# PID options with RPCs

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# Precision timing

- **always been a prominent topic in HEP instrumentation**
  - trigger applications
  - time-of-flight particle identification
- **resistive plate chambers**
  - widely used for large-area applications (in place of scintillators)
  - MRPC achieved < 50 ps time resolution
- **silicon sensors**
  - recently very popular for timing in HEP
  - HL-LHC for pile-up rejection
  - rapid progress for consumer applications (imaging, LIDAR, 3D scanners)

# Precision timing

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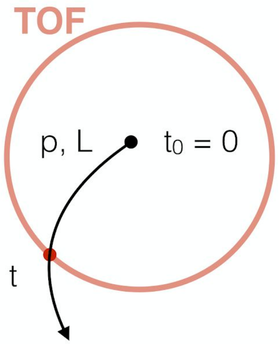
    - ~~rapid progress for consumer applications (imaging, LIDAR, 3D scanners)~~

**but today we are talking about gaseous detectors**

no space for discussion of silicon sensors

# Particle identification

with a TOF detector that measures the time-of-flight



of a particle with momentum p
flying over a trajectory length L

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

$$\begin{aligned}
\left(\frac{\delta m}{m}\right)_p &= \frac{\delta p}{p} \\
\left(\frac{\delta m}{m}\right)_L &= \gamma^2\frac{\delta L}{L} \\
\left(\frac{\delta m}{m}\right)_t &= \boxed{\gamma^2\frac{\delta t}{t}}
\end{aligned}$$

mass resolution

**worsens with $p^2$**

same δm at twice p requires 4-fold better δt
(or 4-fold longer L)

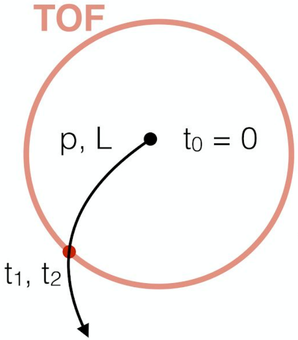
time-of-flight is a viable technique
at **low/intermediate p**

10% resolution on mass for a 5 GeV/c proton ($\gamma^2 = 40$)
requires 0.25% resolution on time-of-flight
assuming L = 5 m, t = 16.97 ns ⇒ t ~40 ps

# Particle identification

capability of a TOF detector is better quantified

by the time-of-flight difference of two particles with unequal mass $m_1$ and $m_2$
flying with the same momentum p over the same trajectory length L (assuming $\beta\gamma > 1$)



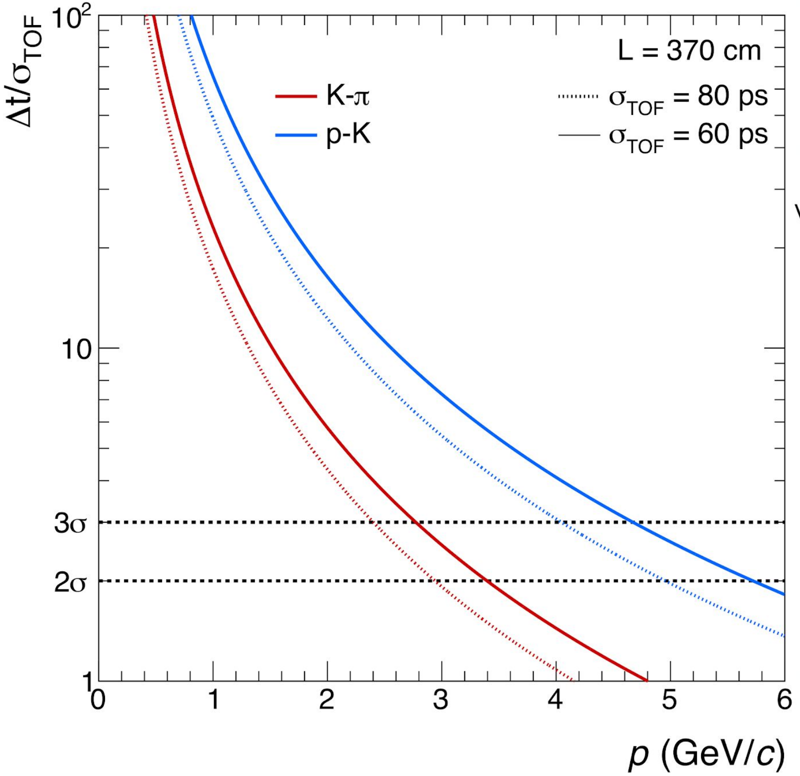
$$t_1 - t_2 = \frac{L}{2c}\left(\frac{m_1^2c^2 - m_2^2c^2}{p^2}\right)$$

with the separation power defined as

$$n_\sigma = \frac{t_1 - t_2}{\delta t}$$

a 5 GeV/c proton reaches the TOF detector which measures
a time-of-flight of t = 16.97 ns over a trajectory of L = 5 m
to be able to tell that this is not a kaon with better than 99% CL (3σ)
the time-of-flight resolution must be better than δt = 70 ps

# Particle identification



$$\Delta t = \quad t_1 - t_2 = \frac{L}{2c}\left(\frac{m_1^2c^2 - m_2^2c^2}{p^2}\right)$$

for a **L = 370 cm** long track

valid for $|\eta| = 0$ straight (high $p_T$ tracks)

**K/π (p/K)** separation

better than 3σ up to about

2.5 (4.0) GeV/c

**3.0 (5.0)** GeV/c

better than 2σ up to about

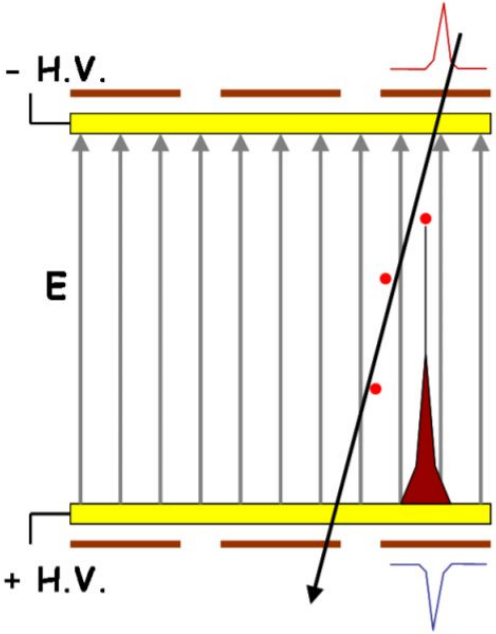
3.0 (5.0) GeV/c

**3.5 (6.0)** GeV/c

# Parallel chambers

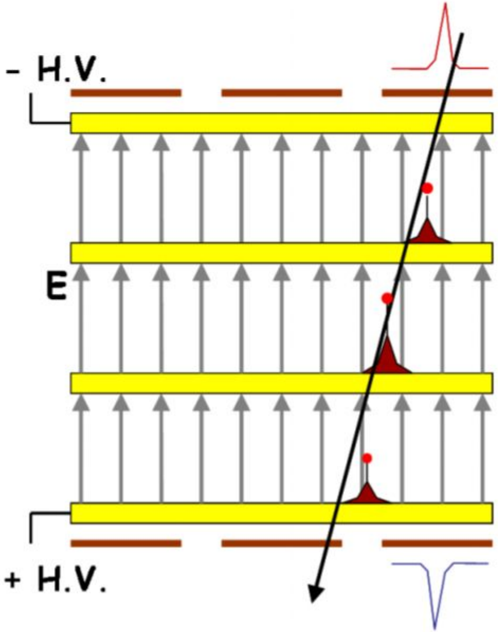
- **Parallel Plate Chamber**
  - one of the first parallel chambers, realised around 1950
  - needed external circuit to quench the discharge → limited rate capability
- **Resistive Plate Chamber**
  - invented in 1980 by Santonico & Cardarelli
  - replaces conductive plates with resistive plates → self-quench, localised V drop
  - 2 mm gas-gap, good time resolution ~ 1 ns
- **Pestov Counter**
  - 100 µm gas-gap, excellent time resolution ~ 50 ps
  - non-commercial glass, high-pressure operation ~ 12 atm
- **Multigap Resistive Plate Chamber**
  - invented in 1996 by Williams within the LAA Project
  - instead of one small gap at high pressure, many gaps at 1 atm

# From the RPC to the MRPC



- **electron avalanche**
  - grows according to Townsend law, $N = N_0 e^{\alpha x}$
  - detectable signals produced by avalanches that cross full gas-gap
  - only ionisation clusters produced close to cathode are important for signal generation
  - only few clusters take part in signal production
- **time jitter**
  - is due to how avalanche develops initially
  - $\sigma_t = 1.28 / (\alpha - \eta)\, v$ *Riegler et al., NIM A 500 (2003) 144*
- **reduce jitter by**
  - increasing Townsend coefficient
  - increasing electron drift velocity
  - have simultaneous signals from many avalanches
- **basically increase the E field**

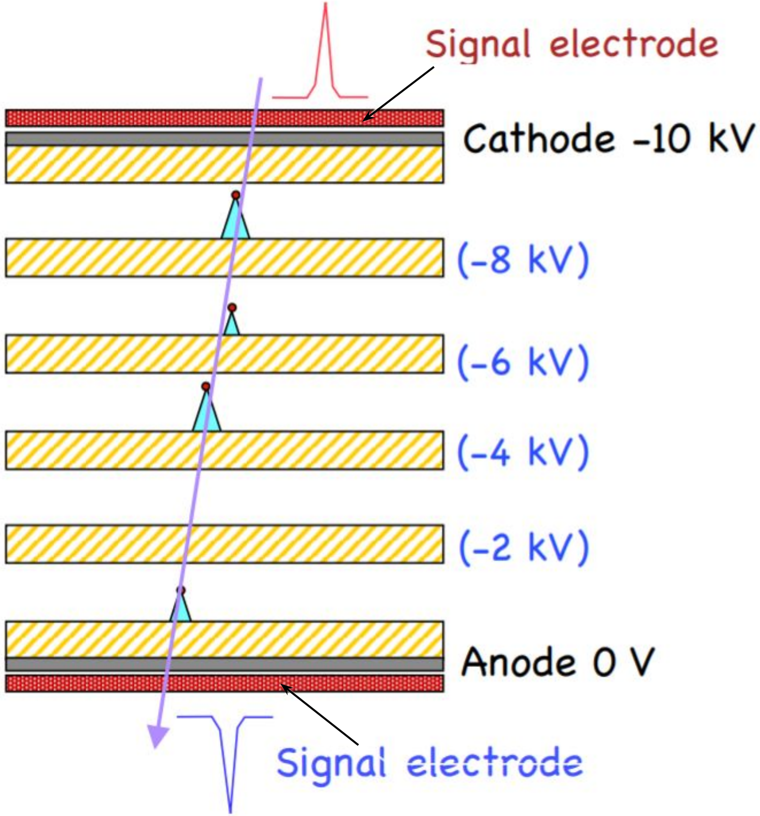
# From the RPC to the MRPC



- **increase gas gain**
  - such that avalanche produces detectable signal immediately
  - this needs an extraordinarily high gas gain
  - we will have streamers, sparks, …
- **need a way to stop avalanche growth**
  - add barriers within the gas gap to stop avalanche development
  - must be invisible to the fast induced signal
  - use resistive plates
- **the Multigap RPC was born**

*Cerron Zeballos et al., NIM A 374 (1996) 132*

# Multigap Resistive Plate Chamber



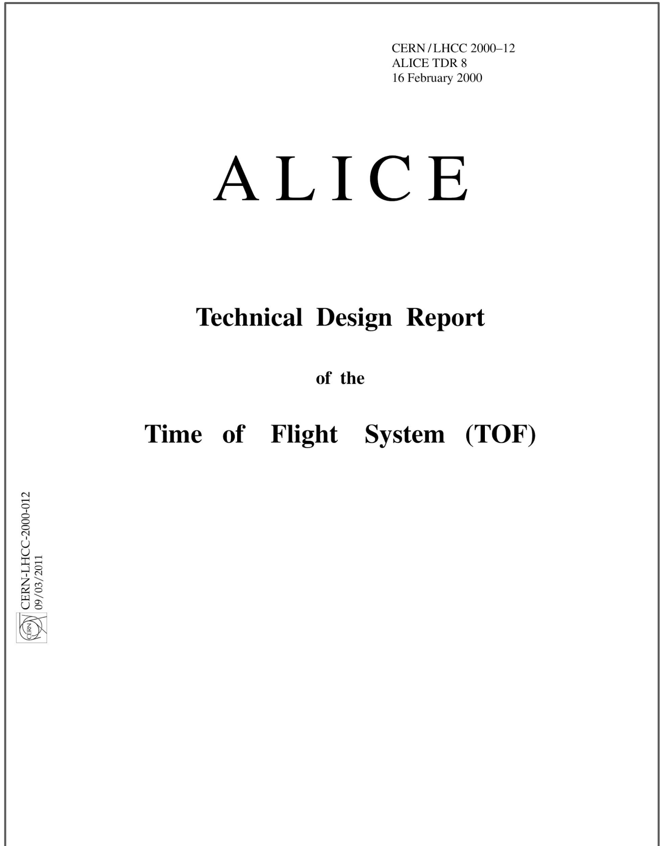
- **stack of equally-spaced resistive plates**
  - with voltage applied to external surfaces
  - all internal plates electrically floating
- **pickup electrodes on external surfaces**
  - resistive plates transparent to fast signal
- **internal plates take correct voltage**
  - initially due to electrostatics
  - but kept at correct voltage by flow of electrons and positive ions
  - feedback principle that dictates equal gain in all gas gaps

**this detector is cheap, easy to build and can cover large areas**

# Multigap Resistive Plate Chamber

**the Multigap RPC has been a game-changer technology**

for precision timing applications → Time-of-Flight detectors



CERN / LHCC 2000–12
ALICE TDR 8
16 February 2000

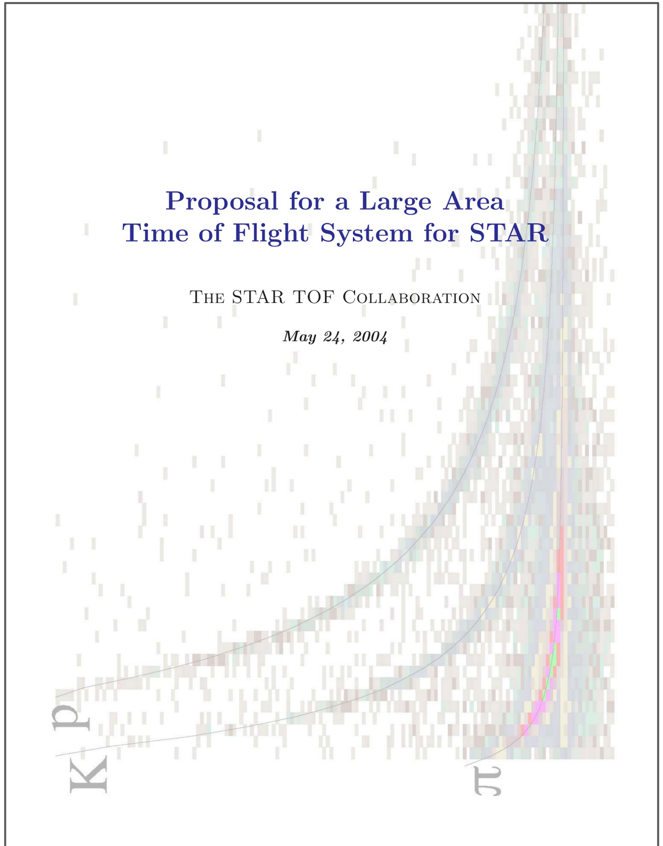
# ALICE

**Technical Design Report**

**of the**

**Time of Flight System (TOF)**

CERN-LHCC-2000-012
09/03/2011



Proposal for a Large Area
Time of Flight System for STAR

The STAR TOF Collaboration

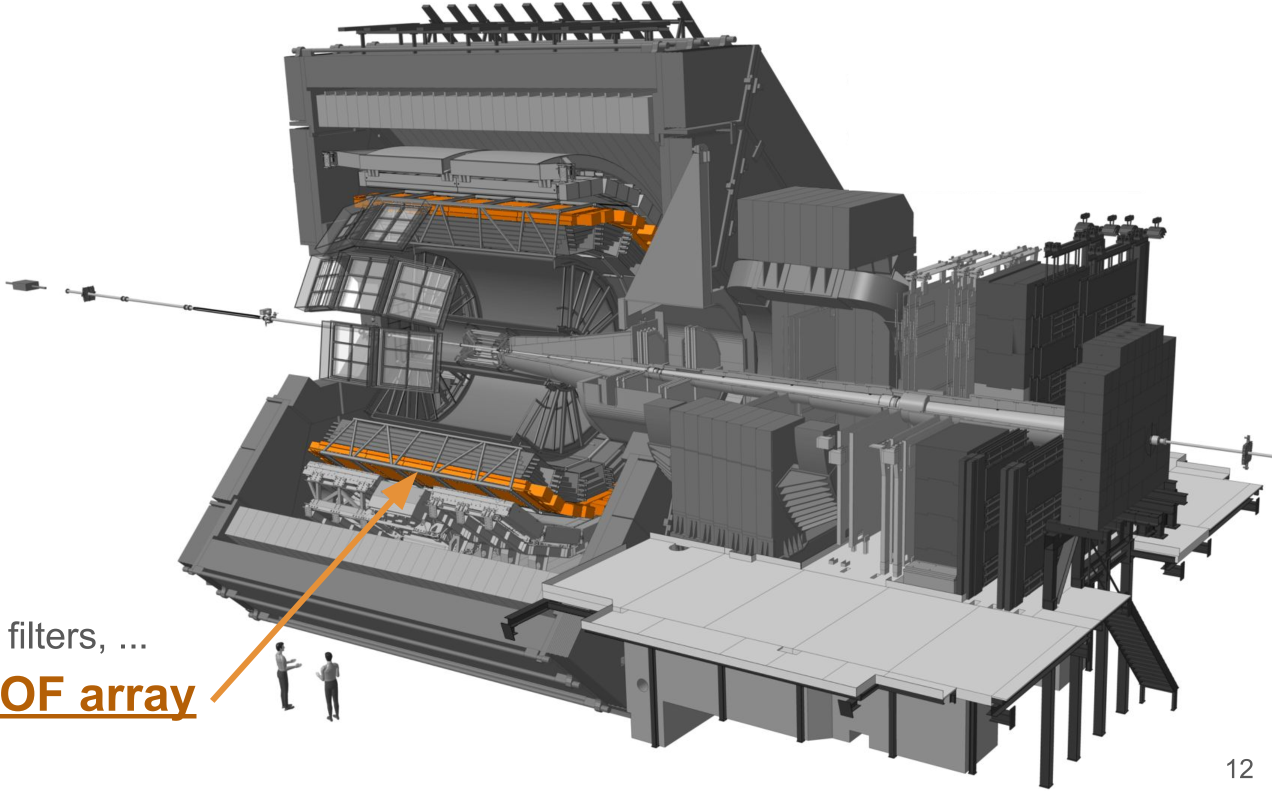
*May 24, 2004*

# The ALICE experiment

## a dedicated general-purpose detector for heavy-ion physics at the LHC

*ALICE, JINST 3 (2008) S08002*
*ALICE, J.Phys.G 41 (2014) 087001*

- **designed to cope with very high multiplicities**
  - $dN_{ch}/d\eta \leq 8000$
  - 3D tracking with TPC
- **low-$p_T$ tracking**
  - moderate B = 0.5 T
  - thin materials
- **employs all known PID techniques**
  - dE/dx in silicon and gas
  - Cherenkov imaging
  - transition radiation, muon filters, ...
- **among which a large TOF array**

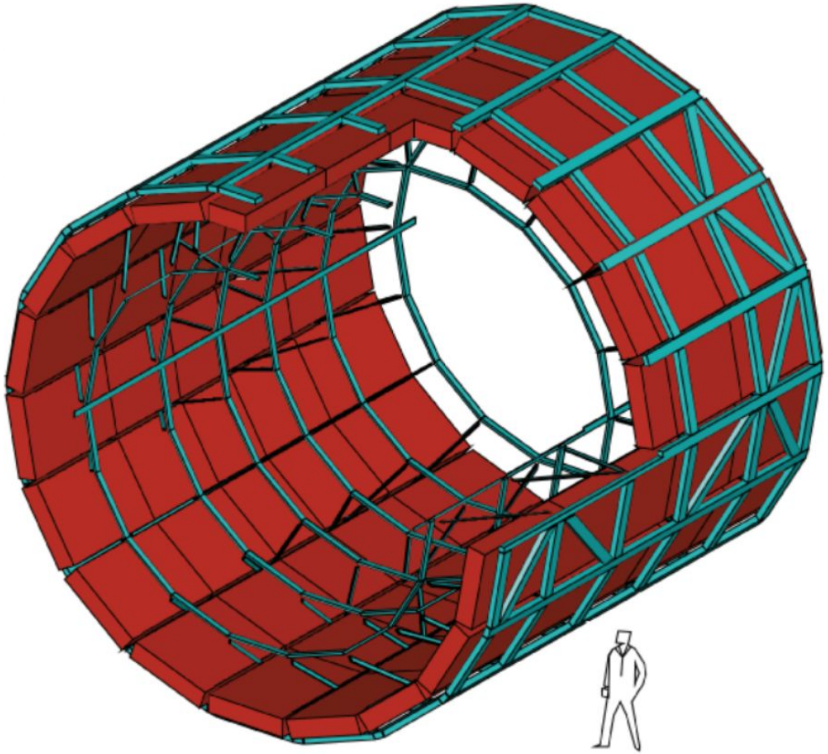


# The ALICE Time-Of-Flight detector

**designed for hadron identification in Pb-Pb collisions**

a detector that had to satisfy several demanding requirements for physics

- **large coverage**
    - ~ 140 m$^2$
- **high efficiency**
    - > 95 %
- **good time resolution**
    - 100 ps
- **high granularity**
    - ~ 10$^5$ channels



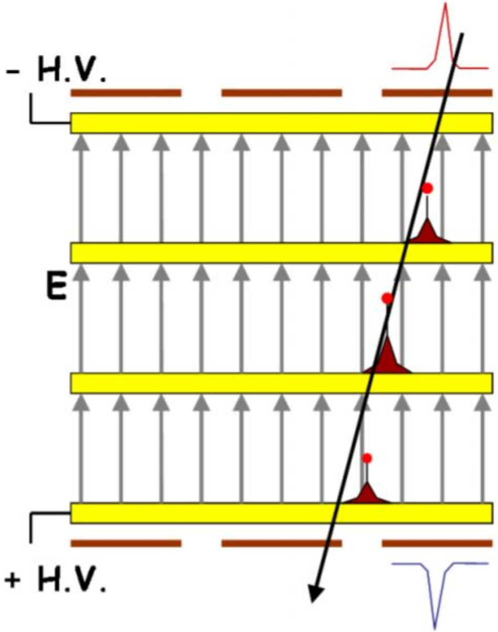
# Similarly the STAR experiment

**needed a Time-of-Flight detector**

roughly half of the produced particles could not be directly identified by the TPC

- **scintillator-based TOF**
  - with Mesh Dynode PMT
  - could meet the requirements
- **but**
  - large size of PMTs
  - enormous cost of PMTs
- **very expensive system**
  - 50 M$ for 10% occupancy
- **think about ALICE-TOF**
  - STAR-TOF area ~ 50 m$^2$

**MRPC**

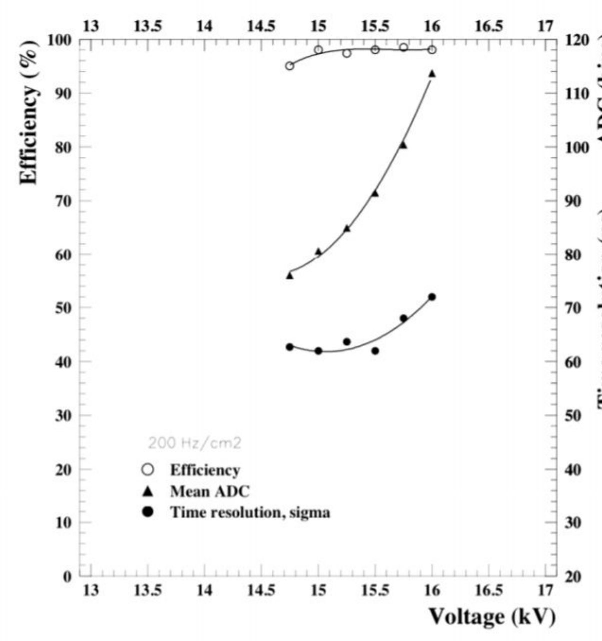


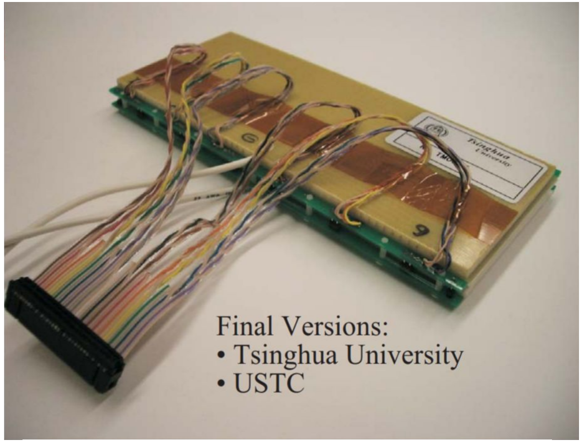
**the advent of MRPC was providential: use a gaseous detector**

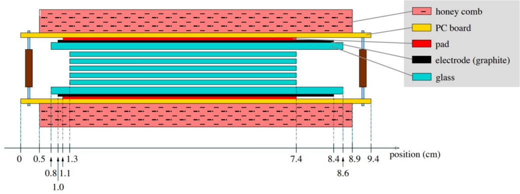
to satisfy the requirements at a reasonable cost

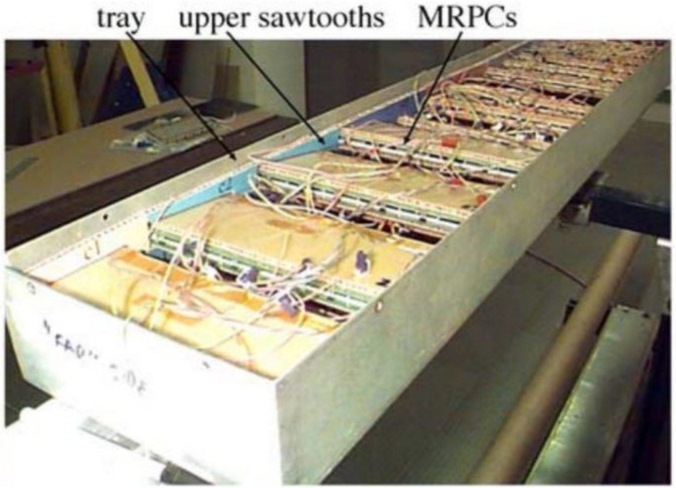
# Full-size STAR-TOF prototype

## prototypes constructed and installed in the experiment (2002-2005)









STAR-TOF MRPC tested at CERN in 2001

(a variant of the MRPC developed for ALICE-TOF)

wide voltage plateau with > 95% efficiency

time resolution below 75 ps

technology proved to be very inexpensive and easy to build

TOFr: first full-sized prototype

a “tray” with 30 MRPCs

$-1 < \eta < 0$

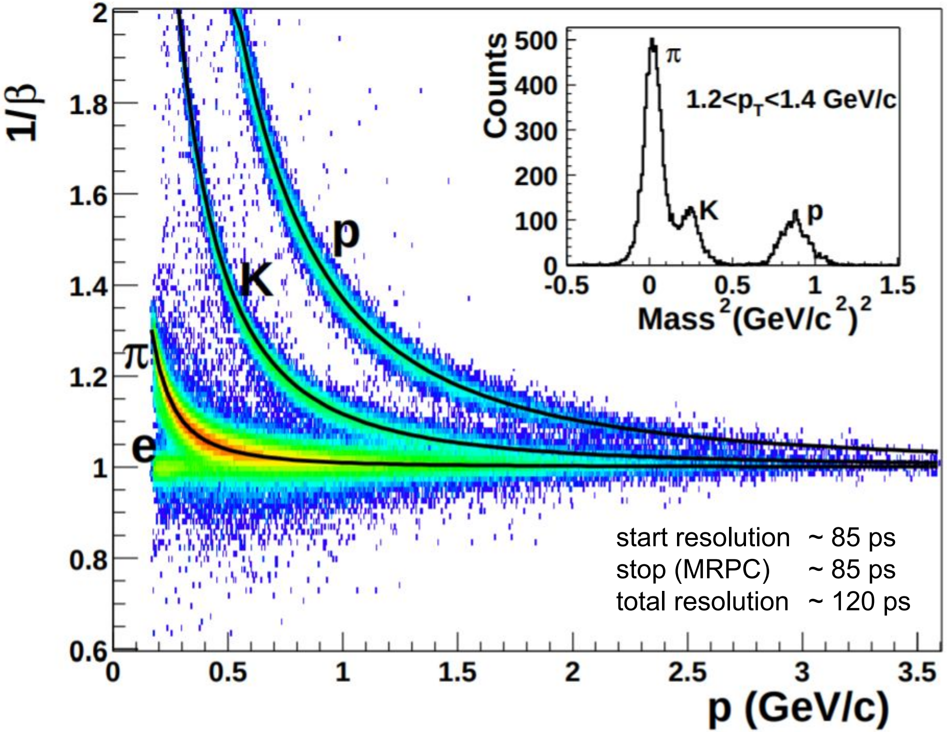
1/60th of $2\pi$

# Full-size STAR-TOF prototypes

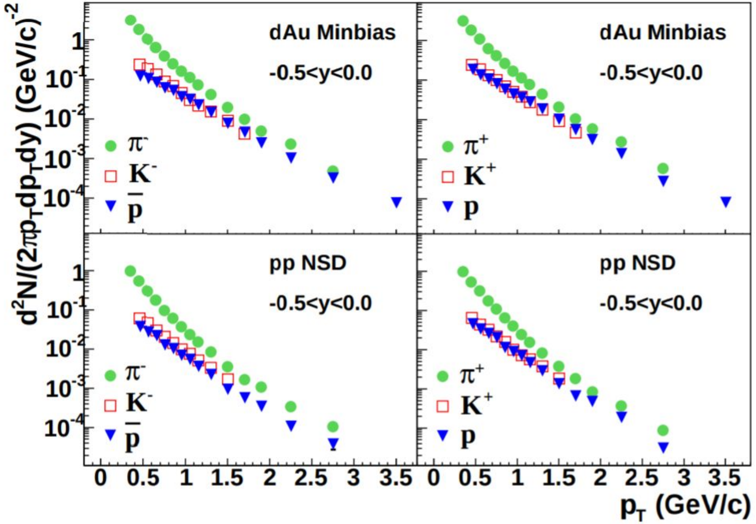
**first physics results from a MRPC-based TOF system**

on hadron $p_T$ distributions & the Cronin effect in pp and d-Au collisions

*STAR, PLB 616 (2005) 8*



start resolution ~ 85 ps
stop (MRPC) ~ 85 ps
total resolution ~ 120 ps



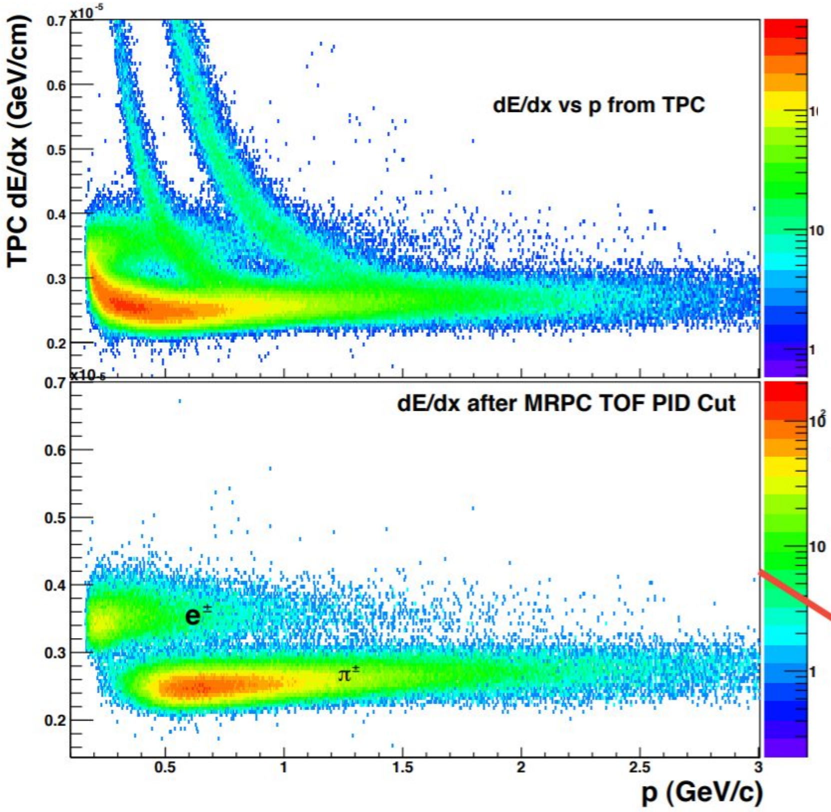
**π/K/p separation up to ~ 1.6 GeV/c**

**(π+K)/p up to ~ 2.8 GeV/c**

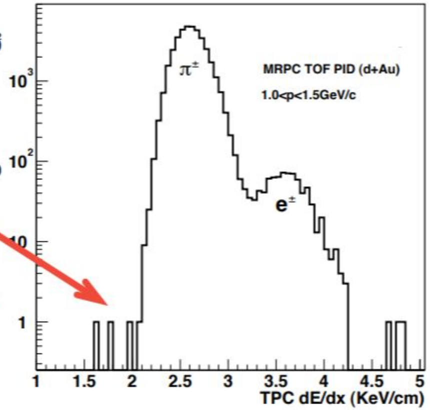
# Full-size STAR-TOF prototypes

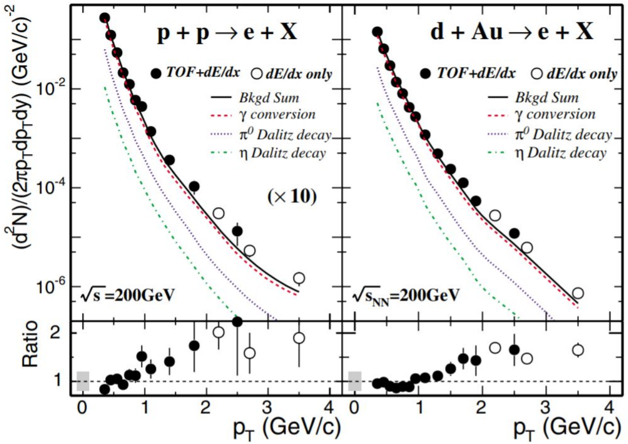
## TOF also works as an effective electron ID detector

in combination with TPC dE/dx



*STAR, PRL 94 (2005) 062301*





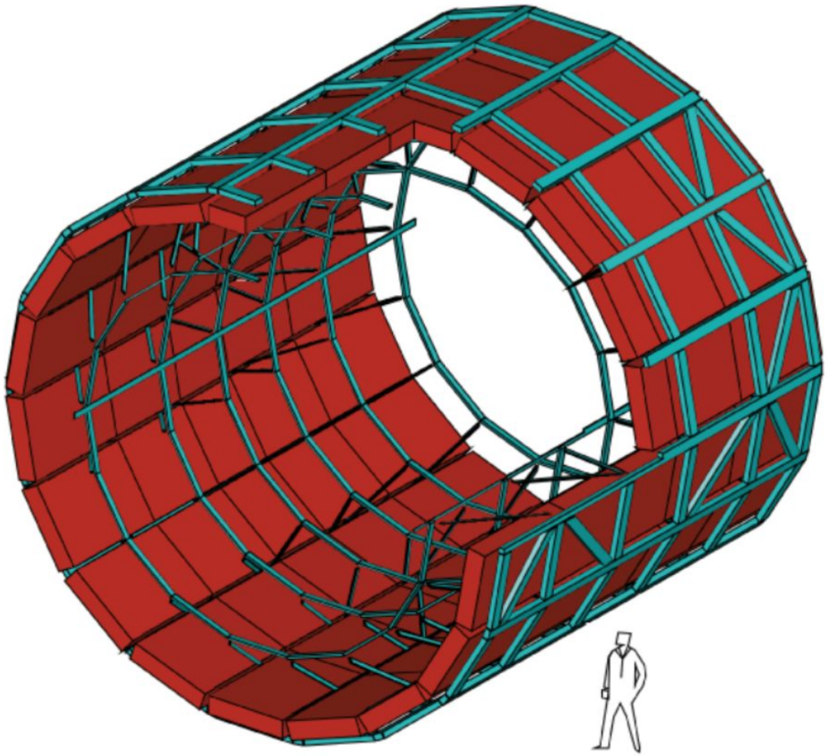
production of electrons in
in pp and d-Au collisions

indirect measurement of the
open-charm cross-section

# The ALICE Time-Of-Flight detector

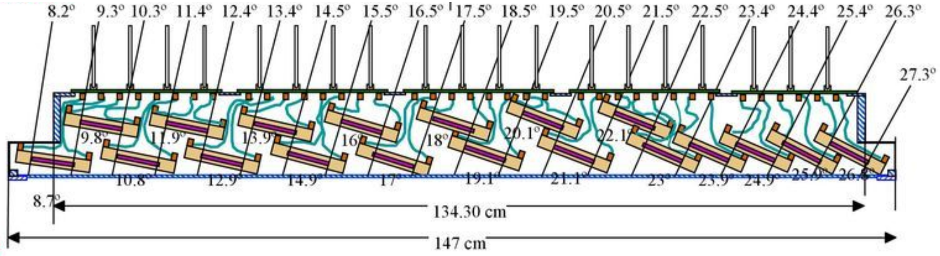
**designed for hadron identification in Pb-Pb collisions**

designed for 3σ π/K separation up to 2.5 GeV/c and p/K up to 4.0 GeV/c

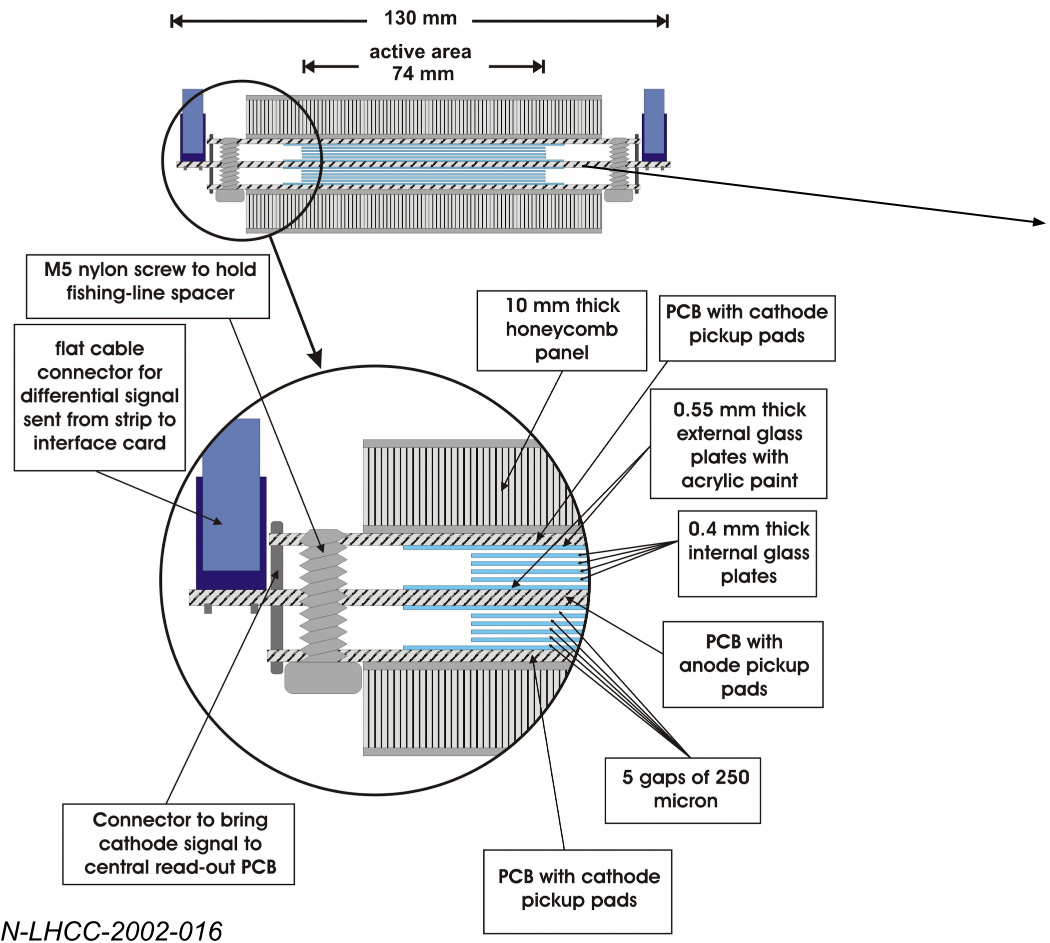


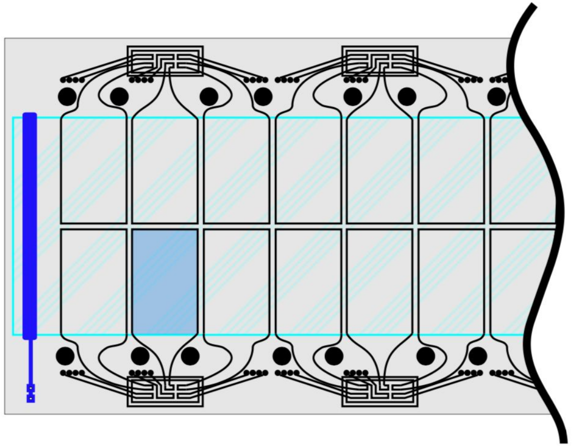
CERN-LHCC-2002-016

- **Design**
  - cylindrical surface
  - $3.7 < r < 4.0$ m from beam line
  - $2\pi$ full azimuthal acceptance
  - $|\eta| < 0.9$ polar acceptance
  - 18-fold segmentation in $\varphi$
  - 5-fold segmentation in z
  - 1638 MRPC strip detectors
  - pointing geometry



# The ALICE-TOF Multigap RPC





*CERN-LHCC-2002-016*

**double-stack design**

two stacks of resistive plates

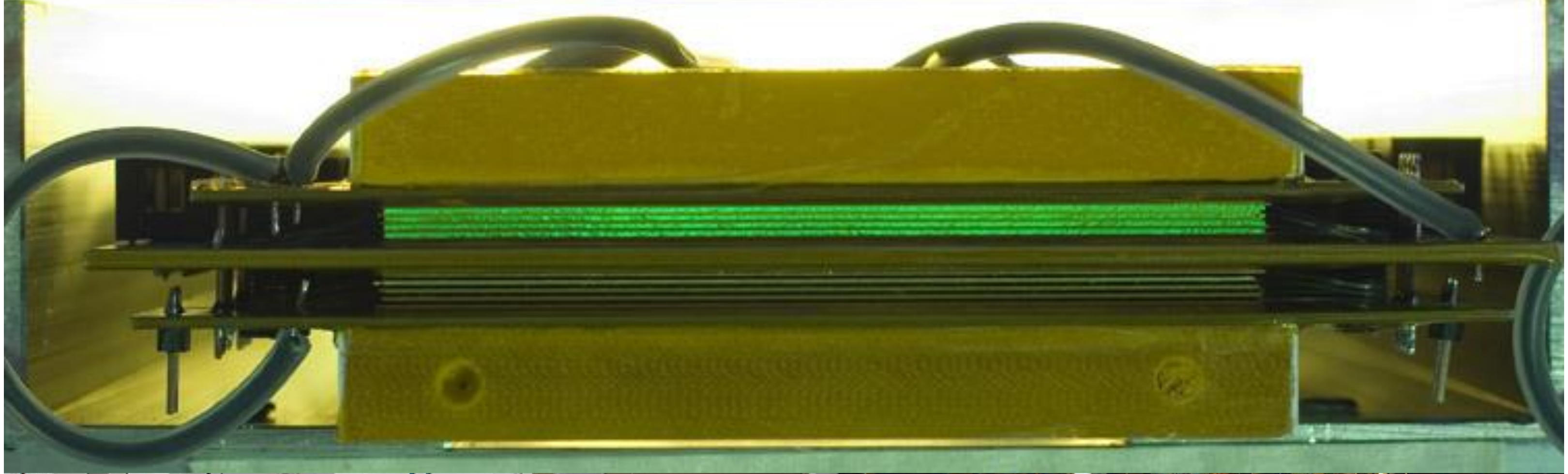
10x 250 μm gas gaps

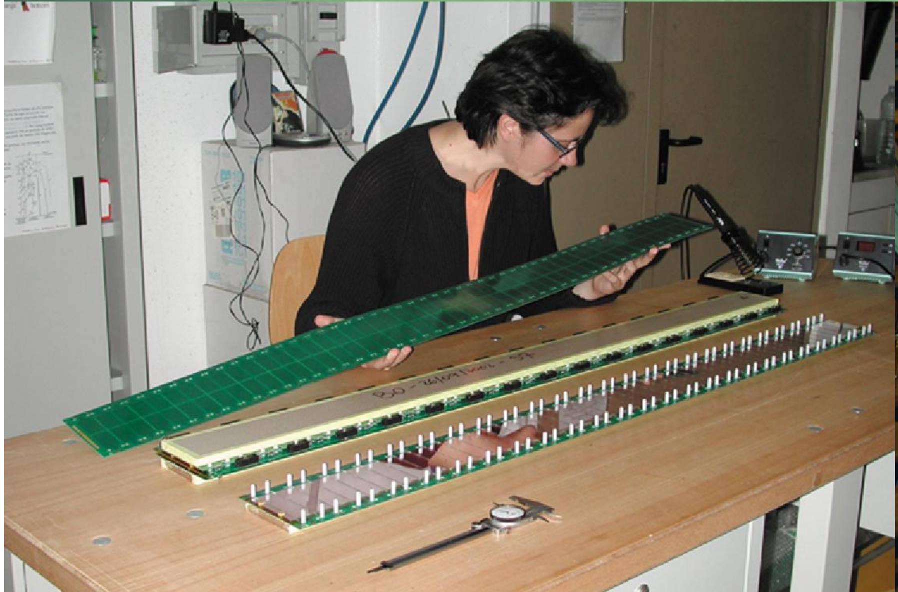
120 x 7.4 cm$^2$ active area

**highly-segmented readout**

96 pickup pads

3.5 x 2.5 cm$^2$





# Front-end electronics

**based on the NINO ASIC chip**

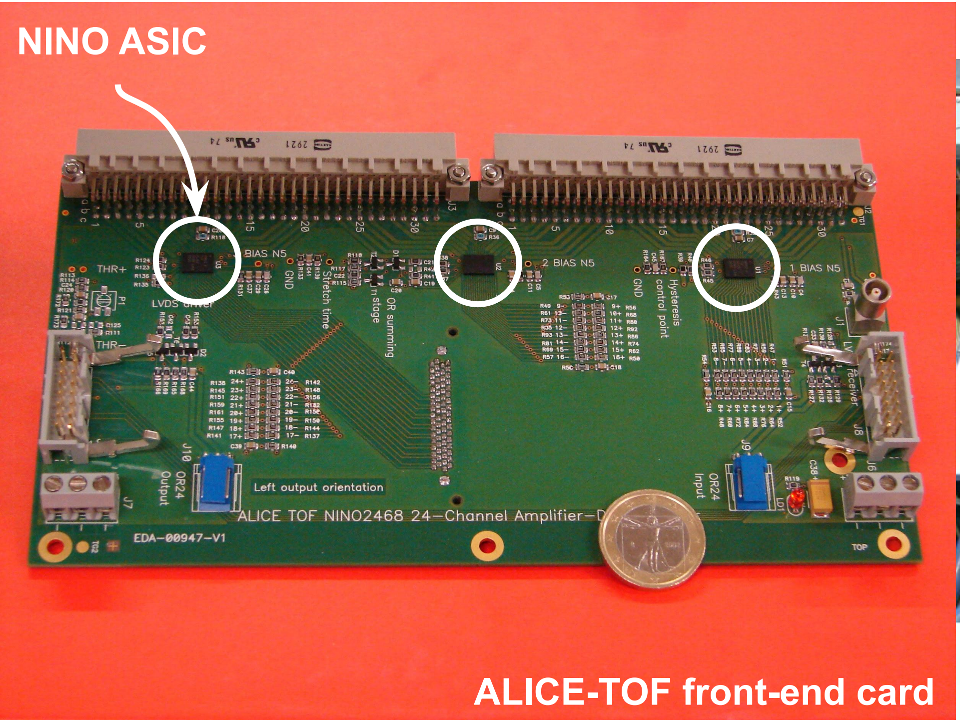
0.25 µm CMOS

*Anghinolfi et al, NIM A 533 (2004) 183*

low power consumption

**differential** amplifier + discriminator

input charge measurement via ToT

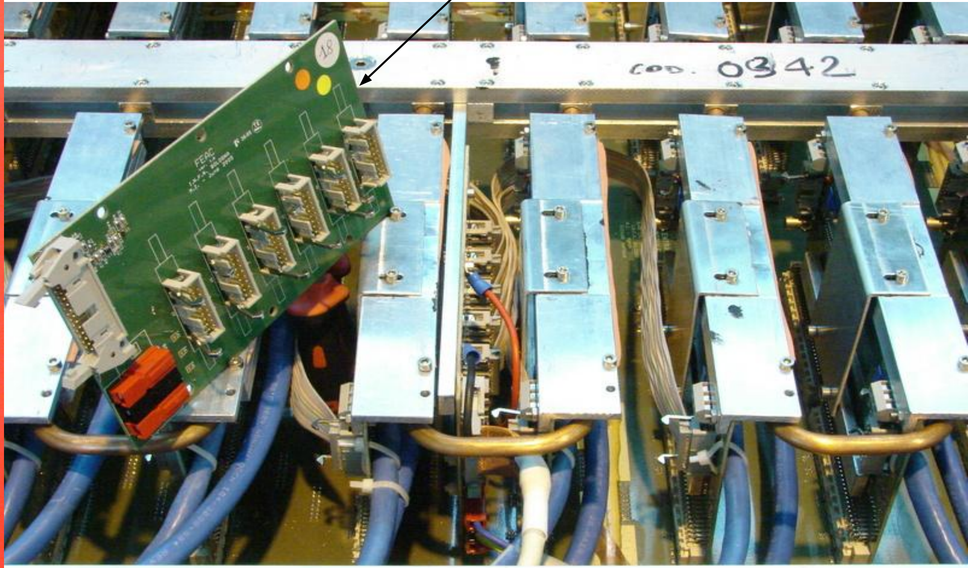


**NINO ASIC**

**ALICE-TOF front-end card**

front-end control card

- OR signals (trigger)
- threshold setup
- voltage monitor



# Readout electronics

**housed in water-cooled custom VME crates**

designed to work in B = 0.5 T

**TDC Readout Module**

multi-hit / multi-event design

based on HPTDC ASIC chip (24.4 LSB)

**Data Readout Module**

interface to DAQ/trigger

**Local Trigger Module**

local trigger + FEE monitor/setup

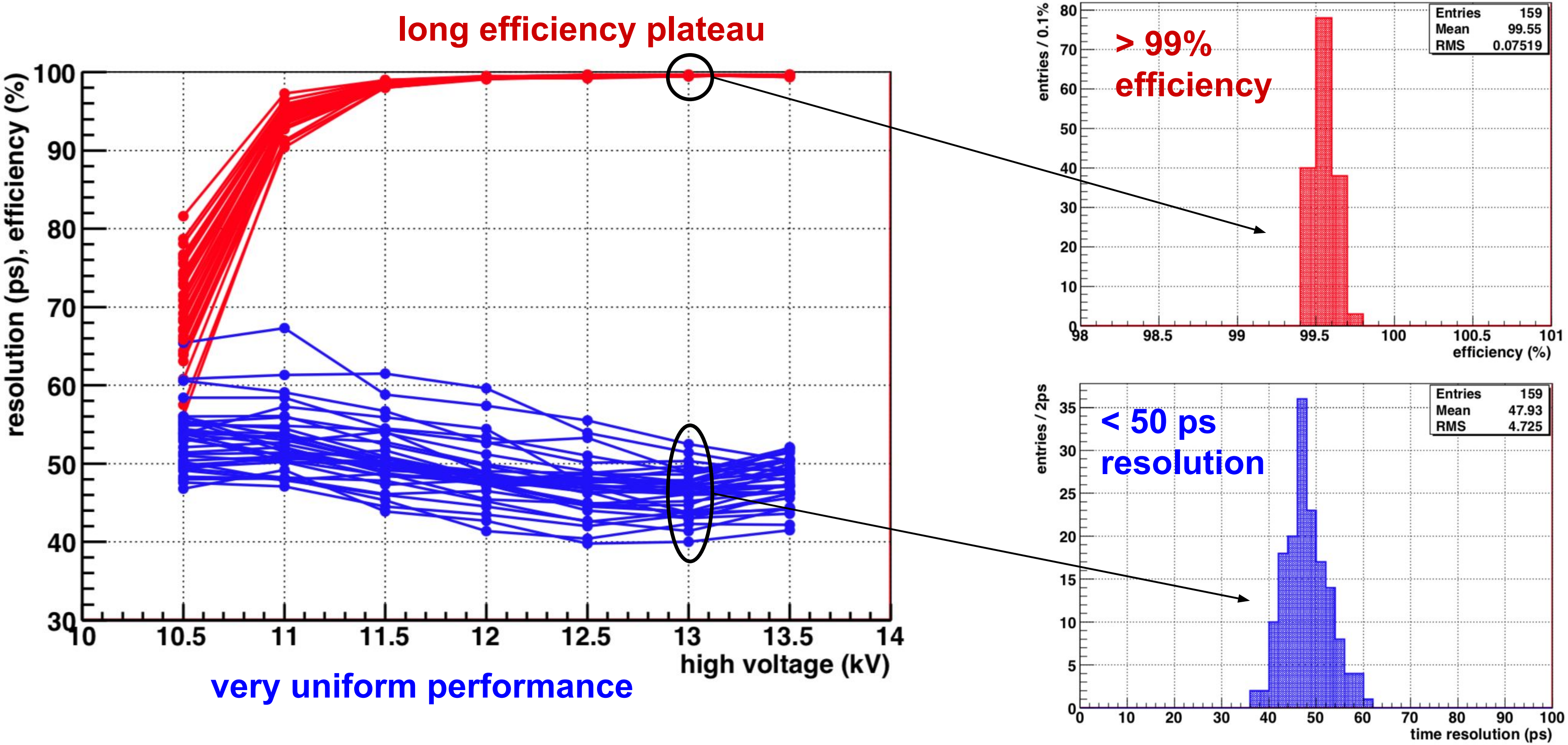
**Clock Distribution Module**

high-quality clock distribution to TRMs

*Akindinov et al, NIM A 533 (2004) 178*

# Test beam performance

## MRPC mass production + final electronics



long efficiency plateau

> 99% efficiency

< 50 ps resolution

very uniform performance

$C_2H_2F_4$ (90%) i-$C_4H_{10}$ (5%) $SF_6$ (5%)

*Akindinov et al, NIM A 602 (2009) 709*

# ALICE-TOF milestones

*Akindinov et al,*
*Nuovo Cim. B 124 (2009) 235*

**← December 2006**

end of MRPC production

**April 2008 →**

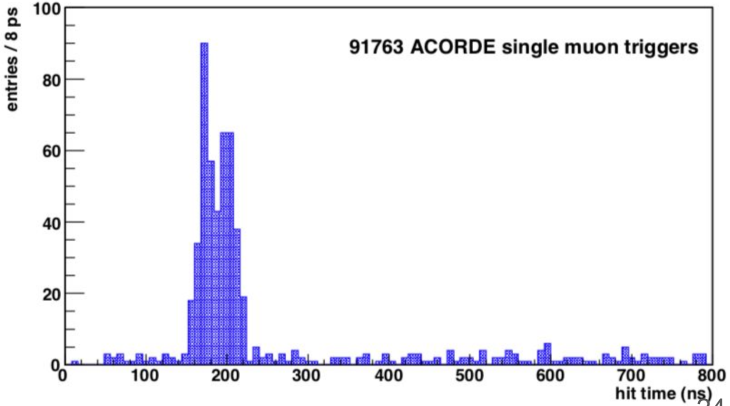
last sector completed
and installed

**← May 2008**

cables, pipes and fibres
connected

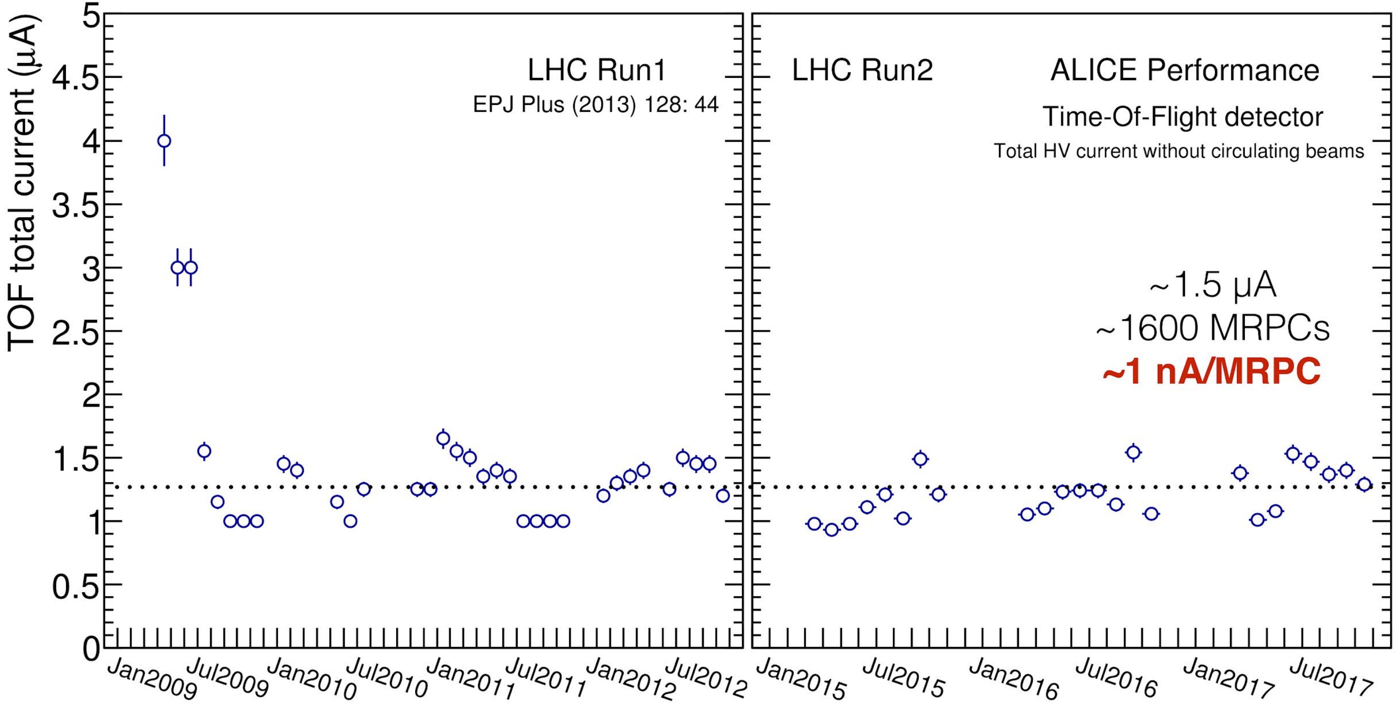
**Summer 2008 →**

commissioning with
cosmic-rays



# Total current

current measurements **without circulating beams**



~1.5 μA

~1600 MRPCs

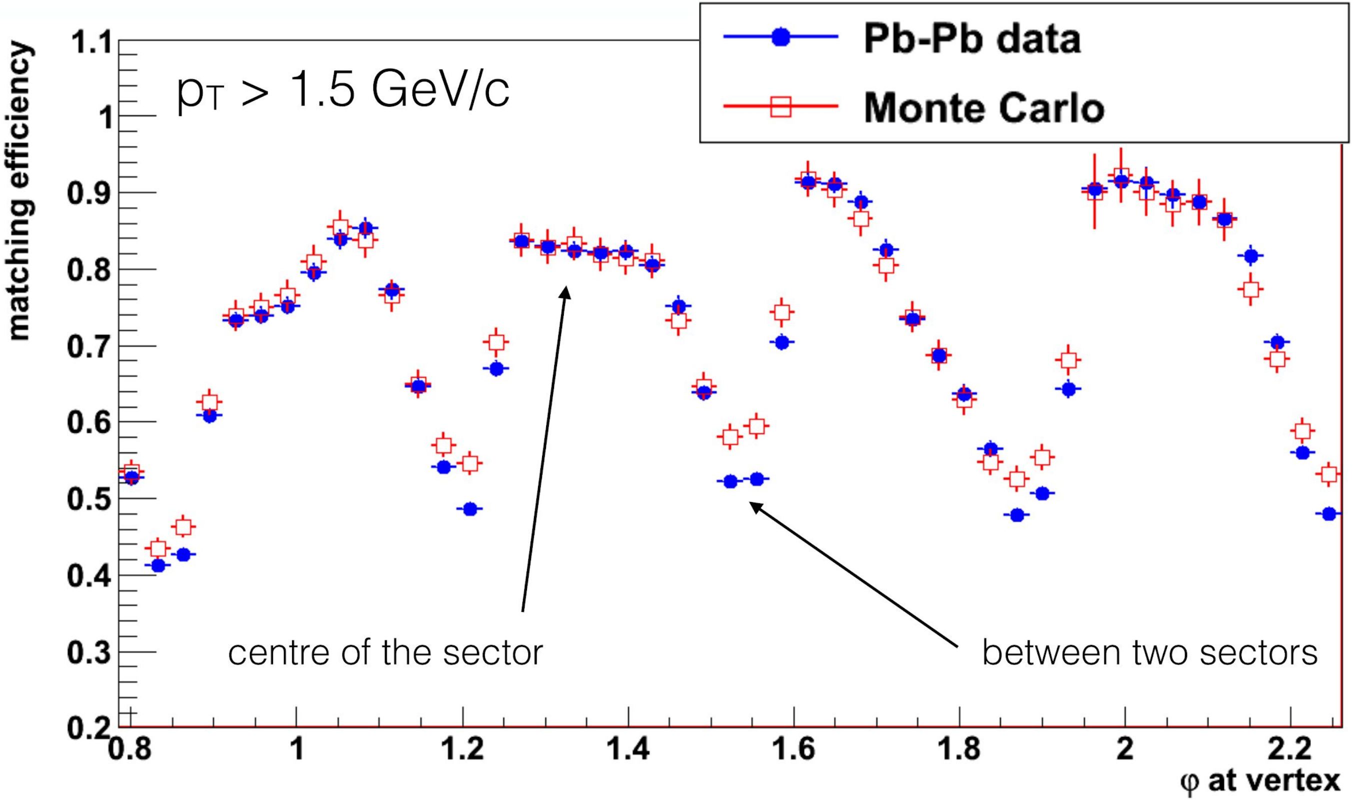
**~1 nA/MRPC**

**very stable operations** over the years

very low currents, no ageing effects

# Efficiency

2010



$p_T > 1.5$ GeV/c

centre of the sector

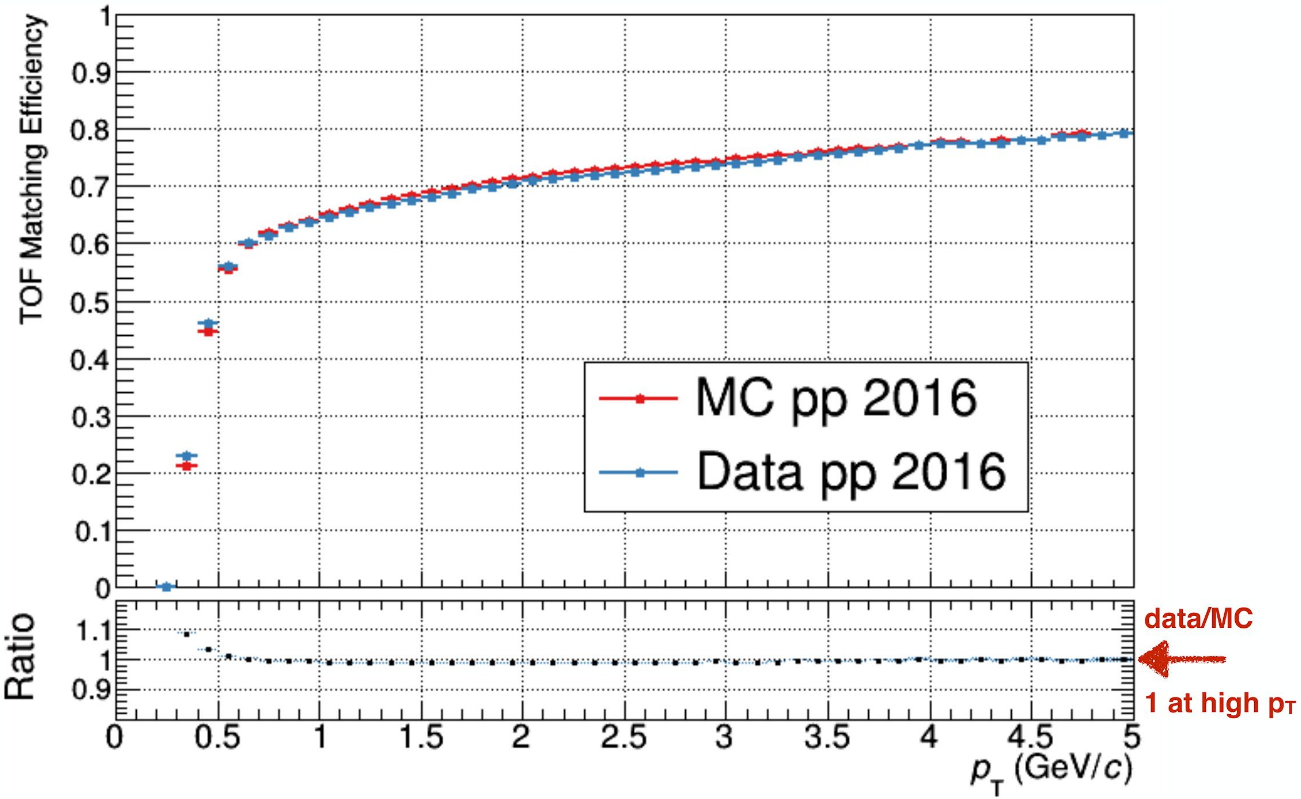
between two sectors

efficiency in **excellent agreement** with simulations

simulation input efficiency from test-beam data

# Efficiency

2016



data/MC

1 at high $p_T$

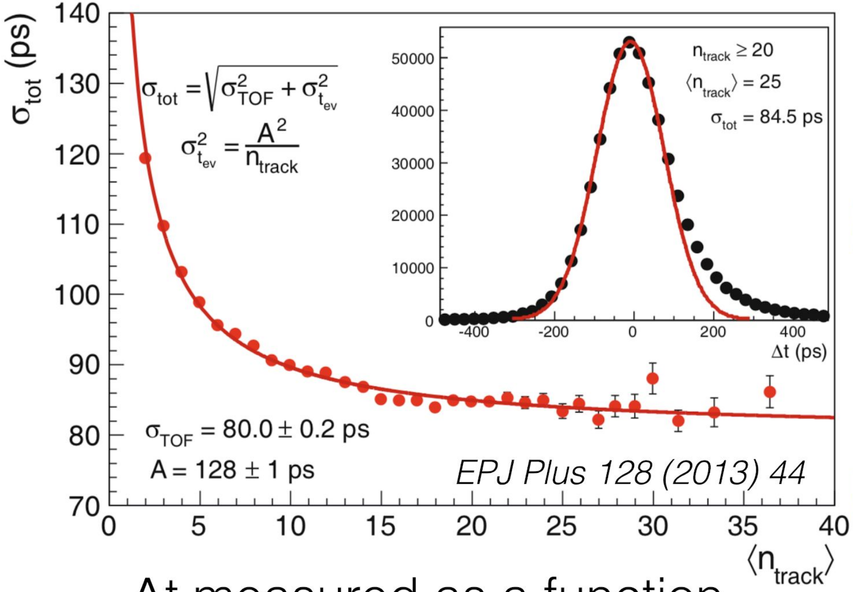
efficiency in **excellent agreement** with simulations

no degradation after 10 years of operation

# Time resolution

total time-of-flight resolution of the ALICE TOF detector

measured with 1 GeV/c pions from p-Pb collisions (2013) over the full detector



*EPJ Plus 128 (2013) 44*

Δt measured as a function of $N_{tracks}$ used for $t_{start}$

**$\sigma(t_{TOF})$ = 80 ps**

**$\Delta t = TOF - t_{exp}(L,p)$**

$t_{exp}$: expected pion time-of-flight (computed numerically)

$\sigma(t_{exp}) \sim 15$ ps (negligible)

**$TOF = t_{TOF} - t_{start}$**

$t_{TOF}$: arrival time of the particle (recorded by the detector)

$\sigma(t_{TOF}) = \sigma(t_{MRPC}) + \sigma(t_{FEE}) + \sigma(t_{calib})$

$t_{start}$ (or $t_{ev}$): start time of the particle (collision time), can be measured (combinatorial algorithm)

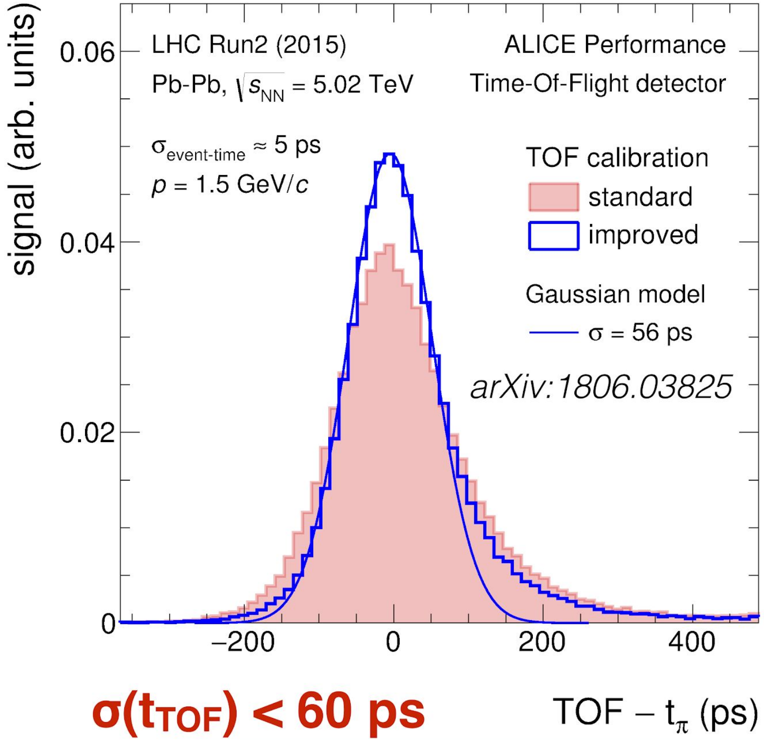
$\sigma(t_{ev}) = A / \sqrt{N_{tracks}}$

timing performance as promised in PPR

# Time resolution

can we do something more? **Improve the calibration**

measured with 1.5 GeV/c pions from Pb-Pb collisions (2015) over the full detector



**$\sigma(t_{TOF}) < 60$ ps**

**$\Delta t = TOF - t_{exp}(L,p)$**

$t_{exp}$: expected pion time-of-flight (computed numerically)

$\sigma(t_{exp}) \sim 2$ ps (negligible)

**$TOF = t_{TOF} - t_{start}$**

$t_{TOF}$: arrival time of the particle (recorded by the detector)

$\sigma(t_{TOF}) = \sigma(t_{MRPC}) + \sigma(t_{FEE}) + \sigma(t_{calib})$

$t_{start}$ (or $t_{ev}$): start time of the particle (collision time), can be measured (combinatorial algorithm)

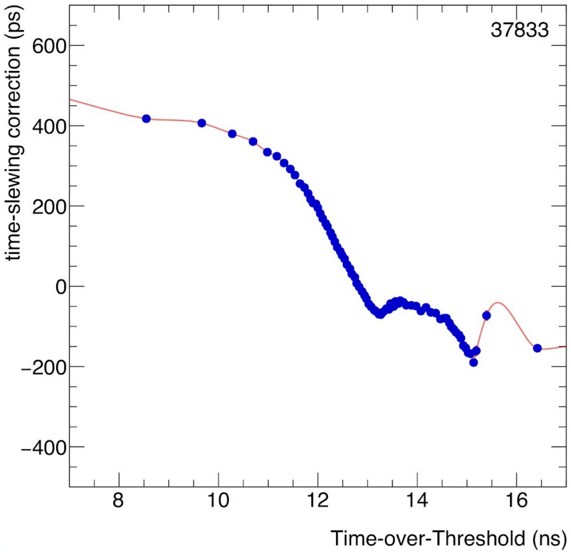
$\sigma(t_{ev}) = 5$ ps (negligible)

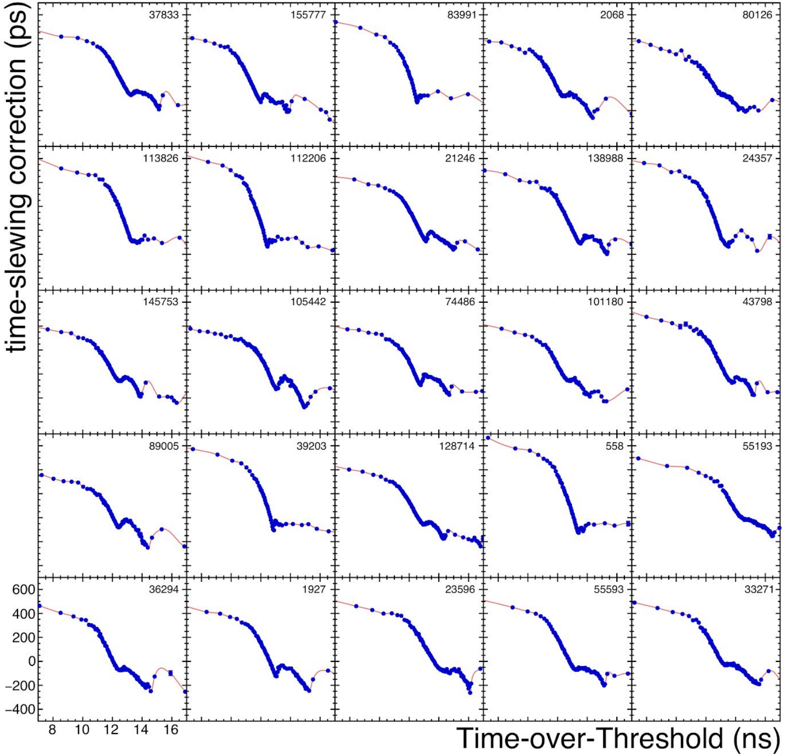
timing performance close to test beam

# Calibration

## **fine tuning** the time-amplitude (time-slewing) correlations

time-over-threshold correction for >150k channels measured with high precision



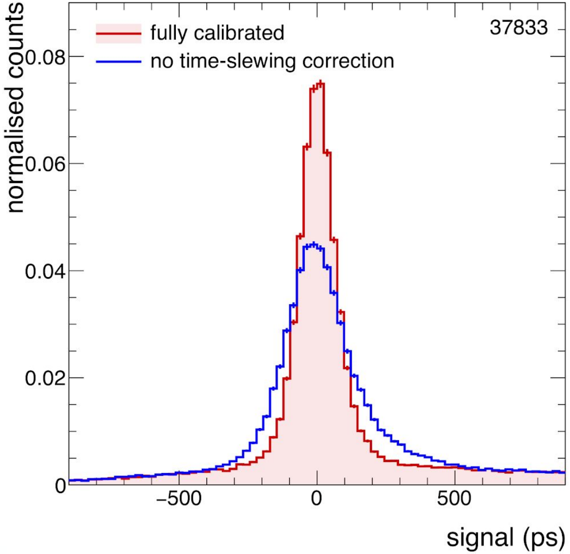


fine-tuned correction by
**closely following the trend**
of the correlation

# Calibration

## **fine tuning** the time-amplitude (time-slewing) correlations

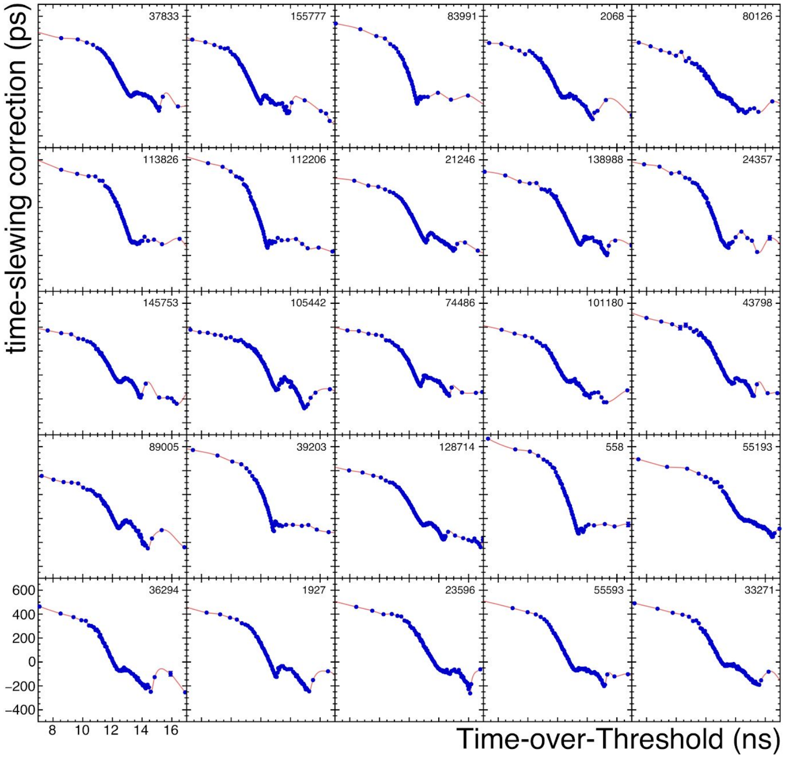
time-over-threshold correction for >150k channels measured with high precision



example of the effect of the

**time-slewing correction**

improvement of ~110-130 ps

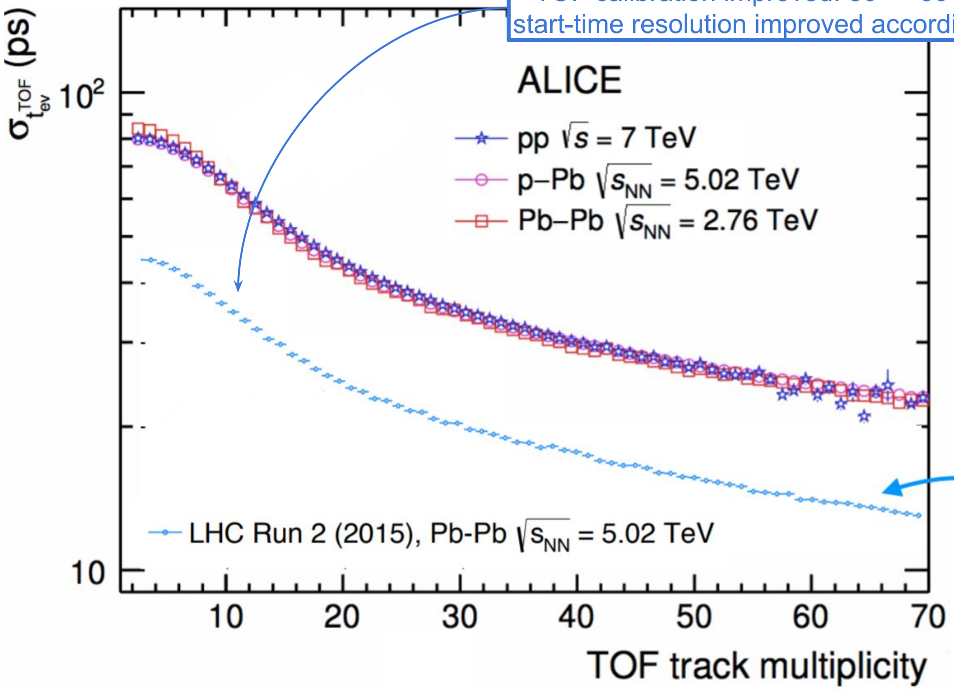


# Start time

**precise event-by-event determination of the collision time**

represents a very important ingredient for PID with a TOF systems
different methods and/or detectors can be employed

- **no start-time measurement**
    - uncertainty from beam bunch size
        - i.e. ~ 200 ps at LHC
- **dedicated start-time system**
    - i.e. ALICE T0 detector
        - quartz-Cherenkov counter
        - ~ 50 ps for single MIP events
        - ~ 25 ps at higher multiplicity
- **self-determined start-time**
    - combinatorial algorithm
        - use tracks that reach TOF
        - $\sigma_{start} \sim \sigma_{stop} / \sqrt{N_{tracks}}$
    - becomes negligible for large $N_{tracks}$

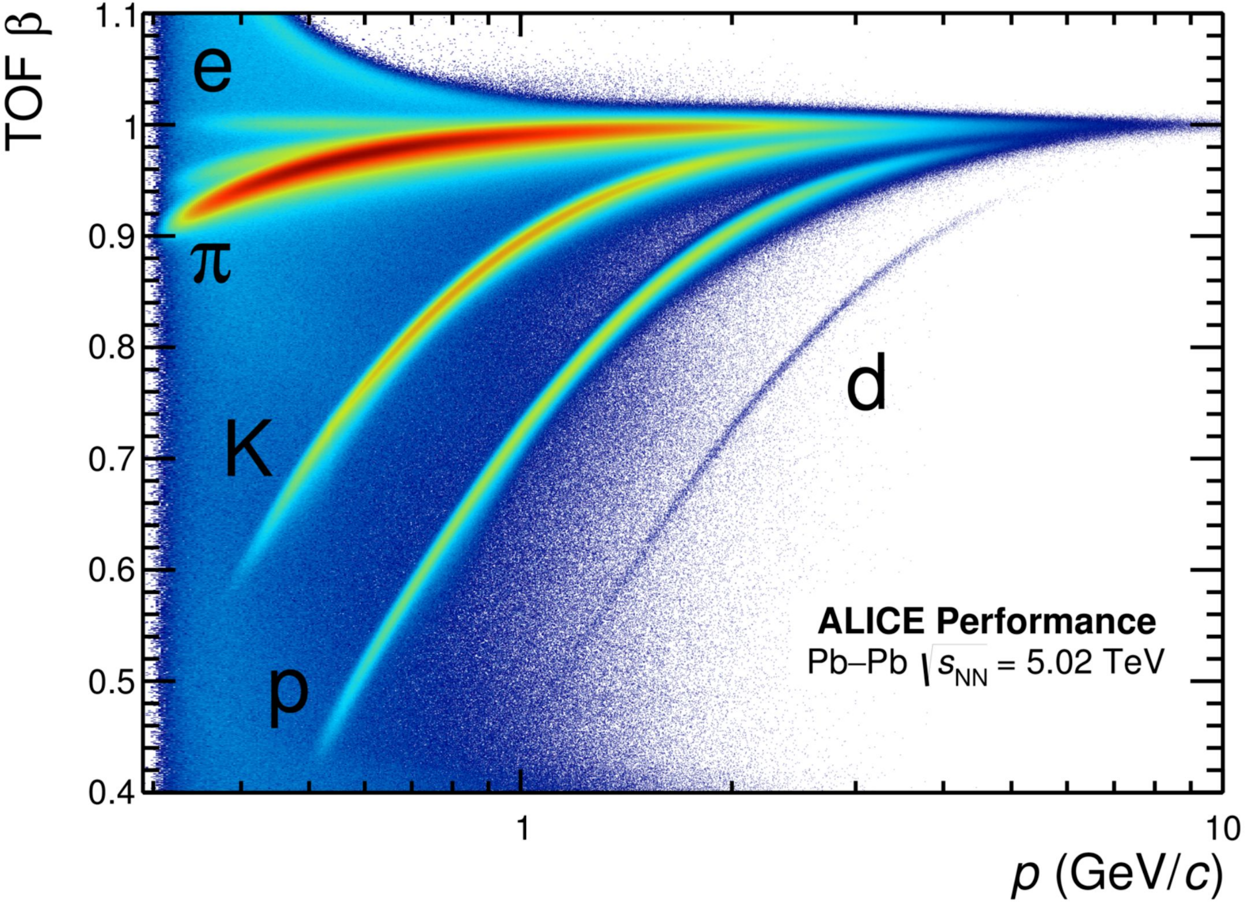


TOF calibration improved: 80 → 60 ps
start-time resolution improved accordingly

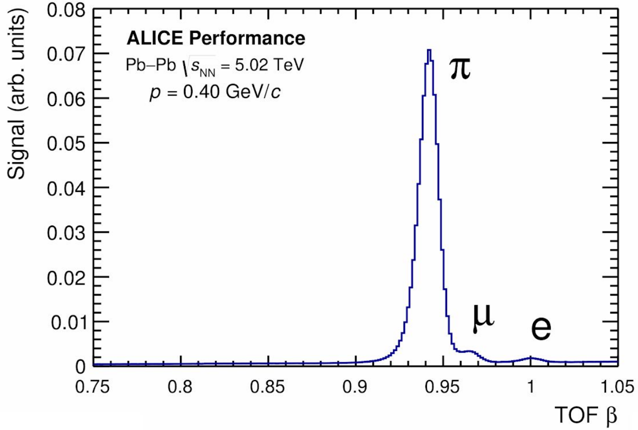
~5 ps

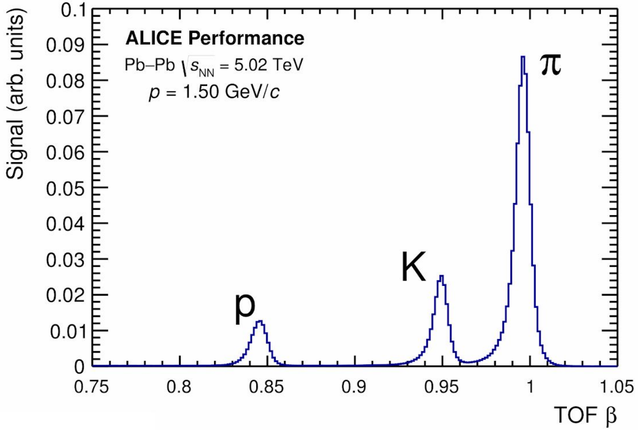
*ALICE, EPJ Plus (2017) 132*

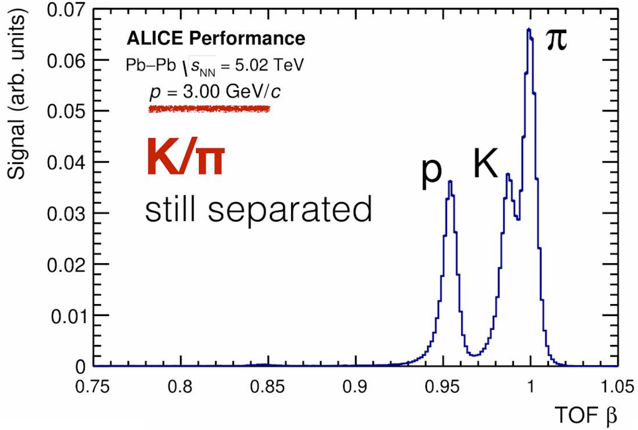
# Performance



# Performance

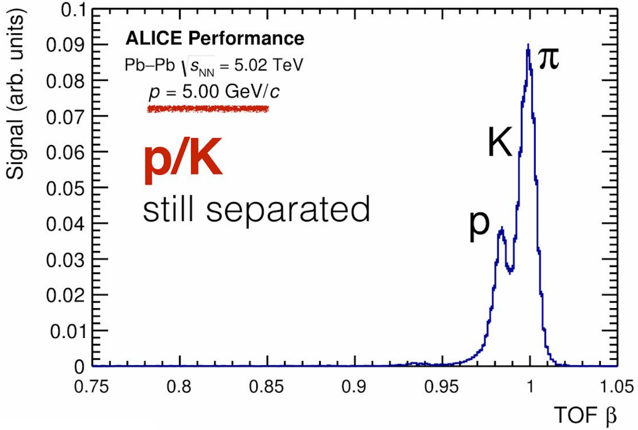






**K/π**

still separated



**p/K**

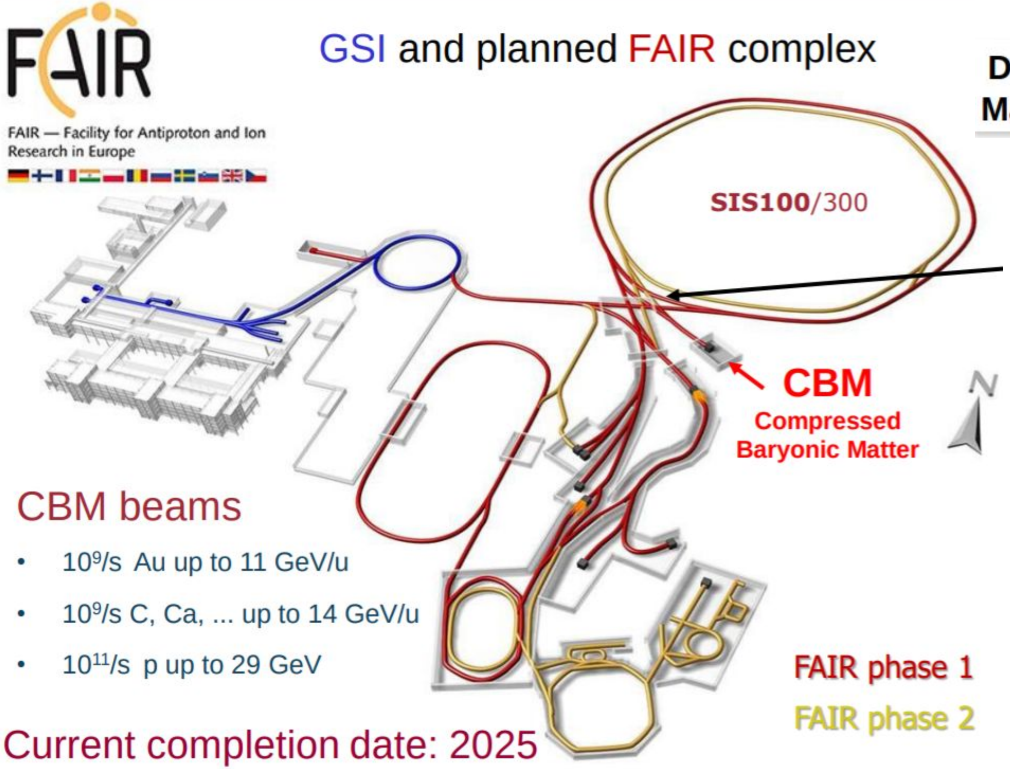
still separated

# The CBM time-of-flight project

## MRPCs at unprecedented high interaction rates

FAIR — Facility for Antiproton and Ion Research in Europe

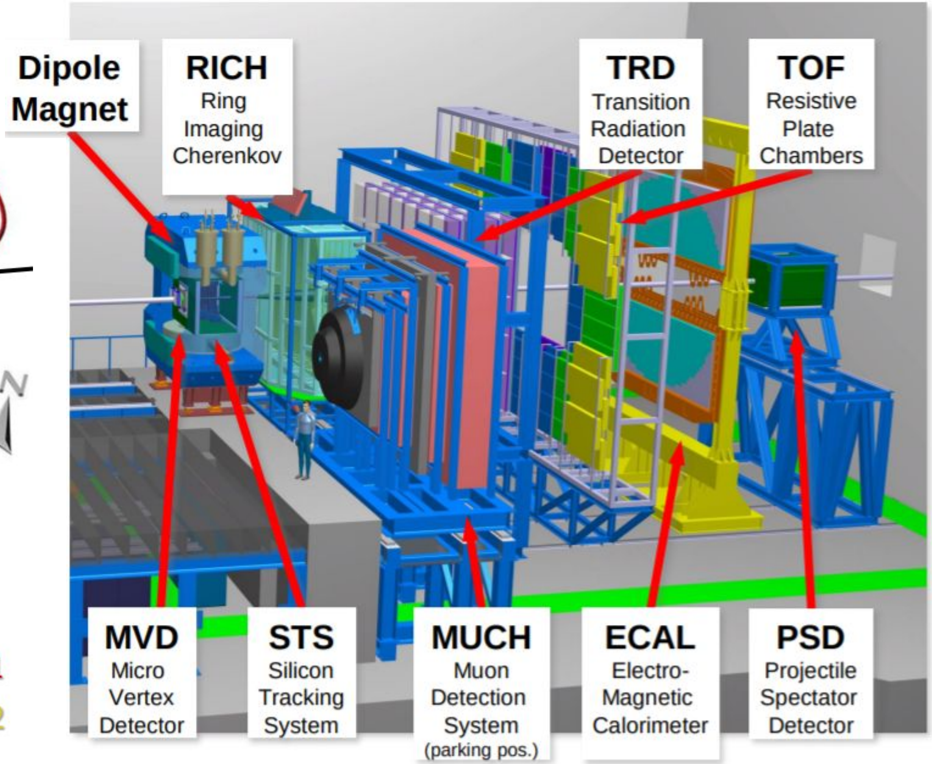
GSI and planned FAIR complex



CBM beams

- $10^9$/s Au up to 11 GeV/u
- $10^9$/s C, Ca, ... up to 14 GeV/u
- $10^{11}$/s p up to 29 GeV

Current completion date: 2025



**Dipole Magnet**

**RICH** Ring Imaging Cherenkov

**TRD** Transition Radiation Detector

**TOF** Resistive Plate Chambers

**MVD** Micro Vertex Detector

**STS** Silicon Tracking System

**MUCH** Muon Detection System (parking pos.)

**ECAL** Electro-Magnetic Calorimeter

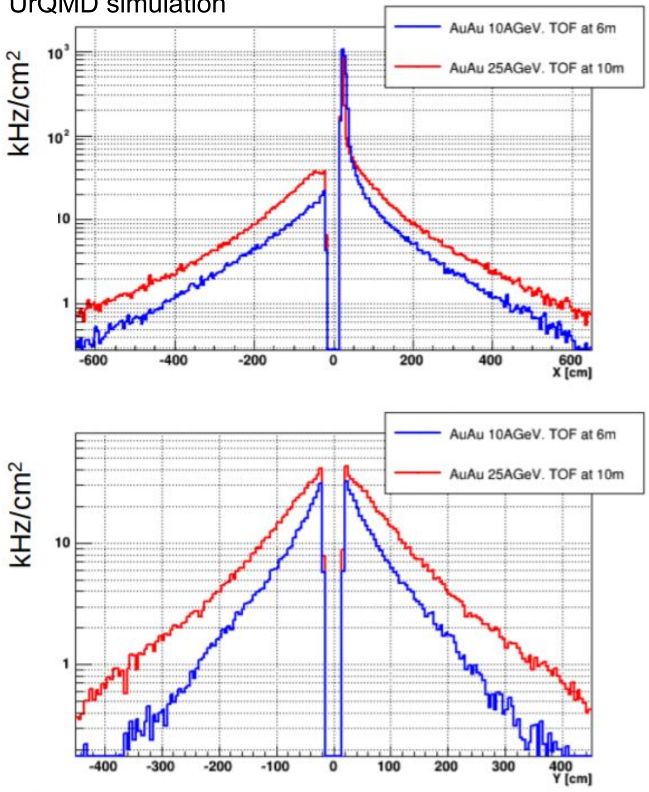
**PSD** Projectile Spectator Detector

# The CBM time-of-flight project

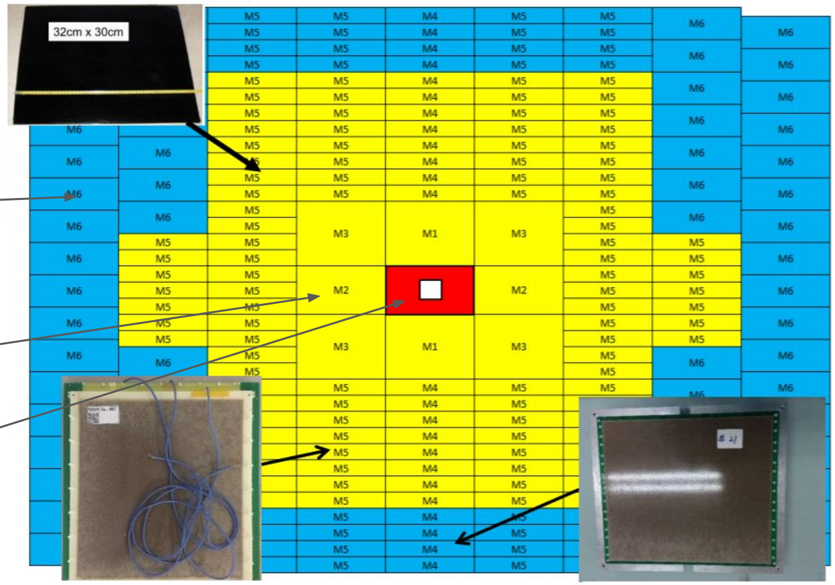
## Au-Au collisions at 10 MHz interaction rate

need TOF detectors with different rate capabilities at different regions
particle flux ranging from 0.1 to 100 KHz/cm2

UrQMD simulation



Low resistivity glass



**float glass MRPC**

**low-resistivity glass MRPC**

**ceramic RPC**

MRPC2 (Tsinghua)

MRPC3 (USTC)

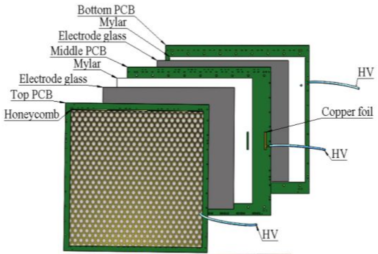
**120 m$^2$, 230 modules, 1400 MRPCs, 100k channels**

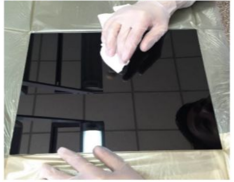
> 95% efficiency, ~ 80 ps full system resolution, < 5 % occupancy

# High-rate CBM MRPC2

**equipped with low resistive glass (~$10^{10}$ Ω cm)**

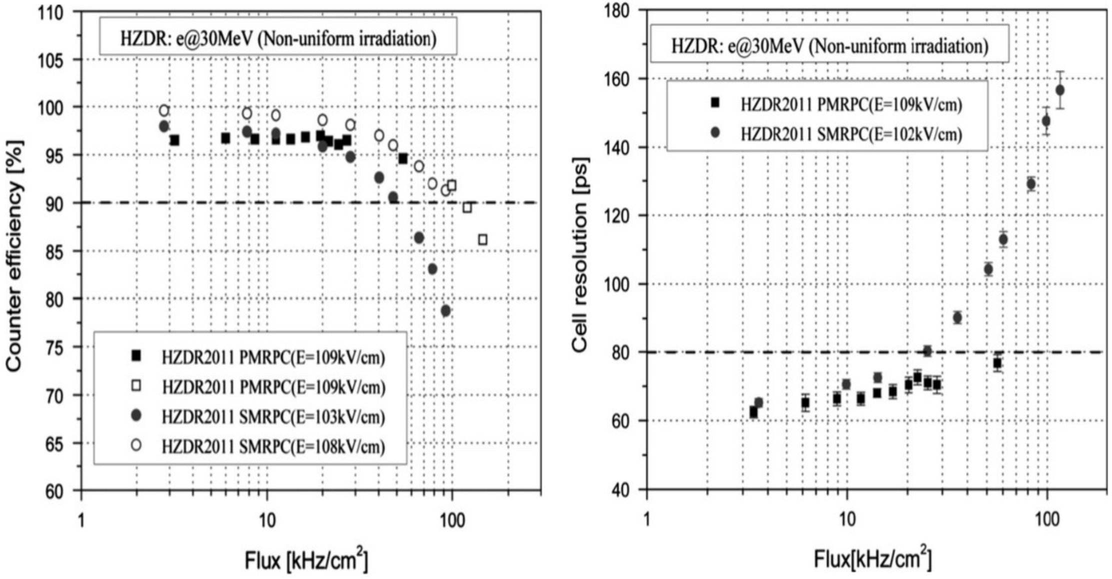
the rate capability of MRPC2 meets the requirement of CBM-TOF in the corresponding high-rate area (1-10 kHz/cm$^2$)





| Dimension | 360 × 338 × 26 mm$^3$ |
|---|---|
| Weight | 3.3 kg |
| Gas gap number | 4×2 stacks |
| Gas gap width | 0.25 mm |
| Glass dimension | 330 × 276 × 0.7 mm$^3$ |
| Strip dimension | 270 × 7 mm$^2$ |
| Strip pitch | 3 mm |
| Strip number | 32 |
| Electrodes | low resistive glass |

*Wang et al., NIM A 713 (2013) 40*



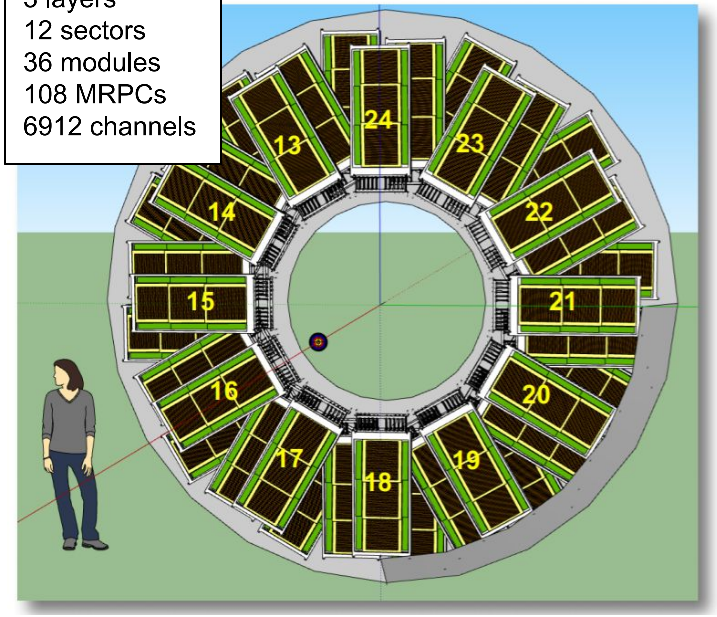
# FAIR phase-0 programs

## FAIR phase-0 is a bridge program until the start of FAIR in 2025

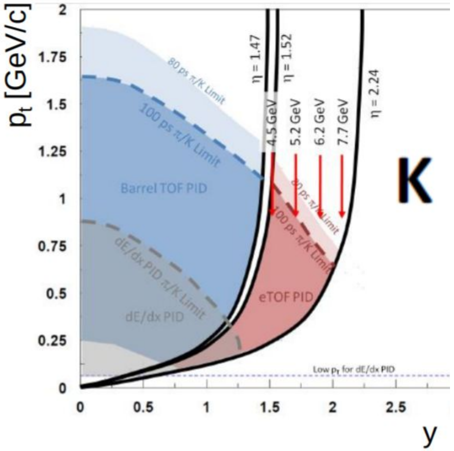
mTOF and eTOF project: installation, commissioning and operation of CBM TOF modules in STAR

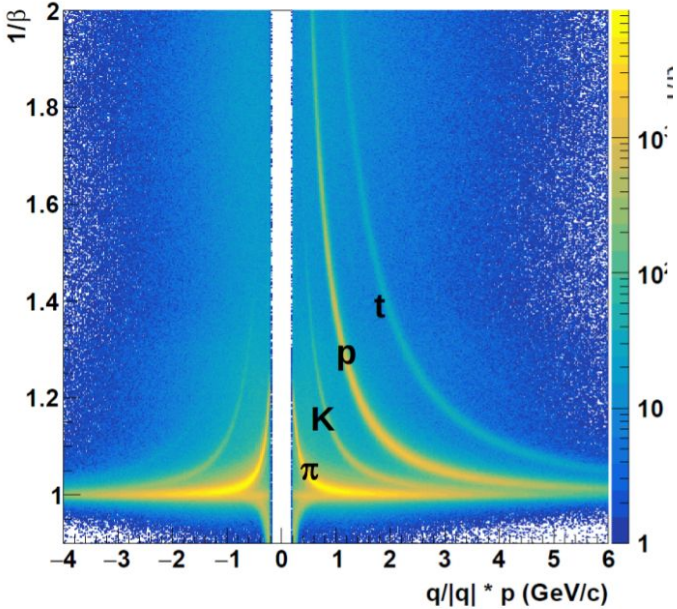
eTOF upgrade: extend η range for π, K, p ID → RHIC-BES (collider and fixed target mode)

3 layers
12 sectors
36 modules
108 MRPCs
6912 channels



STAR eTOF “wheel”
full installation in November 2018





**time resolution in the order of 85 ps**

measured with fast pions

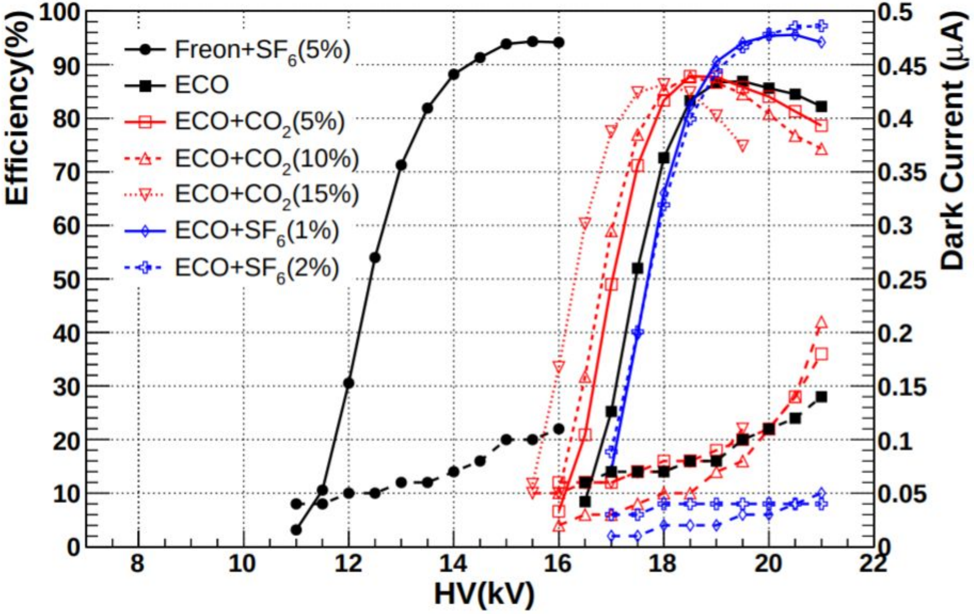
# MRPC with eco-friendly gas

**searching for new eco-gas mixtures**

with low Global Warming Potential and reasonable cost
while keeping excellent timing performance and low noise

- **the “standard” gas mixtures**
  - are HFC based
    - mainly $C_2F_4H_2$ (GWP = 1430)
    - and $SF_6$ (GWP = 23900)
- **several test ongoing**
  - using Ar/$C0_2$ mixtures
    - promising, used also in MPGD
    - and cheap
  - another possible candidate: HFO-1234ze
    - (tetrafluoropropene), GWP < 1
    - here (ECO) test-beam tested

*Baek et al., JINST 14 (2019) 11, C11022*



**similar efficiency plateau at 4kV higher operation**

low dark current, specially low with $SF_6$

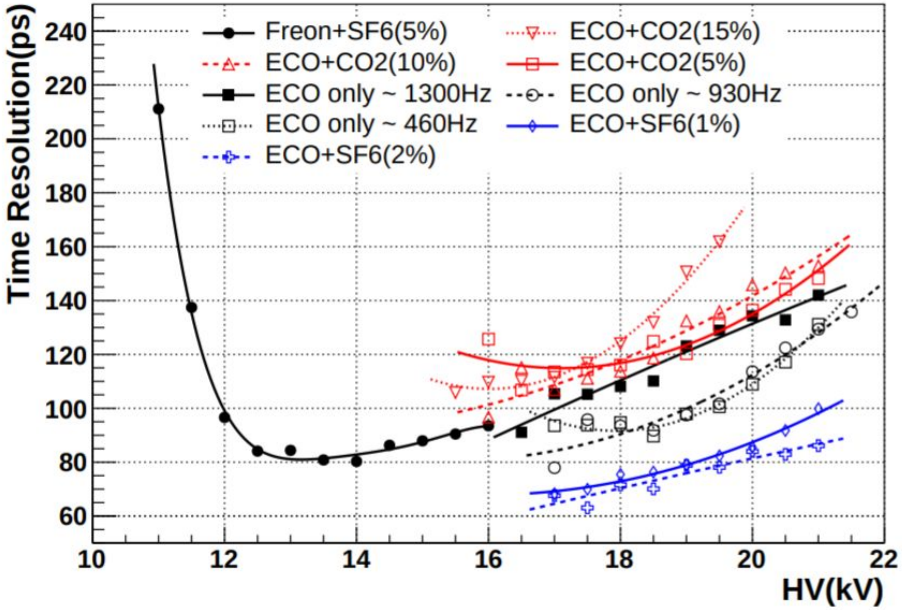
# MRPC with eco-friendly gas

**searching for new eco-gas mixtures**

with low Global Warming Potential and reasonable cost
while keeping excellent timing performance and low noise

- **pure ECO or with $CO_2$**
  - slightly worse performance than STD
    - efficiency plateau unstable
    - higher time resolution
- **adding $SF_6$ to ECO**
  - very similar performance to STD
    - strongly electronegative gas needed
- **ideas to replace $SF_6$**
  - try $CF_3I$ (trifluoroiodomethane)
    - GWP < 5
  - try 3-component mixtures

*Baek et al., JINST 14 (2019) 11, C11022*



**very important and promising directions for the future**

do not forget also efforts to reduce flow and improve recirculation systems

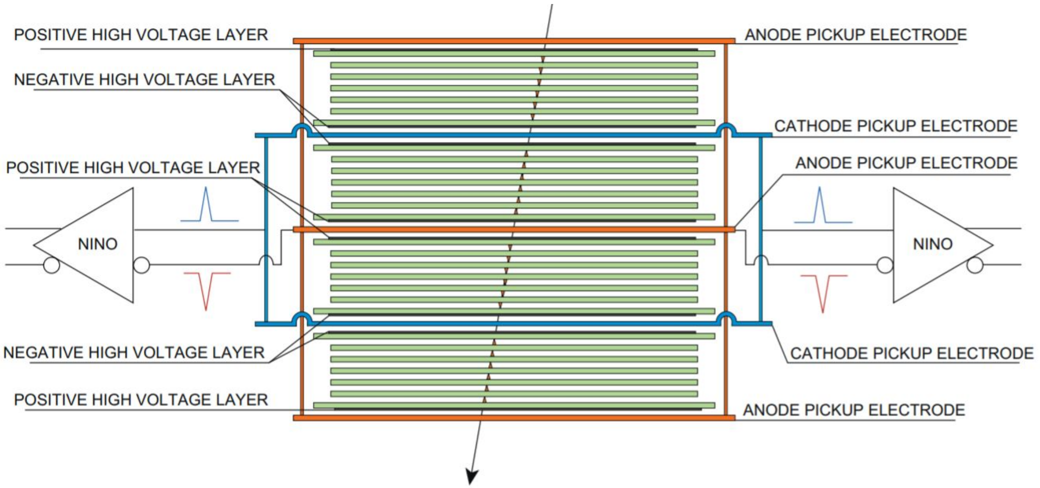
# 20 ps with MRPC

**a number of R&D projects putting effort in improving performance**

high rate capability up to 10 kHz/cm$^2$
ultra-high time resolution better than 20 ps

- **24-gap MRPC detector**
    - 4 stacks each with
        - 6x gas gaps of 160 μm
        - pickup pads between each stack
- **compared to the ALICE MRPC**
    - 2 stacks each with
        - 5x gas gaps of 250 μm
- **one expects**
    - intrinsic time jitter decreases by 2x
        - faster electron velocity
    - narrower charge spectrum

*An et al., NIM A 594 (2008) 39*



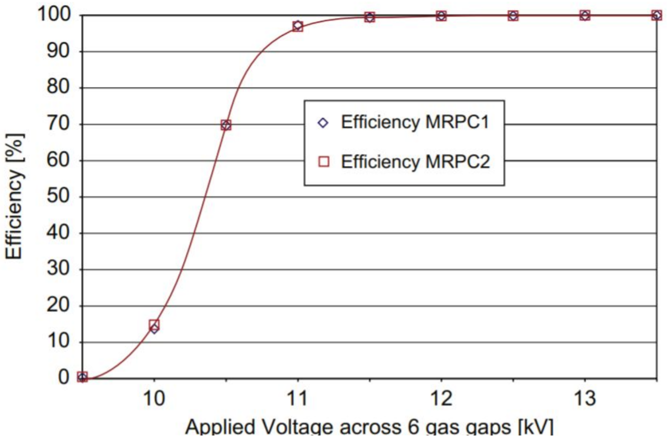
**very important to have good-enough electronics**

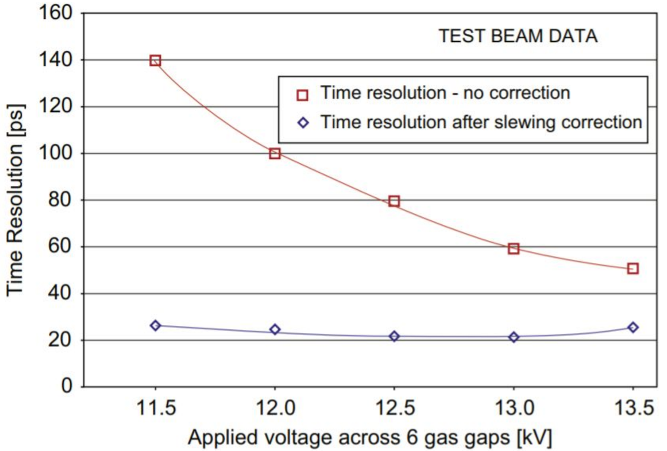
test-beam measurements with NINO ASIC + oscilloscope readout

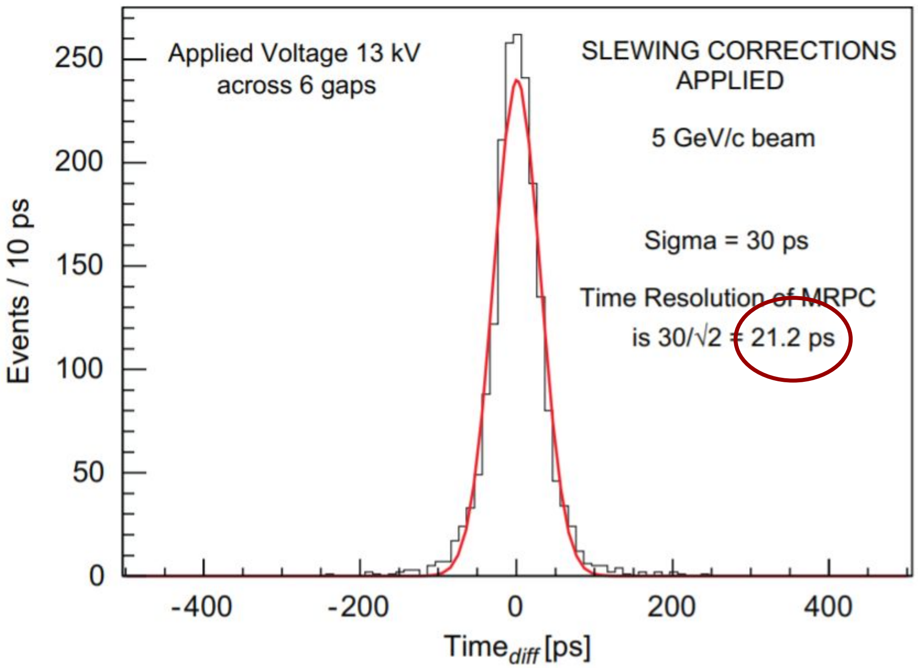
# 20 ps with MRPC

*An et al., NIM A 594 (2008) 39*

CERN-PS test-beam results
$C_2F_4H_2$ (95%)   $SF_6$ (5%)







**outstanding results**

with room for improvements with better electronics

# Summary

- **Time-of-Flight systems in HEP experiments**
    - are an essential part for charged-hadron identification
        - but also for electron identification in combination with dE/dx
    - powerful technique (but only viable) up to intermediate momenta
- **Multigap Resistive Plate Chamber**
    - have become the new standard technology for TOF systems
    - easy to build, excellent performance and stability of operation
        - developed for the ALICE experiment
        - employed by others: STAR, HADES, FOPI, ...
        - and adopted for the future: CBM, SHIP, SOLID, …
    - several important improvements and R&D studies since their invention
        - high rate capability
        - ultra-high time resolution
        - operation with eco-friendly gas mixtures
- **Perspectives for the future**

# Perspectives

**large gaseous TOF arrays** can be successfully built and operated **at colliders**

- excellent performance of **MRPC technology**
  simple, stable, efficient and reliable detectors
  intrinsic resolution can be improved (24-gap MRPC prototypes, < 20 ps)

- **soon improved front-end** (SuperNINO) and **TDC readout** (picoTDC, SAMPIC)
  combined electronics with ~10 ps resolution

- **calibration** of a very large number of channels **can be done**
  ~15 ps contribution in ALICE-TOF (with ~60 ps signals)
  can be < 10 ps for narrower signals

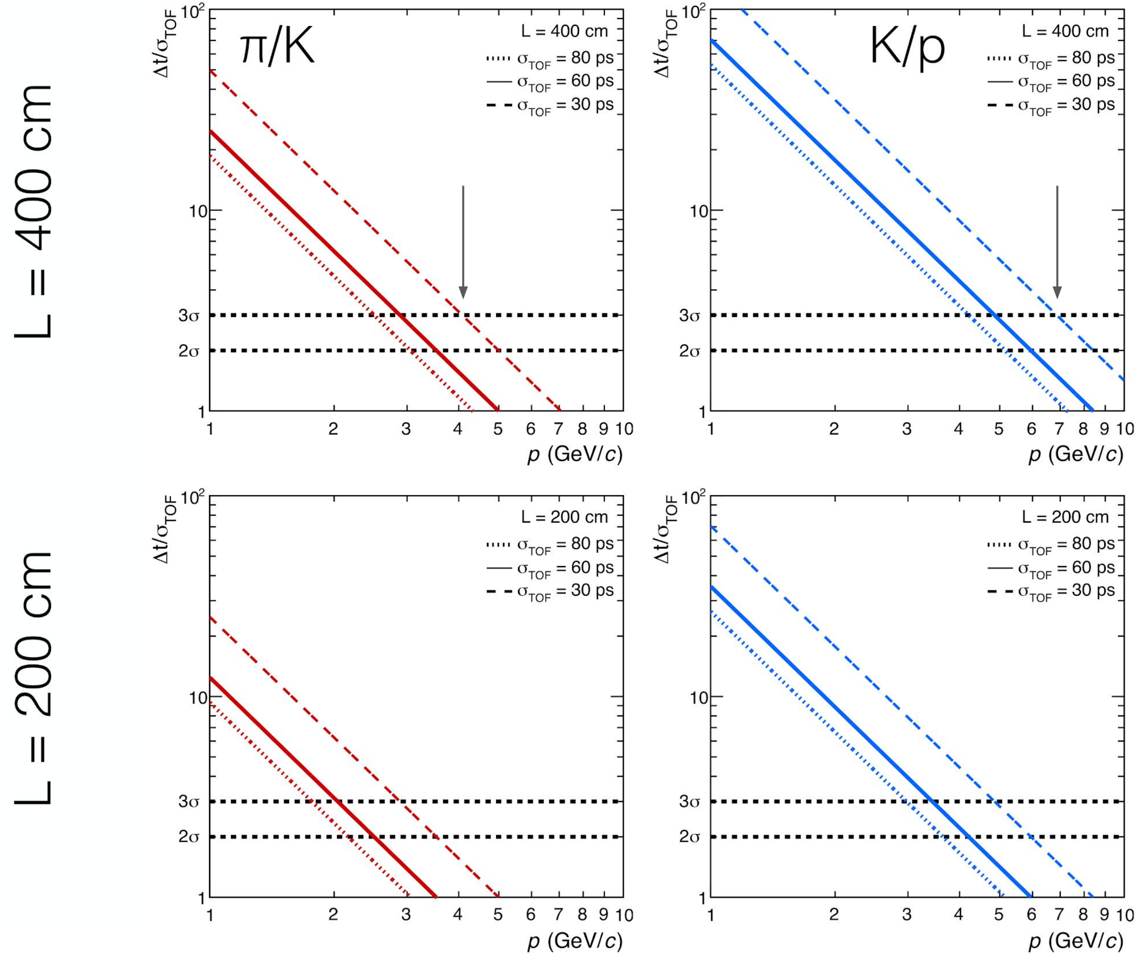
- putting all together → **25 ps**
  20 ps (intrinsic) + 10 ps (electronics) + 10 ps (calibration)

- what about the **start-time**?
  assuming a machine with 5 mm long bunch ($e^-$ beam in BNL EIC proposal)
  ~15 ps start-time uncertainty (if not measured)

- room for **TOF with sub 30 ps** PID performance
  high-momentum TOF (1.4x wrt. ALICE-TOF momentum reach, 3σ K/p up to 7 GeV/c, same dimensions)
  compact TOF (2x smaller radius, 4x smaller area wrt. ALICE-TOF, same momentum reach)

- applications for **future colliders** (EIC, HL-LHC, FCC)

# Perspectives



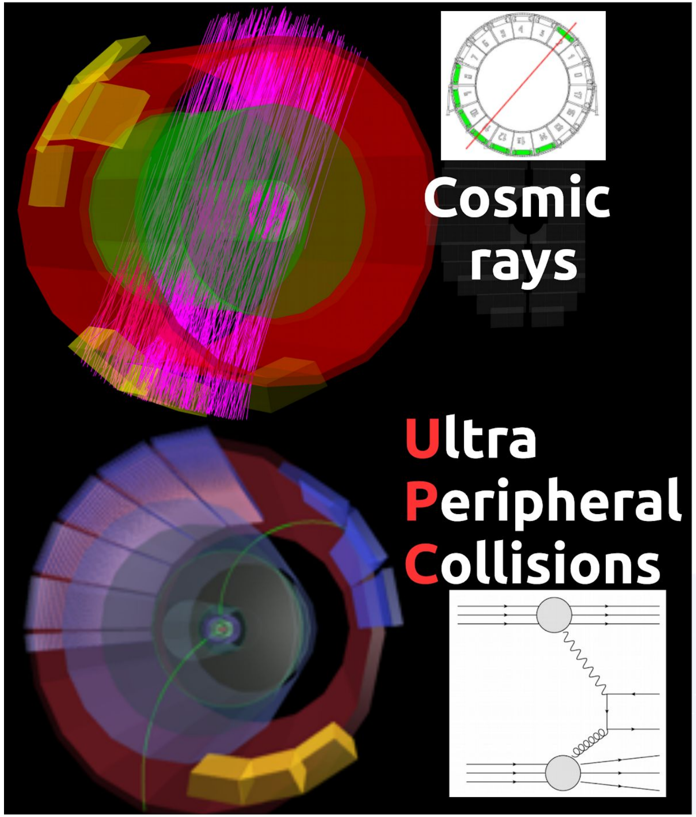
with 30 ps resolution
better than 3σ PID
K/π 4 GeV/c
p/K 7 GeV/c

or build a TOF system
4x smaller area than
ALICE-TOF
better than 3σ PID
K/π 3 GeV/c
p/K 5 GeV/c

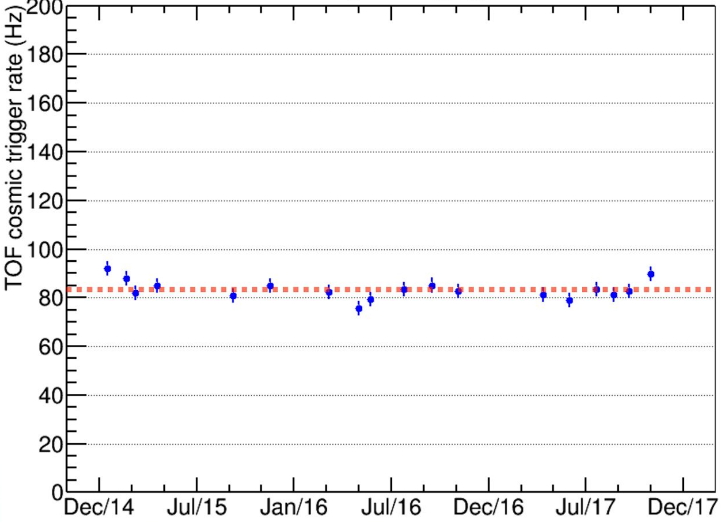
END

# Trigger

TOF provides **triggers for cosmic-ray and UPC physics**



cosmic-ray trigger rate



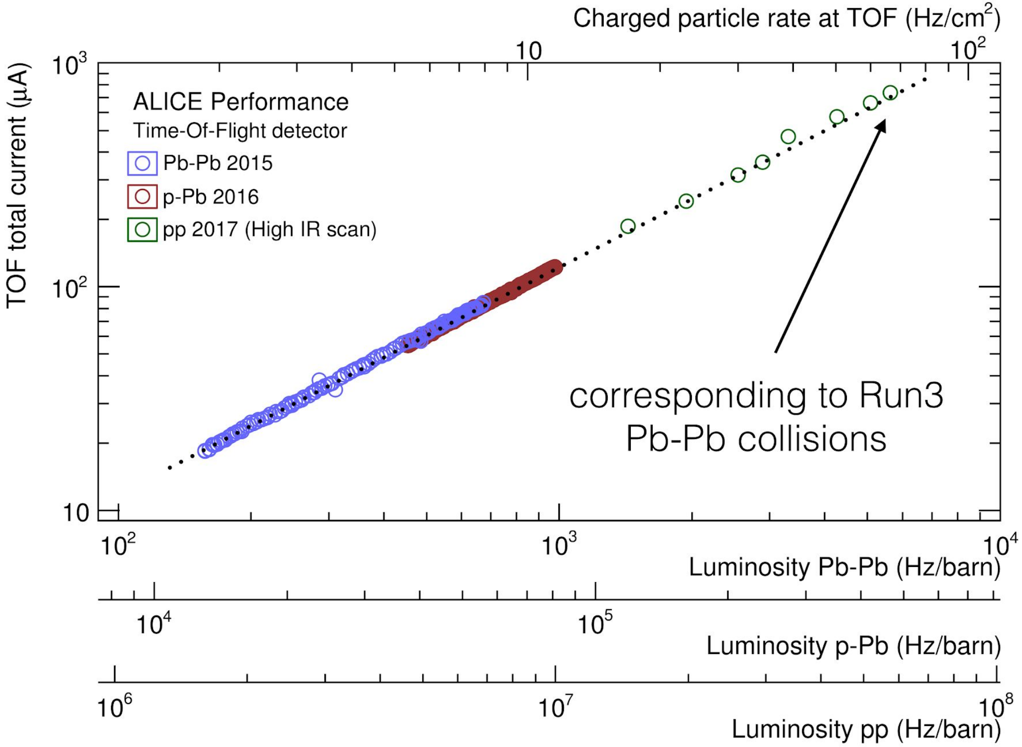
~1700 trigger channels

half MRPC

**very stable** trigger rate

# Total current

current measurements as a function **charged-particle flux**



corresponding to Run3
Pb-Pb collisions

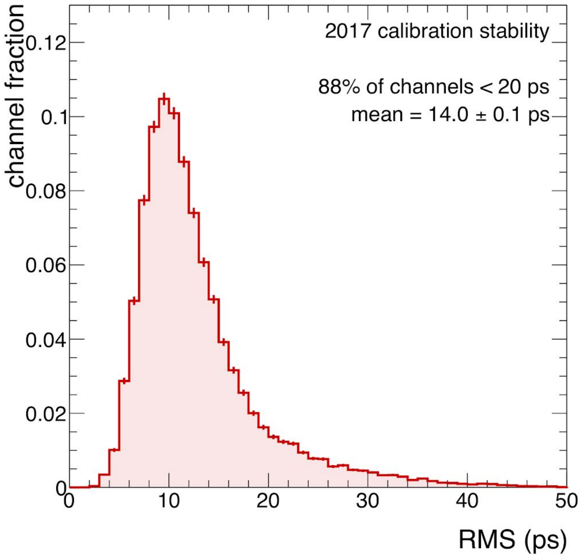
**luminometer**, no sign of deviations up to **very high flux**

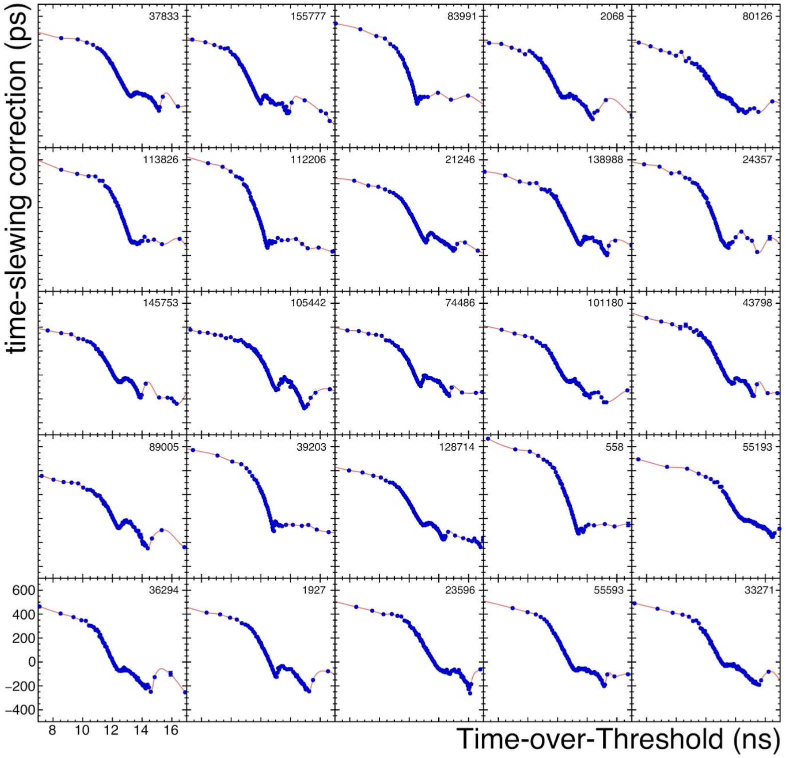
tested highest expected flux for Run3

# Calibration

## **fine tuning** the time-amplitude (time-slewing) correlations

time-over-threshold correction for >150k channels measured with high precision





testing calibration stability

**very stable during the year**

RMS possibly related to $\sigma(t_{calib})$ ~15 ps