The STAR Experiment:

Matthew A. C. Lamont
Brookhaven National Lab

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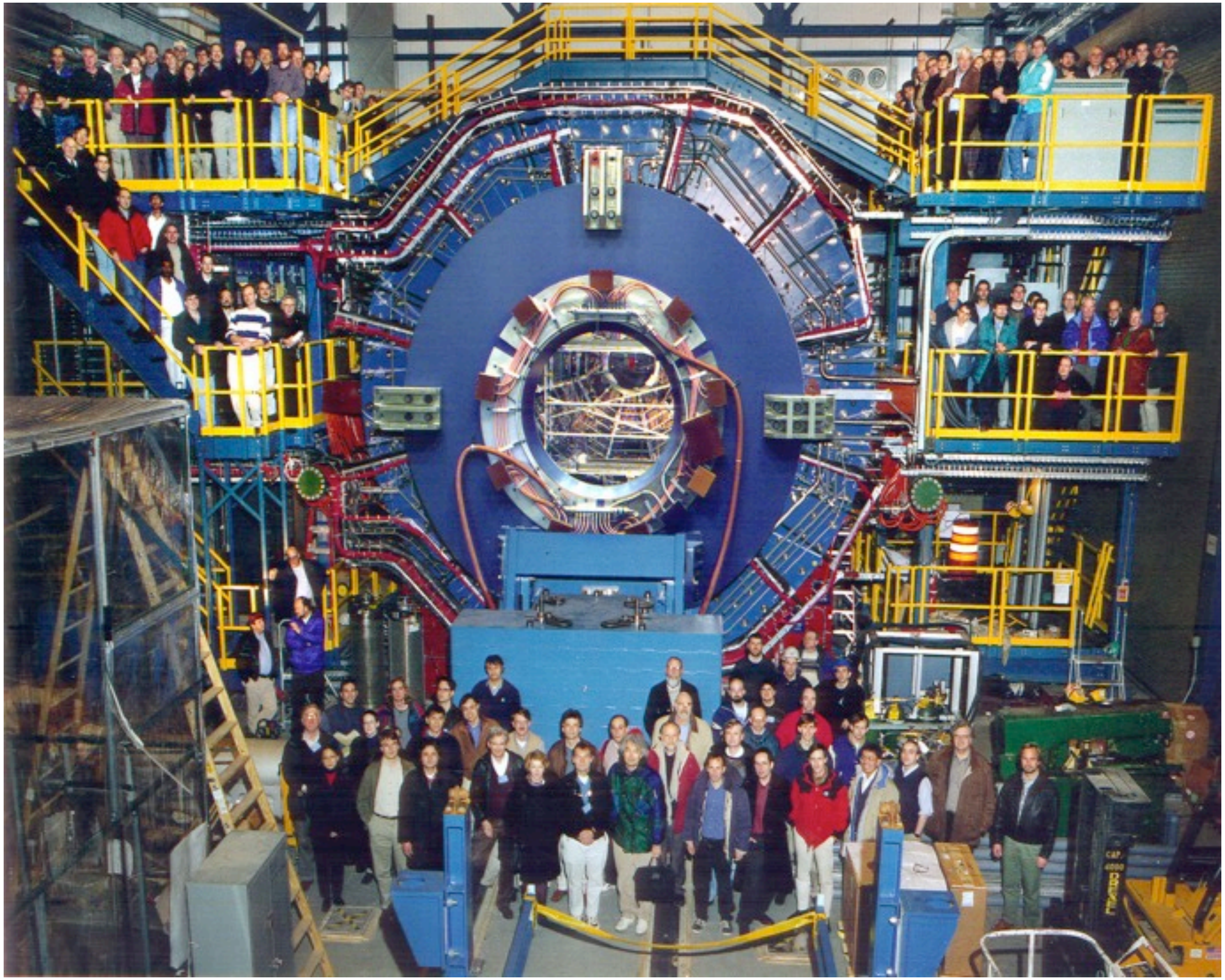
NATIONAL LABORATORY

The STAR Experiment: circa 2000



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The Perfect Detector ?

- Momentum **p**
  - magnetic field × length: B×dl
  - high-pt ⇒ large B×dl ⇒ small p_T tracks curl up
  - low-pt ⇒ small B×dl ⇒ high p_T tracks care straight (p_T res. lost)
- Particle ID
  - γ, e ⇒ hadron blind, little material
  - hadrons ⇒ PID through interaction with material
- Acceptance
  - large acceptance ⇒ lots of data ⇒ slow
  - small acceptance ⇒ few data ⇒ fast
- Energy
  - γ, e ⇒ E.M. Calorimeter
  - hadrons ⇒ Hadronic Calorimeter
- Heavy flavor ID
  - secondary vertices ⇒ high precision Si detectors = material
  - semileptonic decays (c, b → e + X, B → J/ψ (→ e e) + X) ⇒ hadron blind, little material

Particle identification – long lifetime (>5 ns)

Examples: π, K, γ, p, n, …

Charge (if any!) and 4-momentum needed for PID

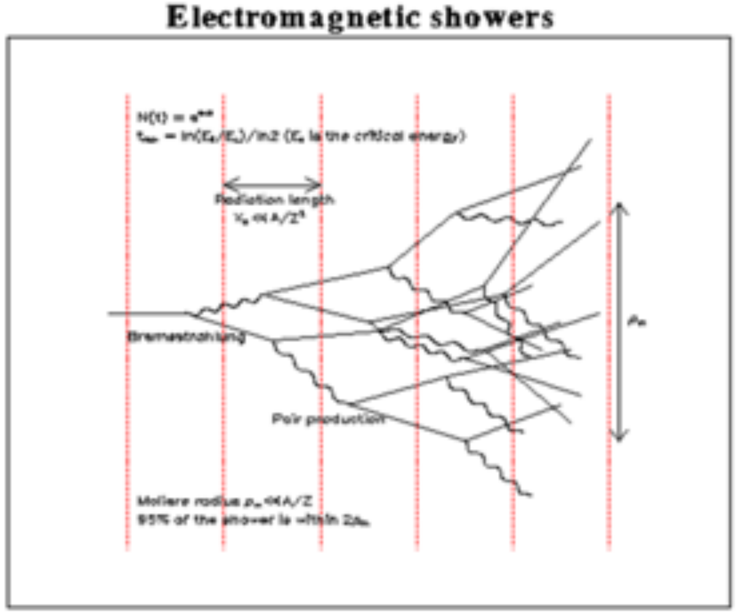
4-momentum from at least two of these quantities:

energy → **calorimetry** →

Fully stop the particle
Convert its energy to
- light, charge…

Collect and read out

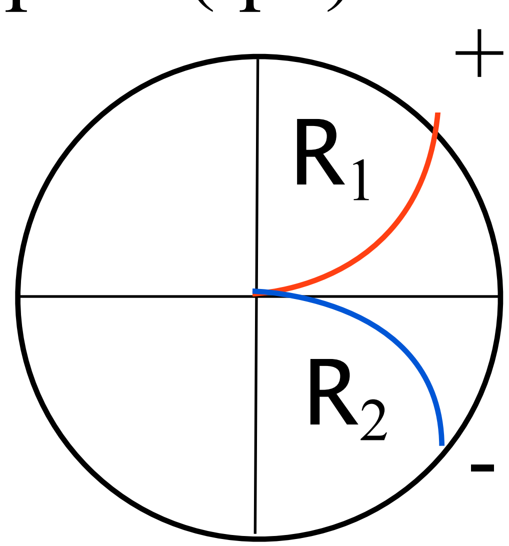
Electromagnetic showers



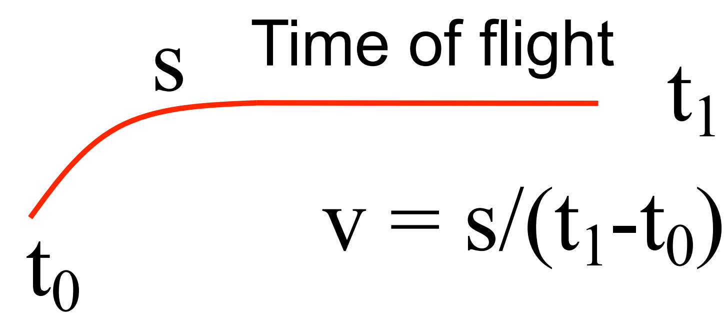
3-momentum → **tracking** →

Follow path of charged particles in magnetic field – get momentum from curvature

$$p_T = (q/c)\times B\times R$$

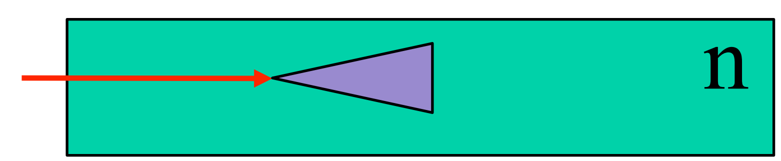


velocity → **time-of-flight + pathlength or Cherenkov-effect**



$$v = s/(t_1 - t_0)$$

Cherenkov



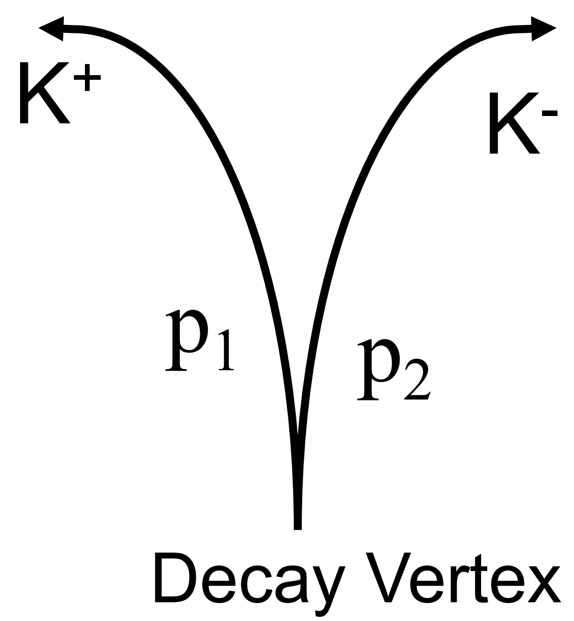
$$\cos(\alpha) = 1/\beta n$$

Particle identification – short lifetime (< 5 ns)

Examples: π^0, ϕ, Λ, …

Have to be reconstructed from their more stable decay products

Assume you want to measure the φ meson via its φ→KK decay by measuring both kaons and reconstructing its invariant mass



$$m^2 = (p_1 + p_2)^2$$

But what if there are more than 2 kaons in the event? Or you take a pion for a kaon? Which two go together?

S = Total - Background

Background could be like-sign pairs or pairs from different events

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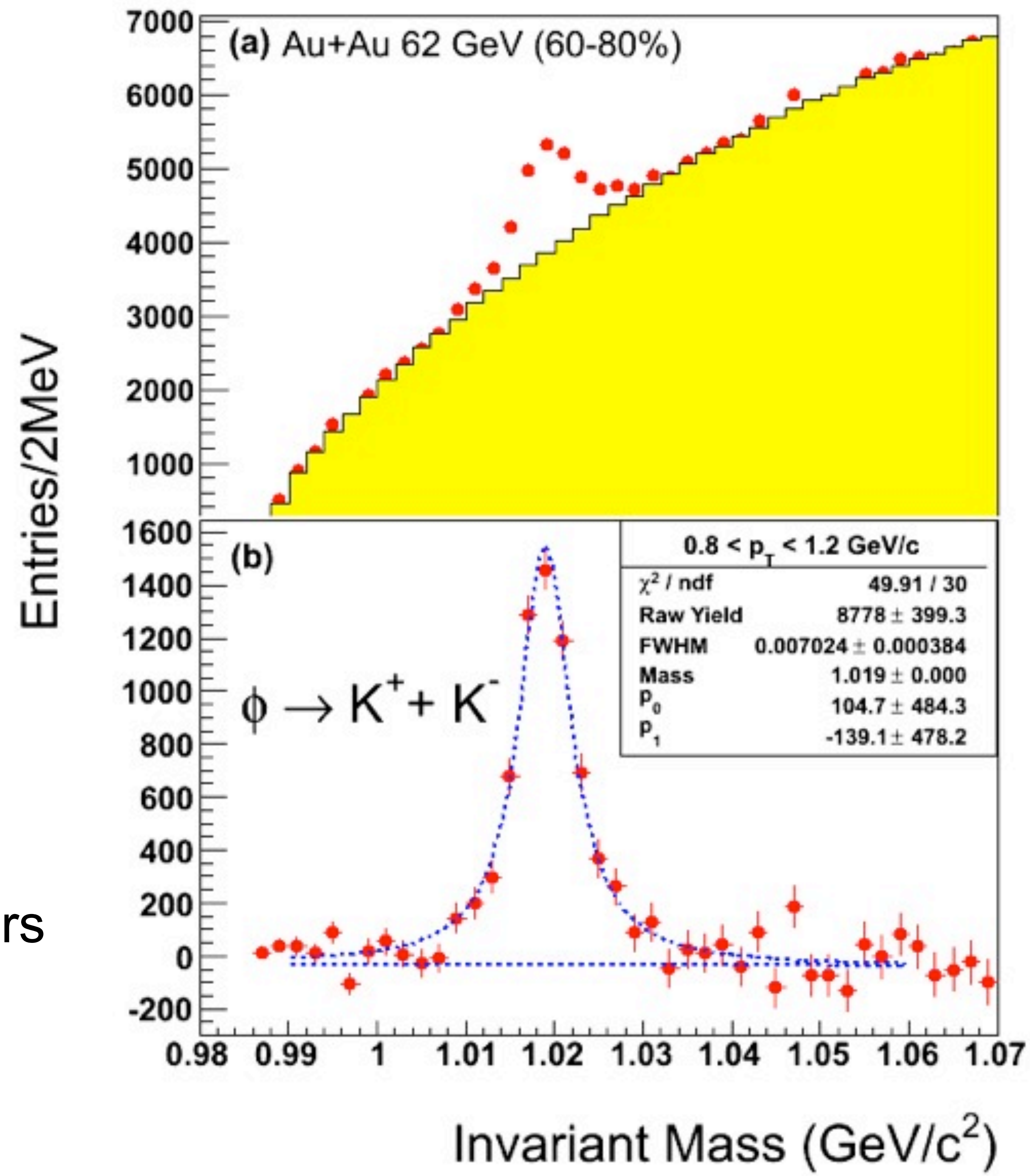

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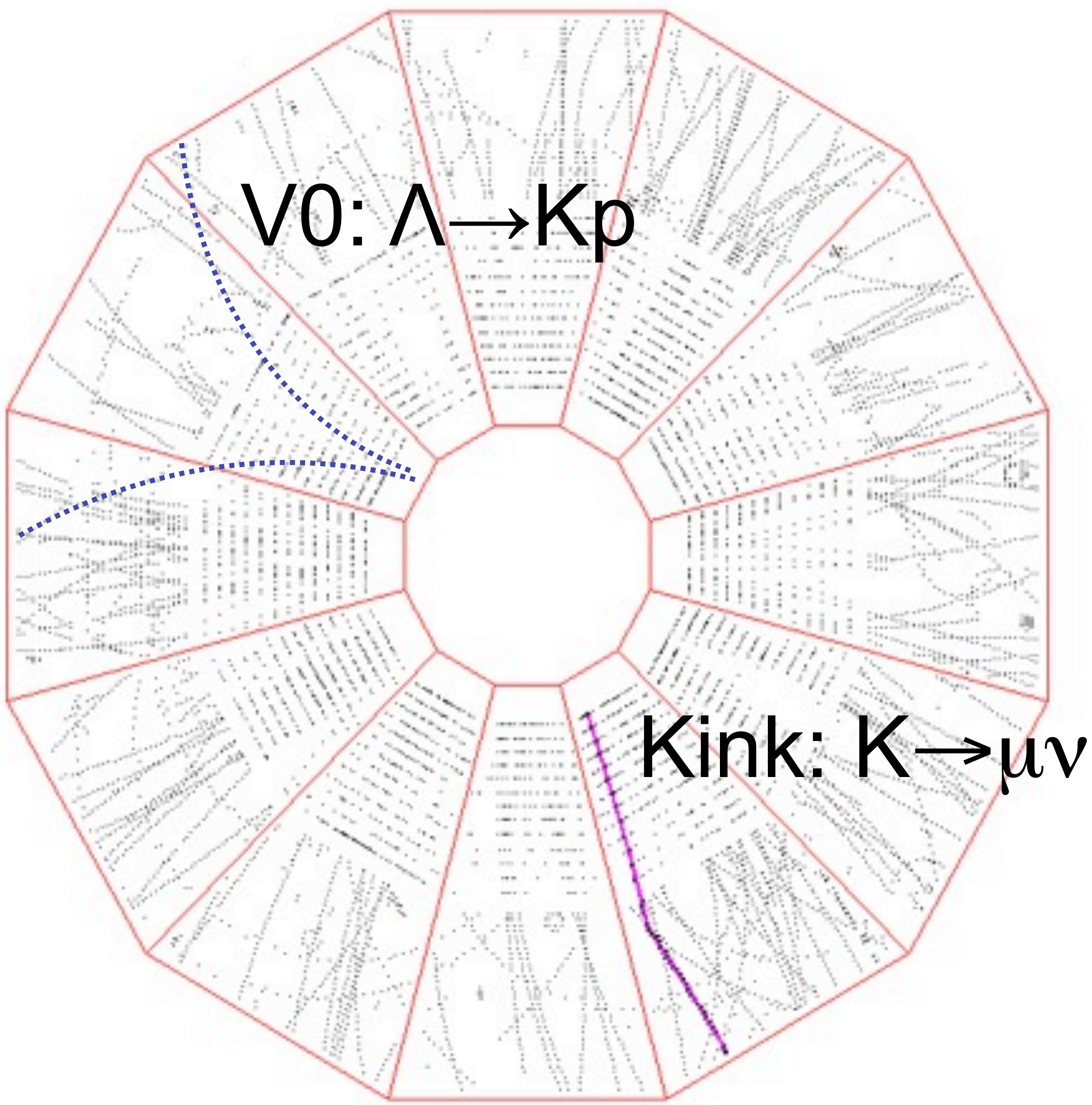
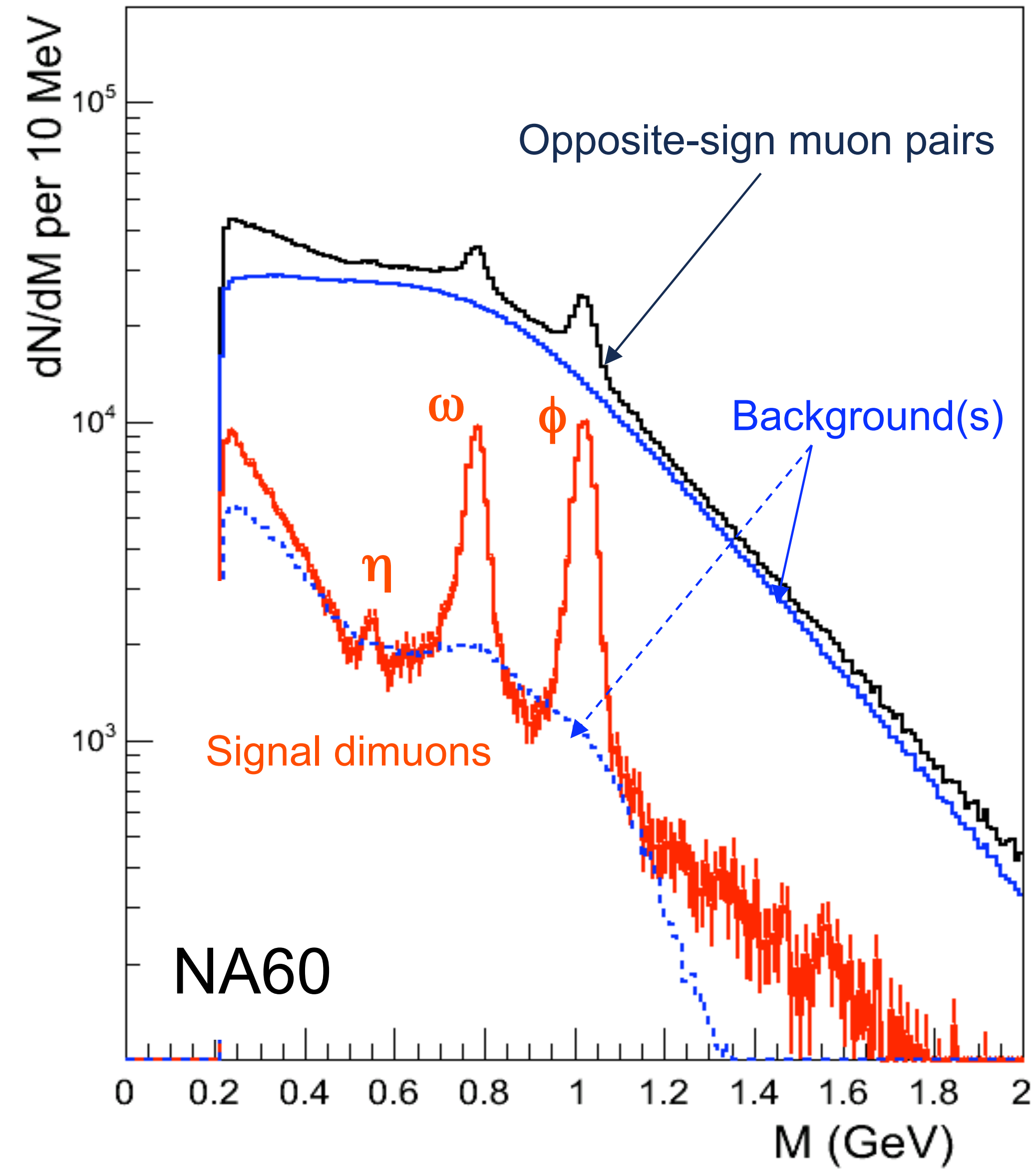
Particle identification – short lifetime (< 5 ns)

Different topologies



What if cτ ~ fm ?



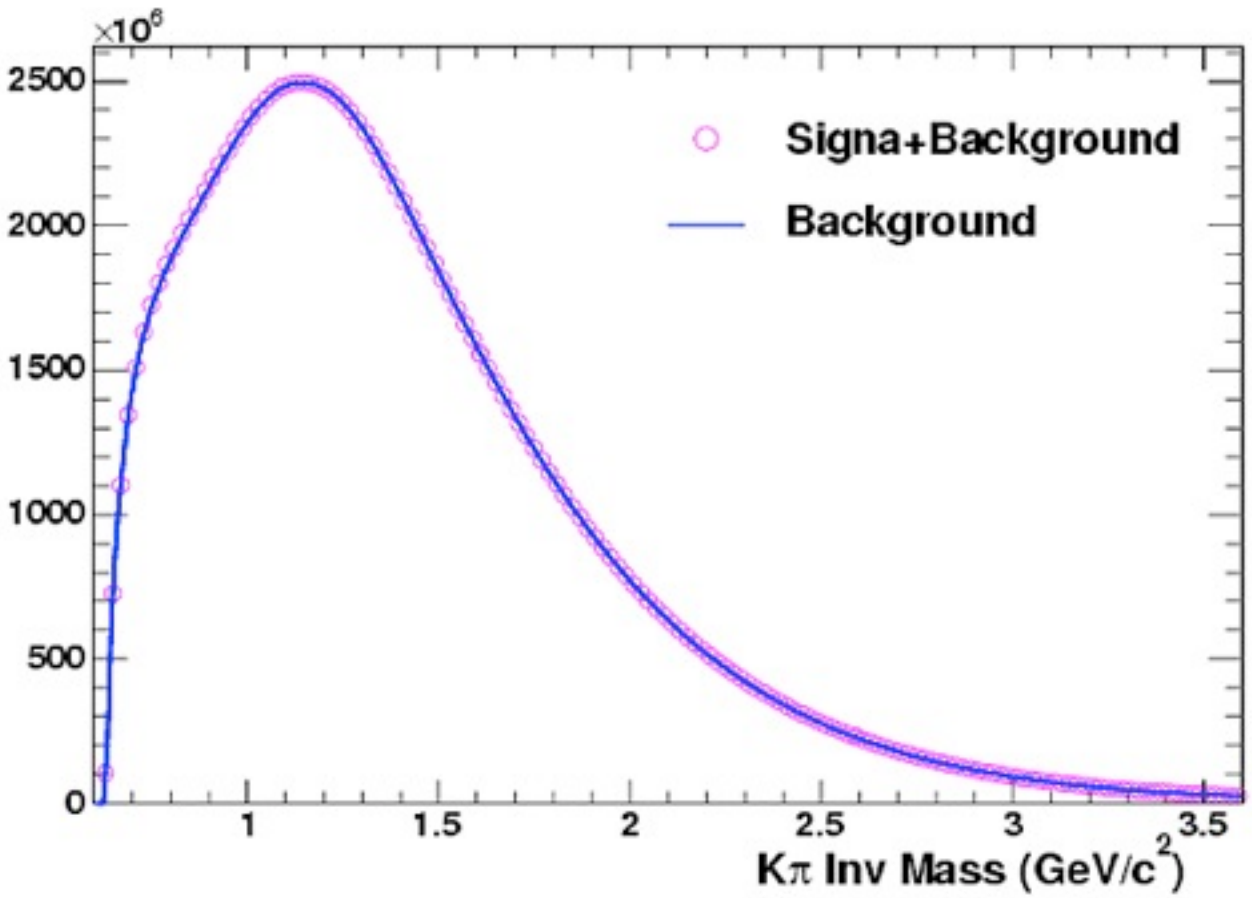
Note weak decaying particle (like Λ, Ω, K^0_s) decay cm away from the interaction vertex - cm are easy to deal with

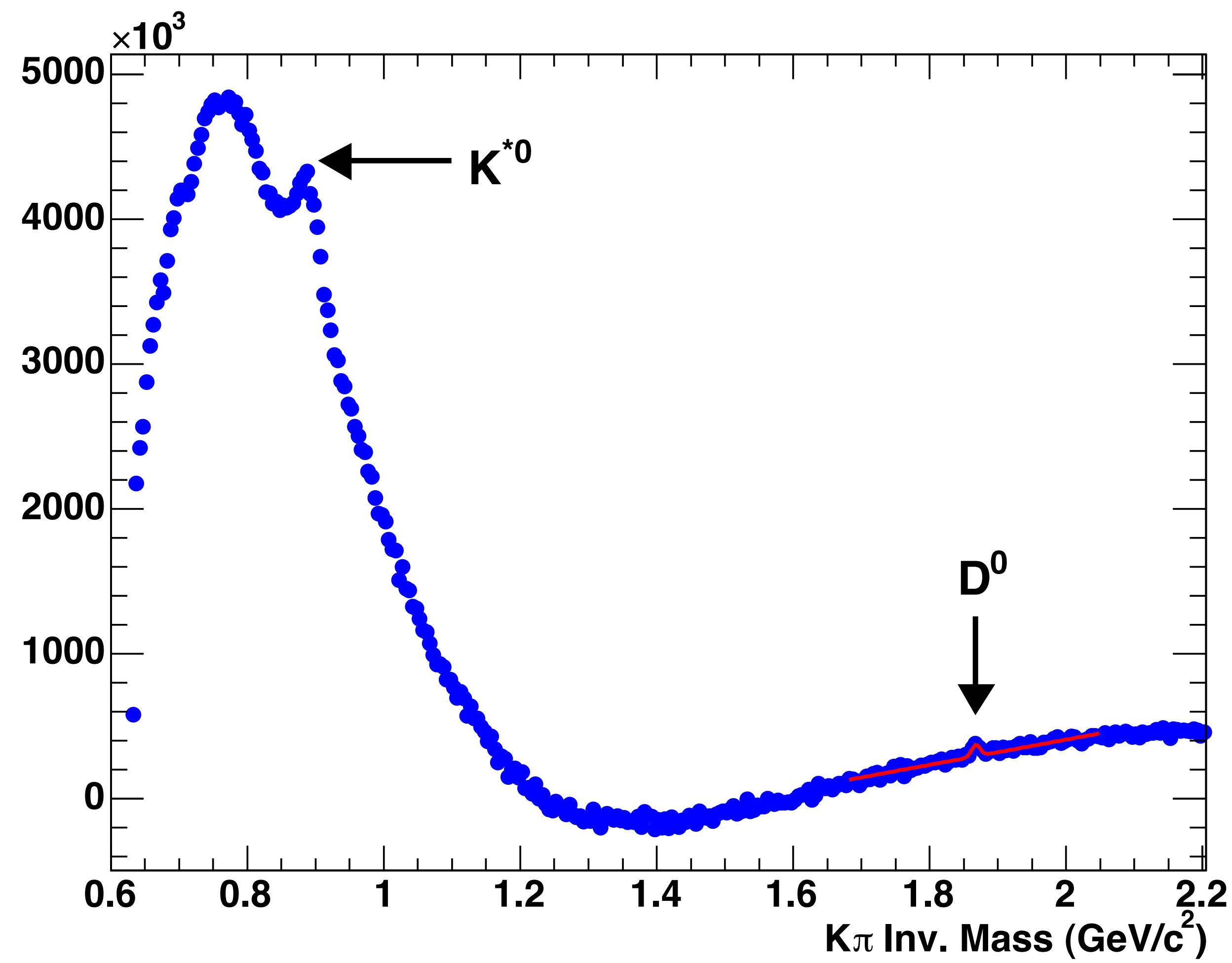
Works as well but usually more background

Particle identification – very short lifetime in <1 mm

Here $D^0 \rightarrow K\,\pi$ ($c\tau$ = 123 μm)

- Brute force method
  - select K and π tracks
  - combine all pairs from same events ⇒ signal+background
  - combine all pairs from different events ⇒ background
  - subtract background from signal+background ⇒ signal





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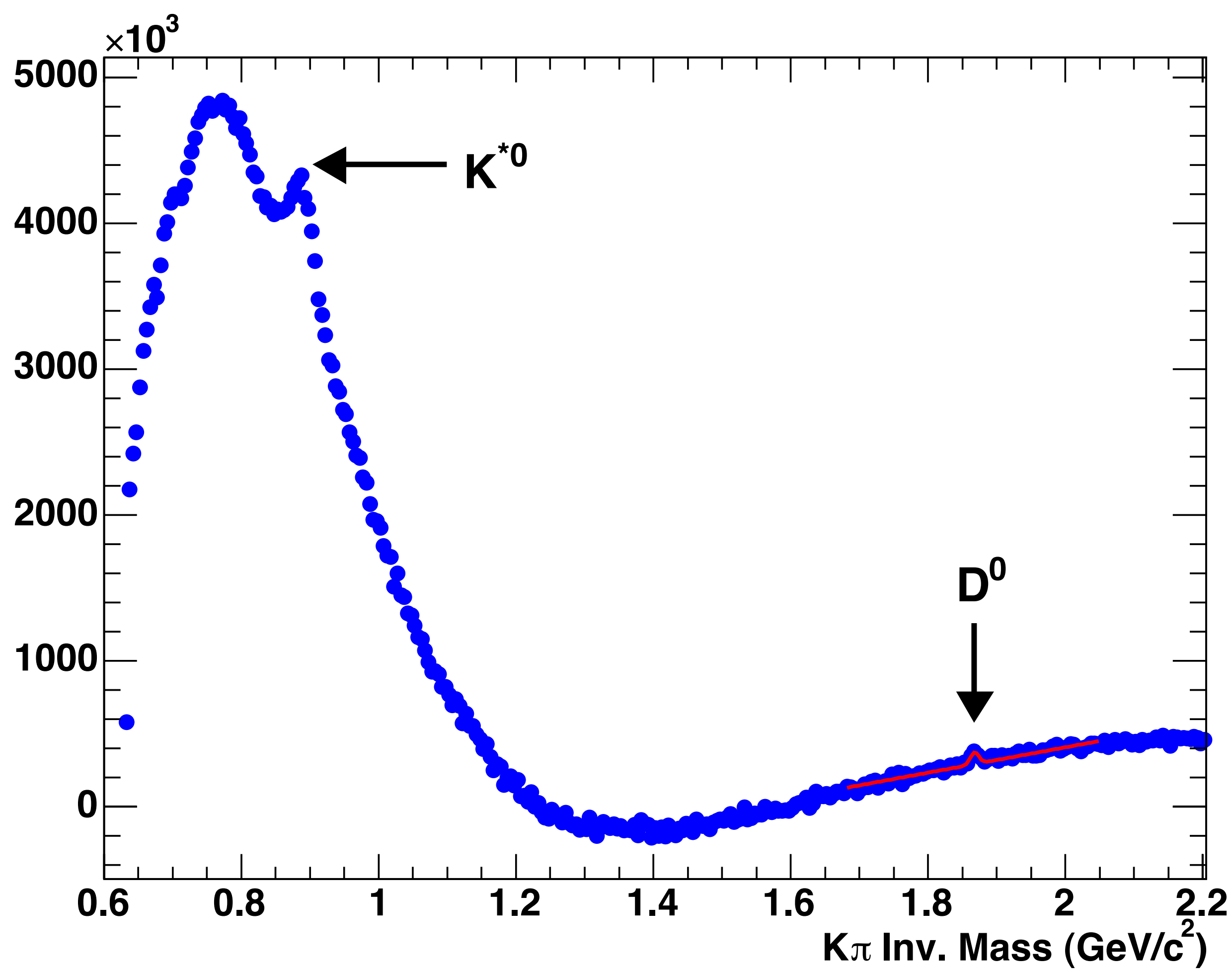
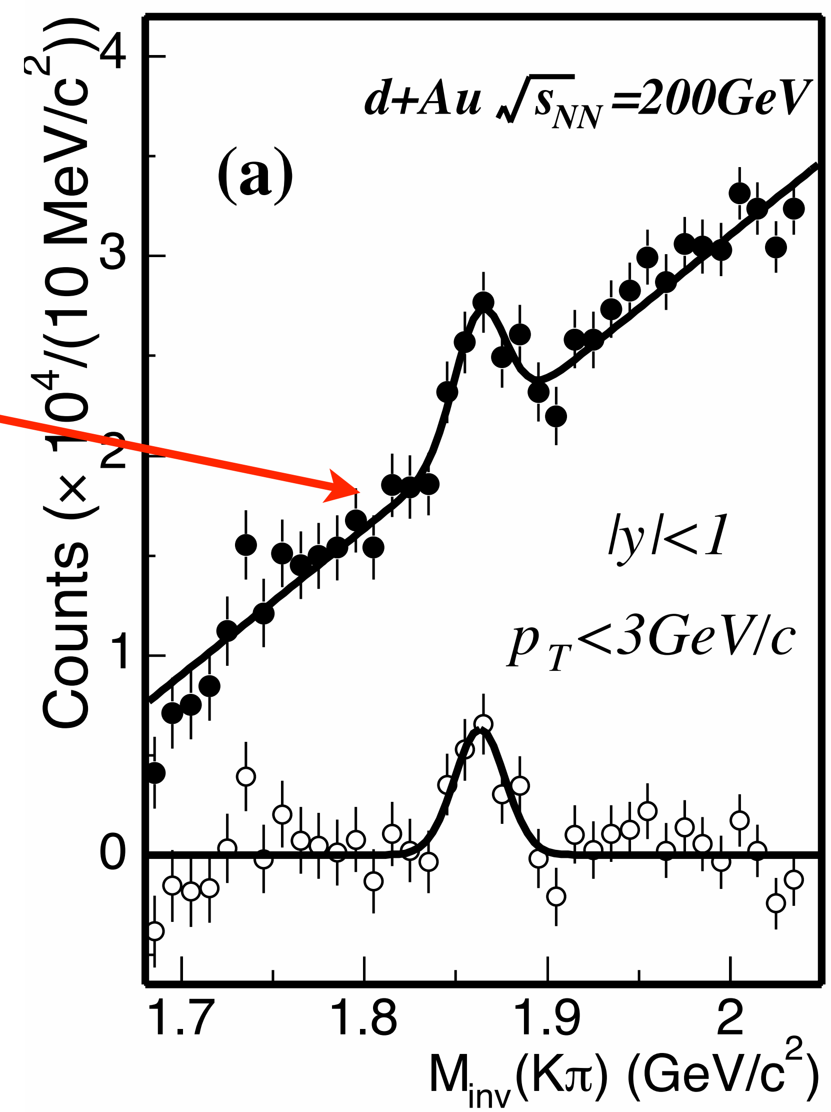


Residual background not eliminated. Needs further work to get to final spectra ....



RHIC experiments in a nutshell

BRAHMS

small experiment - 2 spectrometer arms
tiny acceptance $\Delta\phi$, $\Delta\eta$, measures p_T, has PID
movable arms $\Rightarrow$ large $\Delta\eta$ coverage

PHOBOS

small experiment - "tabletop"
(i) huge acceptance $\Delta\phi$, $\Delta\eta$, no p_T info, no PID
(ii) small acceptance $\Rightarrow$ very low - low p_T, moderate PID

PHENIX

large experiment - 2 central arms + 2 muon arms
moderate acceptance central arms: $\Delta\phi = \pi$, $\Delta\eta = \pm\ 0.35$
leptons (muons in forward arms), photons, hadrons

STAR

large experiment
acceptance central arms: $\Delta\phi = 2\pi$, $\Delta\eta = \pm\ 1$ + forward
hadrons, jets, leptons, photons

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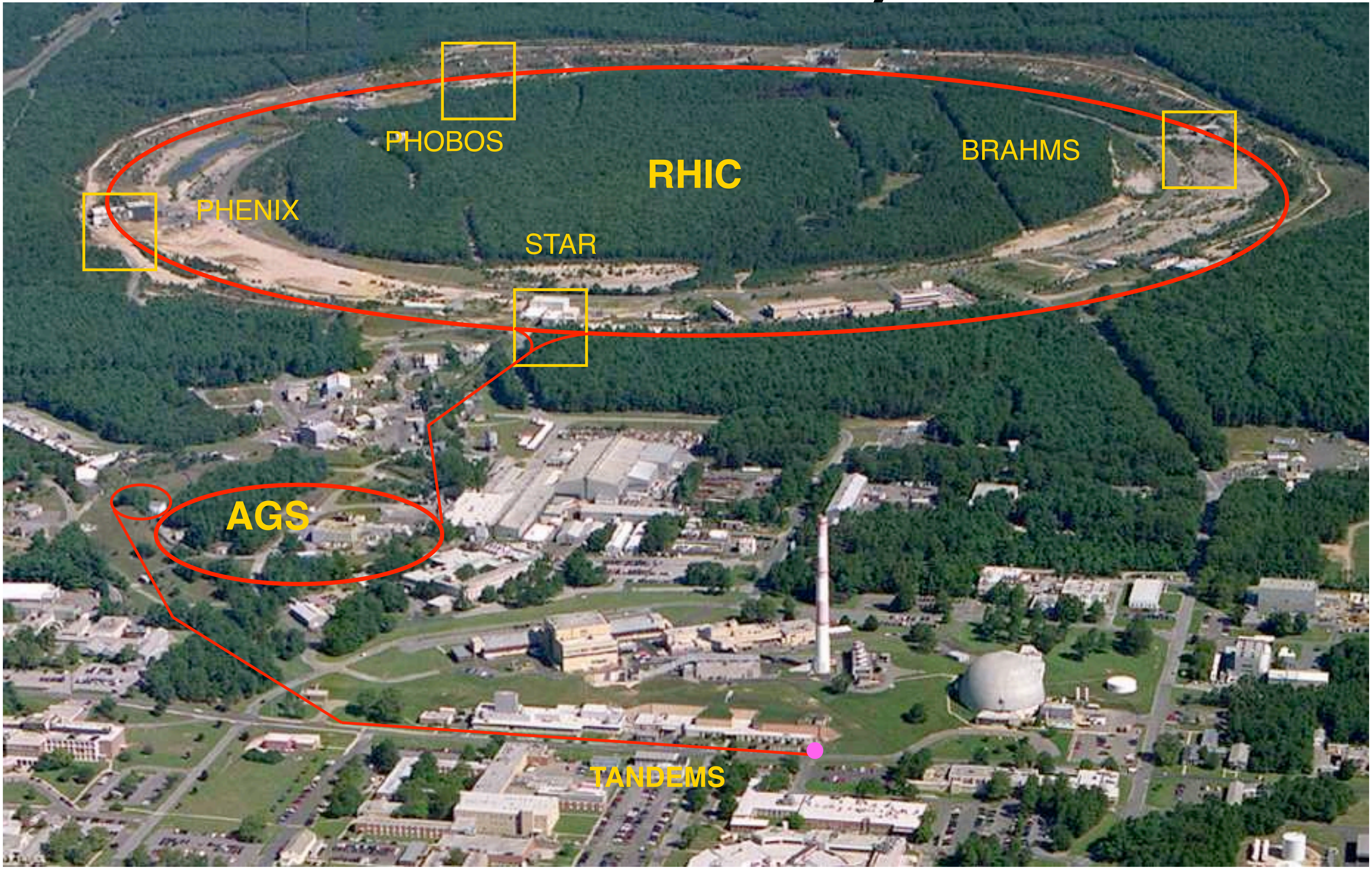
RHIC - Relativistic Heavy-Ion Collider



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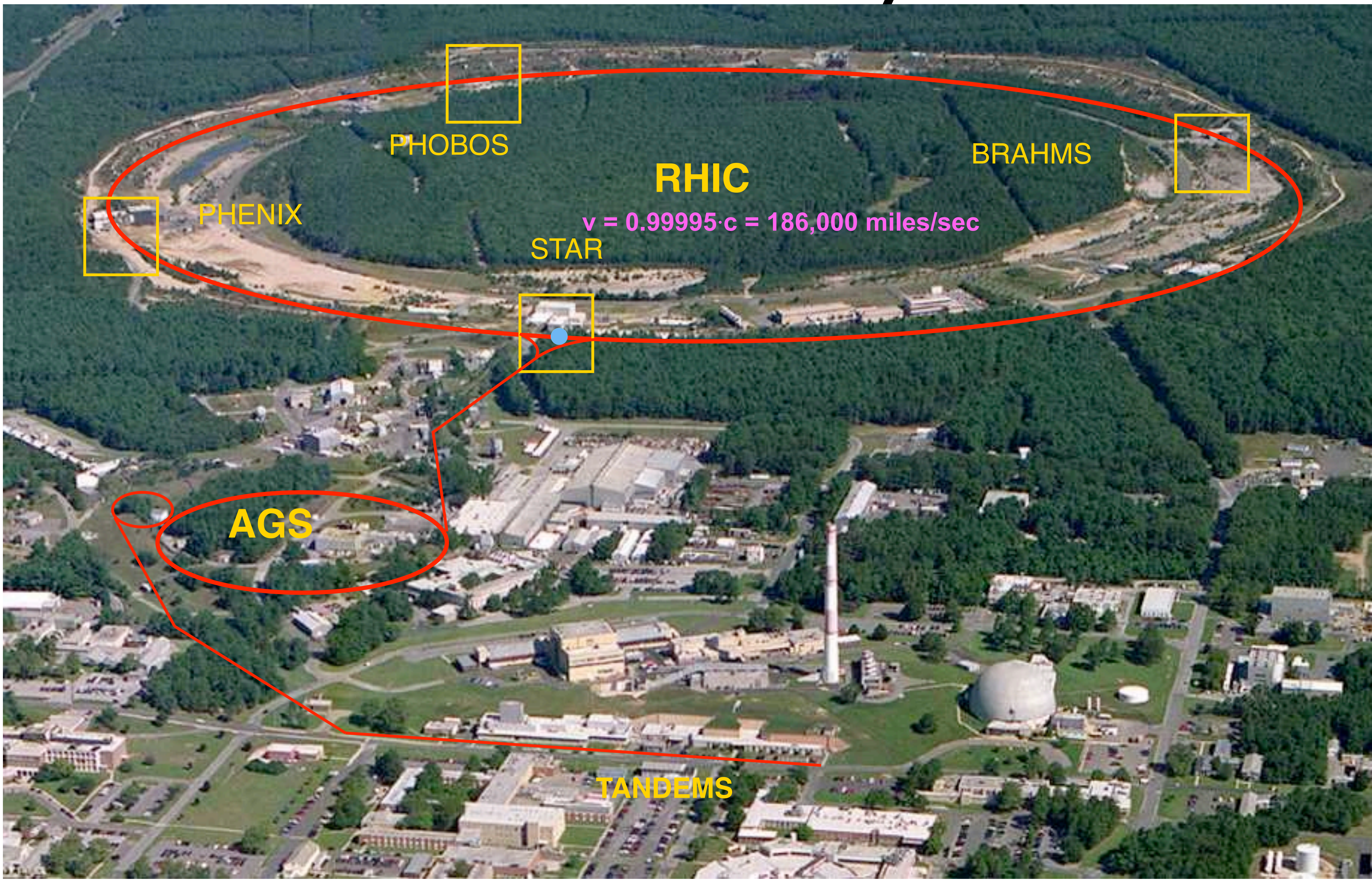

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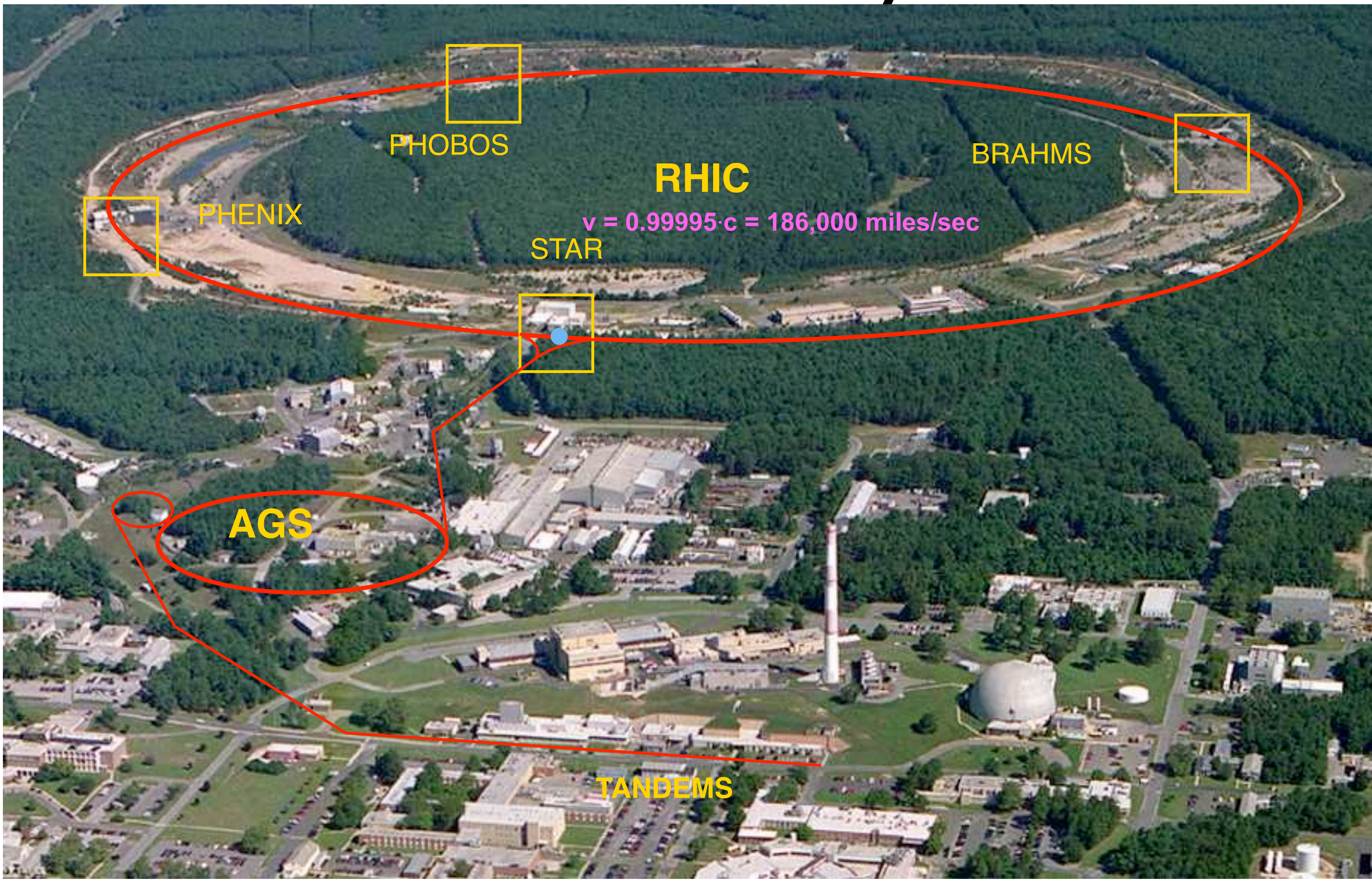

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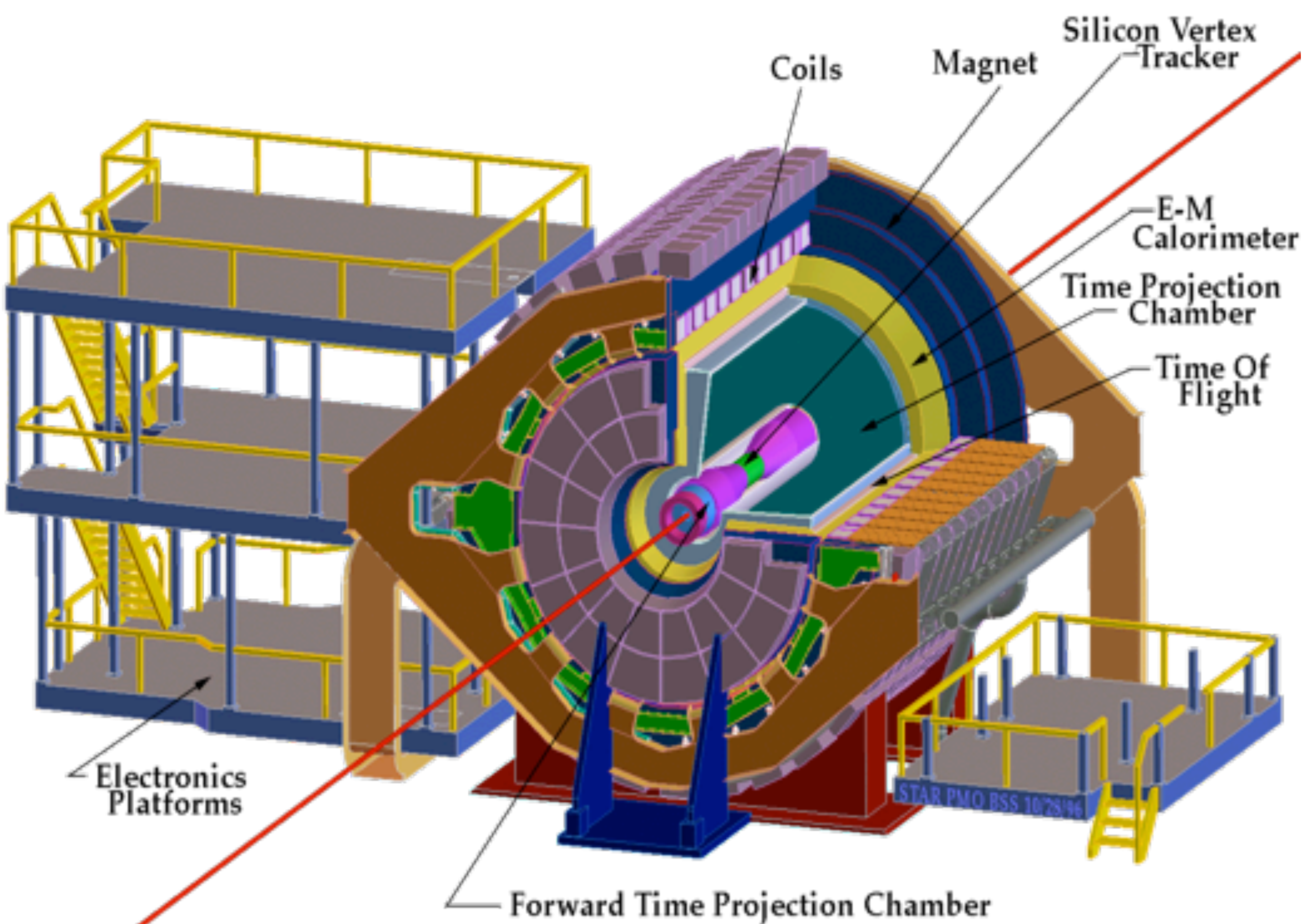
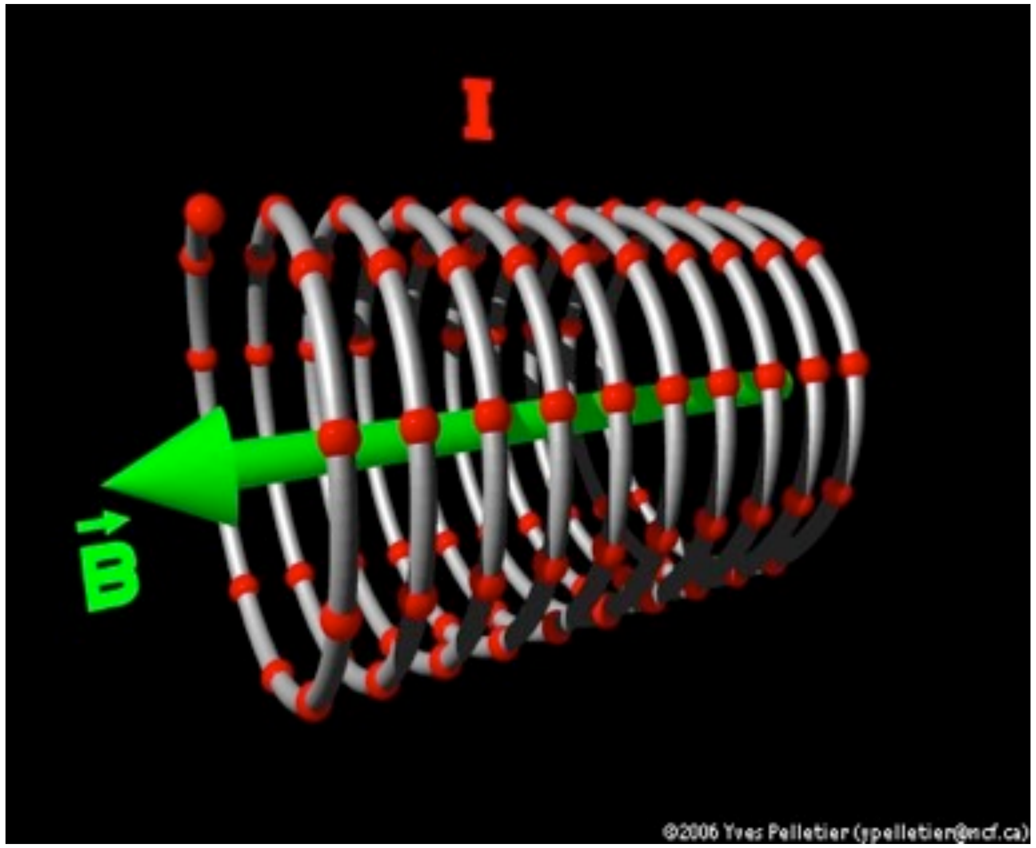
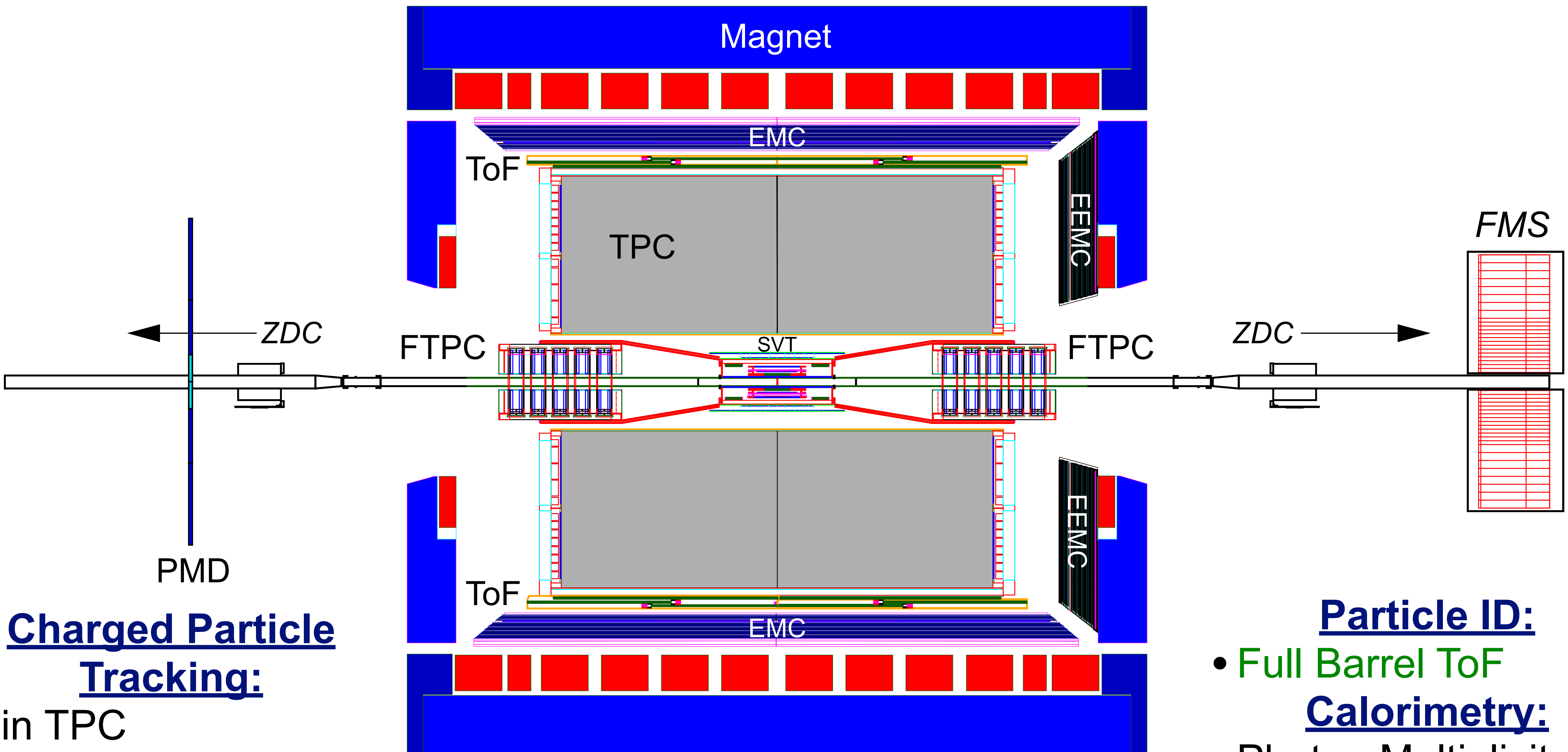
STAR - Solenoidal Tracker At RHIC

- STAR is a large volume (big as a 2 storey house) detector
  - ➡ comprises multiple detector systems
  - ➡ solenoidal magnetic field





STAR Components



Charged Particle Tracking:

- Main TPC
- Forward TPC (FTPC)
- SSD + Intermediate Tracker + Active Pixel Detector = HFT(was SSD +SVT)
- Forward GEM Tracker

Event Characterization & Trigger:

- Beam-Beam Counter (BBC)
- Zero Degree Calorimeter (ZDC)
- Forward Pion Detectors (FPD)

Particle ID:

- Full Barrel ToF

Calorimetry:

- Photon Multiplicity Detector (PMD)
- Barrel EMC
- Endcap EMC
- Forward Meson Spectrometer

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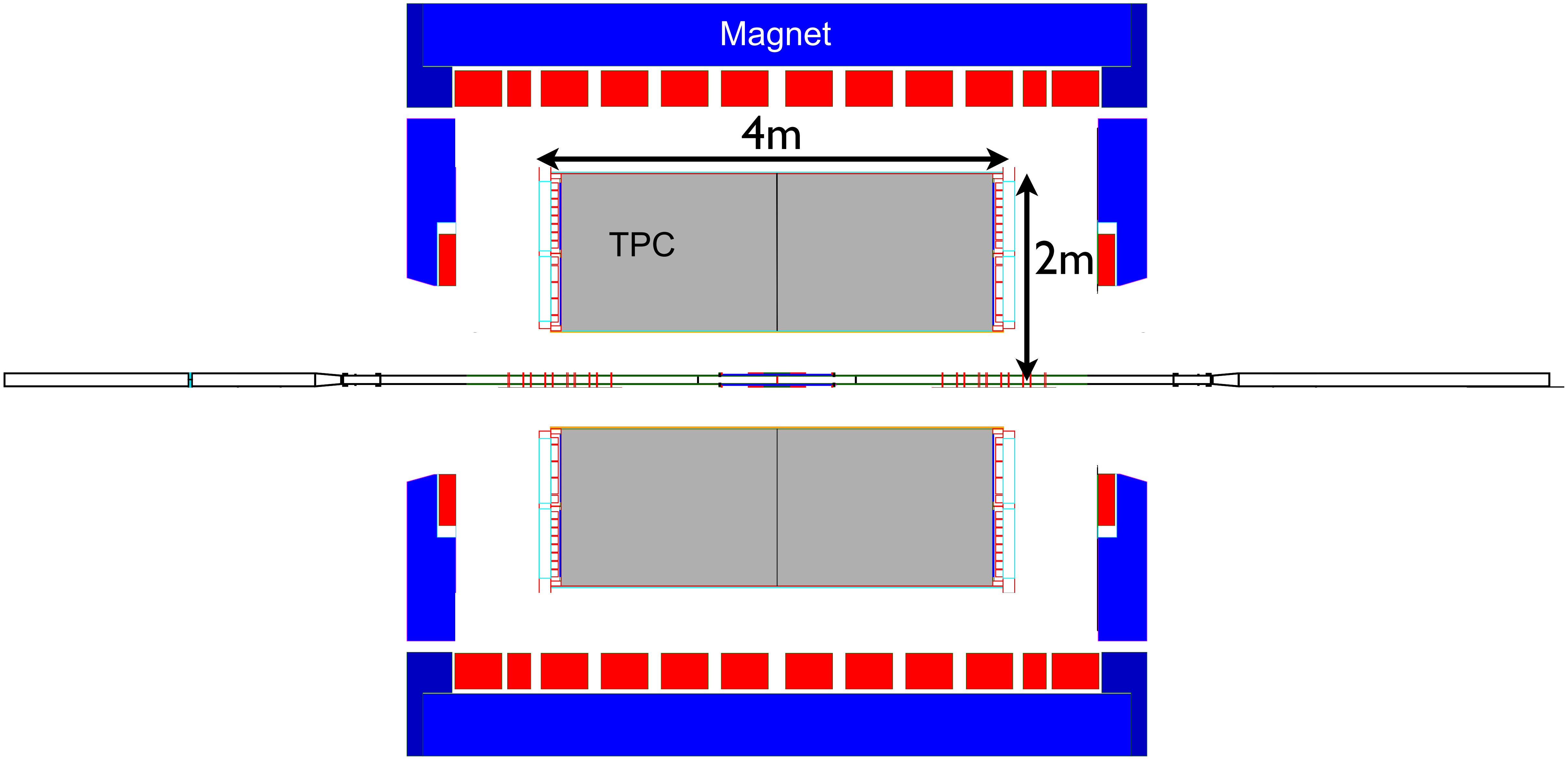
STAR Components - TPC



- TPC - Time Projection Chamber
  - ➡ A 3-dimensional tracking device for charged hadrons
  - ➡ By utilising the solenoidal magnetic field, we can identify the particles in the detector (π,k,p)

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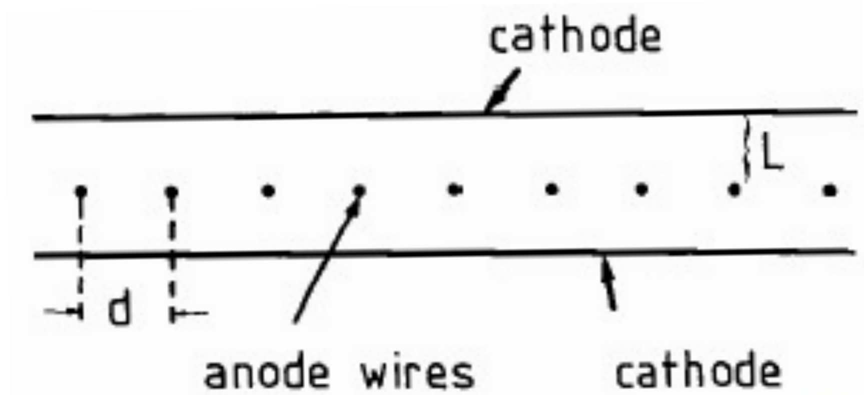
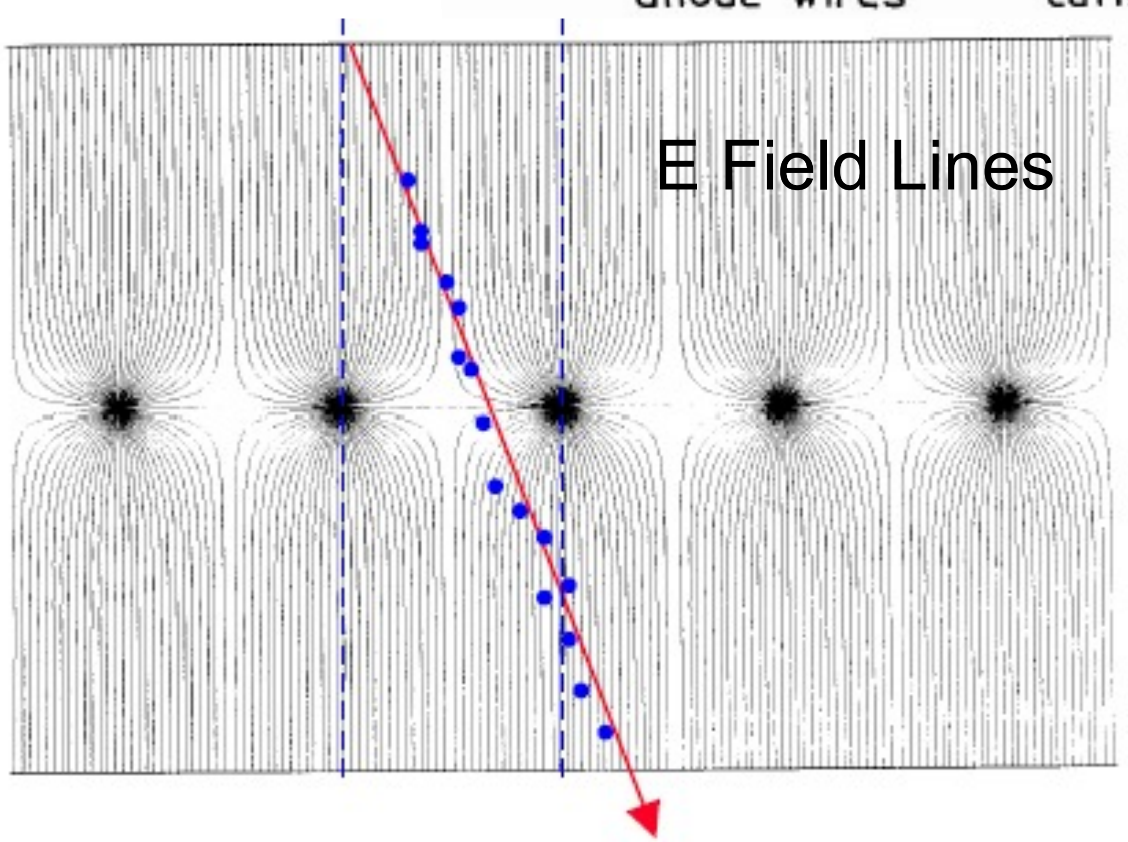
Drift chamber in a nutshell

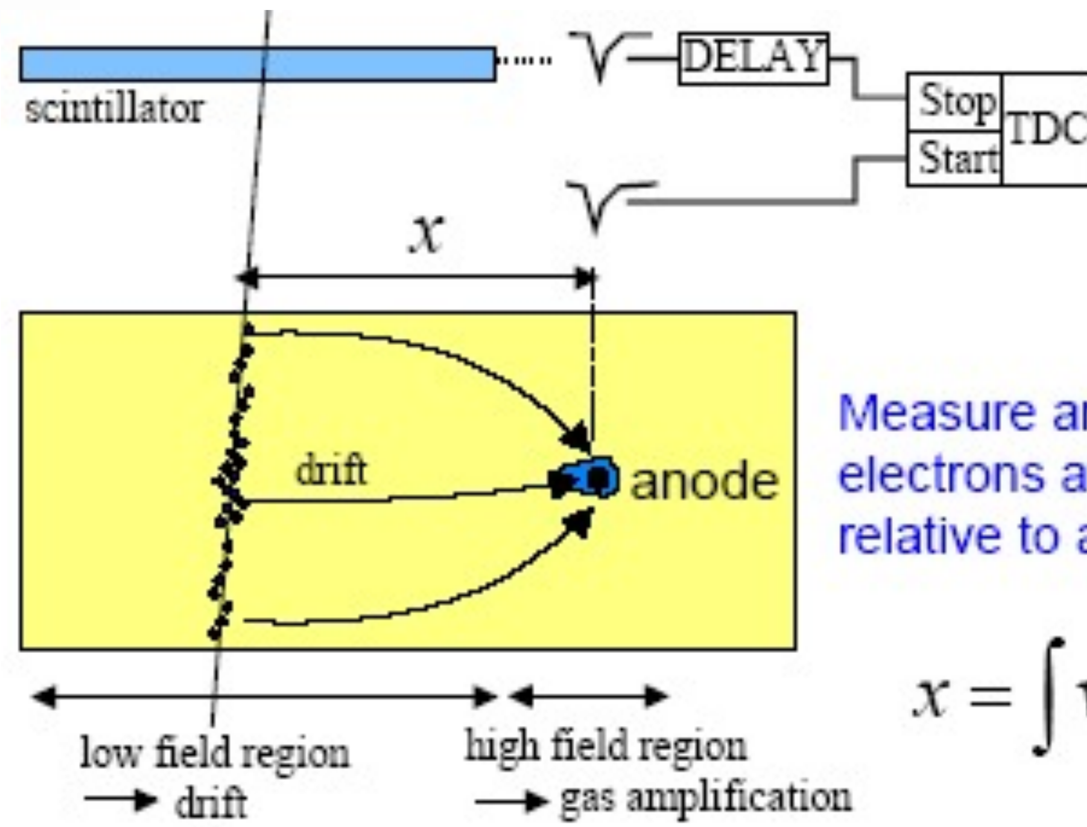
Multi Wire Proportional Chamber

G.Charpak 1968 ,nobel prize 1992



Typical parameters: L=5~8 mm, d=2mm, $\varnothing_{wire}$ =20 μm.





Measure arrival time of electrons at sense wire relative to a time t_0.

$$x = \int v_D(t) dt$$

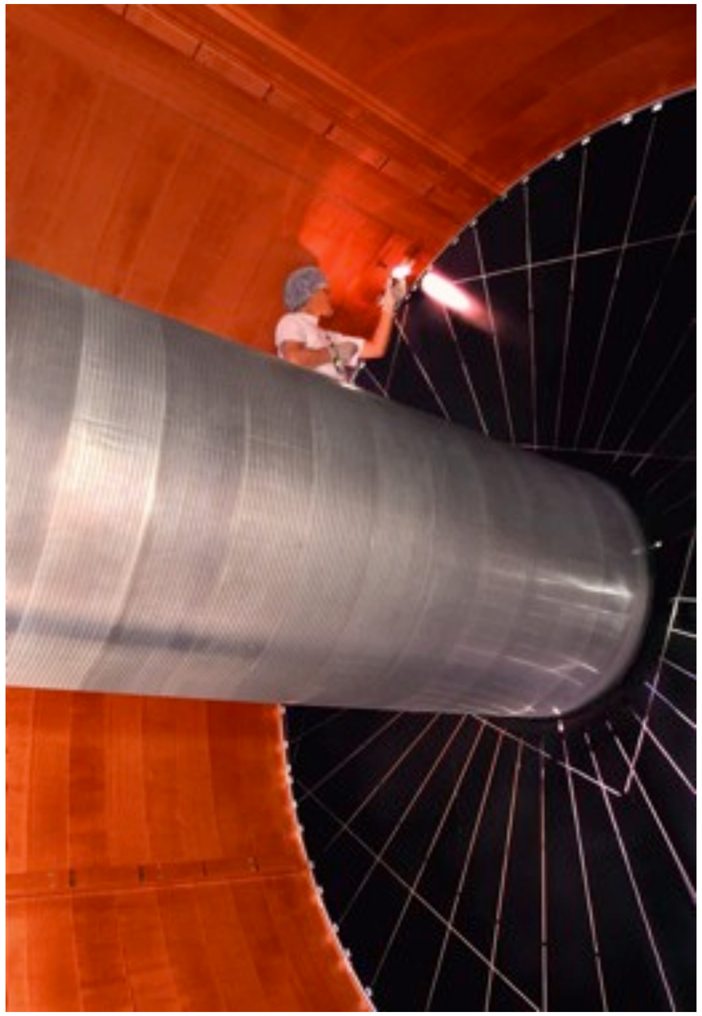
- Address of fired wire(s) give one dimensional information ⇒ $\sigma_x \approx d/\sqrt{12}$
- Improve using drift length time information: typical ~200 μm
- Resolution limits: drift and diffusion effects driven by **E** × **B** effects

Time Projection Chamber (TPC)

Error of momentum measurement: $$\frac{\sigma(p_T)}{p_T} \propto \frac{\sigma(x) \cdot p_T}{B \cdot L^2}$$

⇒ L has to be large ⇒ detector has to be wide (small R_{in}, large R_{out})

Want large η coverage ⇒ z dimension has to be large ⇒ detector has to be long



Cannot achieve this with drift chambers:

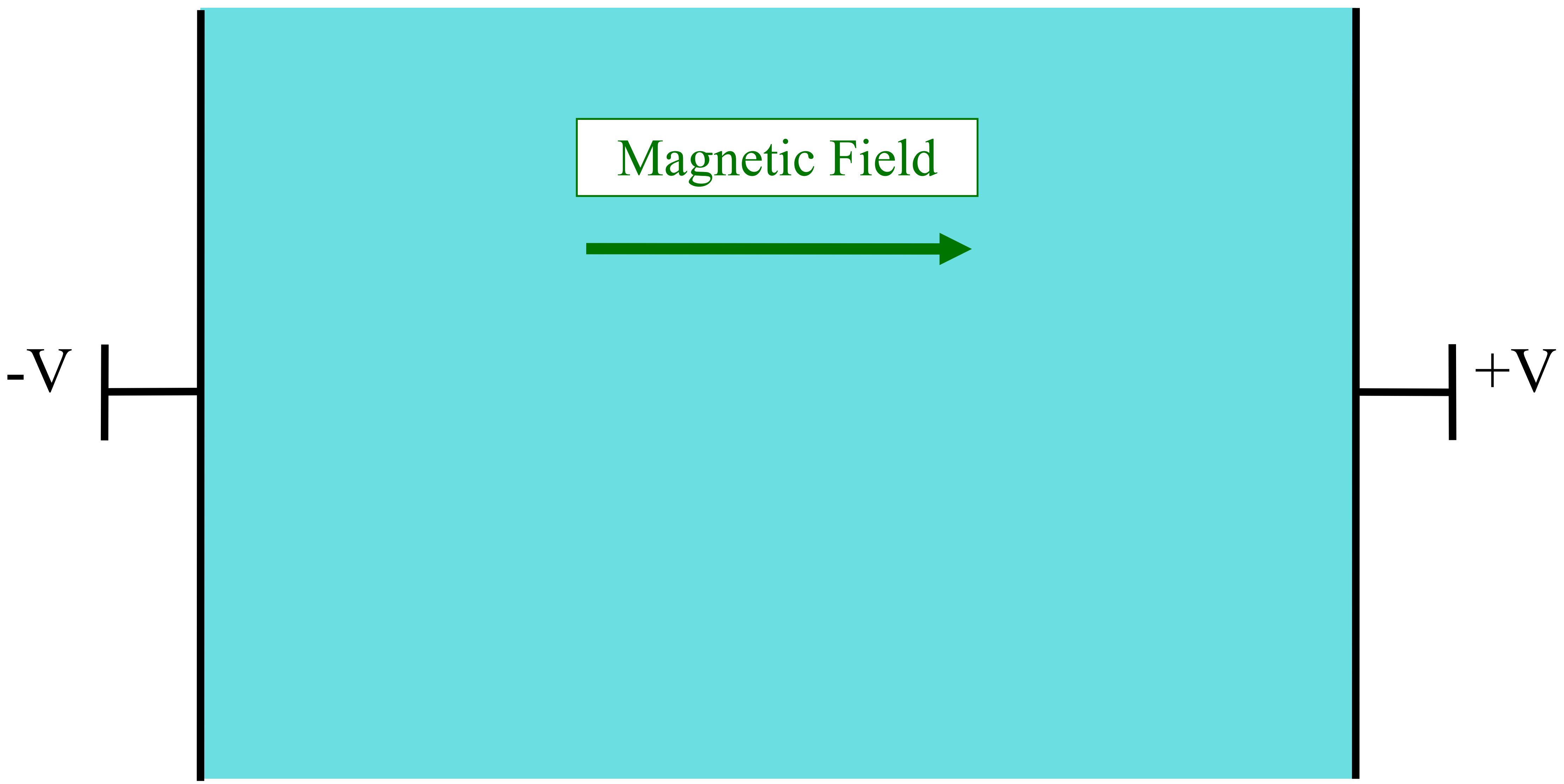
- thousands of wires
- long wires
- complex construction (dead zones)

Solution: let the electrons drift over long distances

⇒ TPC: essentially a huge gas filled box

Think of a TPC as a 3D CCD camera

The basic concept of a TPC



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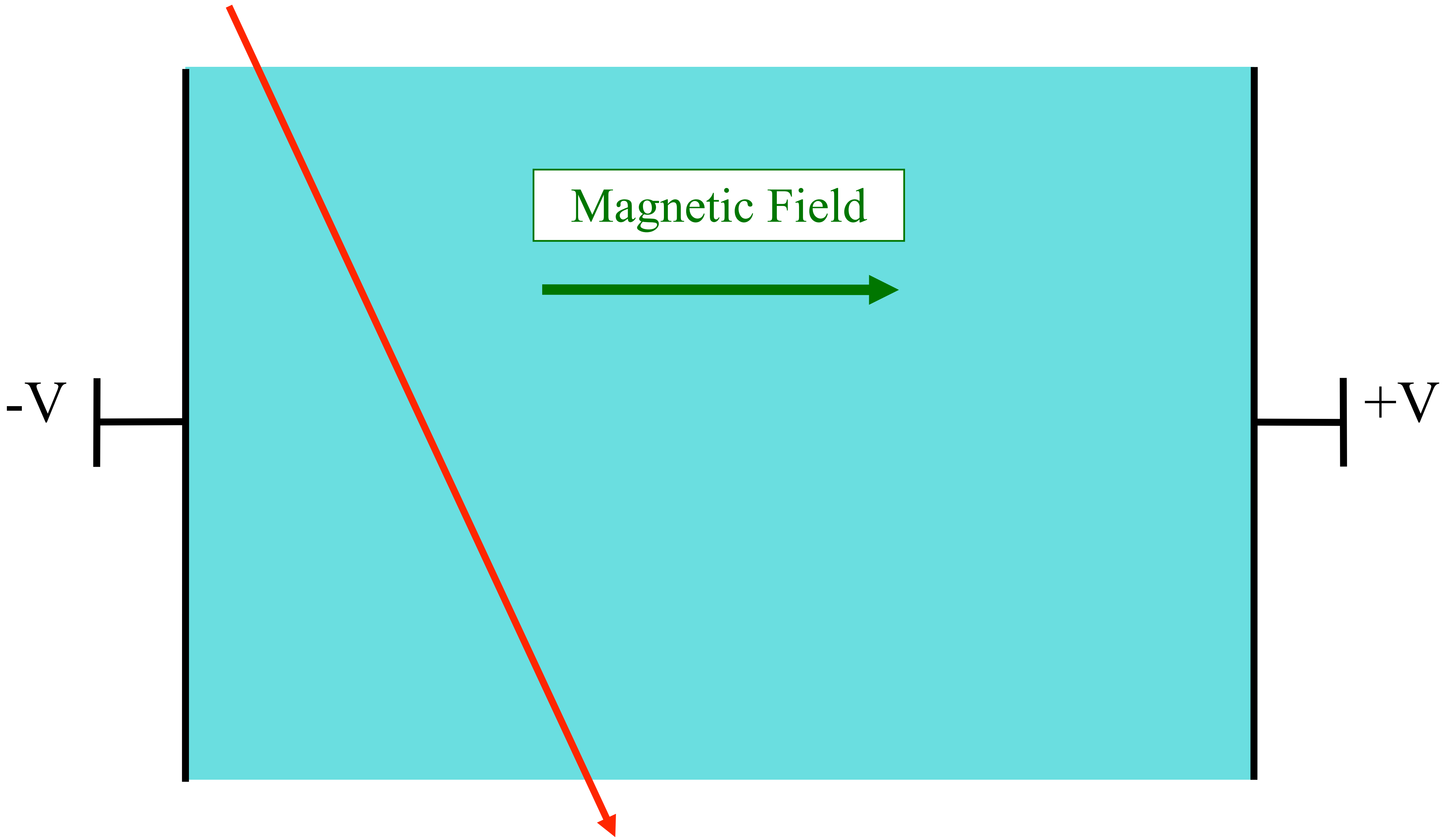

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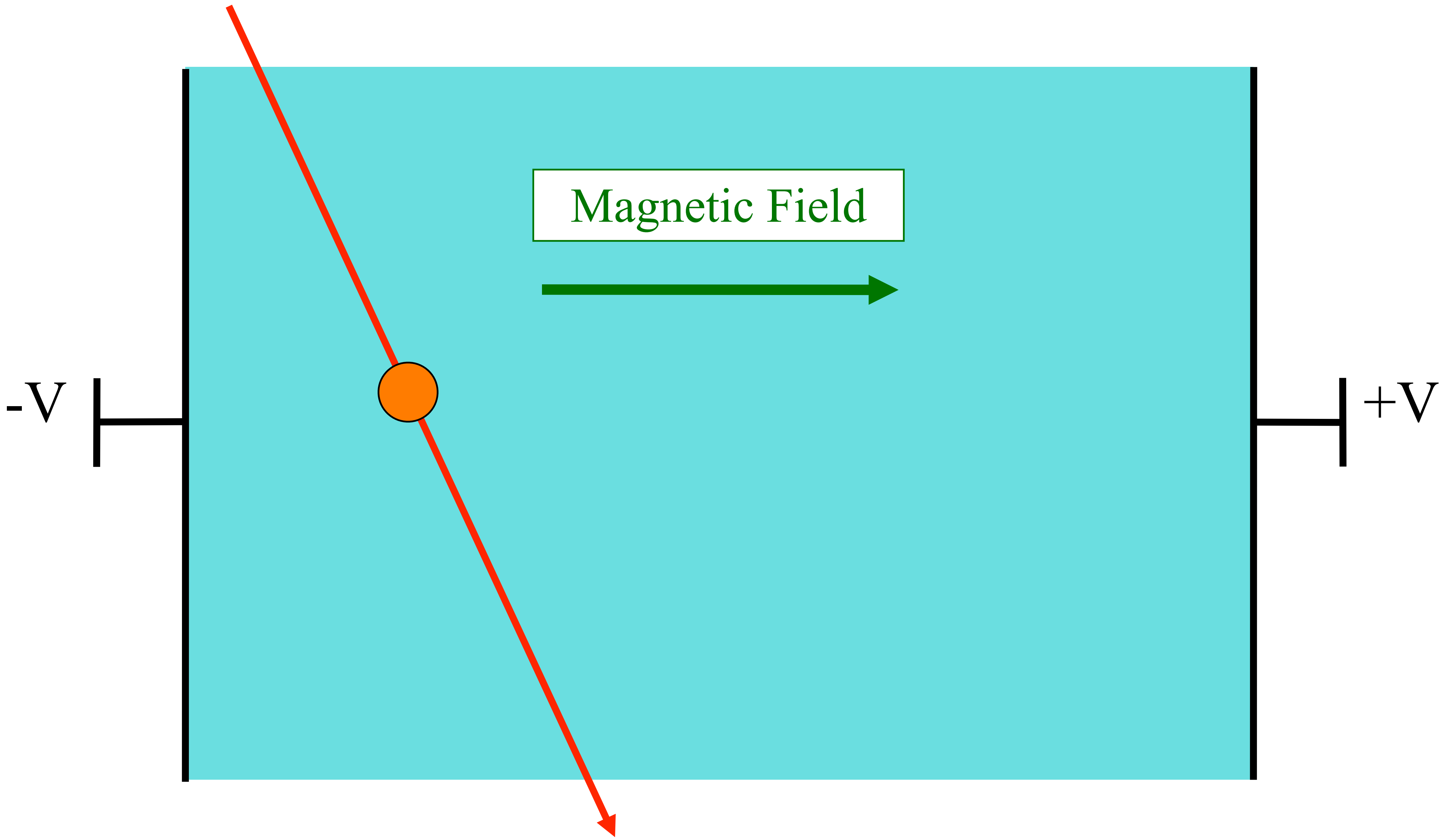

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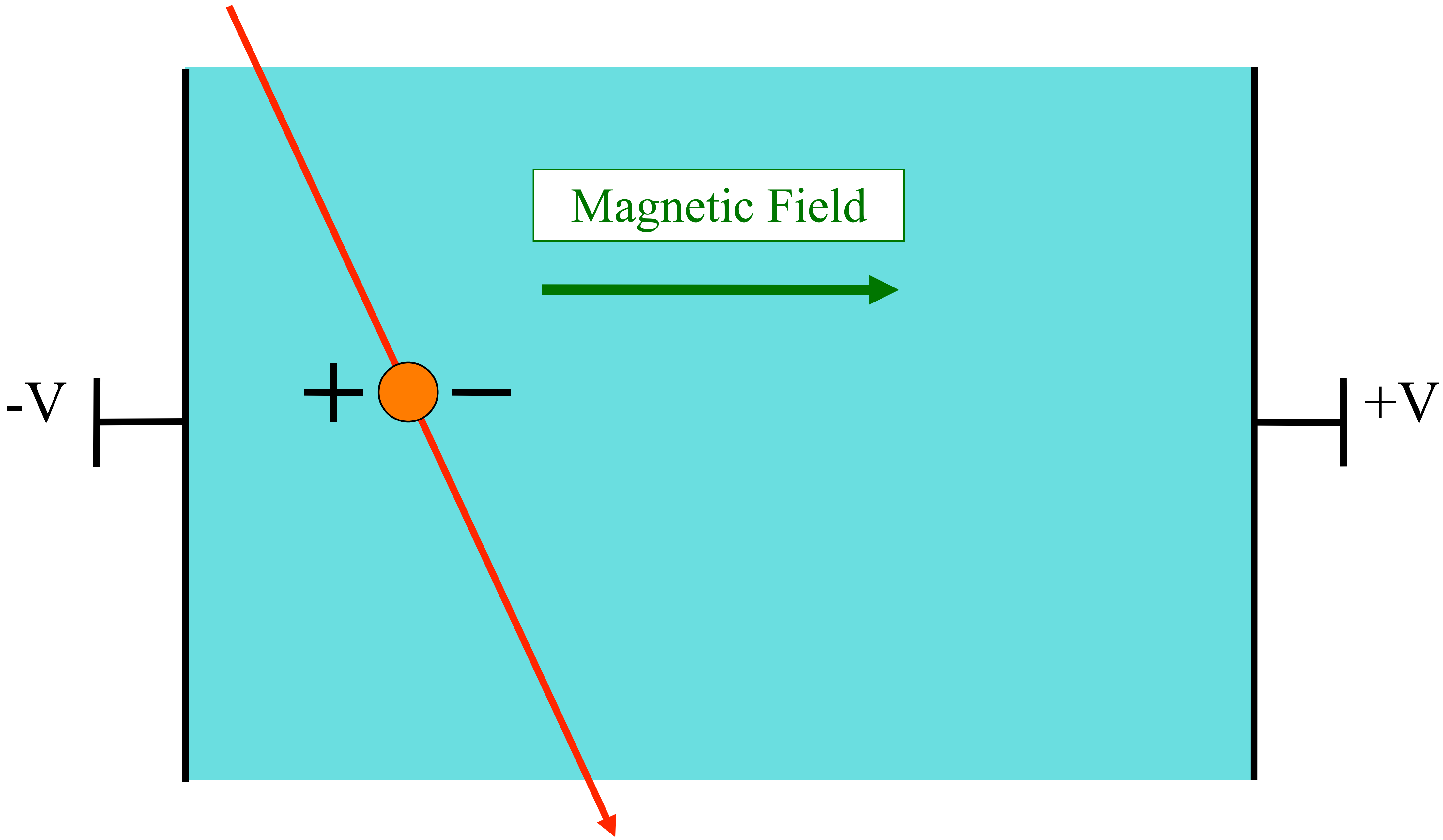

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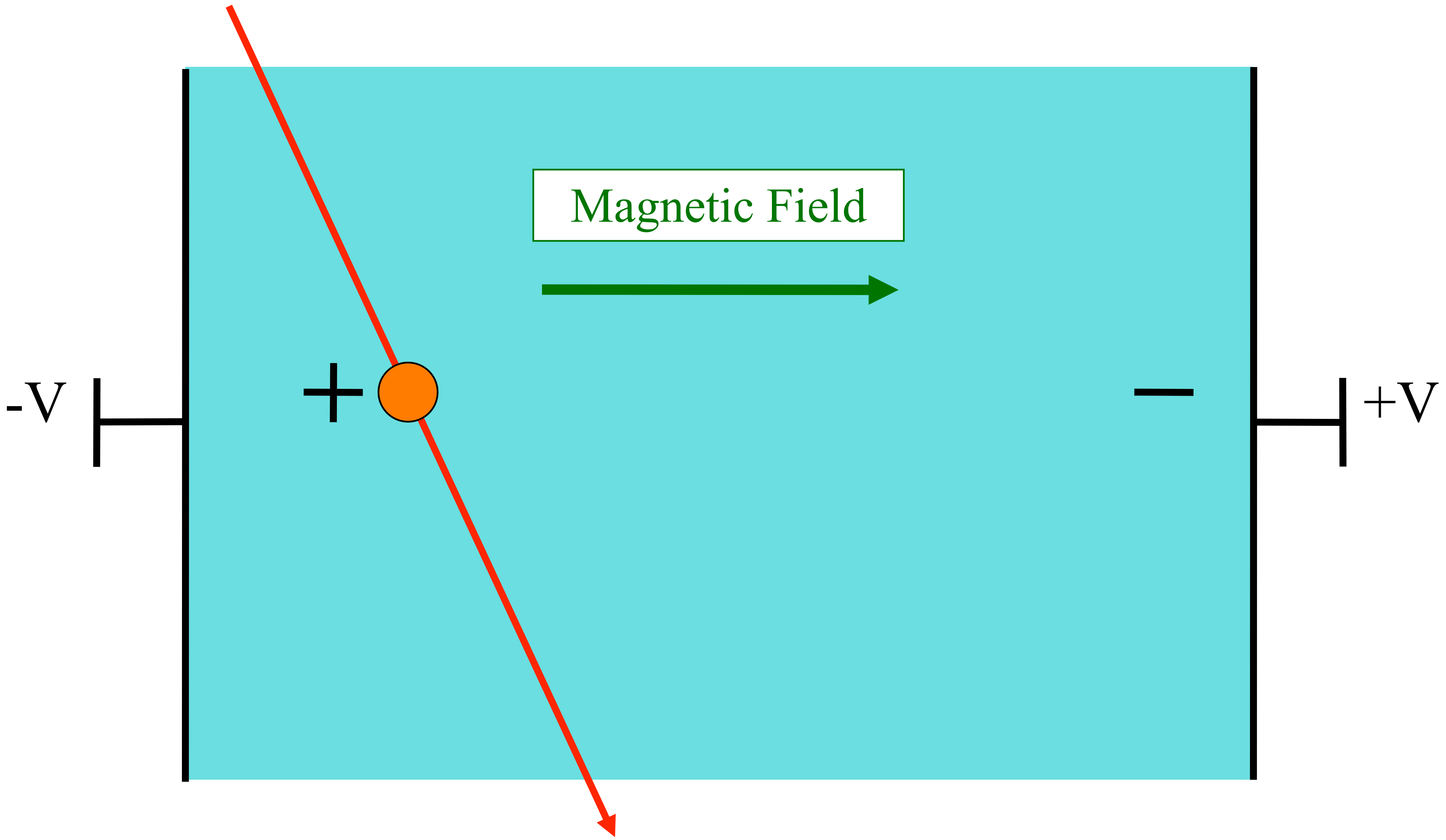

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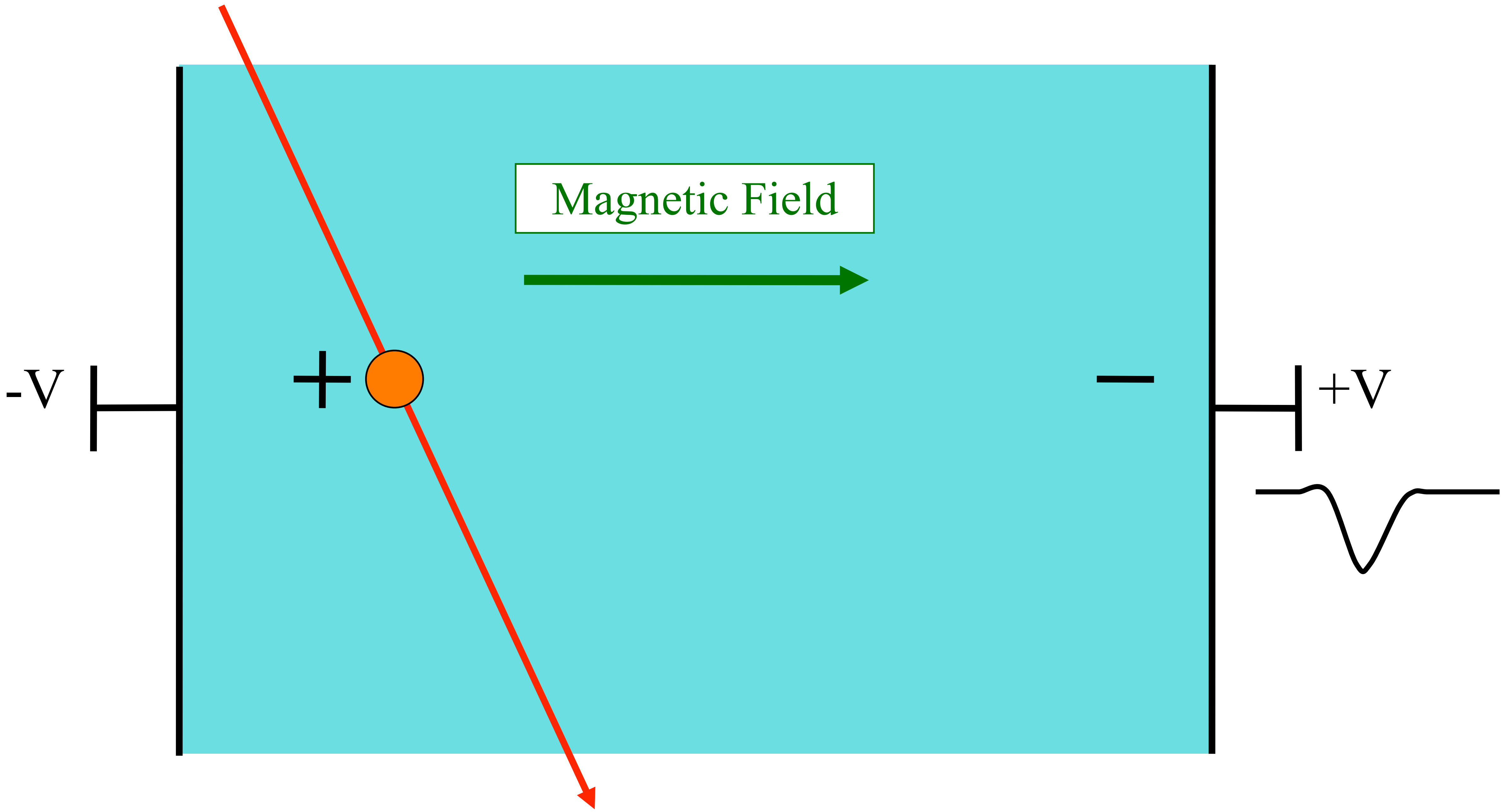

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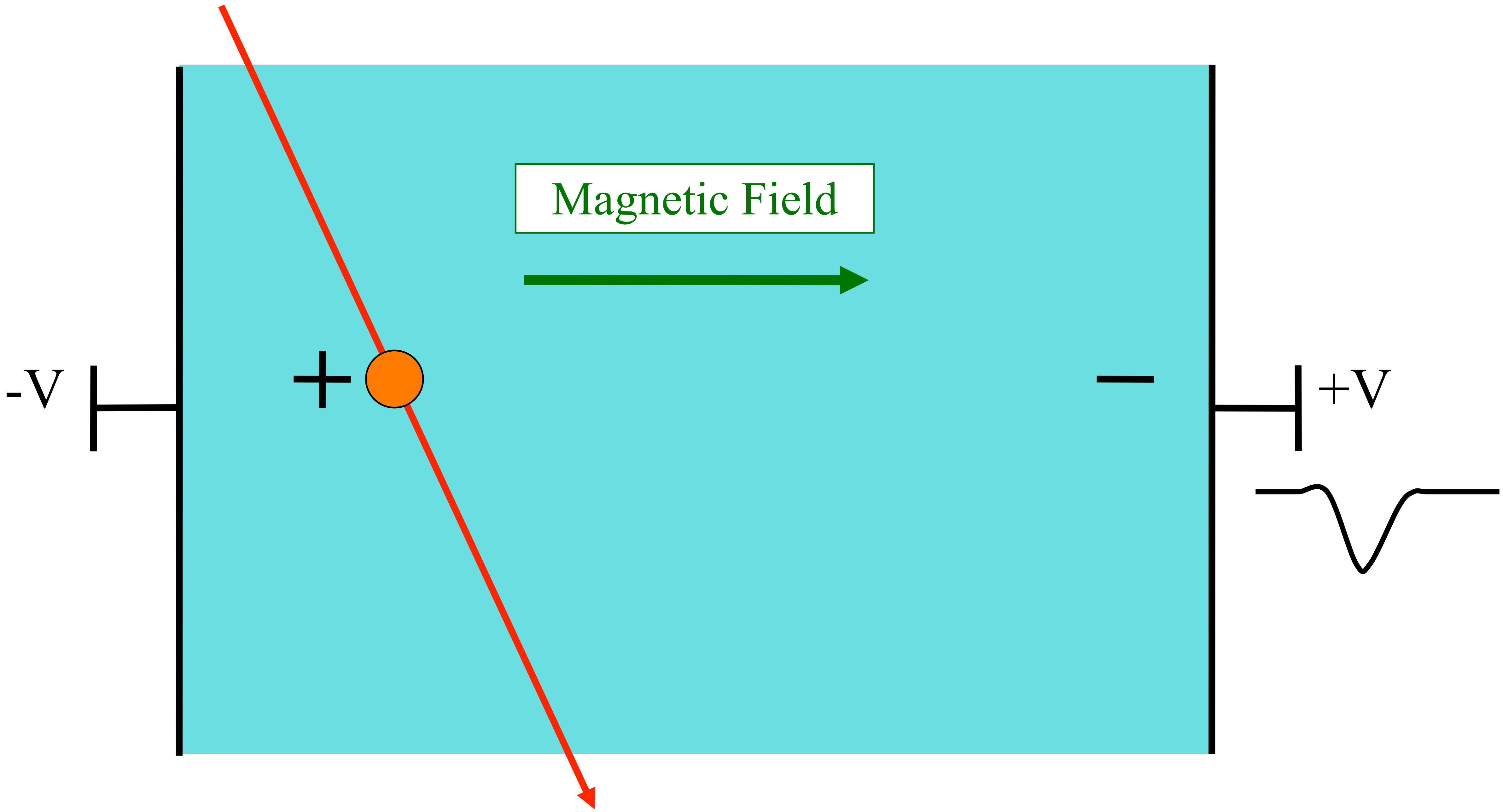
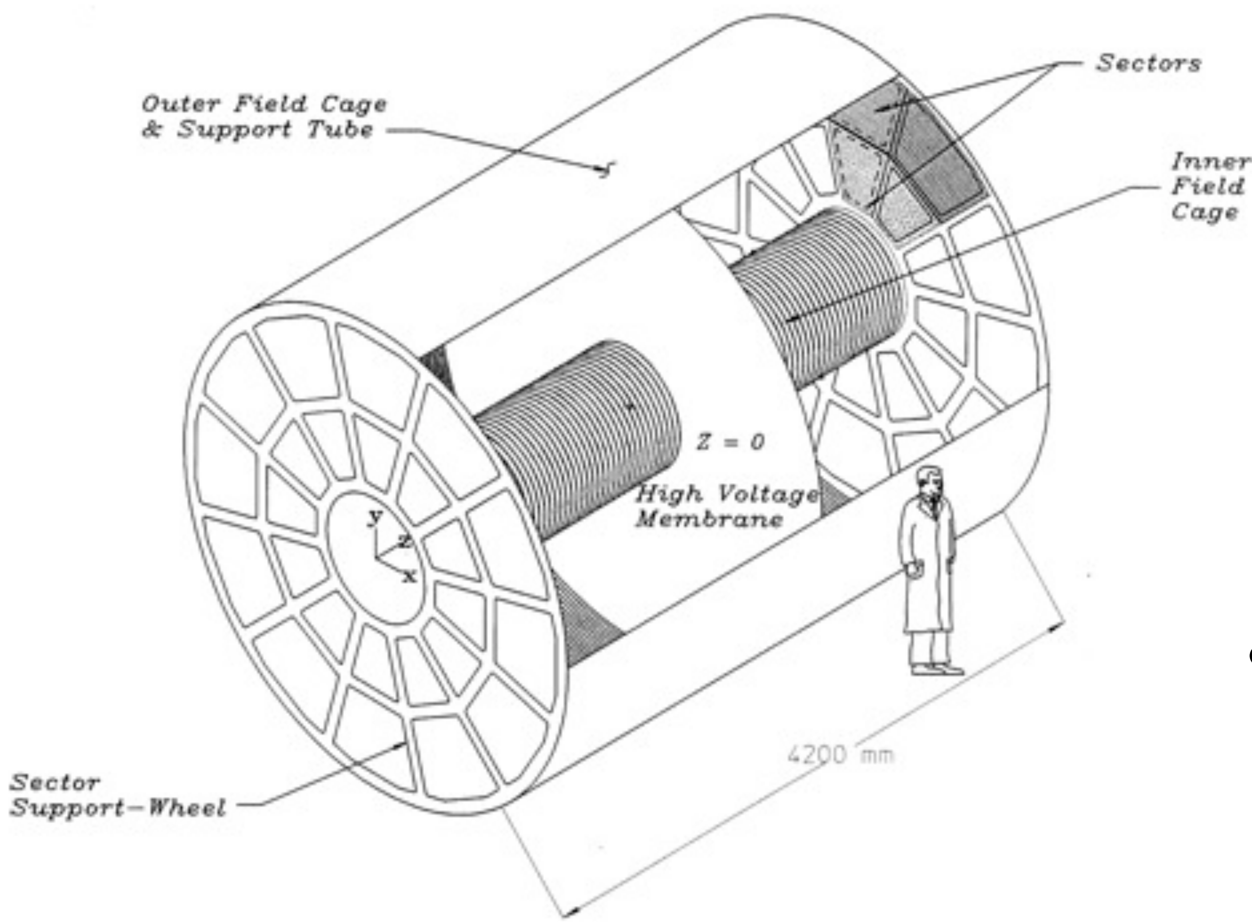
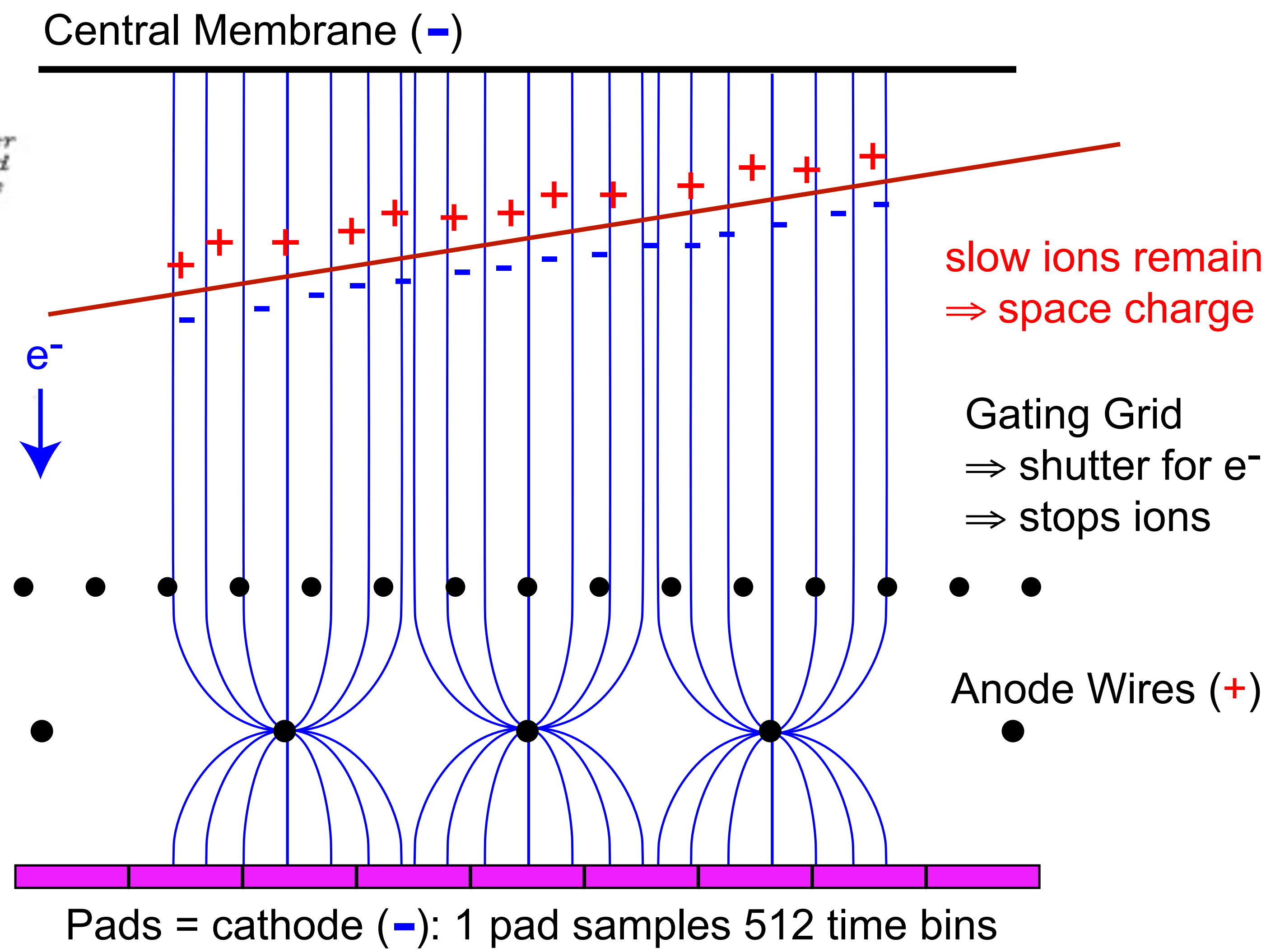


The time to reach the end of the TPC determines the distance drifted in the gas.

A **3-D camera** to measure particle positions.

TPC Details





STAR TPC

- 140,000 electronics channels (pads)
- 512 time bins
- 140,000 x 512 = 72 million pixel
- With new electronics can run at 1000 Hz

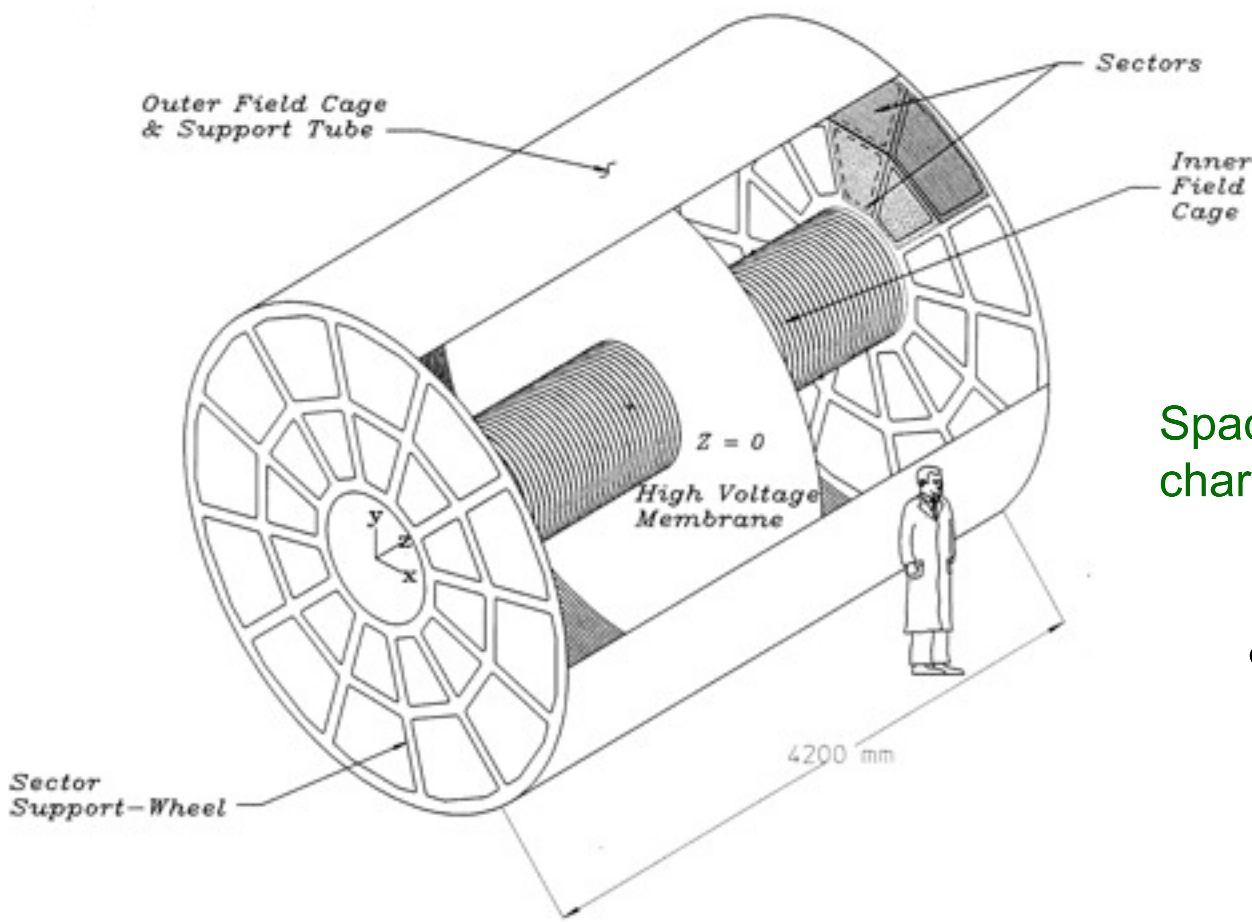
Gating Grid:

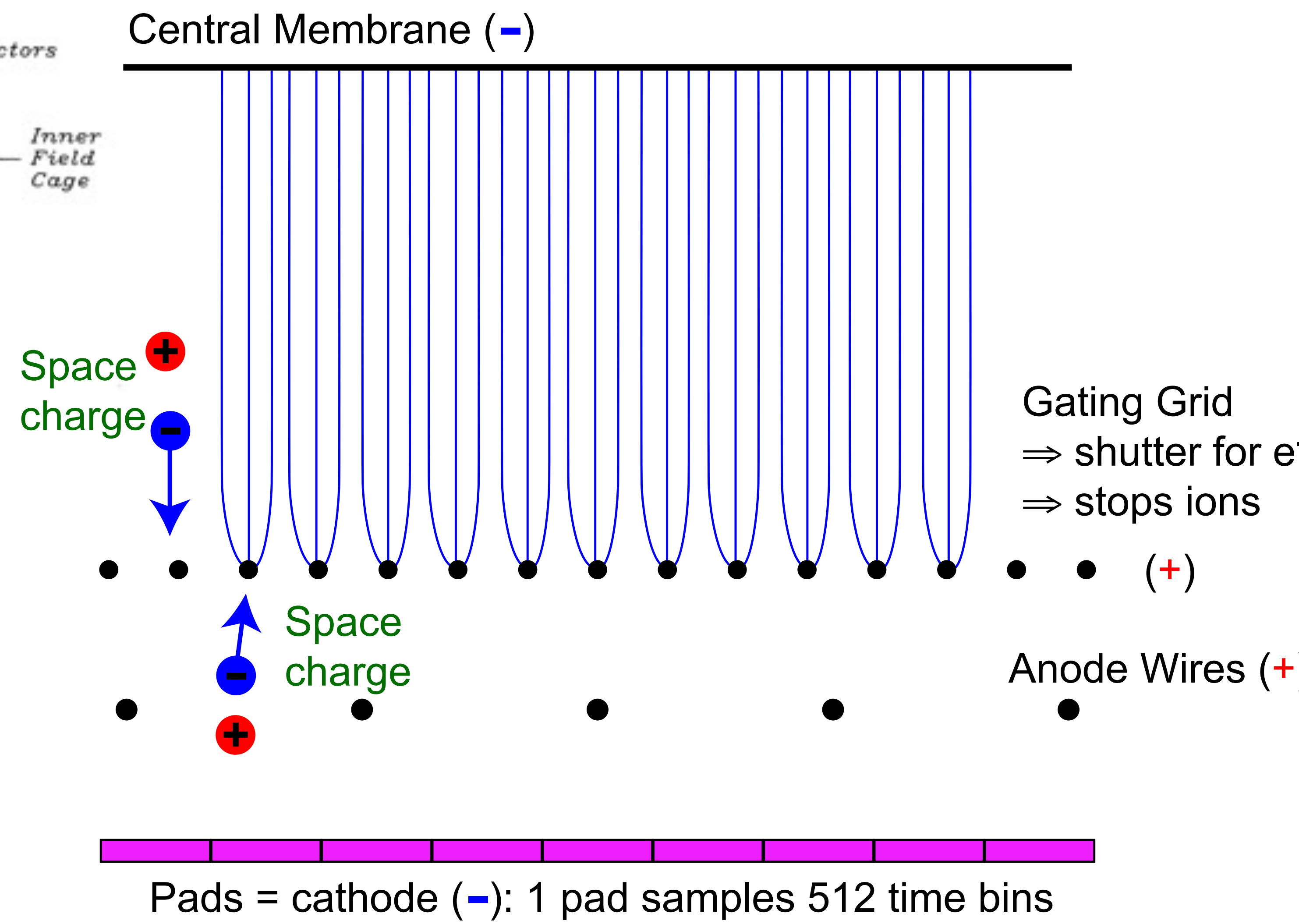
- Designed to reduce charge injection into amplifiers

Slow ions left in volume:

- accumulate, create space charge
- space charge creates distortions

TPC Details





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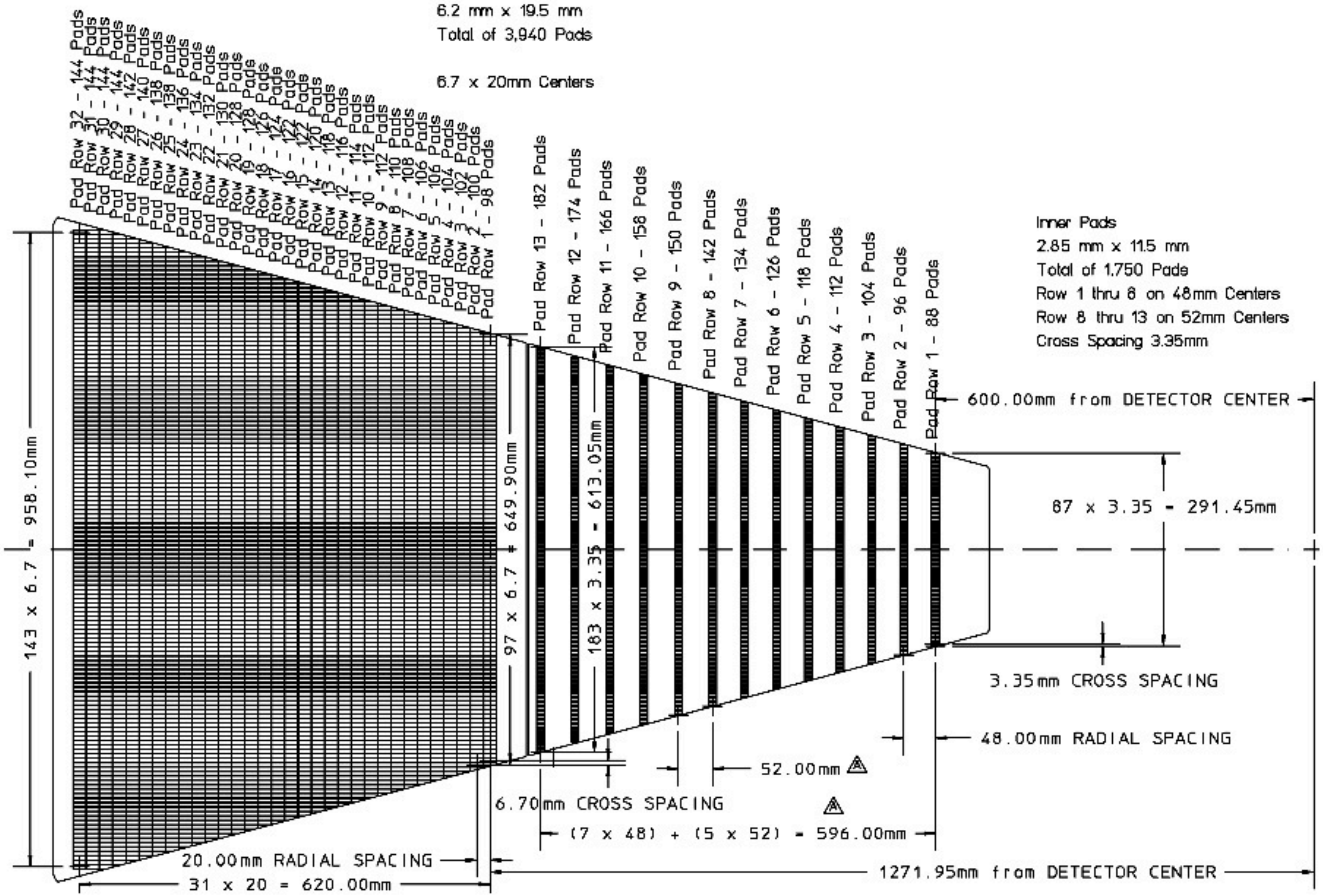
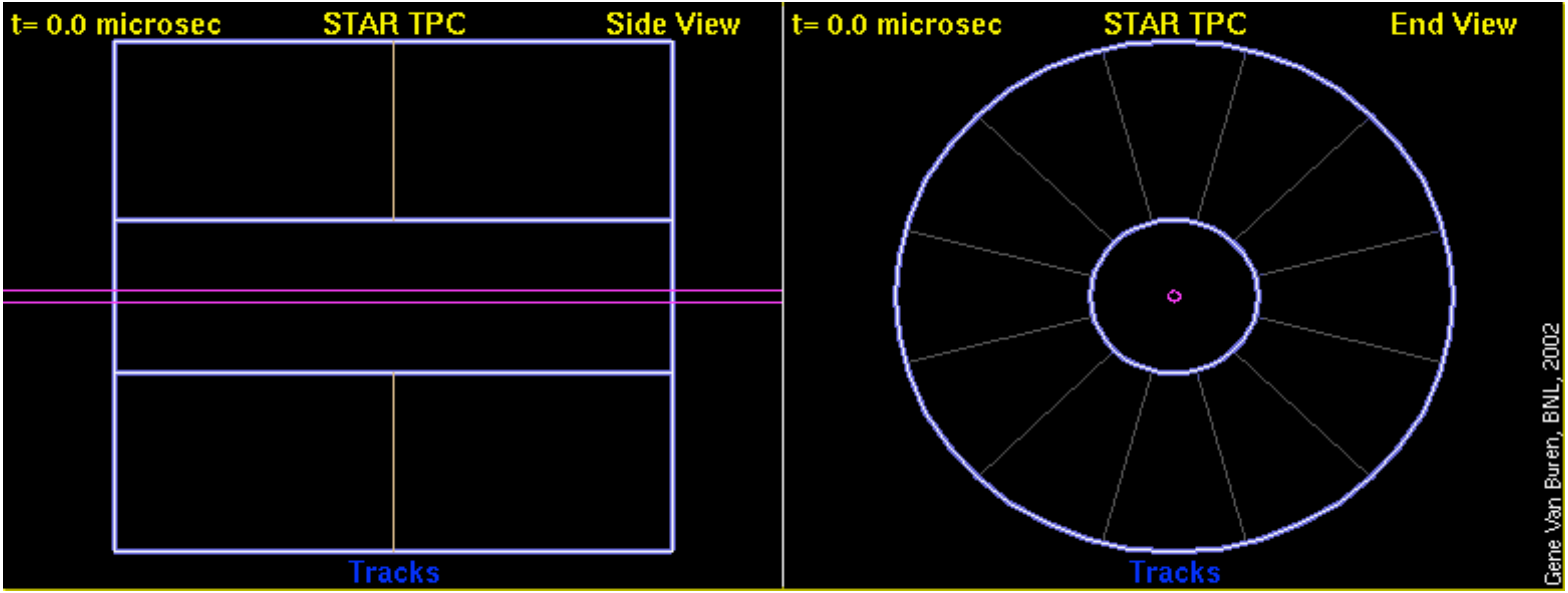

6.2 mm x 19.5 mm
Total of 3,940 Pads
6.7 x 20mm Centers
Pad Row 32 - 144 Pads
Pad Row 1 - 98 Pads
Pad Row 13 - 182 Pads
Pad Row 12 - 174 Pads
Pad Row 11 - 166 Pads
Pad Row 10 - 158 Pads
Pad Row 9 - 150 Pads
Pad Row 8 - 142 Pads
Pad Row 7 - 134 Pads
Pad Row 6 - 126 Pads
Pad Row 5 - 118 Pads
Pad Row 4 - 112 Pads
Pad Row 3 - 104 Pads
Pad Row 2 - 96 Pads
Pad Row 1 - 88 Pads
Inner Pads
2.85 mm x 11.5 mm
Total of 1,750 Pads
Row 1 thru 8 on 48mm Centers
Row 8 thru 13 on 52mm Centers
Cross Spacing 3.35mm
600.00mm from DETECTOR CENTER
87 x 3.35 = 291.45mm
3.35mm CROSS SPACING
48.00mm RADIAL SPACING
52.00mm
6.70mm CROSS SPACING
(7 x 48) + (5 x 52) = 596.00mm
1271.95mm from DETECTOR CENTER
20.00mm RADIAL SPACING
31 x 20 = 620.00mm
143 x 6.7 = 958.10mm
97 x 6.7 = 649.90mm
183 x 3.35 = 613.05mm

The STAR TPC

Simulation and animation by Gene Van Buren, movie by Jeff Mitchell.

The STAR TPC



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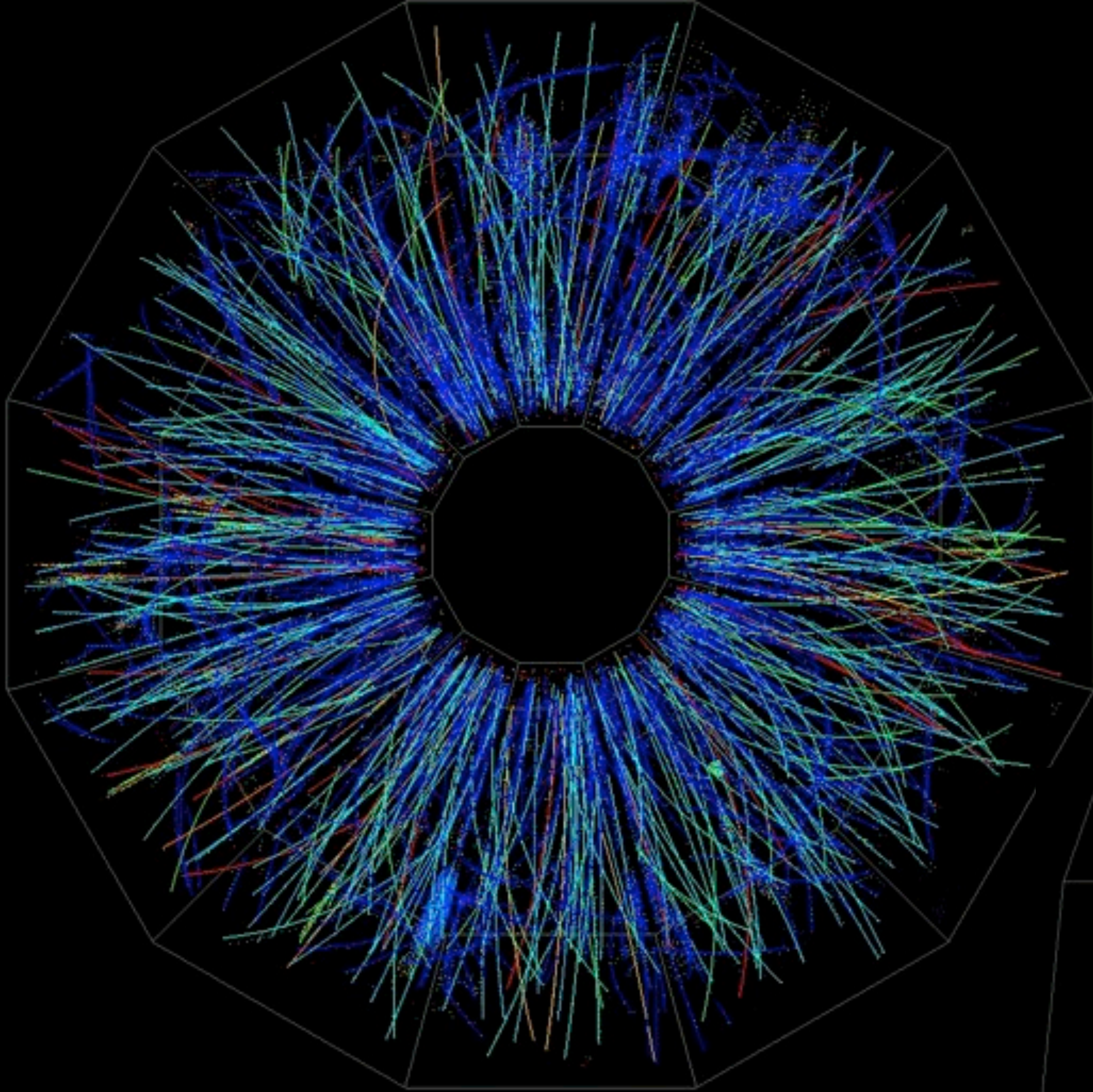
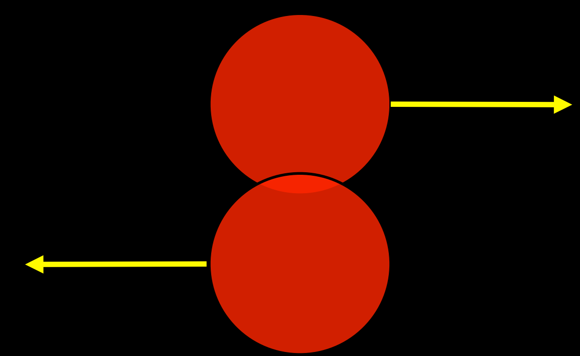
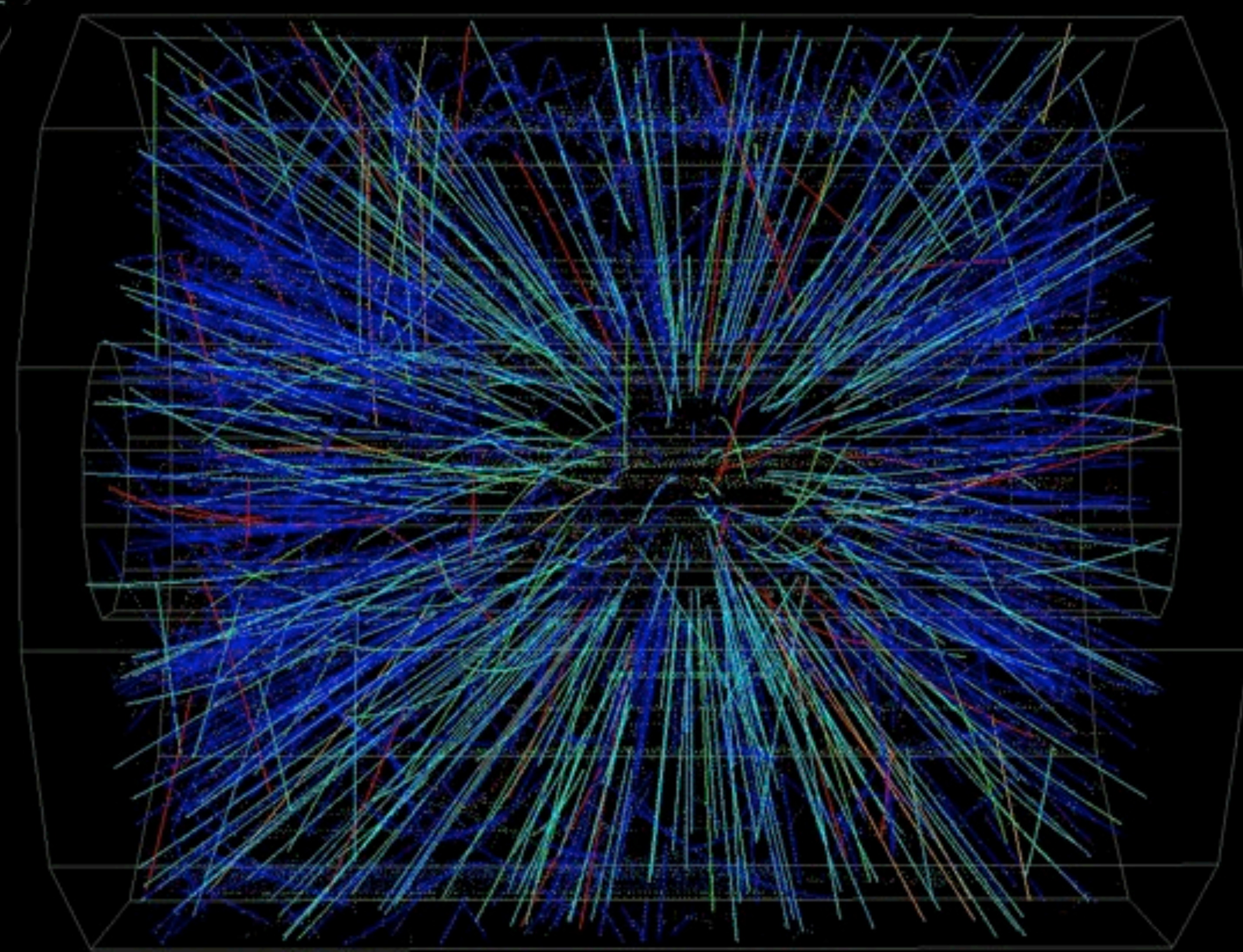
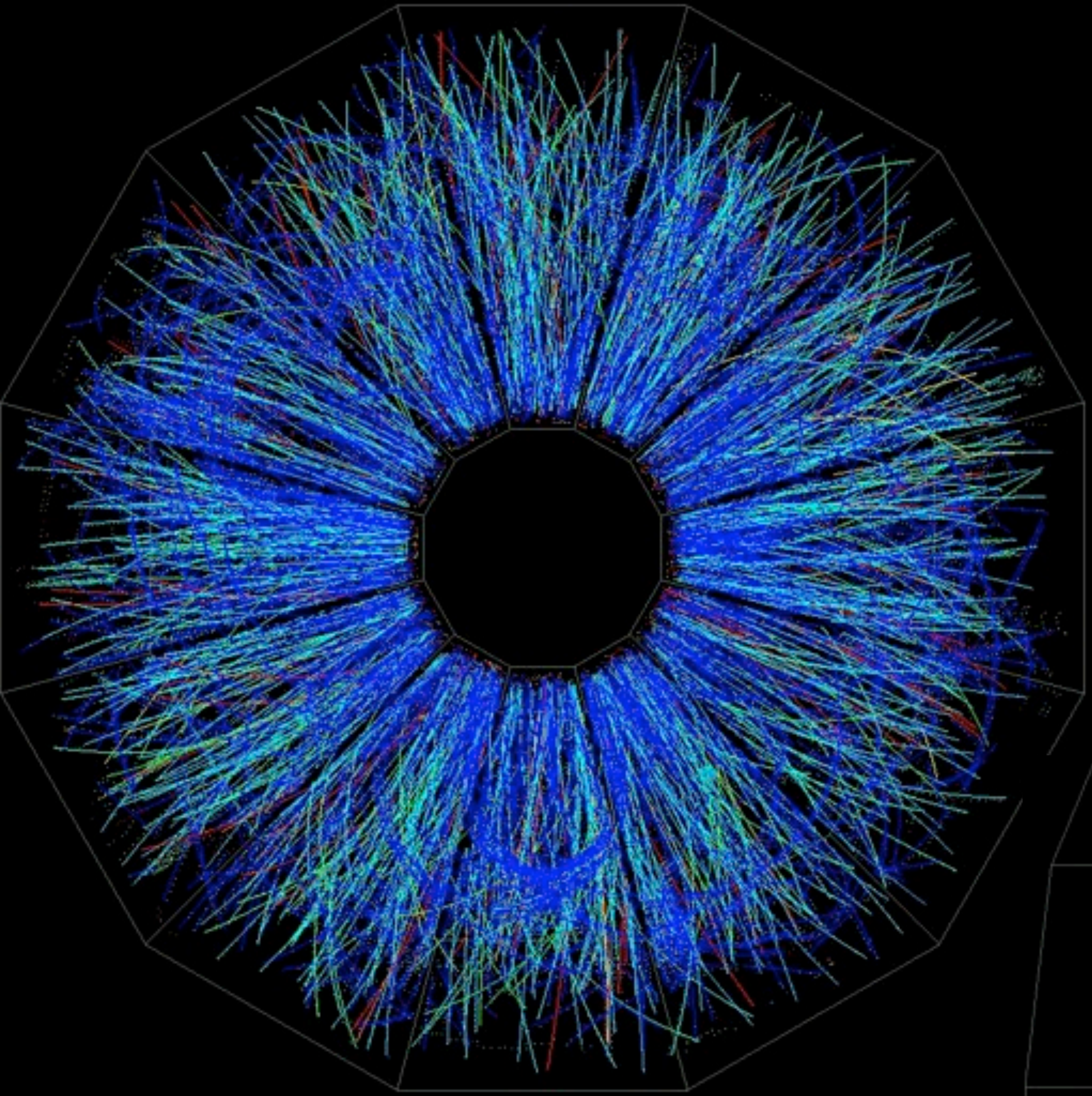


Peripheral Event

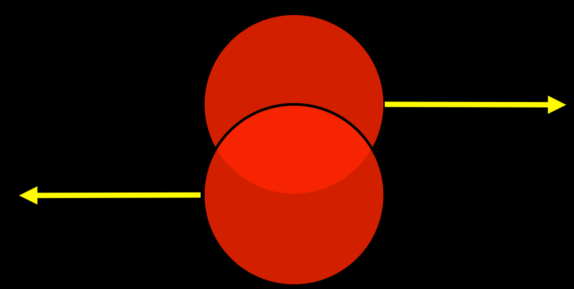


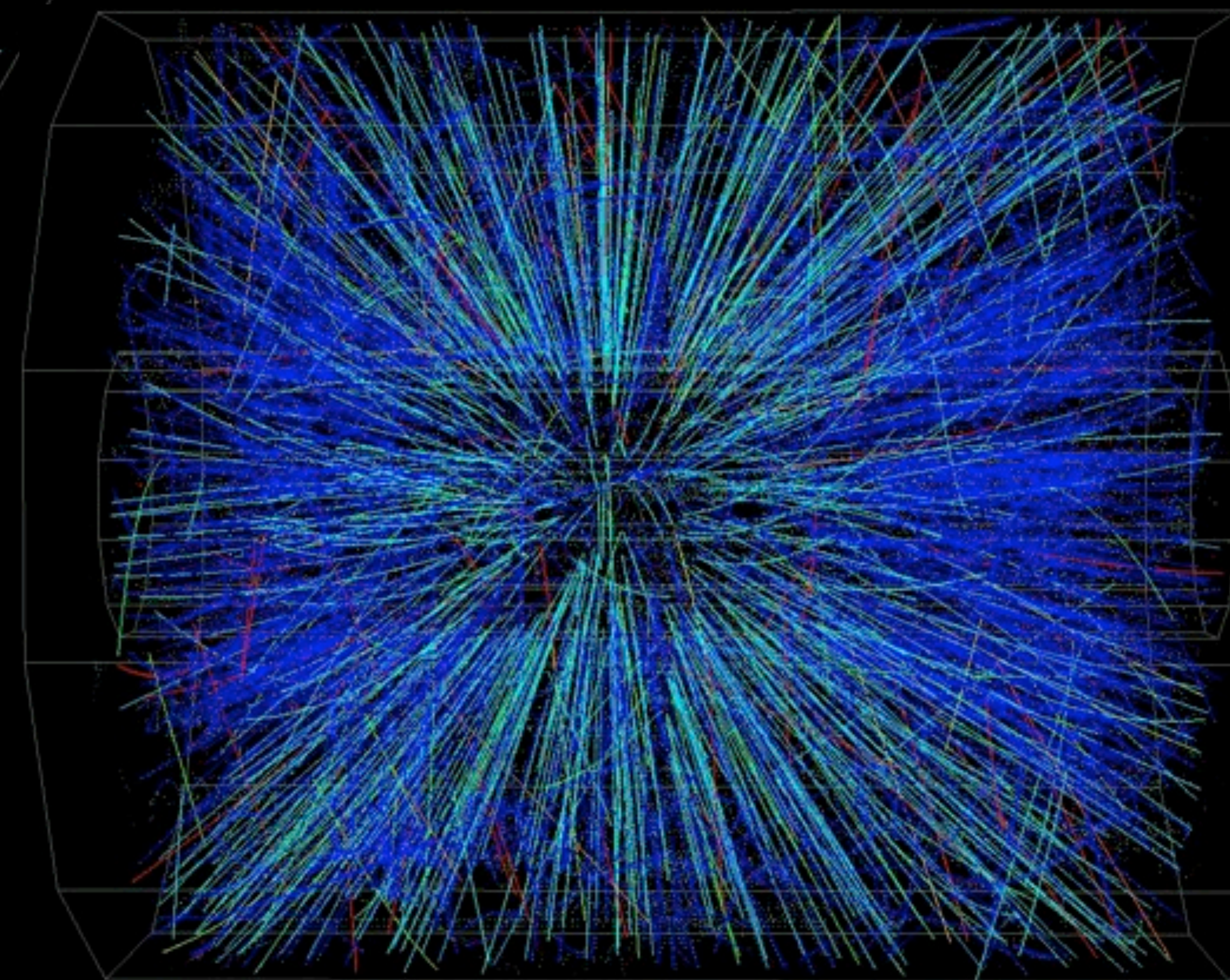


color code ⇒ energy loss



Mid-Central Event





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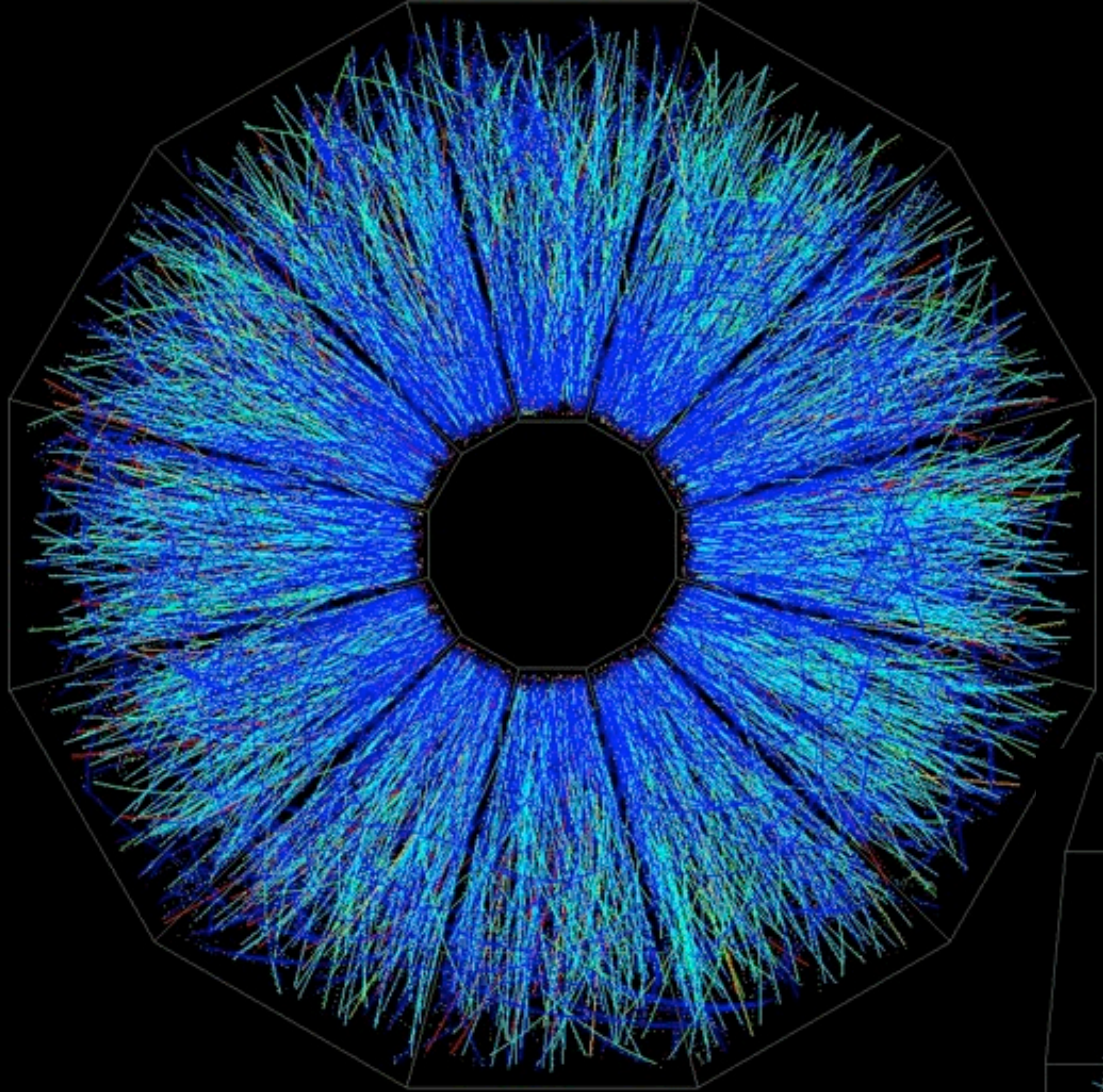
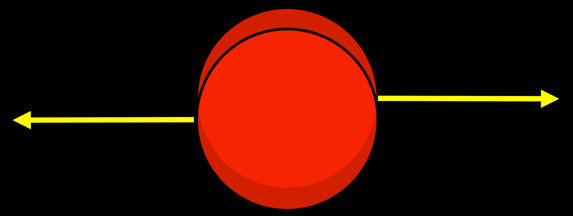
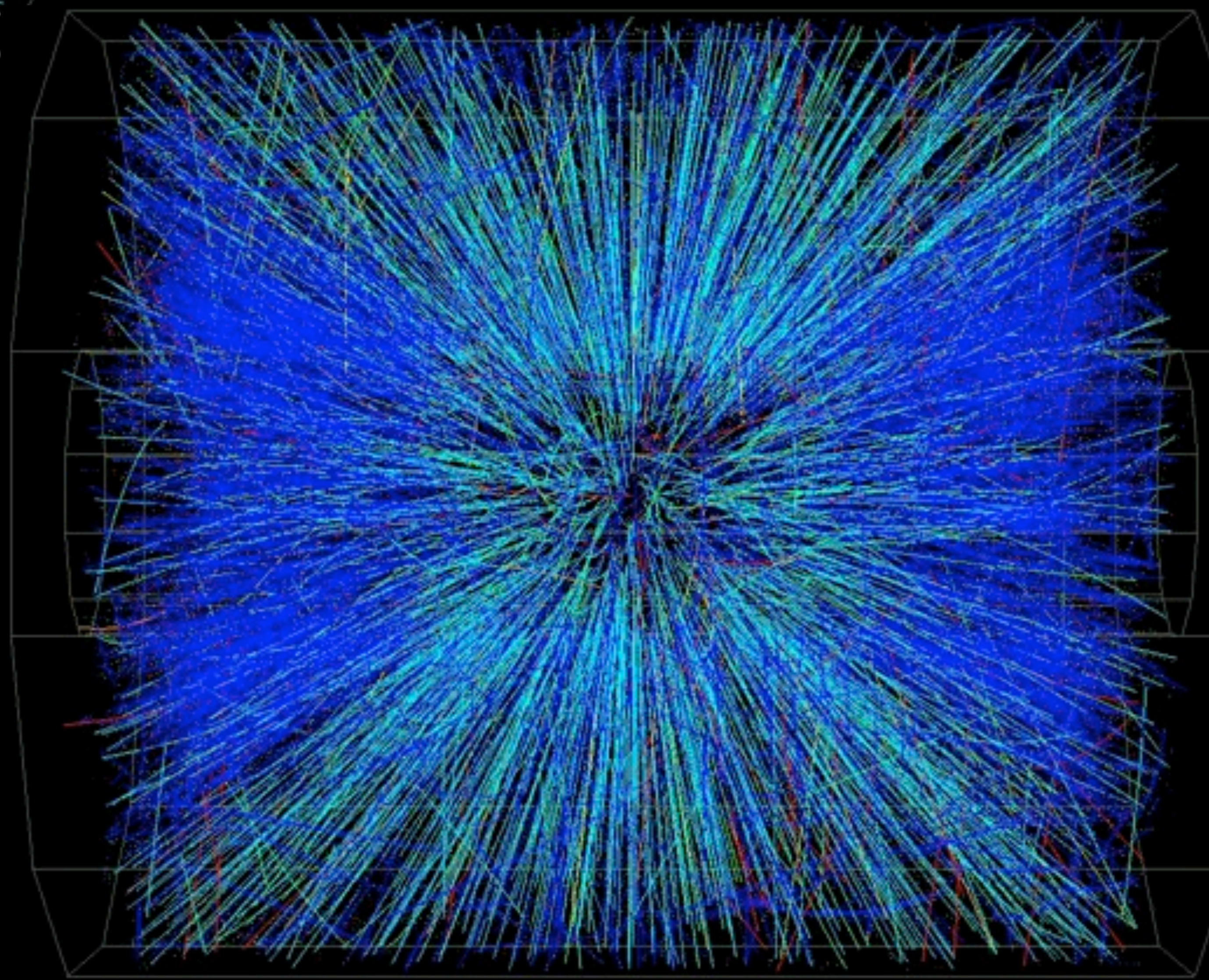


Central Event





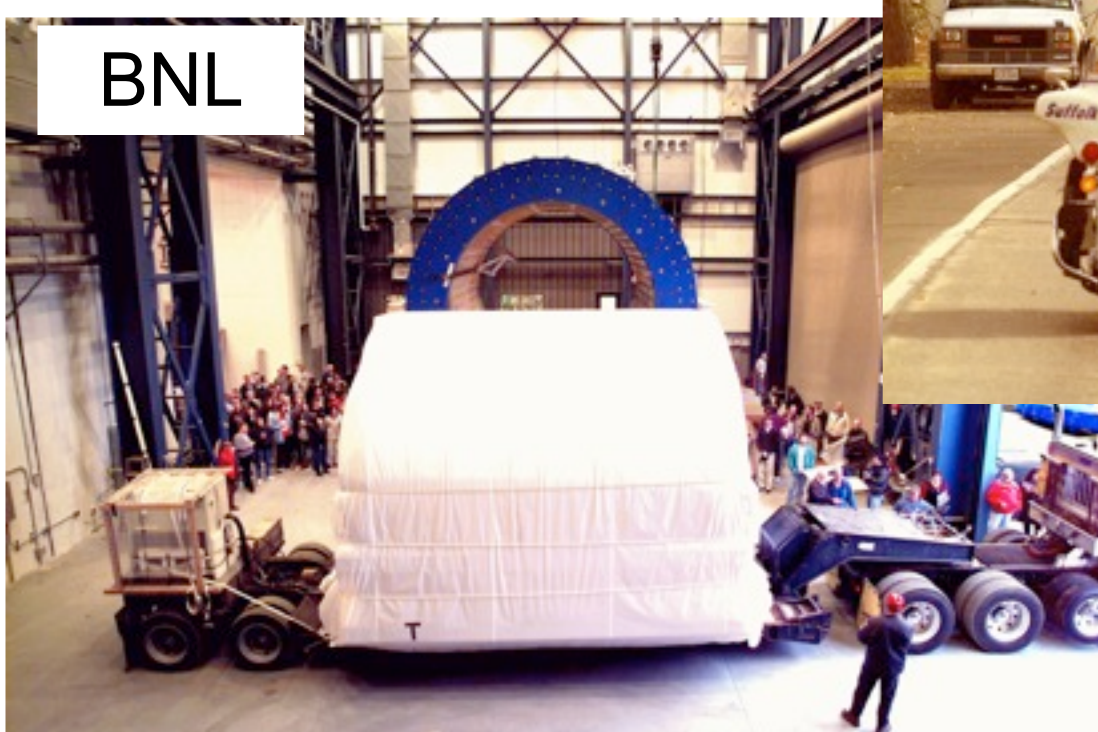
STAR

STAR TPC: from West to East Coast

Berkeley, CA

US Air Force

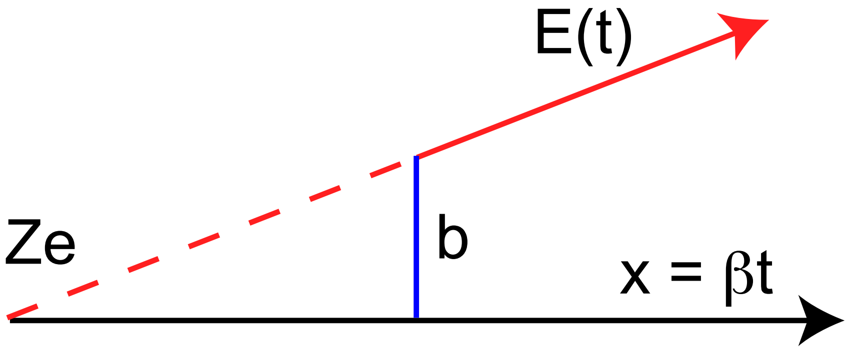
Long Island, NY



BNL

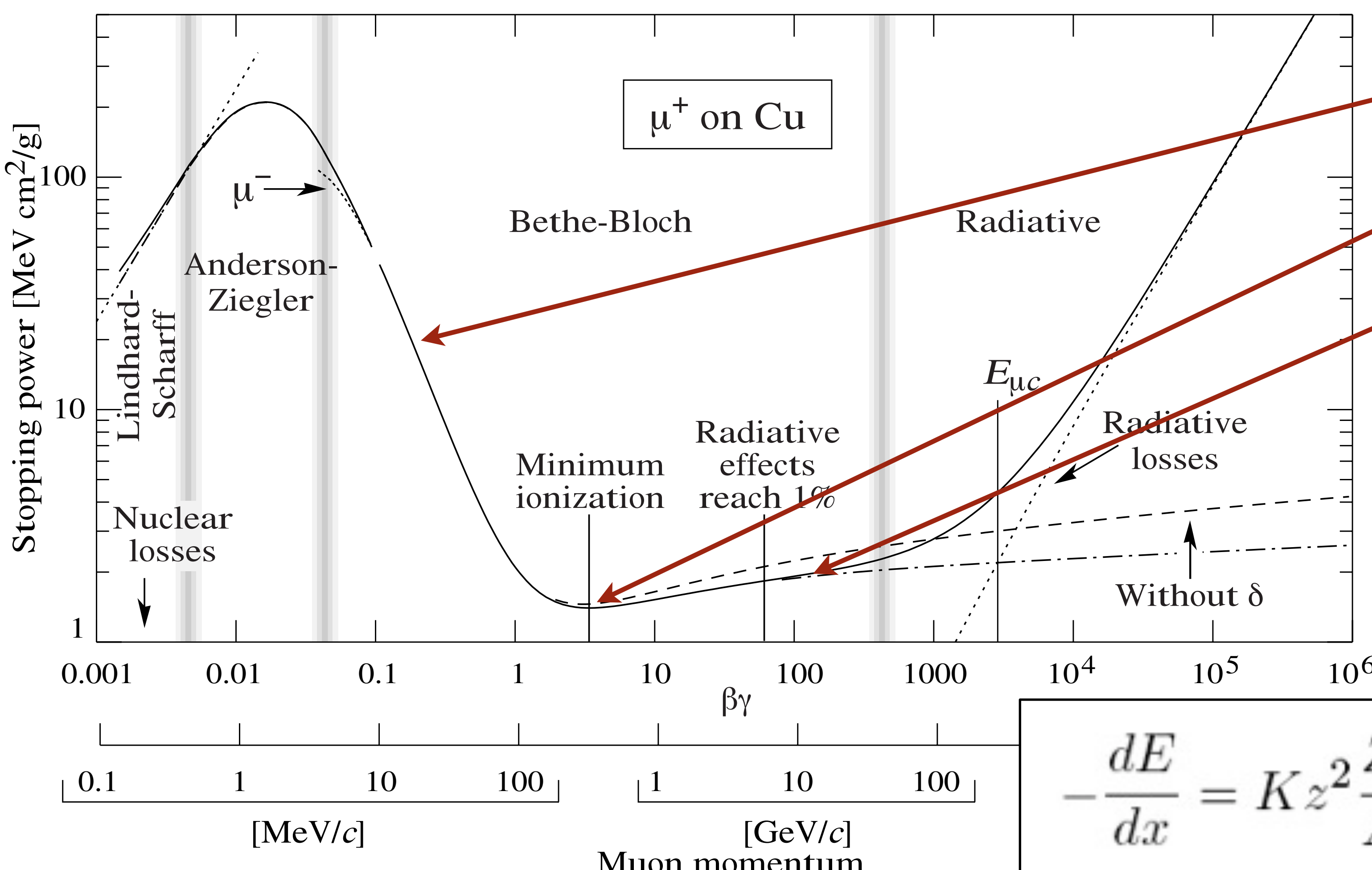
Particle Identification by dE/dx in STAR's TPC

- Elementary calculation of energy loss:
  - Charged particles traversing material give impulse to atomic electrons:



$$p_y^e = e\int E_y(t)dt = e\int E_y(t)\frac{dx}{\beta} = \frac{2Ze^2}{\beta b}$$

$$\text{Energy transfer} = \frac{(p_y^e)^2}{2m_e} \propto \frac{1}{\beta^2}$$



- $\langle dE/dx\rangle \sim 1/\beta^2$ region
- MIP $\beta\gamma \approx 3\text{-}4$
- relativistic rise $\langle dE/dx\rangle \sim \ln\gamma^2\beta^2$

Bethe-Bloch Formula

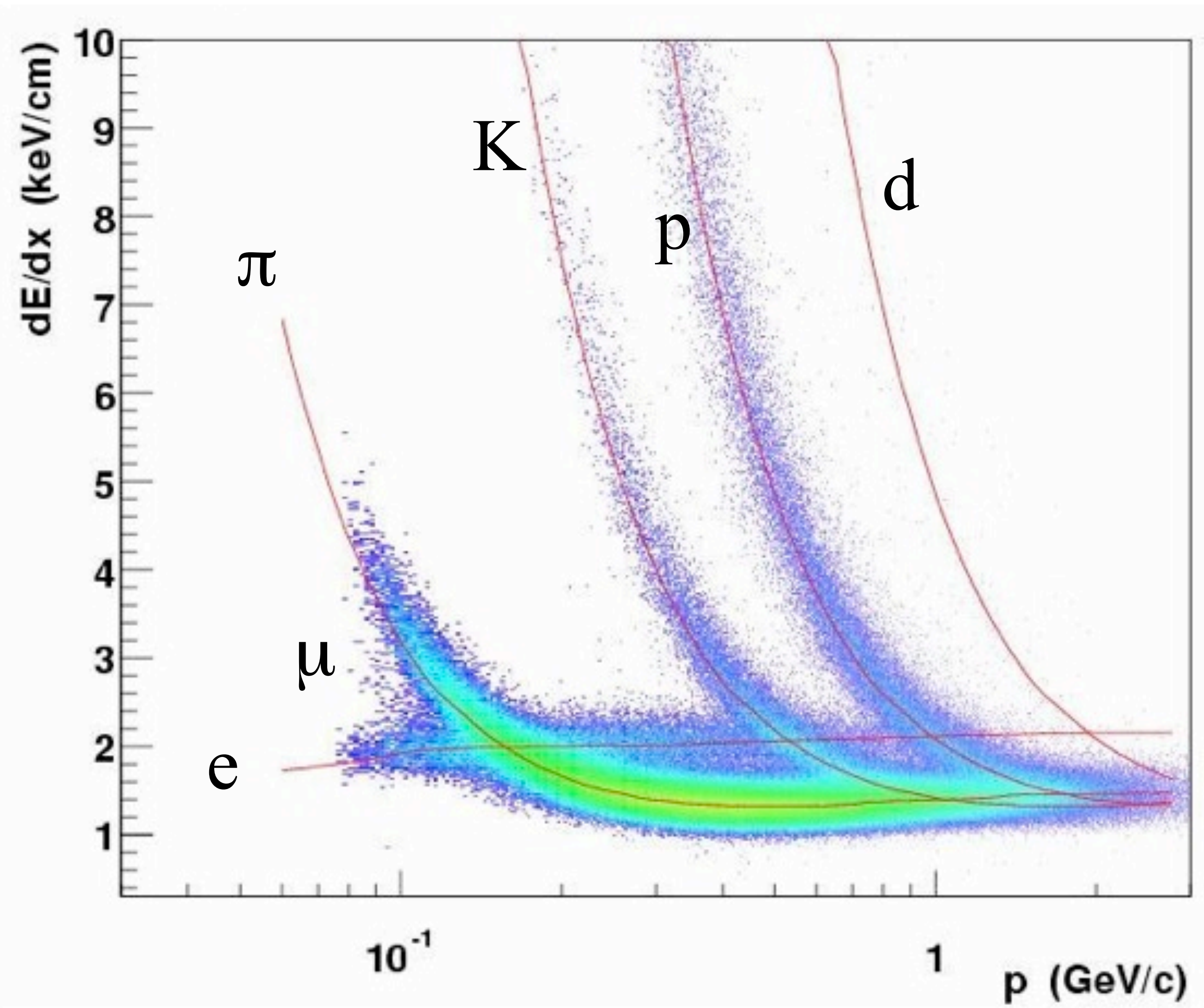
$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Particle Identification by dE/dx in STAR's TPC

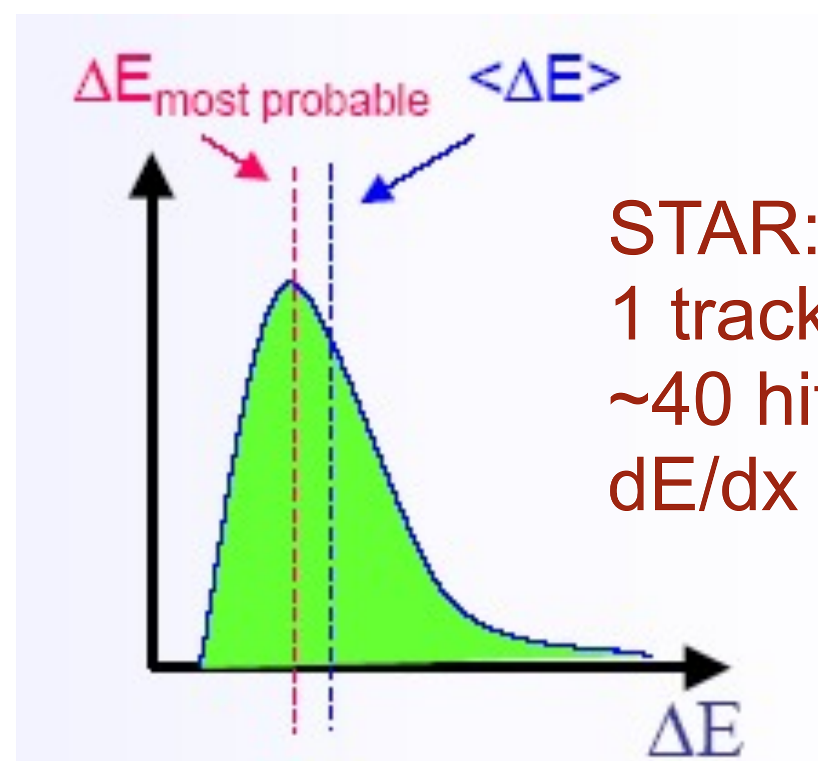
$$p = mv = m_0 \beta\gamma c$$

$$\frac{dE}{dx} \propto \frac{1}{\beta^2} ln(\beta^2\gamma^2)$$

Simultaneous measurement of **p** and **dE/dx** defines mass $m_0 \Rightarrow$ particle ID

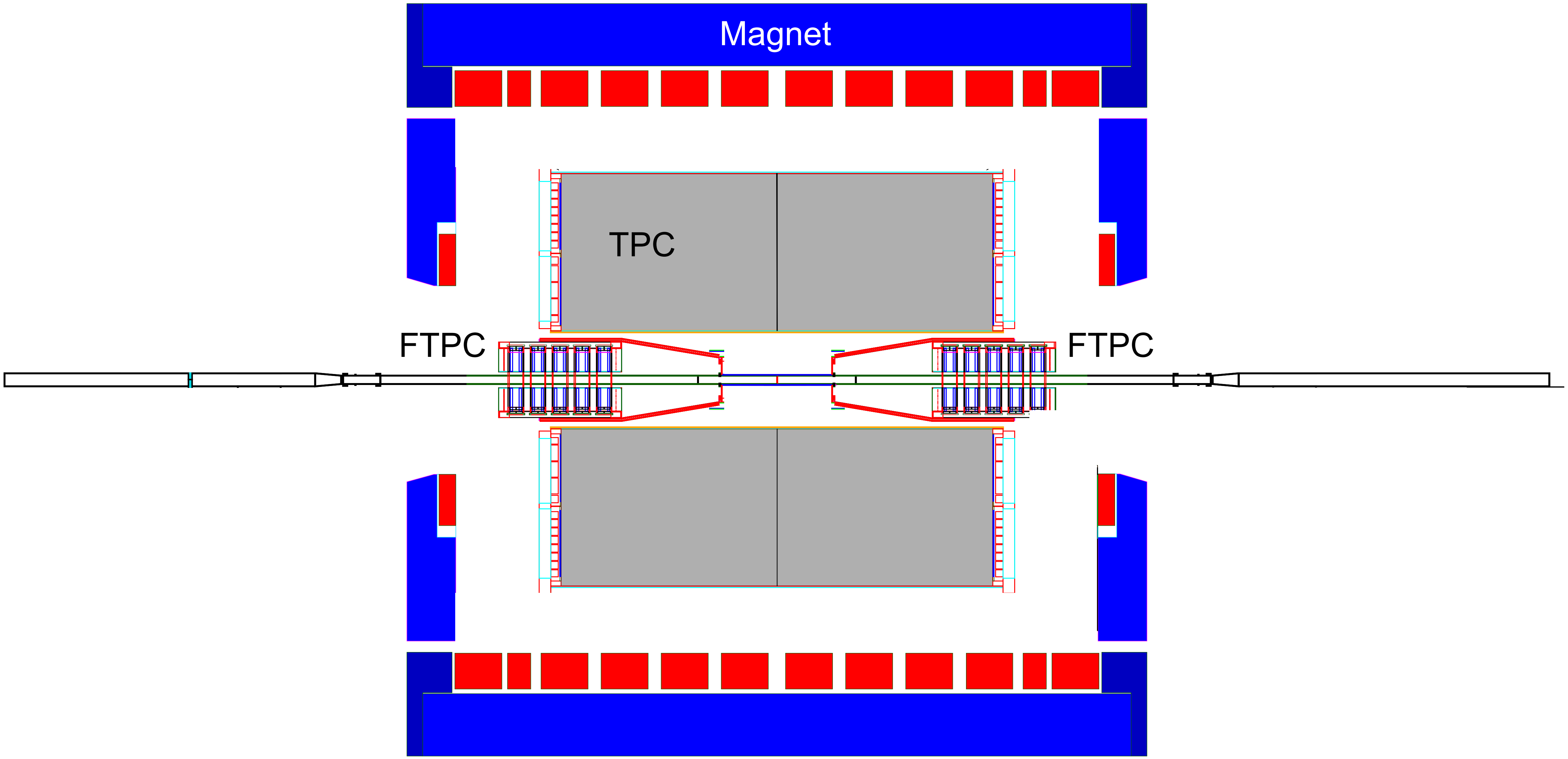


Real detector (limited granularity) can not measure <dE/dx> !
It measures the energy ΔE deposited in a layer of finite thickness δx.
For thin layers or low density materials:
→ Few collisions, some with high energy transfer.
Energy loss distributions show large fluctuations towards high losses: "Landau tails"



STAR:
1 track has ~40 hits = 40 dE/dx values

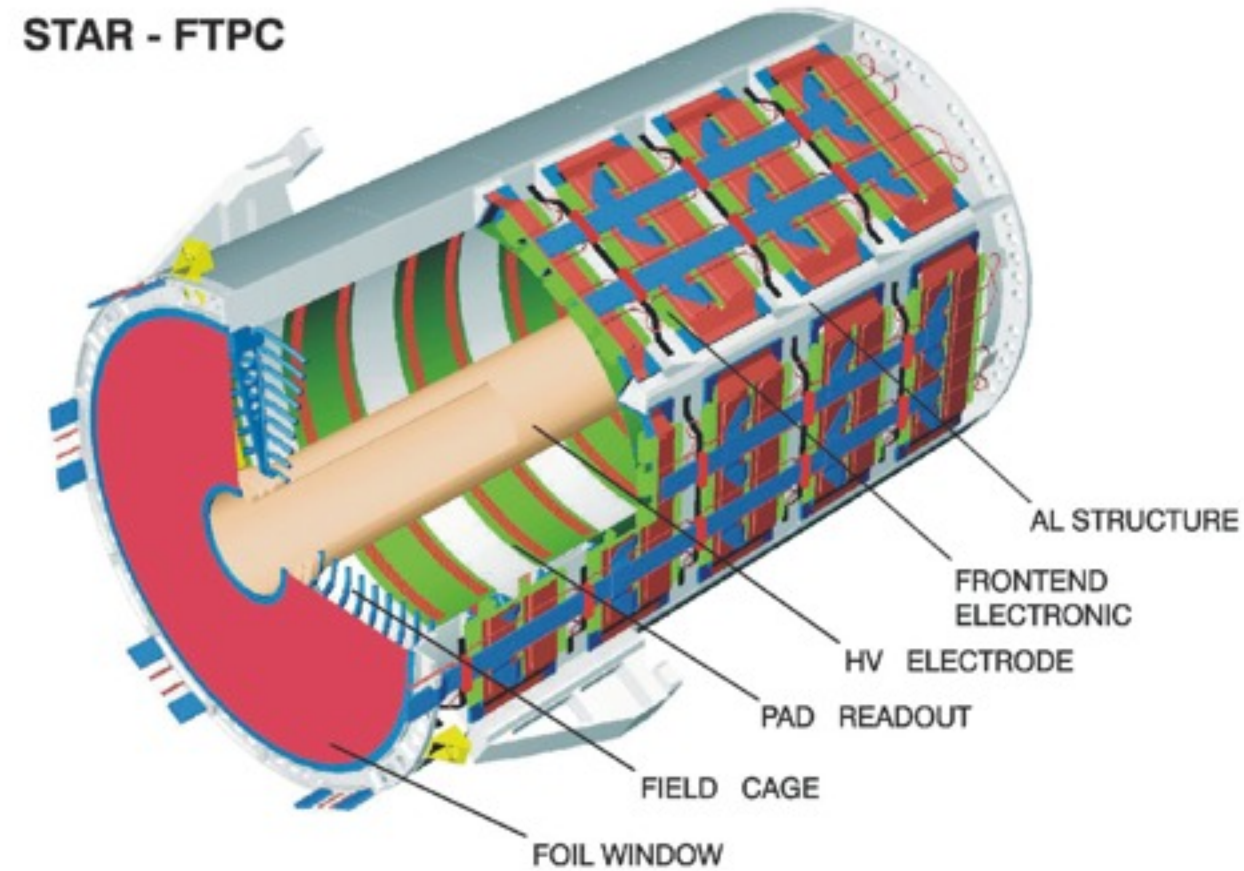
STAR Components - FTPC



- FTPC - Forward Time Projection Chamber
  - ➡ A 3-dimensional tracking device for charged hadrons
  - ➡ Chambers are at small angles - different areas of rapidity compared to the main TPC

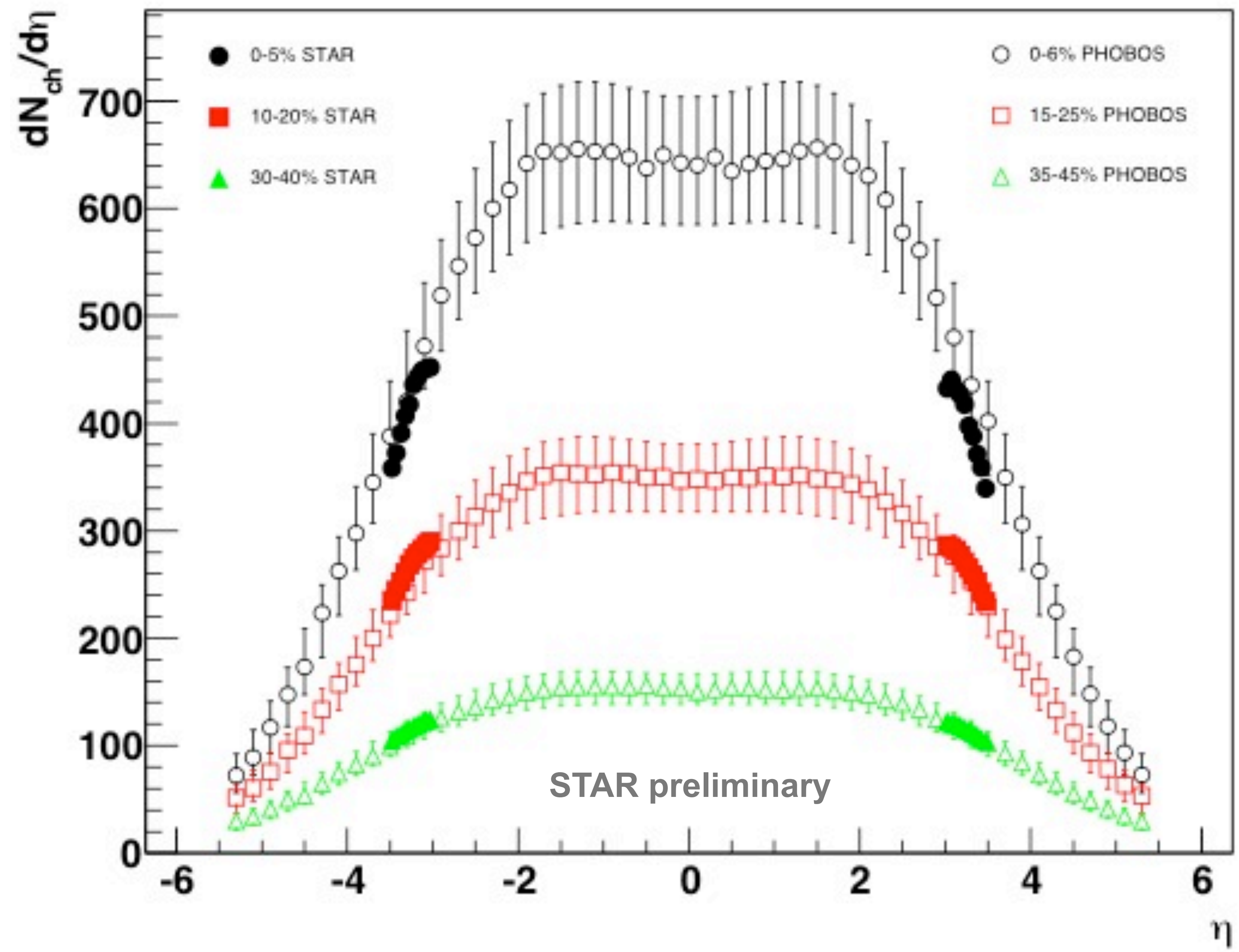
The Forward TPCs

Volume	
inner radius	7.73 cm
outer radius	30.05 cm
chamber length	120 cm (|z| = 150 – 270 cm)
acceptance	η=2.5 –4.0 (θ=2° - 9°)
Field properties	
drift cathode voltage	10-15 kV
drift electrical field	240-1400 V/cm (radial, $\perp$ beam)
Solenoid magnetic field	0.5 T (|| beam)
Gas properties	
gas mixture	Ar(50%)-CO_2(50%)
drift velocity	0.3 – 2.0 cm/μs
trans. Diffusion DT	100-130 μ m/$\sqrt{}$cm
long. Diffusion DL	100-130 μ m/$\sqrt{}$cm
Lorentz angle	4 deg.



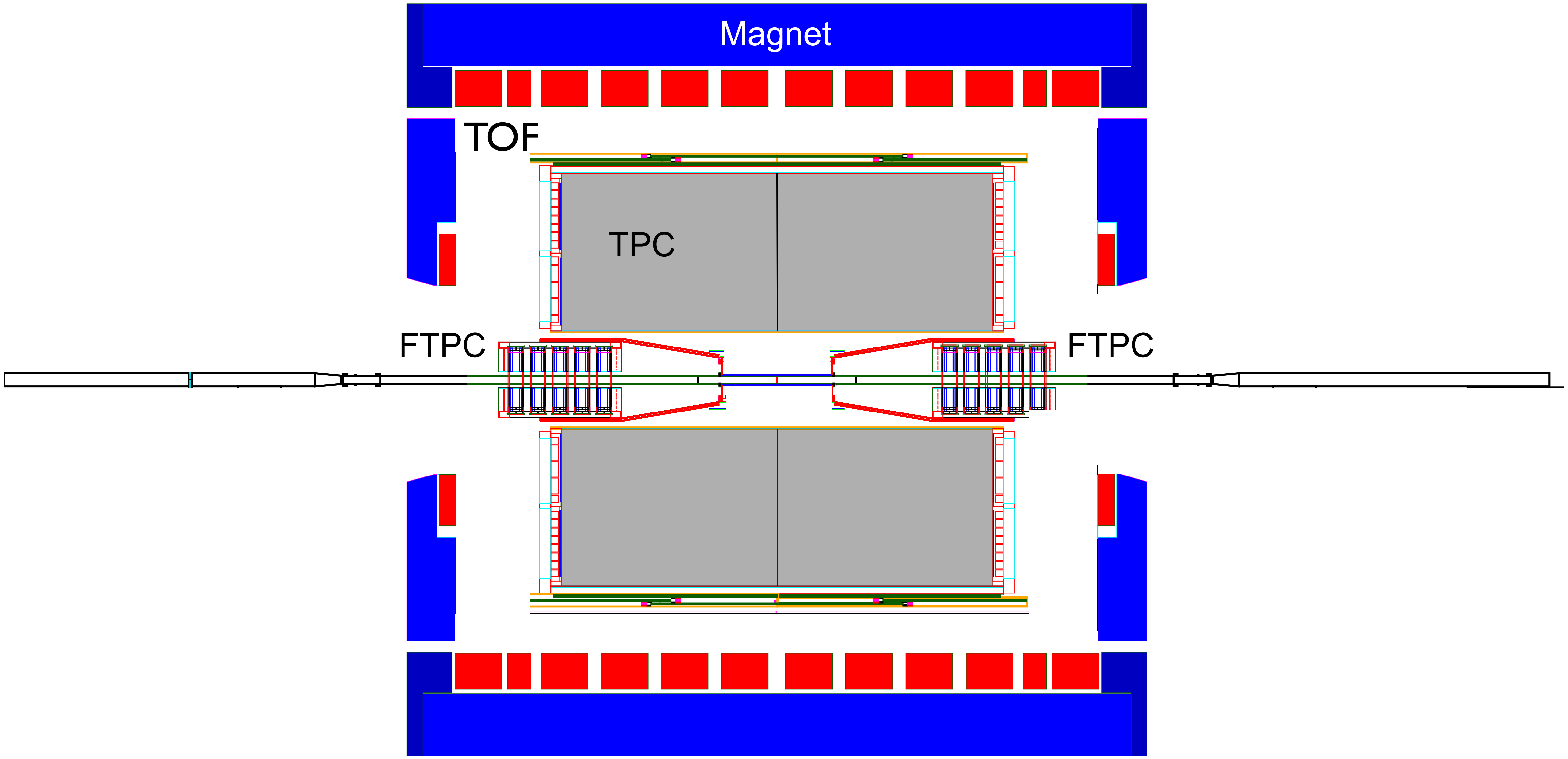
2 FTPCs
2.5 < || < 4.0
6 azimuthal sectors (~ 60 deg) with 10 rows in z-direction
electron drift radial and perpendicular to magnetic field
spatial resolution: ~ 200-300 microns
2-track resolution: 2-2.5 mm

Au+Au dN/dη distribution



- Good agreement between PHOBOS and STAR-FTPC measurements
- Au+Au data are not corrected for background

STAR Components - TOF



- TOF - Time Of Flight
  - ➡ A "barrel" detector which goes outside the TPC
  - ➡ Allows us to identify particles up to higher momentum than the dE/dx in the TPC itself

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How a TOF works

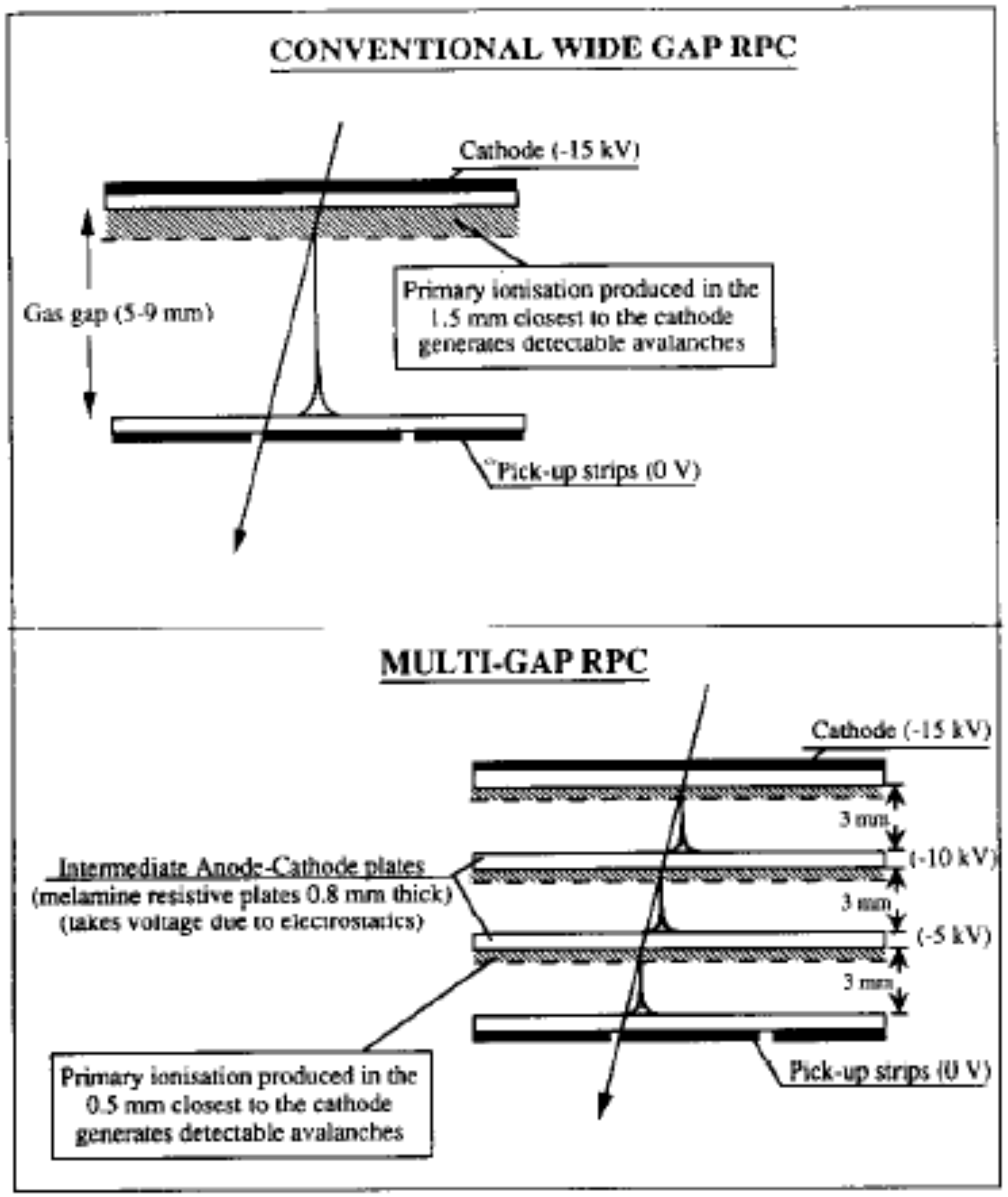

Fig. 1. Schematic diagram and principle of operation of multi-gap RPC compared to a conventional 9 mm single gap RPC.

- Need a trigger detector to determine the "start time" of an event
- Need a final detector to measure the "end time" of an event
- A Multi-Gap Resistive Plate Chamber is used in STAR to measure the time-of-flight
  - ➡ Just like a TPC, a particle crosses the gas detector and ionises the gas

$$\frac{1}{\beta} = c\Delta t/s$$

$$M = p\sqrt{((\frac{1}{\beta})^2 - 1)}$$

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STAR TOF Design

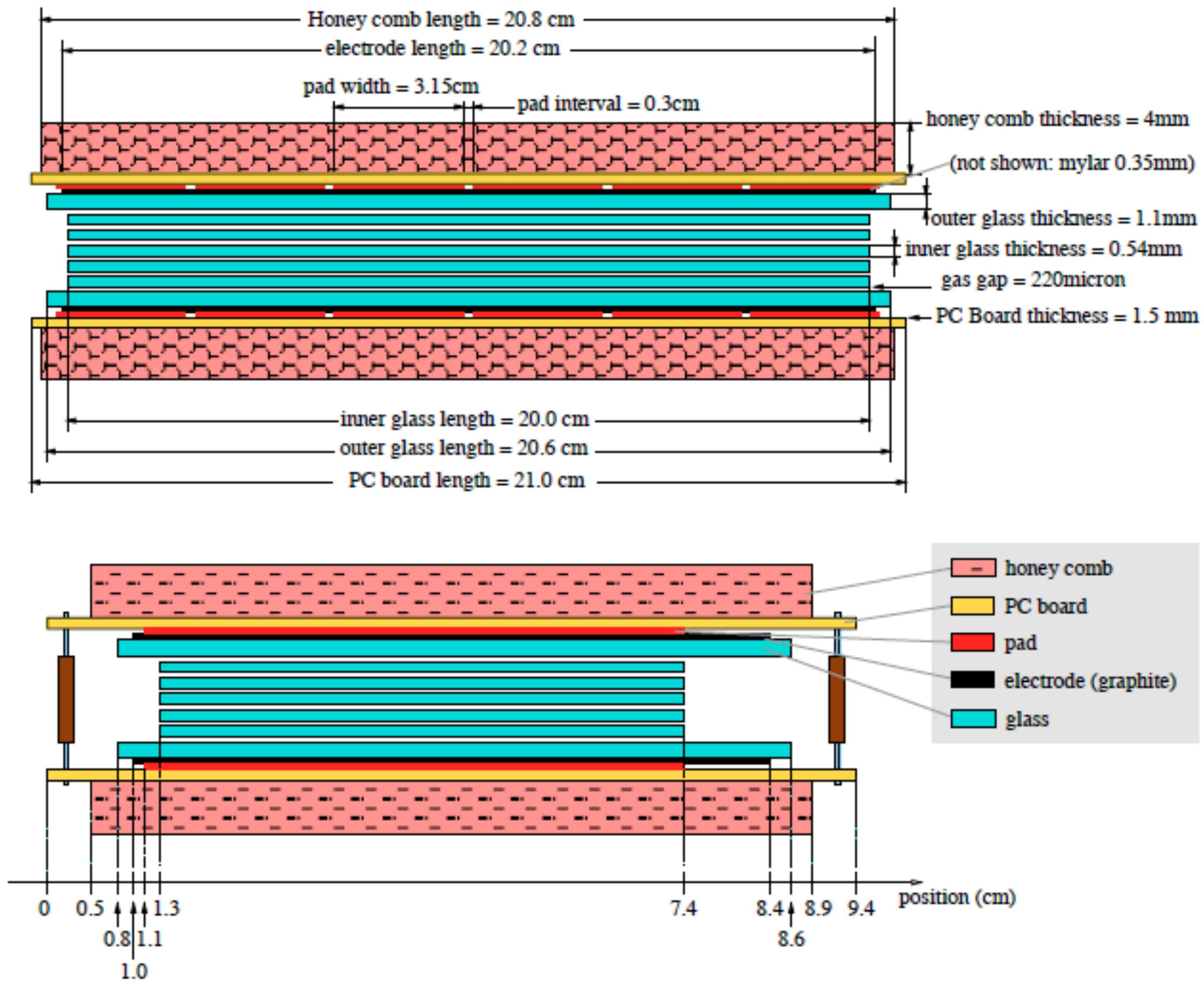
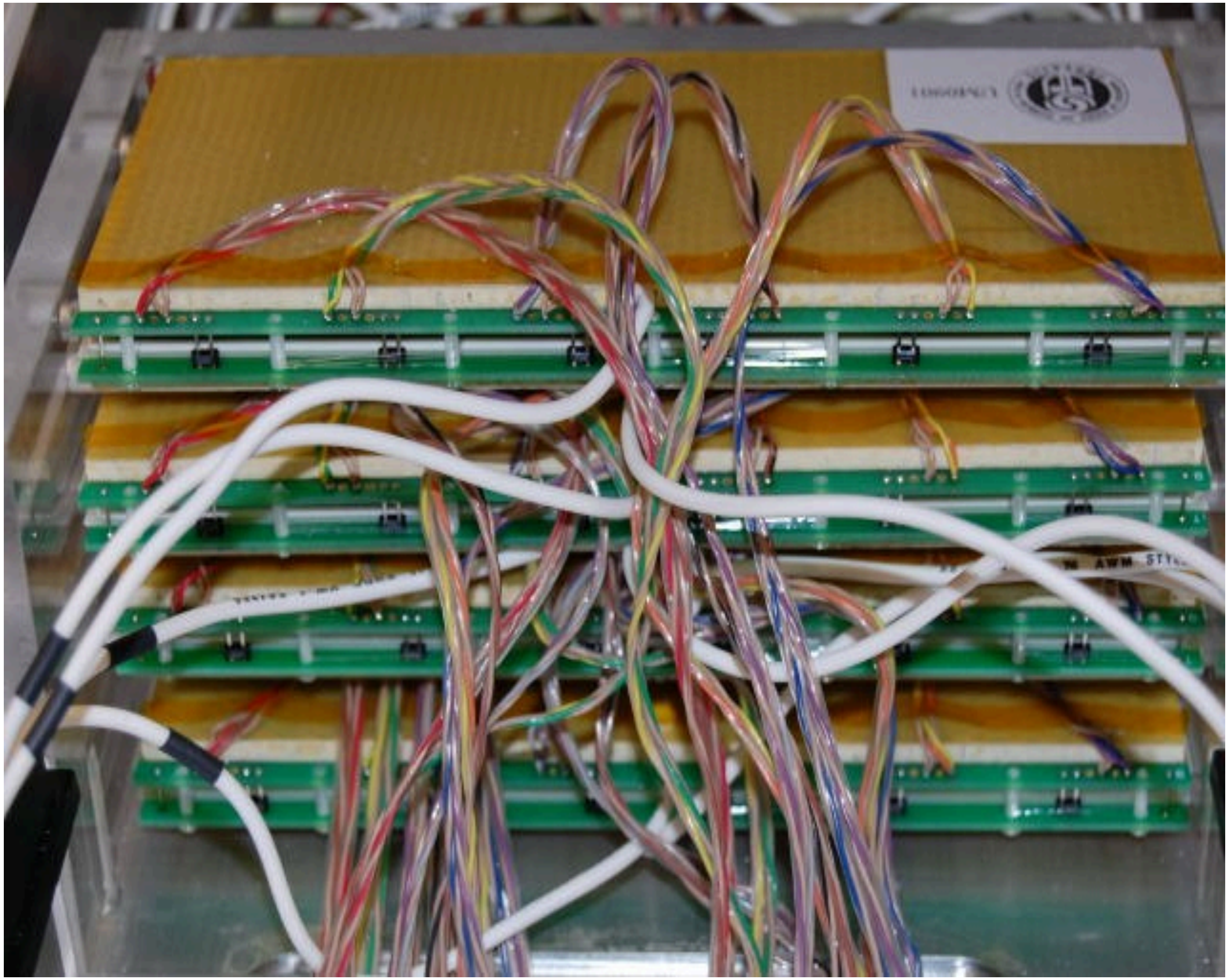
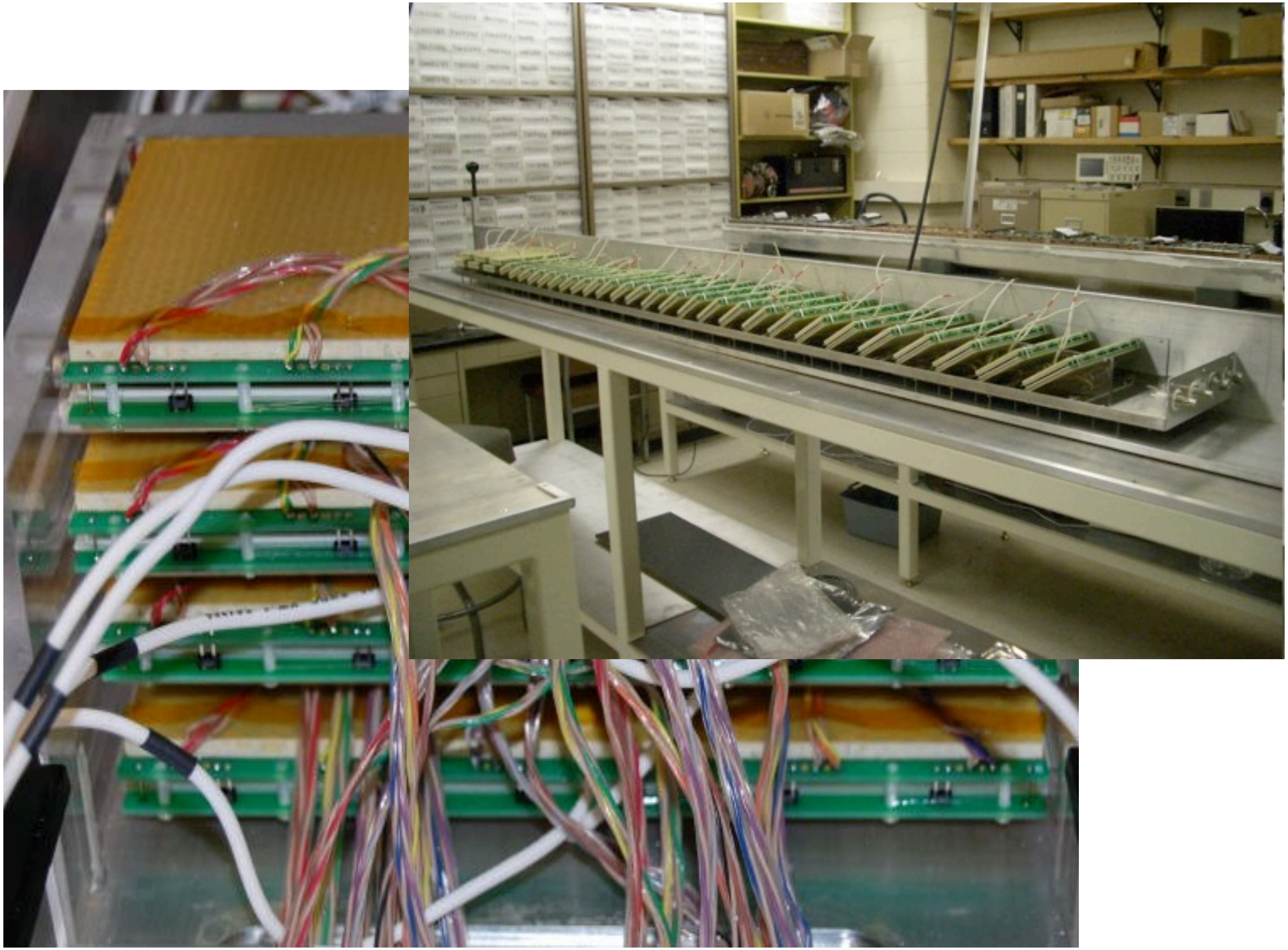


Figure 23: Two side views of the structure of an MRPC module. The upper(lower) view shows the long(short) edge. The two views are not shown at the same scale.

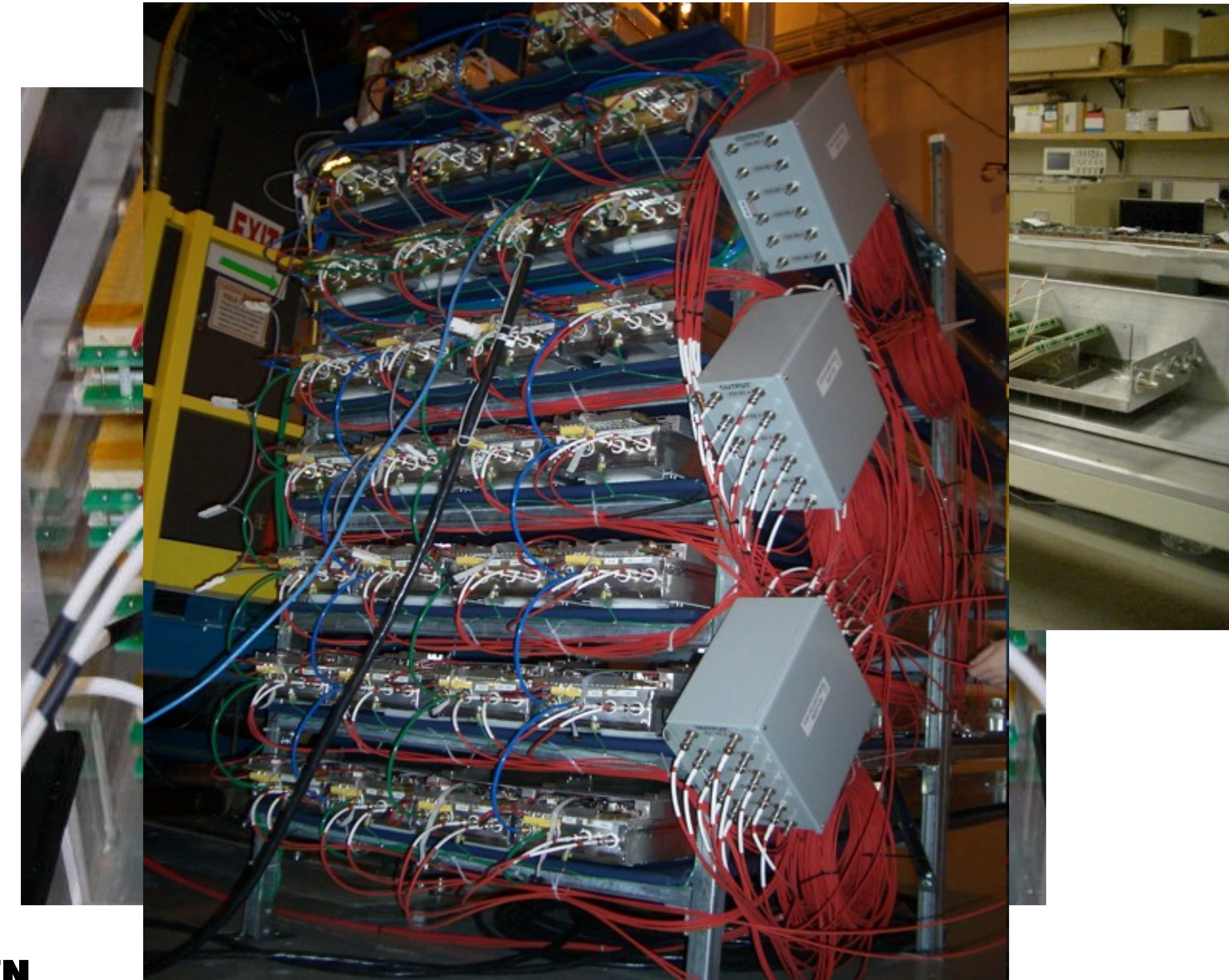
STAR TOF pictures



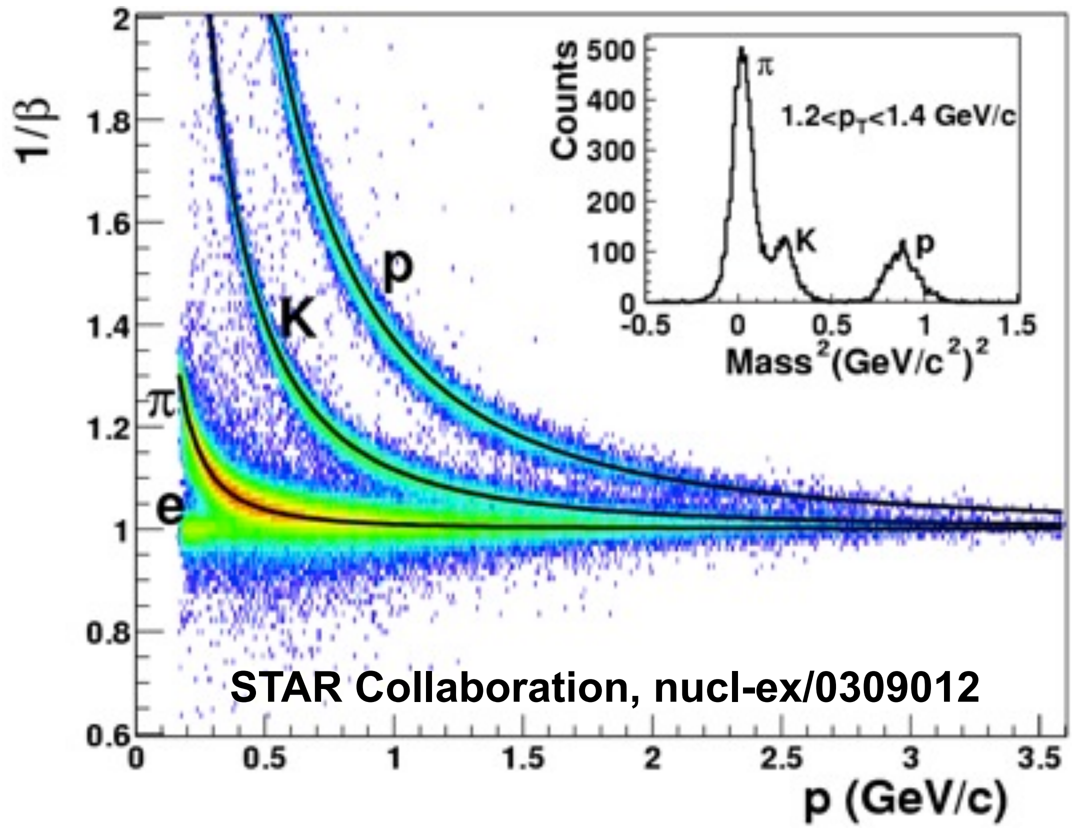
STAR TOF pictures

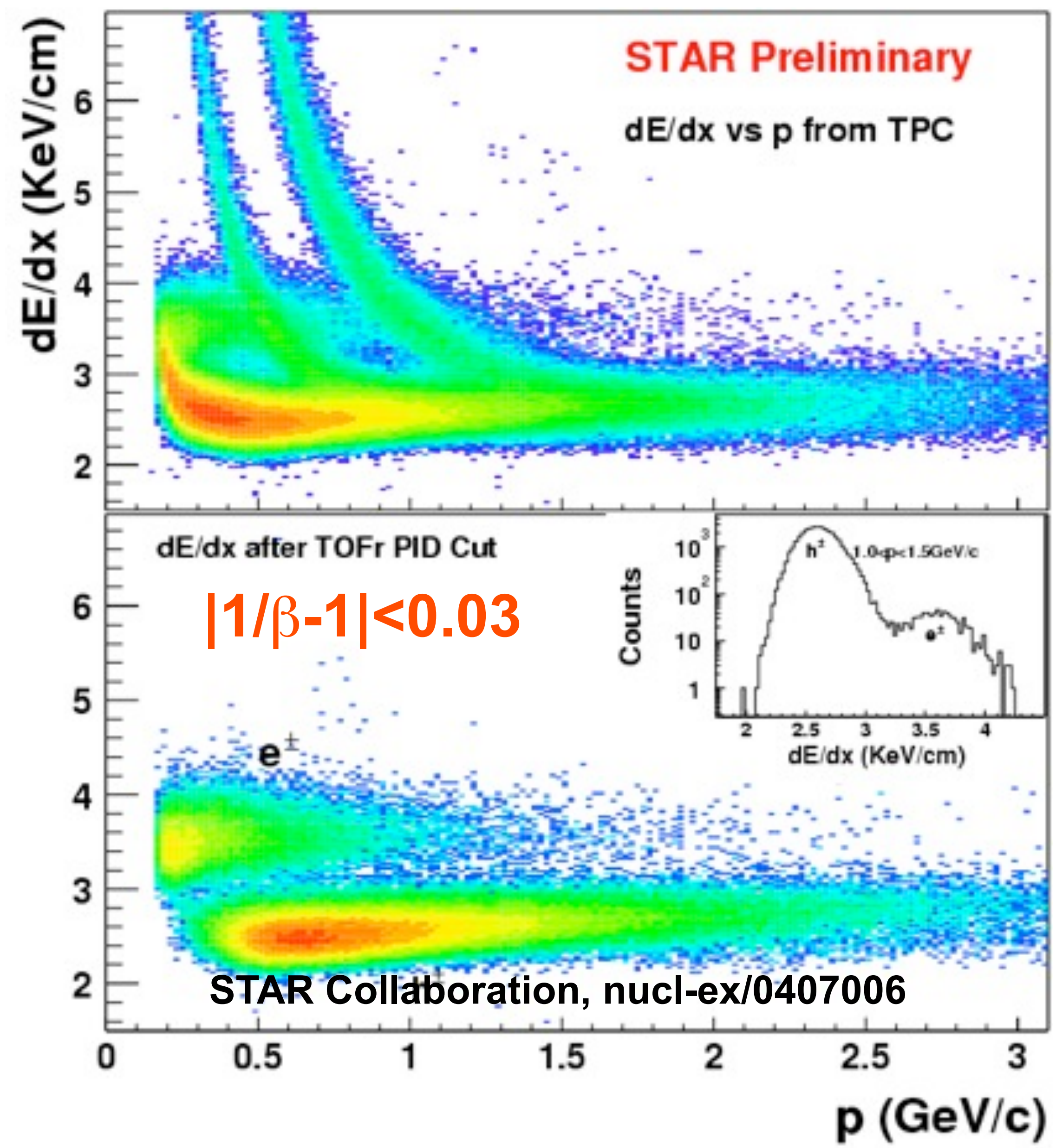


STAR TOF pictures



STAR TOF Performance





TOF PID: (π, K) ~ 1.6, p ~ 3 GeV/c
STAR Collaboration, PLB616(2005)8

Clean electron PID can be obtained up to P_T < 3 GeV/c. → measure the semileptonic decay of open charm. (STAR Collaboration, PRL94(2005)062301)

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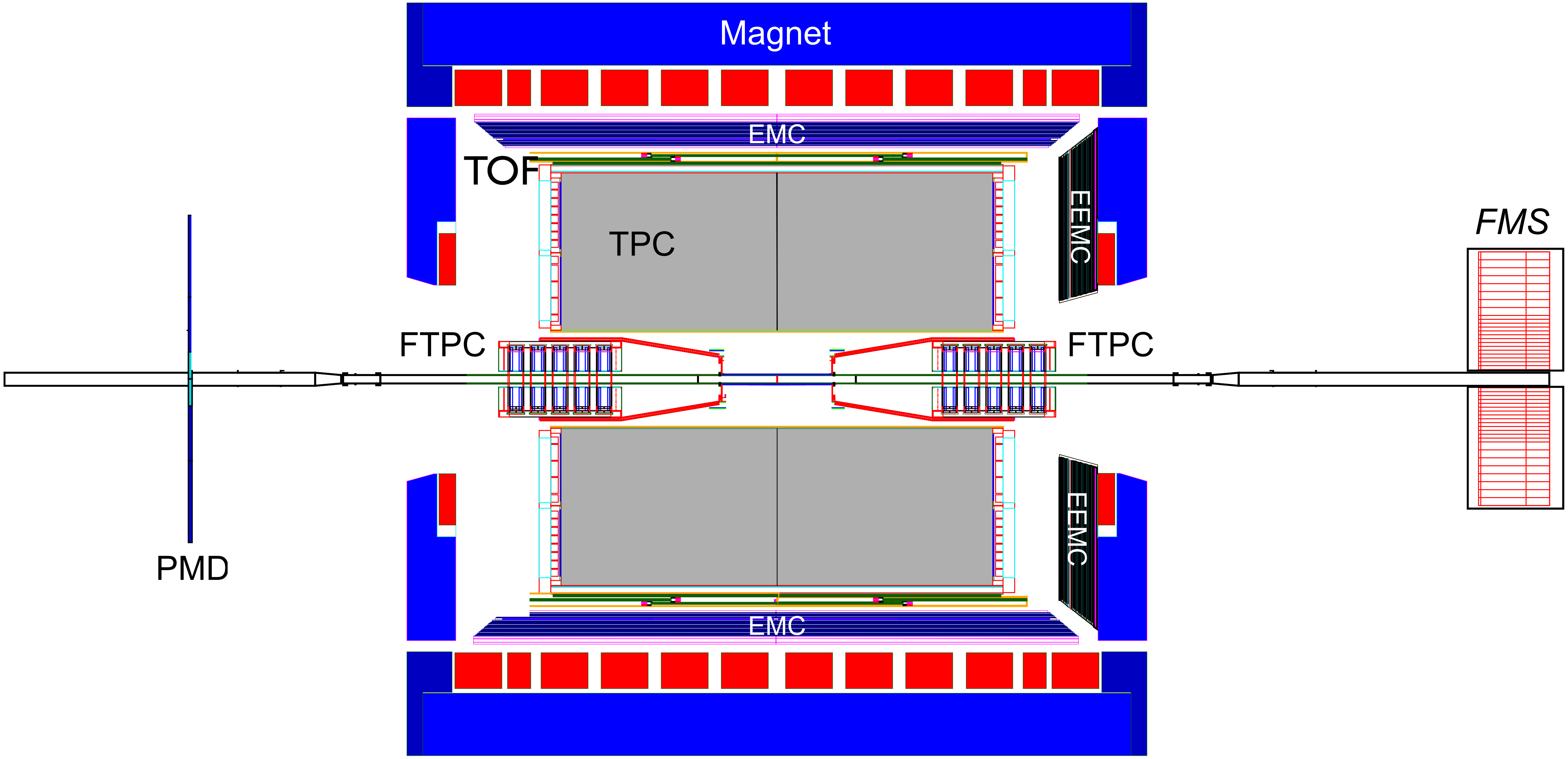
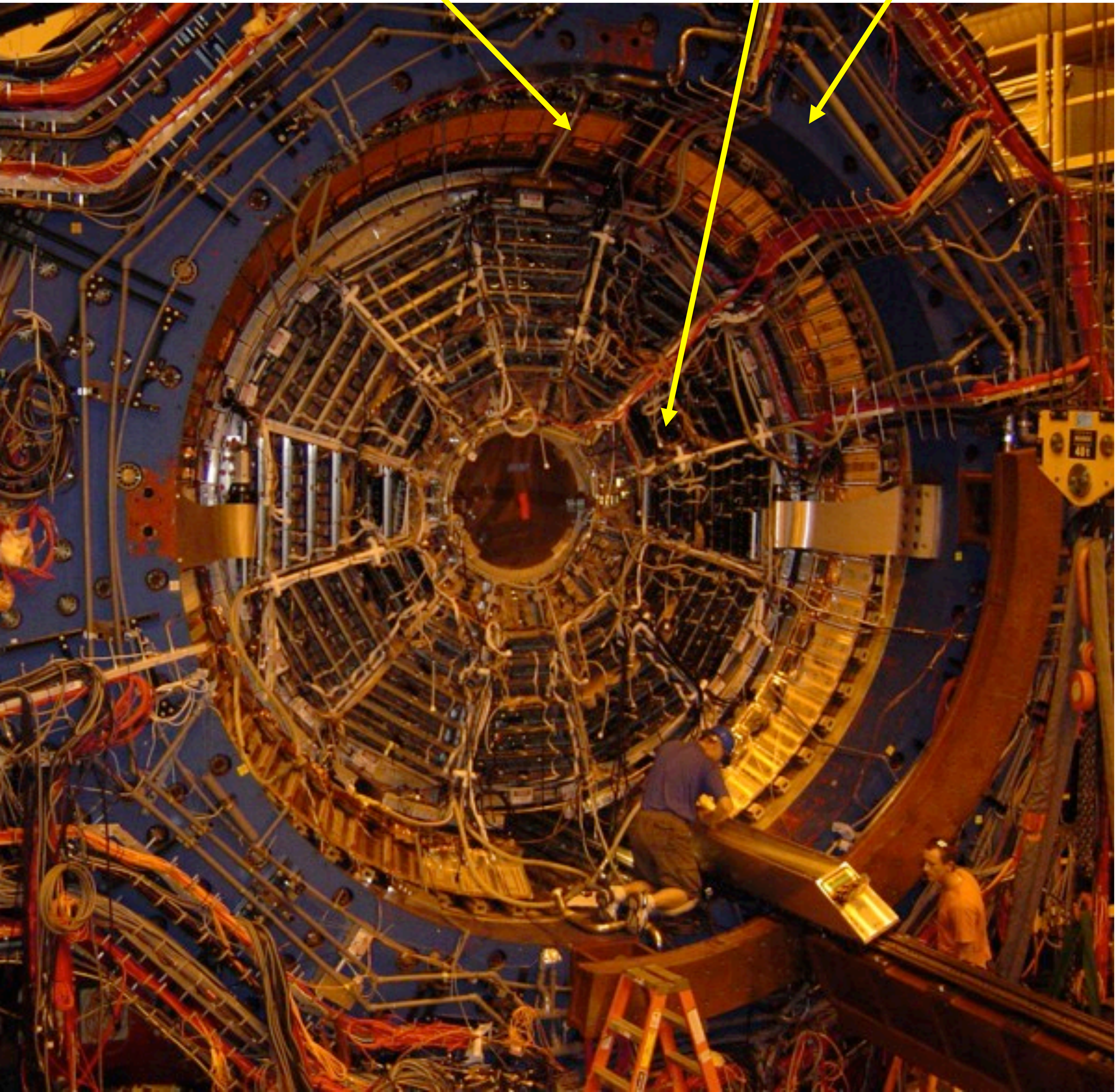
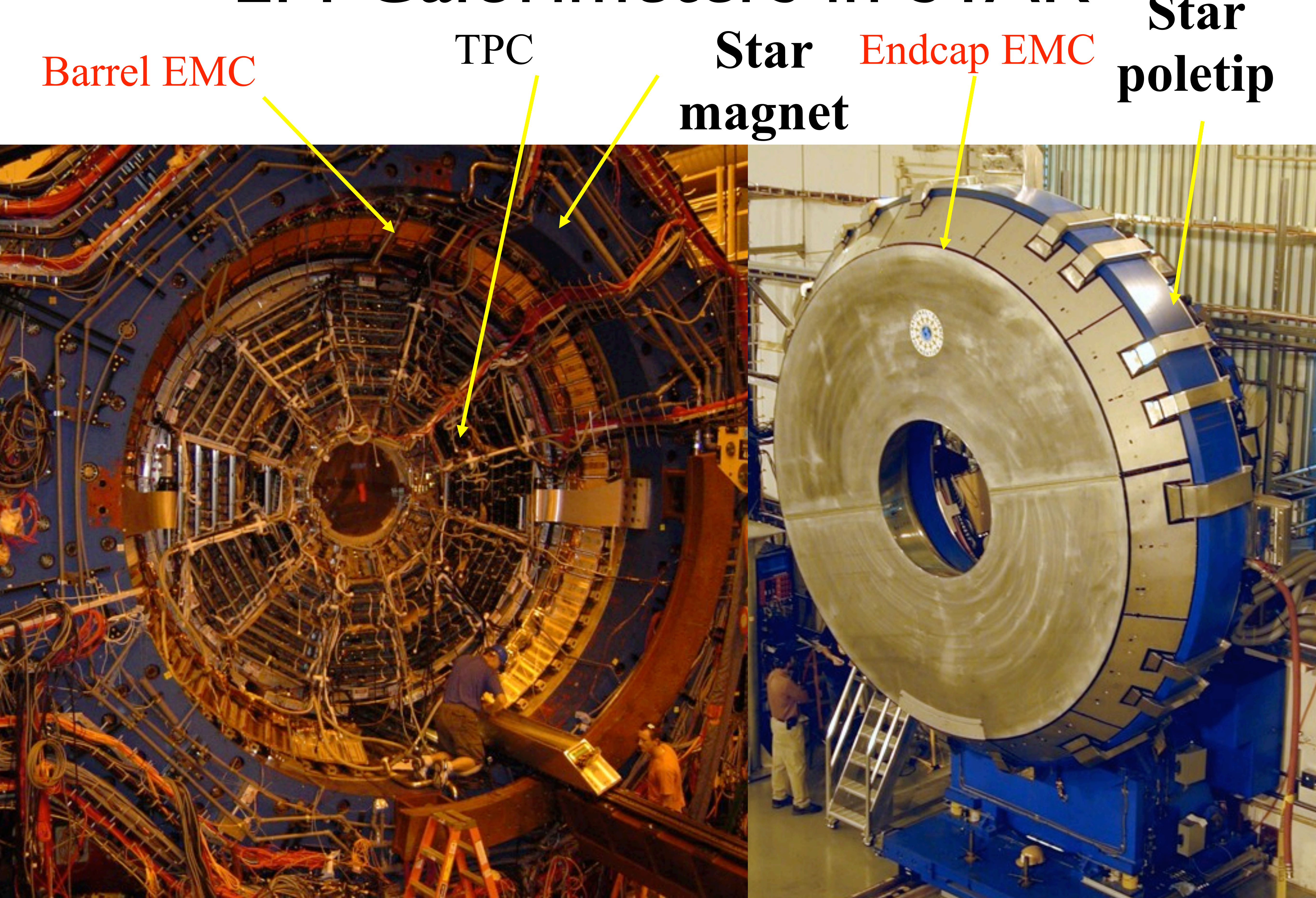
STAR Components - Electromagnetic Calorimetry



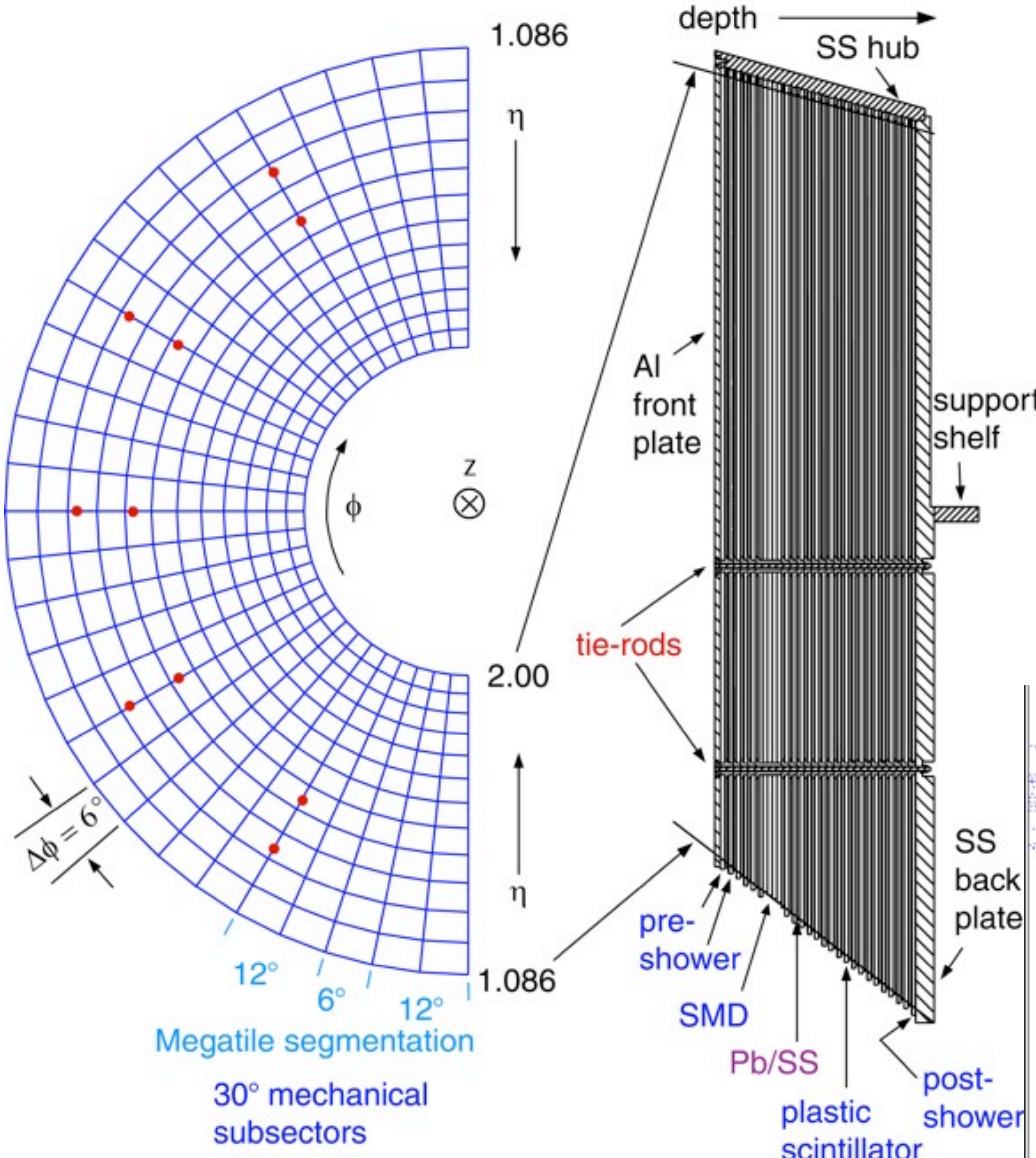
EM Calorimeters in STAR



EM Calorimeters in STAR

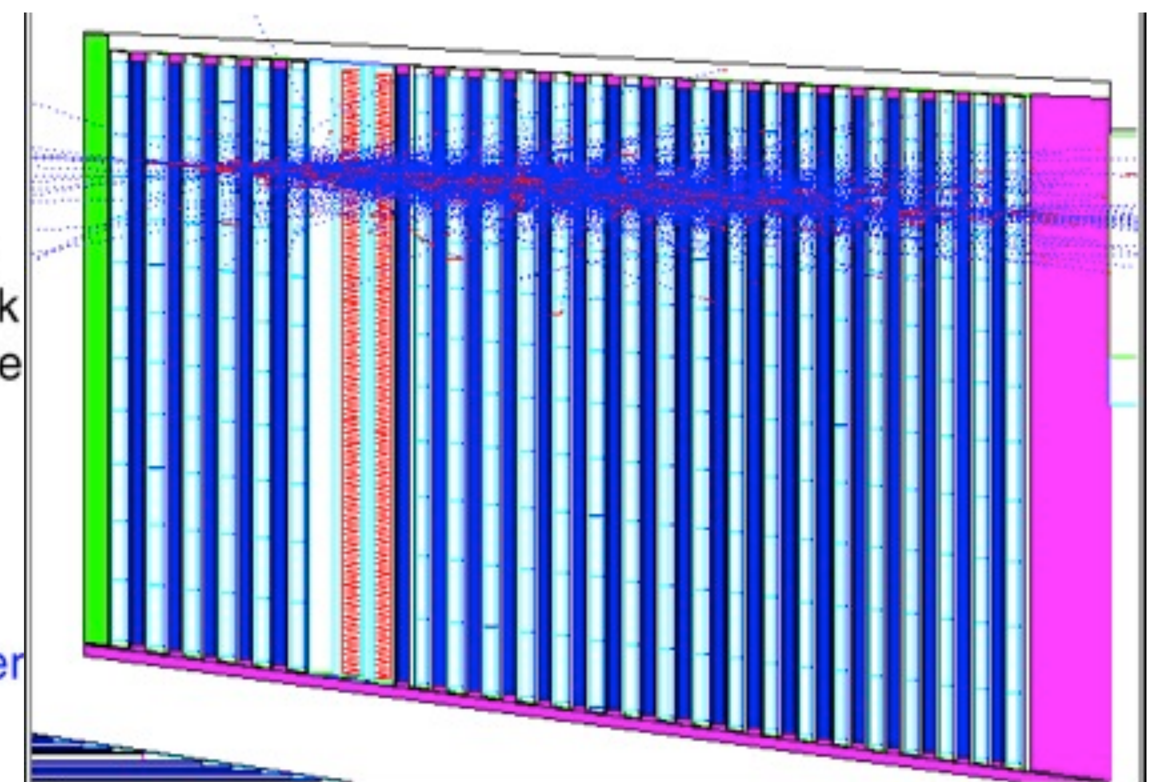


Endcap ElectroMagnetic Calorimeter



- Pb Scint sampling calorimeter
- 21 radiation lengths
- 720 projective towers
- Depth Segmentation
  - 2 preshower layers, e/h π^0/γ disc.
  - High position resol. SMD π^0/γ disc.
  - Postshower layer e/h discc.
- L0 trigger- high tower, jet patches

Simulated EM Shower



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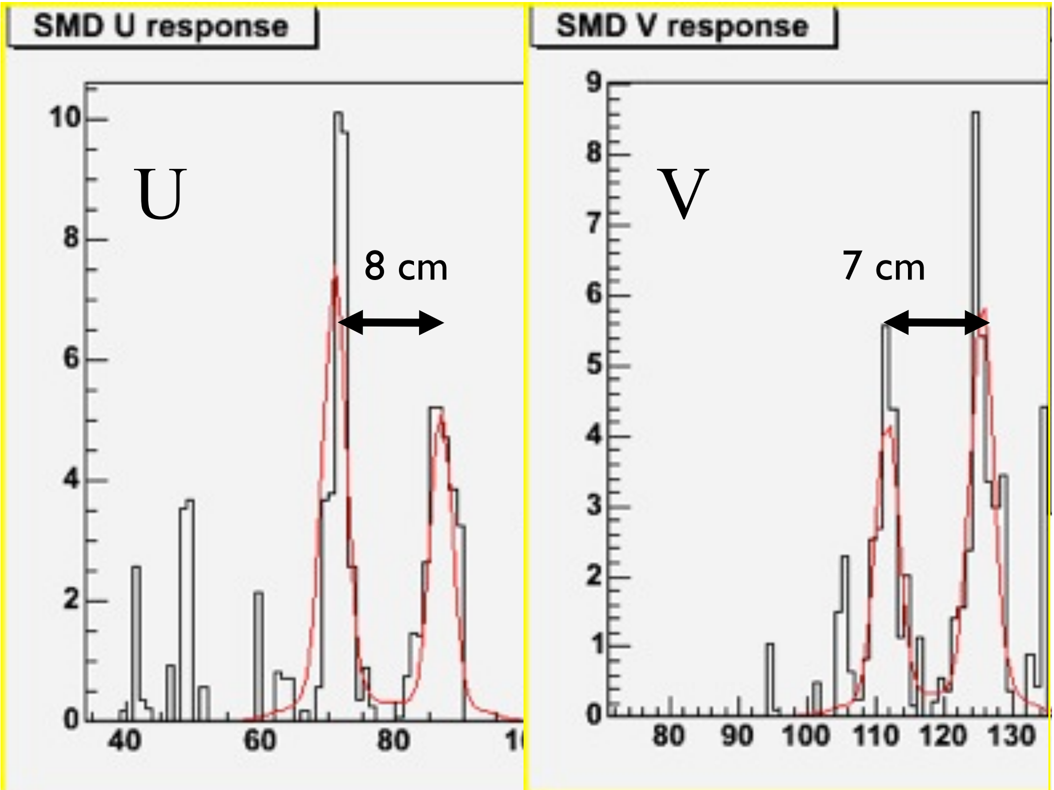
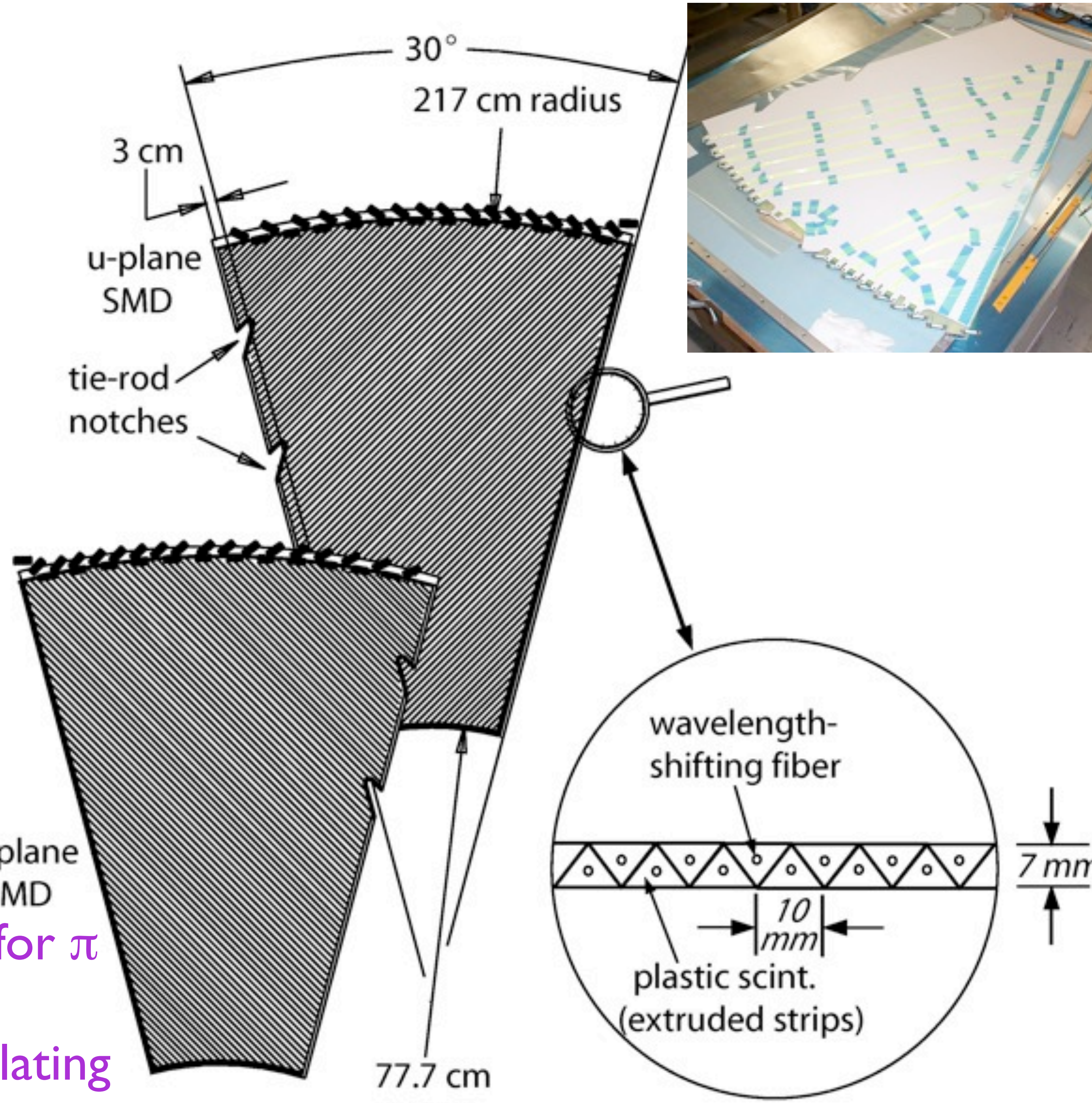
Shower Maximum Detector EEMC



SMD profiles for a 9 GeV π^0 candidate



- Resolves closely spaced showers for π – γ ID
- ~7000 individually read out scintillating strips
- U and V plane in each 30°sector
- Essentially no coverage gaps

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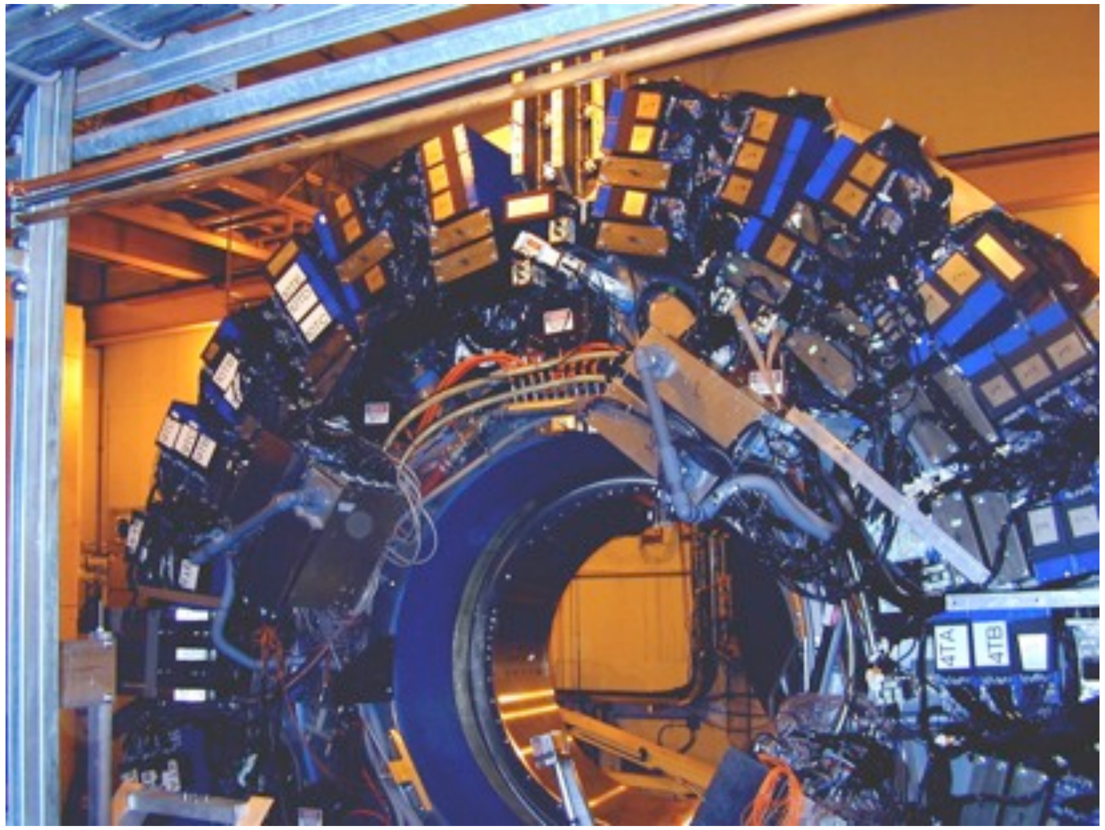
Detector Readout and Trigger

Light carried out of magnet on fibre optics
Photomultiplier tubes for all signals
Digitized every beam crossing (110 ns)
Stored in pipeline for transfer on trigger
Tower energy can generate level 0 trigger
Highest tower



PMTs and electronics on back of poletip

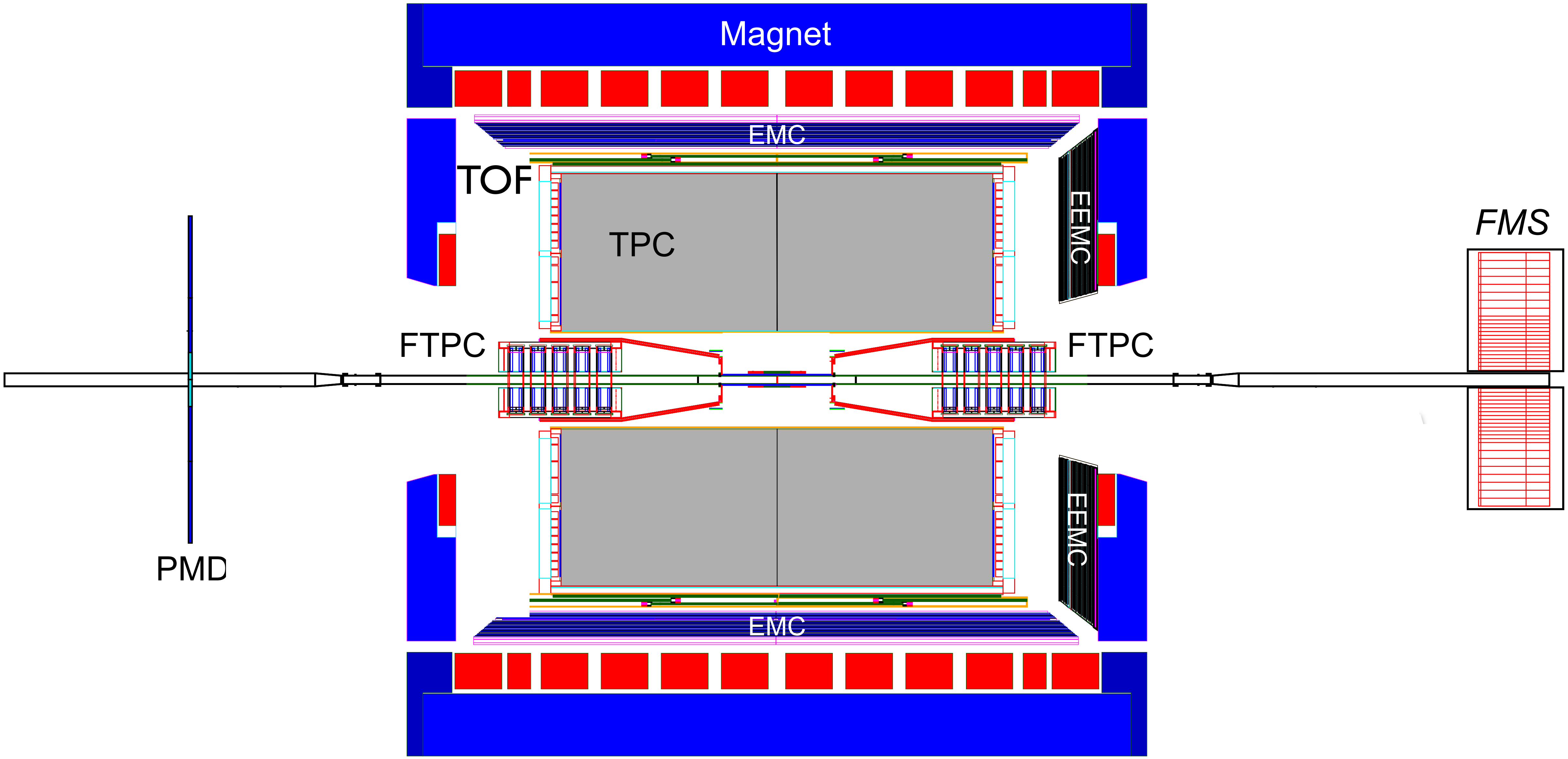
Total energy

Jet patch (1/6th in φ) summed energy
Coincidences between jet patches and other detectors

Tower Energy signal PMT Box

16 ch MAPMT and miniturized electronics For SMDs and Pre/Post Shower

STAR Components - FMS

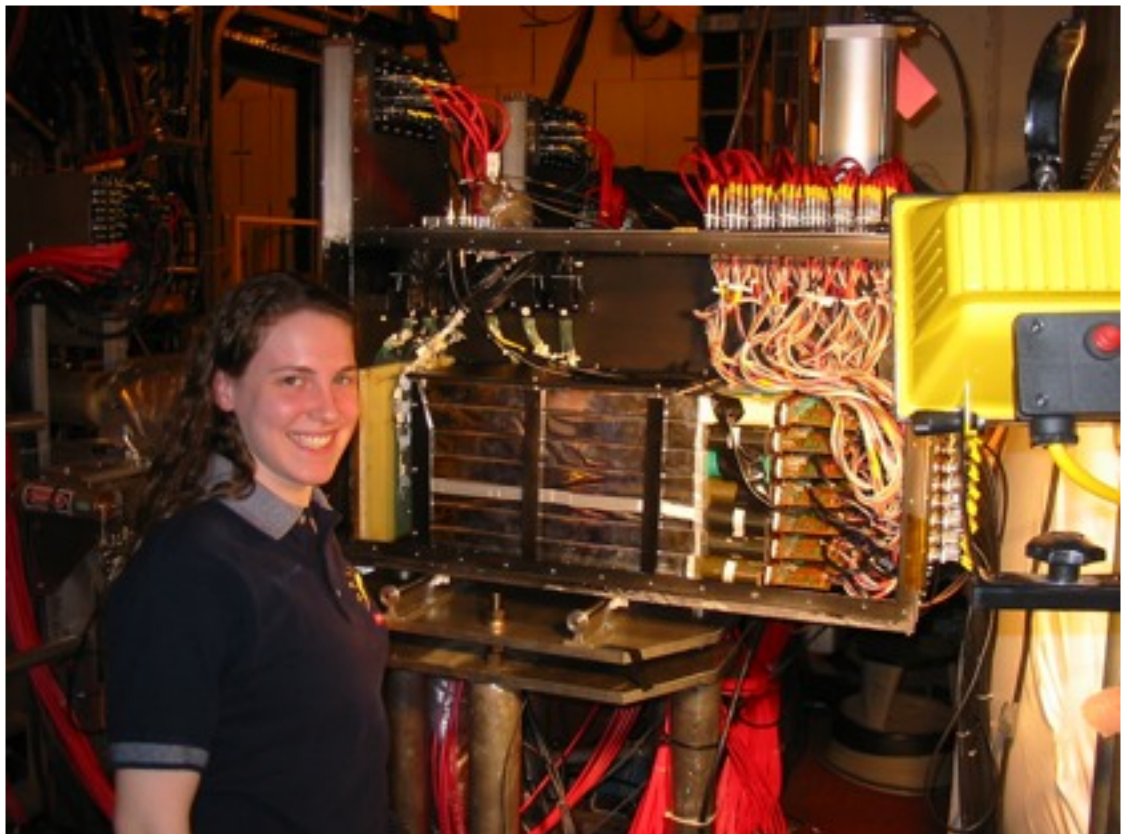


- FMS - Forward Meson Spectrometer
  - ➡ A calorimeter at very forward angles
  - ➡ Can probe initial state effects in nuclei

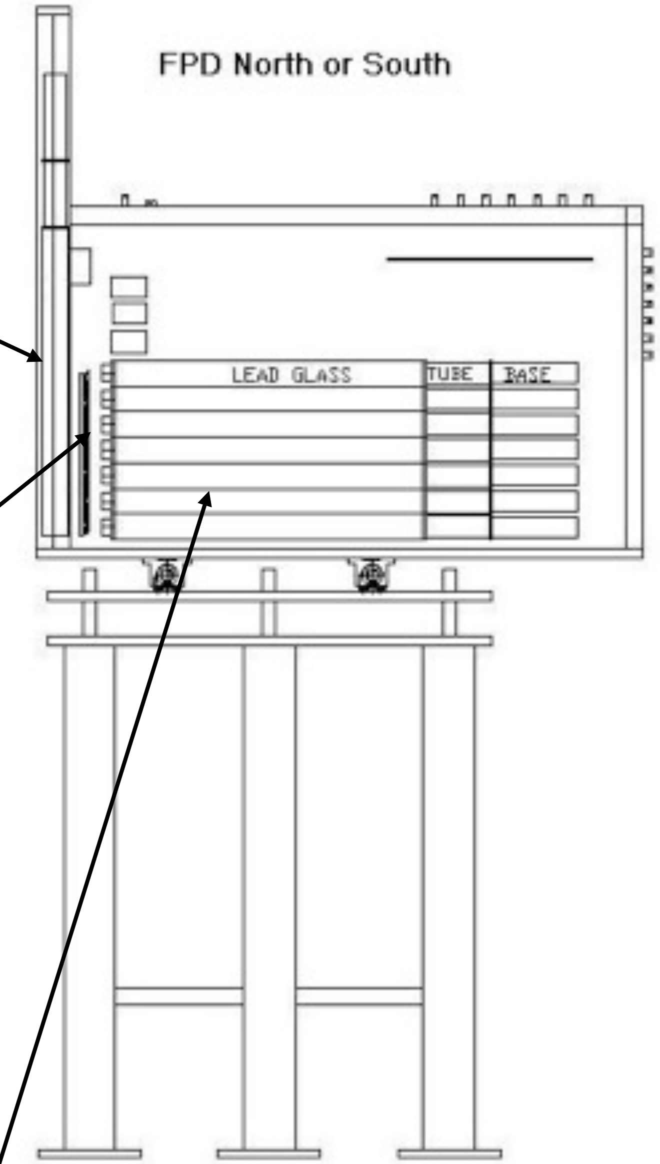
The STAR Forward π^0 Detector

$\pi^0 \rightarrow \gamma\gamma$

Rebecca Lamb, RPI undergraduate
(BNL/SULI program 1/03 – 5/03)



Pre-Shower Detector
7 vertical lead-glass crystals with PMT+base.

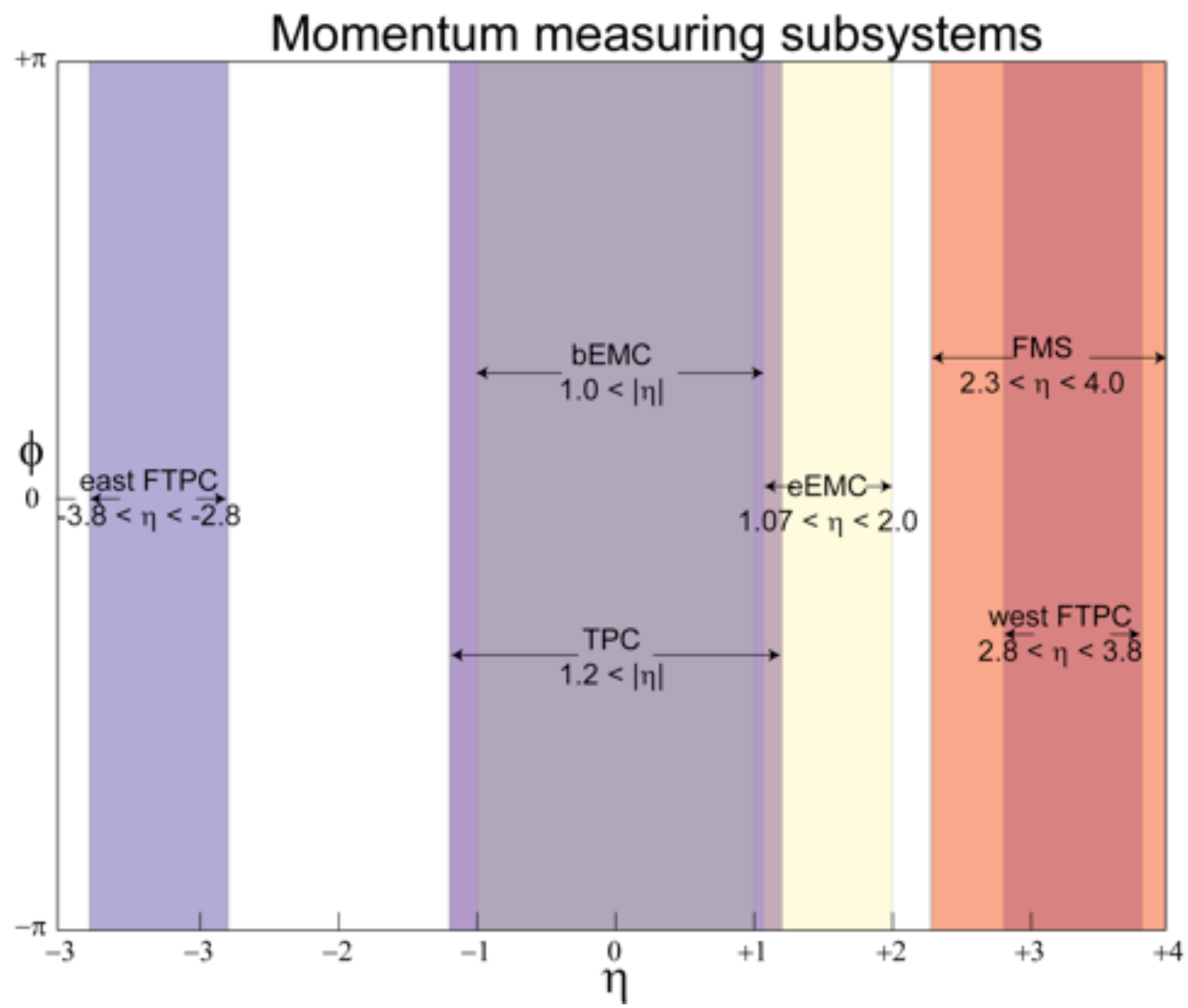


Lead-glass detectors built by IHEP, Protvino group for FNAL E-704 experiment.

Shower Maximum Detector
Horizontal and Vertical Planes
Each made of 48 strips of plastic scintillator with a wavelength shifting optical fiber through the center of each
Multianode PMTs

Lead Glass Calorimeter
7x7 matrix of 3.8cm x 3.8cm lead-glass crystals with PMT+base.

From FPD to FMS



- Full azimuth spanned with nearly contiguous electromagnetic calorimetry from $-1<\eta<4$ $\Rightarrow$ approaching full acceptance detector

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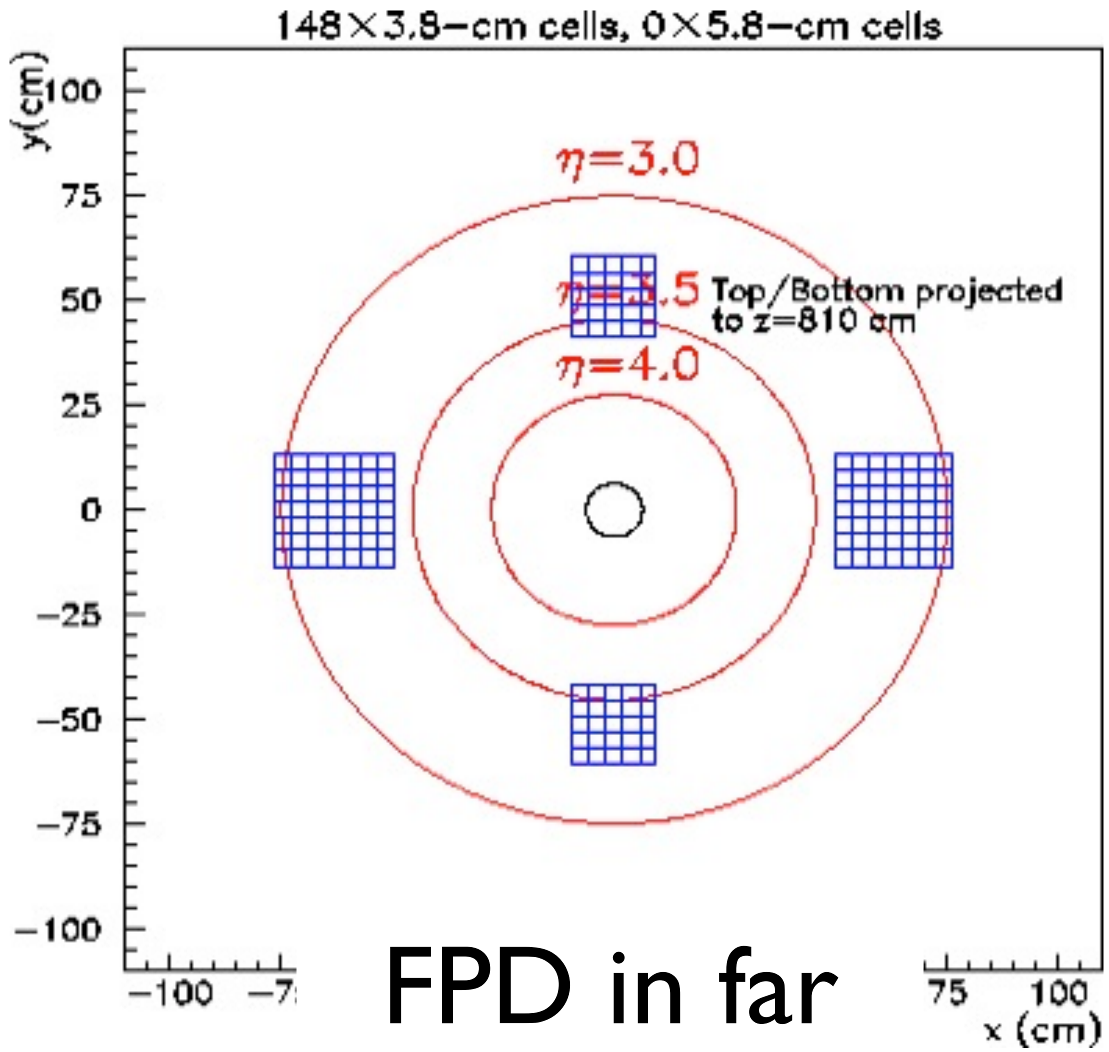
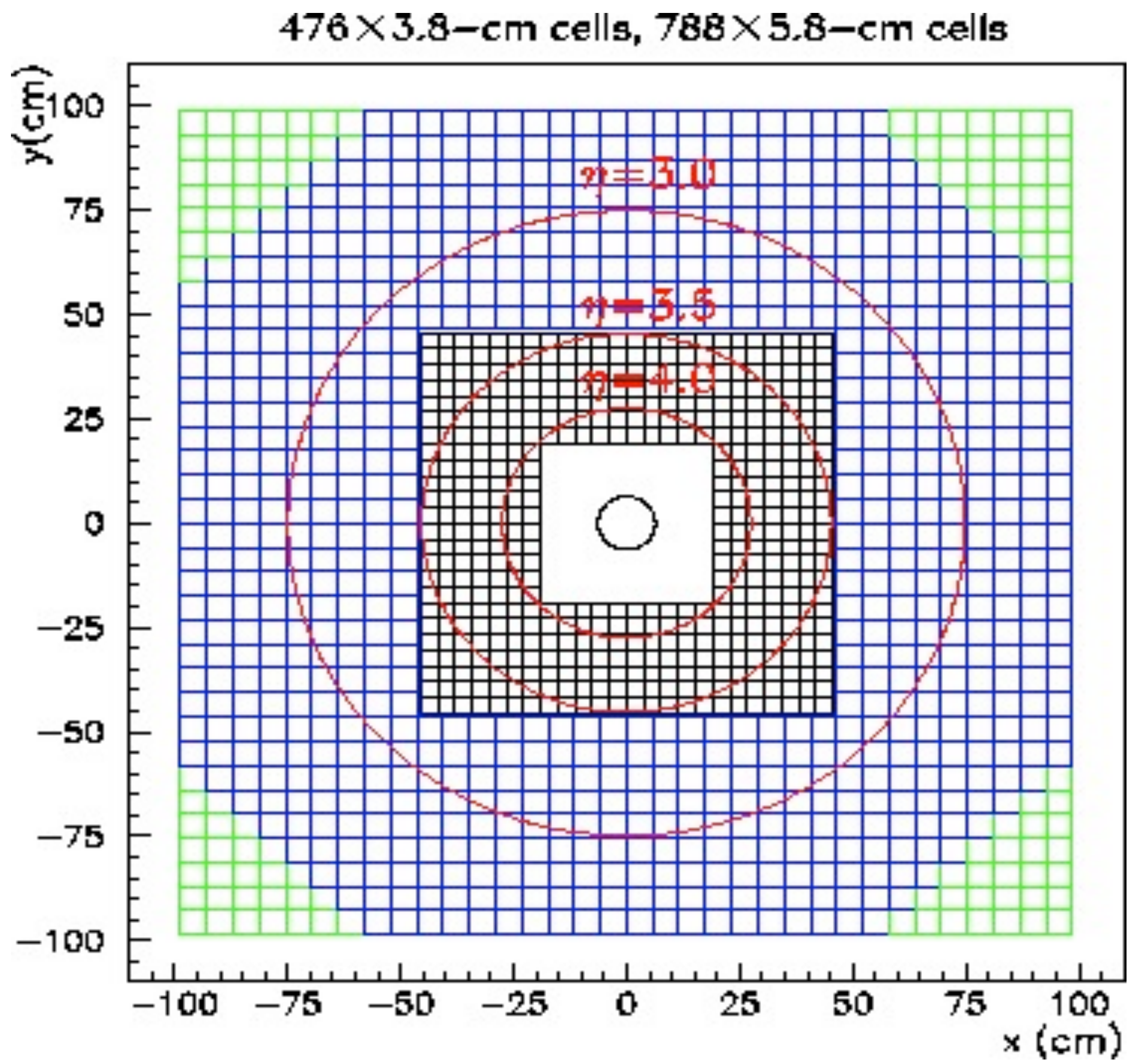
From FPD to FMS



FPD in far position

uth

From FPD to FMS



- 50× larger acceptance than run-3 FPD west-south module used for dAu

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What comes next for STAR?

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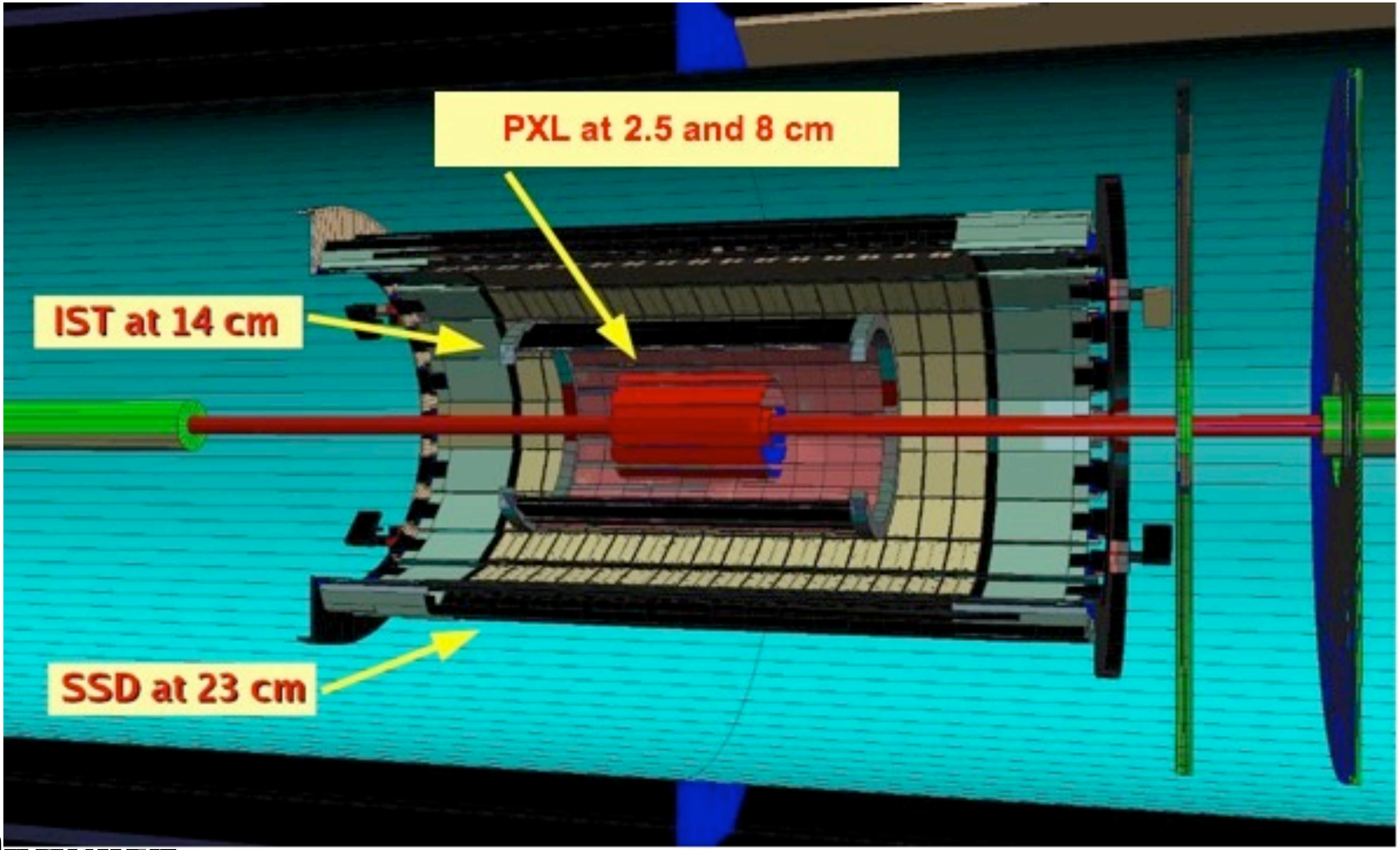
Heavy-Flavour Tracker

STAR Tracking Upgrade to identify mid-rapidity Charm and Bottom hadrons through direct reconstruction and measurement of the displaced vertex



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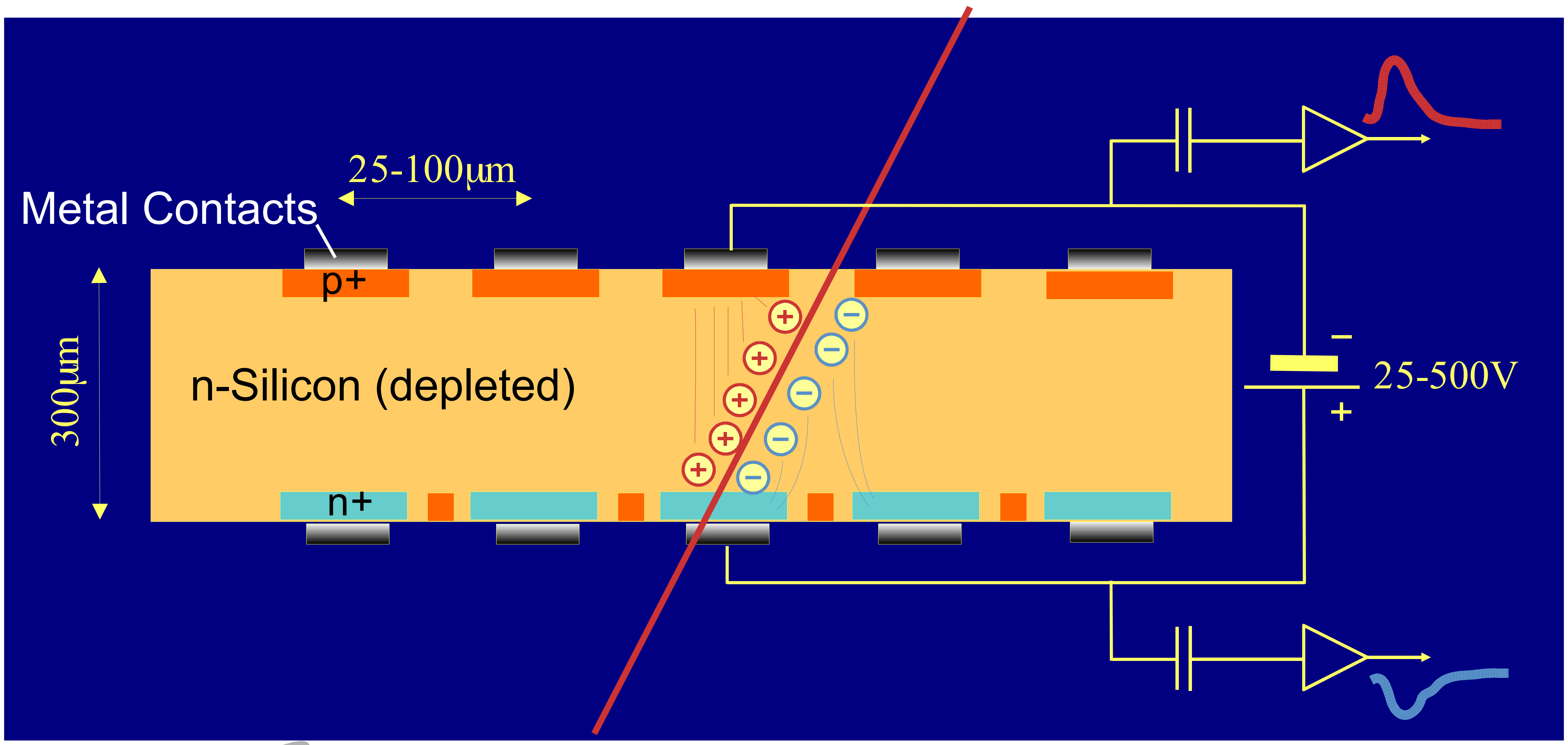
Silicon detectors in a nutshell

Basic motivation: charged particle position measurement

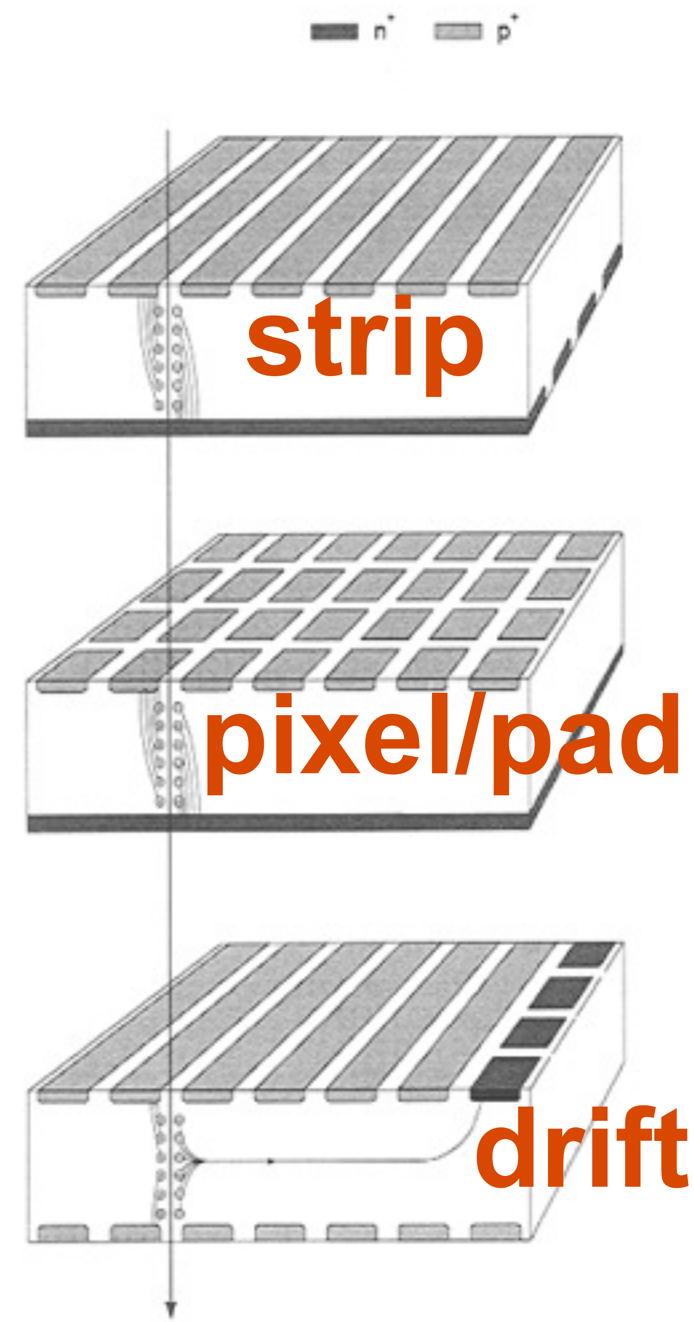
Use ionisation signal left behind by charged particle passage

- Ionisation produces electron-ion pairs, use an electric field to drift the electrons and ions to the oppositely charged electrodes.
- In a solid semiconductor, ionisation produces electron-hole pairs. For Si need 3.6 eV to produce one e-h pair. In pure Si, e-h pairs quickly recombine ⇒ n-doped (e carriers/donors) and p-doped (holes are carriers) silicon ⇒ p/n junction creates potential that prevents migration of charge carriers



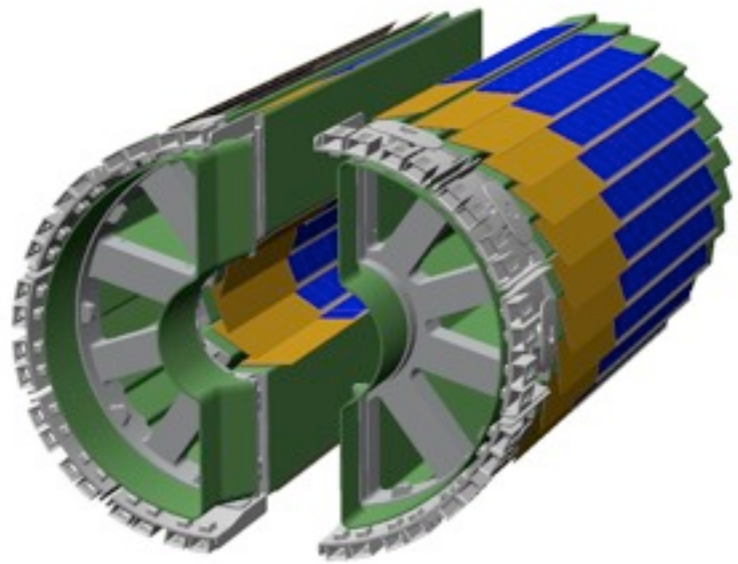
Types of silicon detectors

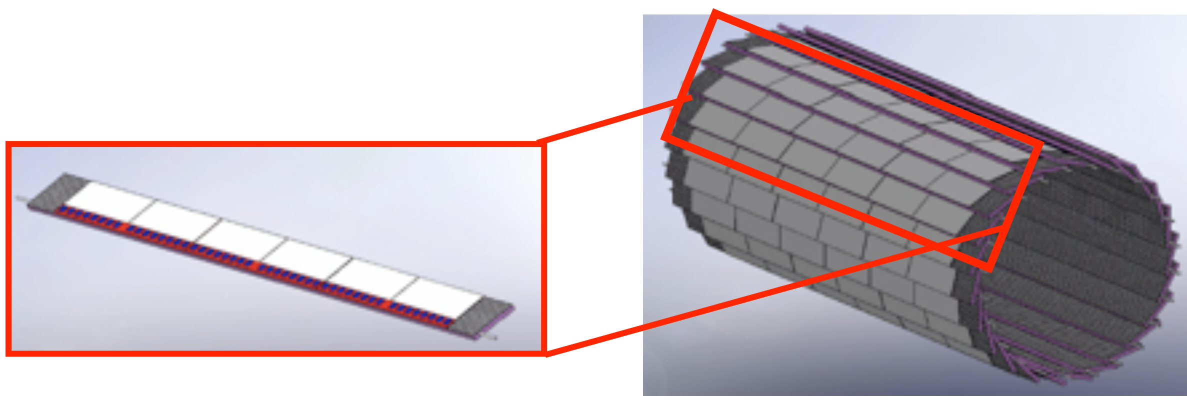
- Strip devices
  - High precision (< 5μm) 1D coordinate measurement
  - Large active area (up to 10cm x 10cm from 6" wafers)
  - Single-sided devices
  - 2nd coordinate possible (double-sided devices)
  - Most widely used silicon detector in HEP
- Pixel devices
  - True 2D measurement (20-400μm pixel size)
  - Small areas but best for high track density environment
- Pad devices ("big pixels or wide strips")
  - Pre-shower and calorimeters
  - Multiplicity detectors
- Drift devices

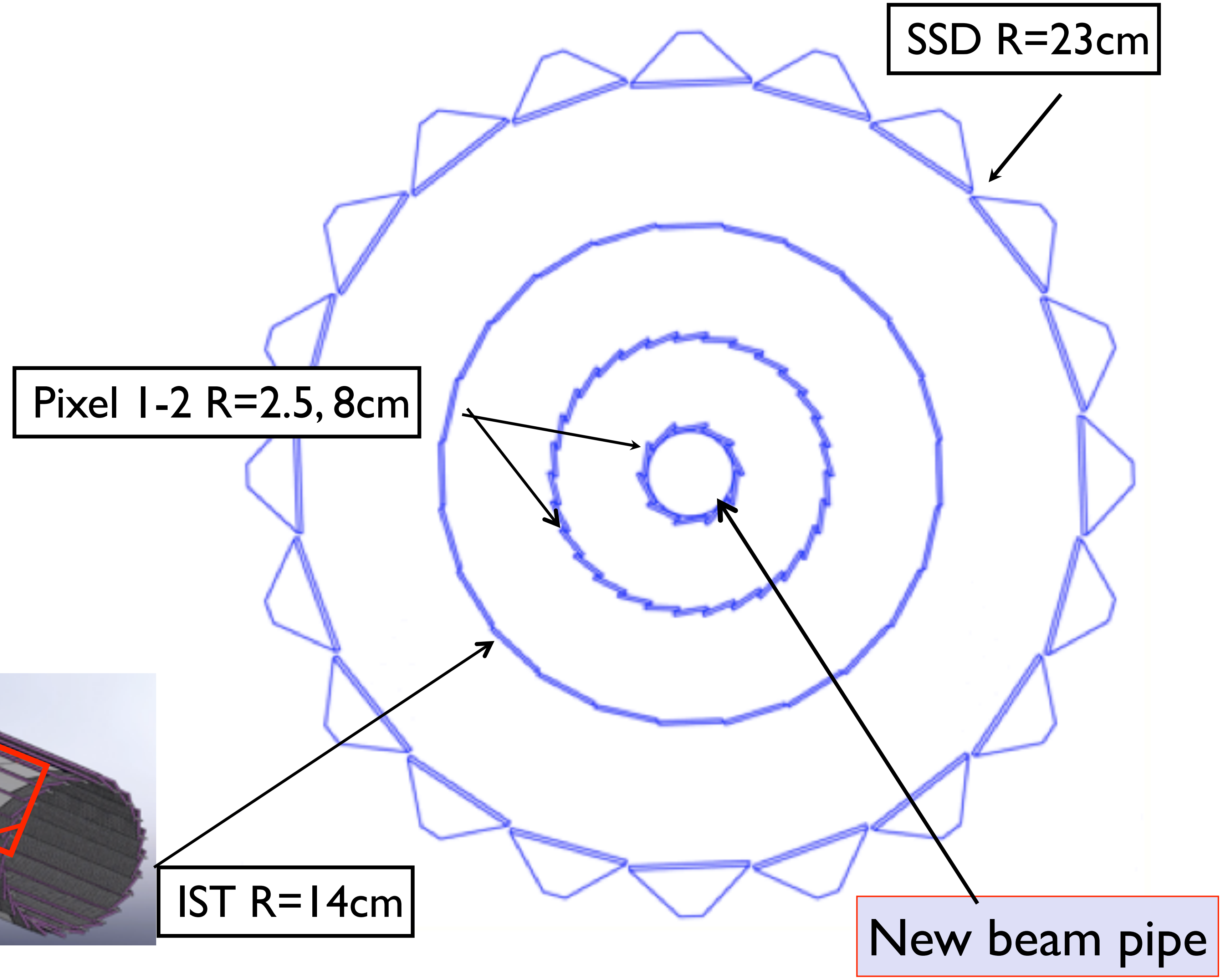


HFT

Technology

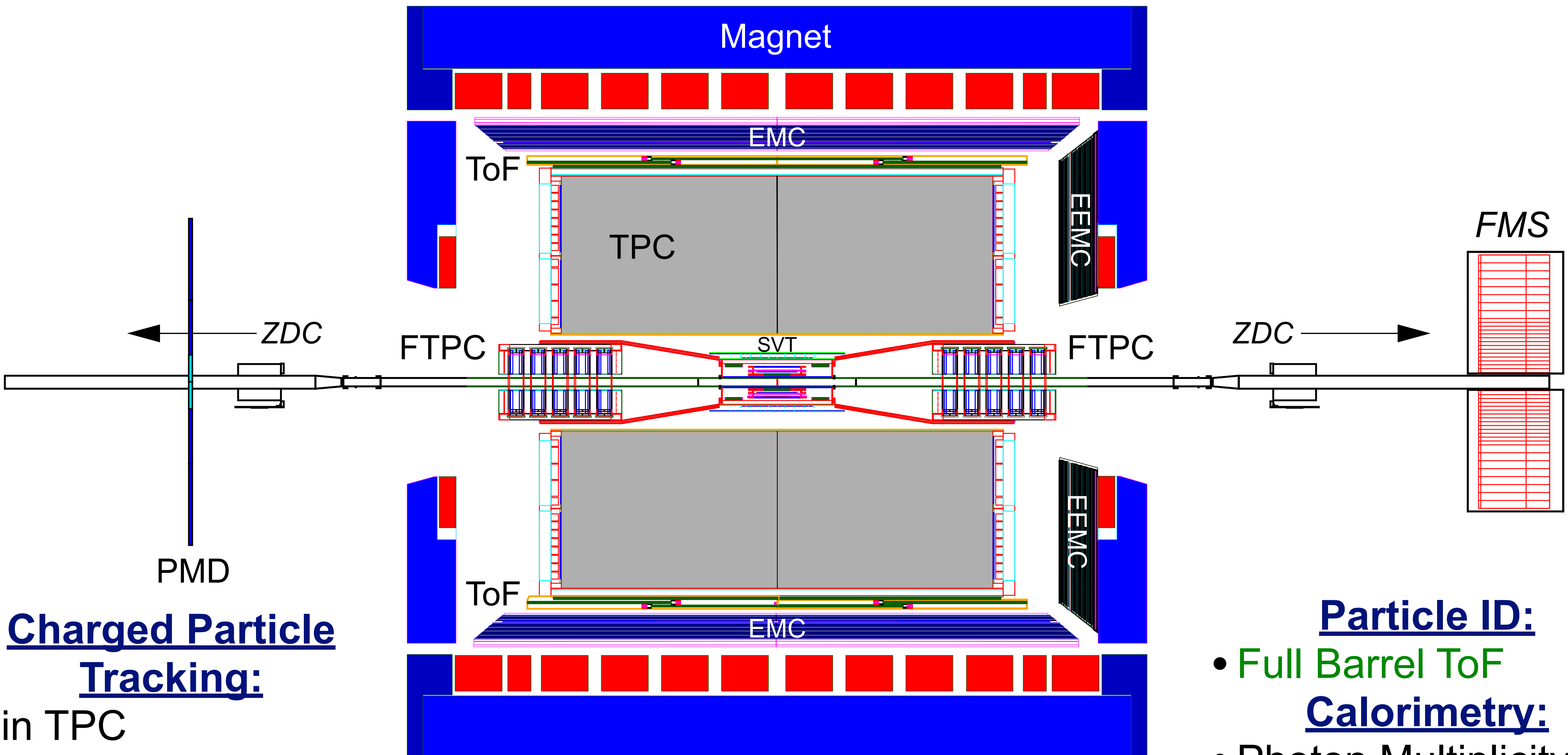






	Technology	Hit resolution R-ϕ (μm - μm)	Radiation Length
SSD	double sided strips	30 - 857	1% X_0
IST	Silicon Strip Pad sensors	170 -1700	1.2% X_0
PIXEL	Active Pixels	8.6 - 8.6	0.3% X_0

STAR Components



Charged Particle Tracking:

- Main TPC
- Forward TPC (FTPC)
- SSD + Intermediate Tracker + Active Pixel Detector = HFT(was SSD +SVT)
- Forward GEM Tracker

Event Characterization & Trigger:

- Beam-Beam Counter (BBC)
- Zero Degree Calorimeter (ZDC)
- Forward Pion Detectors (FPD)

Particle ID:

- Full Barrel ToF

Calorimetry:

- Photon Multiplicity Detector (PMD)
- Barrel EMC
- Endcap EMC
- Forward Meson Spectrometer

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Summary

- Four RHIC experiments
  - large: PHENIX, STAR (upgrade in progress)
  - small: BRAHMS, PHOBOS (now decomissioned)
- STAR and PHENIX have considerable overlap
  - cross-checks
- No such thing as a perfect detector
  - STAR and PHENIX had to make compromises but still capture the majority of probes and signatures
  - hardly any detector concept that is not used at RHIC
    - TPC, Cherenkov, EM-Calorimeters, Driftchambers, muon chambers, Si-Pad/Strip/Drift, scintillator counters
  - Both experiments are being continuously improved