排他的ドレルヤン反応を用いた核子構造研究のためのミューオン検出器の開発

高位置・高時間分解能

第6回クラスター階層領域研究会

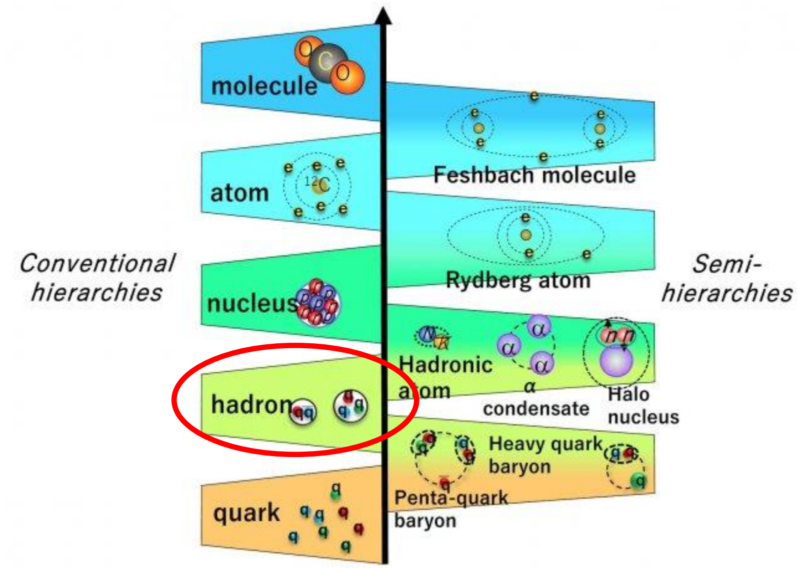
2021/6/19

冨田 夏希 (RCNP, Osaka Univ.)

Nucleon structure

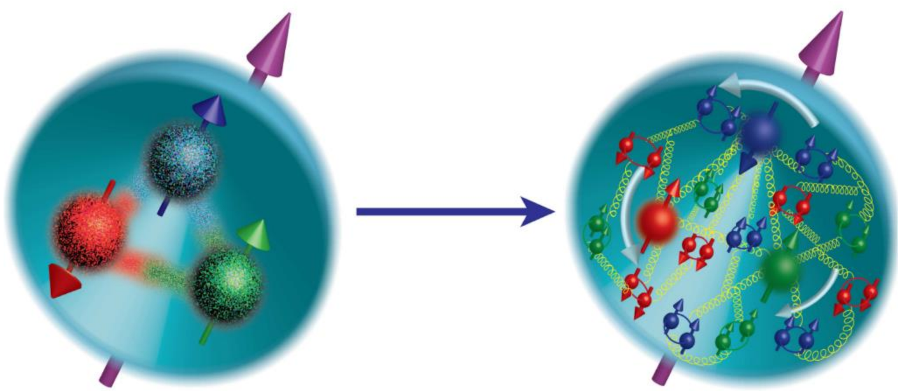
Nucleon = proton & neutron

- the most familiar hadron to us
- stable & easy to probe
- but **its structure is still not well understood**
- It is not a simple 3-body quark system

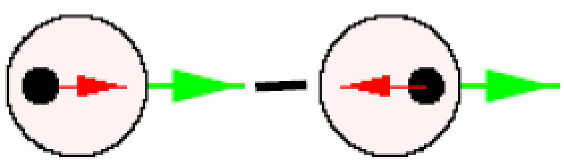


Spin puzzle

quark spin =
~1/3 of nucleon spin



https://www.int.washington.edu/PROGRAMS/17-3/



longitudinally polarized nucleon

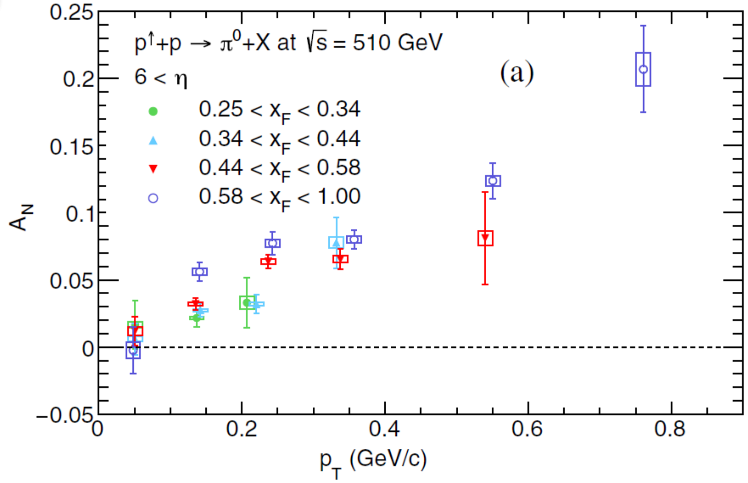
Nucleon structure

Spin asymmetry

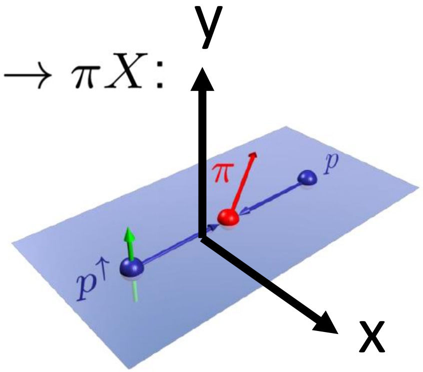
Single spin asymmetry

$$A_N = \frac{d\sigma_{left} - d\sigma_{right}}{d\sigma_{left} + d\sigma_{right}}$$

RPL 124 (2020) 252501

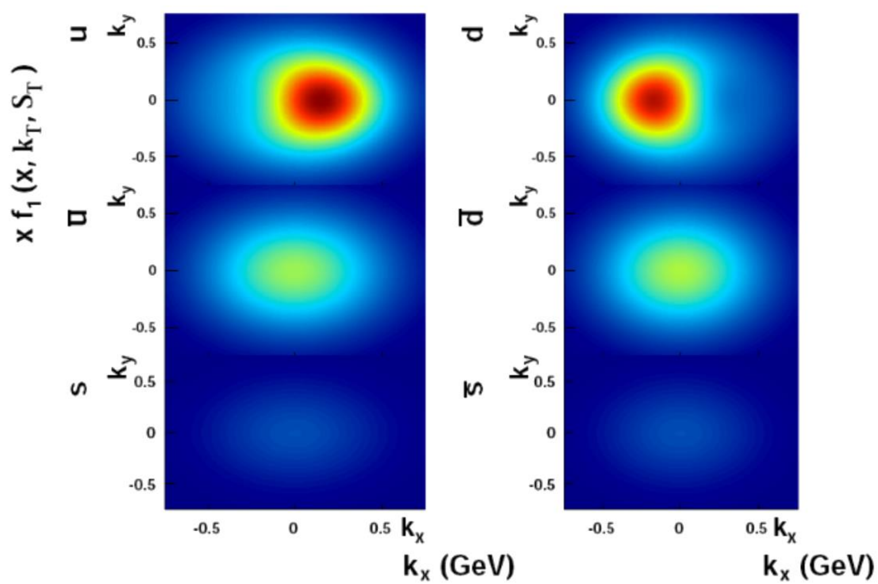


$P^{\uparrow}P \rightarrow \pi X$:



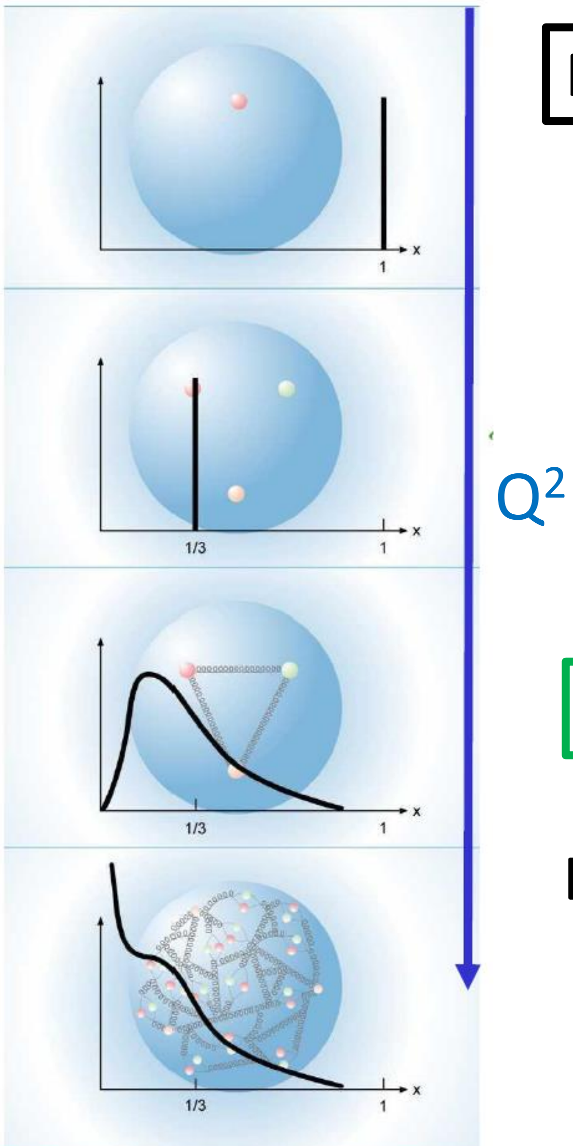
transversely polarized

https://www.int.washington.edu/PROGRAMS/17-3/



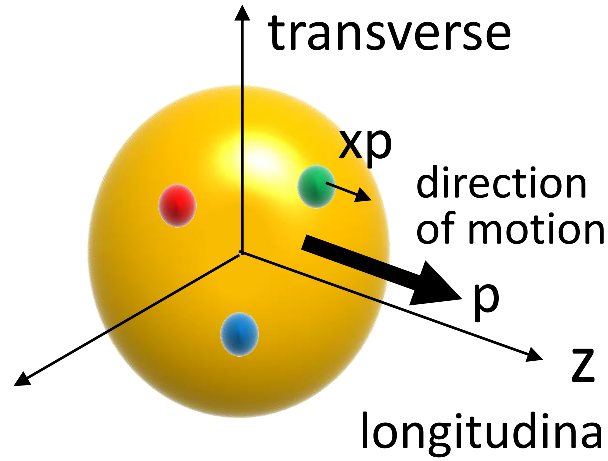
Asymmetric quark momentum distributions of transversely polarized proton

Parton distribution function



Parton = quark + gluon

as a function of x
(longitudinal
momentum fraction
carried by the parton)



f(x) : parton distribution function

Longitudinal distribution of partons

Depends on

Q^2 : energy scale of the reaction

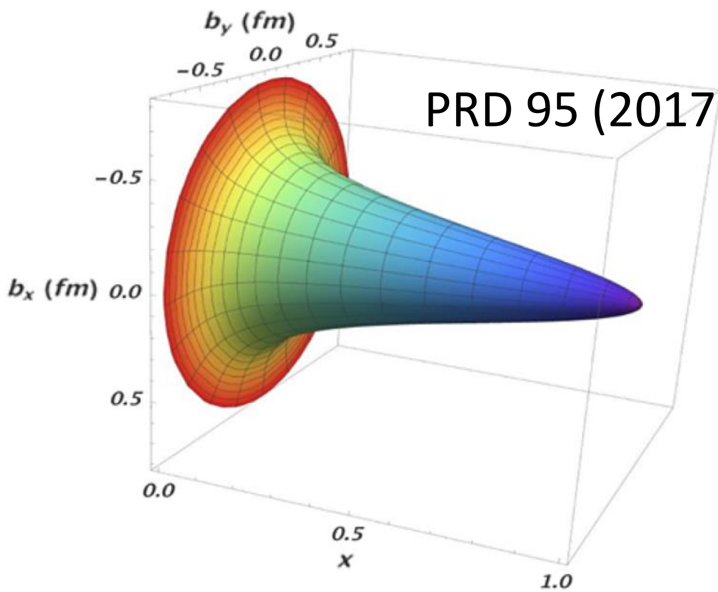
small Q^2 => large scale probe

large Q^2 => small scale probe

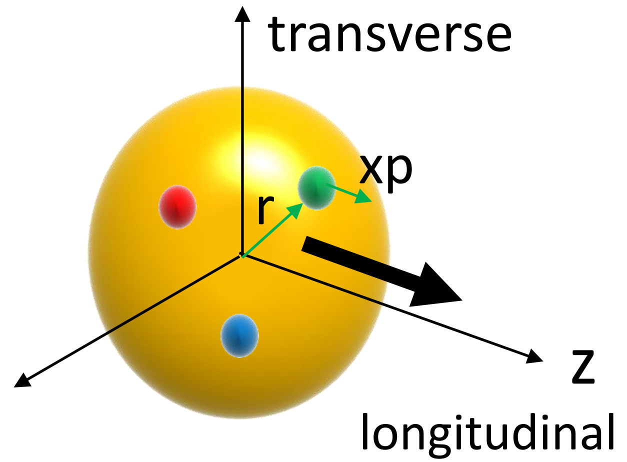
Nucleon 3-D structure

Generalized Parton Distributions (GPDs)

- Transverse position of partons & longitudinal momentum

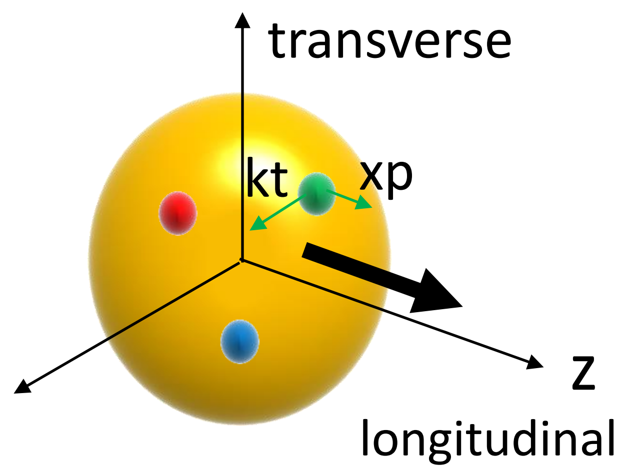


PRD 95 (2017) 011501(R)



Transverse Momentum Dependent Parton Distributions (TMDs)

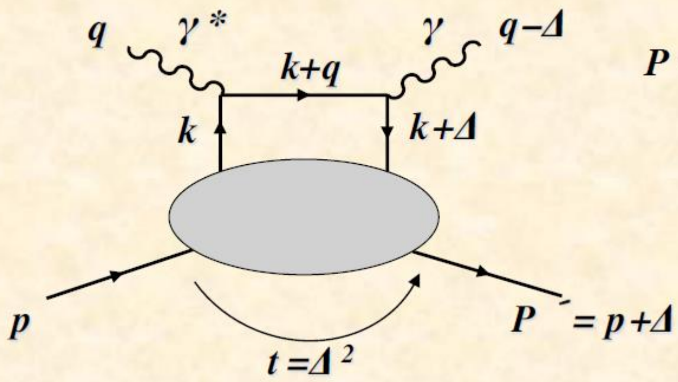
- Transverse momentum of partons & longitudinal momentum



Generalized Parton Distributions

- Unpolarized parton : H, E
- Longitudinally polarized parton : H̃, Ẽ

from S. Kumano
Workshop on The Future of Color Transparency and Hadronization Studies at Jefferson Lab and Beyond



$$P = \frac{p+p'}{2}, \quad \Delta = p' - p$$

Bjorken variable $x = \frac{Q^2}{2p \cdot q}$

Momentum transfer squared $t = \Delta^2$

Skewdness parameter $\xi = \frac{p^+ - p'^+}{p^+ + p'^+} = -\frac{\Delta^+}{2P^+}$

GPDs are defined as correlation of off-forward matrix:

$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle p' | \overline{\psi}(-z/2)\gamma^+\psi(z/2) | p \rangle \Big|_{z^+=0,\vec{z}_\perp=0} = \frac{1}{2P^+}\left[H(x,\xi,t)\overline{u}(p')\gamma^+ u(p) + E(x,\xi,t)\overline{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2M}u(p) \right]$$

$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle p' | \overline{\psi}(-z/2)\gamma^+\gamma_5\psi(z/2) | p \rangle \Big|_{z^+=0,\vec{z}_\perp=0} = \frac{1}{2P^+}\left[\tilde{H}(x,\xi,t)\overline{u}(p')\gamma^+\gamma_5 u(p) + \tilde{E}(x,\xi,t)\overline{u}(p')\frac{\gamma_5\Delta^+}{2M}u(p) \right]$$

Forward limit: PDFs $H(x,\xi,t)\big|_{\xi=t=0} = f(x), \quad \tilde{H}(x,\xi,t)\big|_{\xi=t=0} = \Delta f(x),$

First moments: Form factors

Dirac and Pauli form factors F_1, F_2 $\int_{-1}^{1} dx\, H(x,\xi,t) = F_1(t), \quad \int_{-1}^{1} dx\, E(x,\xi,t) = F_2(t)$

Axial and Pseudoscalar form factors G_A, G_P $\int_{-1}^{1} dx\, \tilde{H}(x,\xi,t) = g_A(t), \quad \int_{-1}^{1} dx\, \tilde{E}(x,\xi,t) = g_P(t)$

Second moments: Angular momenta

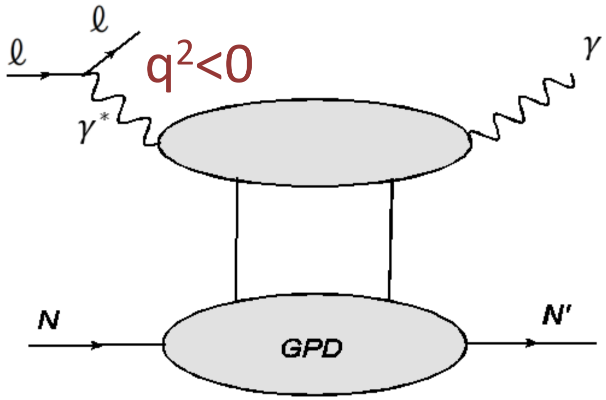
Sum rule: $J_q = \frac{1}{2}\int_{-1}^{1} dx\, x\left[H_q(x,\xi,t=0) + E_q(x,\xi,t=0)\right], \quad J_q = \frac{1}{2}\Delta q + L_q$

$\Rightarrow$ probe L_q, key quantity to solve the spin puzzle!

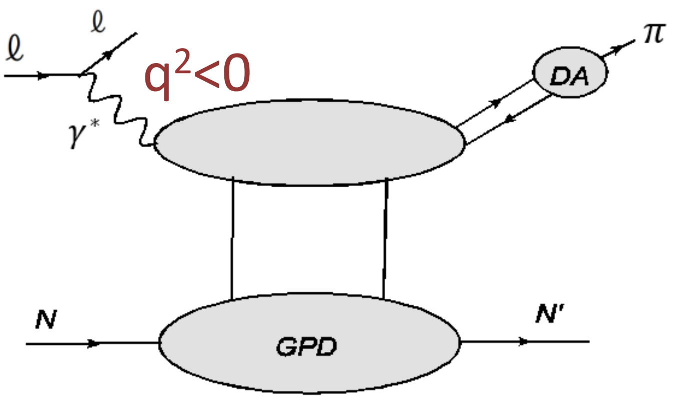
Generalized Parton Distributions (GPDs) measurement

Reaction with large Q^2 (=$-q^2$)

Deeply Virtual Compton Scattering (DVCS)



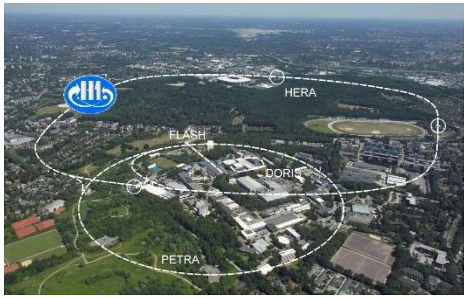
Deeply Virtual Meson Production (DVMP)



PRD 86 031502(R) (2012)

Experiments at

HERA



J Lab

HERMES

2000~

Global fitting of different measurements

Generalized Parton Distributions (GPDs) measurement

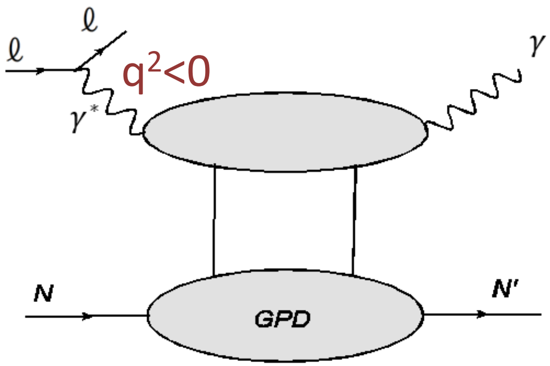
Space-like

Time-like

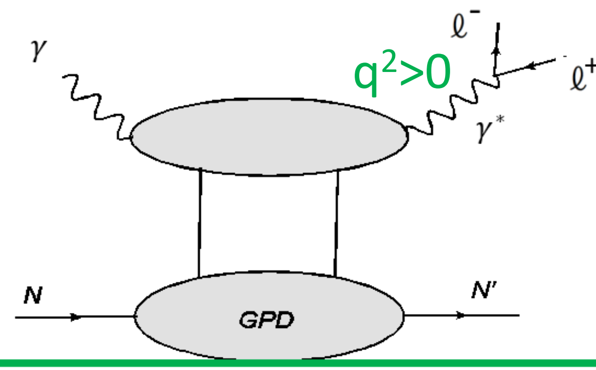
no experimental data

PRD 86 031502(R) (2012)

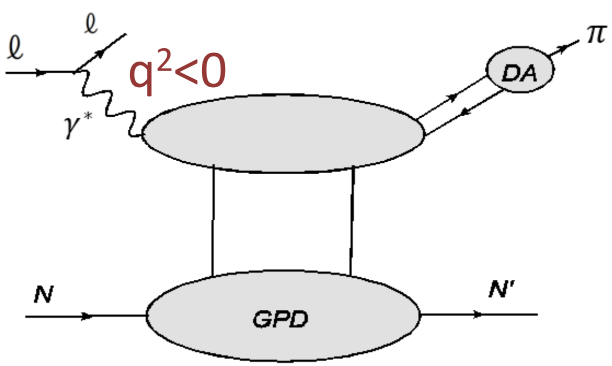
Deeply Virtual Compton Scattering (DVCS)



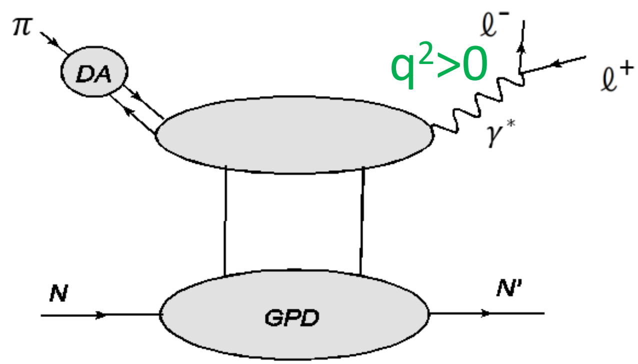
Time-like Compton Scattering (TCS)



Deeply Virtual Meson Production (DVMP)



Exclusive meson-induced DY



Confirmation of the universality of GPDs in different processes

Aim the first measurement of Time-like ($q^2>0$) reaction

Exclusive Drell-Yan cross section

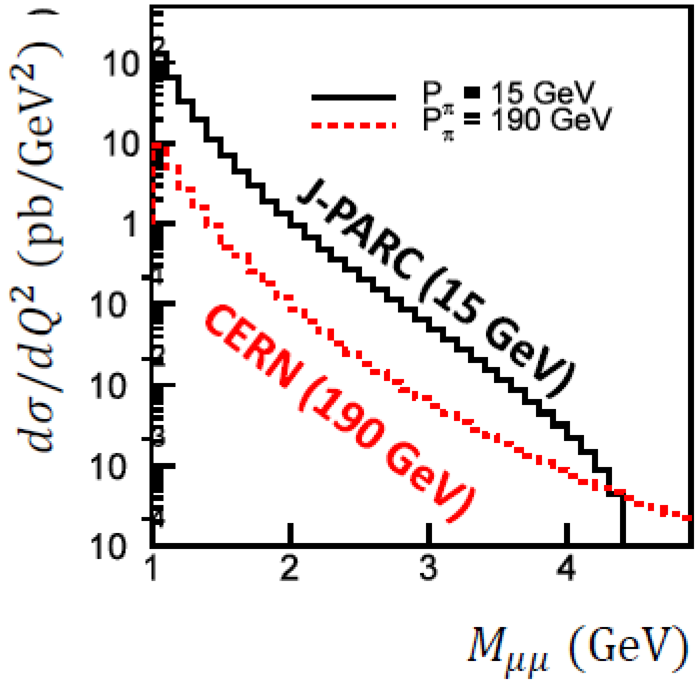
$q\bar{q} \rightarrow \gamma^* \rightarrow l^+ l^-$

$\pi^- p \rightarrow \gamma^* n \rightarrow \mu^+ \mu^- n$

15 GeV/c π^- : 7.5 pb

190 GeV/c π^- : 0.65 pb

E.R. Berger et al., PLB 523 (2001) 265



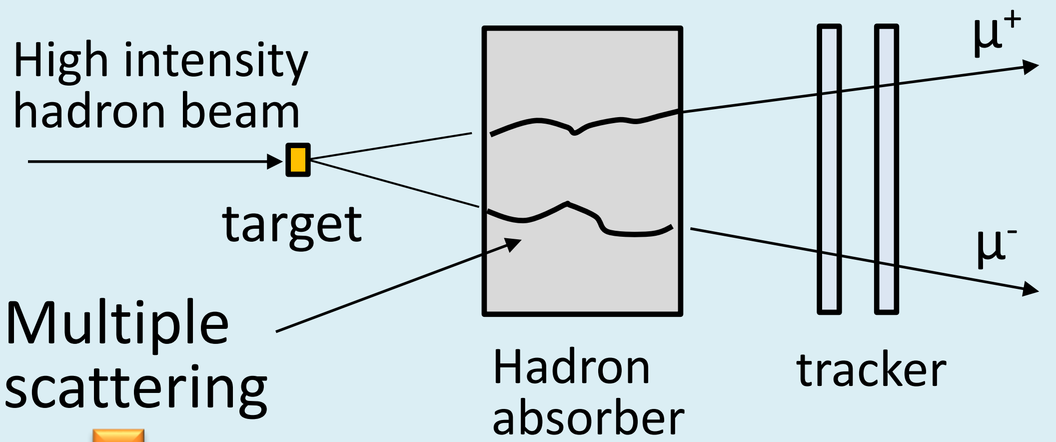
- Beam momentum ~ 10-20 GeV/c
  ⇒ J-PARC high momentum beam line

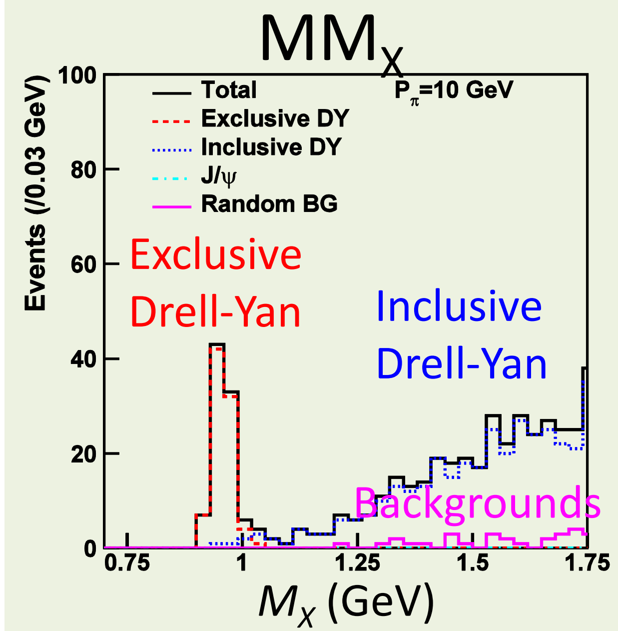
Drell-Yan measurement

$\pi^- p \to \gamma^* n \to \mu^+ \mu^- n$

- Small cross section (~pb) ⇔ Large hadron background (~mb)

Ordinally experimental set up (COMPASS) (Fermilab)



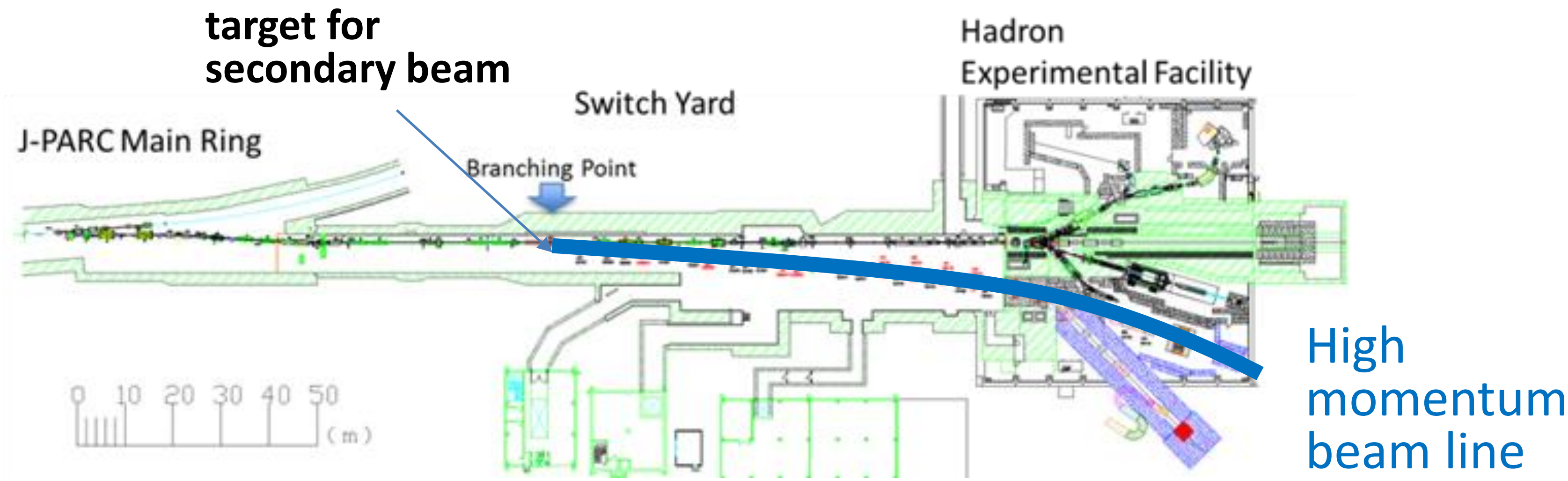


Bad momentum resolution

Cannot separate
- Inclusive Drell-Yan $\pi^- p \to \gamma^* X \to \mu^+ \mu^- X$
- **Exclusive Drell-Yan $\pi^- p \to \gamma^* n \to \mu^+ \mu^- n$**

- High rate, good momentum resolution spectrometer : E50 spectrometer

J-PARC high momentum beam line



- 2020~ : primary proton beam (30 GeV/c)
  E16 experiment (Φ meson in nucleus)

- After E16 : secondary meson beam

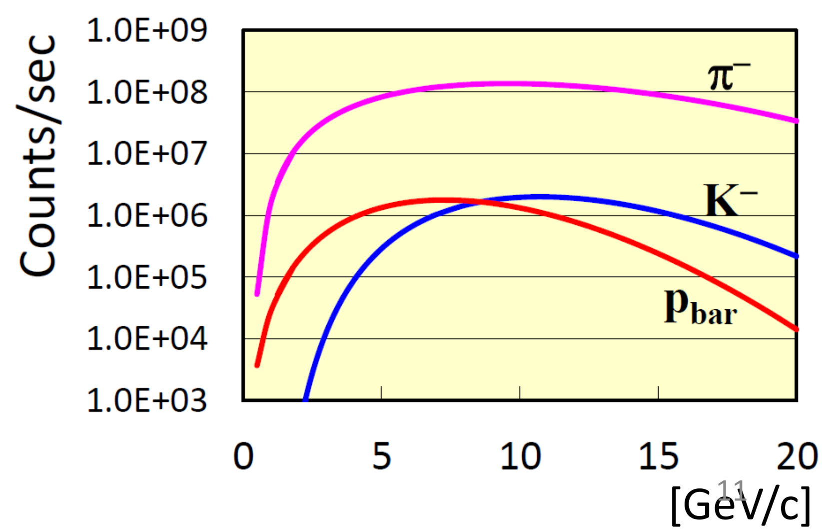
E50 : charmed baryon spectroscopy

E79 : I=3 di-baryon search

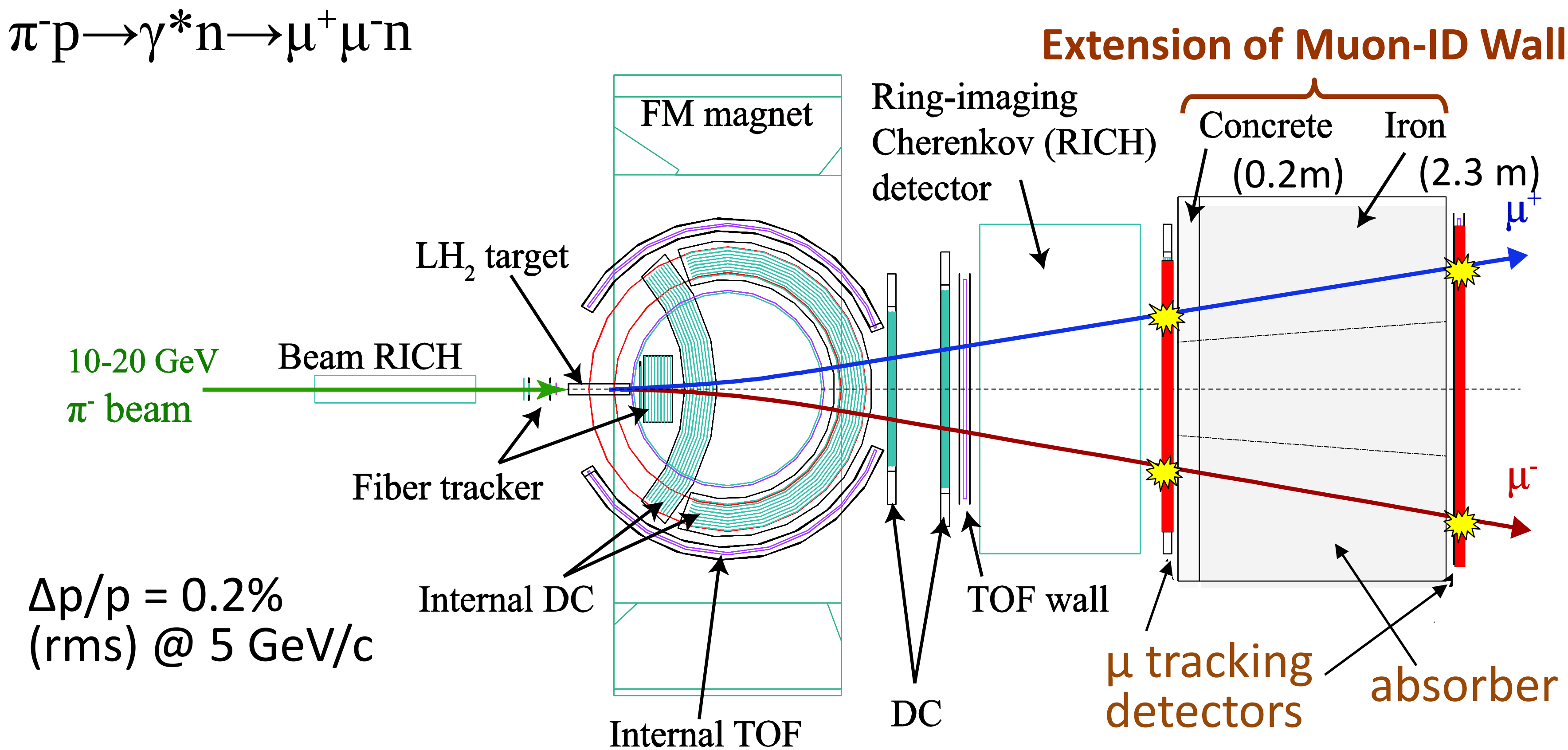
LoI : Ξ (S=-2) baryon spectroscopy

LoI : Λp scattering

- Trigger-less DAQ



E50 spectrometer



- High rate & high momentum resolution spectrometer
  - 計画研究A02

  => μ momentum measurements with high resolution

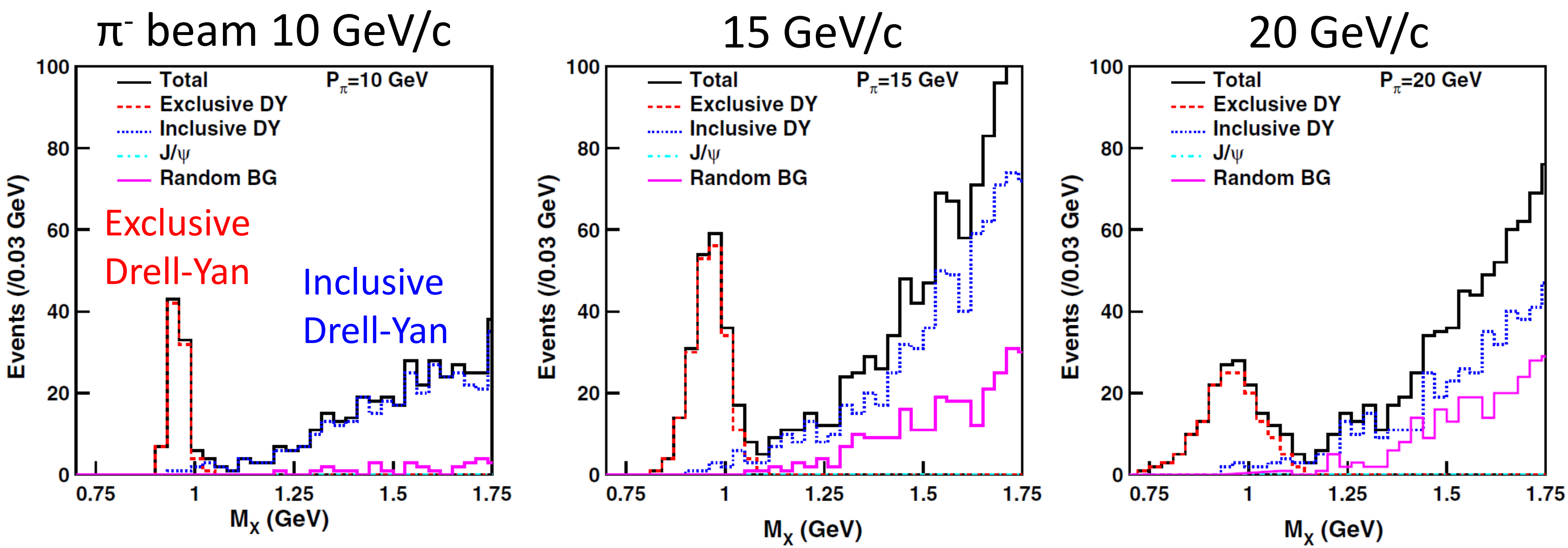
- Additional μ ID system downstream of the E50 spectrometer

  => 公募研究

Experimental feasibility

- PRD 93 (2016) 114034
  - Optimized tracker resolution & absorber thickness

50 days



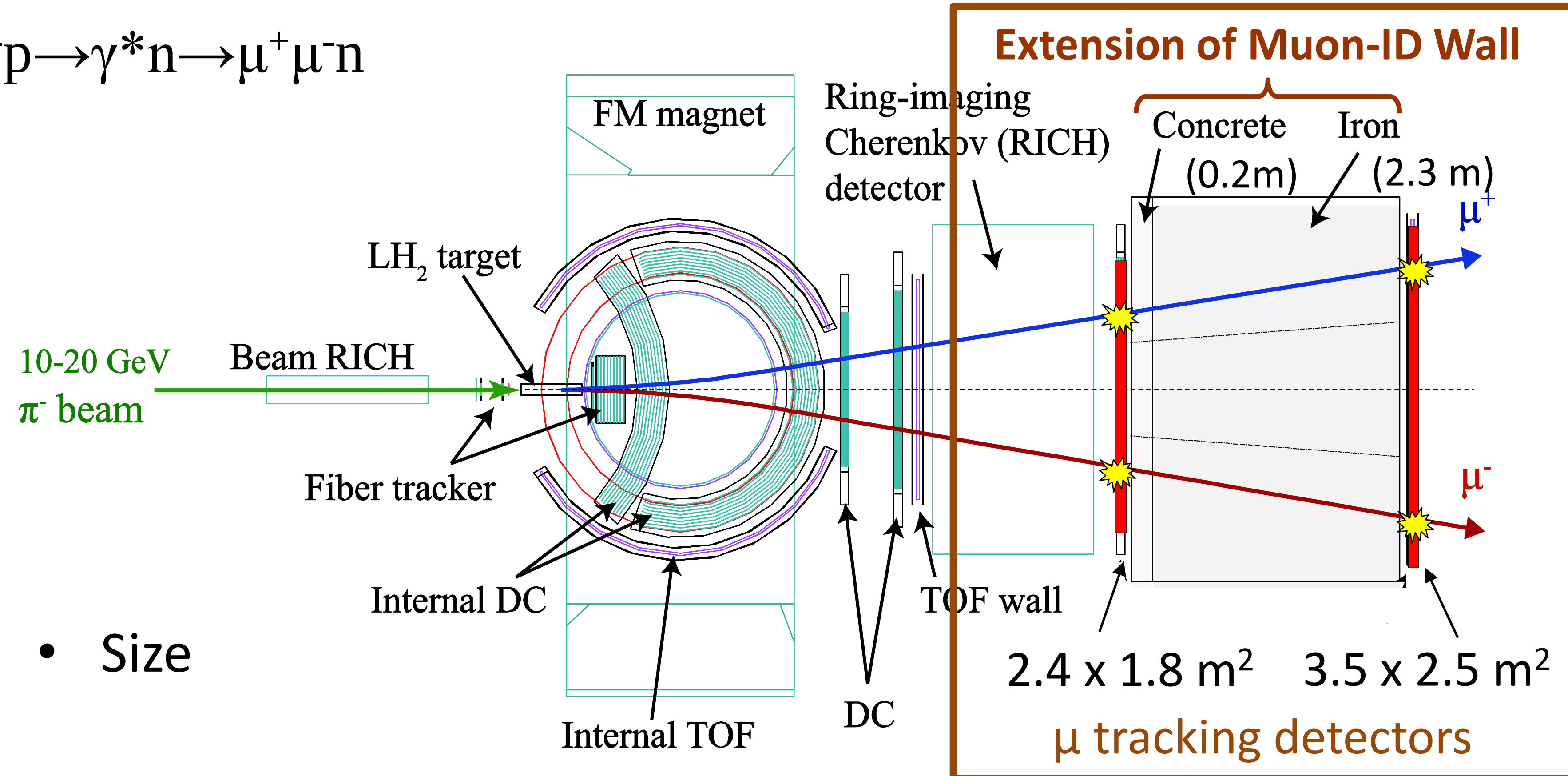
- LoI (W.C. Chang et al.)

https://j-parc.jp/researcher/Hadron/en/pac_1901/pdf/LoI_2019-07.pdf

- Update simulation for proposal

Muon detector

$\pi^- p \rightarrow \gamma^* n \rightarrow \mu^+ \mu^- n$



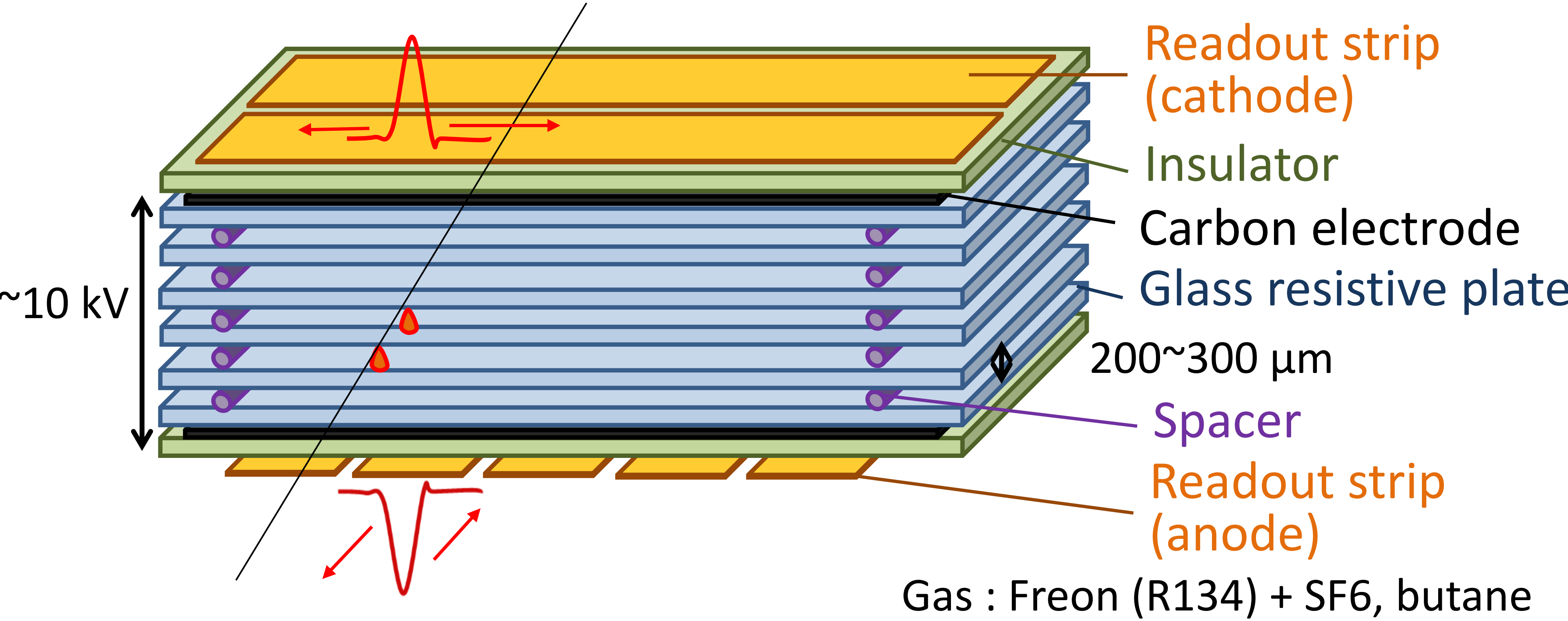
- Size

BG
- μ from π, K decay
- Combinatorial BG from different reactions

- Good position resolution : ~ 1 mm (upstream), ~5 cm (downstream)
- Good timing resolution
- Large area

TOF-tracker using Multi-gap Resistive Plate Chamber

Multi-gap Resistive Plate Chamber (MRPC)



- Resistive Plate -> Avoid discharge
- Small gap -> Good time resolution
- Multi gap -> High efficiency, better time resolution

- Can be used under magnetic field
- Low cost

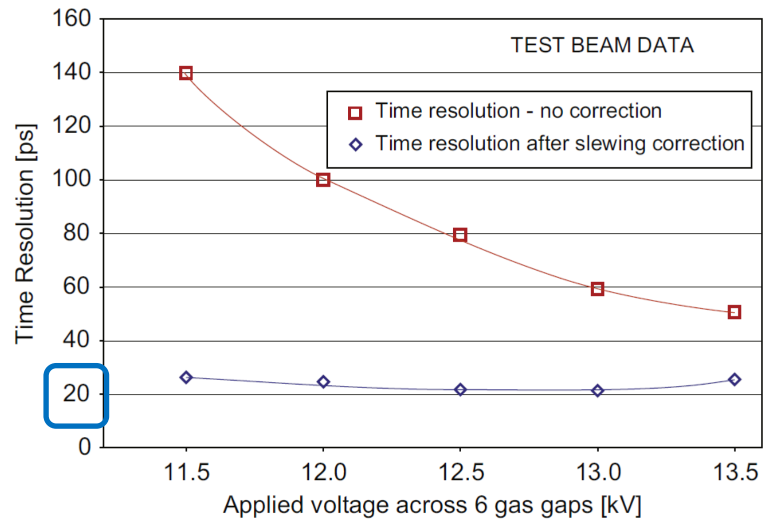
Has been used mainly for TOF

MRPC time resolution

Prototype

- Best : ~20 ps
  - 160 µm x 6 x 4 gap (Avalanche ~ 8 ps)
  - Small trigger : 1 cm x 1 cm
  - 10 GHz oscilloscope

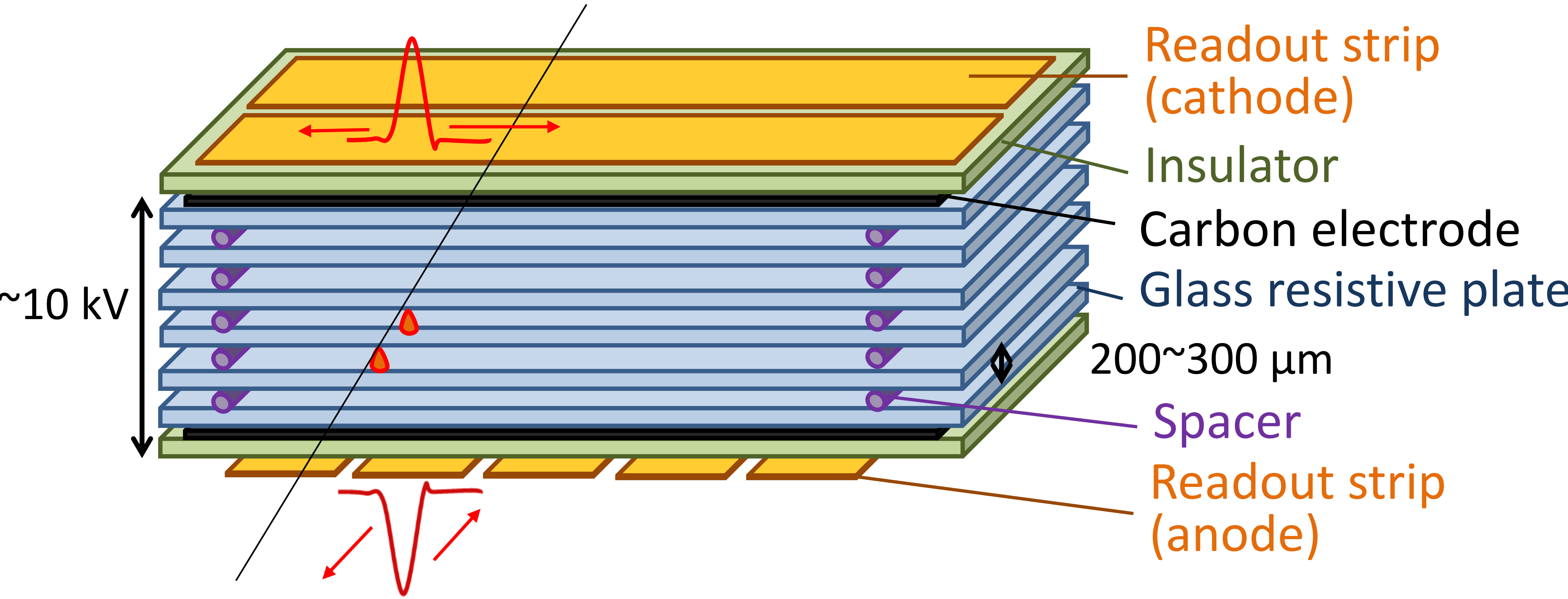
S. An et al., NIM 594 (2008) 39



TOF system

- ALICE (2.4 cm x 3.7 cm readout strip) : ~ 60 ps
- BES III (2.4 cm x 9.1 ~14.1 cm readout strip) : ~ 60 ps
- BGOegg (2.5 cm x 100 cm readout strip) : ~ 60 ps (middle of strip)

Position sensitivity



- Narrow strip pitch -> Good position resolution
- Different strip direction for anode strip and cathode strip

Ability to measure both timing & position by a single detector

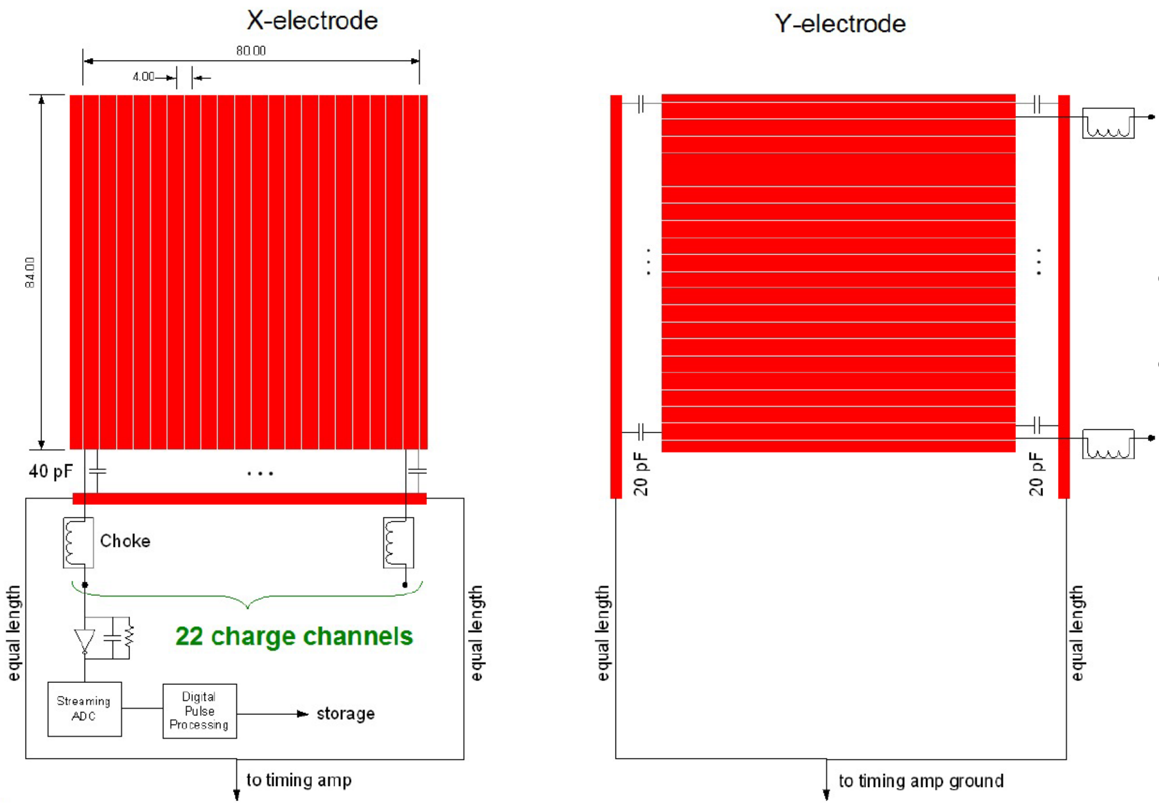
TOF-tracker

A few reports of prototype production
Not used in a physics experiment

⇒ Aim to build the 1st practical TOF-tracker

Example of a prototype TOF-tracker

- A. Blanco et al., JINST 7 (2012) P11012



- **8 cm x 8 cm small** RPC
- **4 mm** pitch readout strip
- 5 x 350 μm gap

- **Charge is induced several strip**

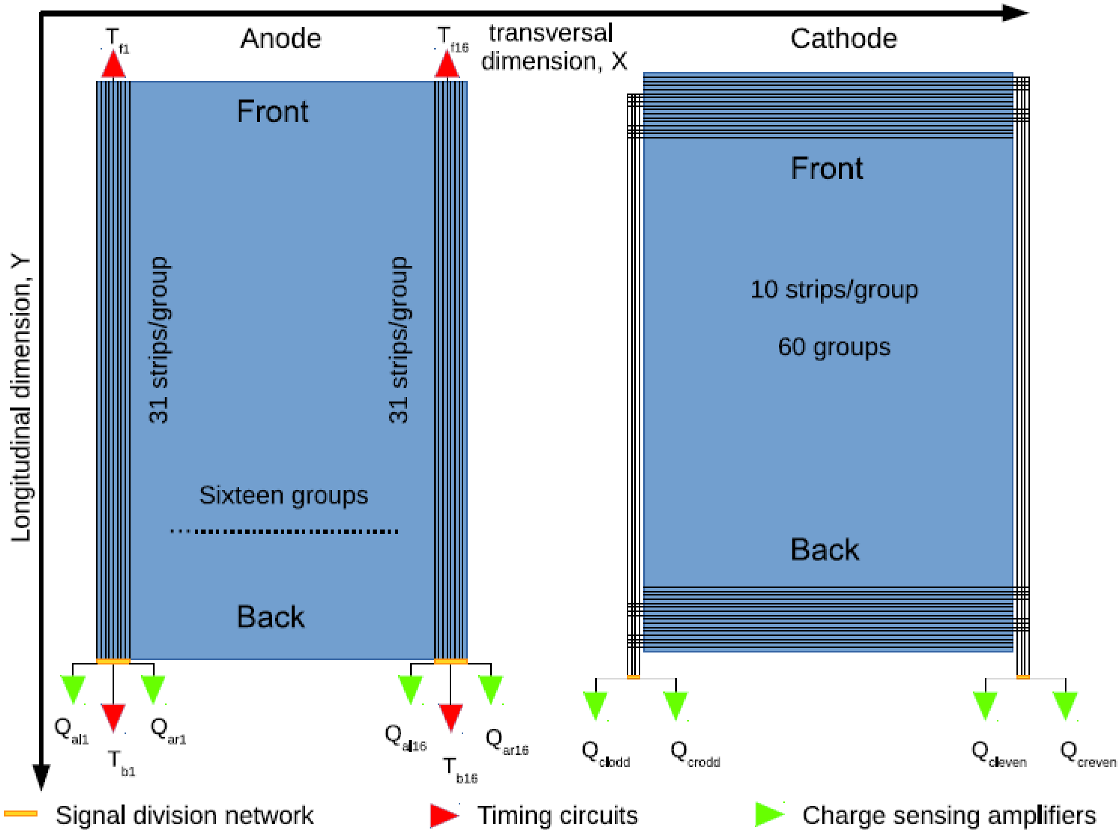
- CR test

- Position resolution = 40-70 μm
- Time resolution ~ 80 ps

It is possible to have σ_X<100 μm, σ_T<100 ps by a single detector

A large prototype TOF-tracker

- P. Assis et al., JINST 11 (2016) C10002



- 1.5 m x 1.2 m
- 2.5 mm pitch strip
- 4 x 300 µm gap

- X : group 31 strips

$$X = \frac{Q_{al_i} - Q_{ar_i}}{Q_{al_i} + Q_{ar_i}} + x_{g_i}$$

- Y : group 10 strips

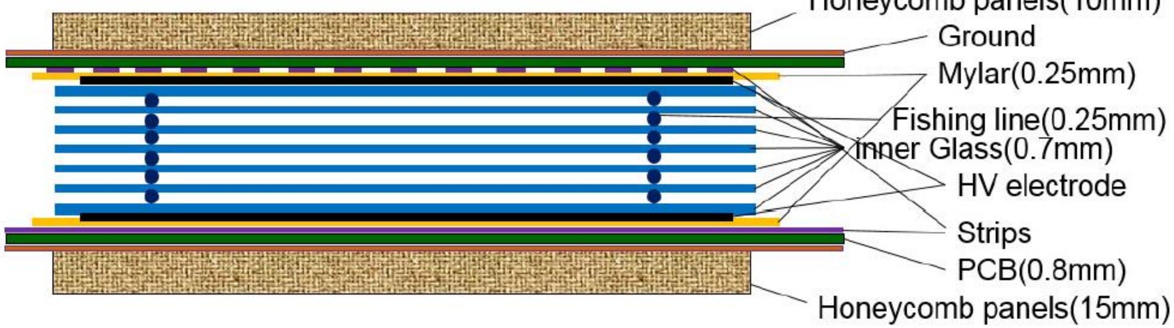
$$Y = \frac{Q_{cl_j} - Q_{cr_j}}{Q_{cl_j} + Q_{cr_j}} + y_{g_j}$$

CR test

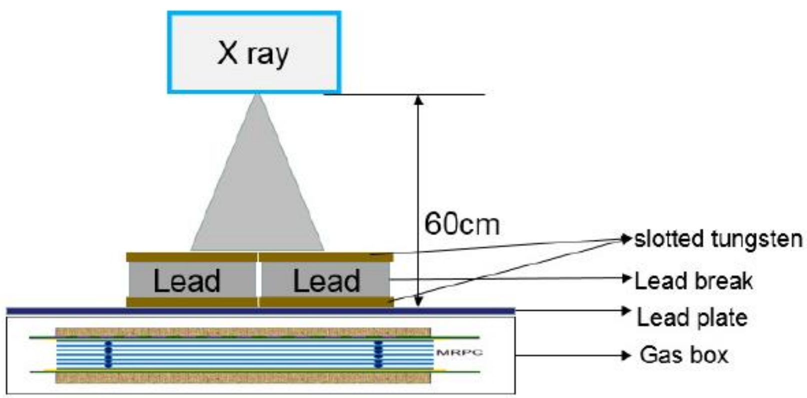
- Position resolution = 1.3 mm (X), 8.1 mm (Y)
- Time resolution = 150 ps
- Efficiency = 92% (tracking), 72% (timing)

A large TOF-tracker

- L. Shi et al., JINST 19 (2014) C12038
- J. Wang et al., JINST 11 (2016) C11008



- 1.16 m x 1.16 m
- 3.64 mm pitch strip
- 6 x 250 μm gap

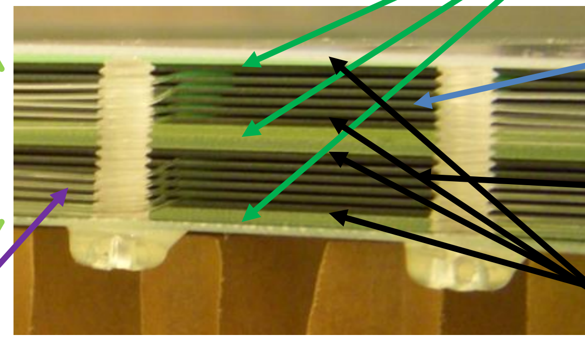


X-ray test with a narrow slit (126 μm)

Position resolution in very narrow region

- Time resolution = 65 ps
- Position resolution = 210 μm ?
- Efficiency = 98.7%

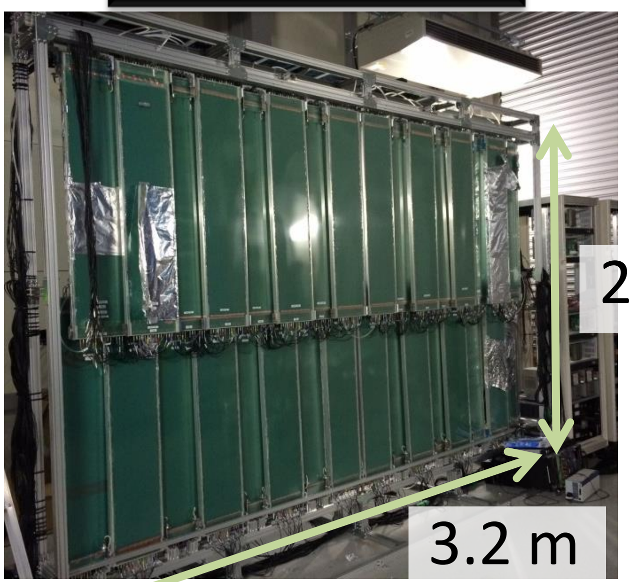
MRPC development



Hand made detector

- Experience
- Material tests

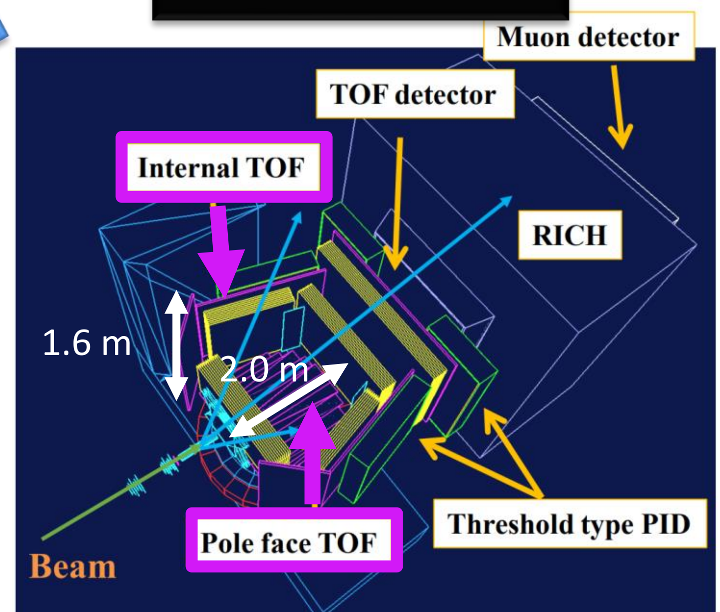
BGOegg-RPC



The 1st TOF-RPC in Japan

N. Tomida et al., JINST 9 C10008 (2014)

E50 TOF-RPC



Developing in A02 group

What is difficult for high resolution MRPC

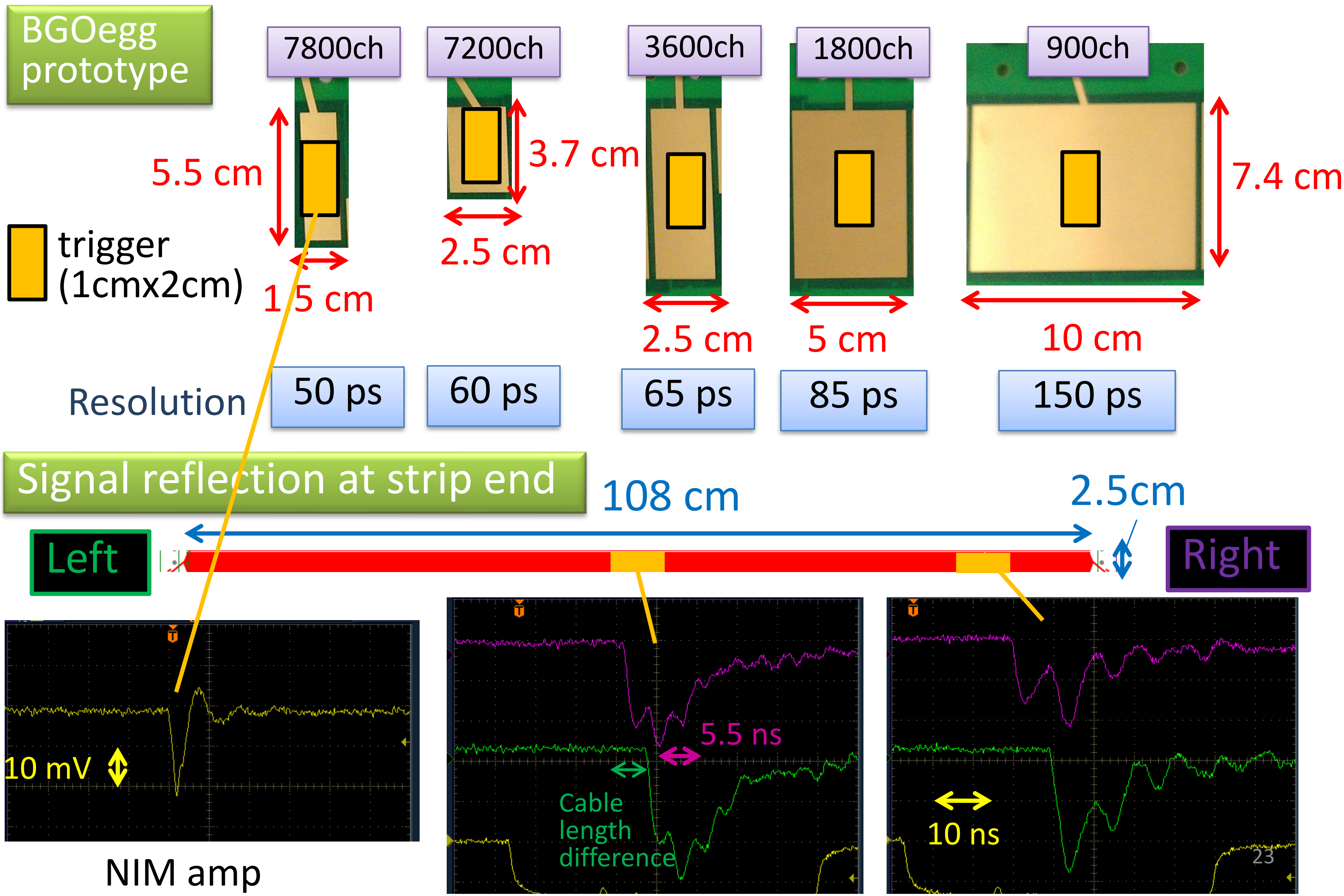
- Avalanche : σ_T ~15 ps (250 μm x 10 gaps), σ_x<100 μm

1. Large readout strip
   - Deterioration of signals during the propagation
   - Reflection at the end of strip
2. High gain & high speed amplifier
   - Small fast RPC signal

RPC	Strip	amp + discri
ALICE	2.4 x 3.7 cm^2	NINO ASIC
STAR	3.15 x 6.3 cm^2	NINO ASIC
BES-III	2.4 x 9.1~14.1 cm^2	NINO ASIC
FOPI	0.2 x 90 cm^2	FEE5
CBM	several geometries	PADI ASIC
BGOegg	2.5 cm x 100 cm^2	Academia Sinica
LEPS2	2.5 cm x 200 cm^2	Academia Sinica

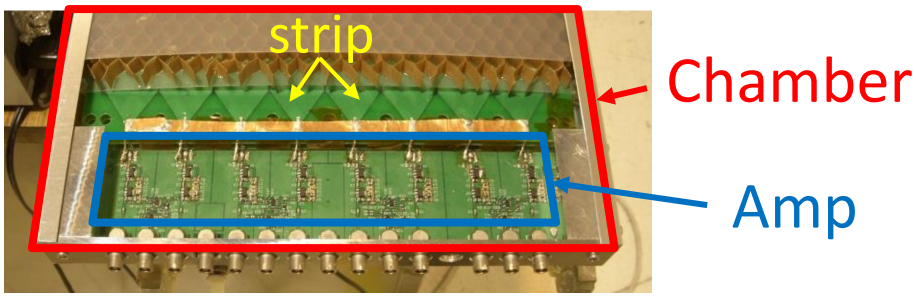
Small strip & custom ASIC amp are mainstream

Large strip

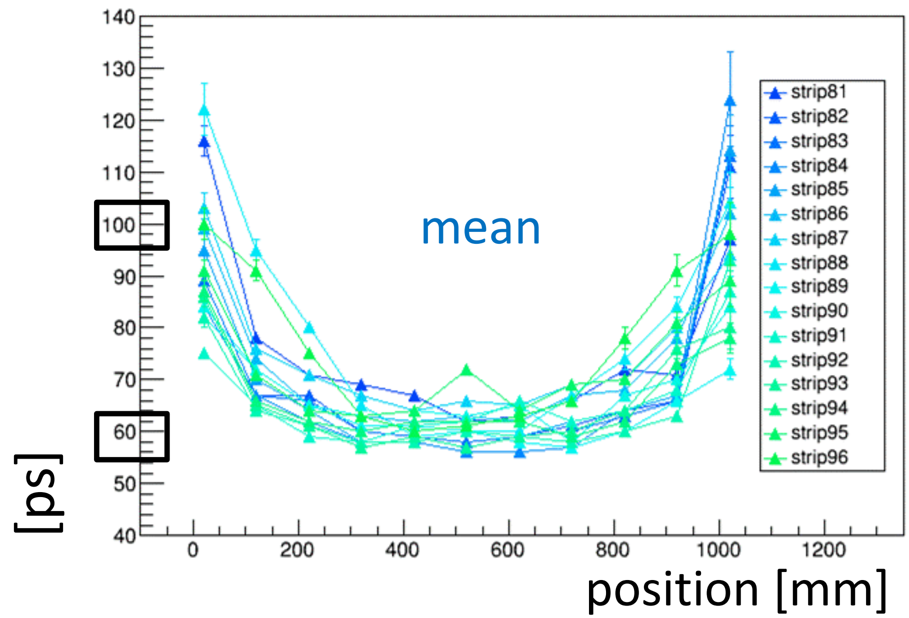

BGOegg prototype
7800ch
7200ch
3600ch
1800ch
900ch
5.5 cm
3.7 cm
7.4 cm
trigger (1cmx2cm)
1.5 cm
2.5 cm
2.5 cm
5 cm
10 cm
Resolution
50 ps
60 ps
65 ps
85 ps
150 ps
Signal reflection at strip end
108 cm
2.5cm
Left
Right
10 mV
5.5 ns
Cable length difference
10 ns
NIM amp

BGOegg-RPC

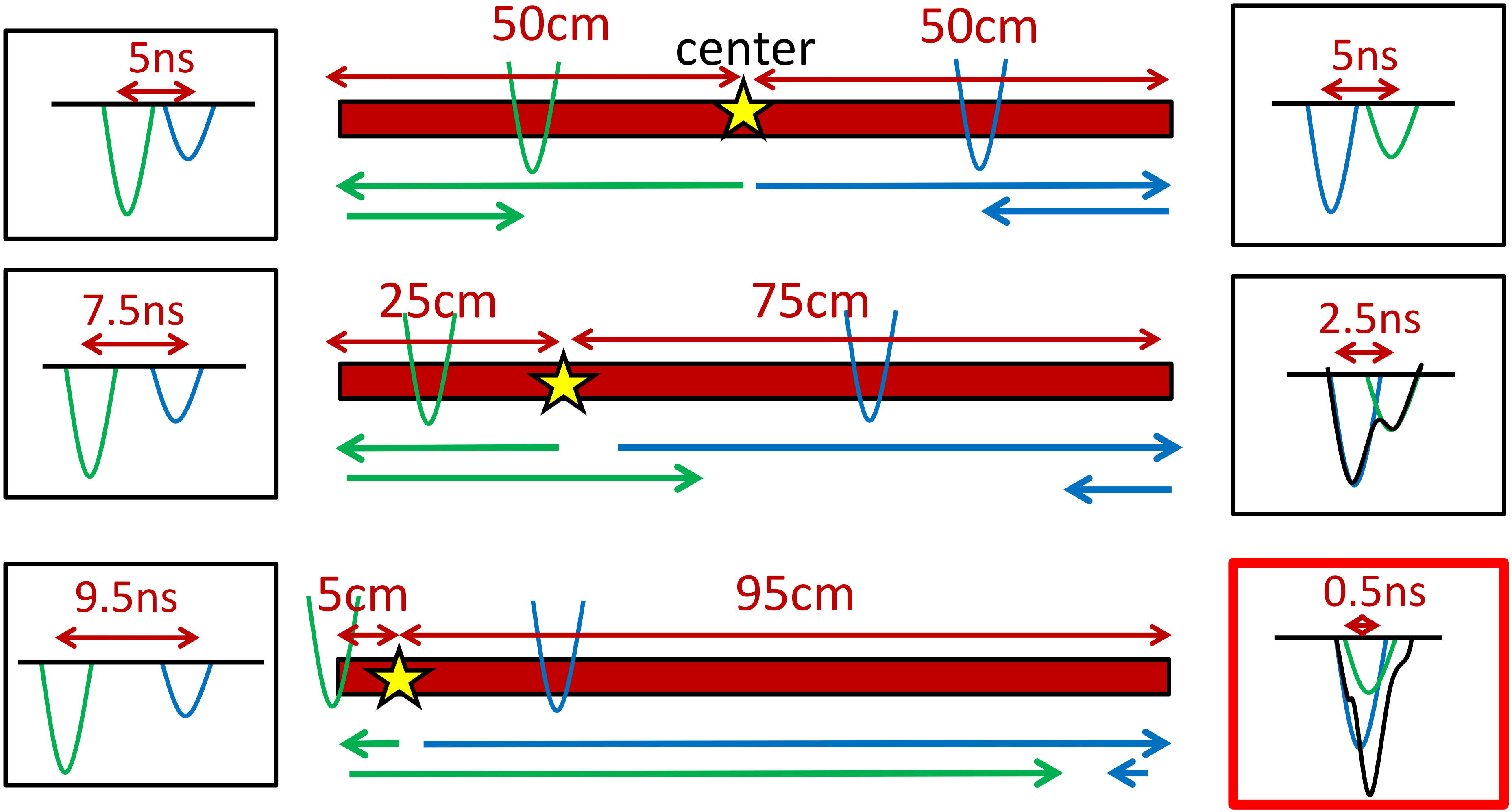
Directly connect
impedance-matched amp



Bad resolution near
the end of strips



Signal reflection effect near strip-end

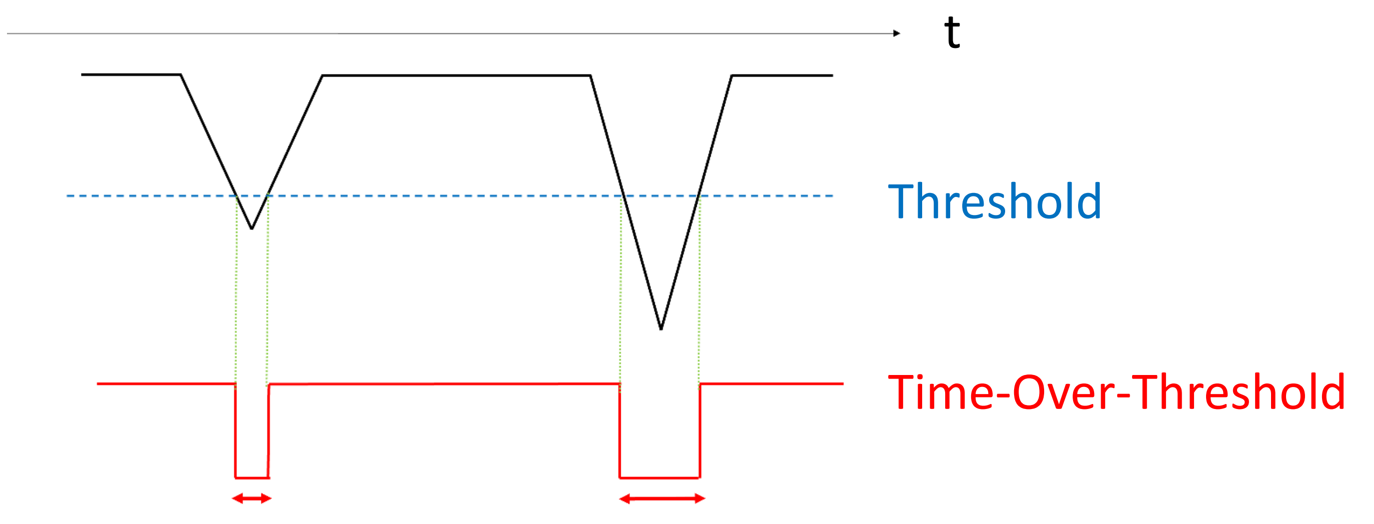


(signal velocity : ~5ns/100cm)

Amp

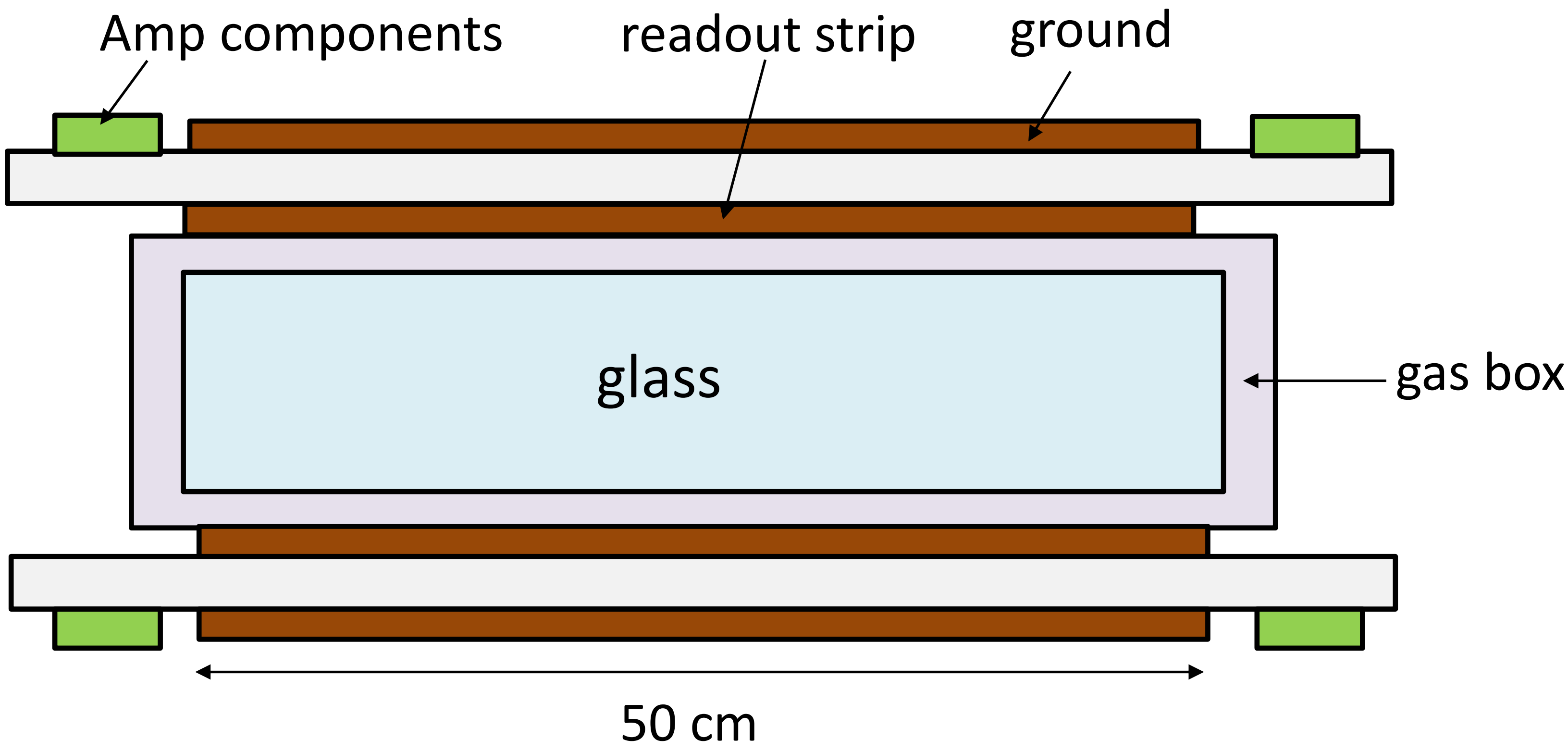
- The chip used for the BGOegg-RPC amp is discontinued
- New amp development with Academia Sinica group in Taiwan
- New amp test with a prototype E50-TOF RPC in July

- Challenge : E50 triggerless streaming DAQ
  - Measure charge & perform time-walk correction using Time-Over-Threshold



Prototype detector

- In preparation
- Place amp components on strip PCB
- Strip width optimization for impedance matching with amp
- Gas tight only glasses



- Different strip pitch, different strip length

Summary

- Nucleon is the most familiar hadron to us
  -but its structure is not well understood
- Aim to measure Generalized Parton Distributions
  at high momentum beam line in J-PARC using E50 spectrometer
- 1st measurement of exclusive Drell-Yan process : $\pi^- p \rightarrow \gamma^* n \rightarrow \mu^+ \mu^- n$
- Build a TOF-tracker using multi-gap resistive plate chamber
  for μ ID system
- Started preparation of a prototype detector