The Present and Future of Time-Of-Flight

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Seminar at Vanderbilt
Nashville, TN
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OUTLINE:

• The TOF technique and
some "conventional" TOF systems...

Too expensive to cover a large area
with the conventional technology...

• A new technology: the MRPC...
high-resn, easy to build, cheaper...

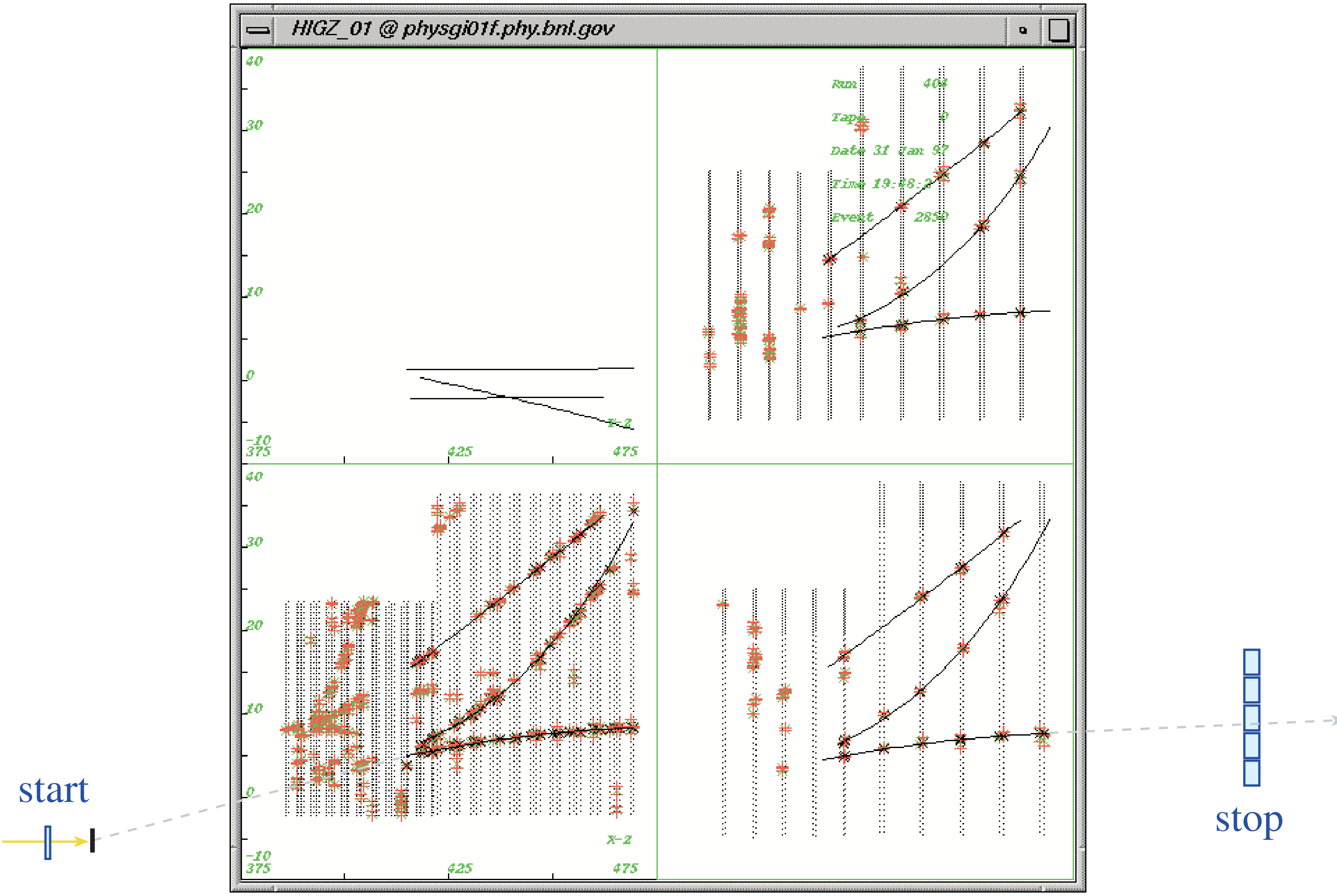
• The MRPCs developed for STAR...

• The STAR TOFr and TOFr' Systems...

• ALICE MRPCs & HARP MRPCs...

• Summary

“Tracking” charged particles through a magnetic field....



Information available following “reconstruction” of a track
→ track trajectory....
→ track momentum components...
→ track path length between any two points on the trajectory...

One can furthermore directly **identify each track** using Time-Of-Flight
→ new or supplemental capabilities for Particle IDentification (PID)

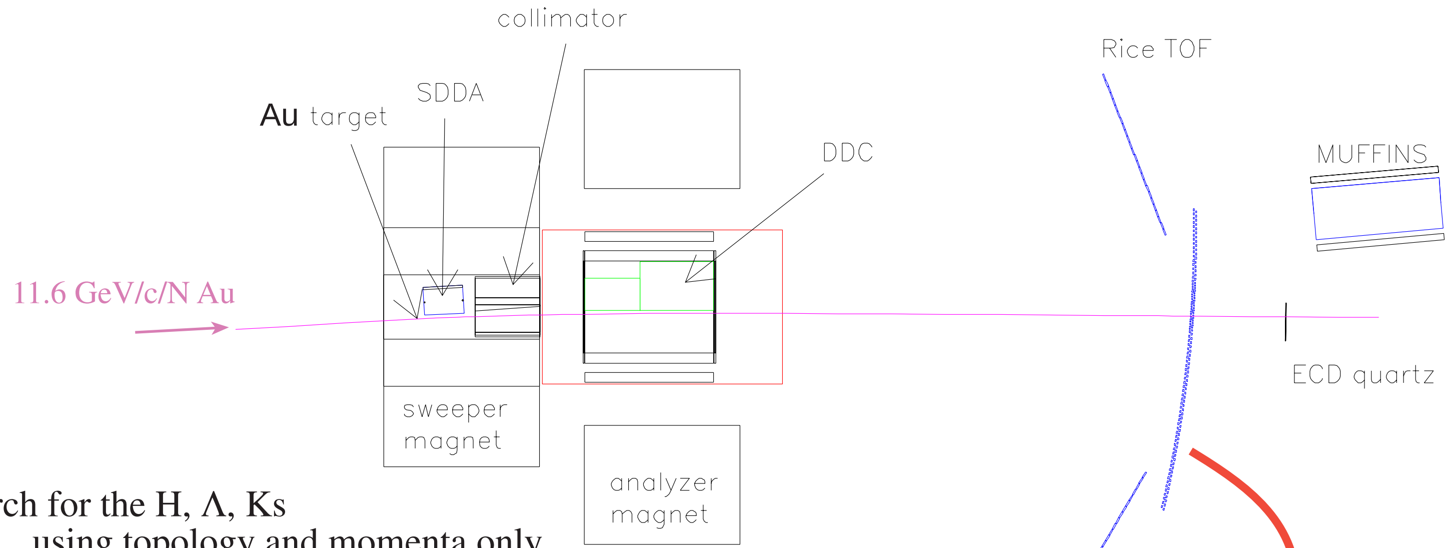
just measure a *time* at one point along this track
relative to a specific reference time.

time = stop time - start time (and lots of corrections)

path length = **velocity** * time → $\beta = S/\Delta t/c$

momentum = **mass** * velocity → $m = p/(\gamma\beta)$

"Conventional" TOF Example 1: BNL-AGS E896 TOF



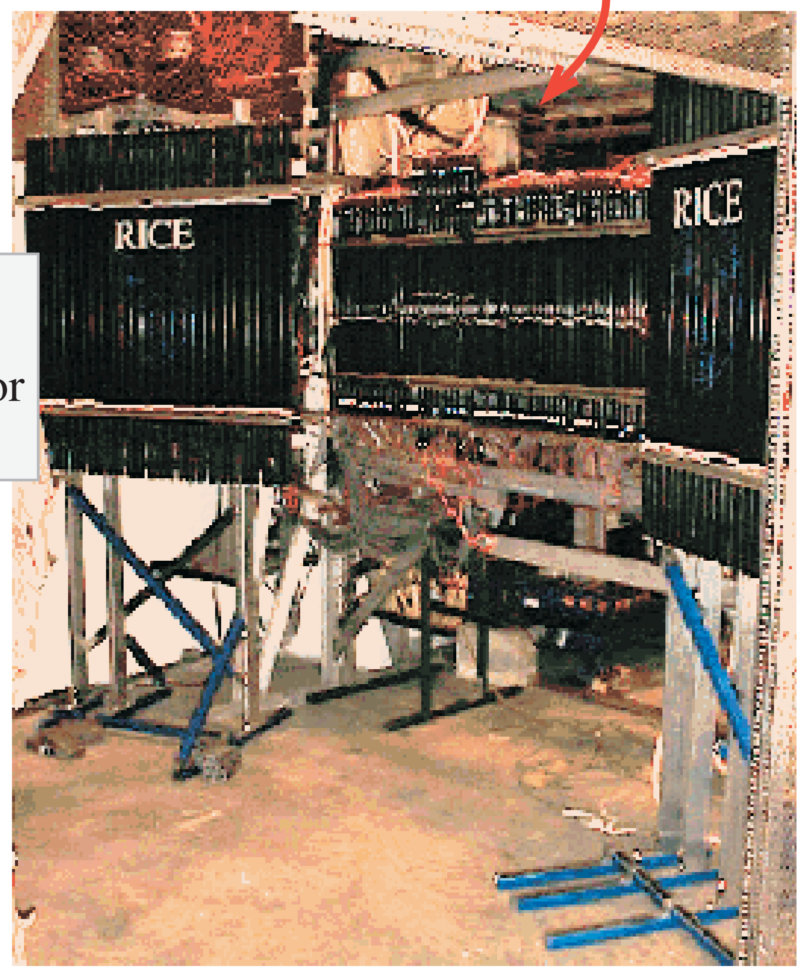
Search for the H, Λ, Ks
using topology and momenta only
BUT.... no direct PID on the charged daughters

does each candidate Λ → p & π-??

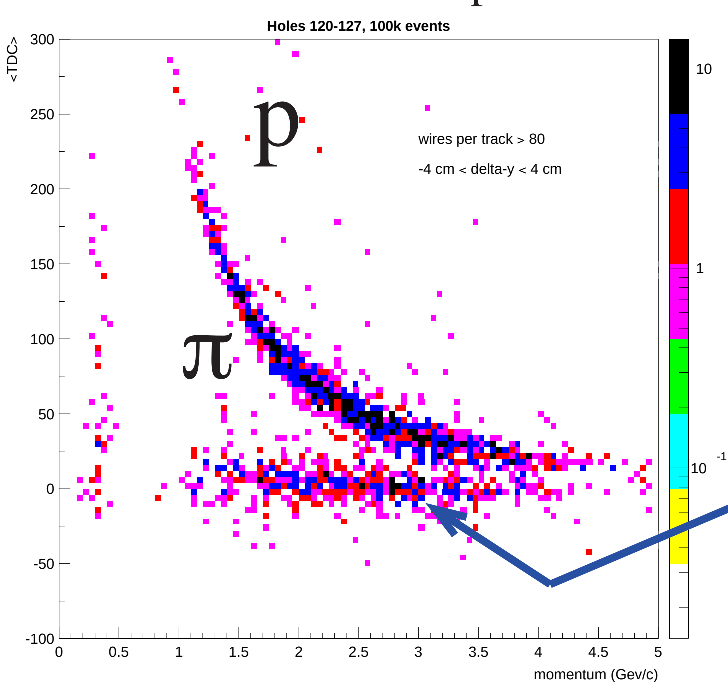
does each candidate Ks → π+ & π- ??

does each candidate H → p & X ??
(X = Σ- → n & π-)

- ~1m-long double-ended slats
- phototubes
- discrimination close to detector
- digitization after long cables



E896 candidates: Λ?→positive....

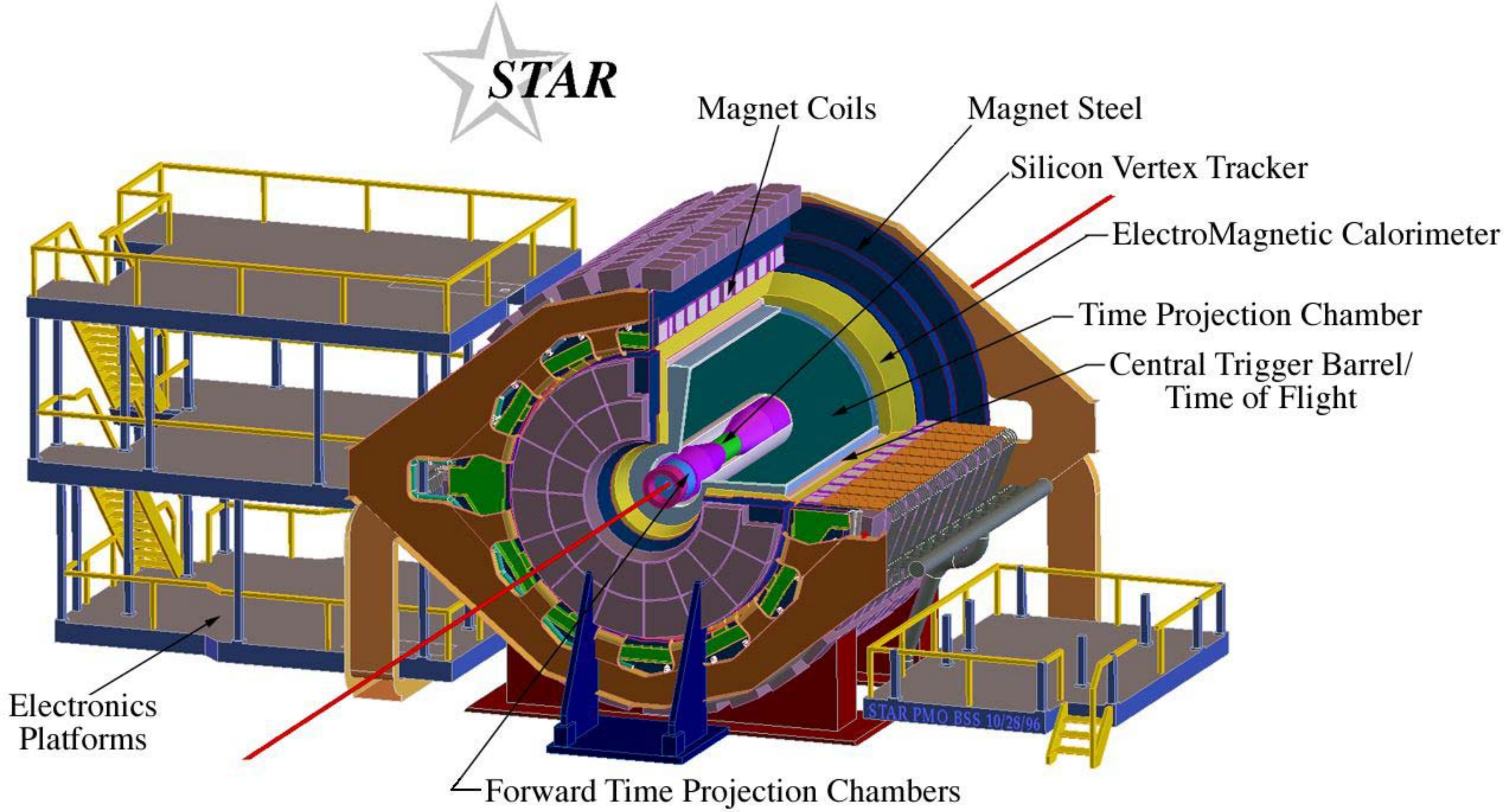


- ~10% of E896's best Λ candidates are *not* Λ's...

  1/3 are really Ks
  2/3 are other backgrounds

- Λ and Ks spectra w/ daughter PID

  (K. Kainz, Ph.D. Thesis, 2001)



RHIC runs so far...

65 GeV/c/N	Au +	65 GeV/c/N	Au
100 GeV/c/N	Au +	100 GeV/c/N	Au
10 GeV/c/N	Au +	10 GeV/c/N	Au
100 GeV/c	p +	100 GeV/c	p
100 GeV/c	d +	100 GeV/c	Au

Run-IV is just about to start!

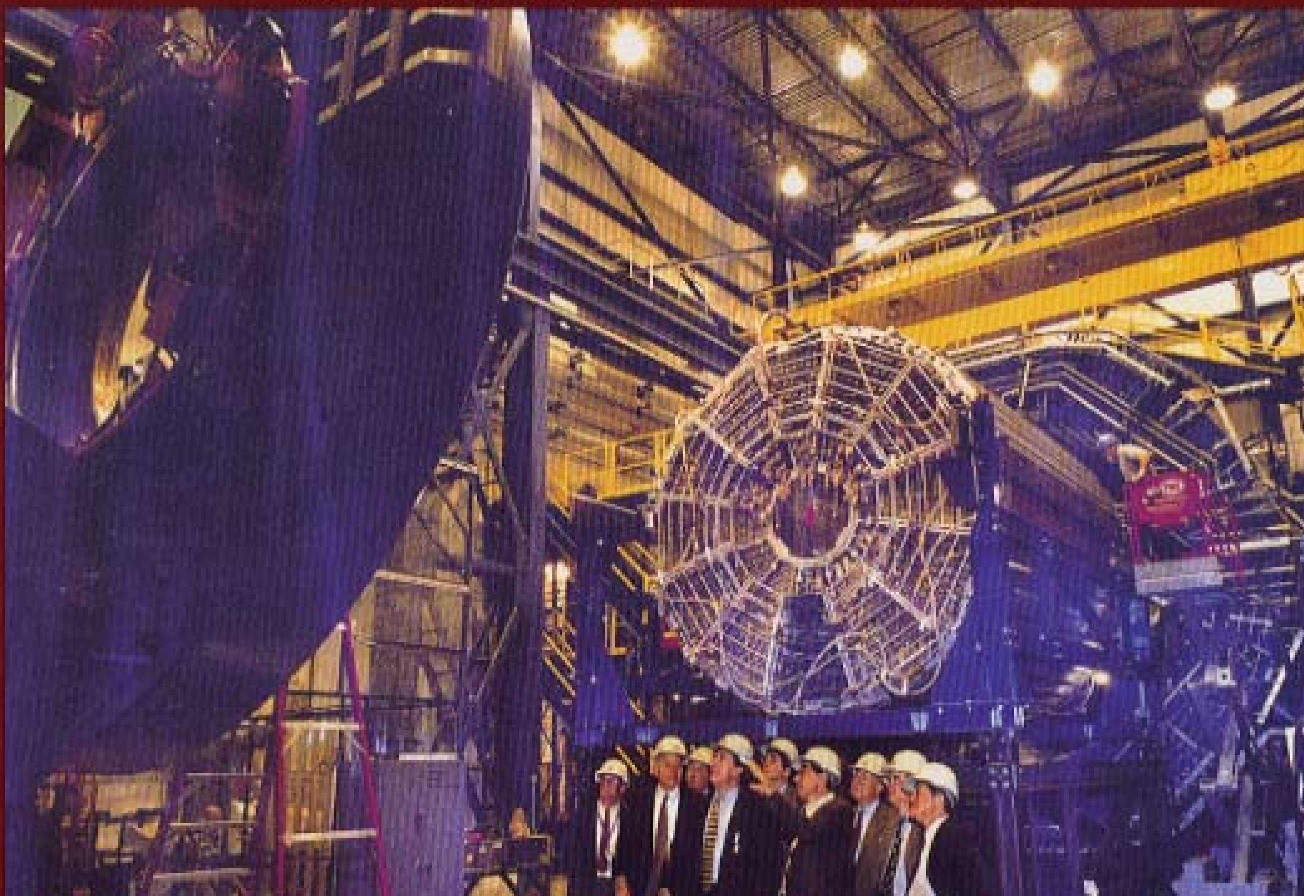
100 GeV/c/N Au + 100 GeV/c/N Au

ALICE at CERN LHC

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERN COURIER

VOLUME 39 NUMBER 1 FEBRUARY 1999



A STAR in the making

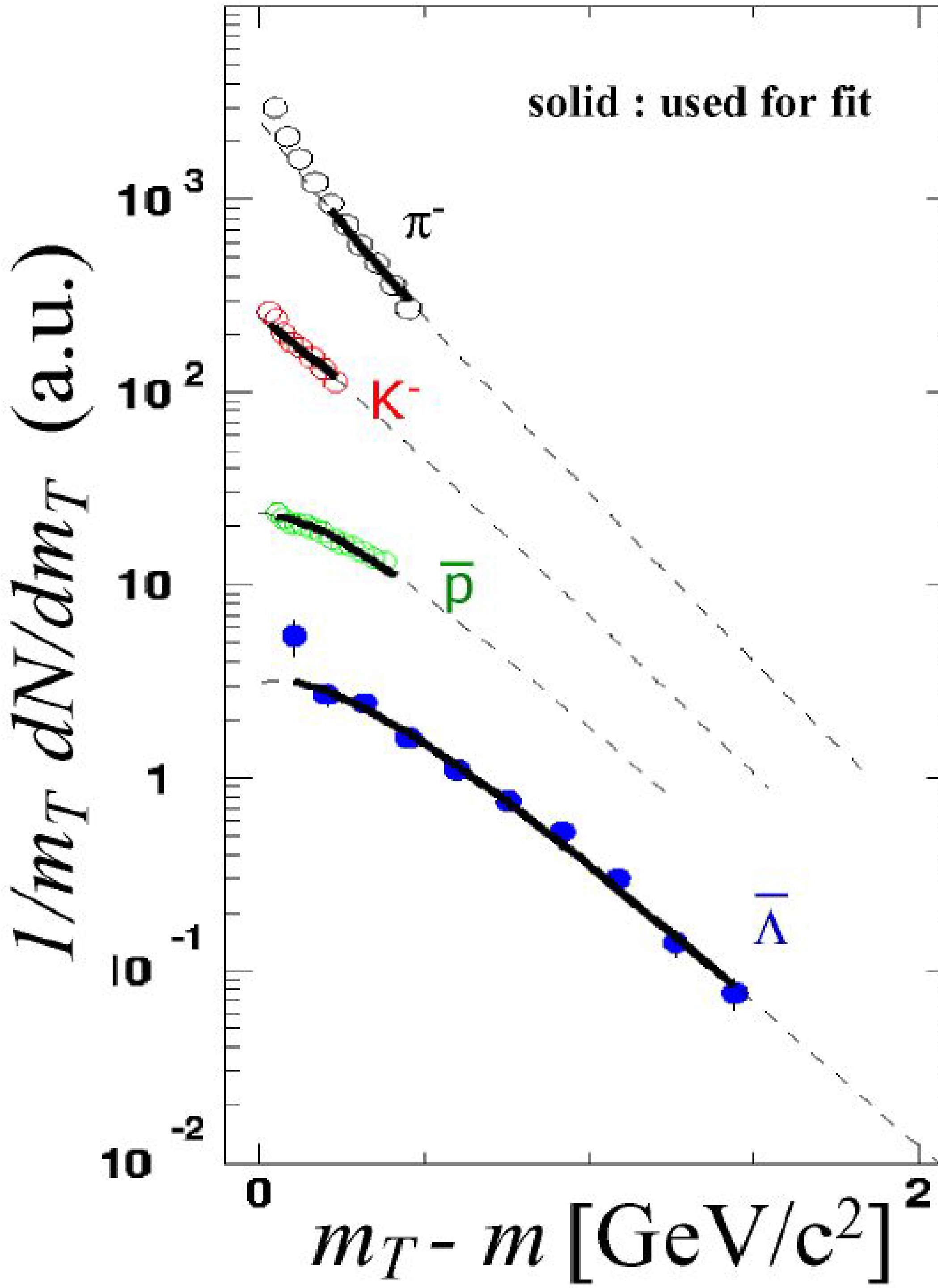
LHC COLD START
Procurement and construction work for CERN's LHC project begin in earnest

EPIC DEVELOPMENTS
Physics helps and is helped by a new generation of microprocessors being tested at CERN

MYSTERIES OF COSMIC RAYS
Unexplained phenomena in the ultra-high-energy area point to gaps in our understanding

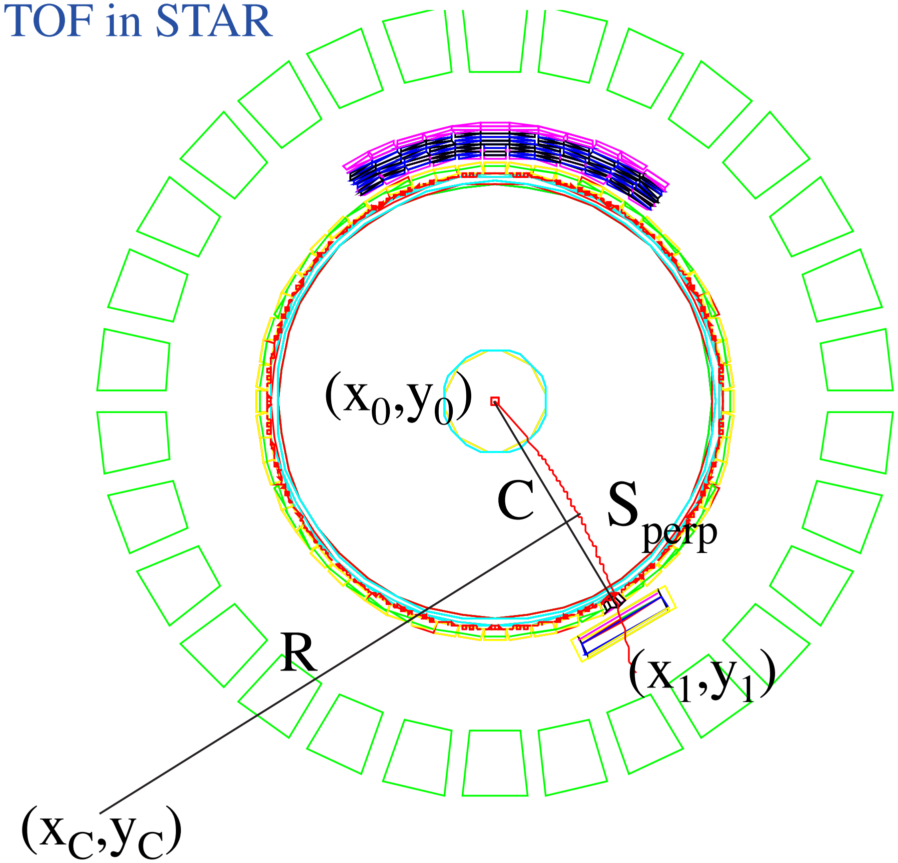
example of STAR's reach w/ TPC dE/dx alone...

(old) plot by
M. Kaneta



the domain of TOF...

TOF in STAR



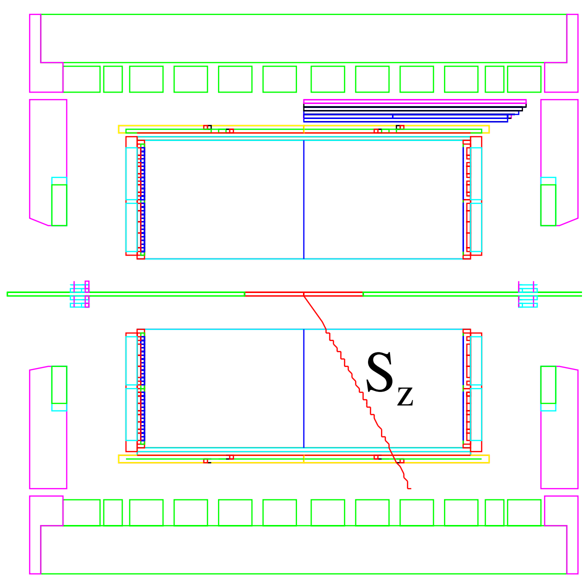
$s = \sqrt{(s_{perp}^2 + s_z^2)}$ with

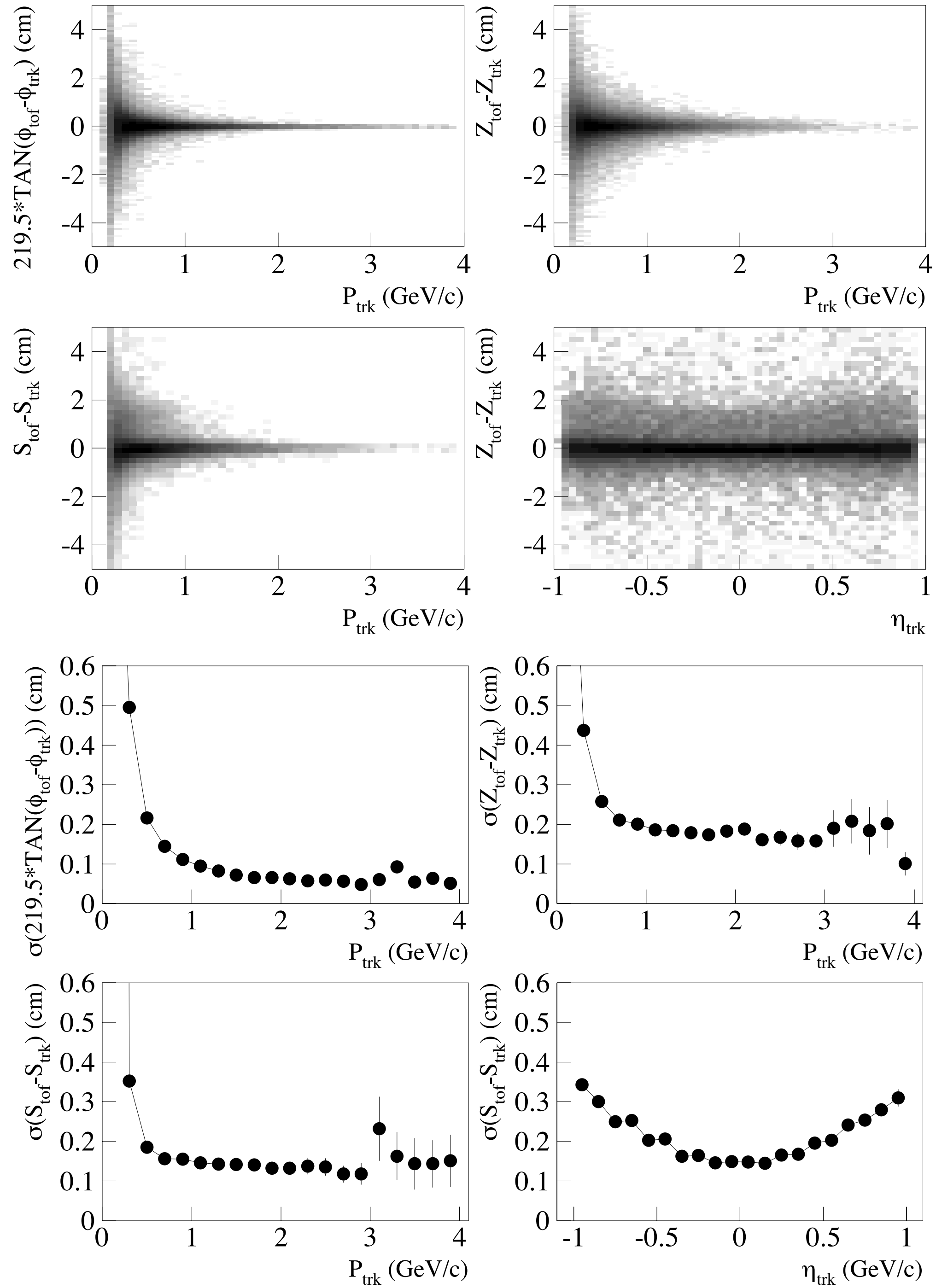
$s_{perp} = 2R \sin^{-1}(C/2R)$

$s_z = z_1 - z_0$

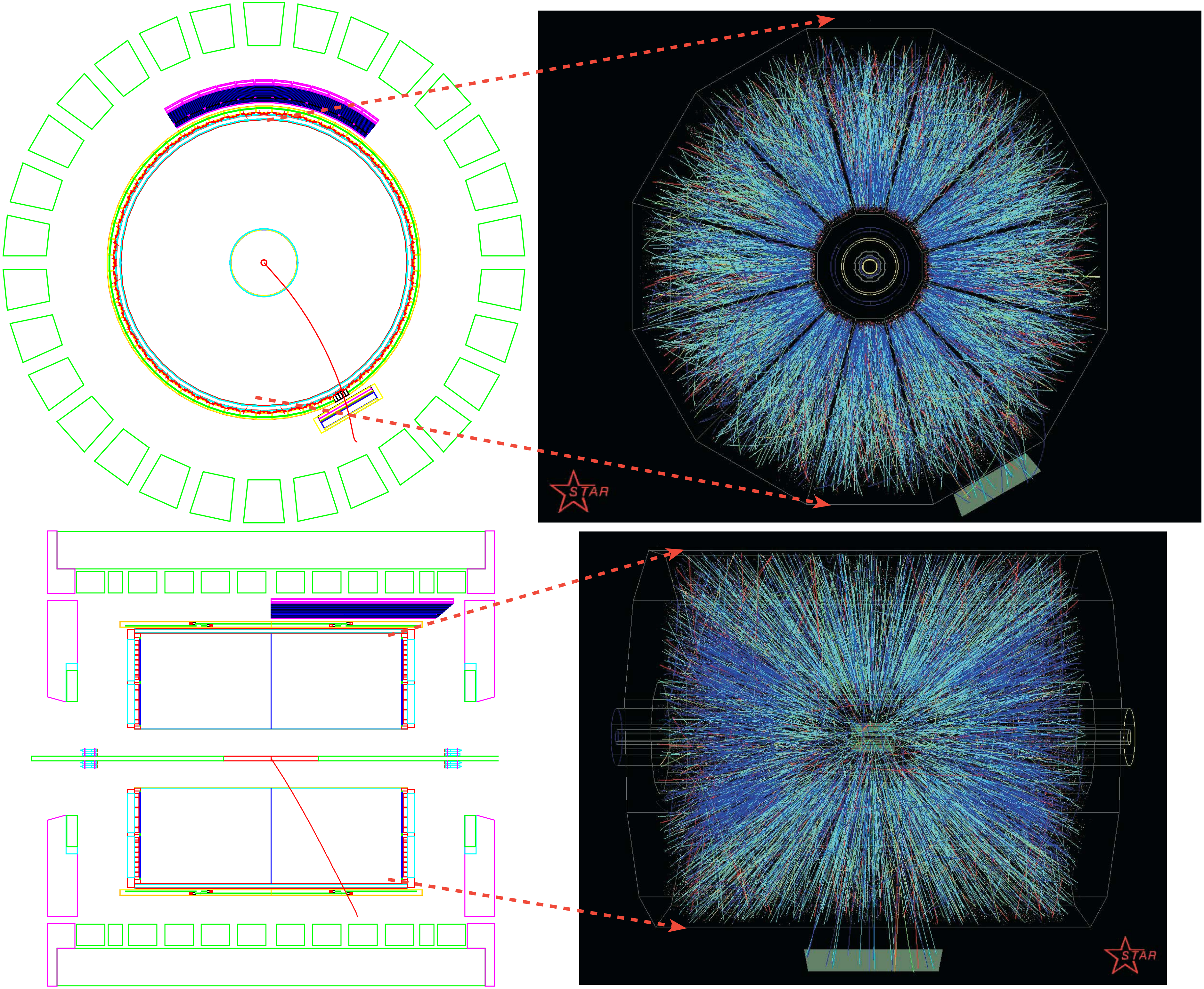
R is the helix radius

$C=\sqrt{((x_1 - x_0)^2 + (y_1 - y_0)^2)}$

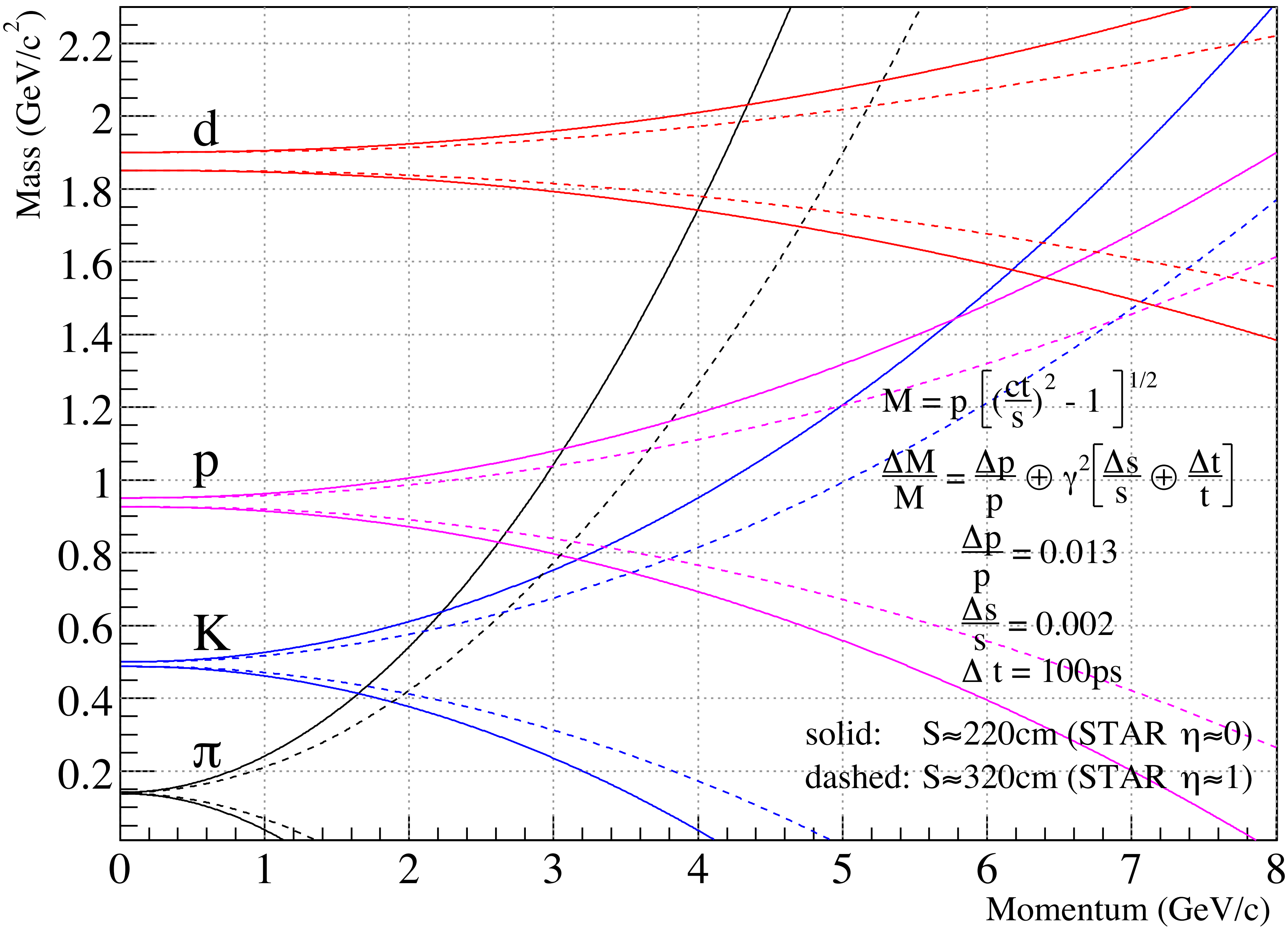




...the STAR TPC an extremely powerful tracker for a TOF system...


STAR
STAR

PID reach for TOF in STAR (here assuming a 100ps TOF system)



in STAR: TOF resolution by far the dominant contribution to total mass resolution...
better total timing resolution of course gives PID to higher momenta...

“Conventional TOF” example 2:

STAR Time-Of-Flight Patch (TOFp/pVPD)

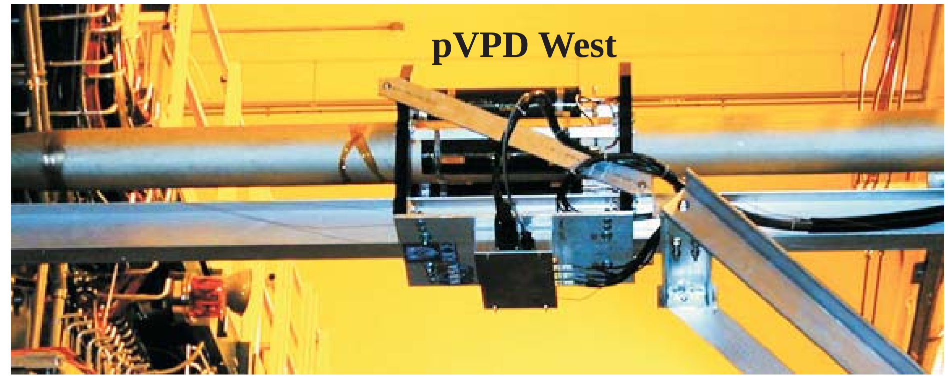
Start detector: pVPD, Stop Detector: TOFp tray

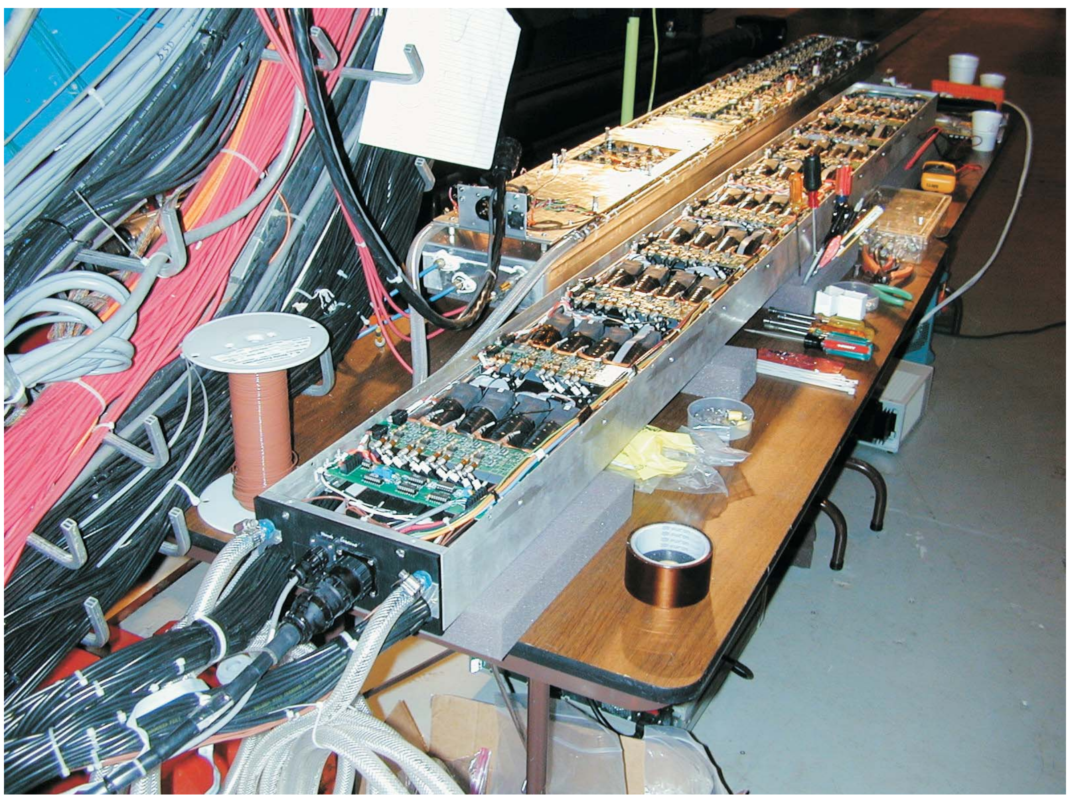
Conventional technology: scint+(mesh)PMT
On-board custom FEE
Camac digitization after long cables

41 total stop channels, $\Delta\eta \sim 1$, $\Delta\phi \sim 6$ degrees

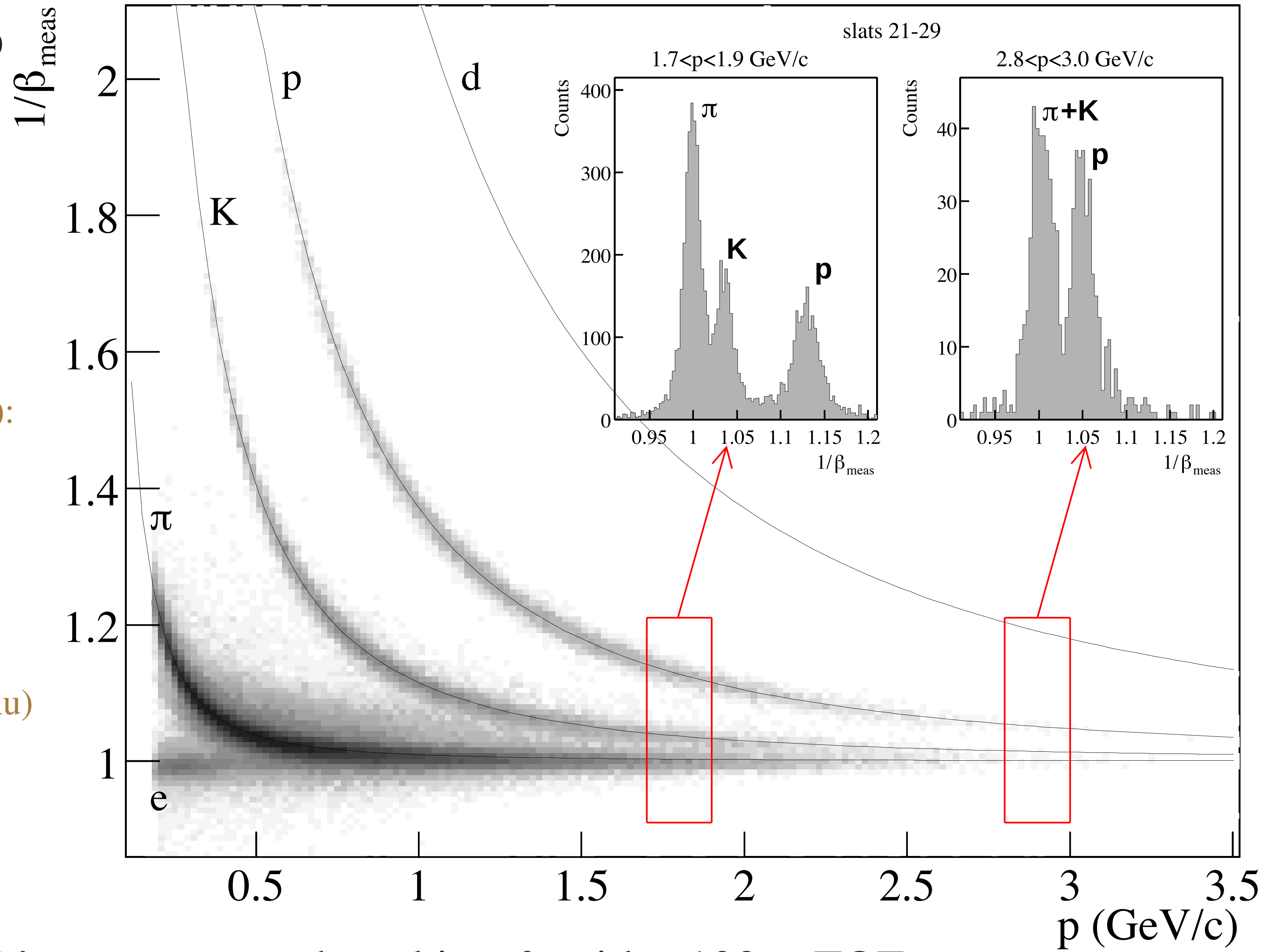
good data from Runs 2 and 3, ready for Run-4...

(also see W.J. Llope et al, nucl-ex/0308022, NIM A in press)





TOFp/pVPD
in Run-II



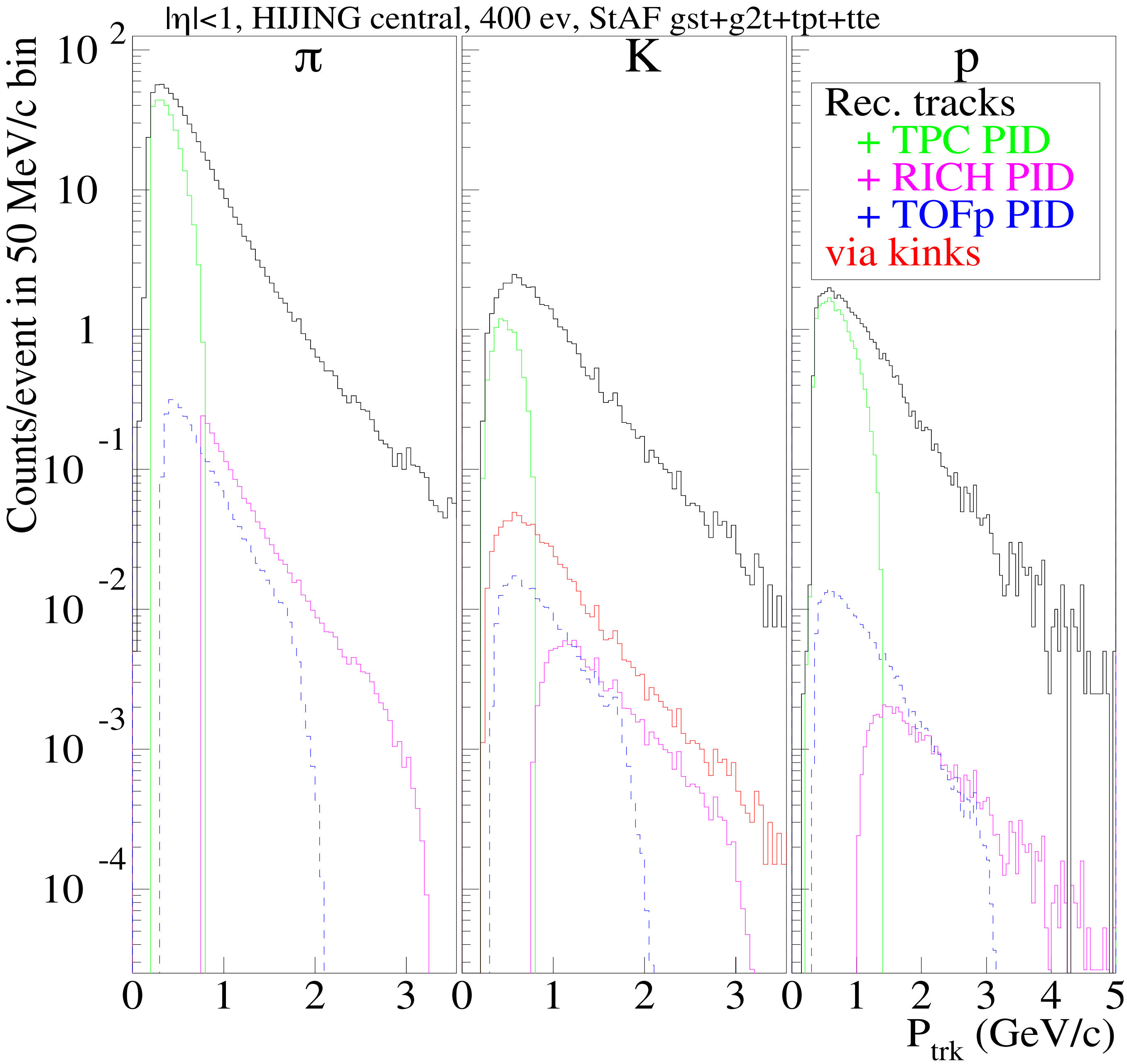
Start resn (pVPD):
~24ps
>99% efficiency

Total resn:
~87ps (all slats)
~79ps (best 25)

(for central Au+Au)

With STAR's geometry and tracking & with <100ps TOF:

- π/K/p direct PID: ~0.3 GeV/c < p < 1.7-1.9 GeV/c
- (π+K)/p direct PID: ~0.3 GeV/c < p < 2.8-3.0 GeV/c



Examples from STAR (for full energy Au+Au collisions)

TPC dE/dx directly identifies ~60% of tracks it can reconstruct

w/ a ~100ps TOF system in STAR's geometry,

→ ~97% of reconstructed tracks can be directly identified

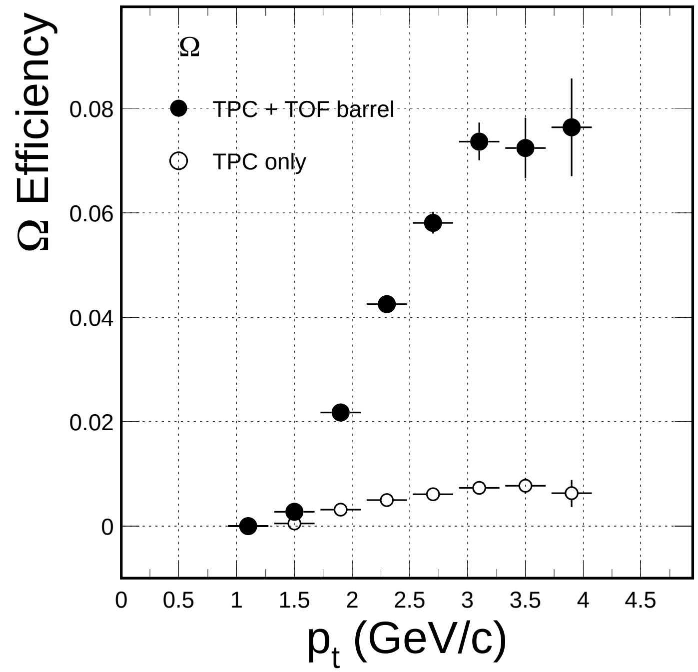
charged hadron PID at even higher momenta:

→ Cerenkov detectors (Aerogel, RICH, ...)

A small-area TOF system is not enough though...

Numerous interesting/relevant topics requiring a large-area system:

- Elliptic Flow for hadrons with no light valence quarks
- Fluctuations/Correlations studies with PID
- Away-side jet fragmentation yields and spectra
- Yields and spectra of high-mass resonances
- Unlike particle correlations
- Charmed hadron flow and yield ratios
- Exotic particle searches (pentaquark, H, ...)
- Heavy quark jets; D,B-meson spectra at high pT
- Lepton, di-Lepton spectra, Vector meson e+e- decays
- e+e- production in ultra-peripheral collisions



TOF PID significantly reduces backgrounds

→ higher-significance results in same-sized data set...

→ reduction of data set required to get same S/B...

and reduces systematic errors from correlated backgrounds due to misidentified particles

BUT

Cost of a ~50m² TOF system for STAR based on the conventional technology is >20M$

Simply can't afford large area TOF systems based on scintillator.

Resistive Plate Chambers

(in avalanche mode)

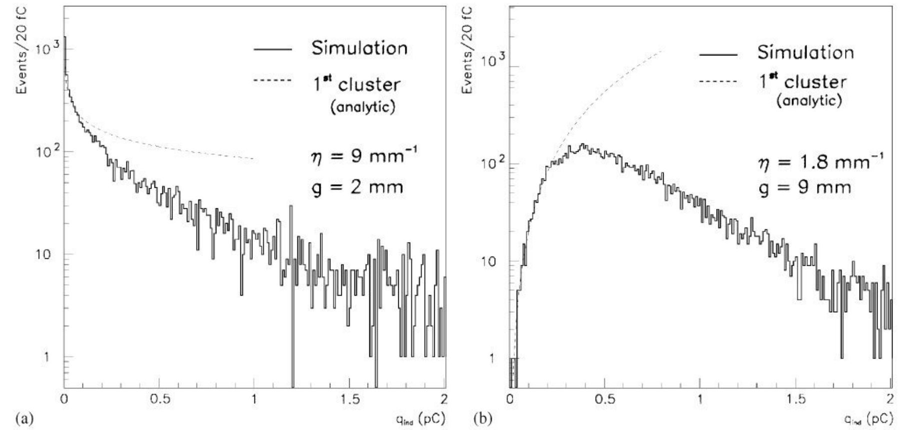


Fig. 1. Comparison between the simulated charge spectra for single (a) narrow ($g = 2$ mm) and (b) wide ($g = 9$ mm) gap RPCs.

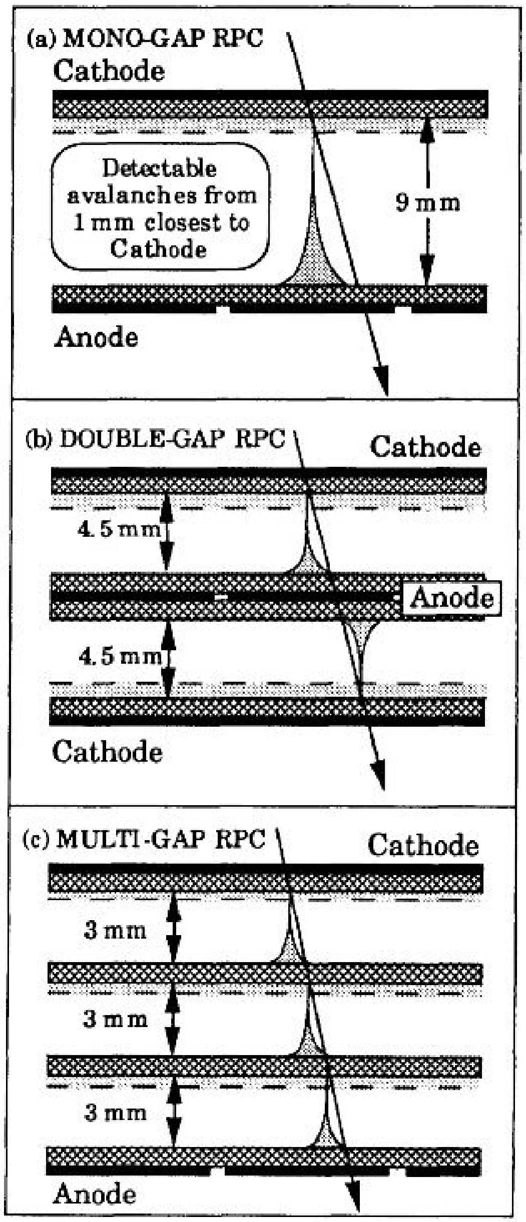


Figure 2. Schematic representation of a monogap RPC (top); a double gap RPC (middle) and a multigap RPC (bottom).

narrow single gaps don't work well in avalanche mode

wider single gaps?

enhanced streamer-free range of operating voltage

but **time resolution suffers**...

- primary ionziation is a stochastic process!
  - → timing jitter from location of ionization in RPC
- avalanches from single primary clusters tend to merge
  - → fluctuations in avalanche development dominate

many narrow gaps!

- characteristic distance for primary ionization decreased
  - → decreased jitter from primary ionization step
- N-independent avalanches, hence an averaging
  - → decreased jitter from avalanche fluctuations

optimizes the timing performance, yet leads to

signals that are "large enough" to work with...

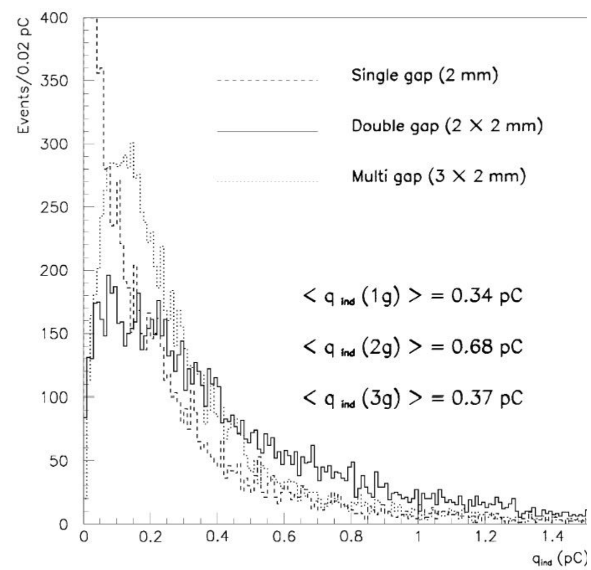
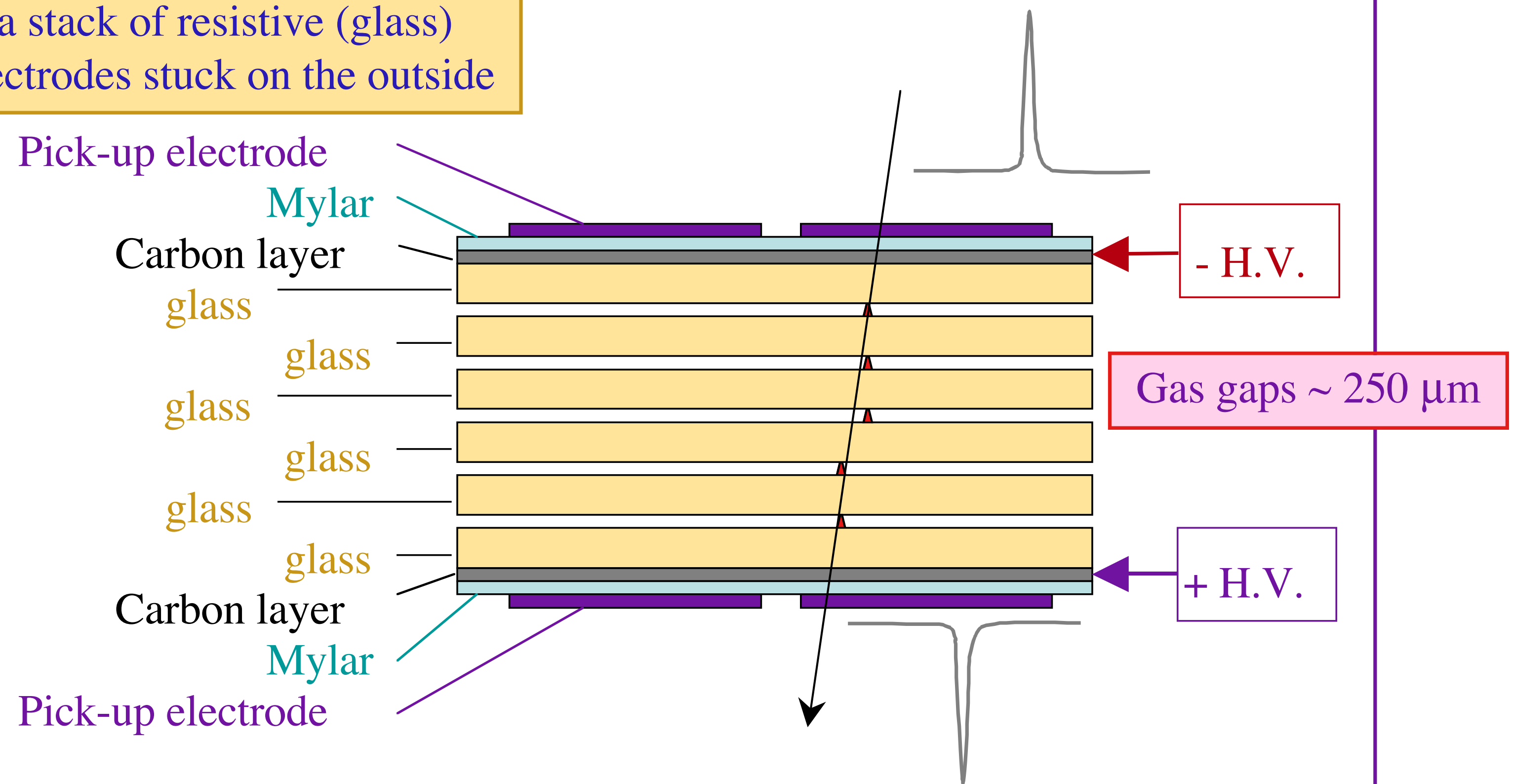


Fig. 3. Monte Carlo charge spectra for single- double- and multi-gap RPCs.

The MULTIGAP Resistive Plate Chamber

Essentially a stack of resistive (glass) plates with electrodes stuck on the outside



Note 1: internal glass plates electrically floating - take and keep correct voltage by electrostatics and flow of electrons and ions produced in gas avalanches

Note 2: resistive plates transparent to fast signals - induced signals on external electrodes is sum of signals from all gaps (also, equal gain in all gaps...)

- HV differential: ~10-15 kV
- Gas in gaps is typically 90-95% Freon R-134a, rest being isobutane and/or SF6
- signals are small: R/O requires careful amplification.

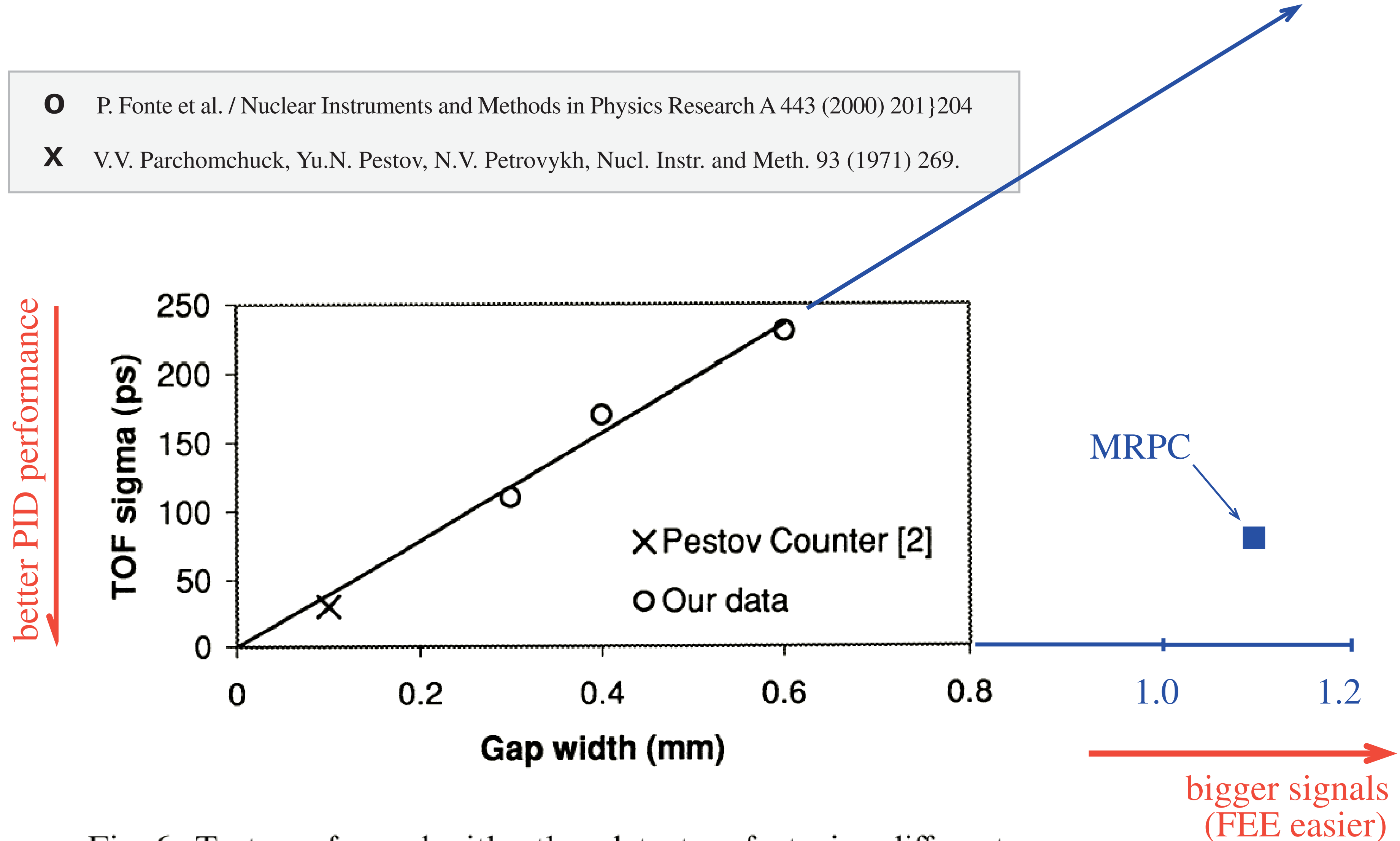


Fig. 6. Tests performed with other detectors featuring different widths of the gas gap suggest that the main contribution to the time jitter is associated to the amplification process in the gas. The timing resolution seems to depend almost linearly on the gap width, with a slope of approximately 40 ps/0.1 mm.

...acts just like the conventional technology...

...all the usual calibration techniques apply...

(ALICE prototype, figures from M. Spegel, NIM A 453, 308 (2000).

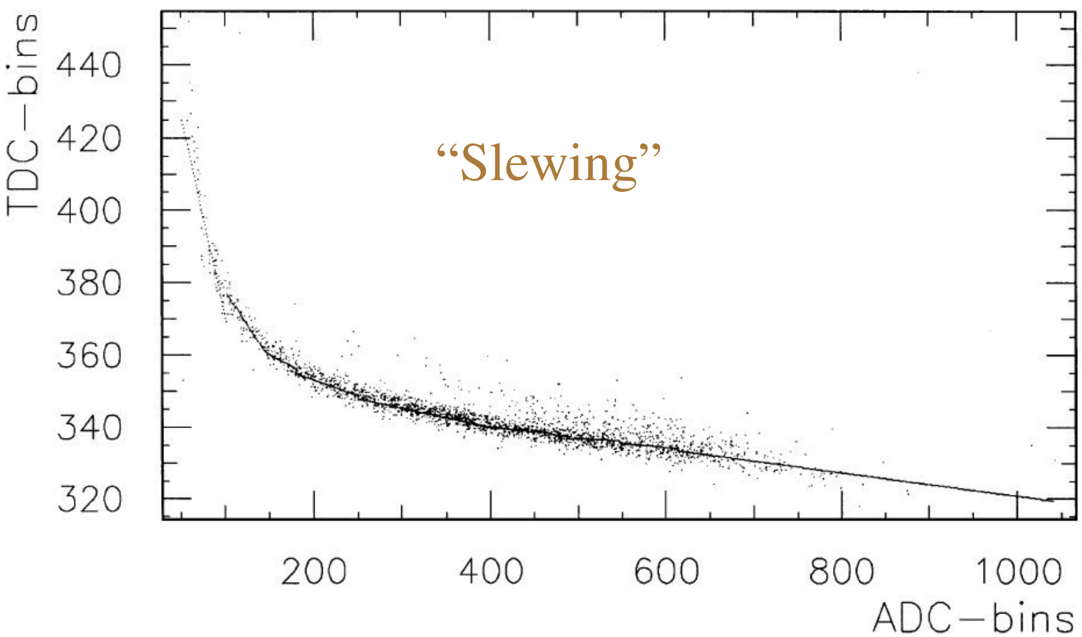


Fig. 4. Correlation of raw time difference between MRPC detector and reference counter and MRPC signal amplitude.

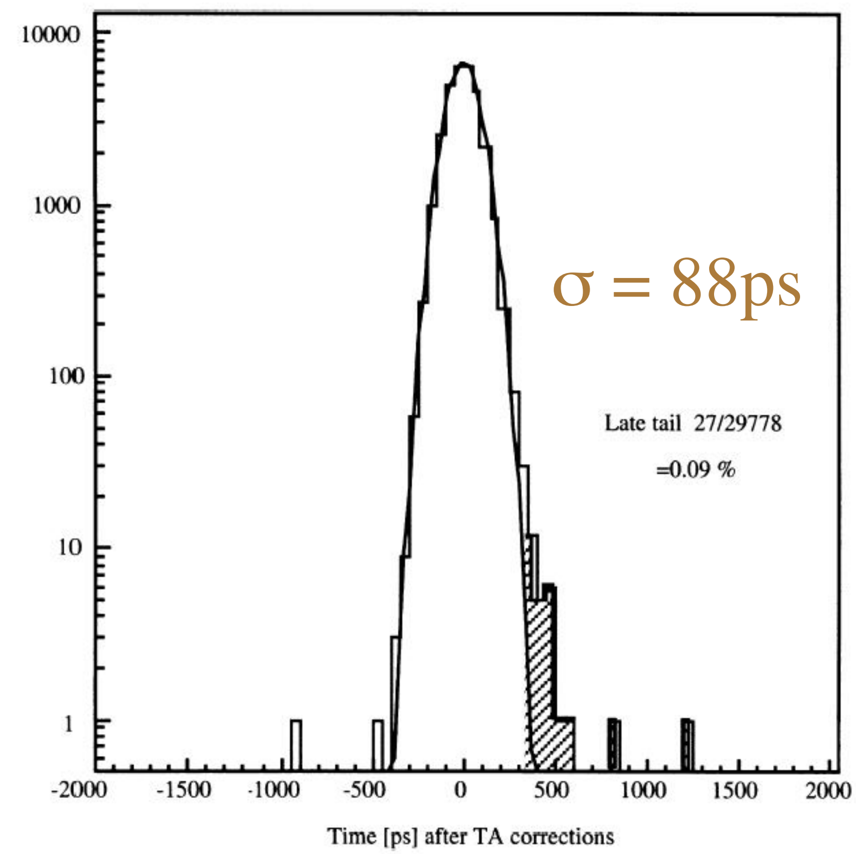
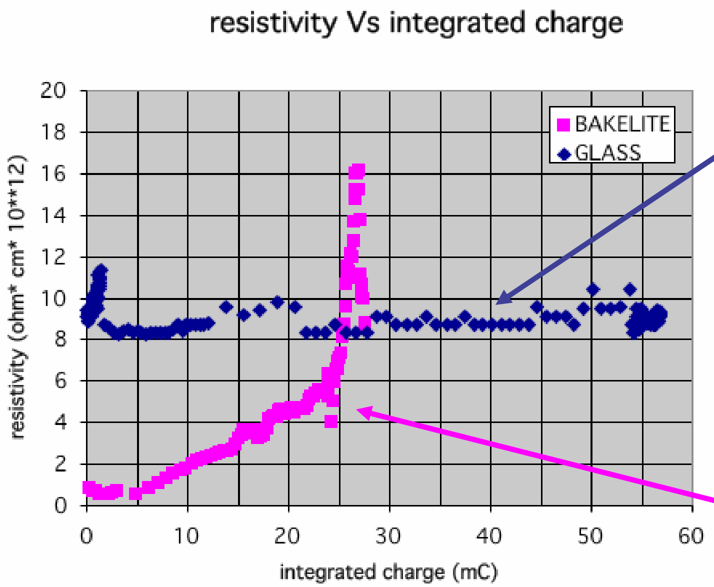


Fig. 5. Time distribution measured with an MRPC with five gaps of 220 μm operated at 12 kV (109 kV/cm). The width of the Gaussian fit is $\sigma = 88$ ps.

MRPCs are chambers w/ resistive plates but aren't, quote, "RPC's".....

1.Float Glass vs. Bakelite +linseed oil

2. Avalanche Mode vs. Streamer Mode



Float Glass:

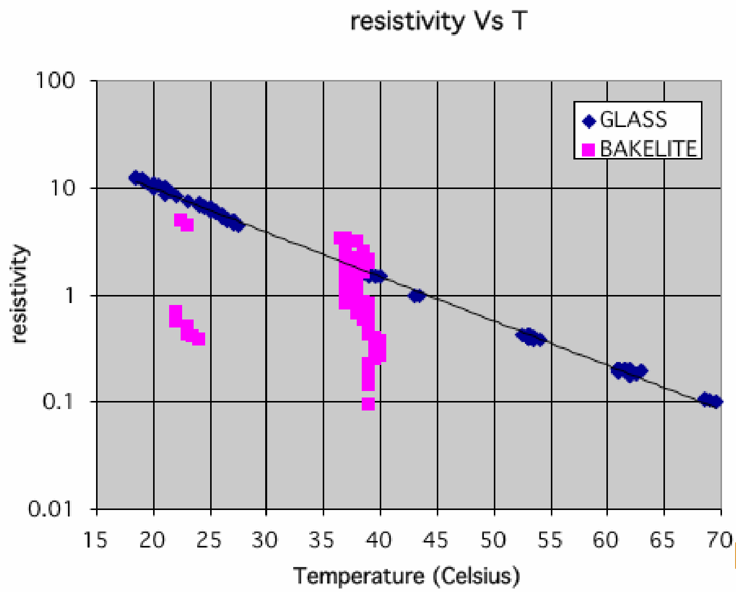
Has a stable resistivity (hopping conductivity)
$\rho=10^{12}$-10^{13} Ωcm at normal temperature

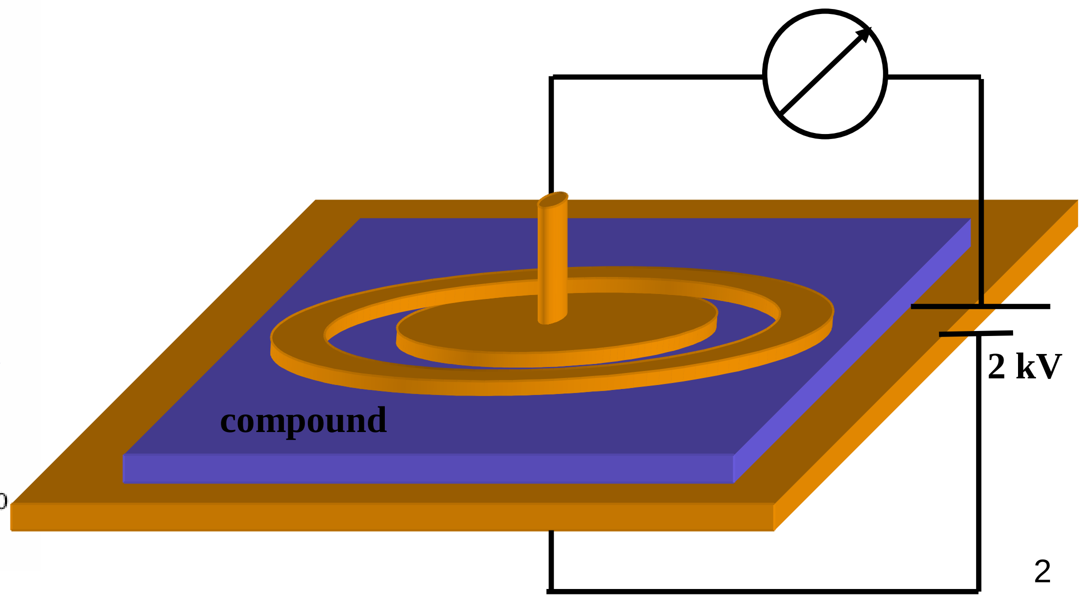
Resistivity depends only on temperature

$$\rho=\rho_{20}10^{(T-20)/25}$$

Bakelite:

$\rho=10^{10}$-10^{12} Ωcm at normal temperature
resistivity increases with the integrated charge (ionic conductivity)
Need a surface treatement with linseed oil





C.Gustavino, 20-22 october 2003, Clermont-Ferrand

ALICE TOF prototype tested at GIF over 200 days
$7\mathrm{x}10^{9}$ events/cm^{2} at 50 Hz/cm^{2} $\rightarrow$ 54 years Alice running at 30days/year

Chemical analysis (Chromatography) of the outgoing gas from both MRPCs (CH1, CH2) by CERN EST/SM-CP :
measured concentration of Fluorine under the limit of detection (0.02 **ppm**), I.e. no trace of HF in the samples

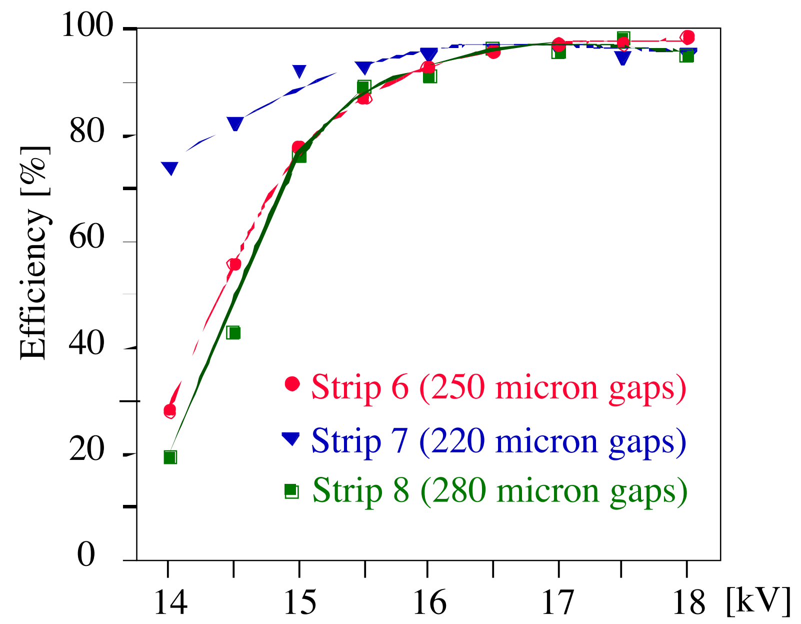
- Active detector volume is 2% of the total volume of the gas box;
- Diffusion for the gas exchange between strip and the surrounding gas.

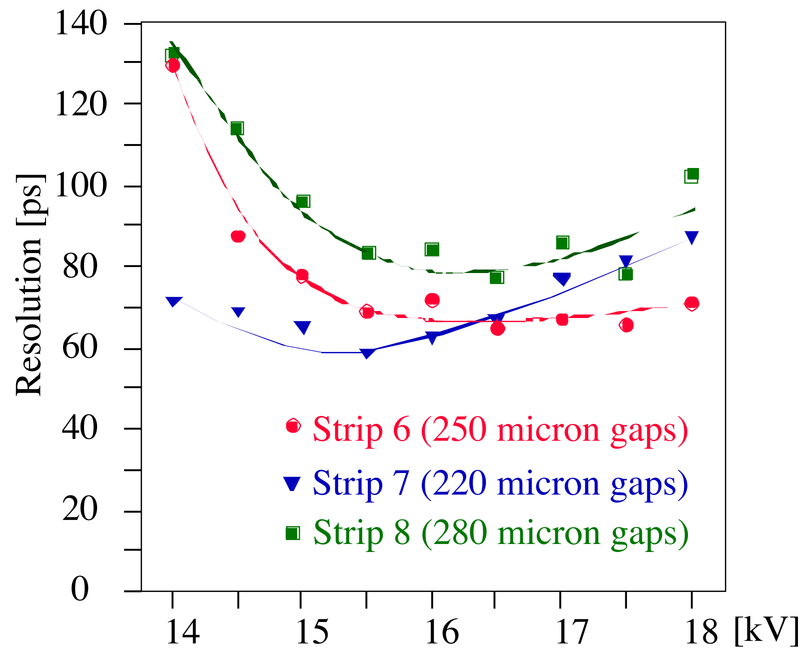
- No sign of degradation;
- No increase of dark current;
- No degradation in efficiency;
- No degradation in time resolution;

MRPCs are (relatively) easy to build!

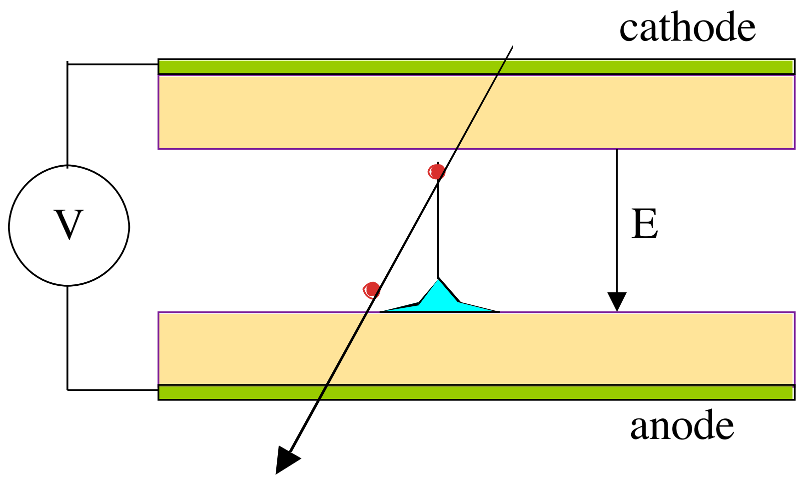
Big change in gap size ⟶ small change in operating voltage. Large ‘plateau’ region where efficiency high, time resolution excellent and gap can vary by ± 30 μm

Thus device with this excellent time resolution can be built with very ‘relaxed’ mechanical tolerances



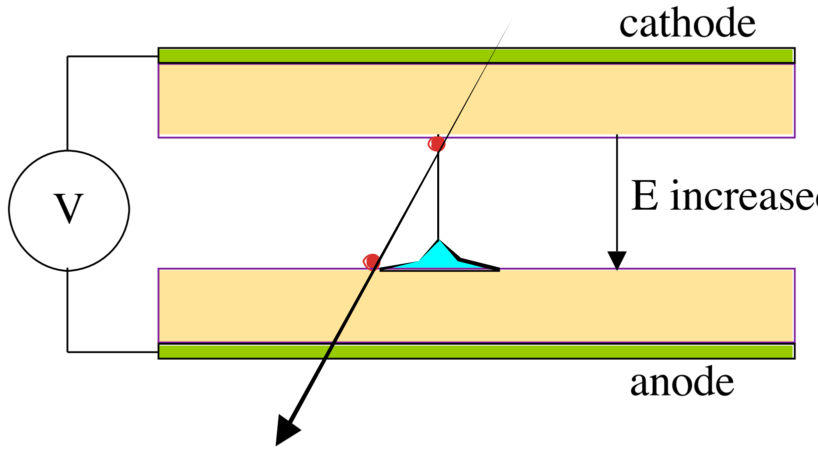


MRPCs apparently aren’t very sensitive to tolerances on the gas gaps....



Charged particle passes through gas gap and creates clusters of electrons and positive ions electrons avalanche towards anode →fast signal on external electrodes - etc

Now consider smaller gap



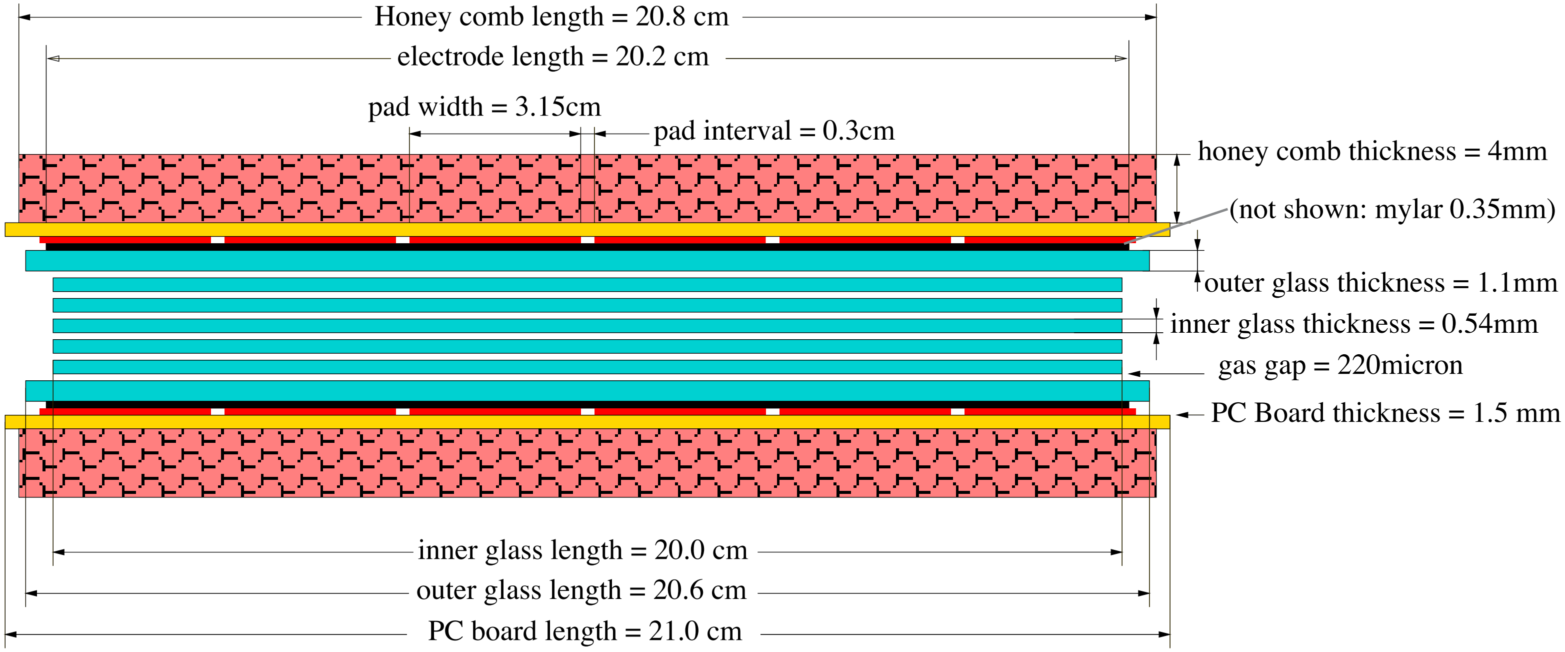
E increased (same V - smaller gap)

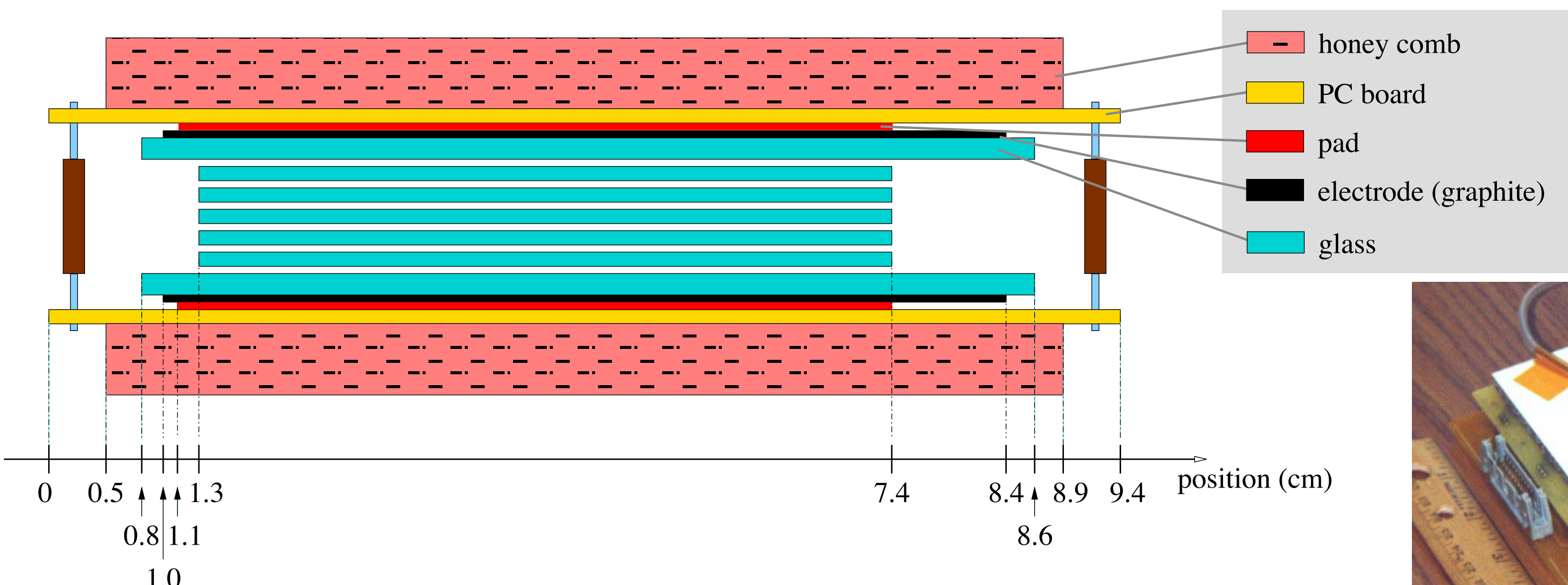
Thus Townsend coefficient higher - bigger avalanche (i.e. higher gain)

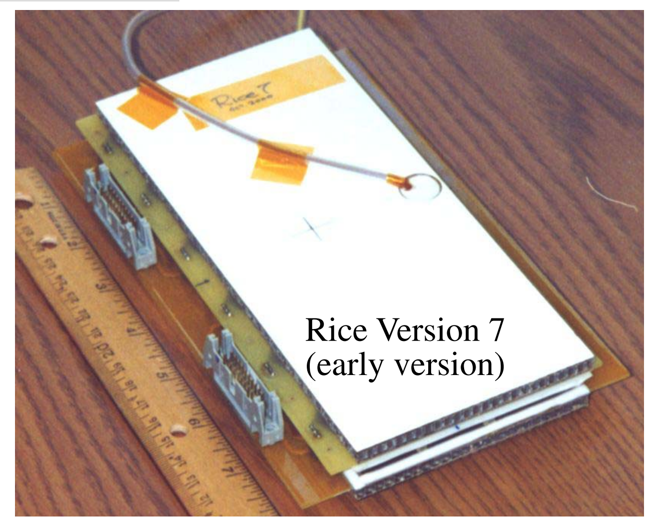
however gap smaller therefore less distance for avalanche to grow (i.e. lower gain)

Apparently we are working in region where both effects cancel (by ‘magic’ it is rather an exact cancellation)

STAR’s Variant...





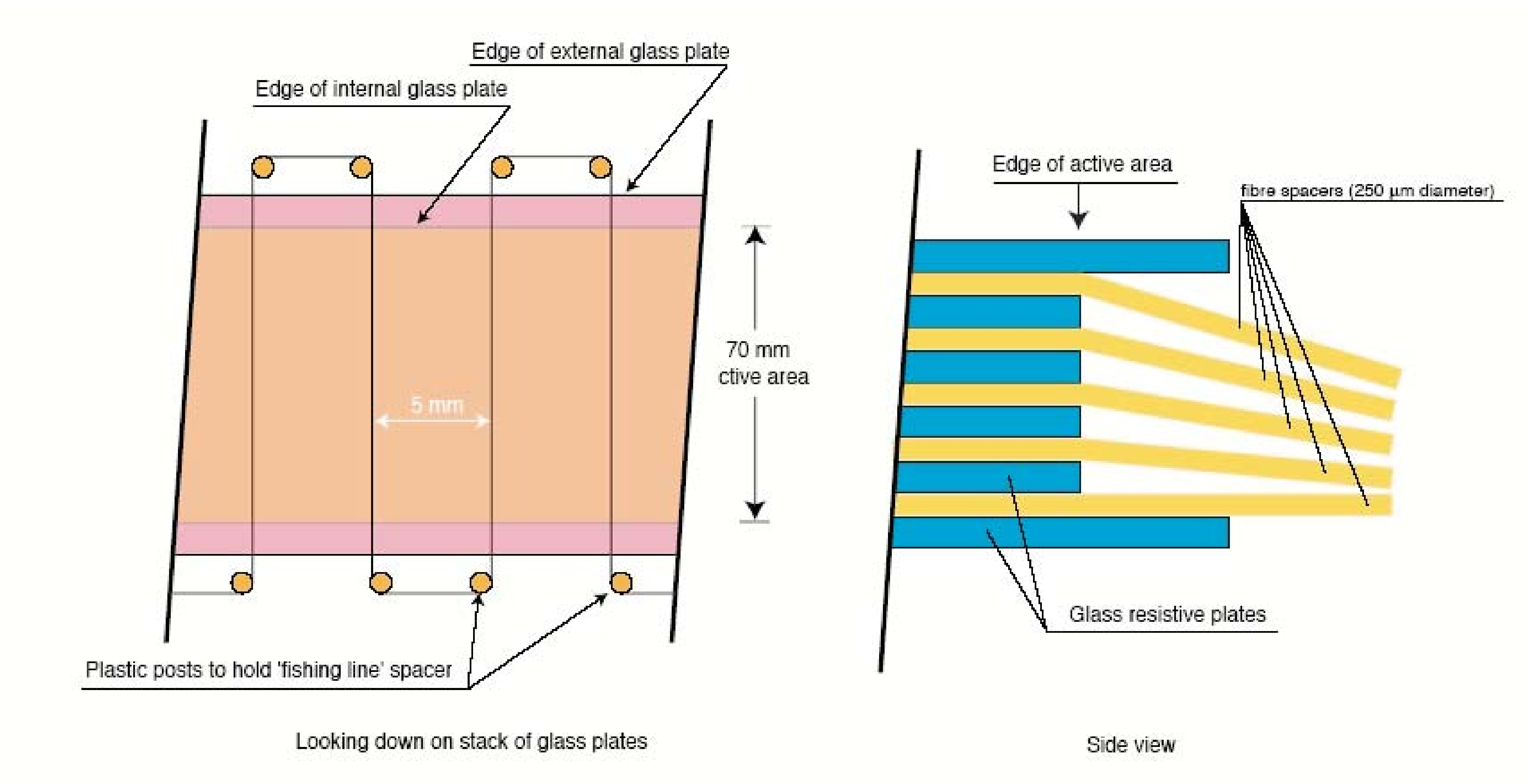


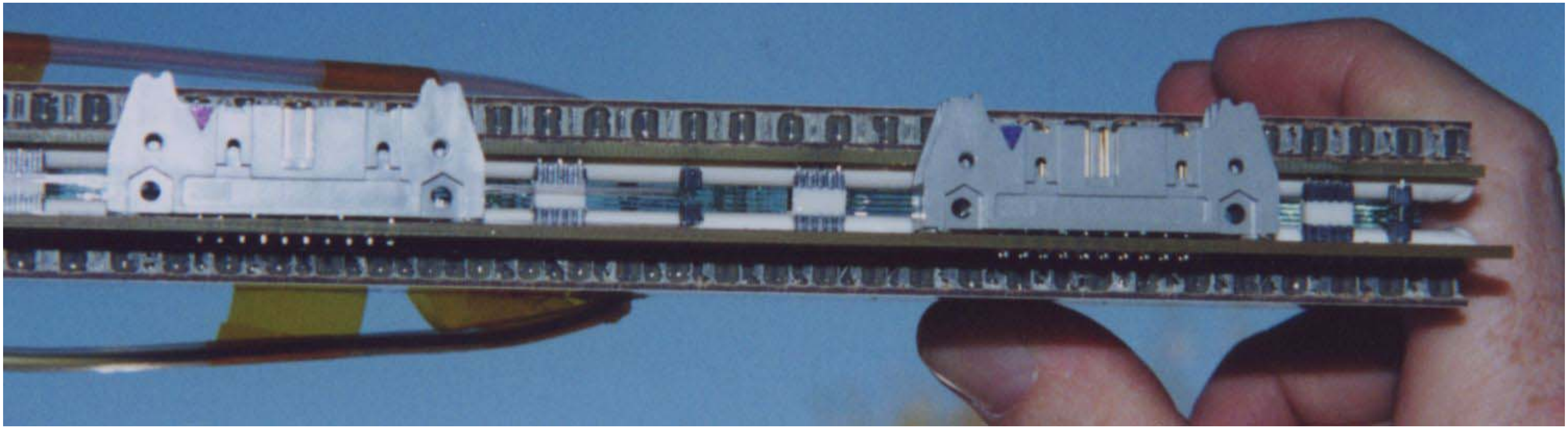
all components are more-or-less “off the shelf”

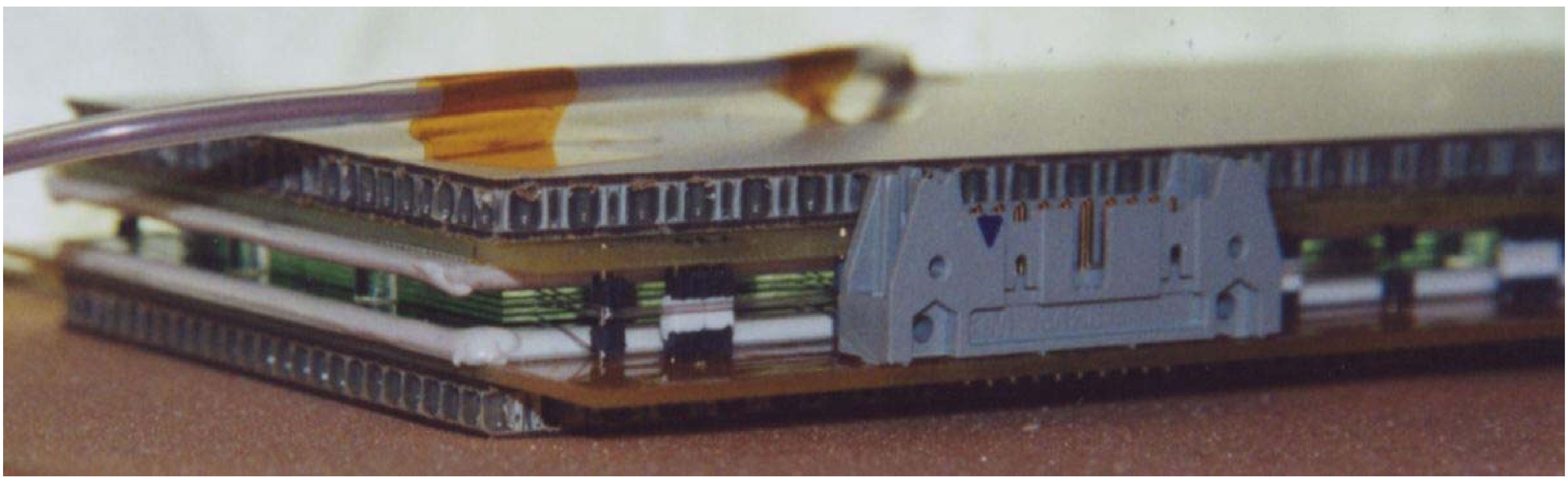
Spacing of inner glass plates is set by *monofilament fishing line...* (ALICE, HARP, & STAR)

- available in a variety of diameters in ~20μm steps around 200μm...
- gap size very uniform: ±10 μm...
- very difficult to compress...

Glass plates are just common float glass...





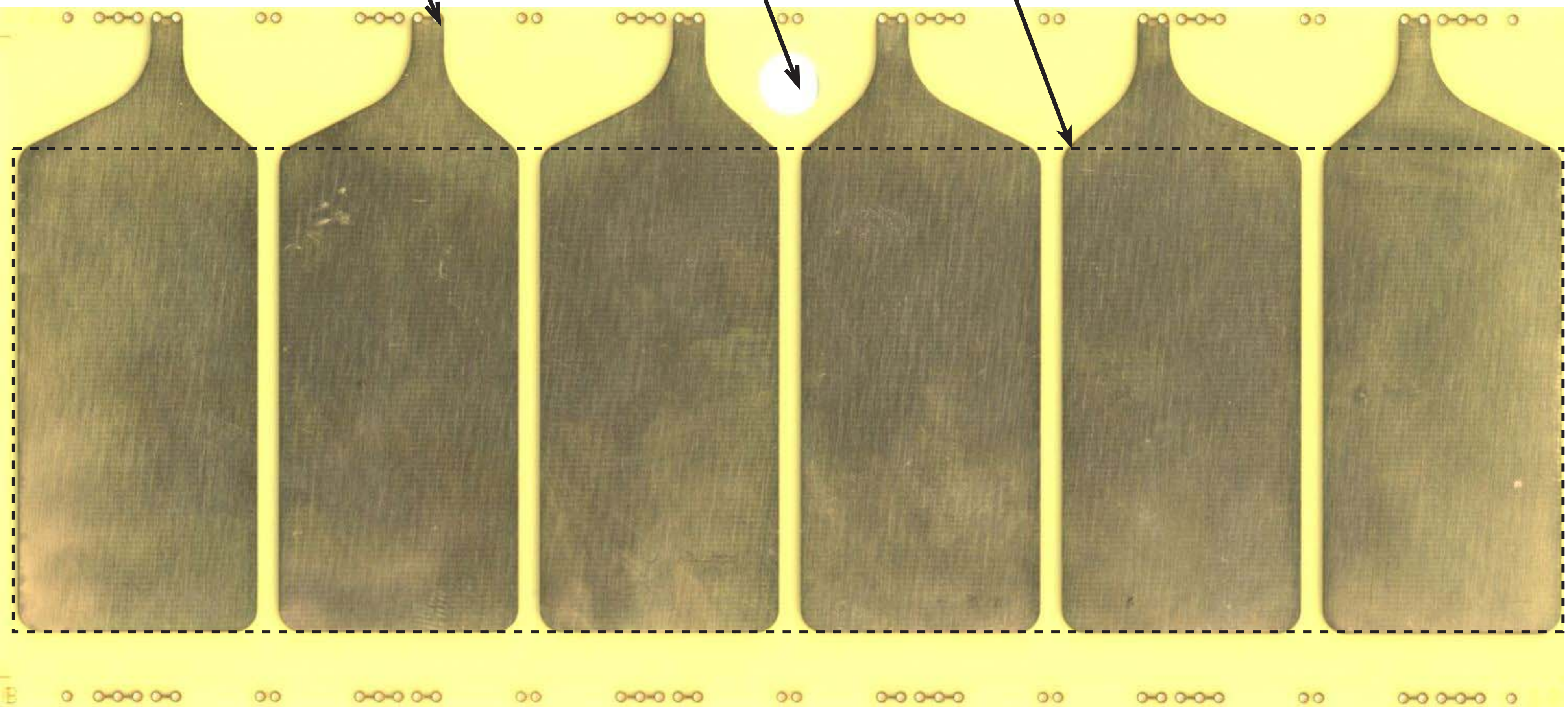


Readout Pads

region of pads above thin glass indicated by dashed box

hole to pass HV through to graphite layer

pins for signal output



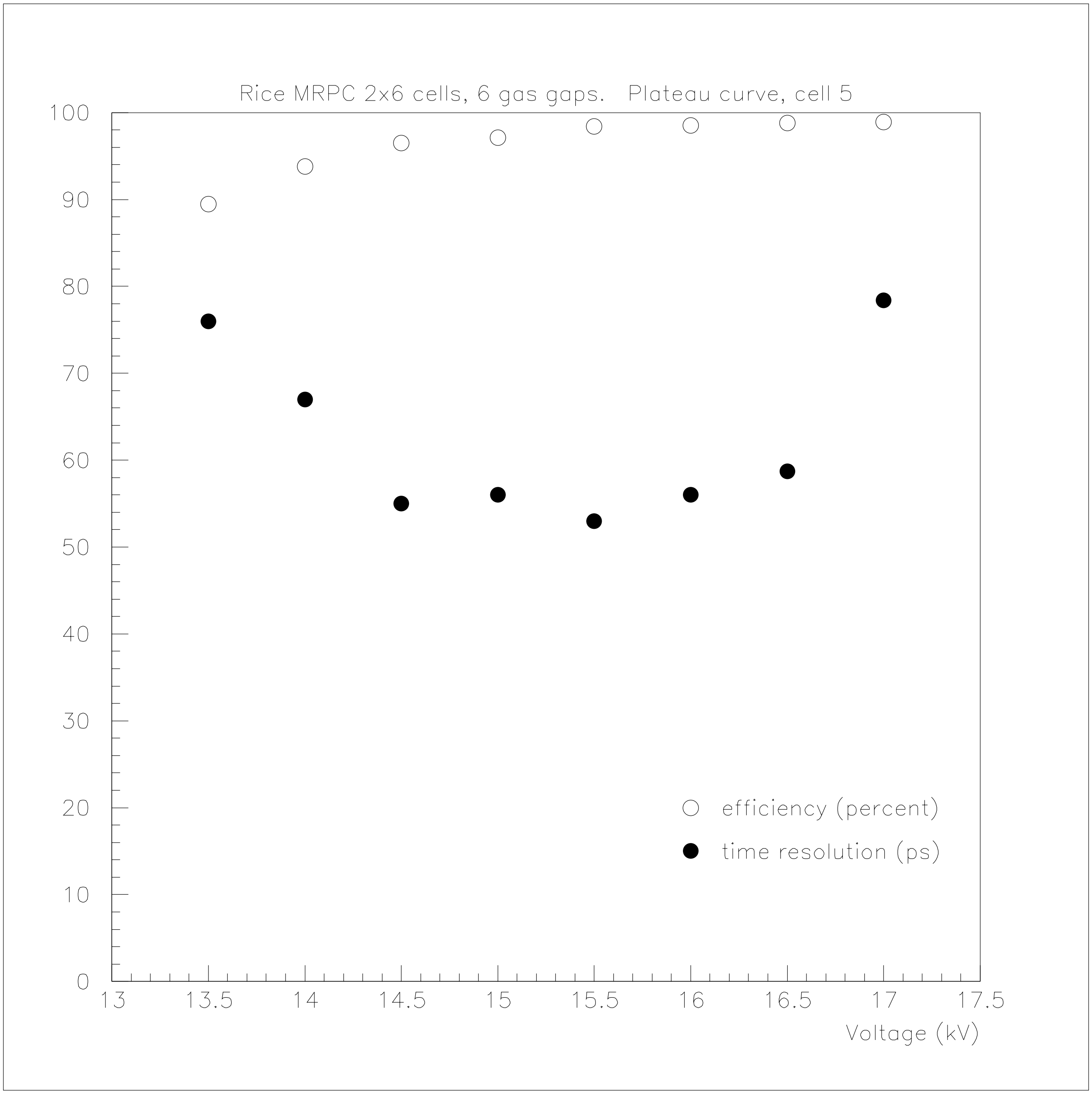
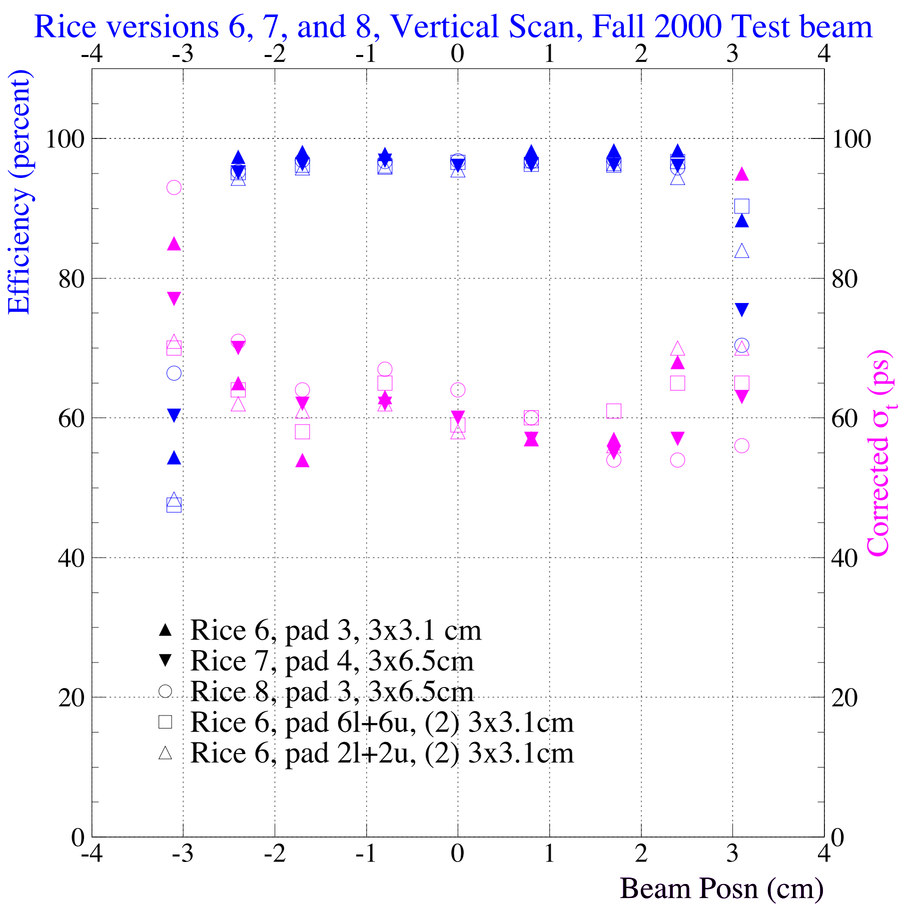
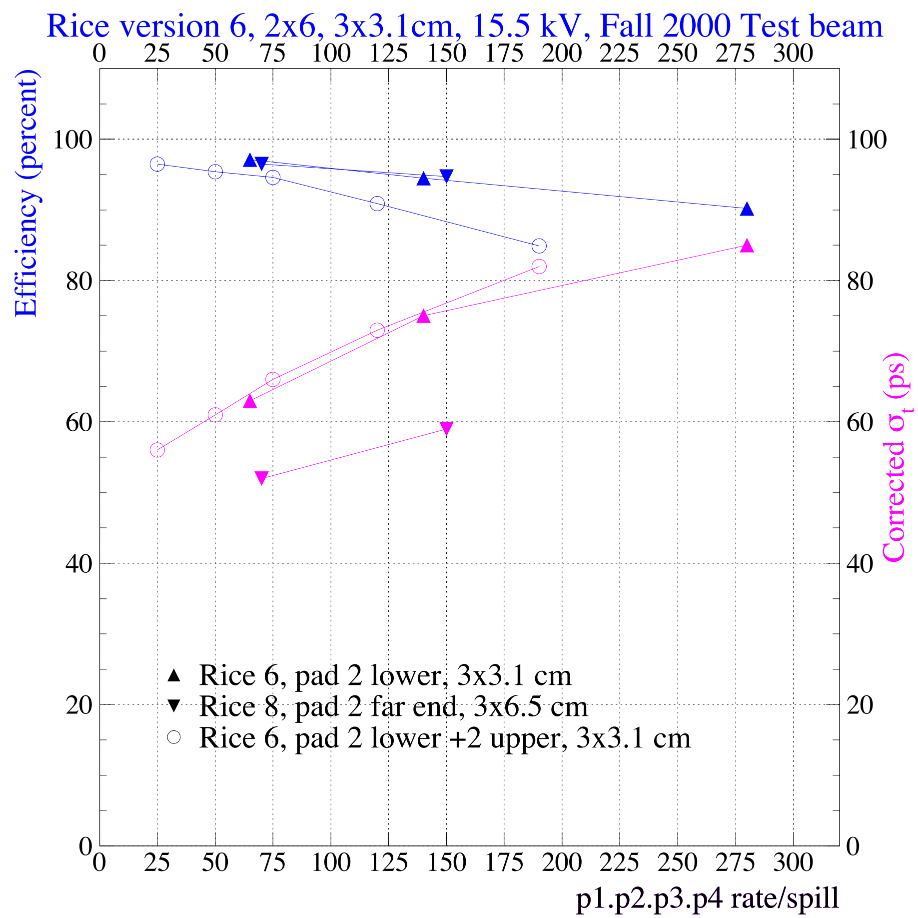


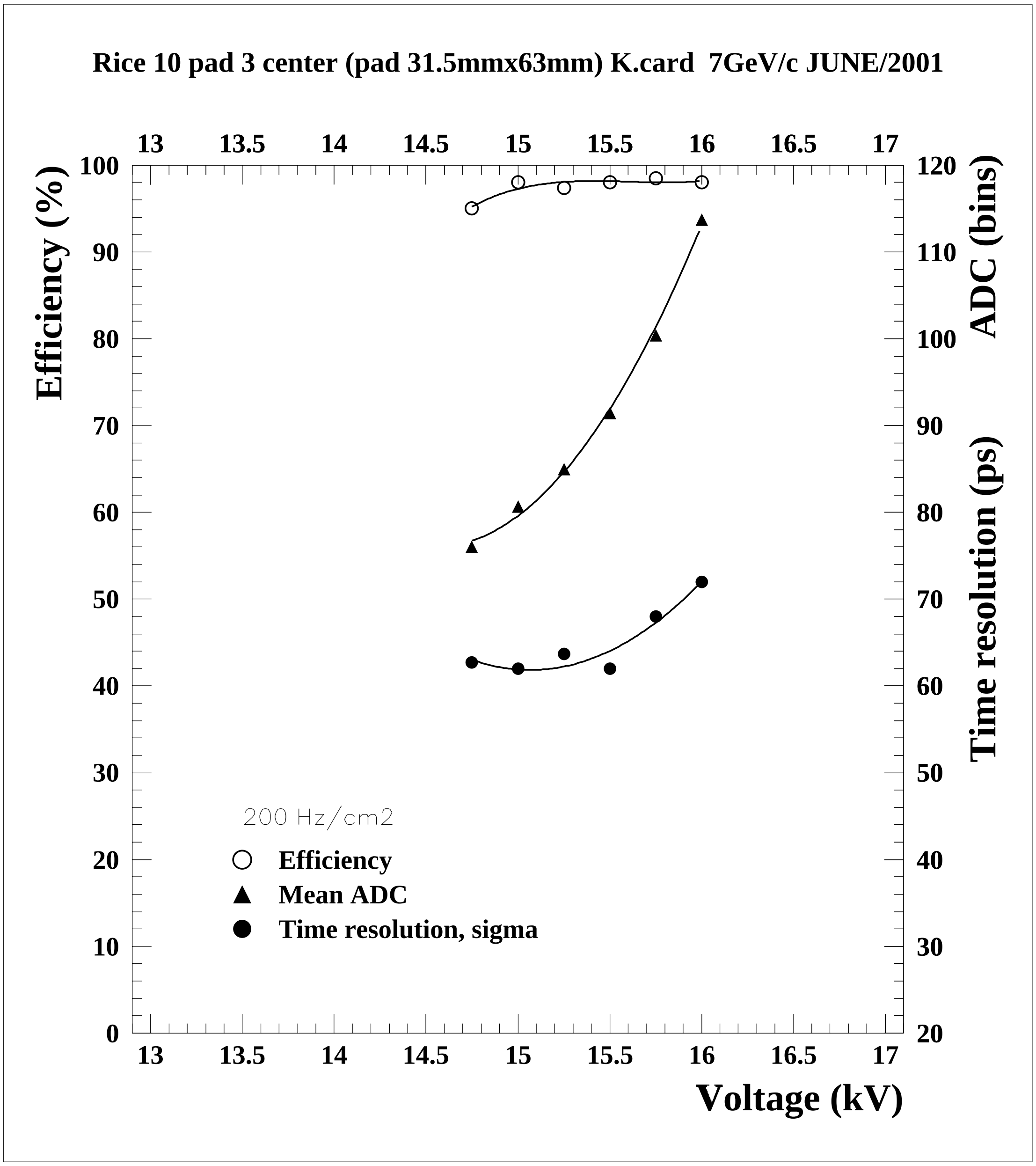
Fig. 2. The efficiency and corrected time resolution (σ) versus voltage for the prototype with 2x6 pads and pad area of 3x3 cm^2.

Position Dependence w.r.t. Pads



Rate Dependence





Rice versions 6-8

good & uniform & reproducable performance....

Rice versions 9, 10, ...

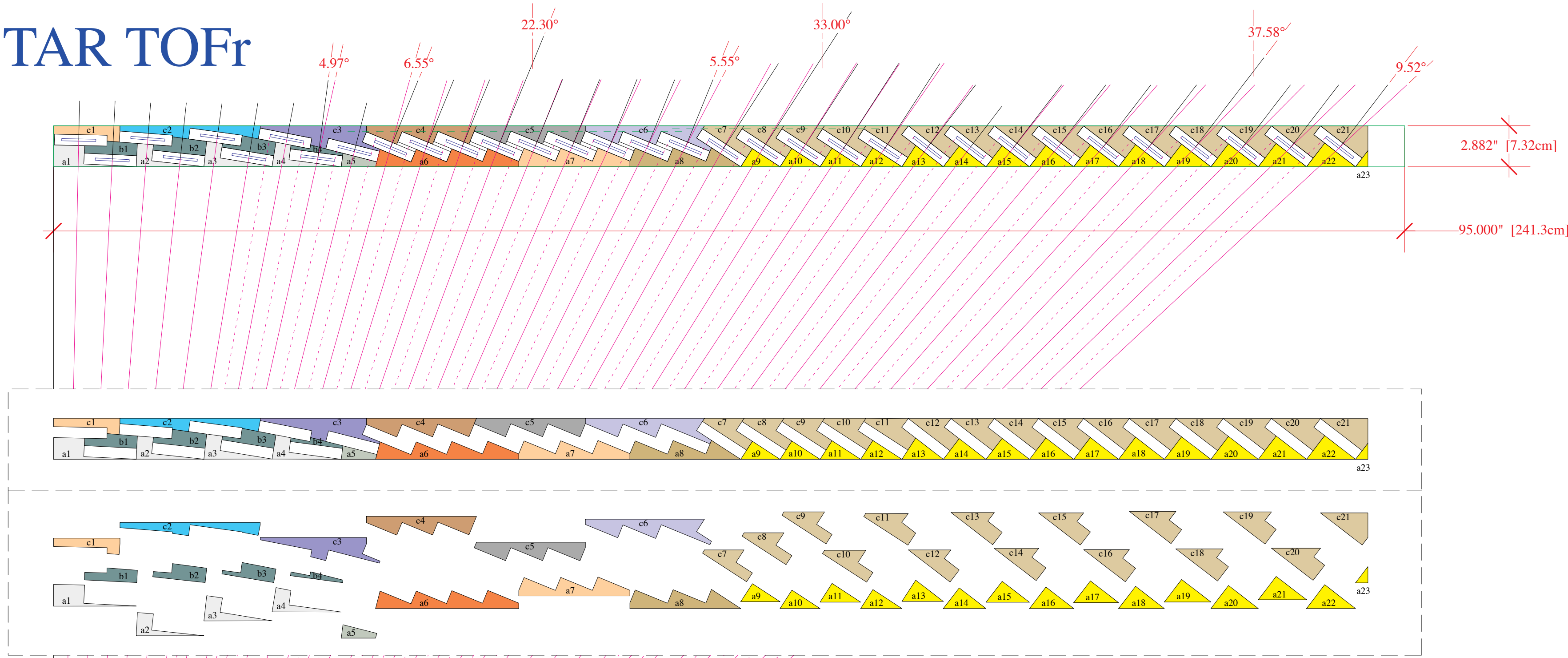
no more changes to MRPC interior structure (glass, gaps, ...)

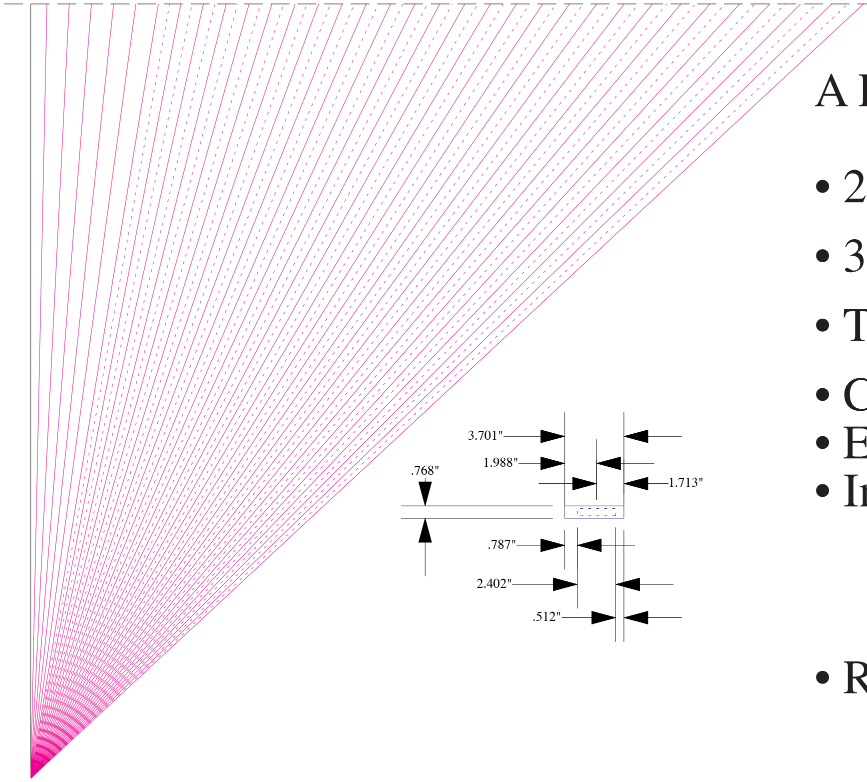
only optimization (minimization of dead space etc....)

Final version is Rice 11

Now also have excellent production at USTC and Tsinghua (China)...

STAR TOFr



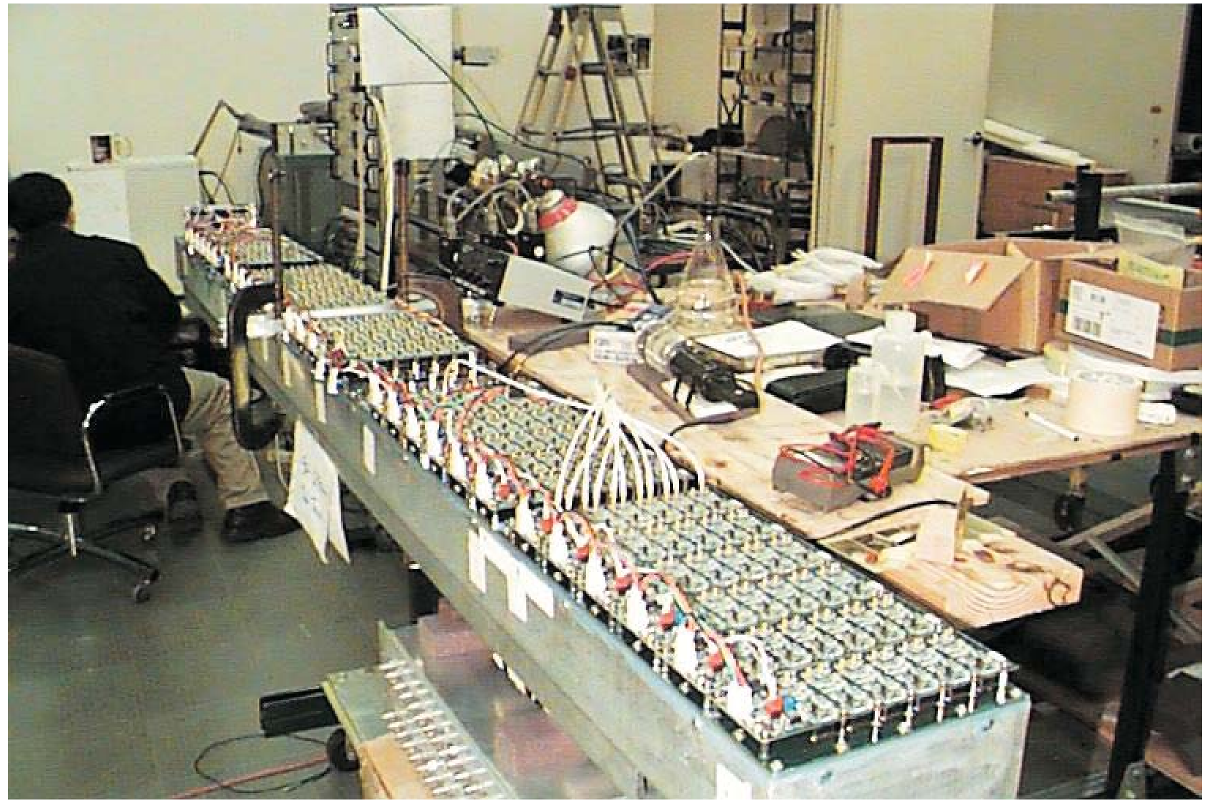


A First Prototype for Large-Area MRPC TOF for STAR

- 28 MRPC modules fabricated at USTC and CERN
- 33 FEE boards fabricated at Rice
- Tray design and construction at Rice
- Construction completed February 16, 2002
- Extensive testing at AGS radiation area, Spring 2002
- Installed in STAR before RHIC Run-III, Fall 2002

→ Realistic test of viability of this technology in an actual collider experiment......

- Ran throughout RHIC Run-III... no failures, under continuous HV for months...



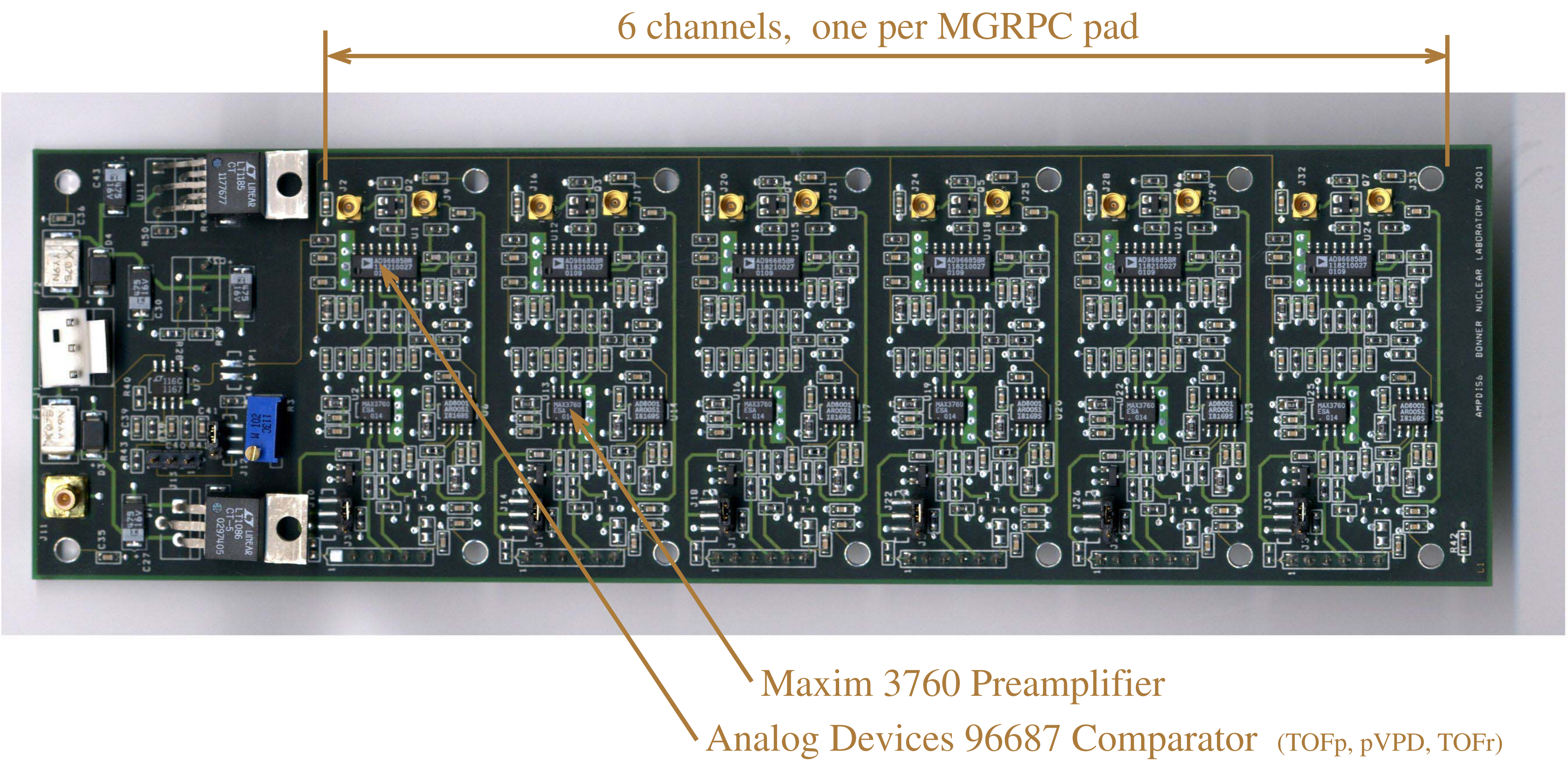
TOFr’s Front-End Electronics

typical MIP hit in a STAR MRPC equivalent to **~25 fC** (not a typo)

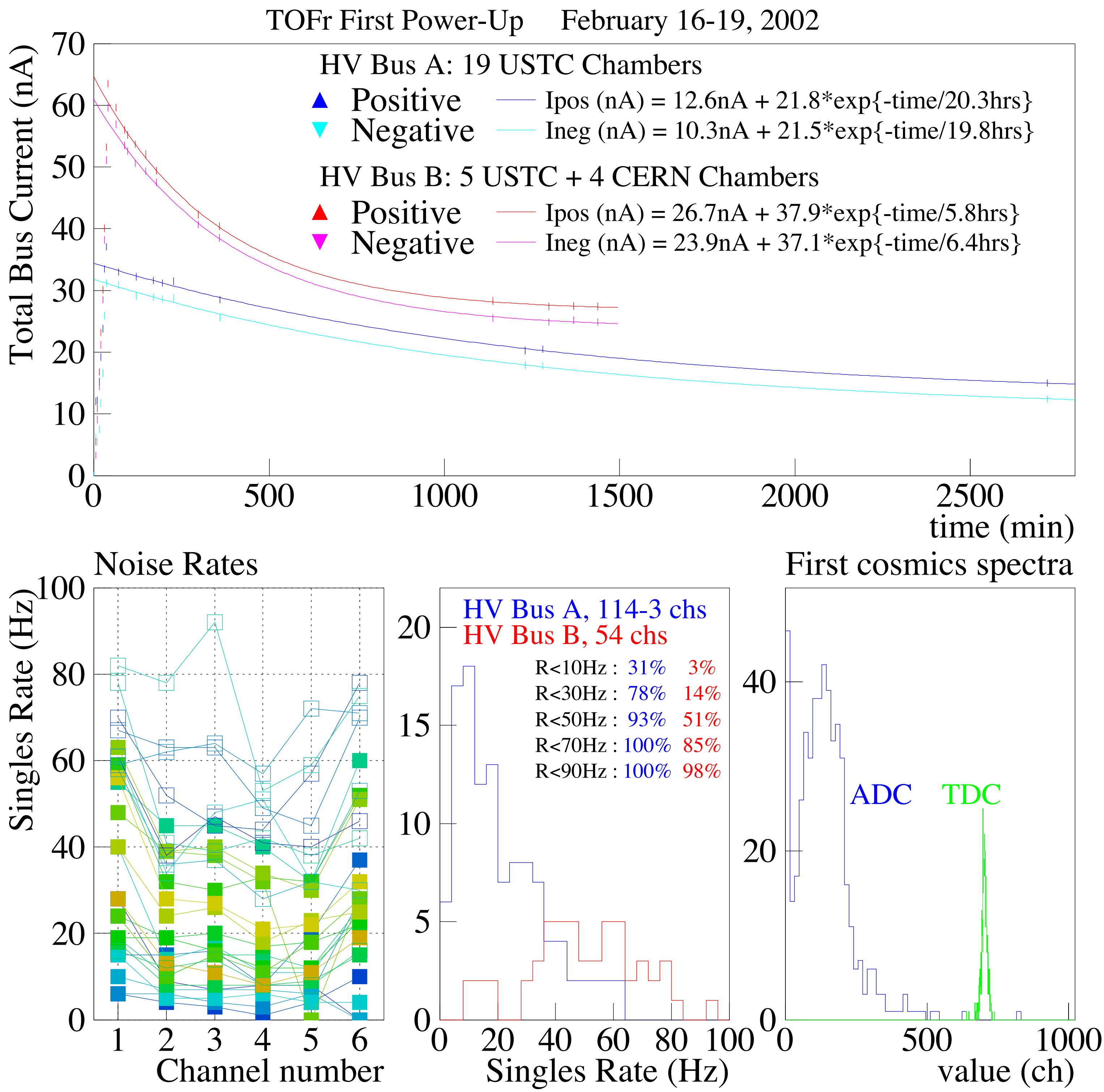
need to amplify first

- rise time of [detector+FEE] practically limited only by bandwidth of this preamp
- major breakthrough came w/ adoption of MAXIM 3760

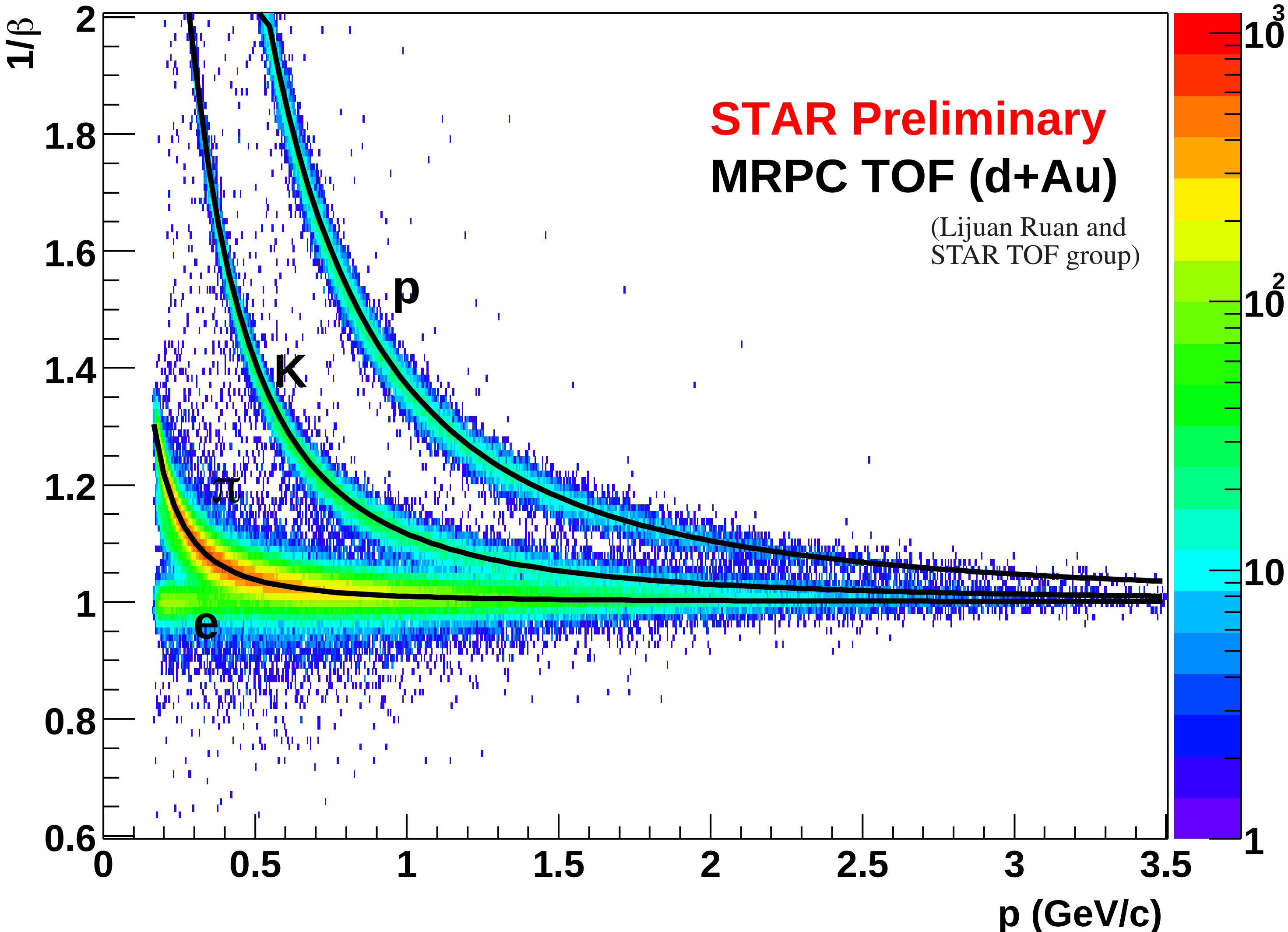
then discriminate using standard components



Initial Testing of TOFr just after construction...



TOFr+pVPD in RHIC Run-III (d+Au)



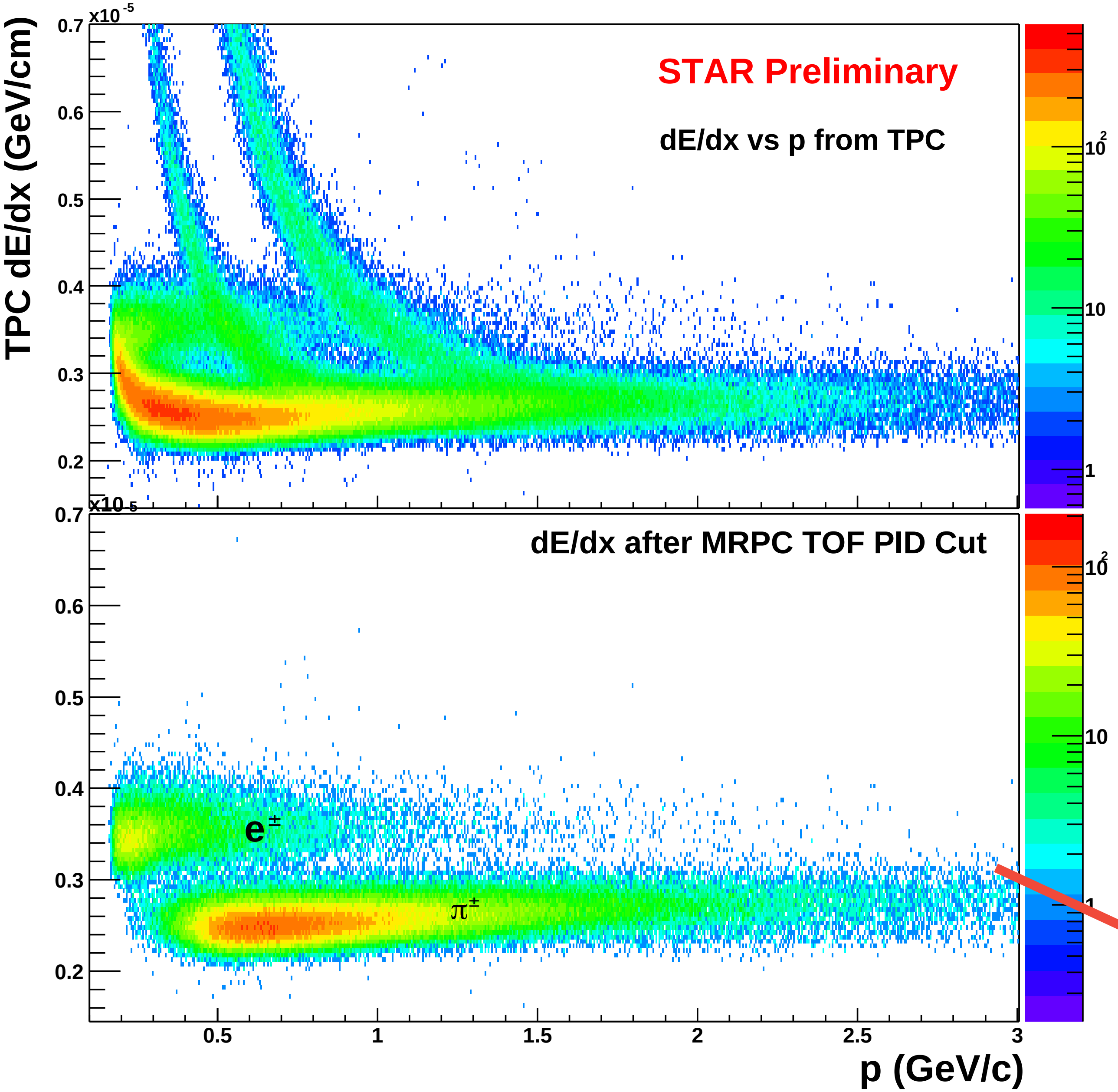
start resolution	~85ps
stop (MRPC) resn	~85ps
total	~120ps

→ π/K/p to ~1.6 GeV/c, and (π+K)/p to ~2.8 GeV/c

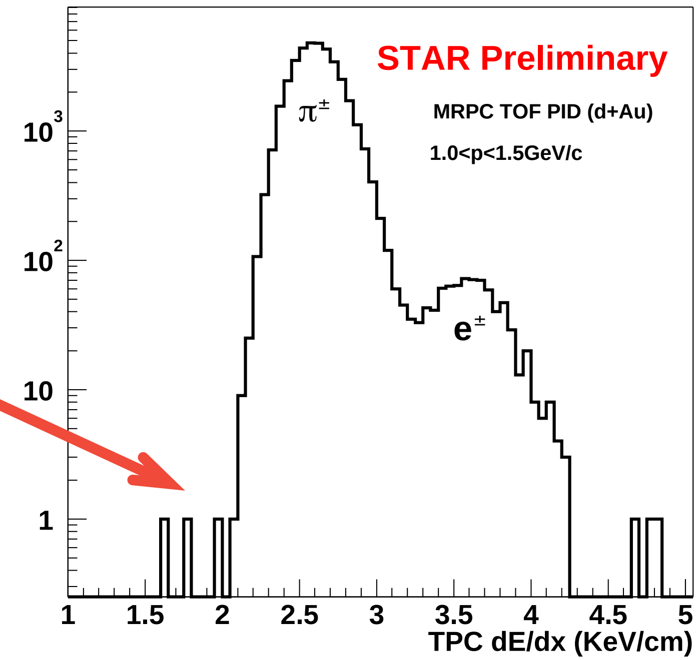
First physics result from an MRPC-based TOF System
on hadron Pt-distributions & the Cronin Effect in RHIC d+Au collisions
(J. Adams *et al.*, STAR Collaboration, nucl-ex/030912, submitted to PRL)

TOF in STAR also allows effective *electron PID*...

most powerful in (low) momentum regions where STAR EMC-based e-PID is difficult....



(Xin Dong and
STAR TOF Group)



The second-generation prototype
for RHIC Run-IV:

STAR TOFr'

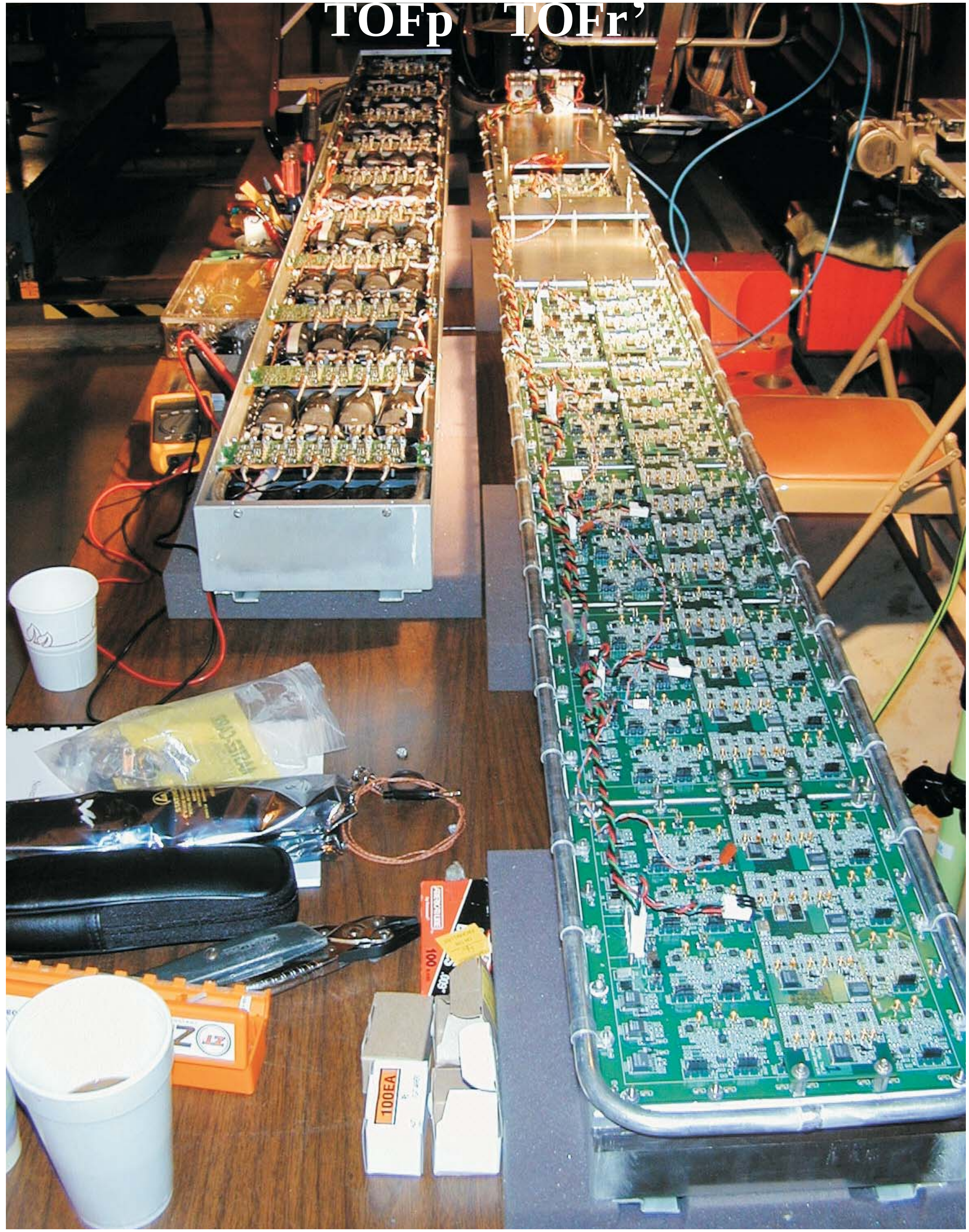
similar module arrangement...

new "showbox" tray design...
vastly simpler fabrication
better gas hermiticity

FEE layer now closes the box...

same camac digitization
over long cables into TOFp DAQ

test implementation of "Jalepeno"
based on CERN HPTDC chip
separate path to STAR DAQ

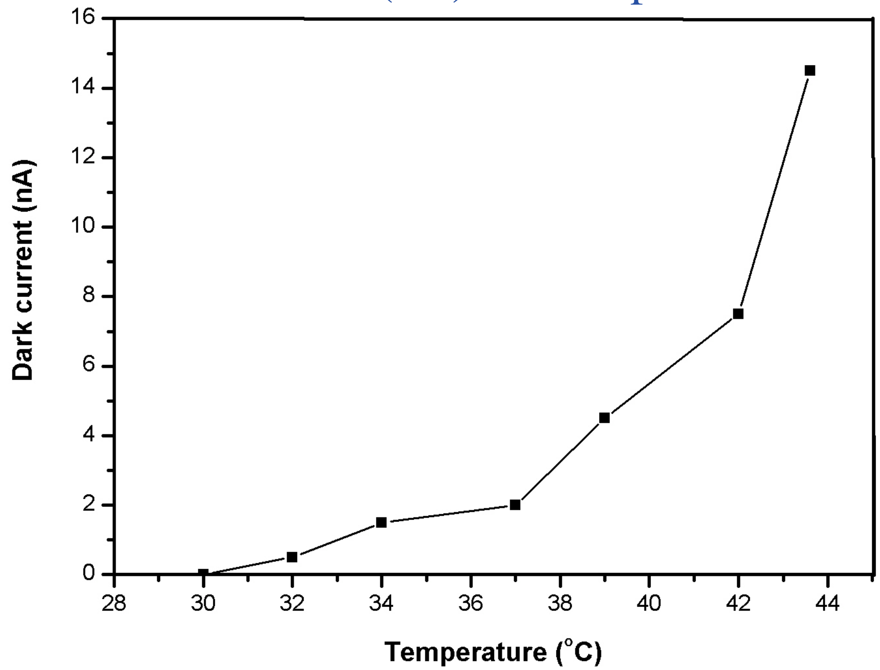


Since the FEE “close the gas box” now, the interior of TOFr’ runs hotter than in TOFr...

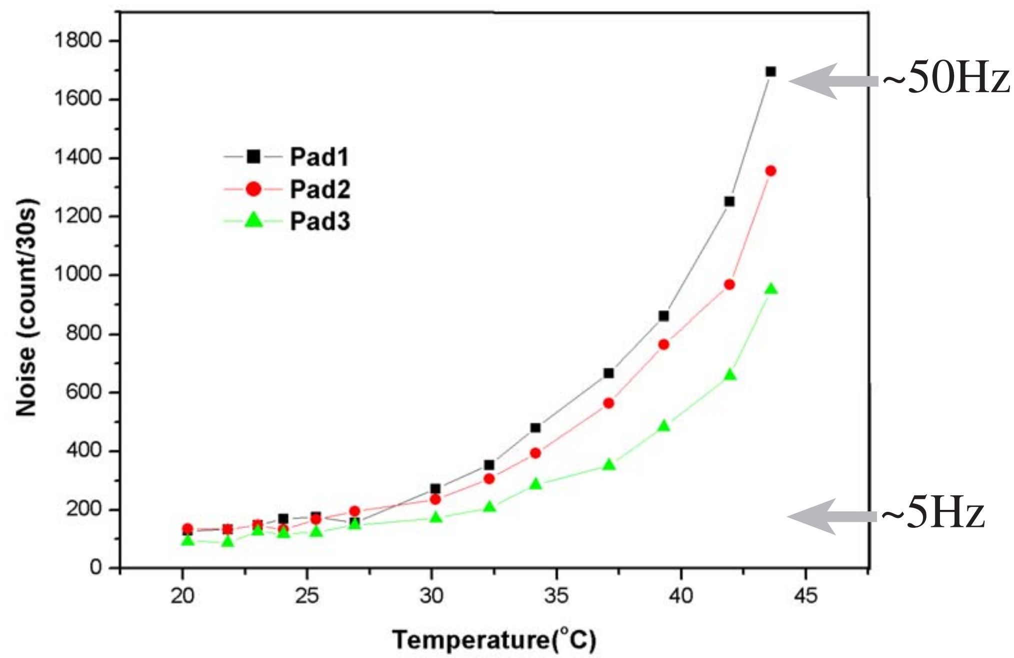
MRPC noise rates and HV current draw depend on temperature...

(results for STAR MRPCs, W. Yi et al., Tsinghua)

Dark Current (nA) vs. Temperature



Noise Rate (counts/30s) vs Temperature

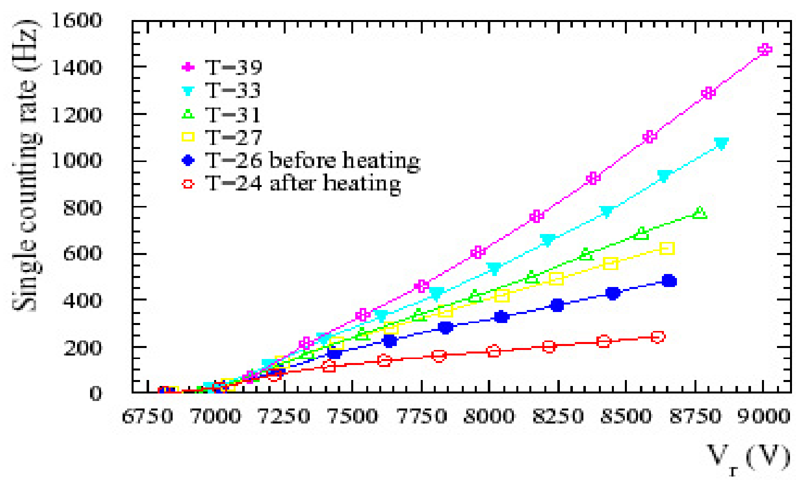


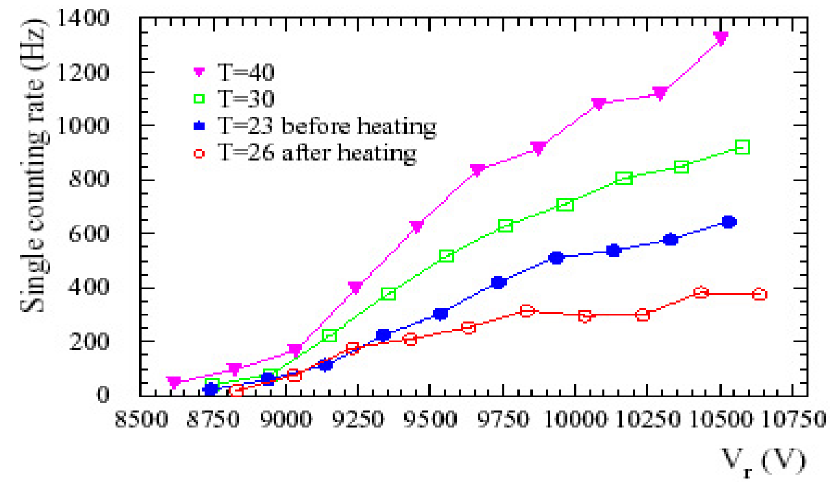
...looking forward to the data to come from TOFr’ in RHIC Run-IV...

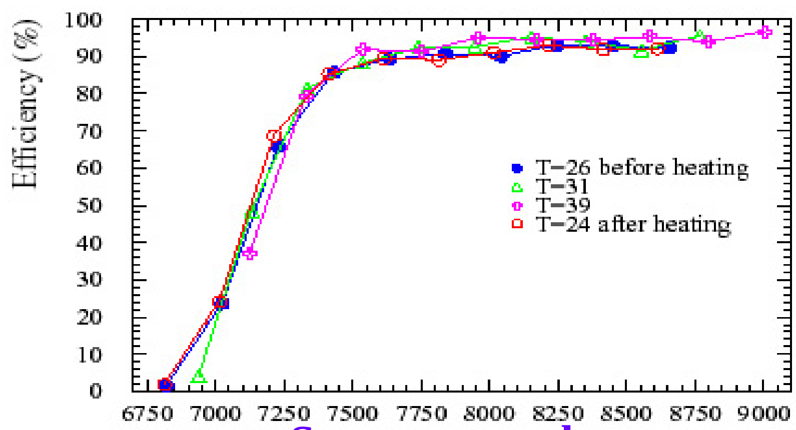
not expecting major penalty in the timing resolution...

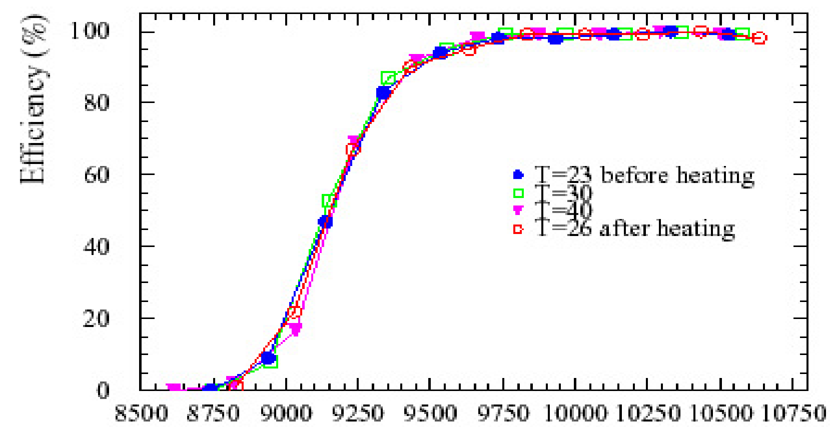
...increased temperature improves the rate capability!

Aging: temperature tests









Streamer mode

Argon/TFE/C_4H_{10}/SF_6= 48/47/4/1

Avalanche mode

TFE/C_4H_{10}/SF_6= 95/4/1

$$V=V_0*T/T_{ref}*P_{ref}/P$$

Differently from Bakelite, Glass RPC do not suffer high temperatures

STAR has officially adopted (our variant) of MRPCs for its large-area system...

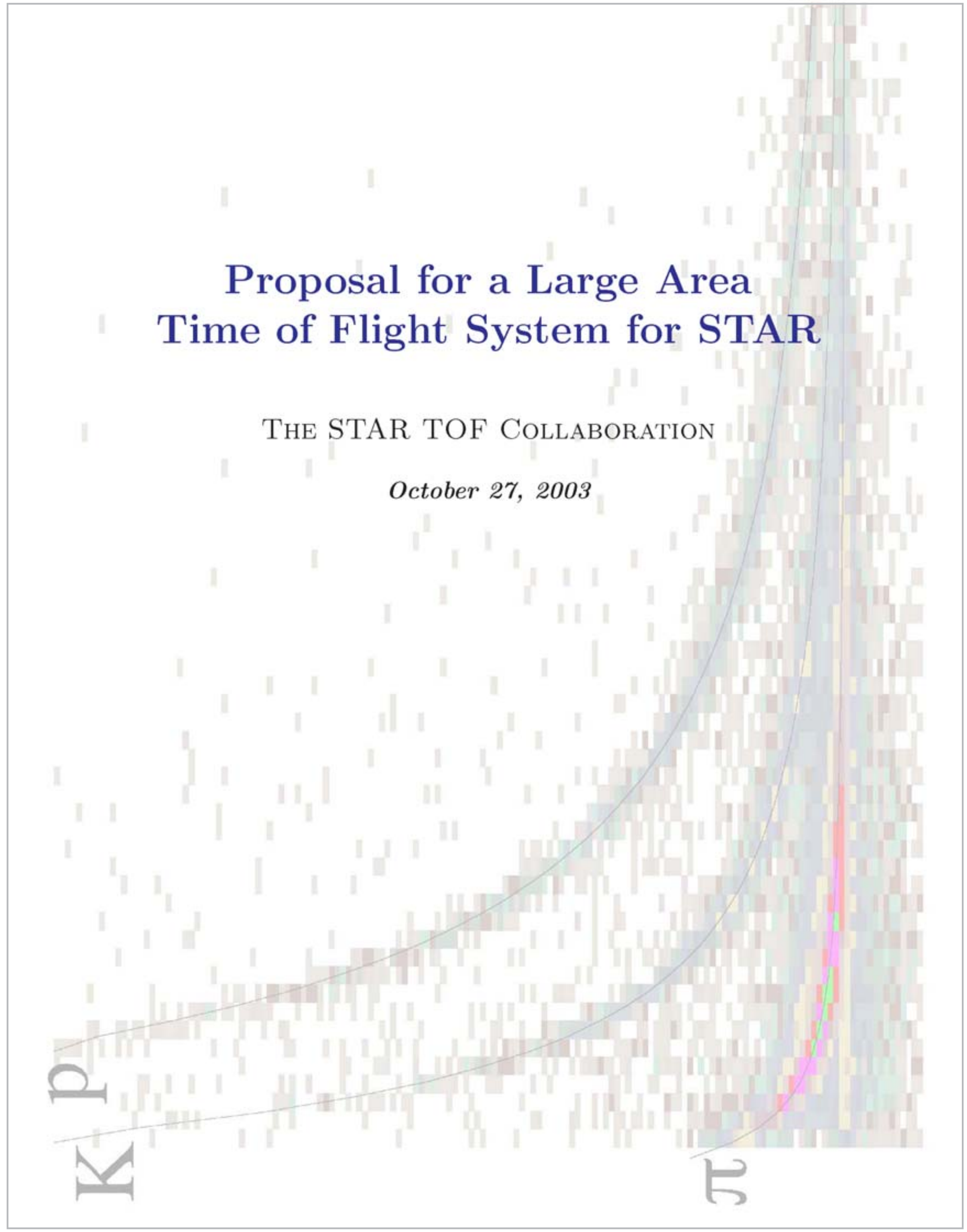
- cover entire cylindrical surface of TPC
  $\Delta\phi=2\pi$, $-1<\eta<1$
- ~50 m^2 total area
  120 trays
  32 MRPCs/tray
  6 channels/MRPC $\rightarrow$ 23,040 chs
- 3840+ MRPCs contributed by China
- Tray fabrication & testing in Texas
- Digitization on-board
  (major R&D now is on electronics)

- US Cost: 4.1 M$
  Chinese contribution: 2.3 M$ (US$ equiv.)

Proposal now under review by
BNL DAC & PAC, & US DOE....

Proposing construction during FY05→FY07
...project complete 2/15/07.

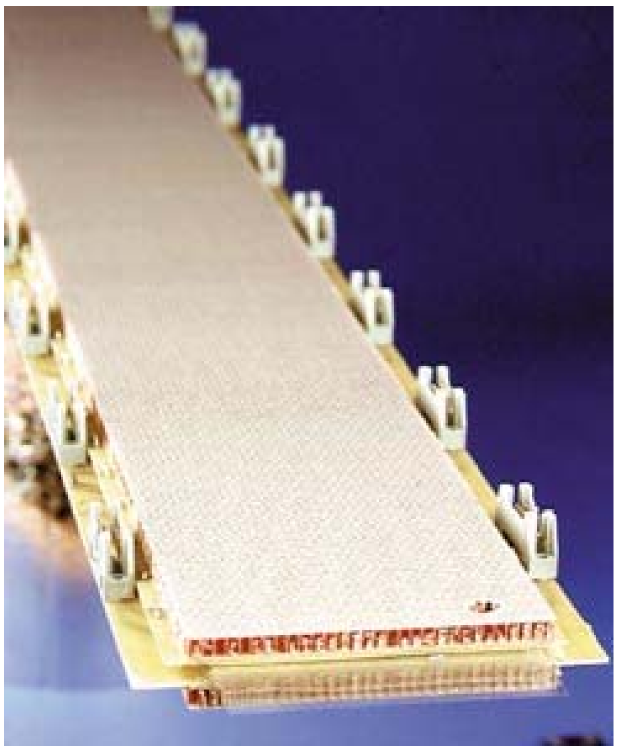
increasingly larger patches each RHIC run until full system there...



http://wjllope.rice.edu/~TOF/TOF/Documents/TOF_20031027.pdf

Bookshelf

MRPC



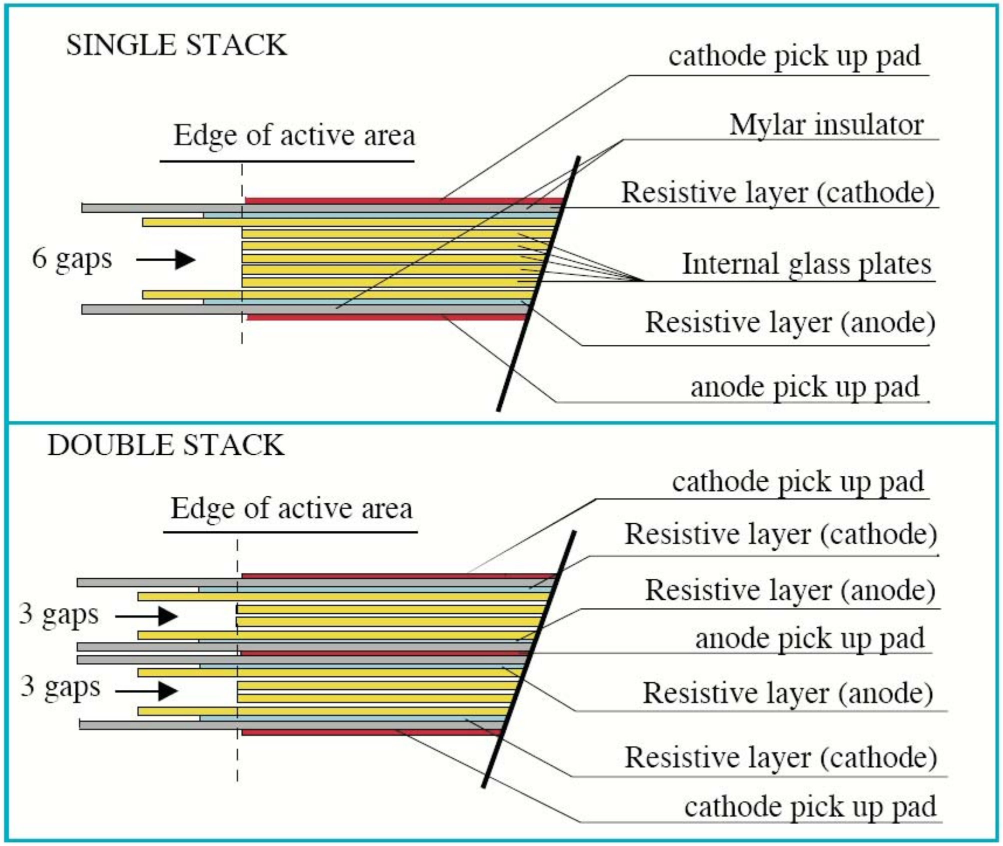
The ALICE experiment at the LHC will use multigap resistive plate chambers (MRPCs) like this in its time-of-flight (TOF) system. The MRPC is a stack of resistive plates that define a number of independent gas gaps (10 in the case of the ALICE TOF), allowing full detection efficiency and excellent time resolution (< 50 ps). This device was developed by Crispin Williams et al. within the framework of the LAA project detector R&D initiated by Antonino Zichichi.

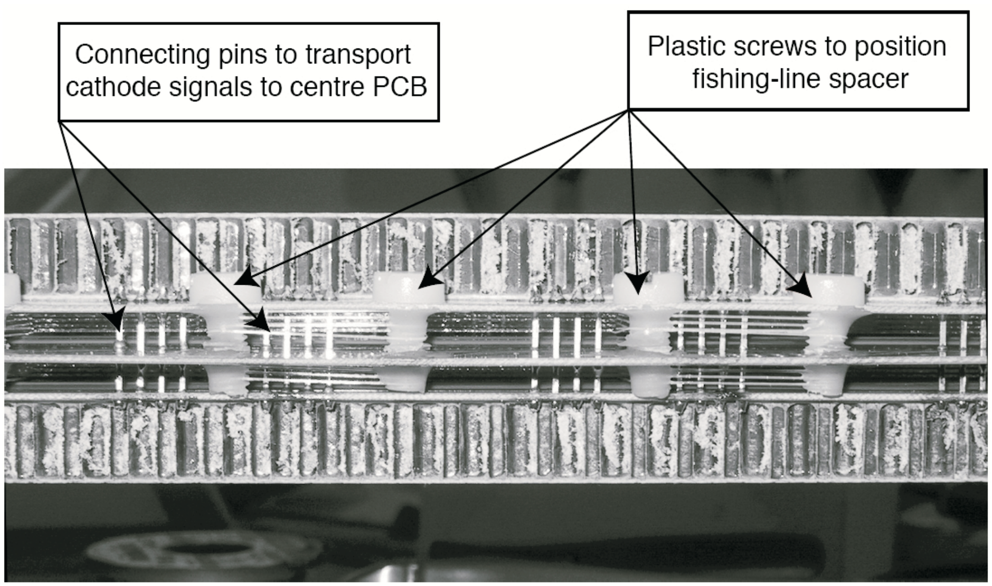
Back to Article

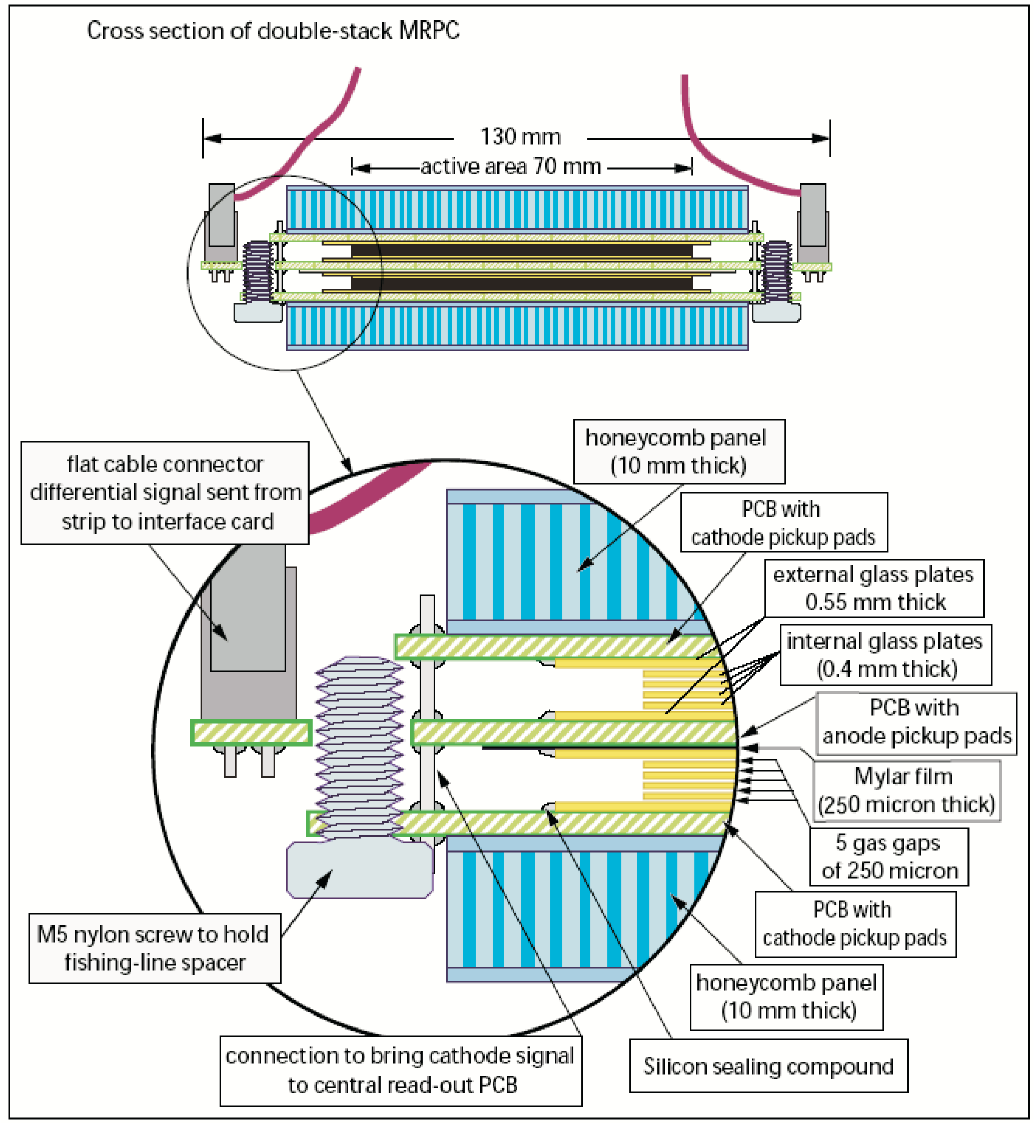
ALICE MRPCs

single and double stacks...

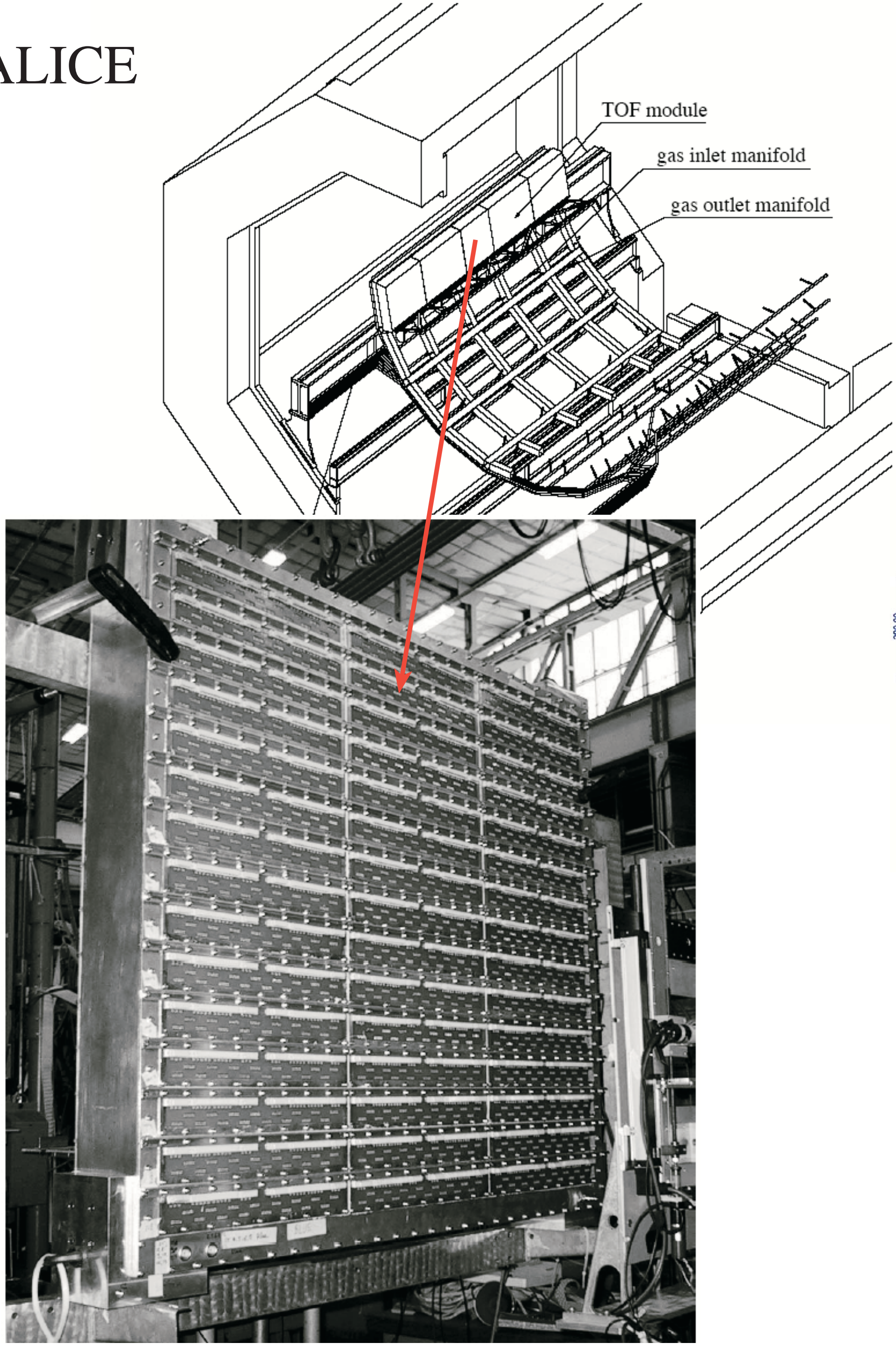
long and narrow...







ALICE



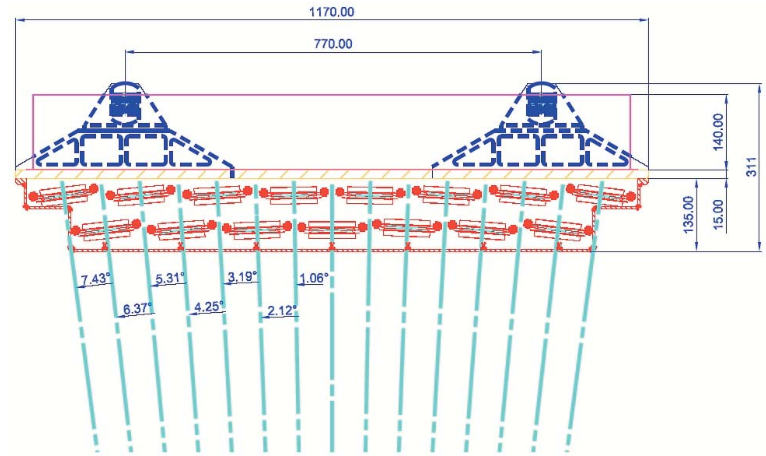


Figure 3.4: Central TOF module showing the positions and tilt angles of the MRPC strips.

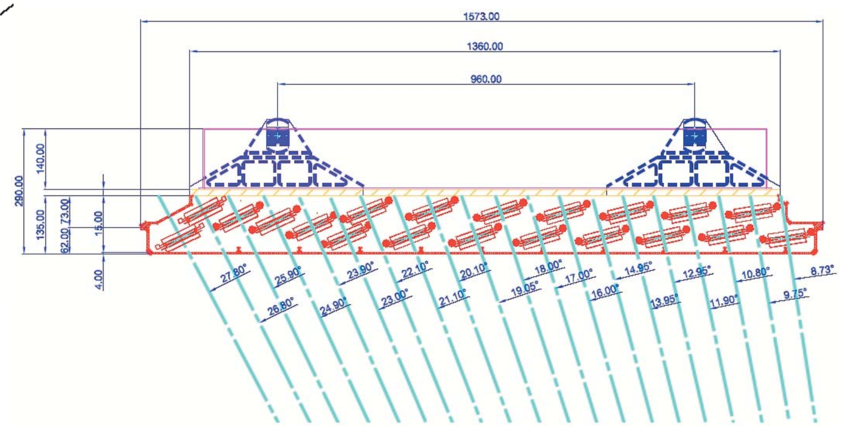


Figure 3.5: Intermediate TOF module showing the positions and tilt angles of the MRPC strips.

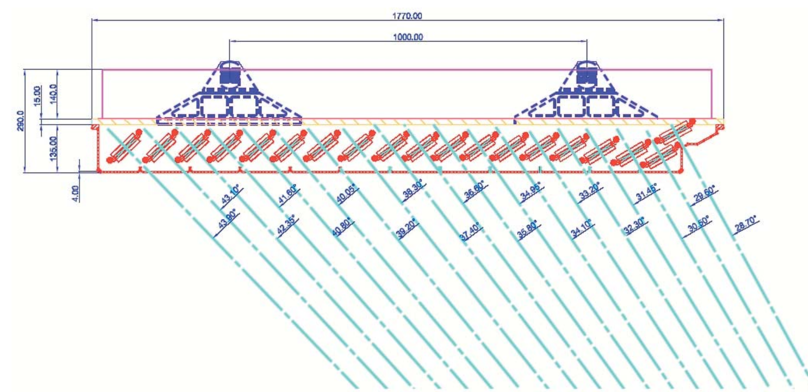
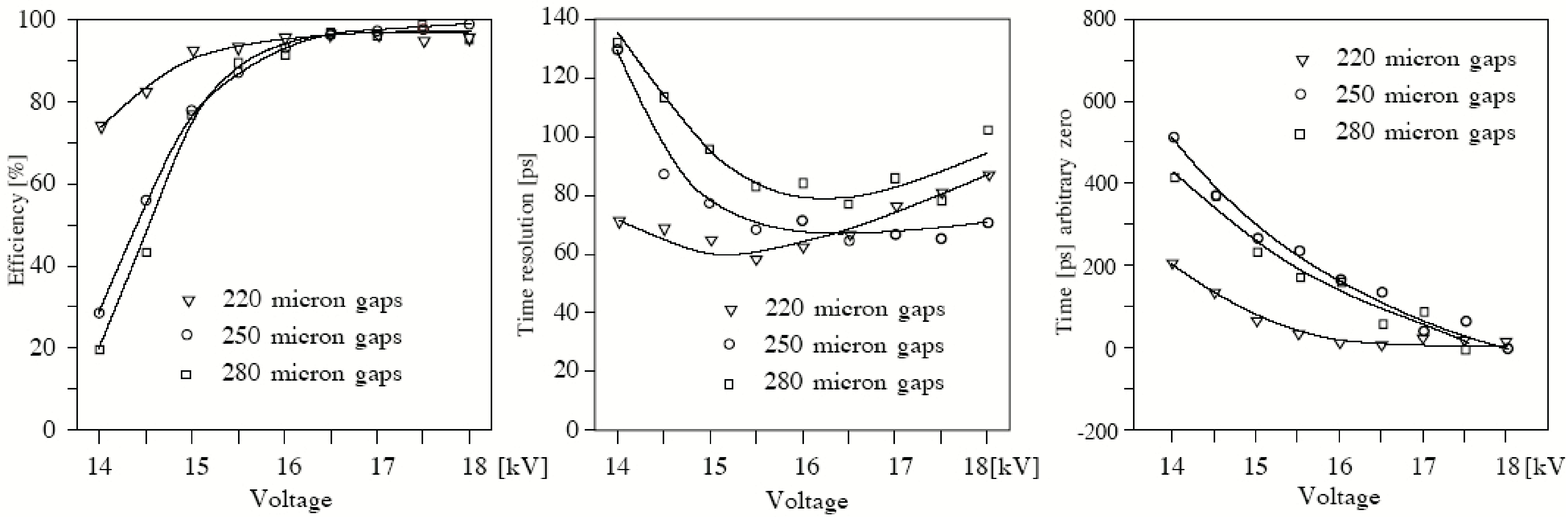


Figure 3.6: External TOF module showing the positions and tilt angles of the MRPC strips.

ALICE performance
(from proposal addendum, 2002)



efficiency near and above 95% for HV in range 16 – 18 kV.

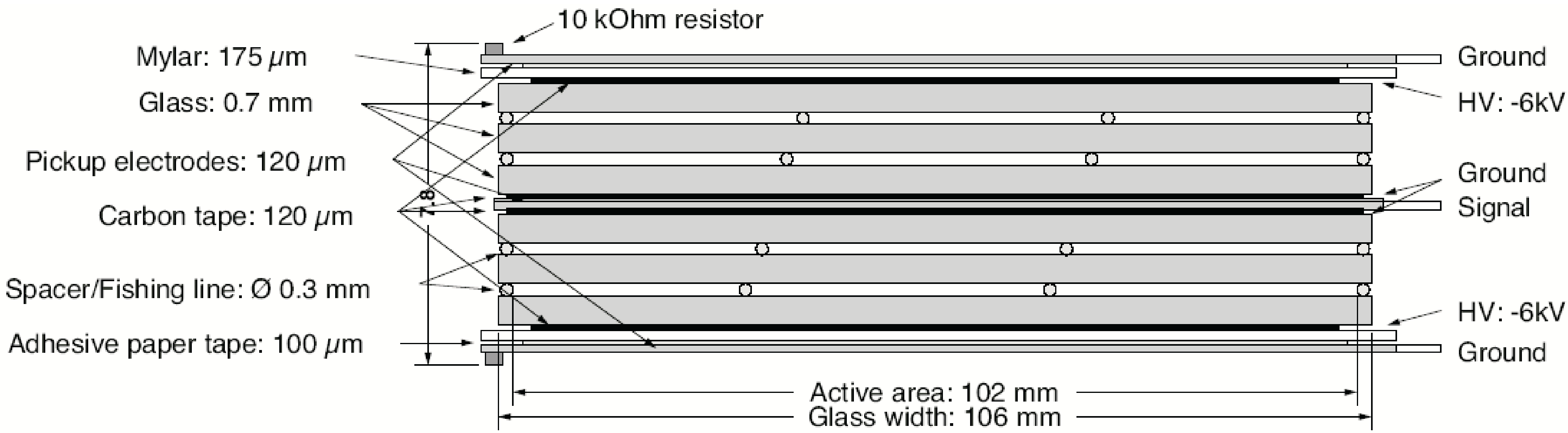
time resolution in this range is 60-80ps for 220 μm gaps

time walk reasonable...

HARP TOF

two implementations
- barrel around target TPC to reject out of time tracks...
- forward wall for PID...

looking for ~200ps or better...



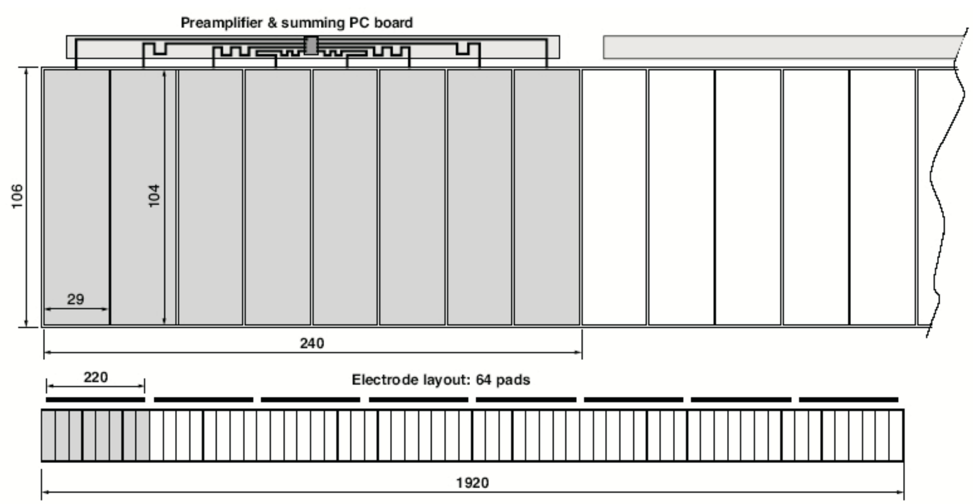
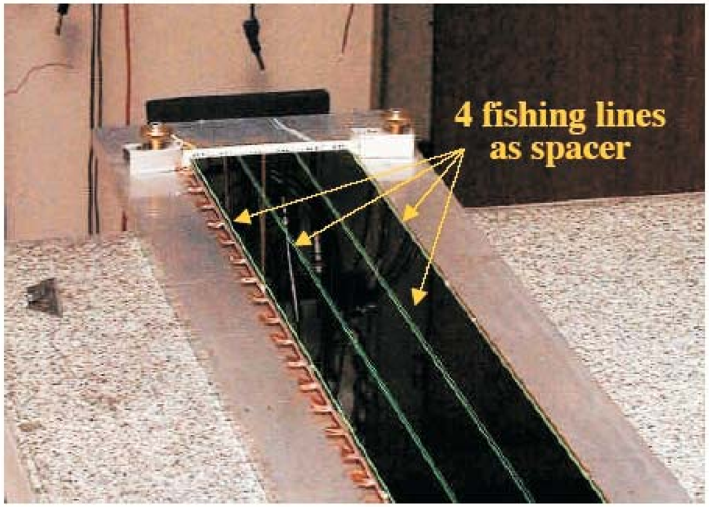
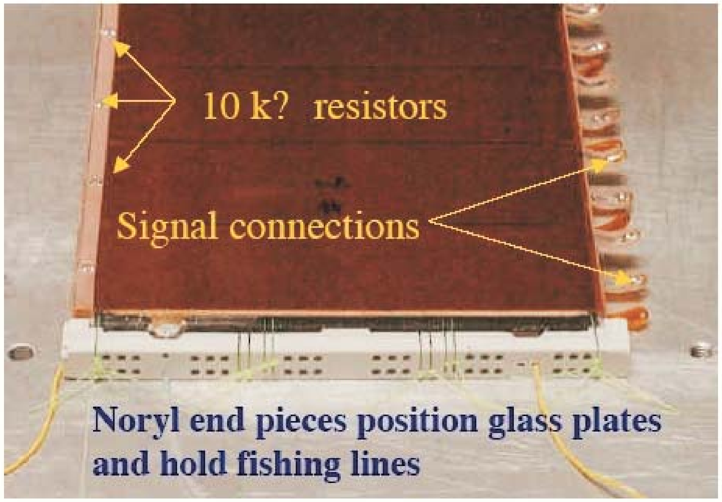


Fig. 4. Layout of the readout electrodes; eight pads are connected to the same preamplifier

HARP TOF

- Prep. of plates: long
- Stacking easy: = 1 hr



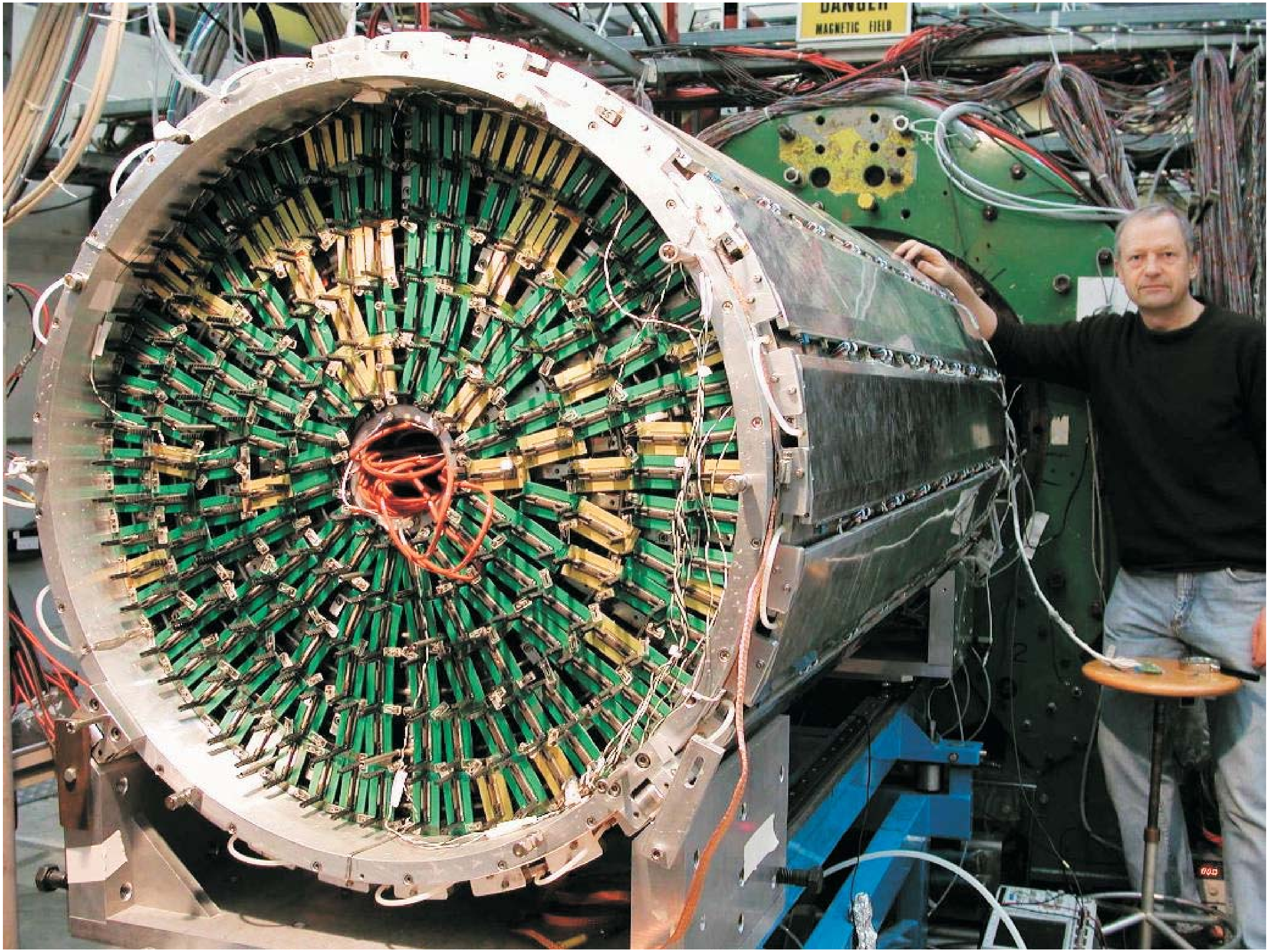


- HV test in air before integration in housing
- Stack -> box + test: 2 hrs

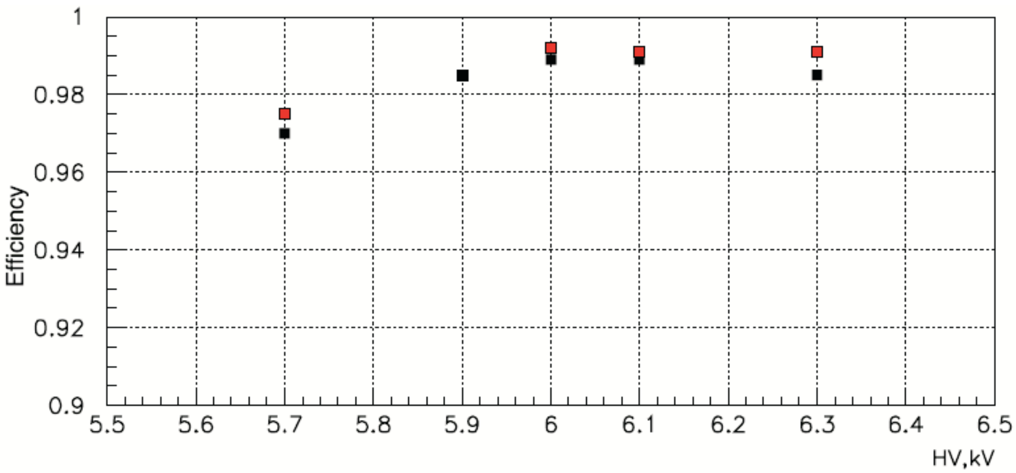
- Glass stack placed in aluminium housing with removable cover (O-ring)
- Box: 2m x 10mm x 150mm
- 64 signal feedthroughs along edge on one side
- 8 plug-in preamplifier cards
- HV supply on one end
- Gas in/out on two ends

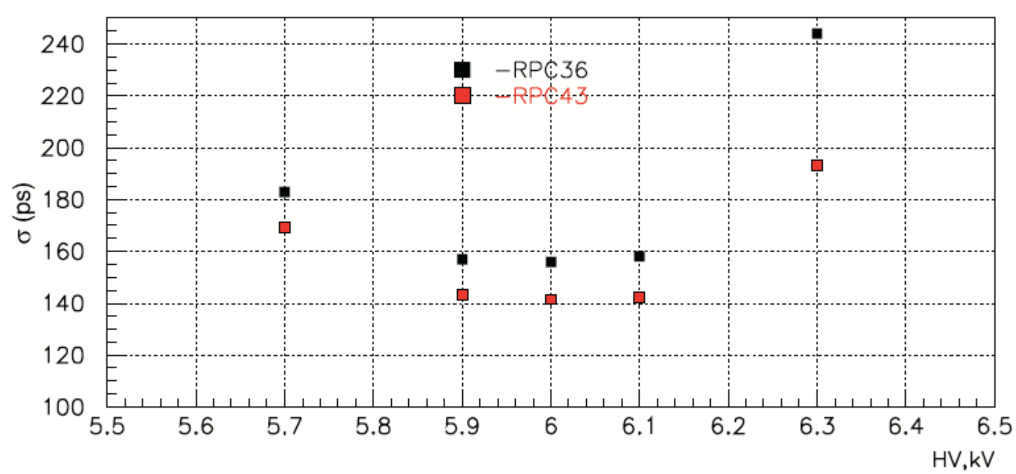
HARP TOF

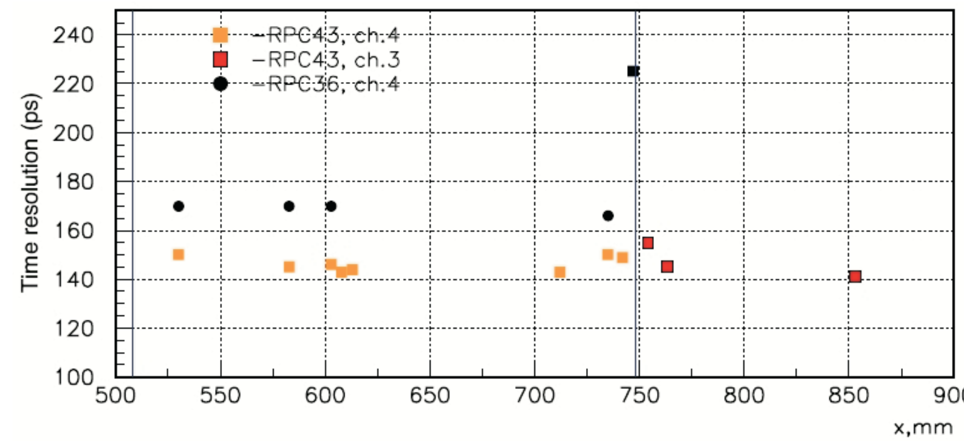
showing here the barrel TOF (@target)
also have forward wall w/ same MRPCs

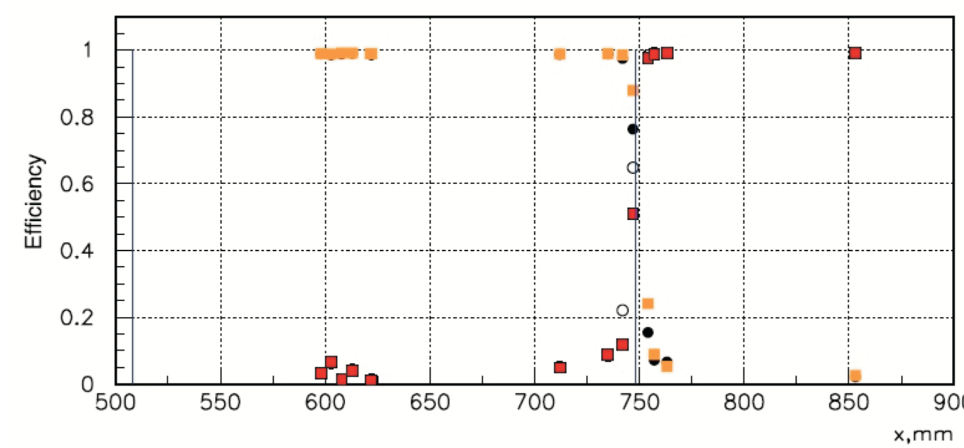


HARP TOF









>98% efficiency at HV plateau...

~140-160ps resolution....

uniform response across pads...

Summary

TOF remains a viable technique for Particle Identification in modern experiments...

The conventional technology of Scintillator+PMTs is extremely well-understood...

The new MRPC technology is becoming well-understood, and is a lot cheaper...

TOF generally works best over momentum ranges not covered by other techniques (dE/dx, Cerenkov)

MRPC detectors

- are not “RPC’s”...
- are dirt cheap (parts <30$/module), and relatively easy to construct...
- can outperform the conventional technology...
- slew, and have finite signal propagation times inside the pads, just like single-ended scintillator...
  - all the usual calibration techniques and software apply...
- are sensitive to the local temperature
  - higher temperatures $\rightarrow$ higher current draw and noise rates, better rate capability...
    - degradation to timing performance not expected (based on test beam experience)...
  - detectors not damaged by high temperatures...
- exhibit aging effects that are very small...
  - lengthy GIF-testing of ALICE MRPCs showed no significant effects...
  - more experience is still needed though... (TOFr’ contains many modules used in TOFr)

Bottom Line: MRPCs are worth considering for PHENIX... (how can i help?)