Particle Identification at STAR

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Outline

- **Introduction**
  - ✓ QCD phase diagram
  - ✓ Evolution of Heavy-ion collisions
- **STAR at RHIC and ALICE at LHC**
- **Particle Identification**
  - Time Projection Chamber (TPC)
  - Time of Flight (TOF)
  - Photon Multiplicity Detector (PMD)
- **Summary**

QCD Phase Diagram

- Phase structure of the strongly interacting matter represented in the Quantum Chromodynamics (QCD) phase diagram, as a function of temperature and baryon chemical potential.

✓ **RHIC Top Energy**

- QCD at high energy density and/or temperature
- Properties of Quark-Gluon Plasma (QGP)
- Proton spin structure

✓ **Beam Energy Scan**

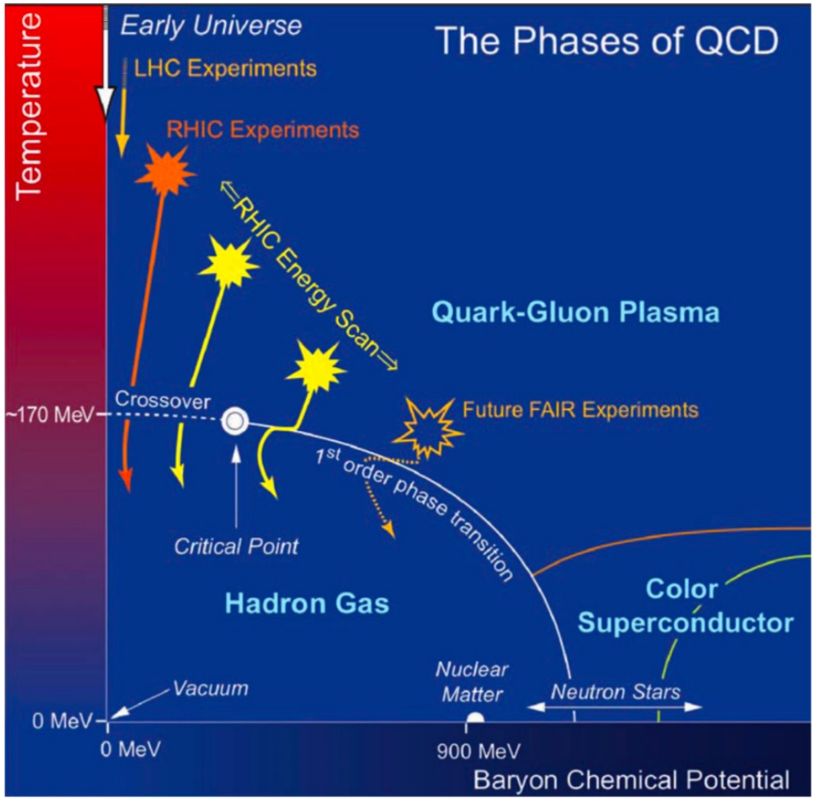
Au+Au $\sqrt{s_{NN}}$ = 7.7 - 62.4 GeV

- QCD phase transition
- Search for critical point
- Turn-off of QGP signatures

✓ **Fixed-Target Program**

Au+Au $\sqrt{s_{NN}}$ = 3.0 - 7.7 GeV

- High baryon density regime (μ_B ~420 – 720 MeV)

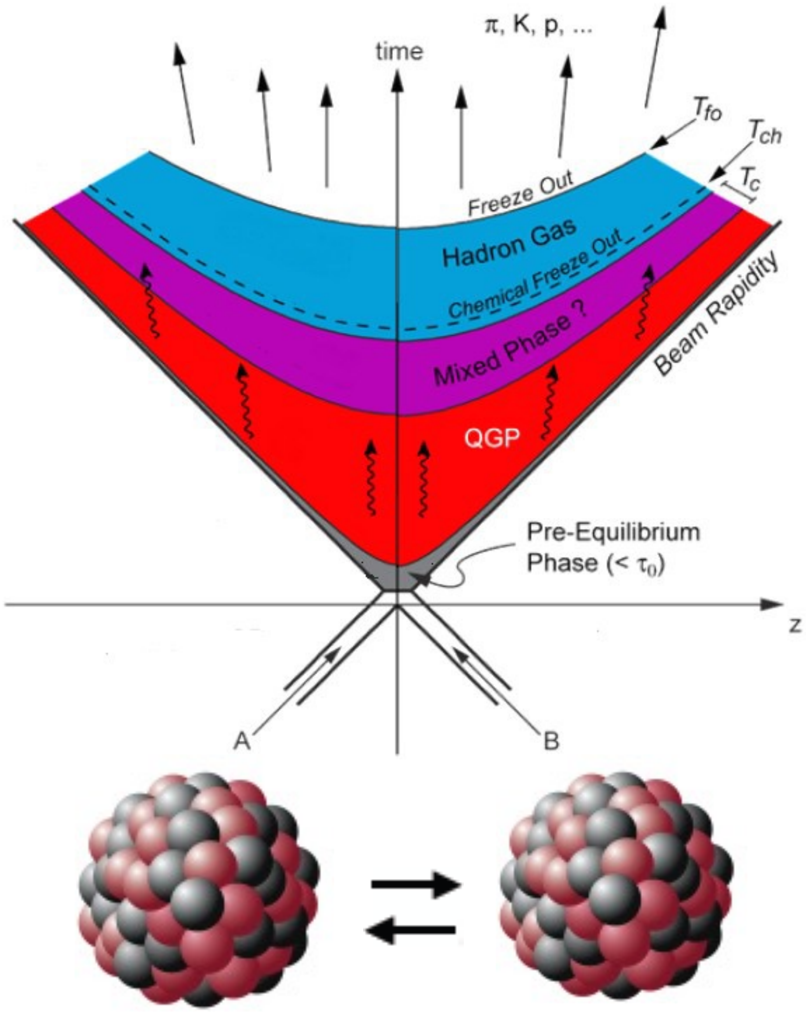


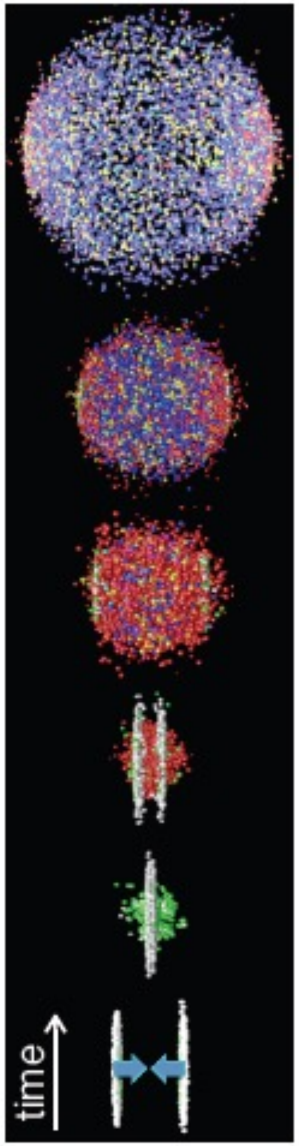
STAR: arXiv: 1007.2613 [nucl-ex]

Heavy-Ion Collisions

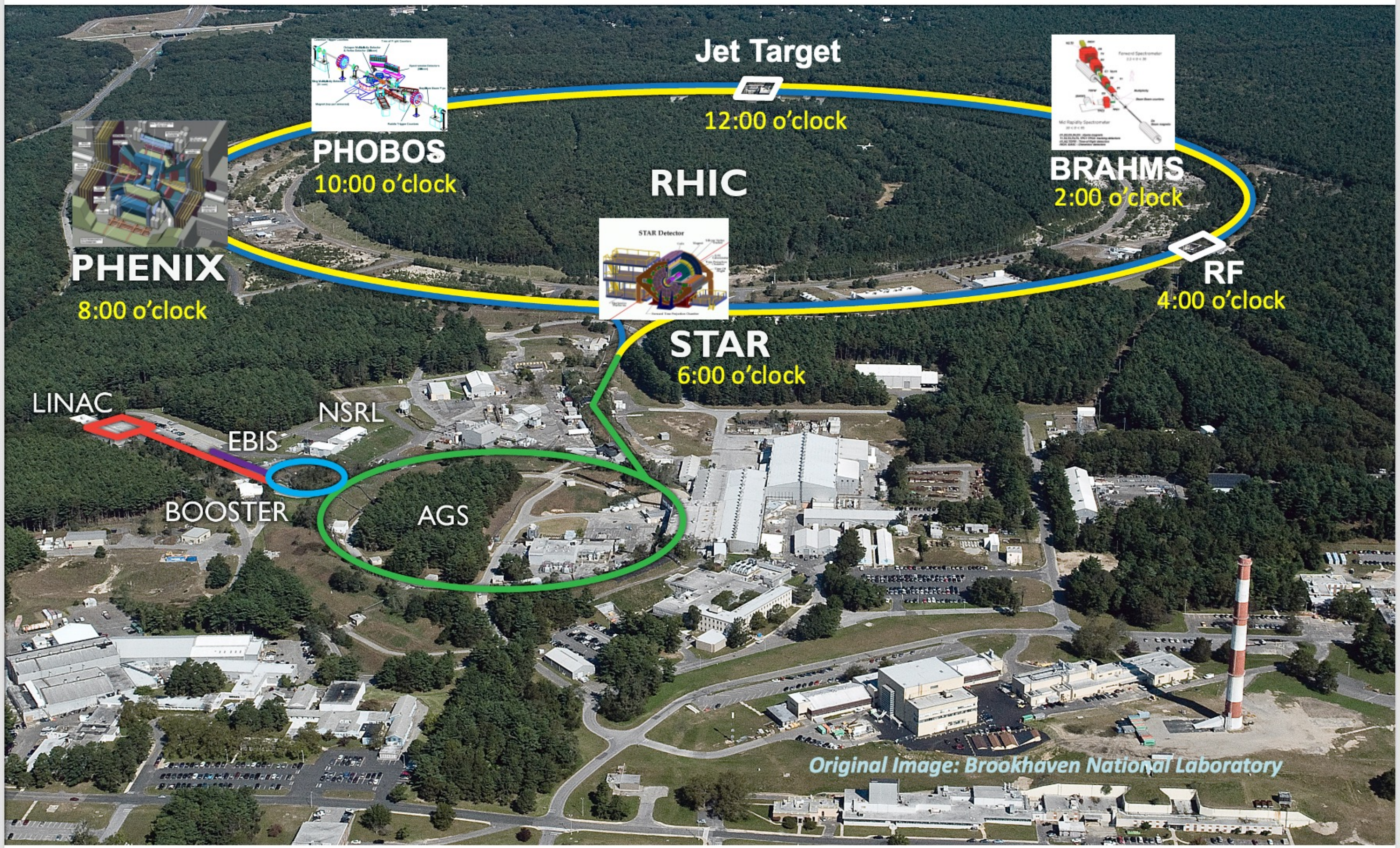
- Ultra-relativistic heavy-ion collisions: create the conditions for deconfinement and QGP formation ($\varepsilon > \varepsilon_c$).
- Expansion of the medium is governed by the relativistic hydrodynamics.
- System expands and cools down until it converts to a gas of hadrons ($T < T_c$).
- After chemical and thermal freeze-out, the particles come out of the system freely and get detected in the detectors.

Space-time Evolution of the Collision





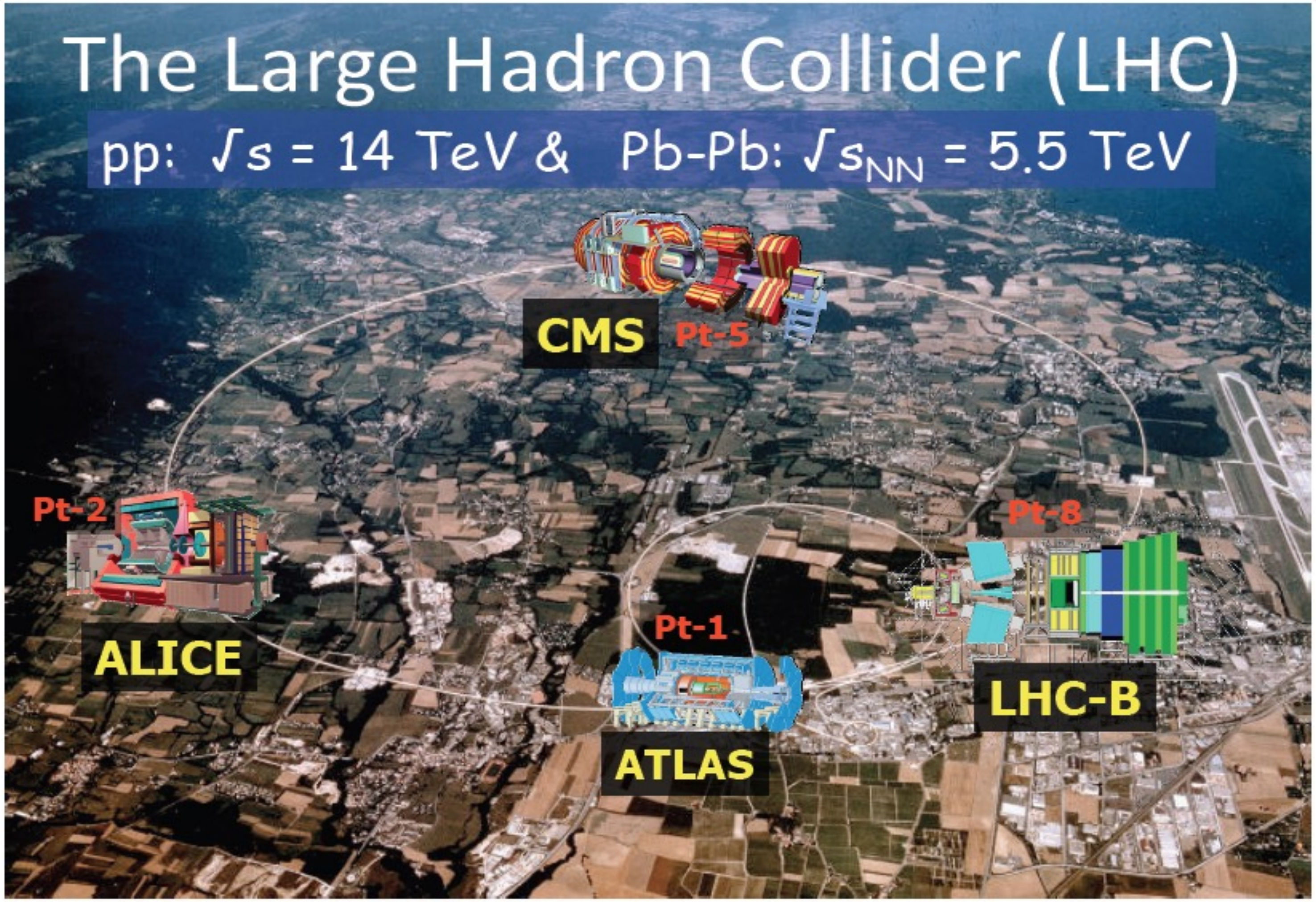
Relativistic Heavy-Ion Collider (RHIC)



- **The most versatile particle collider**
  - ✓ The only polarized proton collider in the world
  - ✓ Type of collisions: p+p, p+Au, d+Au, Cu+Au, Cu+Cu, Ru+Ru, Zr+Zr, Au+Au, U+U,...
  - ✓ Center-of-mass energy for Au+Au collisions: 3.0 - 7.7 - 200 GeV

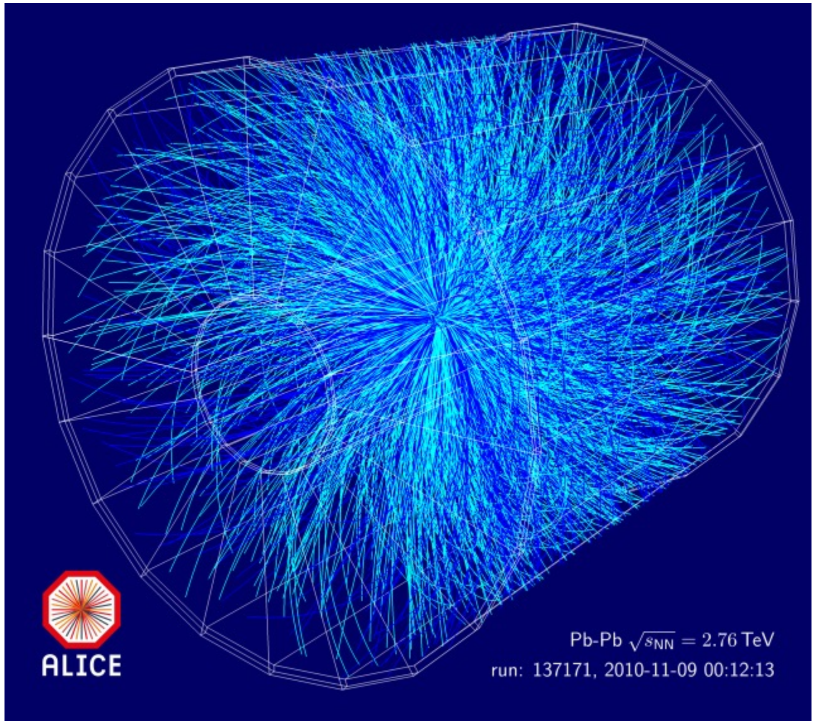
Fixed-Target mode   Collider mode

Large Hadron Collider (LHC)

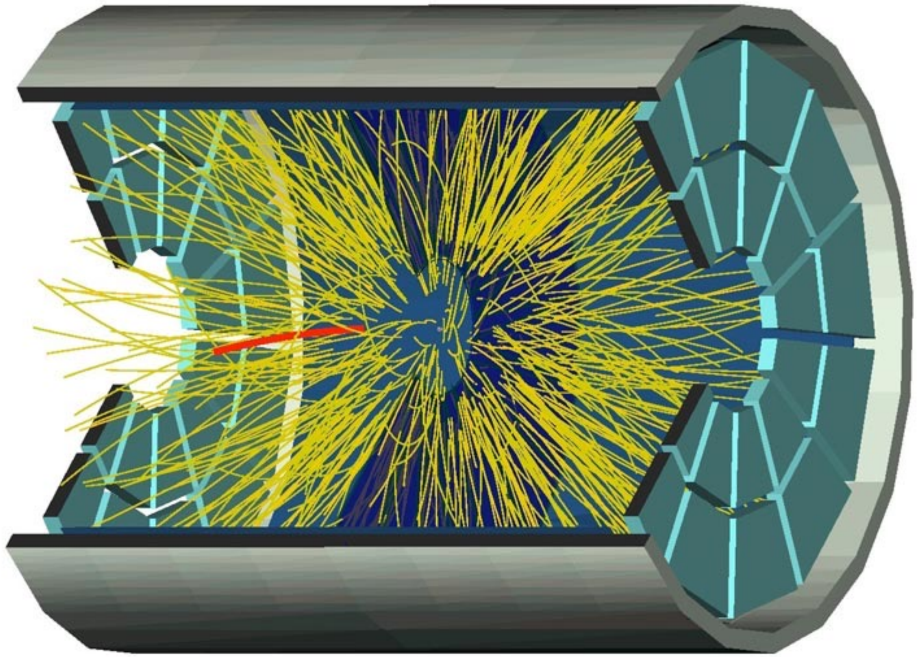


- **The world's largest and highest-energy particle collider**
  - ✓ Type of collisions: p+p, p+Pb, Pb+Pb, Xe+Xe, ...
  - ✓ Center-of-mass energy: p+p: 0.9 TeV - 13 TeV; p+Pb: 5.02 TeV, 8.16 TeV; Pb+Pb: 2.76 TeV, 5.02 TeV; Xe+Xe: 5.44 TeV

Particle Production



ALICE, Pb+Pb@2.76 TeV



STAR, Au+Au@200 GeV

- Relativistic heavy ion collisions produce thousands of particles.
- It is a challenge for the development of detection systems capable of simultaneous measurements and identification of those particles.

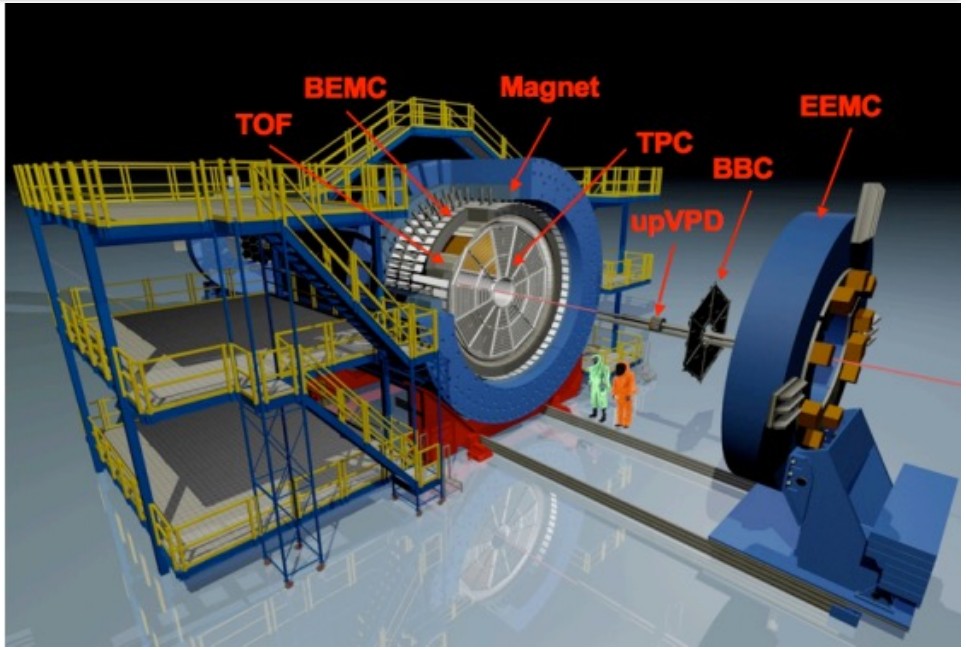
Solenoidal Tracker At RHIC (STAR)

Trigger Detectors:
Zero Degree Calorimeter (ZDC)
Beam Beam Counter (BBC)
Electro Magnetic Calorimeters (BEMC and EEMC)

Time Projection Chamber (TPC), |η| < 1.0:
Tracking, Vertexing, PID

Time of Flight (TOF), |η| < 0.9:
PID

Photon Multiplicity Detector (PMD):
-3.7 < η < -2.3



Operational: 2000 – till date

Nucl. Instr. Meth. A 499, 624 (2003)

A Large Ion Collider Experiment (ALICE)

Inner Tracking System (ITS), |η| < 0.9:
Vertexing, Tracking

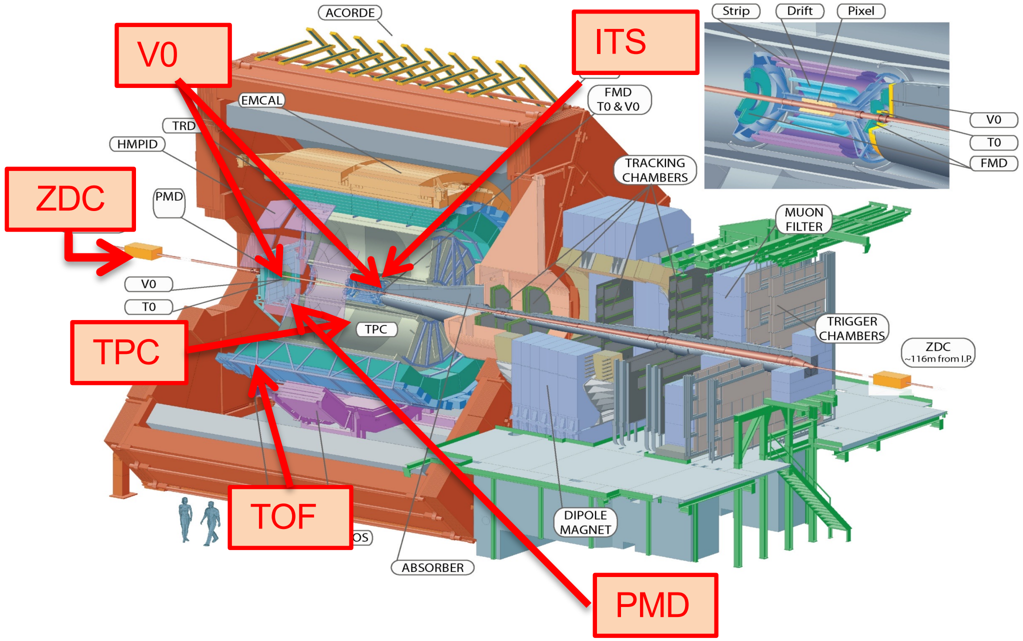
Time Projection Chamber (TPC), |η| < 0.9:
Tracking, PID

Time of Flight (TOF), |η| < 0.9:
PID

Forward detector (V0):
V0A (2.8 < η < 5.1) & V0C (-3.7 < η <-1.7)
Trigger, Centrality Estimator

Photon Multiplicity Detector (PMD):
2.3 < η < 3.9

Forward Multiplicity Detector (FMD):
1.7 < η < 5.0 & -3.4 < η < -1.7



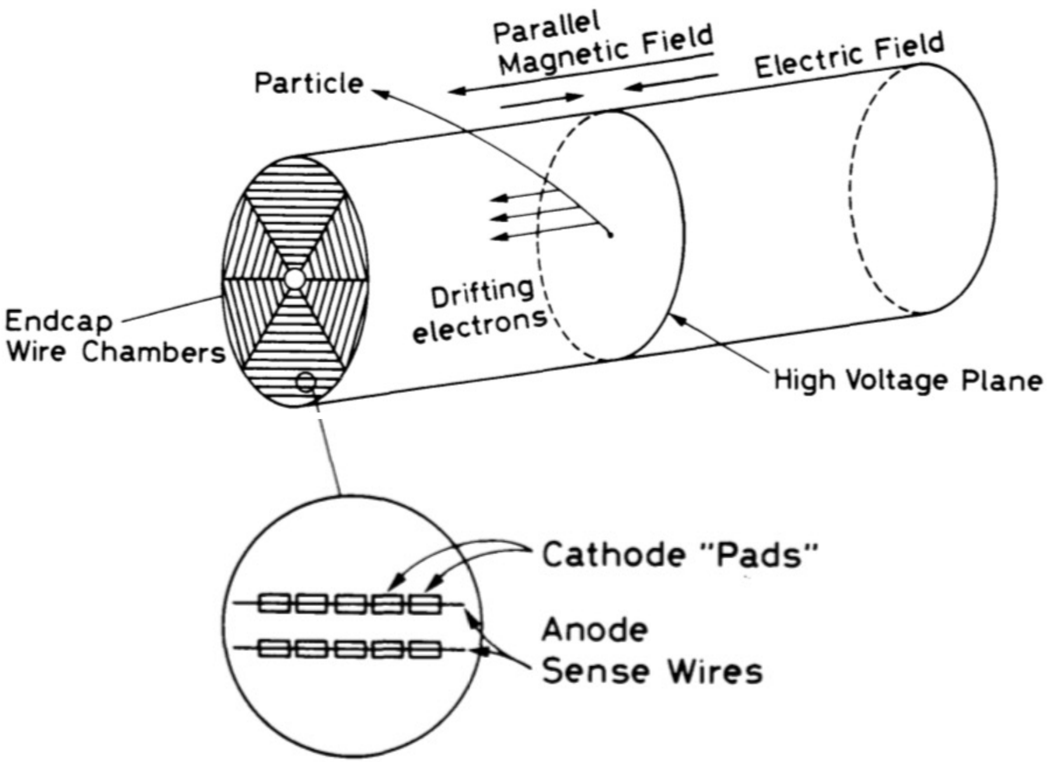
Operational: 2010 – till date

Int. J. Mod. Phys. A 29 (2014) 1430044

Time Projection Chamber (TPC)

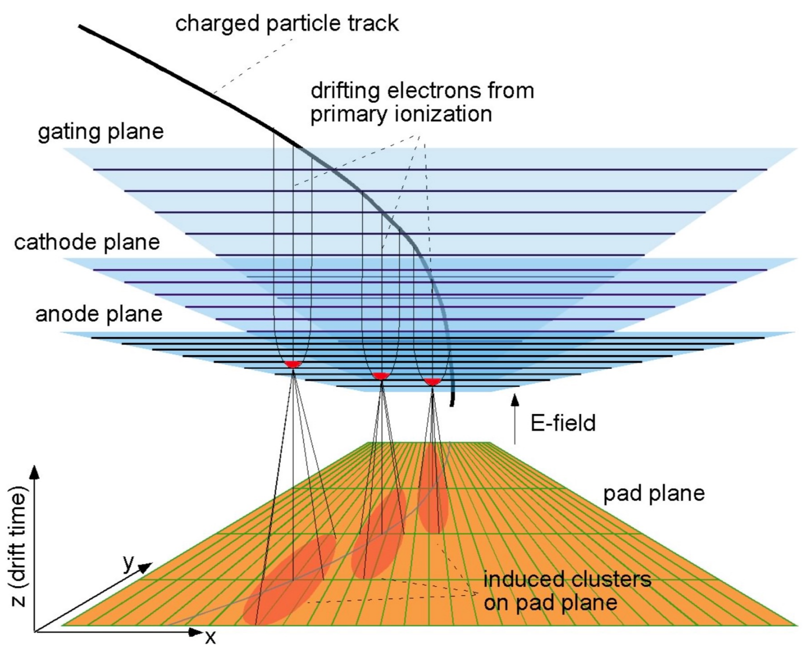
- The most sophisticated ionization detector is the TPC.
- A three-dimensional tracking detector capable of providing information on many points of a particle track along with information on the specific energy loss (*dE/dx)* of the particle.
- The TPC makes use of ideas from both the MWPC and drift chamber.

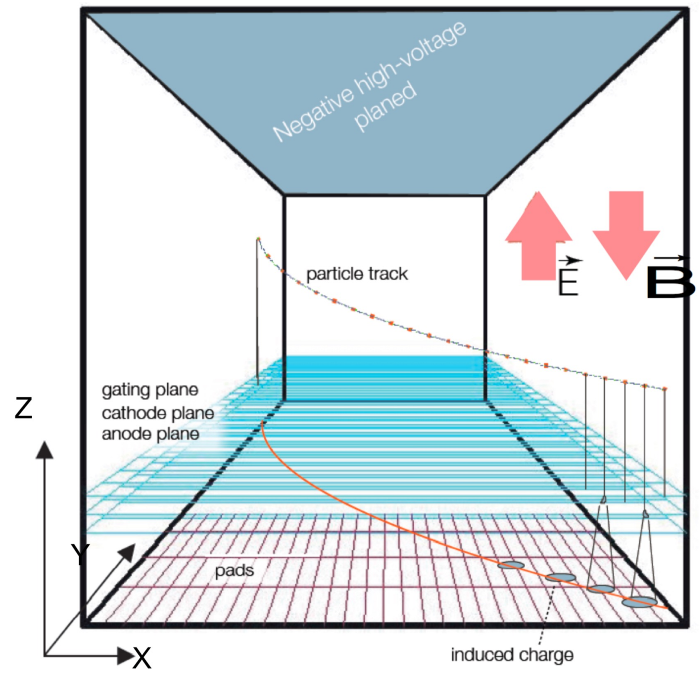
- ✓ A large gas-filled cylinder with a thin high voltage electrode at the center.
- ✓ When voltage is applied, a uniform electric field directed along the axis is created and a parallel magnetic field is also applied.
- ✓ The ends of the cylinder are covered by sector arrays of proportional anode wires arranged as shown.
- ✓ Parallel to each wire is a cathode strip cut up into rectangular segments. These segments are also known as cathode *pads.*



TPC Operation

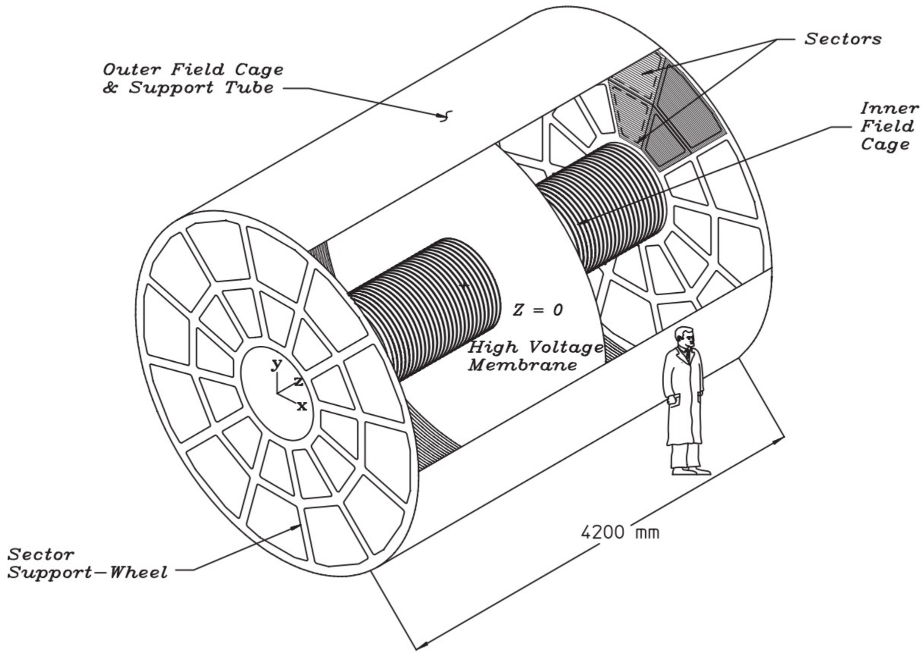
- Particles emanating from IP pass through the cylinder volume producing free electrons which drift towards the endcaps where they are detected by the anode wires as in a MWPC.
- X-coordinate is given by charge sharing among cathode pads, Y-coordinate is given by the wire and pad row number, Z-coordinate is given by the drift time (**v_{drift} critical**!)
- Space charge is an issue and gating grids are used to control ion flow.
- Signal amplitudes from the anode provide information on the *dE/dx* of the particle.
- Momentum of the particle is known from the curvature of its trajectory in the magnetic field.

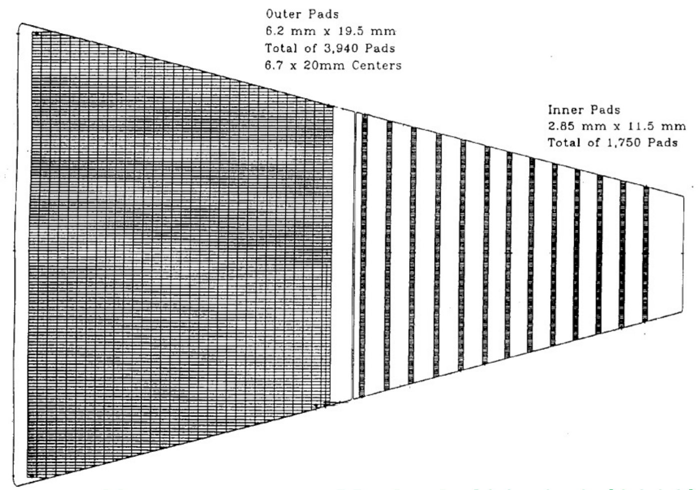




Time Projection Chamber: STAR

- TPC is the primary tracking device at STAR
- Used for measuring momenta and identifying charged particles
- It is in the form of a cylinder 4.2 m in length and 4 m in diameter
- The central membrane is maintained at a voltage of −28 kV with respect to the detection planes and acts as cathode
- A uniform electric field of ∼135 V/cm is maintained between the central membrane and the readout end caps.
- TPC volume is filled with P10 gas (90% Ar and 10% CH_4) regulated at a pressure of 2 mbar above the atmospheric pressure.
- Each of the two endplates houses 12 readout sectors
- Each inner sector contains 13 pad rows and outer sector contains 32 pad rows.

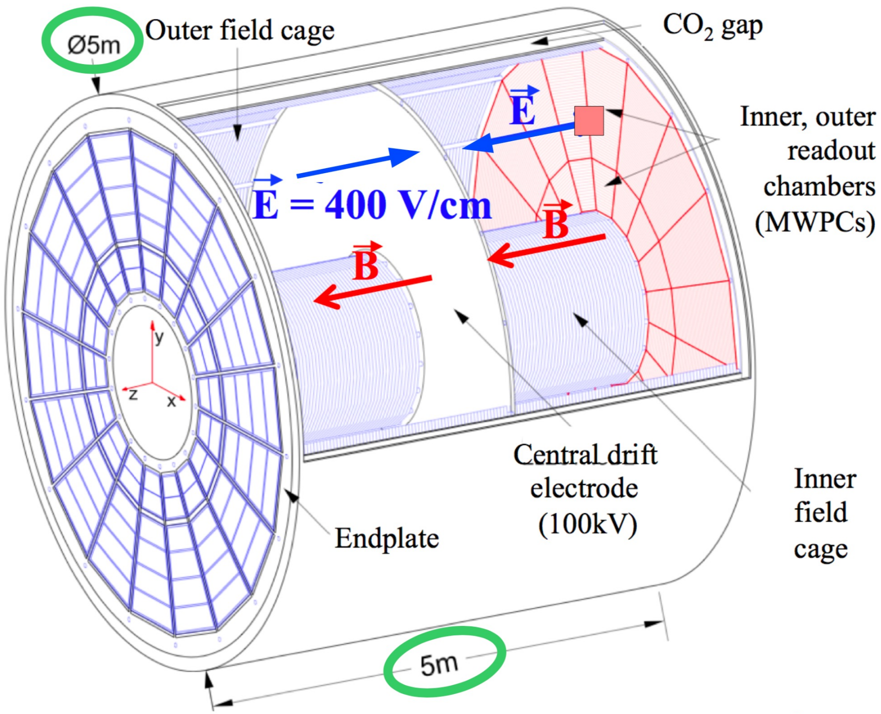




Nucl. Instrum. Meth. A 499, 659 (2003)

Time Projection Chamber: ALICE

- Largest TPC ever built
- Gas volume: ~92 m^3 (active volume)
  $Ne–CO_2–N_2$ (86-9-5) mixture
- Highly segmented readout chambers
- Each of the two endplates houses 18 inner and outer readout chambers (IROCs and OROCs).
- 72 readout chambers: Multi Wire Proportional Chambers with pad readout
- Each sector contains 159 pad rows.
- Half a million pads! (557,568 channels)



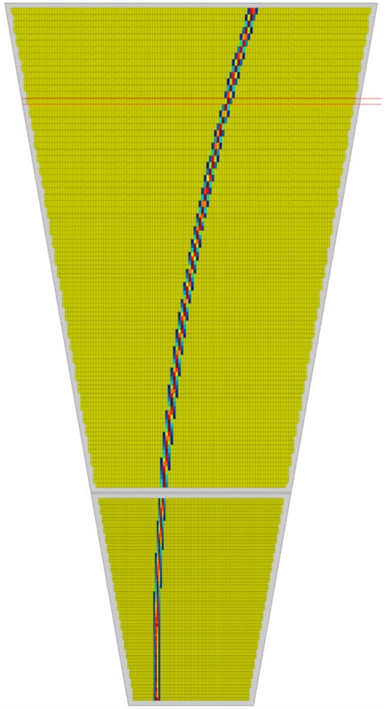
http://cdsweb.cern.ch/record/451098.

dE/dx measurement using TPC

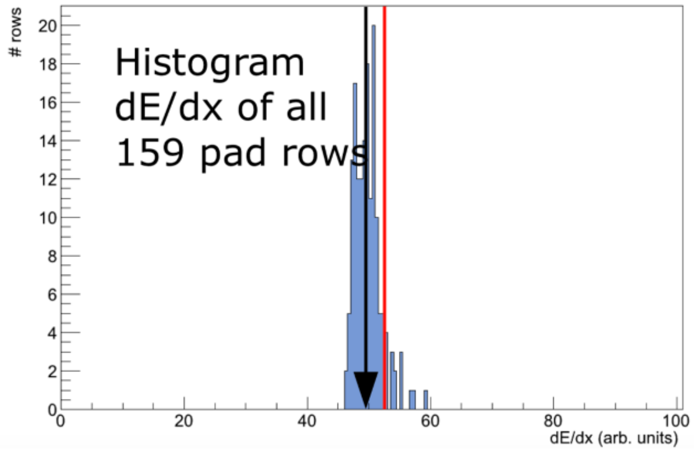
- Identification of the charged particles can be achieved by TPC through their energy loss (dE/dx)

- For a given track momentum and particle mass, the ionization energy loss can be described by the Bethe-Bloch formula

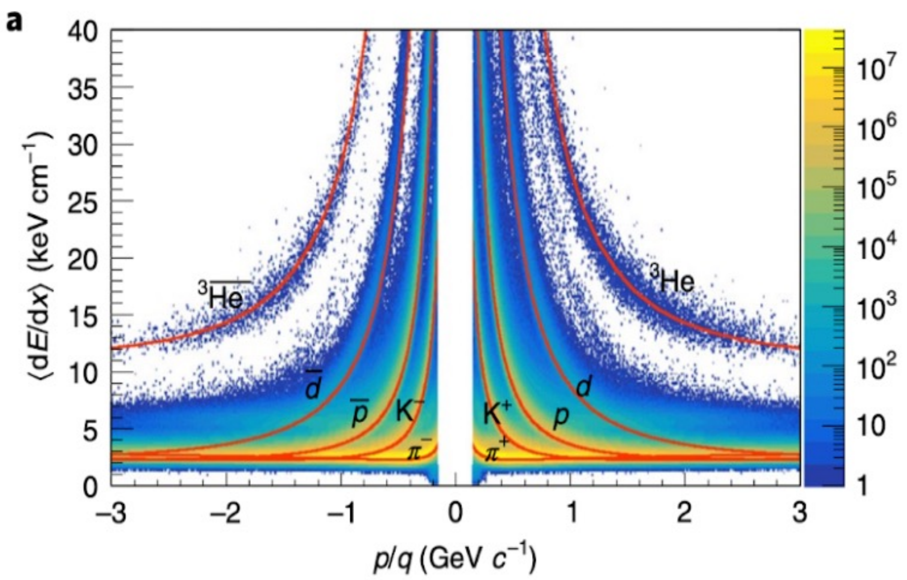
$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I}\right) - \beta^2 - \frac{\delta^2}{2}\right]$$



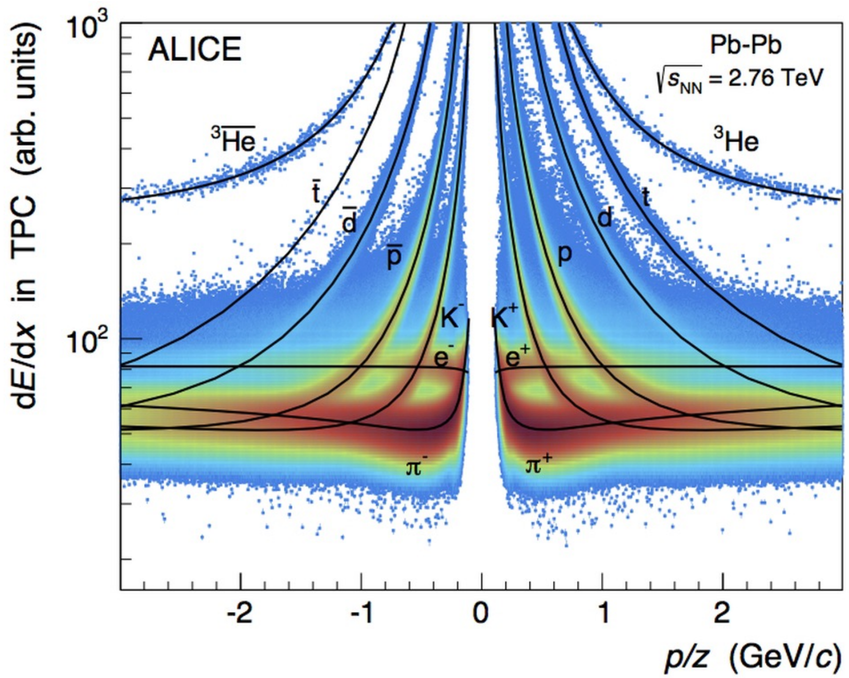
- Ionization fluctuations are large and hence the truncated mean of the dE/dx measured



Identification Technique: TPC



STAR, Nature Phys. 16, 409 (2016)



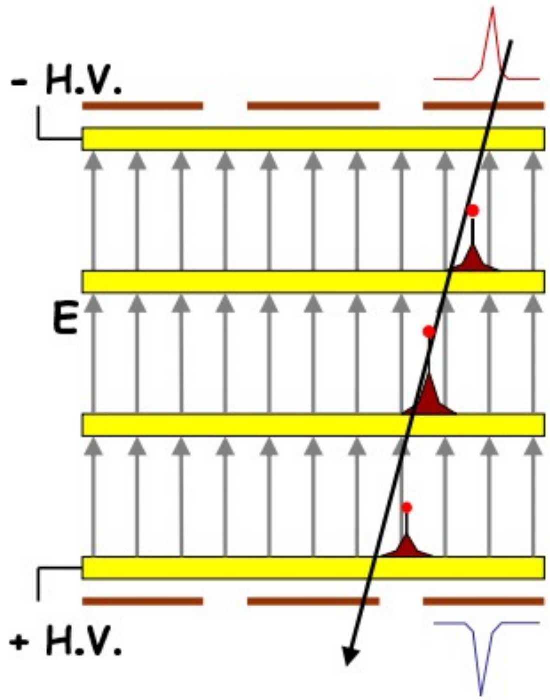
ALICE, Phys. Rev. C 93, 024917 (2016)

✓ Specific ionization energy loss (dE/dx) from TPC is used for the identification of the charged particles

Time Of Flight (TOF)

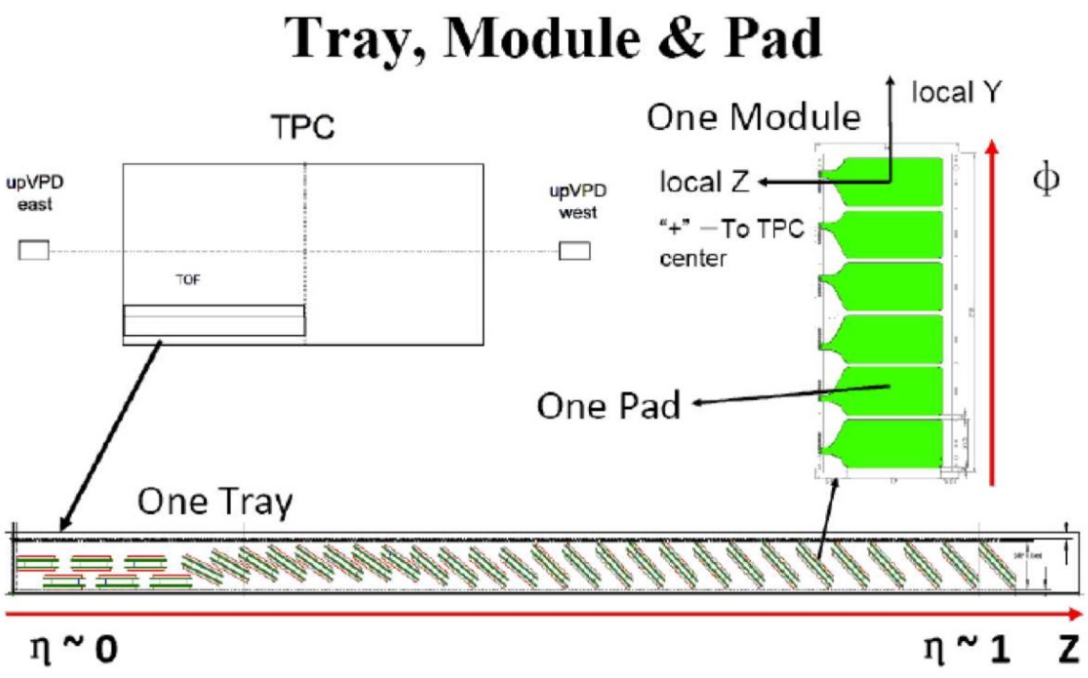
- TOF detector uses the difference between the collision event time and time of arrival of the particles at the detector to identify them.
- It provides the particle identification in the intermediate momentum range
- TOF is a gas detector based on Multi-gap Resistive Plate Chamber (MRPC)
- The electrons produced by ionization start avalanching immediately; there is no drift time associated.
- TOF technique is based on the measurement of the particle time-of-flight t over a known trajectory length L
- Mass square of the particle:

$$m^2 = \frac{p^2}{c^2}\left(\frac{c^2t^2}{L^2} - 1\right)$$



Time Of Flight: STAR

- TOF consists of a total of 120 trays (60 on east side and 60 on west side) that cover the full azimuth and have a pseudo- rapidity range $|\eta| < 0.9$.
- There are 32 MRPC modules in each tray, placed along beam (Z) direction.
- In each module, there are 6 read-out strips (called as pad or channel) along the azimuthal direction.

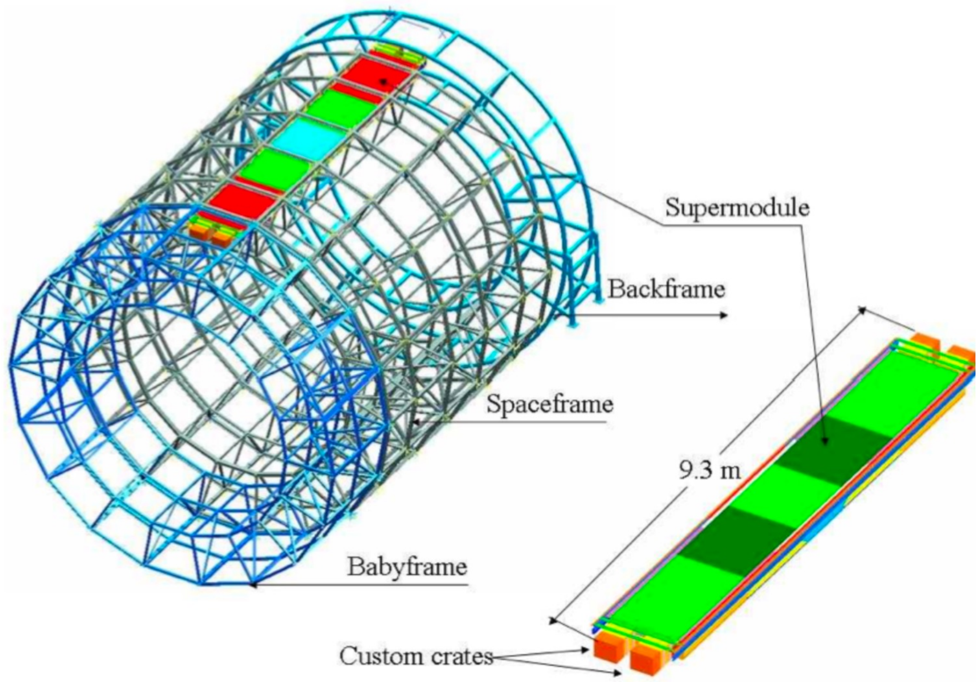


Nucl. Instrum. Meth. A **661 (2012) S110**

- Start time for TOF provided by two VPDs installed at a distance of 5.4 m from the center of the TPC along the beam direction
- The timing resolution for each VPD and TOF tray is on nano second level before any calibration.

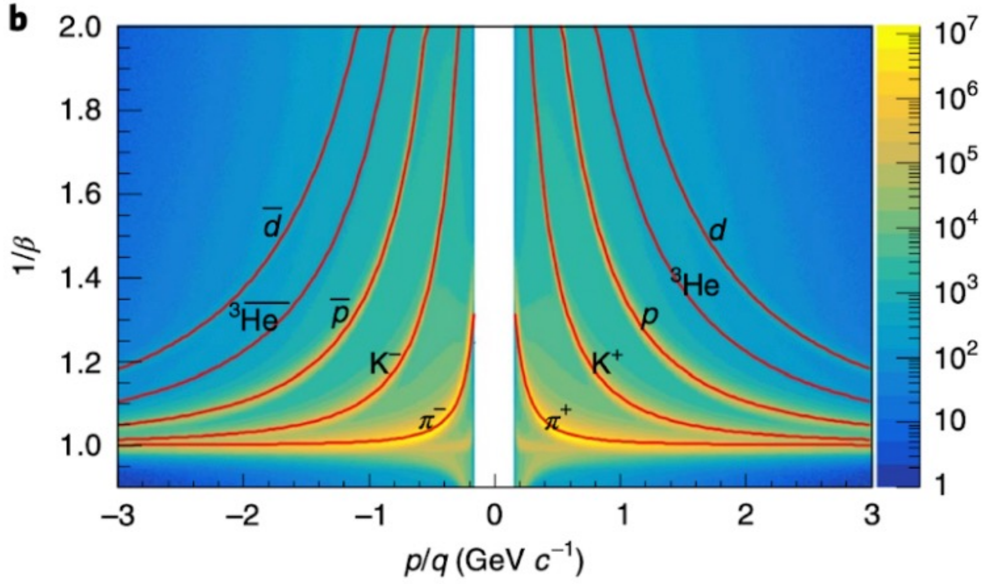
Time Of Flight: ALICE

- TOF is located at radii from 2.70 to 3.99 m and covers a pseudo-rapidity of $|\eta| < 0.9$
- The basic unit of the TOF system is a 10-gap double-stack MRPC strip 122 cm long and 13 cm wide, subdivided into two rows of 48 pads.
- It consists of 90 modules, are arranged in 18 sectors in ϕ and in 5 segments in z-direction
- It has about 160 000 channels.
- MRPC strip operated in a $C_2H_2F_4$ (90%), i-C_4H_{10} (5%), SF6 (5%) gas mixture.
- It achieves a very good time resolution of about 40 ps.

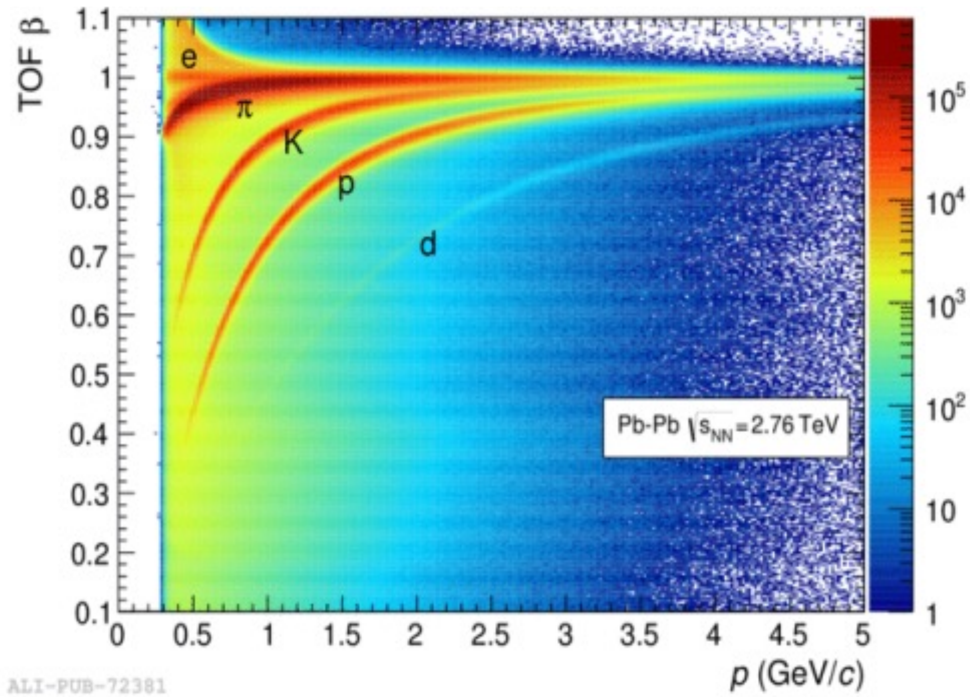


http://cdsweb.cern.ch/record/430132

Identification Technique : TOF



STAR, Nature Phys. 16, 409 (2016)

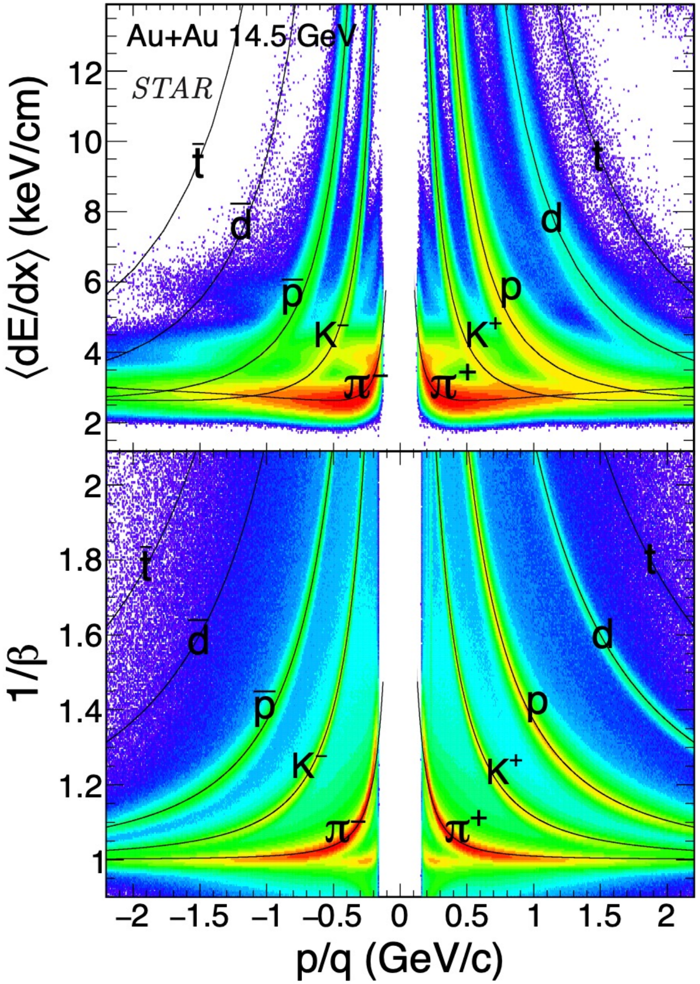


ALICE, Phys. Rev. C 93, 024917 (2016)

$$N\sigma_{TOF} = \frac{time_{measured} - time_{expected}}{\sigma^{PID}_{TOF}}$$

✓ TOF detector is used for the identification of the charged particles

Particle Identification Technique

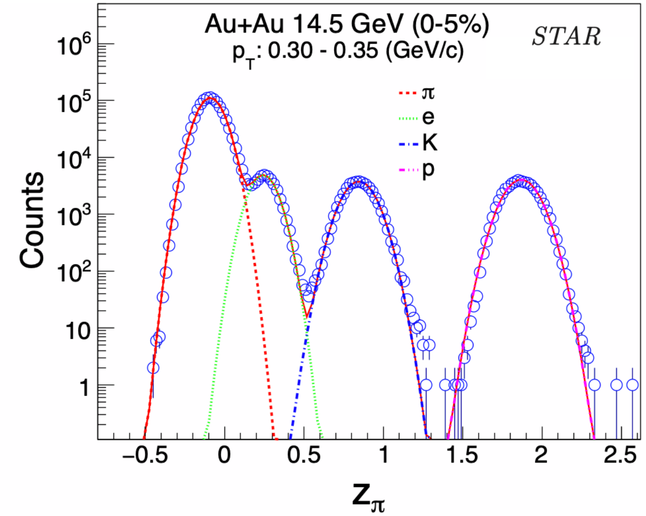


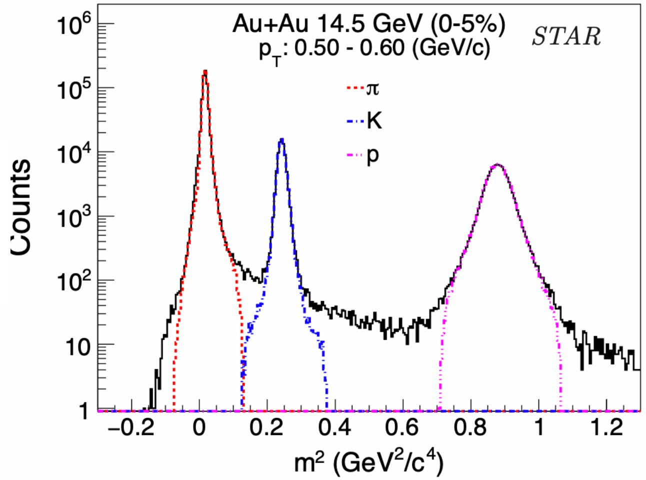
TPC:

$$z_X = \ln\left(\frac{\langle dE/dx\rangle}{\langle dE/dx\rangle_X^B}\right)$$

TOF:

$$m^2 = p^2\left(\frac{c^2T^2}{L^2} - 1\right)$$

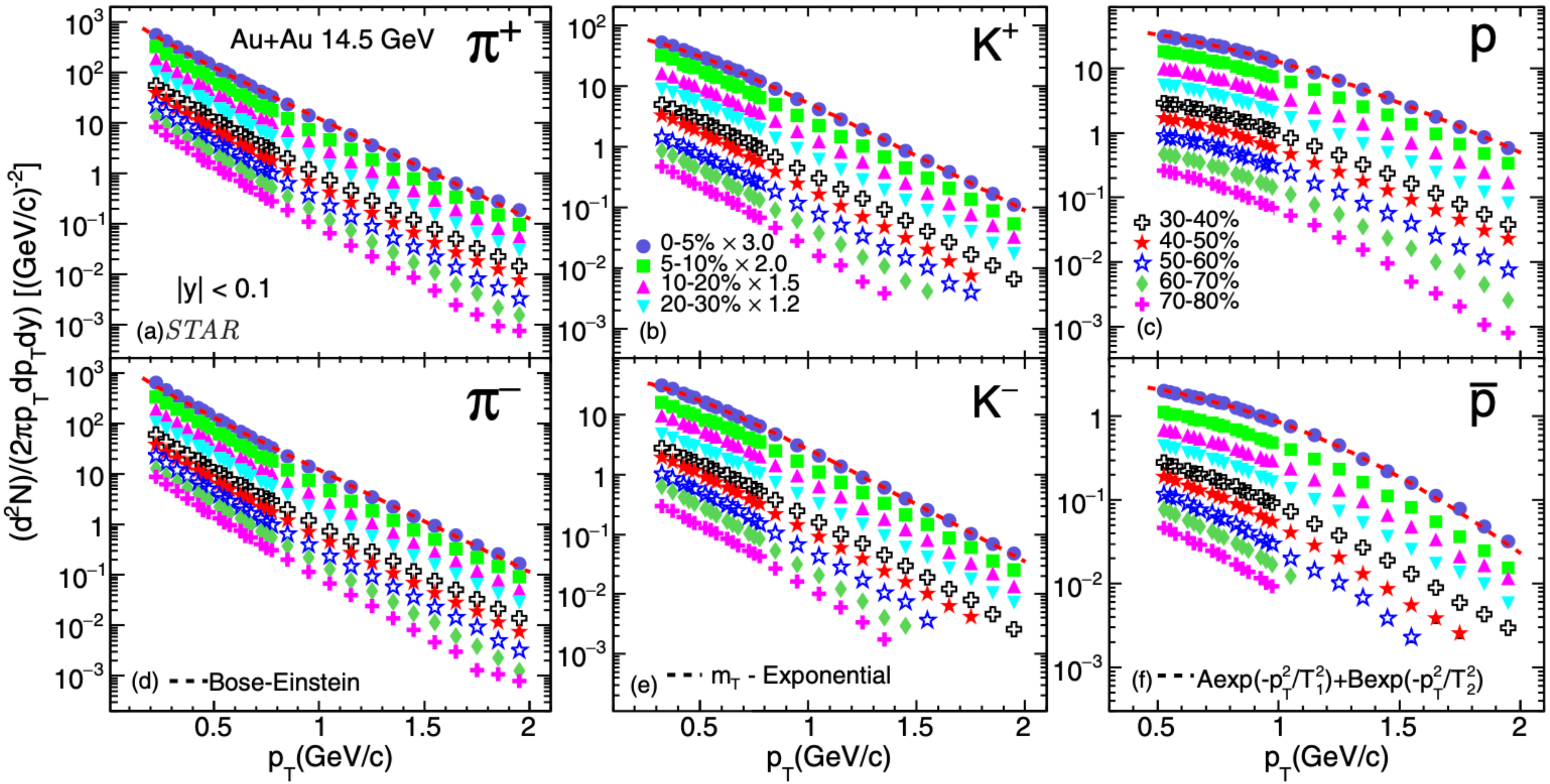




✓ STAR uses energy loss (dE/dx) information from TPC and time of flight information from TOF to identify the particles.

STAR: PRC 101 (2020) 24905

Particle Spectra

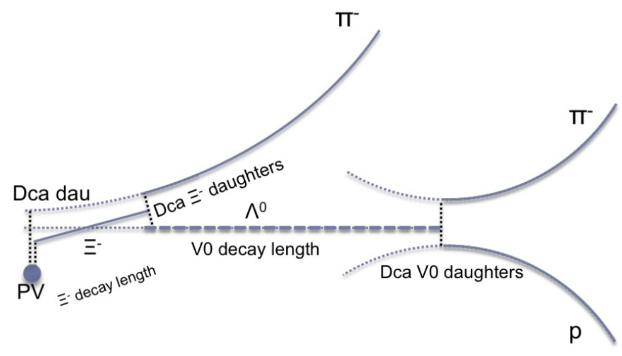


- Transverse momentum spectra of π, K and p in Au+Au collisions at $\sqrt{s_{NN}}$ = 14.5 GeV.
- Used to study the bulk properties of the medium produced.

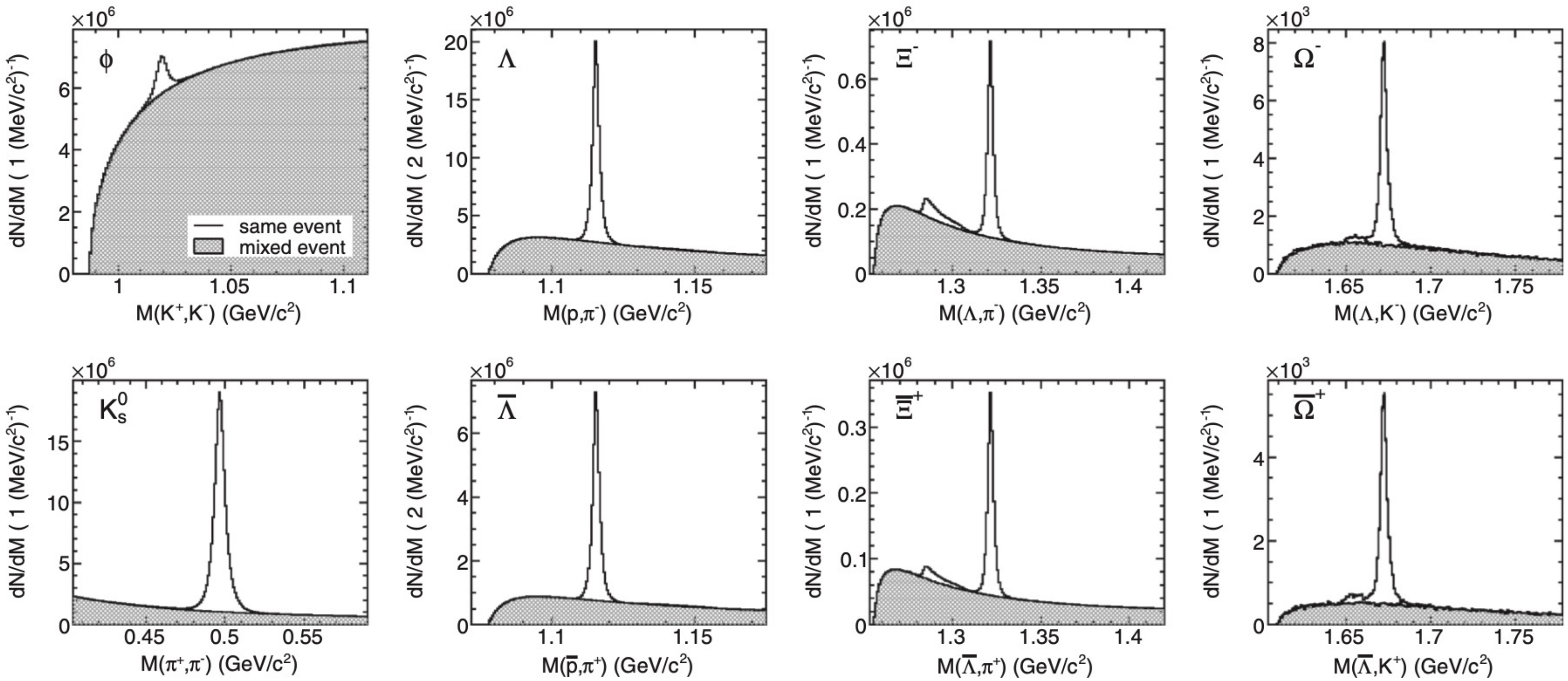
STAR: PRC 101 (2020) 24905

Reconstruction of (multi-)strange hadrons

- $K_s^0 \rightarrow \pi^+ + \pi^-$ (69.2%)
- $\phi \rightarrow K^+ + K^-$ (49.2%)
- $\Lambda(\bar{\Lambda}) \rightarrow p + \pi^-(\bar{p} + \pi^+)$ (63.9%)
- $\Xi^-(\bar{\Xi}^+) \rightarrow \Lambda + \pi^-(\bar{\Lambda} + \pi^+)$ (99.887%)
- $\Omega^-(\bar{\Omega}^+) \rightarrow \Lambda + K^-(\bar{\Lambda} + K^+)$ (67.8%)

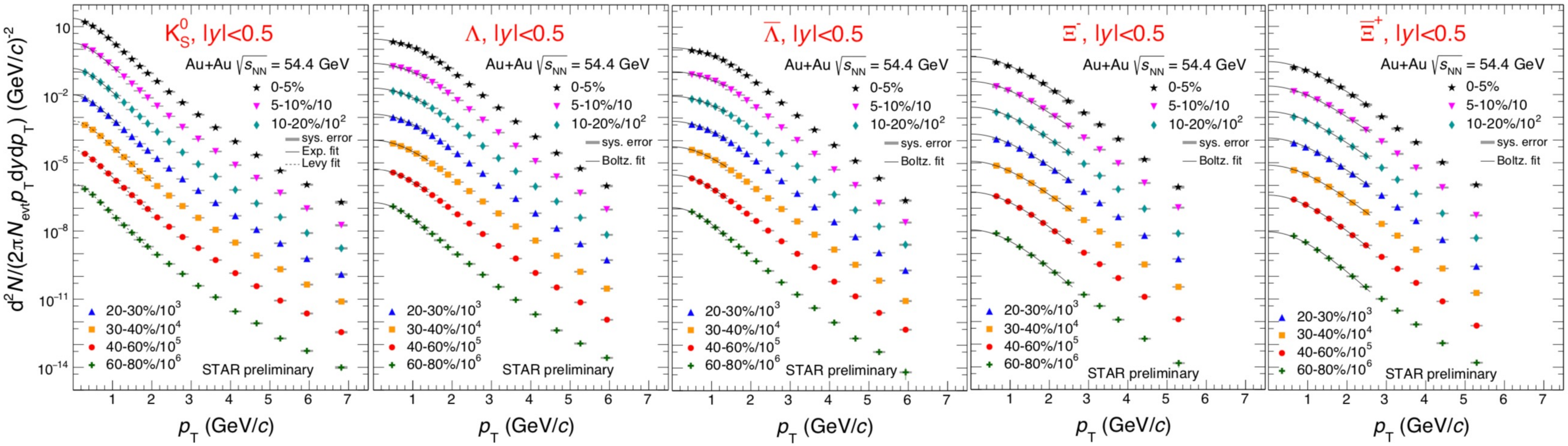


$$m_{inv} = \sqrt{(E_1 + E_2)^2 - (\vec{p_1} + \vec{p_2})^2}$$

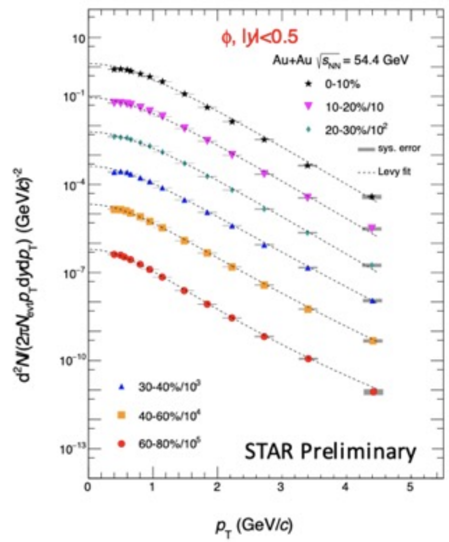


Phys. Rev. C 88, 014902 (2013)

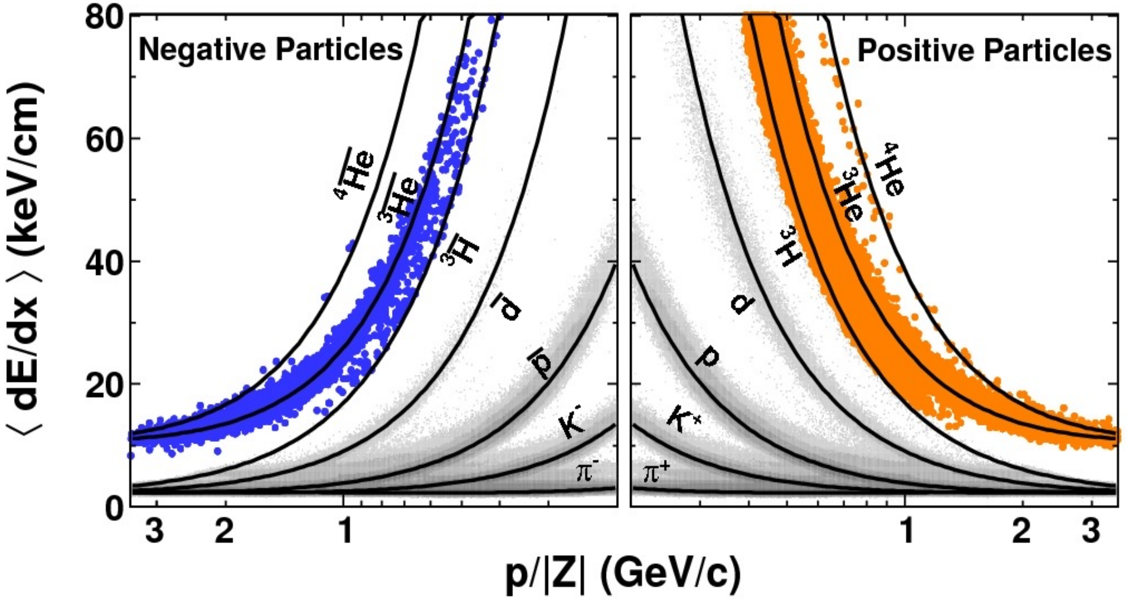
Spectra of (multi-)strange hadrons



➢ Transverse momentum spectra of (multi-)strange hadrons



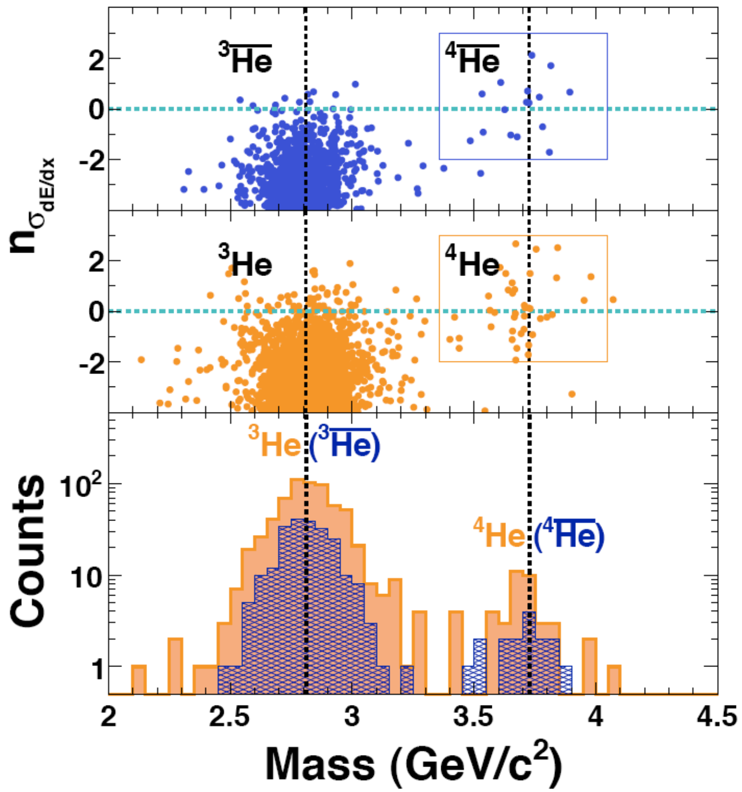
Discovery of anti-α



STAR, Nature 473, 353 (2011)

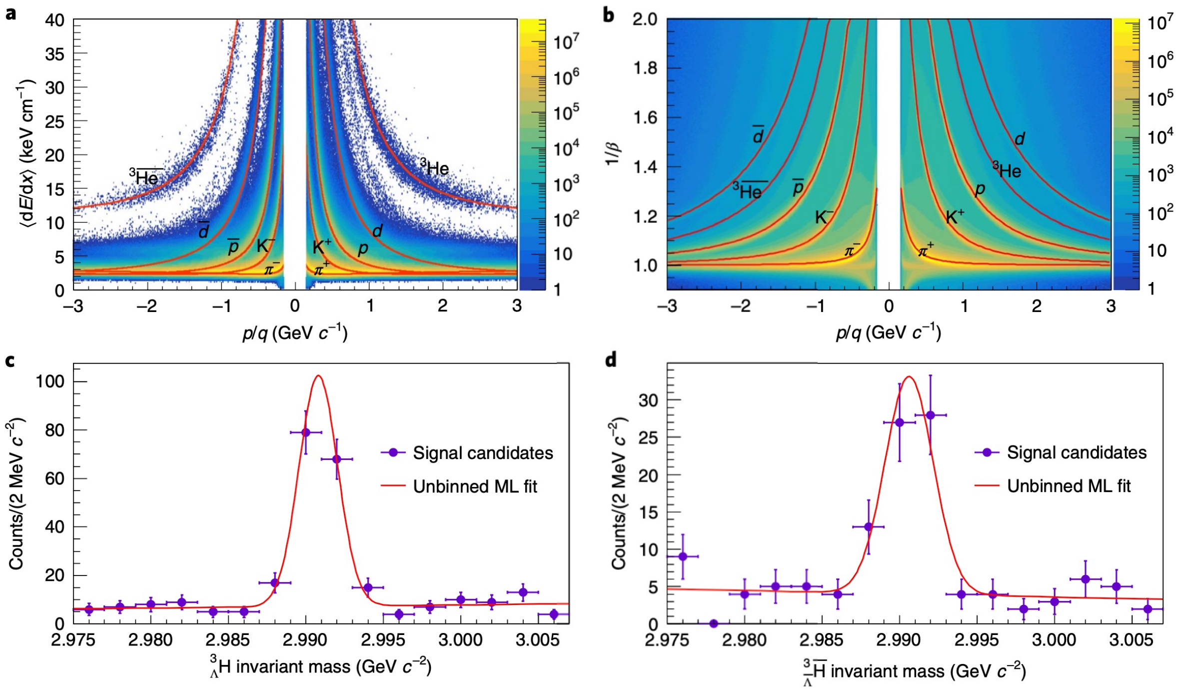
$$n\sigma_{dE/dx} = \frac{1}{R}\ln\frac{\langle dE/dx_{measured}\rangle}{\langle dE/dx_{predicted}\rangle}$$

$$m = \frac{p}{c}\times\sqrt{\frac{t^2c^2}{L^2}-1}$$



- ➢ Combined measurements of energy loss and the time of flight allow a clean identification of anti-α.
- ➢ In total, 18 counts were identified.
- ➢ Provides the point of reference for various searches for new phenomena in the cosmos.

Reconstruction of (anti-)hypertriton



$^{3}_{\Lambda}\mathrm{H}(^{3}_{\Lambda}\overline{\mathrm{H}})$ reconstructed through

$$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$$

$$^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$$

Fit function:

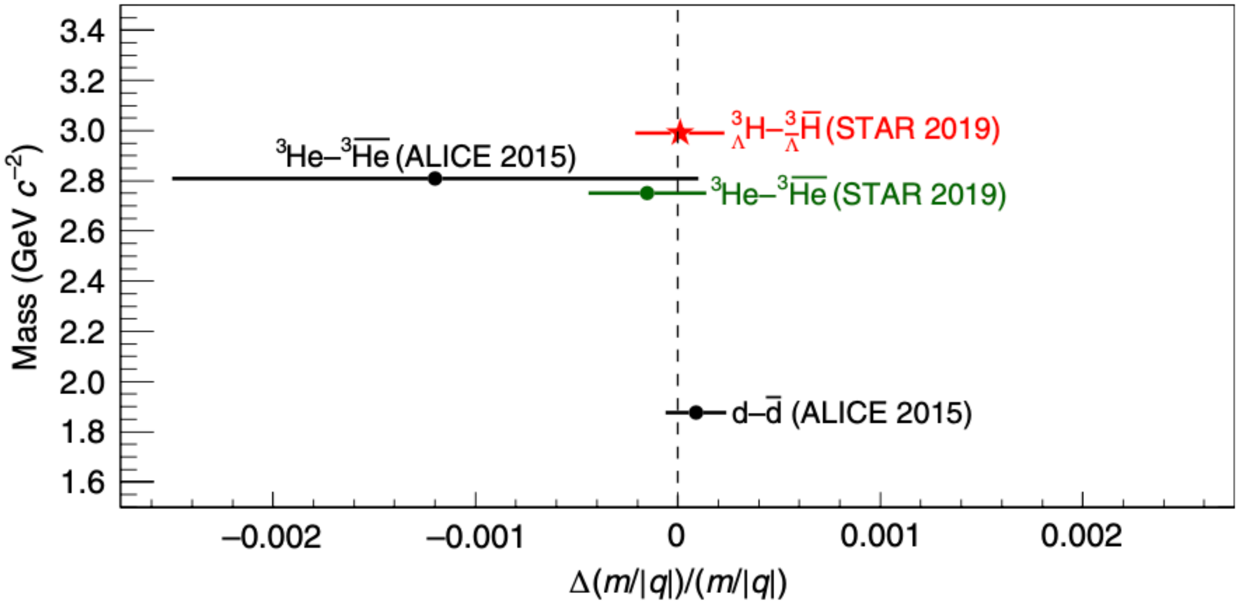
$$N_{sig}\left(\frac{1}{\sqrt{2\pi\sigma^2}}e^{-\frac{(x-\mu)^2}{2\sigma^2}}\right) + N_{bkg}(ax+b)$$

Due to the good performance of PID and high spatial resolution in STAR:

- Invariant mass distributions obtained with excellent signal/background ratio.
- Signal/background is higher by factor of 23 relative to the earlier measurements.
- Significance of signal: 11.4 for $^{3}_{\Lambda}\mathrm{H}$ and 6.4 for $^{3}_{\Lambda}\overline{\mathrm{H}}$.

STAR, Nature Phys. 16 (2020) 409

Mass difference between ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$



$$m_{{}^{3}_{\Lambda}\mathrm{H}} = 2,990.95 \pm 0.13(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})\ \mathrm{MeV}\ c^{-2}$$

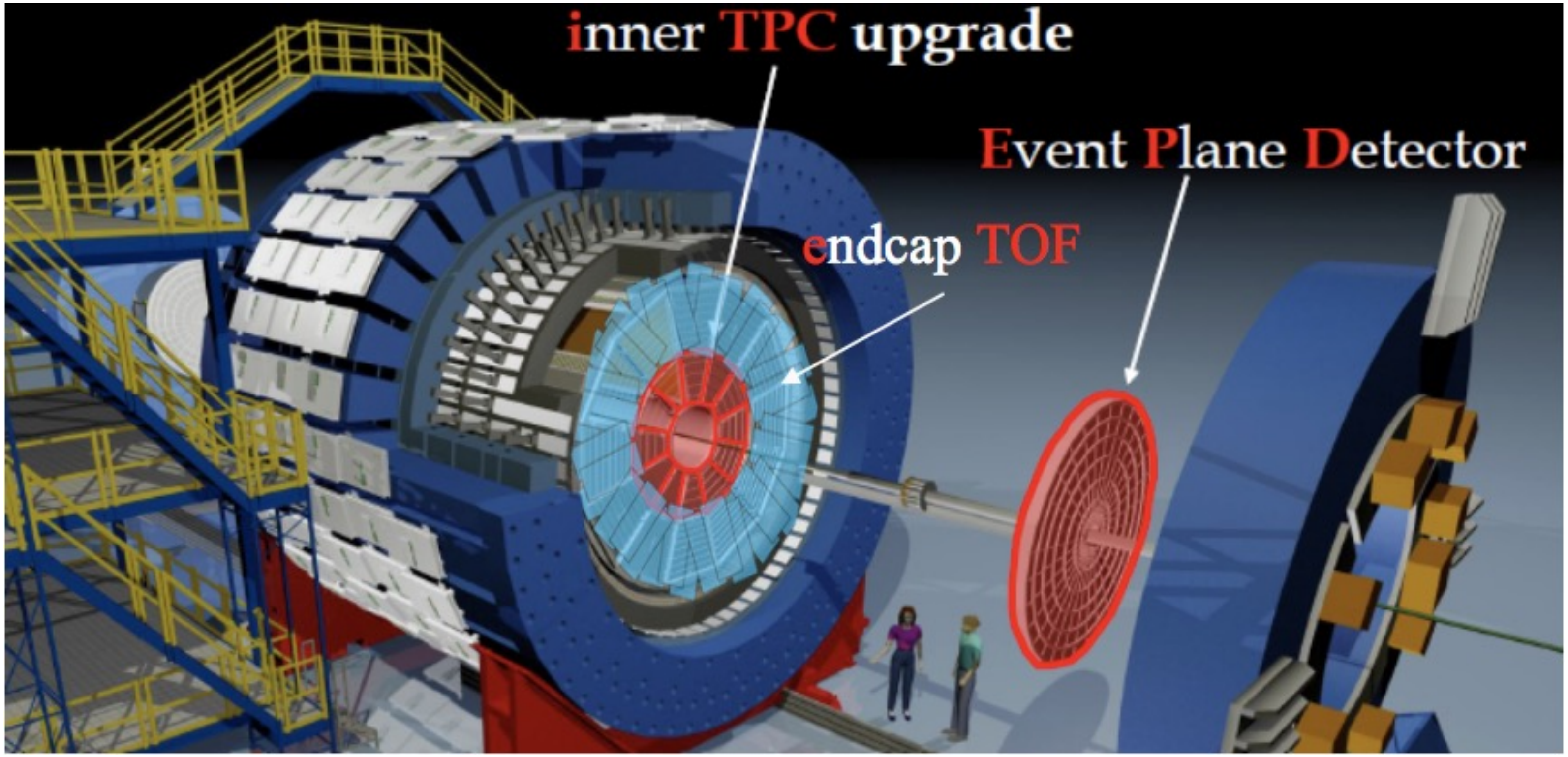
$$m_{{}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}} = 2,990.60 \pm 0.28(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})\ \mathrm{MeV}\ c^{-2}$$

$$\frac{\Delta m}{m} = \frac{m_{{}^{3}_{\Lambda}\mathrm{H}} - m_{{}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}}}{m} = (\ 0.1 \pm 2.0(\mathrm{stat.}) \pm 1.0(\mathrm{syst.})) \times 10^{-4}$$

- ✓ CPT testing in hypernuclei sector for the first time.
- ✓ No violation of CPT symmetry observed with high precision.

STAR, Nature Phys. 16 (2020) 409

STAR Upgrade



iTPC upgrade	EPD upgrade	eTOF upgrade
$\|\eta\|<1.5$	**$2.1<\|\eta\|<5.1$**	**$-1.6<\eta<-1.1$**
p_T >60 MeV/c	Better trigger & b/g reduction	Extend forward PID capability
Better dE/dx resolution Better momentum resolution	Greatly improved Event Plane info (esp. 1st-order EP)	Allows higher energy range of Fixed Target program
Fully operational in 2019	**Fully operational in 2018**	**Fully operational in 2019**

✓ All 24 inner sectors of TPC are replaced with 40 pad-row readouts.

ALICE TPC Upgrade

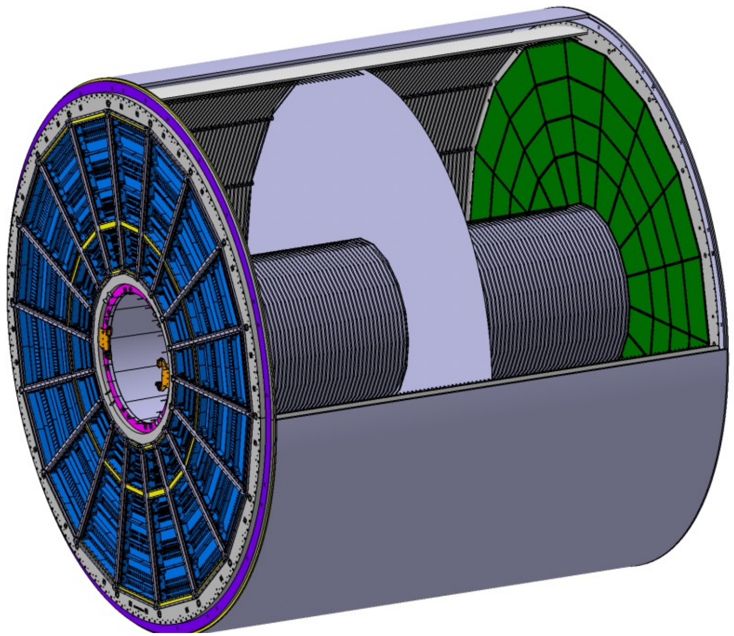
- ALICE upgrade is to exploit the increased Pb–Pb luminosity delivered by the LHC
  A minimum-bias interaction rate of up to 50 kHz

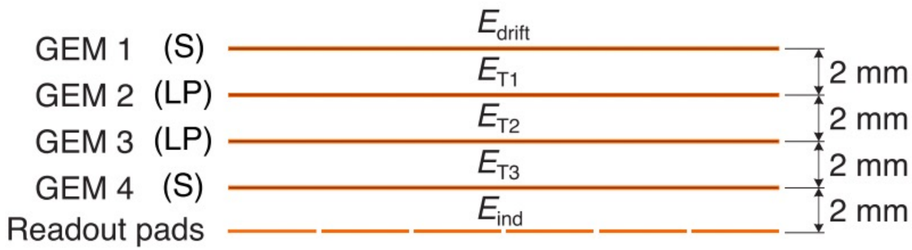
- Replacement of the MWPC-based readout chambers by Gas Electron Multipliers (GEMs)

- GEM detectors arranged in stacks containing four GEMs each, and continuous readout electronics based on the SAMPA chip

- The selected gas, Ne-CO_2-N_2 (90-10-5) provides robustness against primary discharges.

- Upgrade of the ALICE TPC was completed in 2020.

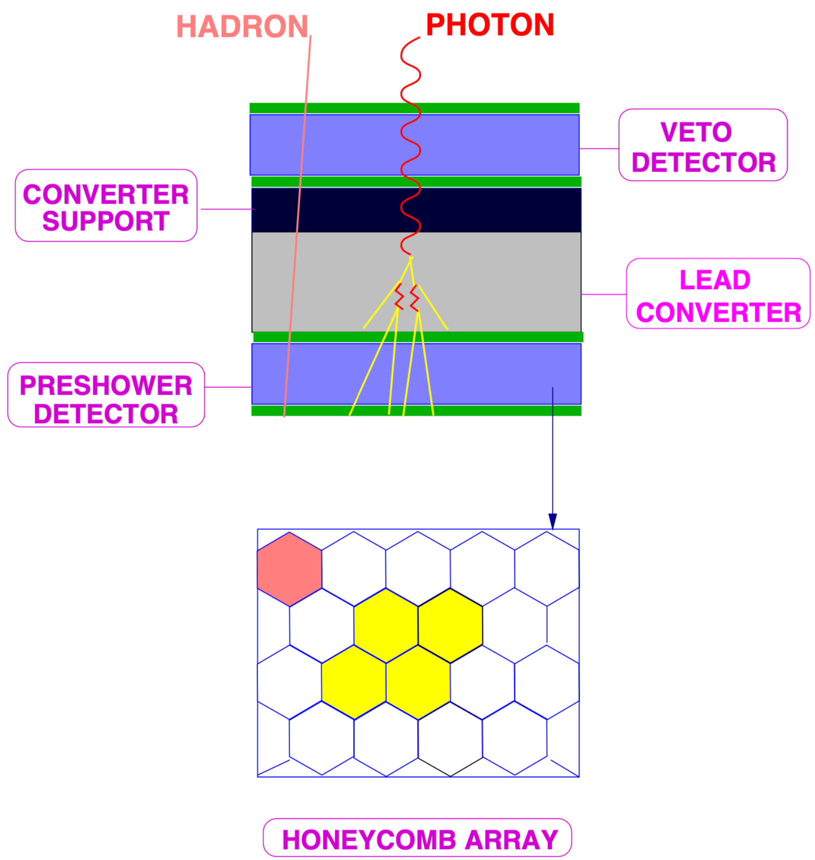




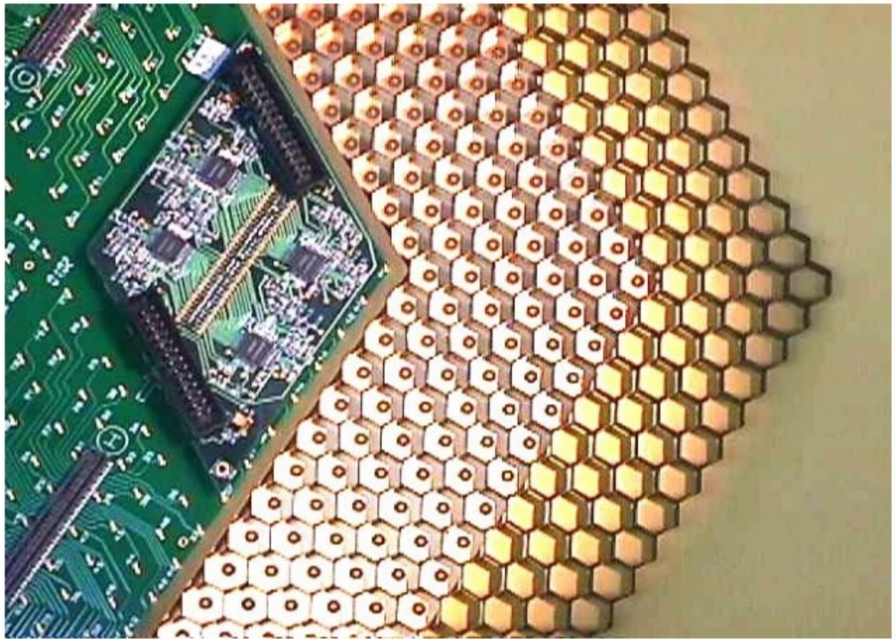
arXiv:2012.09518v2

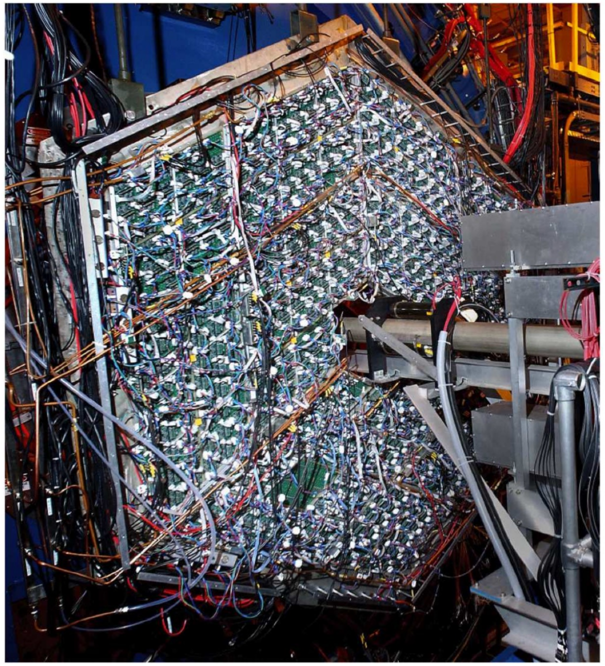
Photon Multiplicity Detector (PMD)

- The PMD is a preshower detector having fine granularity and full azimuthal coverage.
- It consists of a Charged Particle Veto (CPV) plane and a Preshower detector plane with $3X_0$ thick lead converter in between.
- Photons passing through a converter initiate an electromagnetic shower and produce large signals on several cells of the sensitive volume of the detector.
- Hadrons normally affect only one cell and produce a signal representing minimum-ionizing particles.
- It measures the multiplicity and spatial distribution of photons on an event-by-event basis.



Photon Multiplicity Detector: STAR



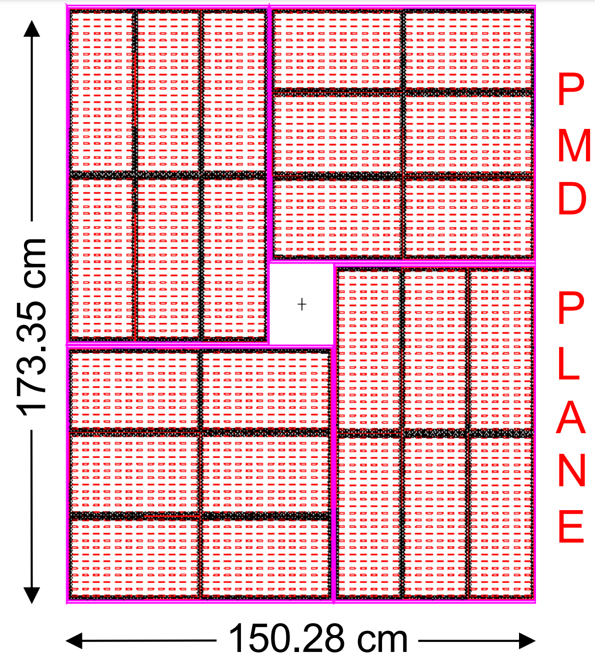


- PMD was installed (on east side) at 540 cm from the center of the TPC outside the STAR magnet.
- It covers a pseudorapidity region $-3.7 < \eta < -2.3$ with full azimuthal angle.
- Each plane consists of 12 super modules arranged in the form of a hexagon and has 41,472 hexagonal honeycomb cells.
- It is based on a proportional counter design using Ar + CO_2 gas mixture in ratio 70:30 by weight.
- PMD completed data taking at STAR in 2011.

Nucl. Instrum. Meth. A 499, 751 (2003)

Photon Multiplicity Detector: ALICE

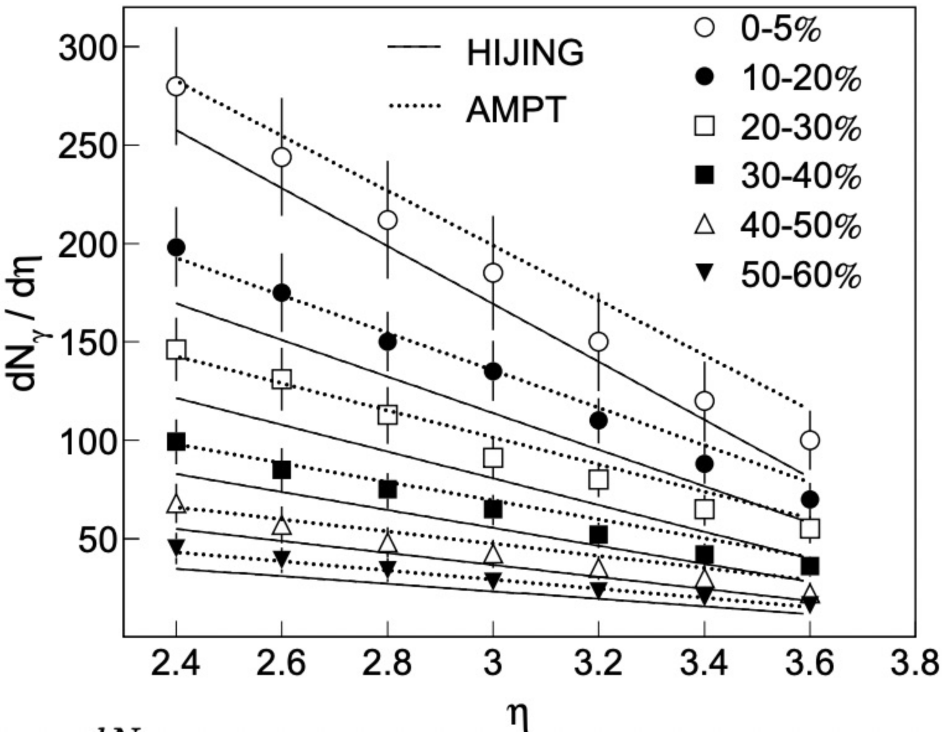
- ✓ Total no. of cells in PMD = 221184
- ✓ Sensitive medium: Gas (Ar + CO_2 in the ratio 70:30)
- ✓ Z-distance = 363.5 cm from IP
- ✓ η-coverage = 2.3 to 3.9
- ✓ Φ-coverage = 0 to 2π
- ✓ Cathode : Copper plate
- ✓ Anode : Gold plated tungsten wire
- ✓ Operating voltage : -1350V to -1400V
- ✓ Total no. of modules = 48
- ✓ No. of cells in one module = 4608
- ✓ Cell depth = 5 mm and cross section = 0.23 cm^2
- ✓ Cell wall thickness = 0.2 mm

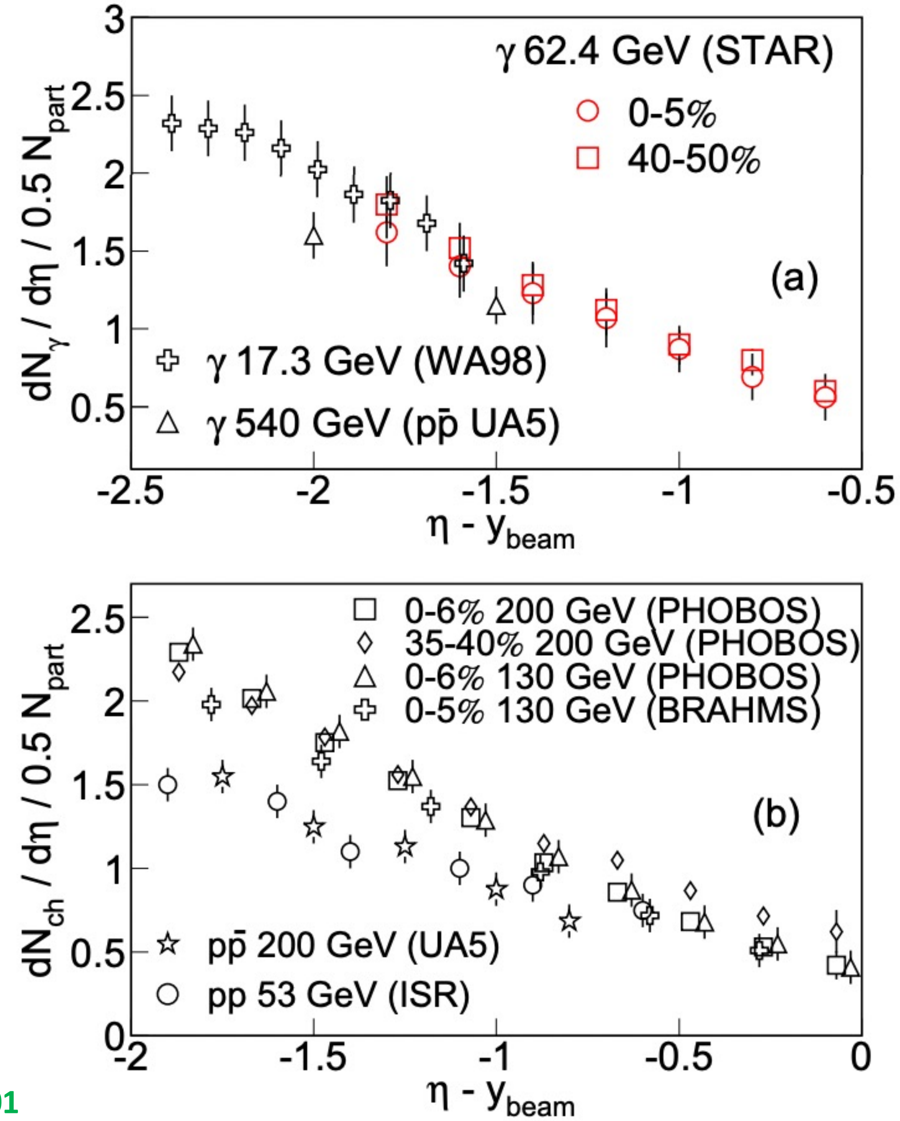


http://cdsweb.cern.ch/record/451099

➢ PMD completed data taking at ALICE in 2018.

Photon Multiplicity Detector: STAR

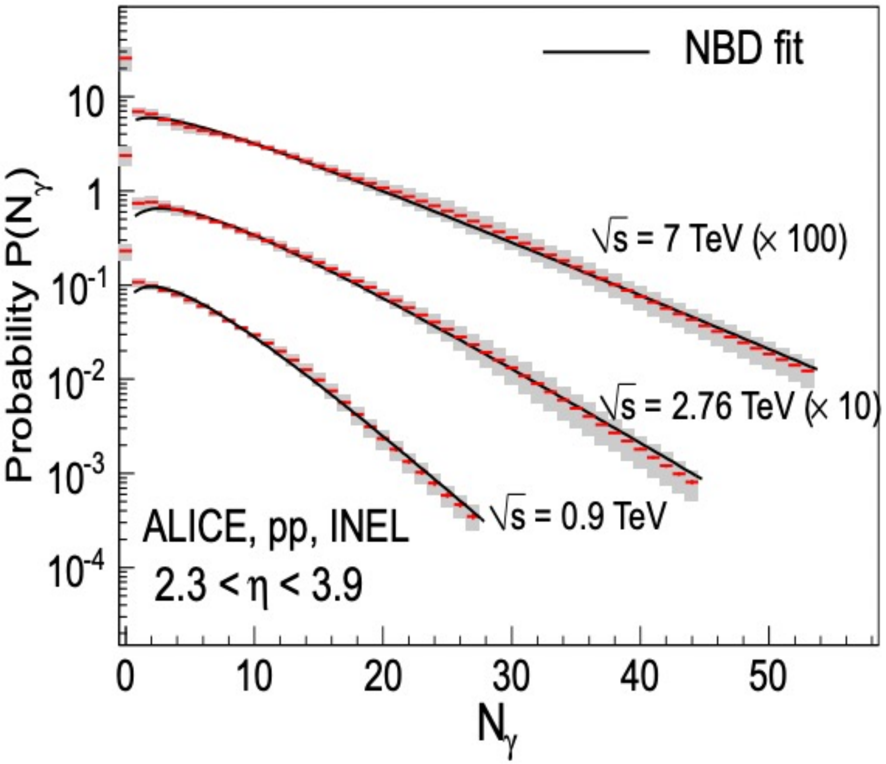


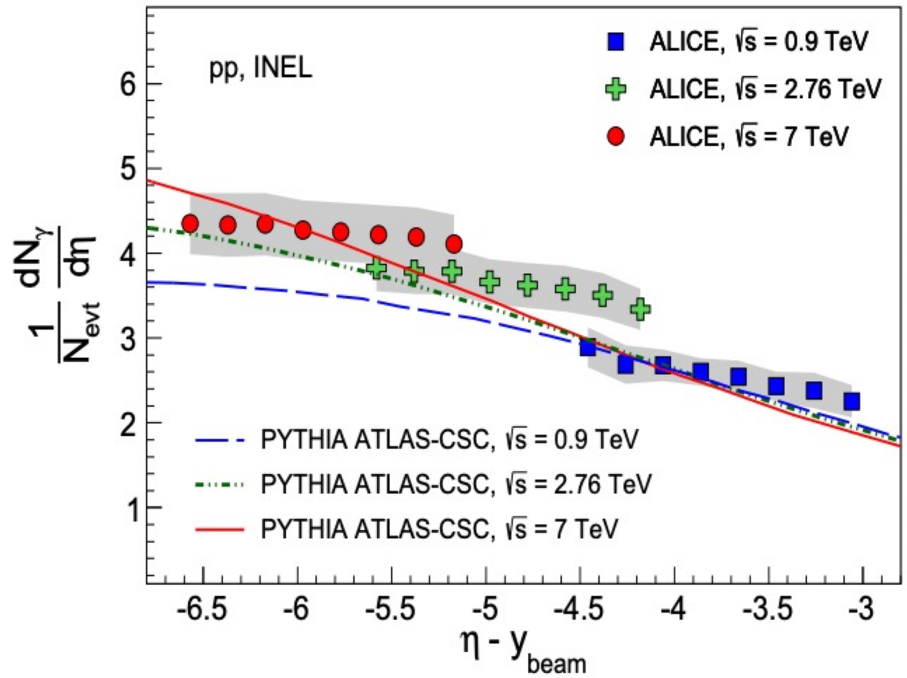


- Photon results from the SPS and RHIC are consistent with each other, suggesting that photon production follows an energy independent Limiting Fragmentation behavior.

Phys. Rev. Lett. 95 (2005) 062301
Phys. Rev. C 73 (2006) 034906

Photon Multiplicity Detector: ALICE





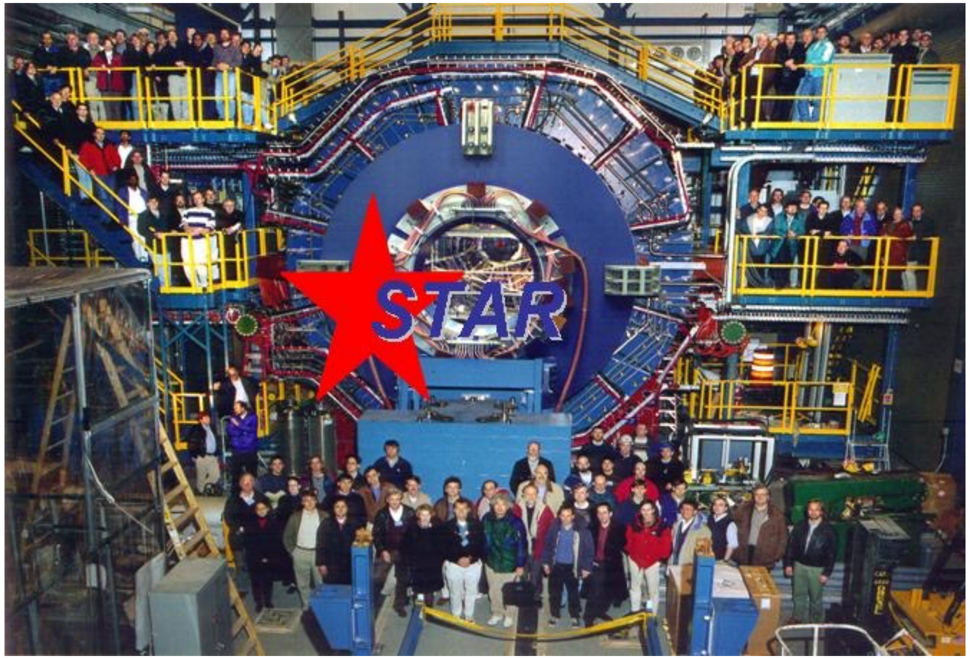
- Photon multiplicity distributions are well described by single NBD functions.
- In the range of the present measurement, limiting fragmentation behavior is not observed.

Eur. Phys. J. C (2015) 75:146

Summary

- Particle identification is one of the main strengths of the STAR and ALICE experiment.
- It is a crucial ingredient for detailed studies of the strongly interacting matter formed in ultrarelativistic heavy-ion collisions.
- STAR and ALICE provides PID information via various experimental techniques, allowing for the identification of particles over a broad momentum range.
- Several studies based on identified particles are already done.
- More exciting results are expected to come with new and upgraded detectors.

Acknowledgement



STAR Collaborators

ALICE Collaborators

Thank You