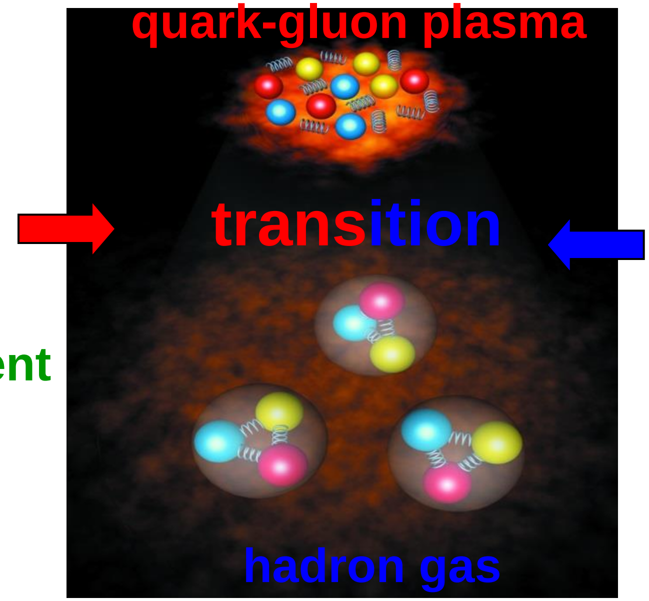
The NA61/SHINE Experiment at the CERN SPS (& future prospects)

study of hadro production in hadron-nucleus and nucleus-nucleus collisions at the CERN SPS

Dec. 05, 2013

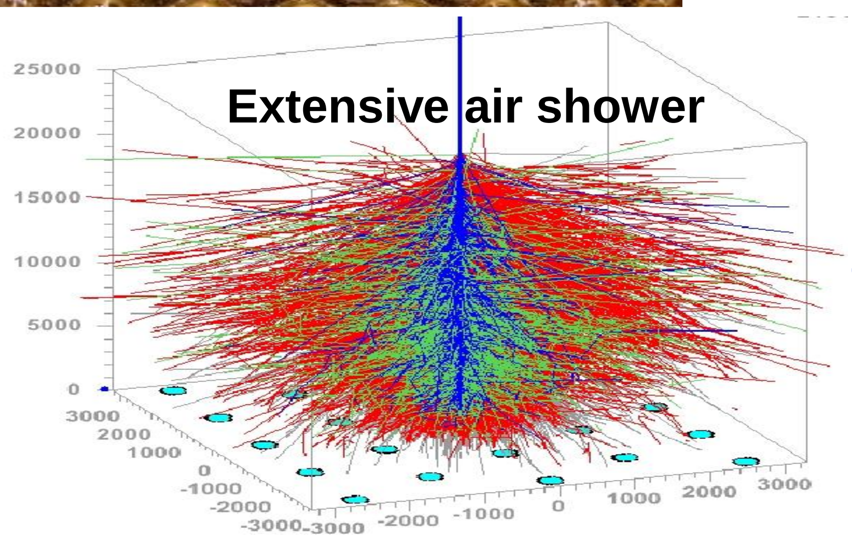
Alessandro Bravar

NA61 physics program



Physics of strongly interacting matter in heavy ion collisions
Search of the QCD critical point
Study the properties of the onset of deconfinement

Measurement of hadron production off the T2K target (p+C) to characterize the T2K neutrino beam

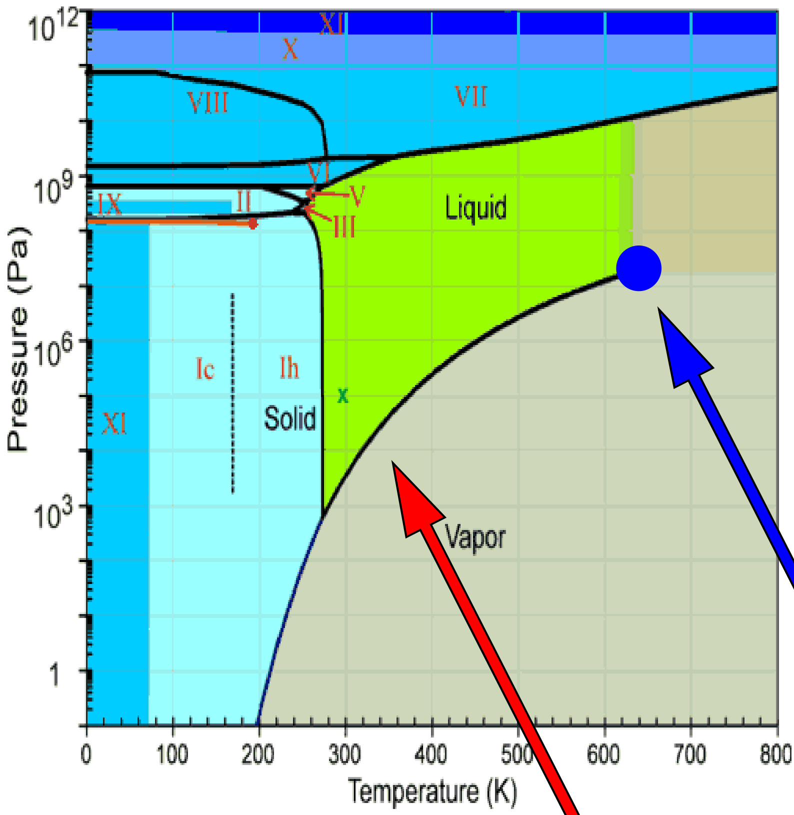


Measurement of hadron production in p+C interactions for the description of cosmic-ray air showers

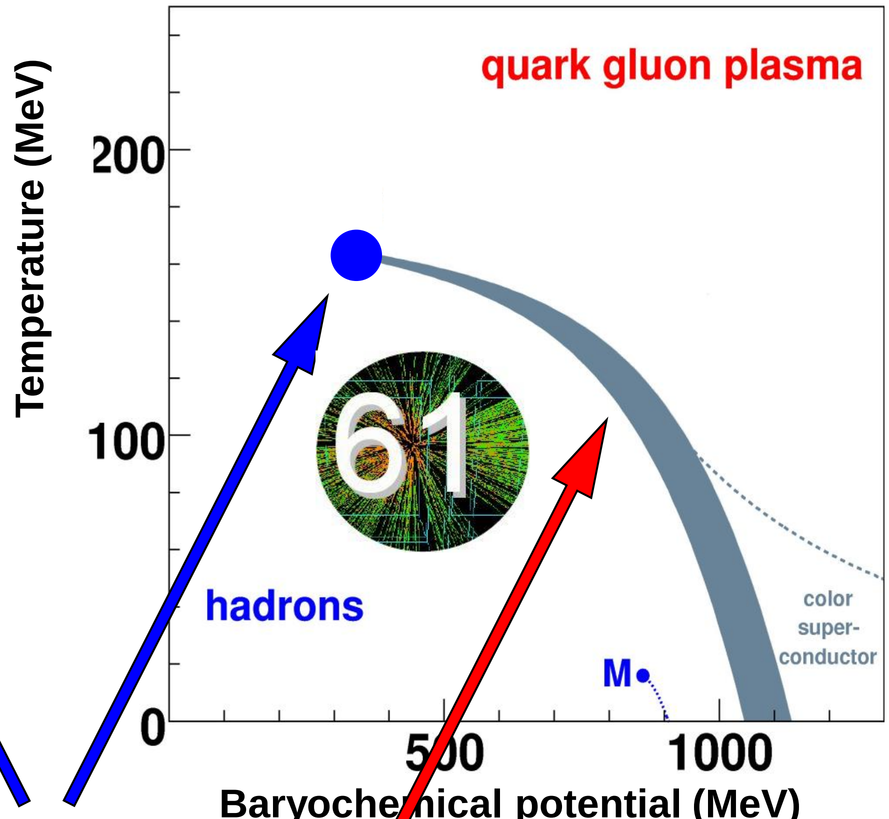
Study the Onset of Deconfinement

QCD phase space

water



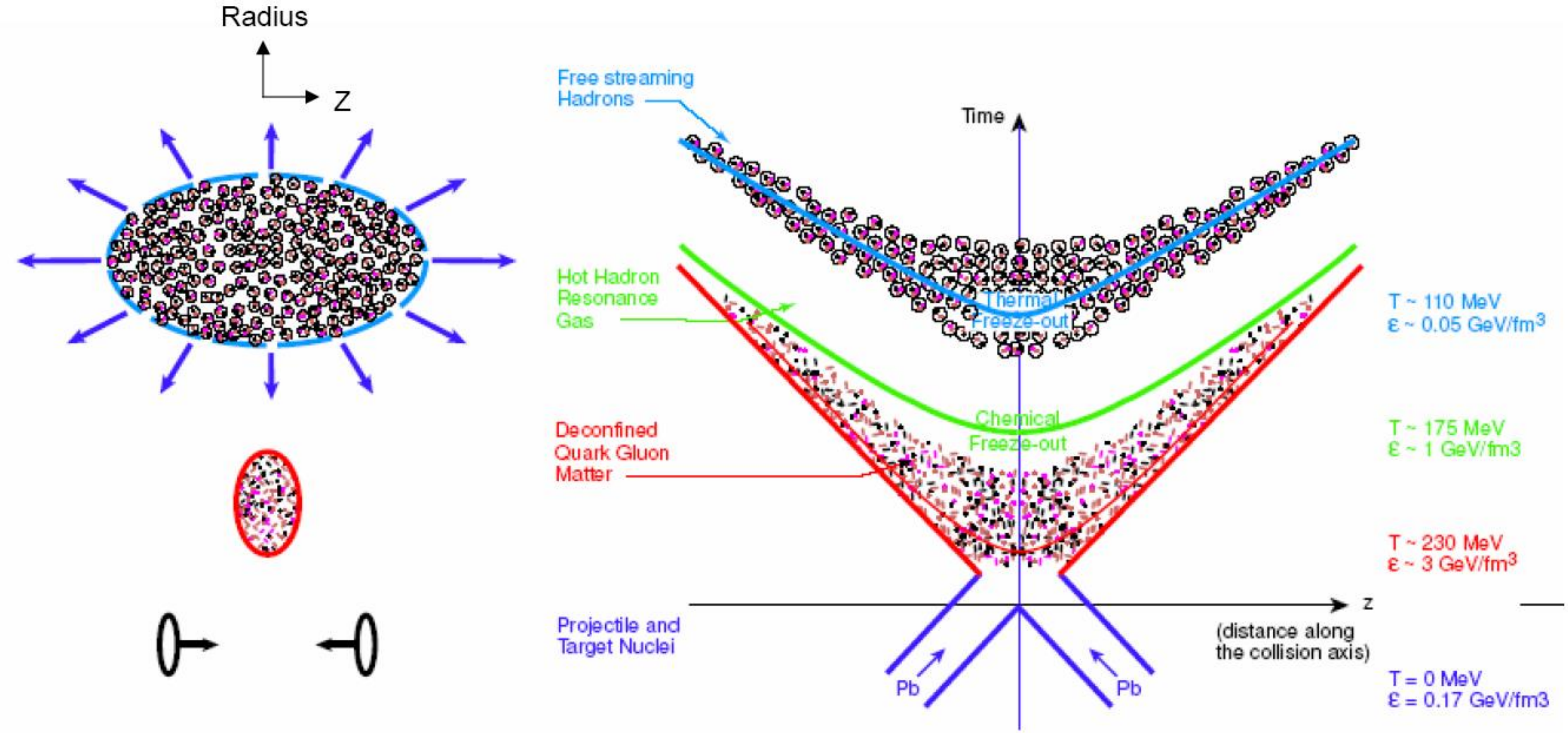
strongly interacting matter



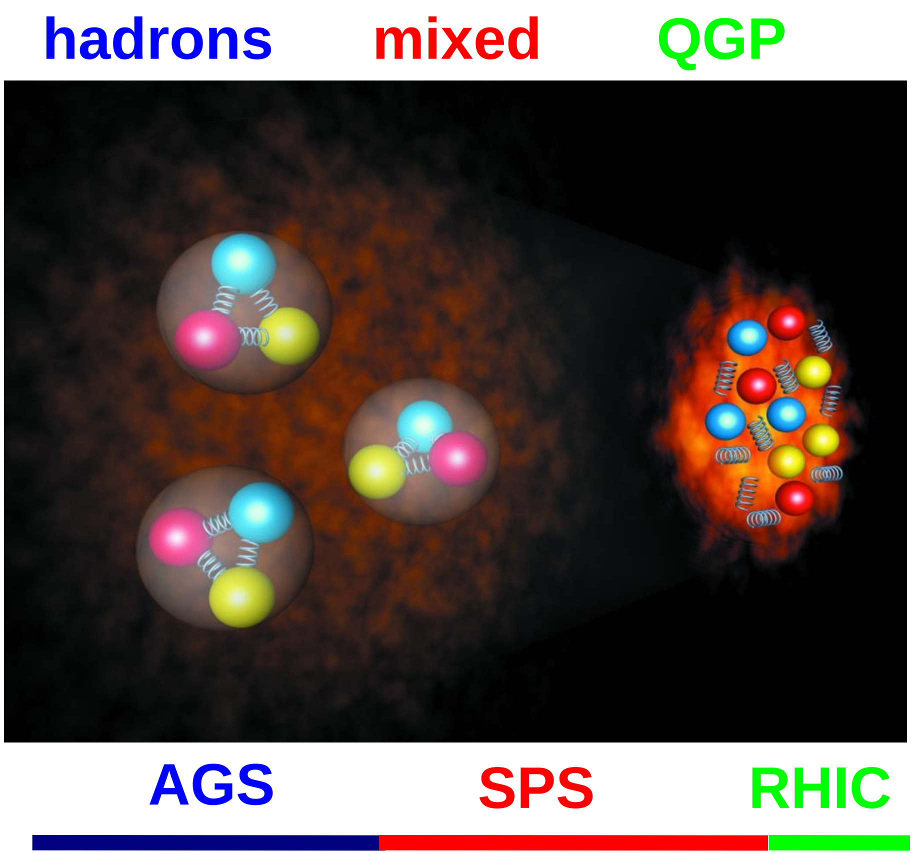
critical point

1^{st} order phase transition

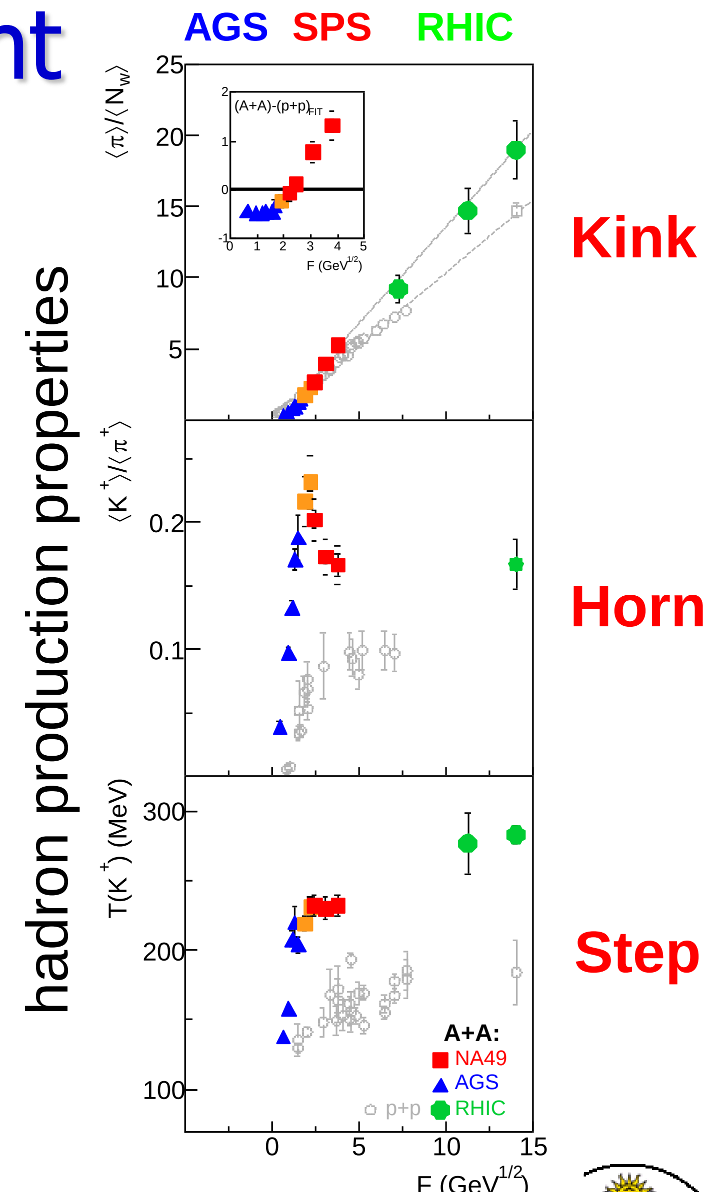
Schematic of Relativistic Heavy Ion Collisions



Evidence of Deconfinement



collision energy



collision energy

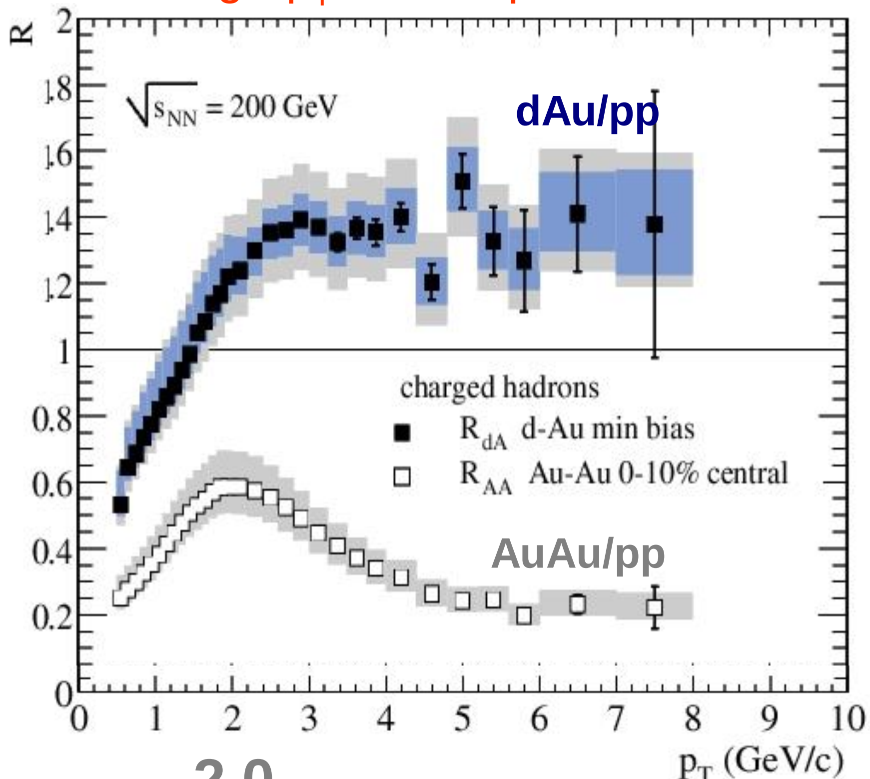
NA49 results (PRC77:024903):
evidence for the onset of deconfinement
at the low CERN SPS energies

High-p_T Suppression at RHIC (& LHC)

The observation of the suppression of high p_T hadrons in central Au+Au collisions with respect to p+p interactions is one of the most important RHIC discoveries

PHENIX at RHIC

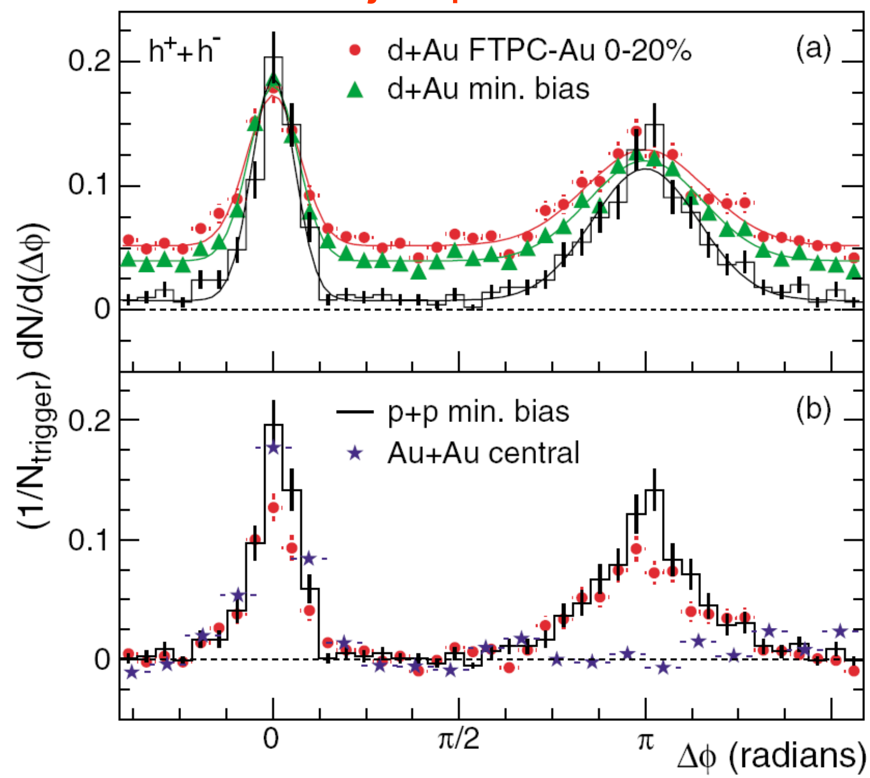
high-p_T hadron production



2.0

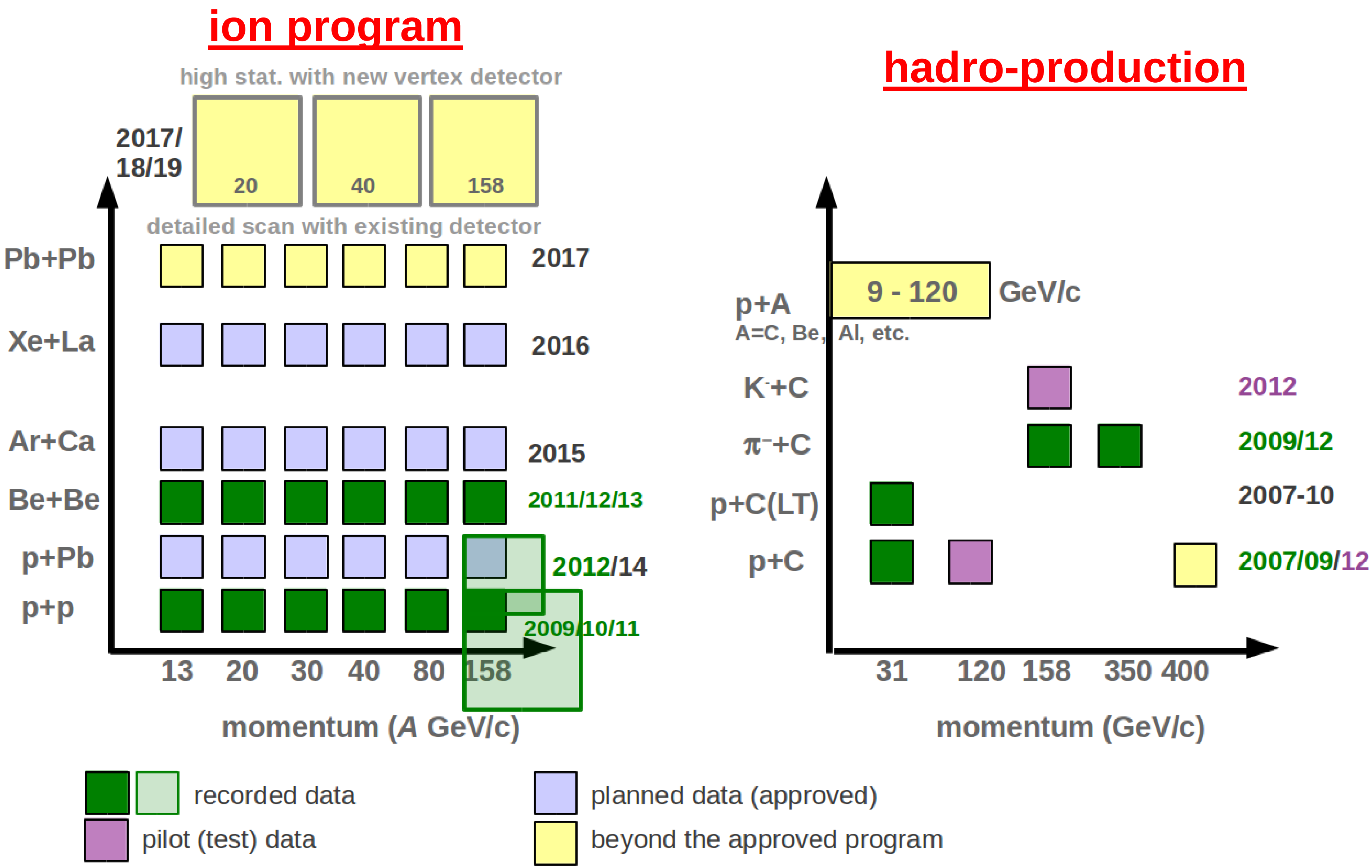
STAR at RHIC

"di-jet" production



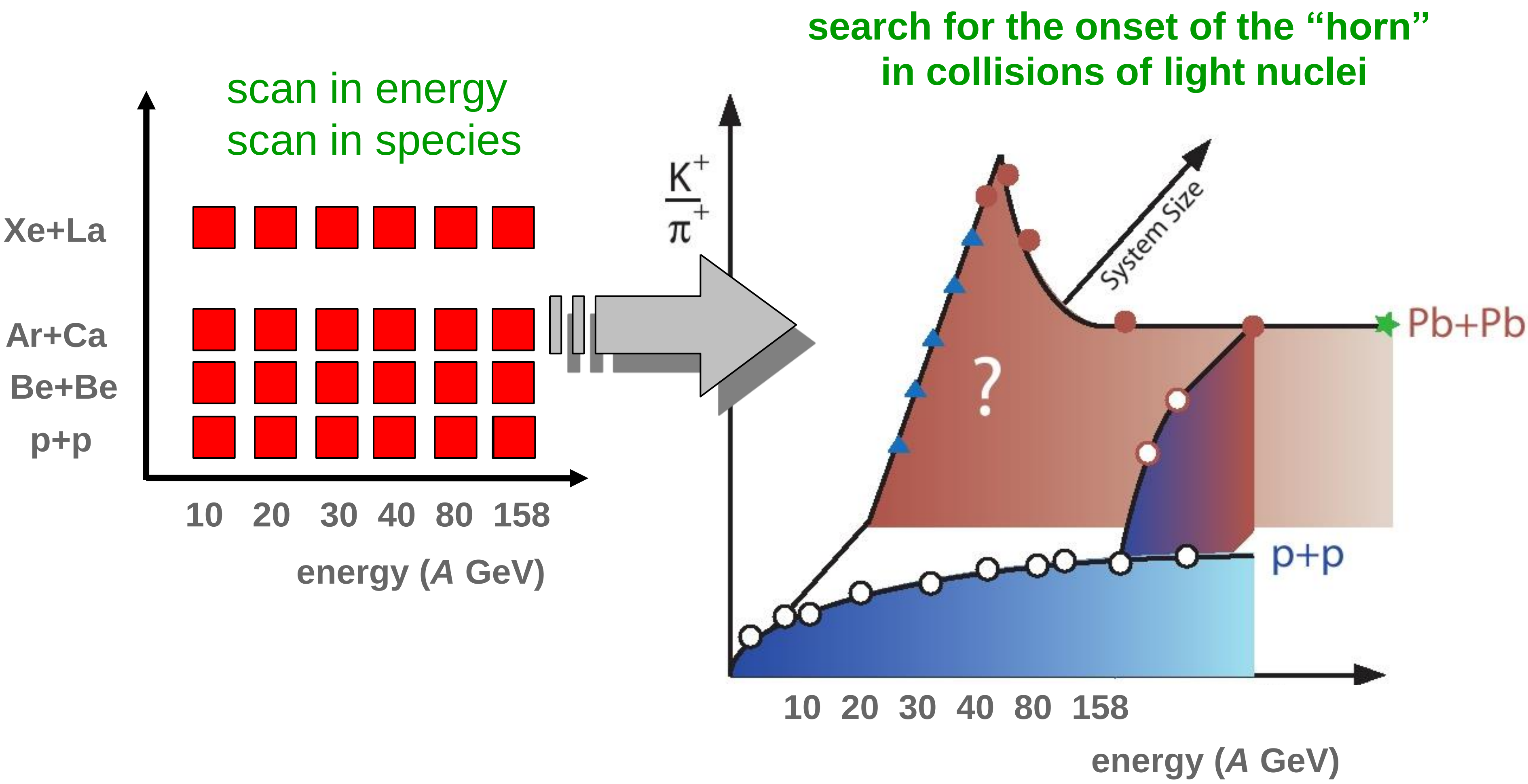
Study of energy dependence of the high p_T suppression in Au+Au collisions (jet quenching in high density matter) is necessary for its final interpretation

NA61 Data Taking

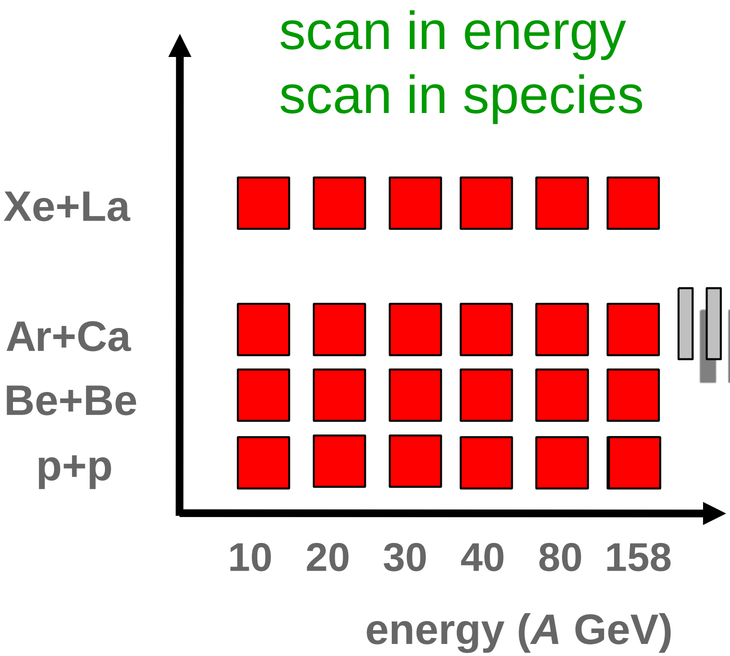


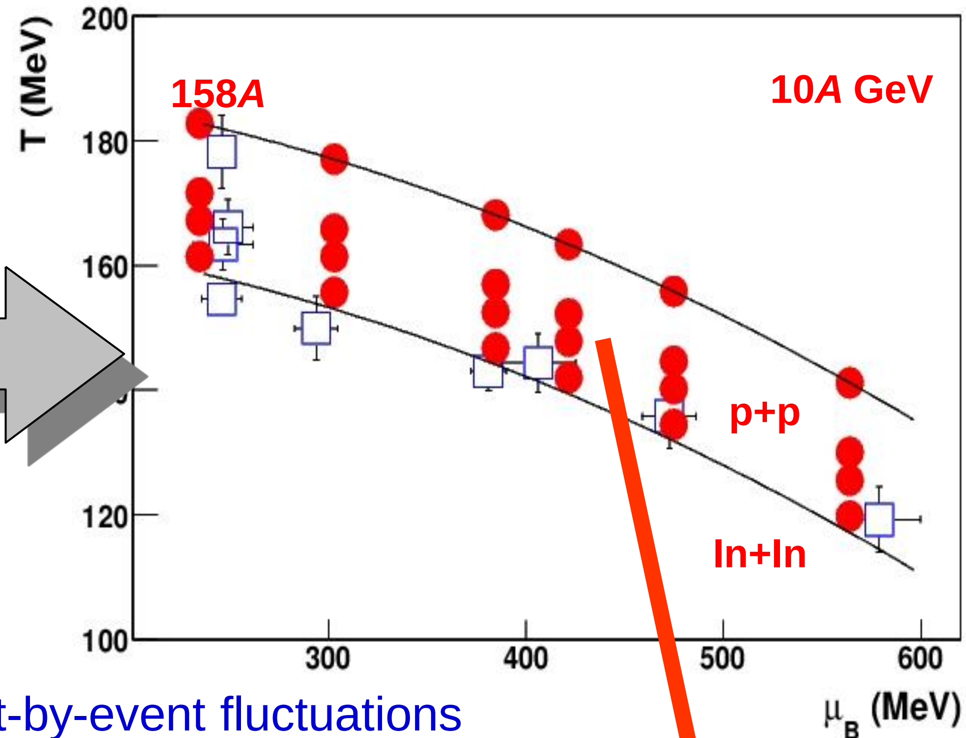
the first 2D scan in A+A collisions

Study the Onset of Deconfinement

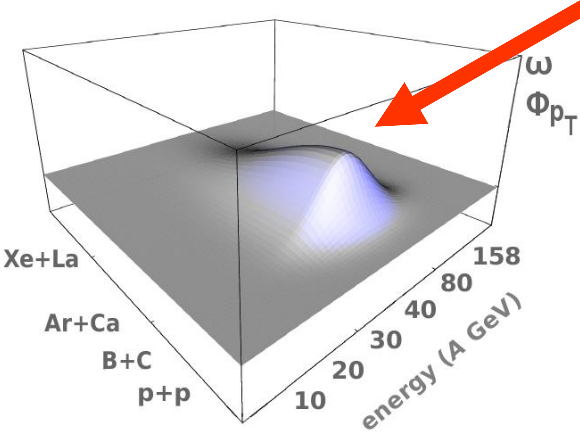


Search for the QCD Critical Point



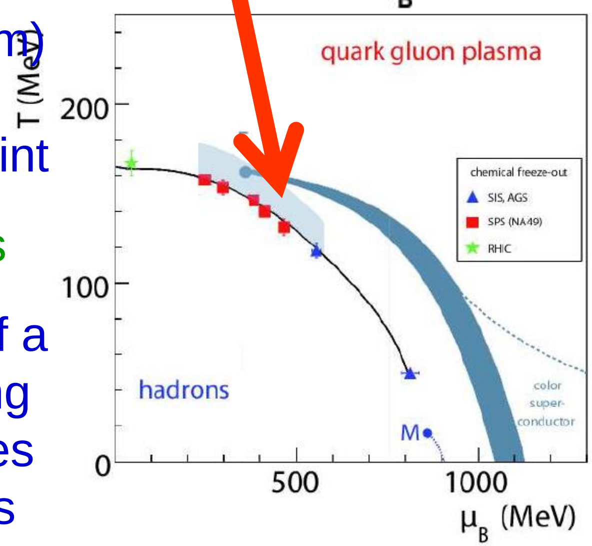


large event-by-event fluctuations (multiplicity, transverse momentum) expected when the system hadronises close to the critical point

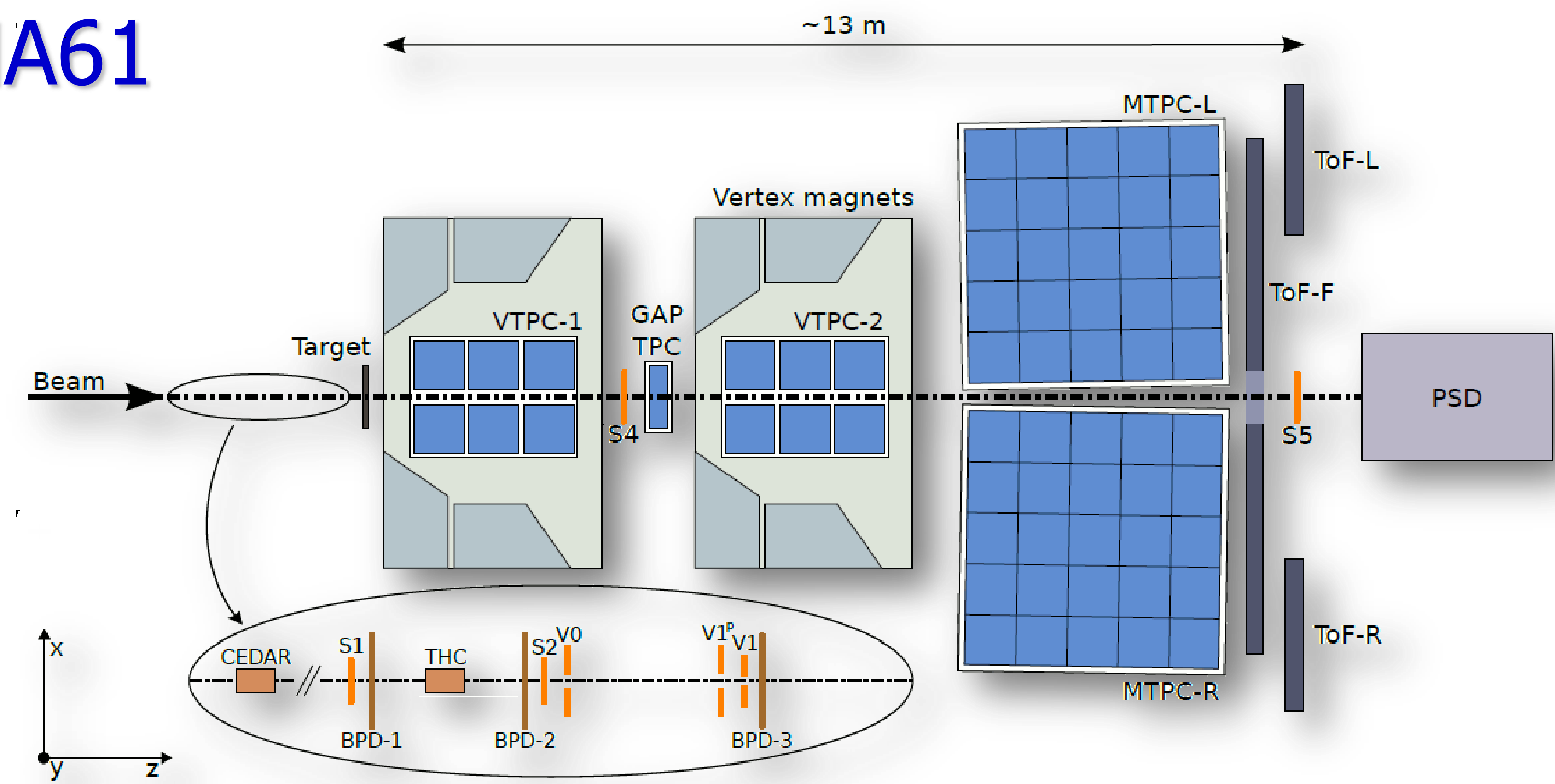


search for the hill of fluctuations

lattice QCD indicates existence of a critical point of strongly interacting matter at freeze-out termperatures accessible around SPS energies



NA61



large acceptance spectrometer for charged particles (> 70% of charged particles detected)

4 large volume TPCs as main tracking devices

2 dipole magnets with bending power of max 9 Tm over 7 m length

high momentum resolution $\Delta p/p^2 \sim 10^{-4}$

vertex resolution $\sigma_z \sim 5$ mm

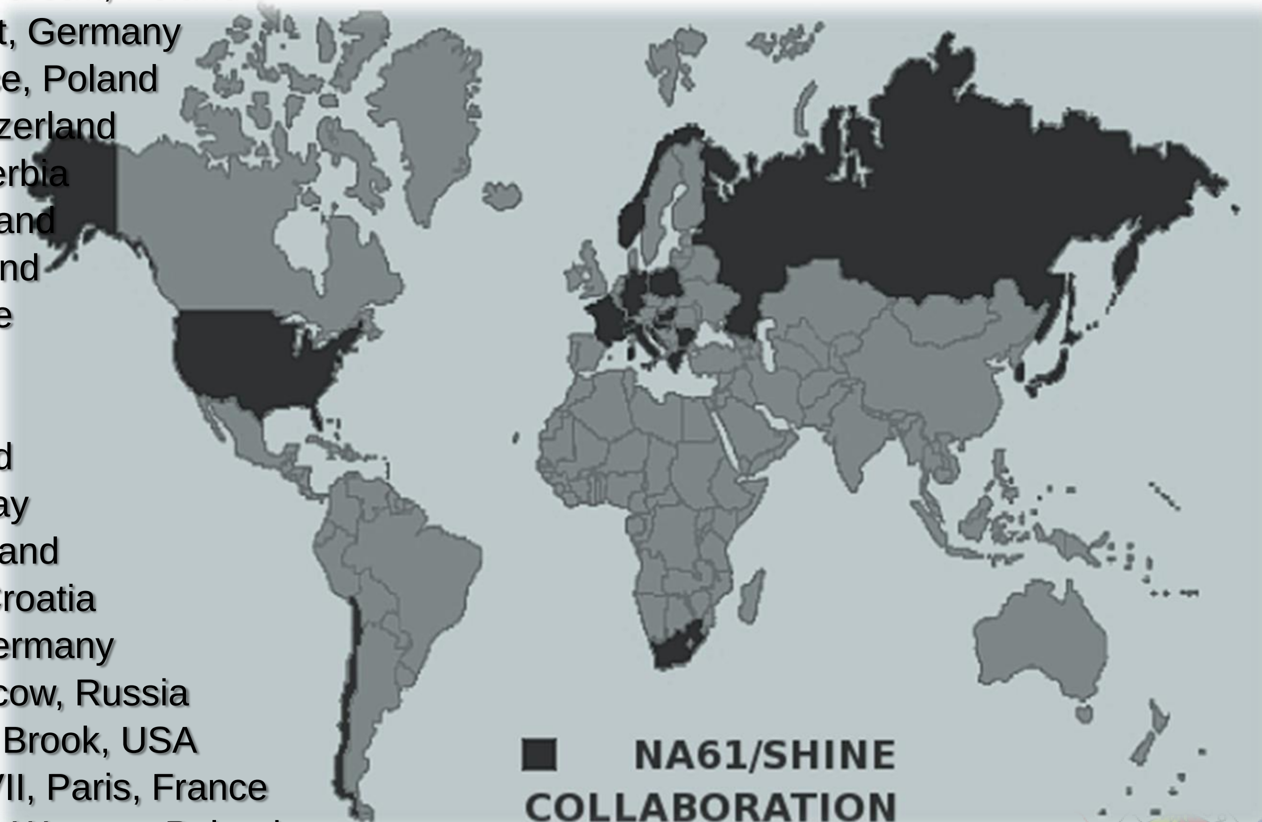
good particle identification: σ(ToF-L/R) ≈ 100 ps, σ(dE/dx)/<dE/dx> ≈ 0.04, $\sigma(m_{inv}) \approx 5$ MeV

new ToF-F to entirely cover T2K acceptance (σ(ToF-F) ≈ 110 ps, 1<*p* <4 GeV/*c*, θ < 250 mrad)

NA61 Collaboration

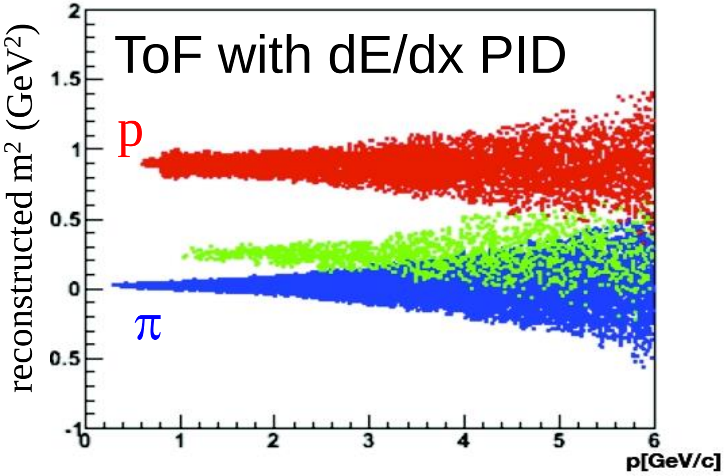
KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
The Universidad Tecnica Federico Santa Maria, Valparaiso, Chile
Faculty of Physics, University of Warsaw, Warsaw, Poland
Faculty of Physics, University of Sofia, Sofia, Bulgaria
Karlsruhe Institute of Technology, Karlsruhe, German
Joint Institute for Nuclear Research, Dubna, Russia
Warsaw University of Technology, Warsaw, Poland
Fachhochschule Frankfurt, Frankfurt, Germany
Jan Kochanowski University in Kielce, Poland
University of Geneva, Geneva, Switzerland
University of Belgrade, Belgrade, Serbia
Jagiellonian University, Cracow, Poland
University of Silesia, Katowice, Poland
University of Athens, Athens, Greece
ETH, Zurich, Switzerland
University of California, Irvine, USA
University of Bern, Bern, Switzerland
University of Bergen, Bergen, Norway
University of Wrocław, Wrocław, Poland
Rudjer Boskovic Institute, Zagreb, Croatia
University of Frankfurt, Frankfurt, Germany
Institute for Nuclear Research, Moscow, Russia
State University of New York, Stony Brook, USA
LPNHE, University of Paris VI and VII, Paris, France
National Center for Nuclear Studies, Warsaw, Poland
St. Petersburg State University, St. Petersburg, Russia
Institute for Particle and Nuclear Studies, KEK, Tsukuba, Japan
Laboratory of Astroparticle Physics, University Nova Gorica, Nova Gorica, Slovenia

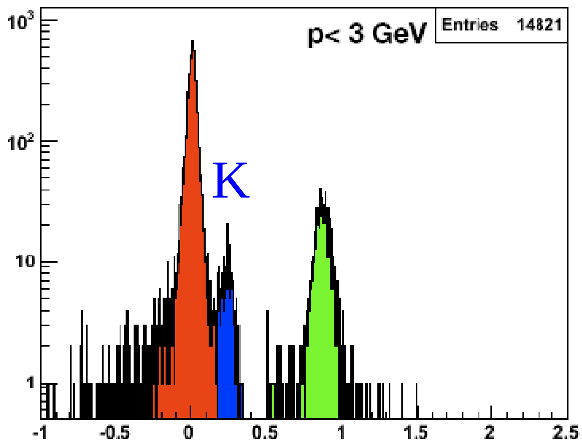
~ 140 physicists from 30 institutes and 15 countries



Particle identification

Time of Flight measurements

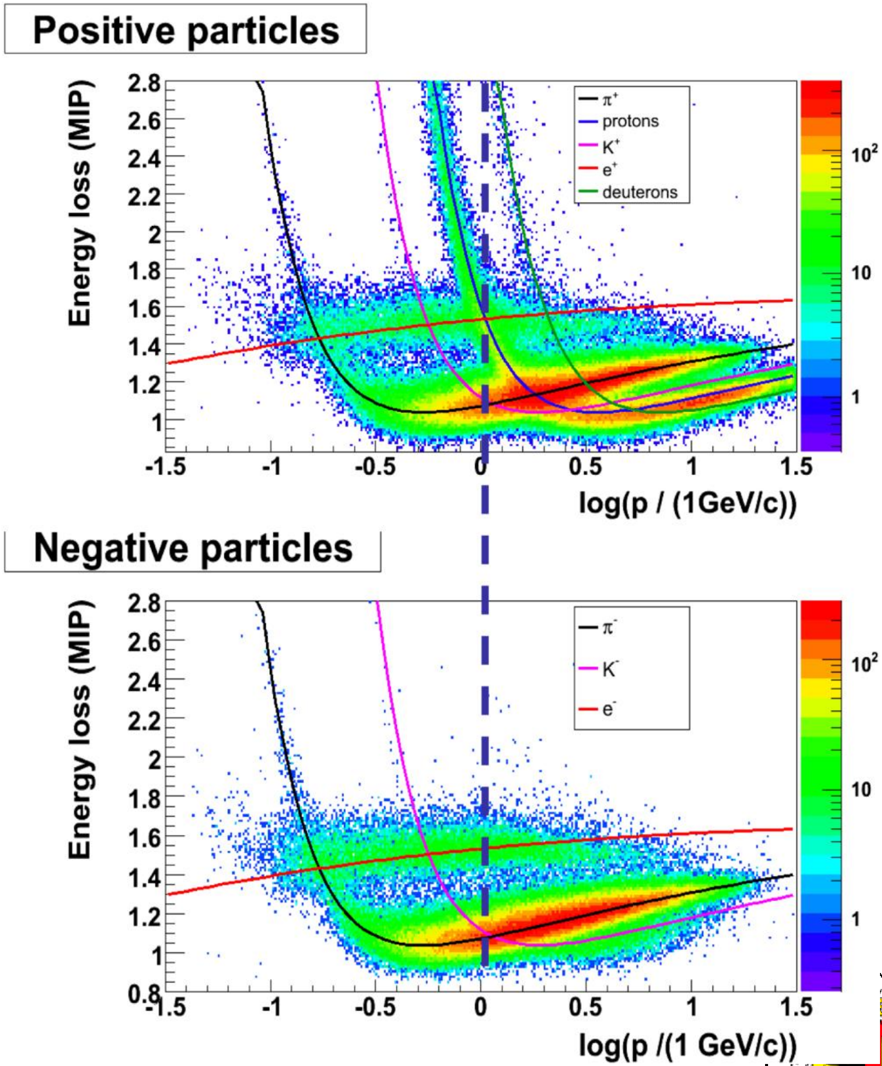




reconstructed m² (GeV²)

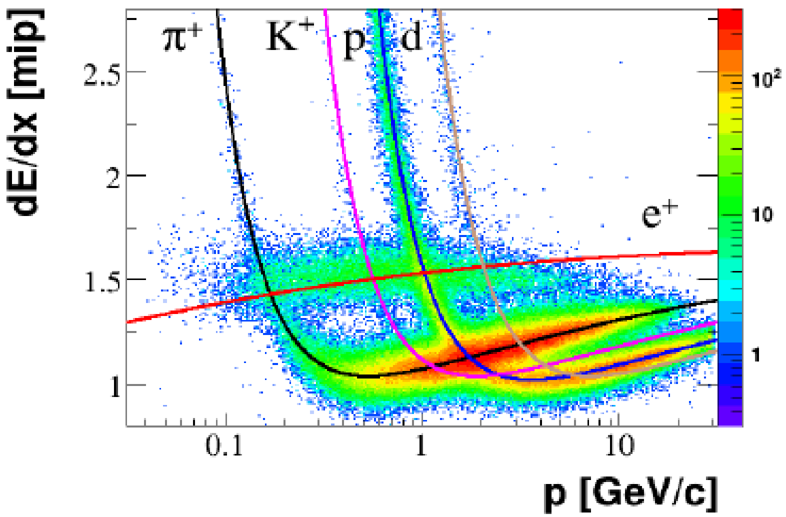
σ (ToF) ~ 110 ps
5 σ π/K separation up to 4 GeV/c

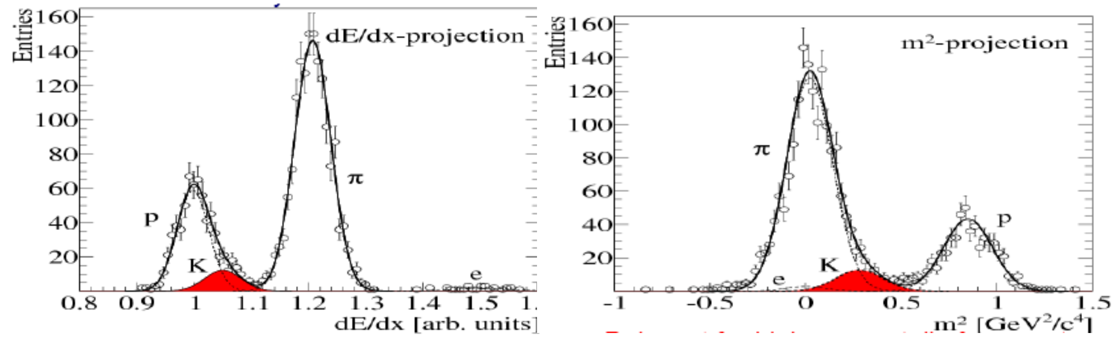
Energy loss in TPCs
Bethe-Bloch curves (dE/dx) for different particles

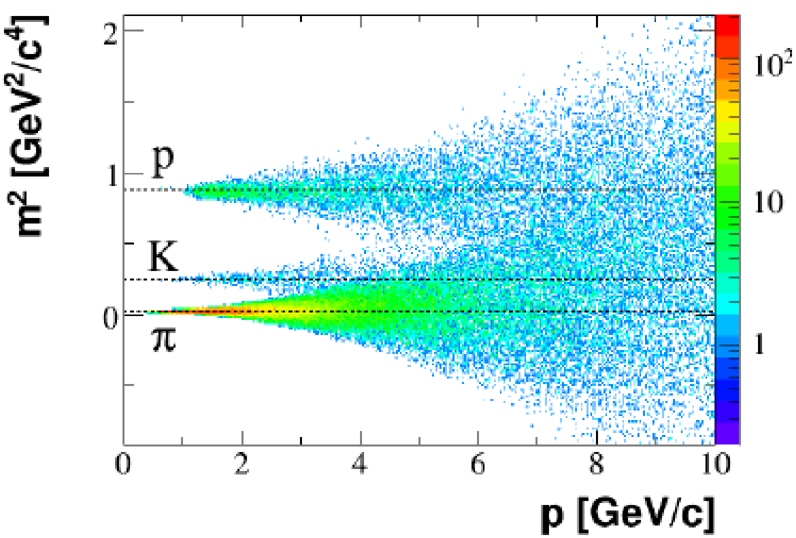


σ(dE/dx)/<dE/dx> < 5 %

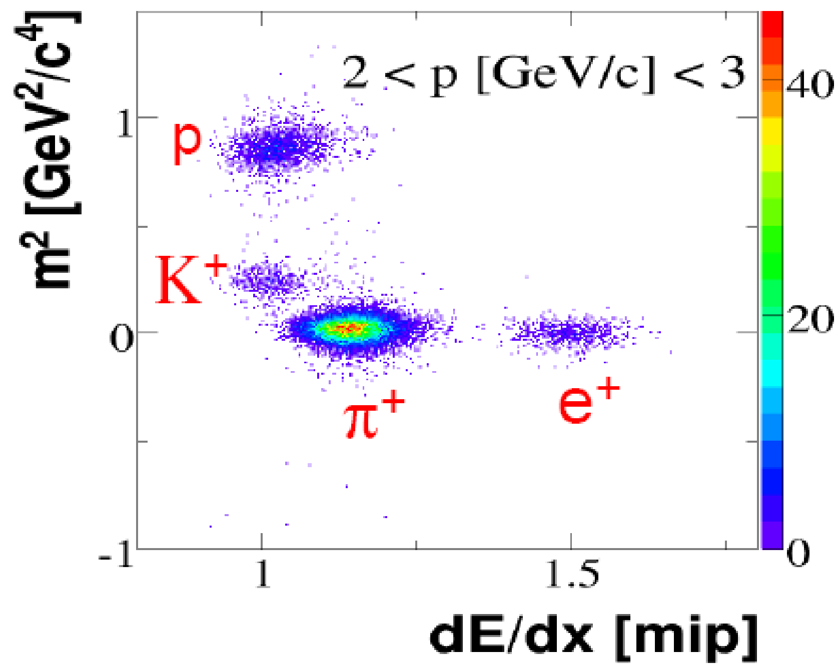
Particle Identification (2)



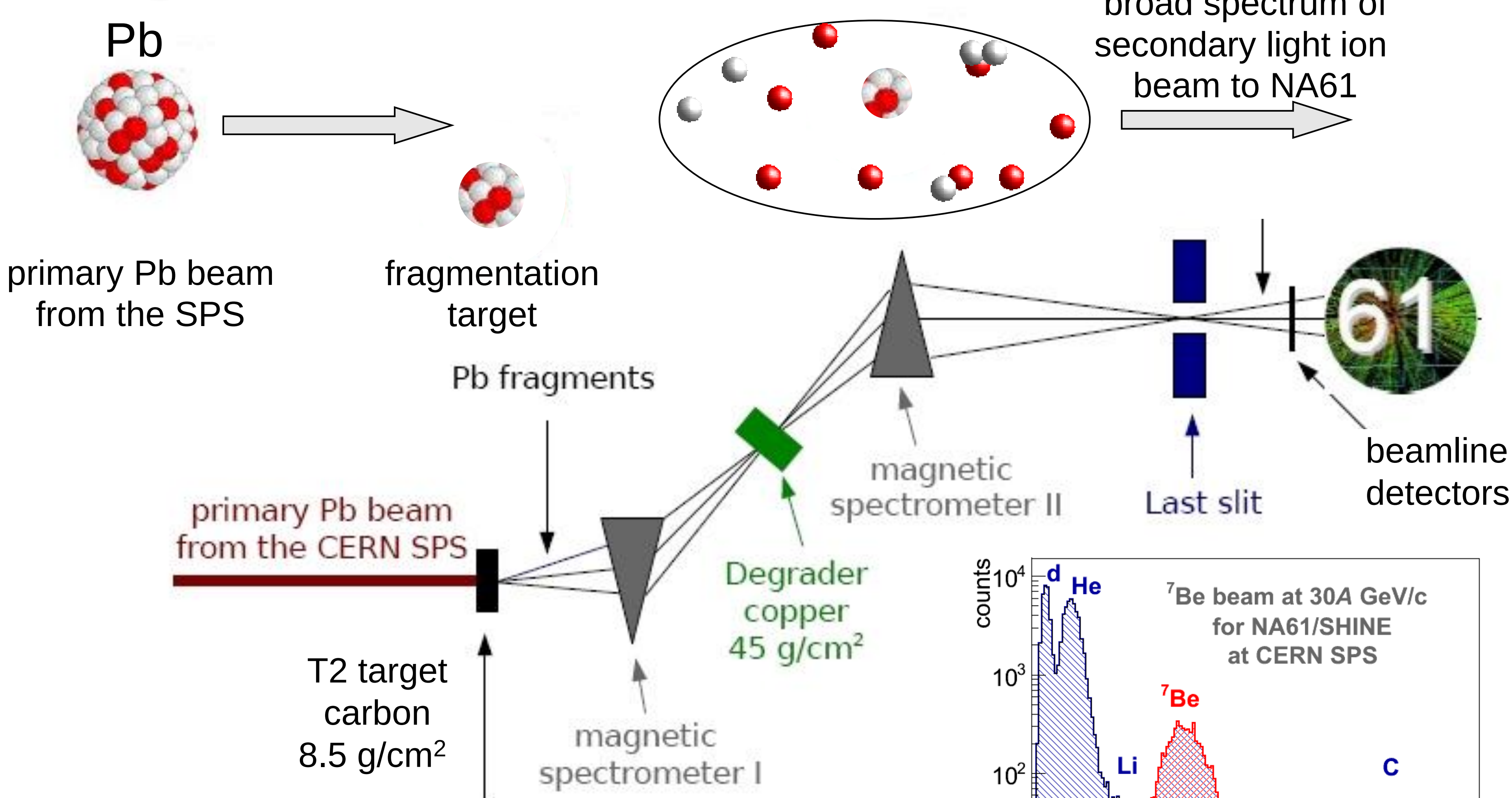


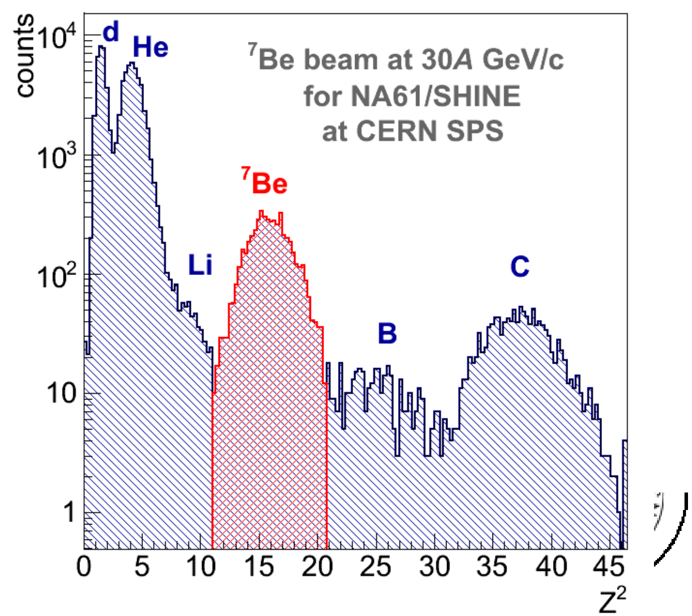


combined ToF + dE/dx
(positively charged particles)



Fragmented Ion Beam for NA61





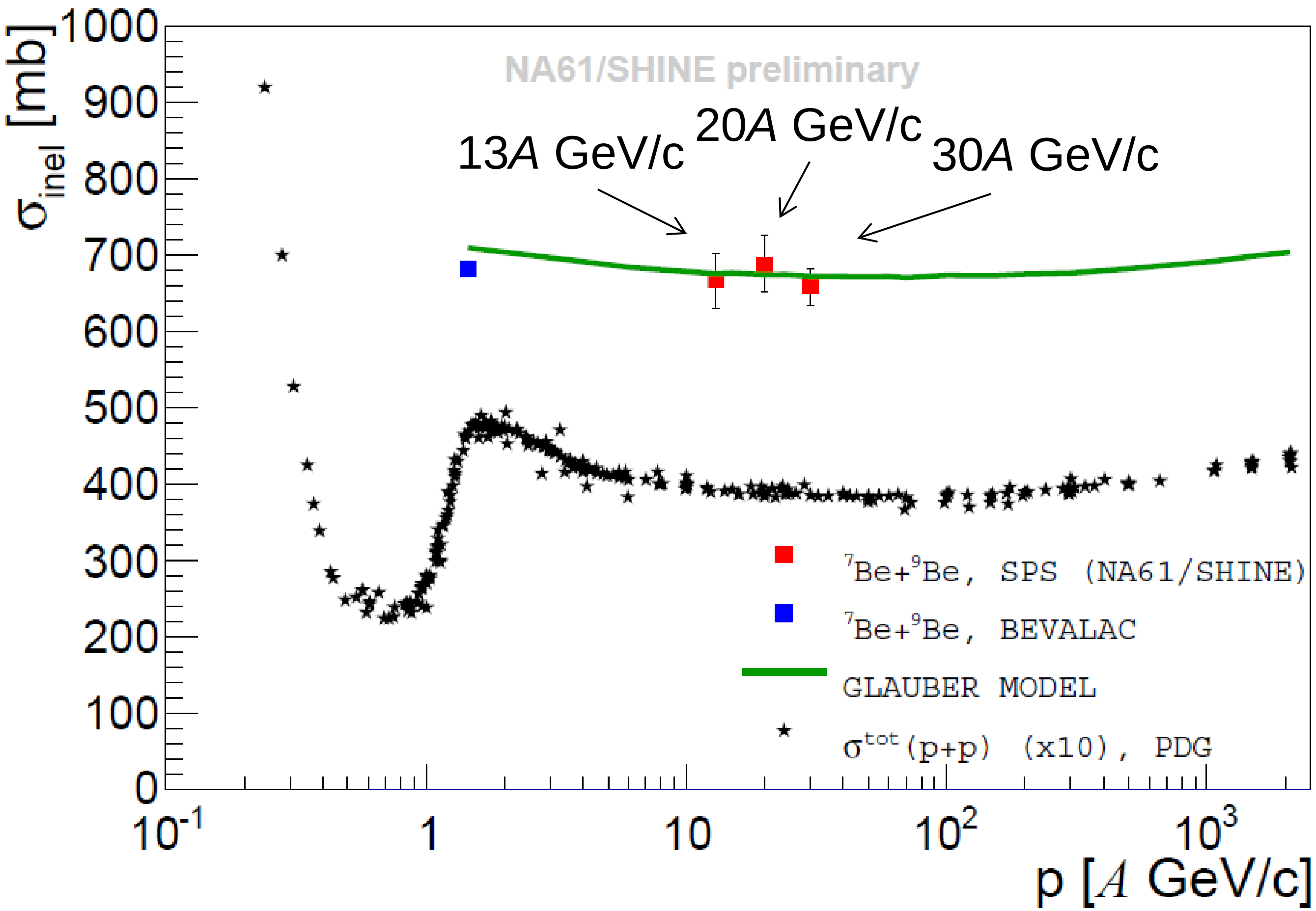
selects beam of nuclei with close Z and A

further ion identification by Z (charge) measurements

momentum per nucleon cannot be changed

$^{7}Be + ^{9}Be$ Collisions (preliminary)

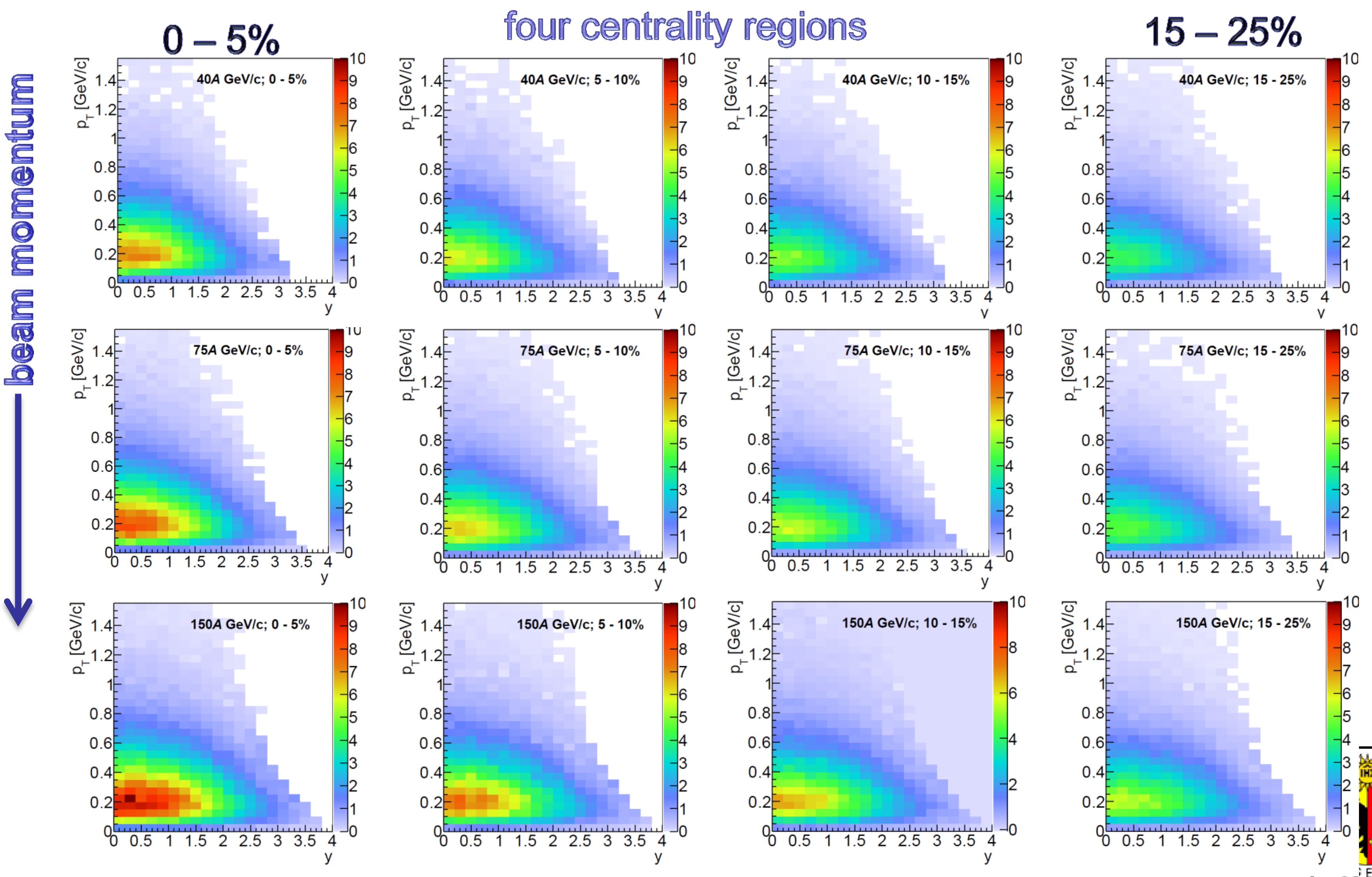
inelastic $^{7}Be+^{9}Be$ cross section



NA61 measurements (combined with the 1*A* GeV/c BEVALAC measurement) established energy dependence of the inelastic cross section

^{7}Be + ^{9}Be Collisions (preliminary)

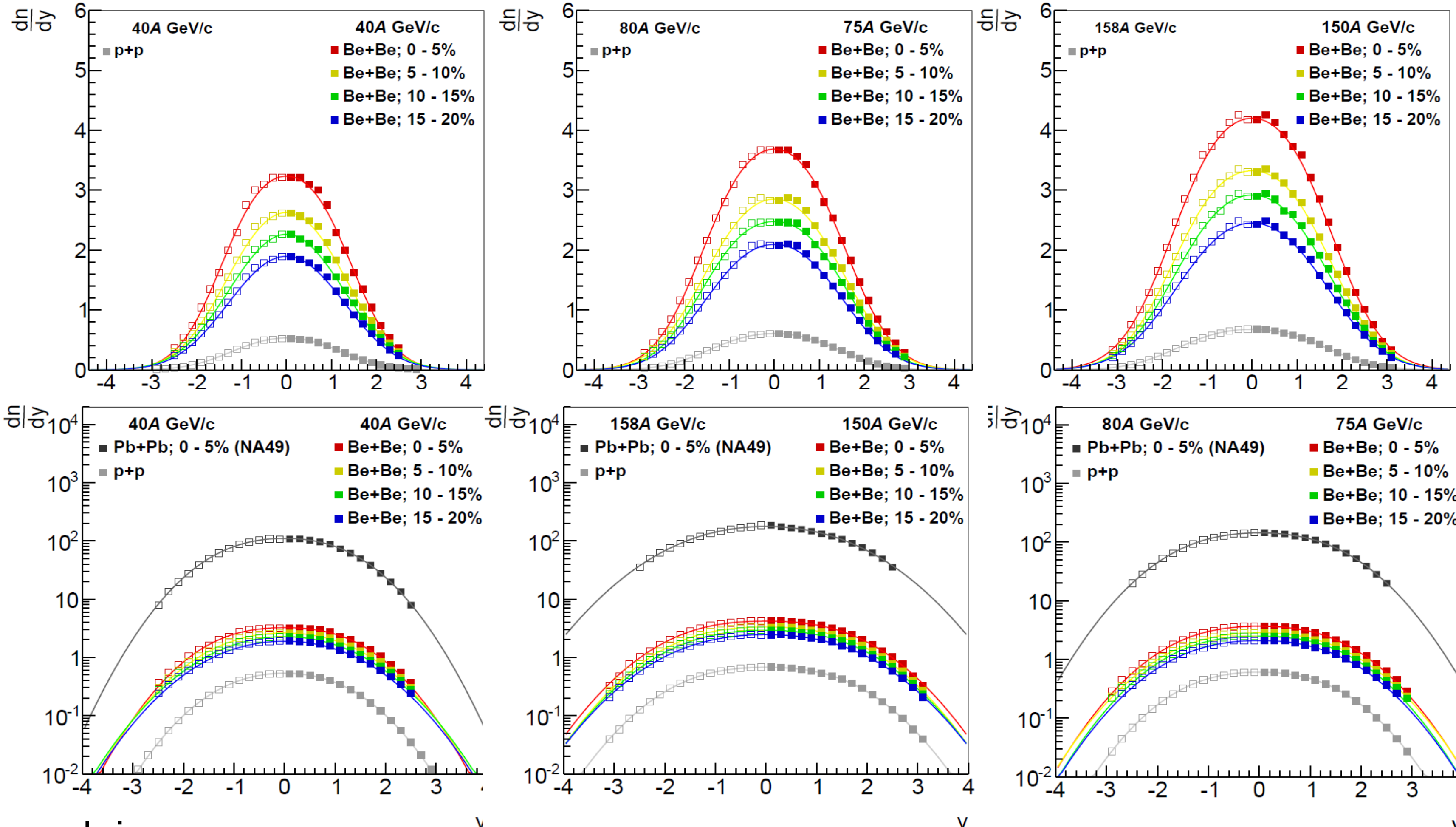
π^- meson spectra in ^{7}Be+^{9}Be collisions



^{7}Be + ^{9}Be Collisions (preliminary)

π^- meson rapidity spectra in ^{7}Be+^{9}Be collisions (integrated in p_T)

comparison with p+p (NA61) and most central Pb+Pb (NA49) collisions

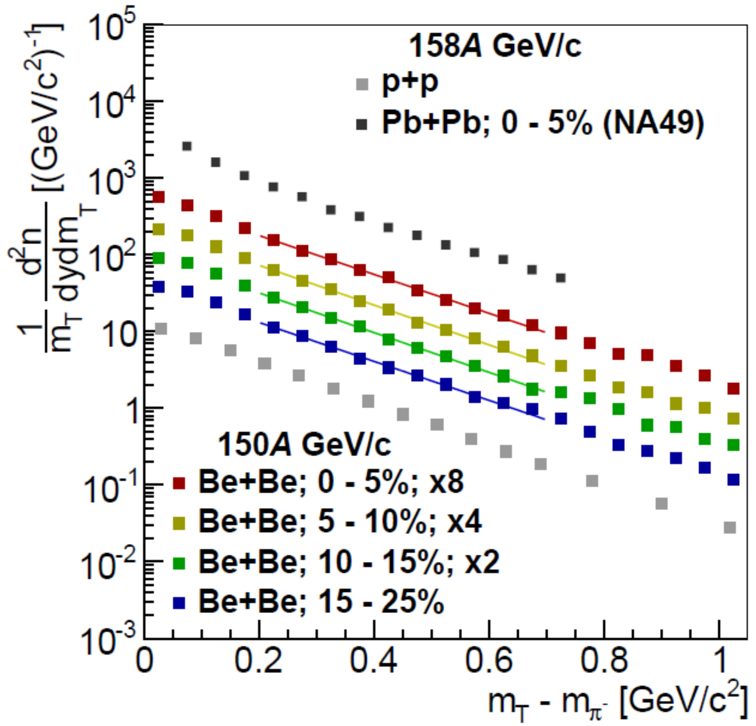


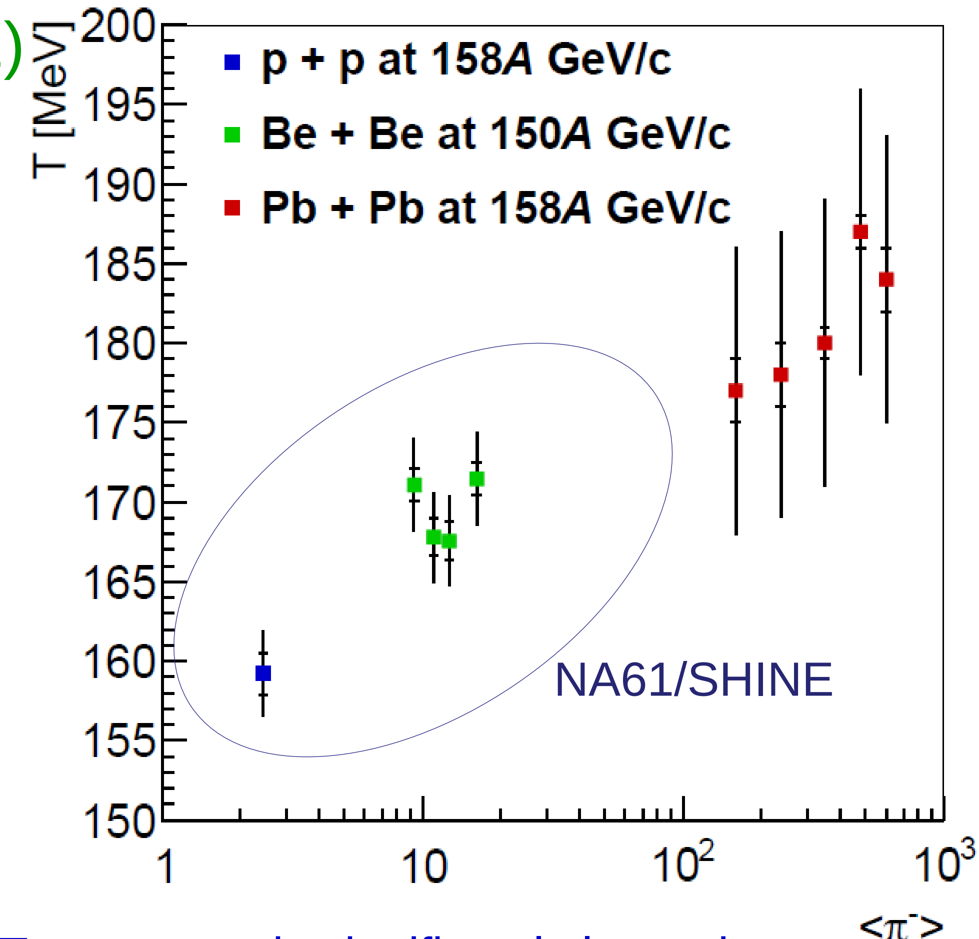
work in progress :

determination of number of wounded nucleons and correction for isospin effects

^{7}Be + ^{9}Be Collisions (preliminary)

π^- m_T spectra and inverse slope T in ^{7}Be+^{9}Be collisions at mid-rapidity (0.0 < y < 0.2)





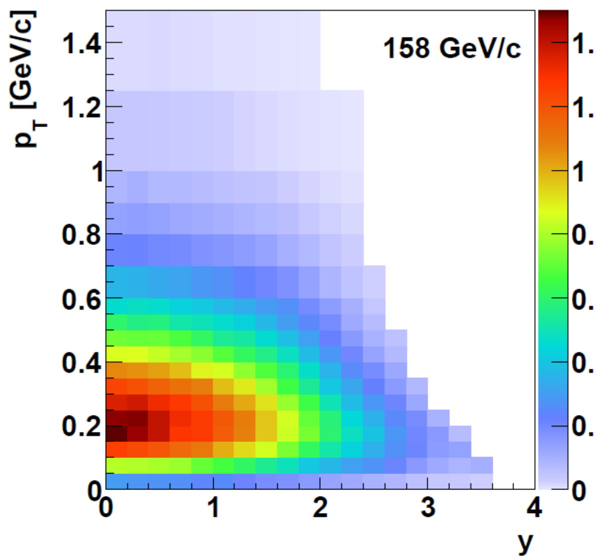
$$\frac{dn}{dm_T} = A\, m_T \exp\left(-\frac{m_T}{T}\right)$$

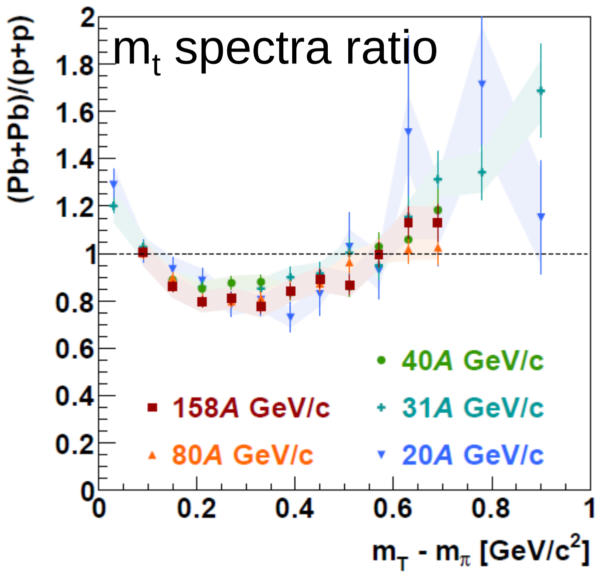
the T parameter is significantly larger in Be+Be collisions than in p+p interactions
⇒ evidence for transverse collective flow in Be+Be collisions

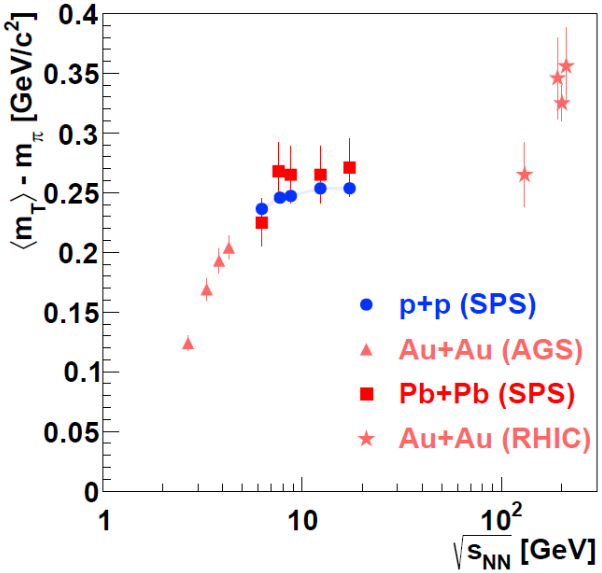
π^- Spectra in p+p Interactions (final)

Reference data for ion program

(h⁻ method)







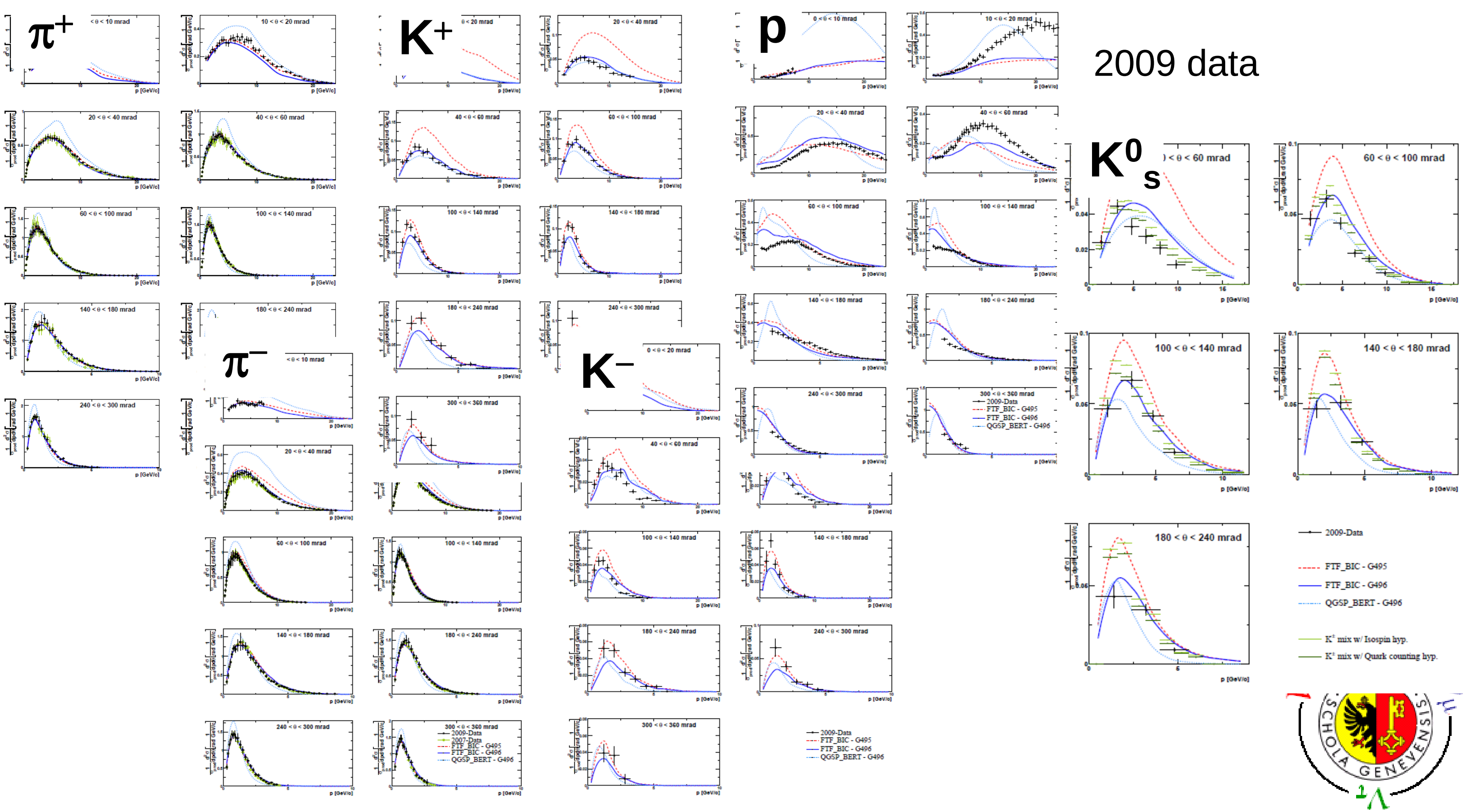
Spectra of π^- in p+p collisions at 20, 31, 40, 80, and 158 GeV/c

Different shape in p+p and central (7%) Pb+Pb, independent of beam energy

Mean transverse mass independent of system size

NA61 Measurements for T2K (preliminary)

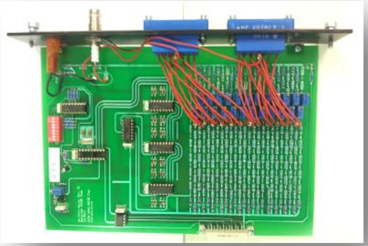
Results for the full set of identified hadrons produced in p+C interactions at 31 GeV/c



NA61 Upgrades

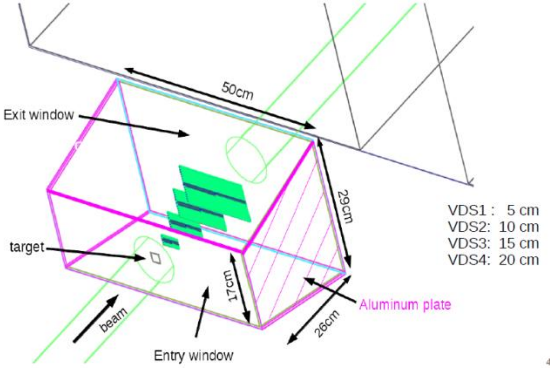
Facility modifications

- Projectile Spectator Detector (2014)
  - Cooling system
  - Slow control system
  - LED for the control of the readout gains
  - INR Moscow



- The ToF-L/R (2014)
  - Upgrades of HV distributors
  - University of Belgrade
- Drift velocity monitoring system
  - New monitoring system for the GAP-TPC (ready by summer 2014) and later for other TPCs
  - University of Warsaw

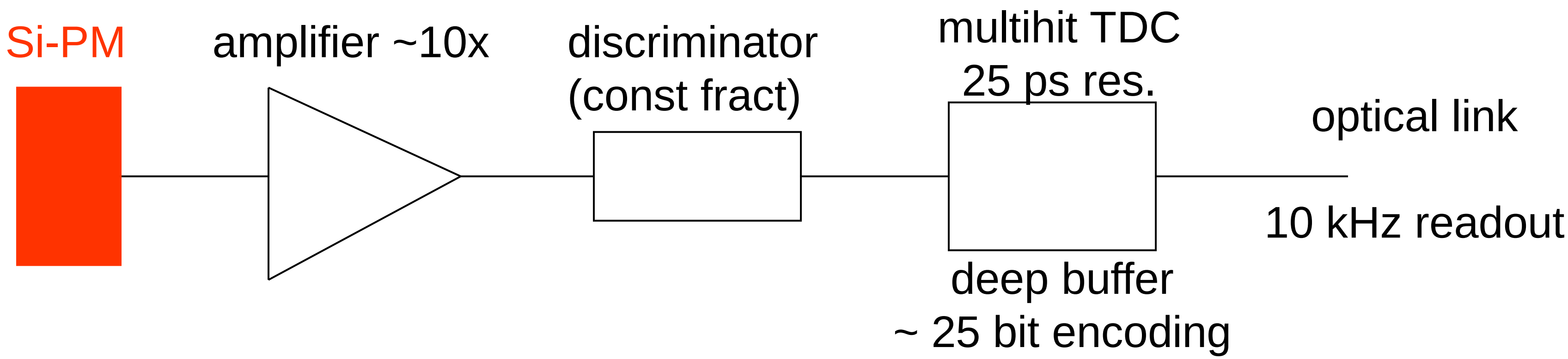
- DRS-based read-out upgrade (2015)
  - Detectors: ToF, PSD and beam detectors
  - University of Geneva, Warsaw, Budapest, Pittsburgh
- Vertex detector (2018)
  - Frankfurt



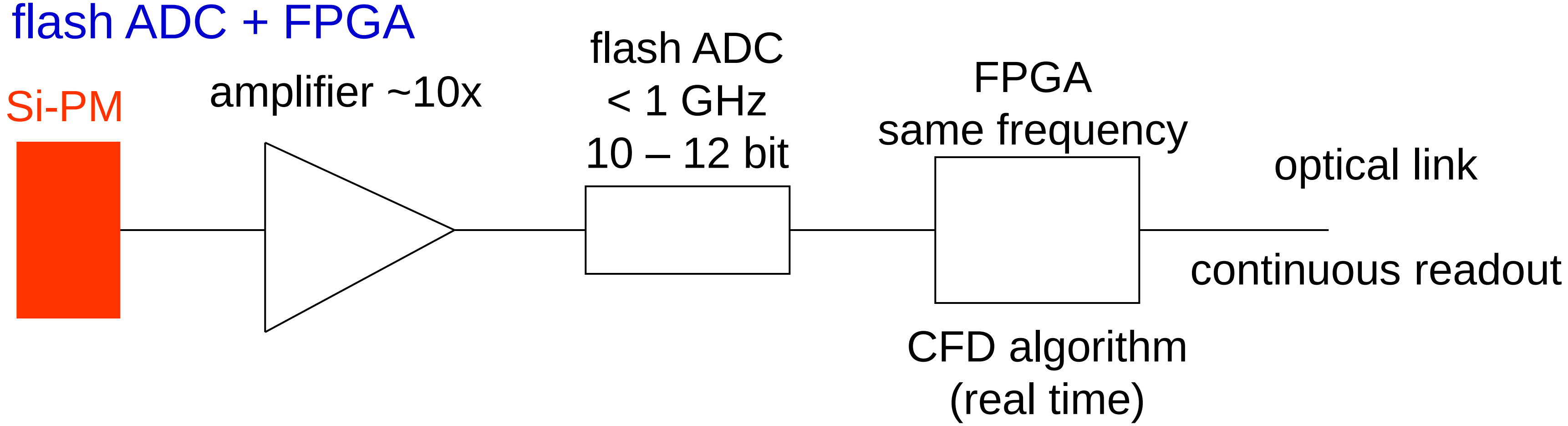
How To Measure Best Timing (1)

basically two options:

1. (CF) discriminator + multihit TDC



2. flash ADC + FPGA

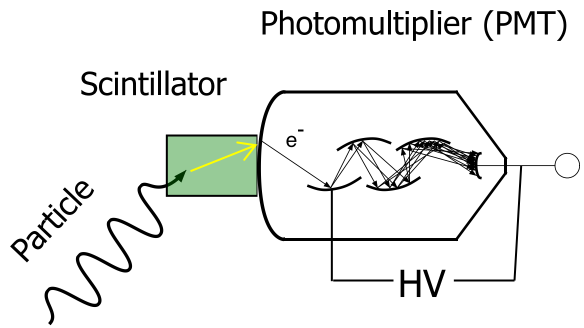


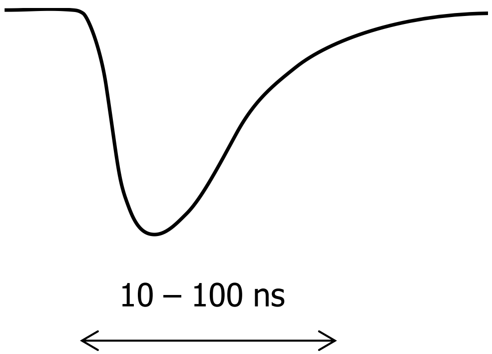
The waveform approach combines different functionalities with no D.T.: CFD, (multi-hit) TDC, Q-ADC, peak-sensing ADC, etc.

PROBLEM: ~10 ps resolution requires very high sampling rate > 1 GHz

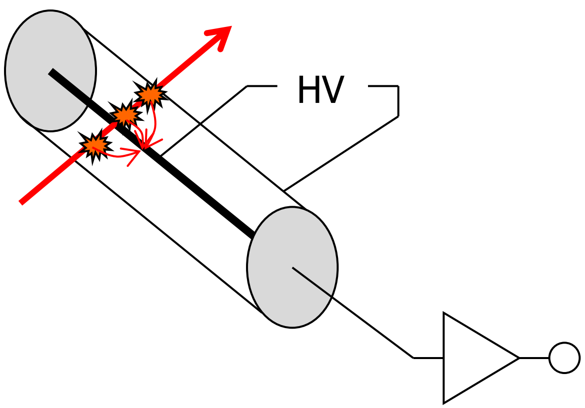
Signals in Particle Physics

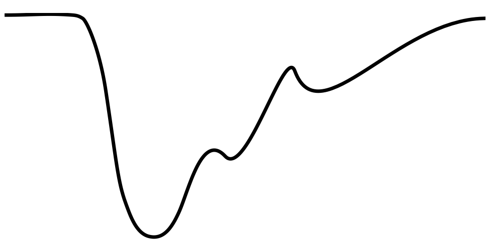
Scintillators
(Plastic, Crystals,
Noble Liquids, …)



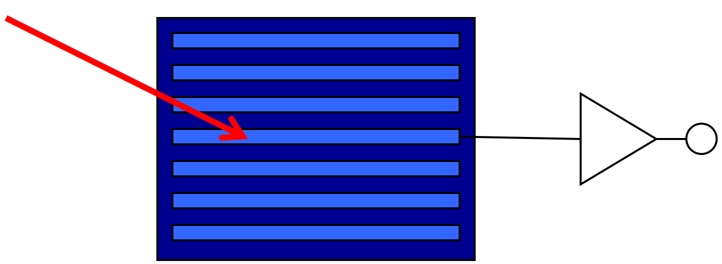


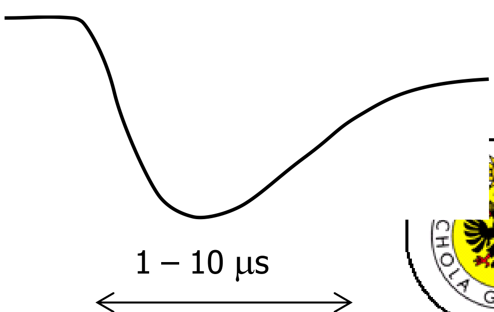
Wire chambers
Straw tubes





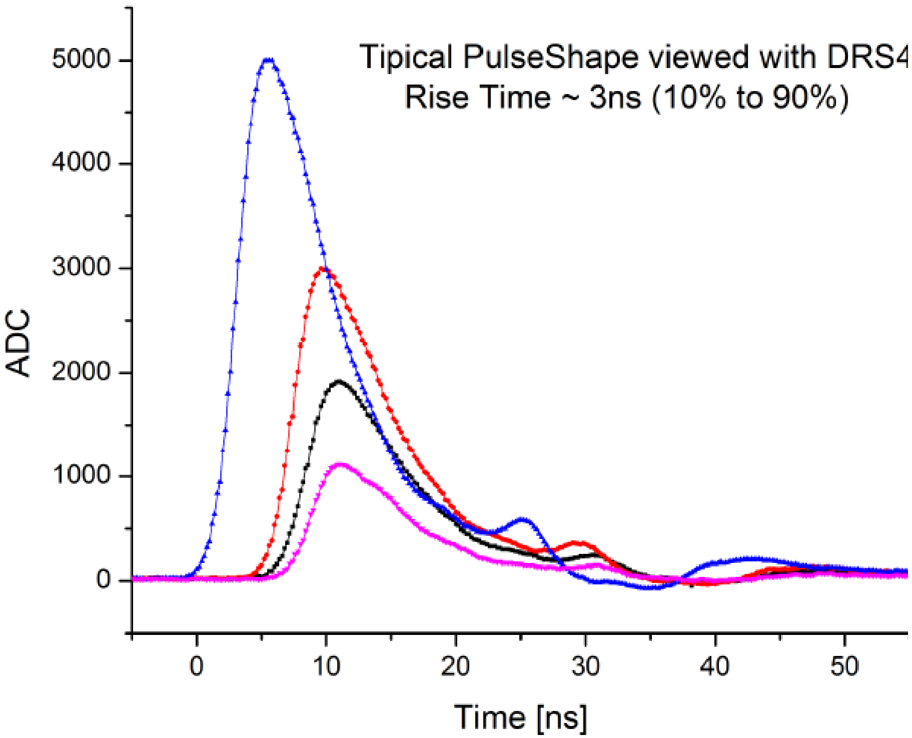
Silicon
Germanium





Waveforms

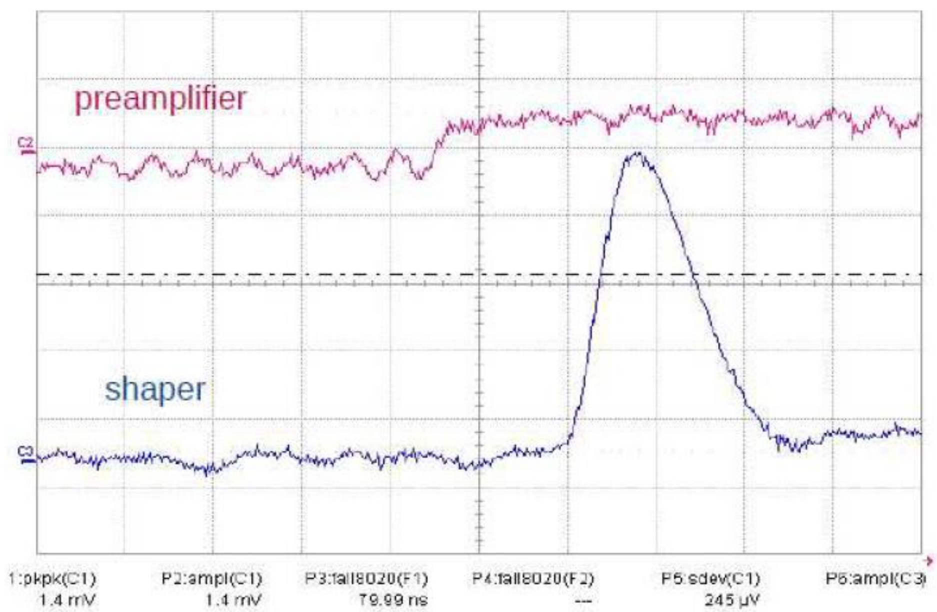
ToF-L signals



risetime ~ 3 ns

→ fast digitization

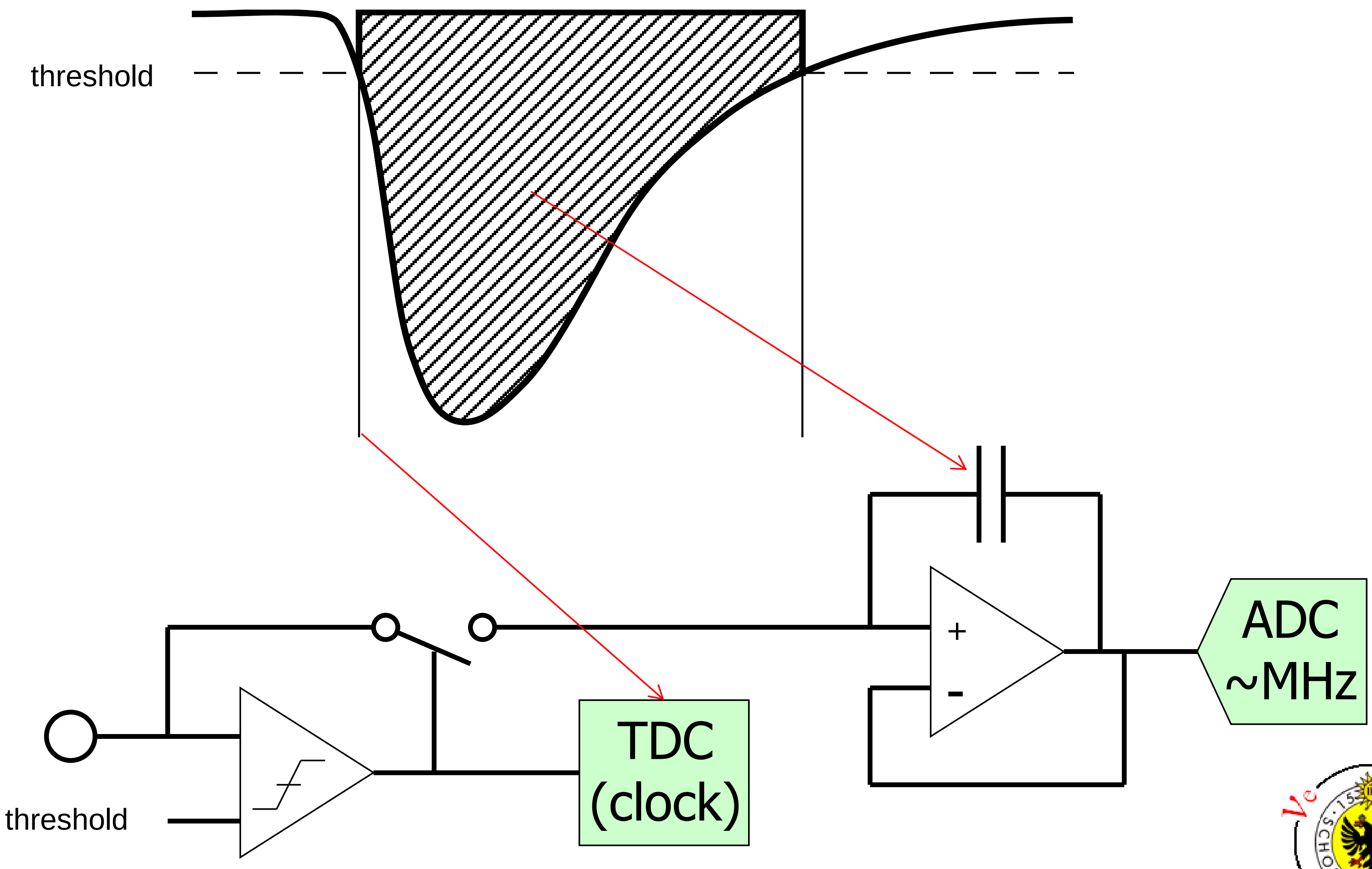
BPD signals



FWHM ~ 120 ns

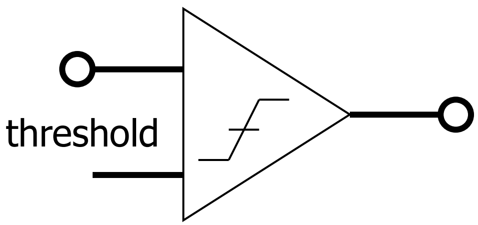
→ slow digitization

“Traditional” Approach

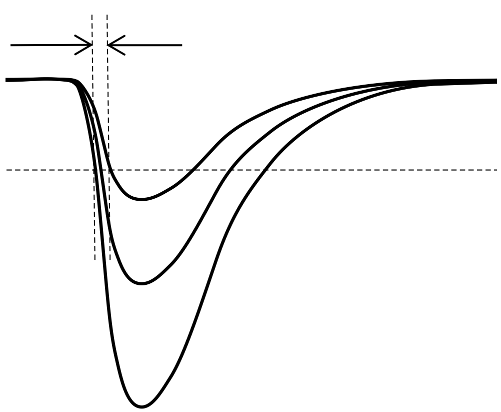


Signal Discrimination

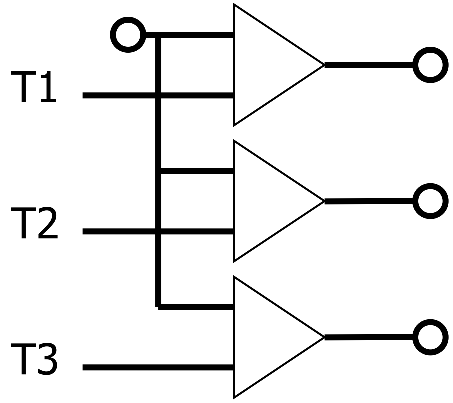
single threshold

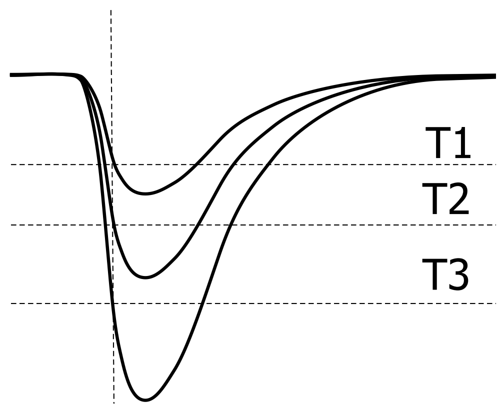


“Time-Walk”

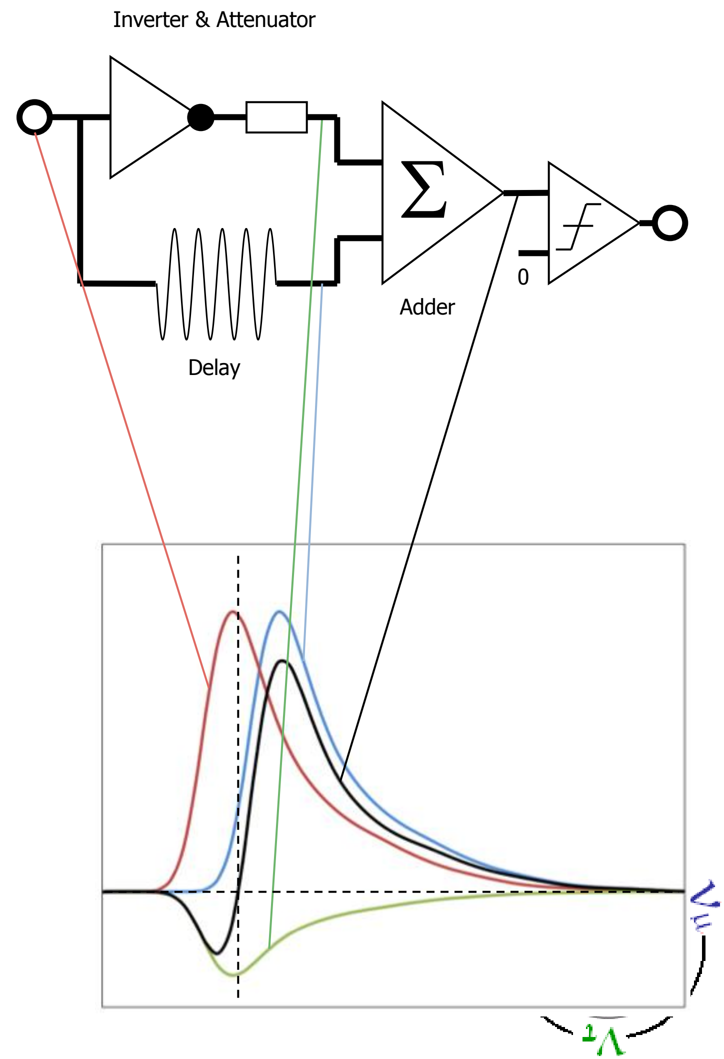


multiple thresholds



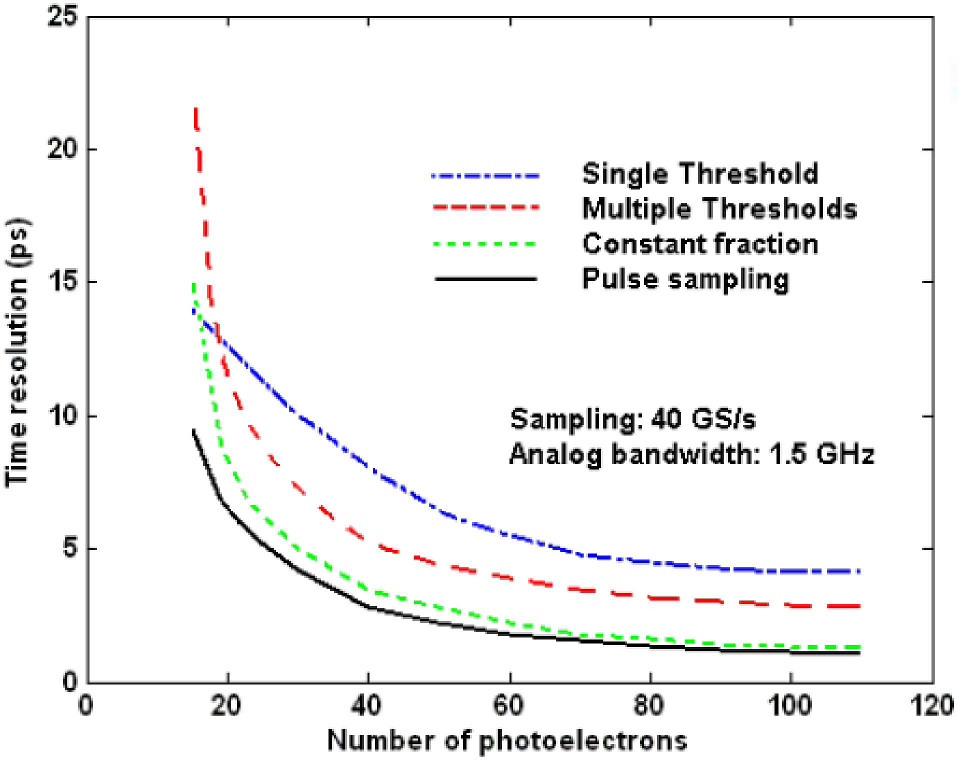


constant fraction (CFD)



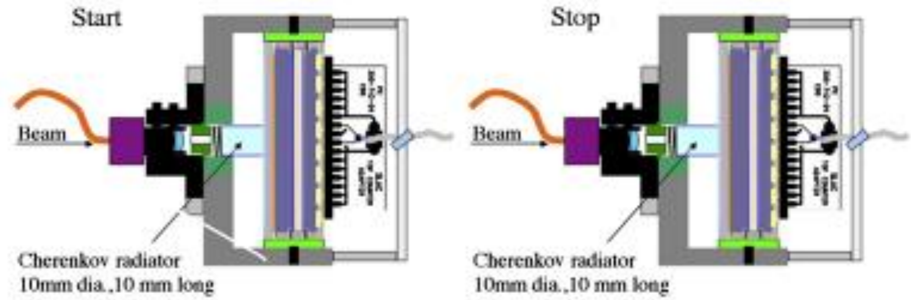
How To Measure Best Timing (2)

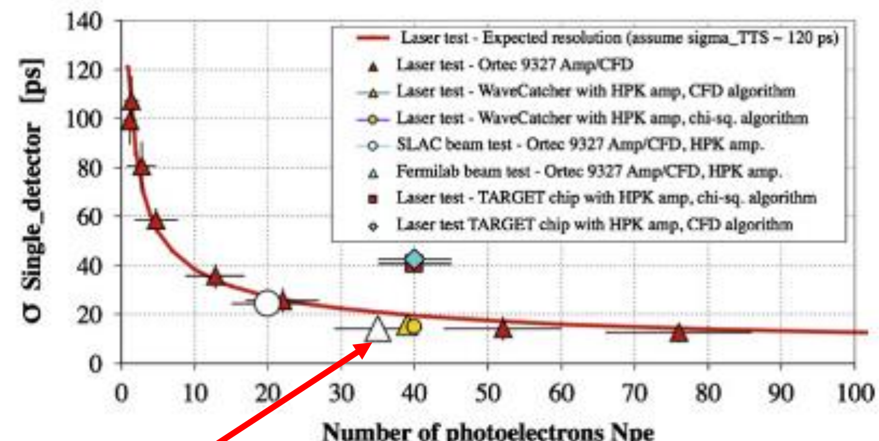
simulation of MCP with realistic noise
and best discriminators



J.-F. Genat et al., arXiv:0810.5590 (2008)

Beam measurements
@ SLAC and FNAL





D. Breton et al., NIM **A629**, 123 (2011)

17 ps (σ) can be achieved with waveform digitizing
(and 40 photoelectrons)

Waveform Digitizing

Advantages :

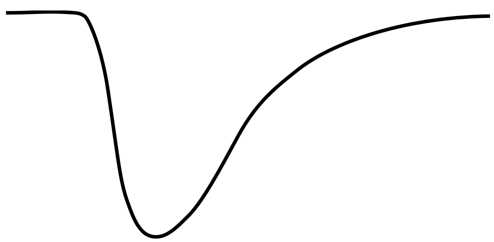
General trend in signal processing (“Software Defined Radio”)

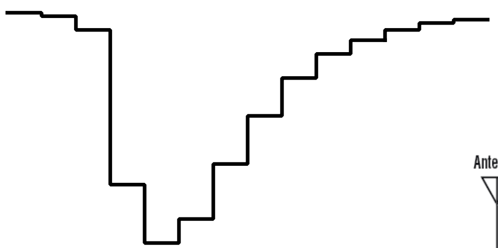
Less hardware (Only ADC and FPGA)

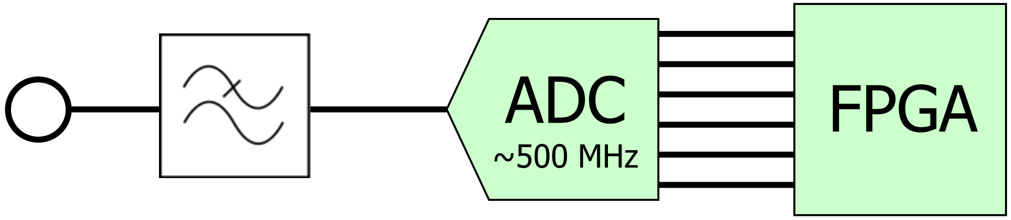
Algorithms can be complex (peak finding, peak counting, waveform fitting)

Algorithms can be changed without changing the hardware

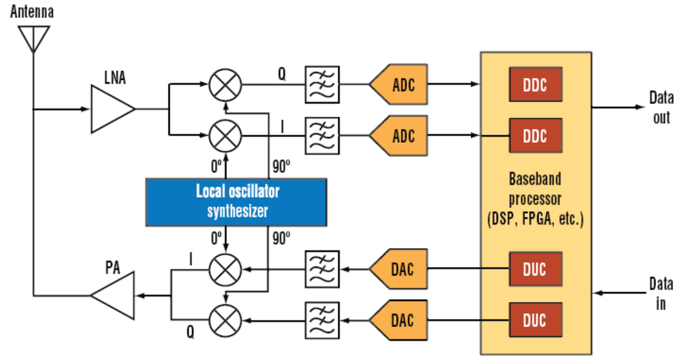
Storage of full waveforms allow elaborate offline analysis





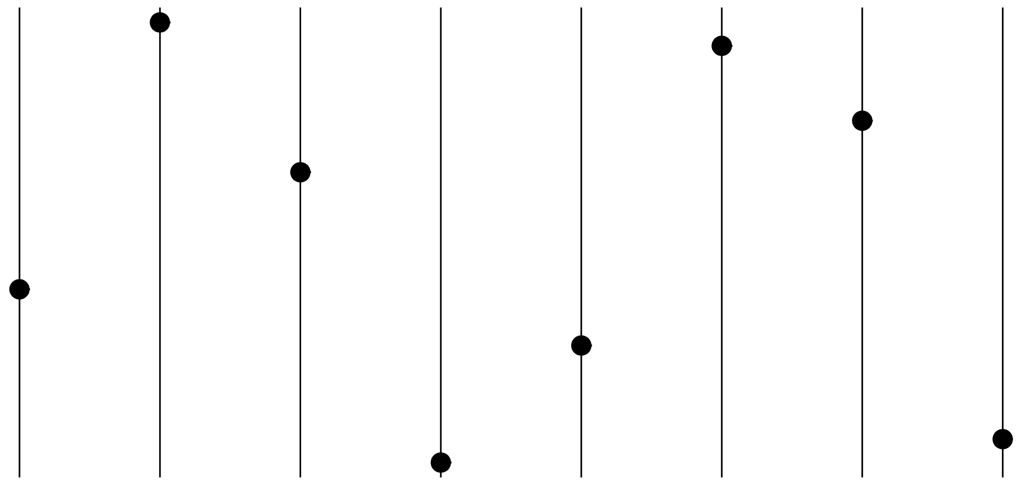


SDR

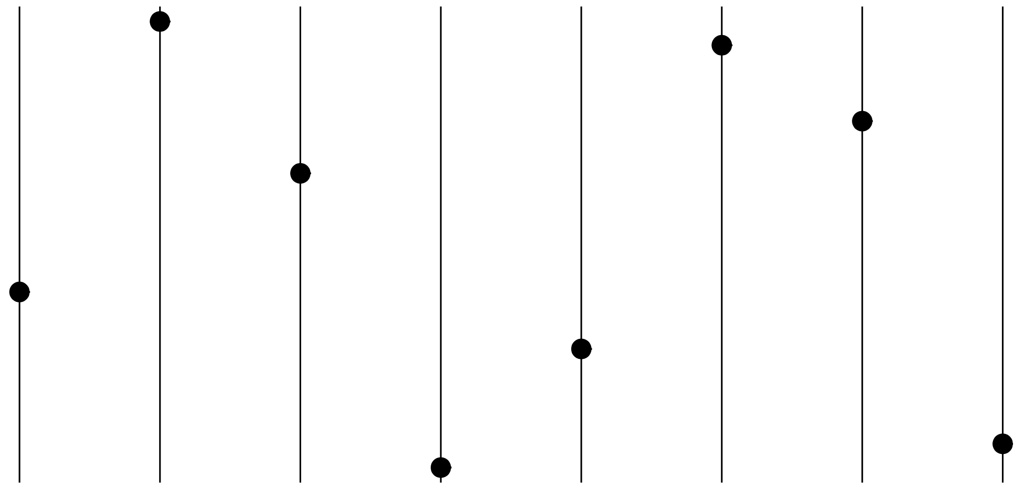


Nyquist-Shannon Sampling Theorem

$f_{signal} < f_{sampling}/2$



$f_{signal} > f_{sampling}/2$



Undersampling of Signals

Undersampling: Acquisition of signals with sampling rates < 2 * highest frequency in signal

Image Processing

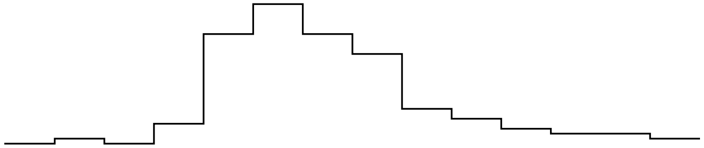
Waveform Processing

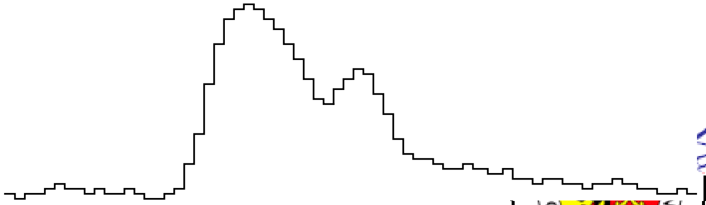
Undersampling of Signals

Undersampling:
acquisition of signals with sampling rates ≪ 2 × highest frequency in signal

Image Processing

Waveform Processing



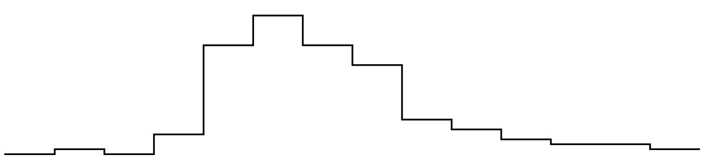


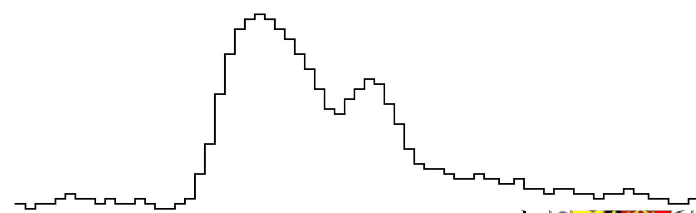
Undersampling of Signals

Undersampling:
acquisition of signals with sampling rates $\ll 2 \times$ highest frequency in signal

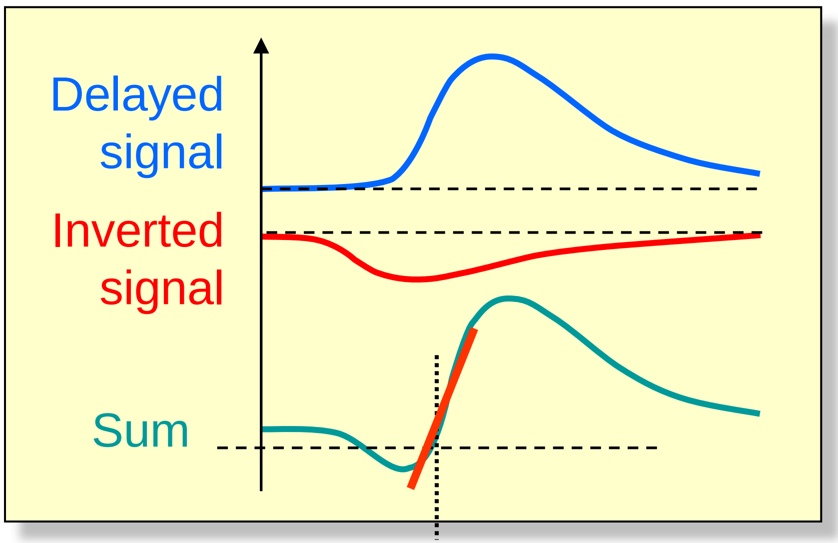
Image Processing

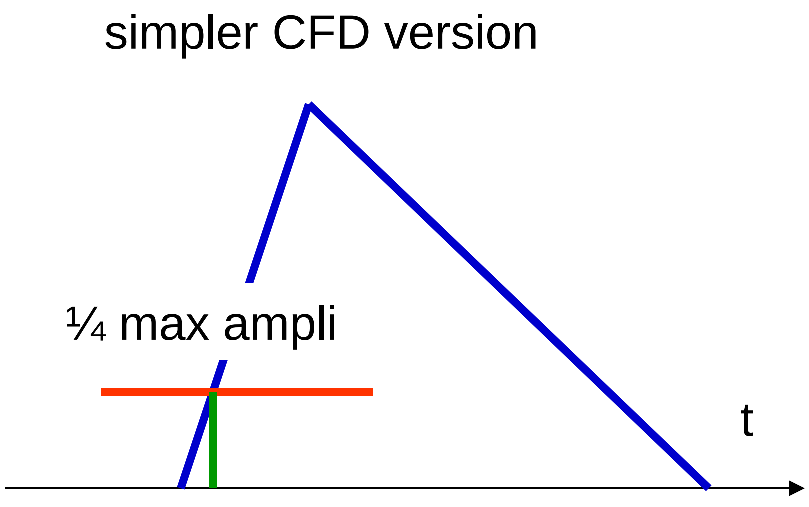
Waveform Processing

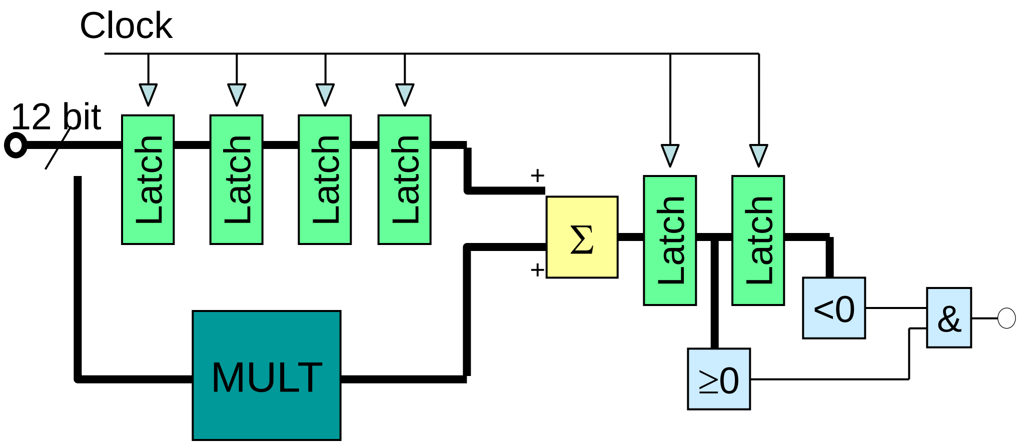




Digital Constant Fraction Discriminator







200 ps sampling

without doing nothing
→ σ = 200 ps / √12 ~ 60 ps

with interpolation can obtain
5 × better performance

Limits of Waveform Digitizing

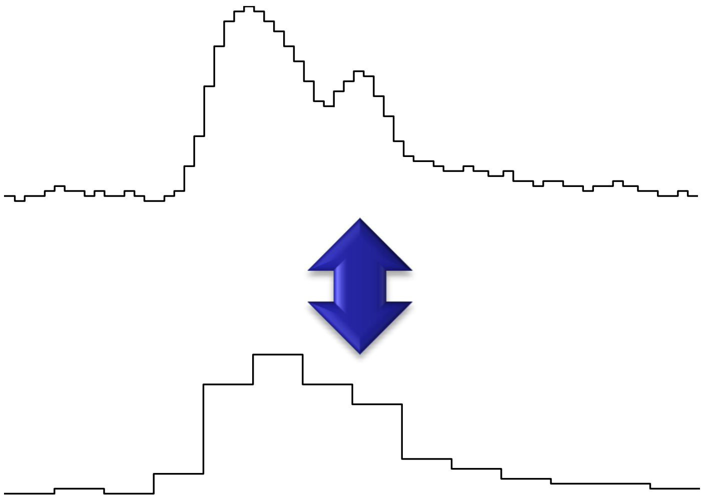
aliasing occurs if $f_{signal} > 0.5 \times f_{sampling}$

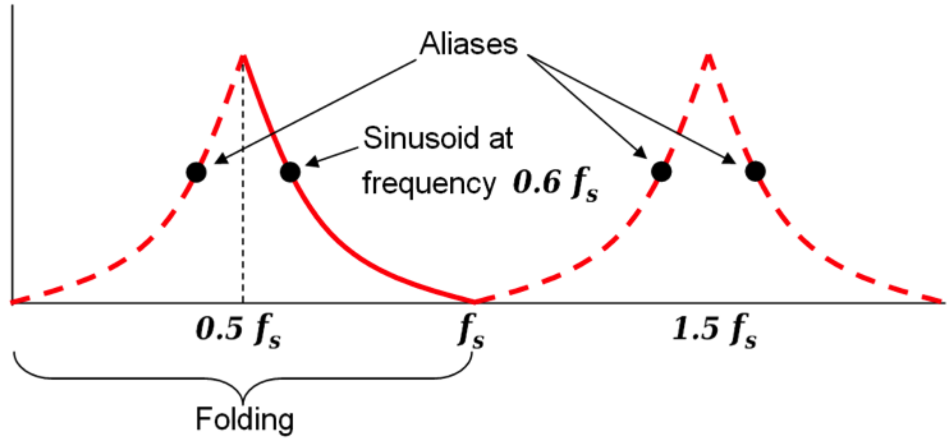
features of the signal can be lost (“pile-up”)

measurement of time becomes hard

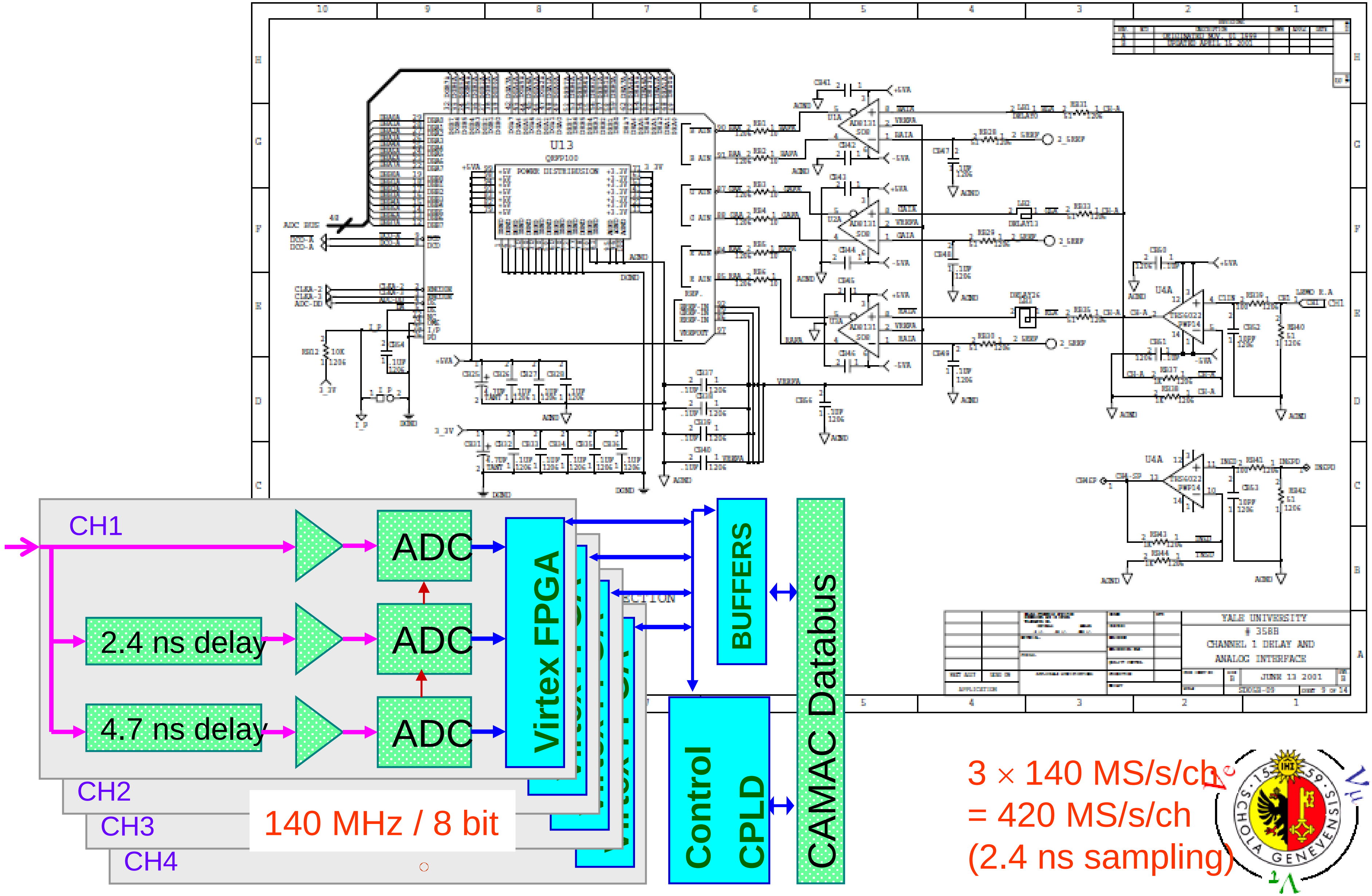
ADC resolution limits energy measurement

need very fast high resolution ADC



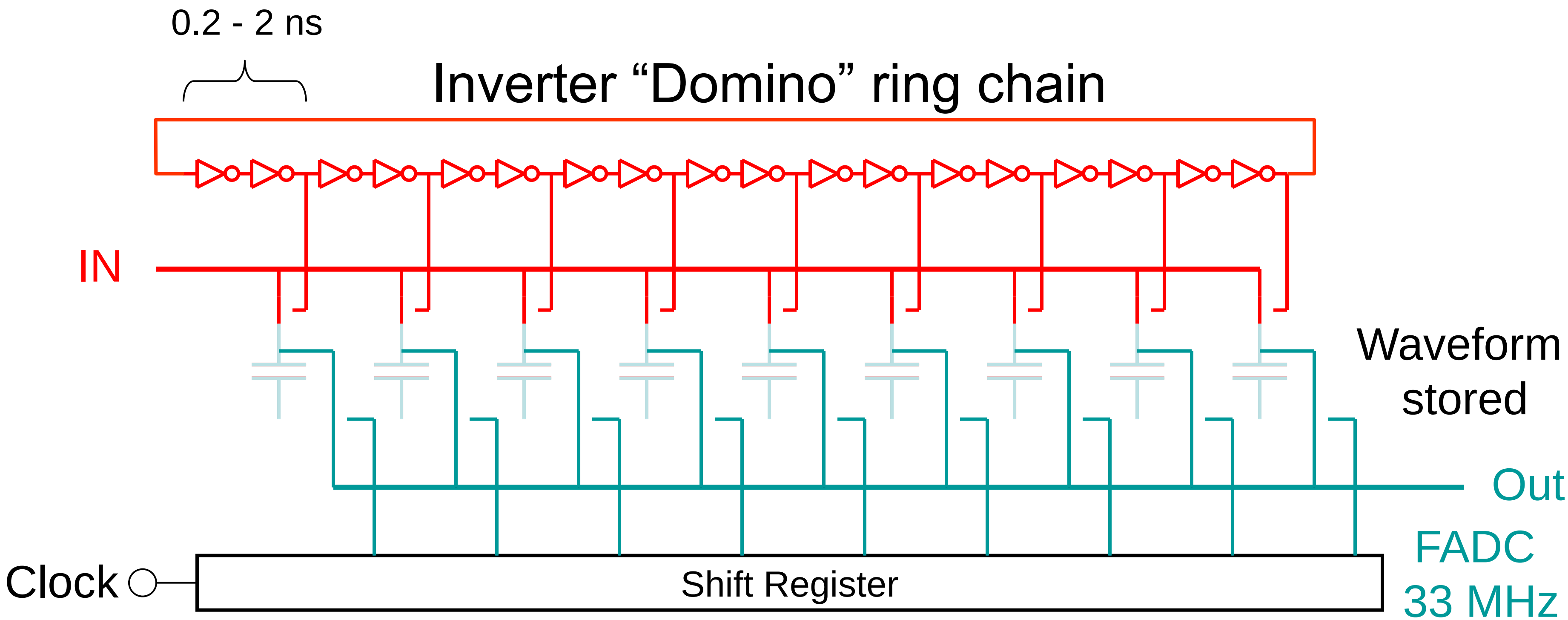


500 MHz WFD (< 2000 a. d.)



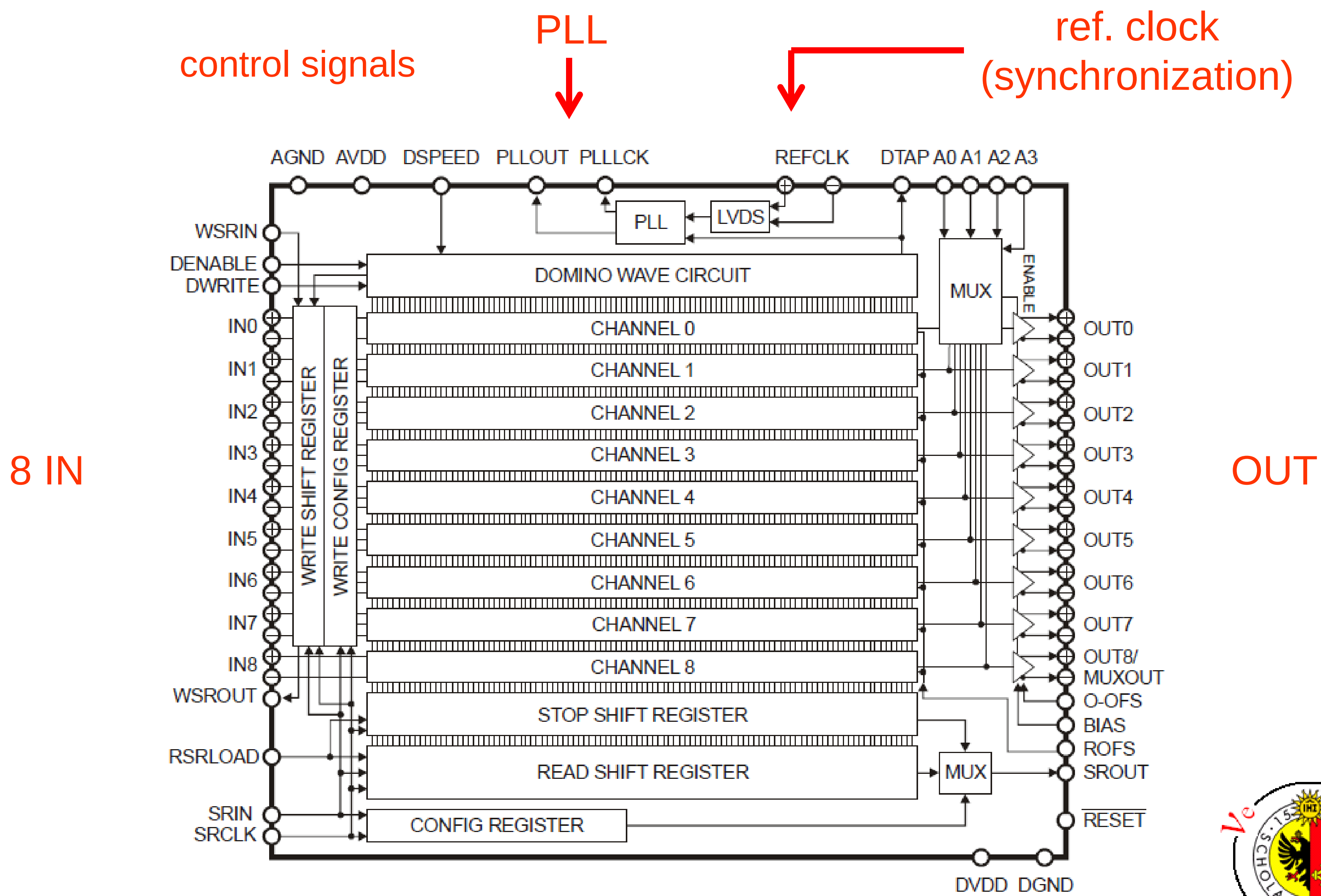
3 × 140 MS/s/ch
= 420 MS/s/ch
(2.4 ns sampling)

Switched Capacitor Array



“Time stretcher” GHz → MHz

DRS Functional Block Diagram



DRS “Philosophy”

waveform stretcher

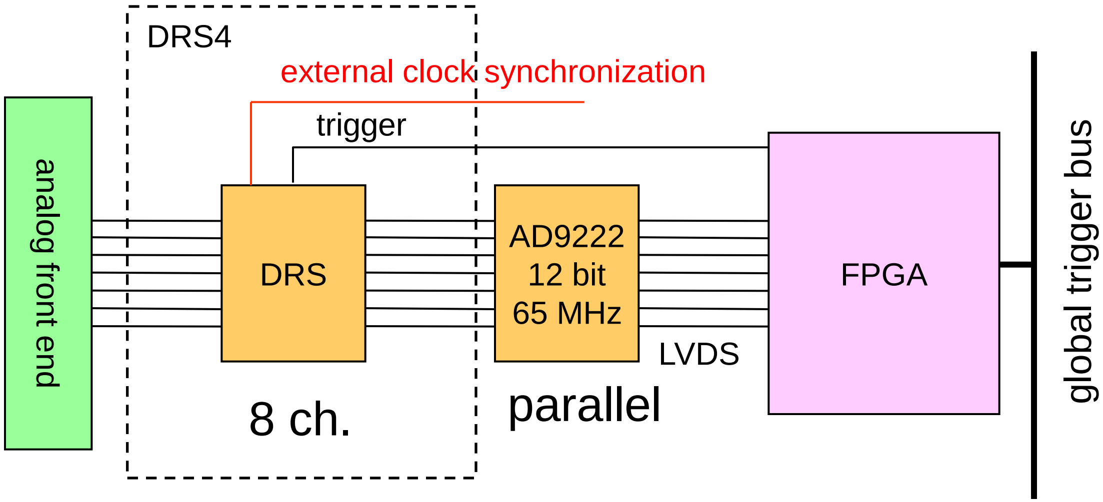
since cannot sample waveforms continuously at ~ 10 GHz rates,
use a ~ 10 GHz capacitor array to store the waveform and digitize with ~ 100 MHz ADC
(introduces some dead time ☹)

based on a circular capacitor array (1024 capacitors per channel), 12 bit resolution

sampling frequency 5 GHz (200 ps)
buffer depth 200 ns
several channels (up to 16) can be daisy chained → increase buffer depth

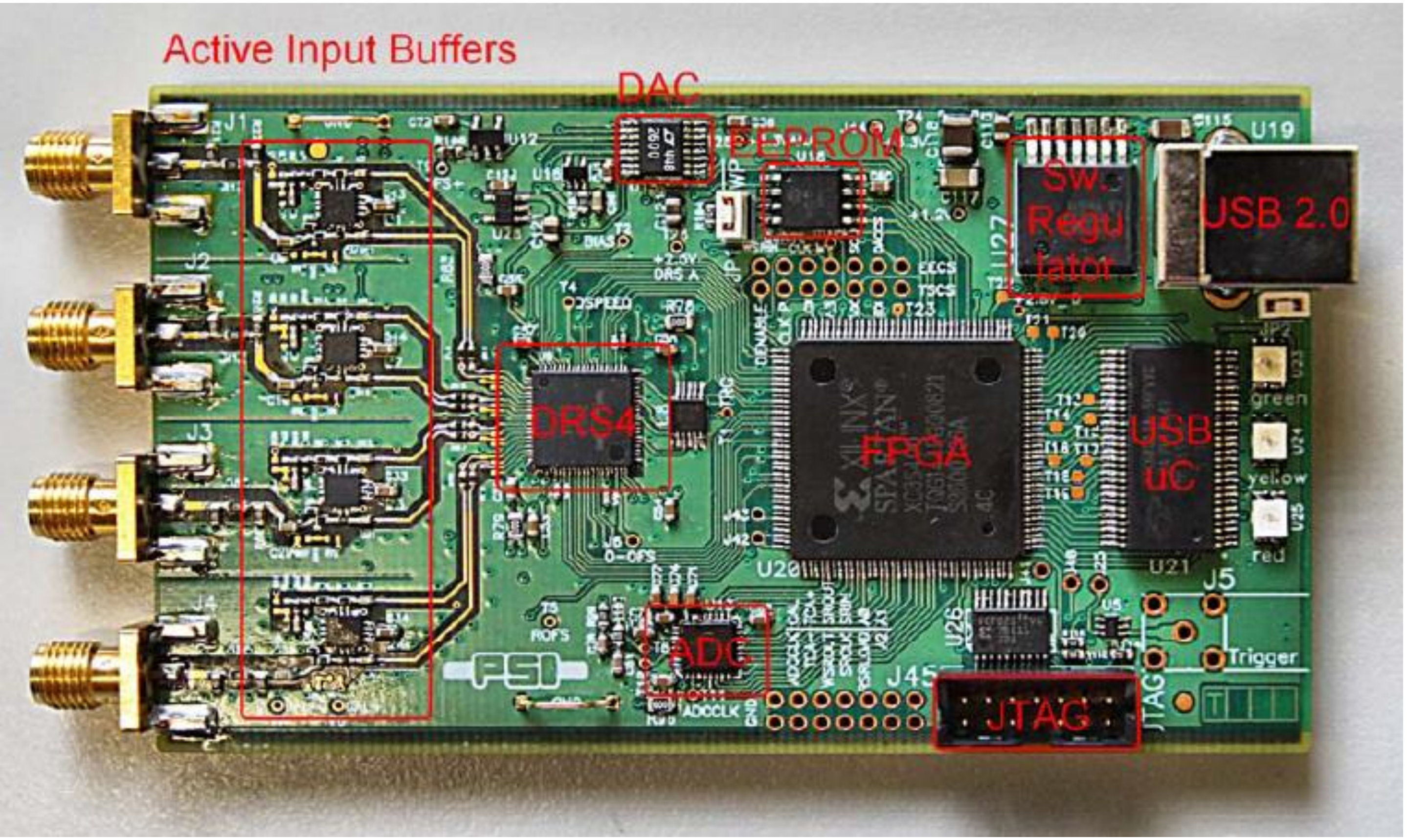
~ GHz sampling → 30 MHz conversion → 30 kHz readout (30 μs d. t.)

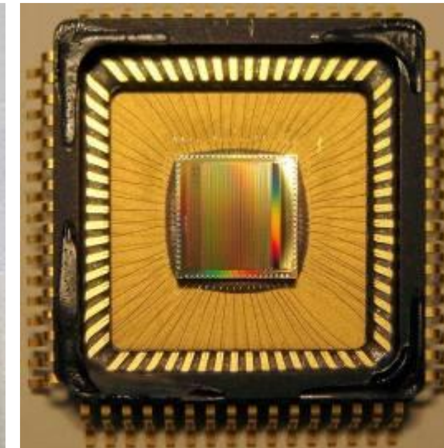
needs frequent “re” calibration in time and energy of the CSCA + synchronization

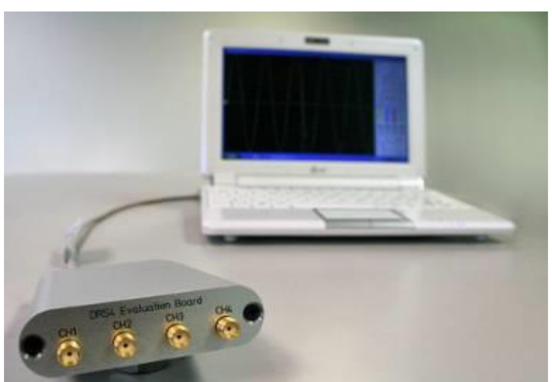


DRS4 @ PSI

http://drs.web.psi.ch







DRS4 Evaluation Board
4 channels
1-5 GSPS
12 bit
USB power

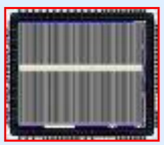
DRS Not the Only One

G. Varner, Univ. of Hawaii

E. Delagnes
D. Breton
CEA Saclay

H. Frisch et al., Univ. Chicago

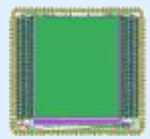
STRAW3 LABRADOR3 TARGET

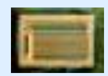


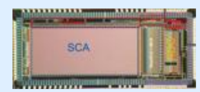
- 0.25 μm TSMC
- Many chips for different projects (Belle, Anita, IceCube …)

www.phys.hawaii.edu/~idlab/

AFTER SAM NECTAR0

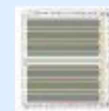






- 0.35 μm AMS
- T2K TPC, Antares, Hess2, CTA

matacq.free.fr

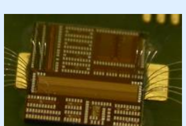


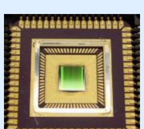
PSEC1 - PSEC4

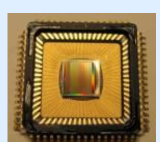
- 0.13 μm IBM
- Large Area Picosecond Photo-Detectors Project (LAPPD)

psec.uchicago.edu

DRS1 DRS2 DRS3 DRS4







2002 2004 2007 2008

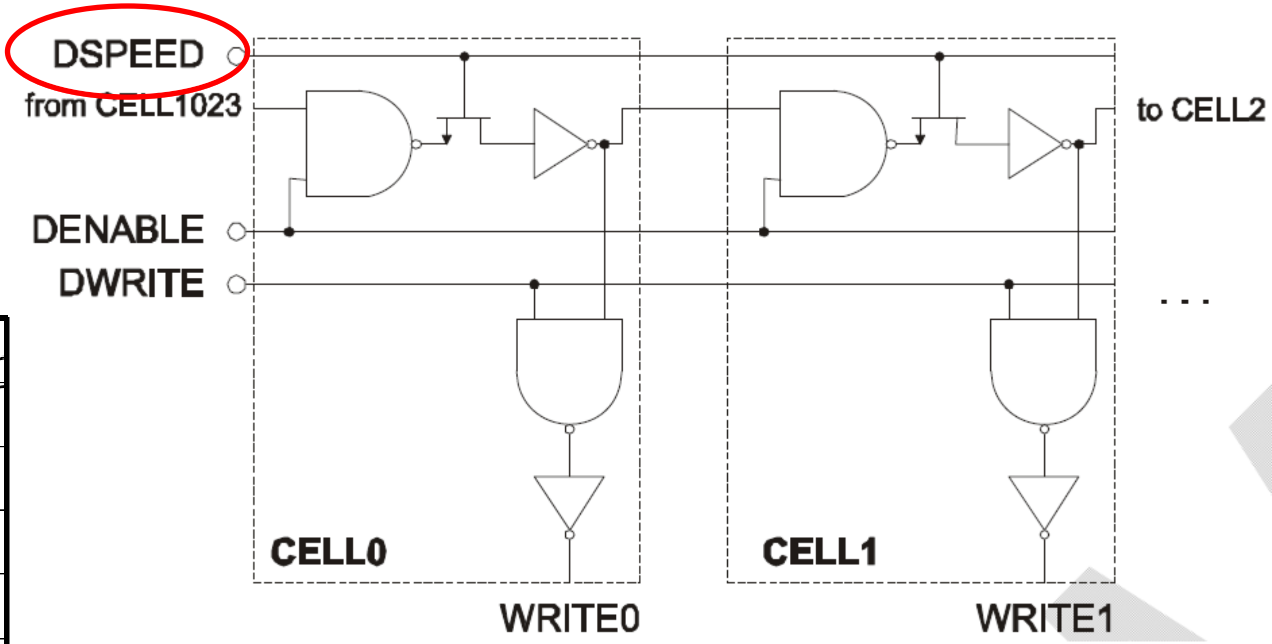
- 0.25 μm UMC
- Universal chip for many applications
- MEG experiment, MAGIC, Veritas, TOF-PET

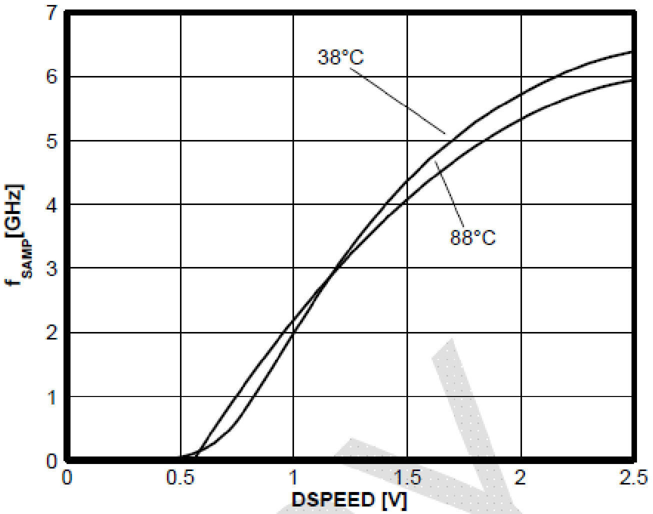
SR
R. Dinapoli
PSI, Switzerland

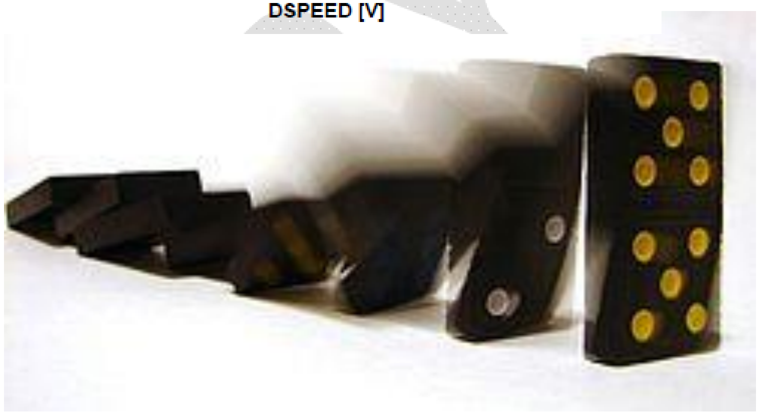
drs.web.psi.ch

Domino Wave Circuit (Digital Delay Line)

voltage regulated
- external
- internal
    via PLL locked to
    external ref. clock



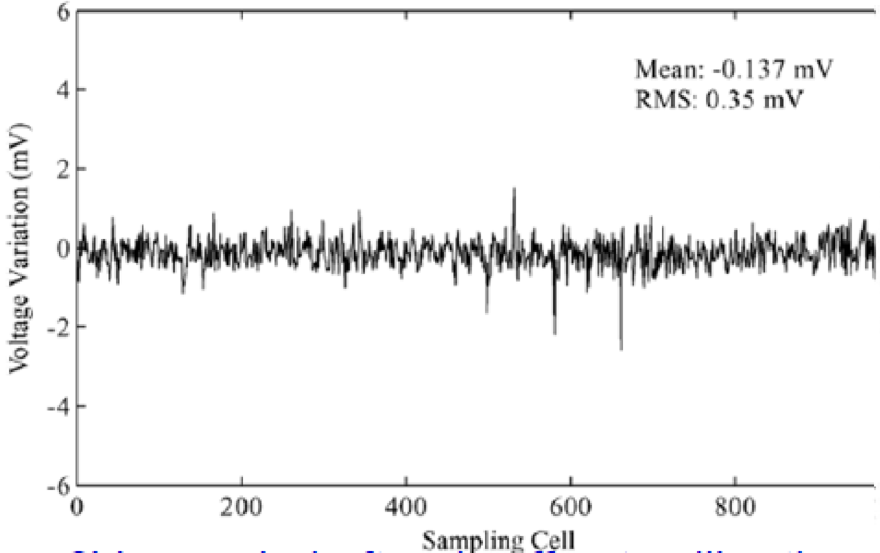




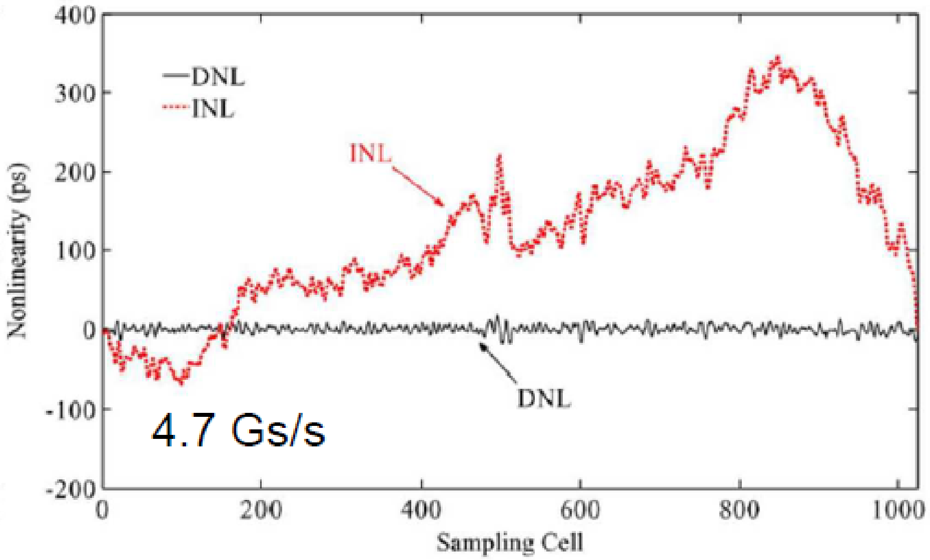
once the domino wave starts,
It continues indefinitely

the speed of the DDL can be varied
with an external control voltage
or
with an external reference clock
phase locked to the digital delay line

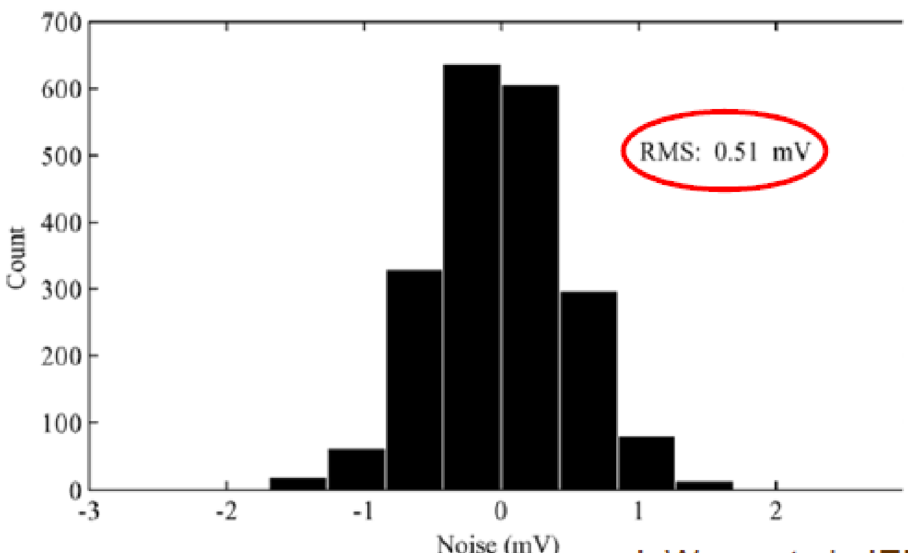
DRS NON-Linearity

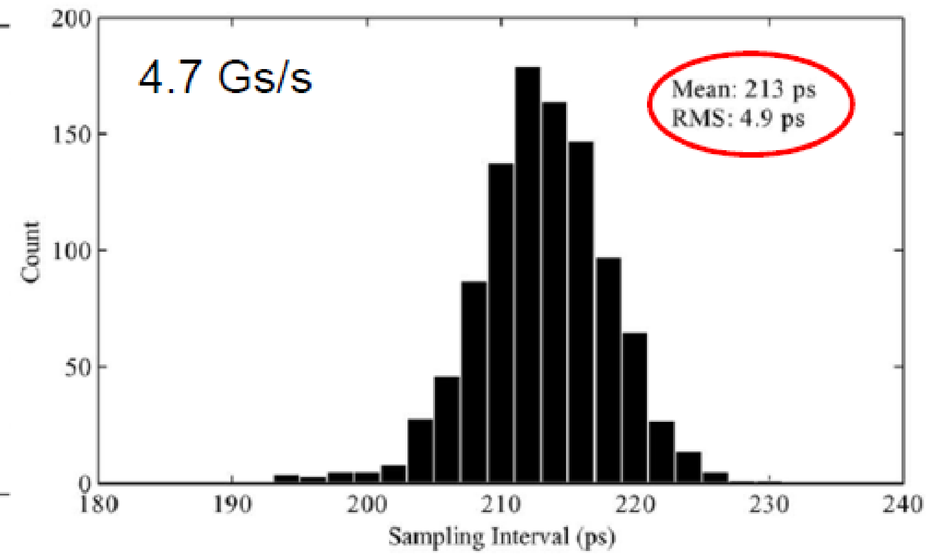


0V recorded after dc off-set calibration



timing nonlinearities

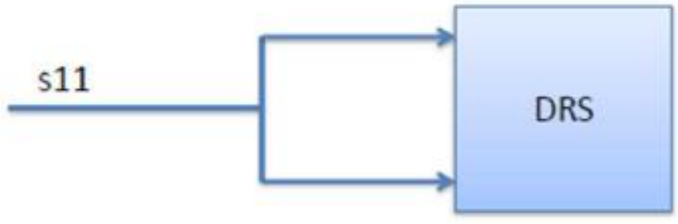




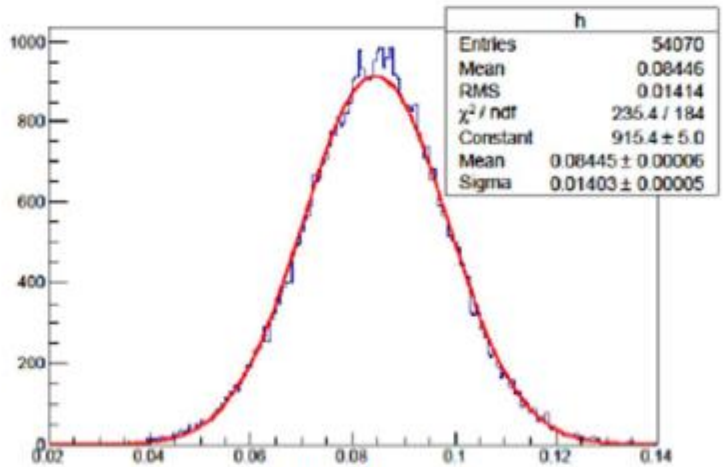
J. Wang et al., IEEE Nucl.Sci.59 (2012) 2435

Intrinsic Performance (1)

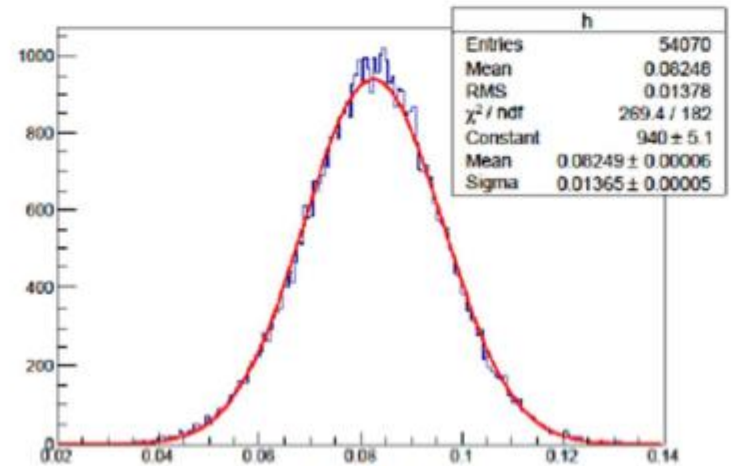
PSI TestBox Exponential Fit Algorithm



$t_1 - t_2$



Uncalibrated



Calibrated

σ = 14.0 ps

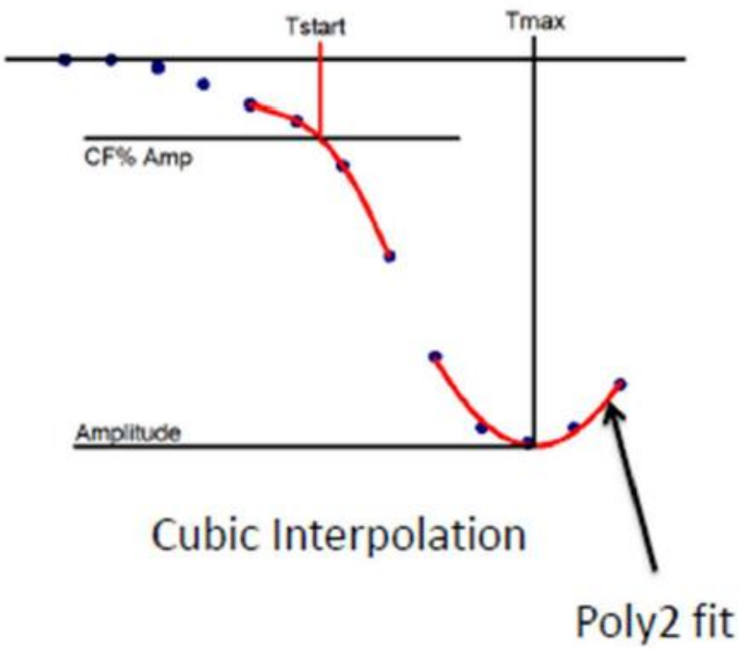
σ = 13.7 ps

with CAEN DRS module better results:

6 – 7 ps for large amplitudes
11–12 ps for small amplitudes

Constant Fraction Algorithms

We observed that simple implementations of the Constant Fraction Algorithm with linear extrapolation do not work …
while fitting the whole waveform is not possible in real life
(for an ideal circuit one can calculate the waveform)



algorithm used:

1. determine max amplitude

   cubic interpolation around the max ampli

2. exponential fit of the leading edge

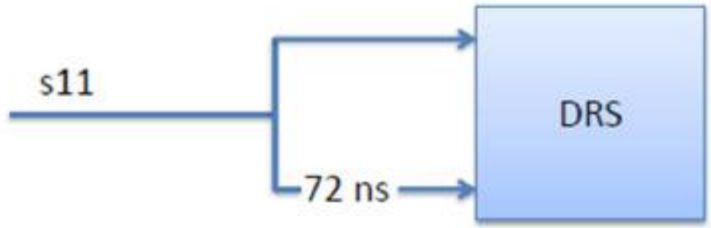
3. def. const. fract. of max. ampli.

   and project on time axis

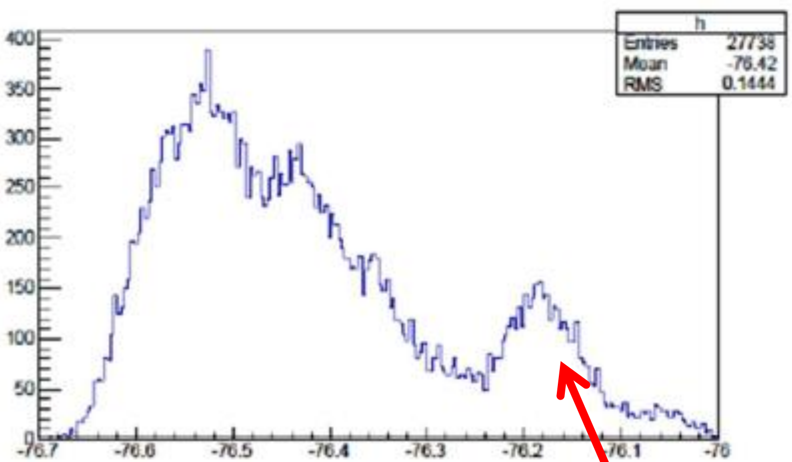
resolution depends on CF

Intrinsic Performance (2)

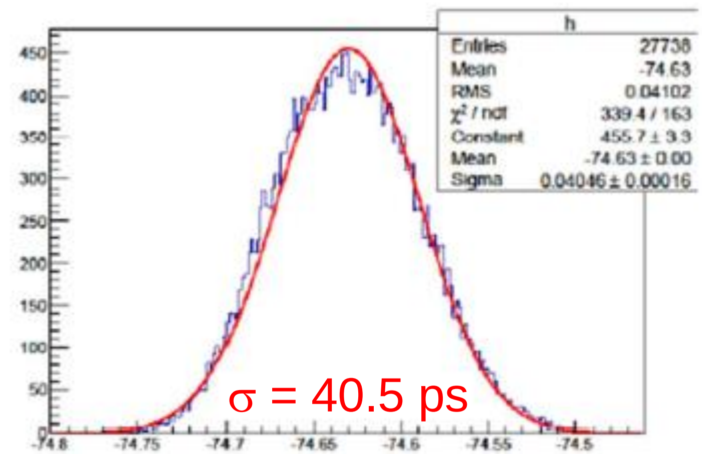
PSI TestBox Exponential Fit Algorithm



$t_1 - t_2$



Uncalibrated



Calibrated

if the two signals are separated in time
1st signal 1st DRS cycle,
2nd signal 2nd DRS cycle
with ~70 ps delay, ~ 30% fall in 2nd cycle

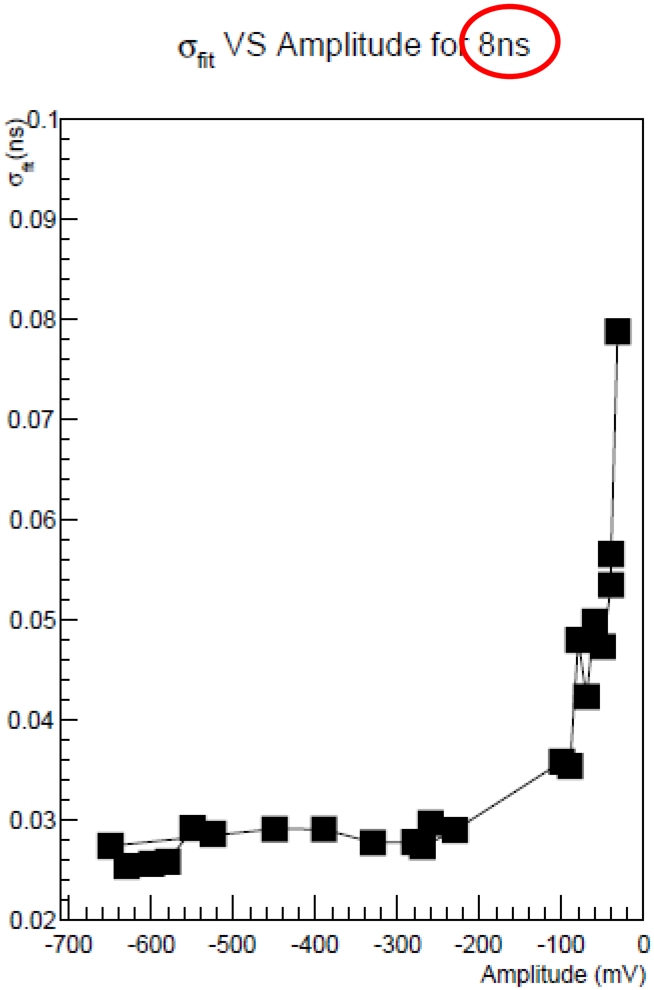
even though the digital delay line is common to all channels in the chip, the capacitor arrays are not uniform
$\Rightarrow$ must calibrate channel by channel

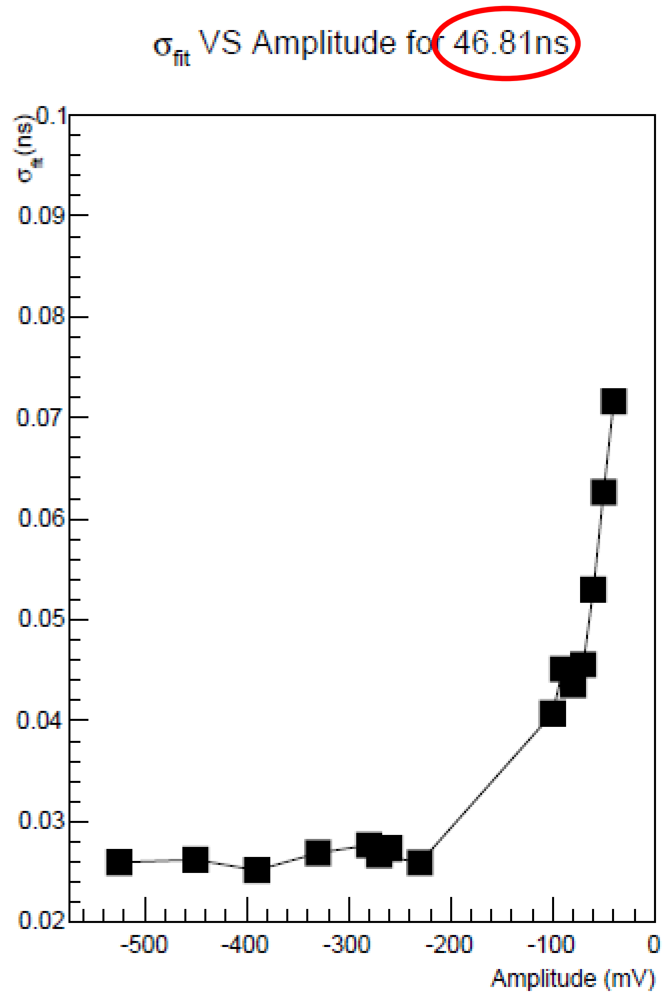
Intrinsic Performance (3)

calibration procedure :

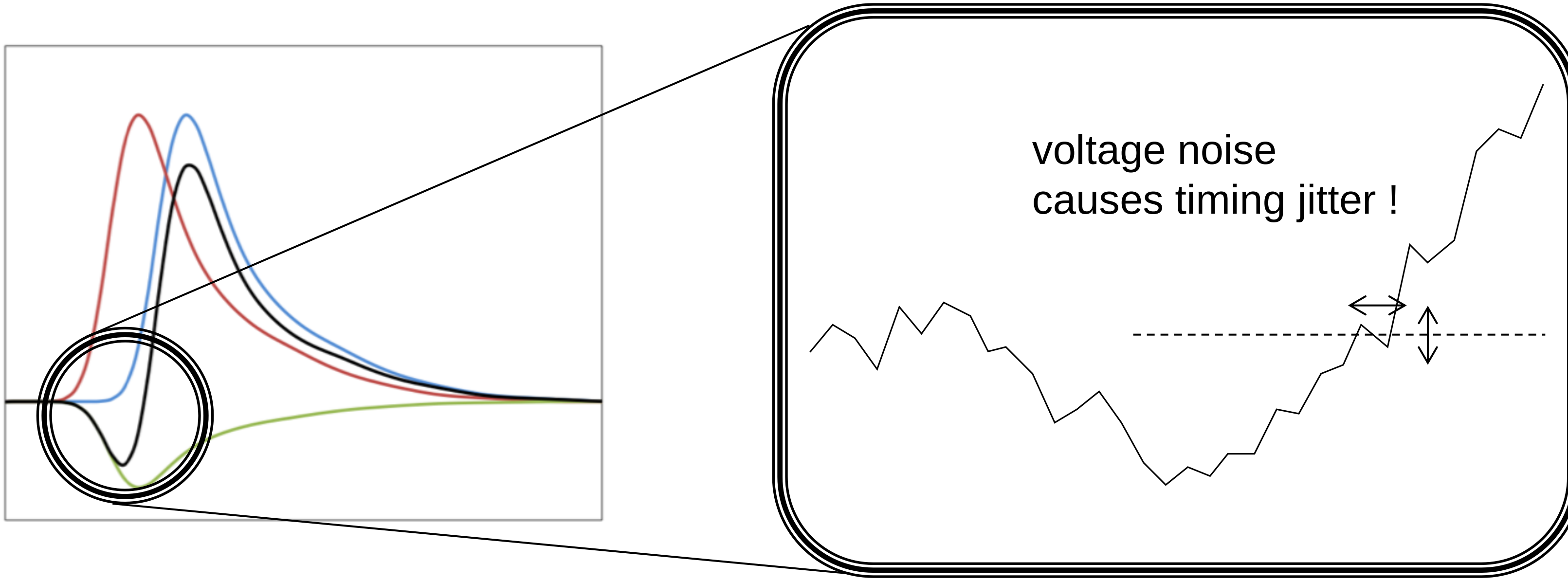
require same rise time for all signals

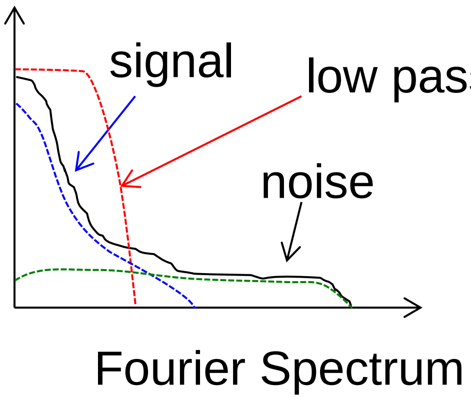
(almost equivalent to channel by channel calibration)

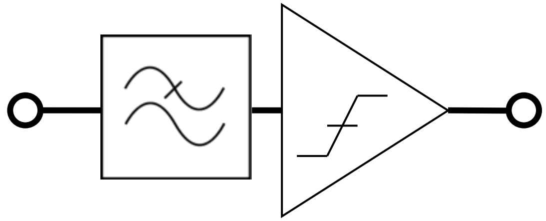


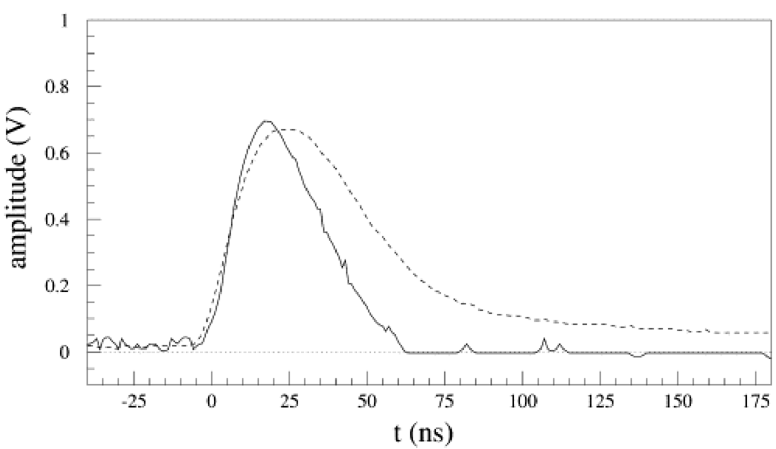


Influence of Noise



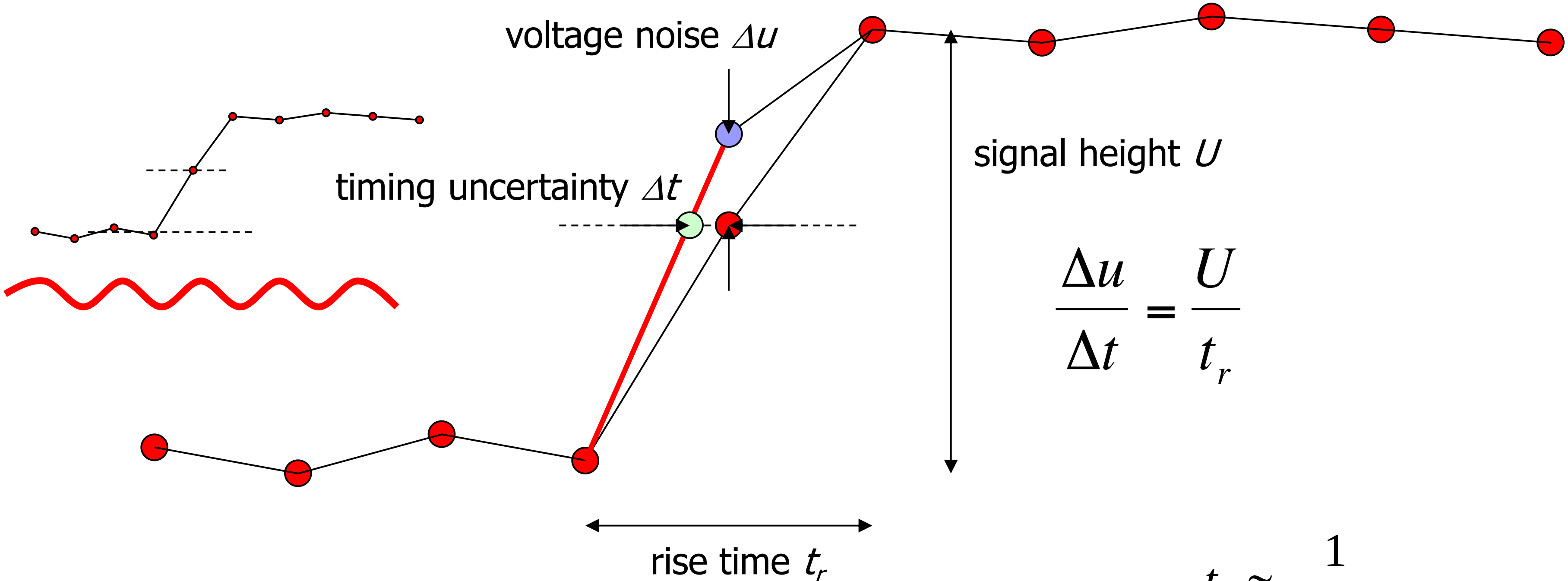






low pass filter (shaper) reduces noise while maintaining most of the signal

Influence of Noise (2)



$$\frac{\Delta u}{\Delta t} = \frac{U}{t_r}$$

$$t_r \approx \frac{1}{3 f_{3dB}}$$

$$\Delta t = \frac{\Delta u}{U} \cdot t_r \Rightarrow \frac{\Delta u}{U\sqrt{n}} \cdot t_r = \frac{\Delta u}{U} \cdot \frac{t_r}{\sqrt{t_r \cdot f_s}} = \frac{\Delta u}{U} \cdot \frac{\sqrt{t_r}}{\sqrt{f_s}} = \frac{\Delta u}{U} \cdot \frac{1}{\sqrt{3 f_s \cdot f_{3dB}}}$$

number of samples on slope

simplified estimation!

Calibration

new time calibration :

calibrate each channel individually

⇒ new calibration scheme (internal and external)

⇒ new design of input stage

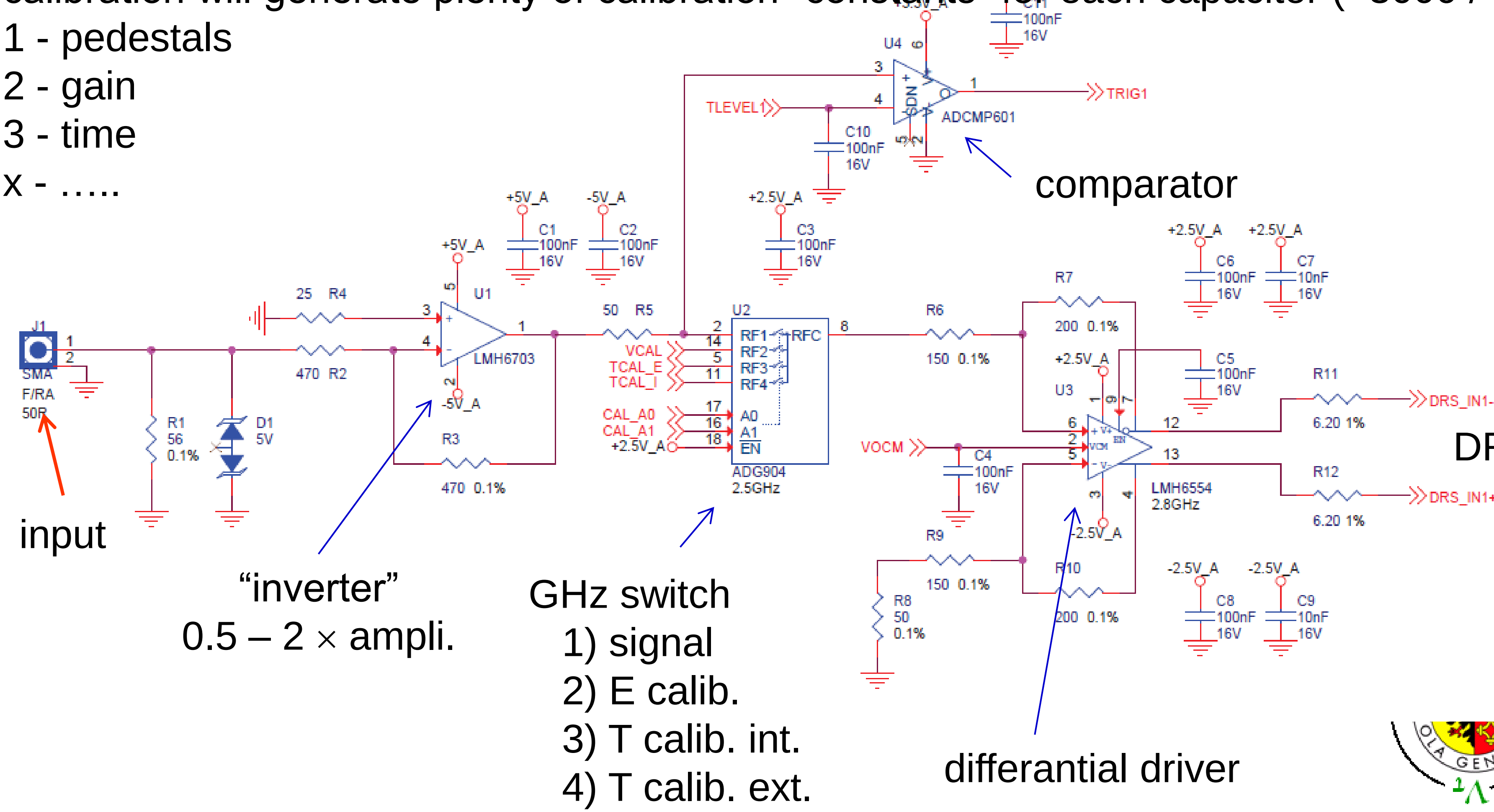
calibration will generate plenty of calibration “constants” for each capacitor (>3000 / ch.)

1 - pedestals

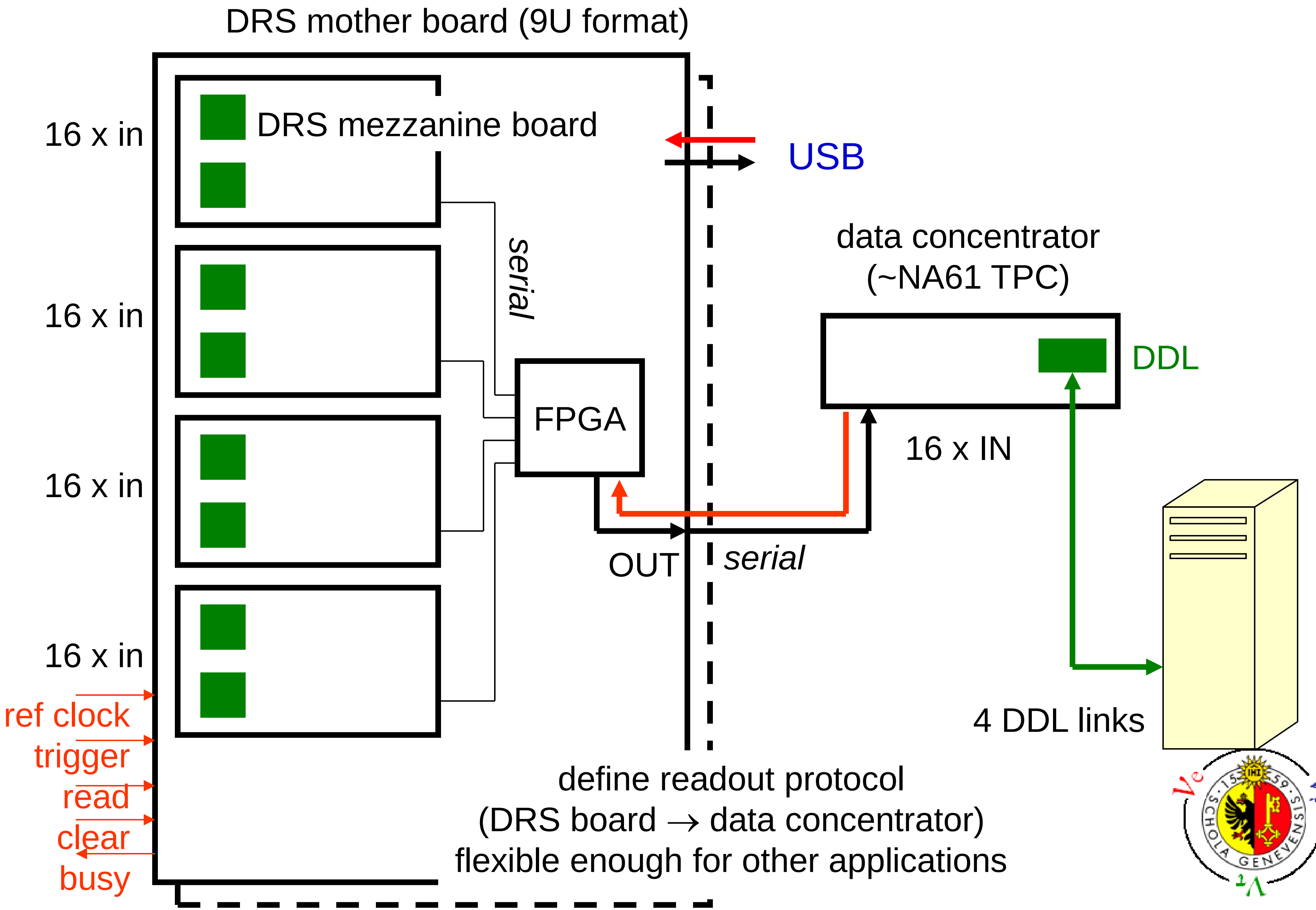
2 - gain

3 - time

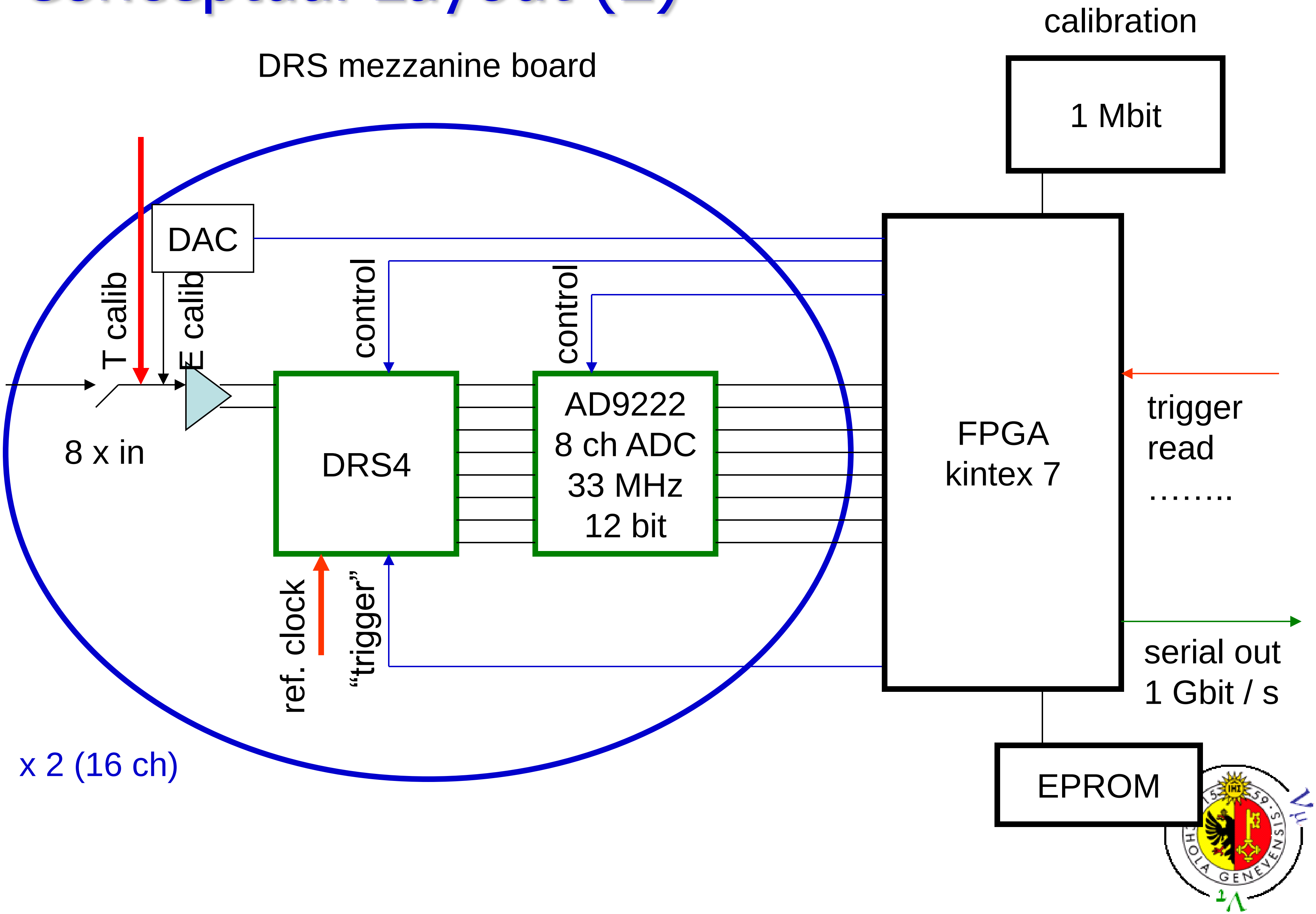
x - …..



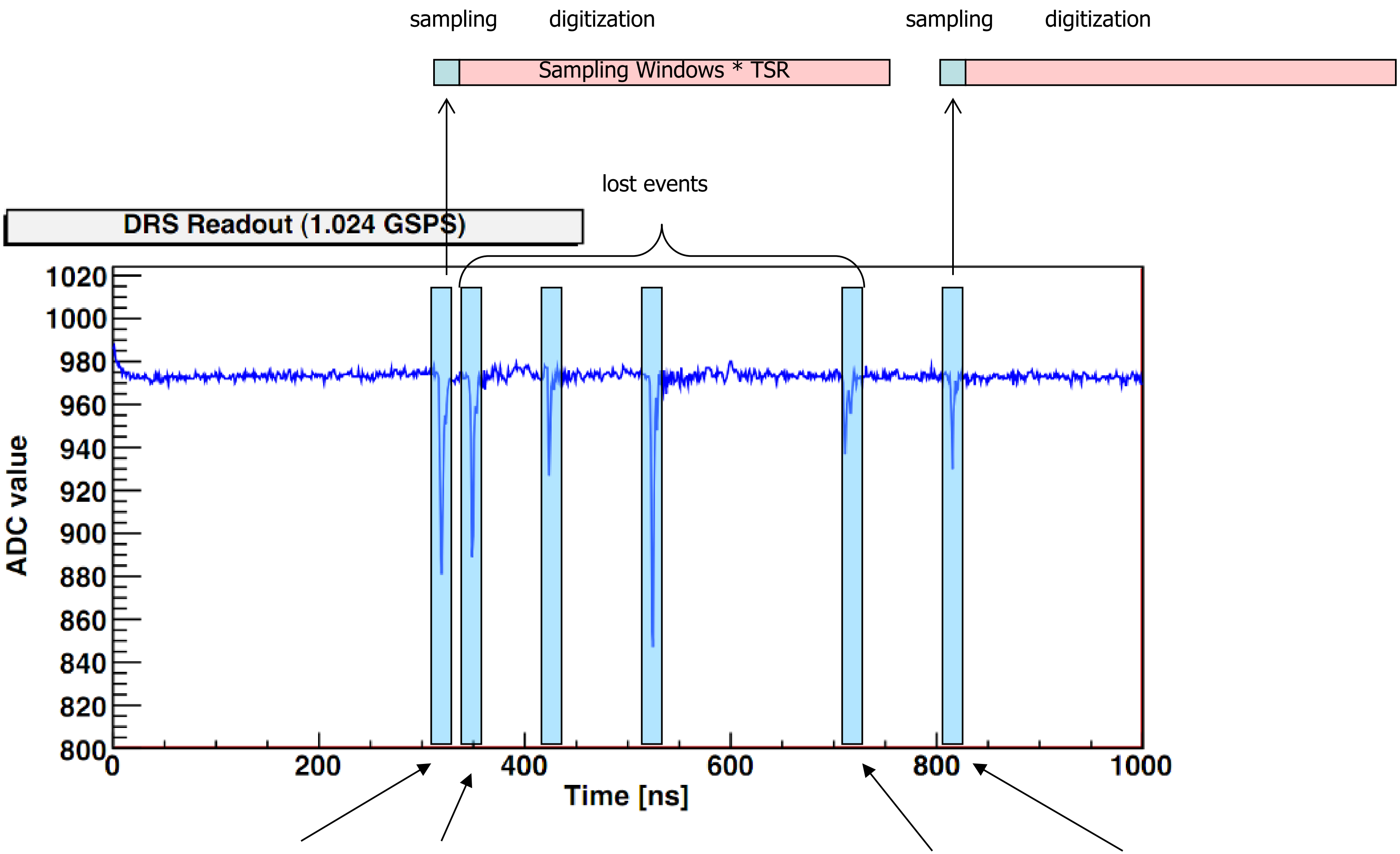
Conceptual Layout



Conceptual Layout (2)



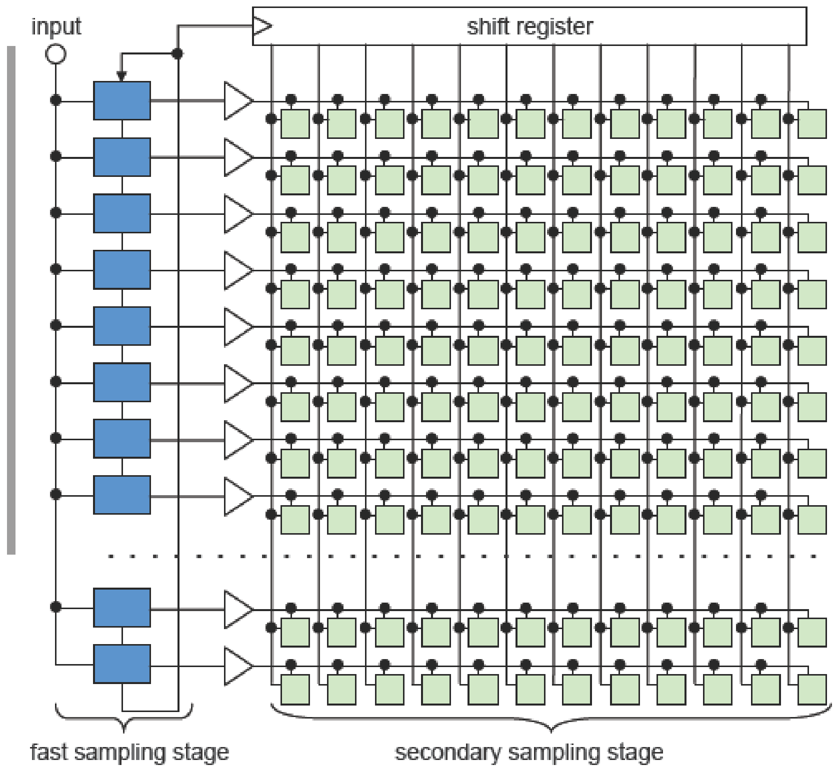
The Dead Time Issue

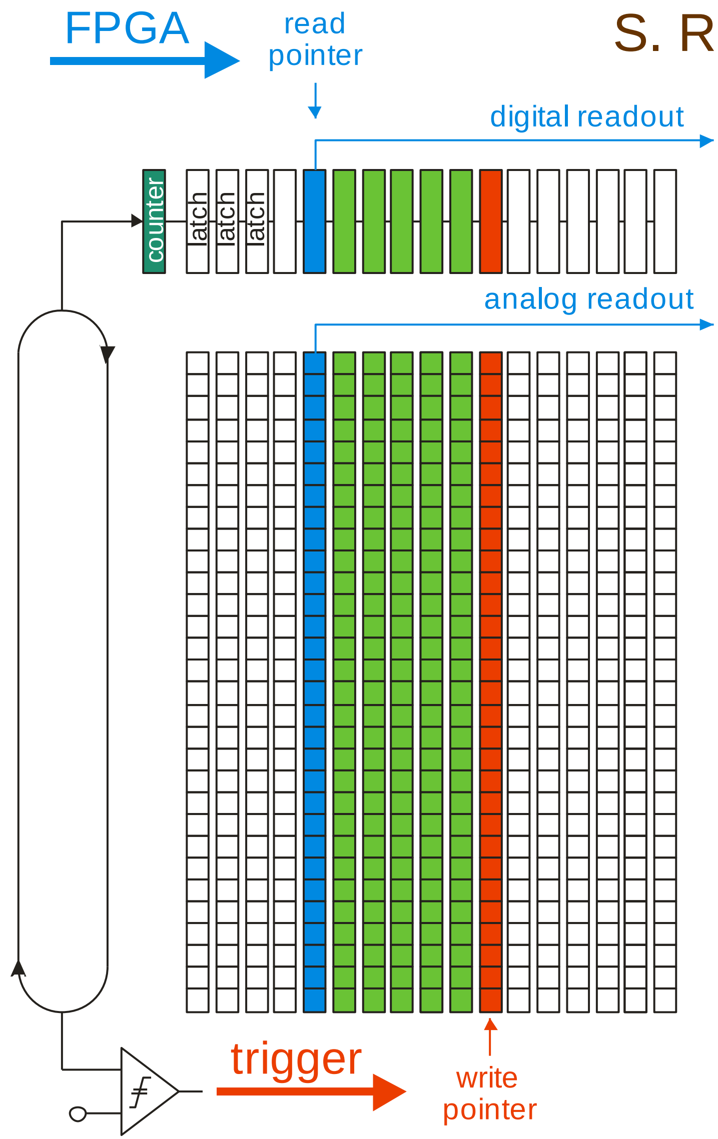


Only short segments of waveform are of interest

The DRS5 Digitizer

S. Ritt





100 ps sample time. 3.1 ns hold time

2 better timing resolution

data driven readout

dead-time-less waveform digitizing

2 MHz sustained event rate

planned for > 2014

Outlook

Completed energy scan for p + p interactions

Large stat for p + Pb underway

Completed energy scan for ^{7}Be+^{9}Be interactions

Inelastic cross-section for ^{7}Be+^{9}Be collisions at 13 to 30*A* GeV/c

Pion spectra in central ^{7}Be+^{9}Be collisions at 40 to 150*A* GeV/c

Hadron spectra in inelastic p+p interactions at 20 to 158 GeV/c

Several upgrades completed or underway (including the DRS)

Highest priority to proceed with ion program: Ar (2015), Xe (2017)

Possible extension of program to Pb+Pb energy scan
with open charm measurements