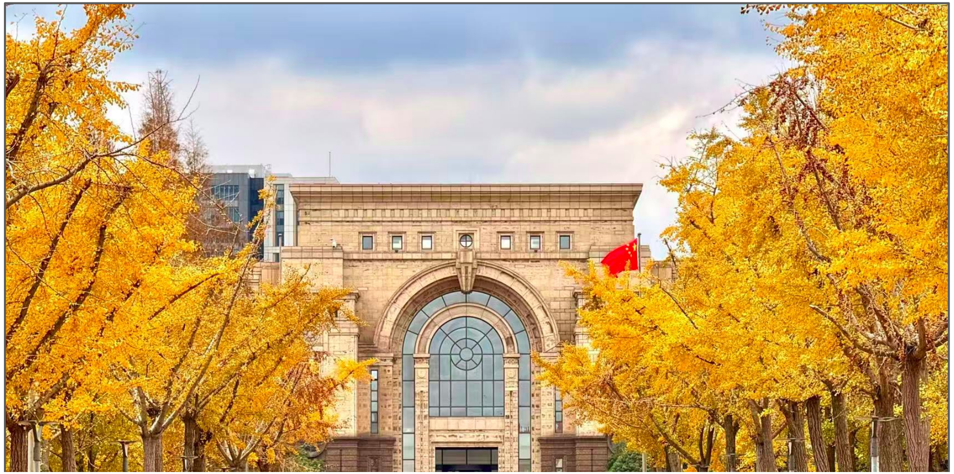

ALICE-TOF

1st lecture

F. Noferini* on behalf of the ALICE-TOF group
*INFN Bologna

Shanghai, China, 4th November 2025
The 1st ALICE Experiment and Heavy-Ion Physics Workshop

Outline

1st lecture

- Role of PID in HEP physics
- PID in ALICE
- The Time Of Flight Det.
- Multigap Resistive Plate Chambers (MRPC) →TOF
- TOF performance in ALICE Run 1/2
- Physics with TOF in Run 2 (few highlights)

2nd lecture

- Usage of TOF PID (+ with other Dets.)
- TOF upgrade in Run 3
- TOF in continuous readout era
- TOF operations in Run 3
- TOF performance in Run 3

Particle Identification (PID) in High Energy Physics (HEP)

In HEP experiments the capability to identify the nature of final states is fundamental.
To achieve identification different experimental techniques are used depending on the different particle nature (charged/neutral, hadrons/leptons, stable/unstable) and different momentum/energy ranges:

- Different particle species (charged/neutral, hadrons/leptons, stable/unstable)
- Different momentum/energy ranges

Different PID techniques allow to cover different momentum range and particle species in a complementary ways, we briefly go through some of them:

- dE/dx energy loss
- Transition Radiation Detector (TRD)
- Time Of Flight (TOF)
- RICH (Cherenkov radiation) detector
- decayment with well defined topological properties (V0s and Cascades)
- Calorimetry
- …

Particle Identification (PID) in Heavy Ion Collisions (QGP)

Remind that ~95% of the produced particles are “soft”, i.e. have p_T < 2 GeV/c and many of the soft probes to characterize QGP depends on:

- hadron quark content
  - u,d vs s (i.e. strangeness production)
  - meson vs baryons (i.e. coalescence vs thermal regime)
- hadron masses (i.e. effect of medium expansion: hydrodynamics, collective flow, …)
- leptons

→ PID plays a crucial role

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- **Calorimetry**
- …

4

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- leptons

→ PID plays a crucial role

I assume F. Antinori will convince you about that!

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- **decayment with well defined topological properties (V0s and Cascades)**
- **Calorimetry**
- …

$$\beta = p\sqrt{\frac{1}{m^2c^2 + p^2}}$$

Different PID techniques allow to cover different momentum range and particle species in a complementary ways, we briefly go through some of them **(e.g. ALICE)**

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- **Time Of Flight (TOF)**
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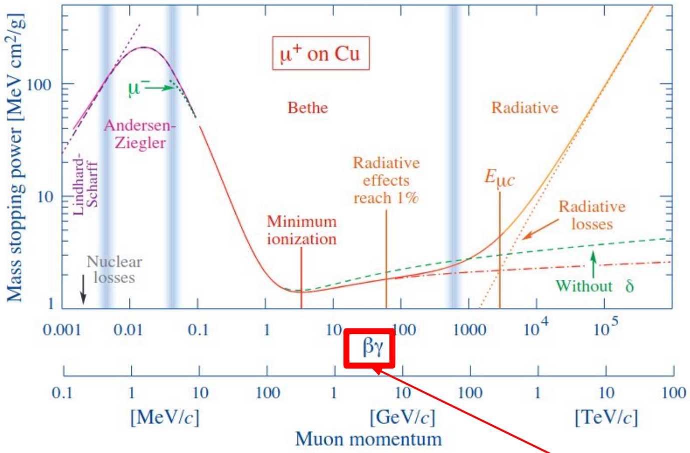
- Calorimetry

Typically, to identify a particle we need to characterize its mass by coupling *p* and $\beta(v/c)$, or *p* and *E*

e.g. ALICE TPC → see A. Schmah lecture (and ITS in Run 1 and Run 2)



We can focus on three main regions:

1. **$1/\beta^2$ region**: for a given momentum strong dependance on particle mass → hadron PID works very well
2. Minimum Ionization
3. Relativistic rise region: at high $\beta\gamma$ radiative processes (bremsstrahlung) start to play a role → **electrons** or hadrons at high momenta

Different PID techniques allow to cover different momentum range and particle species in a complementary ways, we briefly go through some of them **(e.g. ALICE)**

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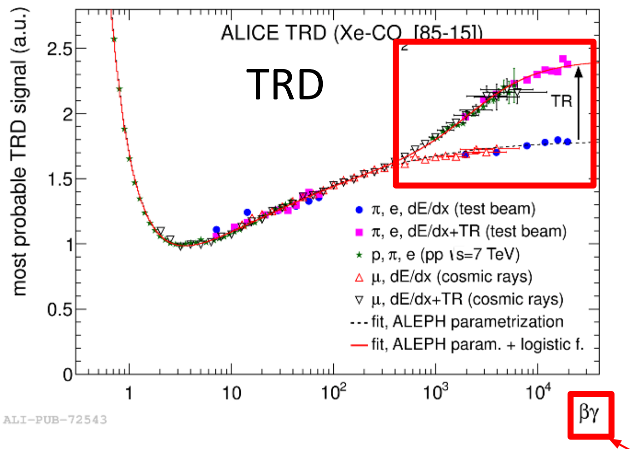

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2. Minimum Ionization
3. Relativistic rise region: at high $\beta\gamma$ radiative processes (bremsstrahlung) start to play a role + transition radiation effect→ **electrons**

Different PID techniques allow to cover different momentum range and particle species in a complementary ways, we briefly go through some of them **(e.g. ALICE)**

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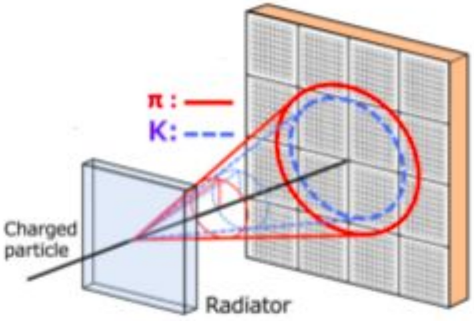

e.g. ALICE HMPID

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

Ring-Imaging Cherenkov Detector allows to identified charged particles by reconstructing the angle of photons emission in a medium when particle move at a speed higher than light speed in the medium **(*β* > *c*/*n*)**

Different PID techniques allow to cover different momentum range and particle species in a complementary ways, we briefly go through some of them **(e.g. ALICE)**

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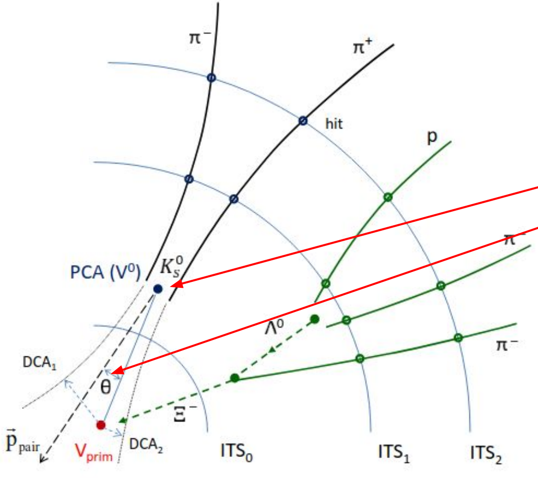
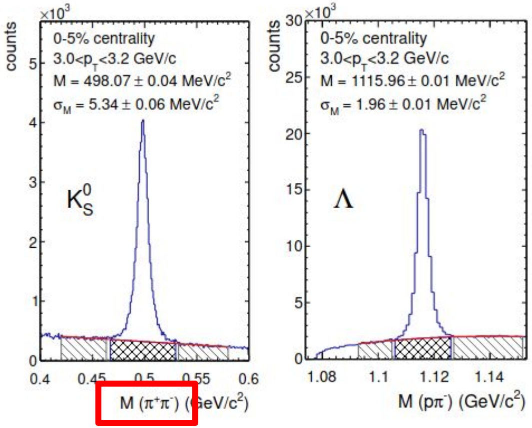


VOs (K_0^s, Λ) and Cascades (Ξ, Ω) can be easily identified through the topology of their decayment:

- secondary vertex reconstruction
- pointing angle to the Primary vertex

thanks to their $c\tau$ of few/several cm

Such cuts allow to strongly reduce the combinatorial background when building invariant mass distribution



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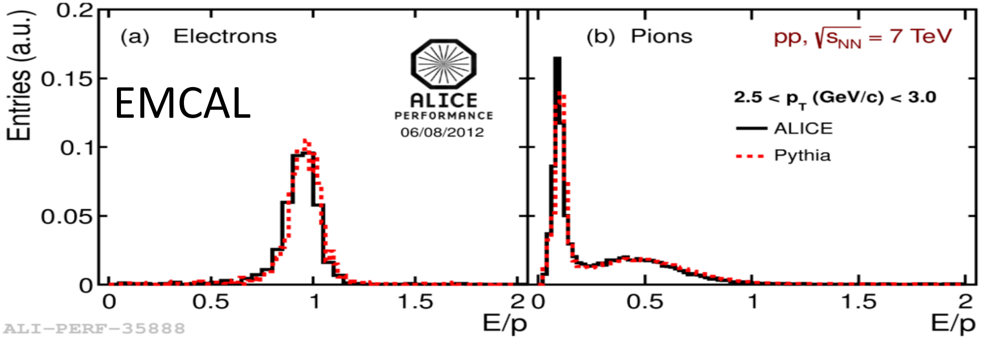

ALICE (**PHOS, EMCAL, DCAL**)

Hadron response (release of energy) differs from only-electromagnetic-interacting particles (lepton and photons)

Different PID techniques allow to cover different momentum range and particle species in a complementary ways, we briefly go through some of them **(e.g. ALICE)**

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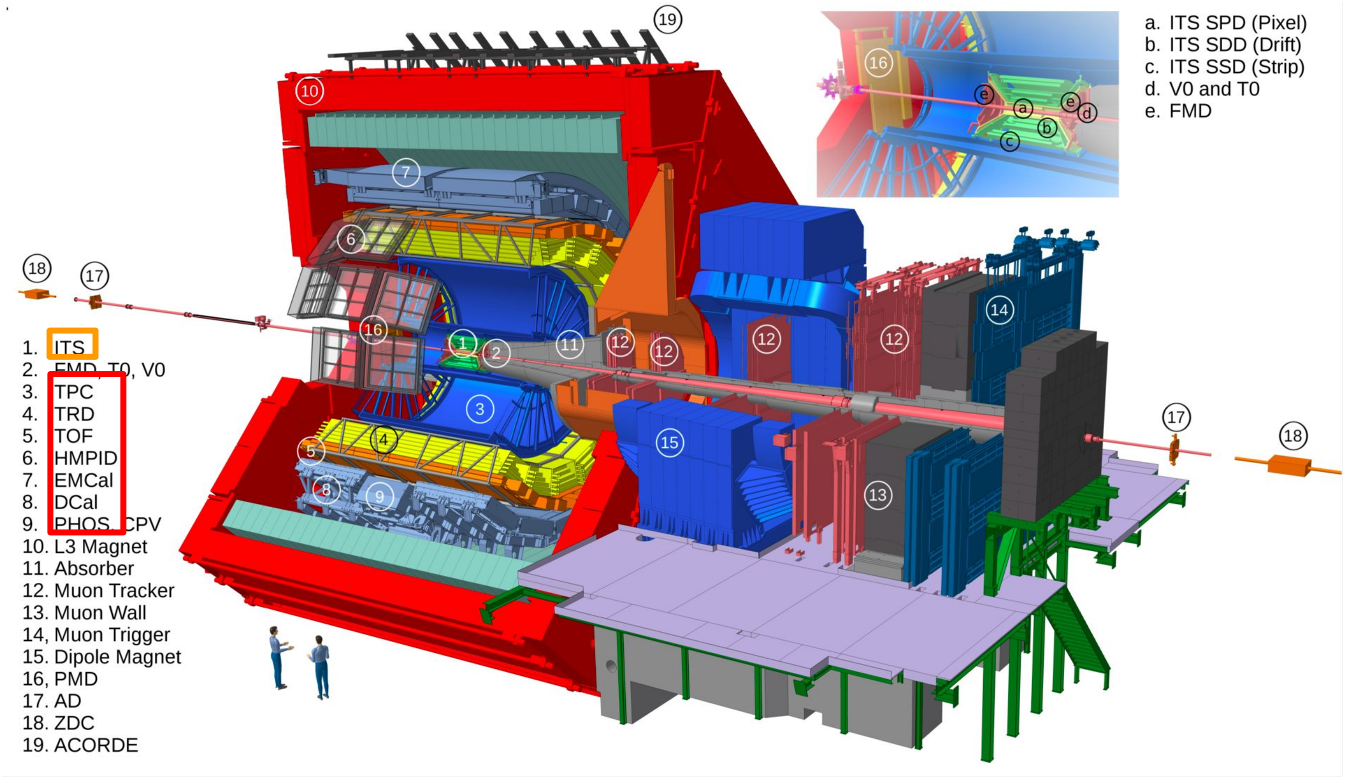
Typically, to identify a particle we need to characterize its mass by coupling p and $\beta(v/c)$, or p and E

ALICE and PID

Different and complementary techniques in a “low” magnetic field (B=0.2/0.5 T) →high acceptance down to very low momenta

(O(100 MeV))



ALICE detector in Run 2

ALICE and PID

Different and complementary techniques in a “low” magnetic field (B=0.2/0.5 T) →high acceptance down to very low momenta

(O(100 MeV))

TOF operates in the intermediate momentum region (hadron separation and more)

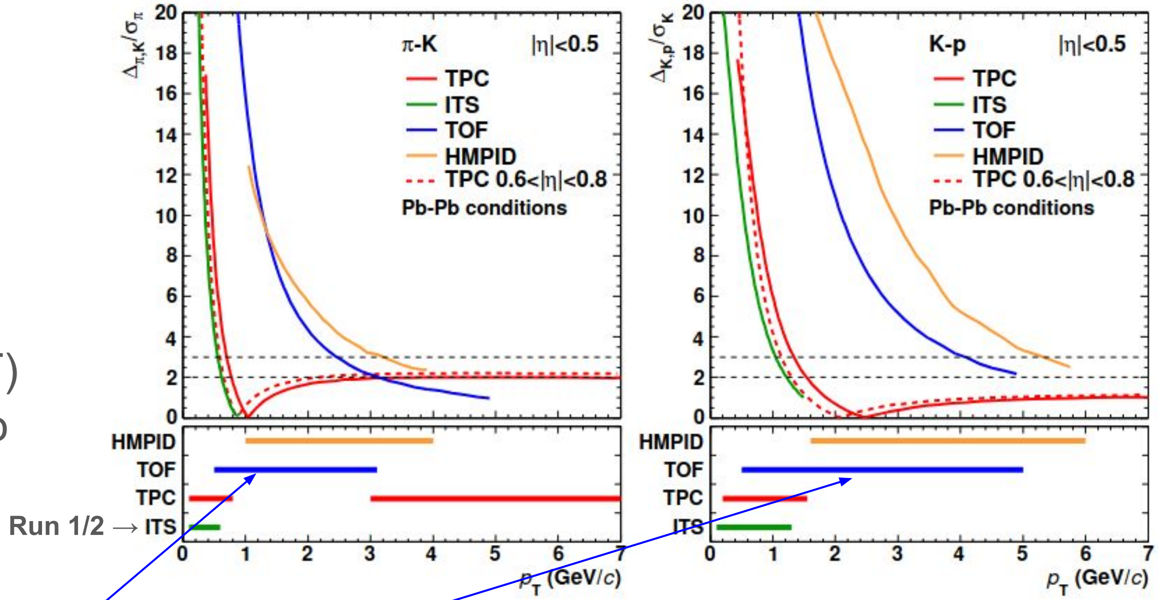
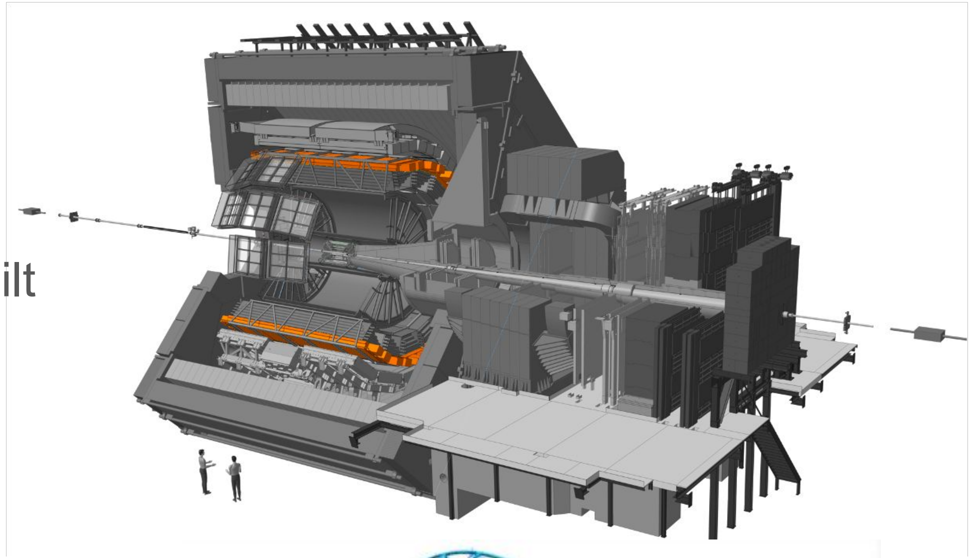


Fig. 46: Separation power of hadron identification in the ITS, TPC, TOF, and HMPID as a function of p_T at midrapidity. The left (right) panel shows the separation of pions and kaons (kaons and protons), expressed as the distance between the peaks divided by the resolution for the pion and the kaon, respectively, averaged over $|\eta| < 0.5$. For the TPC, an additional curve is shown in a narrower η region. The lower panels show the range over which the different ALICE detector systems have a separation power of more than 2σ.

Example from ALICE Performance paper in Run-2 (Int. J. Mod. Phys. A 29 (2014) 1430044)

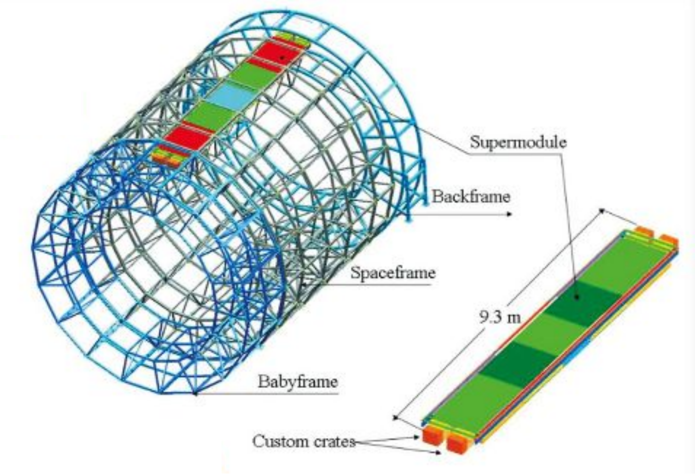
ALICE-TOF group



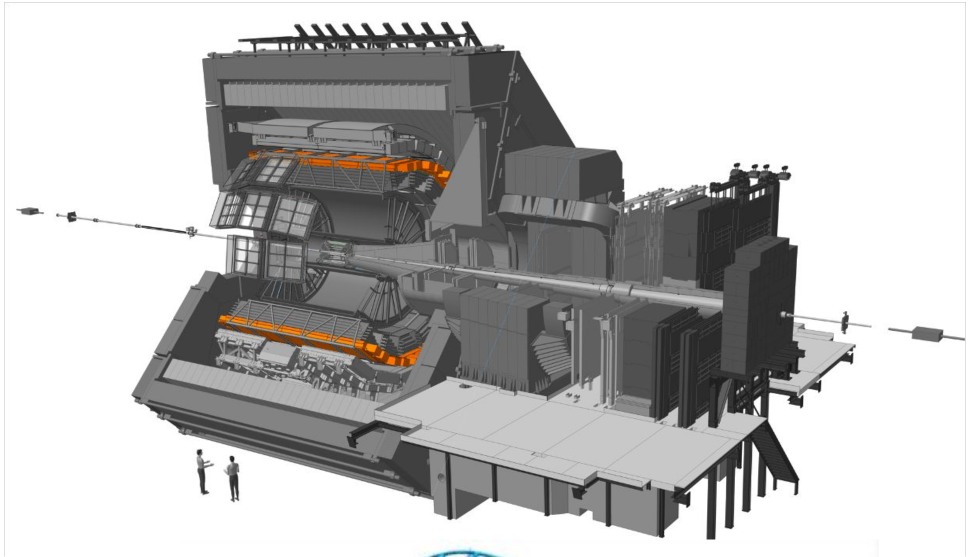
The TOF detector was designed and built by an international collaboration consisting of:

- INFN and University of Bologna,
- INFN and University of Salerno,
- ITEP (Moscow),
- GWNU (South Korea).

Currently, responsibility for TOF is shared by Bologna and Salerno (both INFN and University), after ITEP and GWNU left the collaboration.



ALICE requirement for TOF

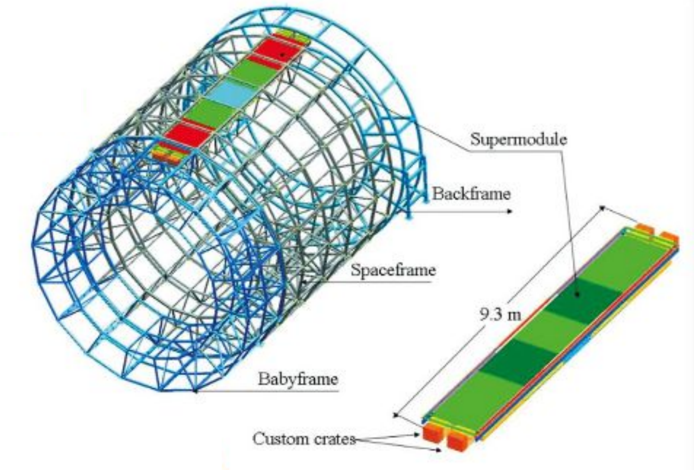


Design requirements

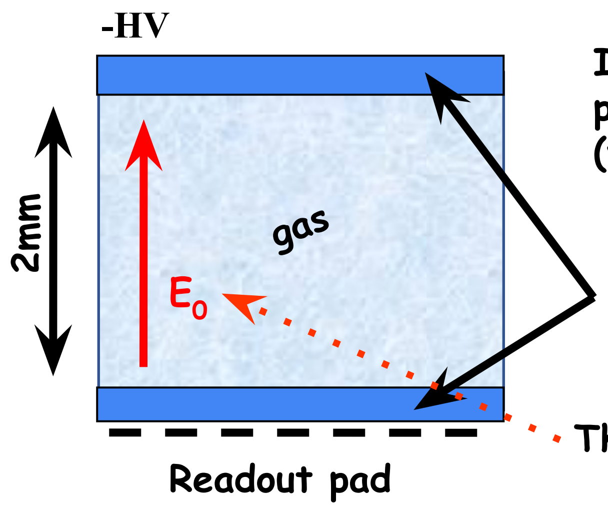
- Large coverage active area (~140 m^2)
- High det. efficiency (> 95%)
- Excellent time resolution (80 ps)
- High granularity (~10^5 channels)

For the technology **we adopted Multi-gap Resistive Plate Chambers (MRPC)** (and innovative technology at that time!) which satisfied all requirements and limited the overall cost.

HOW DOES IT WORK?



MRPC: the idea starting from the RPC
(R. Santonico, R. Cardarelli NIM 187 (1981) 377)



In the simplest configuration the RPC is composed by two parallel resistive plates (electrodes), tipically bakelite (volumic resistivity $\rho = 10^9 - 10^{11}\ \Omega$cm).

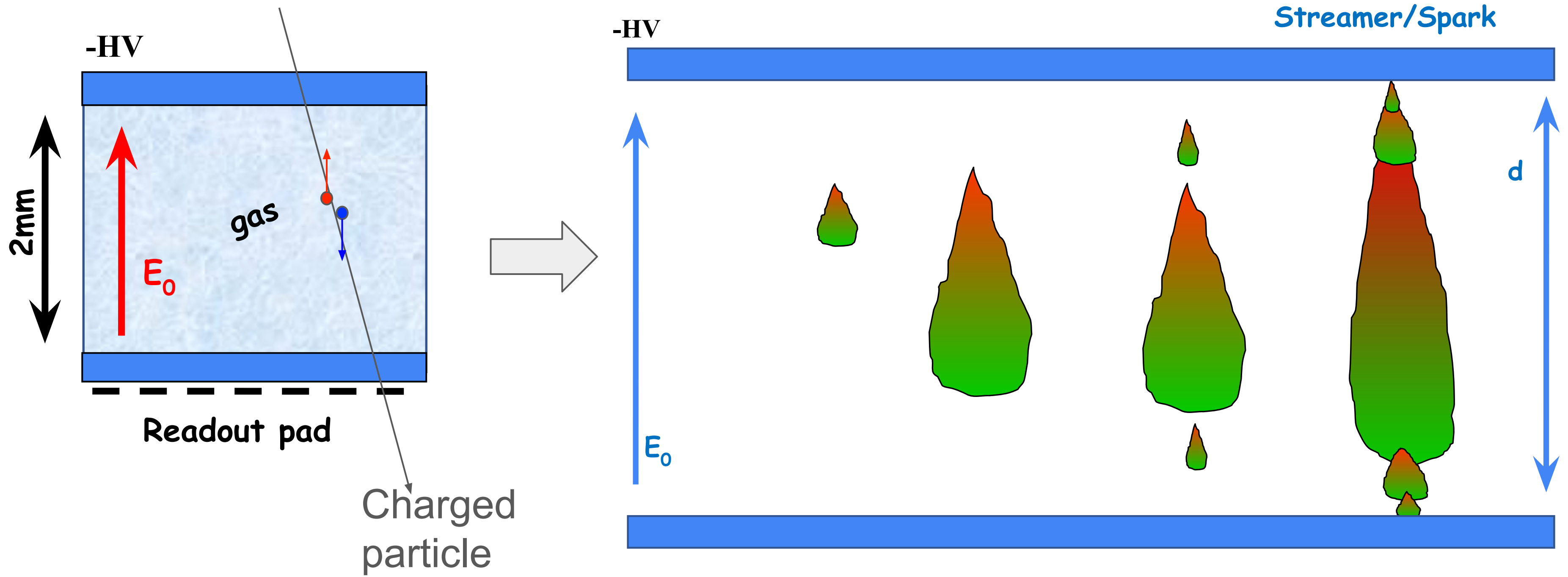
Electrodes: cathode (negative)
anode (positive)

The electric field E is uniform and is ~ 50 kV/cm

Typically, the RPC works in streamer mode with the signals induced on the pickup cells placed externally.

MRPC: the idea starting from the RPC

(R. Santonico, R. Cardarelli NIM 187 (1981) 377)



Charged Particle ➤ Gas ➤ Coulomb interaction (ionization and excitation) ➤ Electron-ion pairs (n_0)

MRPC: the idea starting from the RPC
(R. Santonico, R. Cardarelli NIM 187 (1981) 377)

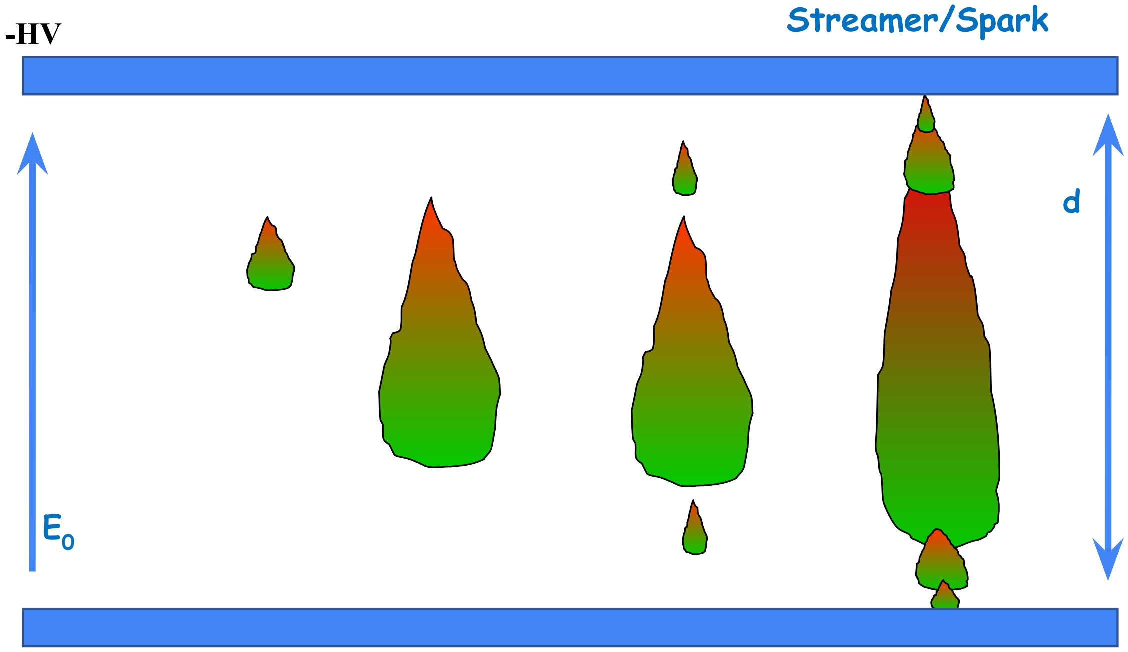
$G = n/n_0 = e^{\alpha d}$

Raether limit: $G = 10^8$

maximum gas gain in an ionization avalanche at which the avalanche transition from proportional amplification to a self-sustaining discharge via streamer formation occurs.

α = Townsend coefficient

[constant in a uniform E]

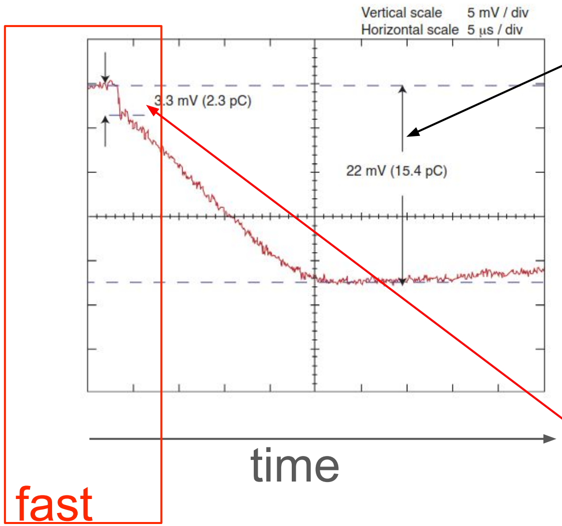


Charged Particle → Gas → Coulomb interaction (ionization and excitation) → Electron-ion pairs (n_0)

How RPC works

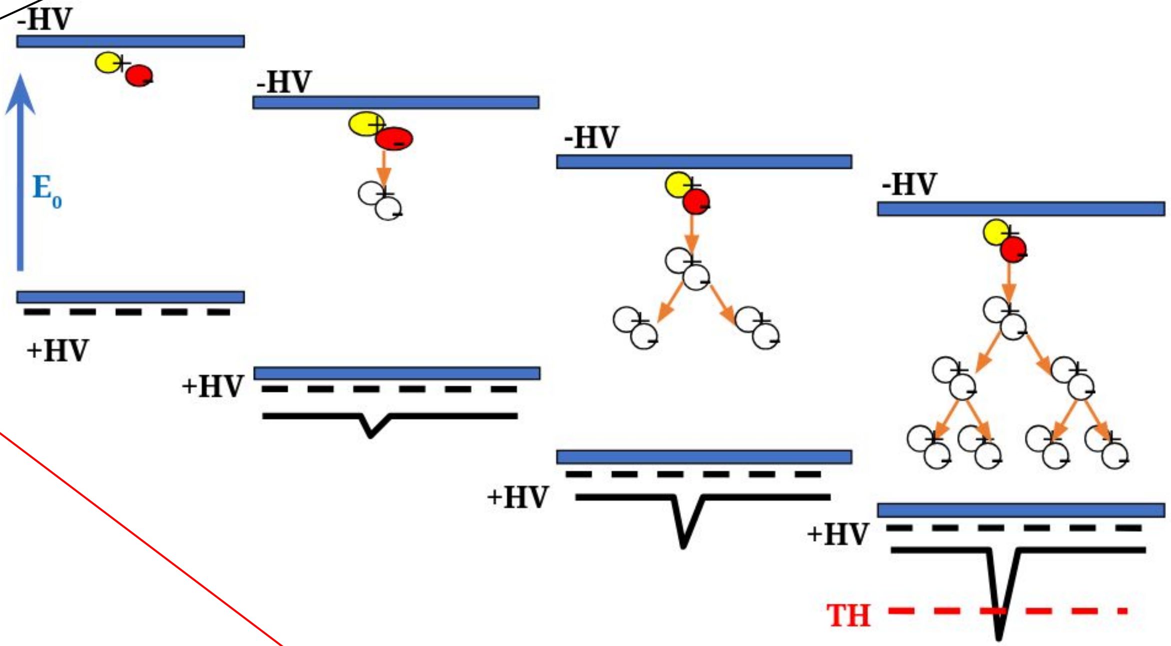
$Q^{TOT} = e\, n_0\, e^{ad}$

$Q^{-} / Q^{TOT} = 1/ad$



2mm RPC

EPJdirect A1, 1–11 (2003)

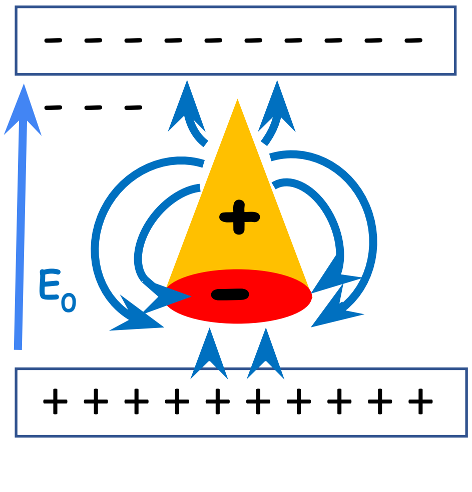


Fast signal = induced signal from the electrons $v_d^- \sim 5 \cdot 10^6$ cm/s (the ions induce a slow signal → v_d^+ two few order of magnitude less)

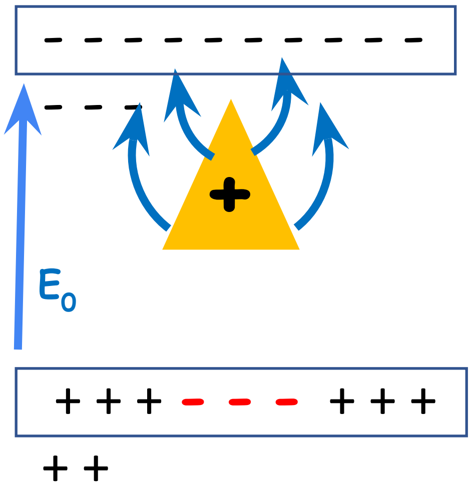
The fast signal pass the threshold after a certain number of steps and this is independent of the position of the avalanche starting point.

$Q^{-} = e\, n_0\, e^{ad} / ad$

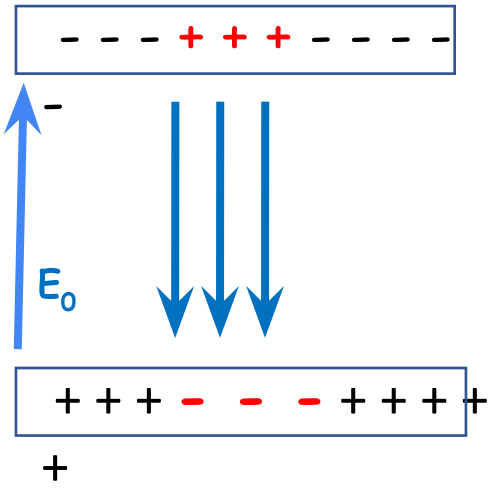
The electric field



After a Δt (of the order of μs) the avalanche is large enough to change the electric field between the electrodes.



The electrons reach the anode and they locally modify the charge on the electrode. The positive ions are much slower and they take longer to reach the cathode.



Locally the electric field is "reversed" and it takes some time to dissipate the charge on the electrodes (RPC: τ~10ms → limiting the rate capability)

From RPC to MRPC

Experimentally good results were obtained by the RPC but with some limitations for our purposes. We needed to:

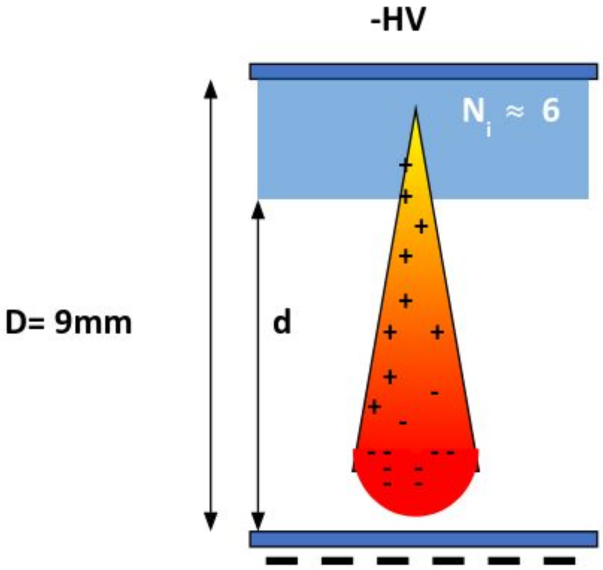
- increase the rate capability limit (from few tens to few hundreds of Hz/cm^2);
- improve the time resolution;
- increase the gain but at the same time to find a way to stop the growth of the avalanche (no streamer mode)
- reduce the current across the gas

The competitive requirements for RPCs do not align with our objectives.

In short, to achieve our goals, we would need to use very small gaps in avalanche mode. However, this would cause a drop in efficiency.

 this led us to the development of the Multigap Resistive Plate Chamber (MRPC)

Example



RPC in avalanche mode: $G = e^{\alpha D} < 10^8 \rightarrow \alpha D < 18$

$Q^- / Q^{TOT} \approx 1/\alpha D \approx 1/18 = 5\%$

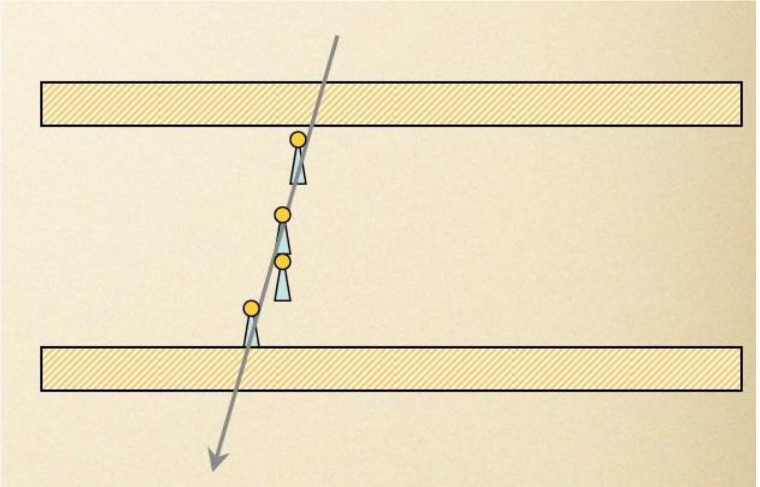
Induced signal $Q_{min}^{fast} \approx 8$ fC

$Q_{min}^{tot} \approx 0.16$ pC ($\approx 10^6$ electrons)

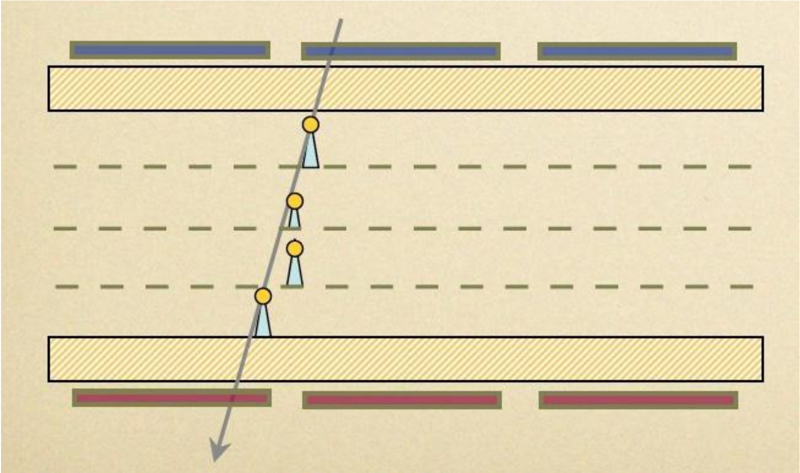
G_{MIN} $10^6 = e^{\alpha d} \rightarrow d \approx 0.75$ D

A measurable signal is produced only if the avalanche starts in the top part (¼) of the gap since we cannot increase the gain enough without streamers

Question: can we increase gas gain such that avalanche produces detectable sign immediately?



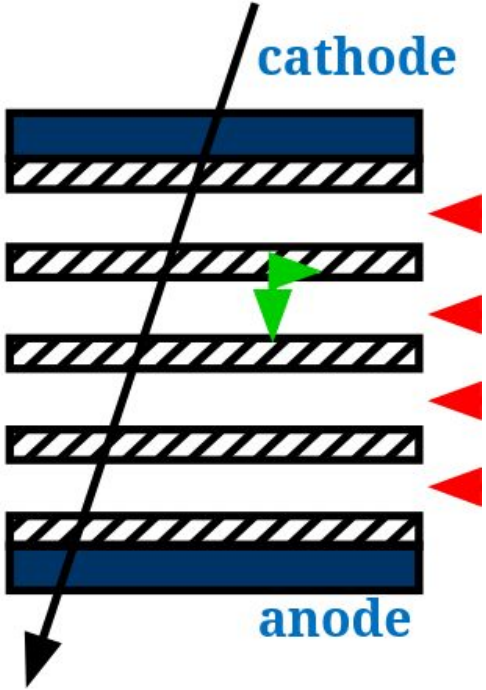
A) Needed very high gas gain (immediate production of signal)
B) Needed way of stopping growth of avalanches (otherwise streamer/sparks will occur)



Answer: add boundaries that stop avalanche development. These boundaries must be invisible to the fast induced signal, induced on external pickup cells.

Multigap Resistive Plate Chamber (MRPC): the idea

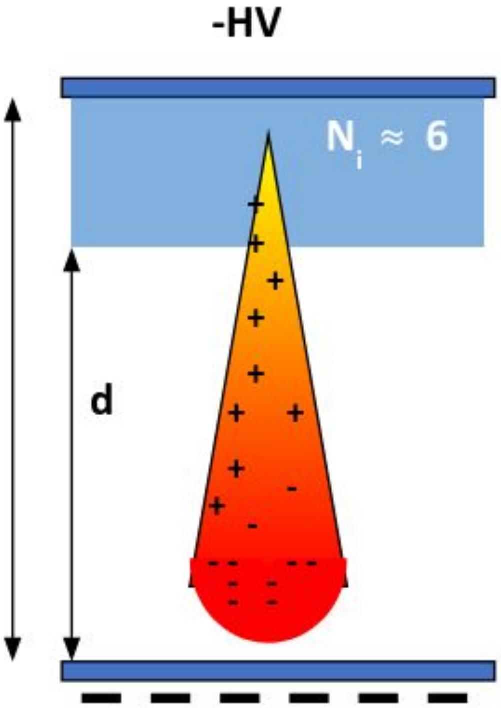
NIM A 374 (1996) 132, A. Zichichi et al.

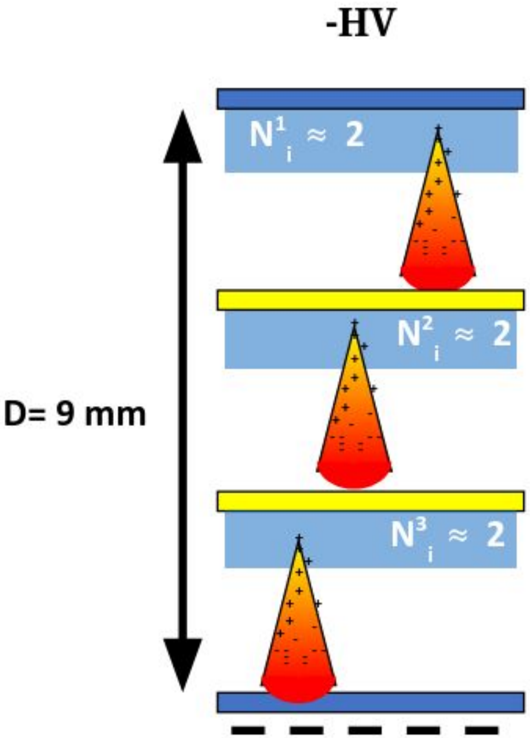


- Stack of equally-spaced resistive plates electrically floating
- Voltage applied to external surfaces
- Pickup electrodes on external surfaces (resistive plates transparent to fast signal)
- Avalanche mode.
- The avalanches in the gas gaps are independent.
- The signal is a “sum” over all the micro-avalanches.

Stability condition: equal gain in all the gas gaps

Improvement of the time resolution

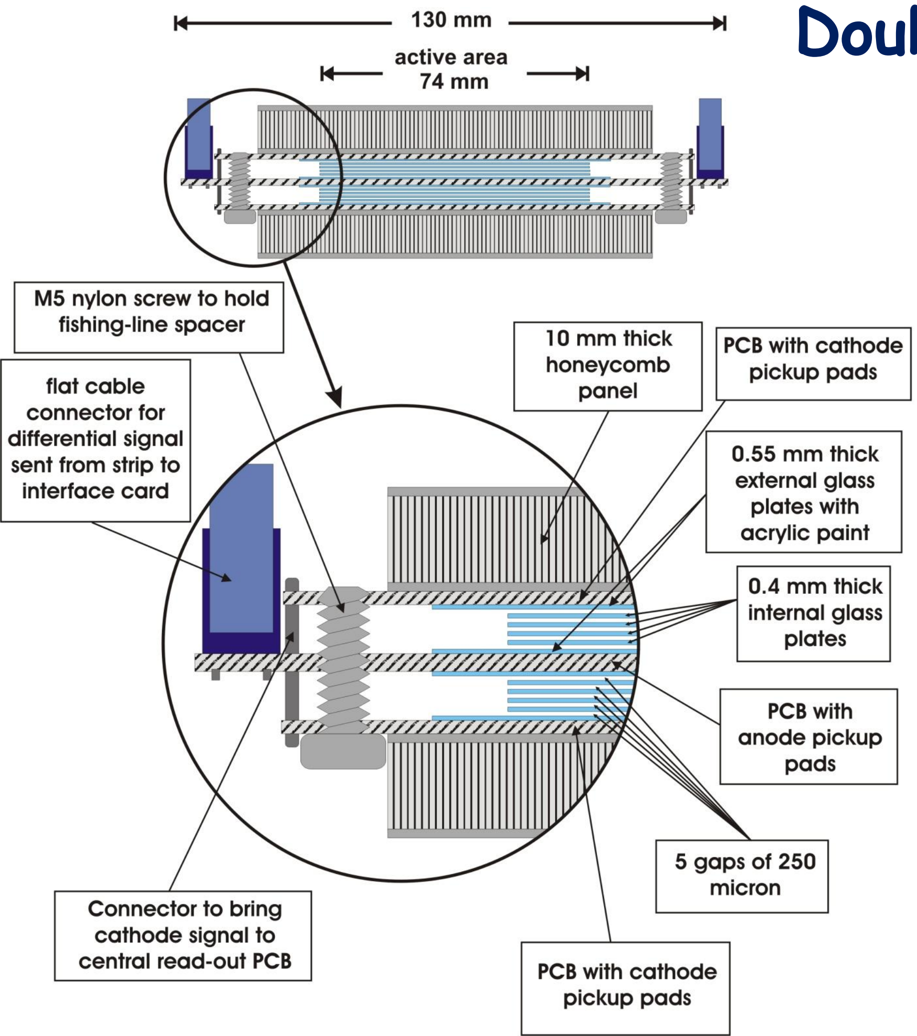




- N_i^{tot} independent clusters
  → high α to have an avalanche in each gas gap
- The total induced signal is the "sum" over the 3 gaps
- Better σ_t because the 3 signals are independent

MRPC in avalanche mode: $G = e^{\alpha D/N gap} < 10^8 \rightarrow \alpha D < 18 \times N$

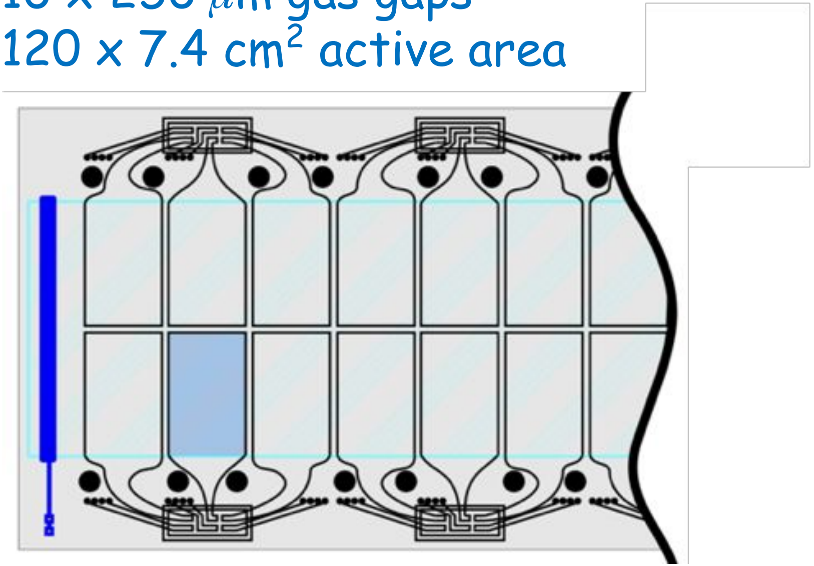
Double stack MRPC: final geometry
CERN-LHCC 2002-016



Two stacks of resistive plates

10 x 250 μm gas gaps

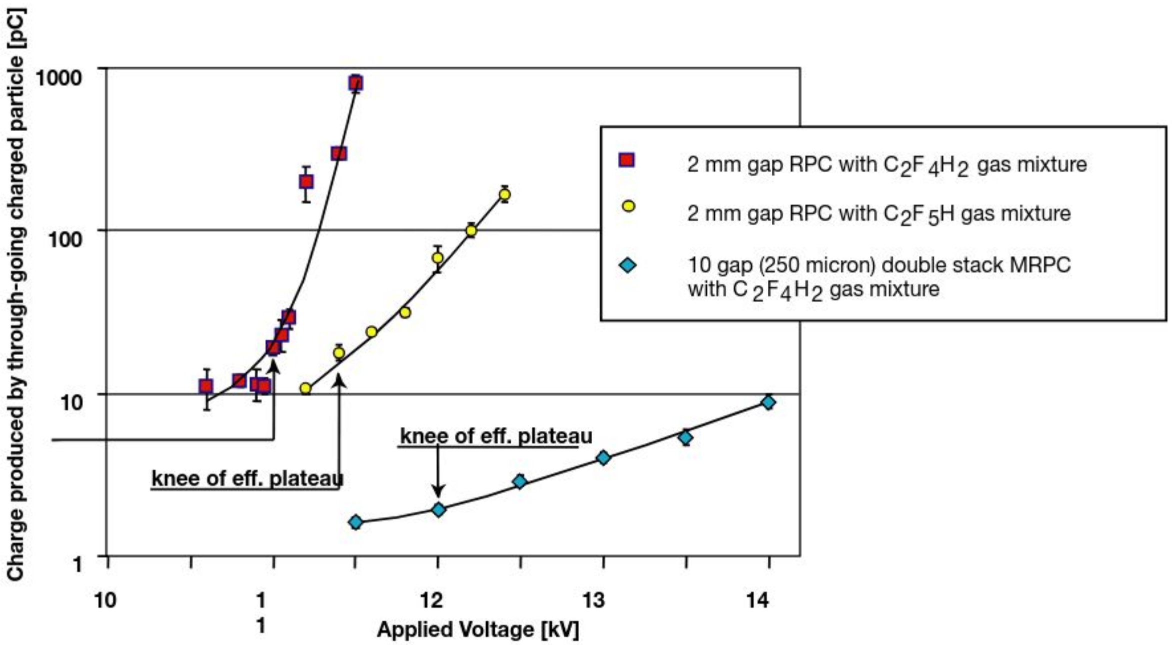
120 x 7.4 cm^2 active area



Highly-segmented readout pads:

96 pickup pads with 3.5 x 2.5 cm^2 area

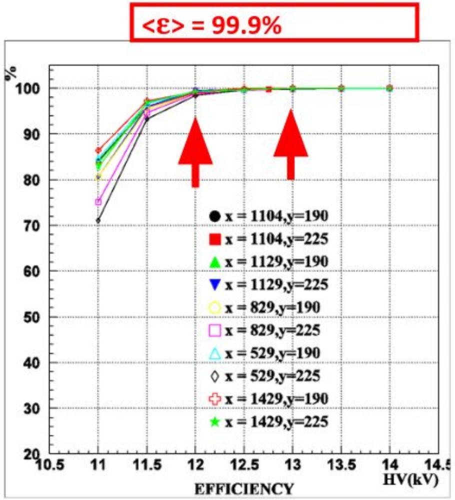
Total charge

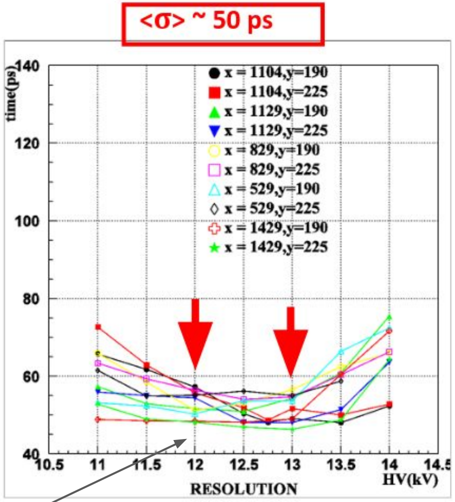


- Average total charge ~ 2 pC
- Slow gain changes with voltage (factor 5 / 2kV)

 Long free-streamer plateau and good rate capability

MRPC at the test beams (I)





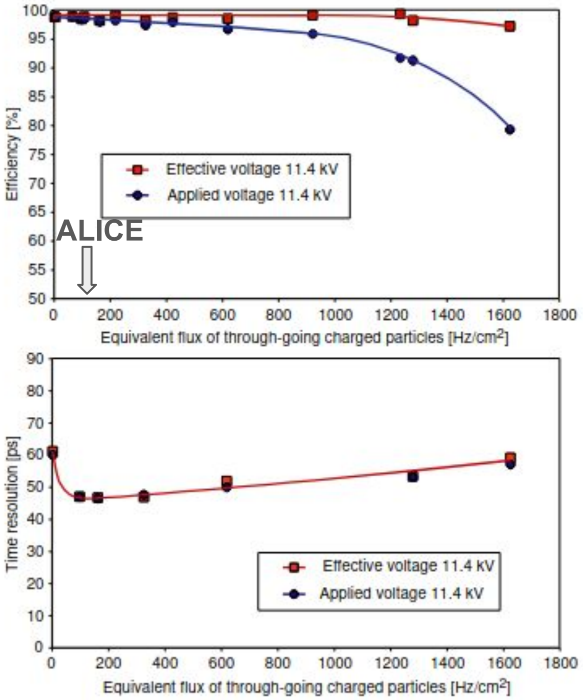
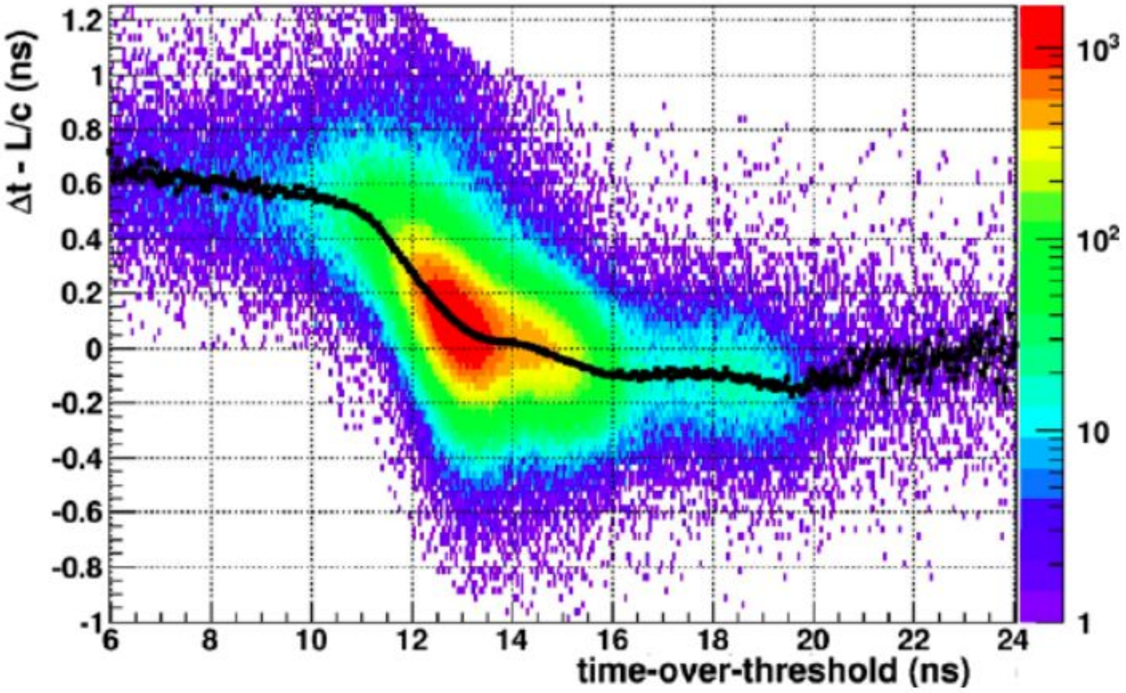


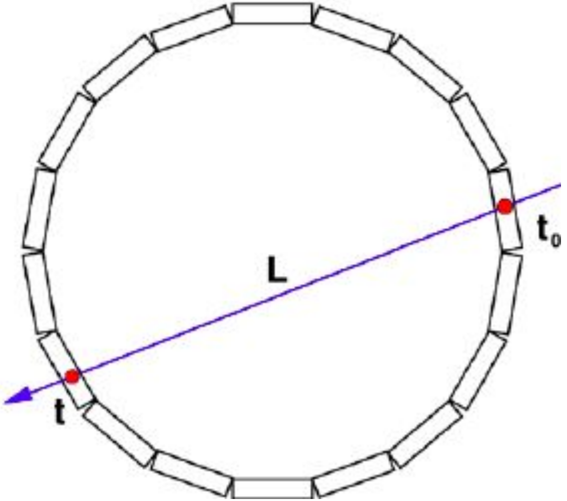
Fig. 6. Efficiency and time resolution versus equivalent flux of charged particles for MRPC tested at the GIF.

With time slewing corrections (next slides)

TOF time corrections

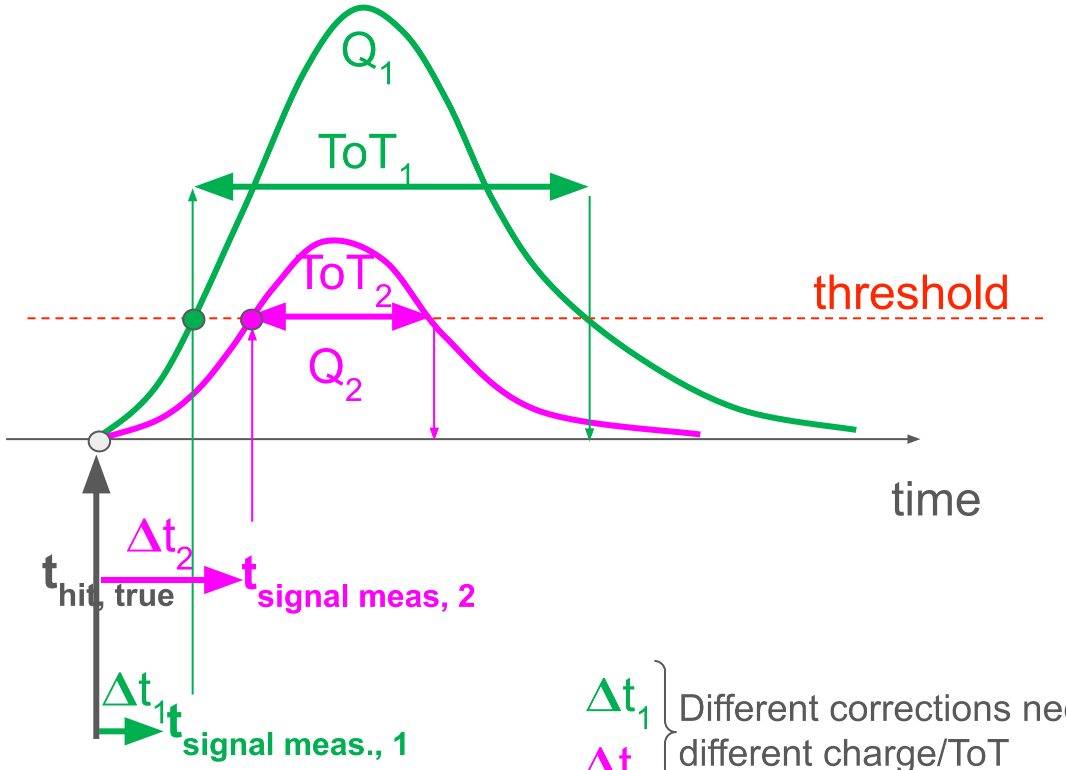


Example with cosmics before of the start of LHC



In order to achieve the best performance we need to correct the hit time for the Time-over-Threshold (proxy for the total charge) since the rising time, $t_{\text{signal over threshold}} - t_{\text{hit}}$' depends on it.

TOF time corrections



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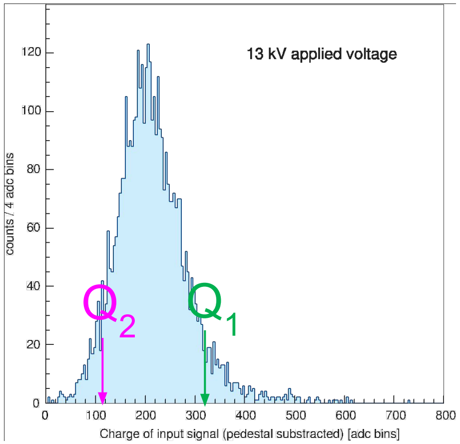


Δt_1, Δt_2: Different corrections needed for different charge/ToT

For larger ToT signal rises faster

Contribution to the total TOF time resolution

$$\sigma^2_{TOF} = \sigma^2_{MRPC} + \sigma^2_{T0} + \sigma^2_{CLK} + \sigma^2_{CLK-TRM} + \sigma^2_{CAL}$$

- σ^2_{MRPC}: MRPC + ELEC. (50 ps)
- σ^2_{T0}: In Pb-Pb with combinational algorithm (5 ps) or T0/FT0
- σ^2_{CLK}: Clock from LHC to TOF crates (15 ps)
- $\sigma^2_{CLK-TRM}$: (10 ps)
- σ^2_{CAL}: TOF calibration uncertainties + Time Walk (30 ps)

Contribution to the total TOF time resolution

$$\sigma^2_{TOF} = \sigma^2_{MRPC} + \sigma^2_{T0} + \sigma^2_{CLK} + \sigma^2_{CLK-TRM} + \sigma^2_{CAL}$$

MRPC + ELEC. (50 ps)

In Pb-Pb with combinational algorithm (5 ps) or T0/FT0

Clock from LHC to TOF crates (15 ps)

(10 ps)

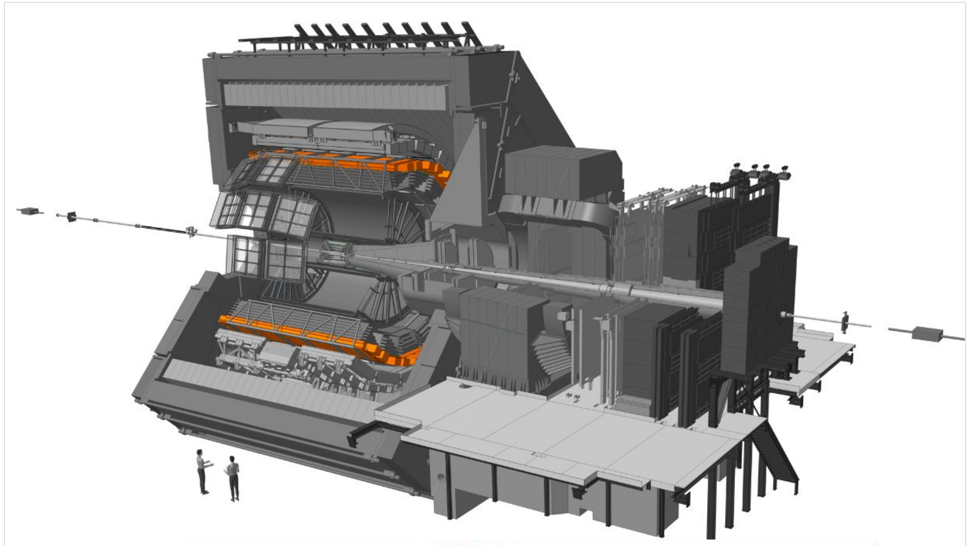
TOF calibration uncertainties + Time Walk (30 ps)

One caveat

$\sigma_{TOF} \neq \sigma_{TOF-PID}$

Effect of reco have to be accounted for

ALICE requirement for TOF

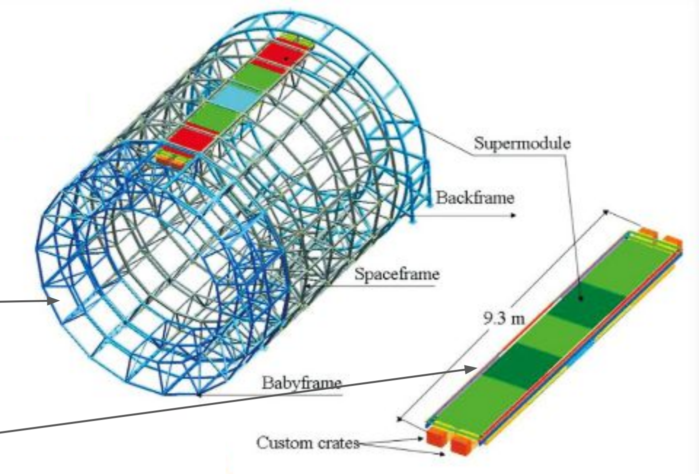


Design requirements

- Large coverage (~140 m^2)
- High det. efficiency (> 95%)
- Excellent time resolution (80 ps)
- High granularity, ~1600 MRPC (x96 pads) →~157k readout channels

TOF geometry

- Internal radius ~3.8 m
- $|\eta| < 0.9$
- Full azimuthal coverage (but a hole in front of PHOS detector)
- 18 sectors in ϕ accordingly to ALICE segmentation in the central barrel → one Supermodule per sector
- 5 Modules per Supermodule



Time Of Flight

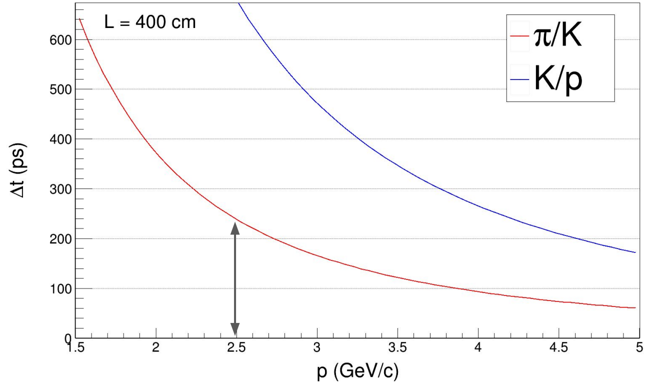
Time of flight technique is based on the simultaneous measurement of momentum (tracking) and speed (TOF detector)

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

m=mass, p=momentum, t=time-of-flight, l=track length

Separation of two mass hypotheses is given by

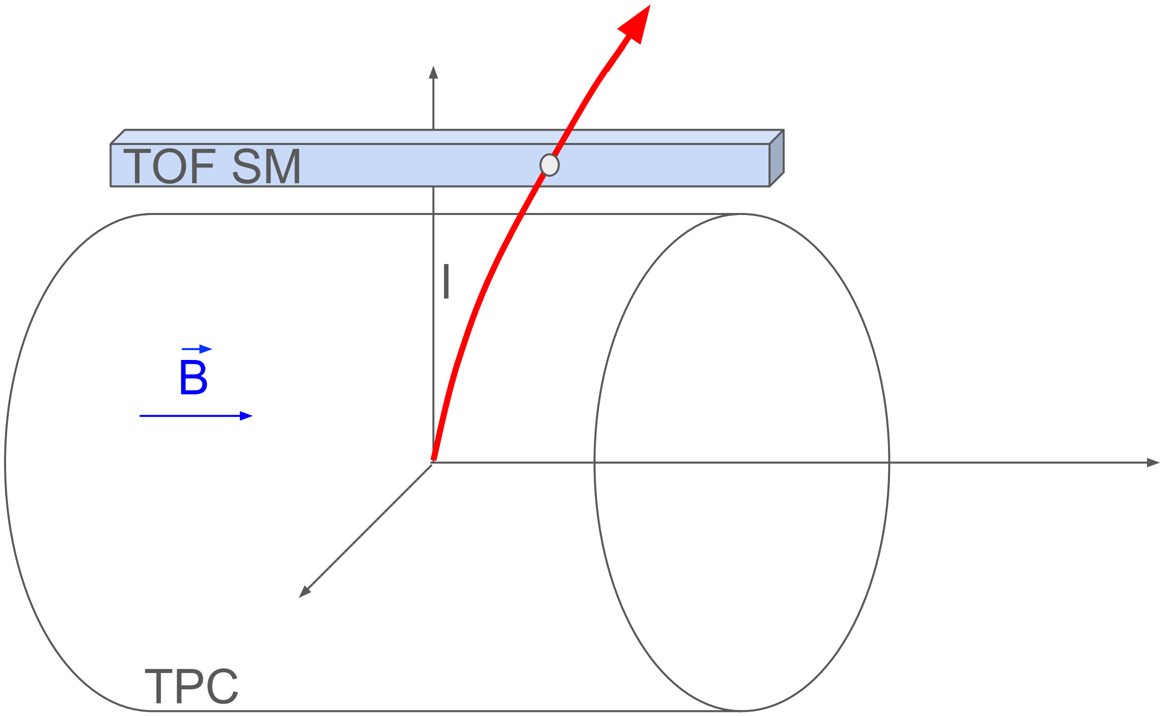
$$\Delta t = \frac{l}{c}\left(\sqrt{1 + \frac{m_1^2c^2}{p^2}} - \sqrt{1 + \frac{m_2^2c^2}{p^2}}\right) \sim (m_1^2 - m_2^2)\,\frac{lc}{2p^2}$$



As soon as such a difference is larger than (2-3 times the) detector time resolution two species can be separated

With a 4 m track length to get a 3 sigma π/K separation at p = 2.5 GeV/c we need 80 ps TOF overall resolution

Matching tracks at TOF

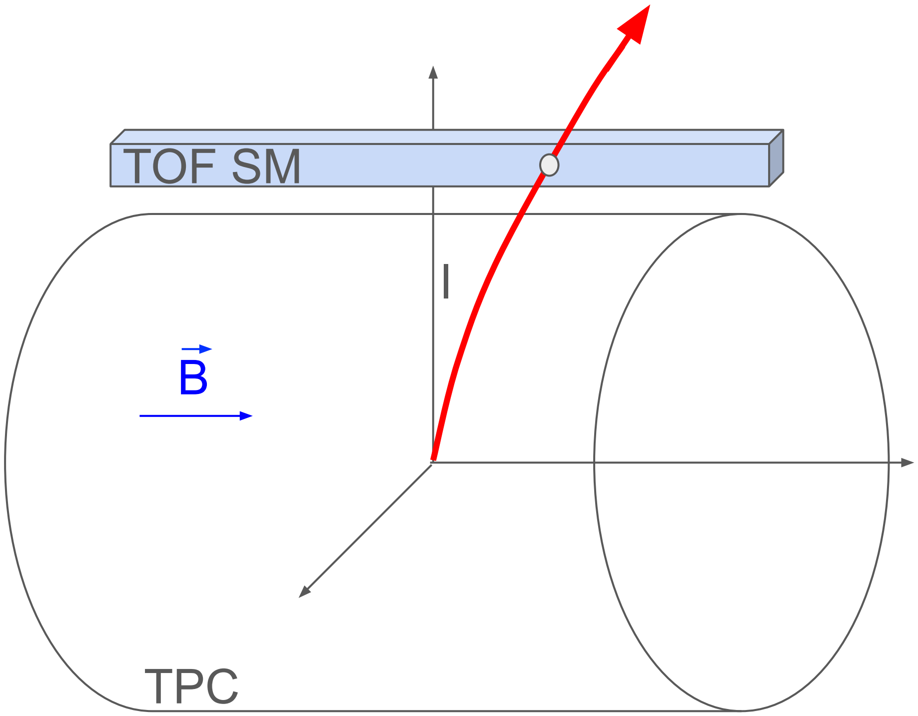


At reconstruction level charged tracks are defined based on the information of tracking detector: ITS, TPC, (TRD) and then they are extrapolated and matched to a TOF signal (if present).

The relevant quantities at this stage are:

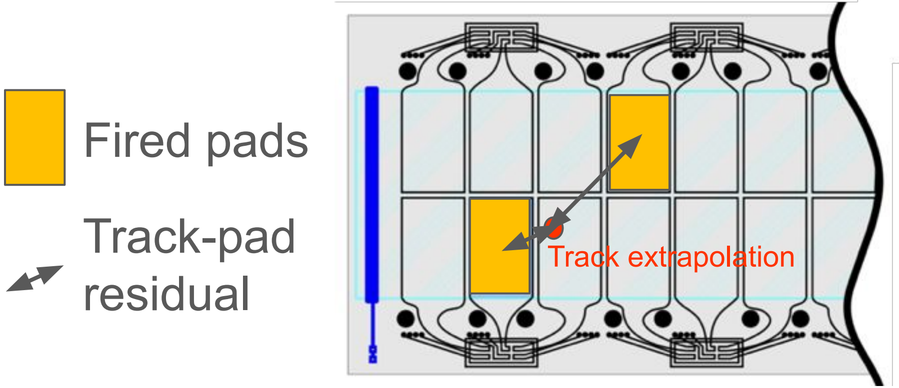
- Spatial residuals between track and TOF pad position
- Track length (l) and expected travel times

Matching tracks at TOF



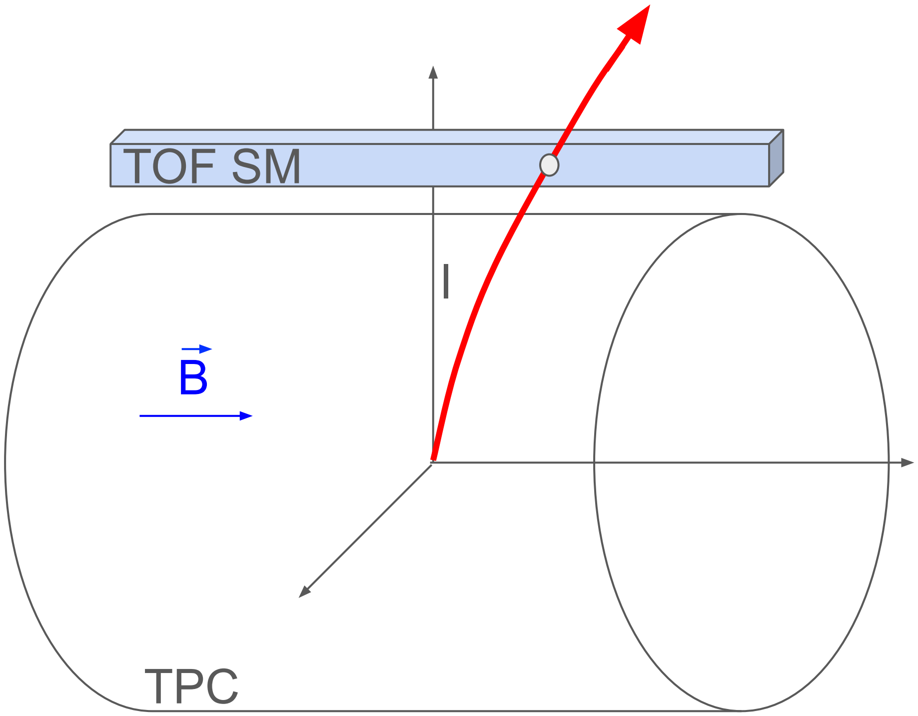
The relevant quantities at this stage are:

- **Spatial residuals between track and TOF pad position**
- Track length (l) and expected travel times



In case of multiple matching-pad candidates a minimization on residuals is applied to select the better association

Matching tracks at TOF



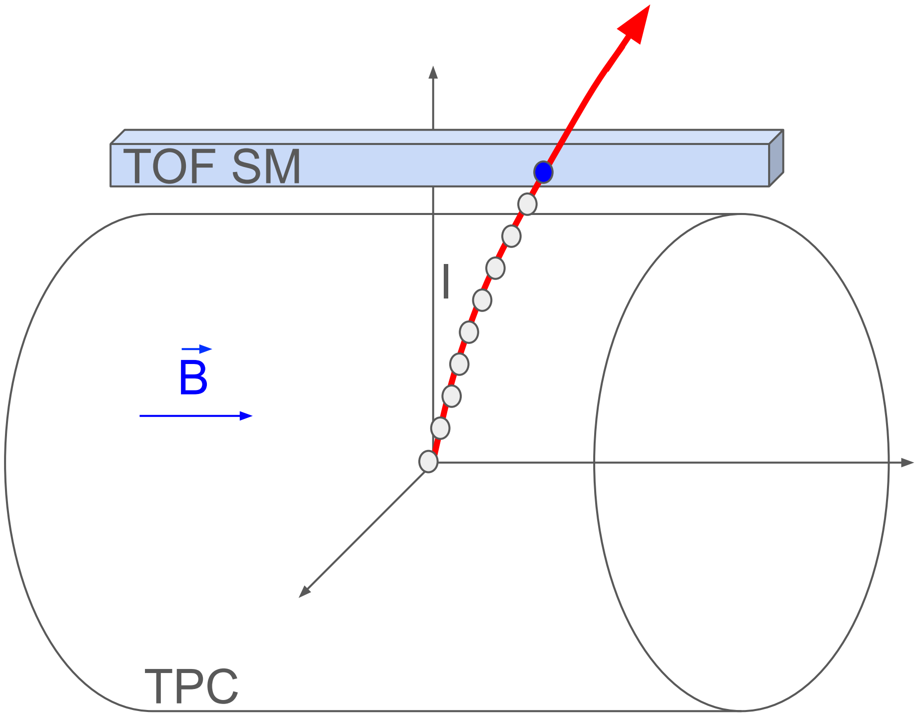
The relevant quantities at this stage are:

- Spatial residuals between track and TOF pad position
- **Track length (l) and expected travel times**

Both momentum and track length are fundamental to reconstruct the mass → we need them with high precision!

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

Matching tracks at TOF



The relevant quantities at this stage are:

- Spatial residuals between track and TOF pad position
- **Track length (l) and expected travel times**

Actually we do something more refined. During track propagation we calculate the travel time for each mass hypothesis taking into account also the energy loss along the path and recomputing momentum at each step *i*

$$t_{exp}^{m} = \sum_{i=0}^{N_{step}} \sqrt{\frac{m^2c^2+p_i^2}{p_i^2c^2}}\Delta l$$

Matching tracks at TOF

Therefore, the variable we use to perform PID with TOF is:

$$\Delta_\pi = t_{TOF} - t_{exp}^{m_\pi} = t_{TOF} - t_{exp}^{\pi}$$

or an analogues variable derived from it (it can be defined for any particle hypothesis: π,K,p,e, μ, light nuclei).

For instance, if we know the resolution for $\Delta t_\pi \rightarrow \sigma_{\text{TOF-PID}}$, we can define:

$$N\sigma_\pi = \frac{t_{TOF} - t_{exp}^{\pi}}{\sigma_{TOF-PID}} = \frac{t_{TOF} - t_{exp}^{\pi}}{\sigma_{TOF}^{\pi}}$$

For the particle under study it is expected to have a Gaussian distribution:

- Centered at zero, Mean=0
- Width = 1

Matching tracks at TOF

Brief recap

If TOF (particle independent) resolution is given by

$$\sigma^2_{TOF} = \sigma^2_{MRPC} + \sigma^2_{T0} + \sigma^2_{CLK} + \sigma^2_{CLK-TRM} + \sigma^2_{CAL}$$

The effective resolution when performing PID has to include also the uncertainties related to t_{exp}, which are particle and momentum dependent.

$$(\sigma^{\pi}_{TOF})^2 = \sigma^2_{TOF} + (\sigma^{\pi}_{exp.\ times})^2$$

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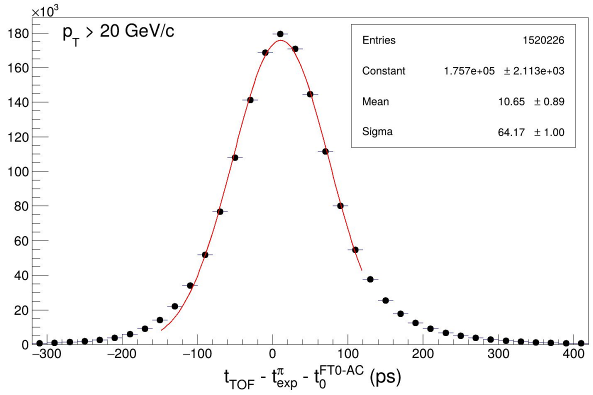
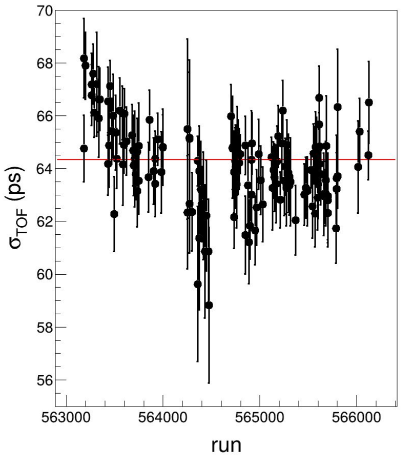


Example from 2025 pp (apass1)

- **σ_{TOF} ~ 65 ps (including T0)**



Matching tracks at TOF

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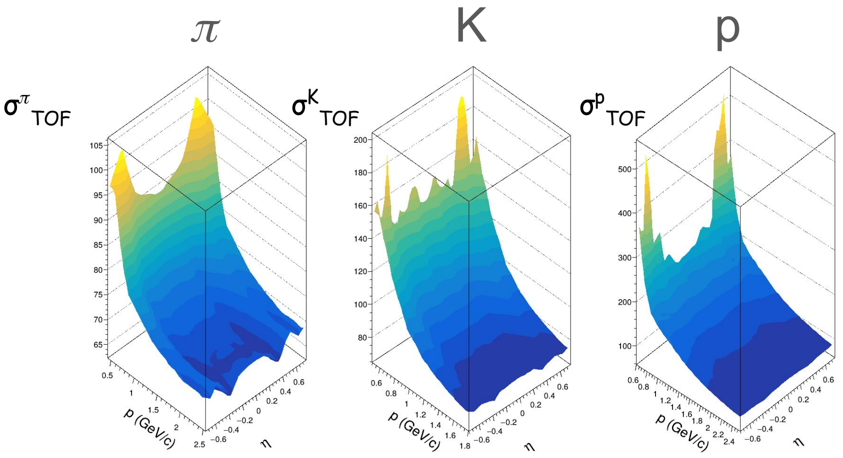
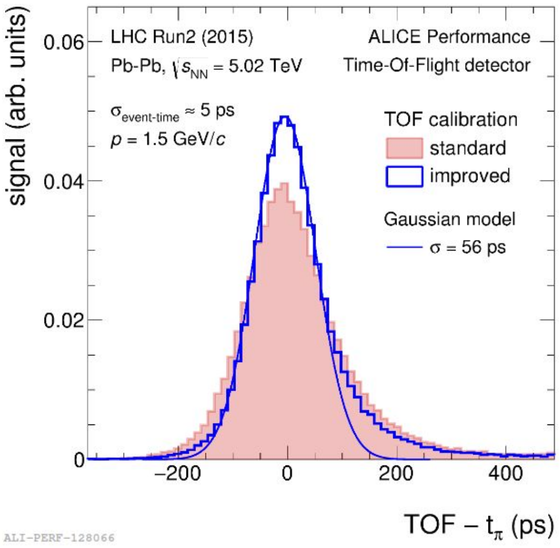


Example from 2025 pp (apass1)

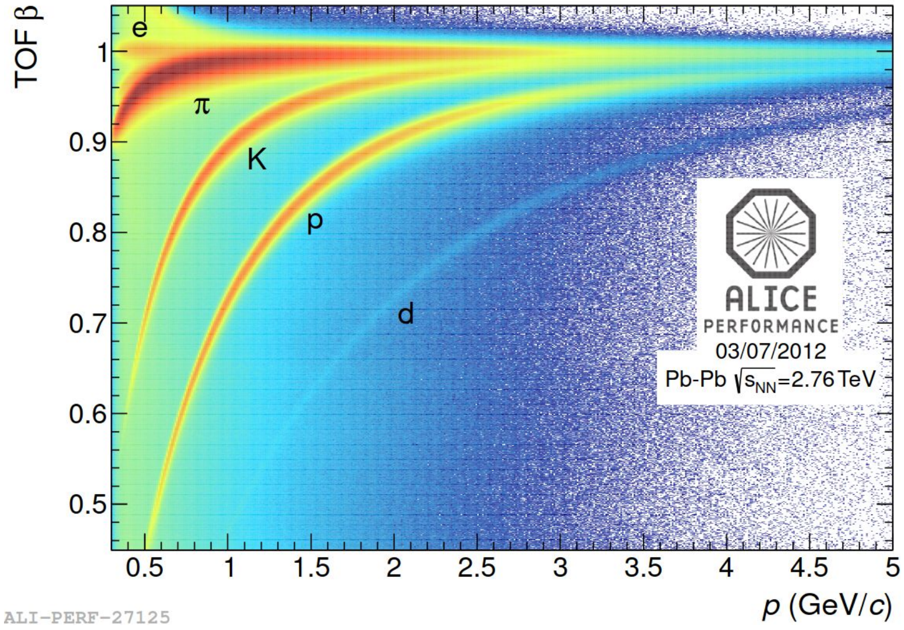
- σ_{TOF} ~ 65 ps (including T0)
- **$\sigma_{exp.\ times}$ higher at low momenta and vanishing at high momenta**
- **$\sigma_{exp.\ times}$ higher for heavier particle**

Few highlights of TOF perf. and physics

TOF performance achieved in Run 2



In Run 2 we saw the best TOF resolution of 56 ps (Gaussian model) in Pb-Pb collisions when T0 contribution is negligible



An excellent separation power was reached for hadrons (but also light nuclei, e.g. d) allowing a reach physics program with TOF

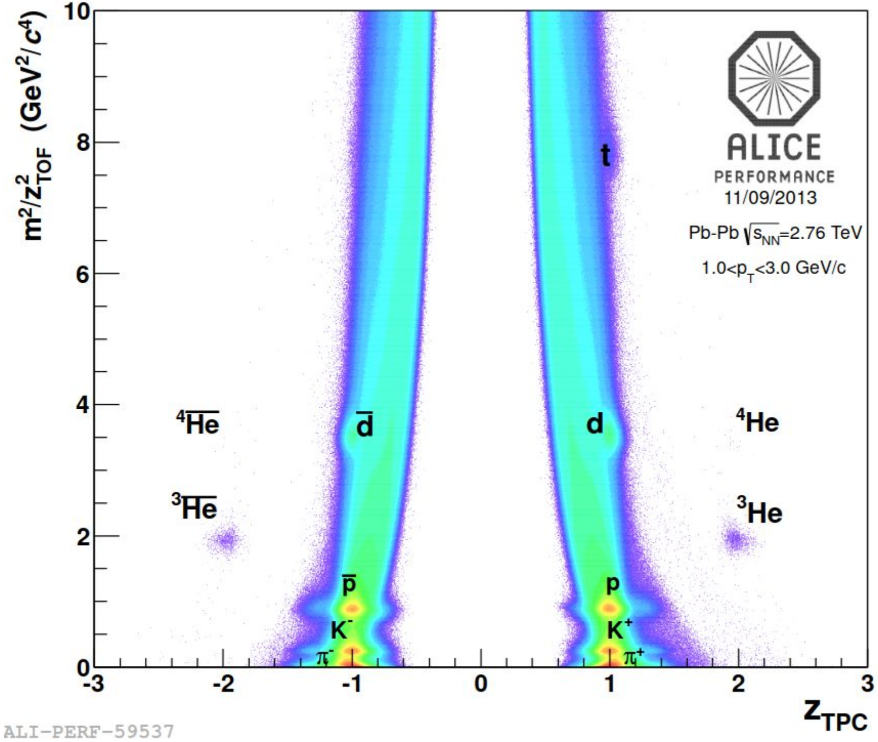
Combining multiple-PID info

More advance PID technique were used to profit from PID infos provide by more than one detector (e.g. TPC+TOF).

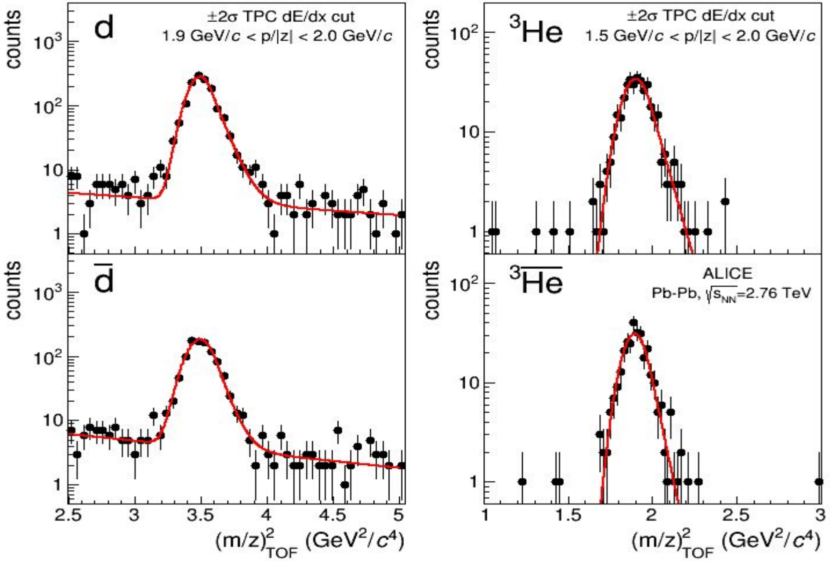
More info in the next lecture

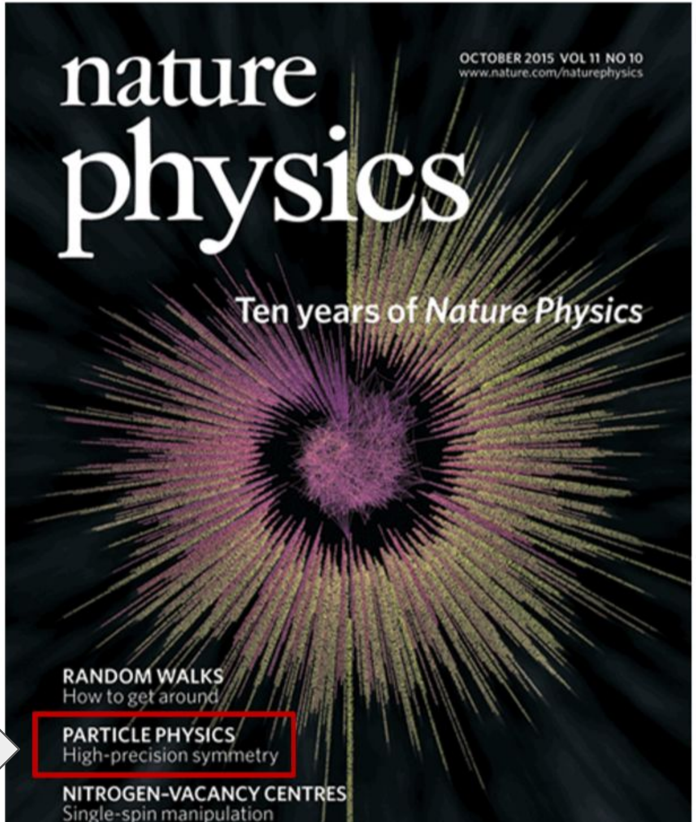
$$\mu_{TOF}^2 = \left(\frac{m}{z}\right)_{TOF}^2 = \left(\frac{p}{z}\right)^2 \left[\left(\frac{t_{TOF}}{L}\right)^2 - \frac{1}{c^2}\right]$$

$$z_{TPC}^2 = \frac{(dE/dx)_{TPC}}{(dE/dx)_{\text{expected for } m_{TOF},\ z=1}}$$



Precision measurements



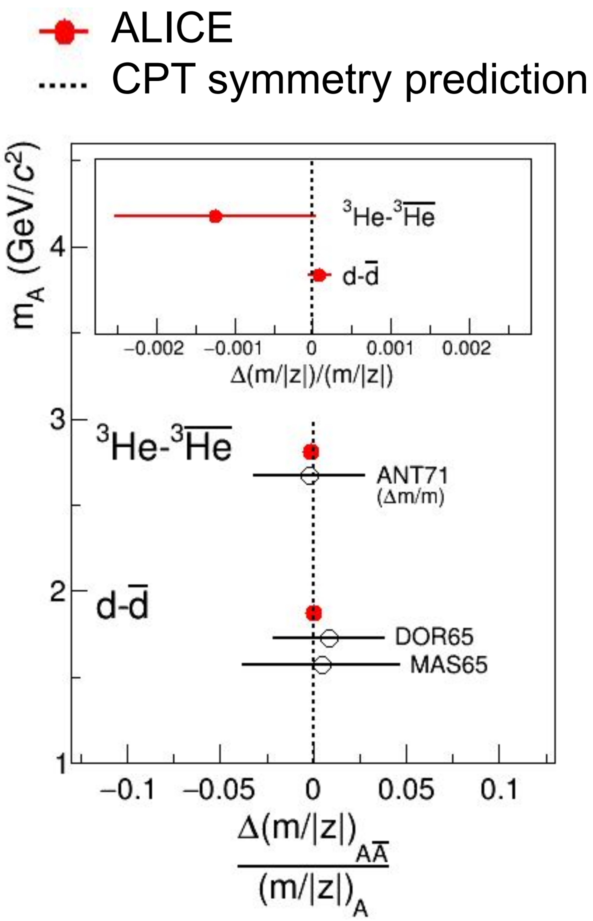


Stability of detector was also very good and we got a very high control of detector effects → pushing the performance at the limit and performing high precision measurement.

Results published in Nature Phys. 11 (2015) 811

http://www.nature.com/nphys/journal/v11/n10/full/nphys3432.html

Result: mass differences



Deuteron-Antideuteron case

$$\frac{\Delta\mu}{\mu} = [0.9 \pm 0.5\ (\text{stat.}) \pm 1.4\ (\text{syst.})] \times 10^{-4}$$

Highest precision direct measurements of mass difference in the sector of nuclei

Improvement by one to two orders of magnitude compared to previous measurements obtained more than 40 years ago

Thanks for your attention!!!