Modern Time-Of-Flight

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Cyclotron Institute Colloquium
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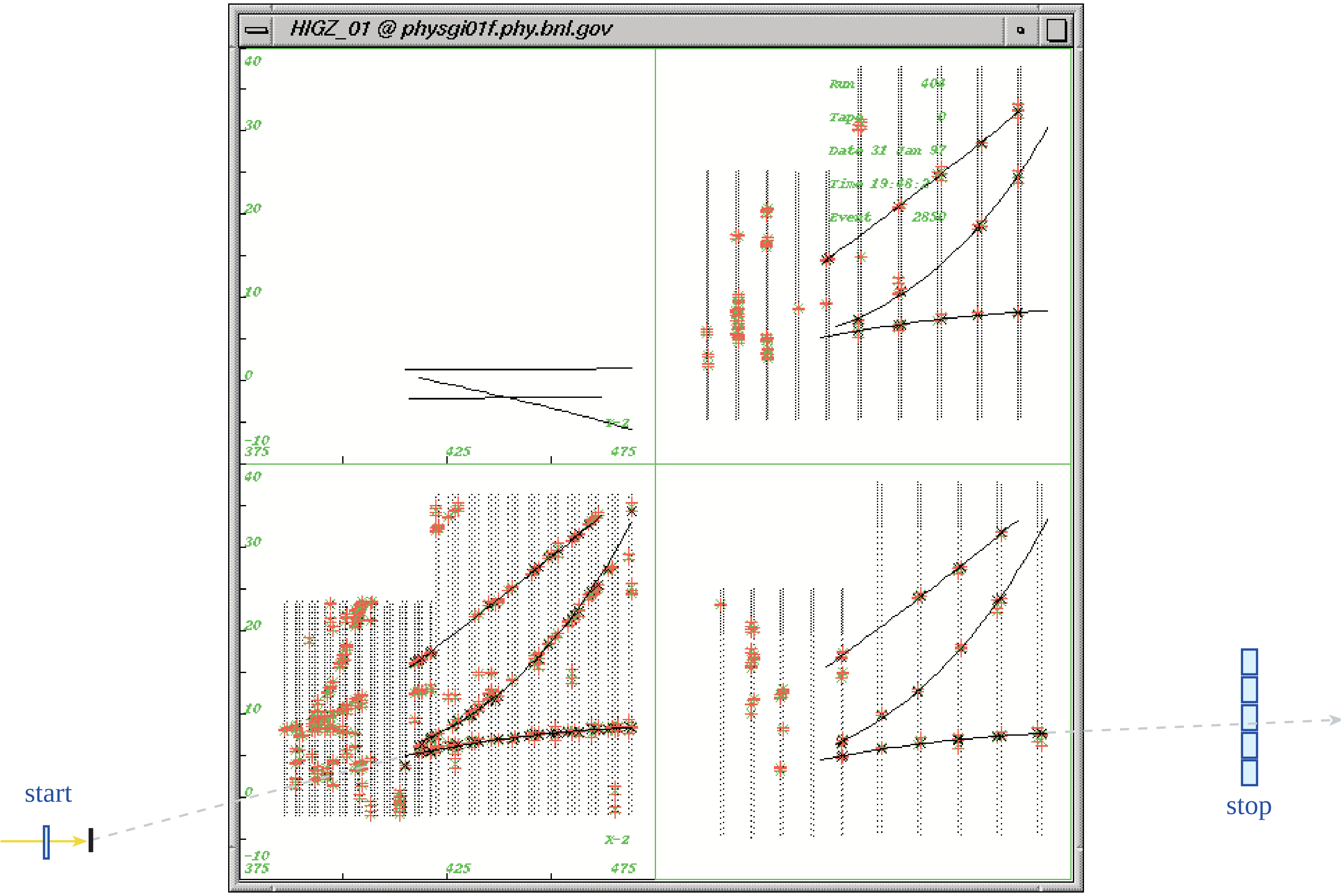
OUTLINE:

- TOF philosophy & Particle IDentification...
- Examples of Conventional TOF detectors
  E896 TOF and STAR TOFp/pVPD
- Other PID techniques, & physics topics with
  no TOF, a little TOF, and a lot of TOF.
- The looming problem:
  general need for large area TOF, but
  large area Conventional TOF can be *expensive*
- A new technology → towards "Modern" TOF
  ...as fast, easy to build, and <1/10th the price...
- New production prototype for STAR: "TOFr"
- Summary and outlook...
  ...towards STAR TOFR (tens of sq. meters)...

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



Information available following “reconstruction” of a track
→ track trajectory....
→ track momentum components...
→ (w/ some “extrapolation”) track total path length between two points

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

To assign a mass for a given track, measure a *time* at one point along this track relative to a specific reference time.

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

distance = rate * time → $\beta = S/\Delta t/c$

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

Time of Flight Reason for Being: (charged) Particle Identification

Things you can do with a TOF system (to be illustrated on the coming slides)

- Optimization of PID capabilities of other detectors for tracks in a common acceptance
- Spectra for primary tracks: transverse momentum and rapidity distributions by species
- Searches: significant suppression to backgrounds by requiring the 2(3) tracks assumed to be daughters of a decaying particle of interest are each the correct species for this assumption.

Depending on what you're trying to identify, you'd need....

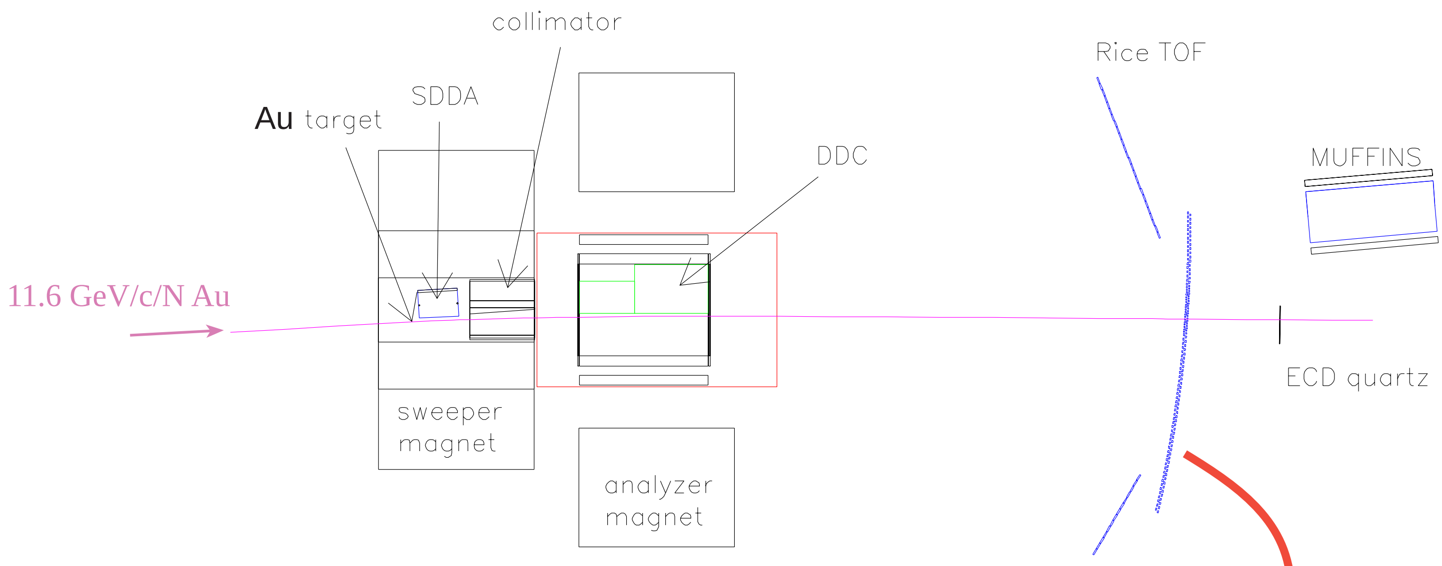
Sufficiently accurate tracking	$\sigma(p)/p$~few percent, $\sigma(S)$~few mm-cm
Sufficiently long flight paths	S~few meters
Start detector with sufficient resolution	$\sigma(tstart) \sim$ 20-60ps
Stop detector with sufficient resolution	$\sigma(tstop) \sim$ 50-100ps
Digitization with sufficient resolution	~100ns/~11bits, $\sigma \sim$ 20ps
Lots of software for the corrections Slewing, Timing offsets, conversion factors, ...	$\sigma(corrections) \sim$ 20-30ps
Monitoring: rate scalars, temperature along cable paths, etc. etc........	

Total resolution on time differences is typically 70-150ps after all the corrections

time differences between different particle species (pion, Kaon, proton, fragments) can be large!

Now to a few concrete examples.....

“Conventional” TOF Example 1: BNL-AGS E896 TOF



Search for the H, Λ, Ks using topology and momenta only

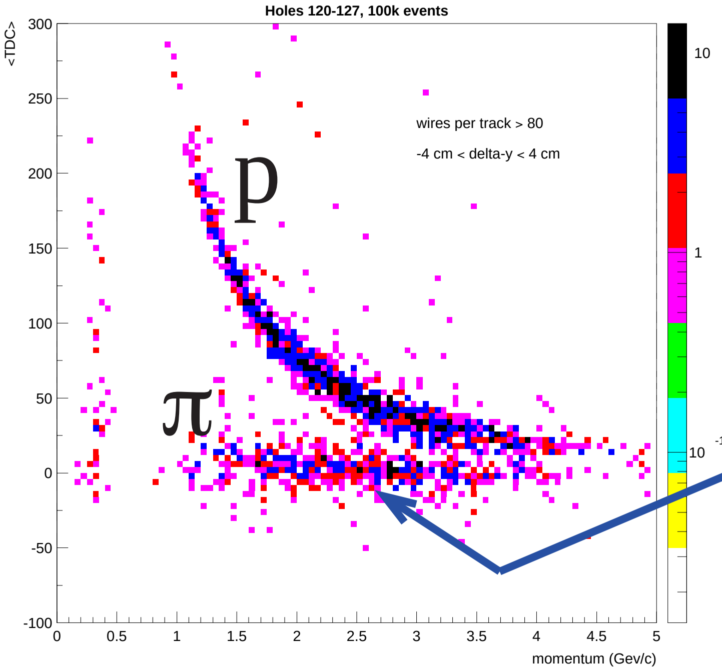
BUT.... no direct PID on the charged daughters

does each candidate Λ → p & π-??

does each candidate Ks → π+ & π- ??

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

E896 candidates: Λ?→positive....



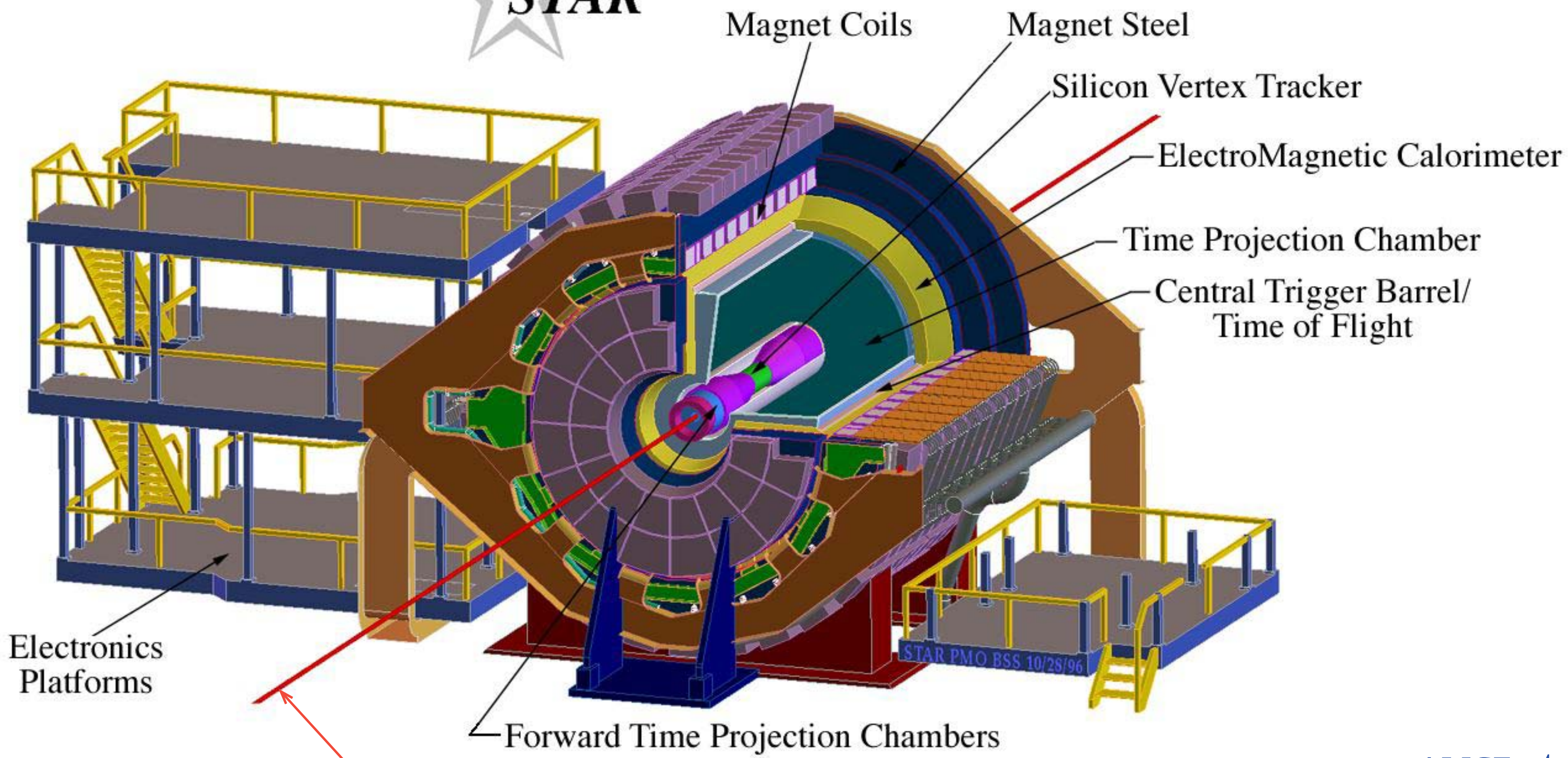
- ~10% of E896’s best Λ candidates are *not* Λ’s...

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

- Λ and Ks spectra w/ daughter PID

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

STAR



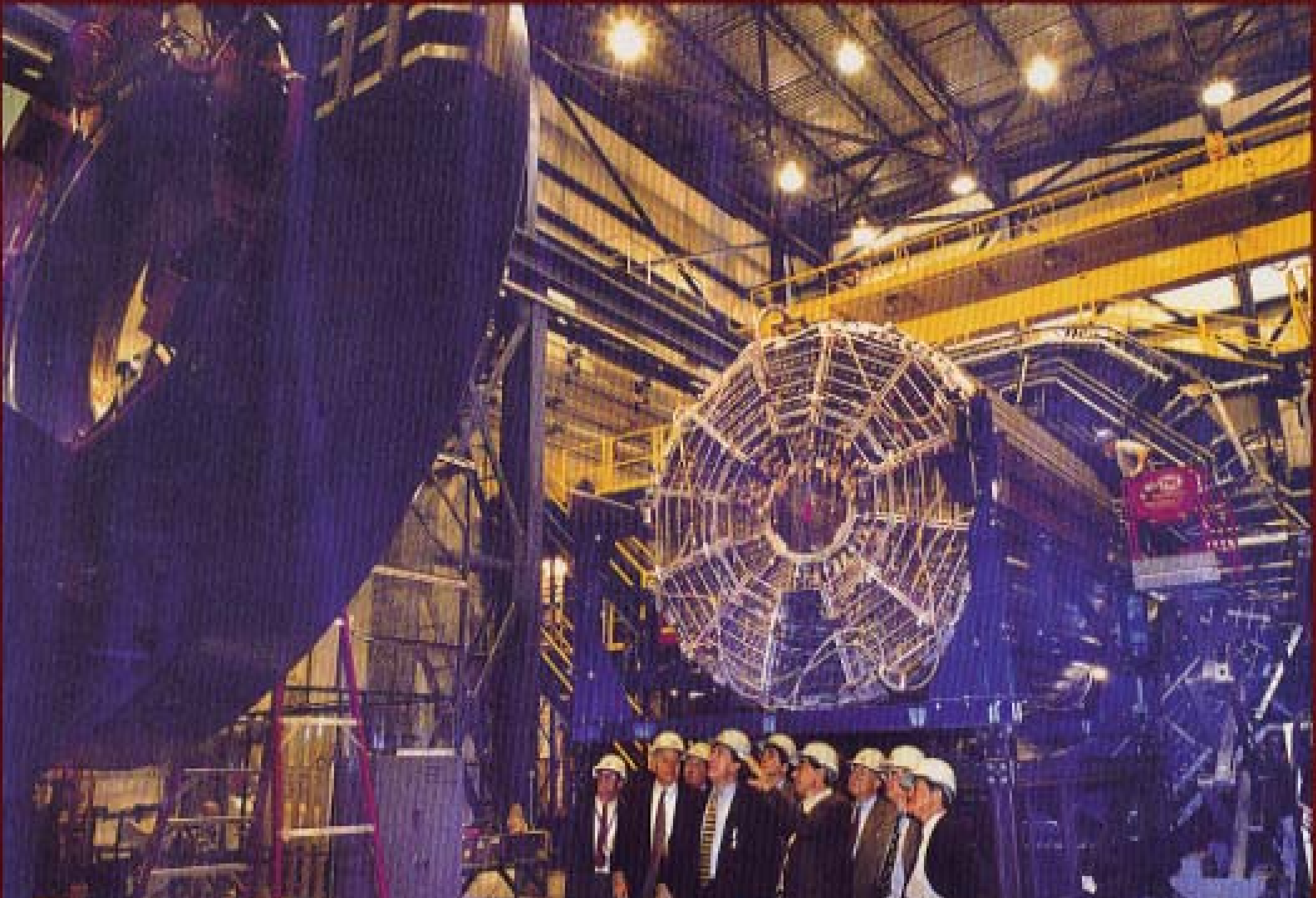
100 GeV/c/N Au + 100 GeV/c/N Au
10 GeV/c/N Au + 10 GeV/c/N Au
100 GeV/c p + 100 GeV/c p
and there will be others!

ALICE at CERN LHC

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERN COURIER

VOLUME 39 NUMBER 1 FEBRUARY 1999



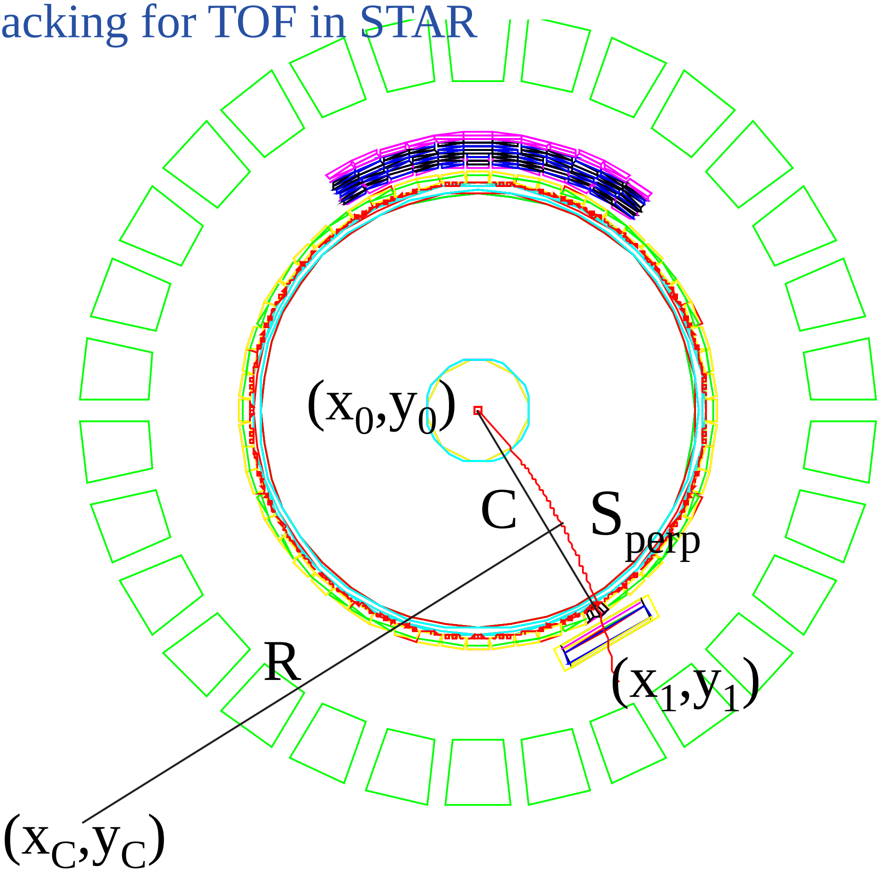
A STAR in the making

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

Tracking for TOF in STAR



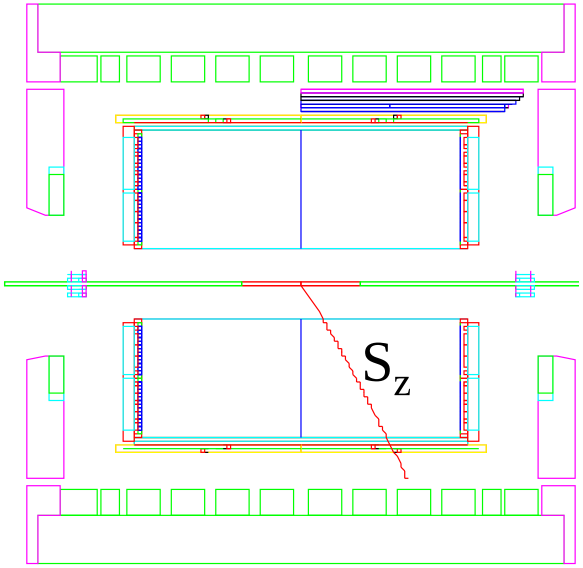
$s = \sqrt{(s_{perp}^2 + s_z^2)}$ with

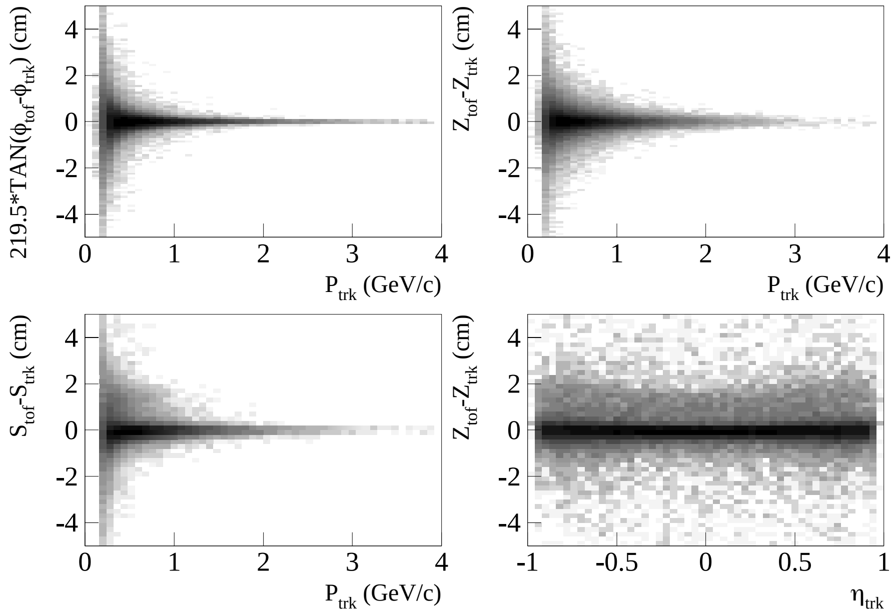
$s_{perp} = 2R \sin^{-1}(C/2R)$

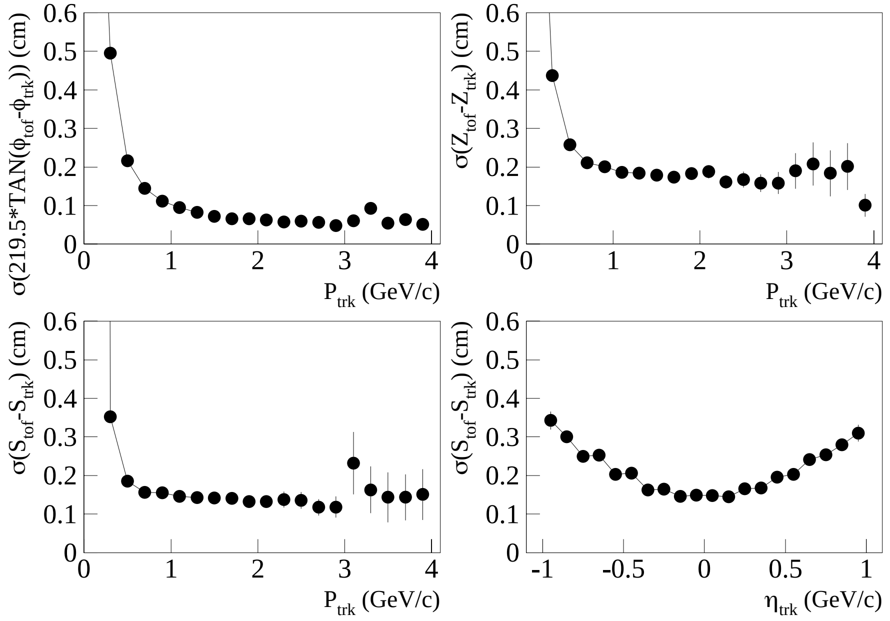
$s_z = z_1 - z_0$

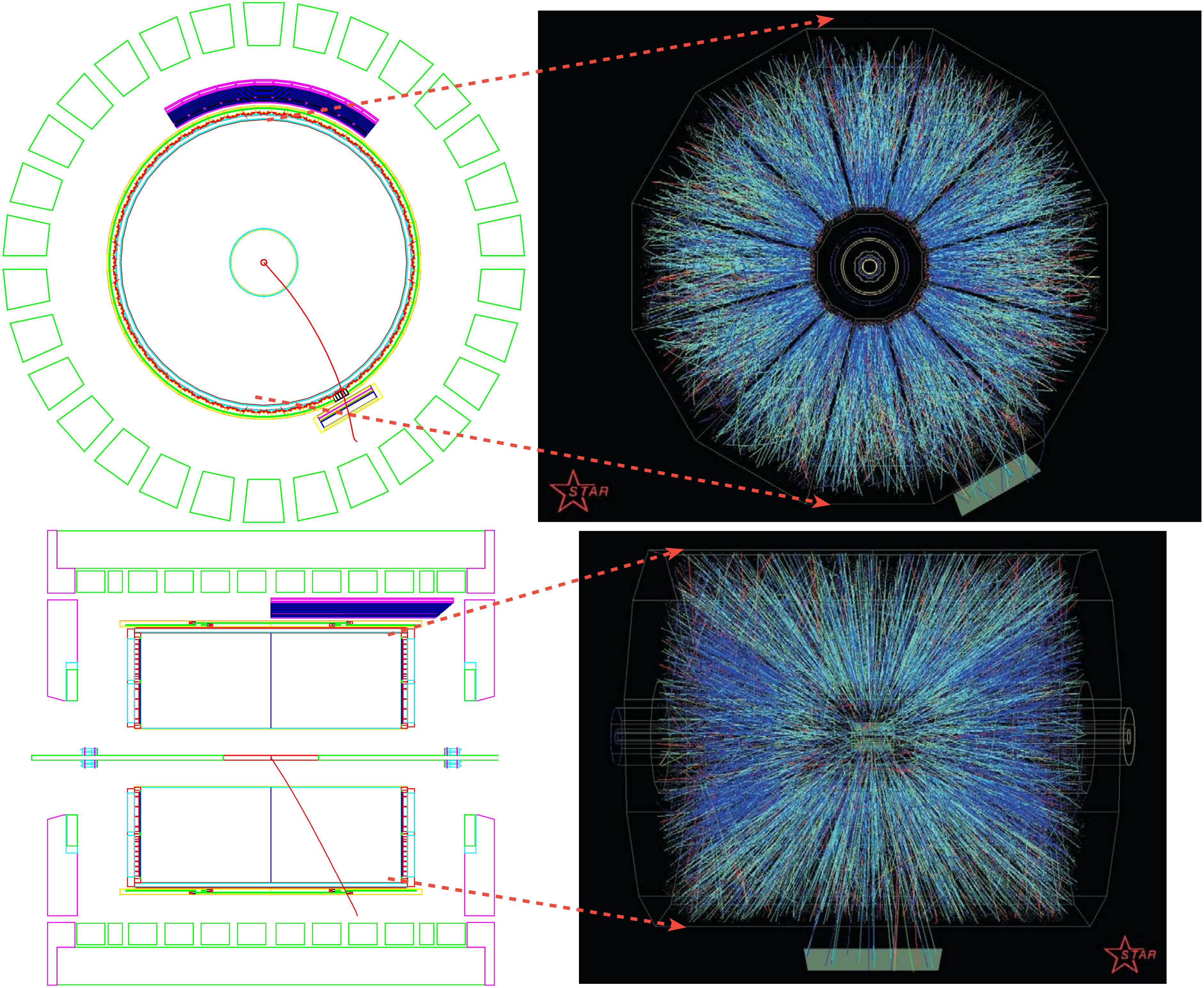
R is the helix radius

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





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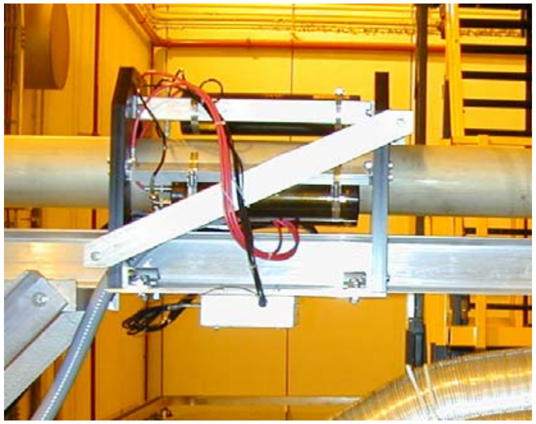
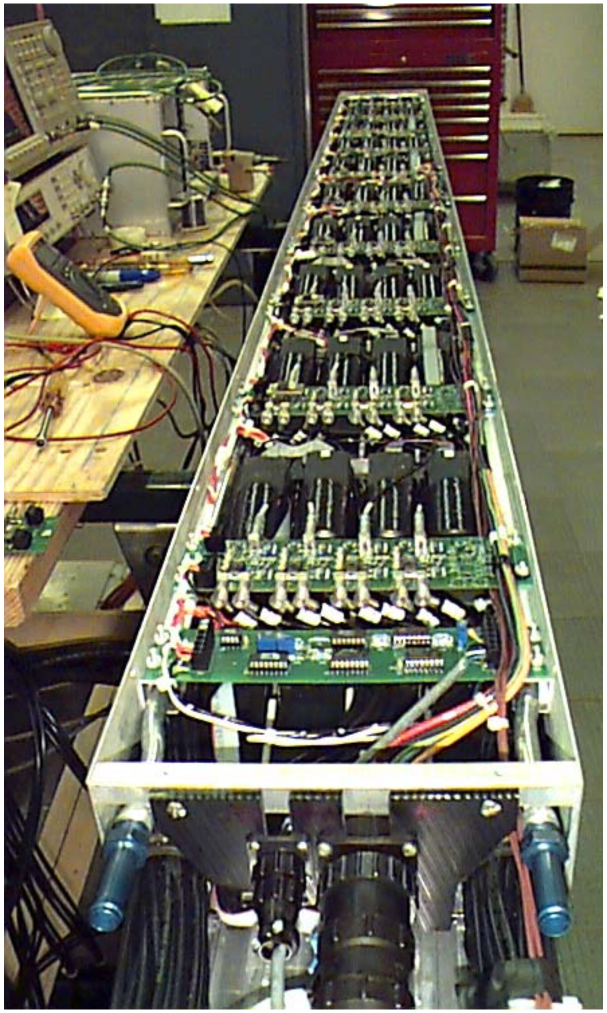
STAR

Conventional TOF Example 2: STAR TOFp

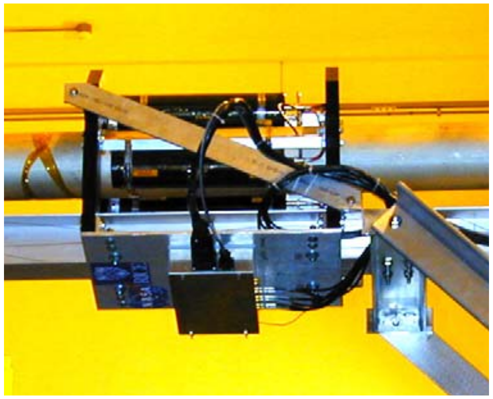
pVPD East



TOFp tray



pVPD West



Hardware

- Start: 6 pVPD channels
- Stop: 41 TOFp channels
- Local trigger: scalers
- Temp. monitoring: 28 TCs
- Correlated noise: 60Hz ramp

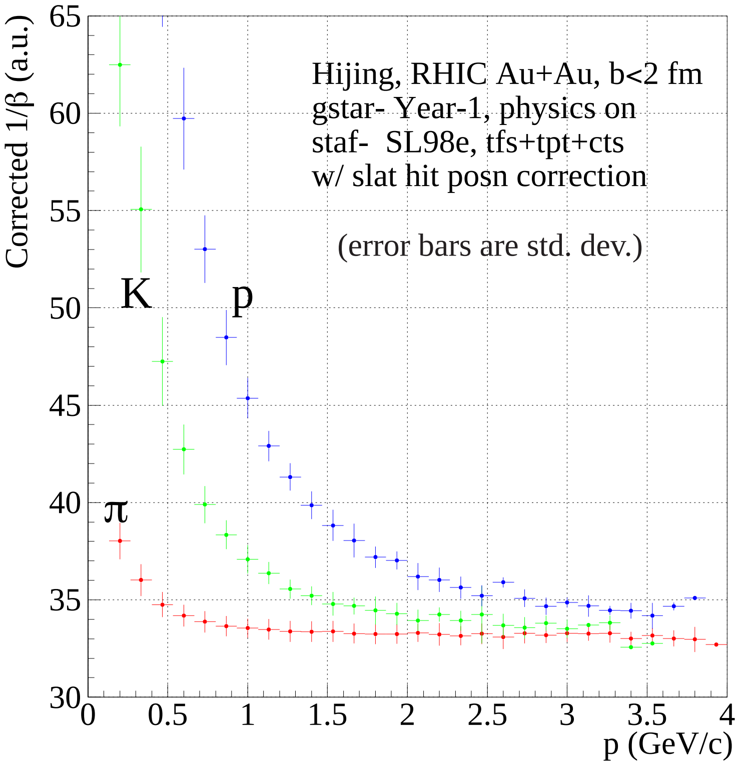
Operations

- pVPD active since 8/25
- TOFp active since 10/9
- Collected events:

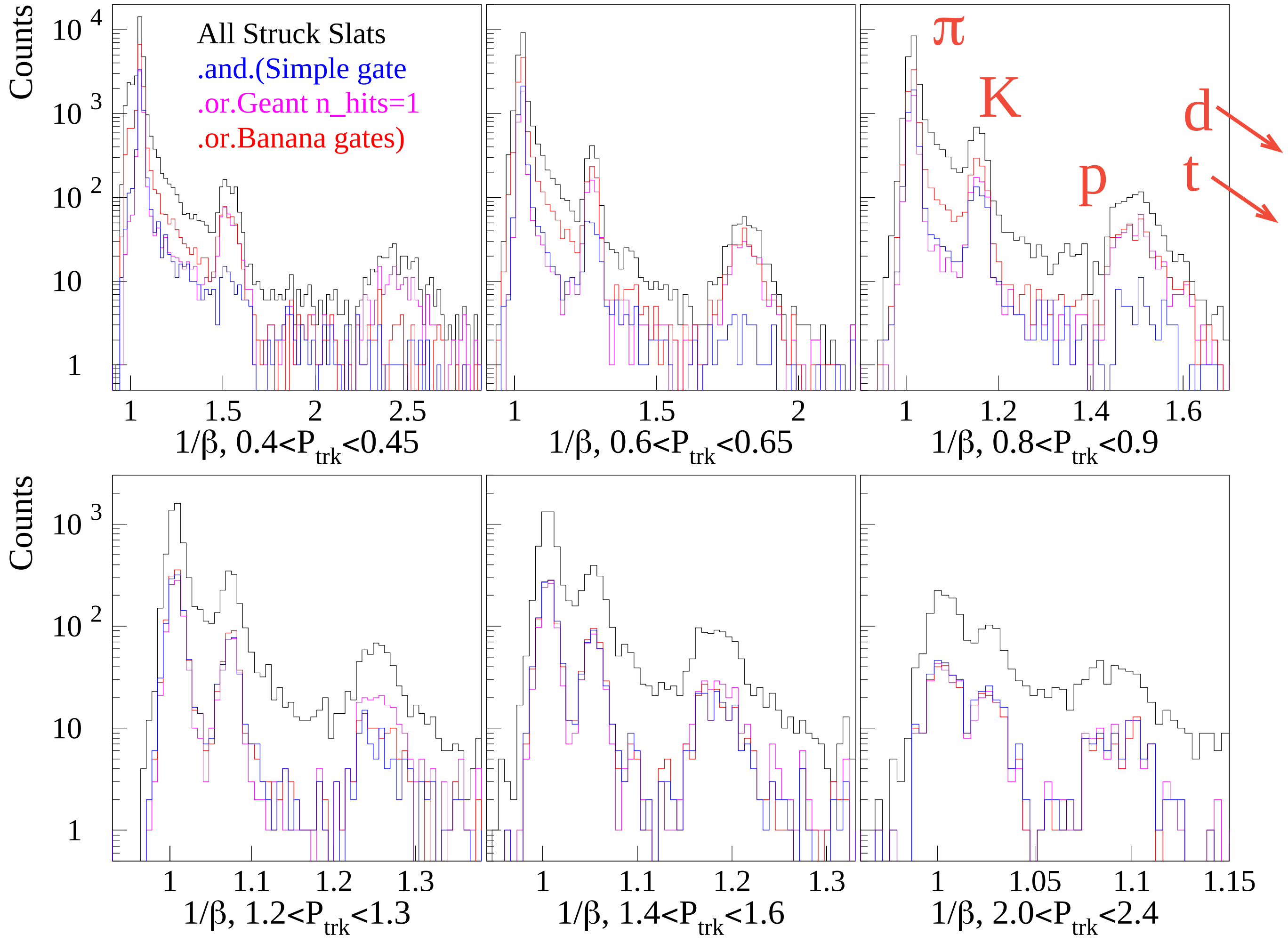
AuAu Central (200GeV): 2.7M
AuAu Minbias(200GeV): 1.5M
AuAu Central (22GeV): 72k
AuAu Minbias (22GeV):216k
pp (200GeV): 21.8M (100.00%)

Given STAR's geometry
& a 100ps TOF system:

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



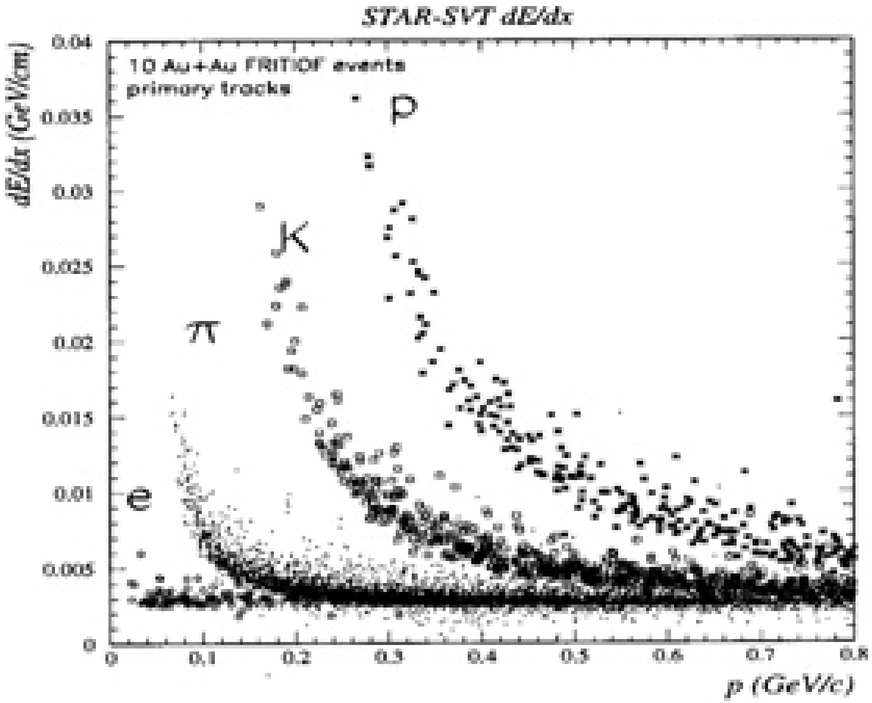
Venus, b<2fm, all phys on, 13.3hrs at 1Hz w/ 1 tray

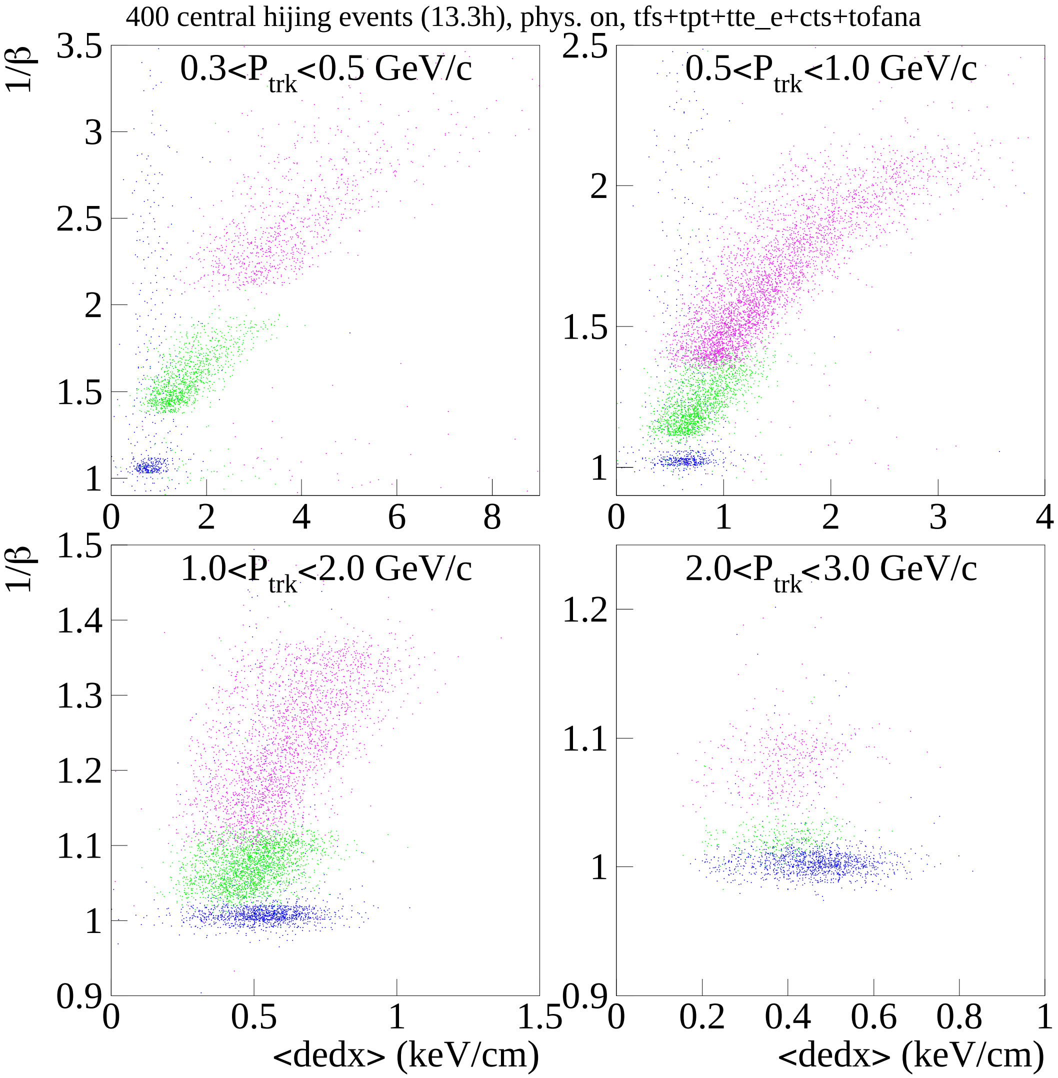


PID using other kinds of detectors: dE/dx.....

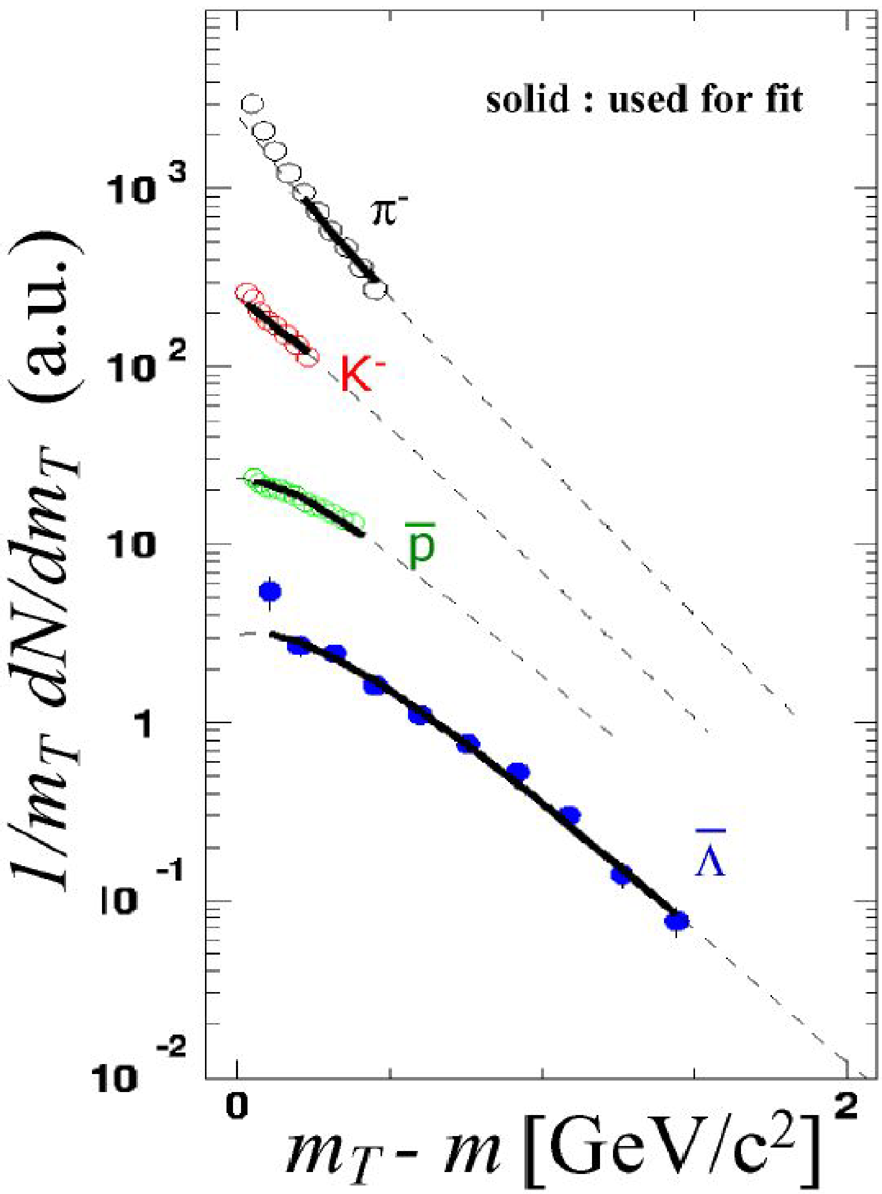
- π/K/p direct PID for
  ~0.1 GeV/c < p < 0.6 GeV/c

- (π+K)/p direct PID for
  ~0.1 GeV/c < p < 1.0 GeV/c





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



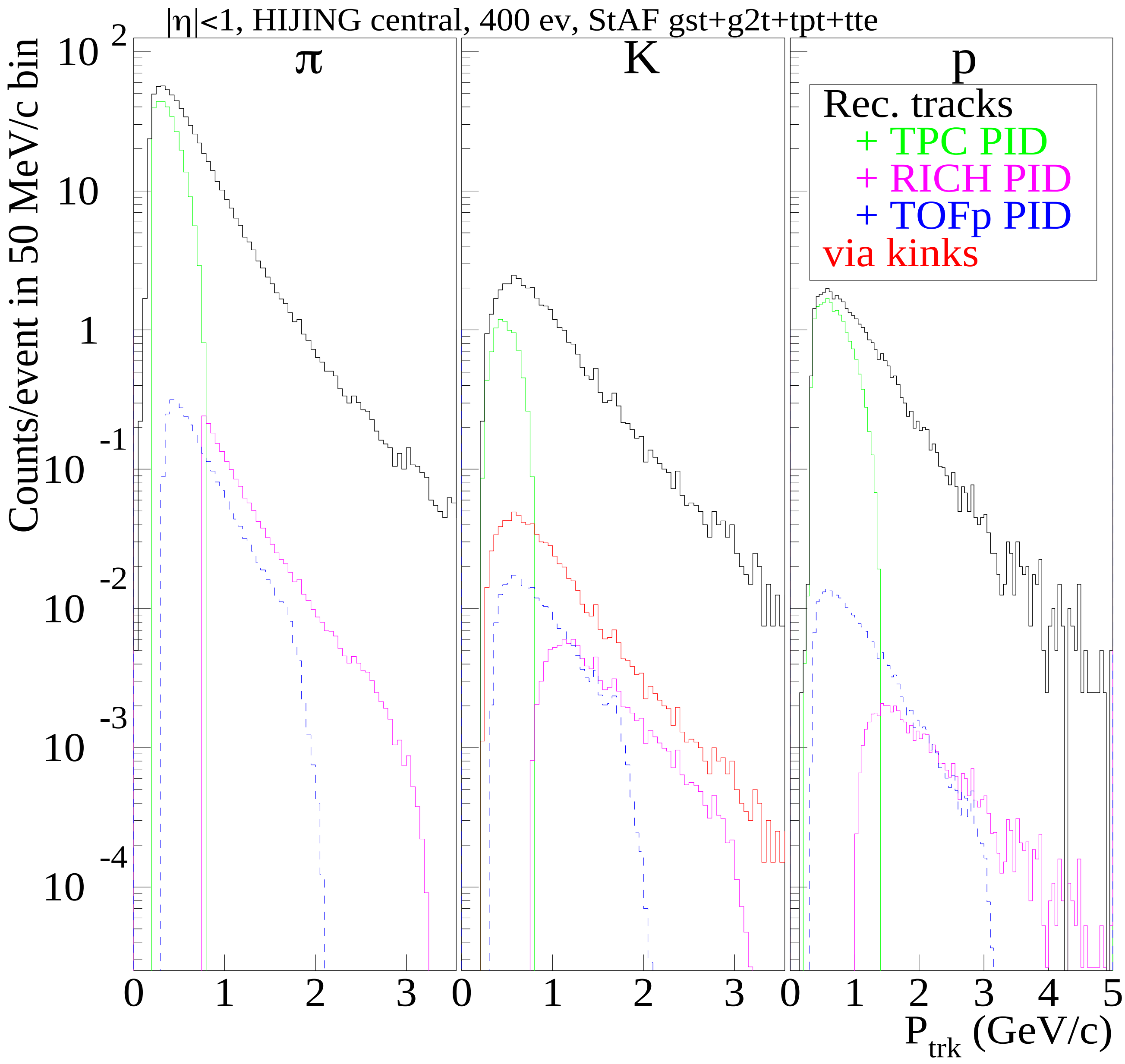
plot by
M. Kaneta

- acceptance w/ direct PID is in a region of momentum that is *soft*...
- uncomfortably *long* extrapolation to higher momenta...

TOFp (conventional & small area) should extend the reach of this plot by a factor of 2.

...but a small area TOF such as TOFp only gets you so far....

PID using other kinds of detectors (cont.)



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

want charged hadron PID at even higher momenta?

→ you want a RICH detector... (see *e.g.* M. Murray)

Physics requiring Large-Area TOF in STAR, example 1

$K^{\star 0}(892)$ production in Relativistic Heavy Ion Collisions at $\sqrt{s_{NN}} = 130\ GeV$

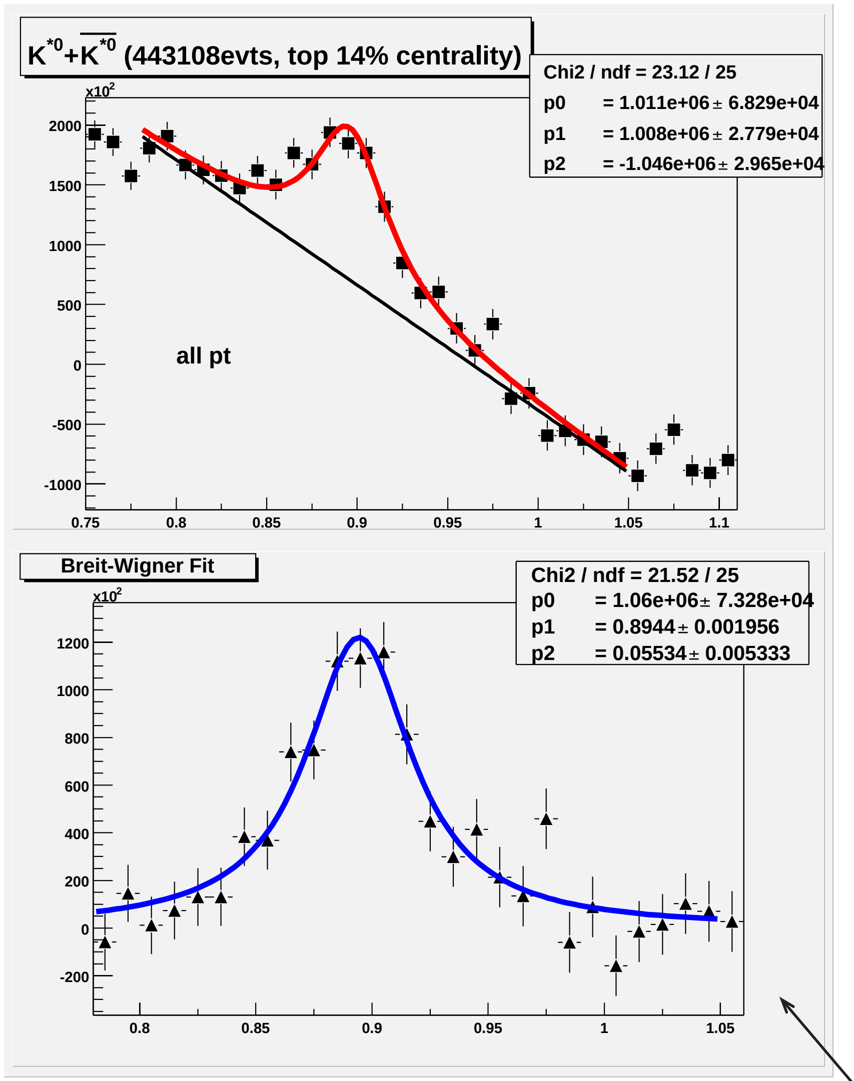
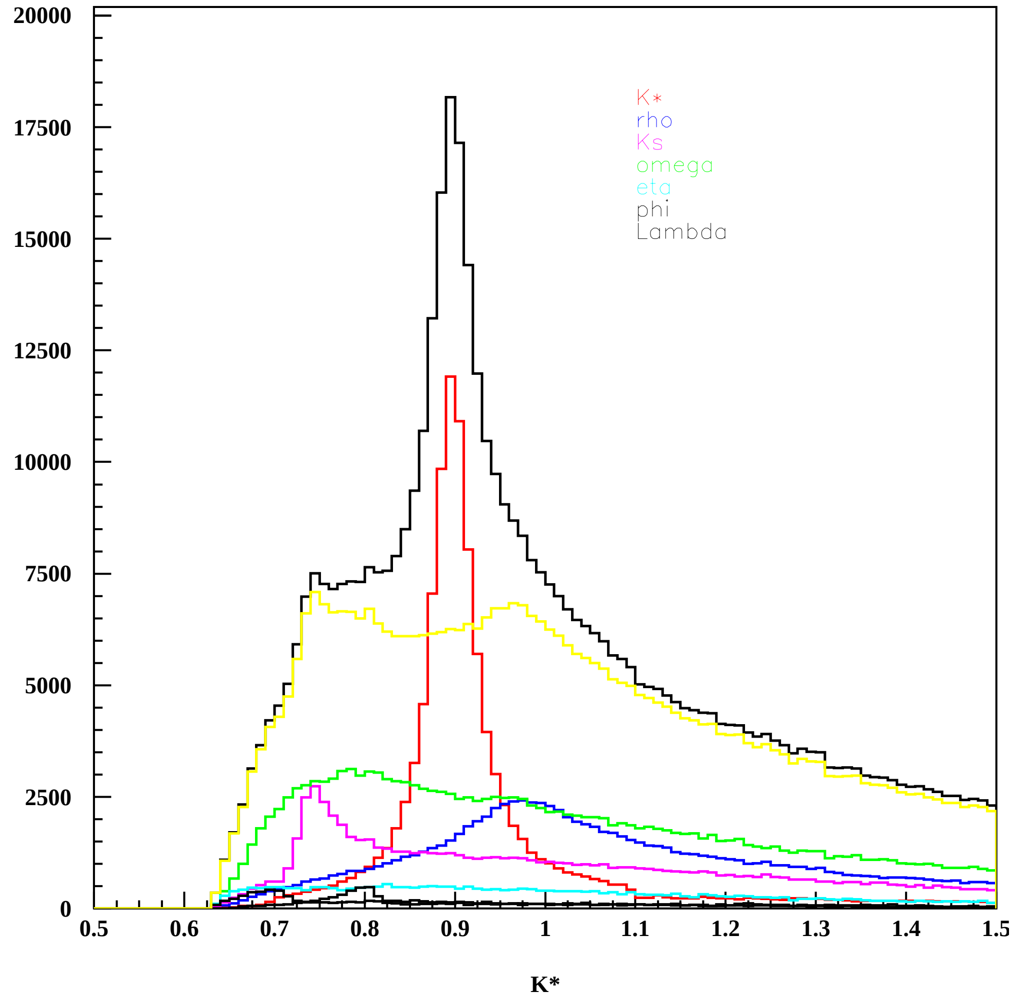


FIG. 2: $K^{\star 0}$ mass plot after mixed-event background subtraction for top 14% centrally triggered events. A combination of linear background and simple Breit-Wigner resonant function is used to fit the distribution on top panel. On the botton panel is the linear background subtracted distribution with Breit-Wigner function fit. The mass and width are found to be consistent with the standard values.

(plots by Zhangbu Xu)



includes “partial PID” based on dE/dx....

Physics requiring Large-Area TOF in STAR, example 2

$\bar{d}$ and $^{3}\overline{He}$ production in $\sqrt{s_{NN}} = 130$ GeV Au+Au collisions

(analysis by Dave Hardtke)

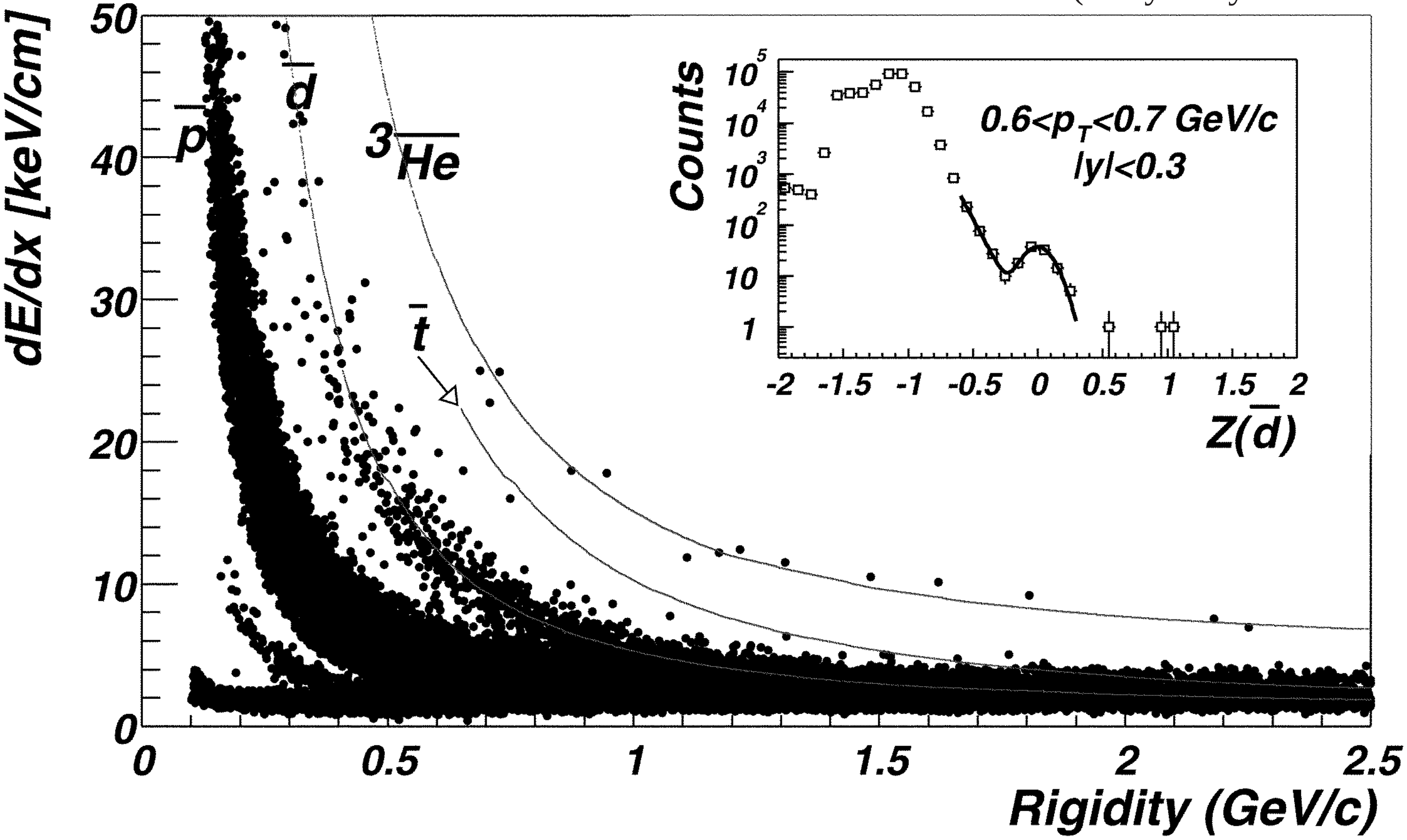


FIG. 1: Ionization (dE/dx) versus rigidity (|momentum/nuclear charge units|) for negative tracks. The π^- and K^- bands have been suppressed. Also plotted are the Bethe-Bloch expectations for $\bar{d}$, $\bar{t}$ and $^{3}\overline{He}$. Inserted is a projection of the Z variable (see text) for one transverse momentum bin ($0.6 < p_T < 0.7$ GeV/c).

based on dE/dx alone, STAR

can easily identify 3-He (anti)fragments
can identify only the lower momenta (anti)deuterons
can identify only a tiny *tail* of the (anti)triton spectrum

all three bands (and the important “reference” p and pbar bands)
are well-separated out to much higher momenta with TOF information

Time to touch base with Reality....

Cost for Conventional detectors alone:

Scintillating Plastic	75 $/ch.
Hamamatsu Mesh Dynode PMT	1500 $/ch.
Cockroft-Walton PMT Base	75 $/ch.
	1650 $/ch.

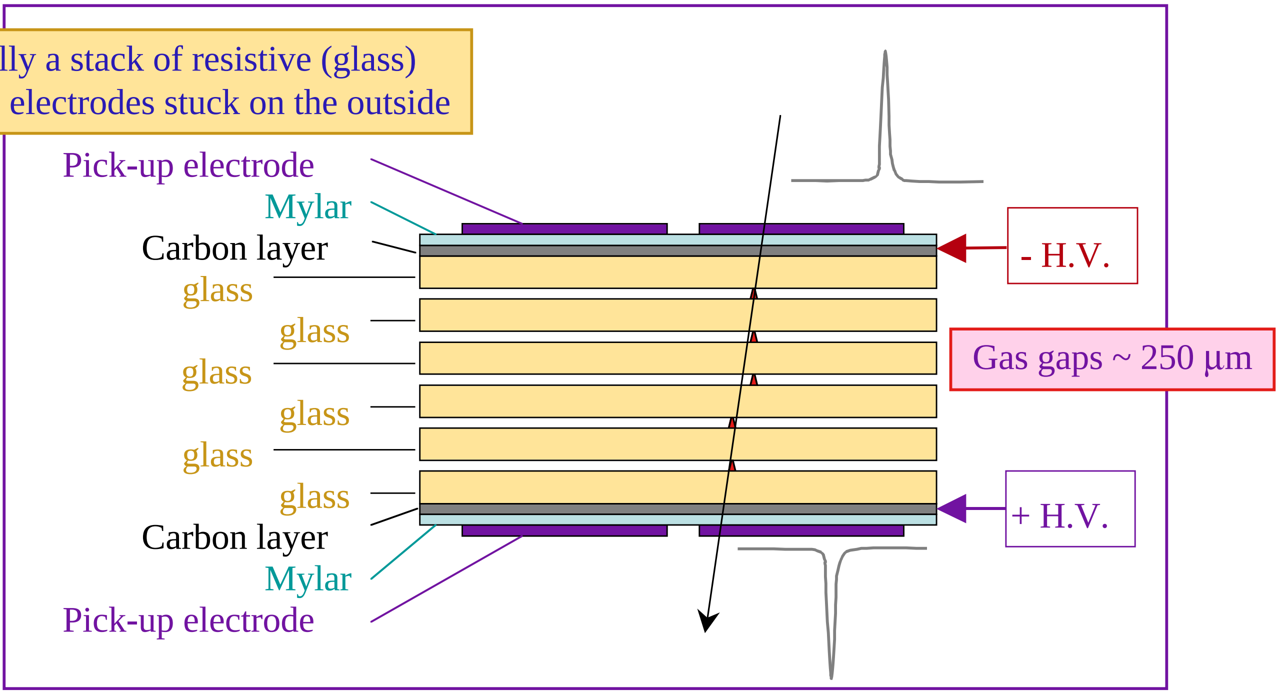
60 ch/tray * 120 trays implies 7200 chs → 12 M$
now add in the rest of the system! → 16? M$

Waaaaaayyyyyy too expensive to have any chance of getting funded....

Since ~1998, groups at
CERN (C. Williams *et al.*) and RICE (G. Eppley *et al.*)
have been collaborating to develop a New Technology for TOF....

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

Resistive Plate Chambers

(in avalanche mode)

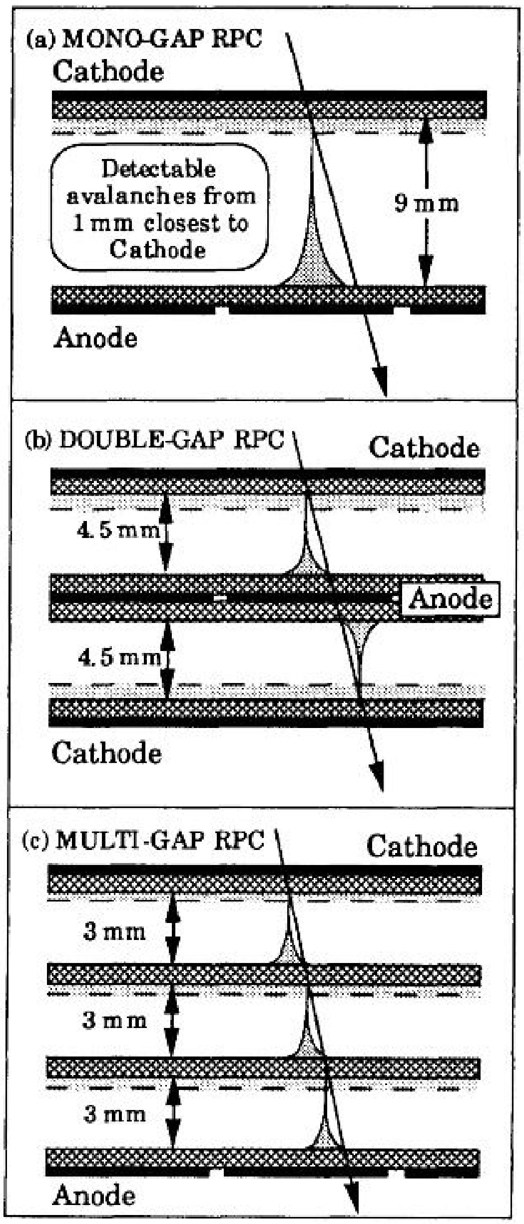


Figure 2. Schematic representation of a monogap RPC (top); a double gap RPC (middle) and a multigap RPC (bottom).

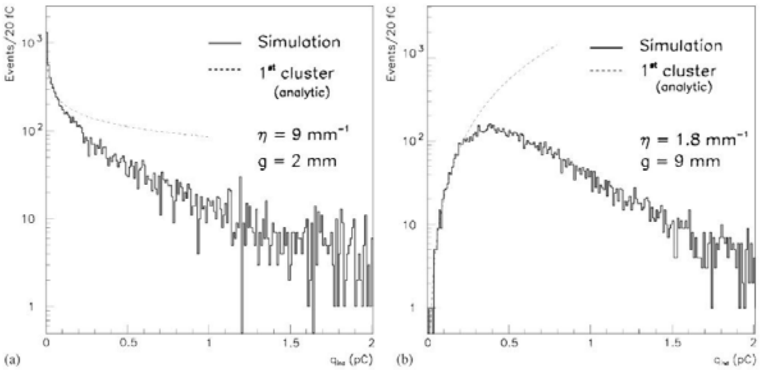


Fig. 1. Comparison between the simulated charge spectra for single (a) narrow ($g = 2$ mm) and (b) wide ($g = 9$ mm) gap RPCs.

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

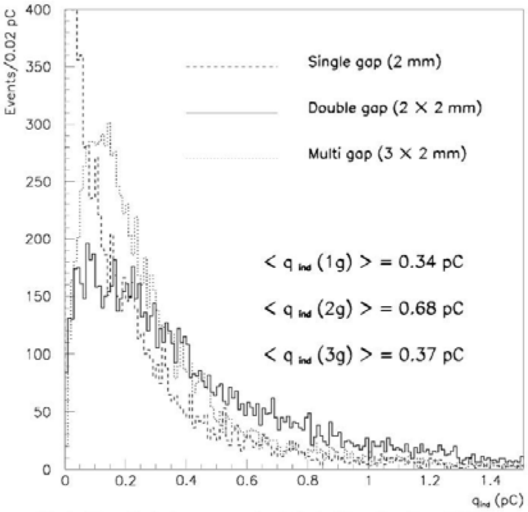


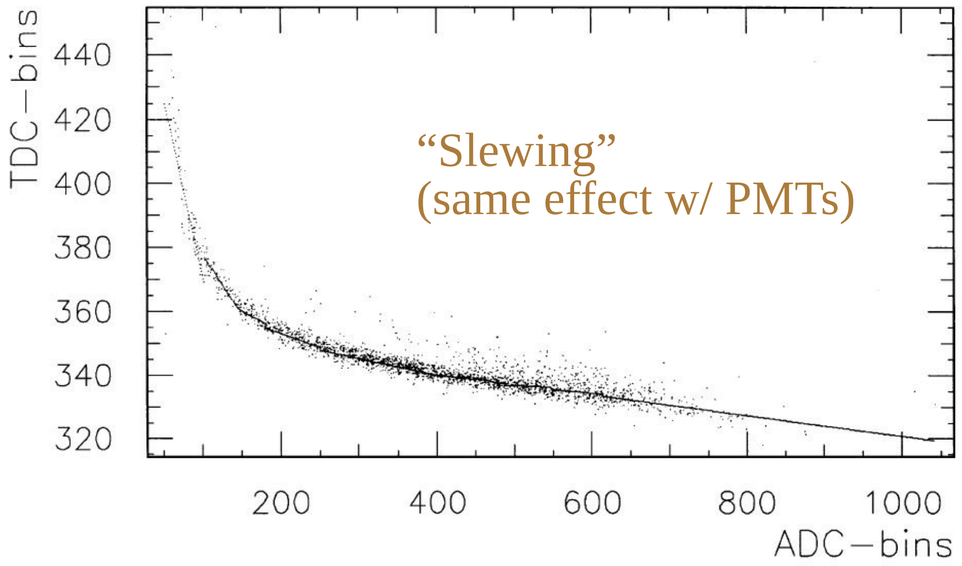
Fig. 3. Monte Carlo charge spectra for single- double- and multi-gap RPCs.

With many small gaps,

- the resistive plates are transparent to the fast signals generated by the avalanches in each gas gap. The induced signal is the *sum over all gaps*.

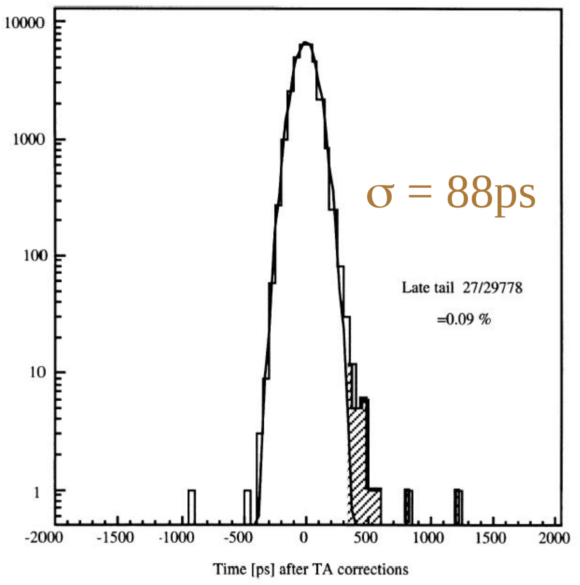
- the internal resistive plates are electrically floating, so the stable state is *equal gain in all gaps*.

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



“Slewing”
(same effect w/ PMTs)

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



σ = 88ps

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.

For Additional Details.... (articles in blue are “must reads”!)

“The development of the multigap resistive plate chamber”, M.C.S. Williams, Nucl. Phys. B (Proc. Suppl.) **61B**, 250 (1998).
“Microstreamers and the micro-gap Resistive Plate Chamber”, E. Cerron-Zeballos *et al.* (inc. Lamas-Valverde, Platner, & Roberts), NIM A **411**, 51 (1998)
“Effect of adding SF6 to the gas mixture in a multigap resisitve plate chamber”, E. Cerron-Zeballos *et al.* (inc. Lamas-Valverde, Platner, & Roberts), NIM A **419**, 475 (1998)
“A very large multigap resisitive plate chamber”, E. Cerron-Zeballos *et al.* (inc. Lamas-Valverde, Platner, & Roberts), NIM A **434**, 362 (1999)
“Recent Progress on RPCs for the ALICE TOF system”, M. Spegel for the ALICE Collaboration, NIM A **453**, 308 (2000)
“A new high-resolution TOF technology”, P. Fonte *et al.*, NIM A **443**, 201 (2000)
“A Multigap Resistive Plate Chamber prototype for the Time-Of-Flight of STAR at RHIC”, J. Lamas-Valverde *et al.*, Vienna Conference on Instrumentation, 2001 (submitted)

“Optical observation of discharge in resistive plate chamber”, I. Kitayama *et al.*, NIM A **424**, 474 (1999)
“Test beam results on resistive plate chamber prototype at gamma irradiation facility in CERN”, C.H. Chung *et al.*, NIM A **432**, 14 (1999)
“Study of avalanche mode operation of resistive plate chambers with different gas gap structures”, V.V. Ammosov *et al.*, NIM A **441**, 348 (2000)

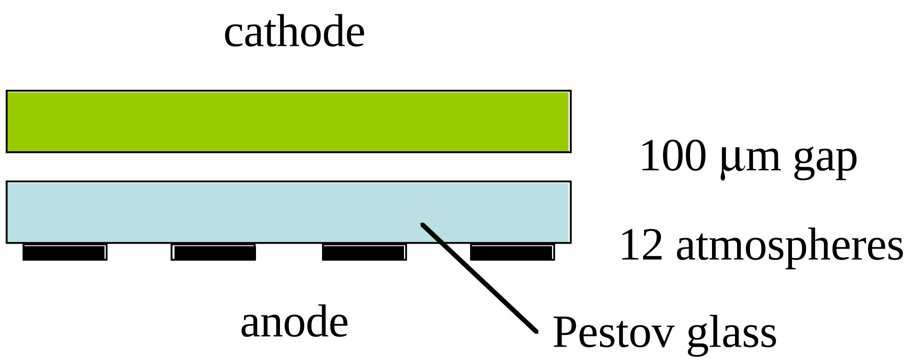
...and on the theory side...

“Resistive Plate Chambers in avalanche mode: a comparison between model predictions and experimental results”, M. Abbrescia *et al.*, NIM A **409**, 1 (1998)
“A simple theory of rsignals induced by a point charge moving in a resistive plate chamber”, Th. Heubrandtner *et al.*, NIM A **419**, 721 (1998)
“The simulation of resistive plate chambers in avalanche mode: charge spectra and efficiency”, M. Abbrescia *et al.*, NIM A **431**, 413 (1999)

Two gaseous detectors considered for ALICE

Pestov counters

Glass electrode and metal electrode

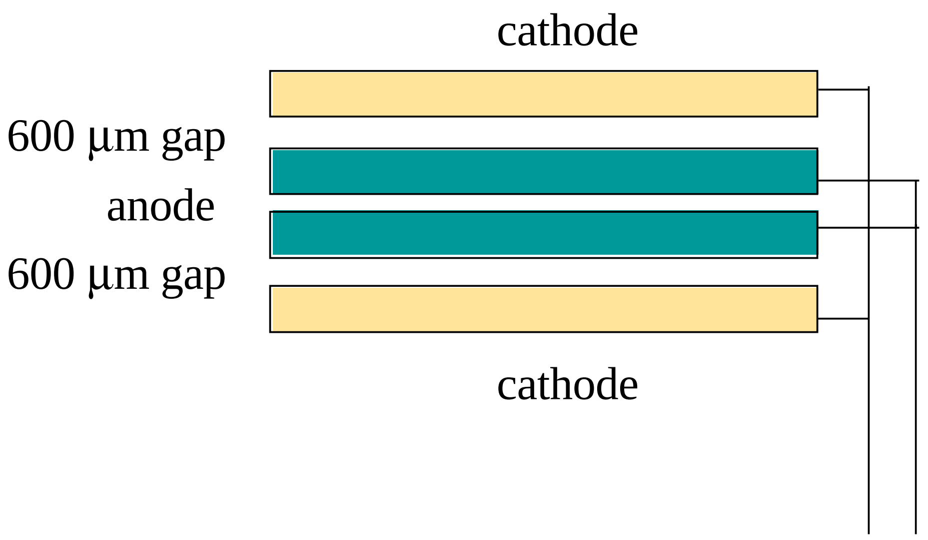


Excellent time resolution ~ 50 ps

But long tail of late events
Mechanical constraints (due to high pressure)
Non-commercial glass

Double gap PPC

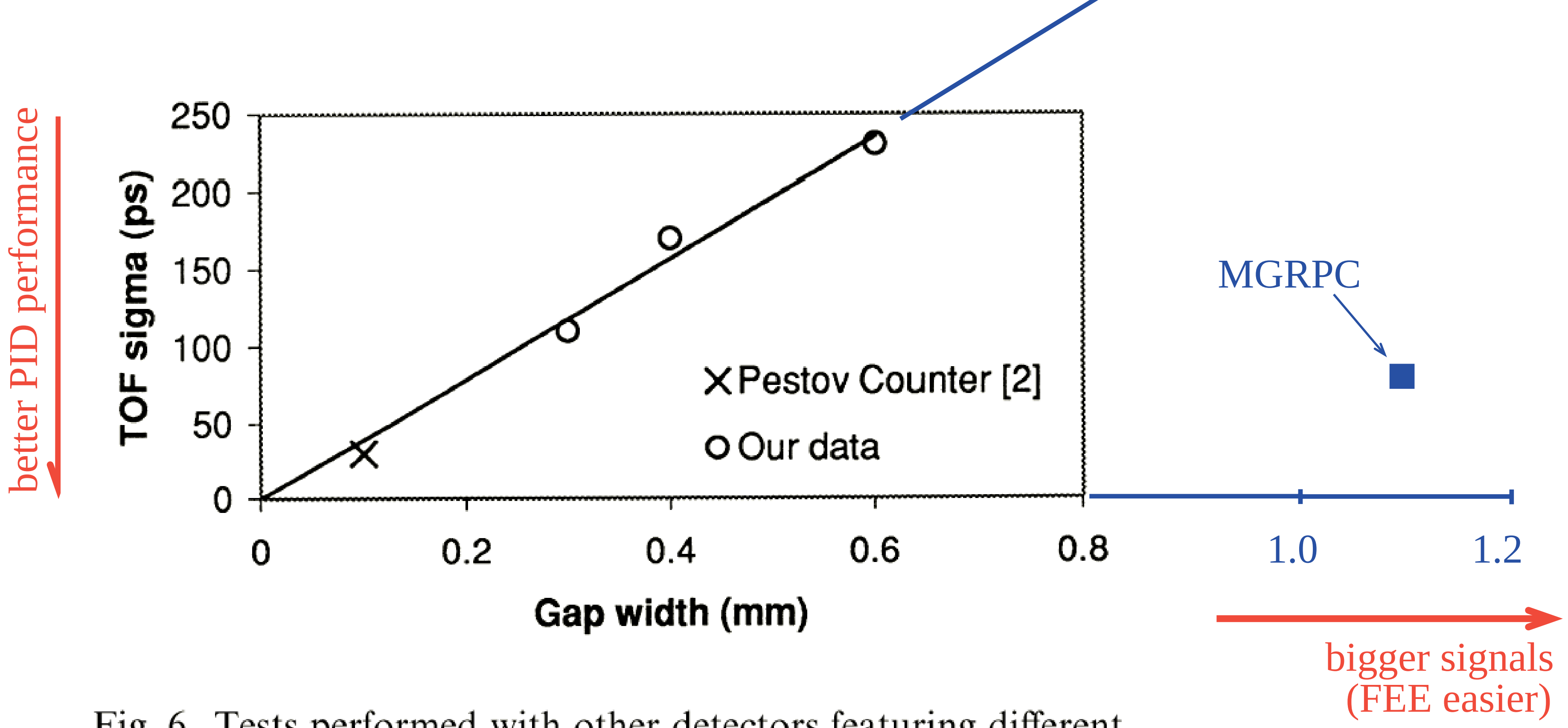
Both electrodes metallic



Marginal time resolution ~ 250 ps
Small signal (to keep sparks at low probability)
Difficult to build

O P. Fonte et al. / Nuclear Instruments and Methods in Physics Research A 443 (2000) 201}204

X V.V. Parchomchuck, Yu.N. Pestov, N.V. Petrovykh, Nucl. Instr. and Meth. 93 (1971) 269.



better PID performance

MGRPC

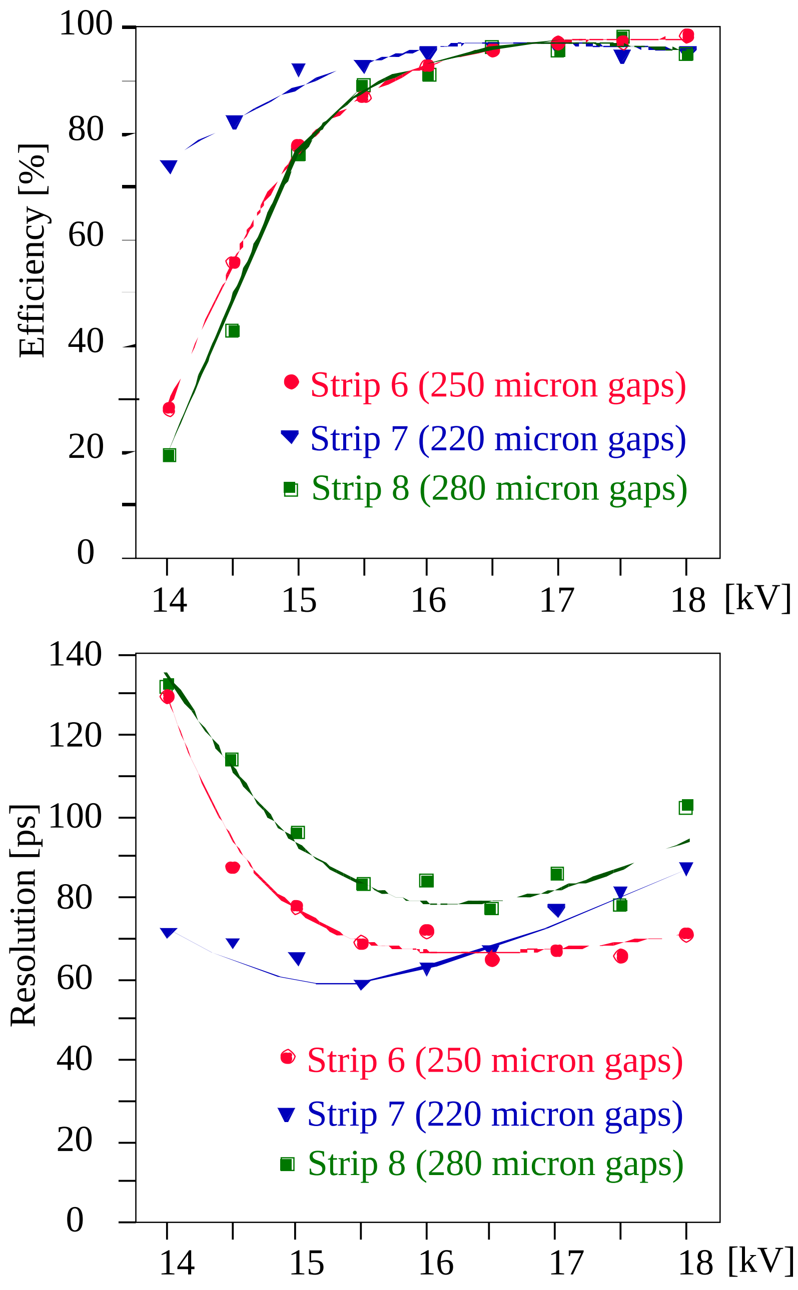
bigger signals
(FEE easier)

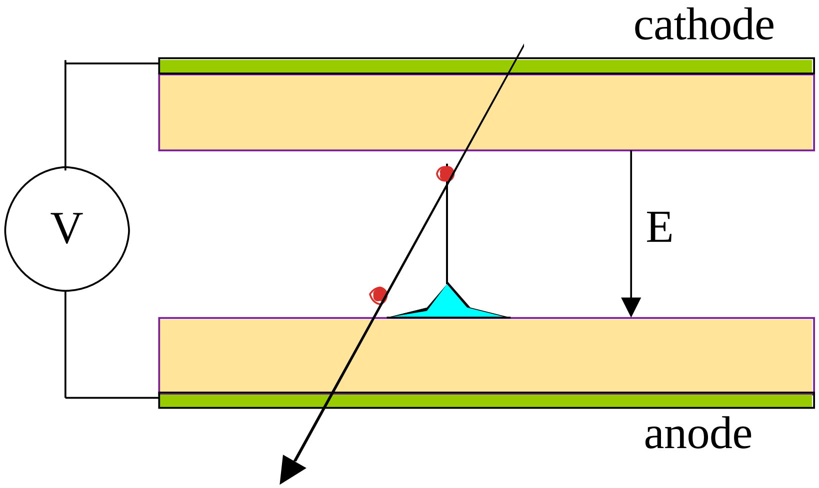
Fig. 6. Tests performed with other detectors featuring different widths of the gas gap suggest that the main contribution to the time jitter is associated to the amplification process in the gas. The timing resolution seems to depend almost linearly on the gap width, with a slope of approximately 40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

MGRPCs 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





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

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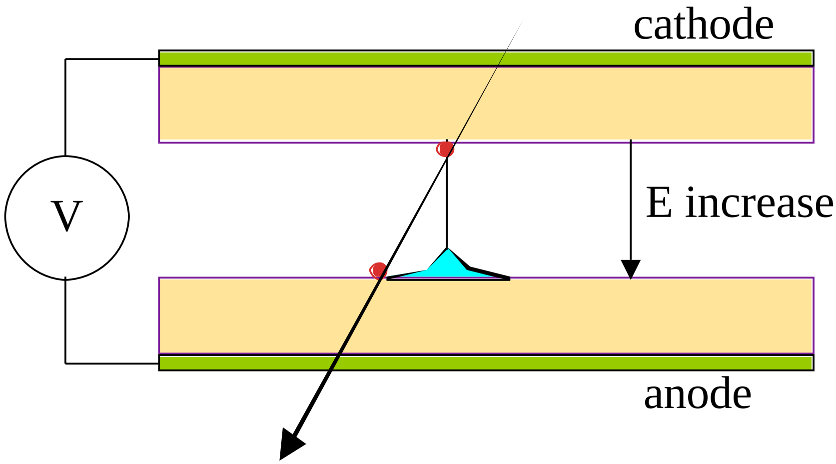
Now consider smaller gap



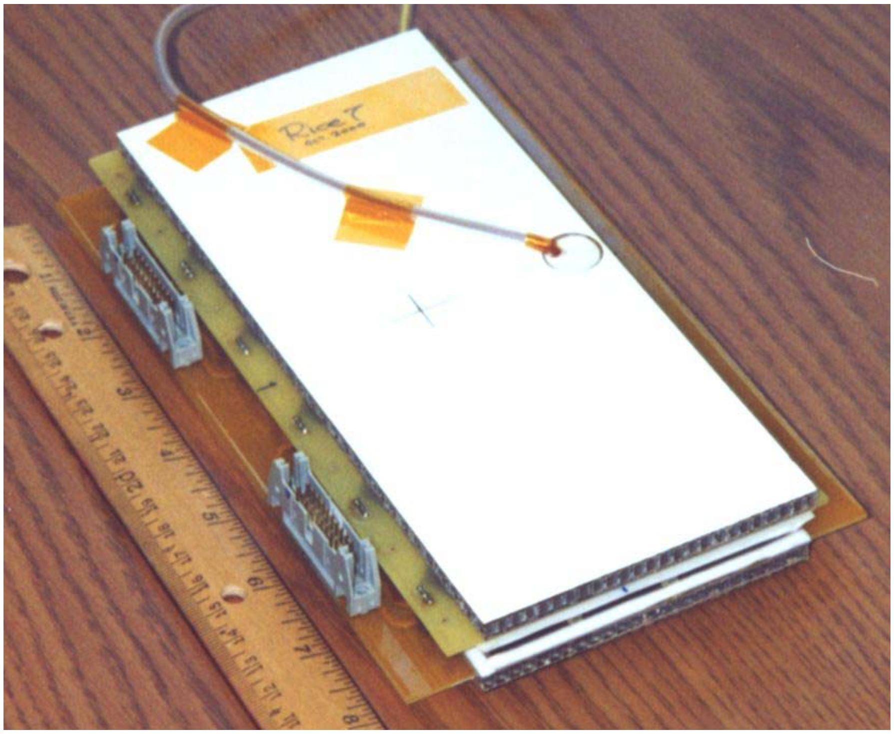
E increased (same V - smaller gap)

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

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

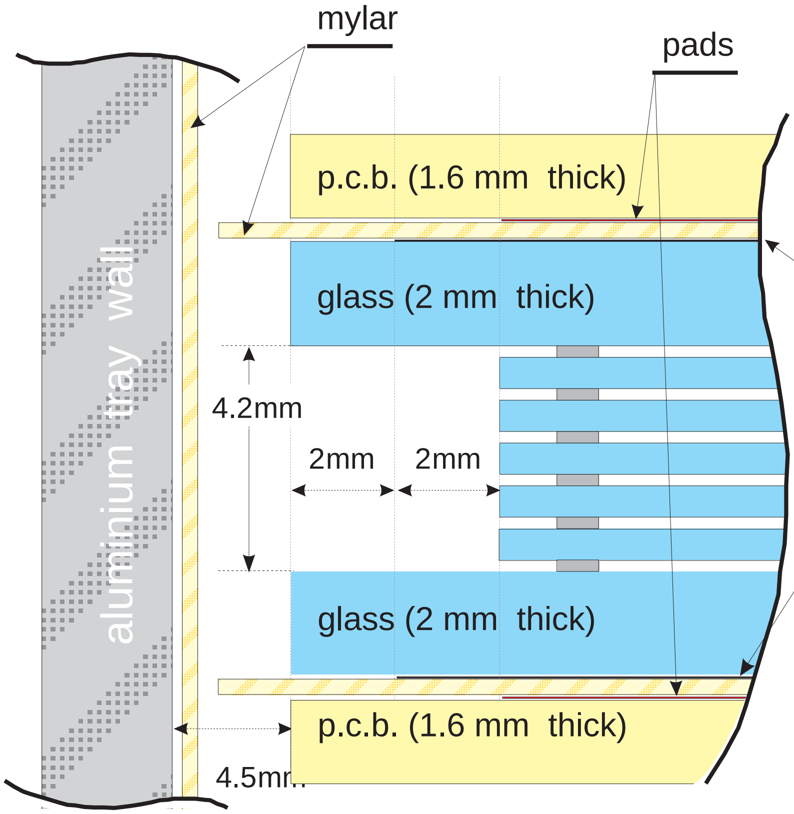
Apparently we are working in region where both effects cancel (by ‘magic’ it is rather an exact cancellation)

Rice Version 7 MGRPC



...costs **~30$/ch**...

...compared to **~1700$/ch**
for equiv. Conventional TOF...

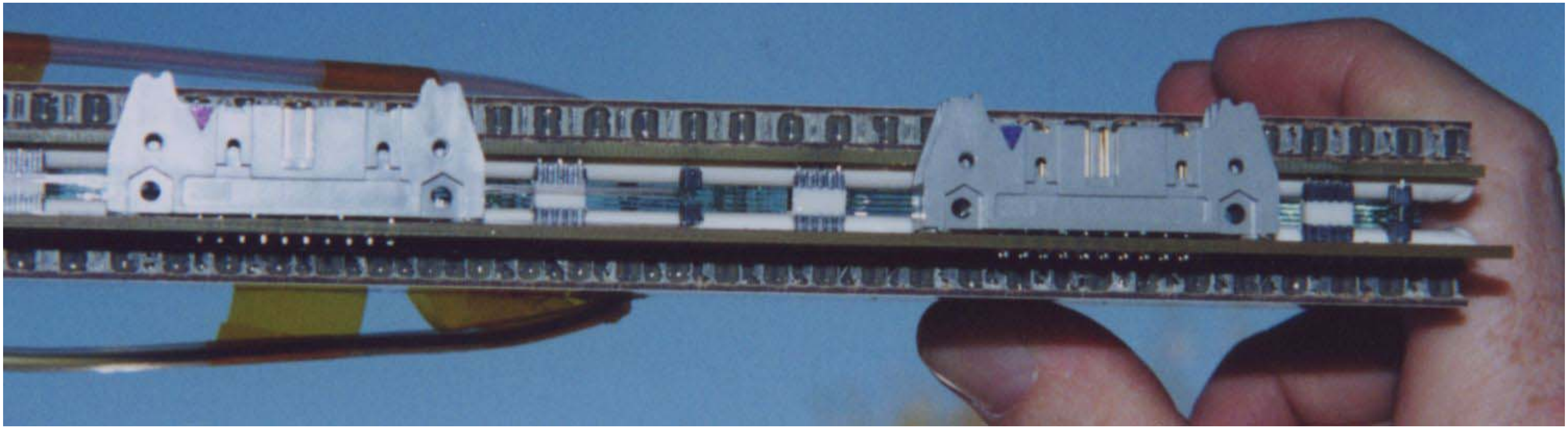


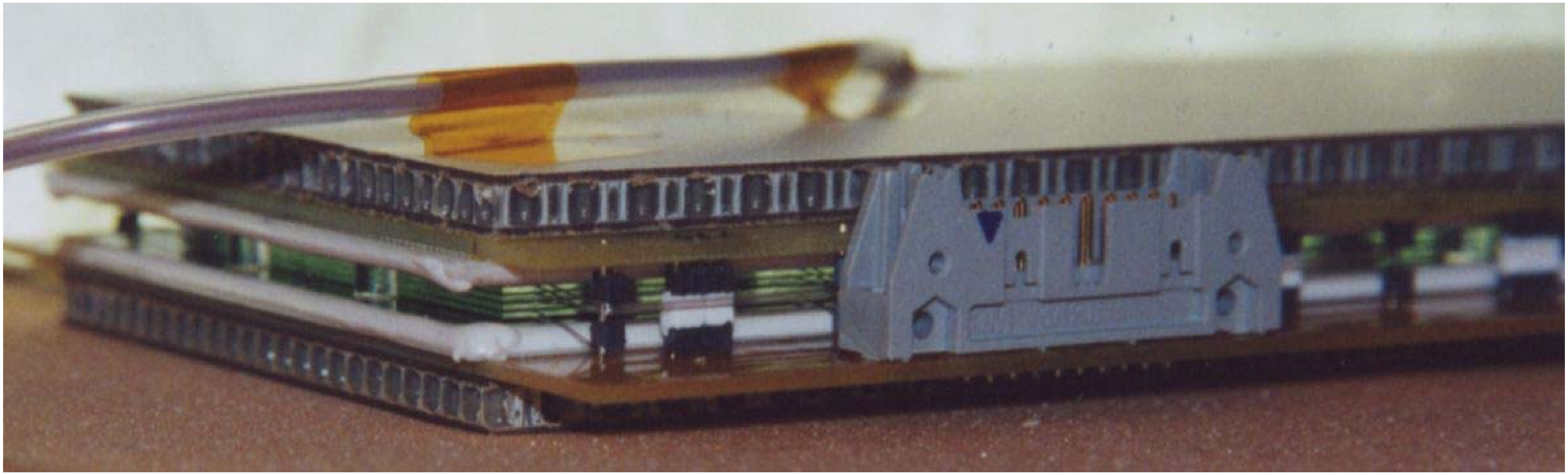
graphite layer
(Anode and Cathode)

spacers are ~220 μm diameter
monofilament (fishing line!)

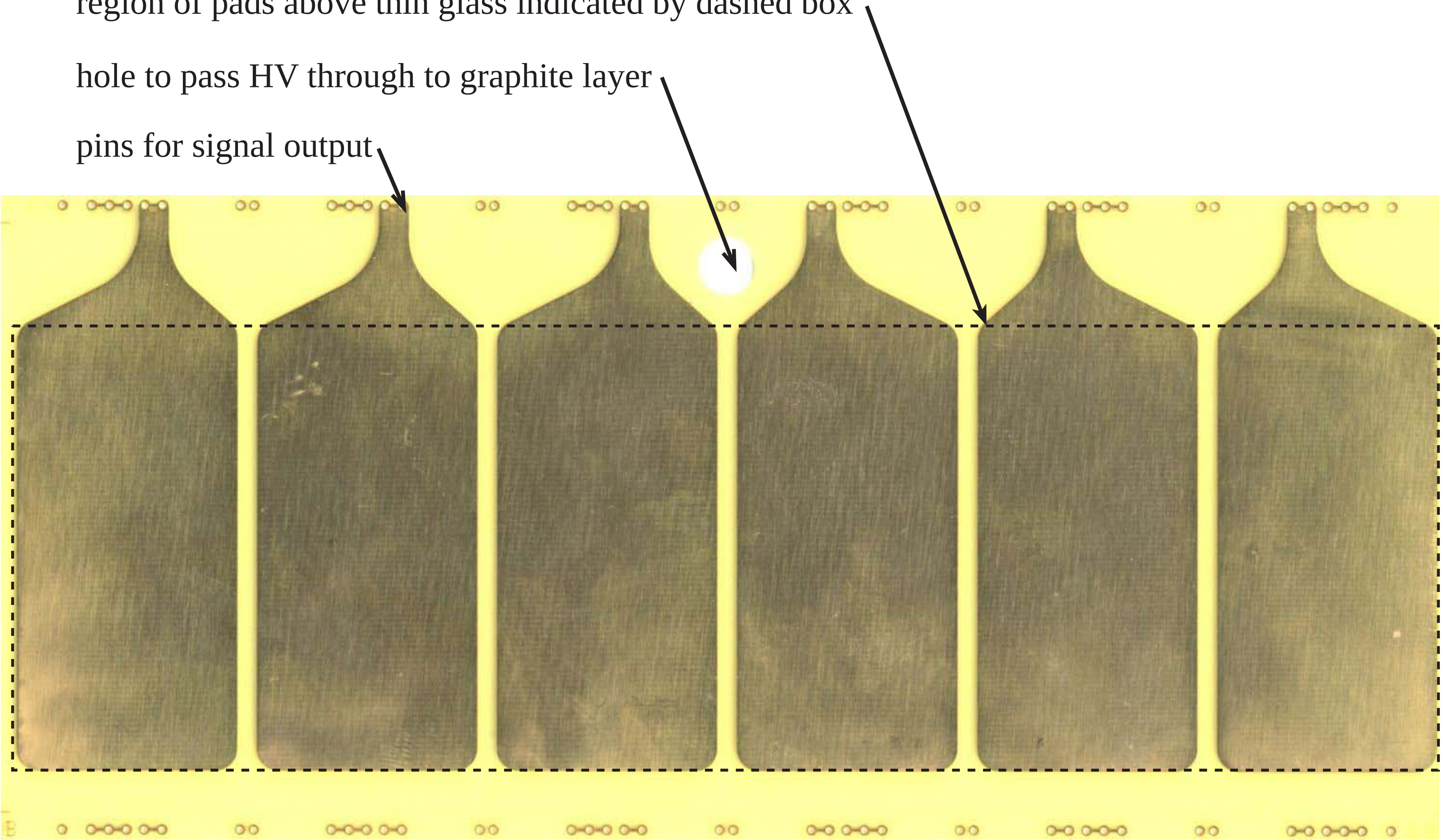
Tray inner dimensions: 213mmx2413mmx85mm

outer glass: 84mm x 204mm (10mm extra width for HV / gnd. connect. included)
graphite layer: 70mm x 200mm
inner glass: 65mm x 195mm
pad size: 31mm x 30mm, distance between pads = 3mm





Readout Pads



region of pads above thin glass indicated by dashed box

hole to pass HV through to graphite layer

pins for signal output

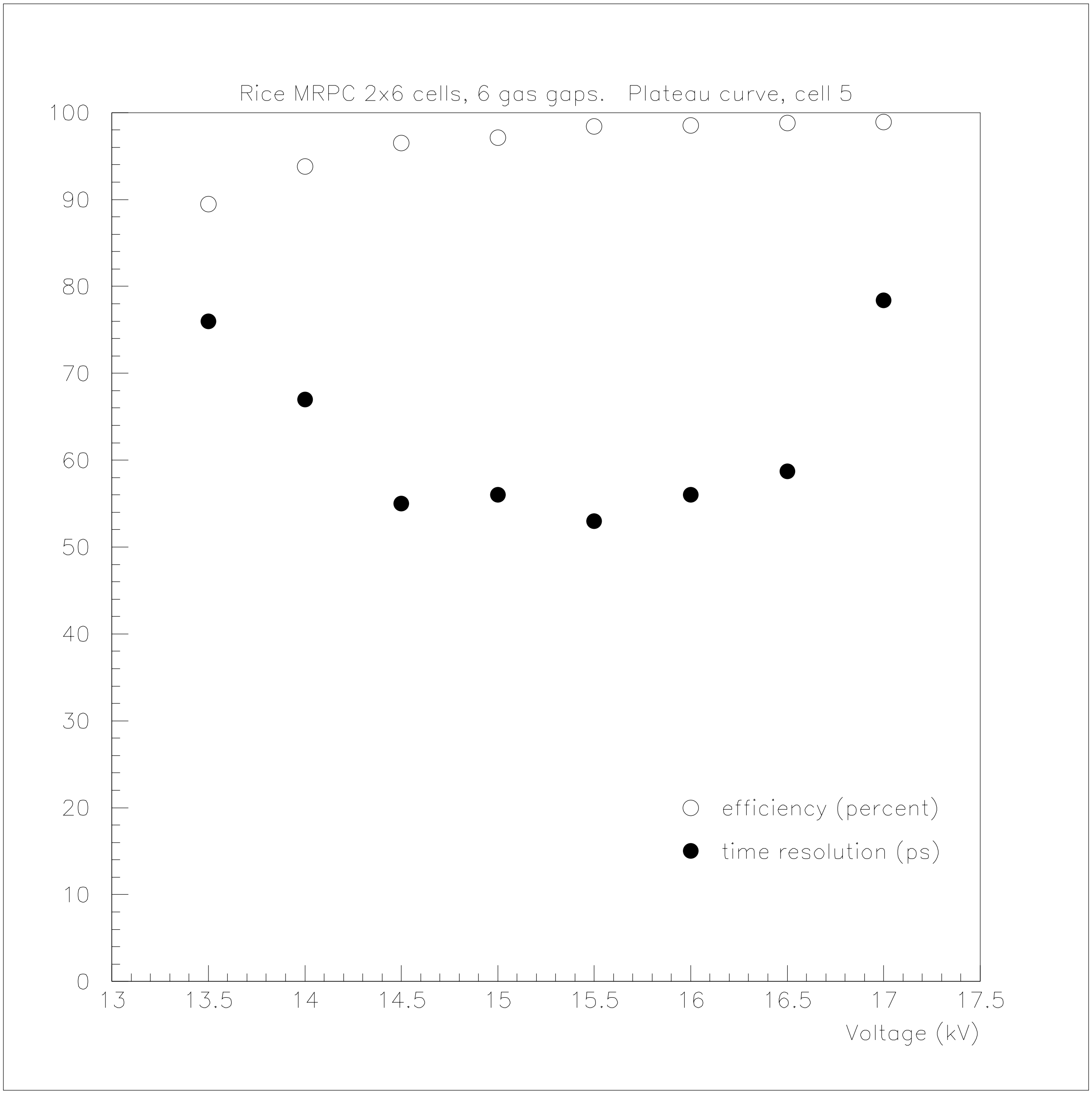


Fig. 2. The efficiency and corrected time resolution (σ) versus voltage for the prototype with 2x6 pads and pad area of 3x3 cm^2.

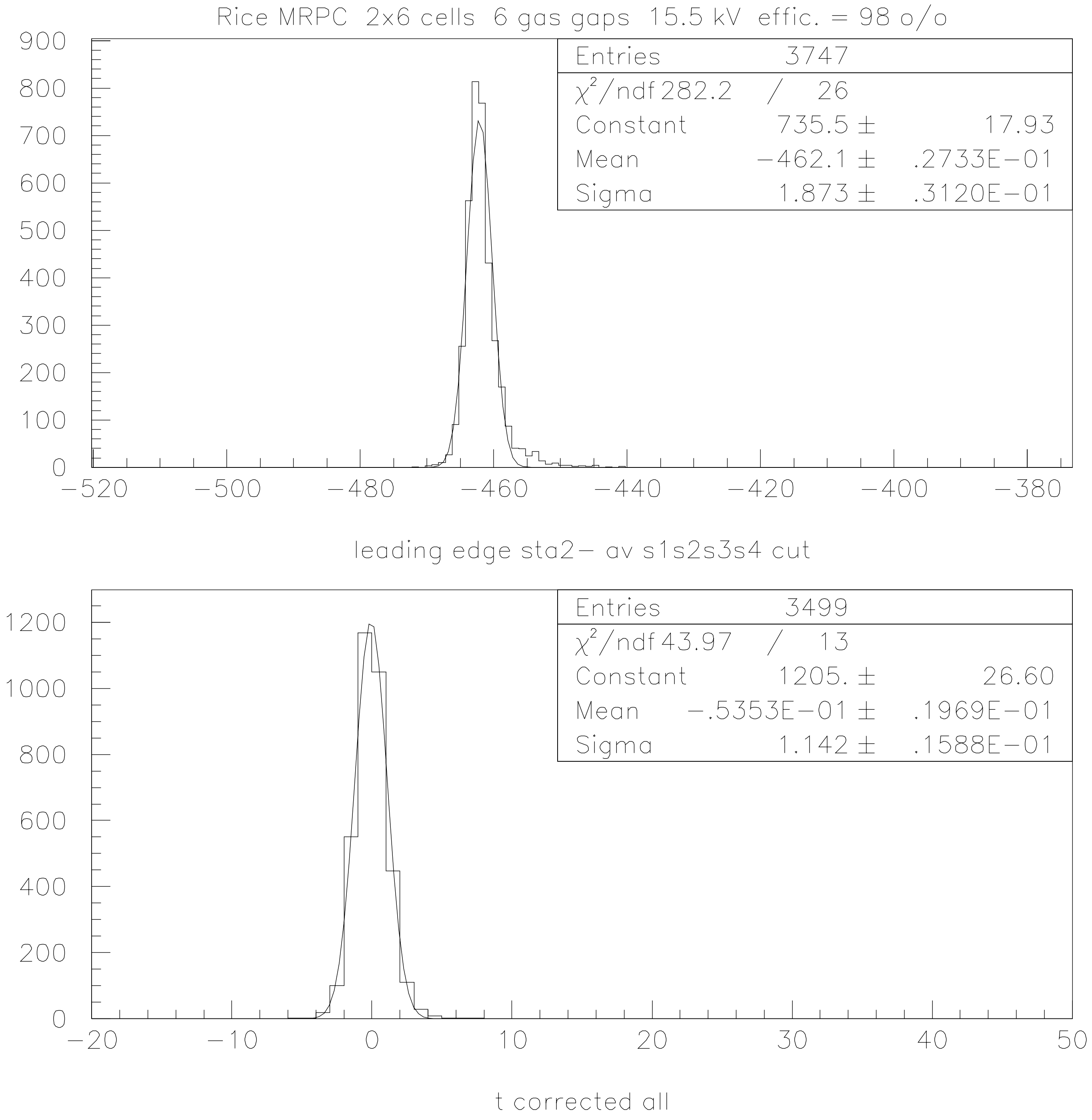
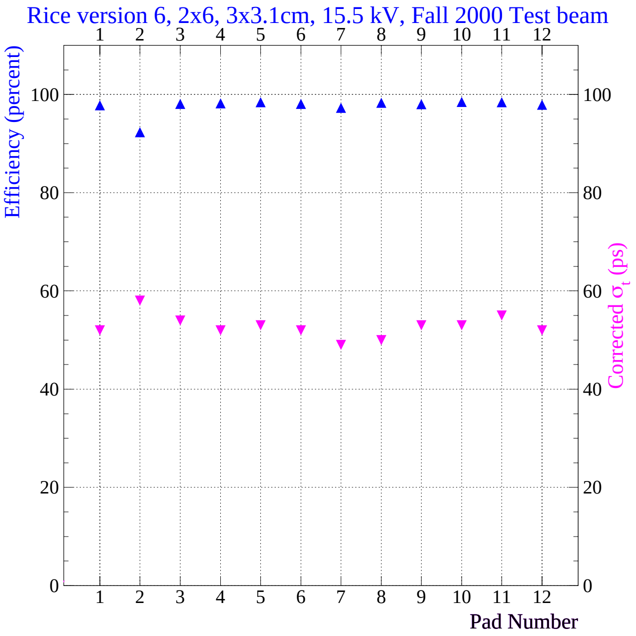
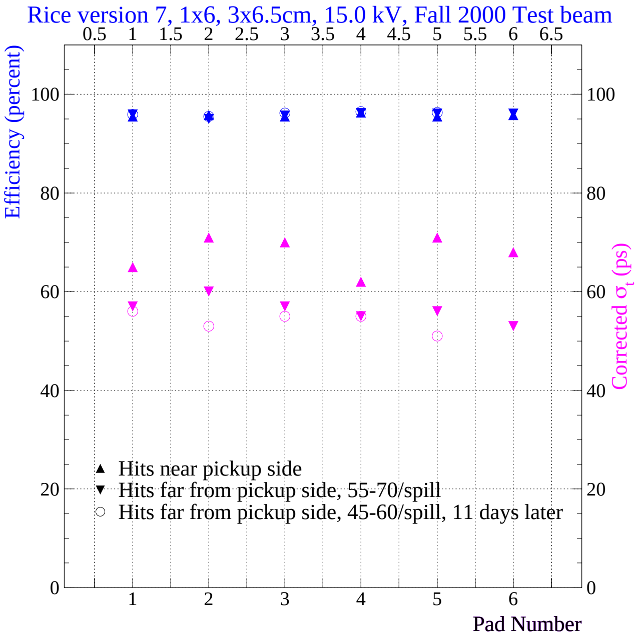
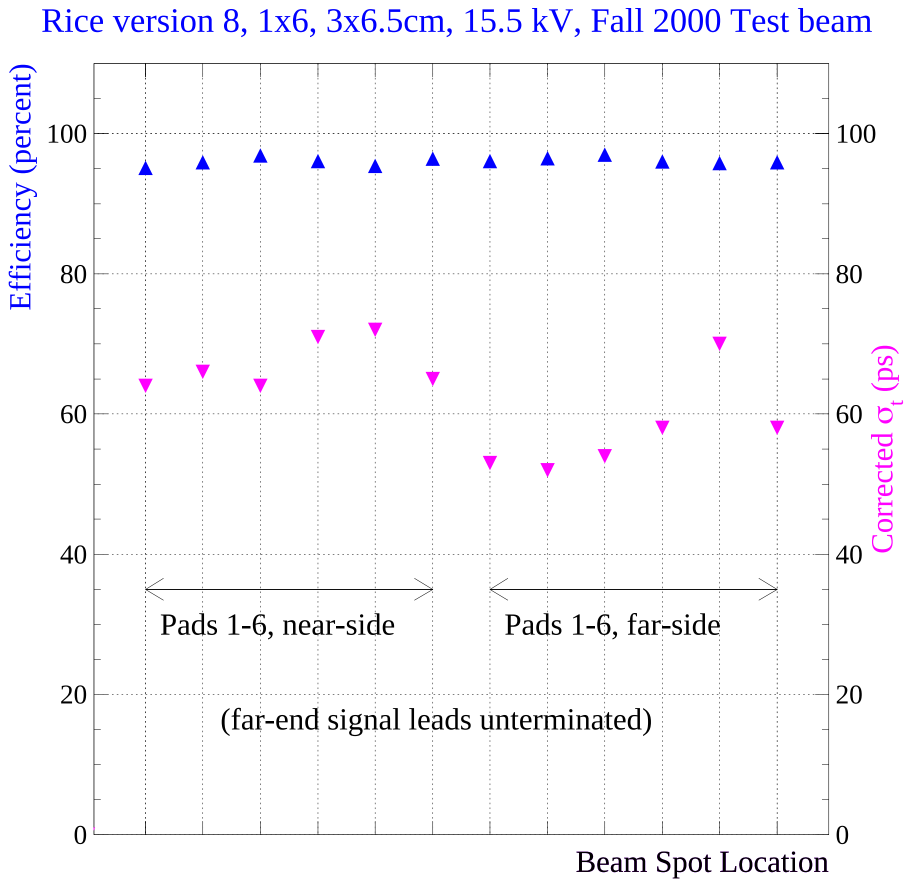


Fig. 1. The histogram on the top shows the raw time, and the histogram on the bottom shows the Time-to-Amplitude corrected time. The distributions are fitted with Gaussians, and the variance, σ, is reported in the boxes in each frame in units of TDC bins, which are 50 ps wide. Comparing the two frames, one observes the overall timing resolution improves from 94 ps to 57 ps following the offline correction for slewing [3] and, by subtracting the mean jitter introduced by scintillators counters, we obtain 90 ps and 50 ps respectively.

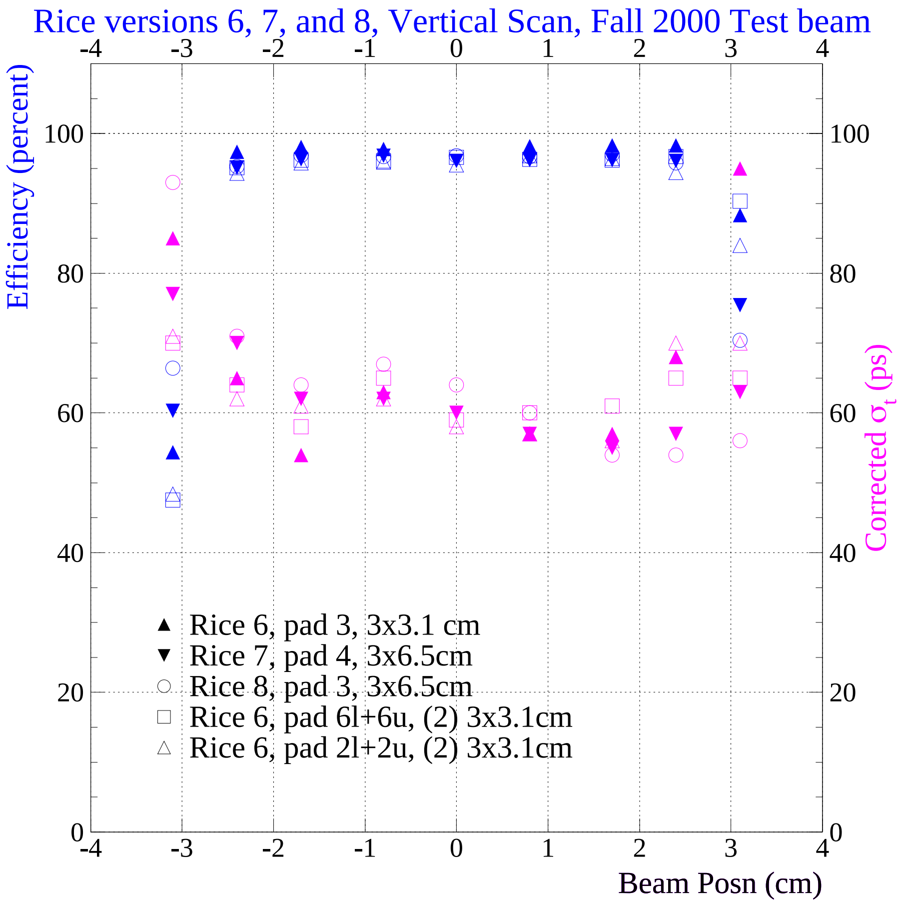
Channel-by-Channel Variations



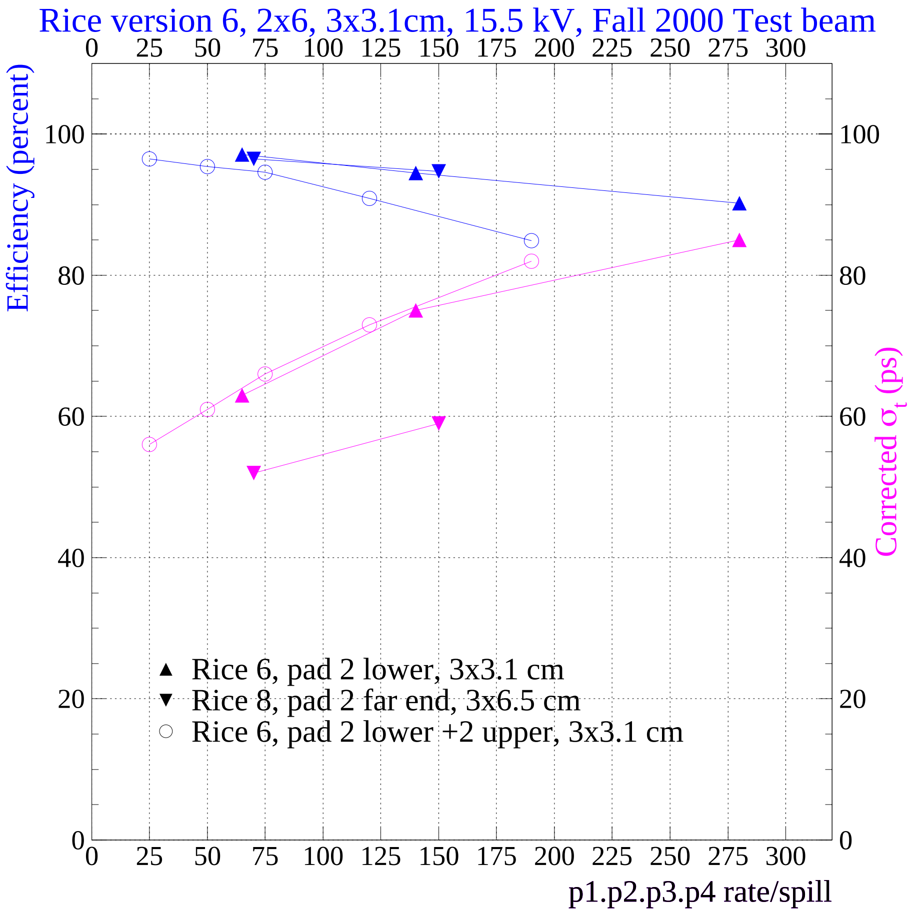


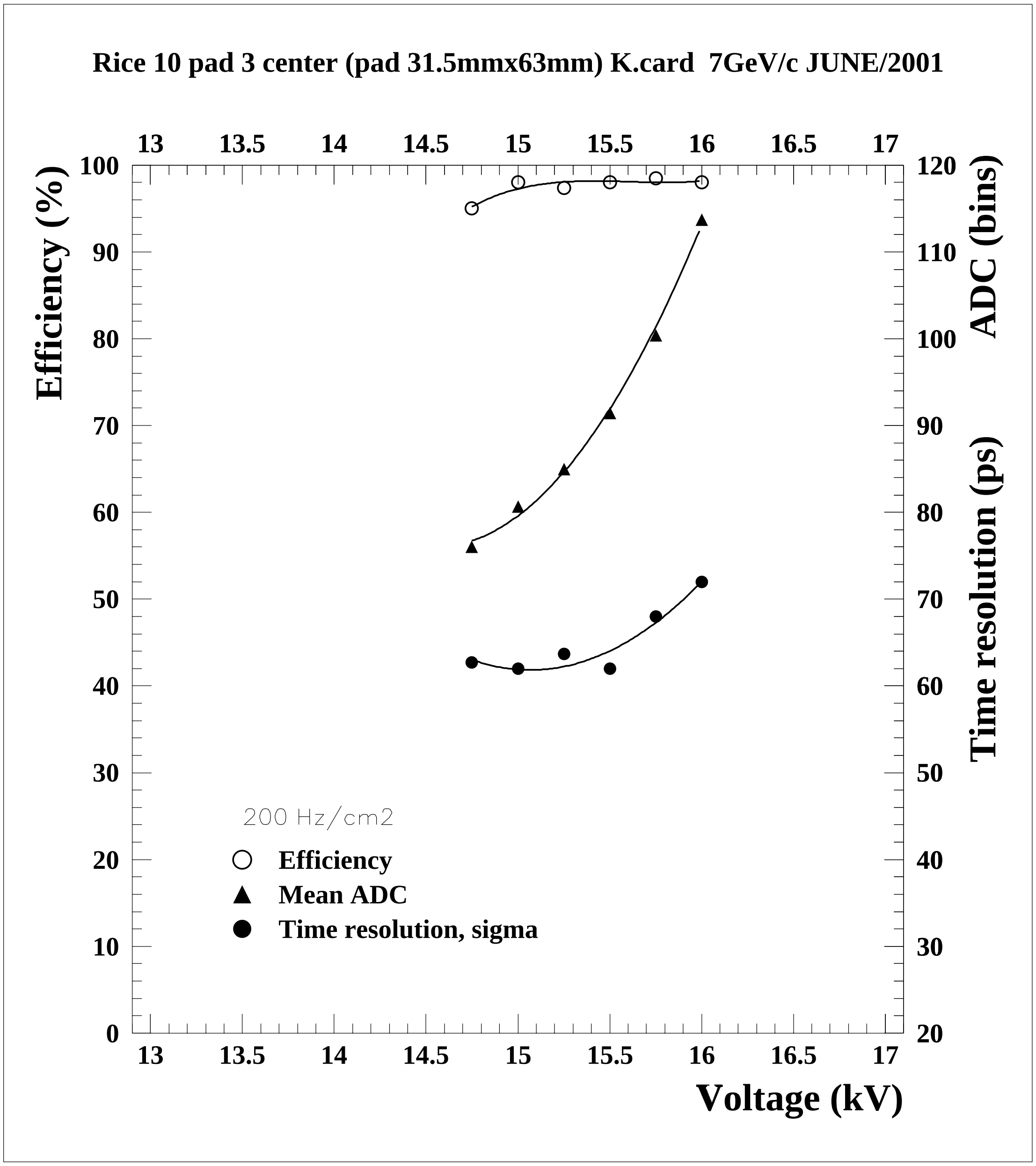


Position Dependence w.r.t. Pads


Rice versions 6, 7, and 8, Vertical Scan, Fall 2000 Test beam

Rate Dependence


Rice version 6, 2x6, 3x3.1cm, 15.5 kV, Fall 2000 Test beam



Rice versions 6-8

good & uniform & reproducable performance....

Rice versions 9, 10, ...

no more changes to MGRPC interior structure (glass, gaps, ...)
only optimization (minimization of dead space etc....)

PROPOSAL

To the

STAR Collaboration

For the construction of a

Single Tray of Multi-gap Resistive Plate Chamber Time-of-Flight for STAR

By the STAR TOF group*

Table of Contents

*Present members:
Bonner Lab at Rice University: B. E. Bonner, G. Eppley, F. Geurts, J. Lamas-Valverde W. J. Llope, G. S. Mutchler, T. Nussbaum, E. Platner, J. B. Roberts, P. Yepes
UCLA: H. Huang
University of Texas at Austin: J. Hoffmann, J. Schambach, H. Ward
And the Chinese RHIC-STAR TOF Group:
  USTC: Wenging Shen, Hongfang Chen, Xiaolian Wang, Ziping Zhang, Cheng Li, Shuwei Ye
  Tsinghua: Kejun Kang, Yuanjin Li
  SINR: Yugang Ma
  IMP (Lanzhou): Wenlong Zhan
  HuaZhong Normal University (Wuhan): Feng Liu
  IHEP (Beijing): Jin Li
  Beijing University: Yajun Mao
Others TBA

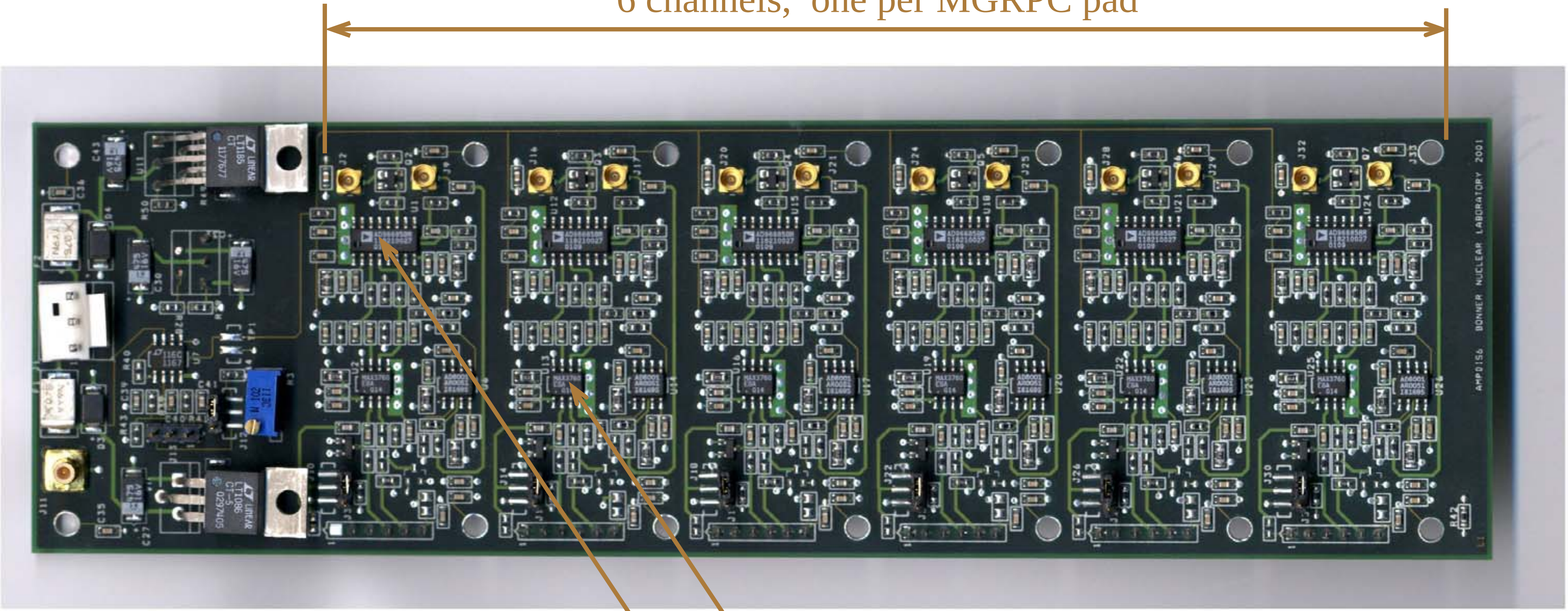
Front-End Electronics

typical MIP hit in a MGRPC 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 for ALICE and STAR FEE development came w/ adoption of MAXIM 3760

then discriminate using standard components

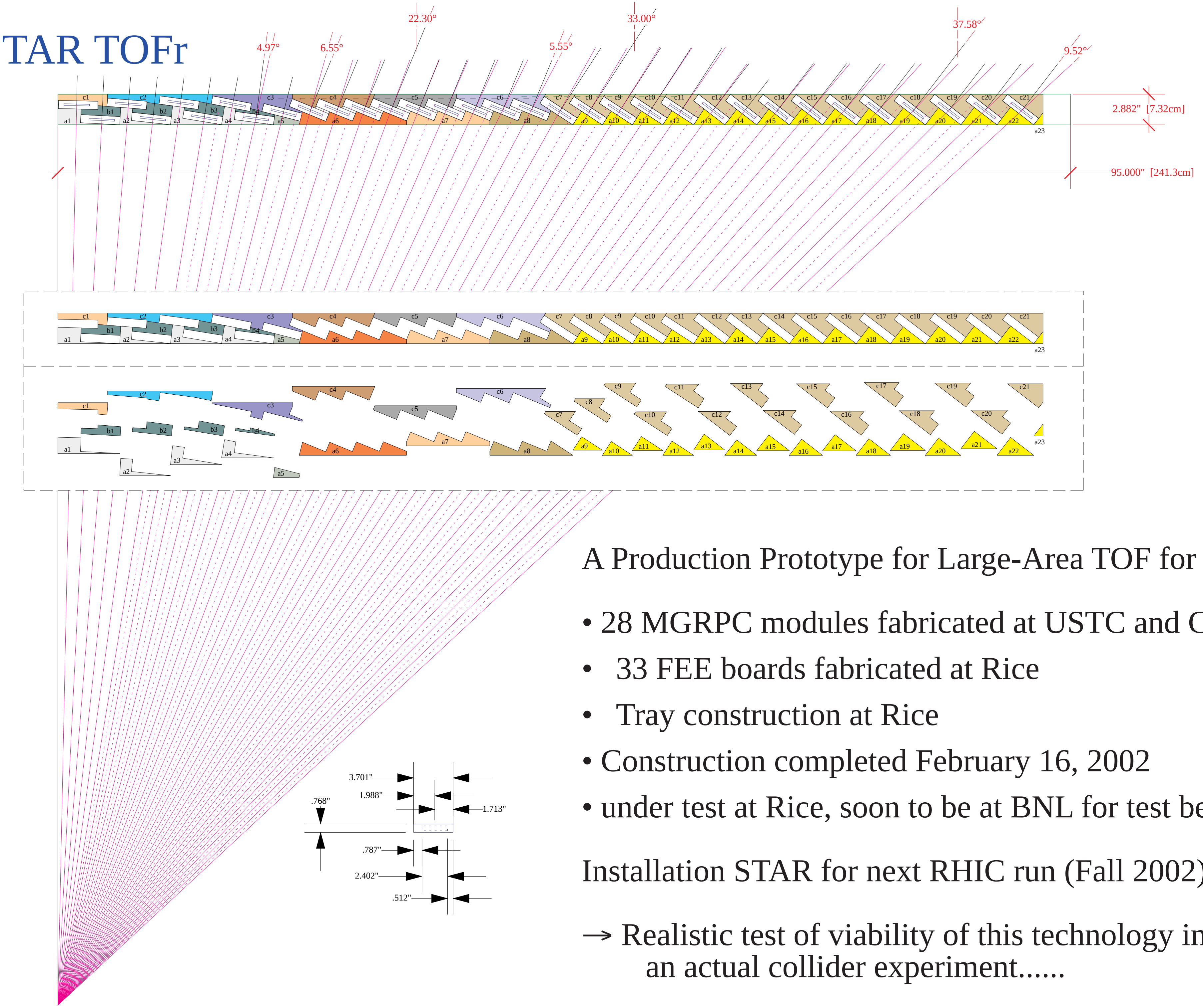


6 channels, one per MGRPC pad

Maxim 3760 Preamplifier

Analog Devices 96687 Comparator (TOFp, pVPD, TOFr)

STAR TOFr

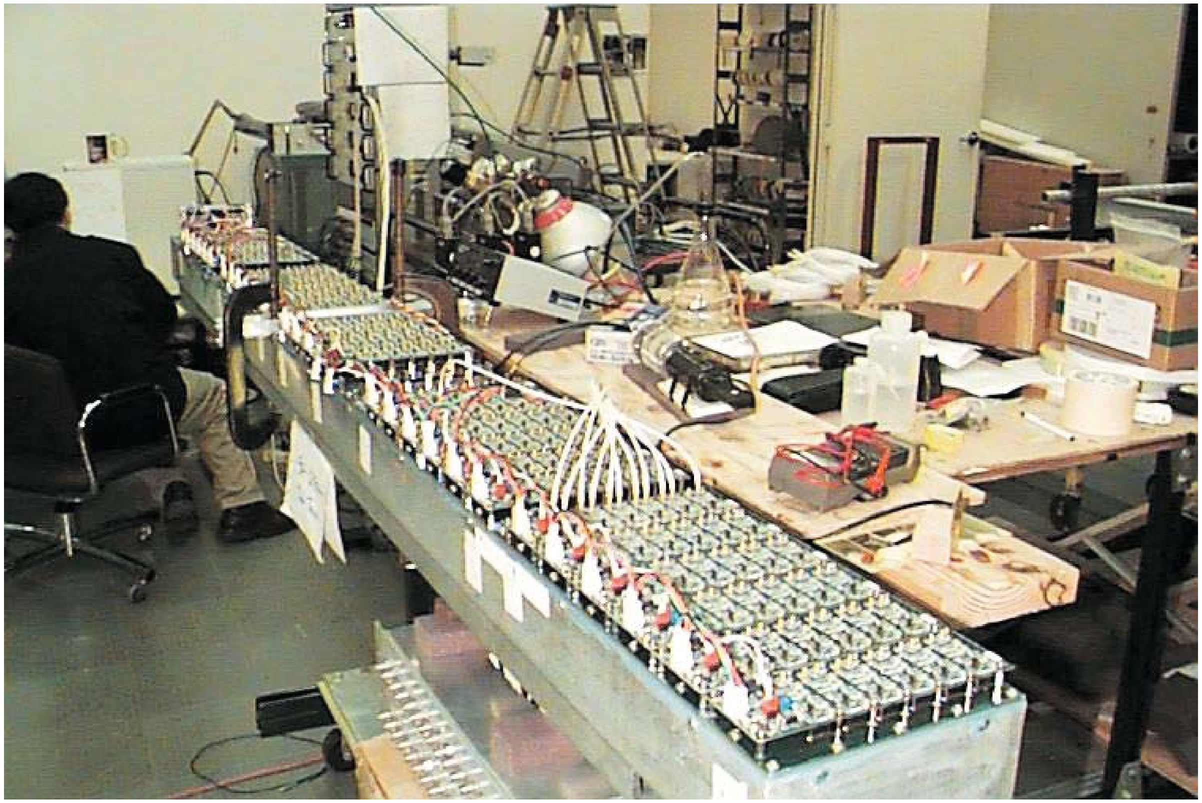


A Production Prototype for Large-Area TOF for STAR

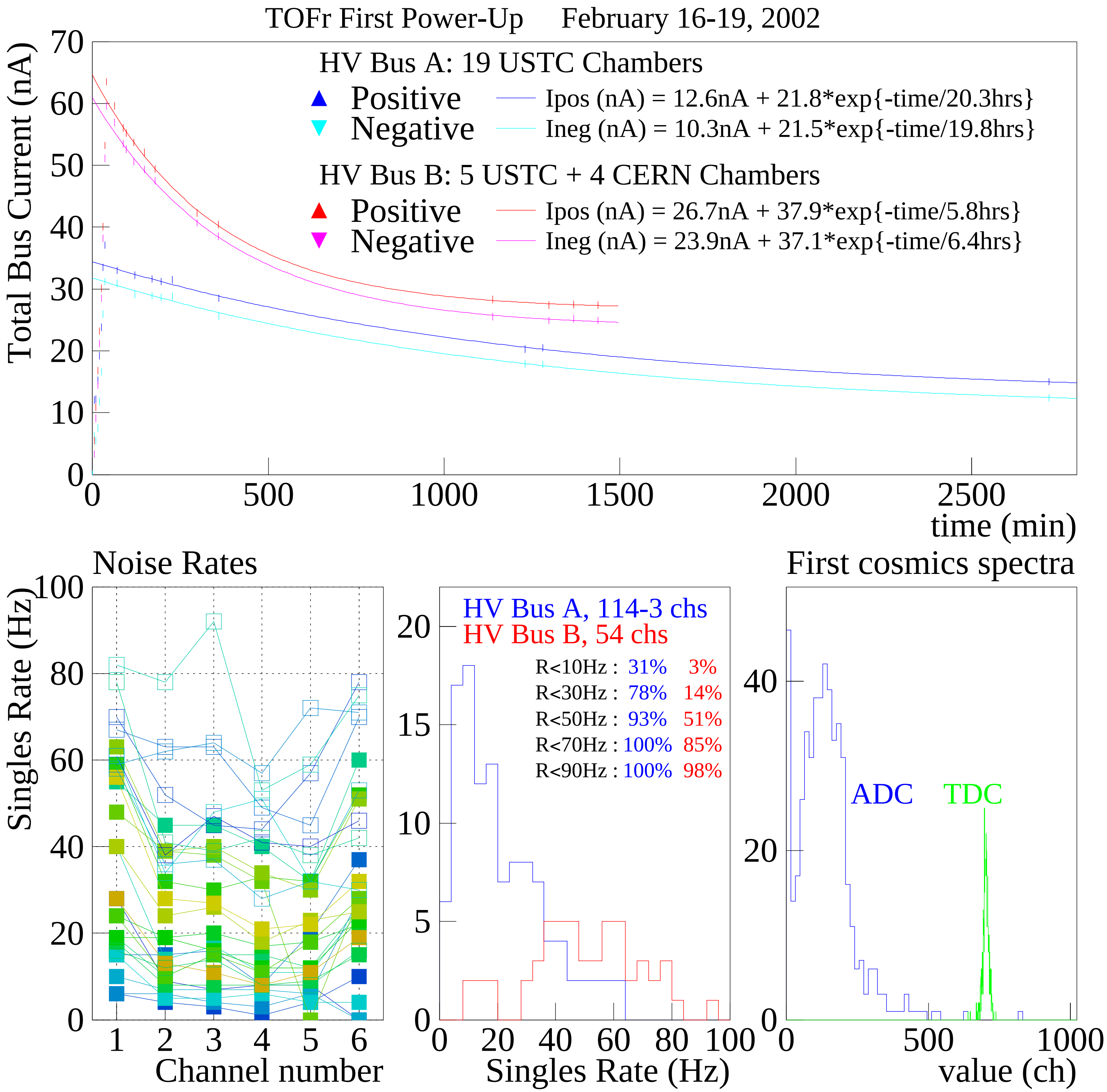
- 28 MGRPC modules fabricated at USTC and CERN
- 33 FEE boards fabricated at Rice
- Tray construction at Rice
- Construction completed February 16, 2002
- under test at Rice, soon to be at BNL for test beams...

Installation STAR for next RHIC run (Fall 2002)

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



TOFr tray appears to work as expected....



Summary/Outlook:

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

MGRPC detectors are dirt cheap and appear to outperform the conventional technology...

Recent Major Successes

- a specific fishing line is a *great* choice for the 220 μm spacer...
- Detector module design (Rice v.11) is now final for STAR... <60ps stop-resolution is typical...
- Maxim 3760 preamp & other standard components is an adequate approach to the FEE...
- Collaboration of US and CN institutions developed...
- A working prototype for STAR now exists!

The basic long-range plan

Study performance of Single tray of MGRPC for STAR, "TOFr," in test beams and in STAR...
Proposal for large-area system, "TOFR," in Spring 2002...
Installation of TOFR in the 2004 shutdown...

Hurdles Still Ahead of Us

- Solving the problems yet to be uncovered...
- Digitization for the large-area system must be "on-board"... (SBIR submitted 2/2002)
  TDC chip w/ required specs does not exist, although CERN efforts look promising...
  We have standing request for these when they become available...
- Marriage of preamp+comparator w/ the digitization on one board...
  Facing the age-old nightmare of analog and digital electronics on the same board...
  ~6 EE-year engineering effort...
- Electronics R&D... (~500+ k$?) spinoff applications exist...
- Building the large-area system itself.... (~5M$? = 4M DOE + 1M CN-contributed)