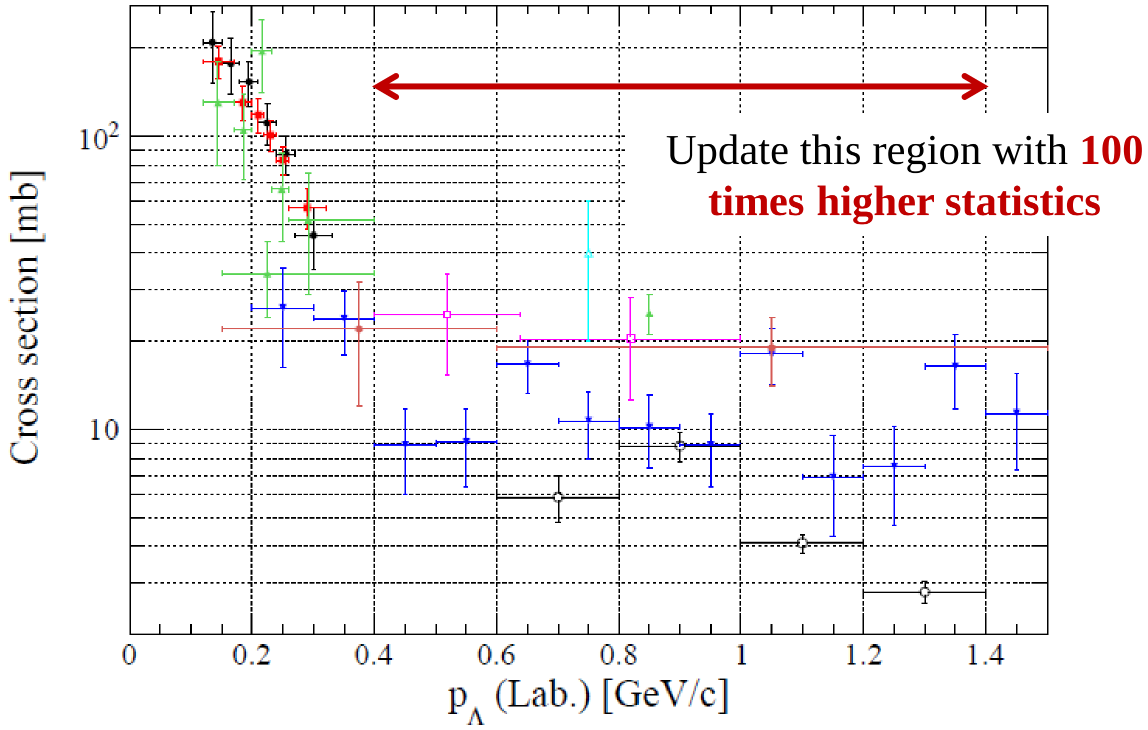
Development of beam TOF system for high statistic Λp scattering experiment

KEK IPNS E-sys
本多良太郎

2023.02.10
新学術領域研究「量子クラスターで読み解く物質の階層構造」
第8回クラスター階層領域研究会

Introduction

Total cross sections of Λp → Λp measured so far.



Our aim

Measure precisely the cross sections of Λp scatterings in the momentum range between 0.4 and 1.4 GeV/c

100 times higher statics of past experiments for

- **Total cross section**
- **Differential cross section**

for each 0.1-GeV/c momentum region

Study of two-body ΛN interaction by **scattering experiment**

Approach to the hyperon puzzle of neutron star

Collaborate with

- B01 ストレンジ・ハドロンクラスター
- A02 クォーククラスター

[1] Phys Rev 175, 1735 (1968).
[2] Phys Rev Lett. 13, 282 (1964).
[3] Phys Rev. 173, 1452 (1968).
[4] Nucl. Phys. B27, 13 (1971).
[5] Phys Rev. 129, 1372 (1963).
[6] Phys. Rev. Lett. 7, 348 (1961).
[7] Phys. Rev. Lett. 2, 174 (1959).
[8] J. Rowley, K. Hicks, and John Price: Talk in 52nd Reimei workshop.

Overview of this experiment

Double scattering experiment.

- $\pi^{-}p \rightarrow K^{*}(892)^{0}\Lambda,\ K^{*}(892)^{0} \rightarrow K^{+}\pi^{-}$
- $\Lambda p \rightarrow \Lambda p$

Beam condition

- Intensity: 60 M/spill
- Momentum: 8.5 GeV/c

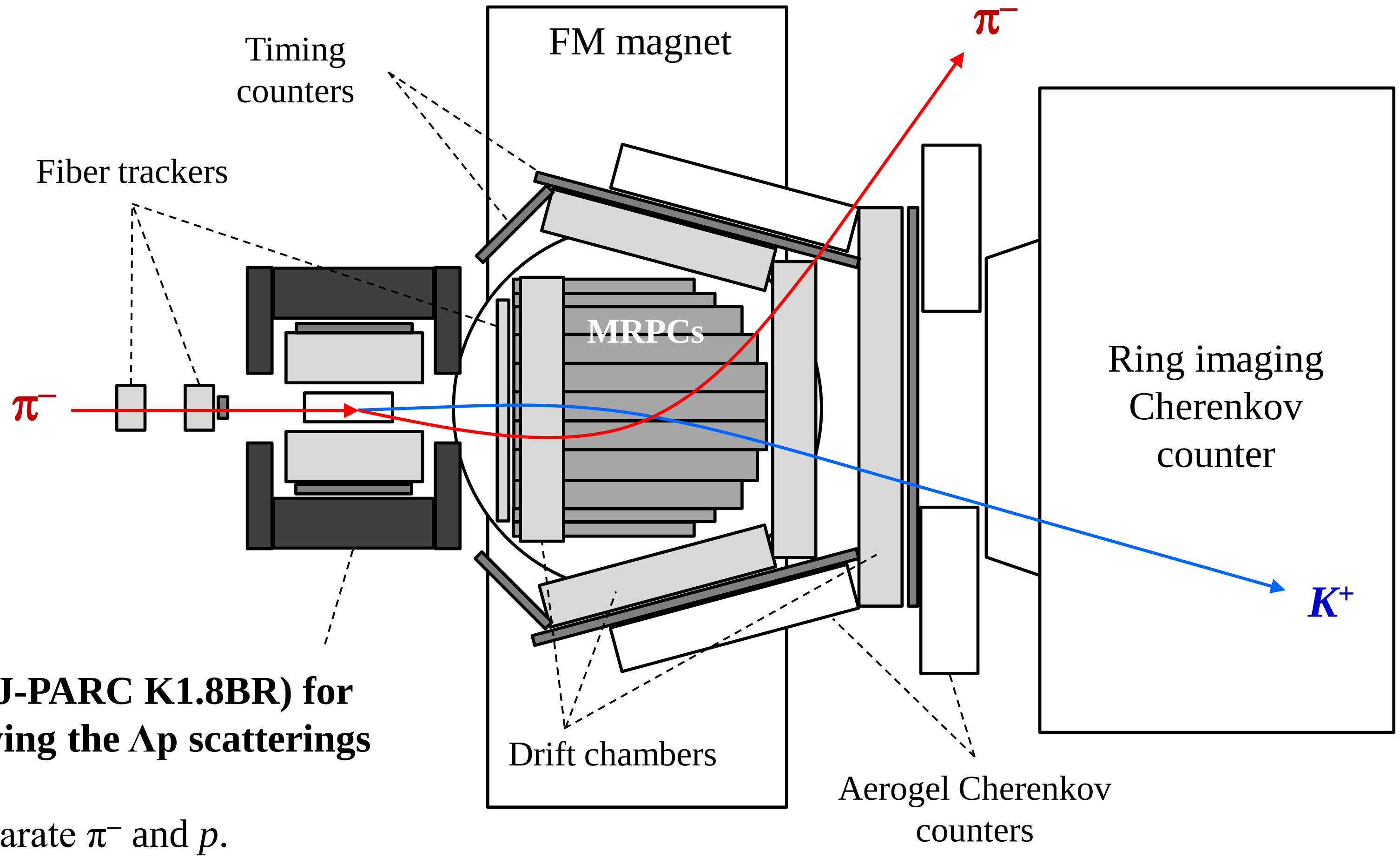
Experimental target

- Liquid hydrogen
- 100 mm in diameter
- 570 mm in length

Spectrometer system

- Missing mass resolution 16 MeV/c^2
- Reconstruction efficiency 66%

Experimental setup of the J-PARC E50 experiment.
(Charmed-baryon spectroscopy)



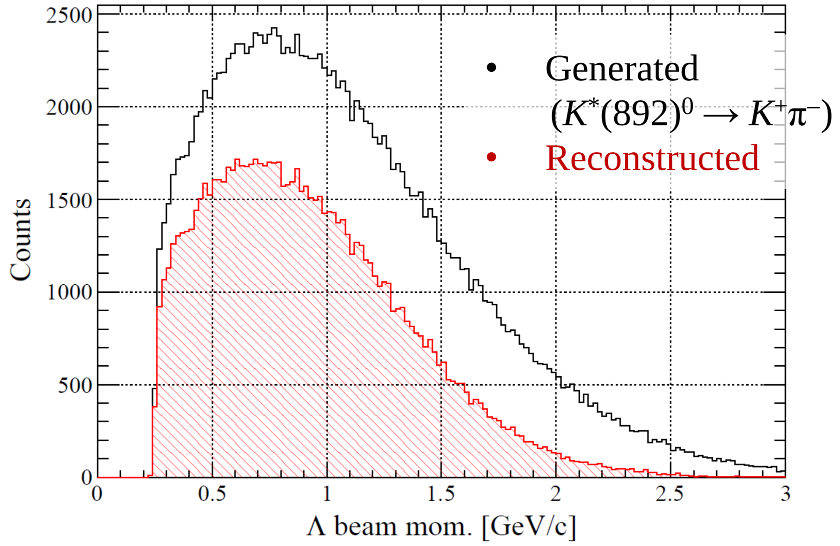
CDS (J-PARC K1.8BR) for identifying the Λp scatterings

Requirements

- PID to separate π^{-} and *p*.
- Momentum analysis to reconstruct Λ.

Reconstruction efficiency

Momentum distribution of the Λ beams (simulated)

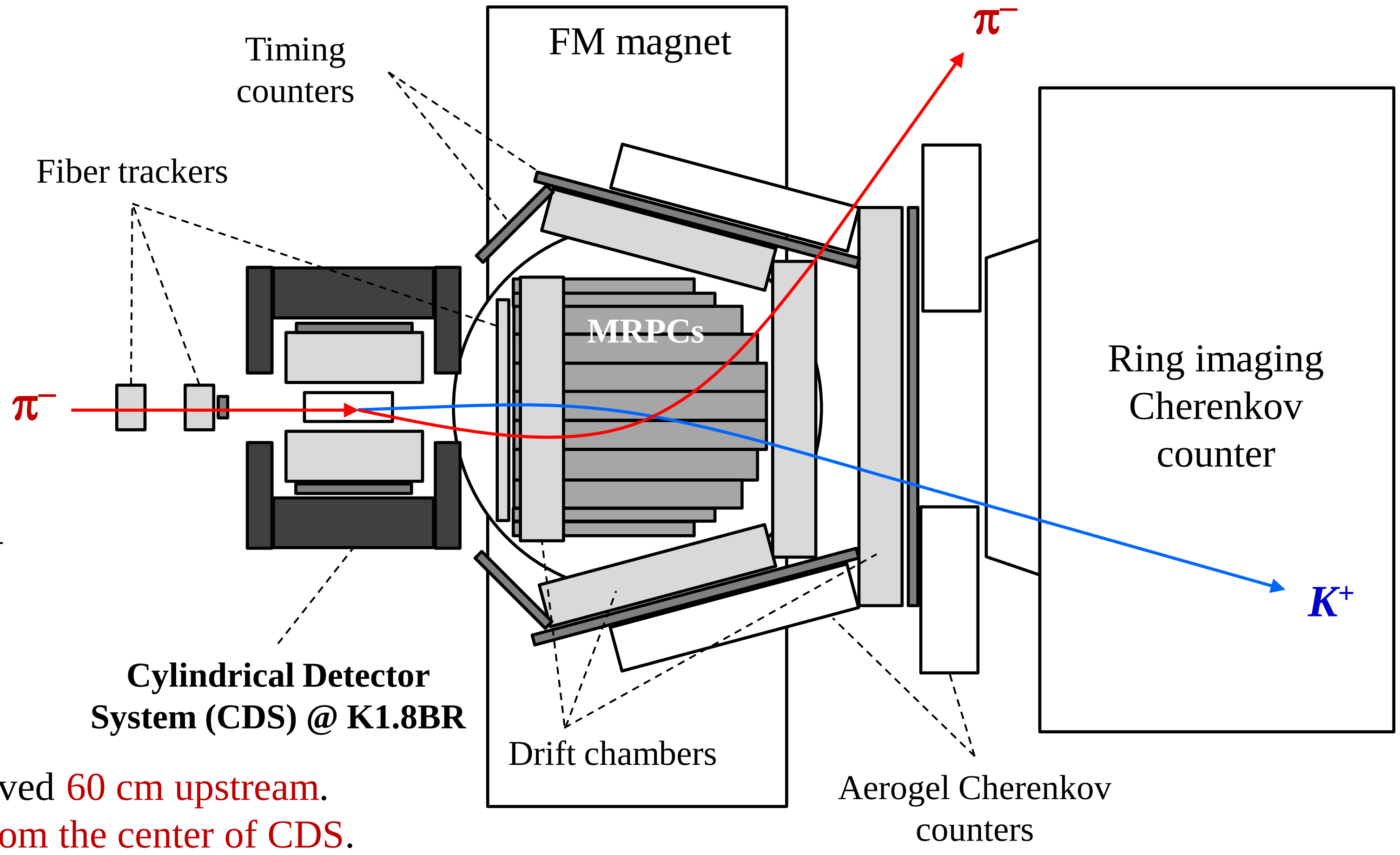


***Angular distribution of the $\pi^- p \to K^*(892)^0\Lambda$ reaction is taken into account

Reconstruction efficiency for $K^*(892)^0 \to K^+\pi^-$

66%

Experimental setup of the Λp scattering experiment



Beam detectors and the target are moved 60 cm upstream.
The target is moved 20 cm upstream from the center of CDS.
End guard hole size 30 mm (φ) → 40 mm (φ)

Aim of this Grant

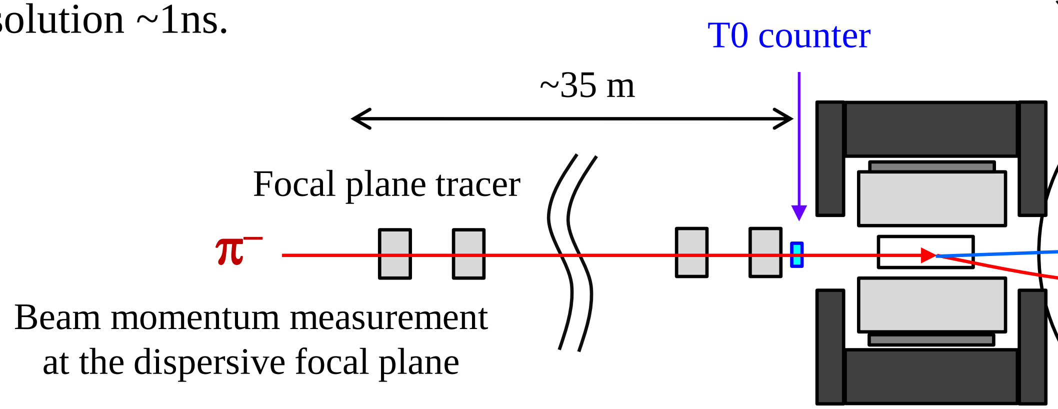
Detector system of the E50 experiment

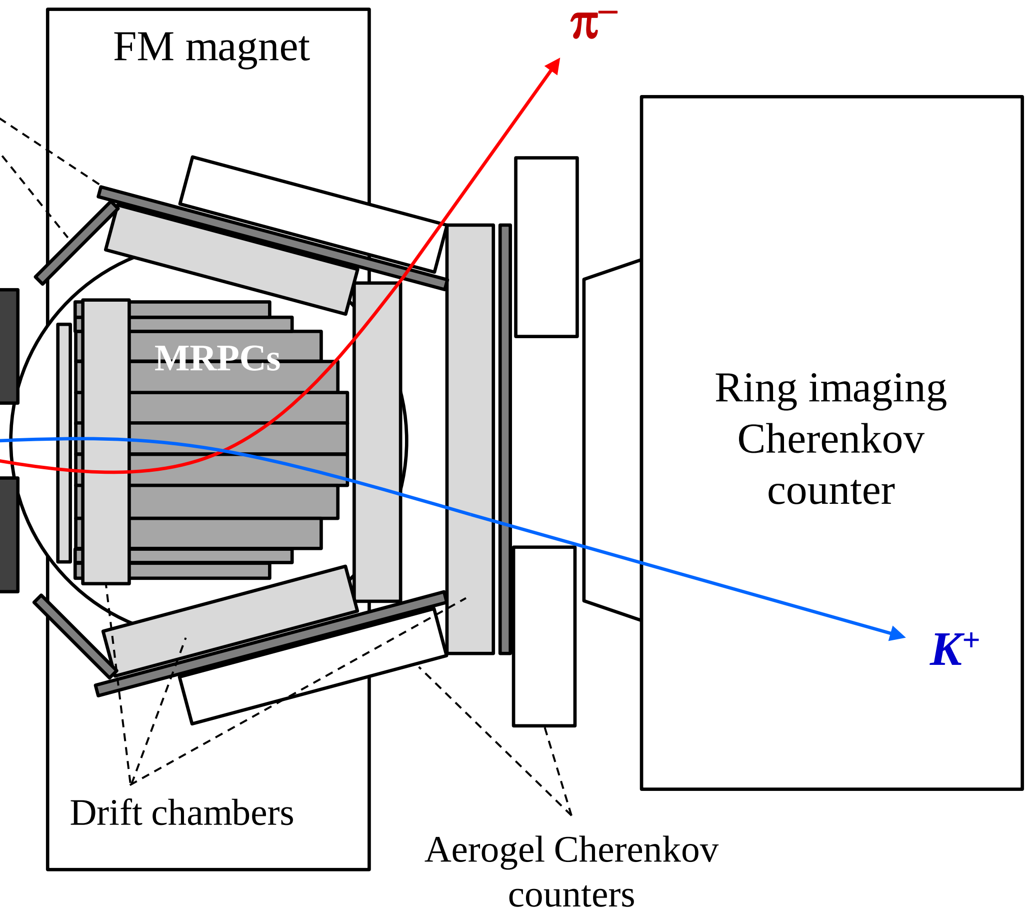
Probability of finding 2 particles in a 10 ns bin.
(Effect of transverse-RF is roughly taken into account)

- $p \sim 0.27$

These two are not distinguishable for the fiber detector having the timing resolution ~1ns.

Experimental setup for the Λp scattering





We need to connect the tracks at the dispersive focal plane and at the target to calculate the missing mass.

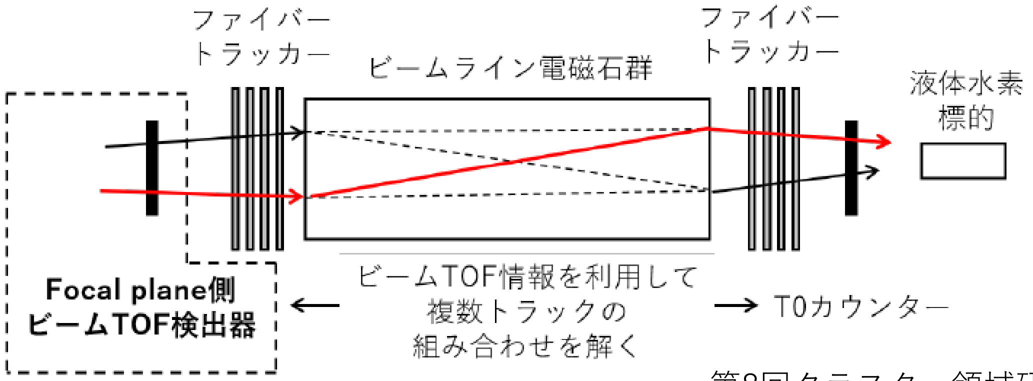
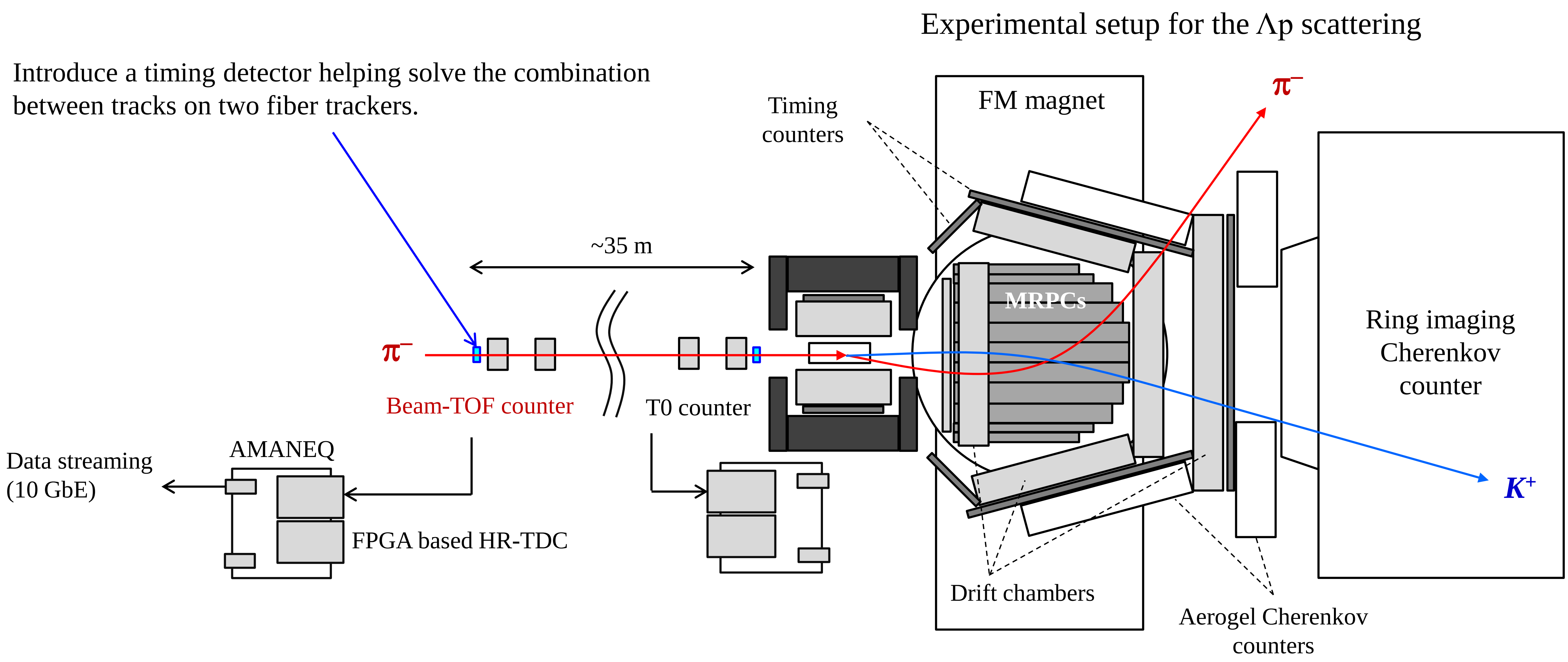


図1：ビーム運動量測定の概略図

Detector system of the E50 experiment

Introduce a timing detector helping solve the combination between tracks on two fiber trackers.



Aim of this Grant

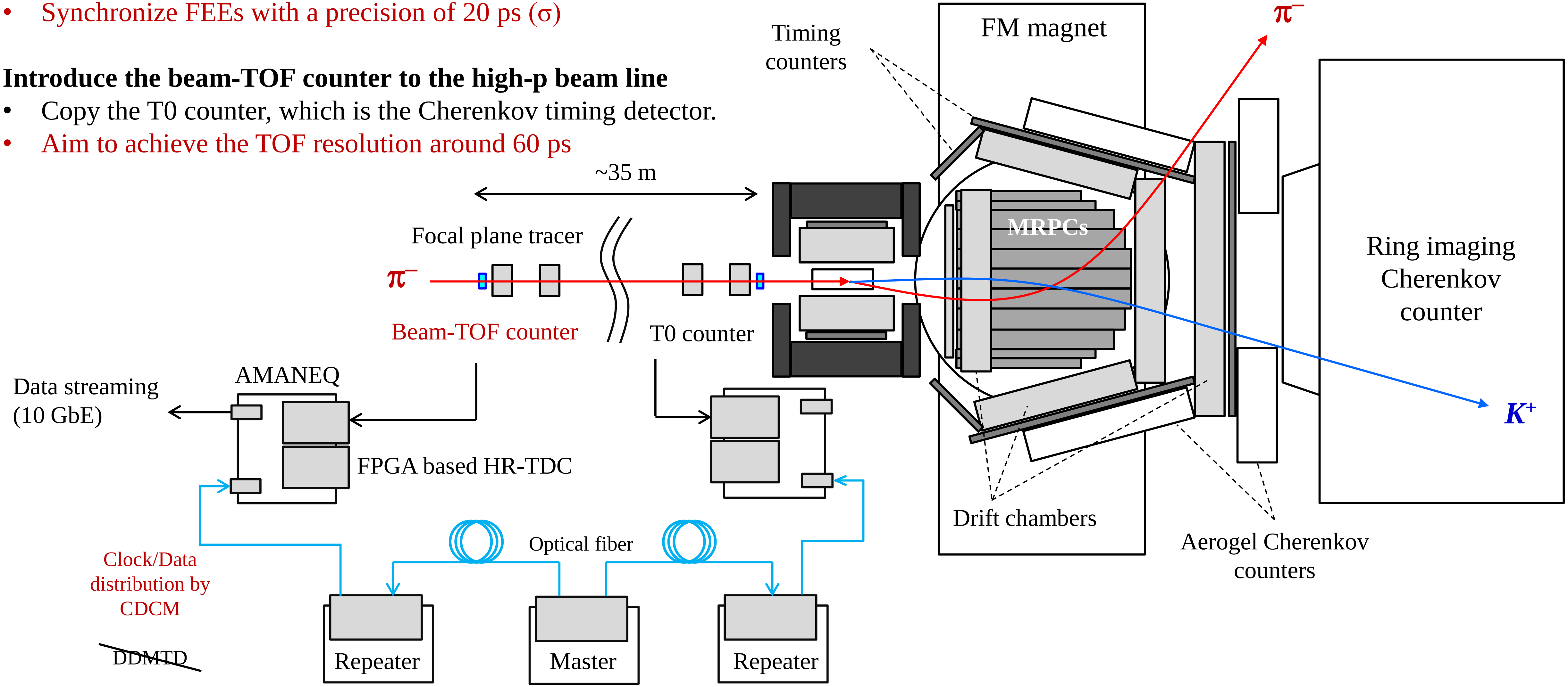
Develop the clock/data distribution system using AMANEQ

- Adopt Clock-Duty-Cycle-Moduration
- Synchronize FEEs with a precision of 20 ps (σ)

Introduce the beam-TOF counter to the high-p beam line

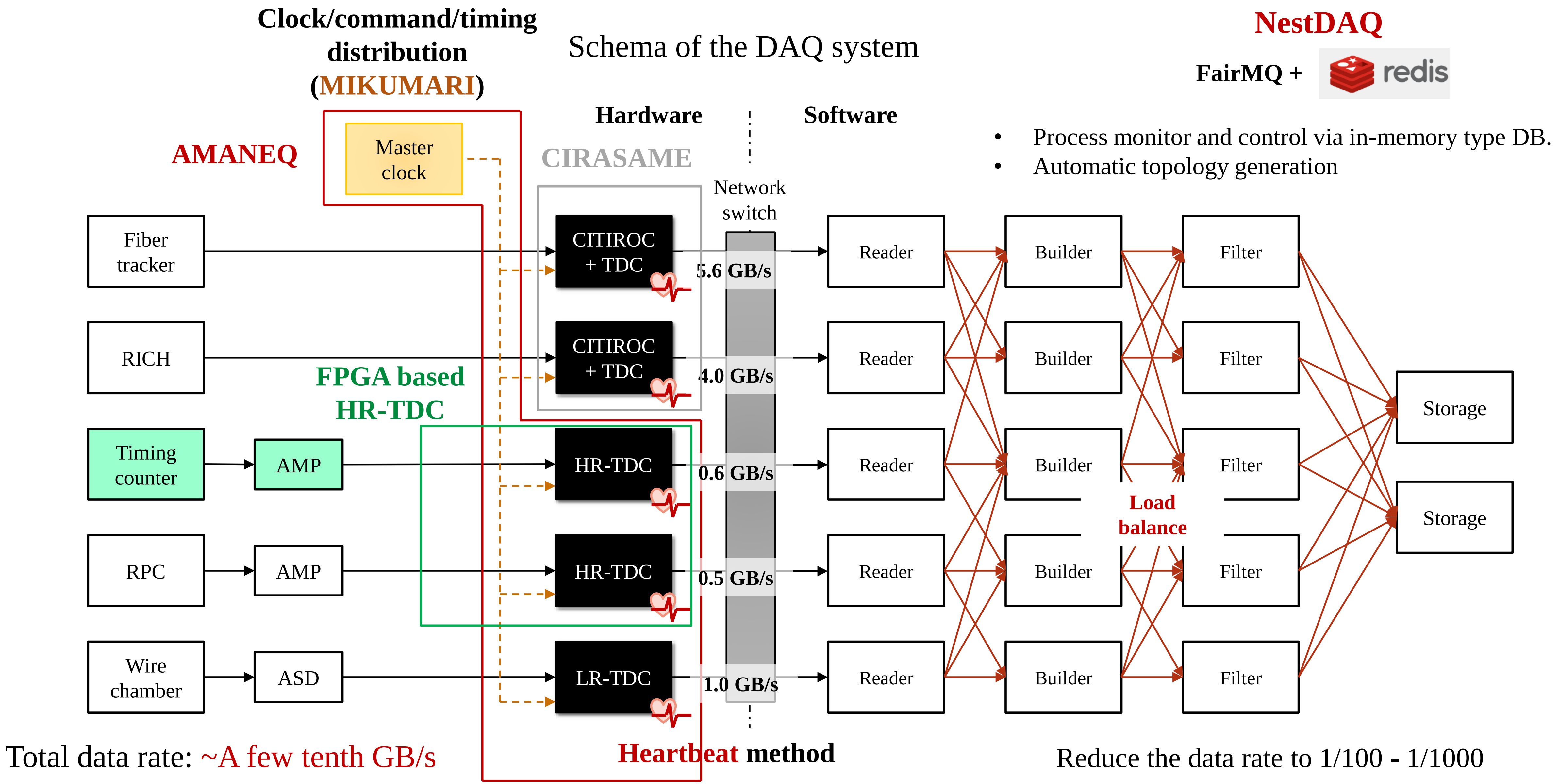
- Copy the T0 counter, which is the Cherenkov timing detector.
- Aim to achieve the TOF resolution around 60 ps

Experimental setup for the Λp scattering



Clock/command distribution system by AMANEQ

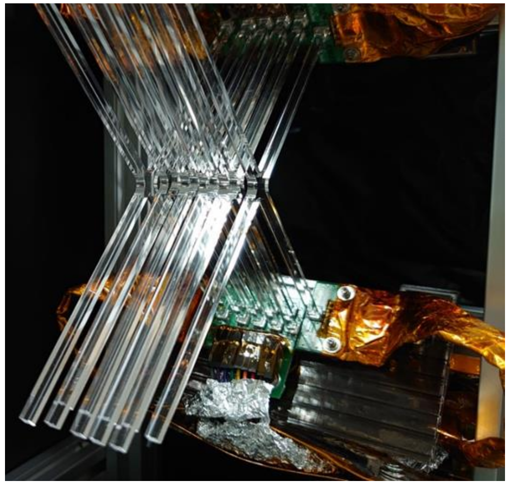
Trigger-less data-streaming-type DAQ system

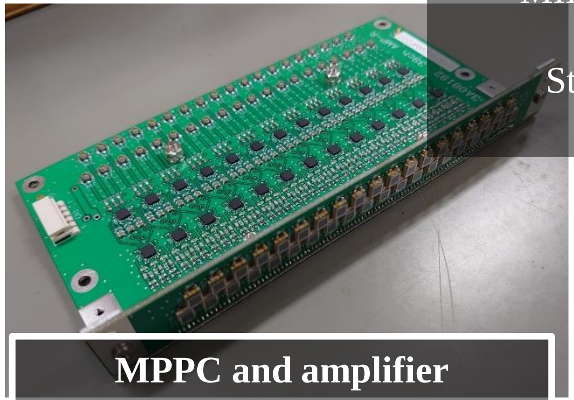


Developed items

Detector

Acrylic Cherenkov radiator
(Bought by this Grant)



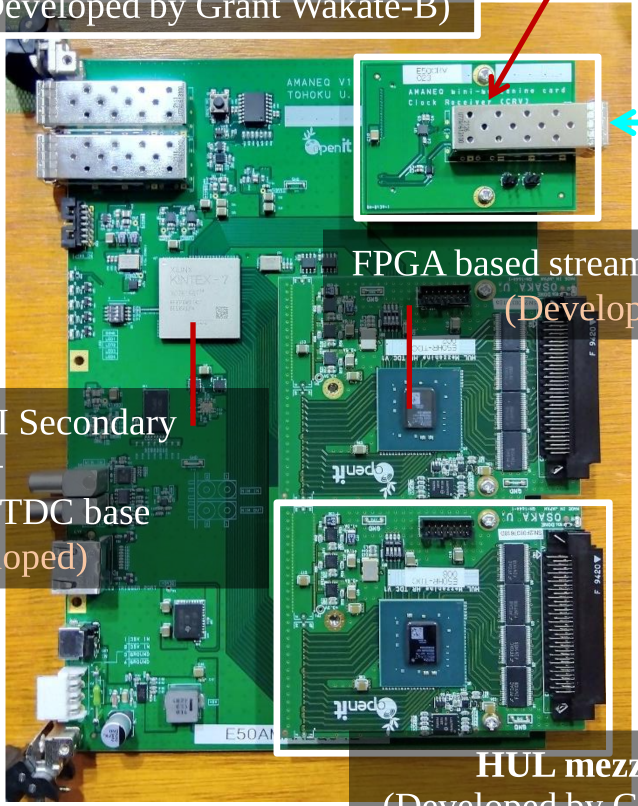


MPPC and amplifier
(Bought by this Grant)

Readout system for trigger-less DAQ system

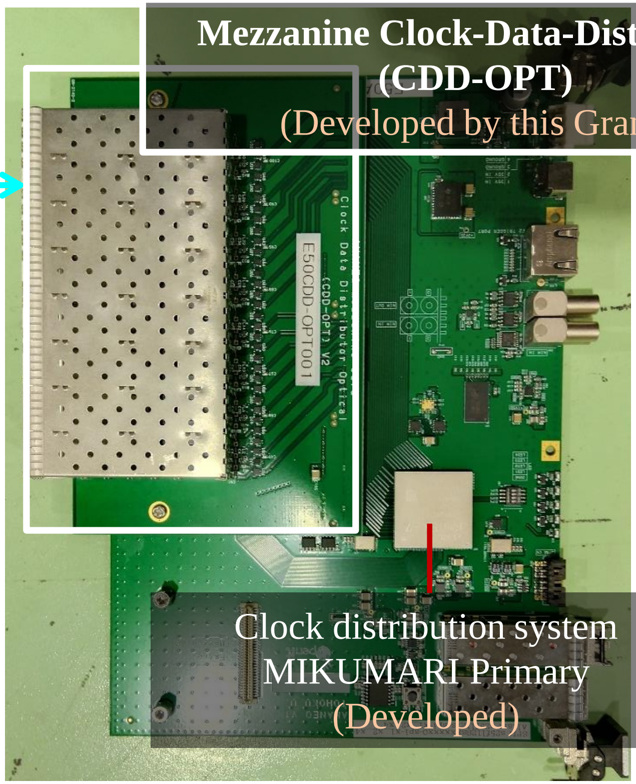
Mini-mezzanine Clock-Receiver (CRV)
(Developed by this Grant)

AMANEQ
(Developed by Grant Wakate-B)



Optical fiber

Mezzanine Clock-Data-Distributor (CDD-OPT)
(Developed by this Grant)



HUL mezzanine HR-TDC
(Developed by Grant 中性子星核物質)

Readout system will be tested in RCNP GR on March!

Clock distribution system
based on clock-duty-cycle-modulation

MIKUMARI
(水分)

Motivation

Precise clock distribution (a few tenth ps in σ) is a key issue for many particle and nuclear experiments.

Typical requirements

- Transferring not only the clock but also synchronous data with predictable latency
- As small as transmission lines

Example solution

\+ 8b10b sign extension + FPGA high-speed serial transceiver (e.g. Xilinx MGT)

It actually works well, but

- It strongly depends on FPGA high-speed serial transceiver function, especially, for clock-data recovery.

Motivation

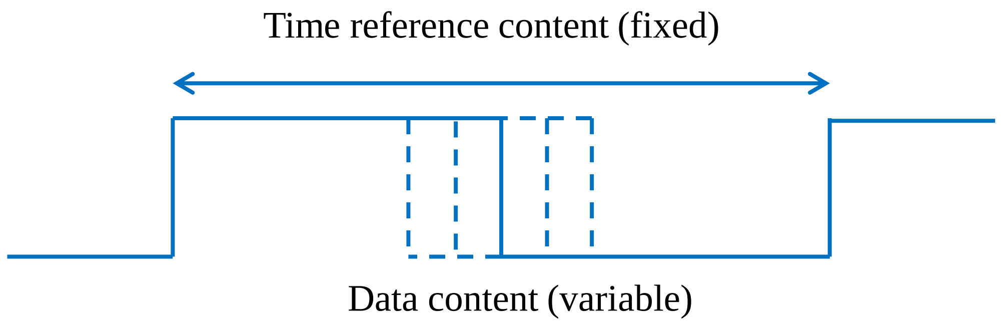
Precise clock distribution (a few tenth ps in σ) is a key issue for many particle and nuclear experiments.

Typical requirements

- Transferring not only the clock but also synchronous data with predictable latency
- As small as transmission lines

Adopting clock-duty-cycle-modulation (CDCM) as a core technology

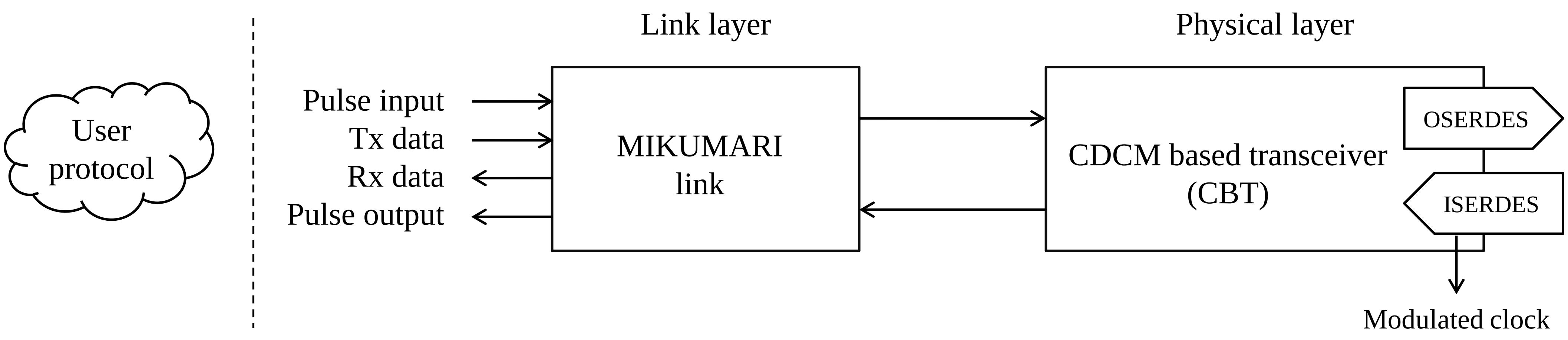
- CDCM is a clock-centric type modulation.
- Data bits are embedded to the trailing edges of the clock signal.



Denis Calvet,
IEEE TNS (Volume: 67, No. 8, Aug. 2020)

- Modulated clock can be directly input to PLLs. Every PLL will be a clock recovery circuit.
- No phase uncertainty if using a PLL having the zero-delay mode. (It exits in a CDR circuit due to clock frequency division.)

Clock distribution system
MIKUMARI
（水分）



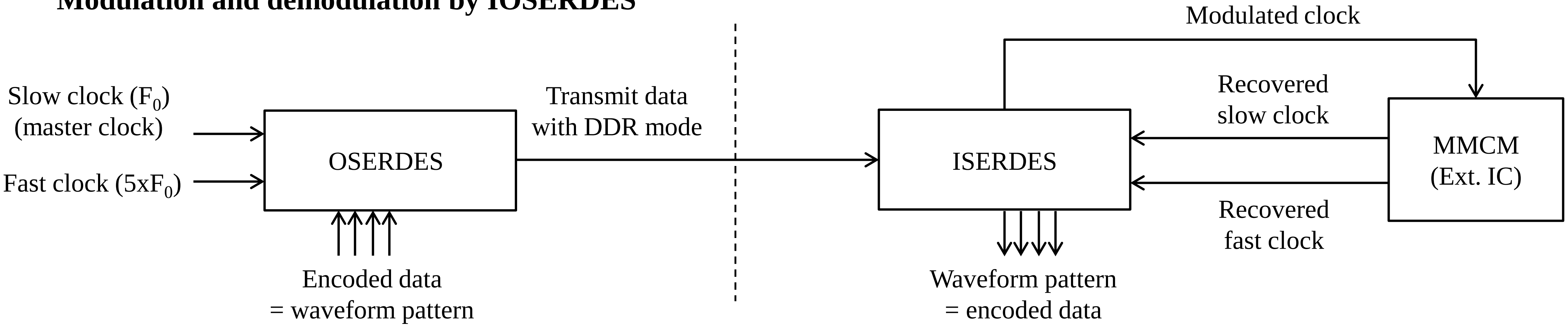
- Data transmission using an arbitral length frame structure
    - Scrambler/Descrambler (PRBS16)
- Pulse transmission with fixed latency

- CDCM modulation
- 8-bit data to 10-bit character extension
    - D, K, and T type characters

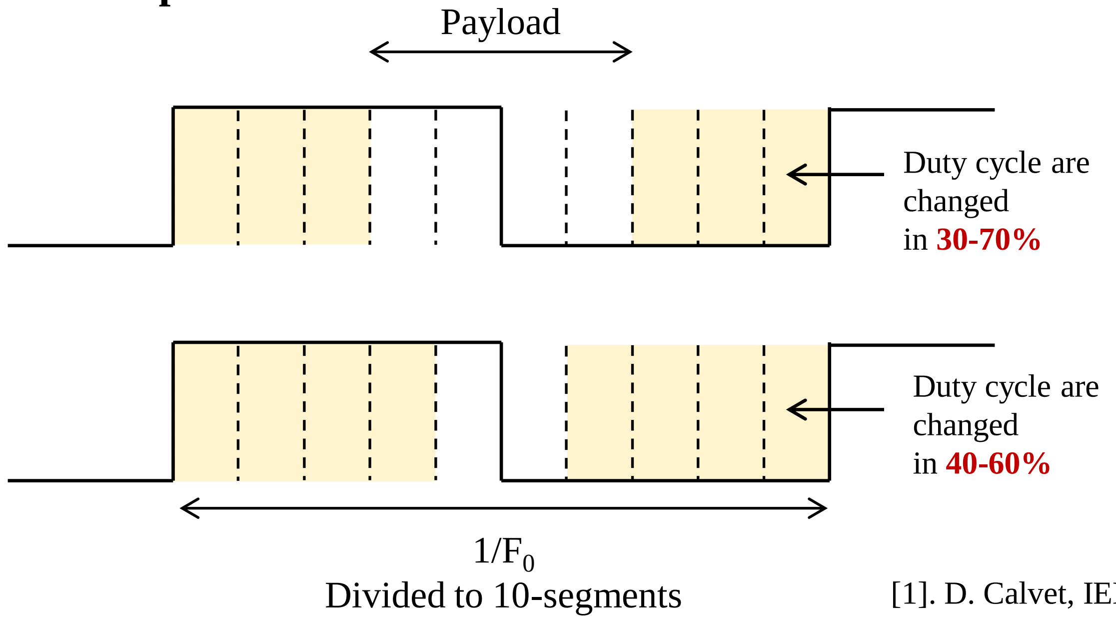
MIKUMARI link is independent from the user defined protocol.
It’s just a link layer protocol.

CDCM by IOSERDES of Xilinx FPGA

Modulation and demodulation by IOSERDES



Waveform pattern



CDCM-10-2.5

CDCM-10-1.5

*0.5 means idle pattern
Naming rule is defined in Ref. [1]

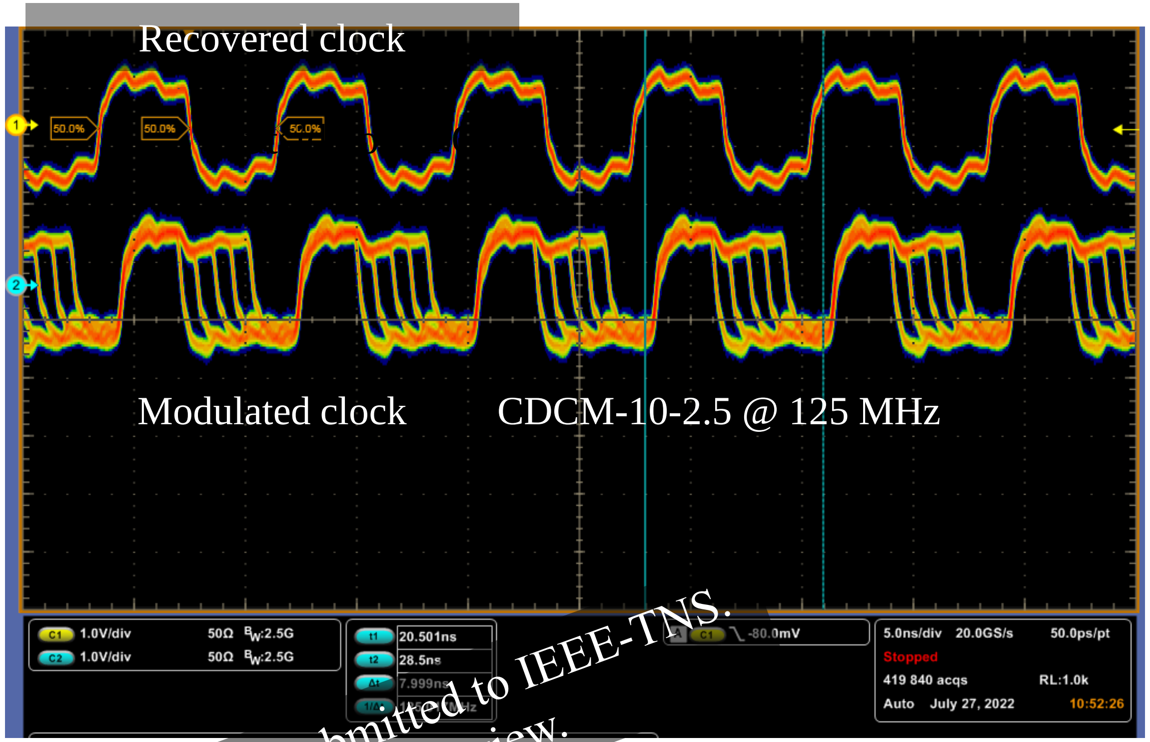
CDCM-10-2.5 encode table

Binary	**Encoded**
00	0000
01	0001
IDLE	0011
10	0111
11	1111

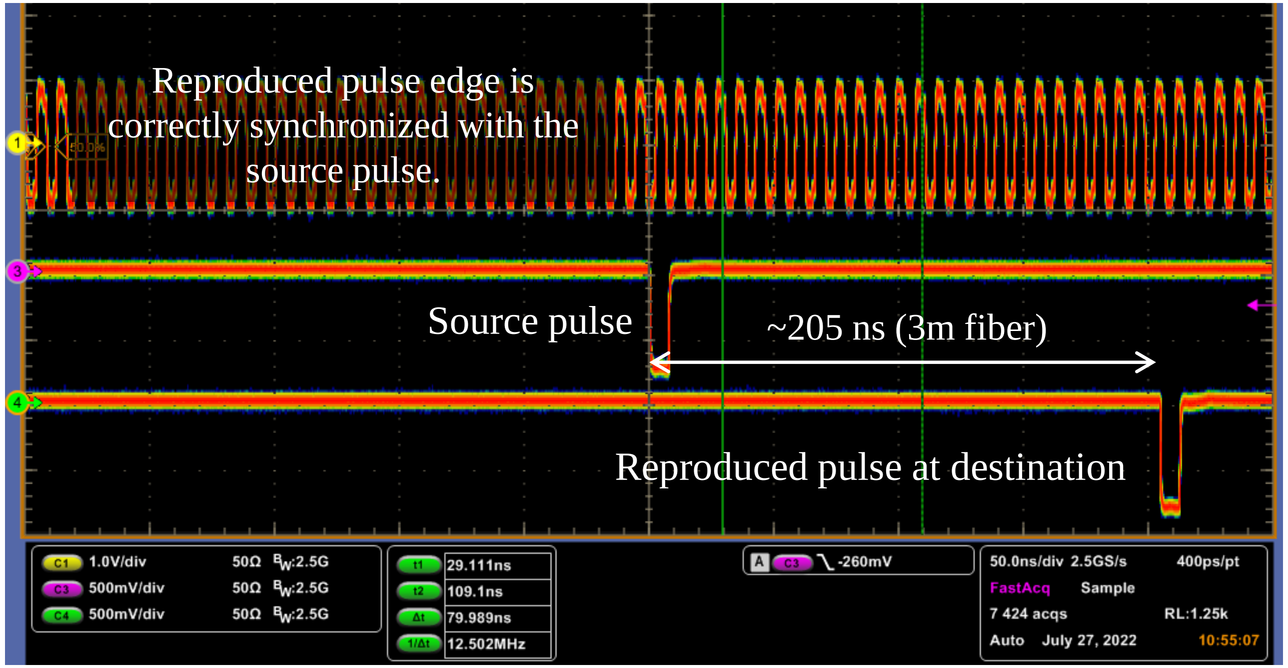
[1]. D. Calvet, IEEE TNS (Vol67, No. 8, Aug. 2020)

Demonstration

Modulated clock signal
and recovered clock signal



Pulse transfer by MIKUMARI link



The paper is submitted to IEEE-TNS.
It's under review.

Quick summary of the obtained results.

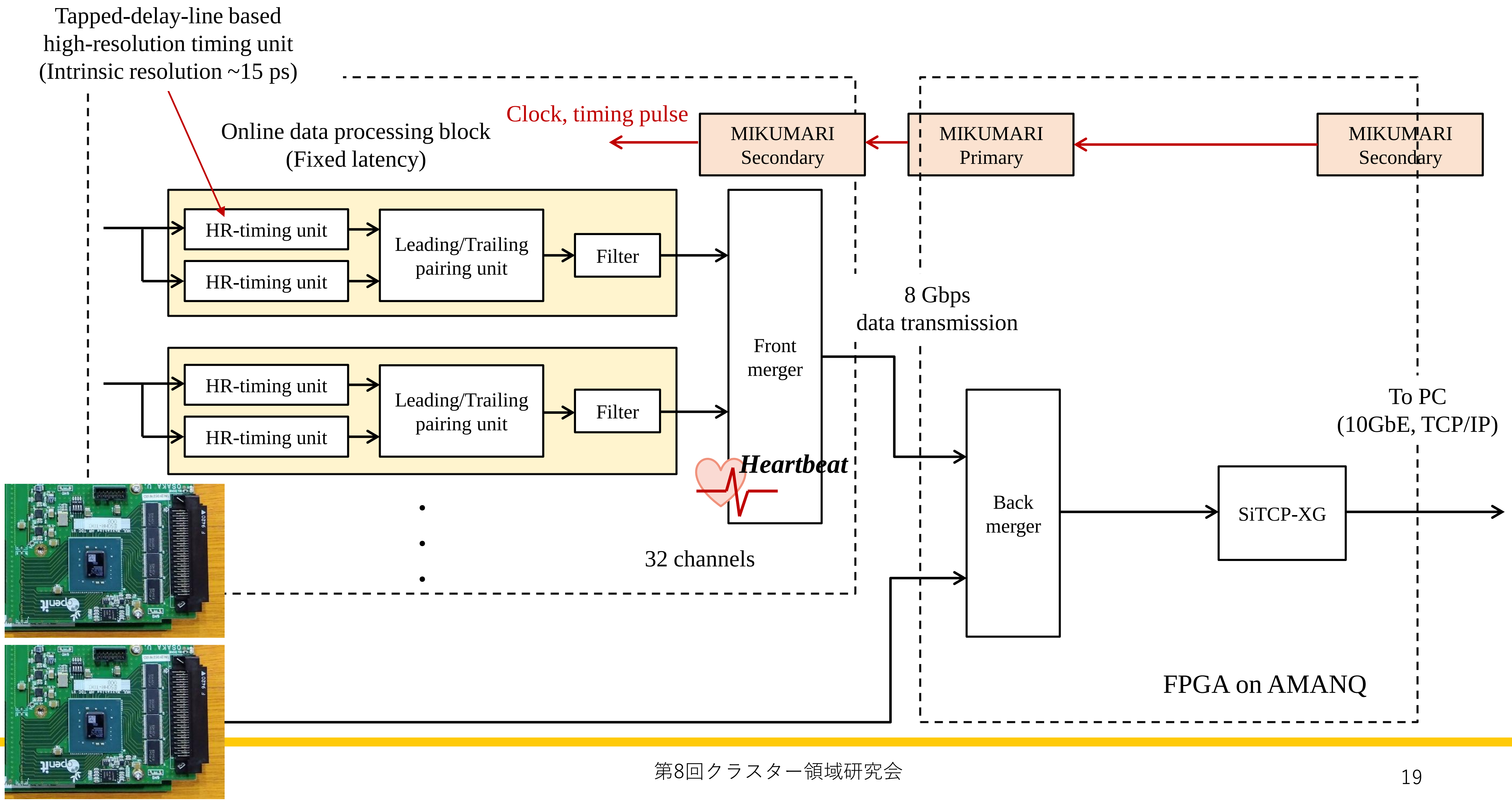
Jitters added per clock recovery are 4.3 and 5.2 ps (σ) for CDCM-10-1.5 and CDCM-10-2.5, respectively.

The synchronization accuracy between two electronics will be
around 15 ps (σ) and 18 ps (σ) for CDCM-10-1.5 and CDCM-10-2.5, respectively, even after repeating 10 times.
This value will satisfy many experimental requirements.

Trigger-less free-streaming type High-Resolution TDC

Str-HR-TDC

Block diagram of the Str-HR-TDC

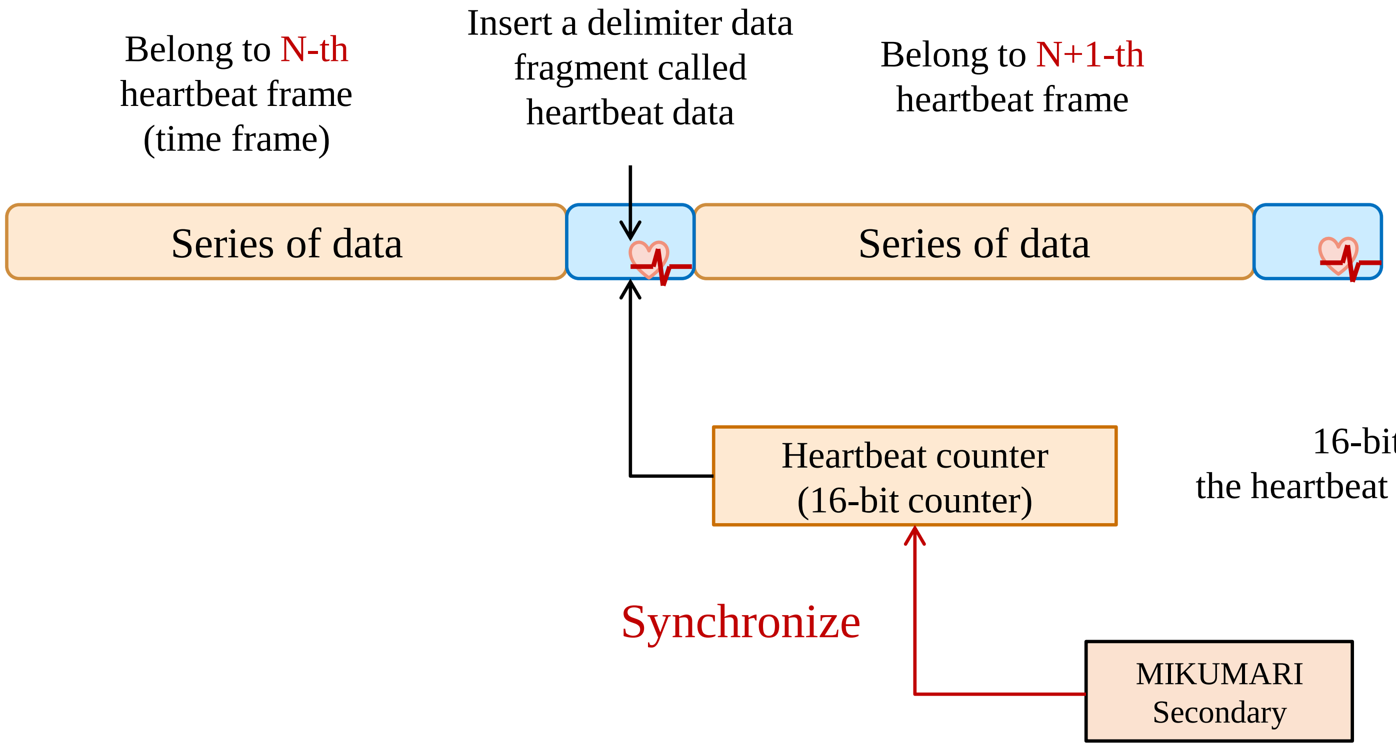


Heartbeat method

We need the continuous timing measurement over 2 s (spill duration of J-PARC slow extraction)

- Required dynamic range: ~10^{12} (10 ps TDC case)

Introduce **heartbeat method**: a technique to reconstruct the time without a long-length time stamp.



R. Honda et al., PTEP, ptab128, https://doi.org/10.1093/ptep/ptab128

16-bit counter driven by 125 MHz clock inserts the heartbeat delimiter word as the boundary of the time frame. (Heartbeat frame = ~524 us)

Dynamic range of ~10^{14} is realized by only 16-bit local counter!

Summary

Physics motivation

- Precision of present two-body ΛN interaction is not enough to discuss the existence of the extra repulsion caused by many-body force.
- Determination of partial wave phase shift is necessary.

A plan of the Λp scattering experiment at the high-p beam line.

- Produce Λ via $\pi^- p \rightarrow K^{0*}(892)\Lambda$
- Measure and identify Λ production by the forward spectrometer in the J-PARC high-p beam line.

Trigger-less free-streaming type beam TOF measurement system was developed

The clock distribution system based on clock-duty-cycle-modulation, MIKUMARI, was developed.

- Jitters added per clock recovery are 4.3 and 5.2 ps (σ) for CDCM-10-1.5 and CDCM-10-2.5, respectively.
- The synchronization accuracy between two electronics will be around 15 ps (σ) and 18 ps (σ) for CDCM-10-1.5 and CDCM-10-2.5, respectively, even after repeating 10 times.

Trigger-less free-streaming type high-resolution TDC was developed.

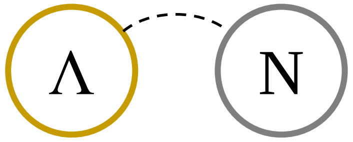
- Tapped-delay-line based high-resolution timing unit was used.
- Introduced the heartbeat method, and thus the dynamic range of ~10^{14} was achieved by only 16-bit local counter.

This system will be the standard TDC system for the future nuclear and particle physics experiments!

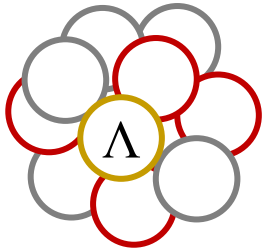
Backup

Introduction

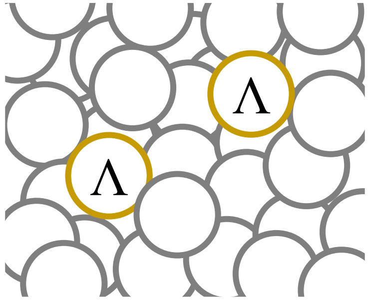
Two-body
ΛN interaction



Λ Hypernuclei



Neutron star



Constructed by scattering data at the dawn.

Explain

Hypernuclear calculation

Constraint

Biding energy.
Level spacing.
Decay mode.

2⊙ mass neutron star

Hyperon puzzle

Lack of data.

Not precise enough to discuss many-body effect from hypernuclei data.

Impede

Trying extract many-body force.

J-Lab

HIHR

Support massive neutron star

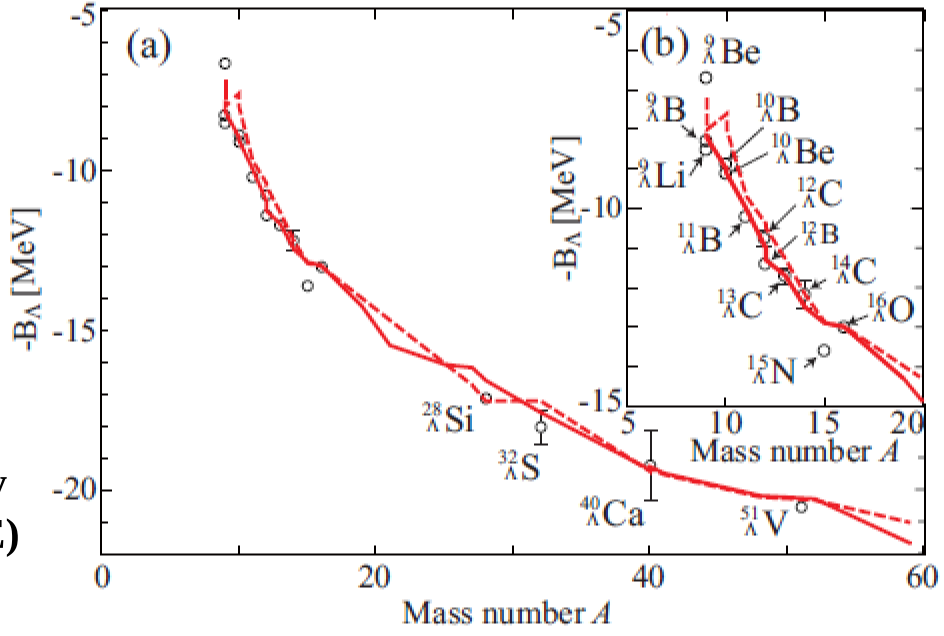
ΛN interaction and hypernuclei

Authors reproduced experimental data using

ΛN interaction
(Nijmegen models)
+
Multi-pomeron exchange potential (MPP)
+
Phenomenological three-body attraction (TBA)

Many-body effect (MBE)

Comparison between experimental data and Hyper-AMD calculation.



M. Isaka et al., PRC95, 044308 (2017)

They discussed the room to add extra repulsion caused by MBE.

ΛN interaction and hypernuclei

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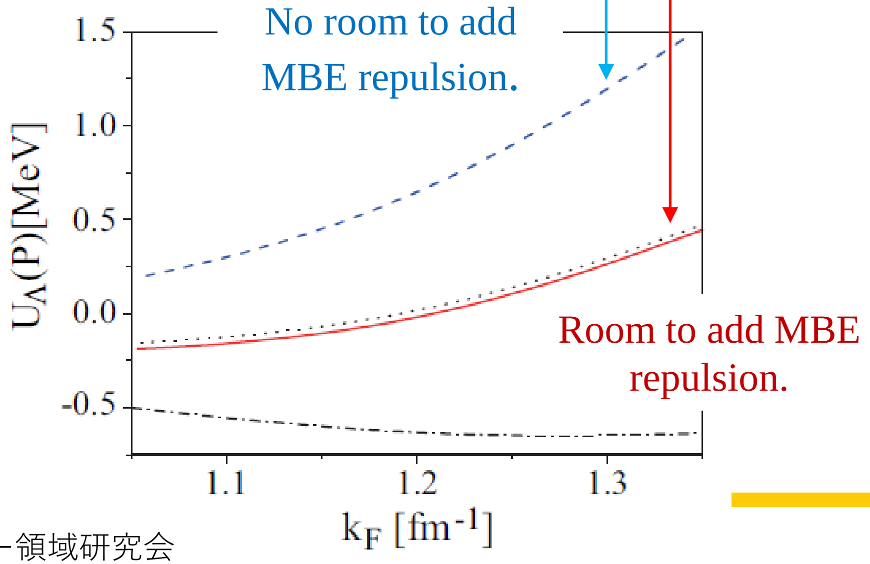
U_Λ from G-matrix calculation
(and *S*-state and *P*-state contribution.)

	U_Λ	$U_\Lambda(S)$	$U_\Lambda(P)$
ESC08a	−40.6	−39.5	+0.5
ESC08b	−39.4	−37.0	−0.6
ESC14	−40.8	−39.6	+0.4
ESC12	−40.0	−40.0	+1.5
ESC04a	−43.2	−38.4	−3.7
NSC97e	−37.7	−40.4	+4.0
NSC97f	−34.8	−39.1	+5.6

M. Isaka et al., PRC95, 044308 (2017)

k_F dependence of U(P)



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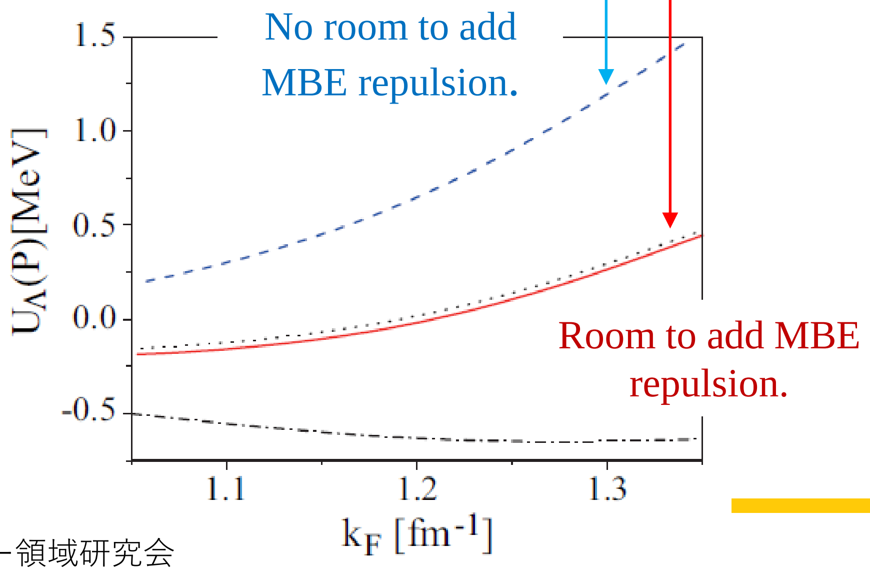
k_F dependence of U(P)



Present scattering data cannot solve this *P*-state (wave) uncertainty.

This is a quite important rising a problem to the ΛN interaction.

Experimental setup

Double scattering experiment.

- $\pi^- p \rightarrow K^*(892)^0 \Lambda$, $K^*(892)^0 \rightarrow K^+ \pi^-$
- $\Lambda p \rightarrow \Lambda p$

Beam condition

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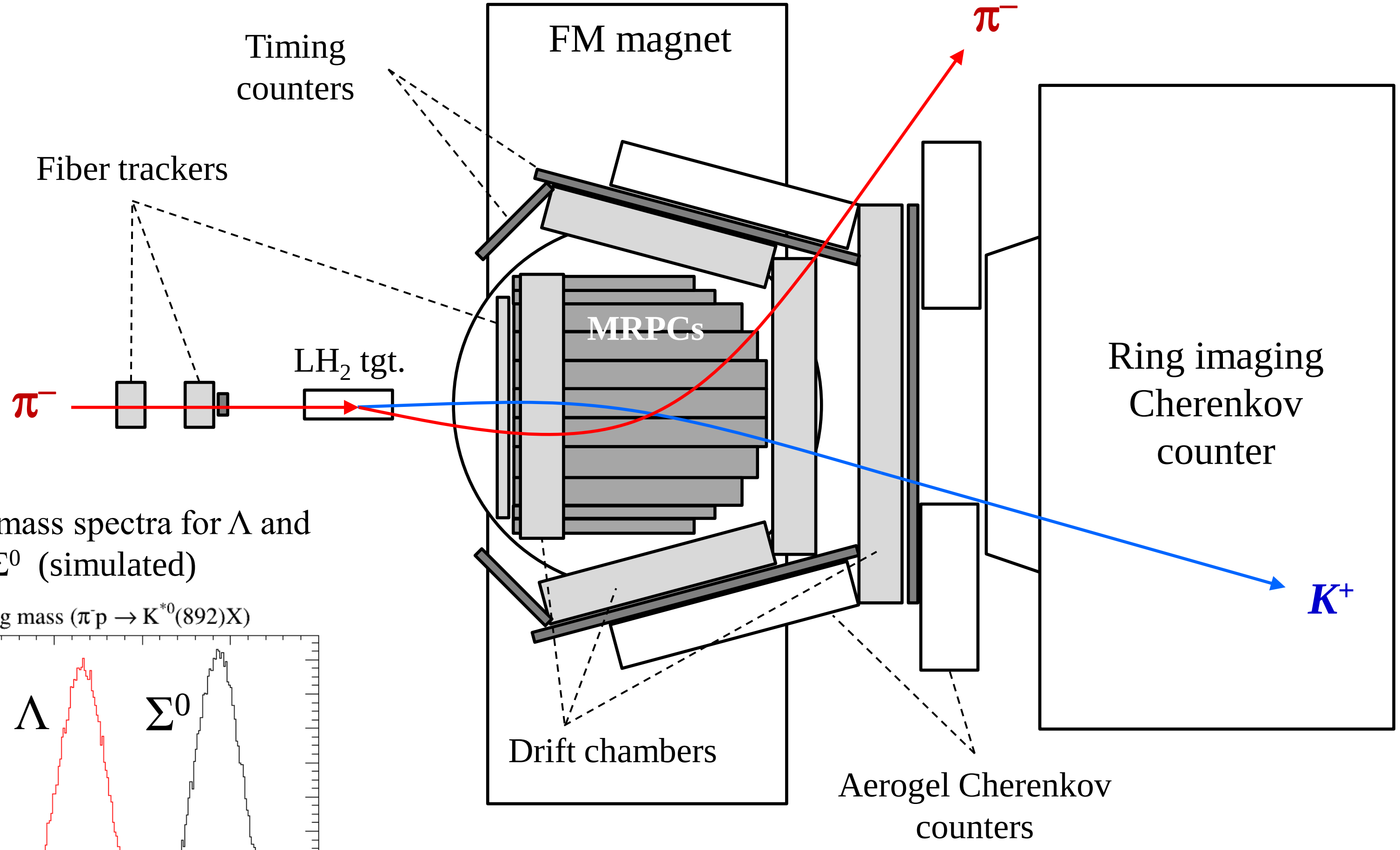
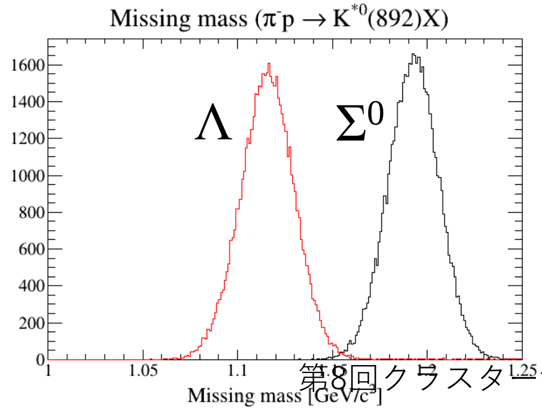


Missing mass spectra for Λ and Σ0 (simulated)



Acceptance of CDS for the Λ scattering

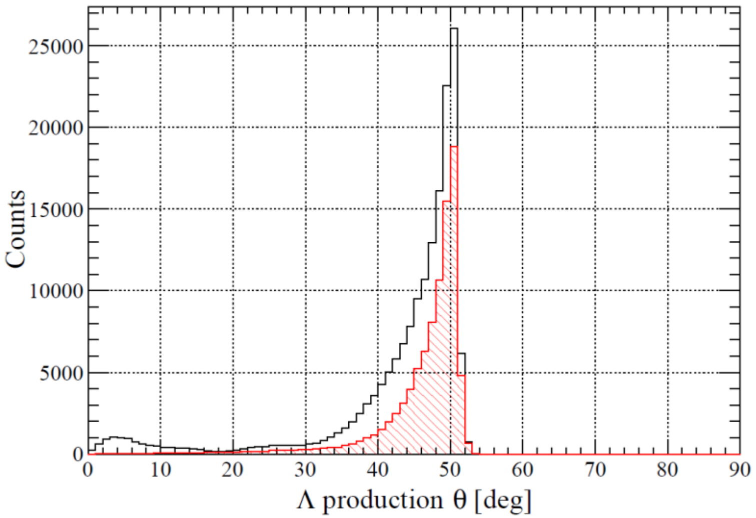
Procedure to identify the Λ*p* scattering

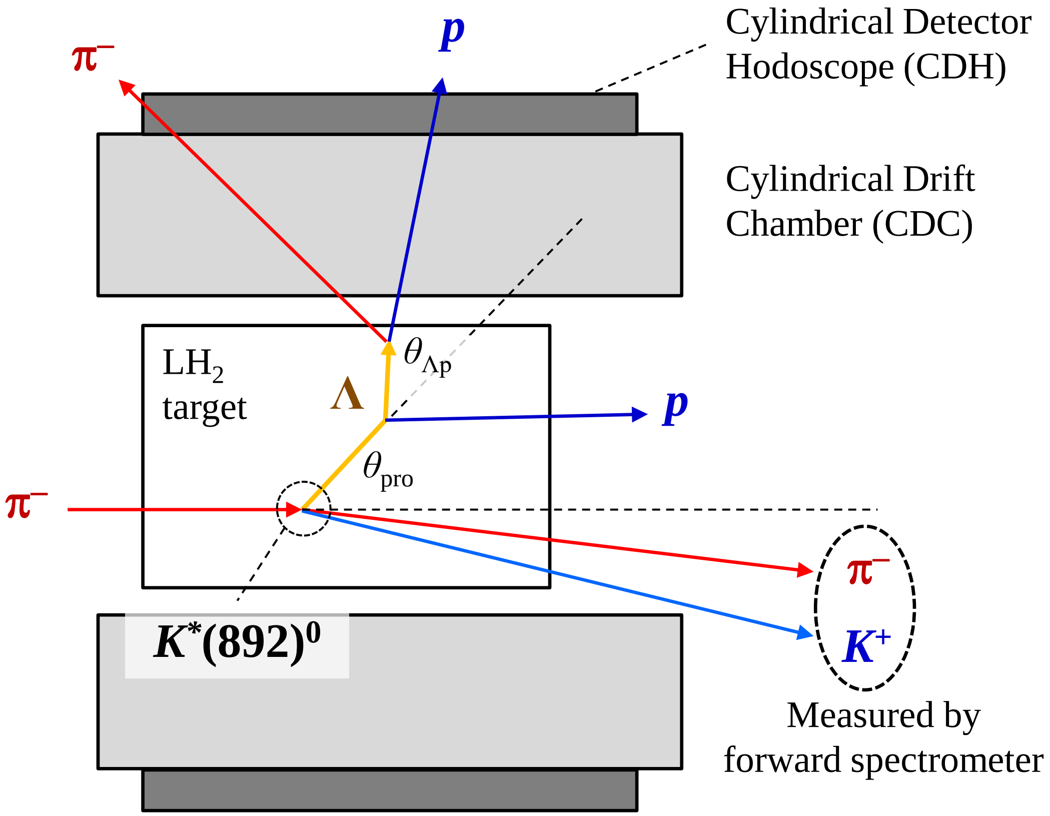
- Momentum vector of initial Λ — Known
- Momentum vectors of
  - Scattered proton
  - Scattered Λ

  } Measure either
- Scattering angle, $\theta_{\Lambda p}$, is obtained.

Check whether these vectors satisfy the Λ*p* scattering kinematics.

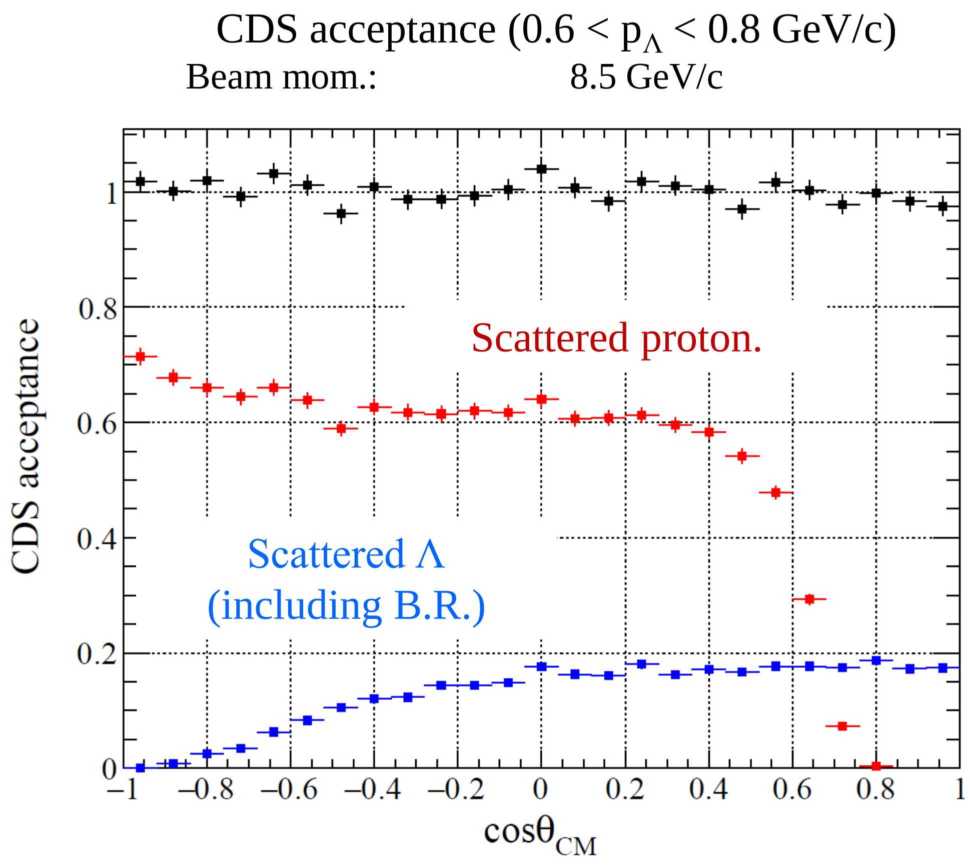
Distribution of the production angle, θ_{pro}.

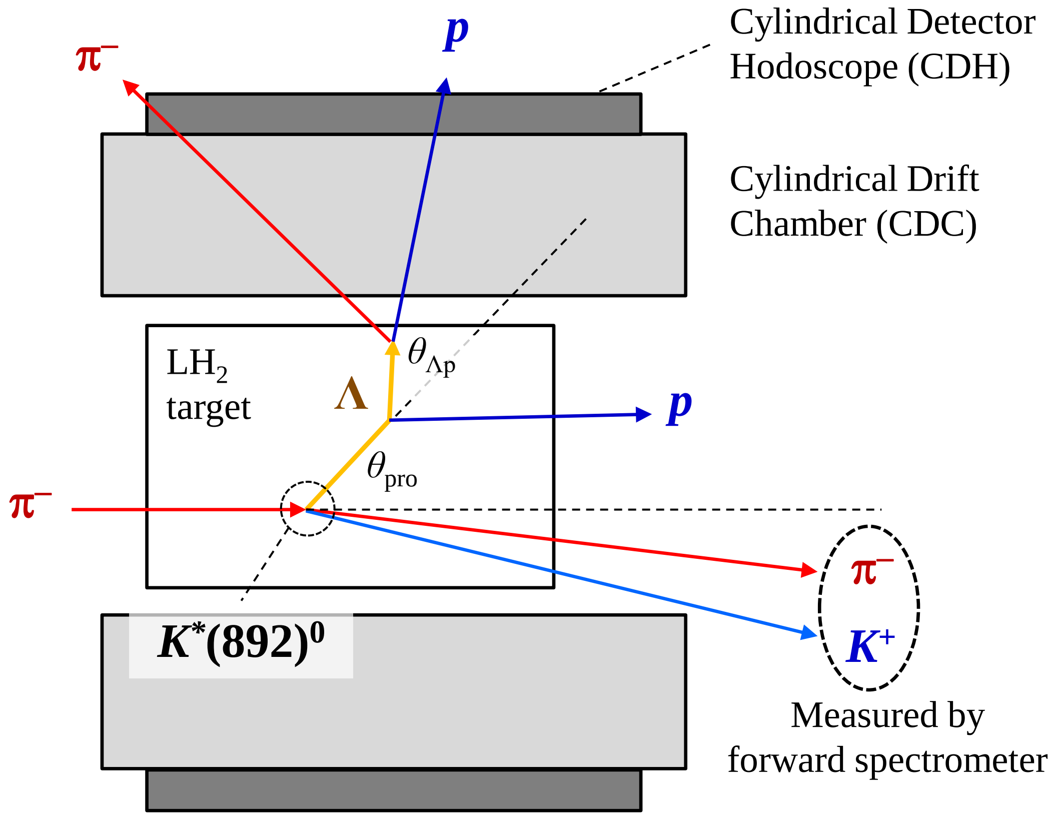




Event topology of the Λ*p* scattering
Decay products from the scattered Λ are detected.

Acceptance of CDS for the Λ scattering





All the region of $\cos\theta_{CM}$ is covered by CDS

Event topology of the Λp scattering
Decay products from the scattered Λ are detected.

Yield estimation of the Λp scattering events

The number of the Λp scattering events happened in the target.

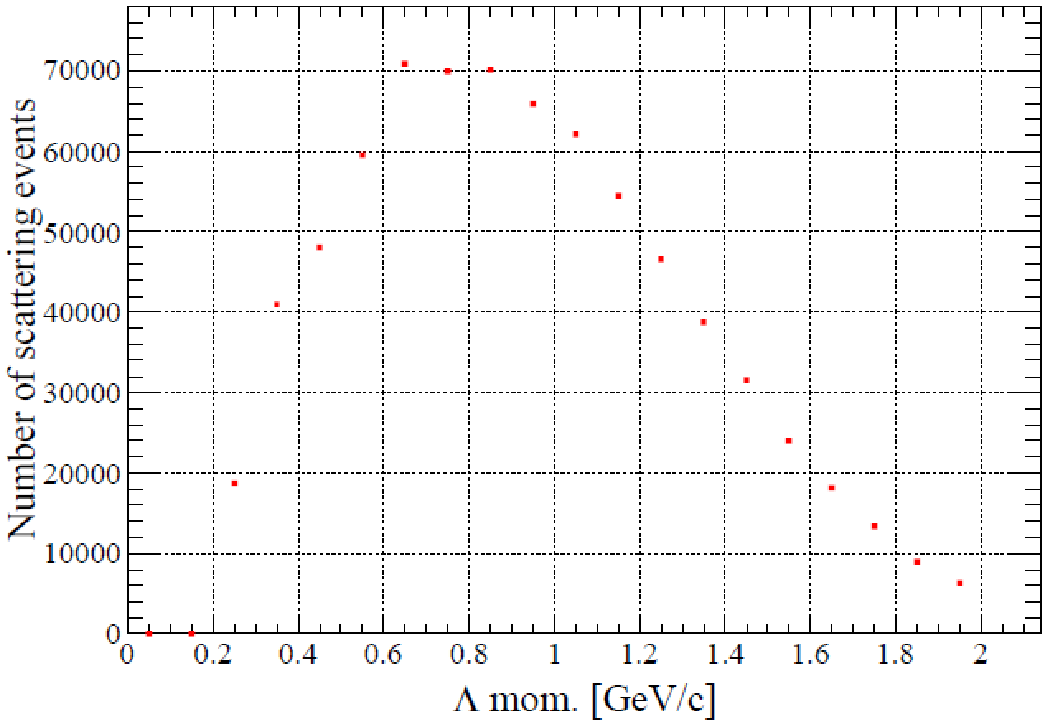
- 3900 events per 1 million Λ beams (Assume σ = 20 mb)

Assume

- CDS acceptance shown in prev. page.
- CDC tracking efficiency of 0.7

At least, 10 new data points between $0.4 < p_{\Lambda} < 1.4$ GeV/c will be obtained in this experiment.

Yields of the Λp scattering events as a function of the Λ beam momentum (30-day beam time)



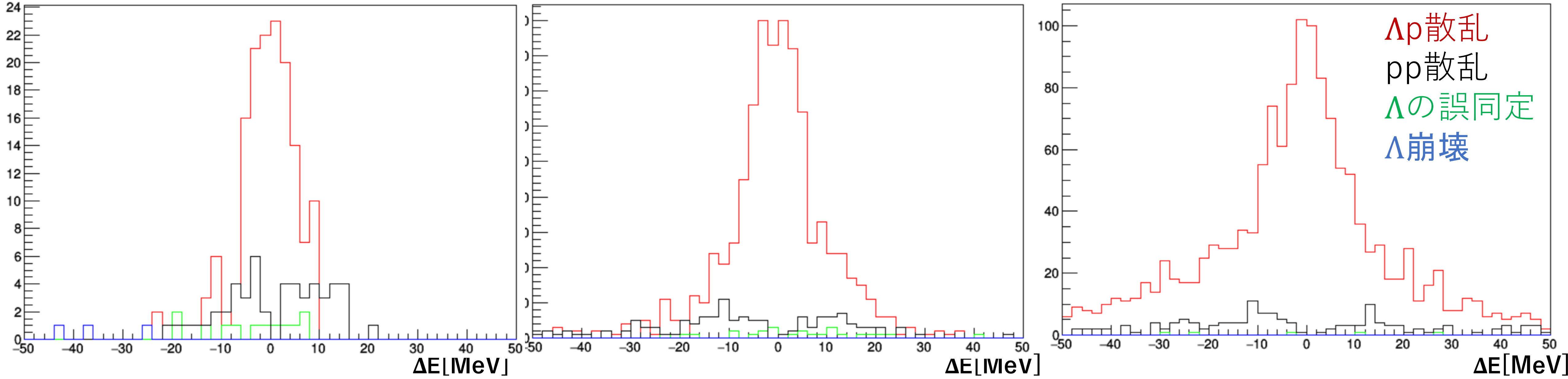
各運動量でのS/N見積もり

生成ビーム1×10^7 / 予定ビーム3.5×10^8で解析

BGを取り除いた後各Λビーム運動量p_ΛでのΔEスペクトラを示す

低運動量領域(< 1 GeV/c) -> 十分なΔE分解能
高運動量領域(> 1 GeV/c) -> 反跳粒子の運動量の増加によりΔE分解能が悪化
一方でΛの寿命が延びるためBGの混入が少なくなる

$0.3 < p_\Lambda$ (GeV/c) < 0.6　　$0.6 < p_\Lambda$ (GeV/c) < 1.0　　$1.0 < p_\Lambda$ (GeV/c) < 2.0



BGとしてπ^-p散乱やπ生成反応(e.x. $\Lambda p \to \Lambda\pi^0 p$)などは考慮していない

収量の角度依存性

中心系での散乱角ごとに (2粒子以上ヒットしたイベント) / (シミュレーション内で生成したイベント) 比をみる

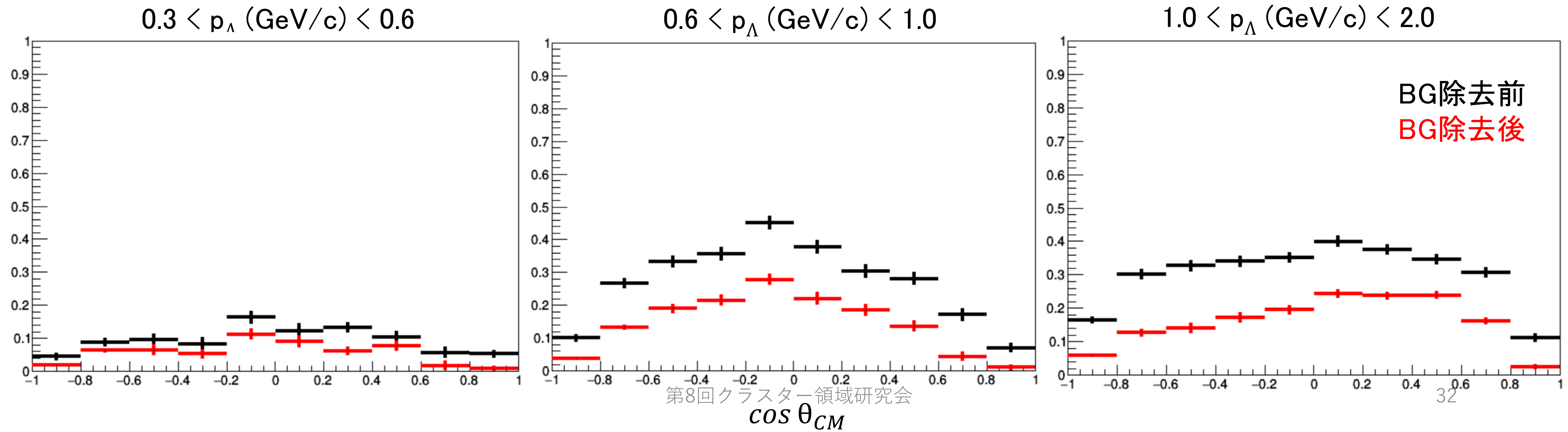
p_Λ (GeV/c) < 0.6領域ではCDS運動量アクセプタンスより検出比が小さくなる

超前方散乱($cos\ \theta_{CM}$ ~1のΛが陽子をかすめるような散乱)まで検出可能

↕

十分な収量をえるためにさらなるBG除去手法の検討へ

角度ごとの検出可能イベント/生成散乱イベント



予想されるΛp散乱事象数

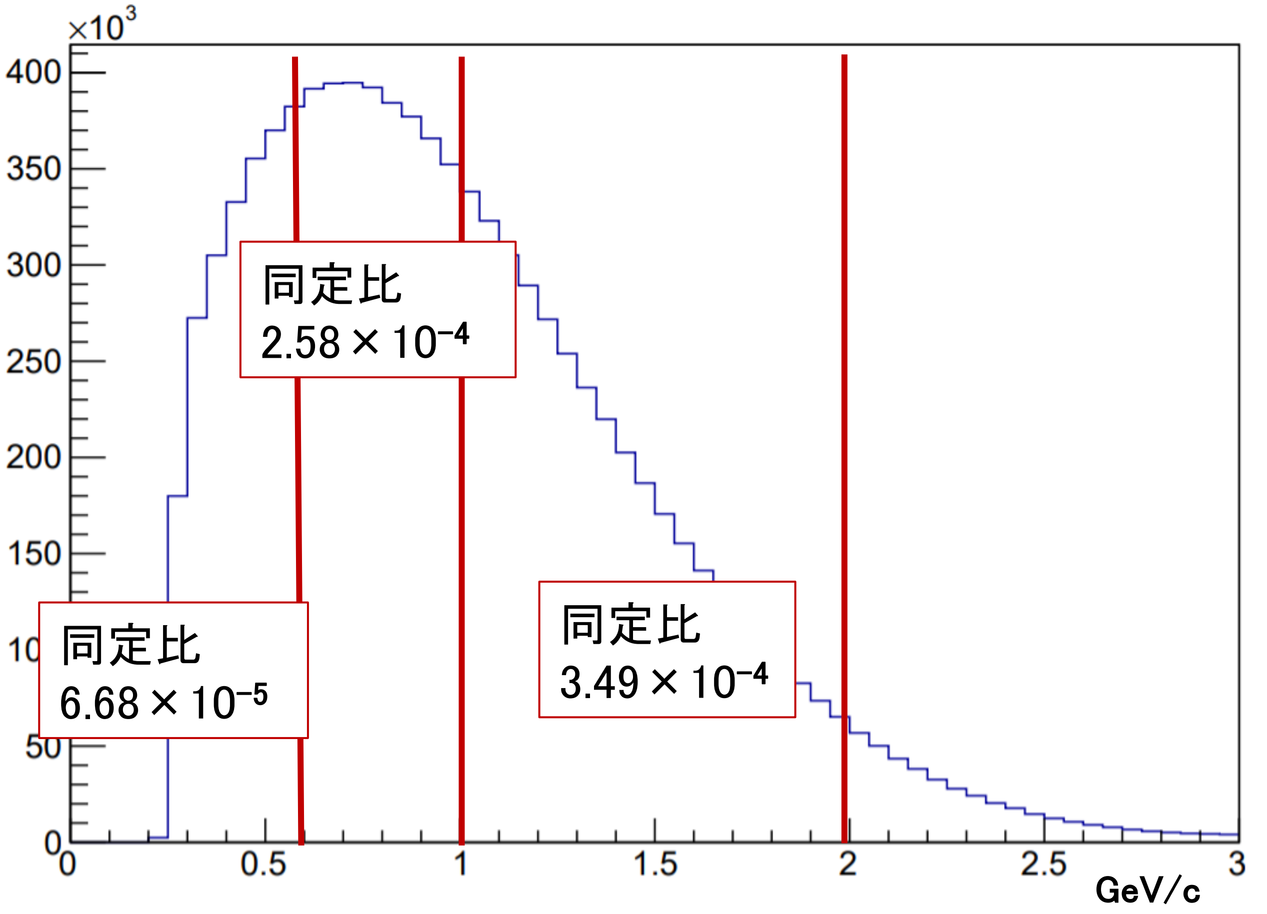
最終的に同定できる散乱同定イベント比を見積もる。

$$\Lambda p\text{散乱同定比} = \frac{\Lambda p\text{散乱同定数}}{\Lambda\text{ビーム数}}$$

（シミュレーション内）

30日間のビームタイムでは
- 総Λビーム数(予定) ～ 3.5×10^8
- Λp散乱同定数 ～6.4×10^4イベント
  （散乱同定比から推定）

実際はここに検出器効率等(0.7程)がかかる



従来にない高統計Λp散乱実験が実現可能になる