $\epsilon_2 \sim 0$,
then in the first term of (*)

$$\ln \frac{1}{\sqrt{(1-\beta^2\epsilon_1)^2 + \beta^4\epsilon_2^2}} \sim \ln \frac{1}{1-\beta^2} = \ln \gamma^2$$

At **high density** and for large T (=photon energy)

$$\epsilon \sim 1 - \left(\frac{\hbar\omega_p}{T}\right)^2 \qquad (\omega_P : \text{plasma freq.})$$

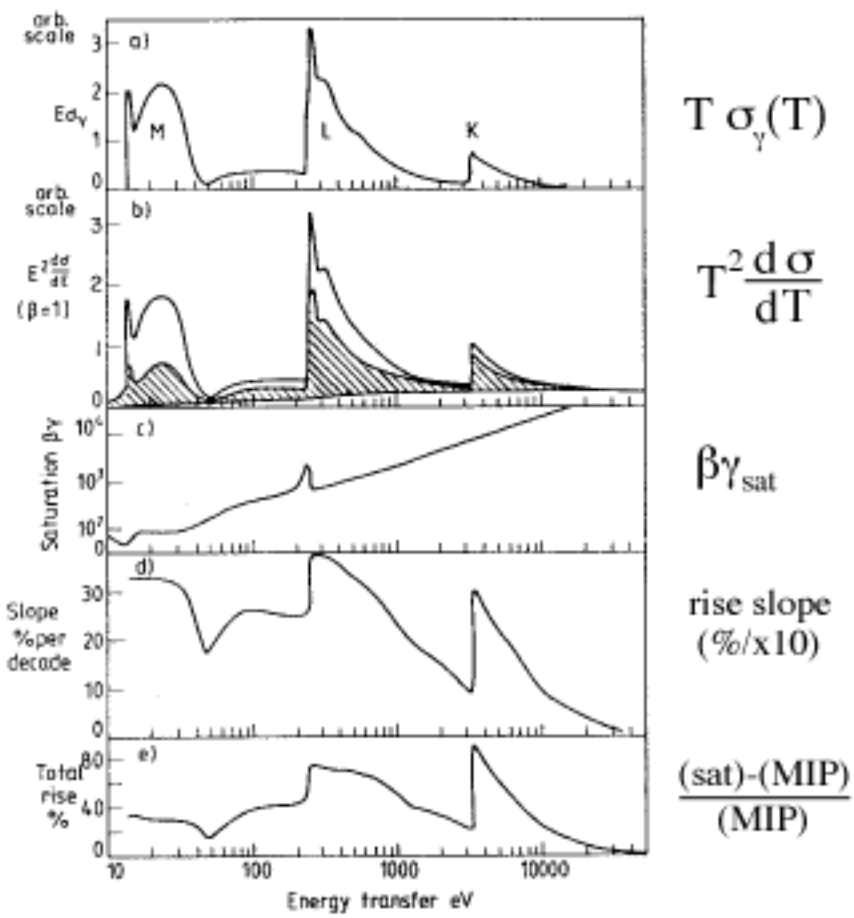
Then for $\beta \sim 1$,

$$\ln \frac{1}{\sqrt{(1-\beta^2\epsilon_1)^2 + \beta^4\epsilon_2^2}} \sim \ln \frac{T^2}{(\hbar\omega_p)^2}$$

Saturates at $\gamma \sim \dfrac{T}{\hbar\omega_p}$

Argon STP(Allison, Cobb)

T: energy loss per collision

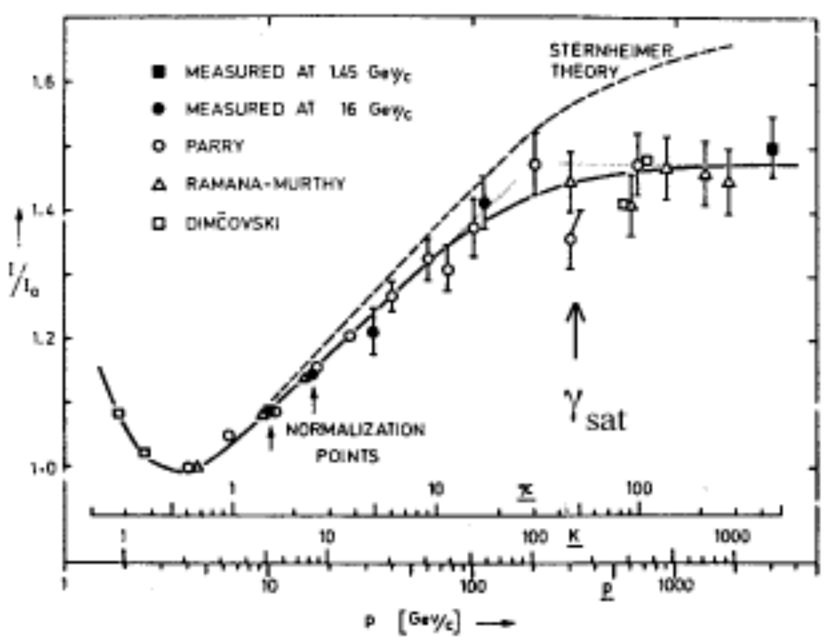


$$\boxed{\gamma_{\text{sat}} \sim \frac{I}{\hbar\omega_p}}$$

$$I \equiv < T > \sim \; 12Z(\text{eV})$$

(effective ionization energy)

$$\boxed{\hbar\omega_p \; \sim \; 20\sqrt{\rho(g/\text{cm}^3)}\;(\text{eV})}$$



Saturation Point for Gasses (1 atm)

gas	I (eV)	$\hbar\omega_p$ (eV)	γ_{sat}	$p_{\text{sat}}^{\pi/K}$ (GeV/c)
He	41.8	0.27	154	21/76
Ar	188	0.82	230	32/115
Xe	482	1.41	341	48/170
CH_4	41.7	0.61	68.4	10/34
C_2H_6	45.4	0.82	55.3	8/28
C_3H_8	47.1	0.96	49.1	7/24
C_4H_{10}	48.3	1.14	42.4	6/21

Saturation point is higher for heavier atoms.
Hydro-carbons: $\gamma_{\text{sat}} \sim 50$.

$dEdx(\pi) \sim dEdx(K)$ at $p_{\text{sat}}(K) \sim 3.6 p_{\text{sat}}(\pi)$.

$\rightarrow \pi/K$ separation starts to degrade at $p_{\text{sat}}(\pi)$
and completely useless at $p_{\text{sat}}(K)$.

Bethe-Bloch Formula (Max-T improved)
(PDG 1998)

$$\frac{dE}{dx} \propto \frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e\beta^2\gamma^2 T_0}{I^2} - \frac{\beta^2}{2}\left(1+\frac{T_0}{T_{\text{max}}}\right) - \frac{\delta}{2}\right]$$

$$T_0 = \min(T_{\text{cut}}, T_{\text{max}})$$

T_{max}: maximum kinetic energy of recoil electron.

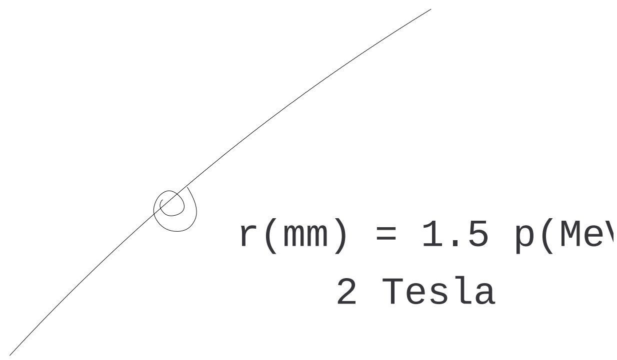
$$T_{\text{max}} = \frac{2P^2 m_e}{M^2 + m_e^2 + 2Em_e}$$

M, E, P: mass, energy, momentum of projectile.

$T_{\text{max}} \sim E$ for $\gamma \gg M/m_e$.
$\longrightarrow$ separate track

T_{cut} : effective cutoff on recoil energy

Effective Cutoff $T_{\rm cut}$



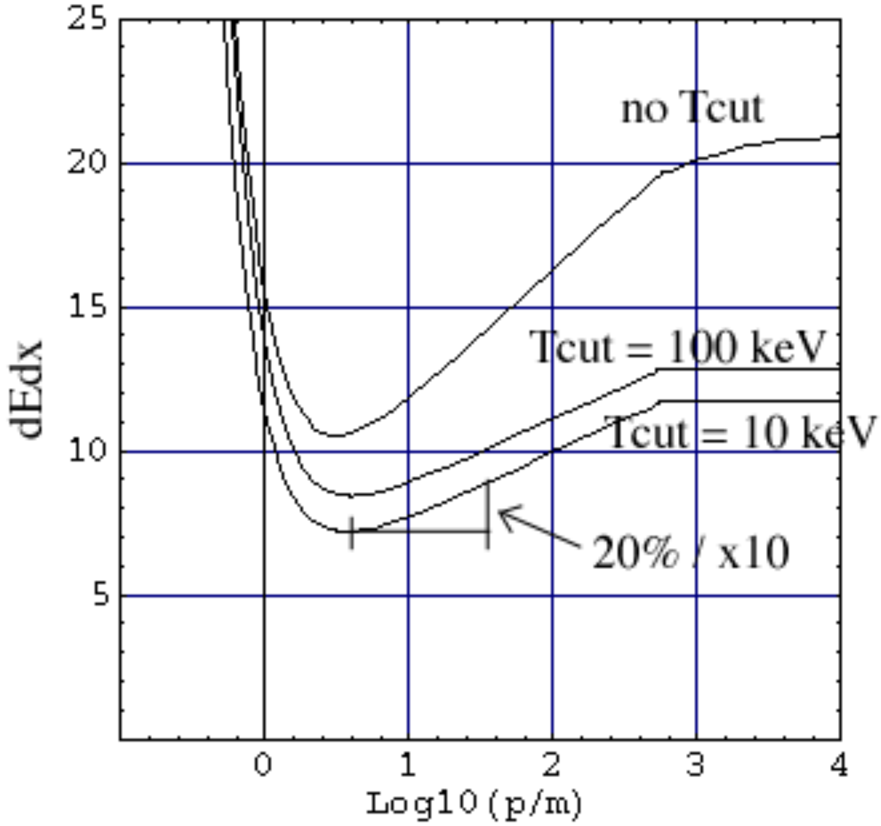
- If the **radius of curler** is larger than order 1 mm, the hit may be rejected.
  $\rightarrow T_{\rm cut} \sim$ a few 100 keV.

- **Average energy deposit**:
  $\sim$ 3 keV/cm for Ar, C_2H_4 ...
  $\sim$ 0.35 KeV/cm for He.

  $\rightarrow T_{\rm cut}$ of a few 100 keV is a cut on the energy deposit on a single drift chamber cell (i.e. the measured pulse height).

Effect of T_{cut}

Ar at STP

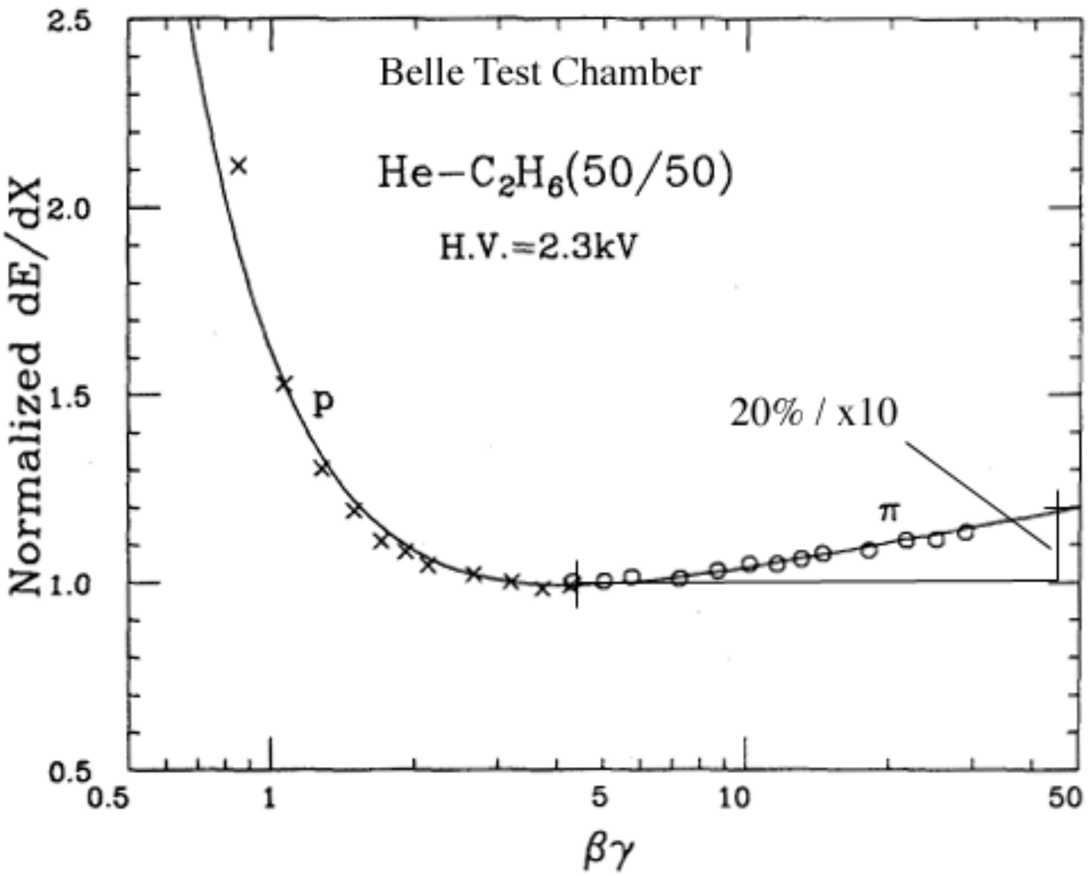


- The kink at $\log_{10} p \sim 2.7$ is due to the density effect:

$$\frac{\delta}{2} \sim -\ln \gamma_{\text{sat}} + \ln \beta\gamma - \frac{1}{2}$$

- The logarithmic rise reduced by about factor of 2 by T_{cut}, but no difference between $T_{\text{cut}} = 100$ keV and 10 keV.

Comparison with data



Discard top 20% of pulse heights.
($T_{\text{cut}} \sim 10$ keV)

Truncated mean dEdx

Relativistic rise is nearly independent of T_{cut} as long as $T_{\text{cut}} \sim 10 - 100$ keV.

$\rightarrow$ cut on the high-side tail (**Landau tail**) to improve dEdx resolution.

CLEO 2.5 example

% hits discarded	dEdx σ/μ (%)
0	8.3
10	6.1
20	5.8
30	5.7
40	5.8
50	6.0
60	6.4

\# hit per track $\sim$ 44.5 without truncation

dEdx resolution

Empirical formula for gas-sampling device (Walenta)

$$\boxed{\frac{\sigma}{\mu}(dEdx) = 0.41 n^{-0.43} (xP)^{-0.32}}$$

n	# sample
x	sample thickness (cm)
P	pressure (atm)

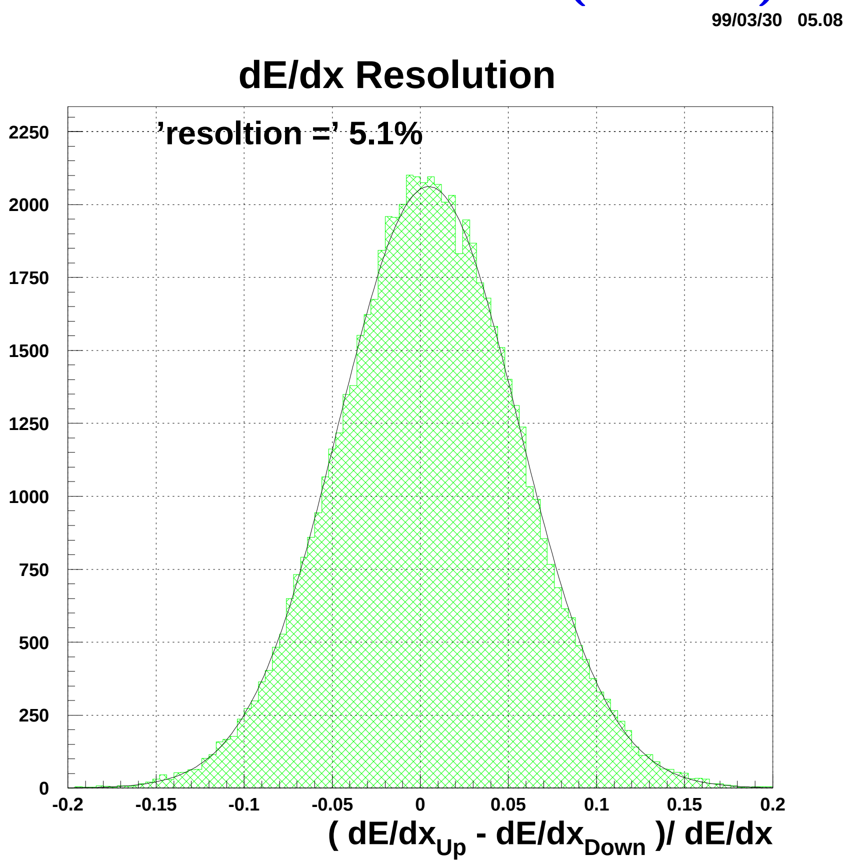
Fairly independent of the type of gas.

The Allison-Cobb obtains $n^{-0.46}$ dependence.

If each layer (xP) is independent, and simply increase the number of samples, one expects

$$\frac{\sigma}{\mu} \propto n^{-0.5}$$

Belle dEdx resolution (cosmic)



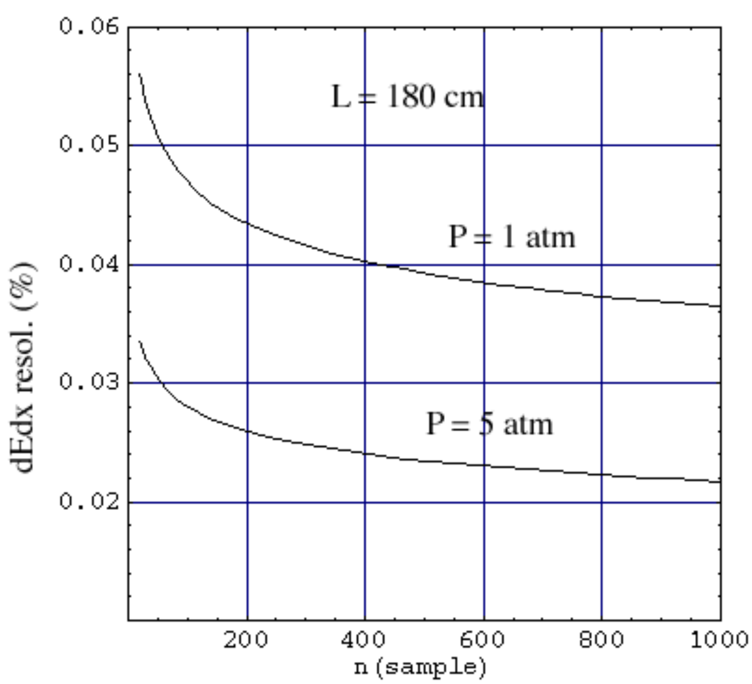
Calibration preliminary

$n = 52$, $P = 1$ atm, $x = 1.5$ cm, $\rightarrow$ expect 5.9%.

Expected and measured dEdx resolutions

det.	n	x(cm)	P	exp.	meas.
Belle	52	1.5	1 atm	6.6%	5.1% (μ)
CLEO2	51	1.4	1 atm	6.4%	5.7% (μ)
Aleph	344	0.36	1 atm	4.6%	4.5% (e)
TPC/PEP	180	0.5	8.5 atm	2.8%	2.5%
OPAL	159	0.5	4 atm	3.0%	3.1% (μ)
MKII/SLC	72	0.833	1 atm	6.9%	7.0% (e)

Optimization: for a fixed total length, increase n:
(use the scaling law)



One cannot indefinitely increase n.

- # of primary iinization n_p

$$n_p \sim 1.5\,Z/\text{cm} \quad (Z : \text{per molecule})$$

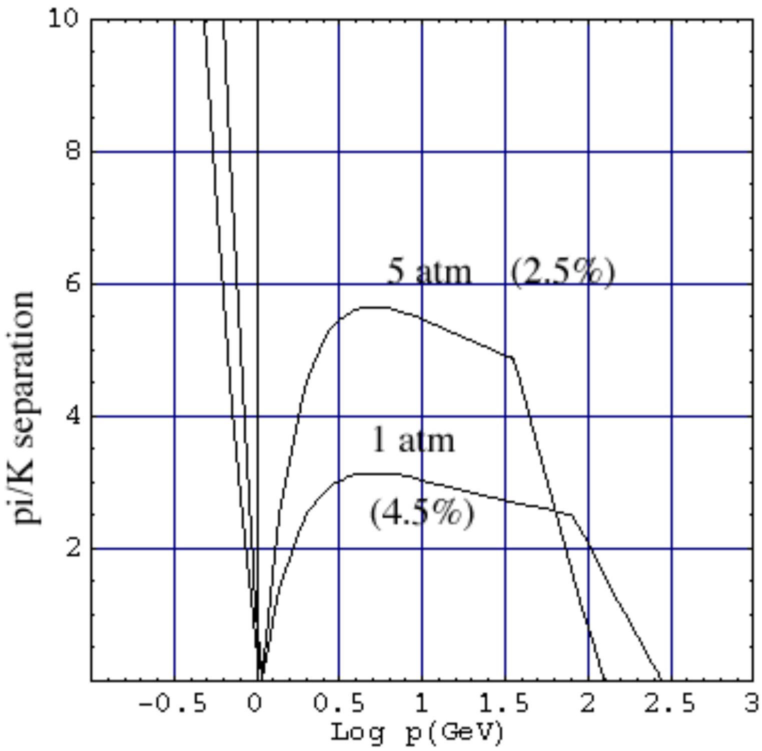
n_p = 2/cm (He), 15/cm (CH_4), 27/cm (Ar)
No gain after $n_p \sim 1$ (i.e. $x \sim$ mm)

- electronical noise

$$\text{Assume} \quad \begin{array}{l} 4.5\% \text{ for 1 atm chamber} \\ 2.5\% \text{ for 5 atm chamber} \end{array} .$$

Note: the higher the pressure, the larger the $\hbar\omega_p$
$\rightarrow$ quicker the saturation.

π/K Separation



1 atm: $> 2\sigma$ for $p < 0.8$, $1.75 < p < 100$ GeV/c

5 atm: $> 2\sigma$ for $p < 0.9$, $1.25 < p < 65$ GeV/c

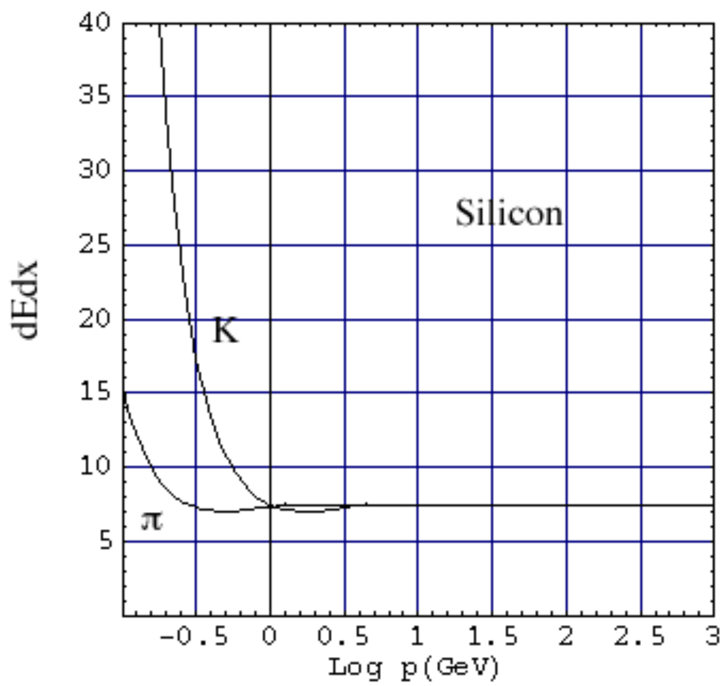
$> 4\sigma$ for $1.75 < p < 50$ GeV/c

dEdx in Silicon

$$\rho(\mathrm{Si}) = 2.33\ \mathrm{g/cm^3} \gg \rho(\mathrm{gas})$$
$$\hbar\omega_p(\mathrm{Si}) \sim 35\hbar\omega_p(\mathrm{gas})$$

$$\gamma_{\mathrm{sat}}(\mathrm{Si}) = \frac{I}{\hbar\omega_p} \sim 5.4\ (\mathrm{ref:}\ \gamma_{\mathrm{min}} \sim 4)$$

$\rightarrow$ Essentially no logarithmic rise



dE in 5 lyrs of 0.3mm-thick Si = 0.6 MeV
($\sim$ 1.5 m of gas) : a Si layer is **'thick'**.

dEdx Resolution in Silicon

At the mercy of landau tail.

- **Babar study (Schumm)**

5 lyrs Si strip, 0.3mm each
Simulation based on the Vavilov model.

Discard top n pulse heights.

n	0	1	2	3	4
$\sigma/\mu(\%)$	13.9	11.3	10.4	11.7	13.7

(π at 450 MeV/c)

- **ALICE study (Batyunya)**

2 lyrs Si strip + 2 lyrs Silicon drift
Simulation based on GEANT.

Discard top 2 pulse-heights.

p_K(GeV/c)	0.44	0.5	0.78	0.88	0.98
$\sigma/\mu(\%)$	8.6	9.1	10.4	10.6	10.6

(Kaon)

π/K Separation by Silicon

4~5 layers of Silicon layers 0.3mm each
$\rightarrow \sim$ 11% resolution near MIP.

Assume $n^{-0.43}$ and $x^{-0.32}$ dependence

$$\frac{\sigma}{\mu}(dEdx) \sim 0.14\, n^{-0.43} x(\text{mm})^{-0.32}$$

Model detector (small): $n = 6$, $x = 0.3$mm.
dEdx resolution $\sim$ 9.7%.

$> 2\sigma$ π/K separation for $p < 0.65$ GeV/c.

- Adequate for slow and stable $\tilde{\tau}$ search.
- But no good for high-P D reconstruction etc.

Dynamic range required to go down to
100 MeV/c: $\sim 20\times$MIP.

Summary

- The scaling law $n^{-0.43}x^{-0.32}$ works reasonably.
  Some but not much margin of imporvement beyhond the prediction.
- At 1 atm and $L = 180$ cm, 4.5% resolution is realistic, 4% maybe tough. $\pi/K > 2\sigma$ sep. up to 100 GeV.
- At 5 atm, 2.5% is achievable, but $\pi/K > 2\sigma$ sep. up to 65 GeV,
  $> 4\sigma$ up to 50 GeV/c.
- The 'blind spot' near 1 GeV/c is 0.95 GeV/c wide for 1 atm, 0.35 GeV/c for 5 atm.
- Number of sampling: larger the better up to around 1000.
- Gas: in general heavier atom the better.

- No relativistic rise for Si:
  effective only for $p < 0.65$ GeV/c.
  The resolution of 10% is readily achievable and adequate for heavy charged particle searches.
- Dynamic range upto 20 MIP is needed.