Experimental Particle Physics

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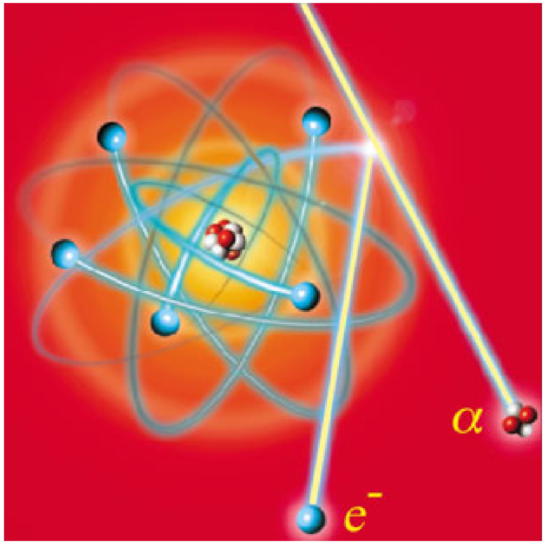
Overview

- Lecture 1: Interactions with matter
  - What particles interact how
  - How can we use these interactions to detect particles?
  - What can we measure?
- Lecture 2: Tracking Detectors

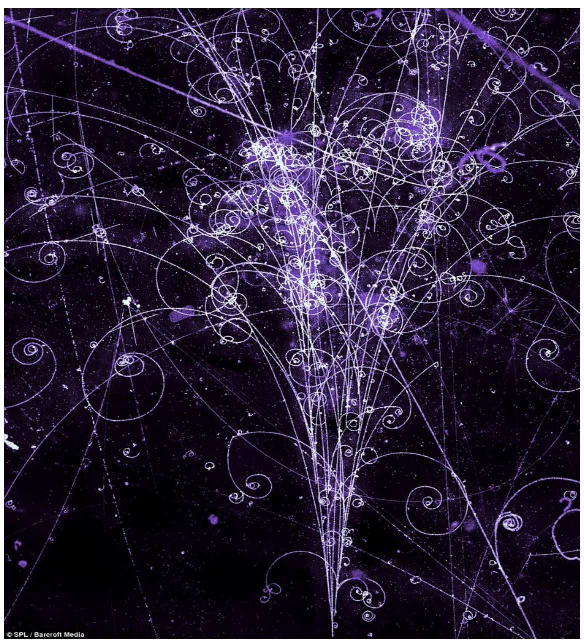
Particle Interactions with matter

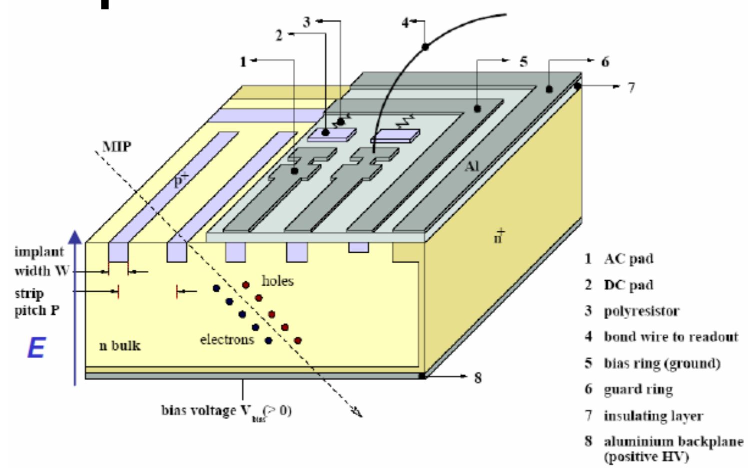
- How do we observe?
- Need interactions to detect particles
- “Seeing” $\rightarrow$ detection of scattered light
- “Feeling” $\rightarrow$ Coulomb force
- “Hearing” $\rightarrow$ acoustic detection of pressure
- Rely mostly on electromagnetic/ Coulomb interactions to observe particles

E-loss of charged particles: Ionisation

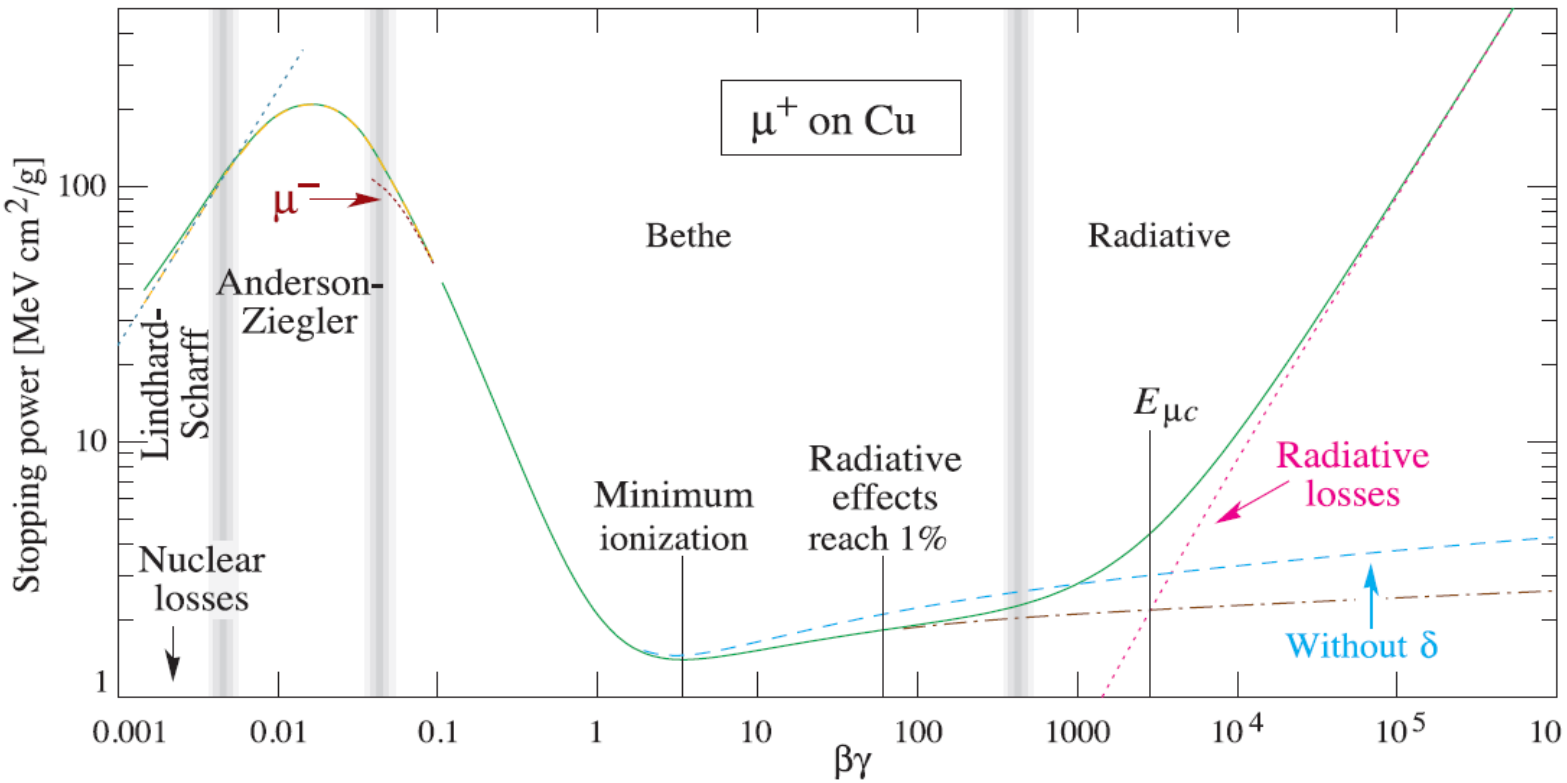


- charged particles heavier than electrons lose energy through collisions with electrons in the atom
- process of Ionisation energy loss has important applications:
  - cancer radiation treatment
  - particle detection





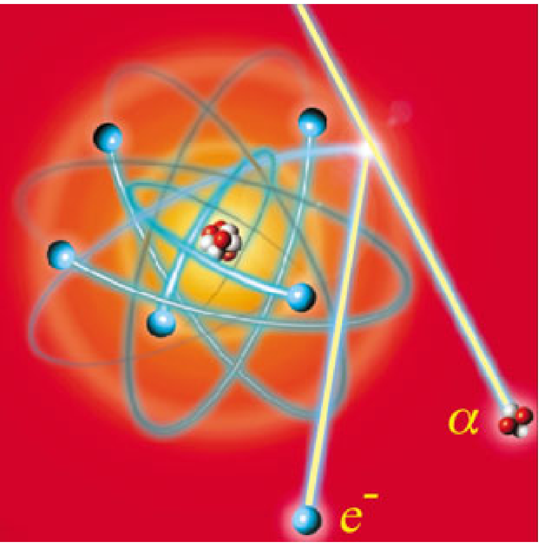
E-loss: Bethe-Bloch Formula

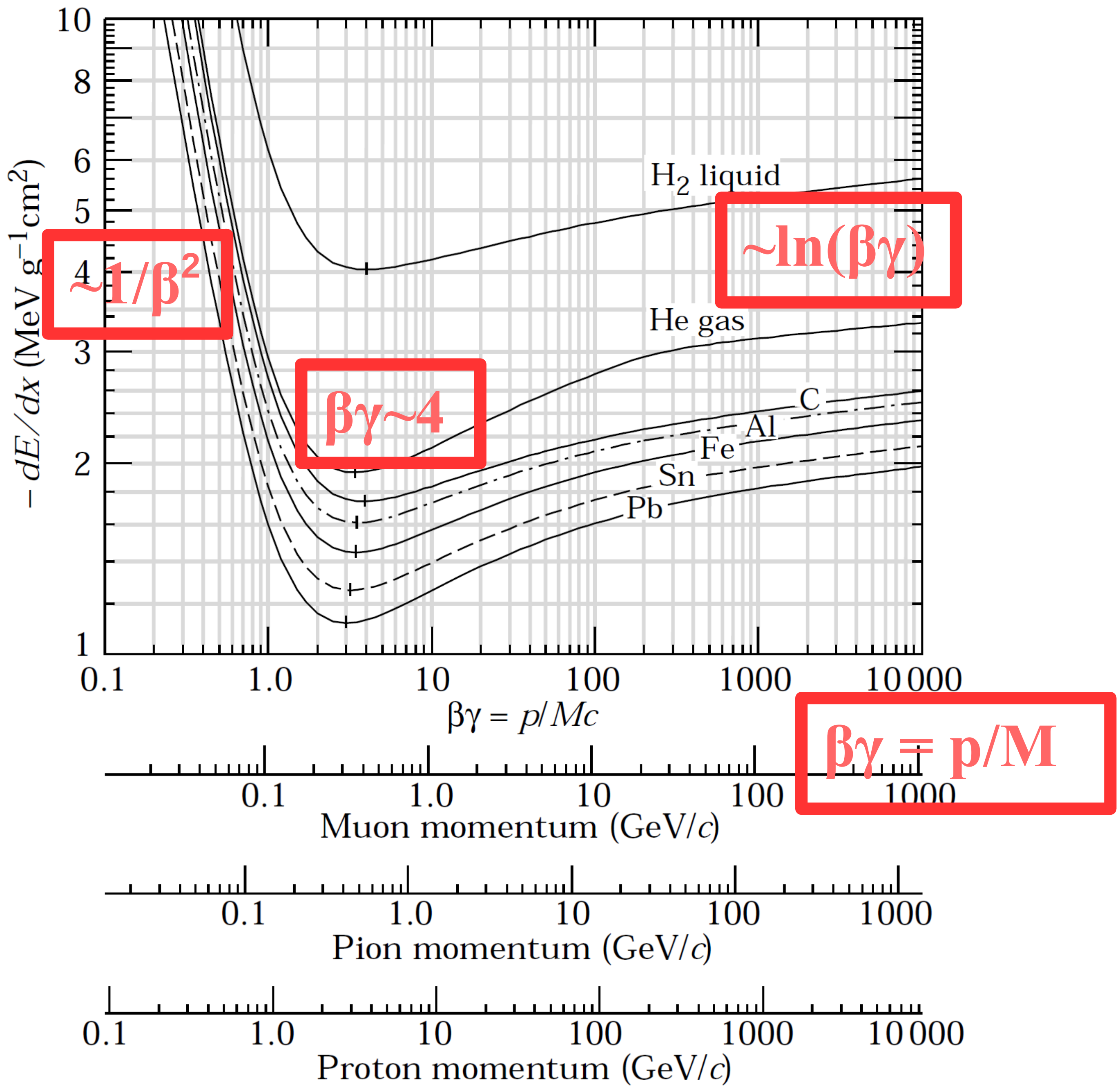


$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

$K = 4\pi N_A r_e^2 m_e c^2 = 0.307 \text{ MeV g}^{-1} \text{ cm}^2$

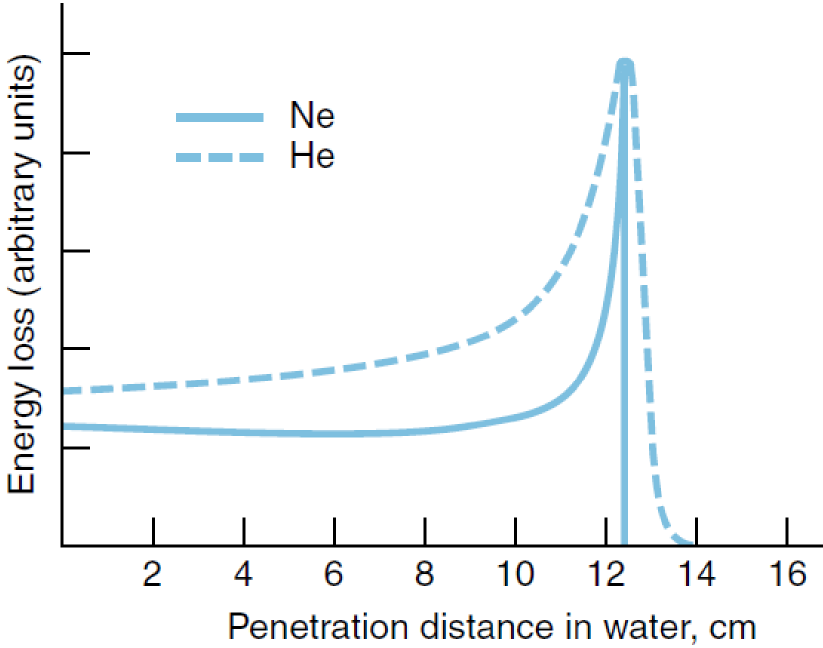
E-loss: Bethe-Bloch Formula

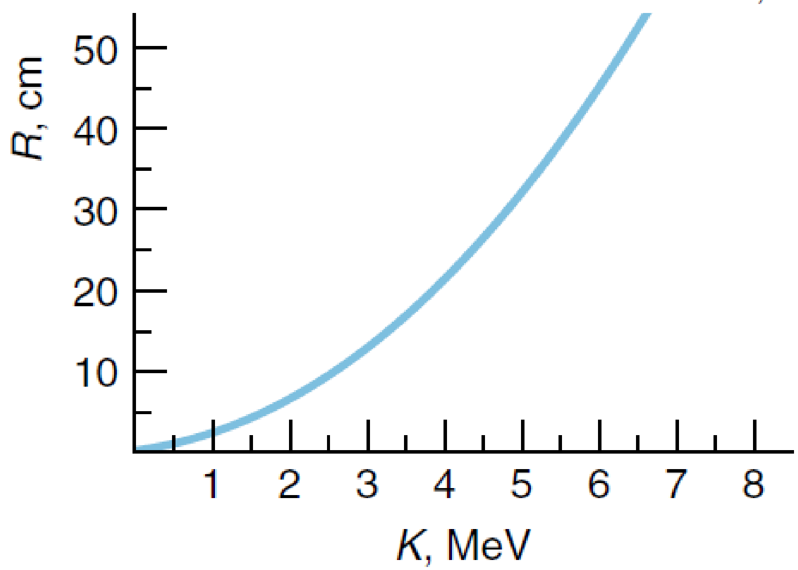


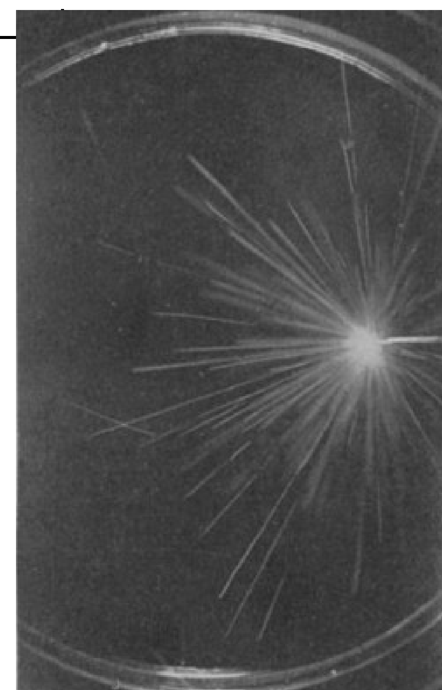


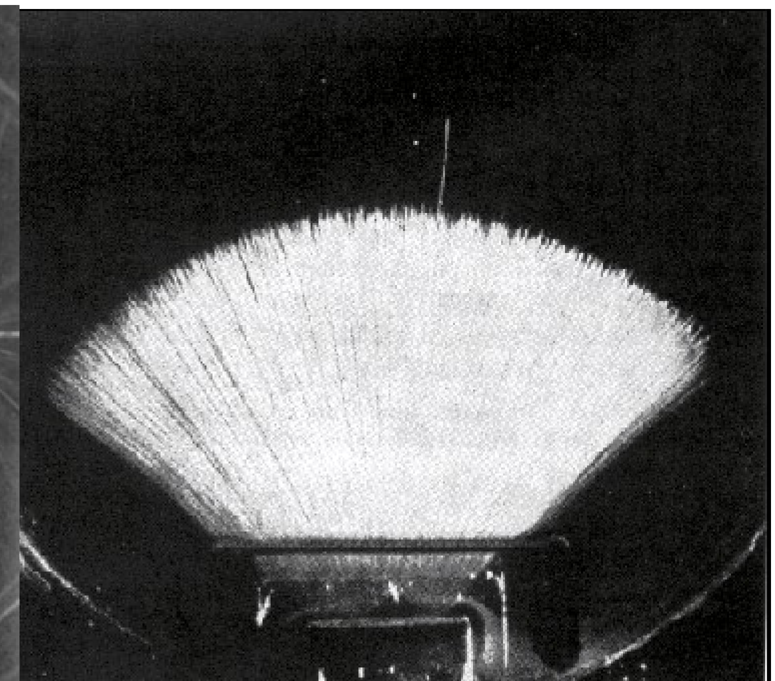
The Bragg Peak

- Limited penetration range
- Particles lose most energy at the end of the path when it is slowest

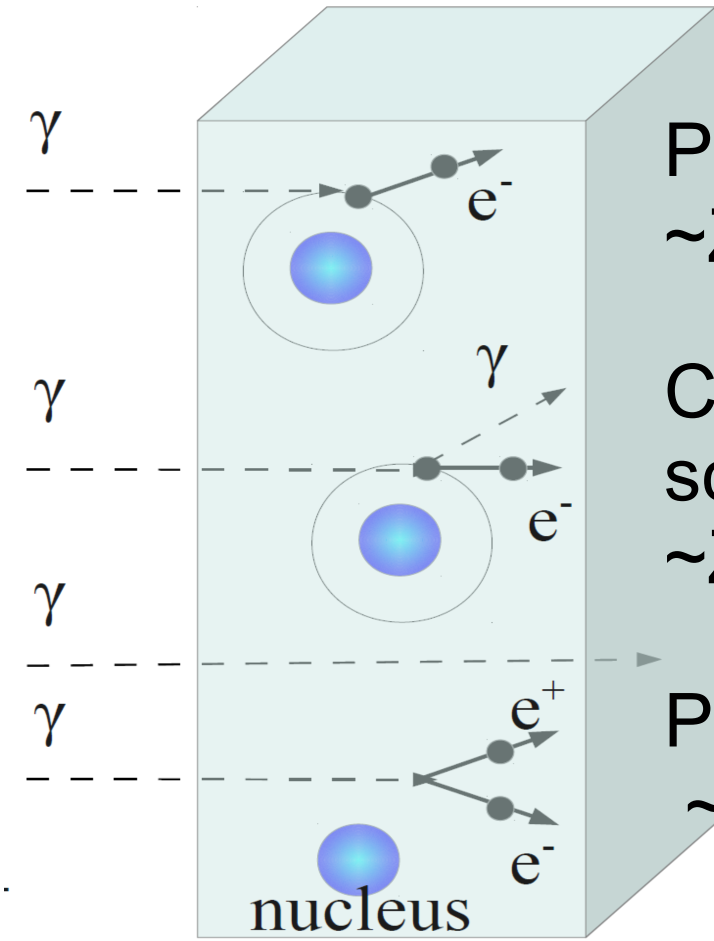








Interaction of Photons



Photoeffect
$\sim Z^5/E^{3/2}$

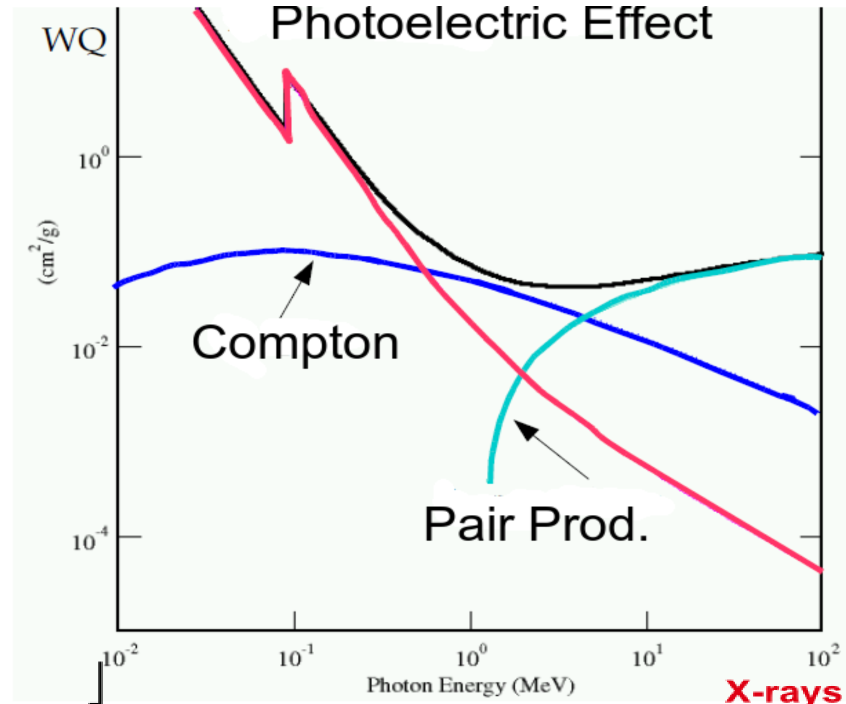
Compton
scatter
$\sim Z \ln E/E$

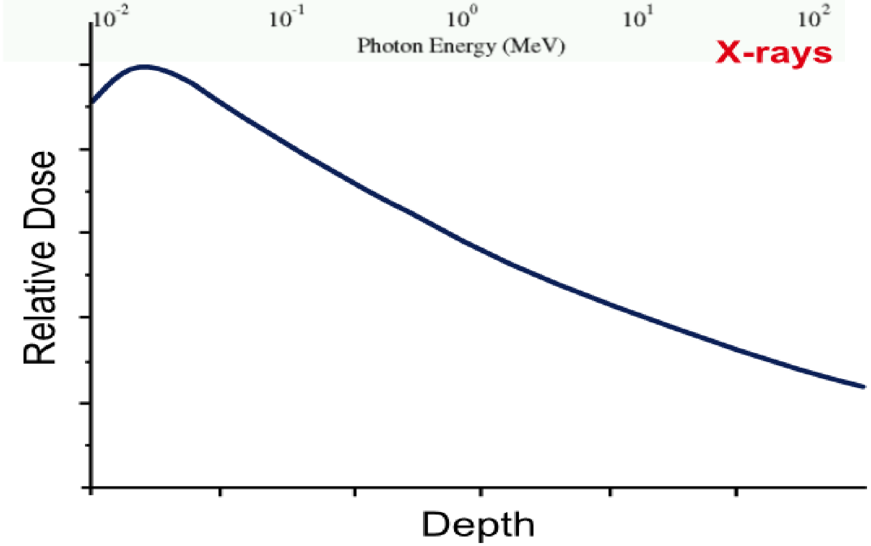
Pair creation
$\sim Z^2$

N Photons lost

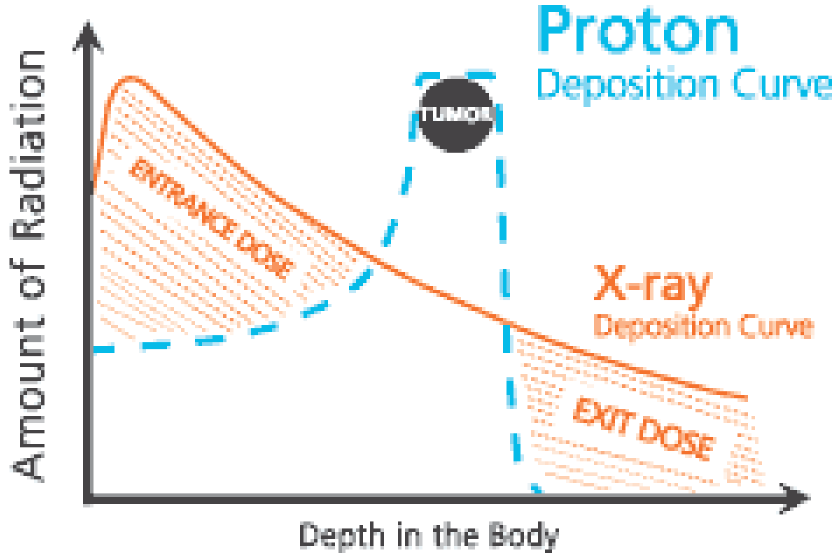
$$dN = -\mu N dx$$

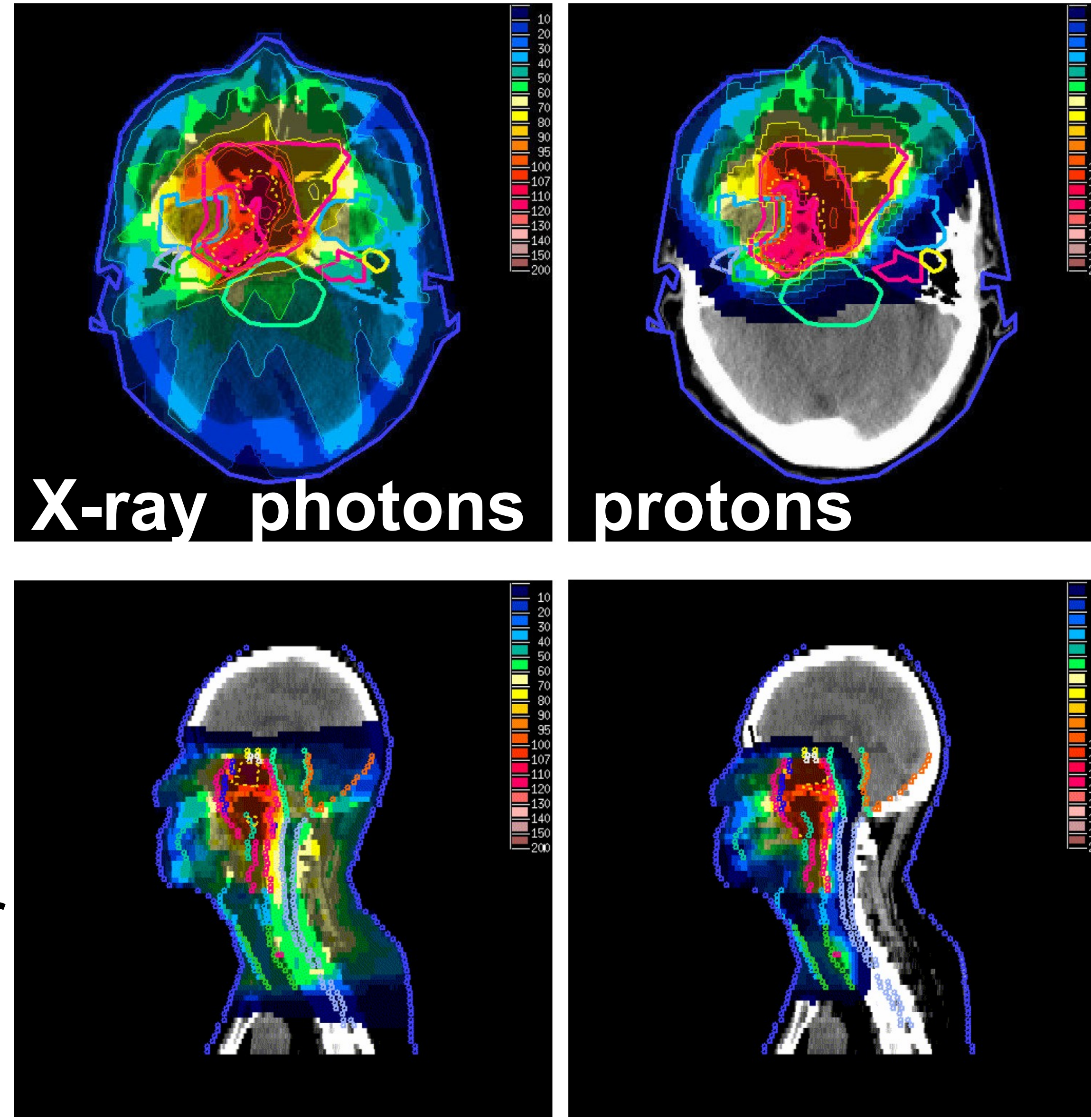
$$N = N_0 e^{-\mu x}$$





Bragg Peak: Cancer Treatment



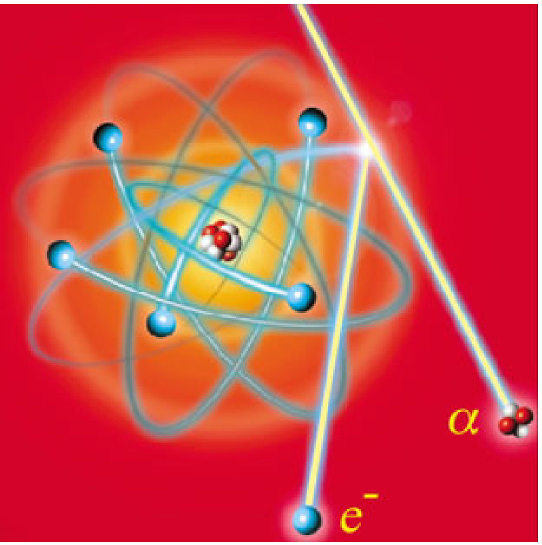


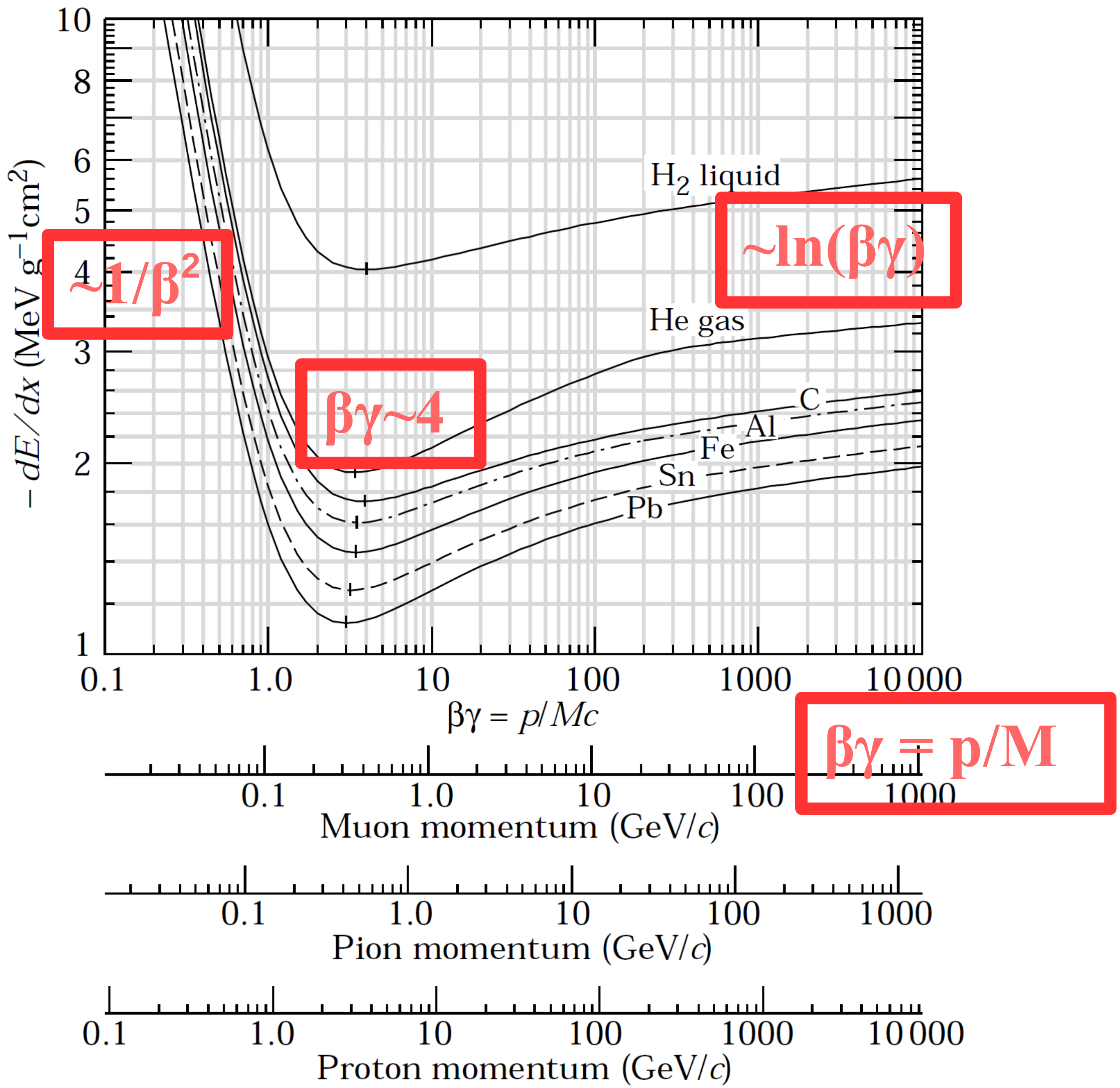
- Protons and carbon ions used to destroy tumors
- Smeared Out Bragg Peak

→ maximum dose at tumor

→ reduced dose for healthy tissue around

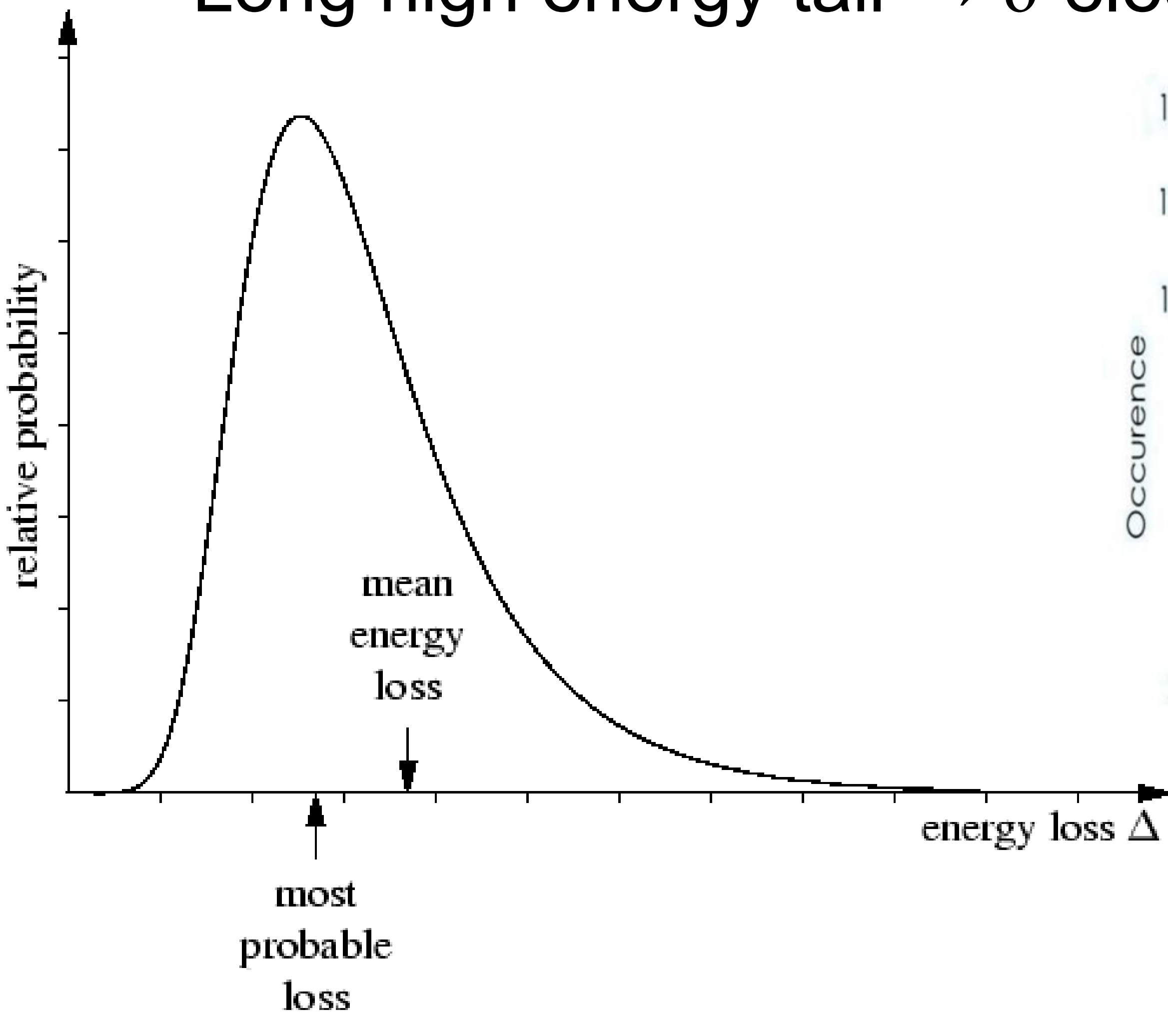
E-loss: Bethe-Bloch Formula

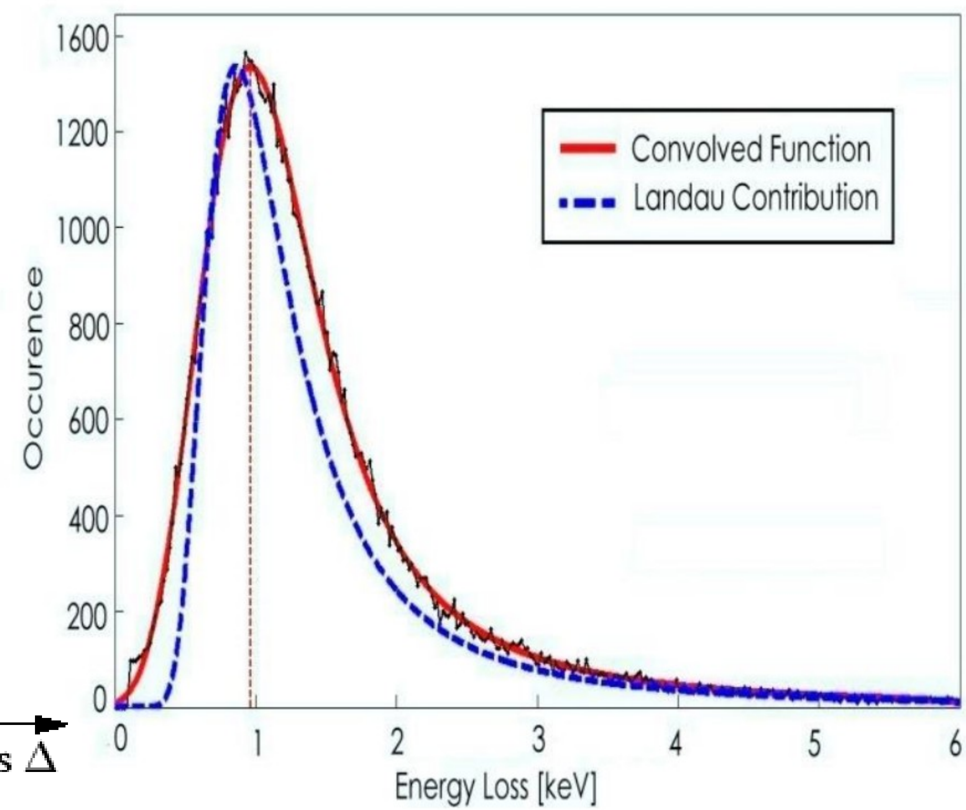




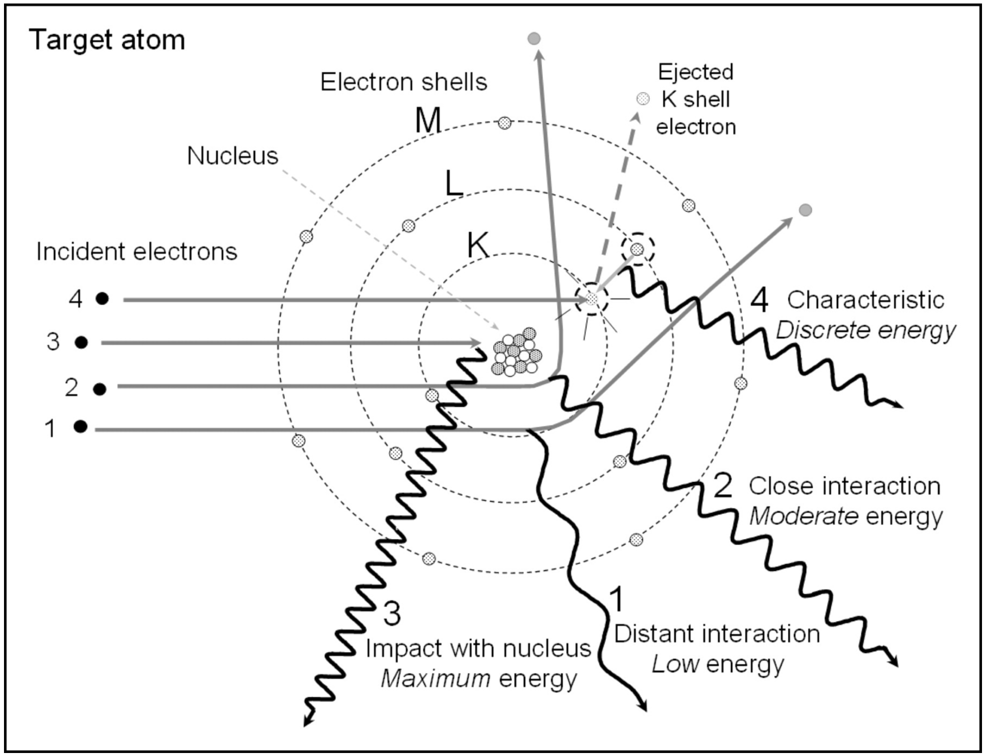
E-loss: Fluctuations

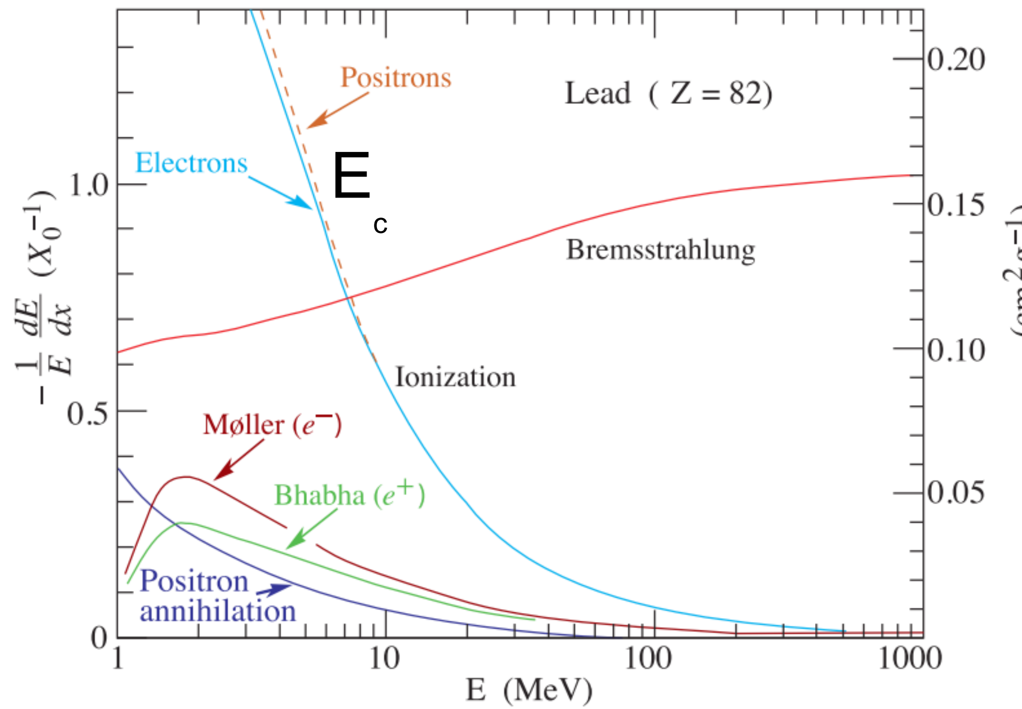
- Landau, Vavilov and Bichsel
  - thin absorber: Landau
  - general treatment: Vavilov → now better descriptions
  - limit Gaussian
- Long high energy tail → δ-electrons





E-loss of Electrons: Bremsstrahlung

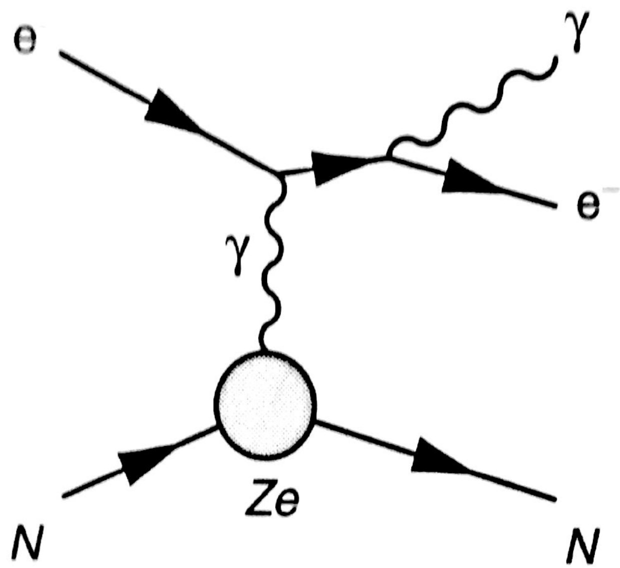


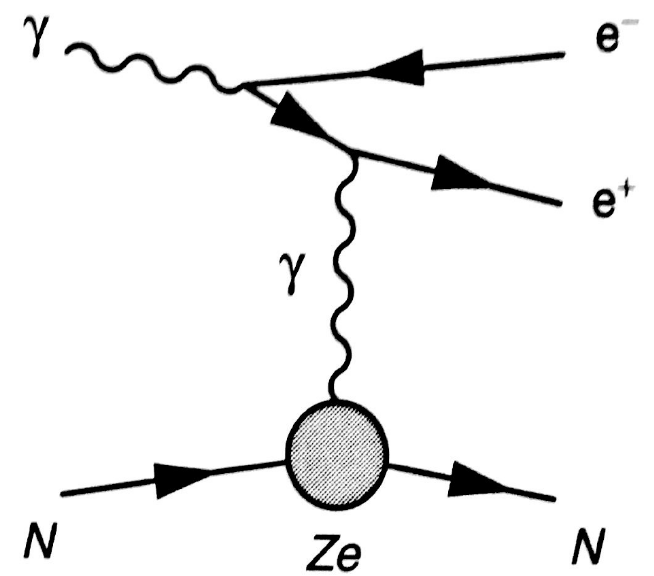


- "Breaking Radiation"
- ~$1/m^2$ → mostly important for electrons/positrons
- above critical Energy E_c:

Bremsstrahlung more important than ionisation

Radiation Length





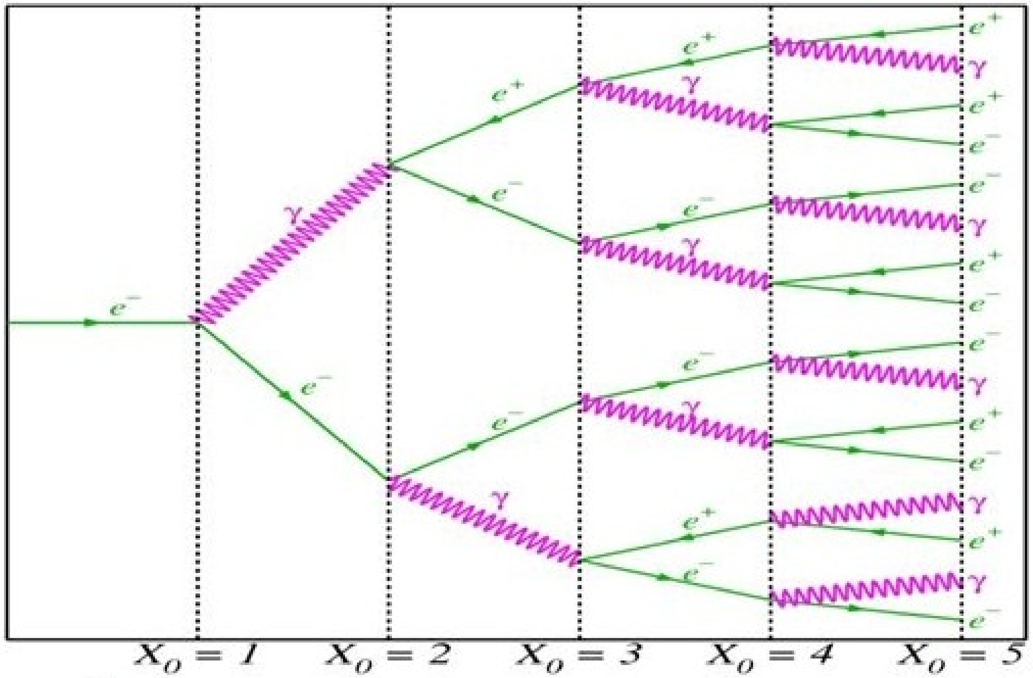
Bremsstrahlung and Pair creation governed by the same principles

Radiation length $L_r = X_0$:

$$\frac{1}{X_0} = 4 N_A \frac{\alpha^3}{m^2} \frac{Z^2}{A} \rho \left(\ln \frac{183}{Z^{1/3}} \right)$$

Typical values: plastic: 30cm, lead: 0.5cm

Electromagnetic cascades



x	0	X_0	$2X_0$	$3X_0$	$4X_0$	
N	1	2	4	8	16	0
<E>	E_0	$E_0/2$	$E_0/4$	$E_0/8$	$E_0/16$	$<E_c$

$$\frac{dE}{dX} = \frac{E}{X_0}$$

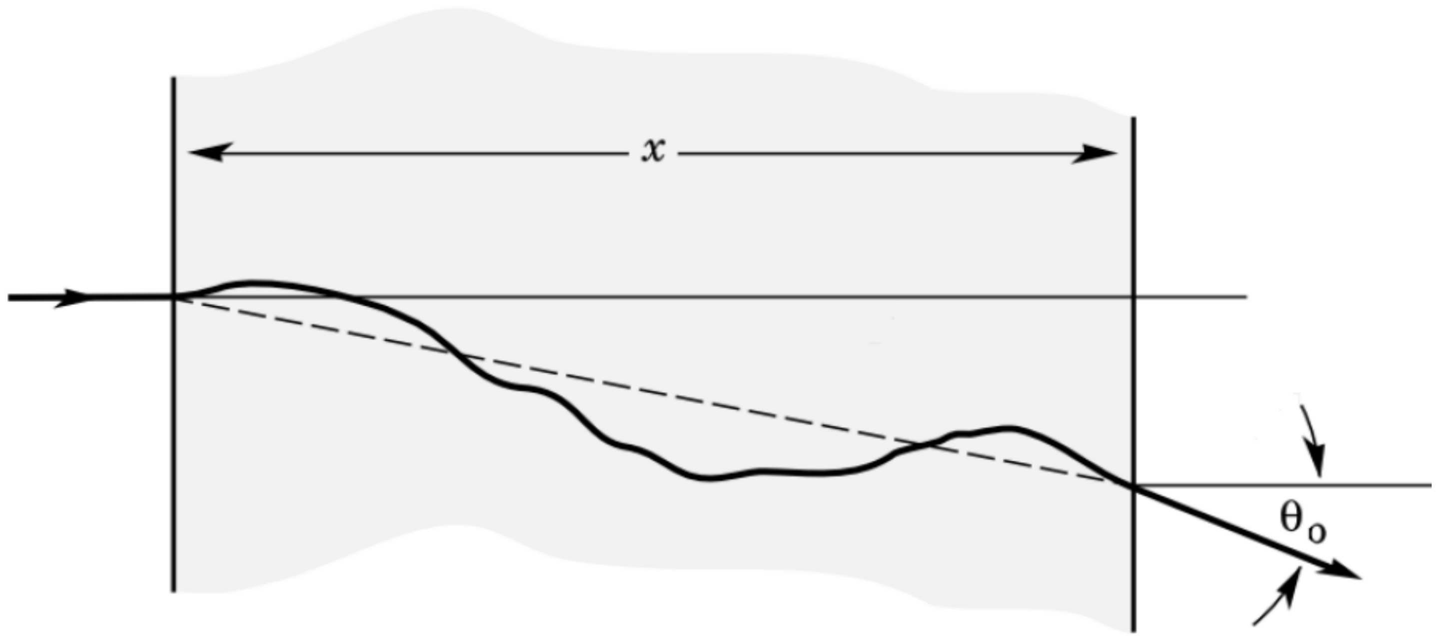
$$N(t) = 2^t ; E(t) = \frac{E_0}{N} = \frac{E_0}{2^t}$$

Shower stops when the critical energy E_c is reached and ionisationloss starts to dominate

$$N_{max} = \frac{E_0}{E_c} = 2^{t_{max}}$$

Multiple scattering

- Multiple Coulomb scattering
- No change in energy
- Average direction change is 0
- But spread!



$$\theta_0 = \frac{13.6\, MeV}{\beta c p} q \sqrt{\frac{x}{X_0}} \left[1 + 0.0038 \ln \frac{x}{X_0} \right]$$

Particle Interactions with matter

Reminder of important interactions:

- Charged particles
  - Ionisation
- Electrons
  - Bremsstrahlung: radiation length
- Photons
  - Photoeffect
  - Compton Scatter
  - Pair creation: radiation length
- Hadrons
  - Strong interaction: nuclear interaction length
- Neutrinos
  - Weak interactions

Particle Interactions with matter

Energy Loss Mechanisms

- **Heavy Charged Particles**
  - Inelastic collisions with atomic electrons
  - Elastic scattering from nuclei
  - Cherenkov radiation
  - Bremsstrahlung
  - Nuclear reactions
  - Hadronic reactions
- **Light Charged Particles**
  - Inelastic collisions with atomic electrons
  - Elastic scattering from nuclei
  - Cherenkov radiation
  - Bremsstrahlung
  - Nuclear reactions
  - Transition radiation
- **Photons**
  - Photo-electric effect
  - Compton scattering
  - Pair production
  - Rayleigh scattering
  - Photo-nuclear reactions
- **Neutral Particles**
  - Elastic nuclear scattering A(n.n)A
  - Inelastic nuclear scattering A(n.n')A*
  - Radiative Capture (n,g)
  - Fission (n,f)
  - Other nuclear reactions
  - Hadronic Showers

Particle Detectors

Measure

- Position
- Time
- Momentum
- Energy
- Particle Identification (e,μ,π,K,p)
  - dE/dX
  - Cerenkov radiation
  - Transition radiation
  - Time of Flight

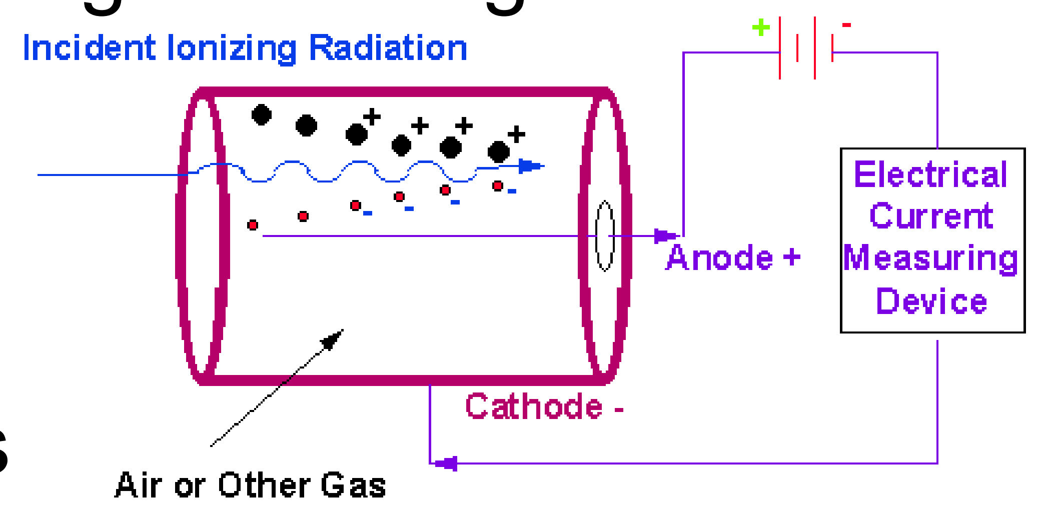
Specialised Detectors for

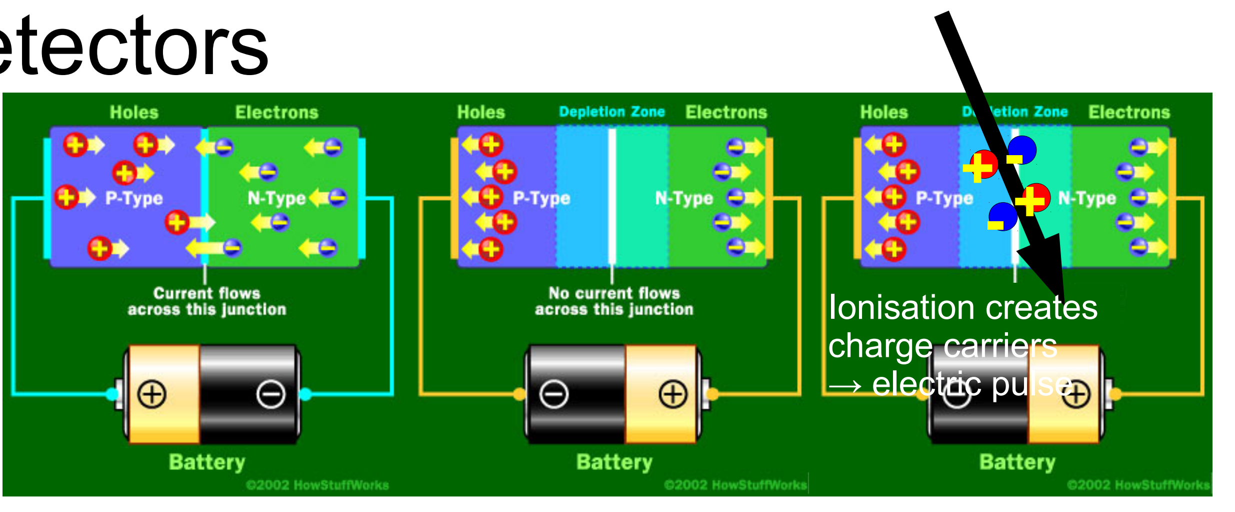
- Neutrino detection
- Neutron detection

Position measurement

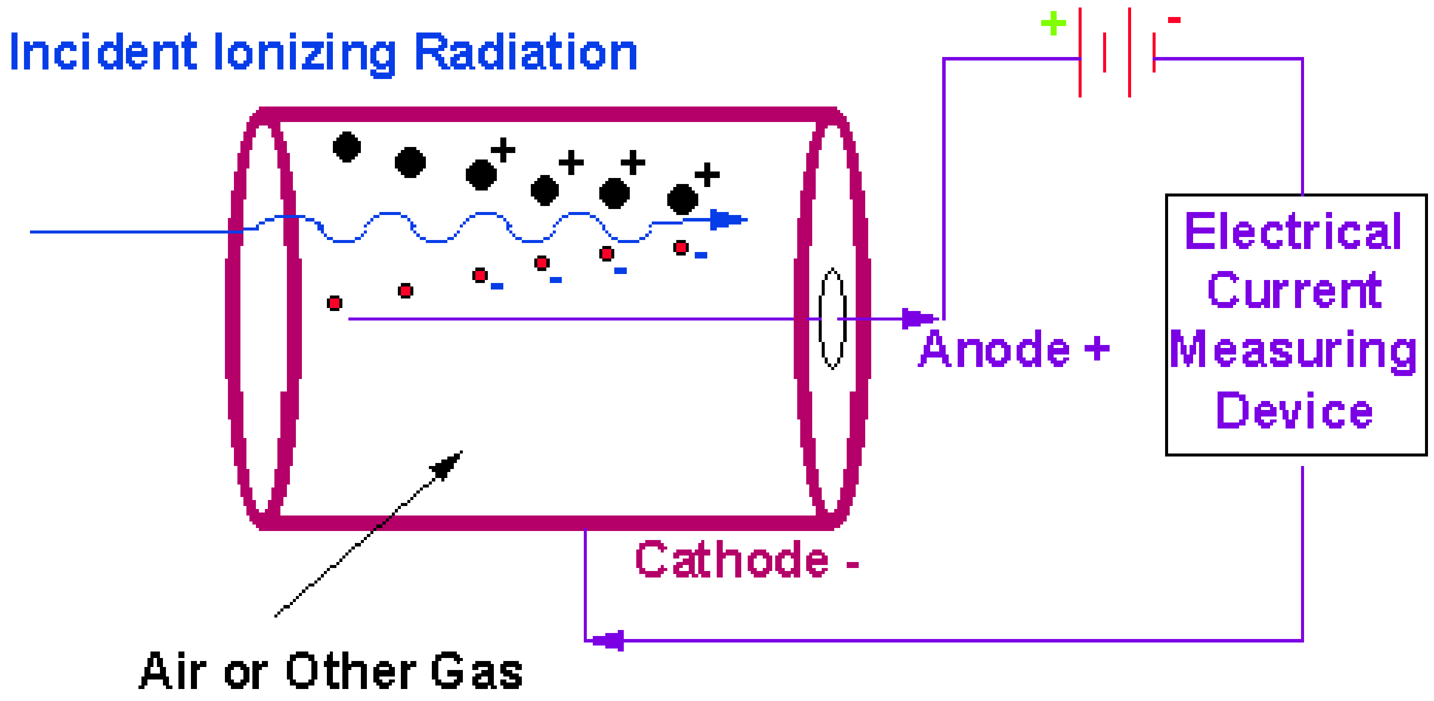
Most detectors record passing of a charge

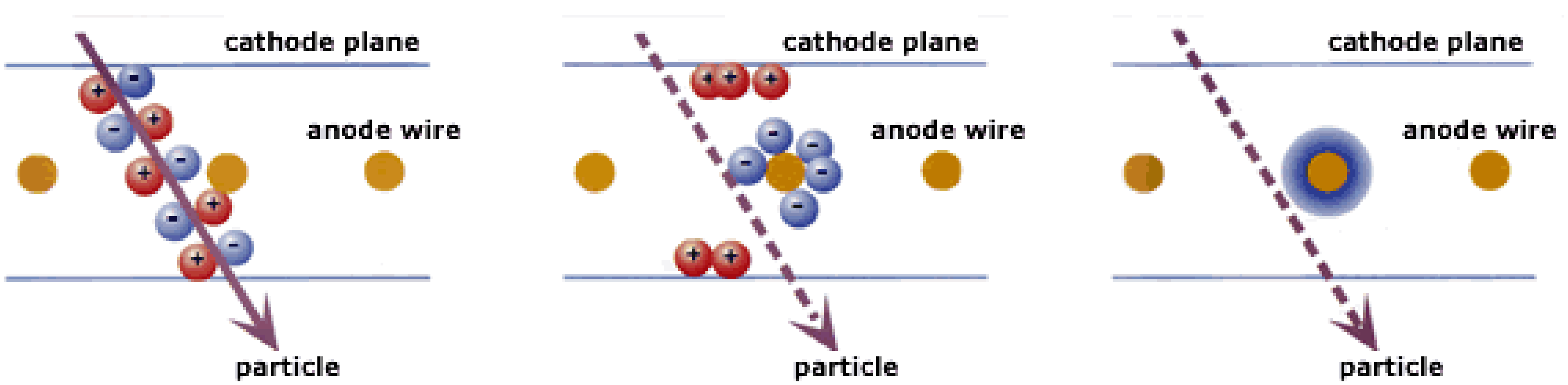
- Scintillators
- Gaseous Detectors
  - Ionisation Chambers
  - Geiger Mueller
  - Proportional Counters
  - Multi wire chambers
  - Micro pattern gas detectors
- Semi-conductor detectors
  - Silicon
  - Germanium
  - Diamond
  - ...



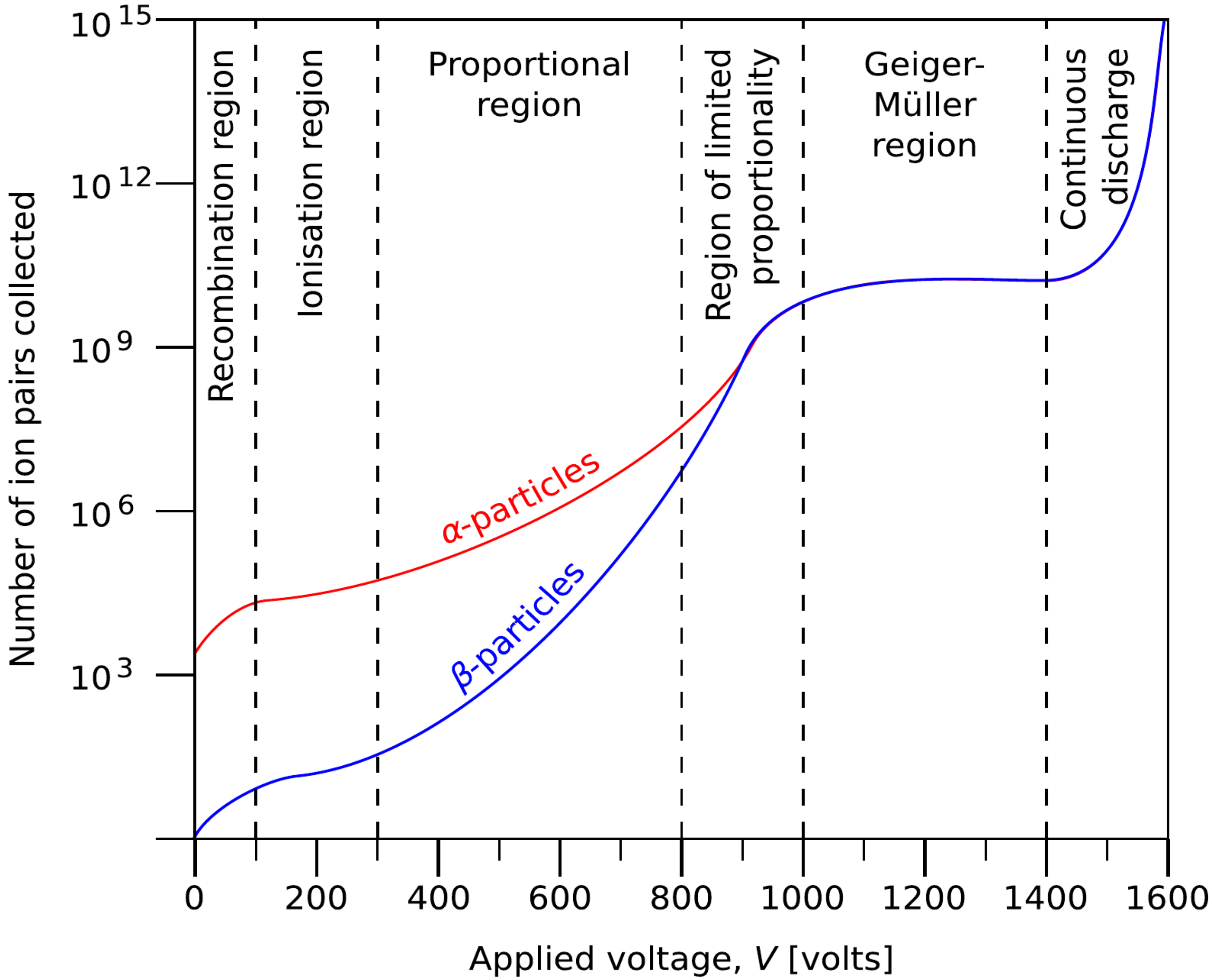


Position: Gaseous Detectors



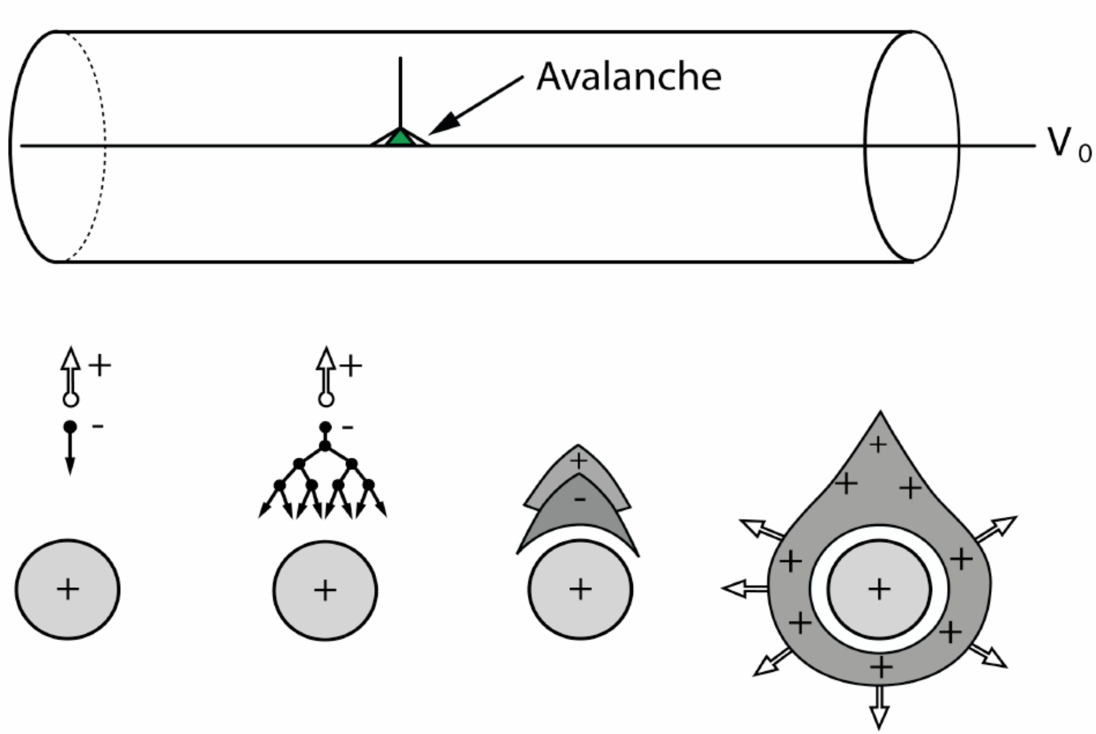


Position: Gaseous Detectors



Proportional counters

- Gas amplification → avalanche
- 1st Townsend coefficient α
- Gas gain M



$$N = N_0 e^{\alpha(E)x}$$

$$M = \frac{N}{N_0} = e^{\left(\int \alpha(E(x))dx\right)}$$

Proportional counters

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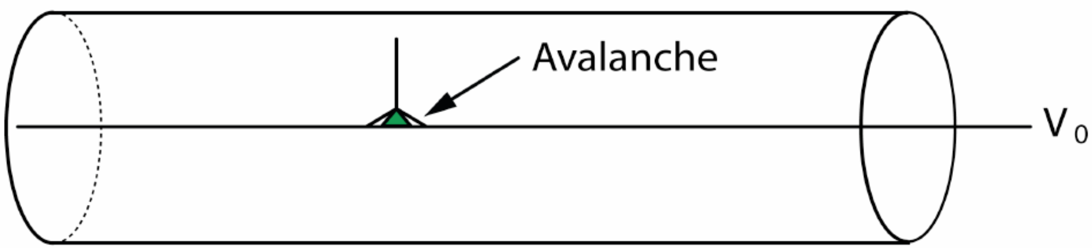

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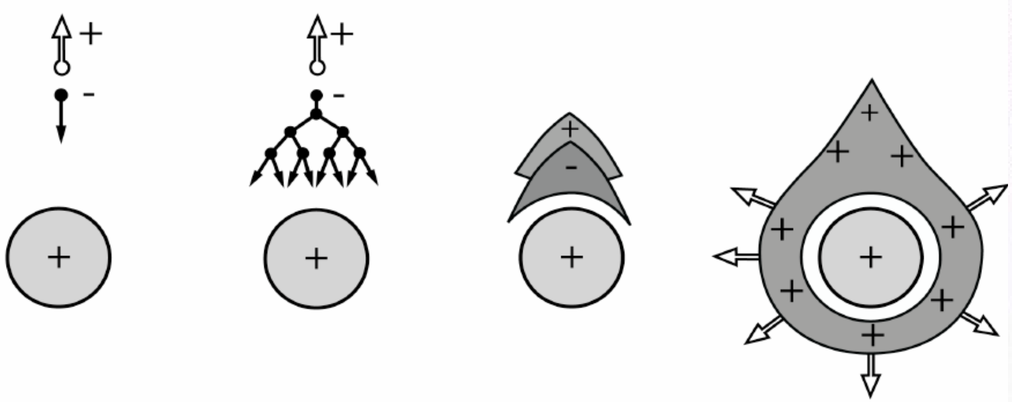
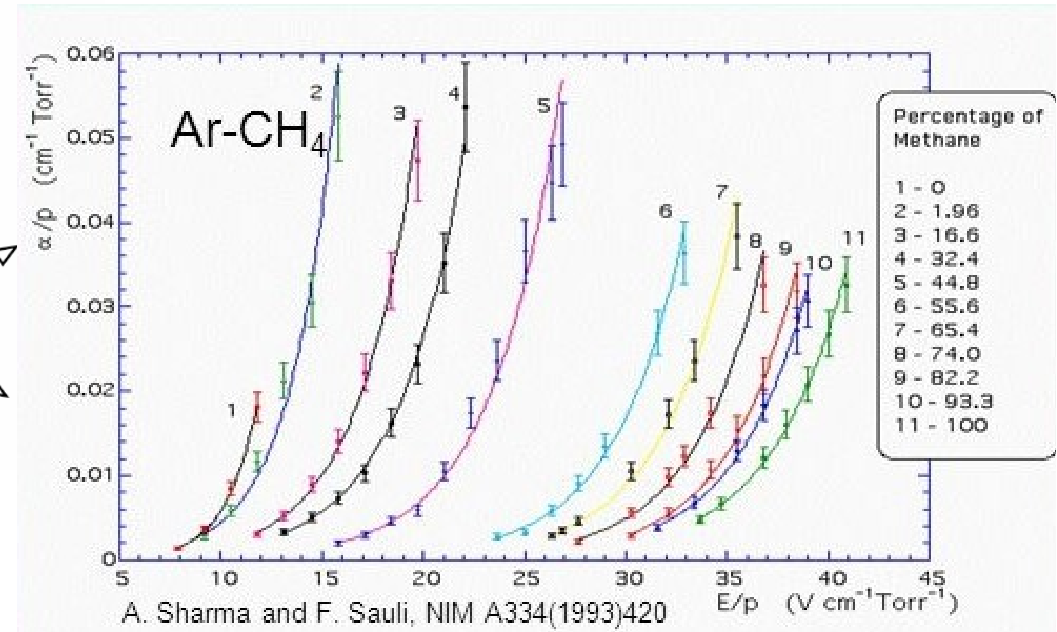
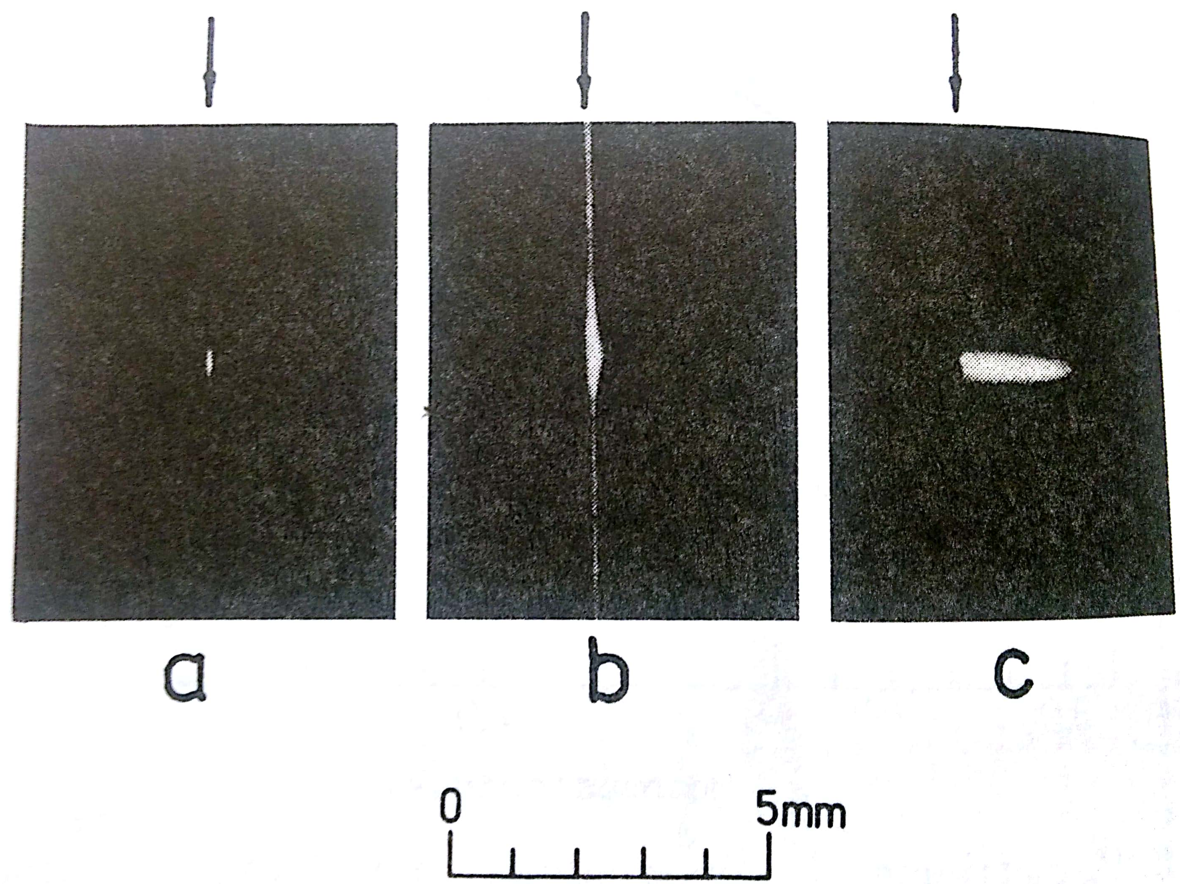




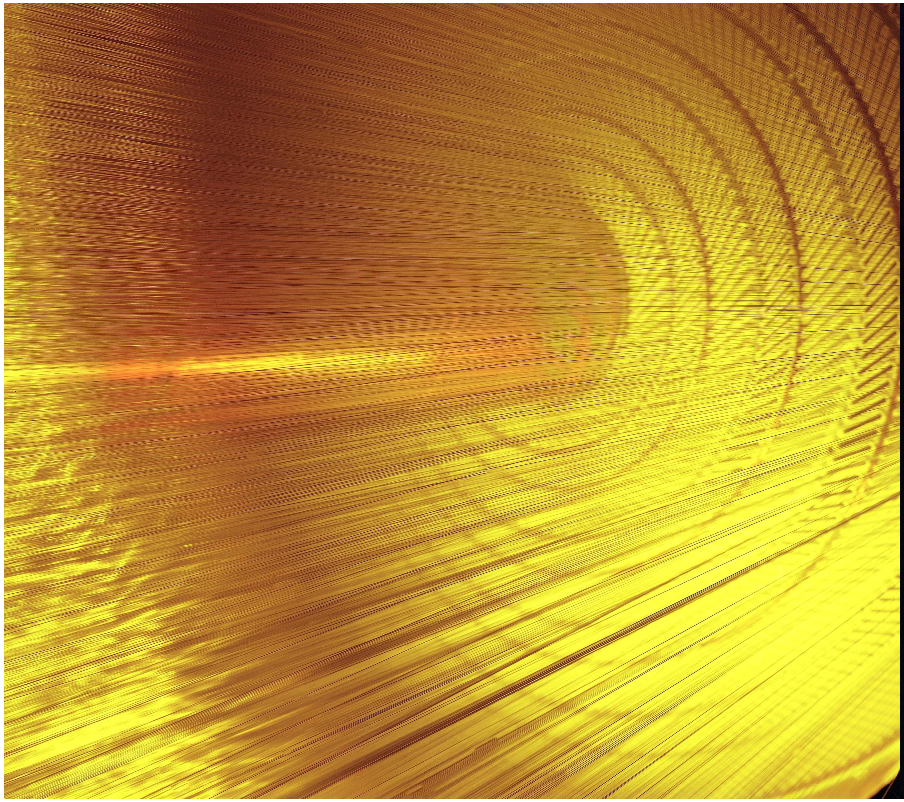
Gas Detectors

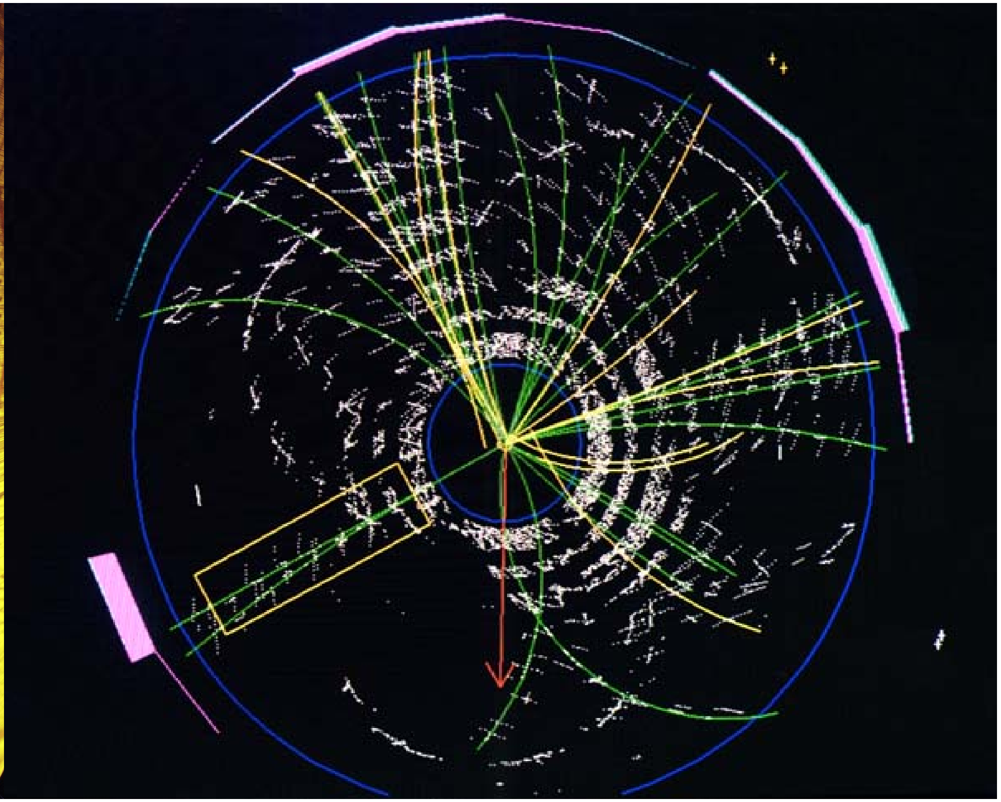
- Gas amplification → avalanche
  - a) none → Ionisation chamber
  - b) Geiger Mueller → saturation
  - c) streamer mode (with Quenchgas)

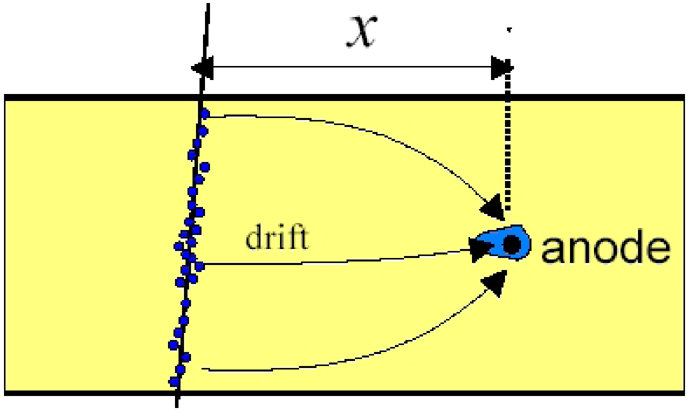


Multiwire proportional drift chambers

- CDF’s multi-wire proportional drift chamber : > 30,000 wires !





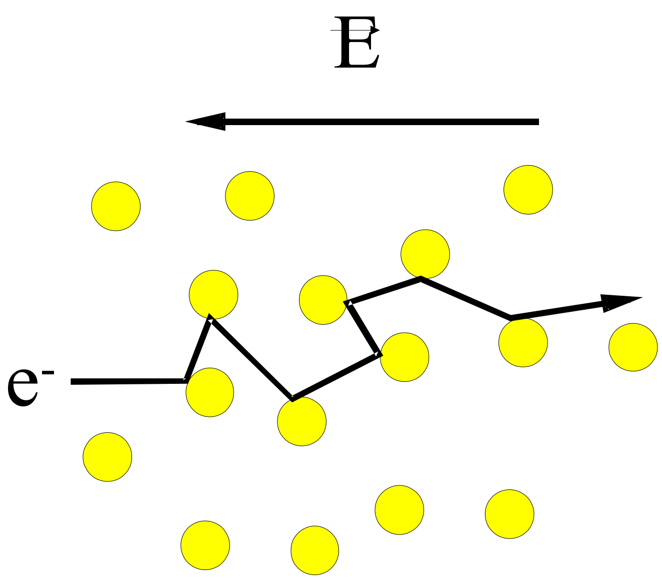


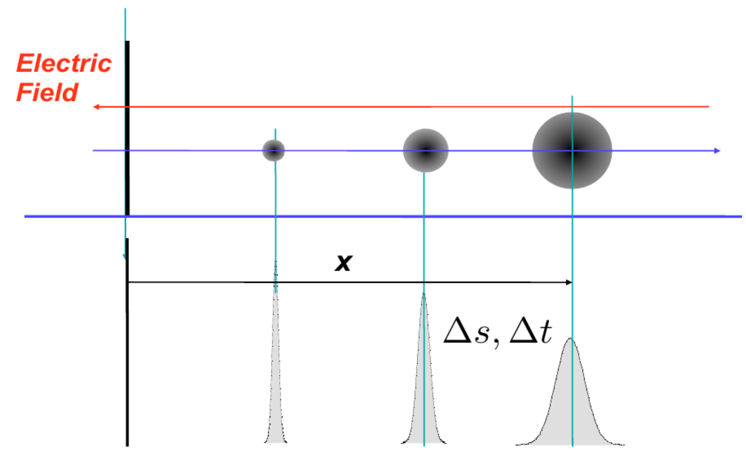
•Translate drift time into position
•Need to reconstruct “track” from a few hits along the path

Diffusion & Drift in Gases

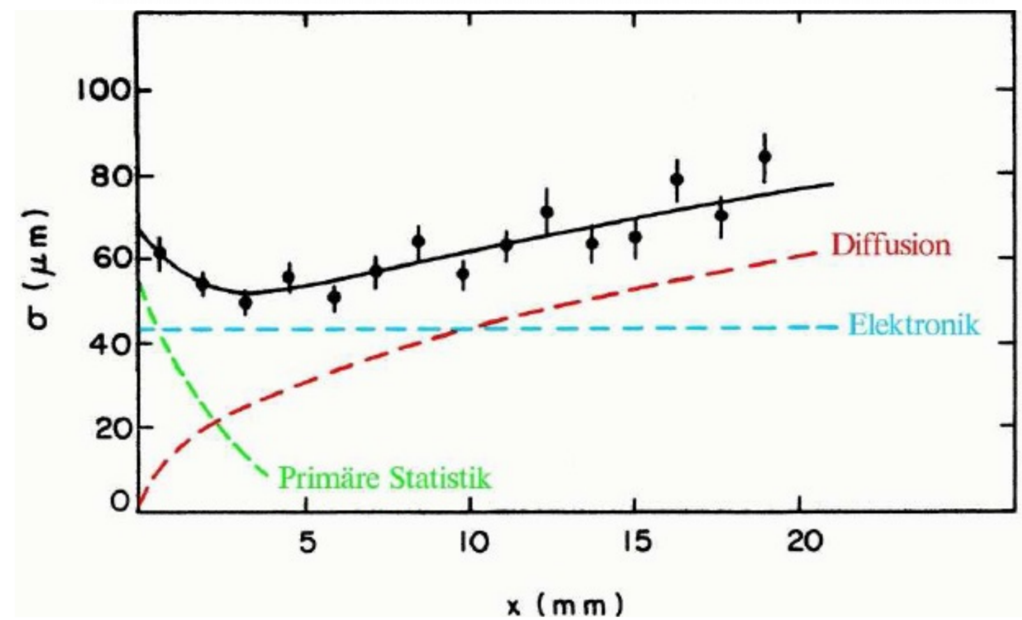
- Diffusion: in all directions
  - Limits resolution!
- Directed drift in electric field:
  - Scattering with gas atoms
  - Typical drift velocities
    - Electrons 5 cm/μs
    - Ions x1000 slower!

$$v_D = \mu E \qquad \mu = \frac{e\tau}{m} \text{ (mobility)}$$



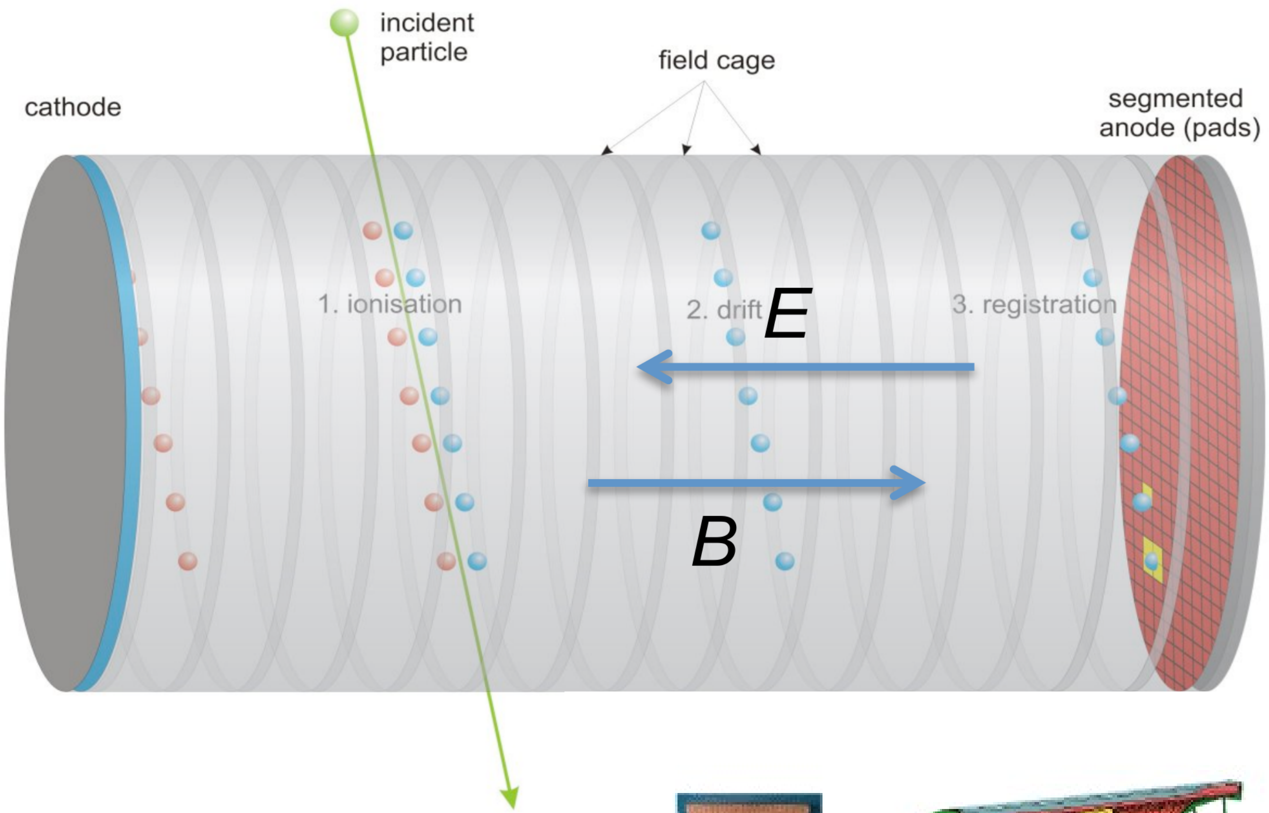


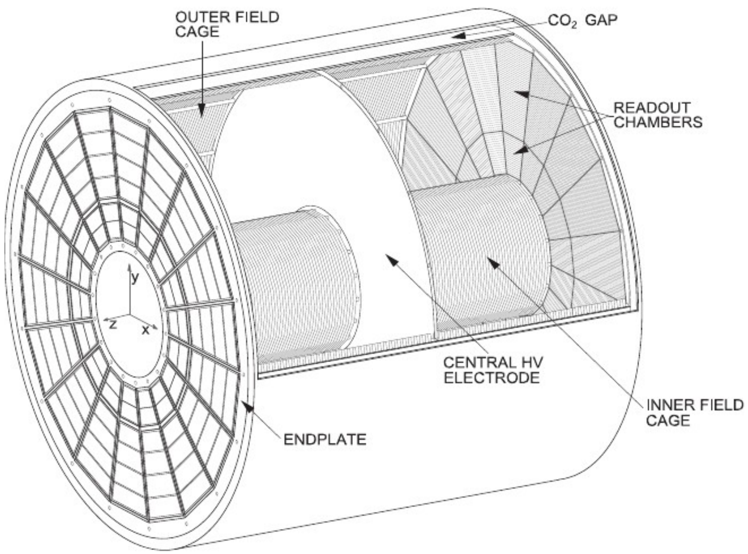
$$\sigma_x^2 = \underbrace{\left(\frac{1}{64N^2}\right)\cdot\frac{1}{x^2}}_{1^{st}\text{ ionization statistics}} + \underbrace{\frac{2D}{v_d}\cdot x}_{\text{diffusion}} + \underbrace{\sigma_{\text{const}}^2}_{\text{electronics, }\delta\text{-electrons}}$$

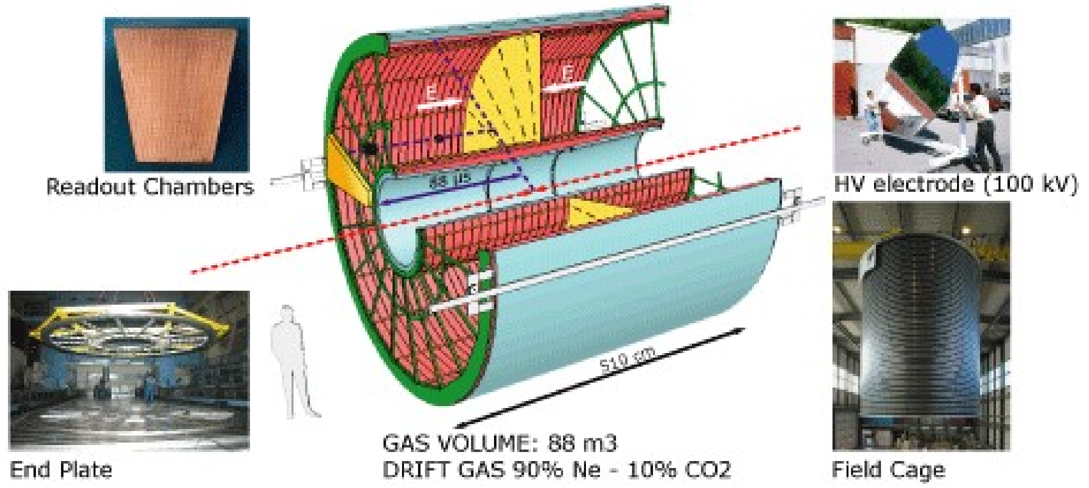


Time Projection Chamber TPC

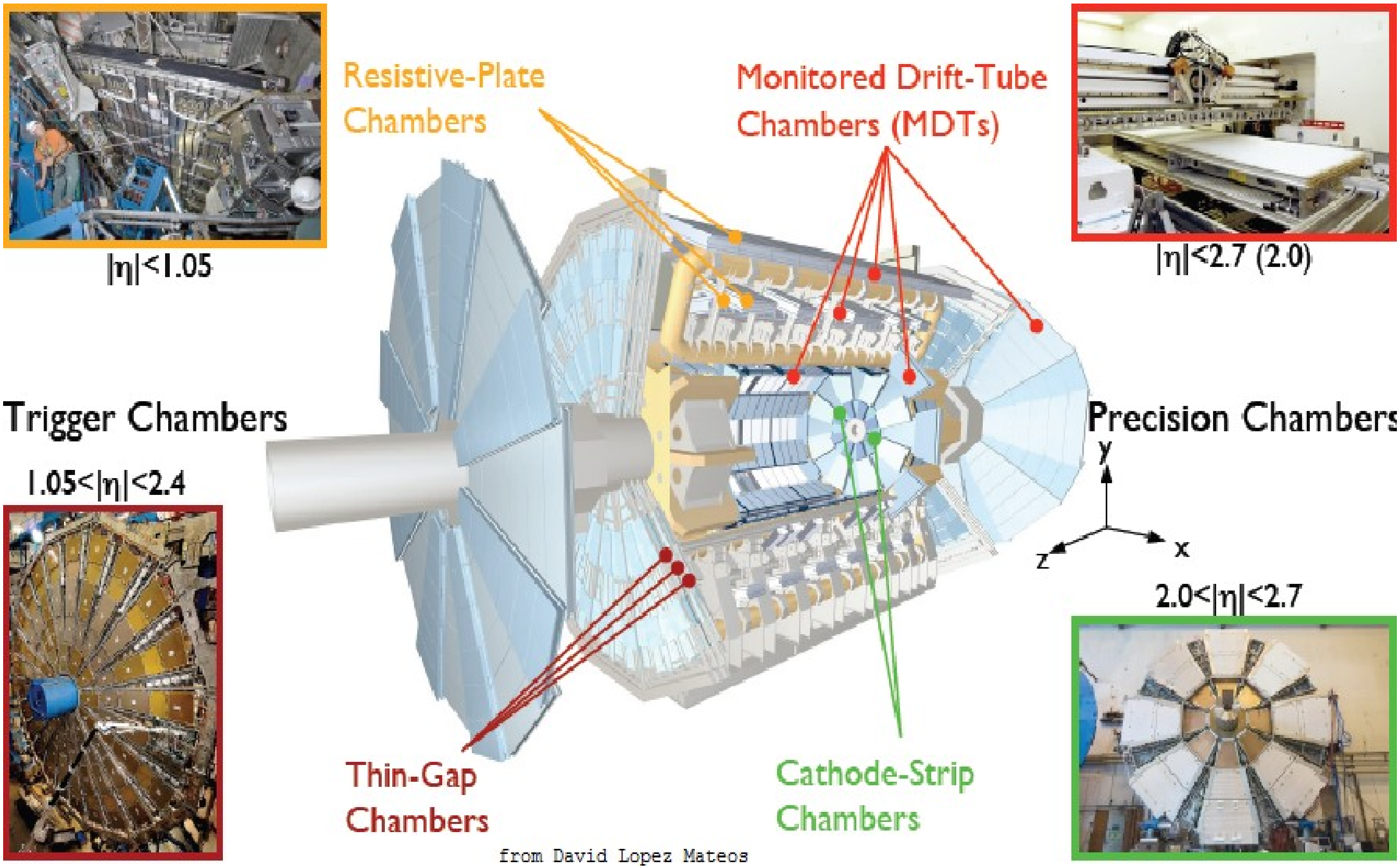
- Perfect detector: almost empty volume!





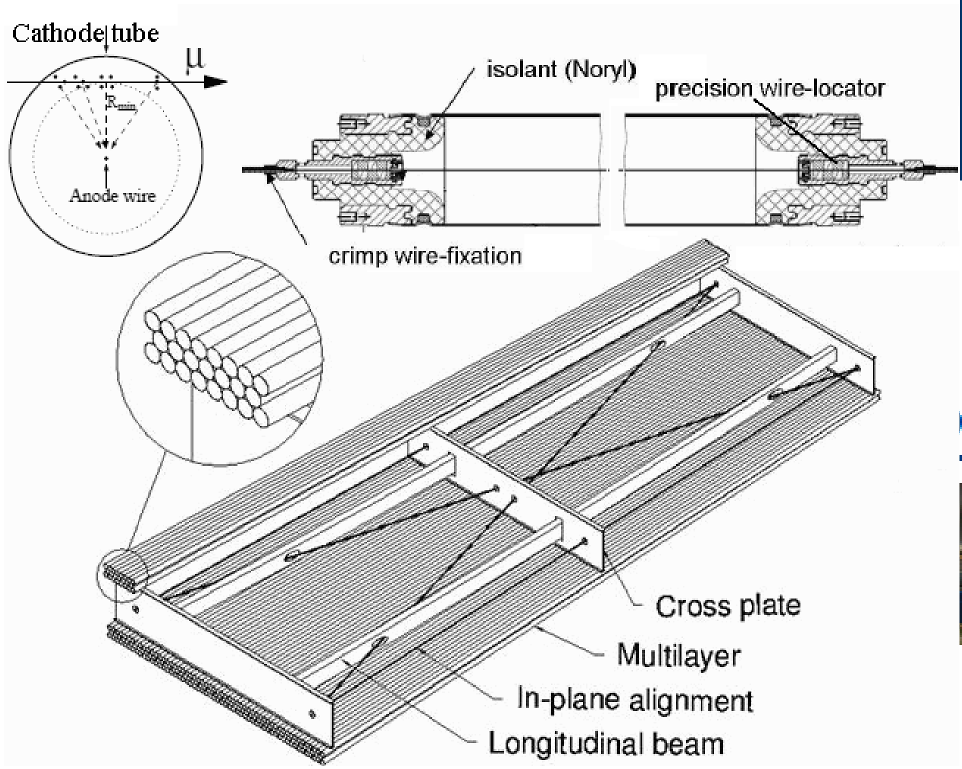


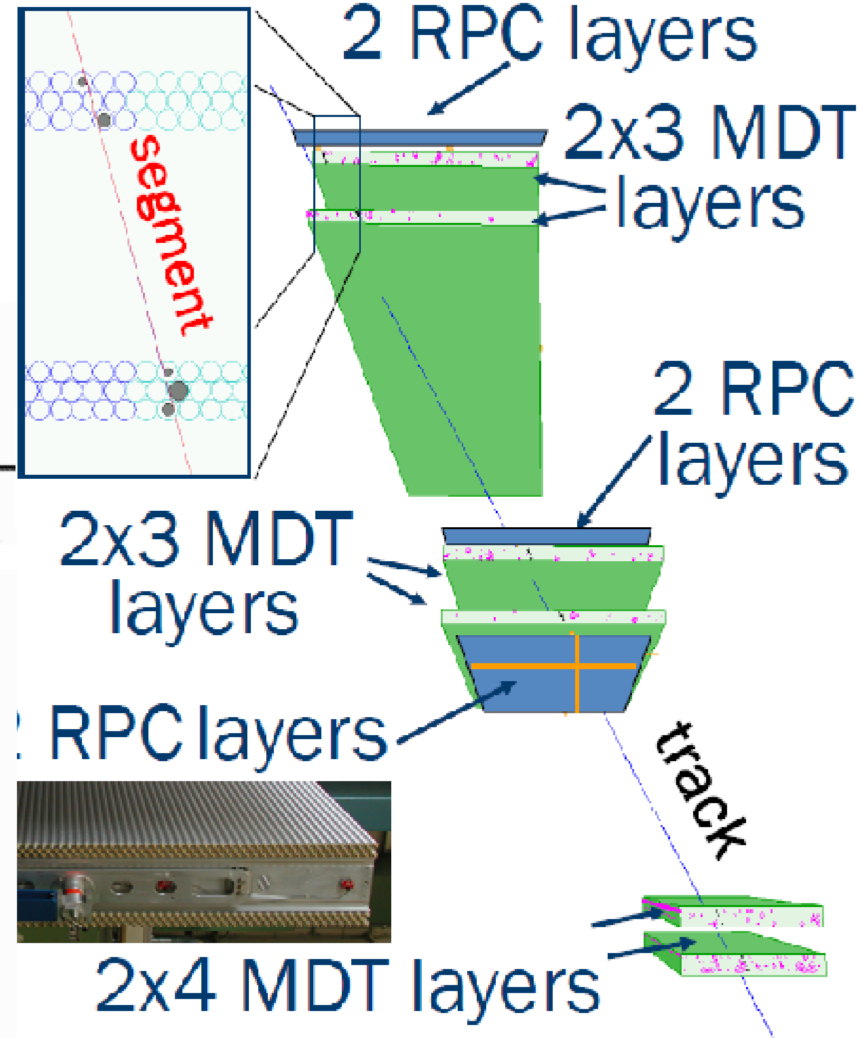
ATLAS Muon System



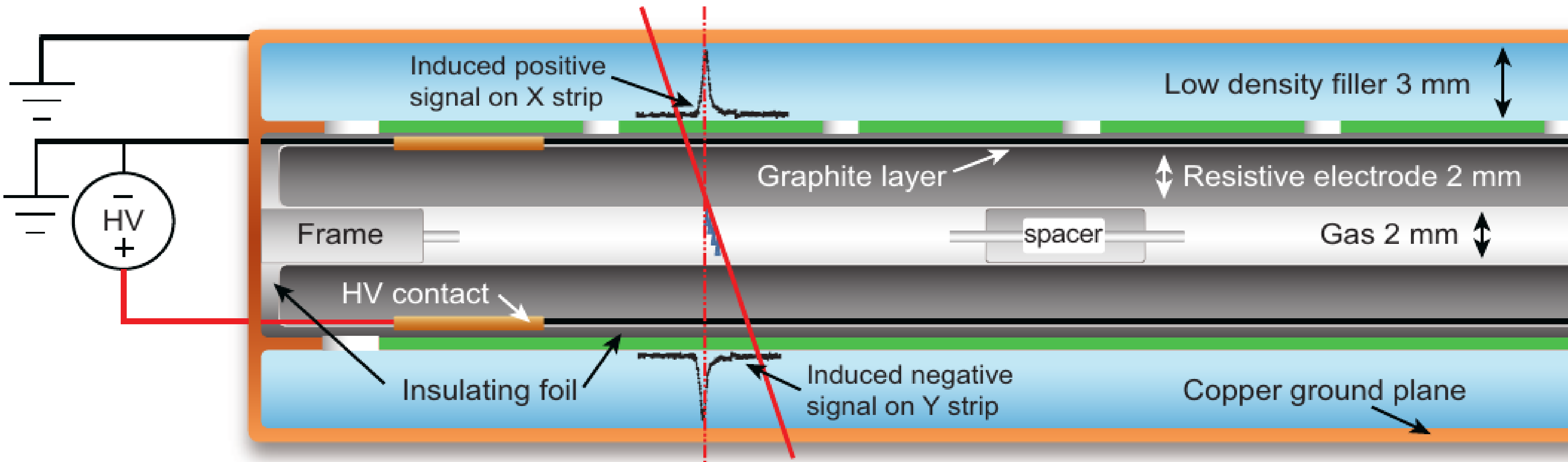
Muons: Monitored Drift Tubes

- Precision chambers
- 3-4 layers of drift tubes
- σ_{Pt} ~10% at 1 TeV

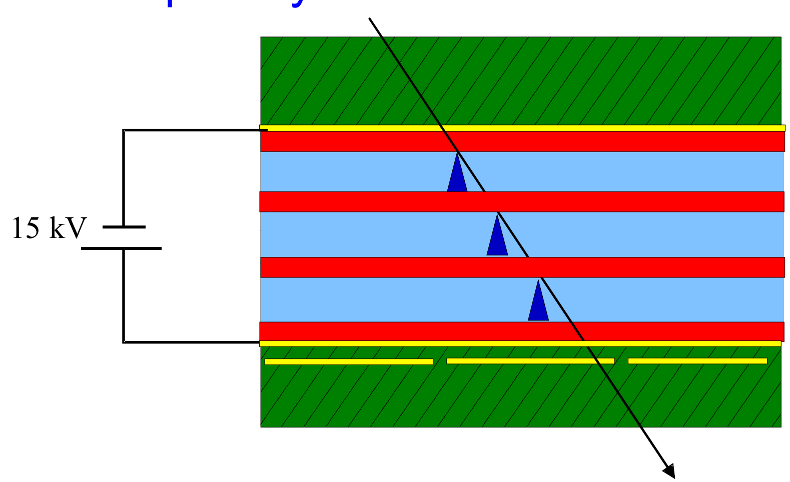




Resistive plate chambers



Time dispersion ≈ 1..2 ns → suited as trigger chamber
Rate capability ≈ 1 kHz / cm²

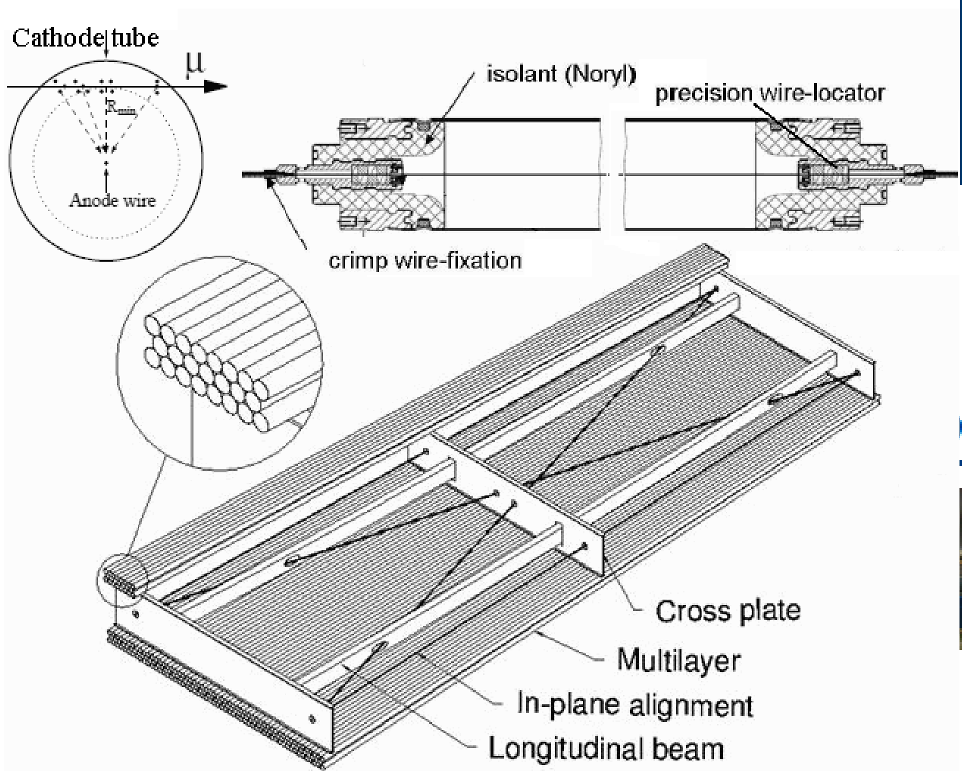


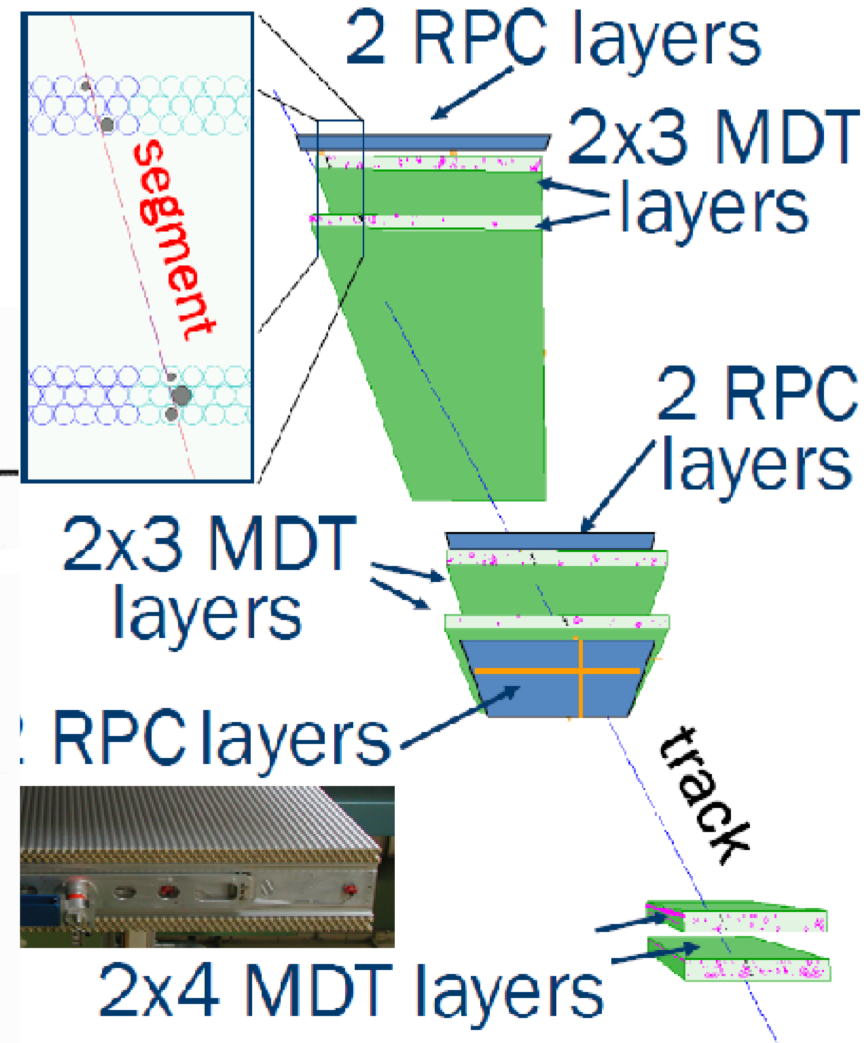
Double and multigap geometries → improve timing and efficiency

Problem: Operation close to streamer mode.

Muons: Monitored Drift Tubes

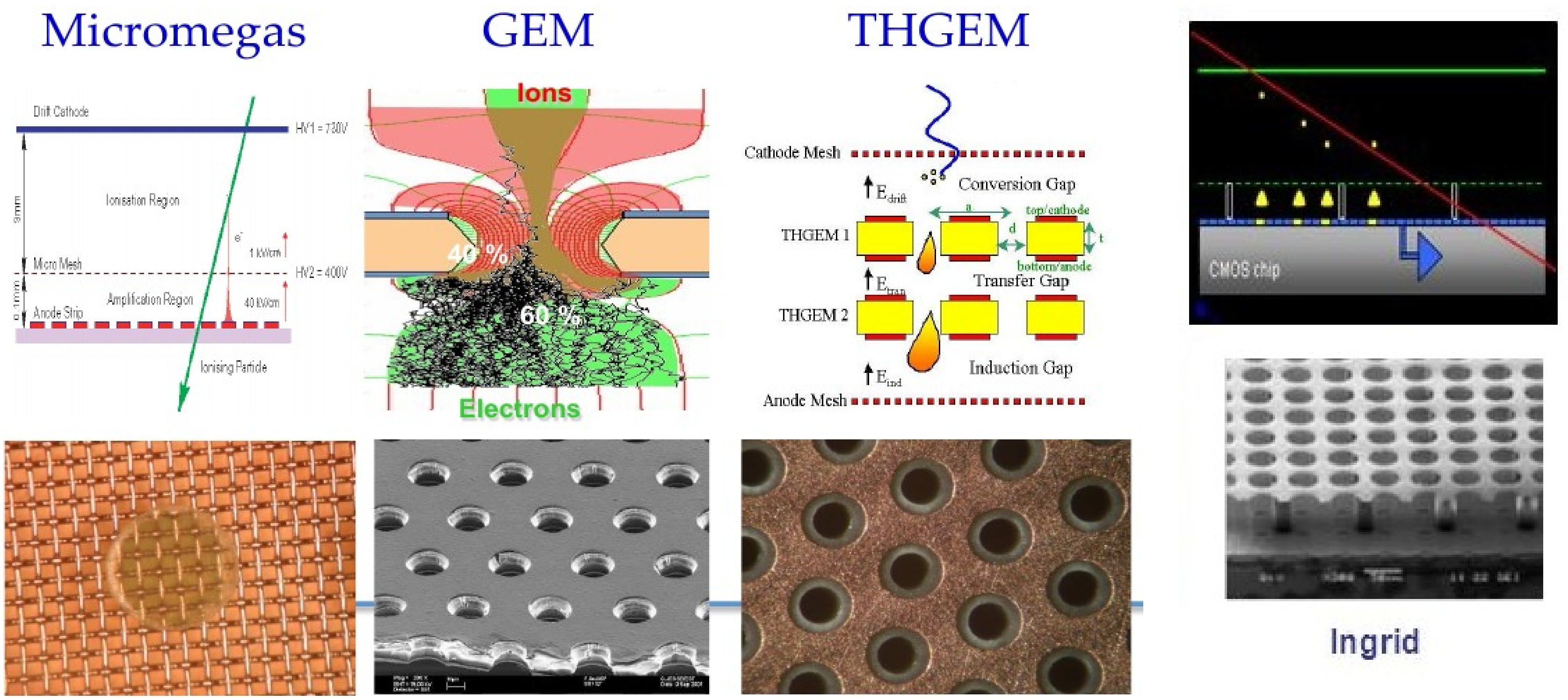
- Precision chambers
- 3-4 layers of drift tubes
- σ_{Pt}~10% at 1 TeV



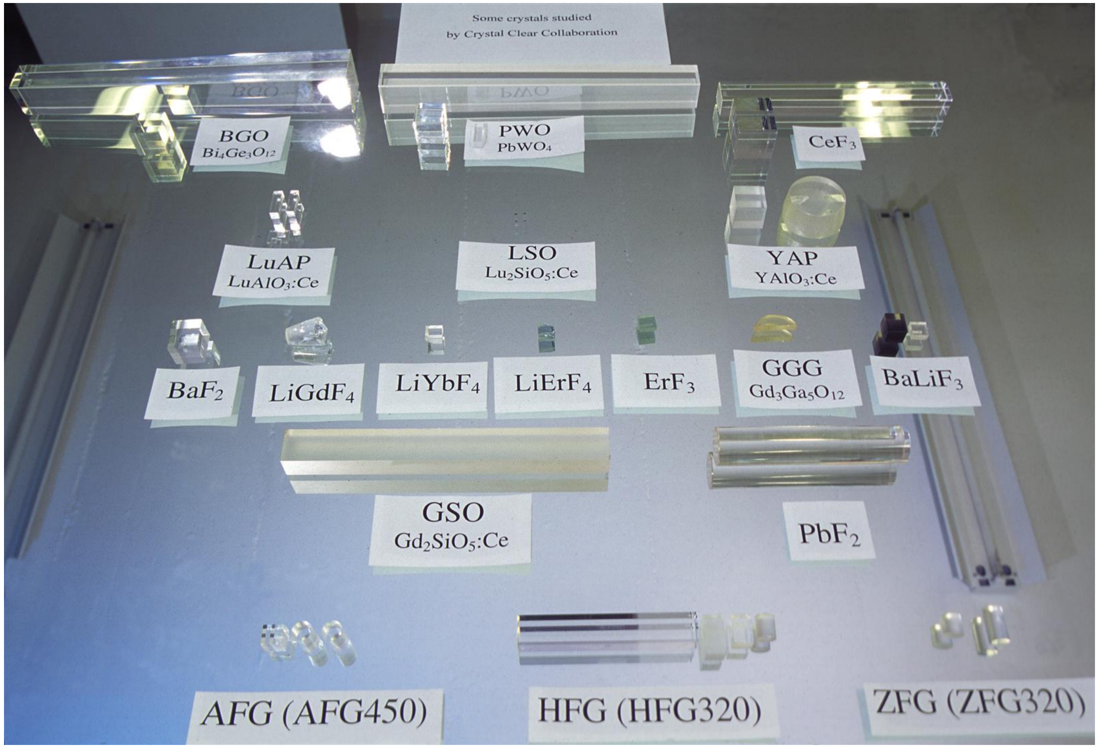


Micro Pattern Gas Detectors MPGD

- Micro fabrication of readout structures
- Microstrip gas chambers
- Gas Electron Multipliers (Thick)
- Good granularity
- Can be fabricated in large areas

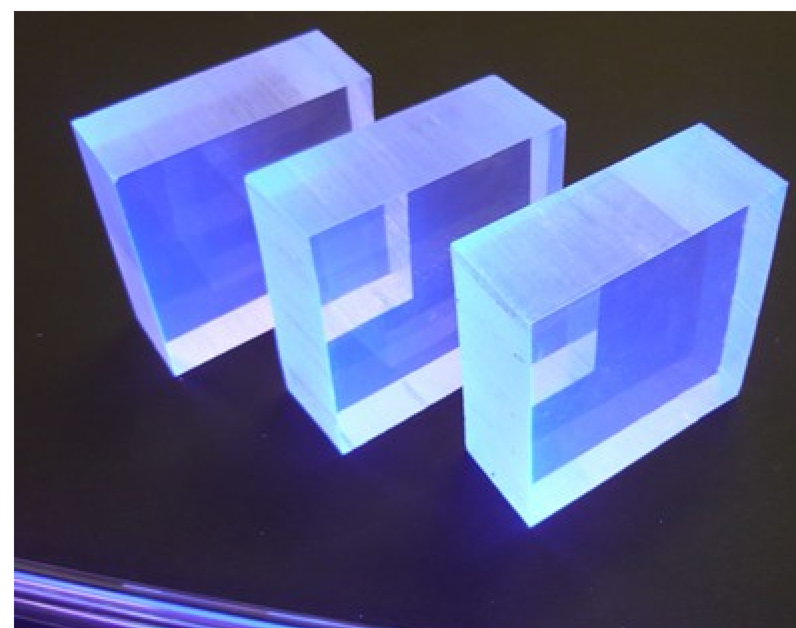


Position measurement: Scintillators

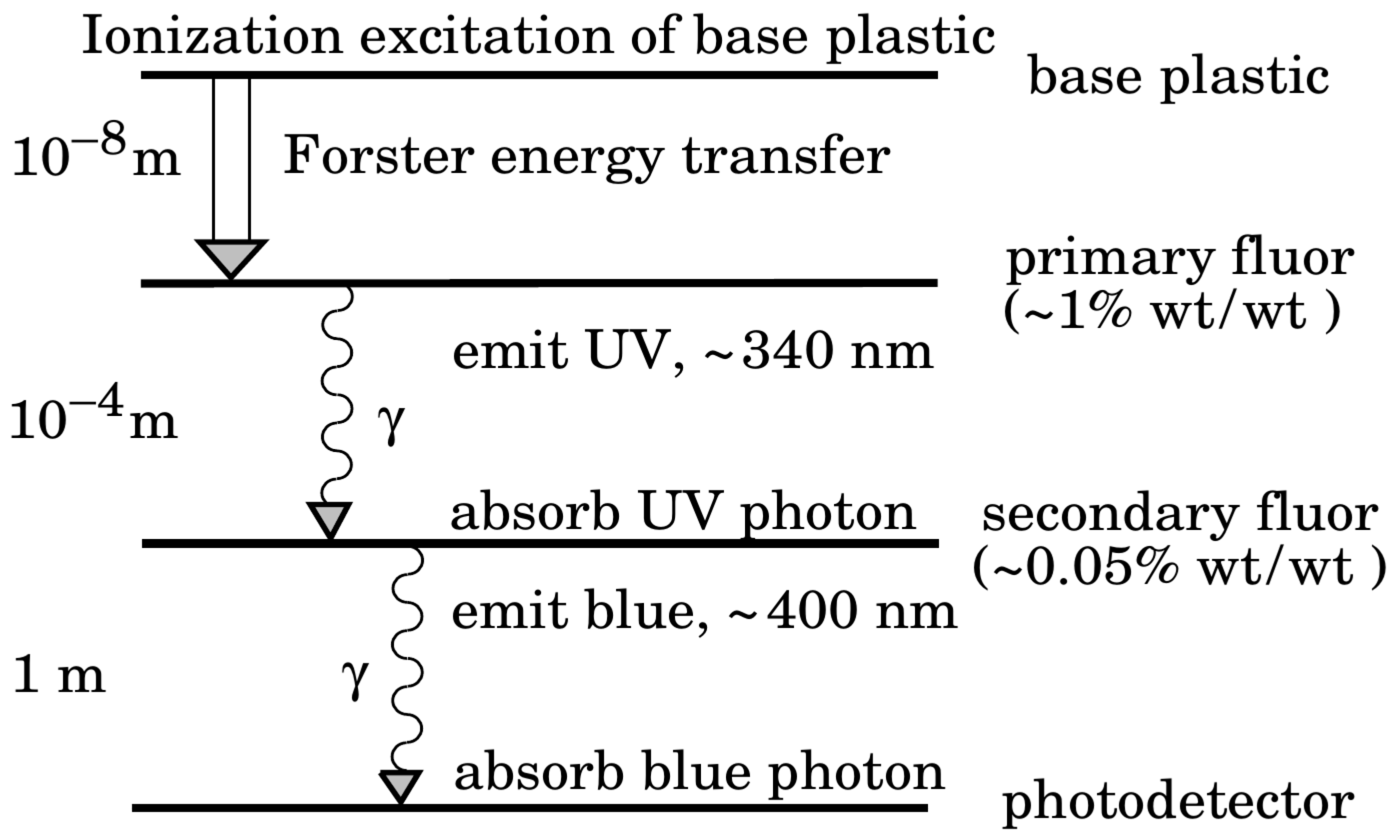


- Organic
  - Plastic, liquid
  - Fast: 1-10 ns
- Inorganic Crystals
  - NaI, BGO,
  - Heavy elements possible
  - better energy resolution
  - Slower: 200-2000ns

	NaI(Tl)	BaF_2	CsI(Tl)	CeF_3	BGO $Bi_4Ge_3O_{12}$	PWO $PbWO_4$	LuAG:Ce
X_0 [cm]	2.59	2.03	1.86	1.66	1.12	0.92	1.41
ρ [g/cm^3]	3.67	4.89	4.53	6.16	7.13	8.2	6.73
τ [ns]	230	0.6 620	1050	30	340	15	60
λ [nm]	415	230 310	550	310 340	480	420	535
$\eta@\lambda_{max}$	1.85	1.56	1.80	1.68	2.15	2.3	1.84
LY [%NaI]	100	5 16	85	5	10	0.5	50

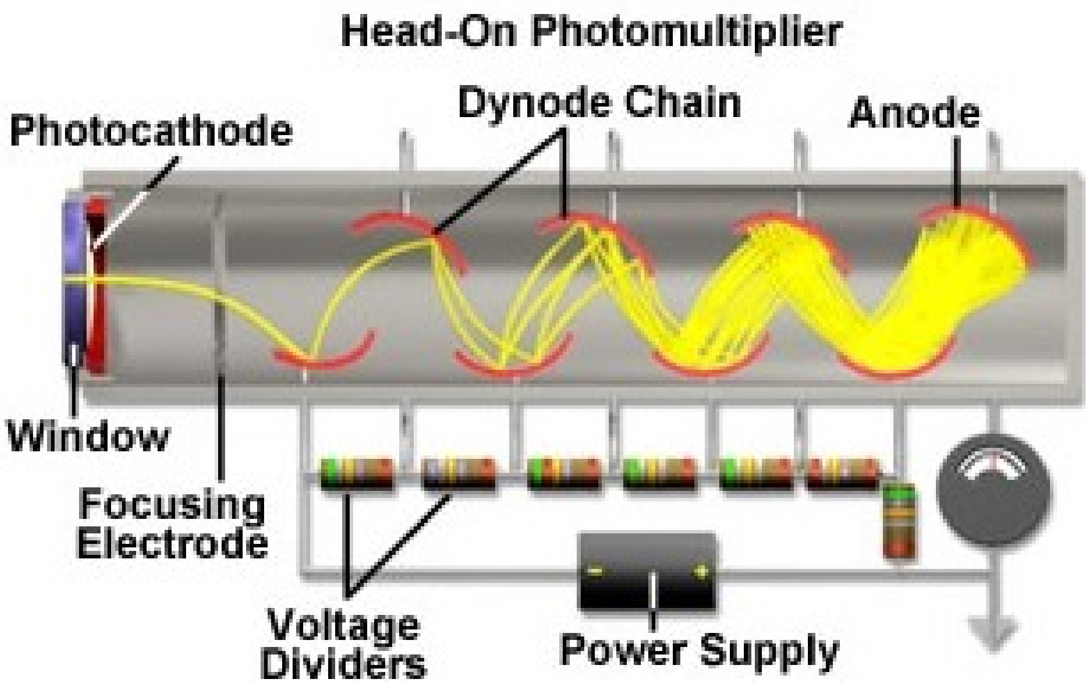


Scintillators: principle

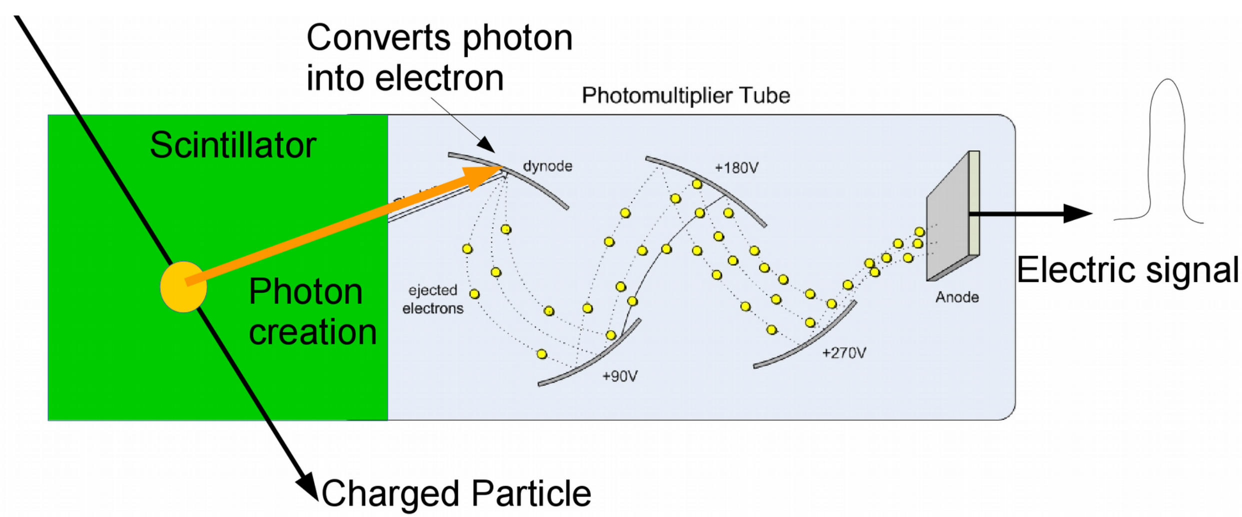


- Plastic Scintillator

Readout: Photomultiplier Tube



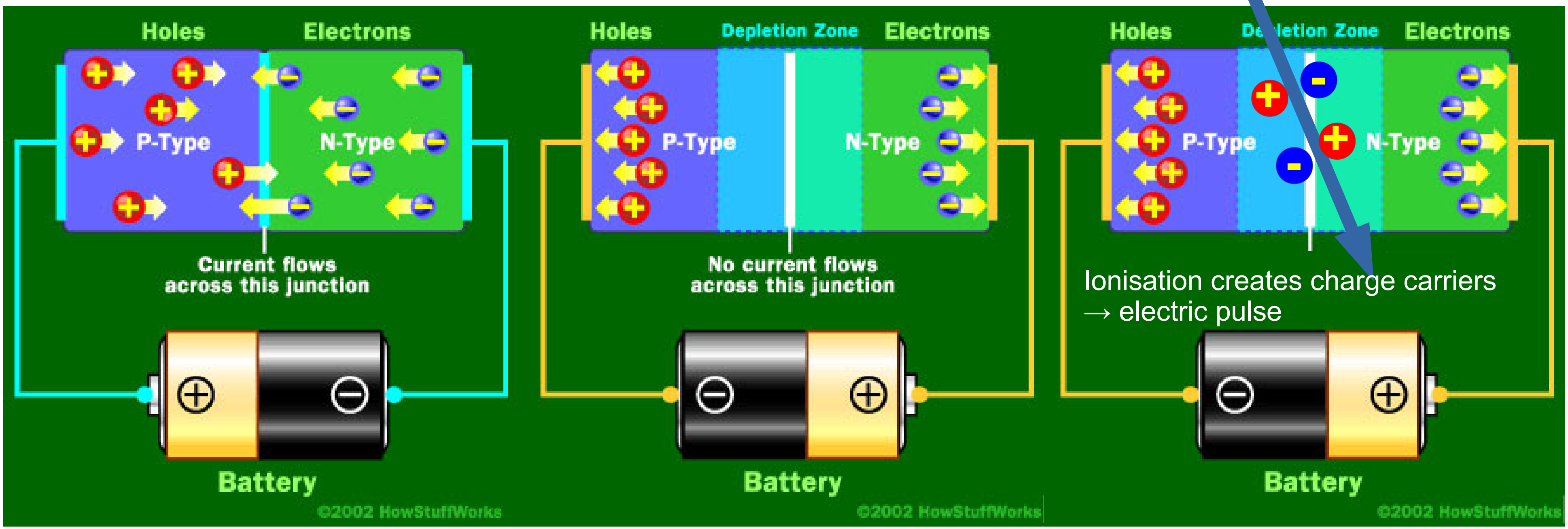
- Convert light into electrical signal
- Amplification
- Come in many different shapes and sizes
- Commonly used to readout scintillators!



Scintillating Fibre (Spaghetti) Trackers

Semiconductor detectors

- Basic principle: reverse biased diode
- Typical material: germanium, silicon
- Good energy resolution: ~3eV per electron-hole pair: N=E/3eV
- Can be finely segmented → excellent position resolution ~µm



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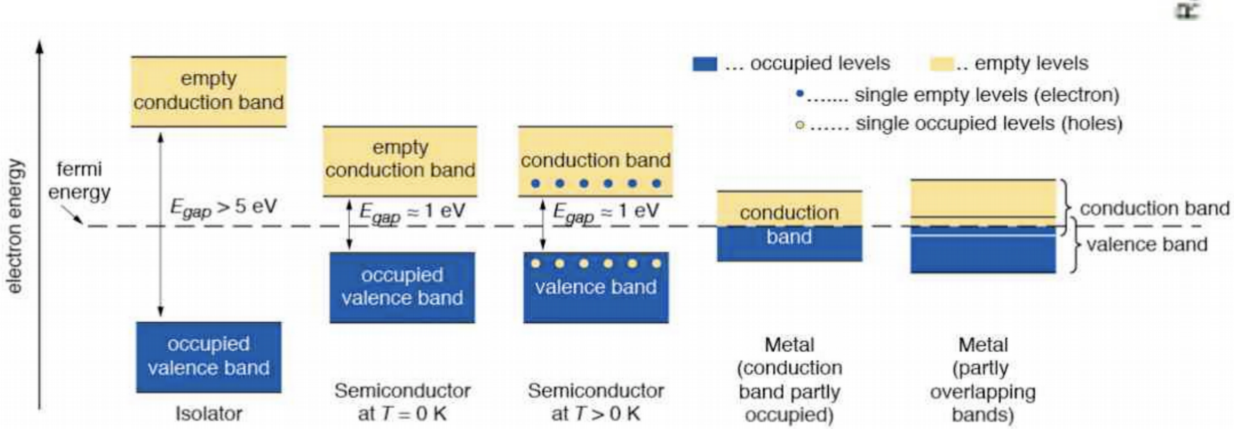
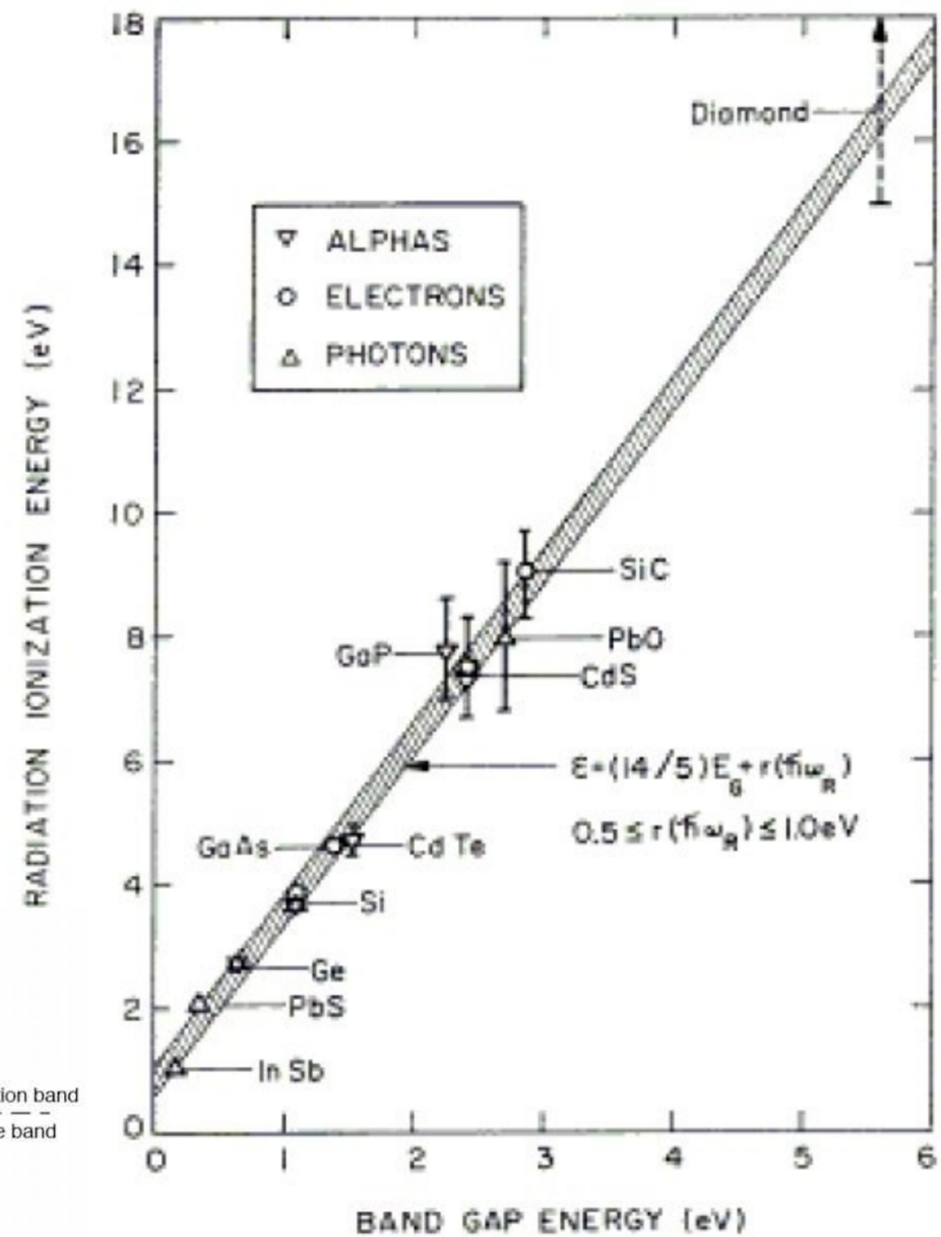


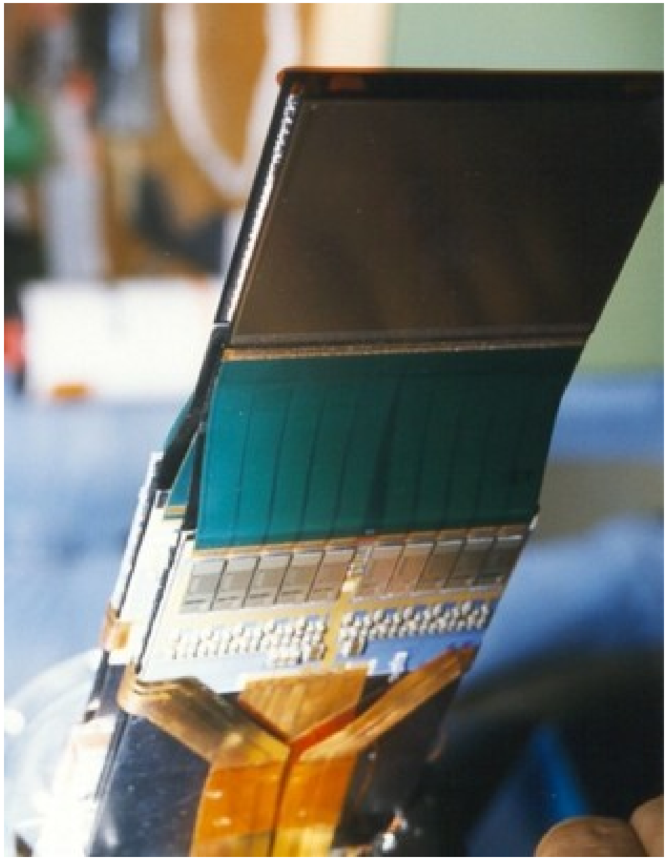


Semiconductor detectors

Germanium detectors

- Excellent $\Delta E/E \sim 0.3\%/\sqrt{E(\text{MeV})}$
- Often used for γ-ray spectroscopy (nuclear physics)

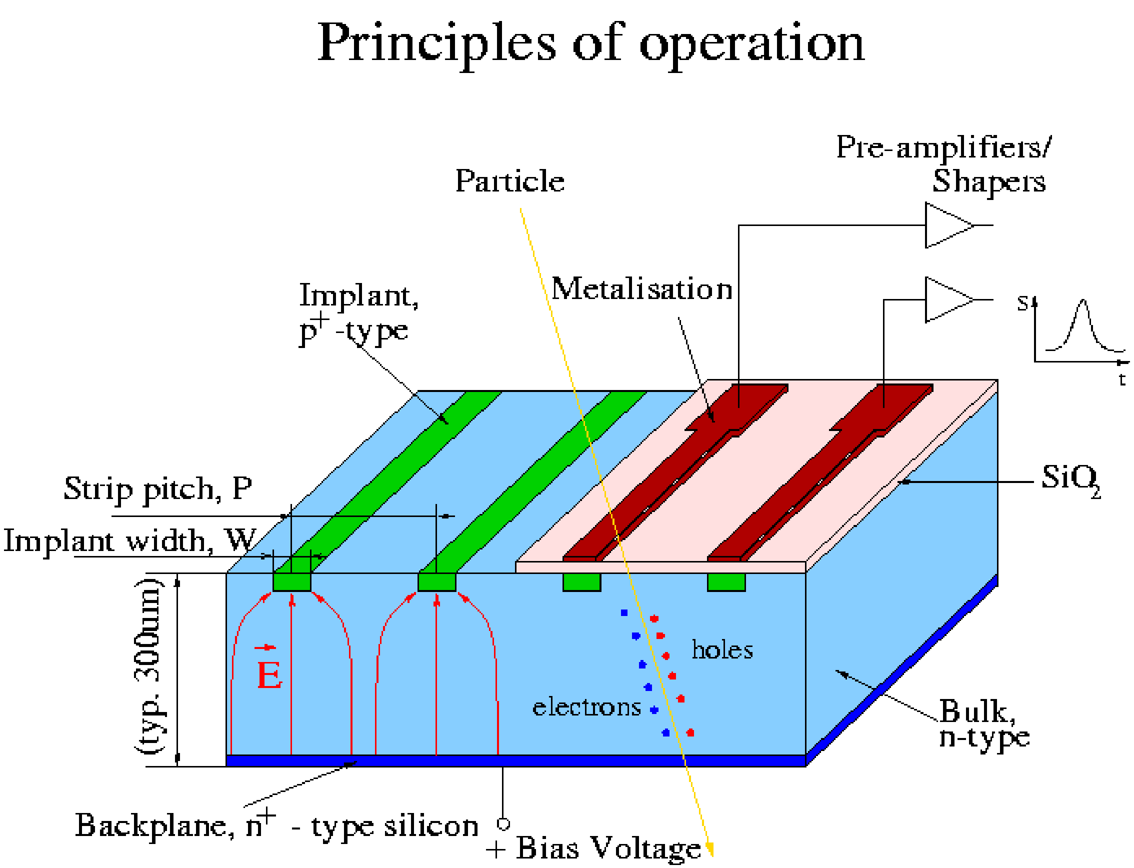
Silicon microstrip detectors

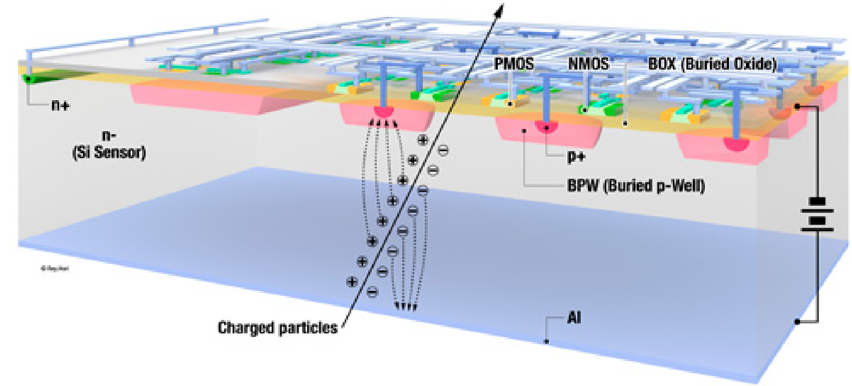


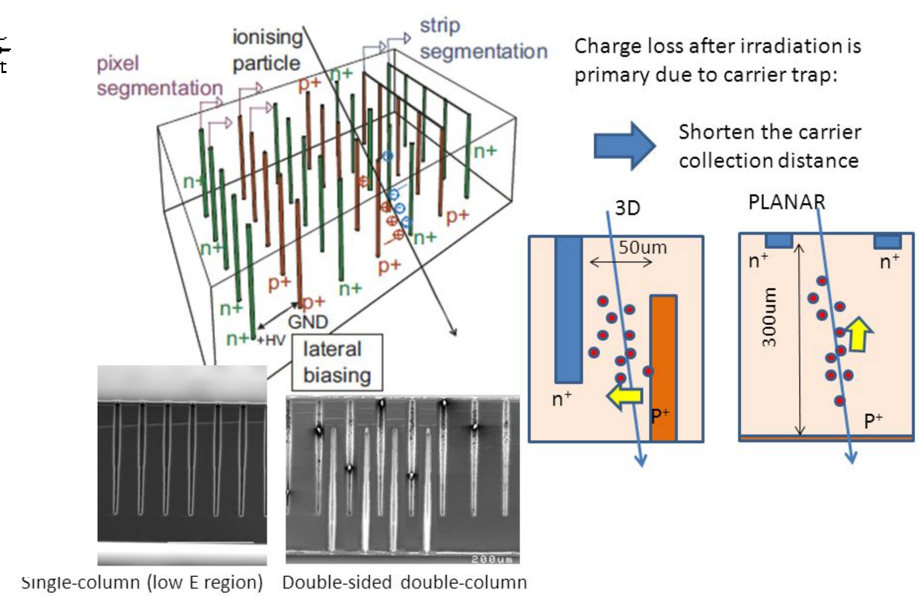
- ~ 5μm position resolution
- "Vertex detectors" in HEP experiments

Position: Semiconductor detectors

Fine spatial segmentation → excellent spatial resolution ~μm





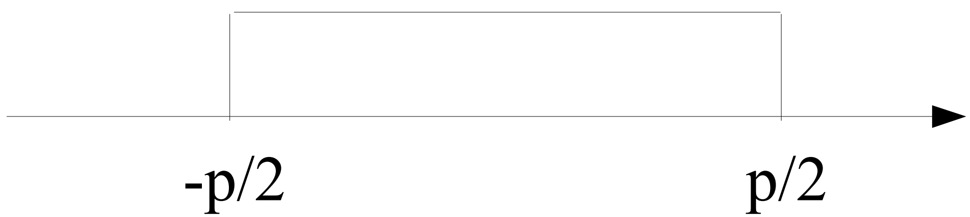


Strips

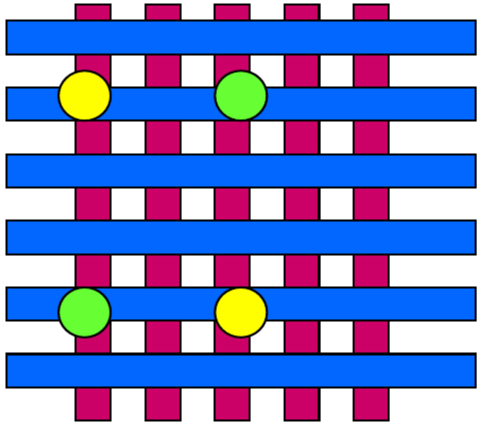
Pixels

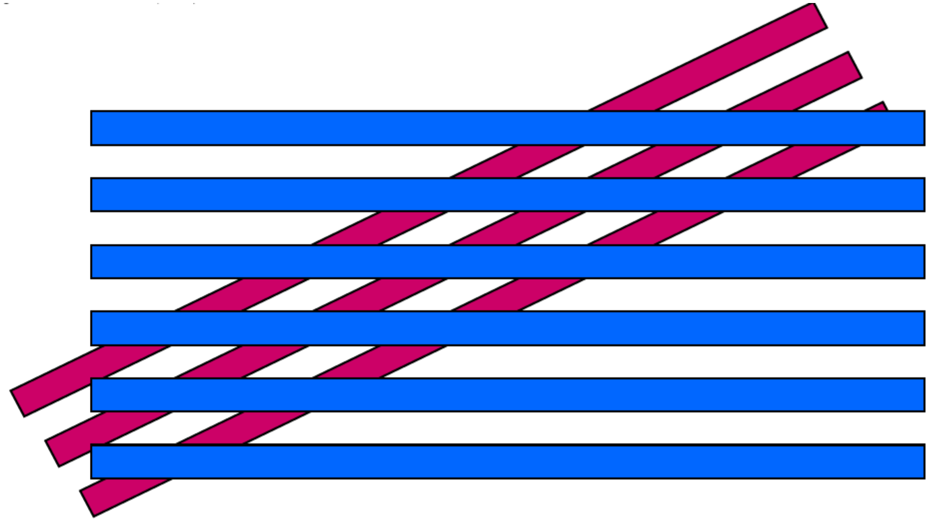
Position: Semiconductor detectors

Fine spatial segmentation → excellent spatial resolution ~µm
Binary readout of pitch p
(variance of constant distribution): $\sigma_x = \frac{p}{\sqrt{12}}$



strips only one coordinate → two layers for space points
Real and ghost hits → shallow stereo angle



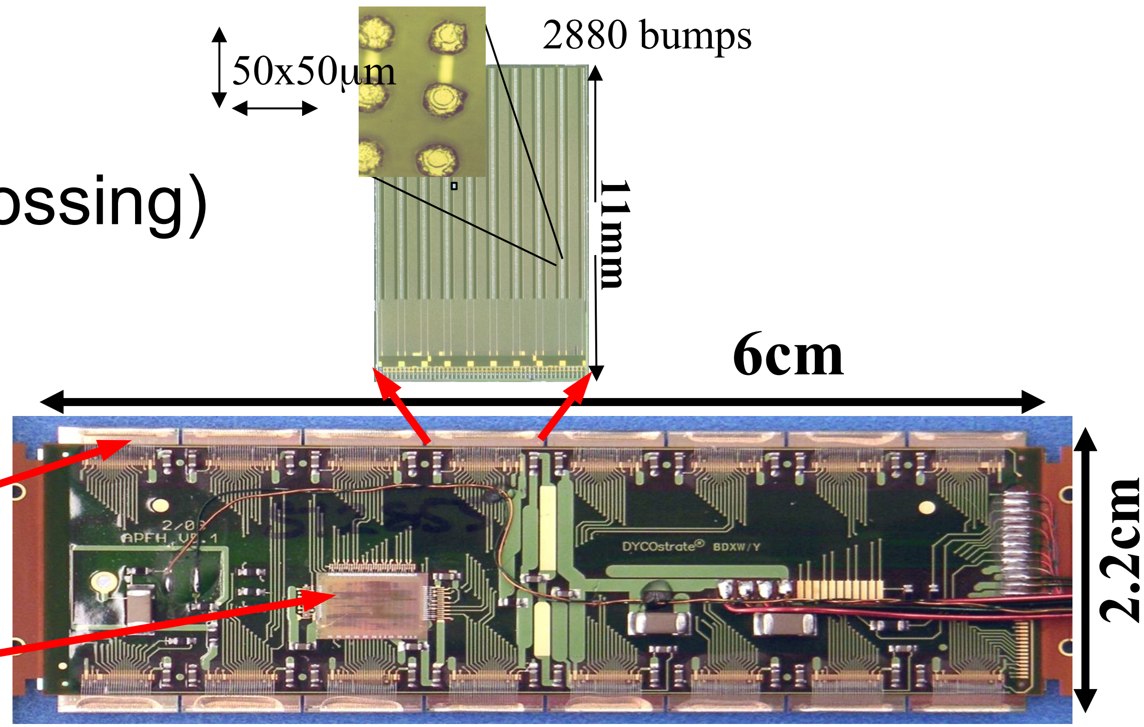


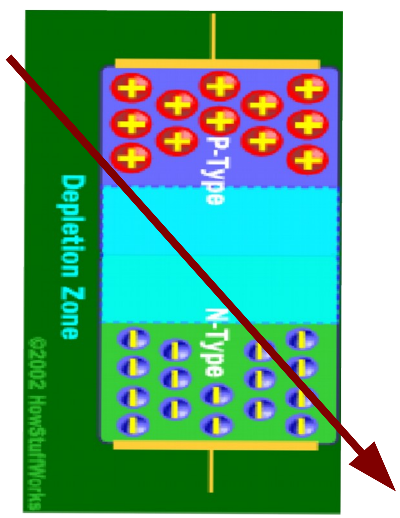
Pixel Module/Silicon Sensor

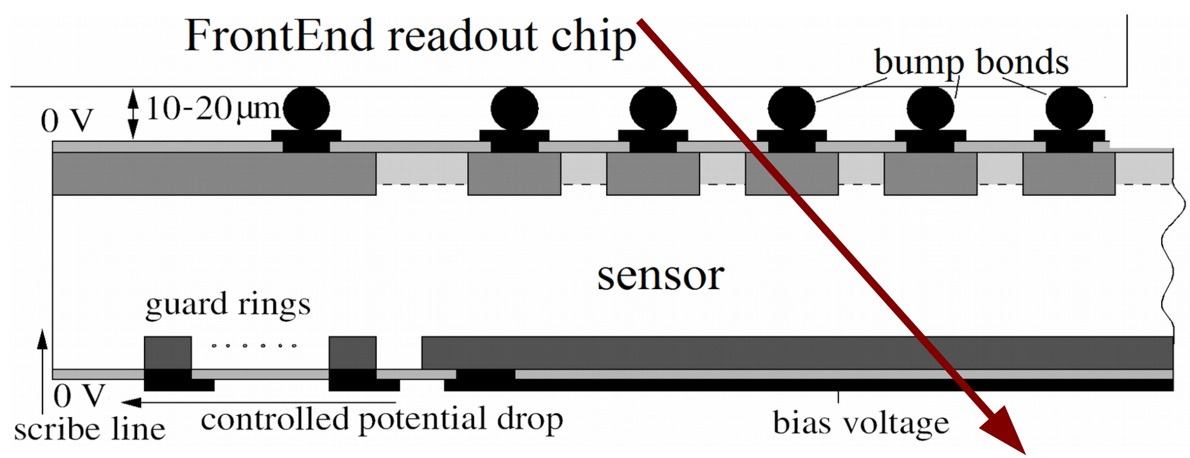
- Good spatial resolution
  → 50μm x 400μm Pixels
- Fast readout (25ns beam crossing)
- Radiation hardness
  → Hybrid chip technology

– 0.25μm CMOS FrontEnd

– 1 sensor bump bonded to 16 FrontEnd chips which are connected to a ModuleControllerChip

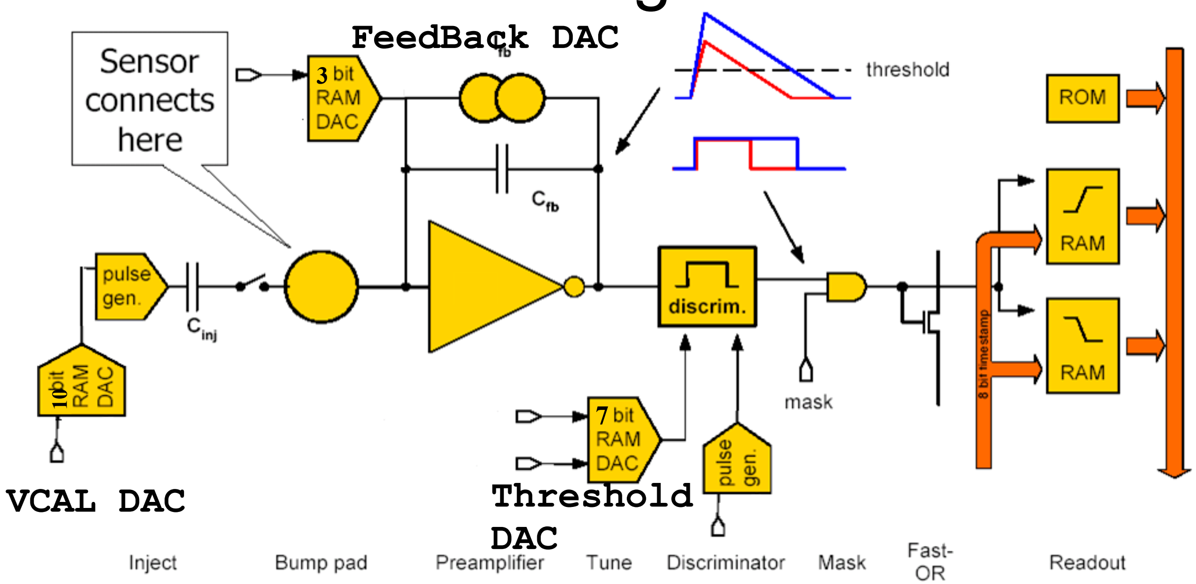


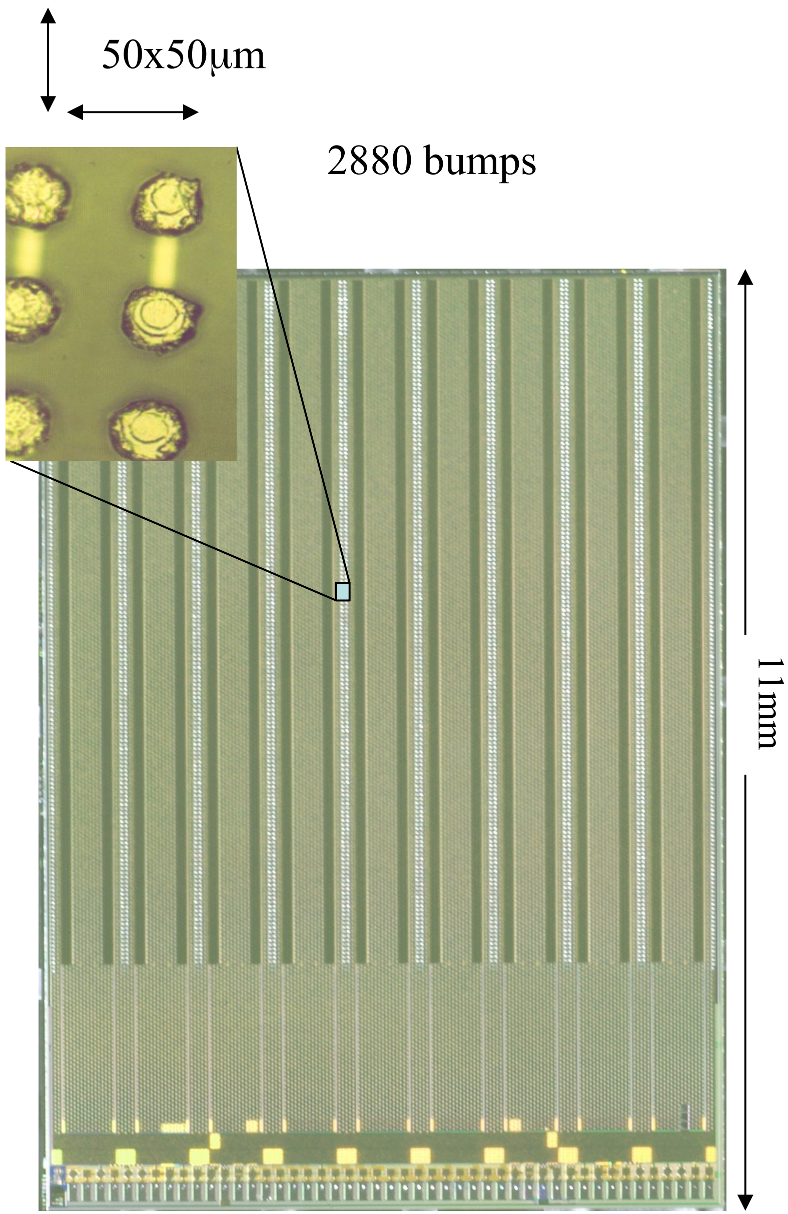




Pixel FrontEnd Chips

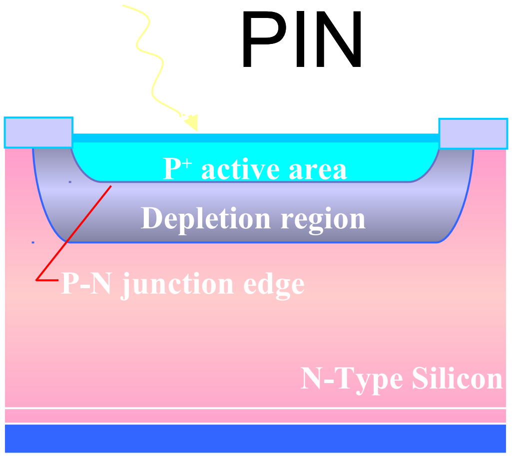
- 2880 channels organized in 18 columns and 160 rows
- connected to sensor via 50 μm pitch bump bonds
- buffering + time stamp logic
- converts charge into Time over Threshold (ToT)
- charge injection
- detailed monitoring

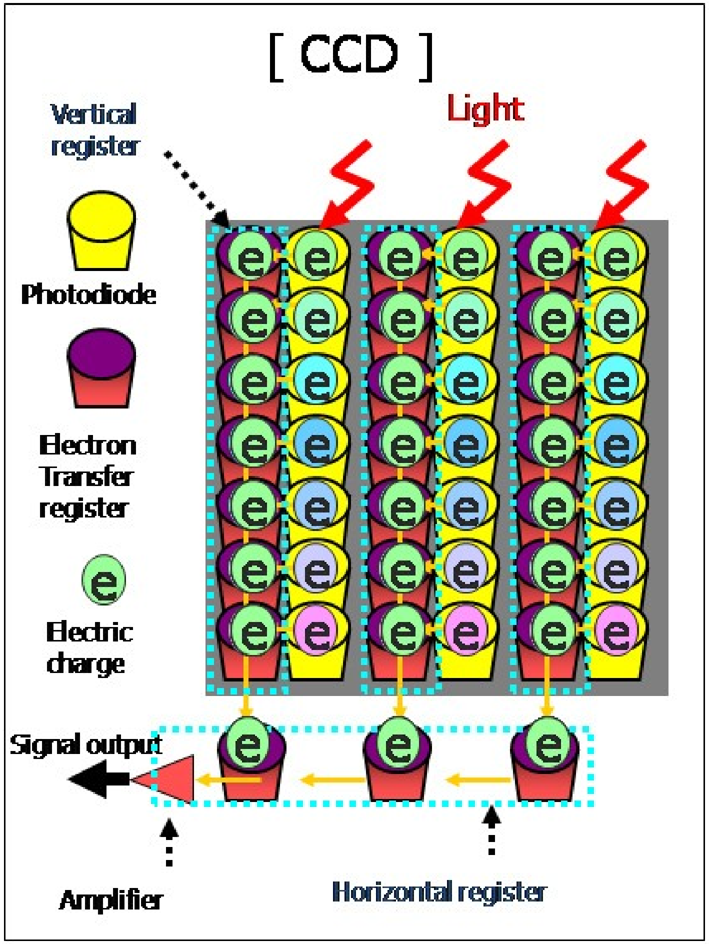


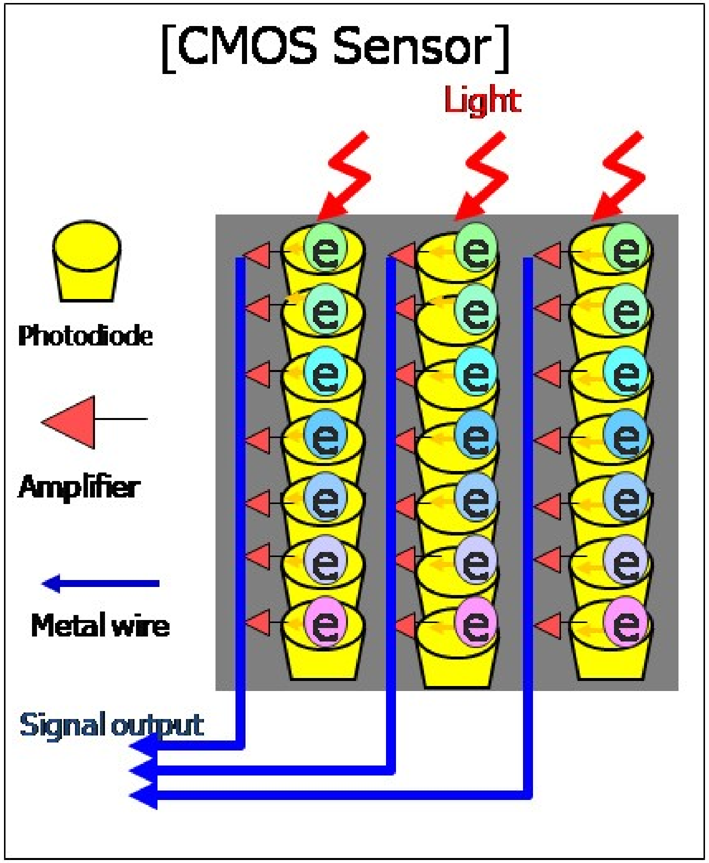


Modern PhotoDetectors

PIN

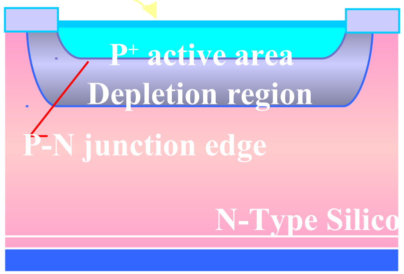




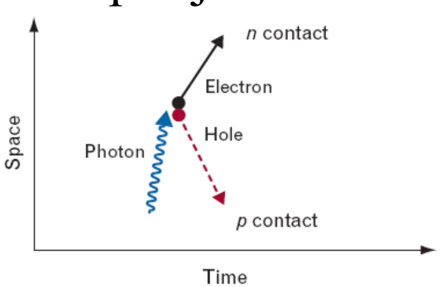


Modern PhotoDetectors

PIN

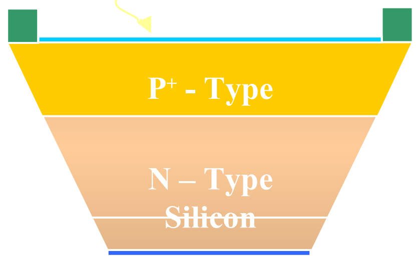


p-n junction

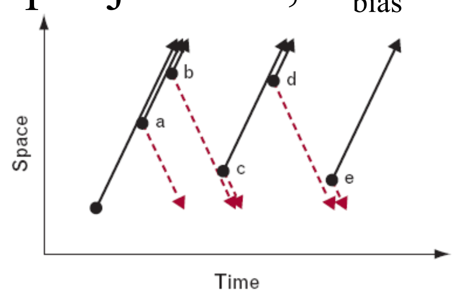


Gain = 1

APD



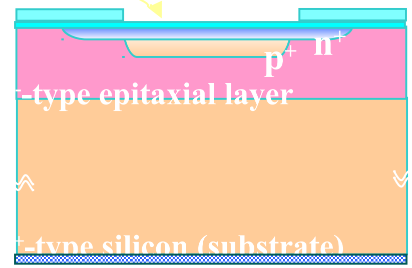
p-n junction, $V_{bias} < V_{BD}$



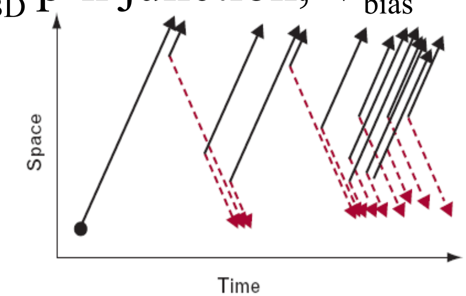
Gain = M (~ 50-500)

- linear mode operation-

GM-APD



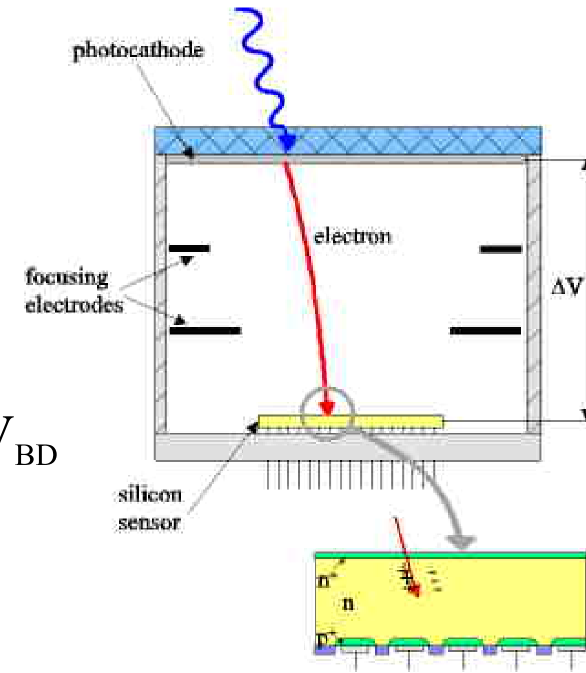
p-n junction, $V_{bias} > V_{BD}$



Gain → infinite

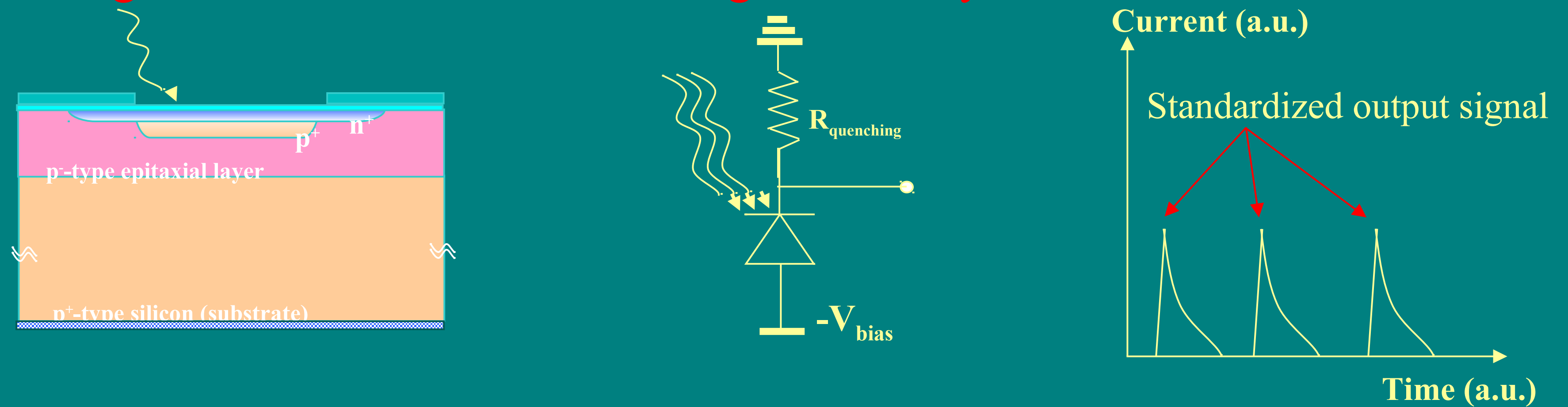
-Geiger-mode operation-

HPD

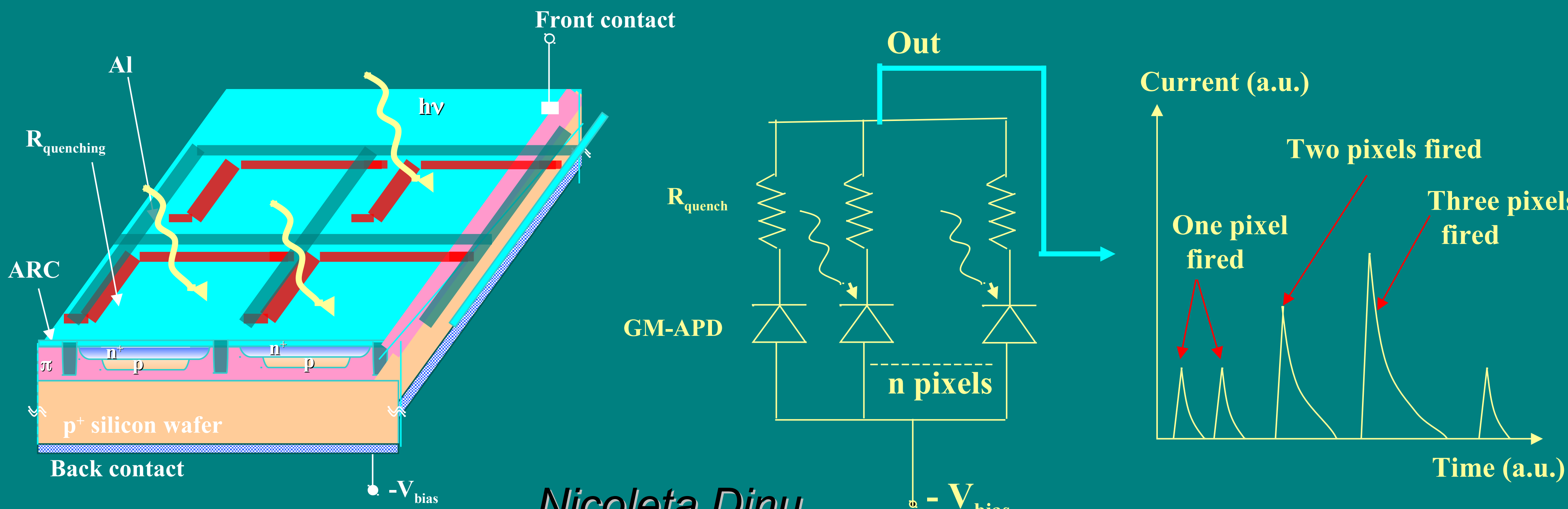


From GM-APD to SiPM

- GM-APD – gives no information on the light intensity



- **SiPM** (proposed by Sadygov and Golovin in the '90)
  - *matrix of tiny pixels in parallel / each pixel = GM-APD + R_{quench}*
  - *output signal is proportional to the number of triggered pixels*



Nicoleta Dinu

Modern PhotoDetectors

		VACUUM TECHNOLOGY			SOLID-STATE TECHNOLOGY		
		PMT	MCP-PMT	HPD	PN, PIN	APD	GM-APD
Photon detection efficiency	**Blue**	20 %	20 %	20 %	60 % / 70 %	50 %	30%
	Green-yellow	40 %	40 %	40 %	80-90 %	60-70 %	50%
	Red	< 6 %	< 6 %	< 6 %	90-100 % / 80 %	80 %	40%
Timing / 10 ph.e		~ 100 ps	~ 10 ps	~ 100 ps	tens ns	few ns	tens of ps
Gain		10^6 - 10^7	10^6 - 10^7	3 - $8x10^3$	1	~200V	10^5 - 10^6
Operation voltage		1 kV	3 kV	20 kV	10-100V	100-500V	< 100 V
Operation in the magnetic field		< 10^{-3} T	Axial magnetic field ~ 2 T	Axial magnetic field ~ 4 T	No sensitivity	No sensitivity	No sensitivity
Threshold sensitivity (S/N>>1)		1 ph.e	1 ph.e	1 ph.e	~100 ph.e	~10 ph.e	~1 ph.e
Shape characteristics		sensible bulky	compact	sensible, bulky	robust, compact, mechanically rugged		

Nicoleta Dinu

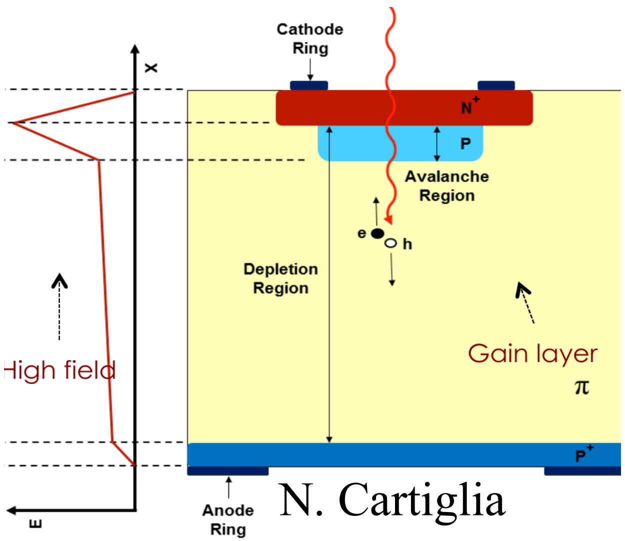
Timing Measurements

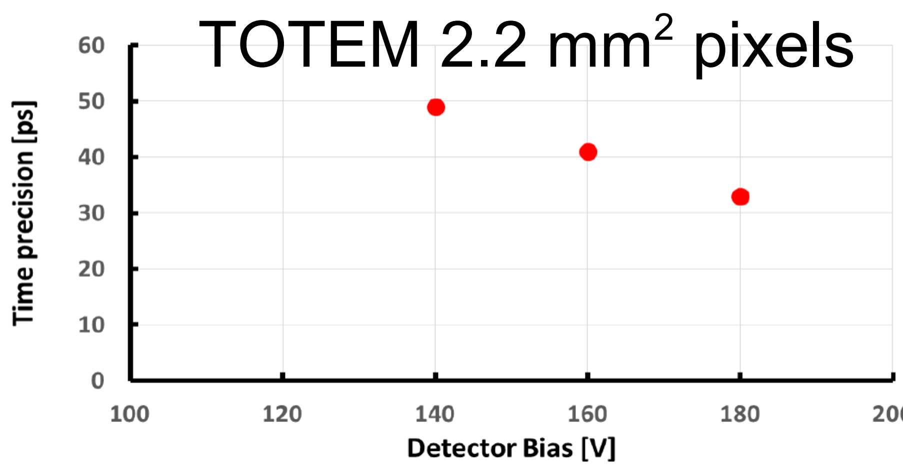
- Fast detectors: scintillator, RPC
- Electronics needs to match!

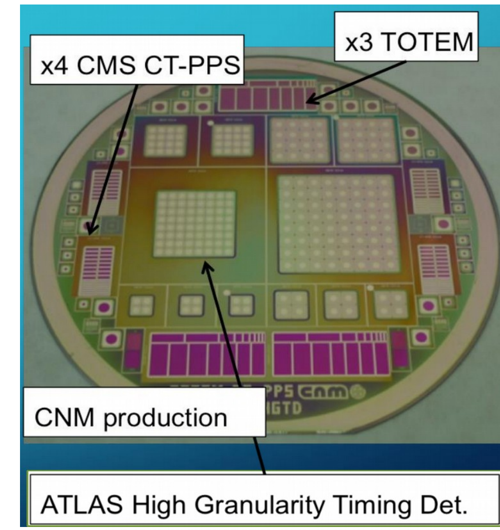
Detector Type	Intrinsinc Spatial Resolution (rms)	Time Resolution	Dead Time
Resistive plate chamber	$\lesssim 10$ mm	1 ns (50 ps[a])	—
Streamer chamber	300 μm[b]	2 μs	100 ms
Liquid argon drift [7]	$\sim$175–450 μm	$\sim$ 200 ns	$\sim$ 2 μs
Scintillation tracker	$\sim$100 μm	100 ps/n[c]	10 ns
Bubble chamber	10–150 μm	1 ms	50 ms[d]
Proportional chamber	50–100 μm[e]	2 ns	20-200 ns
Drift chamber	50–100 μm	2 ns[f]	20-100 ns
Micro-pattern gas detectors	30–40 μm	$<$ 10 ns	10-100 ns
Silicon strip	pitch/(3 to 7)[g]	few ns[h]	$\lesssim 50$ ns[h]
Silicon pixel	$\lesssim 10$ μm	few ns[h]	$\lesssim 50$ ns[h]
Emulsion	1 μm	—	—

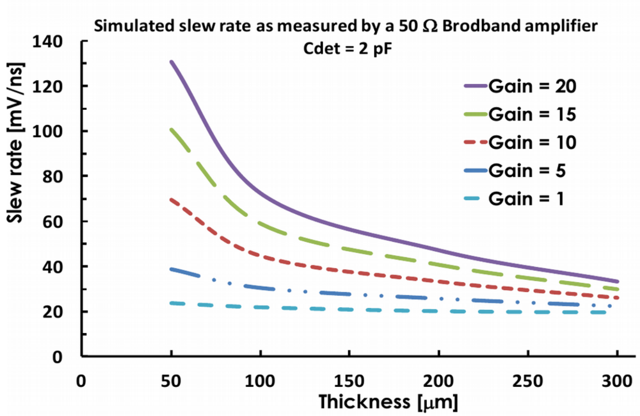
Detector trends: Timing

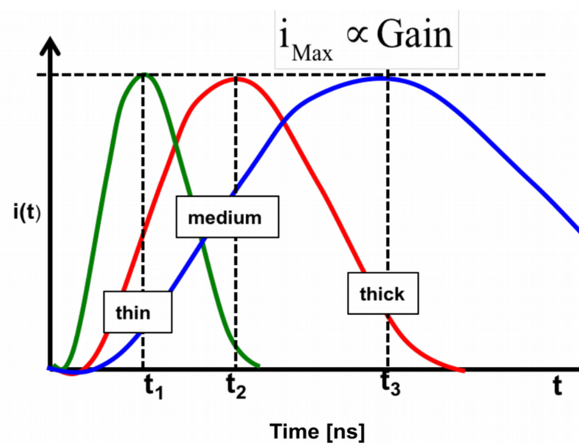
- R&D: use Low Gain Avalanche Diodes (LGAP)
- timing optimised: UltraFastSiliconDetectors (UFSD)

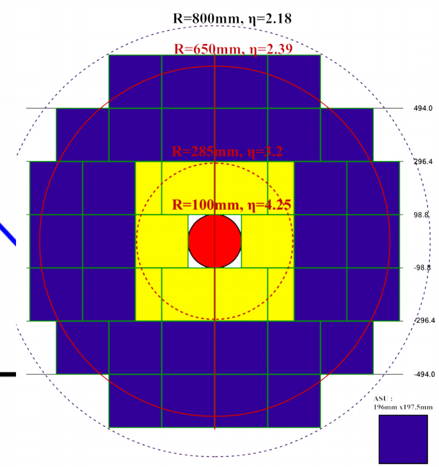


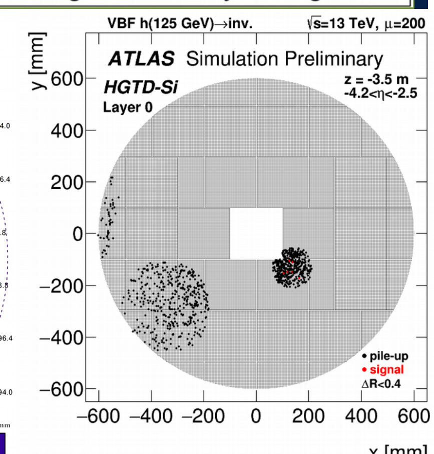










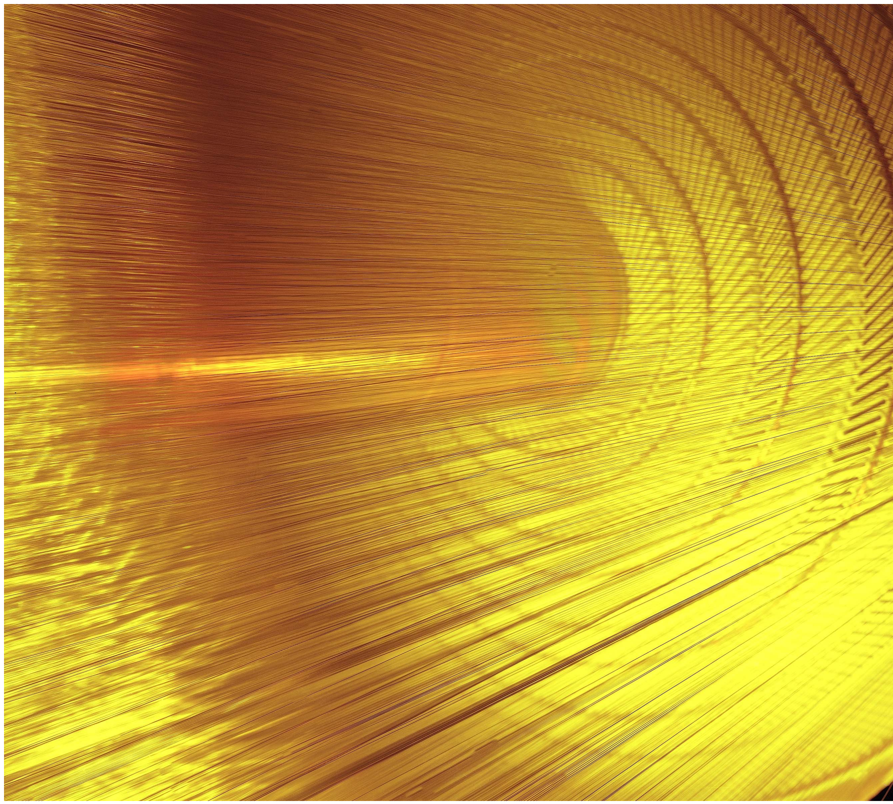


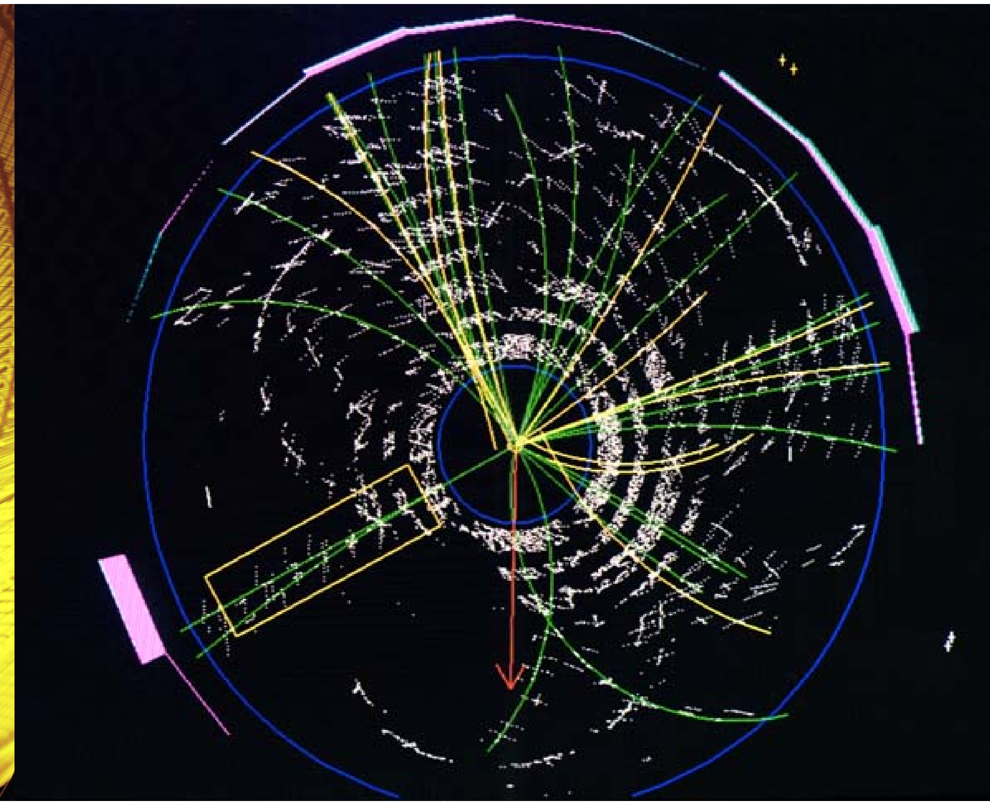
Overview

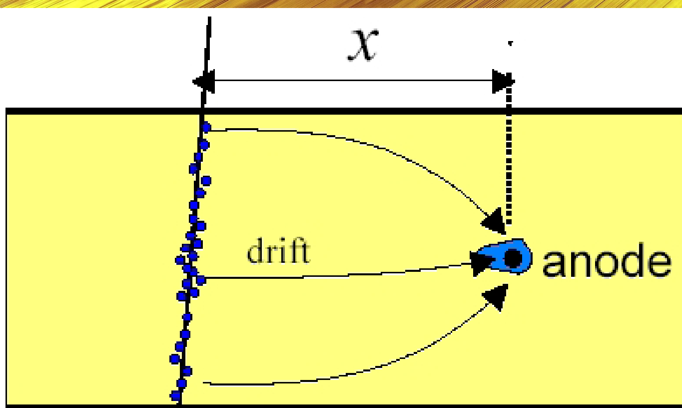
- Lecture 1: Interactions with matter
- Lecture 2: Tracking Detectors
  - How are position measurements combined
    - To measure track parameters
    - momentum
    - Impact parameter
  - How do we find tracks?

Multiwire proportional drift chambers

- CDF's multi-wire proportional drift chamber : > 30,000 wires !

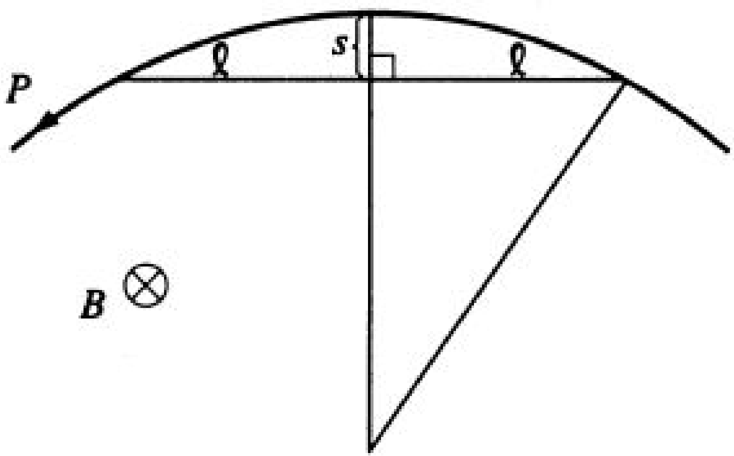


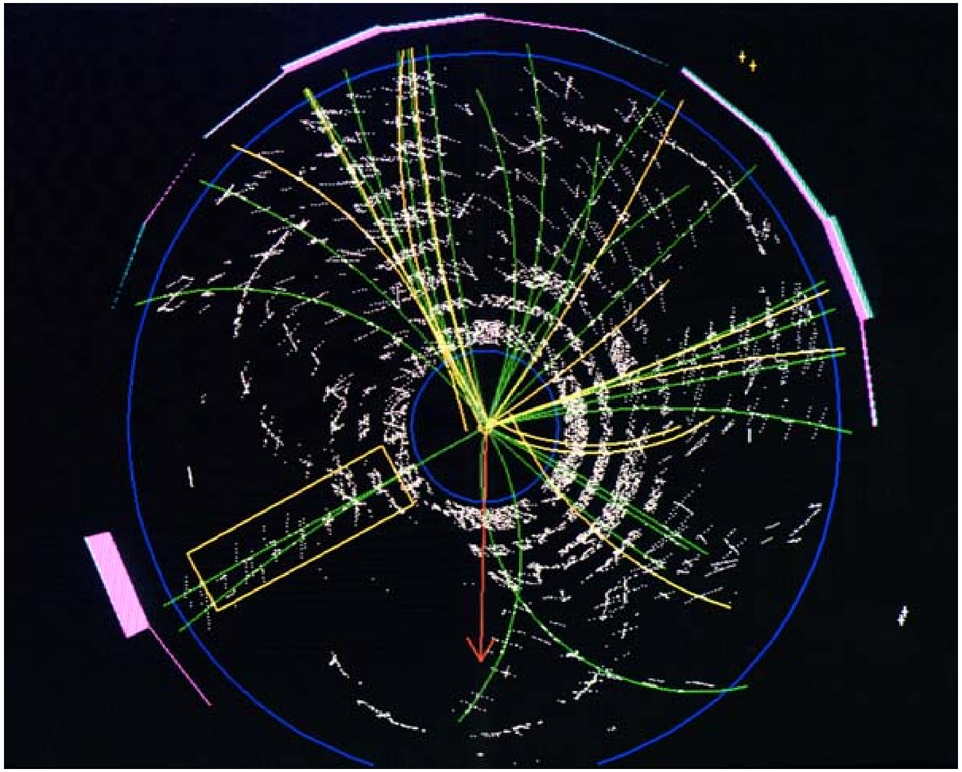




•Translate drift time into position
•Need to reconstruct "track" from a few hits along the path

Momentum measurement





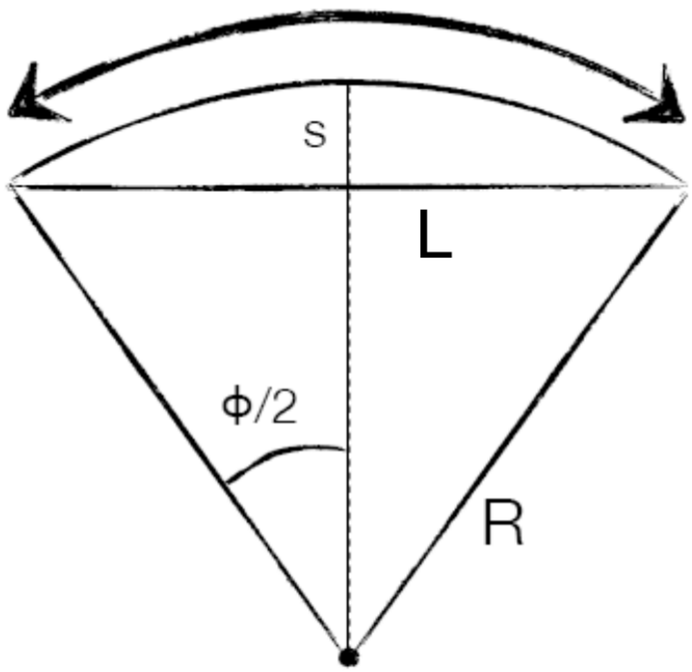
$$\vec{B} \perp \vec{v} \quad \rightarrow \quad F = q\,v\,B = m\frac{v^2}{R} \quad \Rightarrow \quad R = \frac{m\,v}{q\,B}$$

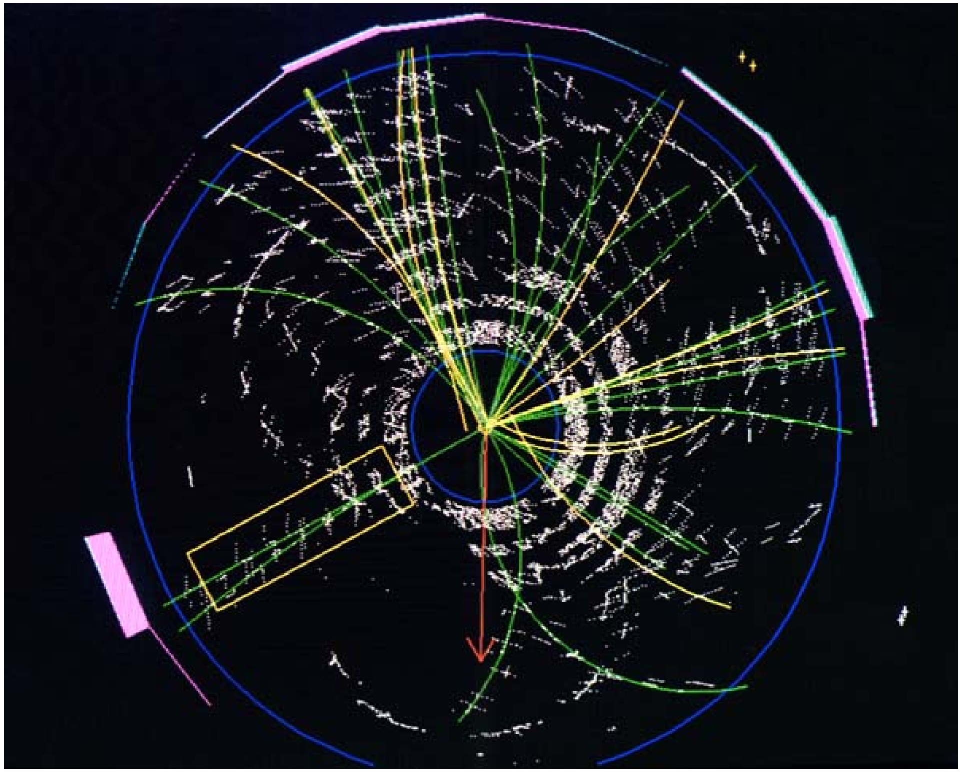
$$\Rightarrow \quad R = \frac{p}{qB}$$

R(m) = 3.3 x p(GeV)/B(Tesla)

- Utilise that charged particles bend inside a magnetic field
- Reconstruct curvature radius
  - R as fitted track parameter

Momentum measurement





$$s = R - d = R - R\cos\frac{\theta}{2} = R\left(1 - \cos\frac{\theta}{2}\right) = R\,2\sin^2\frac{\theta}{4} \sim \frac{R\theta^2}{8} \sim \frac{RL^2}{8R^2} = \frac{L^2}{8R} = \frac{qBL^2}{8p}$$

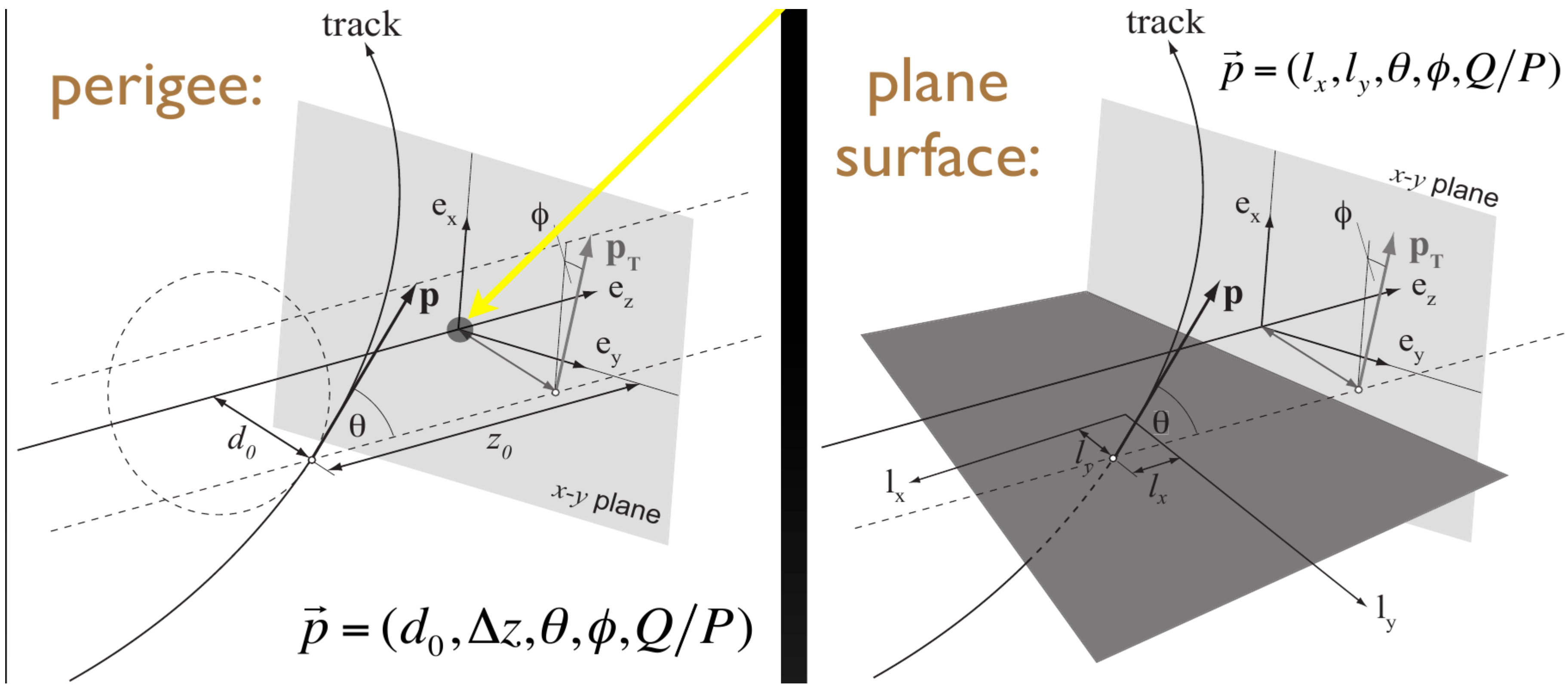
$$for\ 3\ points: \sigma_s^2 = \frac{1}{1-3}\sum \sigma_x^2 \rightarrow \sigma_s = \sqrt{\frac{3}{2}}\sigma_x,$$

$$N\ points\ (Gluckstern): \sigma_s = \sqrt{\frac{720}{64(N+4)}}\sigma_x$$

$$\frac{\sigma_p}{p} = \frac{\sigma_s}{s} \sim \frac{p\,\sigma(x)}{BL^2}$$

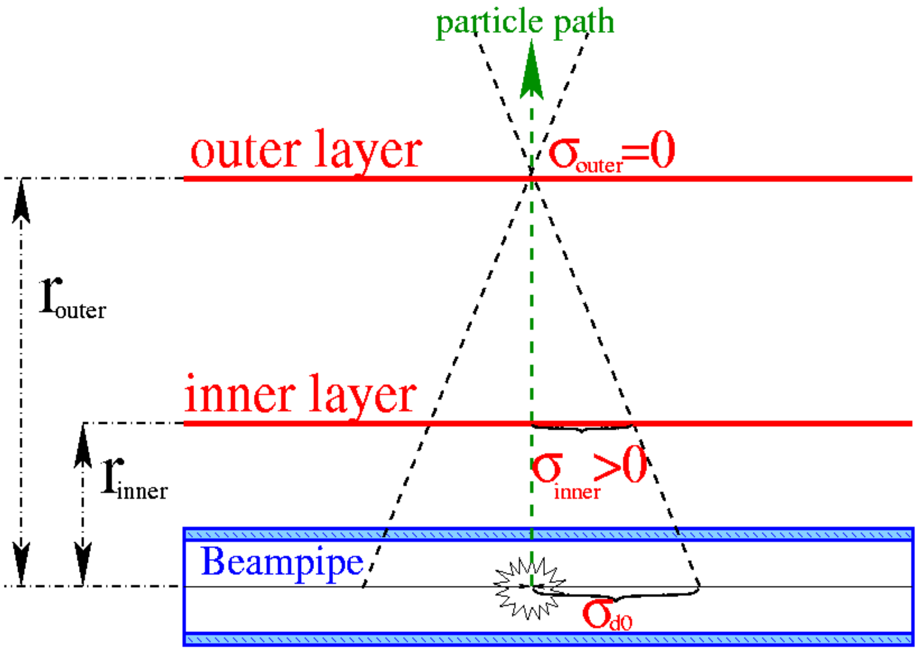
Track parameters

- Charged particles ina magnetic field follow a Helix Trajectory (assuming no energy loss → spiral)



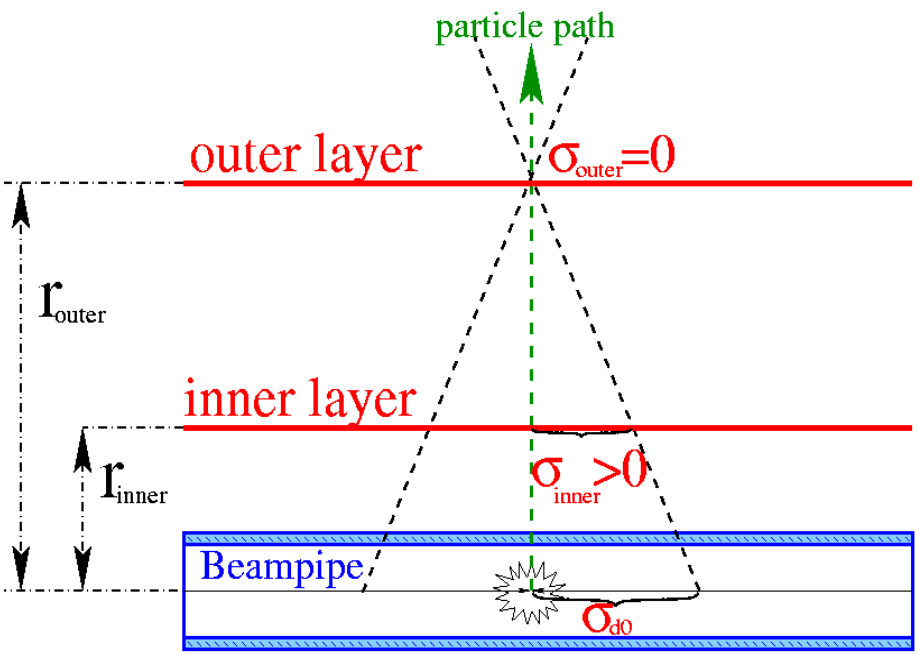
- Parameters:
  - Angles: θ and φ
  - Curvature/Radius: Q/P
  - Impact parameter/Position offset: d0, z0 or li

Impact Parameter resolution σ_{d0}

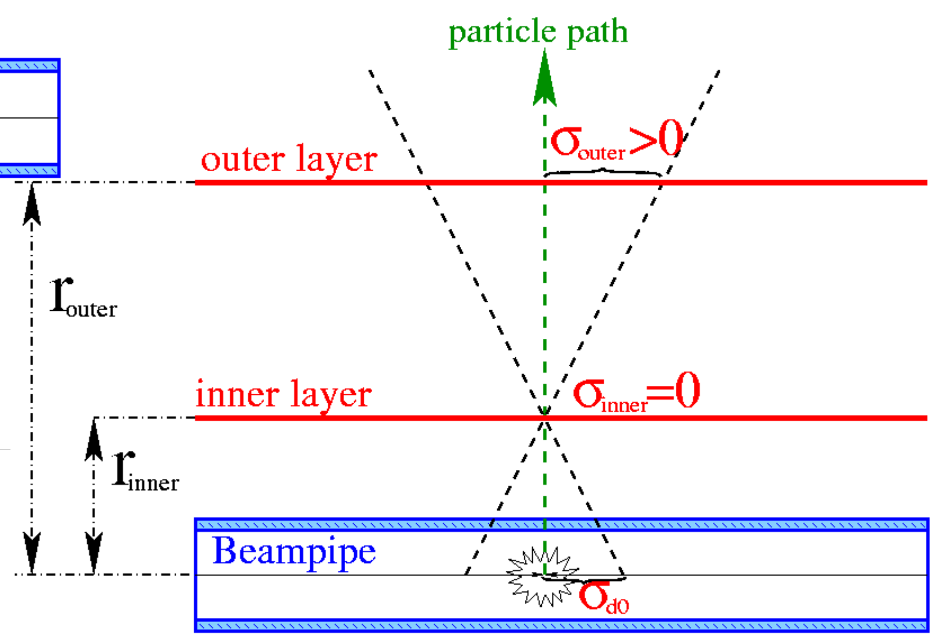


$$\frac{\sigma_{d0}}{\sigma_o} = \frac{r_i}{r_o - r_i}$$

Impact Parameter resolution σ_{d0}



$$\frac{\sigma_{d0}}{\sigma_o} = \frac{r_i}{r_o - r_i}$$



$$\frac{\sigma_{d0}}{\sigma_i} = \frac{r_o}{r_o - r_i}$$

Impact Parameter resolution σ_{d0}

$$\frac{\sigma_{d0}}{\sigma_o} = \frac{r_i}{r_o - r_i}$$

$$\sigma_{d0}^2 = \left(\frac{r_o}{r_o - r_i}\right)^2 \sigma_i^2 + \left(\frac{r_i}{r_o - r_i}\right)^2 \sigma_o^2 + \sigma_{MS}^2$$

$$\sigma_{MS} \sim \frac{1}{p}\sqrt{\frac{x}{X_0}}$$

$$\frac{\sigma_{d0}}{\sigma_i} = \frac{r_o}{r_o - r_i}$$

Impact Parameter resolution σ_{d0}

- inner layer at small radius
- good spatial resolution

$$\frac{\sigma_{d0}}{\sigma_o} = \frac{r_i}{r_o - r_i}$$

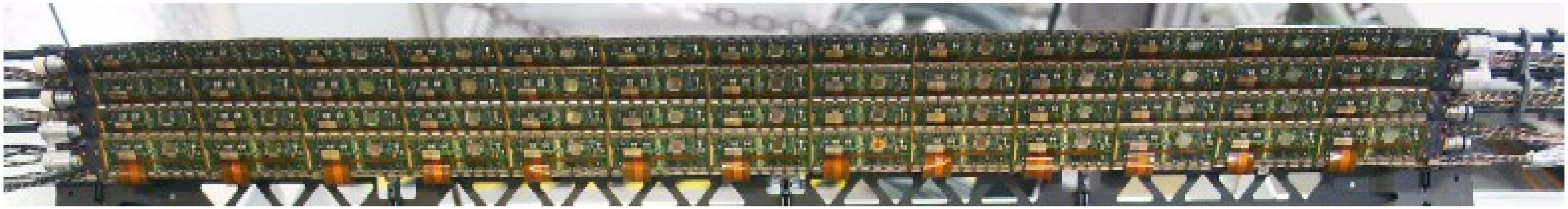
$$\sigma_{d0}^2 = \left(\frac{r_o}{r_o - r_i}\right)^2 \sigma_i^2 + \left(\frac{r_i}{r_o - r_i}\right)^2 \sigma_o^2 + \sigma_{MS}^2$$

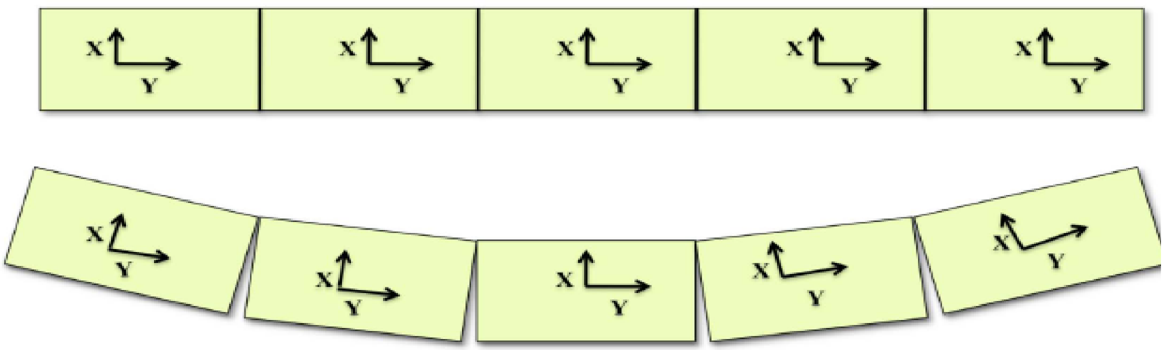
$$\sigma_{MS} \sim \frac{1}{p}\sqrt{\frac{x}{X_0}}$$

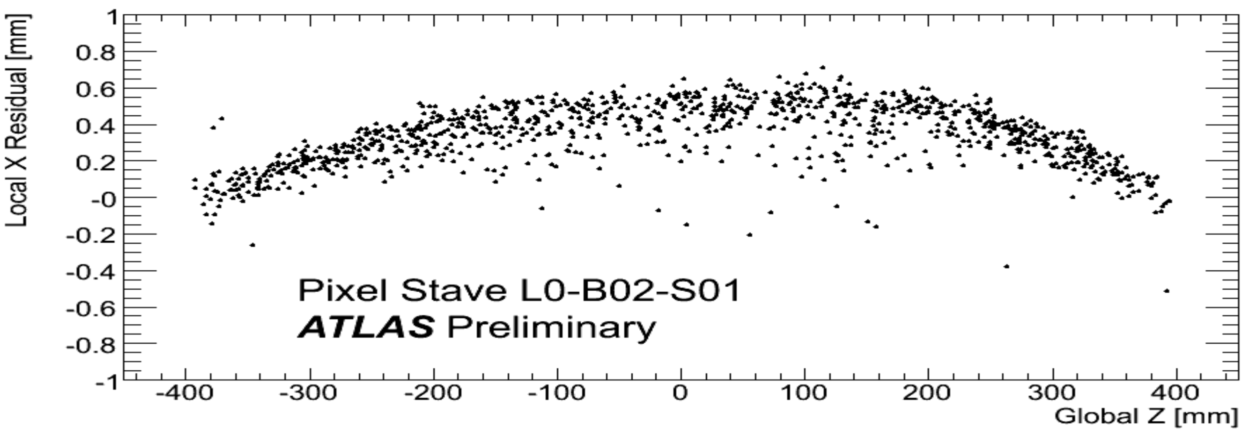
$$\frac{\sigma_{d0}}{\sigma_i} = \frac{r_o}{r_o - r_i}$$

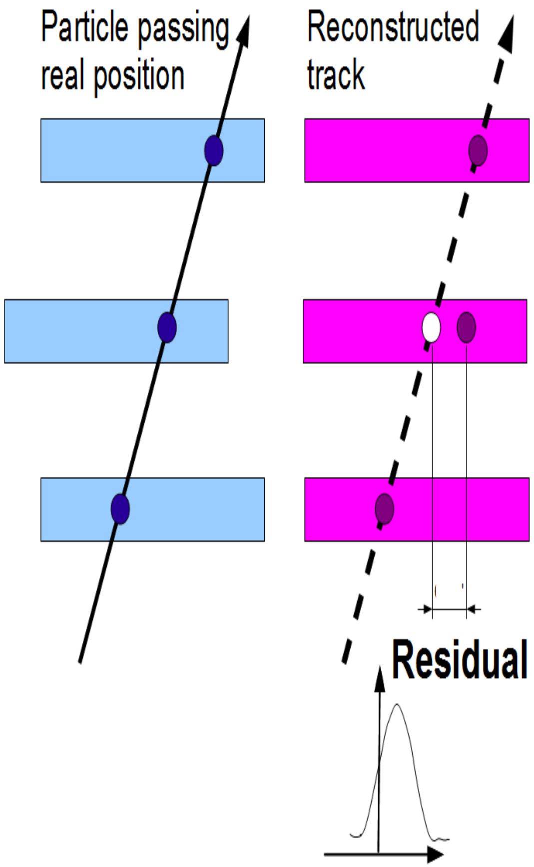
Reduce multiple scattering:
Low material

Cosmics for Alignment: Pixel Bow

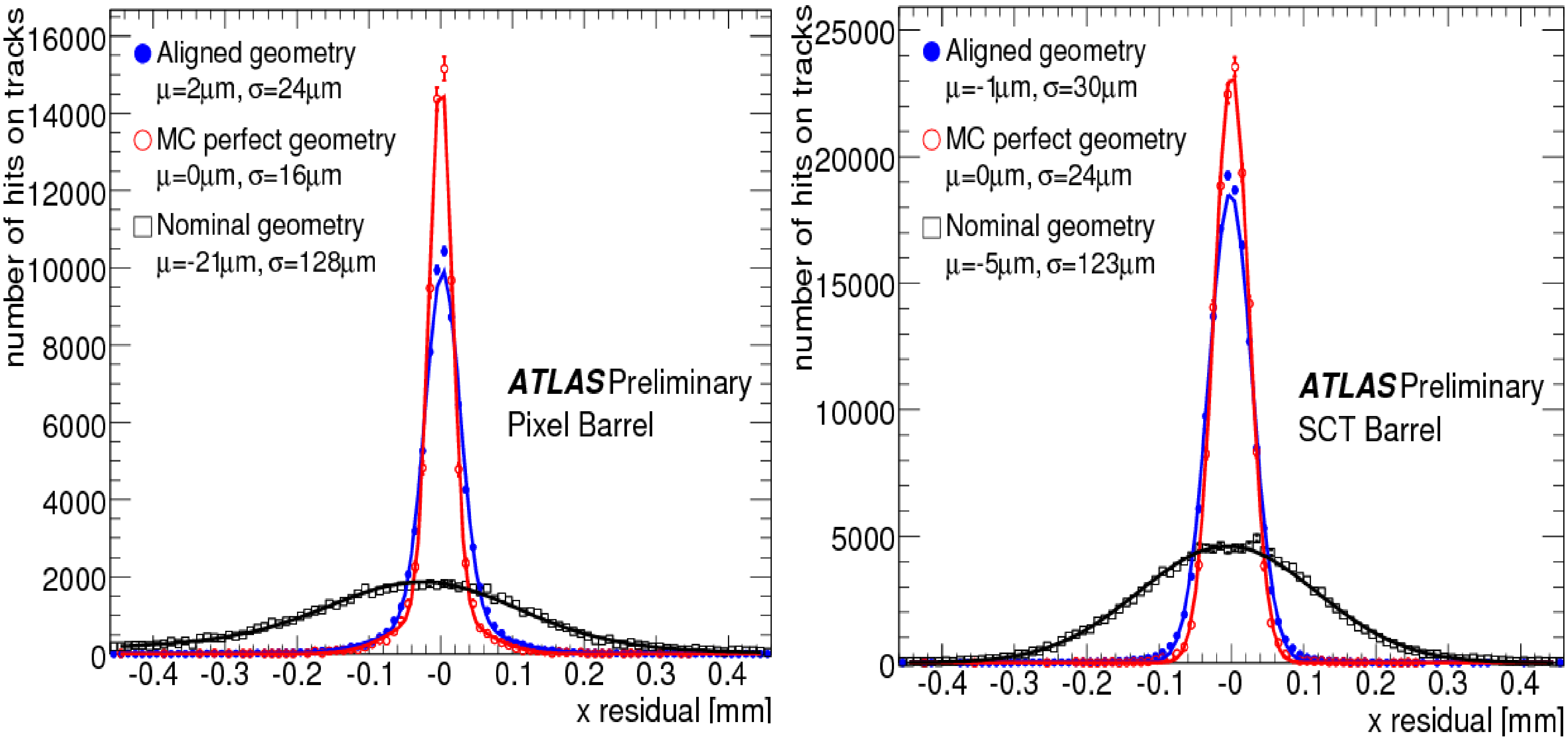








Silicon Alignment



- Dramatic improvement from nominal (survey not included)
- Residuals show no bias
- Achieved resolution close to expected

Detector trends: tracker geometry

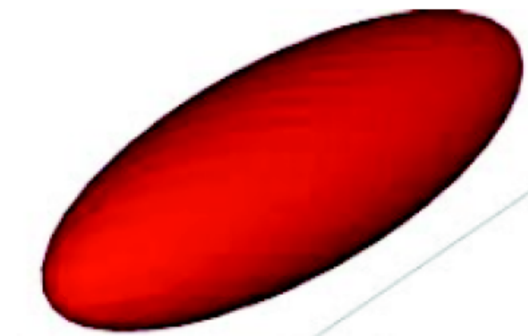
Ideally: constant track density (pixel occupancy) in all sensors
The track density is constant in eta at LHC

- up to phase space limit, which is above eta 2.5 for many processes of interest

Achieved on a cylindrical surface -> barrel-only layout?

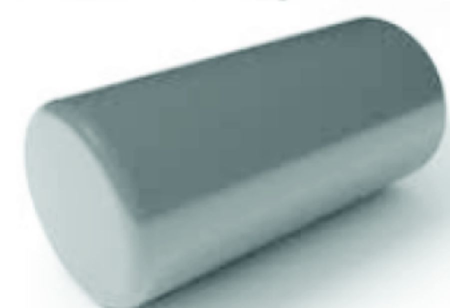
Ideally tracks coming from the I.P. should cross the sensors perpendicularly (to minimize material and minimize number of sensors needed)

- This condition implies a spherical surface for point source, ellipsoid for the LHC beam spot



Transverse momentum accuracy should be constant in eta

- the B field integral along tracks should be constant
- In a solenoidal field this implies cylindrical layers, constatnt radial lever arm
- Reminder: the momentum accuracy is proportional to the square of the radial lever arm

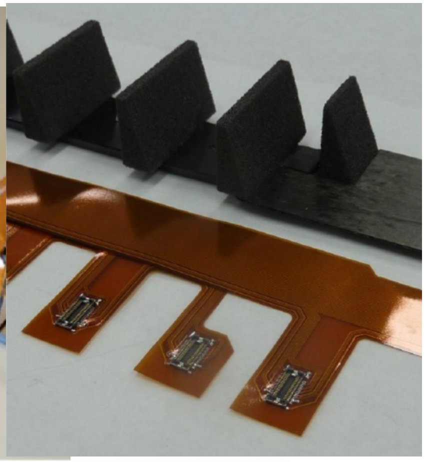


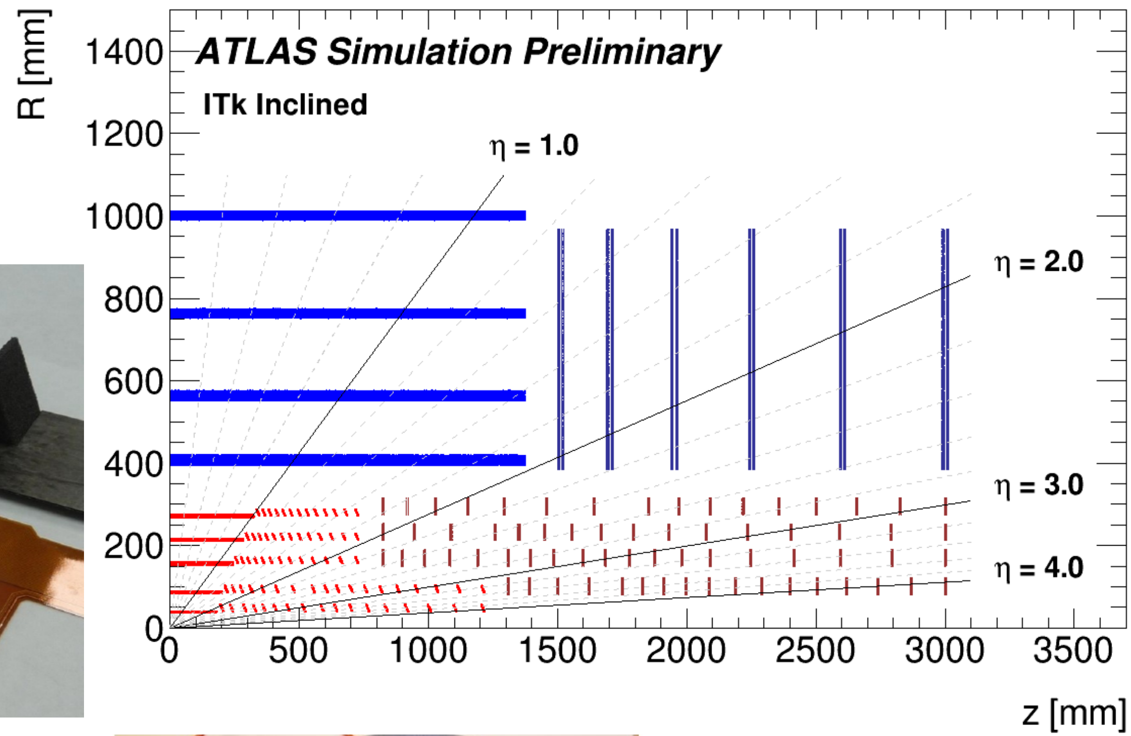
4

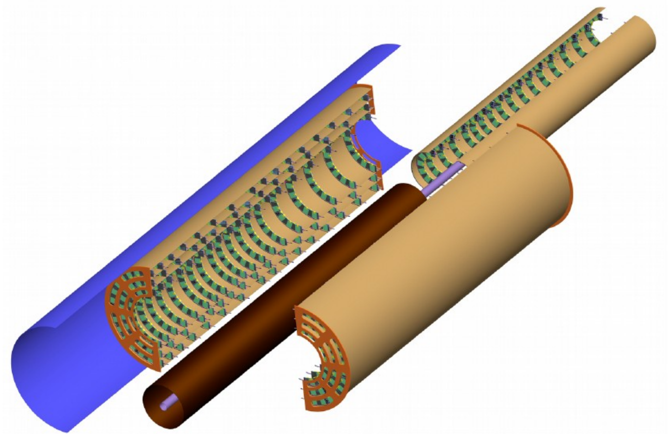
T.Todorov, October 2011

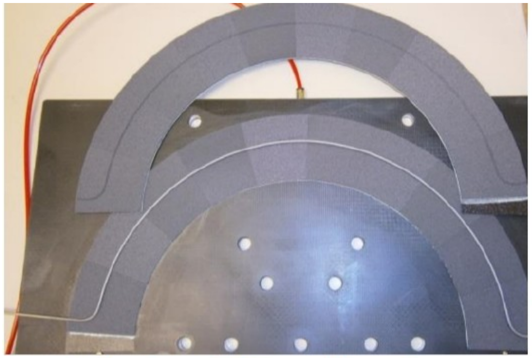
ATLAS: Tracker Upgrade

- Inclined pixel layout
- Endcap Rings

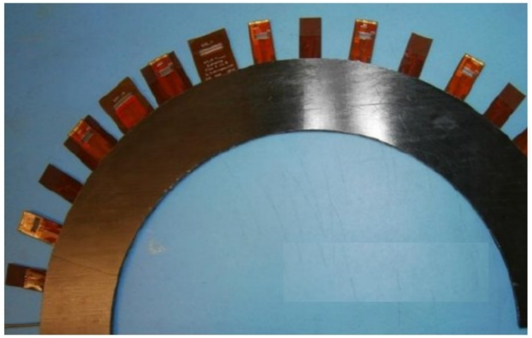






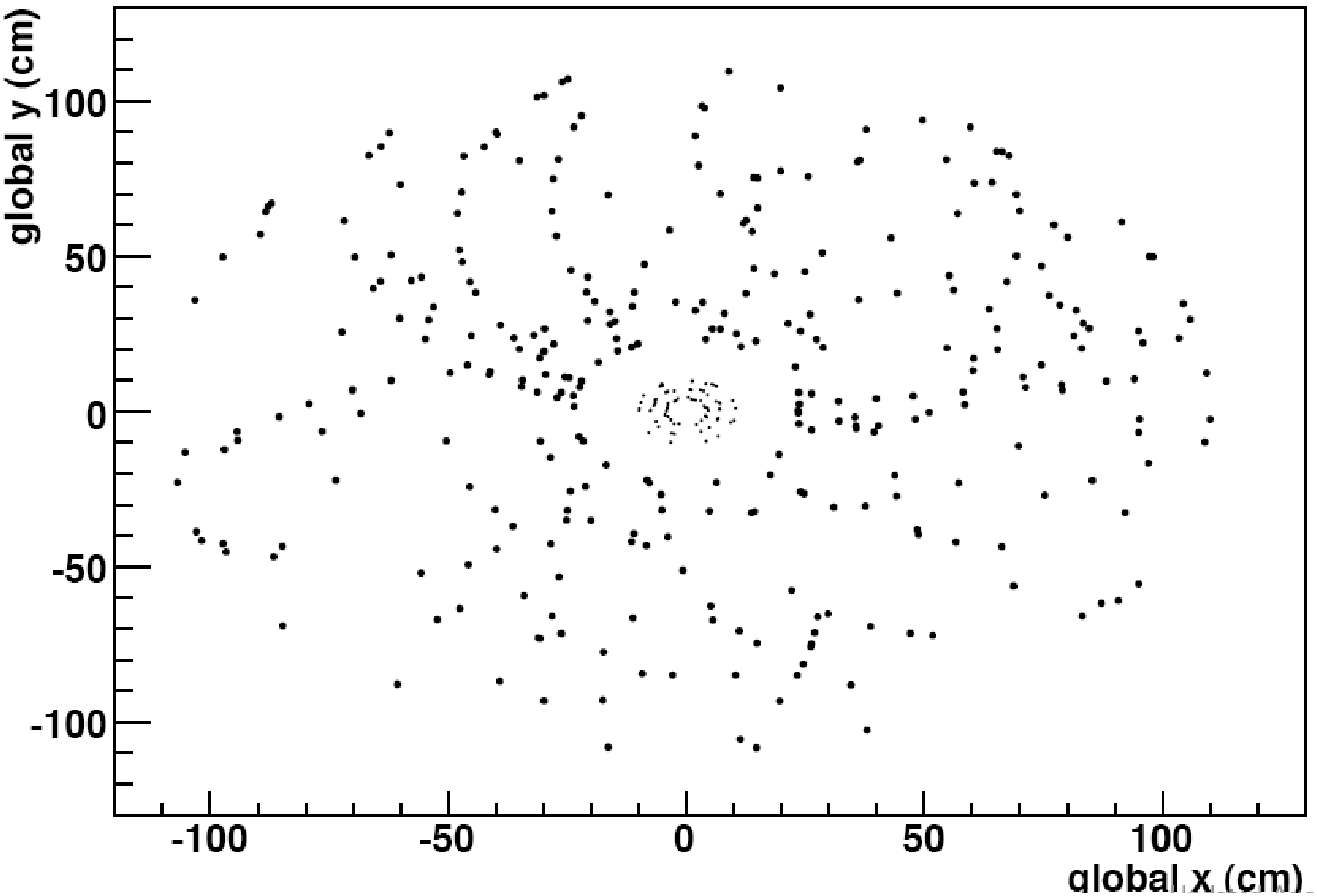


Titanium CO2 cooling pipe embedded in ring.

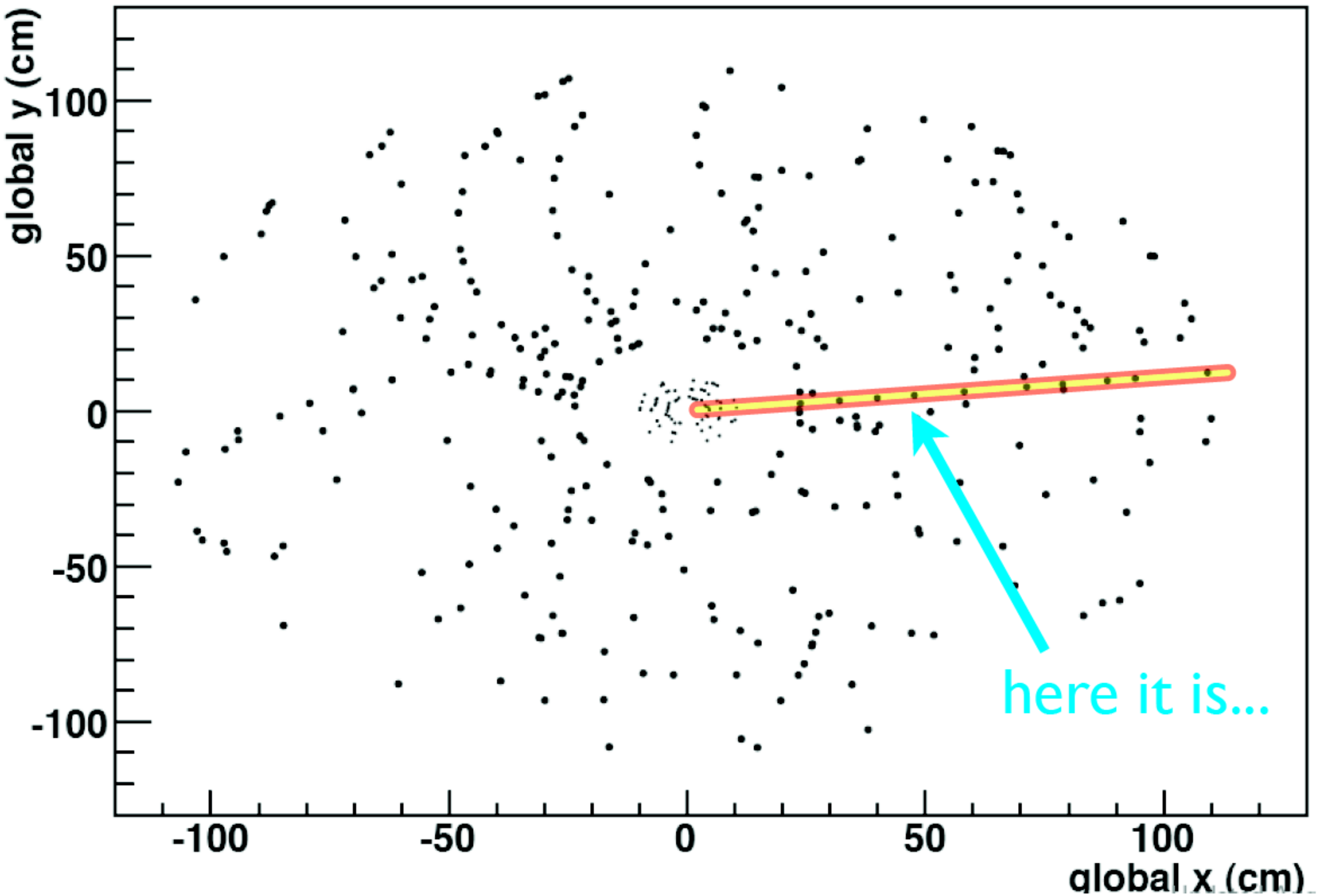


Electrical services (flex) embedded in ring.

Find the 50 GeV Track!

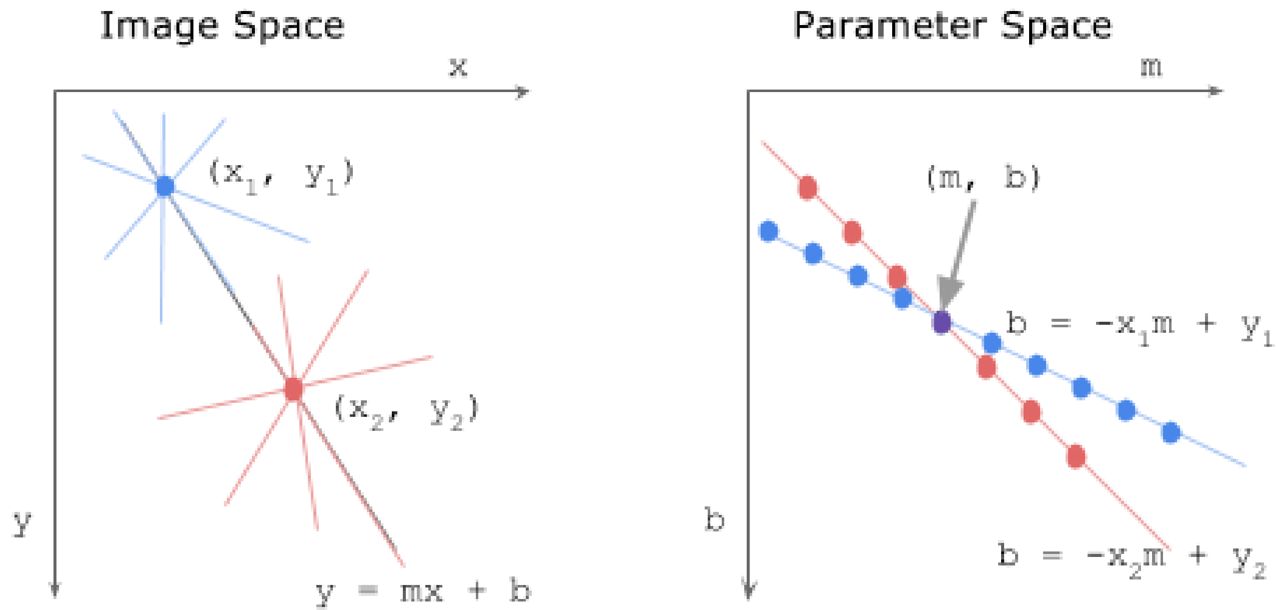


Where is the 50 GeV Track?

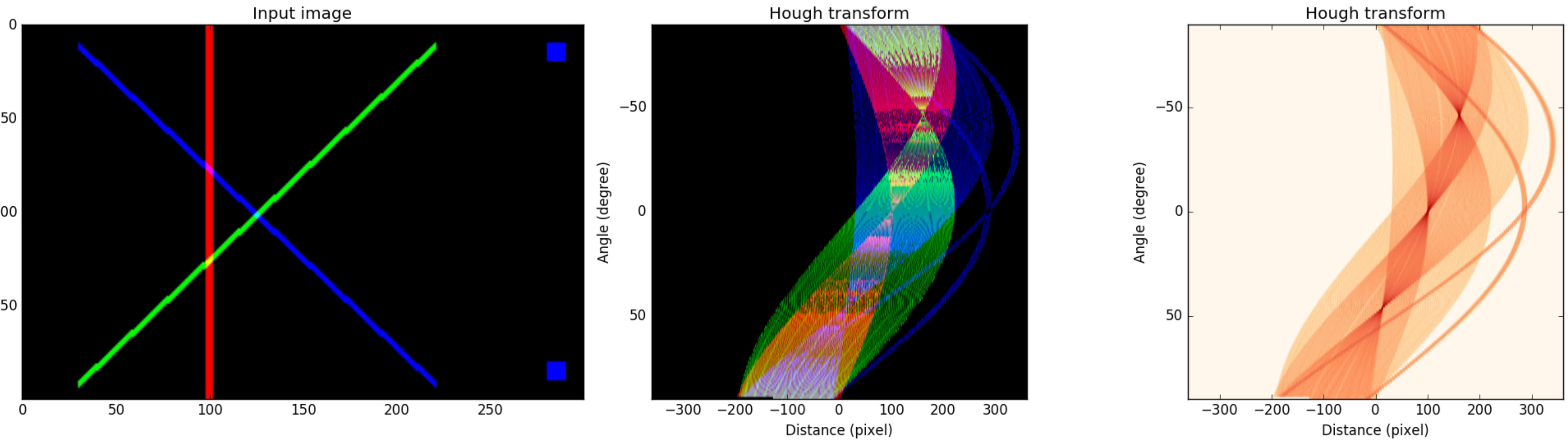


Track finding

- Various methods
  - Local:
    - find seeds (driven by granularity and occupancy)
    - Inside out
    - Outside in
    - Search roads
    - Extend → Kalman filter
  - Global
    - Example:
      Hough transform

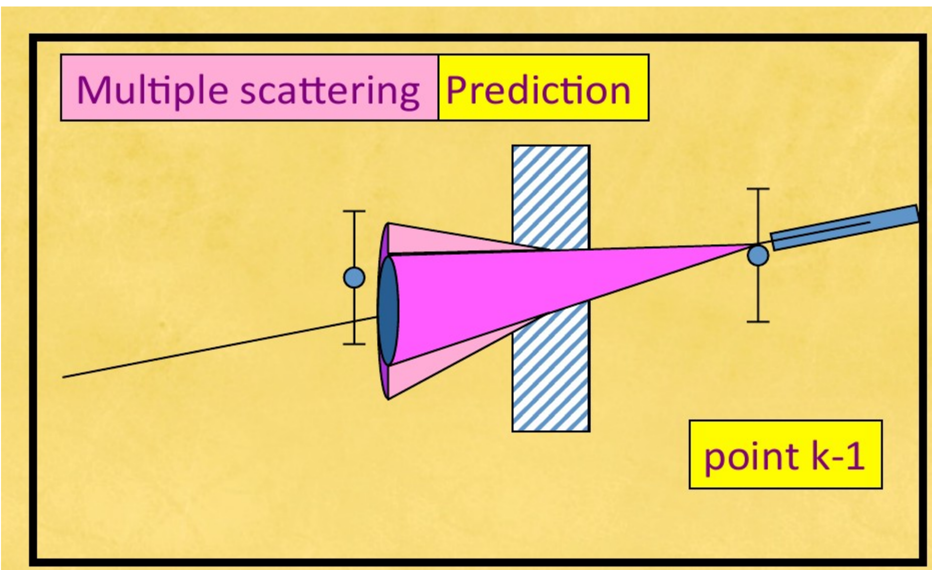


Track finding: Hough Transform

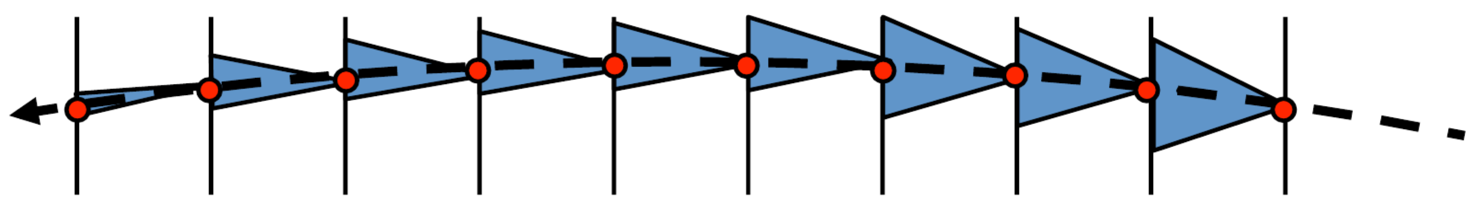


Track finding: Kalman Fitter

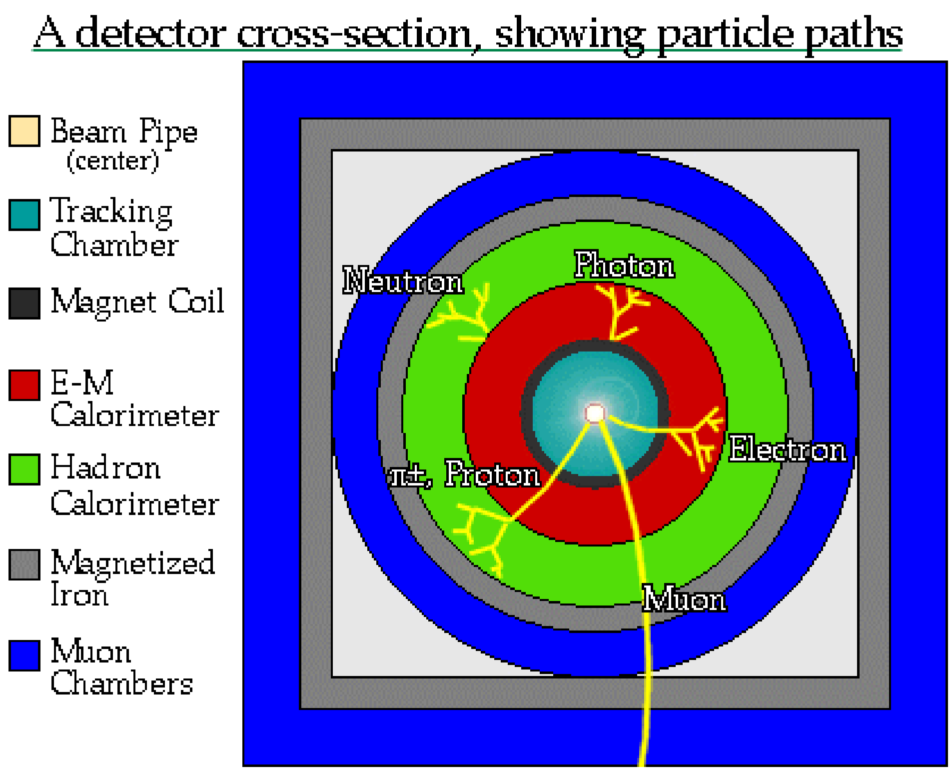
- Update track state (prediction from measurement)
  - Position + covariance
- Look for new hits in predicted search window

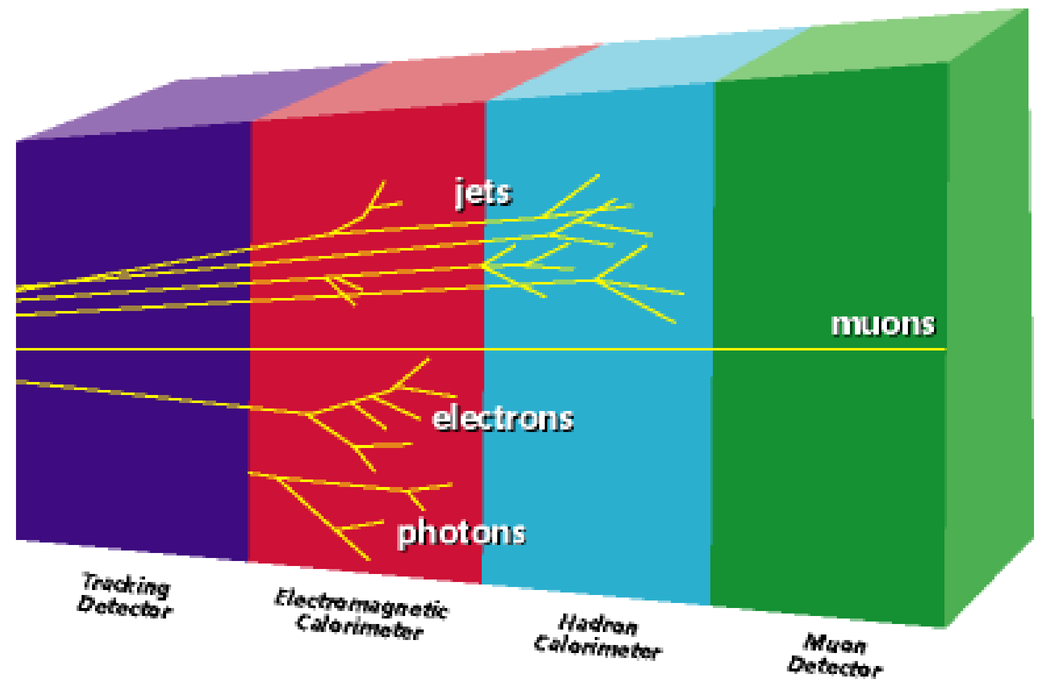


R.Mankel



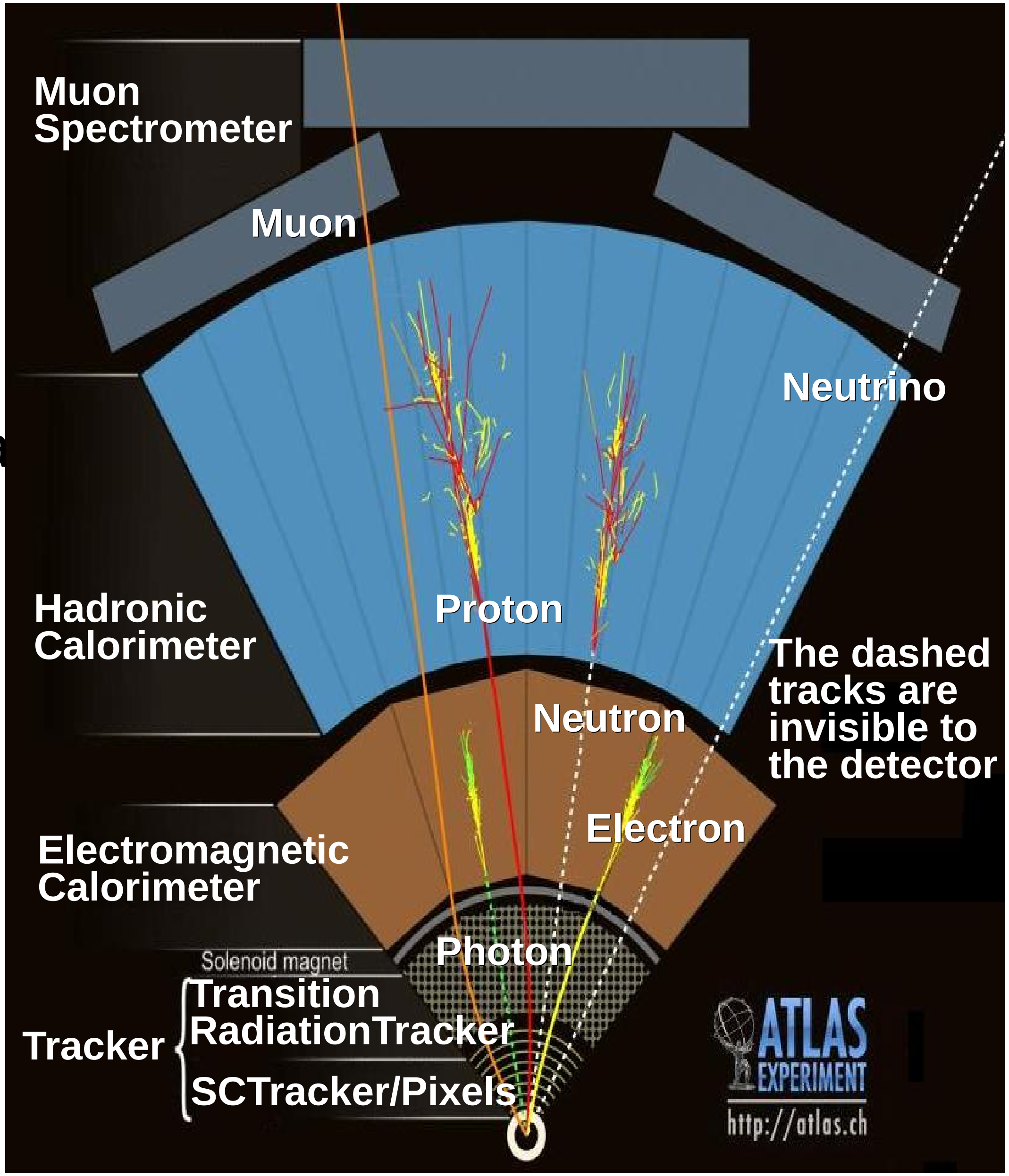
Putting it all together





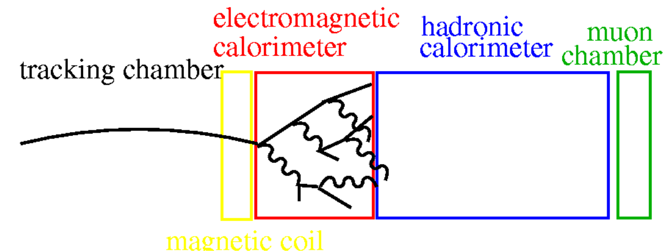
Signatures

- Leptons: e, μ, (τ)
  - Clean, distinctive signature:
    - Track
    - e:Calorimeter μ:MS track
  - distinguished from QCD bkg
  - Reconstruct particle momenta
- Jets
- Missing Et (MET)
- b-jets:
  - B-tagging: exploit b-hadron lifetime
  - displaced vertices
  - Needs excellent tracker
- Resonances:
  - Reconstruct mass peaks from 4-vectors of decay products

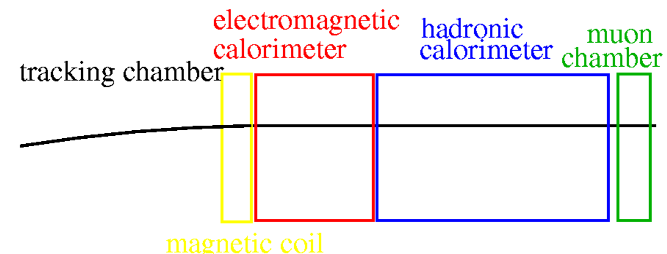


Lepton Identification

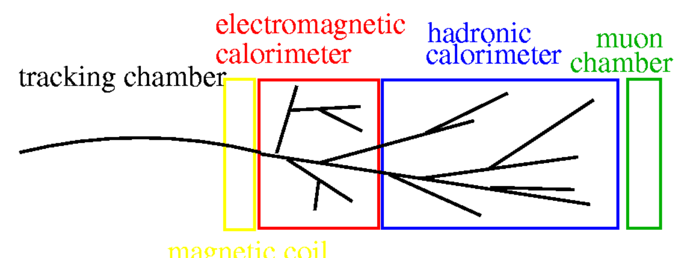
- Electrons:
  - compact electromagnetic cluster in calorimeter
  - Matched to track



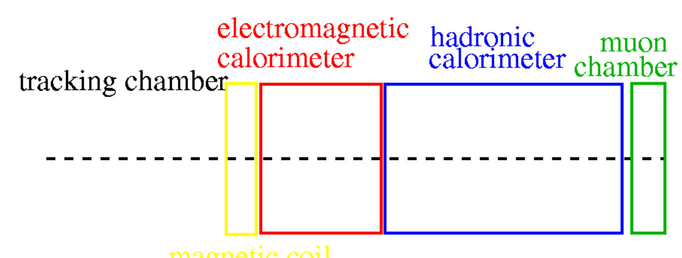
- Muons:
  - Track in the muon chambers
  - Matched to track



- Taus:
  - Narrow jet
  - Matched to one or three tracks



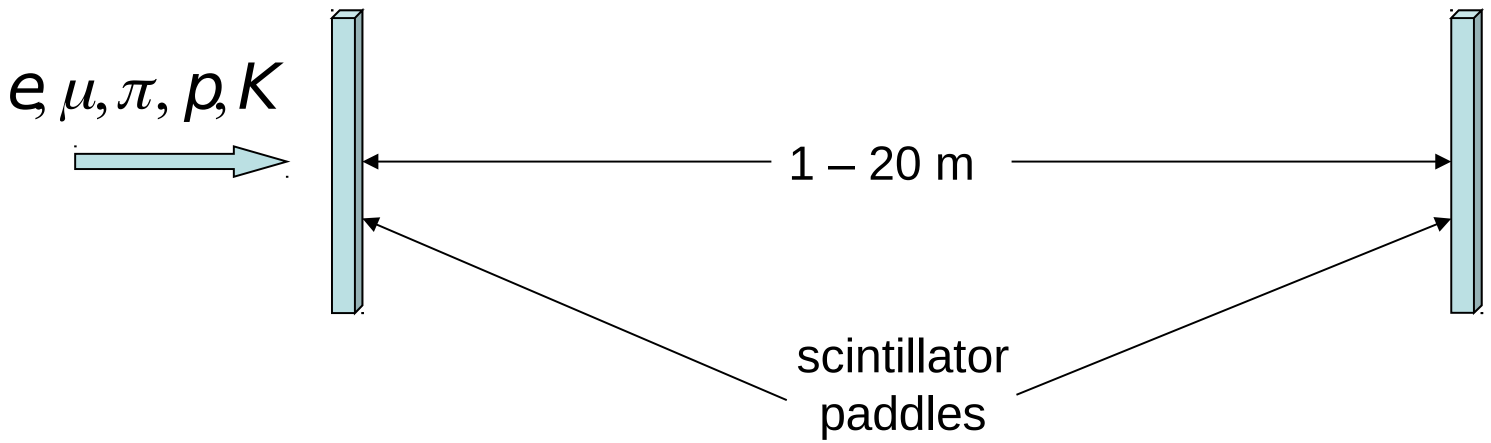
- Neutrinos:
  - Imbalance in pT
  - Inferred from total transverse energy measured in detector

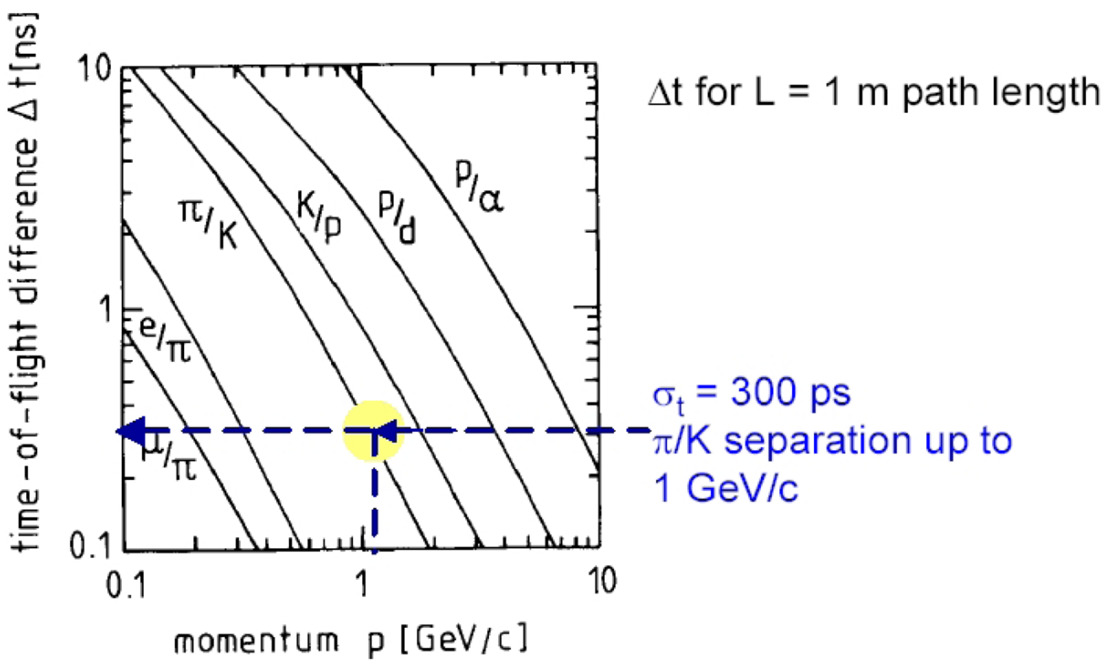


Bonus Slides

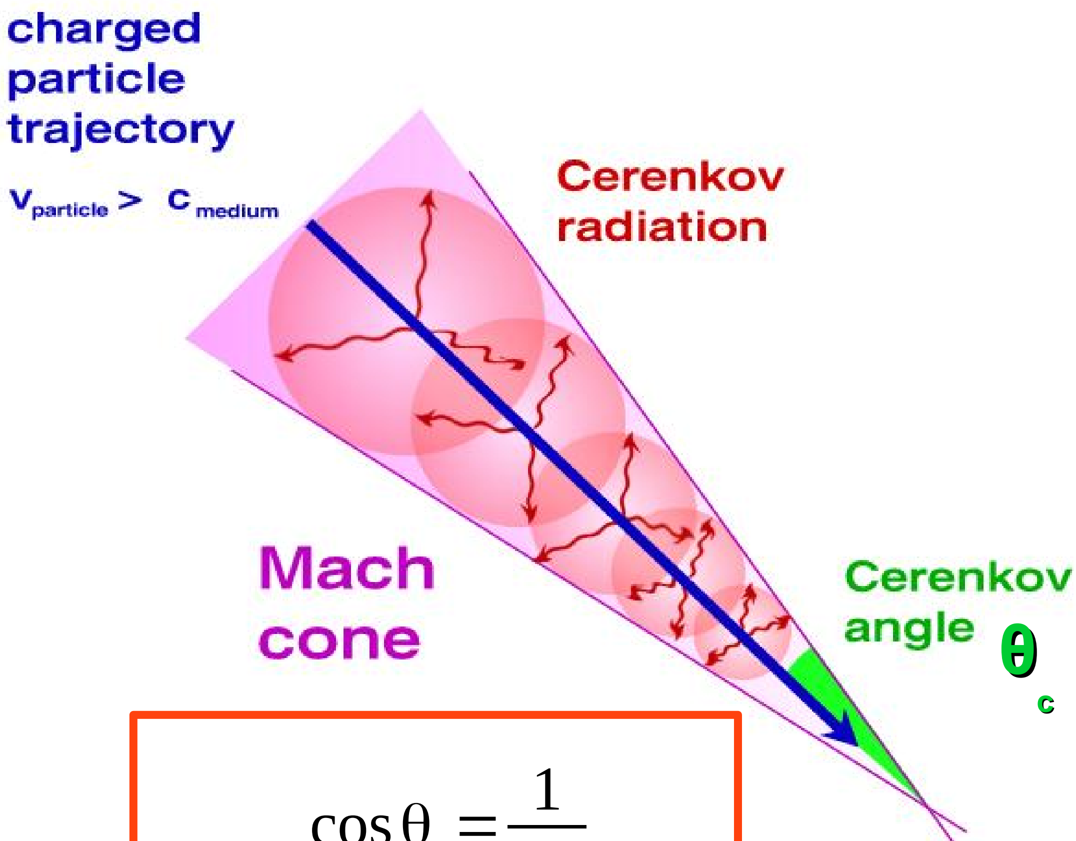
Particle Identification/PID: Time of Flight

- Measure very precisely the time taken for a particle to traverse a known distance : $v = L/(t1-t2)$ $\quad p = \gamma\beta m$



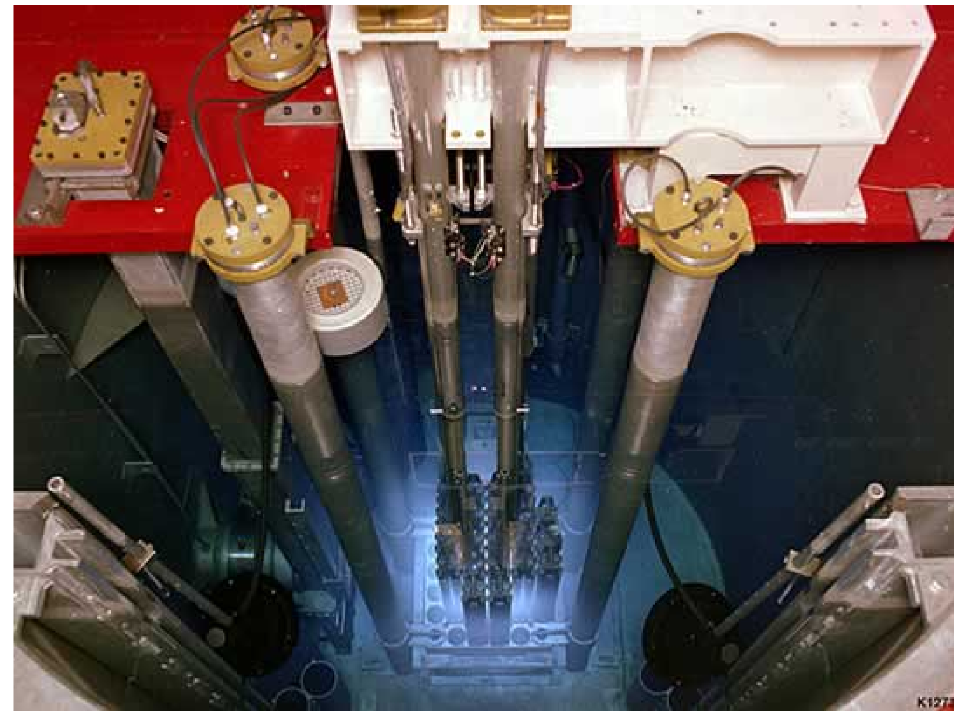


Cerenkov Radiation



$$\cos\theta_c = \frac{1}{\beta n}$$

$$threshold: \beta > \frac{1}{n}$$

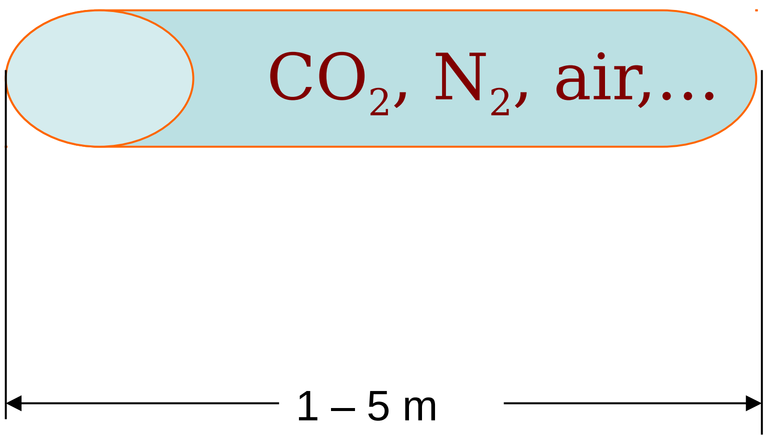


Typical blue Cerenkov light in a nuclear reactor core

PID: Cerenkov Radiation

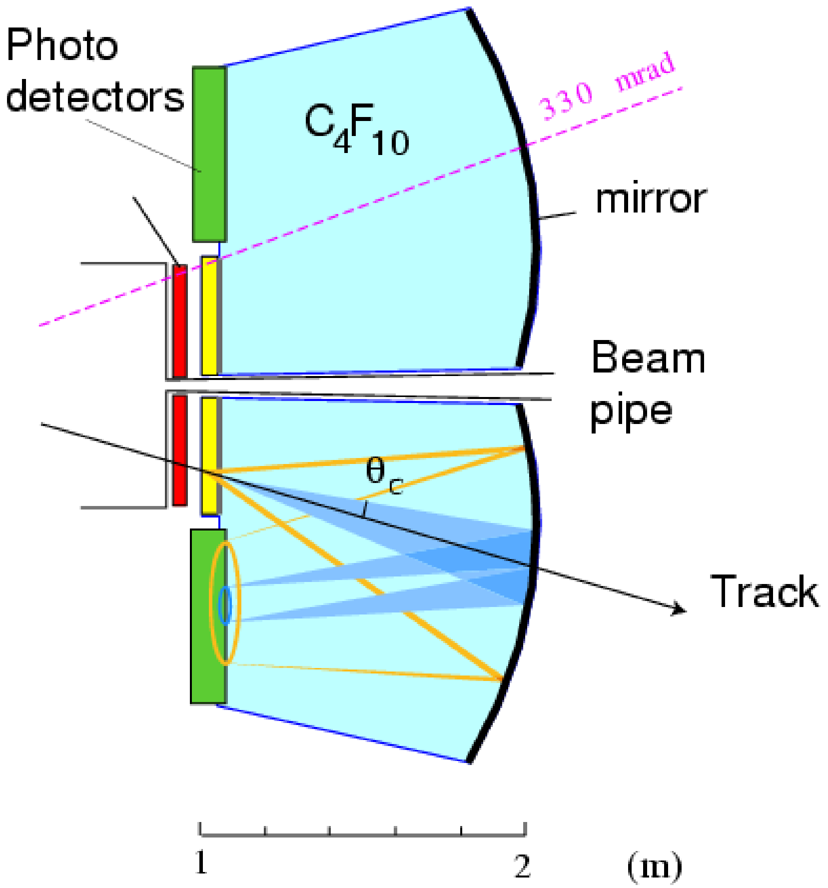
<u>Threshold detectors</u>

Record the presence of Cerenkov radiation emitted in a particular volume, often filled with gas or low density material.

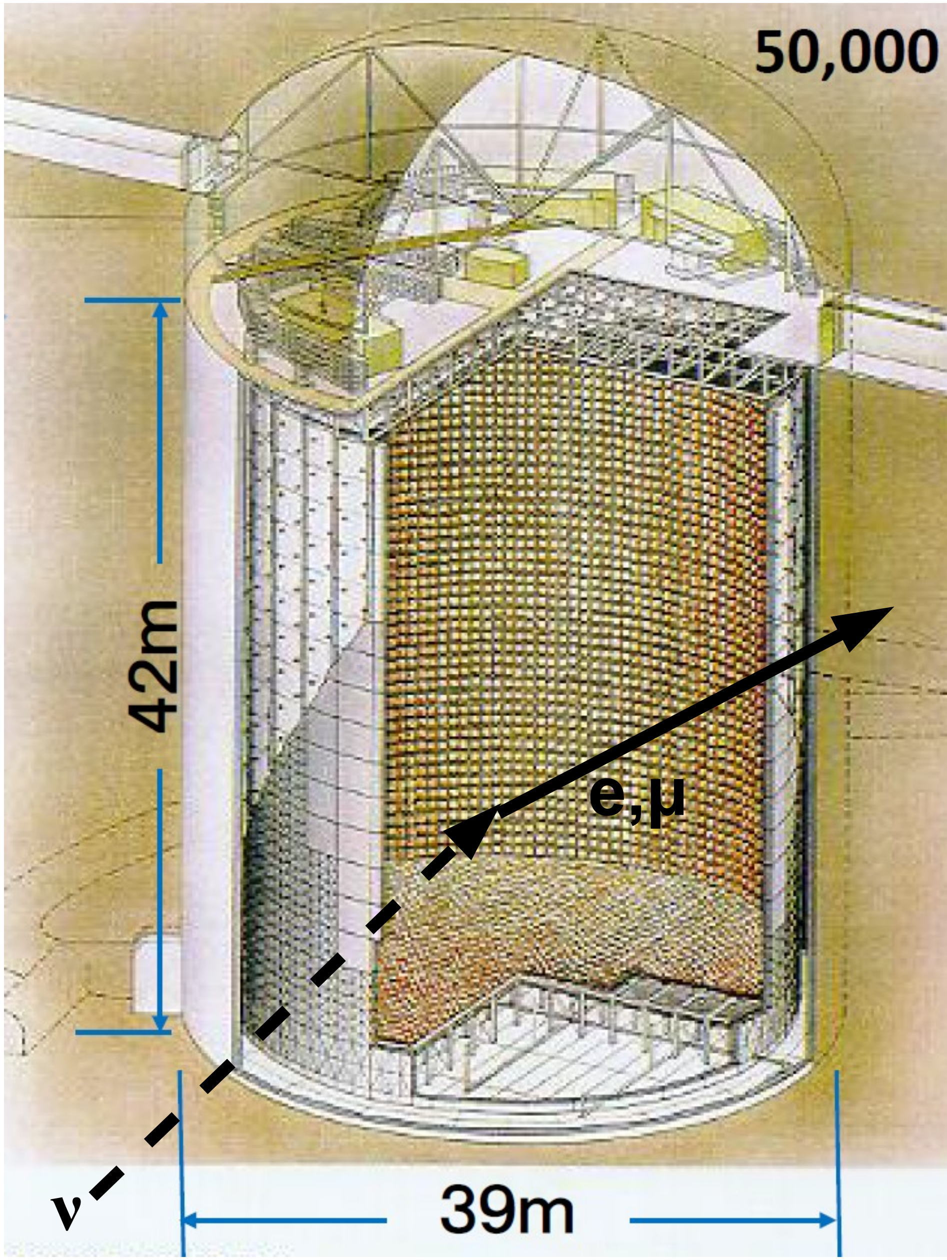


<u>Ring-Imaging Detectors</u>

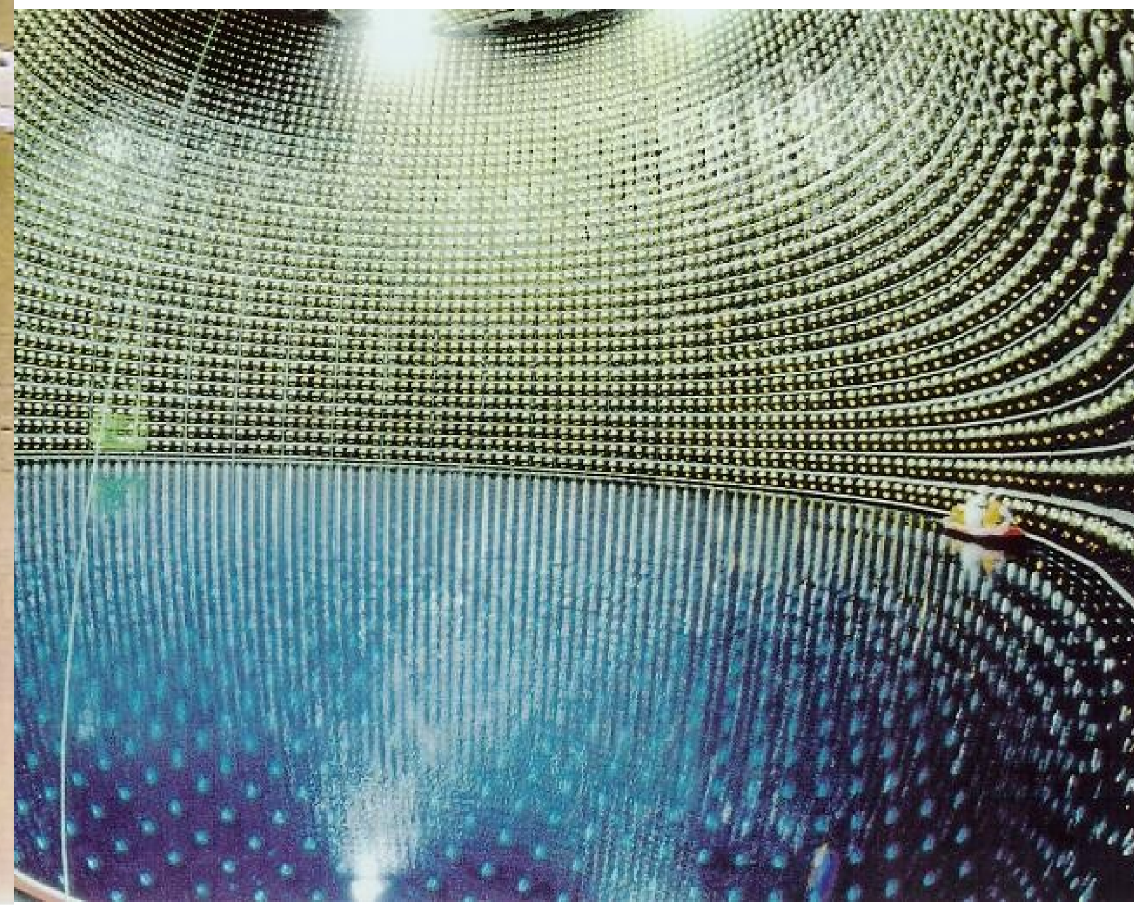
Reconstruct the actual Cerenkov cones themselves - much more complicated but much more powerful.



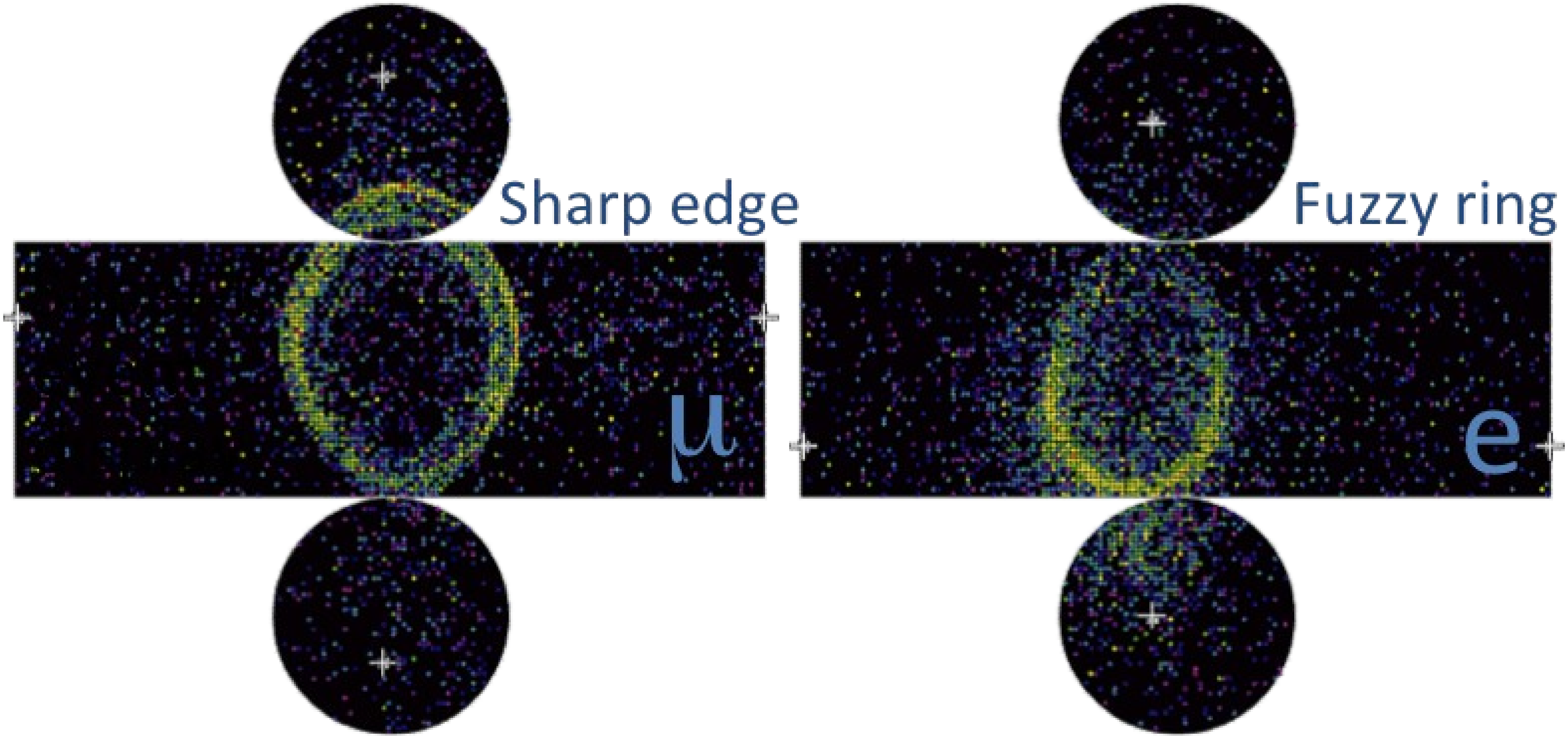
Cerenkov Radiation in SuperK



Detect electrons and muons created by electron and muon neutrinos

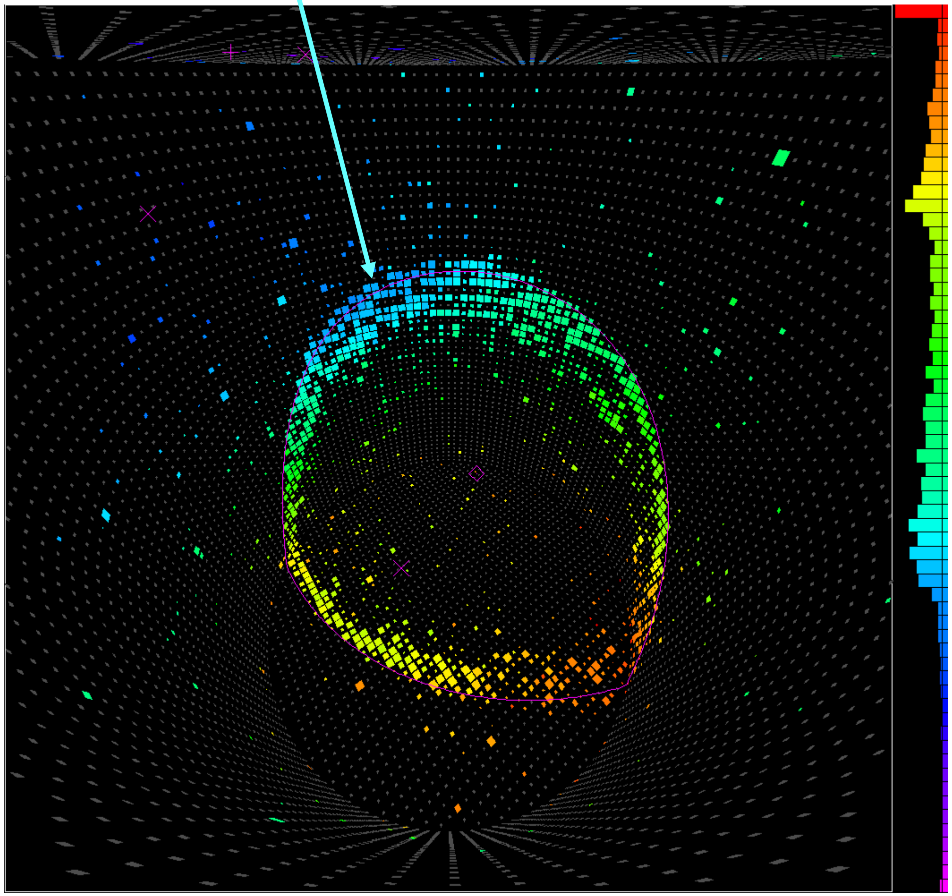


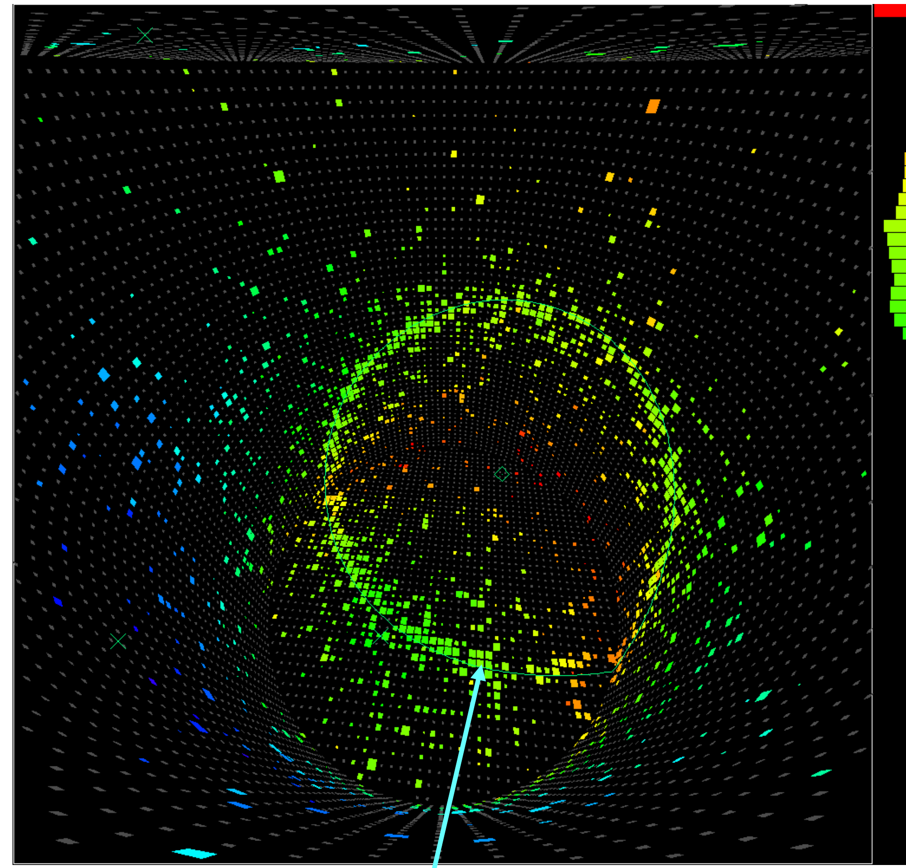
Cerenkov Radiation



Cerenkov Radiation in IceCube

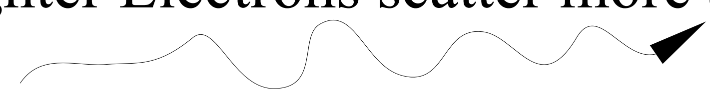
ν_μ produces a μ, which gives rise to a sharp ring



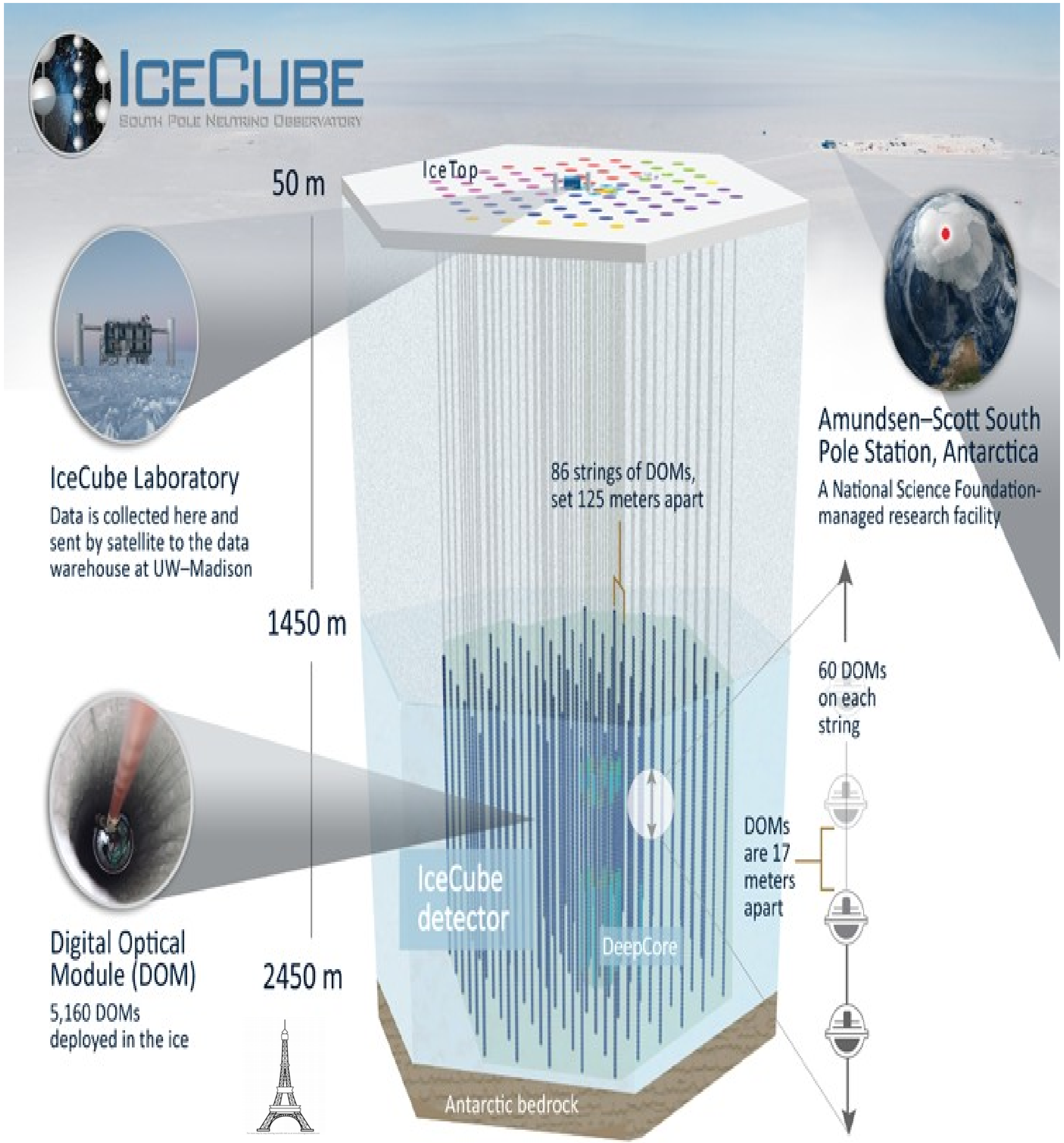


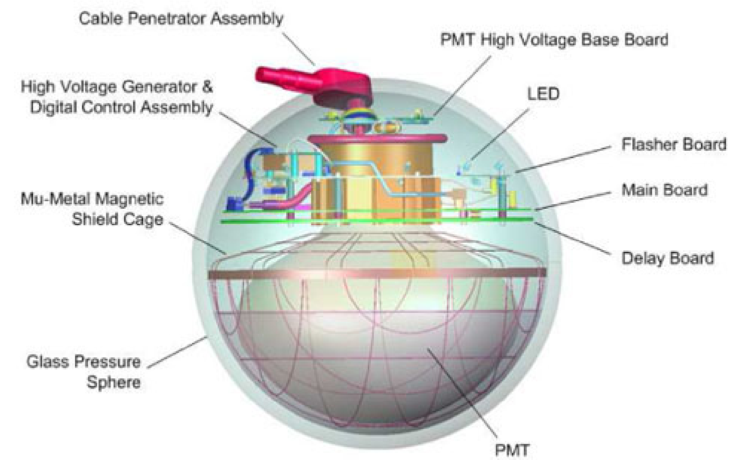
ν_e produces an electron, which gives rise to a “fuzzy” ring

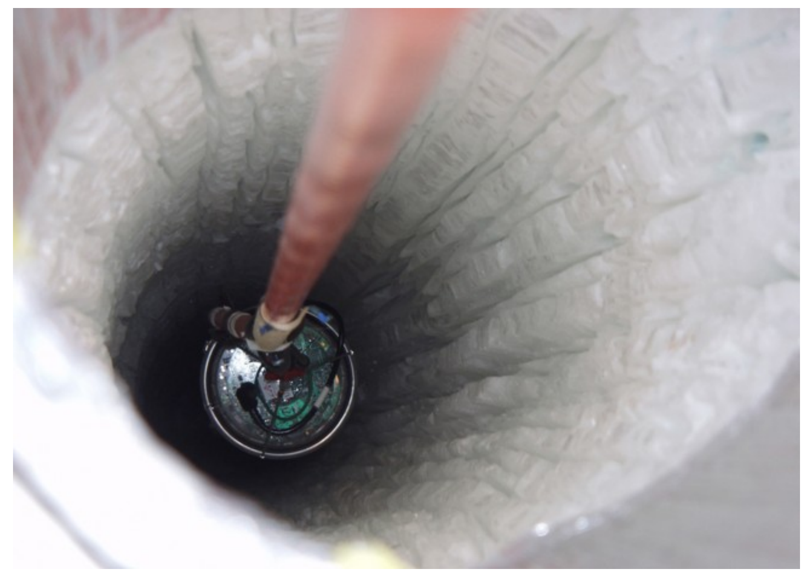
Lighter Electrons scatter more along



Cerenkov Radiation

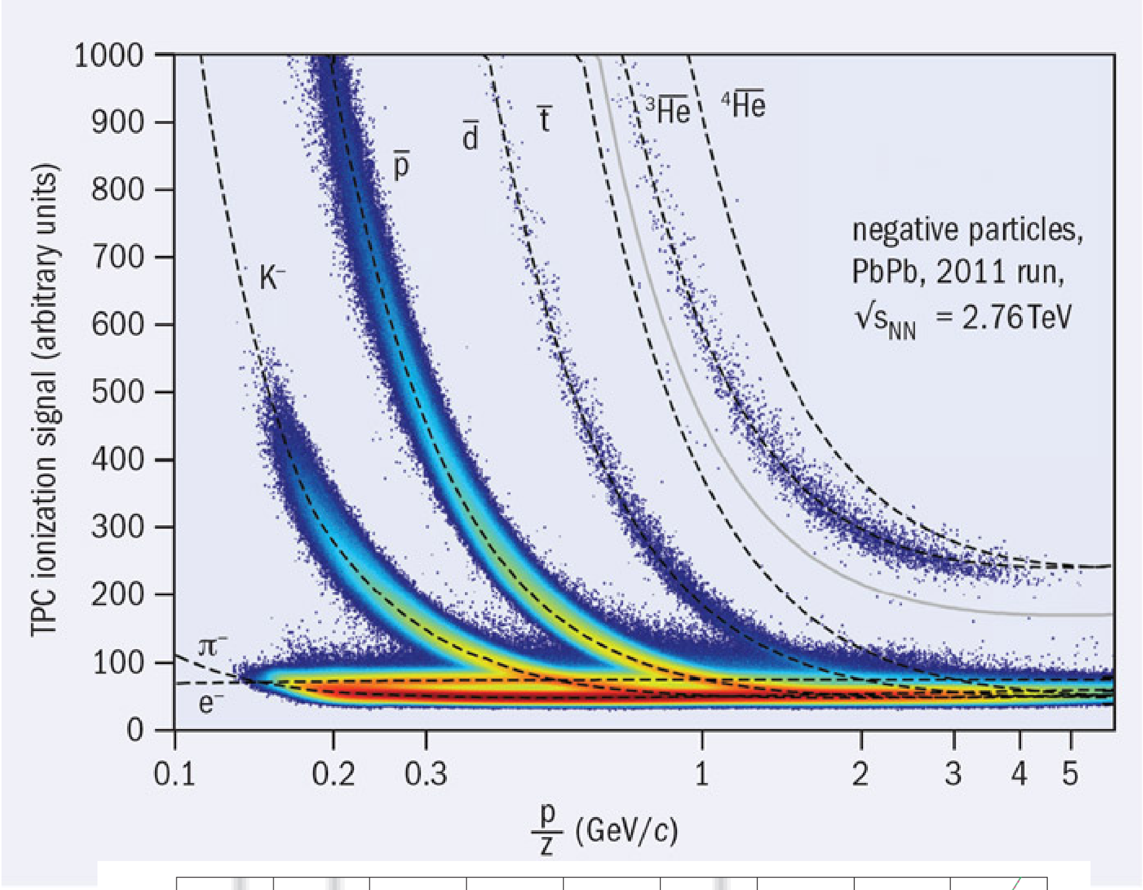


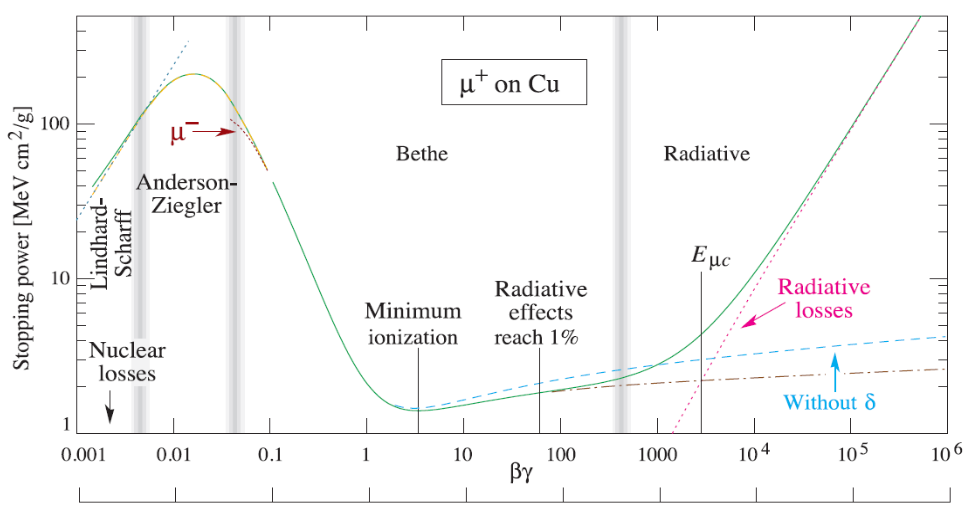




PID: dE/dX

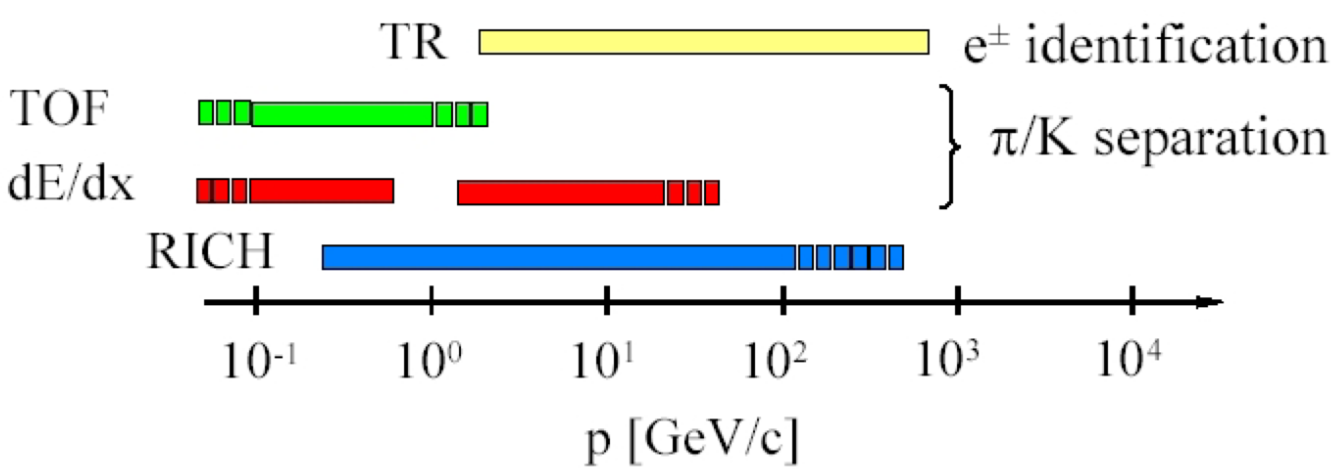
- Typical Bethe-Bloch formula ~ γβ
- p = γβm → γβ = p/m
- Minimum and start of lower rise shifted with mass when plotted versus momentum





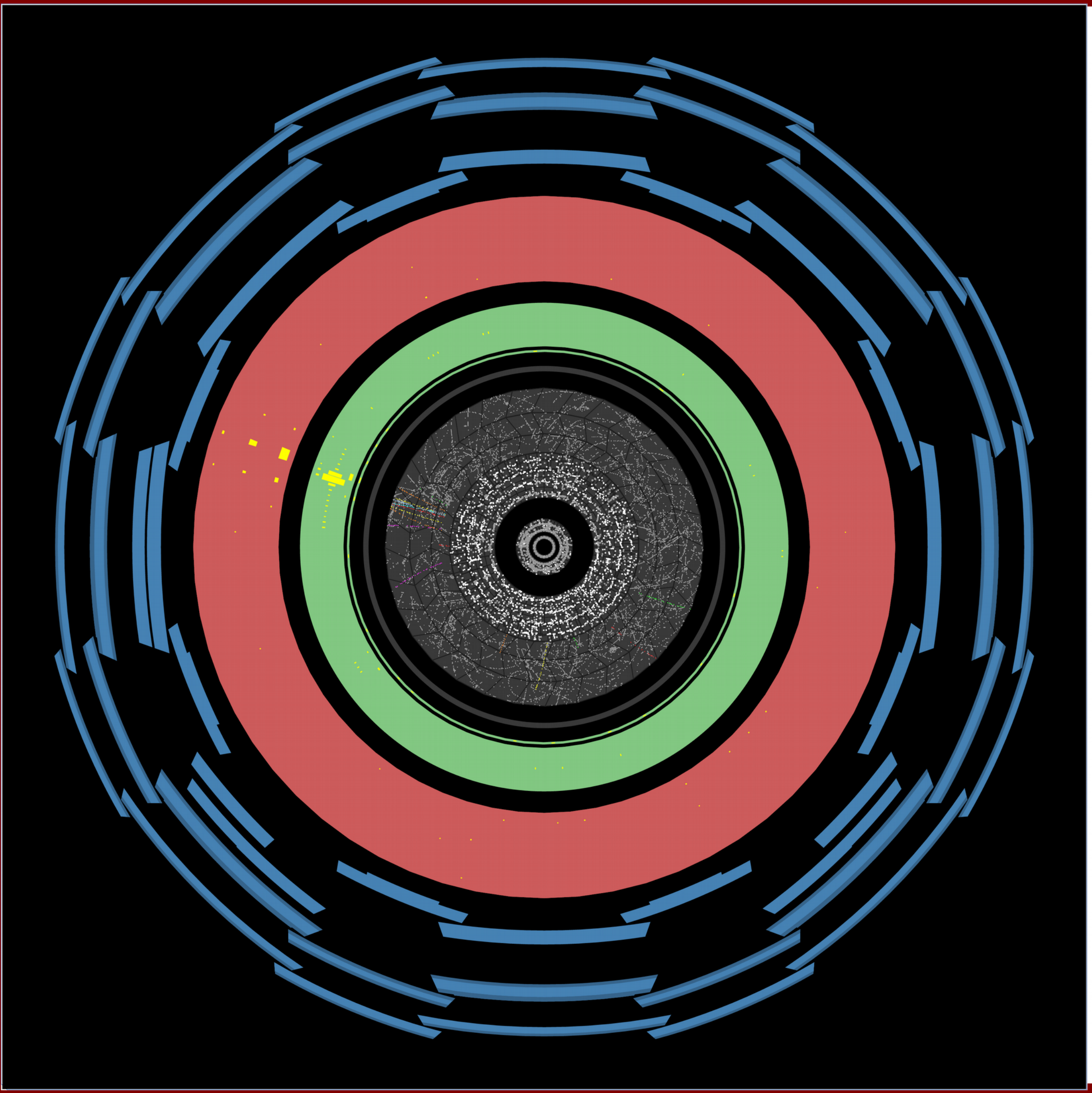
Particle ID summary

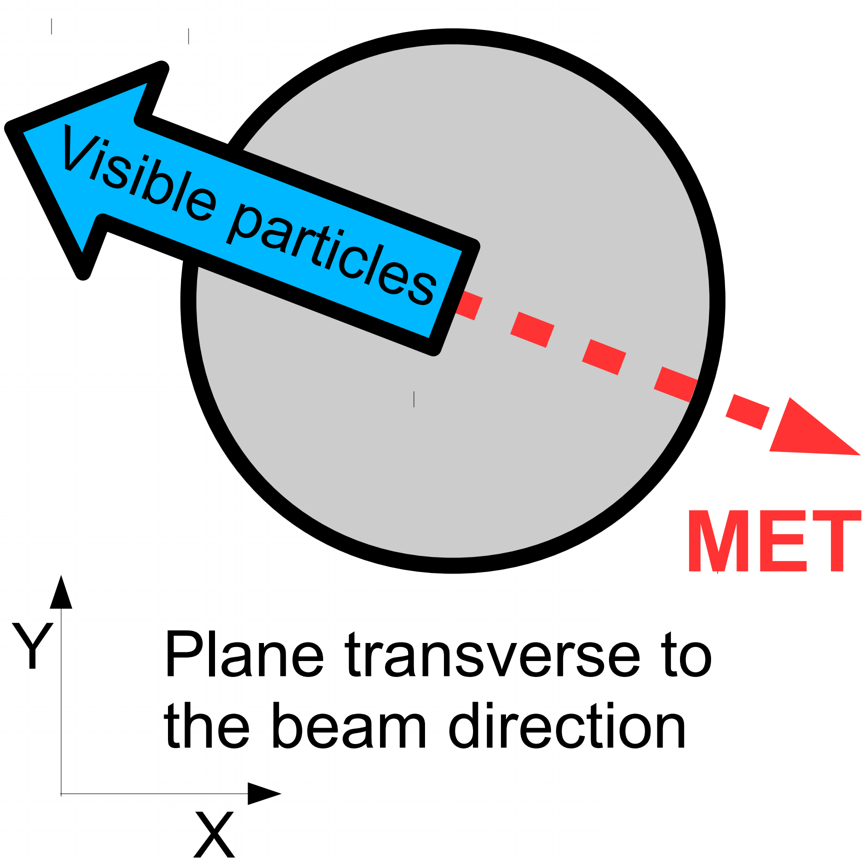
- Different methods work in different regimes
- For $\gamma\beta$ <3 : Time of Flight & dE/dX
- For 3< $\gamma\beta$ <14 : Threshold Cerenkov
- For 14< $\gamma\beta$ <140 : Ring-Imaging Cerenkov
- For 100< $\gamma\beta$ <1000 : dE/dX relativistic rise
- For 1000 < $\gamma\beta$: Transition radition



Bonus Slides

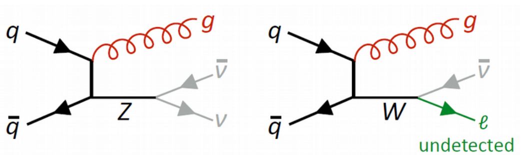
Missing transverse Energy MET



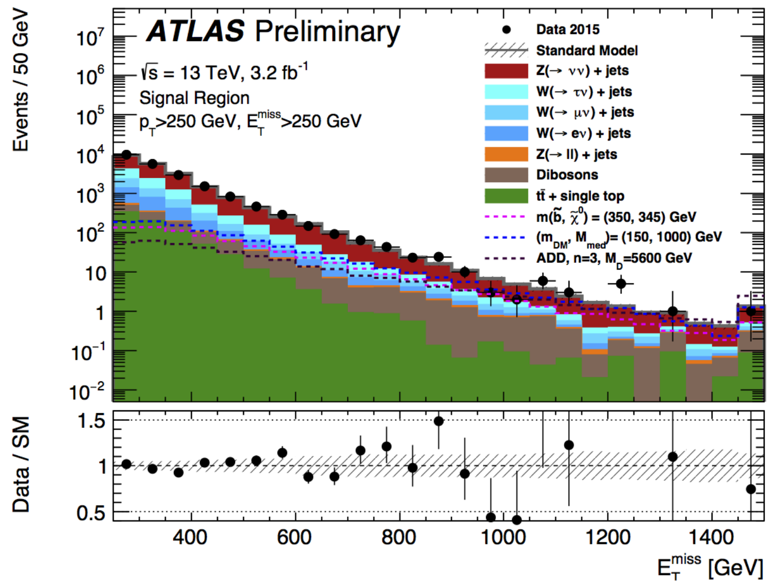


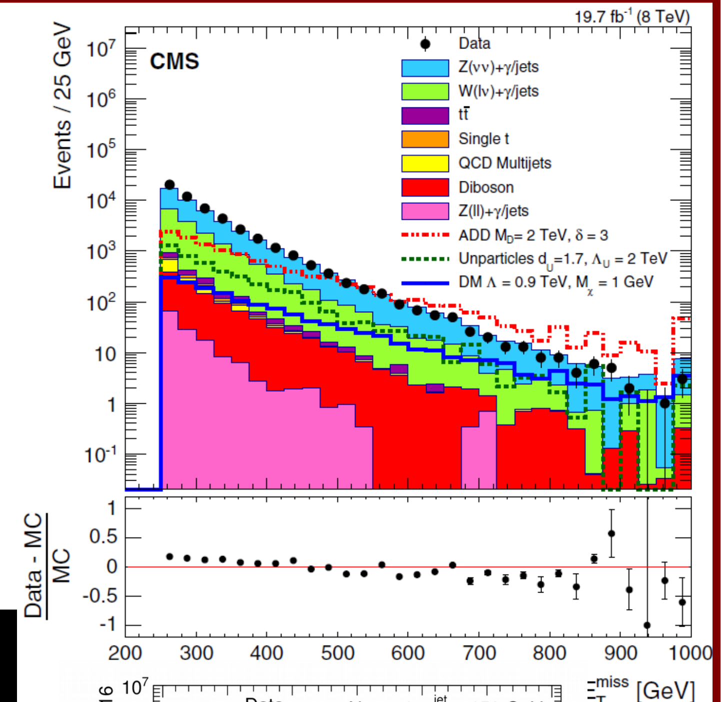
Mono-Jet: Backgrounds

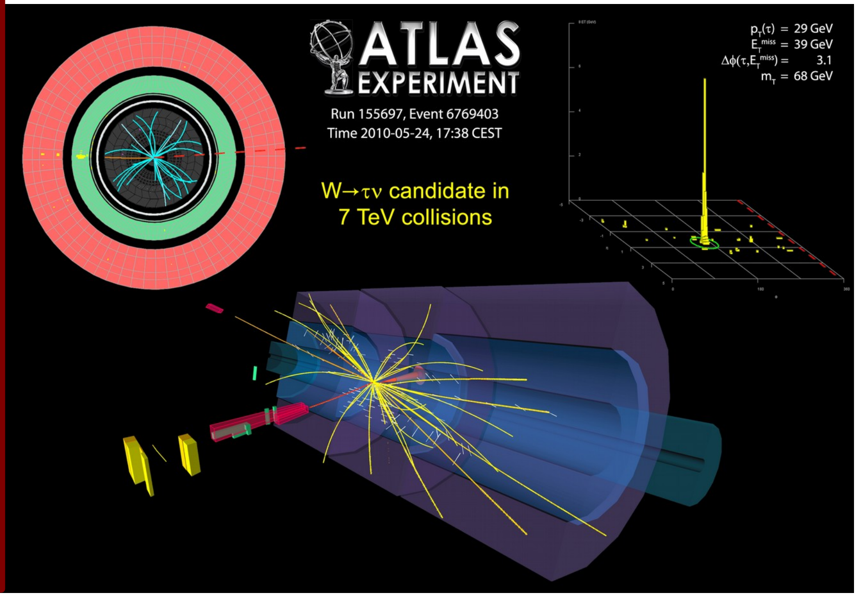
- MET hard to model
- Estimate/measure invisible decays (ν's)

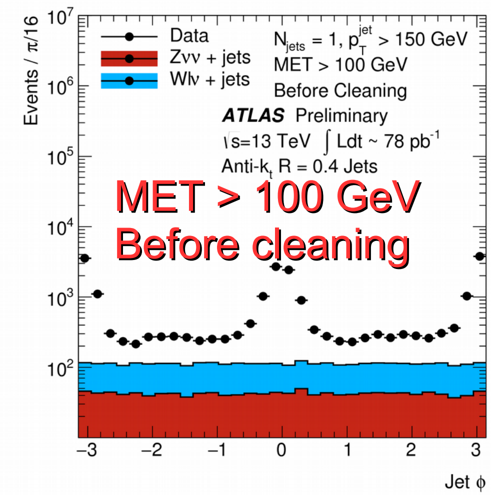


- use Z→ ll & W→ lν to model Z→ νν
- Detector effects & non-collision bkgs are very important too!
- Distributions rather well described



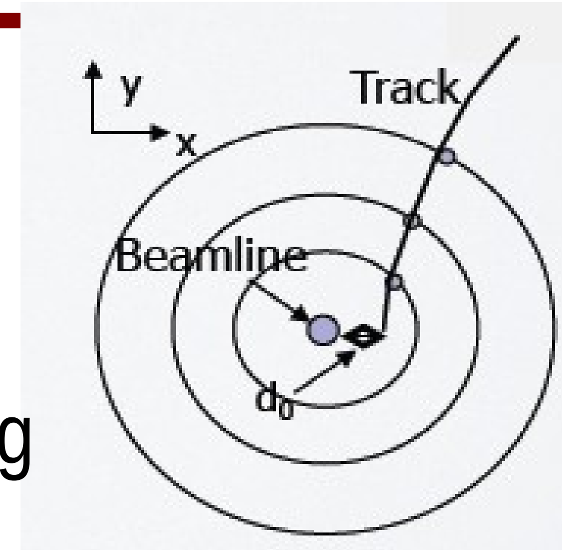


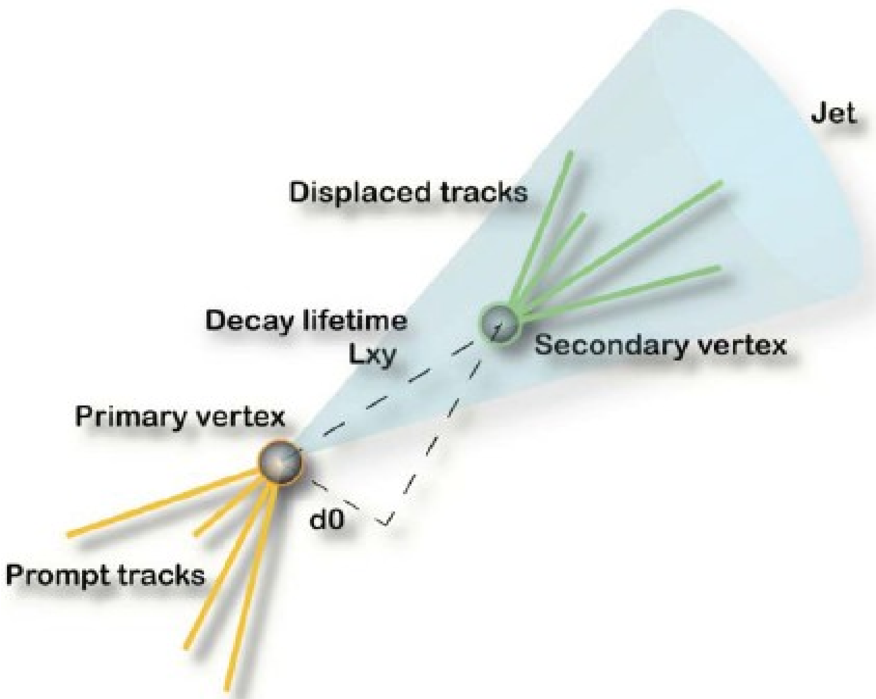


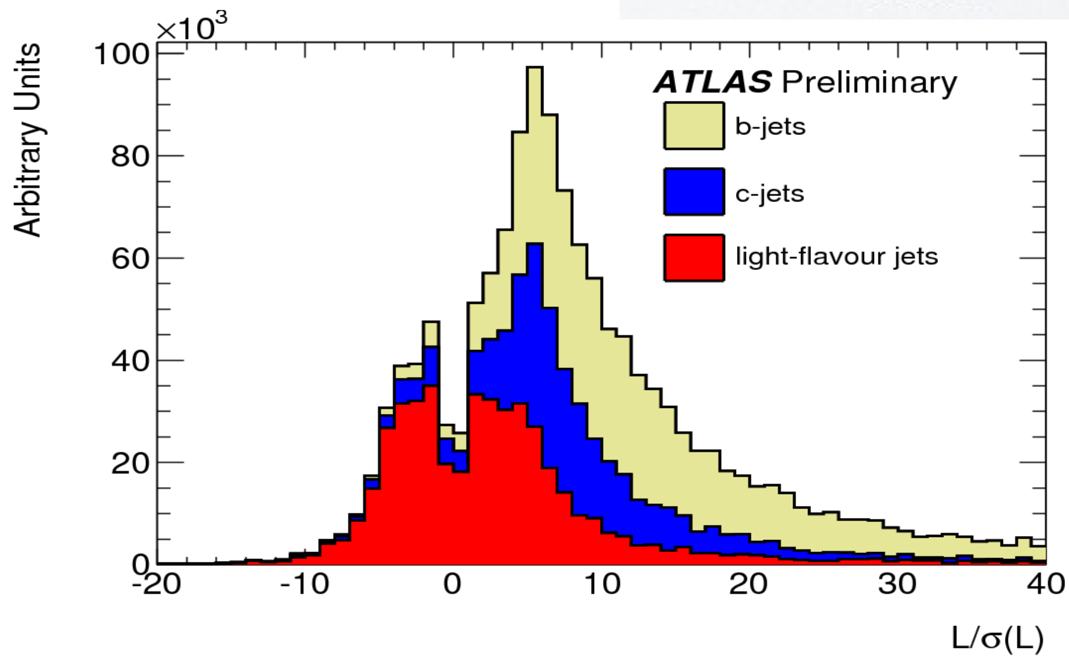


Jets: b-tagging

- Exploit properties of b-meson decay
  - Long lifetime ($c\tau \sim 450\ \mu m$)
    → ~ several mm flight path
    → secondary vertices
  - Semileptonic decays → soft lepton tagging

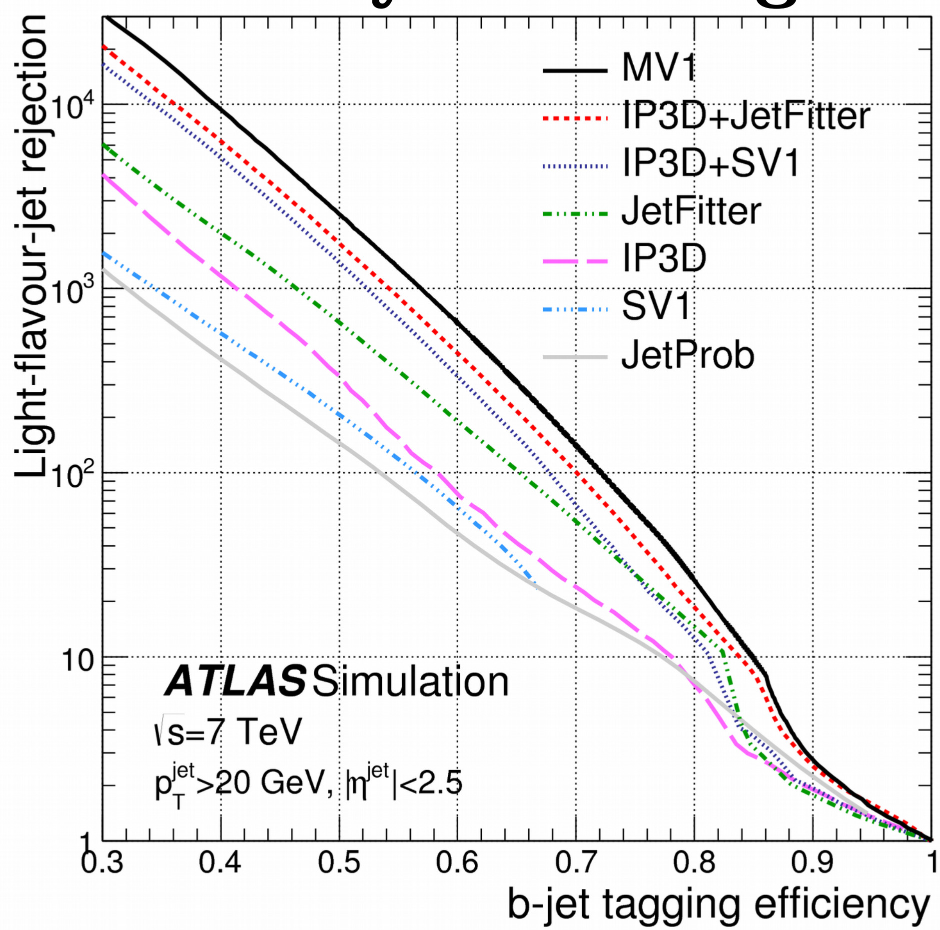


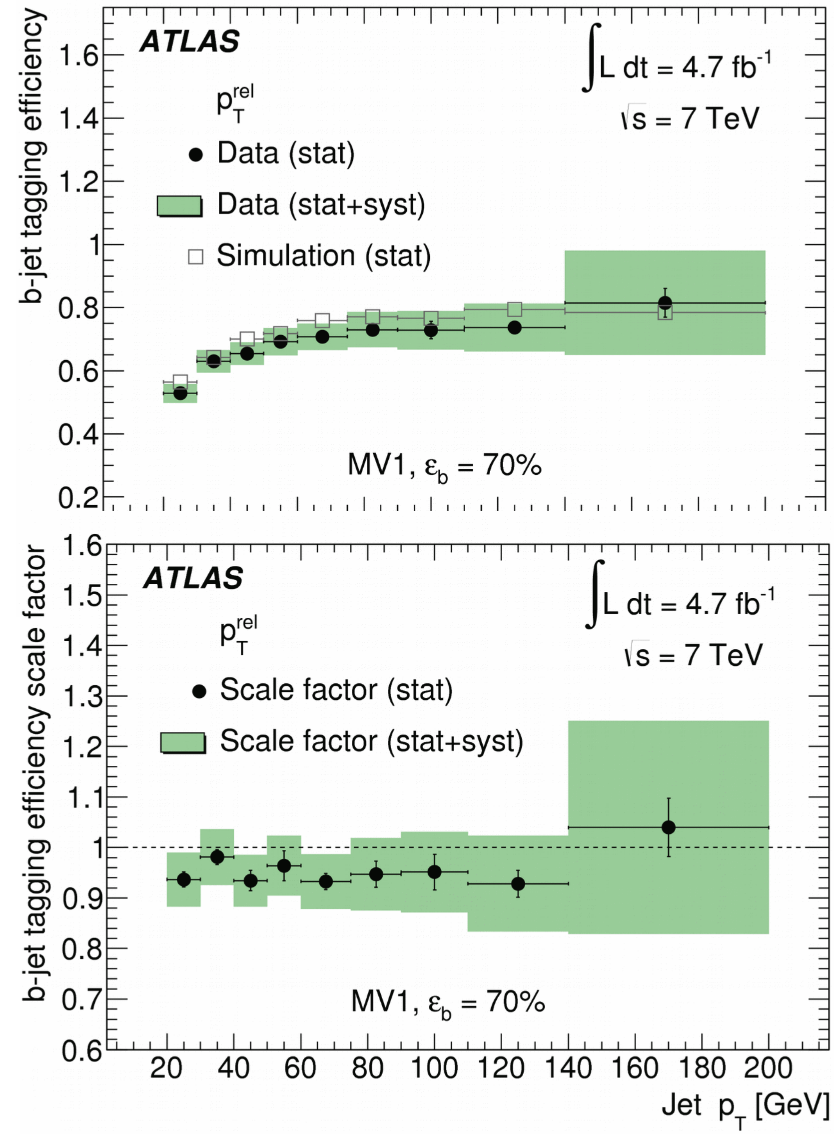




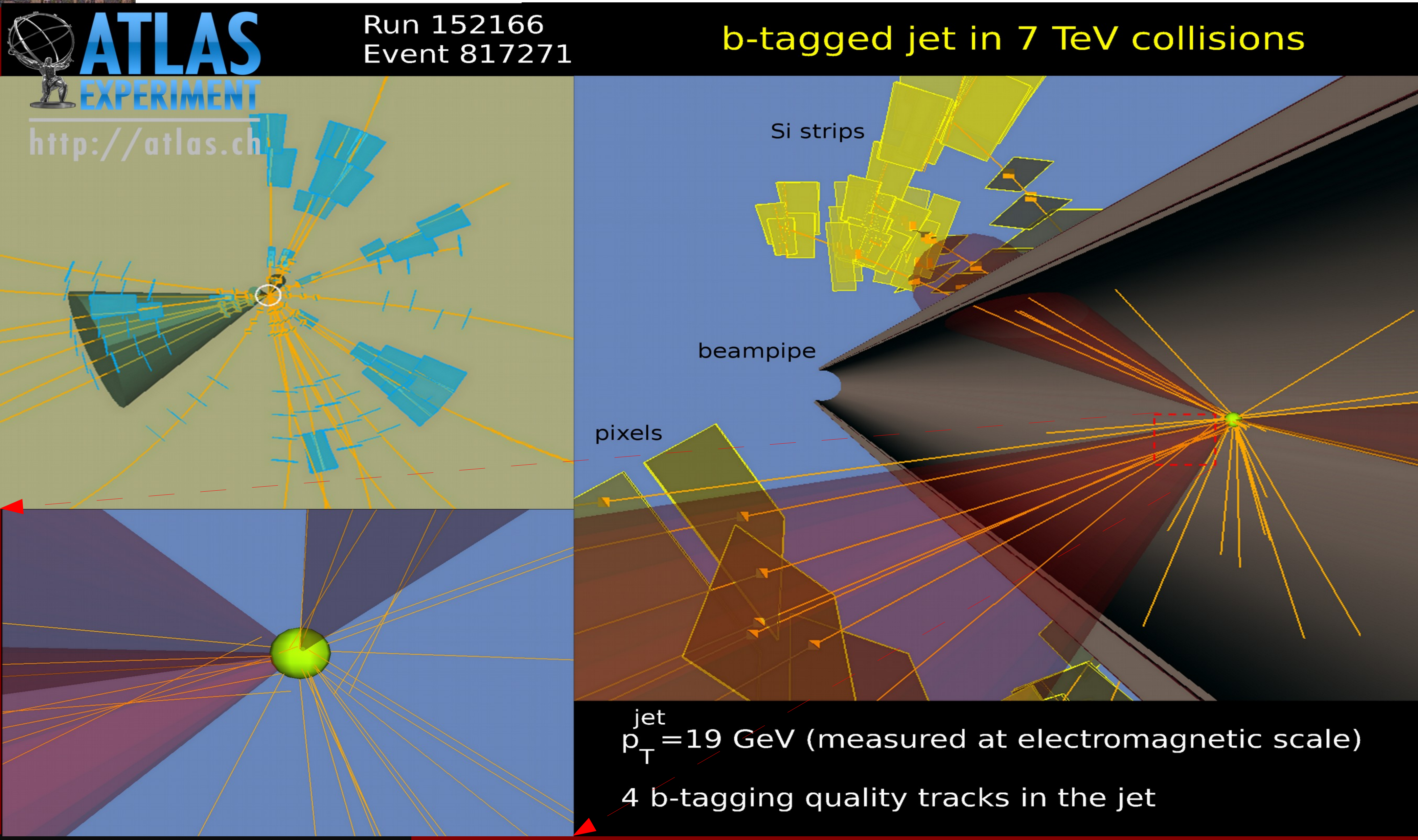
b-tagging

- Figures of merit: efficiency & mistag rate





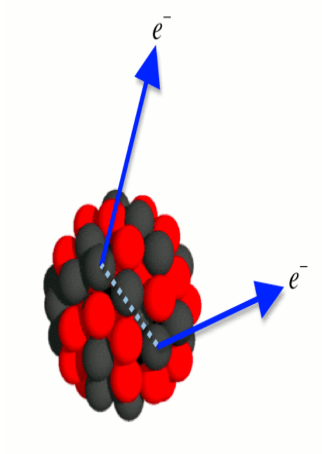
Example of a b-tagged jet

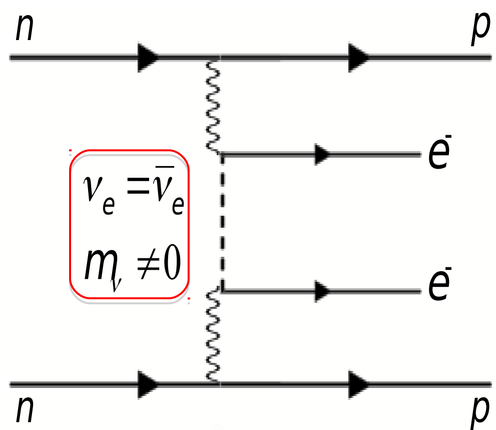


Object Reconstruction

- Tracking
- Find connected clusters in the Calorimeter
- Extrapolate/connect tracks with
  - Electromagnetic Calorimeter → Electron Candidates
  - Muon Spectrometer → Muon Candidates
  - Hadron Calorimeter → Hadronic Jets
  - EM clusters without a track → Photon Candidates
  - Missing Energy/Momentum → Neutrino Candidates
- Reconstruct vertices from Track intersections
  - Displaced vertices → b-jets
  - Displaced vertices of electrons → conversions ($\gamma \rightarrow e^+e^-$)

Experiments: SuperNemo

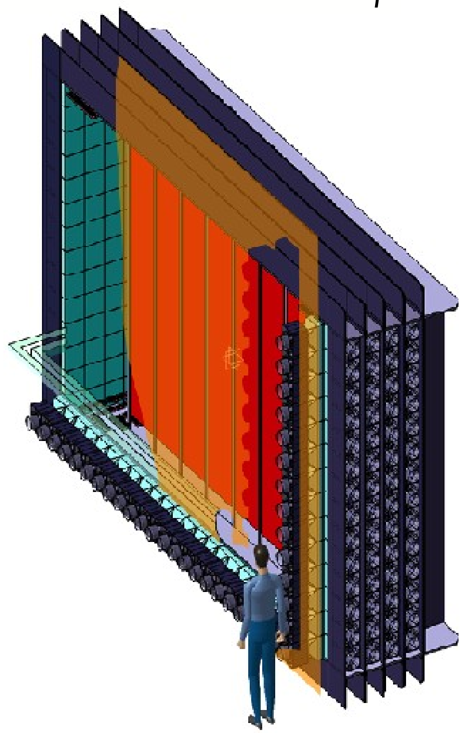


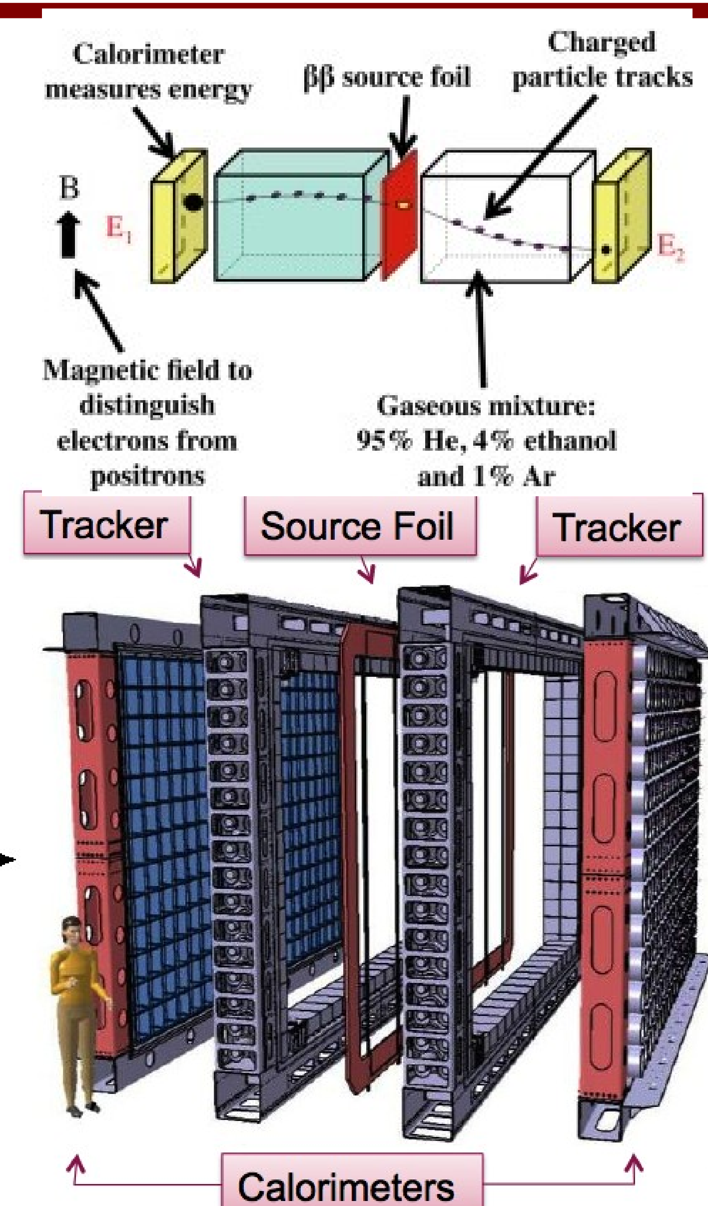


0-Neutrino Double Beta Decay

$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$

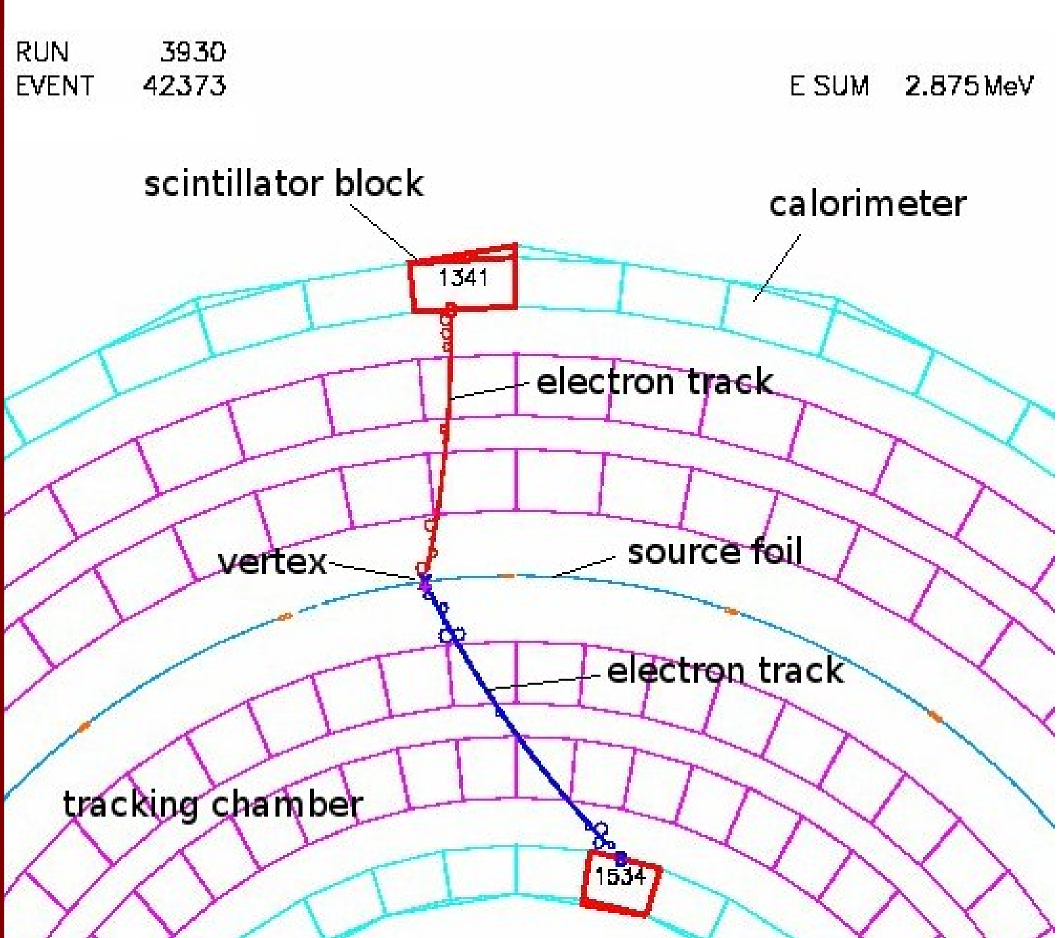
- Lepton number violation: $\Delta L=2$
- Forbidden in Standard Model
- Rate($0\nu\beta\beta$) << Rate($2\nu\beta\beta$)

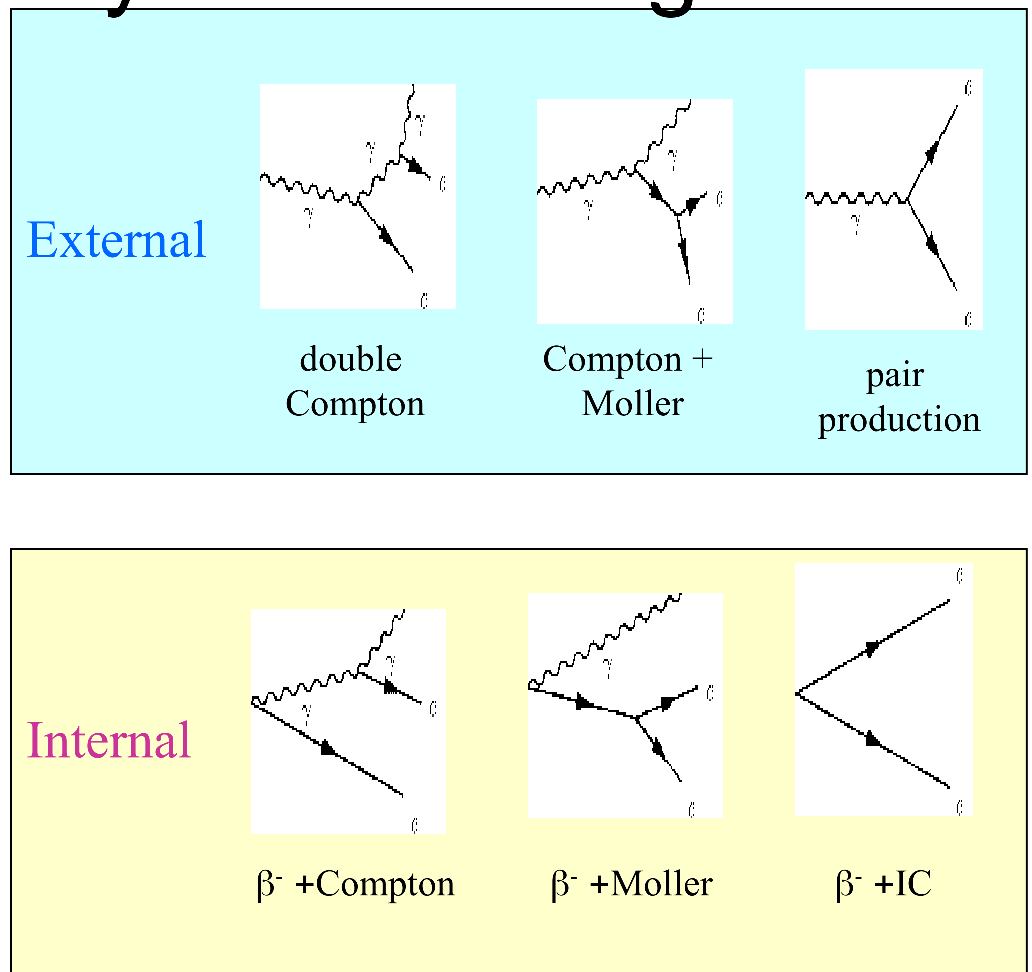




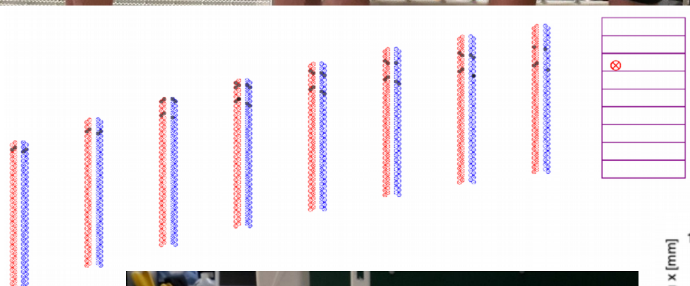
Experiments: SuperNemo

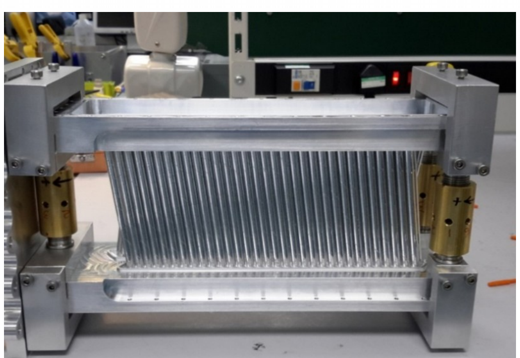
- Tracking & vertexing also key in SuperNemo
- Distinguish real $\beta^-\beta^-$ decays from background





Experiments: g-2





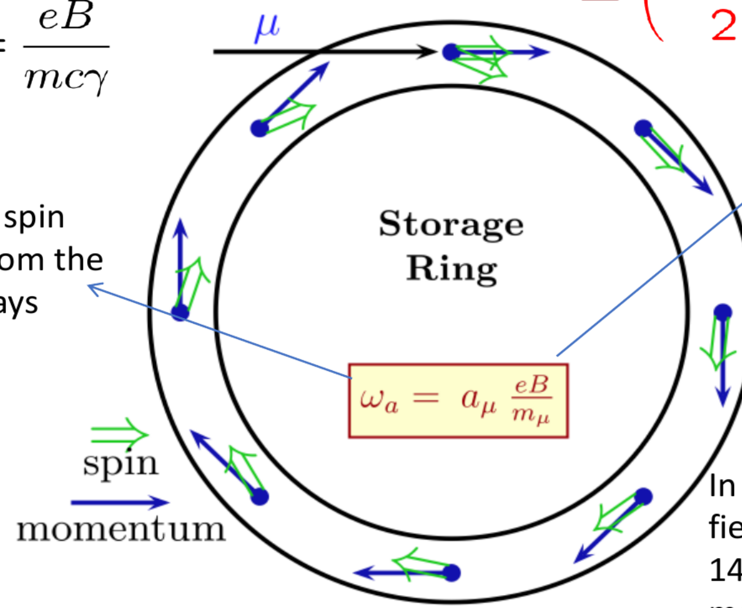
How?

$$\omega_S = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

$$\omega_C = \frac{eB}{mc\gamma}$$

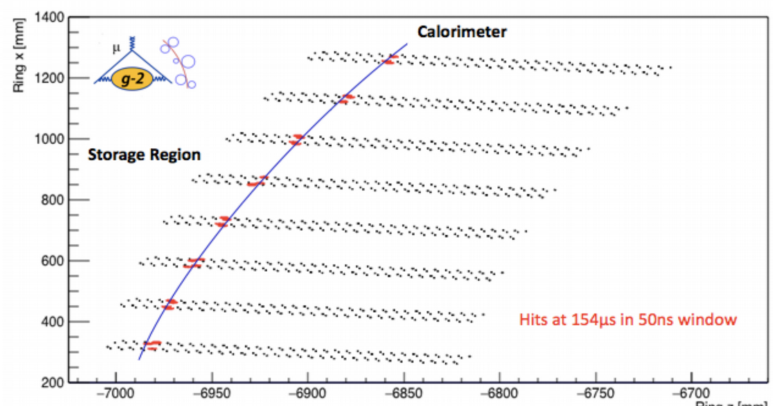
$$\omega_a = \omega_S - \omega_C = \left(\frac{g-2}{2}\right)\frac{eB}{mc} = a\frac{eB}{mc}$$

Measure the spin precession from the positron decays



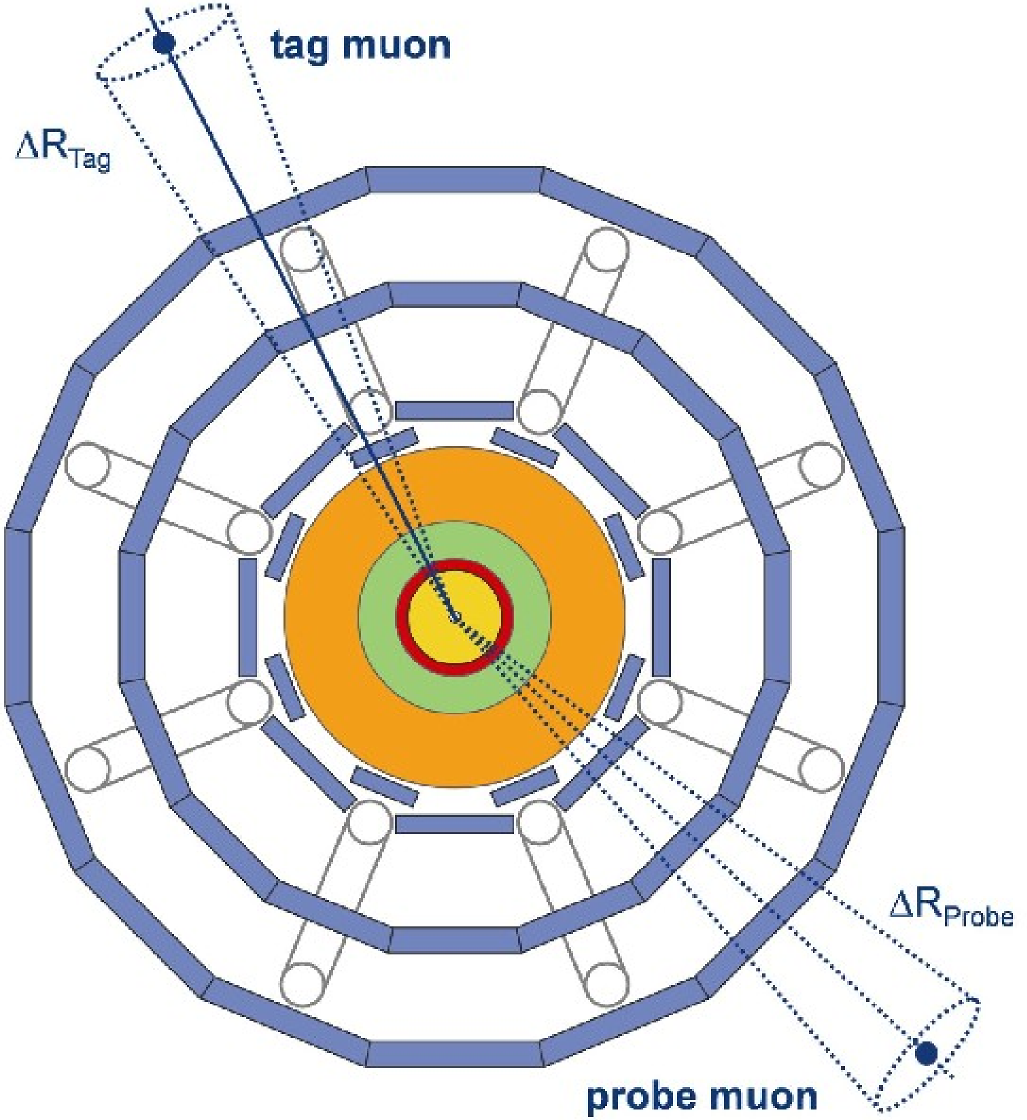
Measure the magnetic field in the ring

In a 1.5 T magnetic field the spin rotates in 144ns and the momentum in 149ns



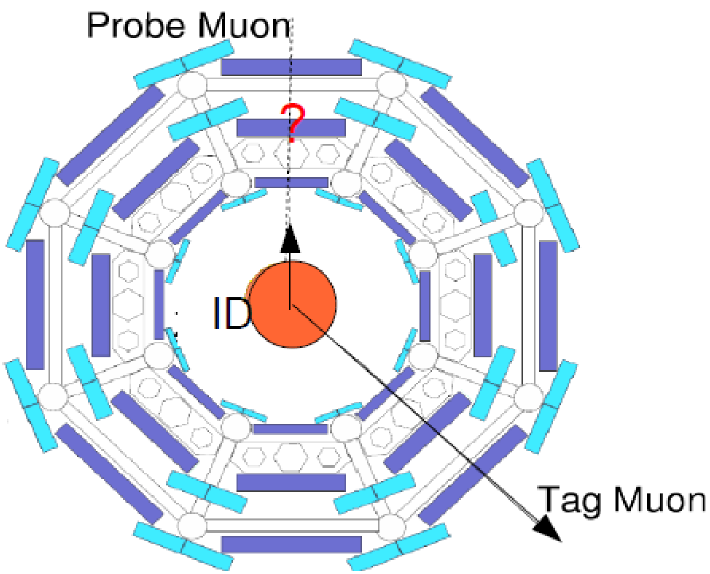
Measuring Efficiency

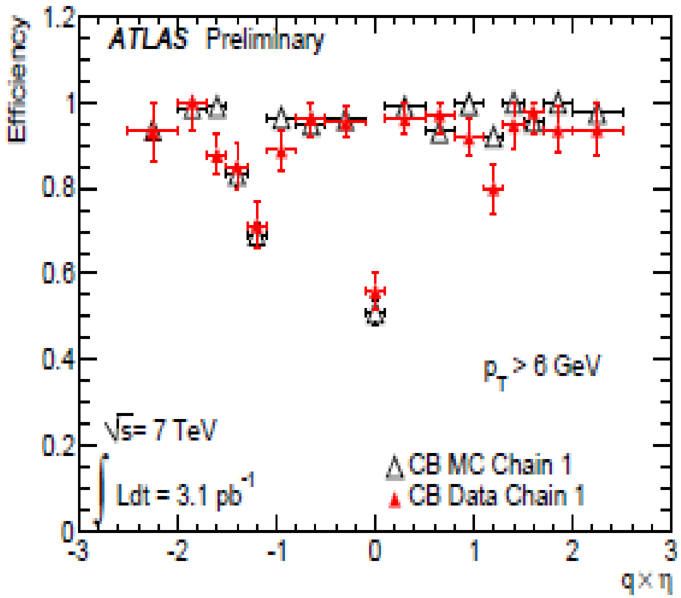
- From MC
  - With scale factor
- Tag & Probe
- With a subsample
  - e.g. collect loose object (10 GeV muons) and measure efficiency of tighter object (20 GeV muons)

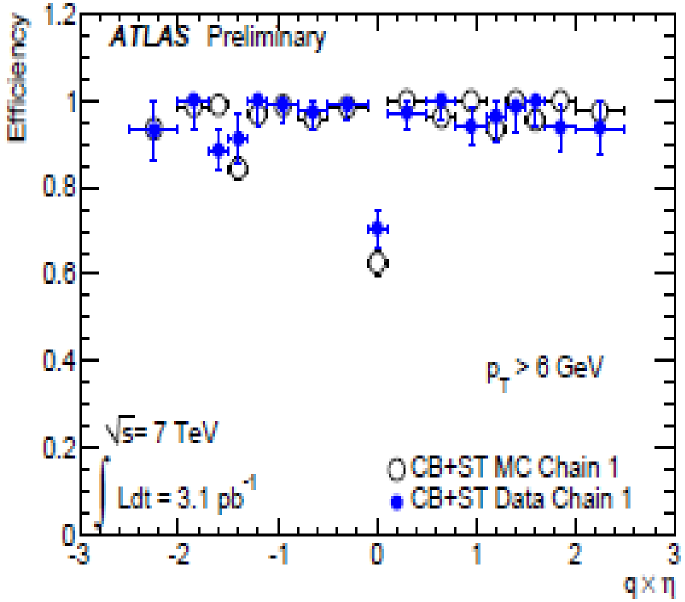


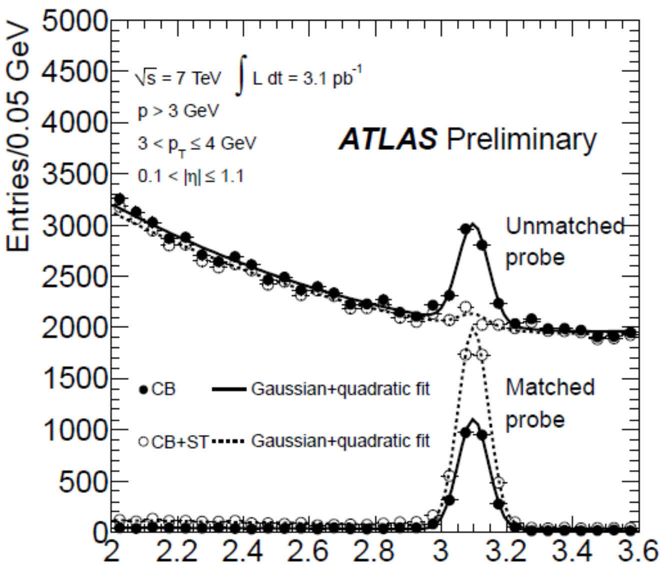
Tag & Probe: Efficiency Measurement

- Use standard candles as muon source ($J/\psi,\Upsilon,Z$)
- Tag with a well reconstructed muon
- Probes: track (reco eff.) , stand alone muon (tracking eff.), reconstructed muon (trigger eff.)





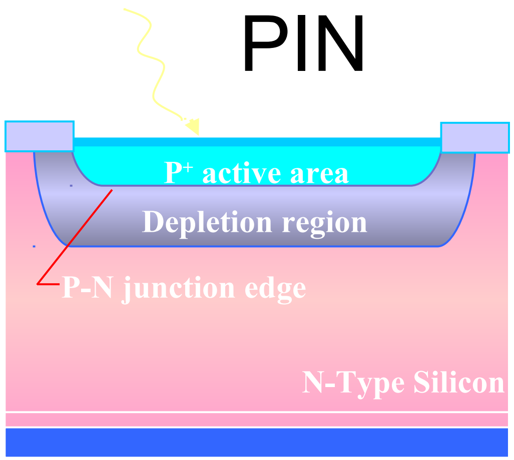


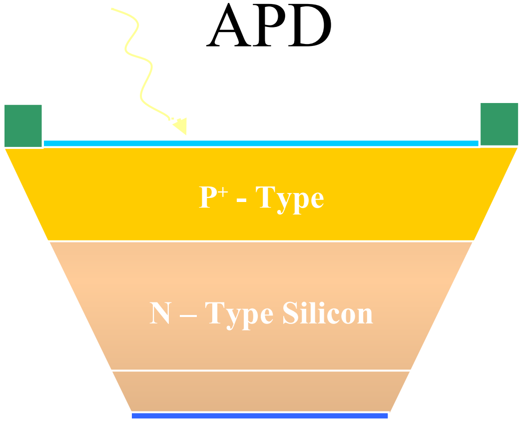


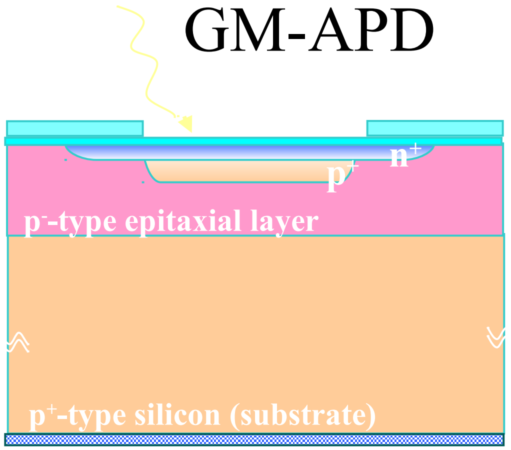
Bonus Slides

Modern PhotoDetectors

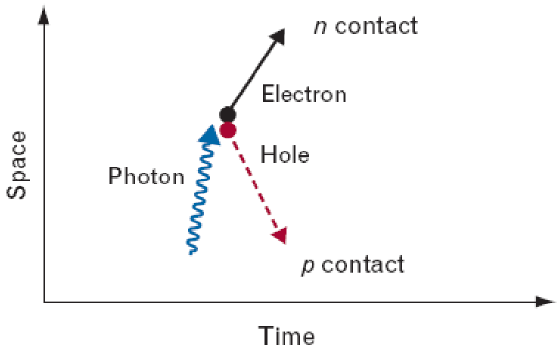
PIN	APD	GM-APD





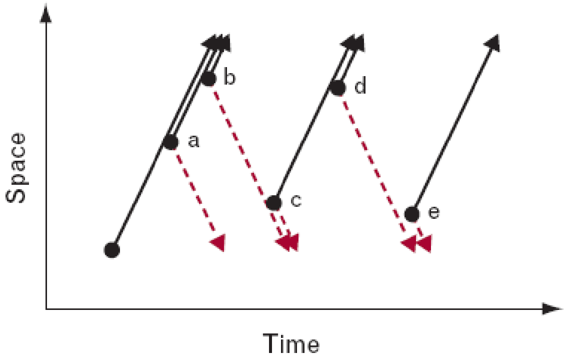


p-n junction



Gain = 1

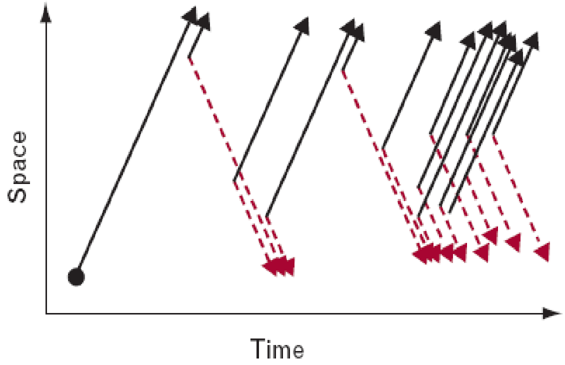
p-n junction, $V_{bias} < V_{BD}$



Gain = M (~ 50-500)

- linear mode operation-

p-n junction, $V_{bias} > V_{BD}$



Gain → infinite

-Geiger-mode operation-

Nicoleta Dinu