J-PARC高運動量ビームラインにおけるチャームバリオン分光実験のデザイン

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Research Center for Nuclear Physics (RCNP)

計測システム研究会 @ RCNP
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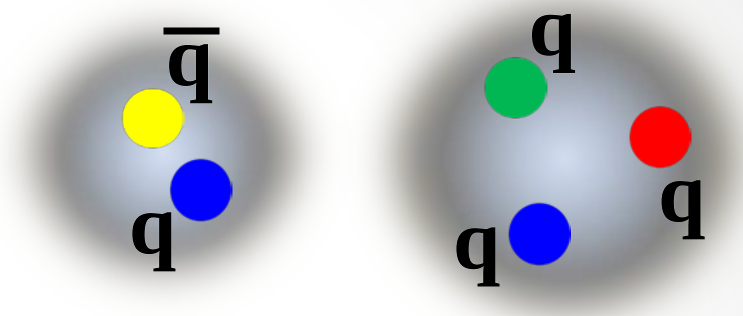
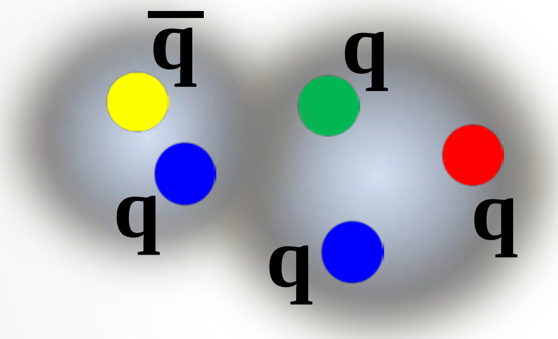
- **Physics motivation**
- **Experiment at J-PARC**
  - **High-momentum beam line**
  - **Design of Spectrometer system**
- **Key devices**
  - **RICH**
  - **High-rate detectors**
  - **DAQ**
- **Summary**

What is a building block of hadrons ?

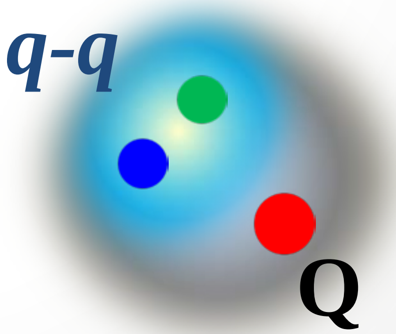
Constituent Quark





Exotic hadron

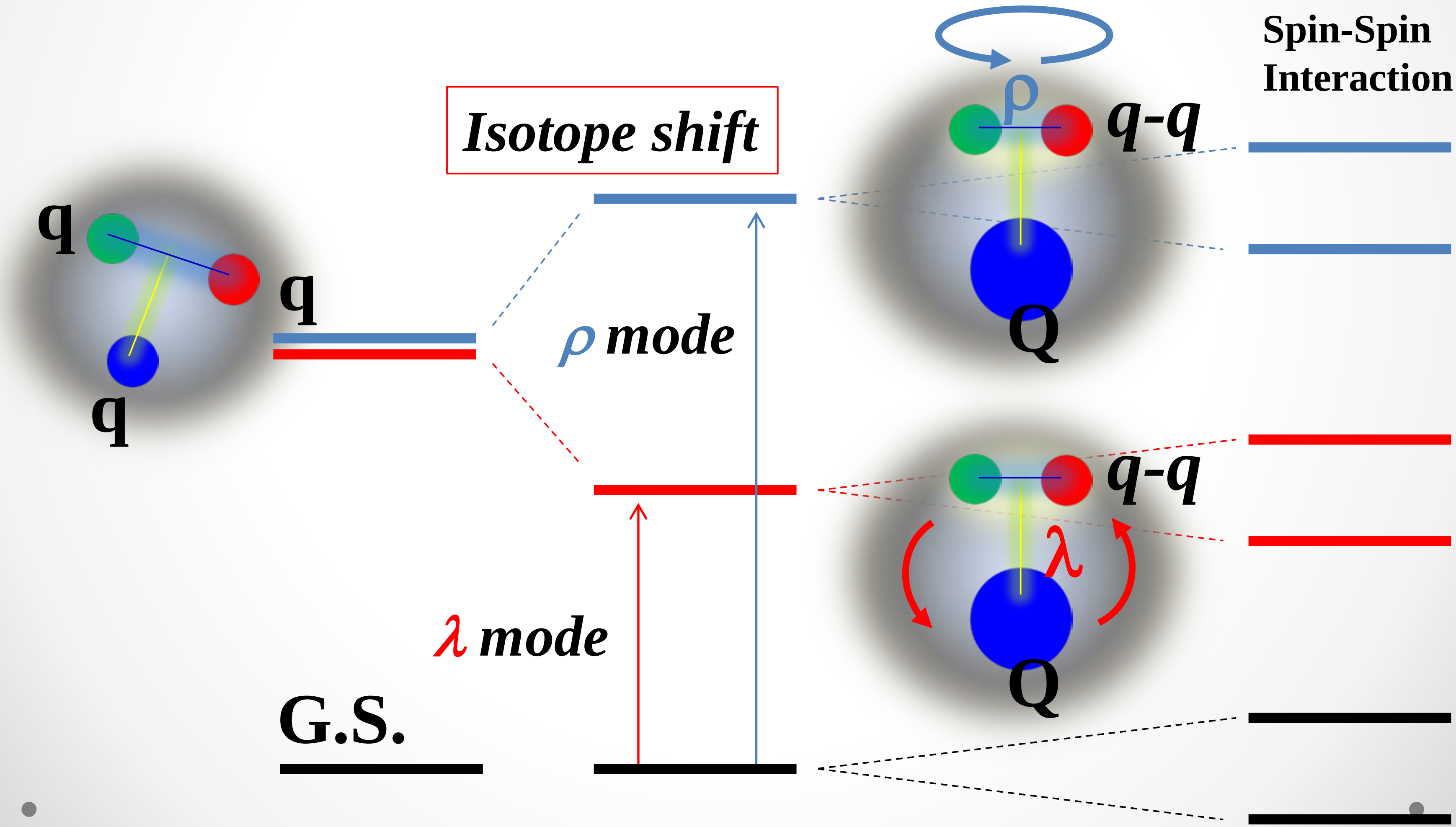
q-q correlation (diquark)



Charmed baryon spectrum: “Excitation Mode”

Heavy Quark: **Weak color-magnetic interaction**

⇒”*q-q*” isolated and developed: “q-q + Q”



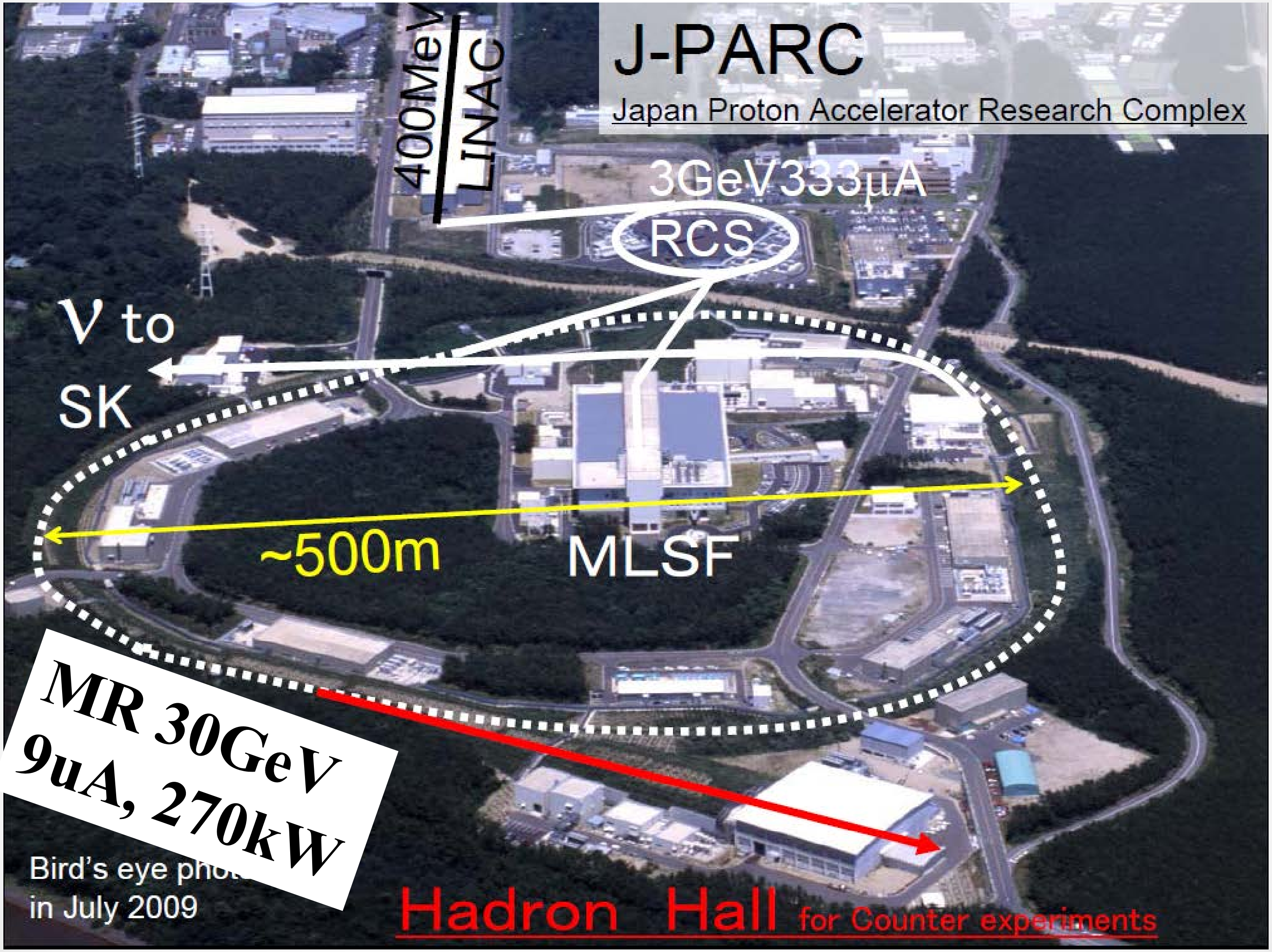
Experiment

High-momentum beam line

Design of Spectrometer system

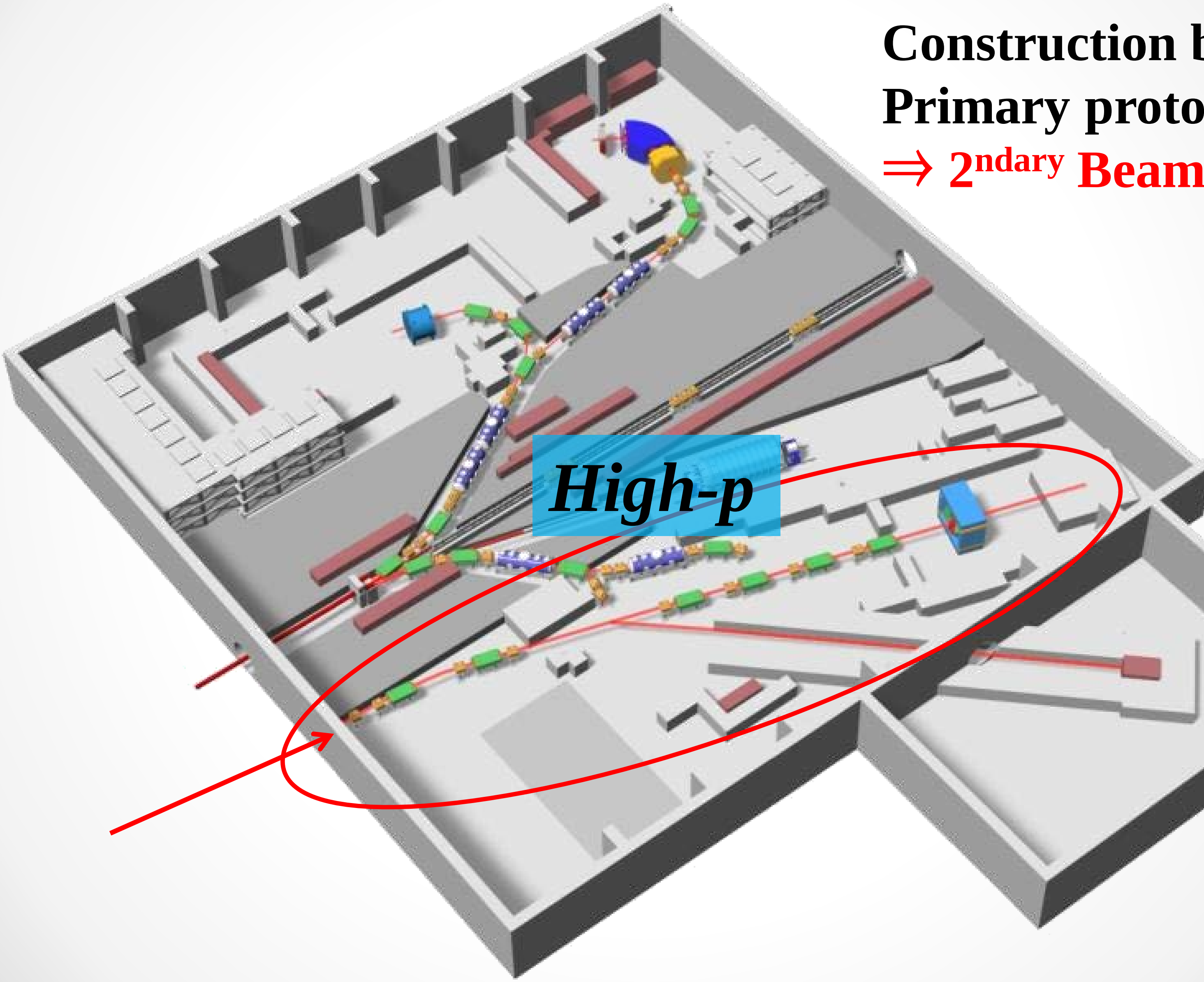
Simulation

J-PARC & Hadron Facility



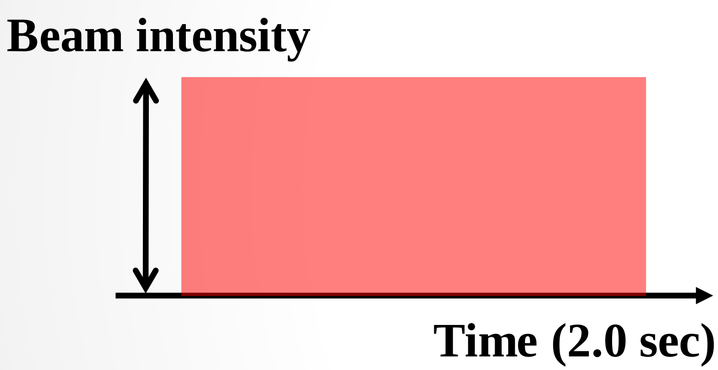
High-momentum beam line

Construction by 2018 ?
Primary proton beam
⇒ 2^{ndary} Beam

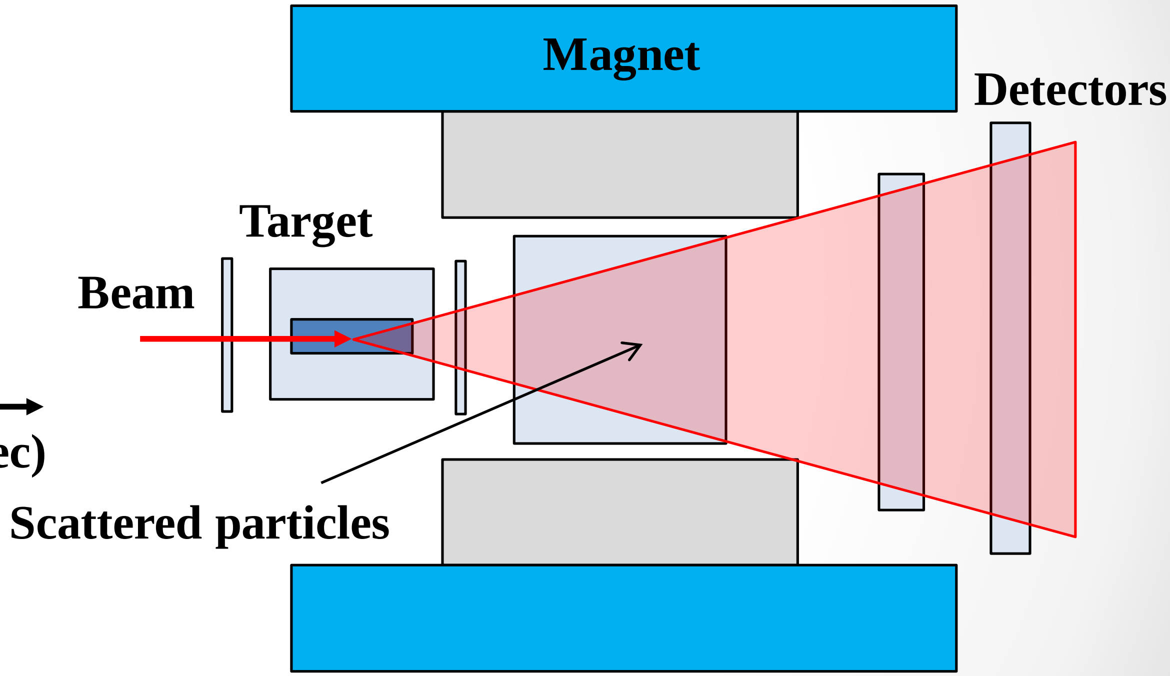


Experimental conditions in Hadron hall

Slow beam extraction
(2.0 sec/ 6.0 sec cycle)



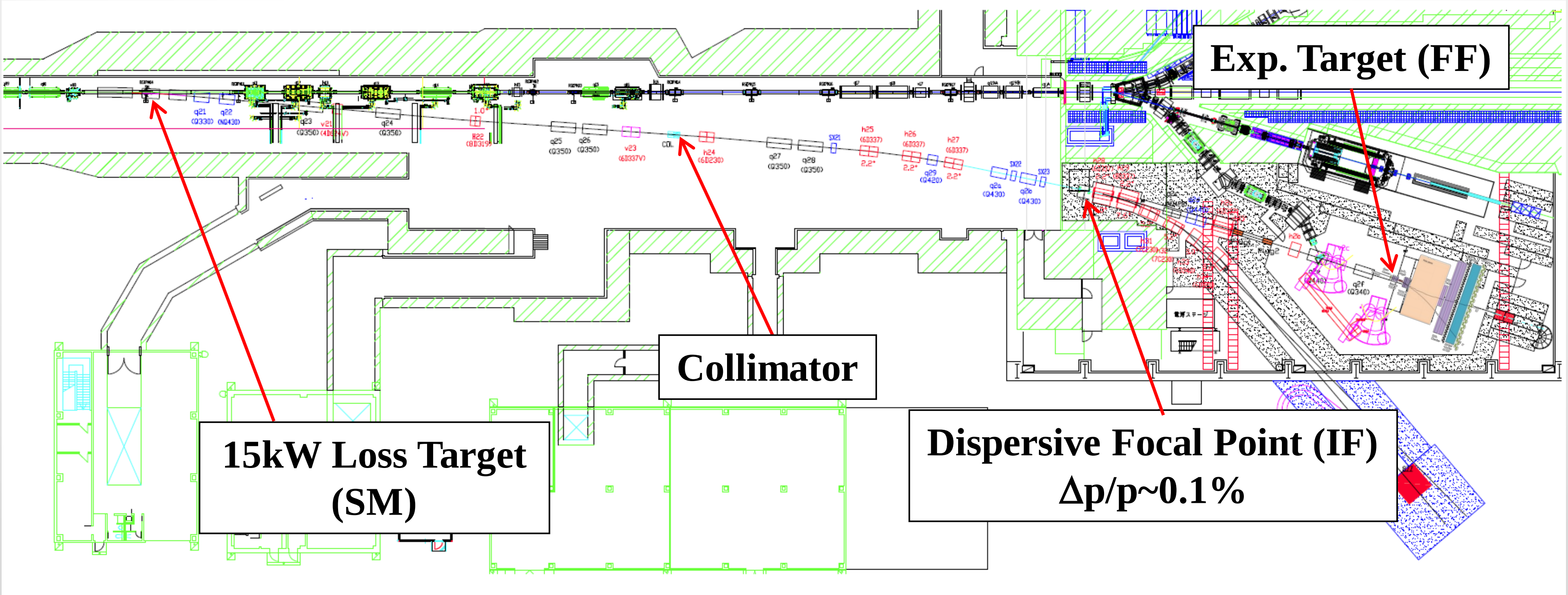
Fixed target experiment
c.f. GR, SKS, LHCb, CLAS, LEPS1&2



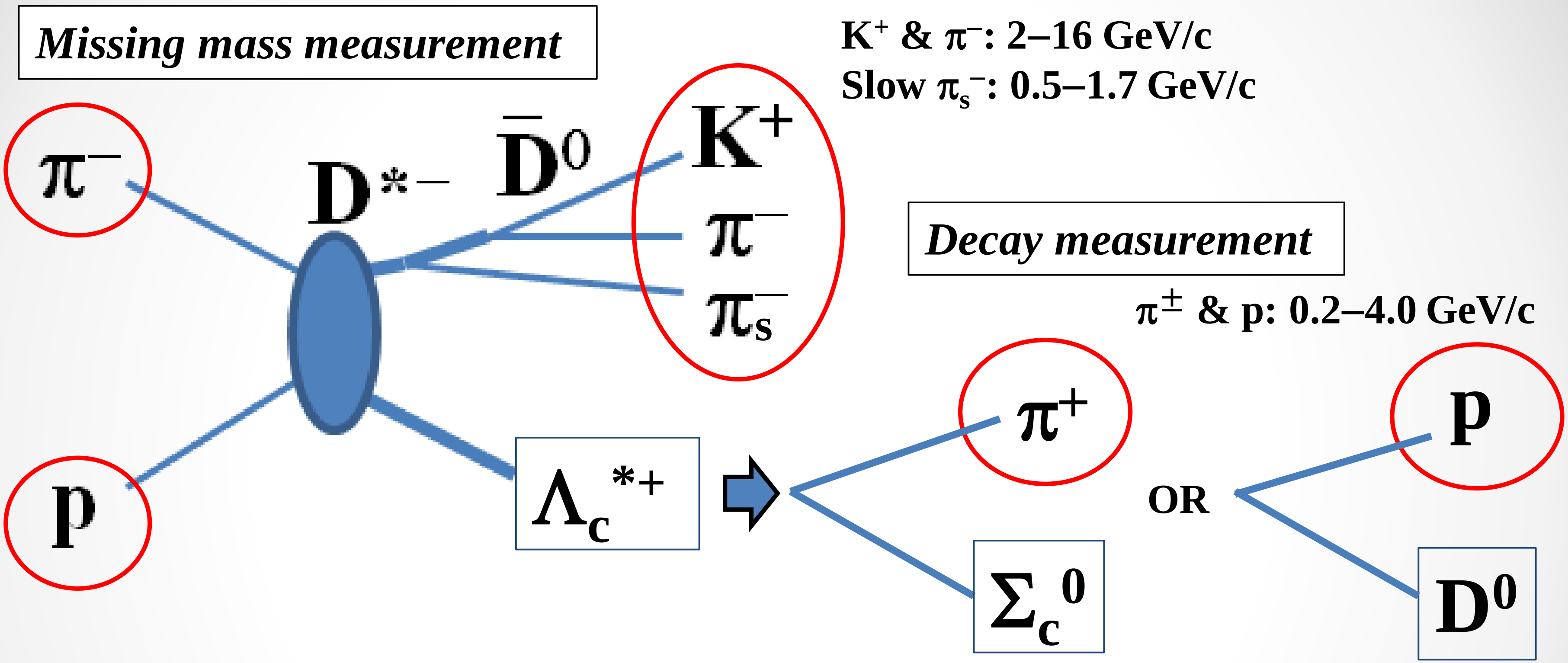
- **DC 2ndary beam: 10^7–10^8 Hz, 100 × 100 mm², $\Delta p/p$ = 2–3%**
  - **Beam measurement is essential.**
- **Forward scattering by In-Flight reaction**

High-momentum beam line for 2ndary beam

- **High-intensity beam: > 1.0×10⁷ Hz π (< 20 GeV/c)**
  - **Unseparated beam**
- **High-resolution beam: Δp/p ~ 0.1%(rms)**
  - **Momentum dispersive optics method**



Experiment



$\pi^- + p \rightarrow Y_c^{*+} + D^{*-}$ reaction @ 20 GeV/c

1) Missing mass spectroscopy

- $D^{*-} \rightarrow \bar{D}^0 \pi_s^- \rightarrow K^+ \pi^- \pi_s^-$: $D^{*-} \rightarrow \bar{D}^0 \pi_s^-$ (67.7%), $\bar{D}^0 \rightarrow K^+ \pi^-$ (3.88%)

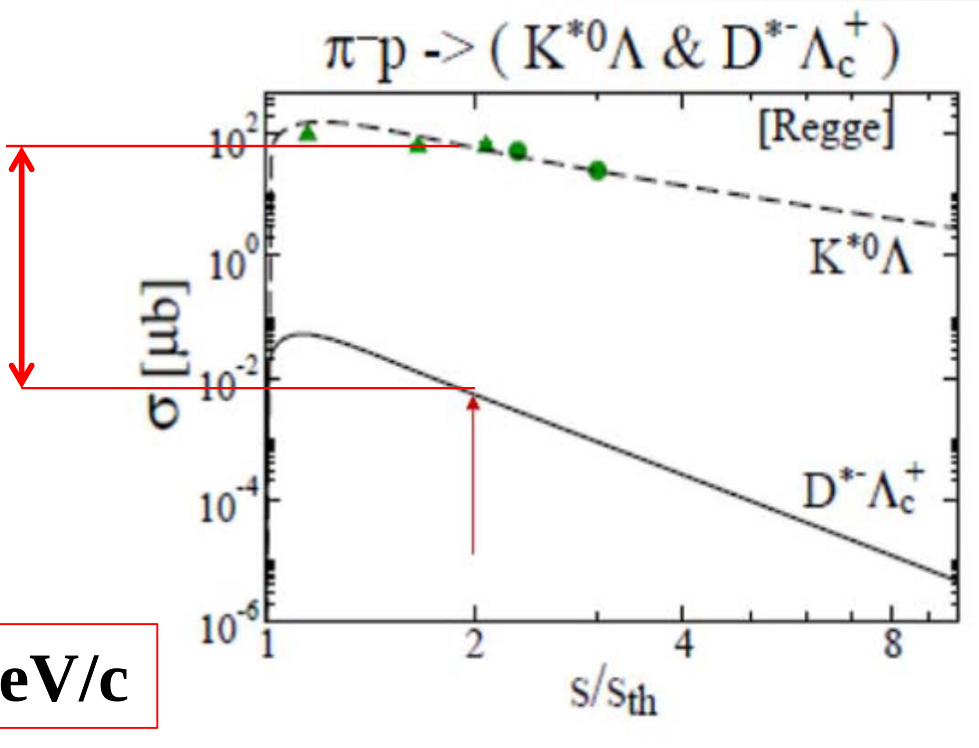
2) Decay measurement

- Decay particles ($\pi^\pm$ & proton) from Y_c^*

Production cross section

High energy 2-body reaction
based on the Regge theory

Normalized
to strangeness production
⇒ Charm production: ~10^{-4}



No old data @ 10-20 GeV/c

✱ **Assumed production cross section: σ ~ 1 nb**

- $\pi^- + p \rightarrow \Lambda_c^+ + D^{*-}$ reaction @ 13 GeV/c: σ < 7 nb (BNL data)

- **High-rate beam & High-rate detector system**
  - Beam intensity: 6×10^7 /2.0 sec spill (~1 MHz/mm)

Old experiments

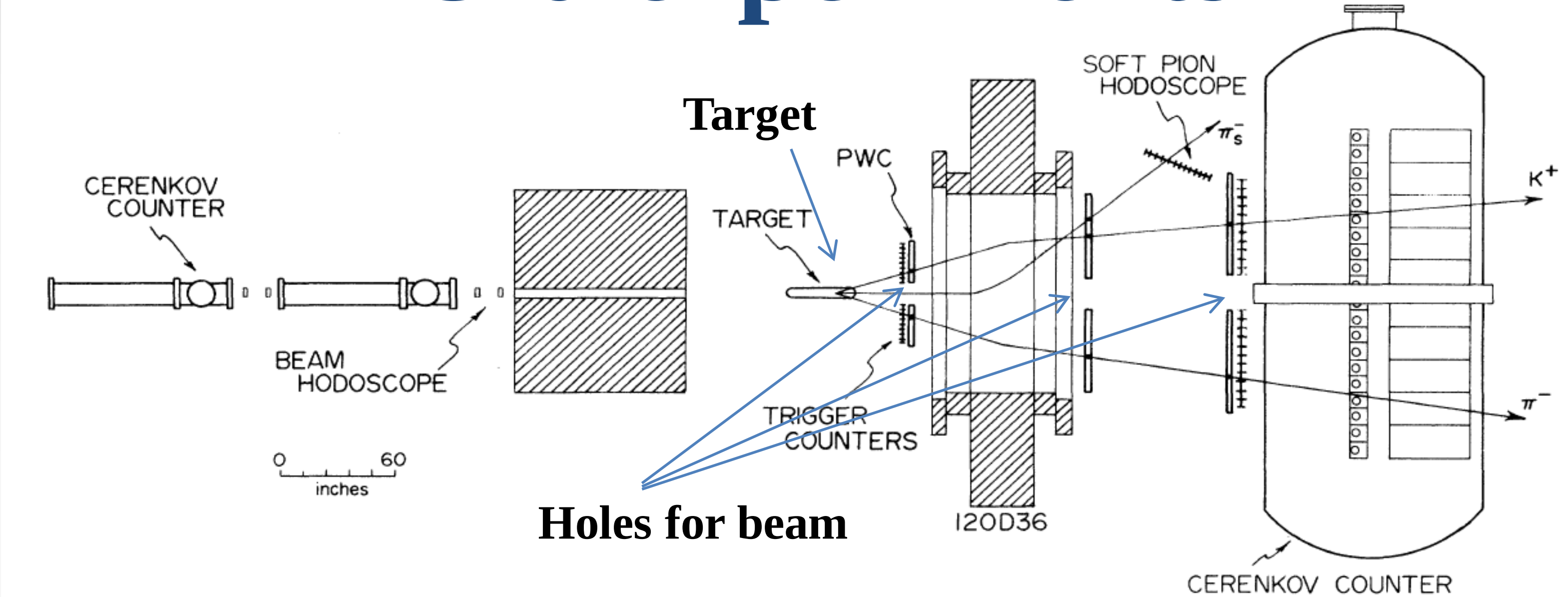


FIG. 1. Plan view of apparatus.

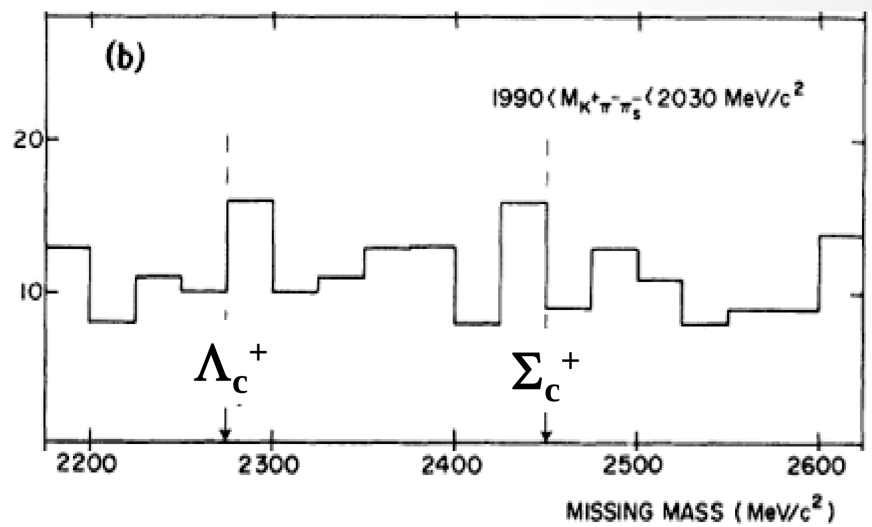
BNL experiment in 1983

- $\pi^- p \rightarrow \Lambda_c^+ D^{*-}$ @ 13 GeV/c
  - $N_\pi = 3 \times 10^{12}$
  - $\Delta M = 20$ MeV

✱ $\Delta p/p < 1$ %

✱ Acceptance = a few 10%

Missing mass spectrum



Design procedure

1) Reaction condition: Kinematics

- Momentum & angular distribution
- Correlations of scattered particles
- Production & decay angle dependences

2) Magnet: Dipole

- Exist magnet or new one
- Gap size: Acceptance
- Magnetic field: Bending power

3) Detector

- Detector choice
  - Size: Acceptance
  - Time & position resolution
  - Configuration: Layer, segment
  - Counting rate per segment: Beam through
- PID type

4) Performance study

- Momentum resolution: Material thickness
- Invariant & missing mass distribution
- Target energy loss struggling & multiple scattering
- PID performance

5) Realistic magnet and detector design

- Full simulation
- Detector R&D, Readout modules, cabling

Beam momentum
& target change

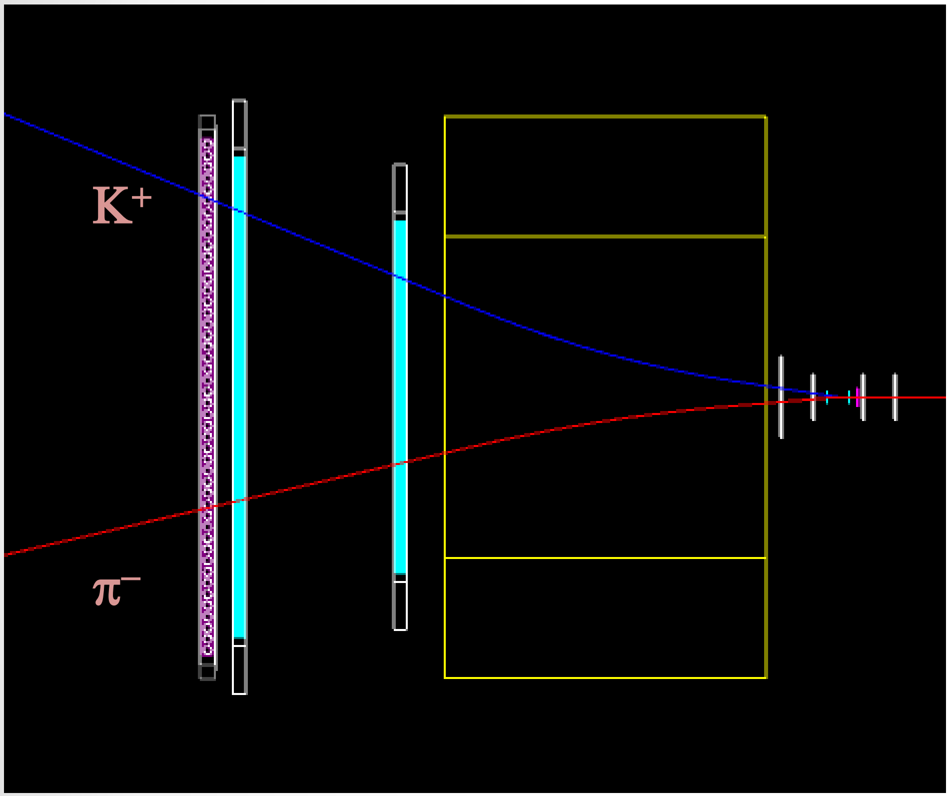
Magnetic field
Strength & Shape

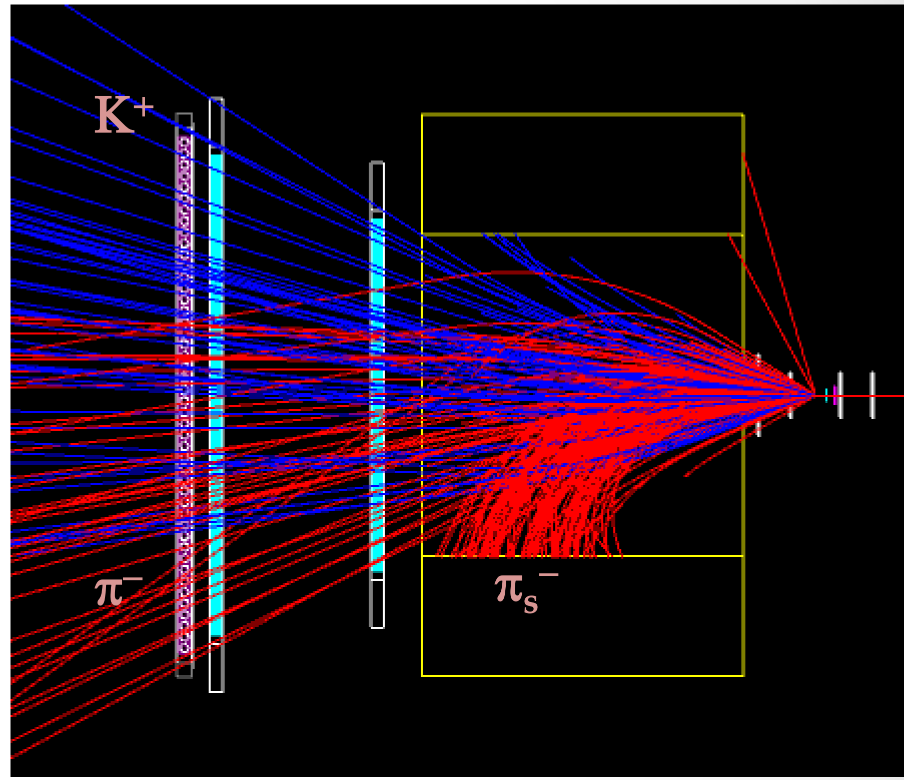
Fast or Slow bending,
Gap size, Magnet shape

Size, Layer,
Segment,
Thickness,
Shape

Feedback to whole procuress
⇒ Minor changes

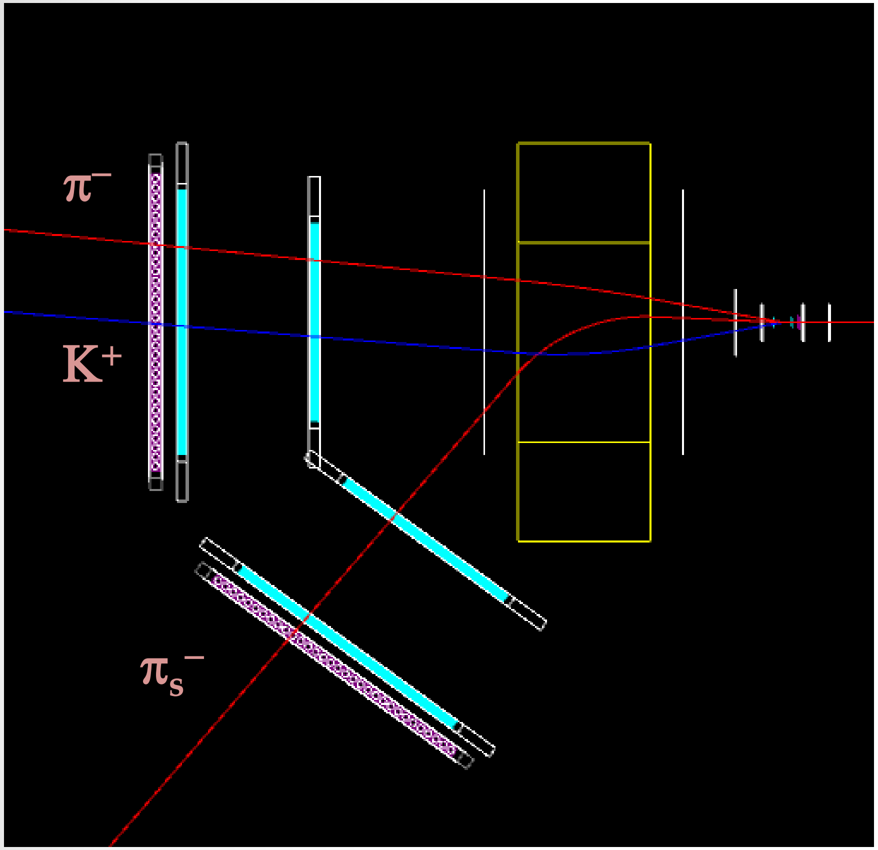
Spectrometer design

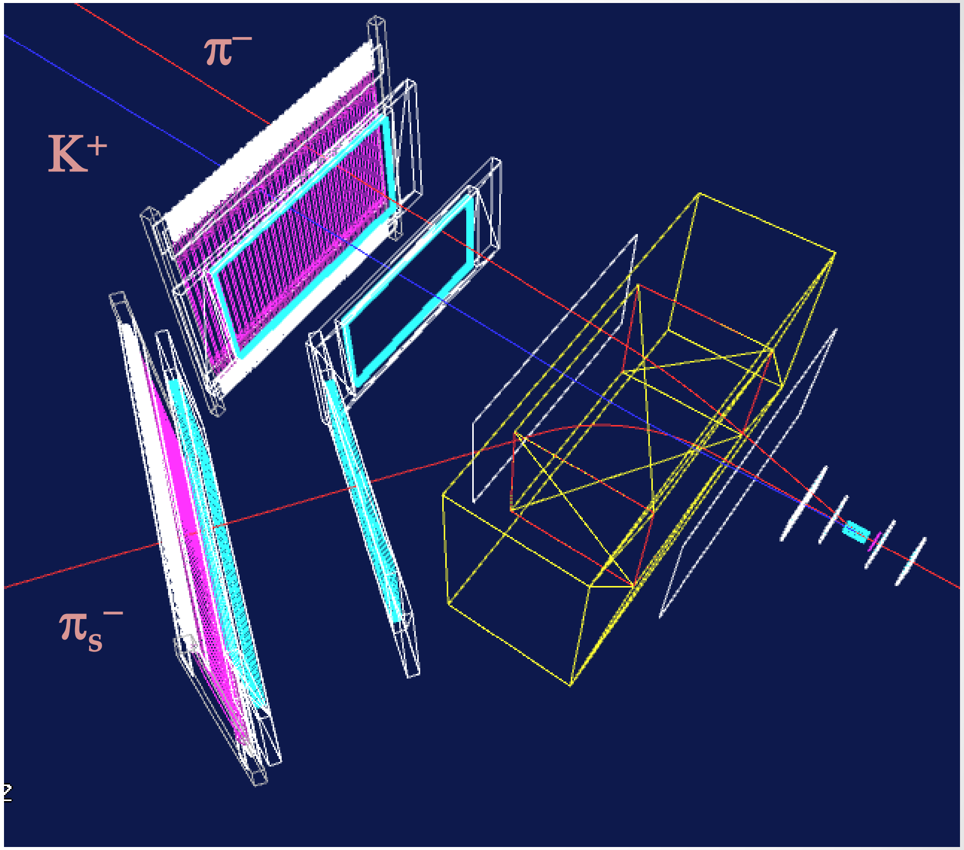




- **Primitive design ⇒ 1) Kinematics & 2) Magnet**
- **Magnet: Toy magnet**

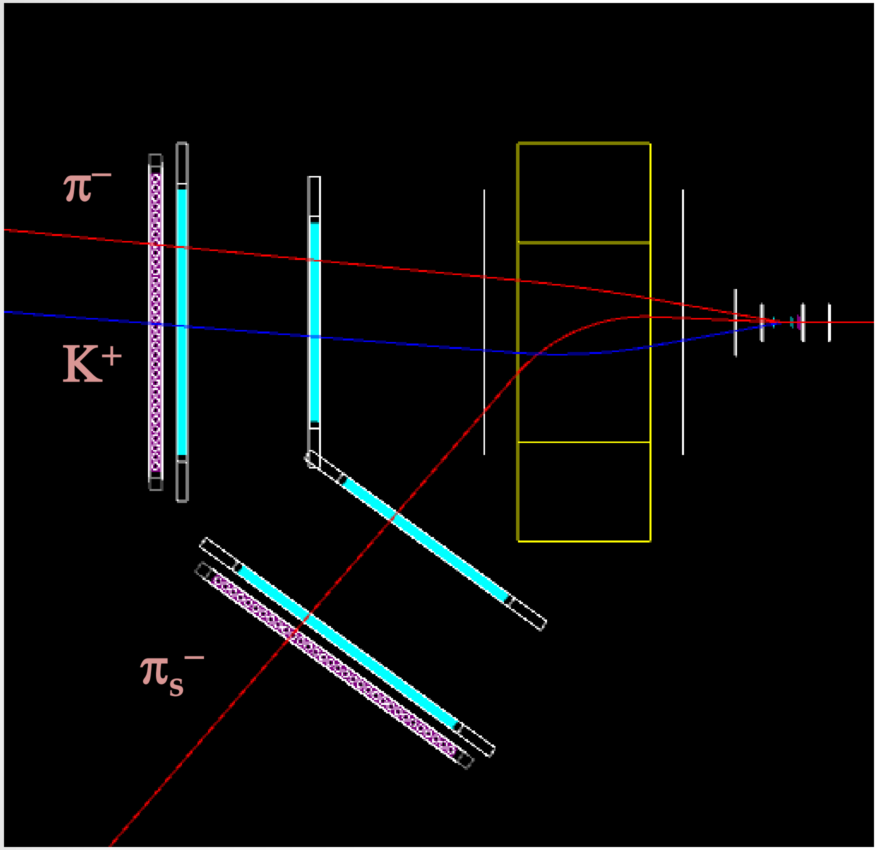
Spectrometer design

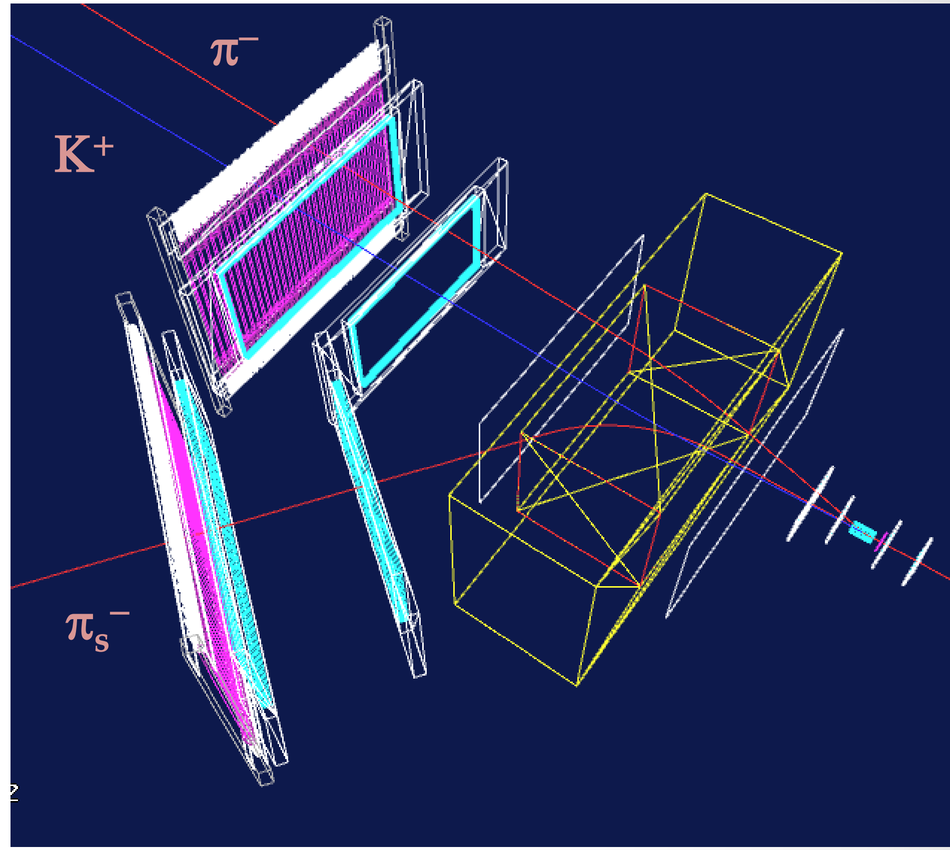




- 2-arm design ⇒ 2) Magnet
- Magnet: Super-BENKEI

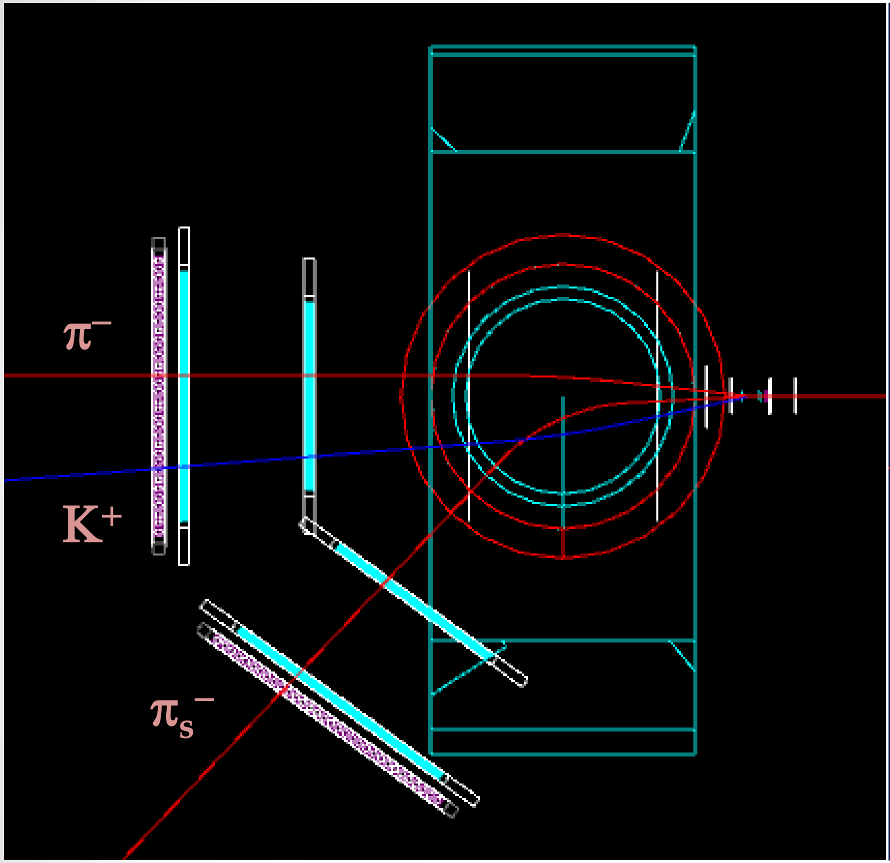
Spectrometer design

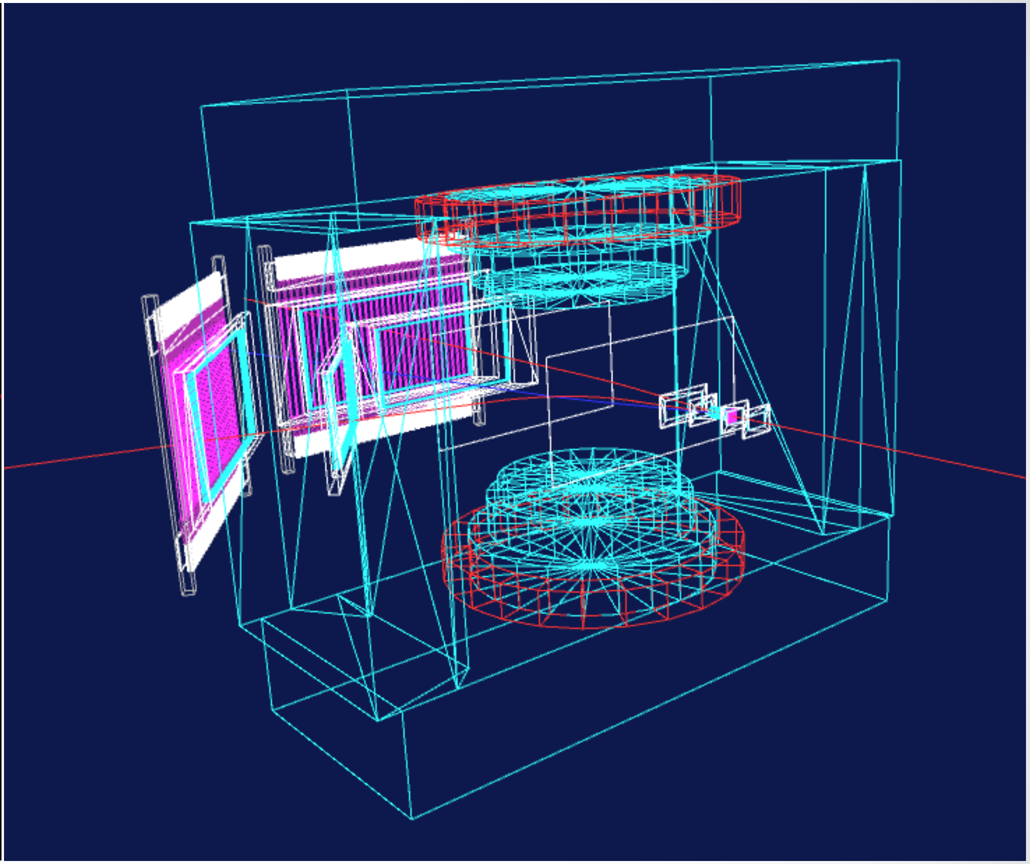




- 2-arm design ⇒ 2) Magnet
- Magnet: Super-BENKEI ⇒ すでに破棄！

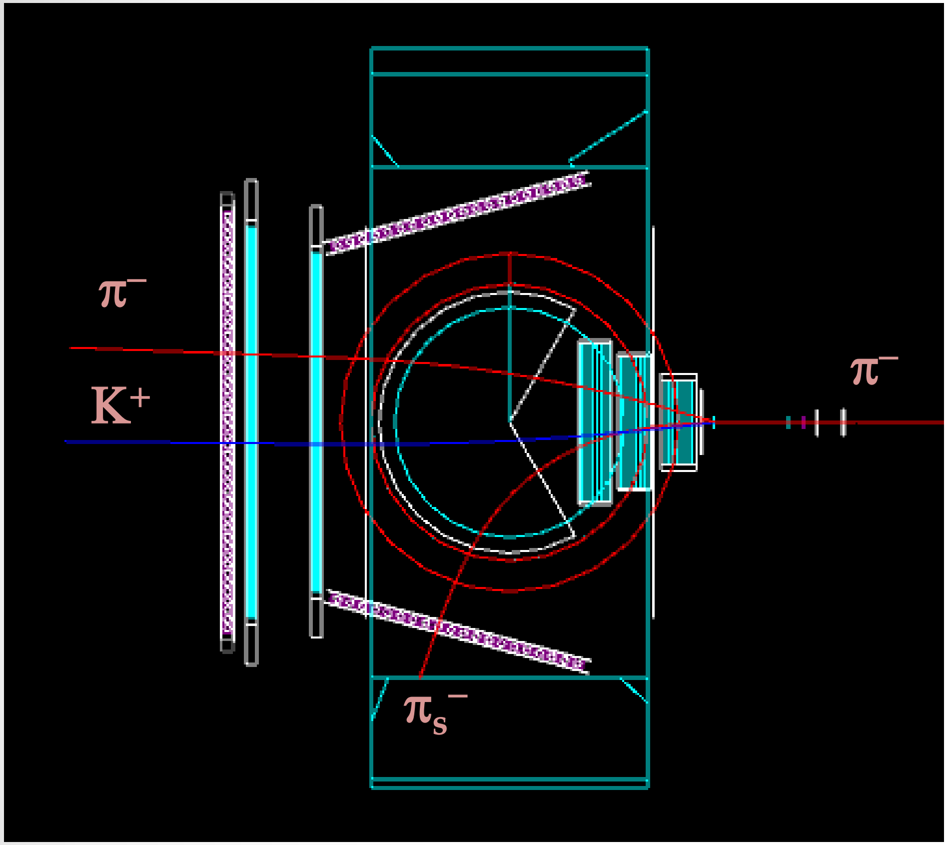
Spectrometer design

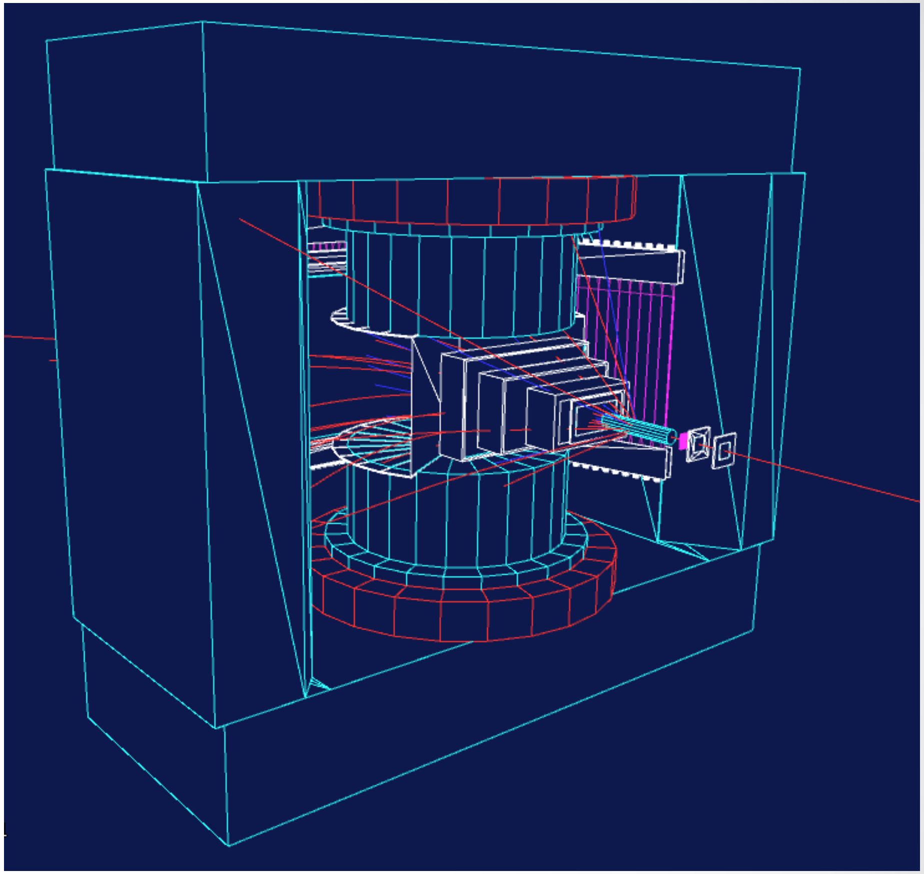




- 2-arm design⇒ 2) Magnet
- Magnet: FM magnet (E16 will use at High-p BL.)

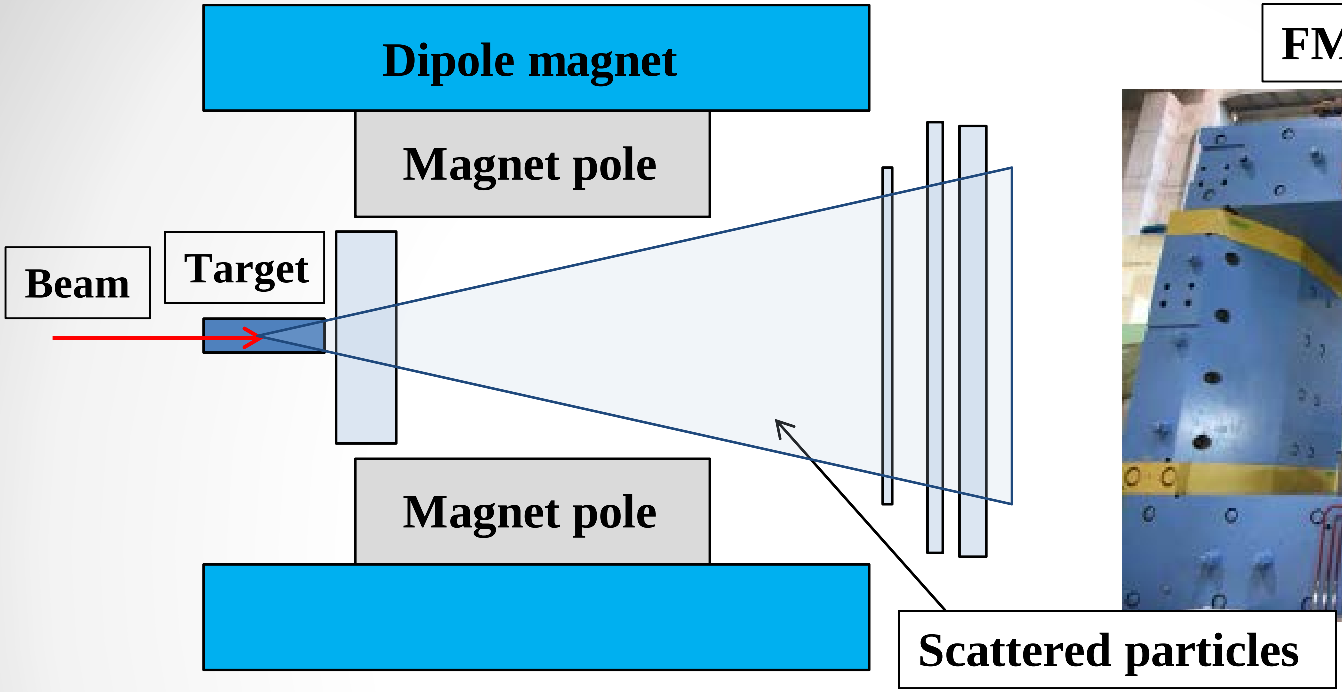
Spectrometer design





- **Single arm design ⇒ 3) Detector & 4) Resolution**
- **Magnet: FM magnet**

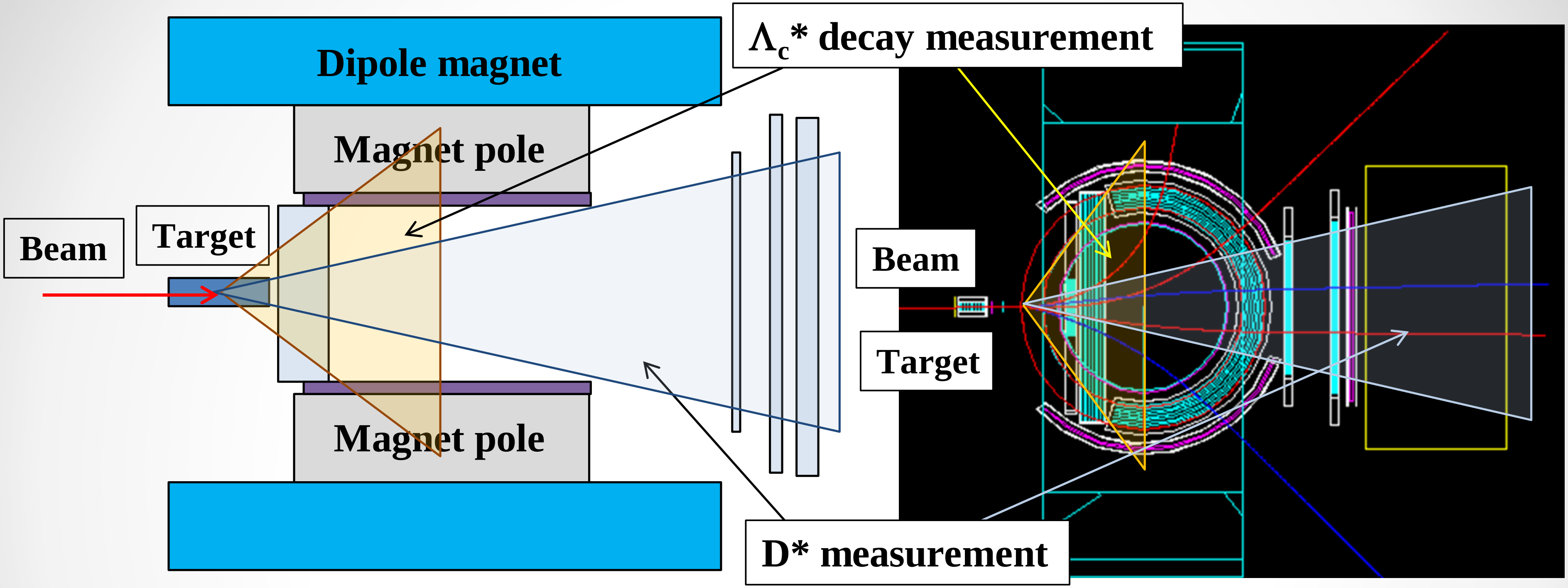
Spectrometer design



FM cyclotron magnet

- **High-rate beam & High-rate detector system**
  - **Beam intensity: 6×10^7 /2.0 sec spill (~1 MHz/mm)**
- **Dipole-magnet spectrometer**
  - **High-resolution: $\Delta p/p < 1\%$**

Spectrometer design



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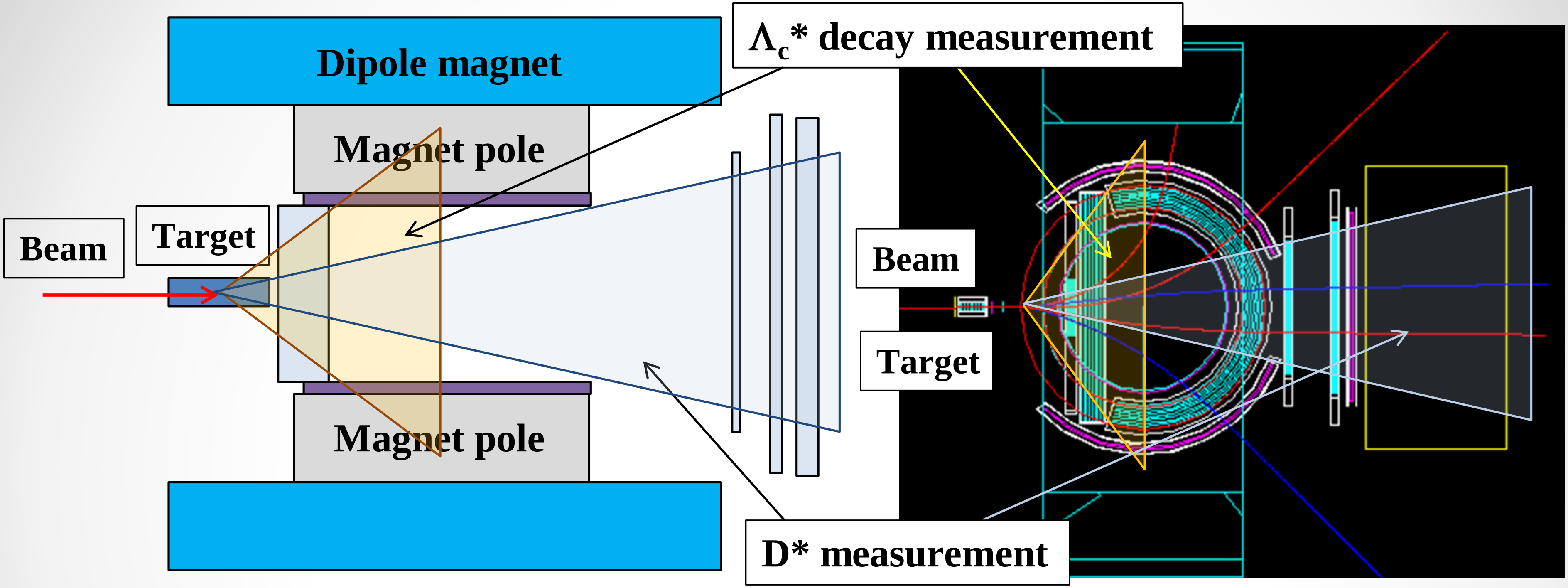
Spectrometer design



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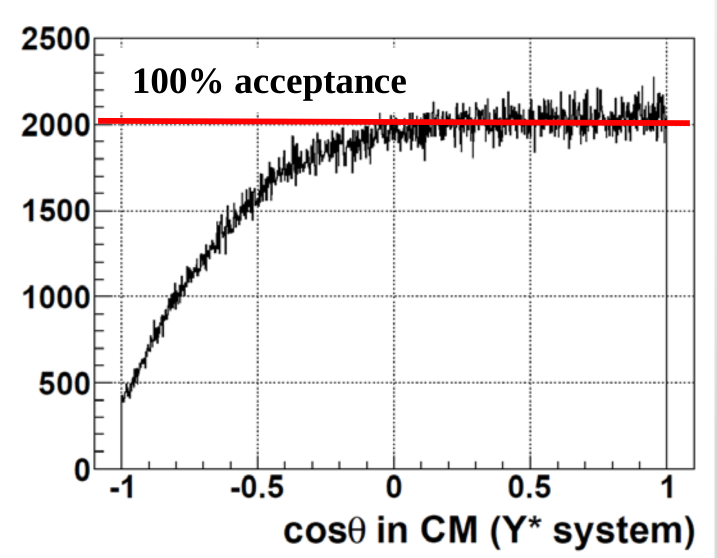

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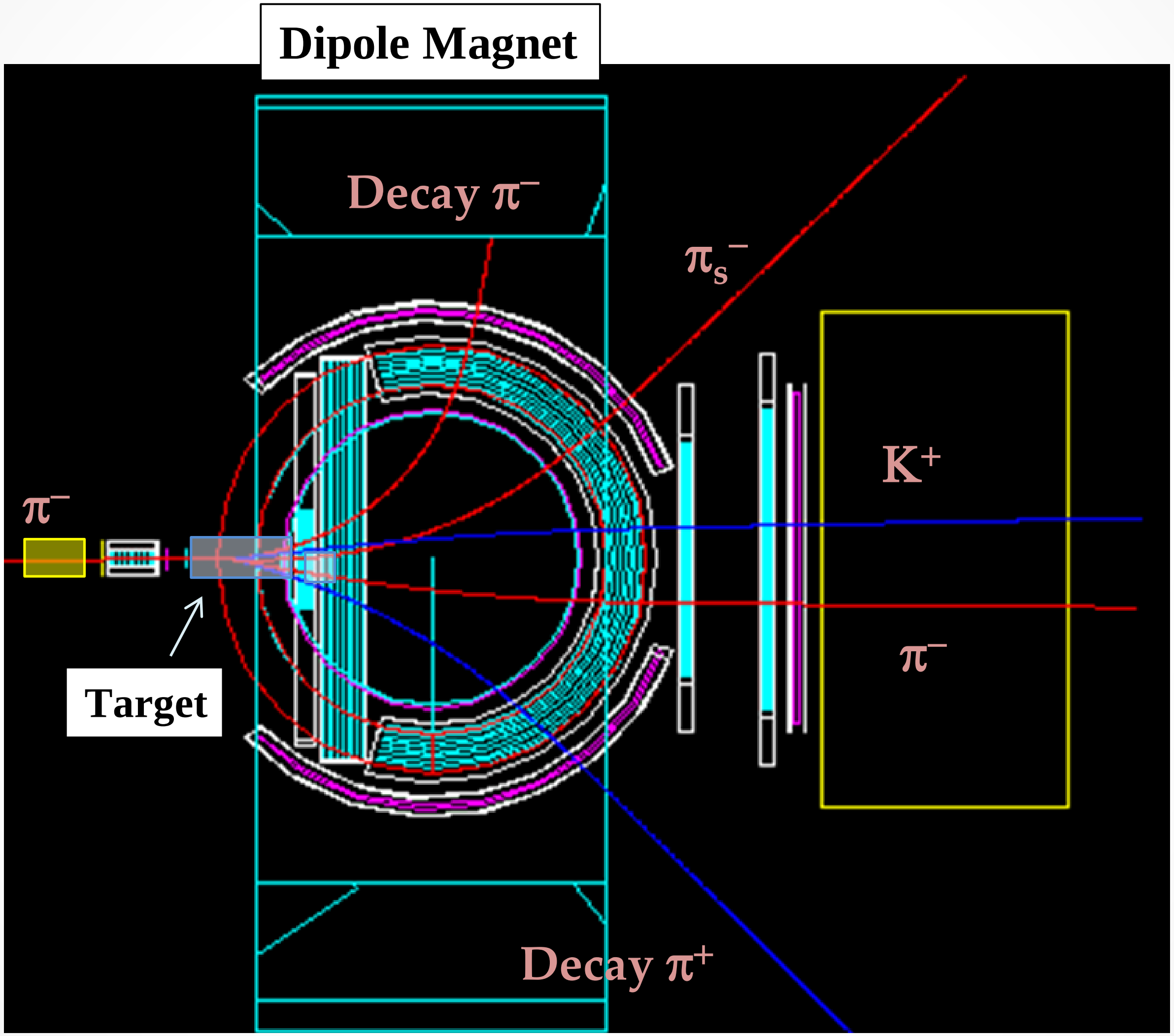
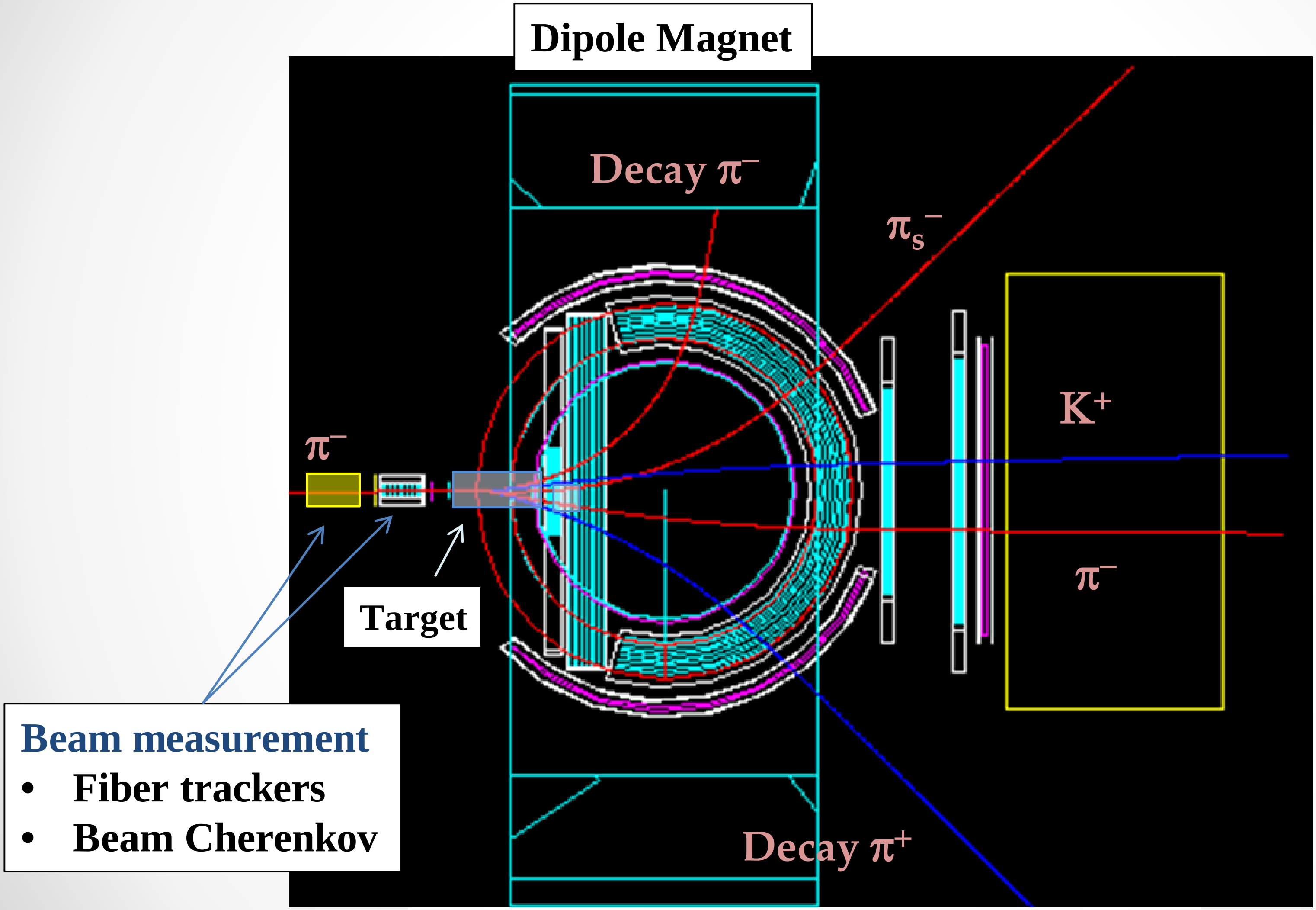
Spectrometer system

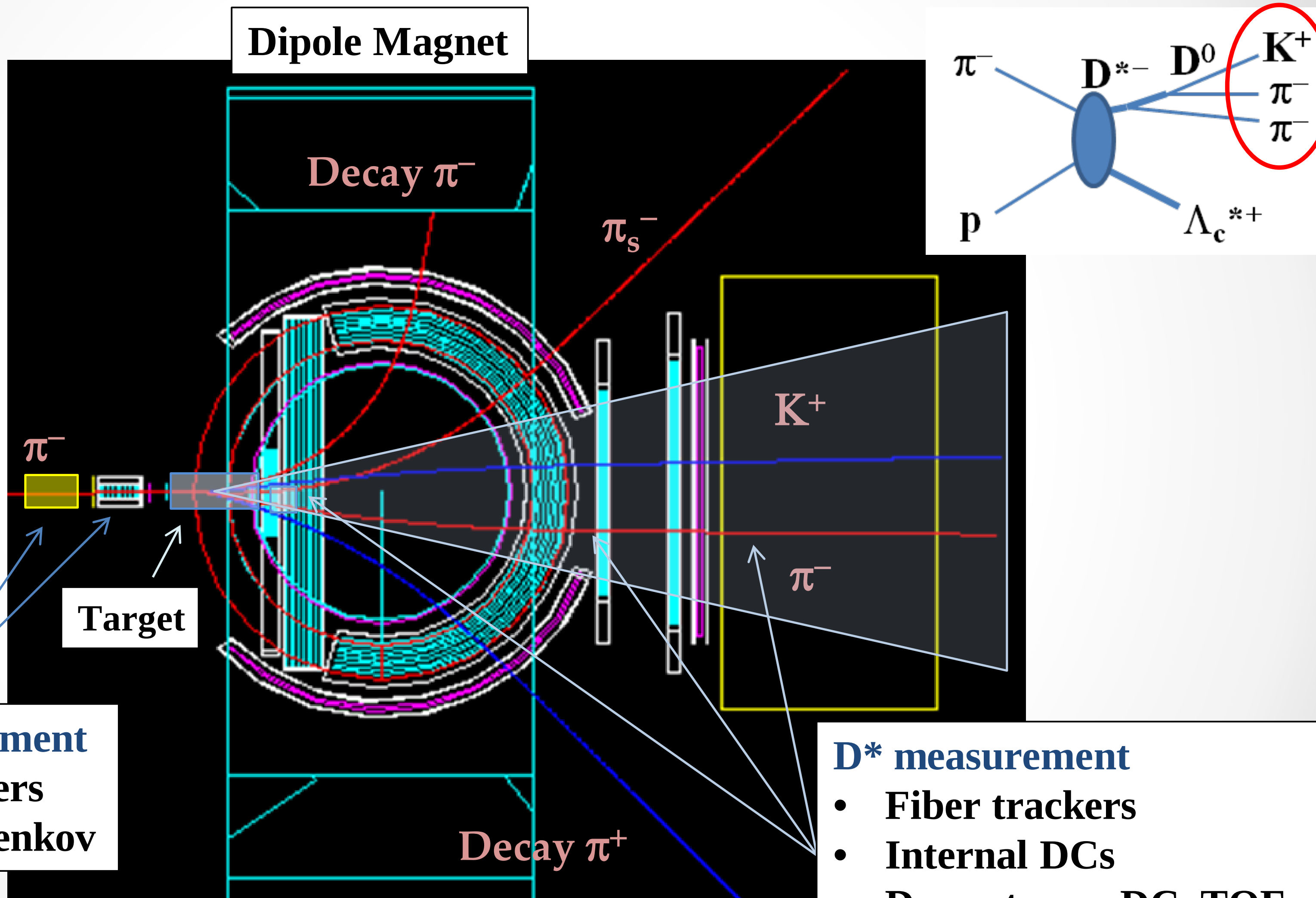


Spectrometer system



Beam measurement
- **Fiber trackers**
- **Beam Cherenkov**

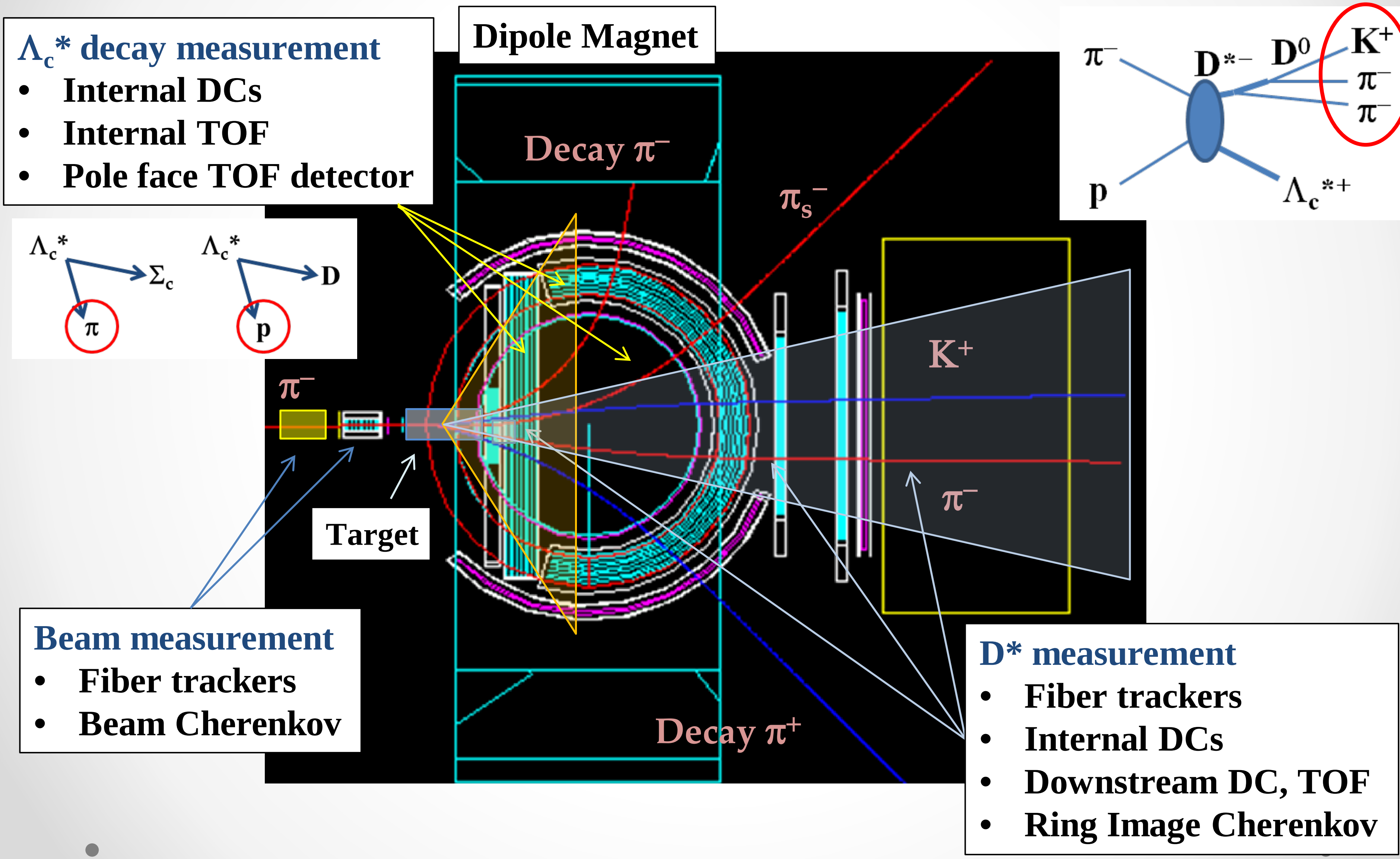
Spectrometer system



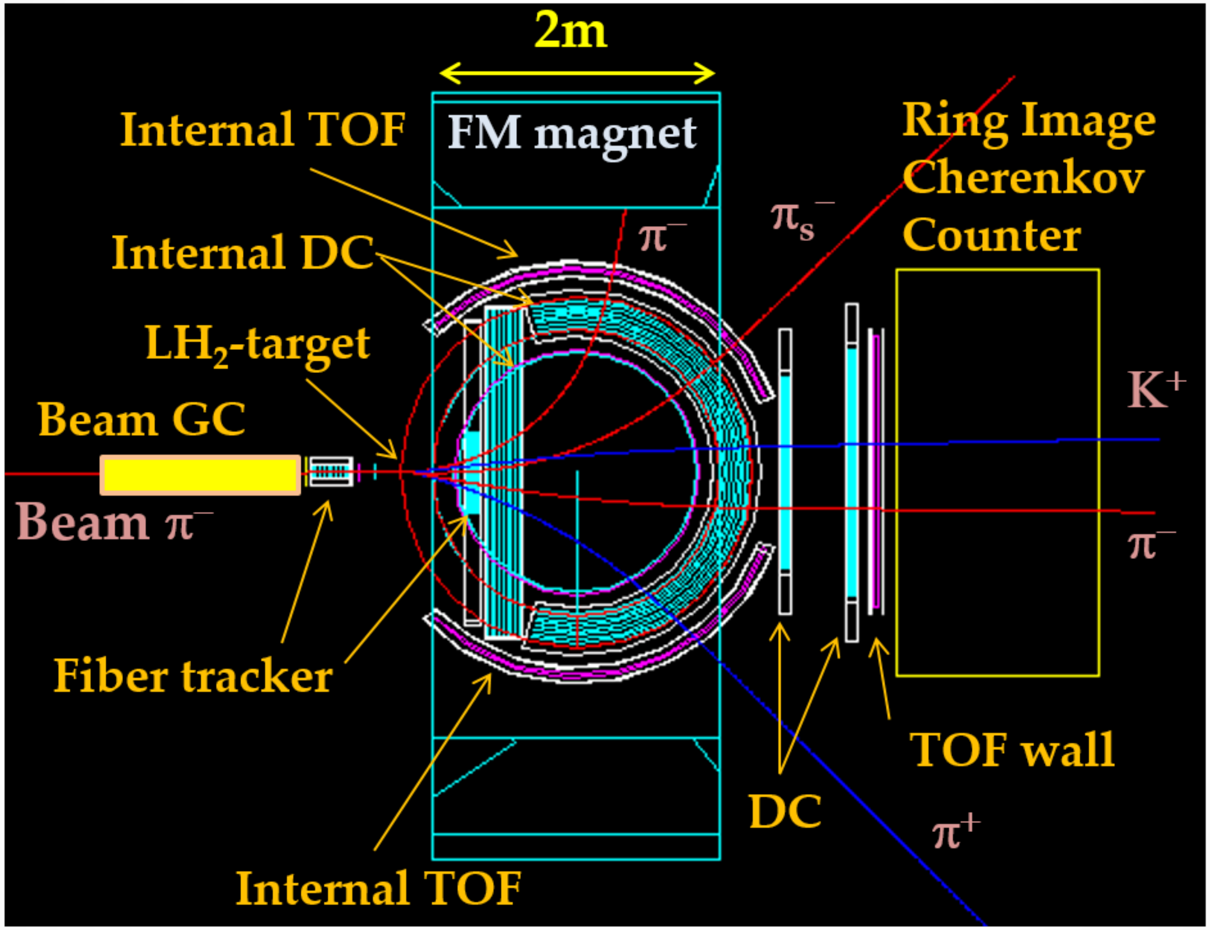
Beam measurement
- Fiber trackers
- Beam Cherenkov

D* measurement
- Fiber trackers
- Internal DCs
- Downstream DC, TOF
- Ring Image Cherenkov

Spectrometer system



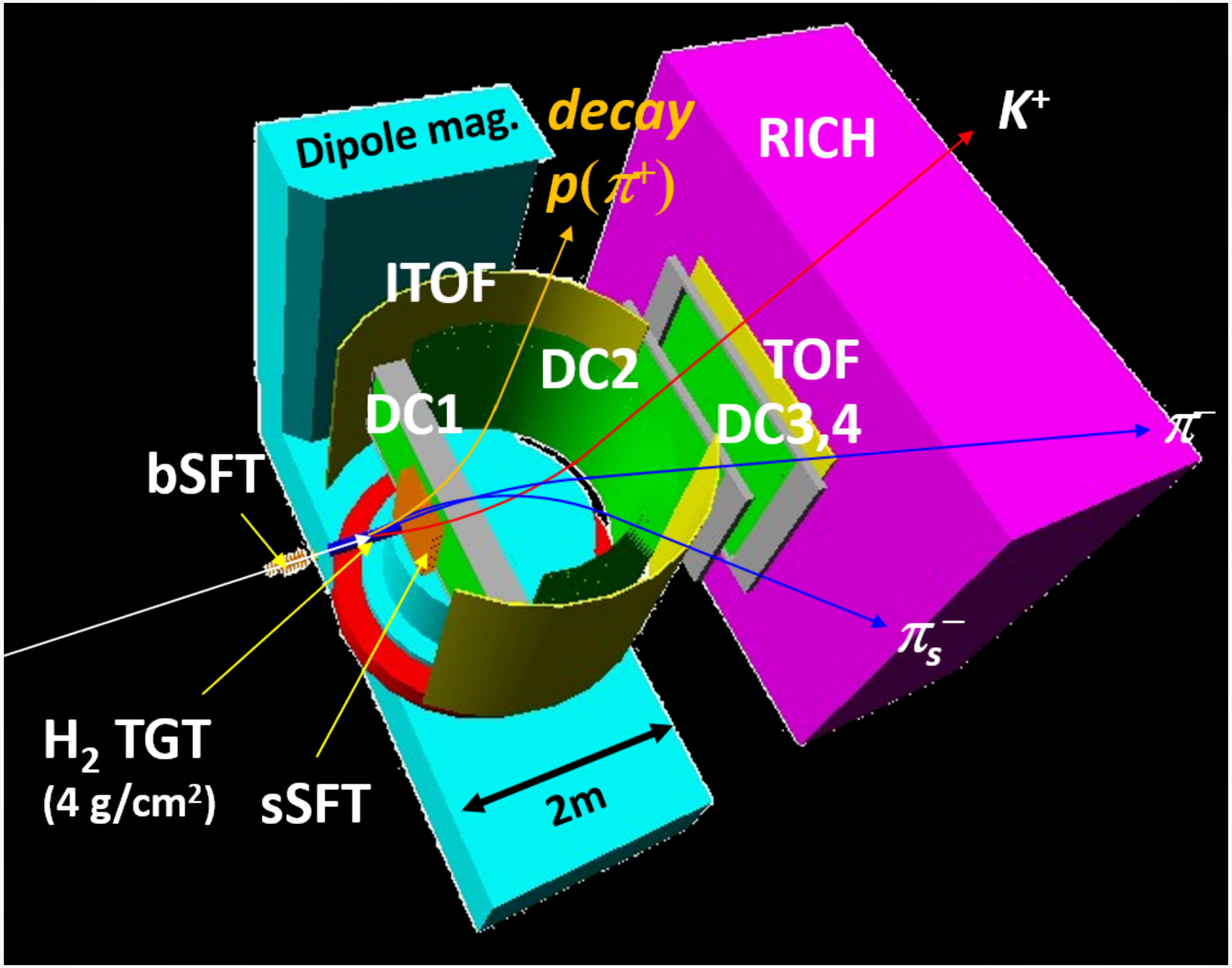
Charmed baryon spectrometer



Large Acceptance Multi-Particle Spectrometer

- **Acceptance: ~50% for D^*, ~80% for decay π/p**
- **Mass resolution: $M_{\Lambda c^*}$ = 10 MeV(rms) @ 2.7 GeV/c^2**

Charmed baryon spectrometer



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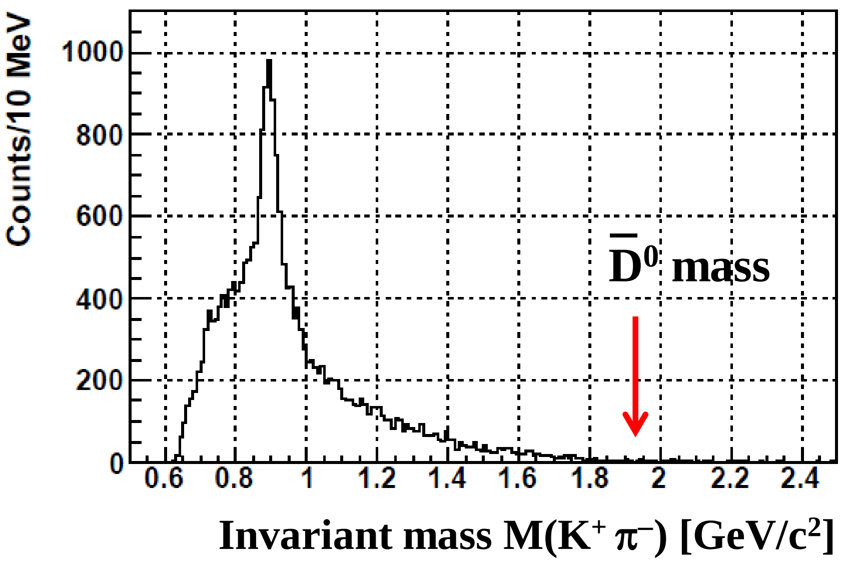
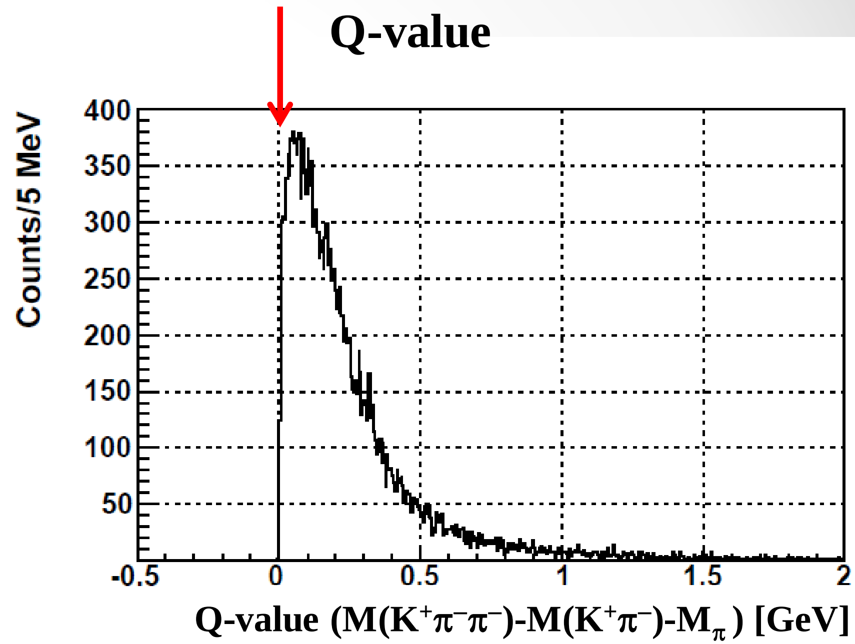
Background spectra @ 20 GeV/c



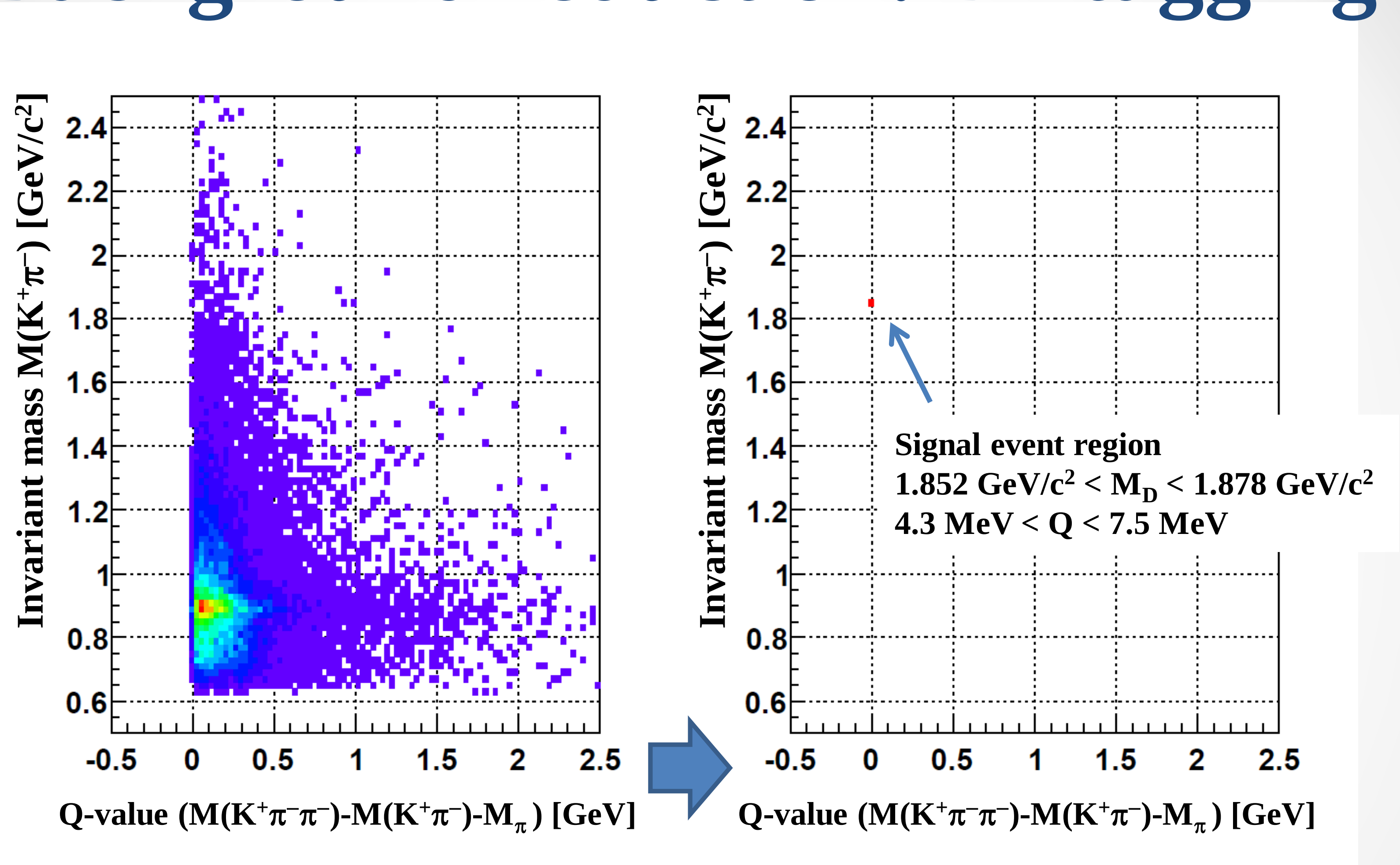


K^+, π^-, π_s^- events

Background = Signal × 10^6

∗ **Both $\bar{D}^0$ mass and Q-value region selected by narrow gate**

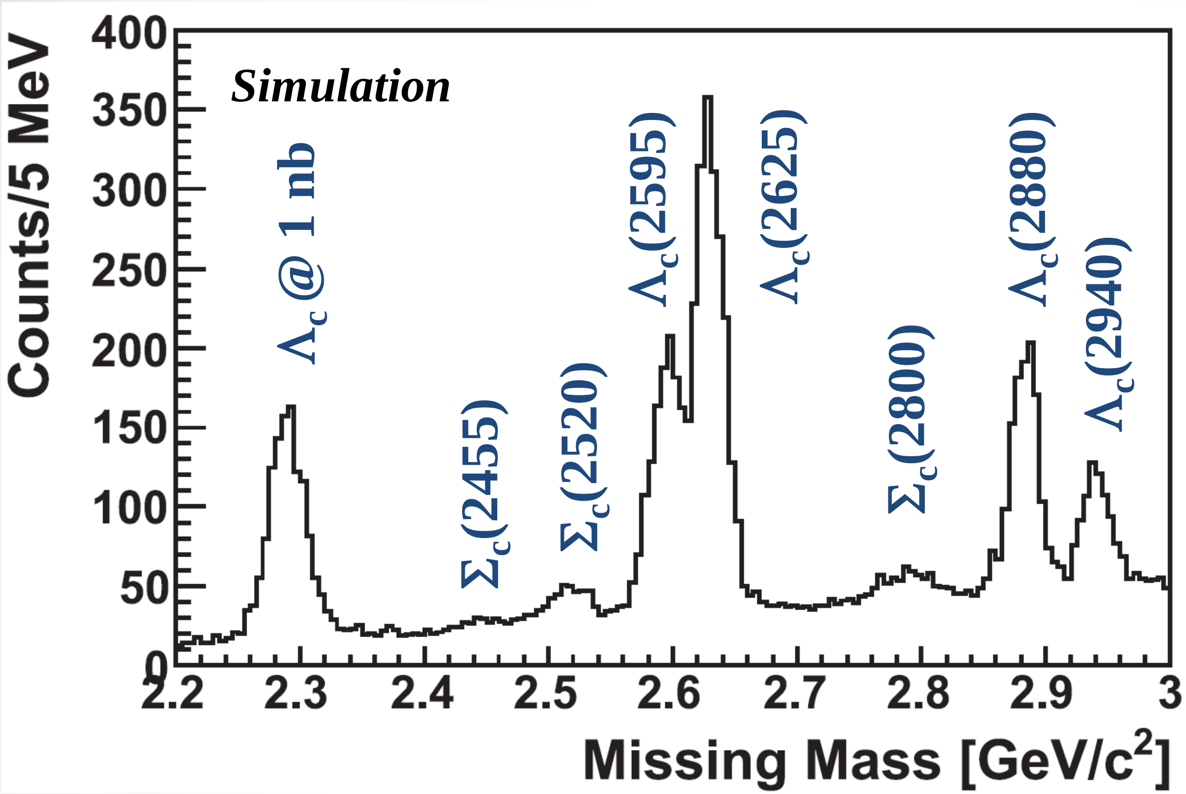
Background reduction: D* tagging



* Both $\overline{D}^0$ mass and Q-value region selected by narrow gate

⇒ More than 10^6 reduction for background events

Expected spectra



Known Mass & Width in PDG

~2000 counts @ N_{pot} = 8.64×10^{13} (100 days, ε_{total} = 0.5)

- **Λ_c(g.s.): 1 nb production cross section**
  - **Production ratio for excited states**
- **Background level and reductions were precisely studied.**

∗ Achievable sensitivity of 0.1–0.2 nb: (3σ level, Γ < 100 MeV)

Key devices

RICH

High-rate detector

DAQ

Requirements

- **Small production cross section of $\pi^{-} p \rightarrow Y_c^{*} D^{*-}$**

⇒ High-rate beam

- **6×10^{7} /spill (30 MHz)**

∗ High-rate detectors

- **Huge background events from hadronic reaction**

⇒ Good PID performance

- **Wide momentum range: 2–16 GeV/c**

∗ Ring image Cherenkov counter

- **High speed data taking for high production rate**

⇒ DAQ system with recent techniques

∗ Pipelined front-end modules with high speed data link

∗ On-line event reconstruction

RICH: Design & simulation

- **Huge background by hadronic reaction**
  - **Wrong PID of π^+ or proton as K^+**

  ⇒ 20 times higher contribution

  ＊3% wrong PID ⇒ Background × 2.4

- **High-momentum PID**
  - **Wide momentum range: 2-16 GeV/c**

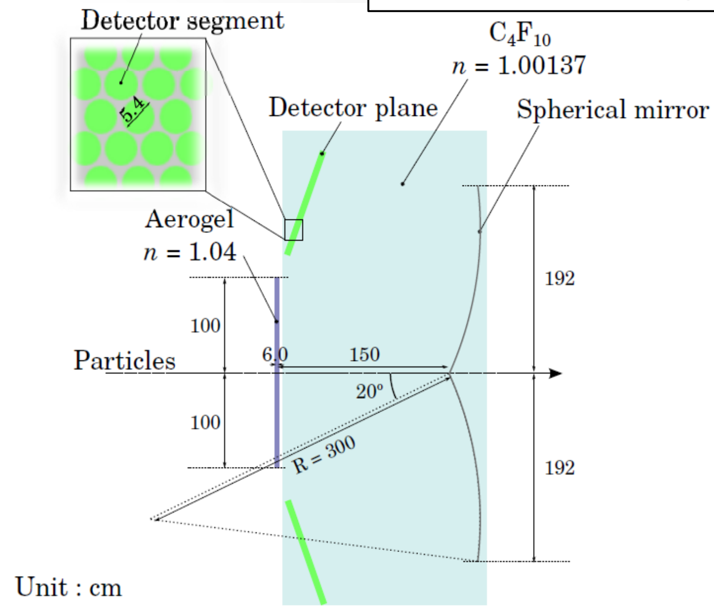
⇒ Hybrid RICH
  - **Aerogel (n=1.04) + C_4F_{10} gas (n=1.00137)**

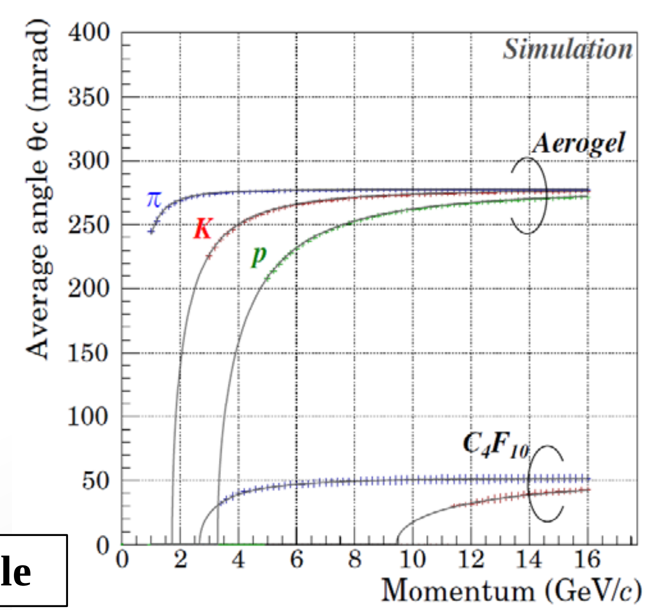
- **Detector plane: 2 × 1 m^2**
  - **Segment size: 5.4 cm**
  - **MPPC (>3 × 3 mm^2 size) + Light guide**
- **Spherical mirror: ~3 m diameter**

- **Performances**
  - **Efficiency of K, π, p: ~99%**
  - **Wrong PID: 0.10%(π→K) and 0.14%(p→K)**

  ⇒ Background × 1.05

Conceptual design





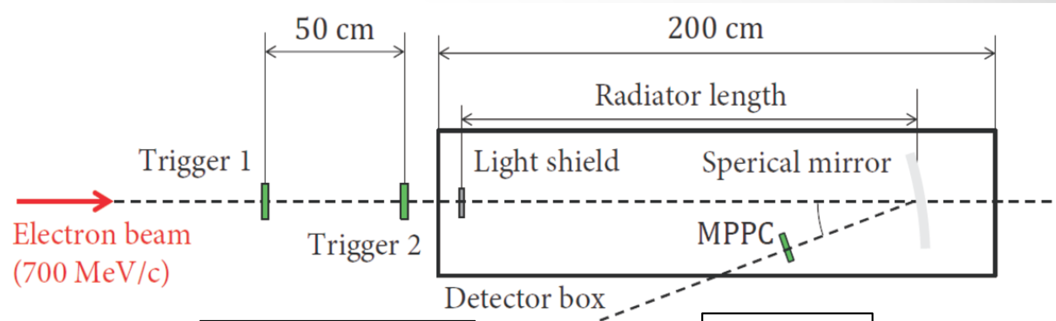
Reconstructed Cherenkov angle

RICH: Test experiment

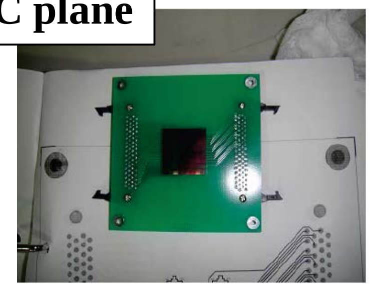
- **To check**
  - **Spherical mirror response**
  - **MPPC performance**

⇒Dependence on both positions and angles

Experimental setup



MPPC plane

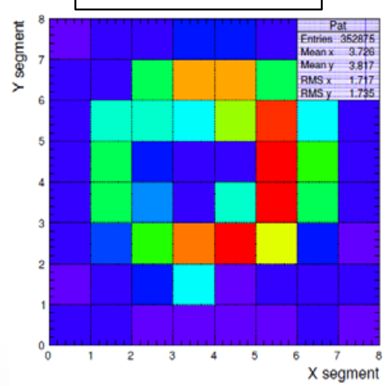


Mirror

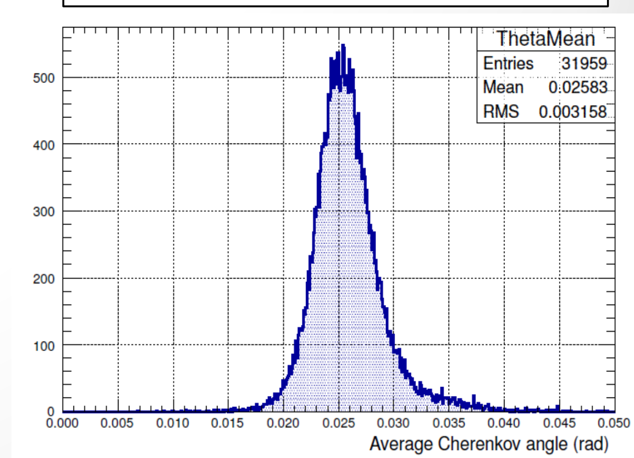
- **GeV-γ beam line in ELPH**
  - **700 MeV electron beam**
  - **Radiator: Air**
  - **MPPC: 8×8 array**

- **Preliminary result**
  - **Cherenkov angle was clearly reconstructed.**
    - $\theta_{Chere.} = 24$ msr
    - $\Delta\theta_{Chere.} \sim 3.0$ msr(rms)
  - **Other analysis on-going**

Hit pattern



Measured Cherenkov angle



＊Feedback to realistic design

Fiber trackers: Candidate

∗ J-PARC beam: Bad time structure
⇒ Narrow time gate
is essential to suppress accidental hits.

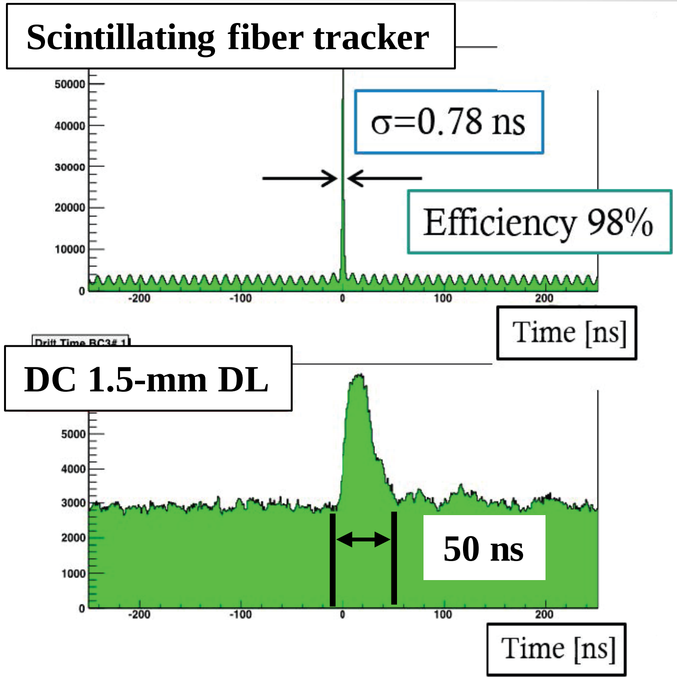
- E50: 60 M/spill (30 MHz)

- **Requirements**
  - 1 MHz/fiber: e.g. 1 mm & 1 mm MPPC (25 μm pixel)
  - Tracking efficiency: ~99%
  - Thin material thickness as possible

1) Focal plane & Beam tracking
2) Fiber Tracker at target downstream

∗ Simulation study on-going
- Accidental rate by using J-PARC beam structure
- Multiple scattering and energy loss effects

∗ Readout electronics development



E10: 12 M/spill (6 MHz) beam

DAQ: Readout channels

By T.N.T

Detector type	# of ch.	rate [MHz/ch]	time resolution [nsec] (σ)	Front-end	TDC LSB [nsec]
BFT,FFT,SFT	9600	1	< 1	MPPC with CITIROC or PETIROC2	1
SRICH	10000	0.xx	< 1	MPPC with CITIROC	1
T0	140	3	< 0.1	MPPC with PETIROC2 or discrete amp	0.025
TOF	160	0.xx	< 0.1	FM-PMT	0.025
RPC	184	0.xx	< 0.1	discrete amp	0.025
DC	7545	0.xx	< 1	DC-FEAT	1

Reaction rate (30 M/spill, 4 g/cm^2 target): 3.63 M/spill × 4 tracks

*** TDC base readout: Pulse height by TOT method**

⇒ Total ~30,000 ch

- **MPPC: ~10,000 (Fiber) + ~10,000 (RICH)**
- **DC: ~7,500**
- **Timing counter (HR TDC): ~500**

DAQ: Scheme

✱E50: Streaming DAQ system

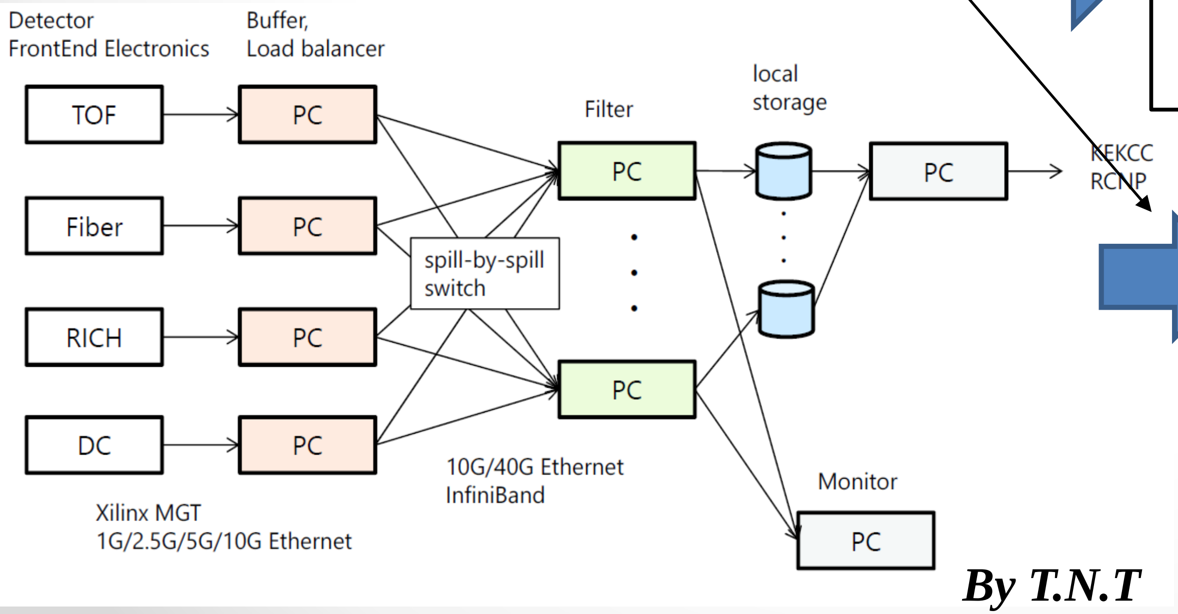
Frontend modules
- ✱Signal digitalization
  - Self or periodic trigger
  - Pipelined system
  - ~30,000 ch

Buffer PCs (~50 GB/spill)
- ✱Event accumulation
  - Several 10 GB memories
  - > 10 spill data

✱**High-speed data link**
Gigabit transceivers, Ethernet

Filter PCs (~50 GB/spill)
- ✱Event reconstruction
  - Several 10 GB memories
  - 100–200 CPUs

Storage (< 0.5 GB/spill)
- Local storage
- Transferred to KEKCC/RNCP



By T.N.T

✱**Data rate: 4 g/cm^2 target and 30 MHz conditions**

DAQ: Trigger-less system

Requirement: On-line momentum analysis is necessary.

Planned E50 system

- **On-line event reconstruction**
- **PC clusters**

⇒ Flexible data taking system

- **Advantages**
  - **Flexibility for byproducts events**
  - **Cost of PCs having many CPUs are lower to produce specific modules.**
  - **Available for other experiments**
- **Disadvantage**
  - **Members have no experience.**

✱Cellular automaton + Kalman filter track fitting (CBM on-line tracking)

- **On-line tracking: ~100 μsec/track/CPU-core with Intel Xeon E4860**
  - **CBM condition: ~200 tracks/event**

⇒ E50 condition: 100-250 CPU

By T.N.T

Main channel

- Y_c baryons: $\pi^- + p \rightarrow Y_c^+ + D^{*-}$
  - $D^{*-} \rightarrow D^0 + \pi^- \rightarrow K^+ + \pi^- + \pi^-$ (3.88%)

    + 2 other charged channel can be used.
    - $D^{*-} \rightarrow D^0 + \pi^- \rightarrow K^+ + \pi^- + \pi^+ + \pi^- + \pi^-$ (8.07%)
    - $D^{*-} \rightarrow D^0 + \pi^- \rightarrow K_S^0 + \pi^- + \pi^+ + \pi^- \rightarrow \pi^+ + \pi^+ + \pi^- + \pi^- + \pi^-$ (2.82%)

1) On-line momentum analysis
   - Fiber diameter (1 mm) and DC cell size (10–20 mm) are assumed.

2) No PID for scattered particles
   - Only charge information is used.

3) $(P^+ + P^-)$ w/ M(“K^+”, “π^-”) > 1.5 GeV/c^2 & $p^+ + p^- > 10$ GeV/c

$\Rightarrow$ “D^0 event” rate: a few 10 kHz (~0.5 GB/spill)

4) $(P^+ + P^- + P_S^-)$ w/ mass gate & mom.

$\Rightarrow$ On-line “D*“ tagging: < 1 kHz (~0.05 GB/spill)

✱ Main channel data rate is expected to be low enough.

Other channels

- Y_c baryons
  - $\pi^- + p \rightarrow Y_c^+ + D^{*-}$: $(K^+ + \pi^- + \pi^-)$
  - $\pi^- + p \rightarrow D_{bar}N\ (c_{bar}d\ udd) + D^{*+}$: $(K^- + \pi^+ + \pi^+)$
- Ξ_c baryons: $R = Y_c$ production $\times$ 1/10
  - $\pi^- + p \rightarrow \Xi_c^0 + D^{*-} + K^+$: $(K^+ + \pi^- + \pi^- + K^+)$
  - $\pi^- + p \rightarrow \beta^{++}(cs_{bar}uud) + D^{*-} + K^-$: $(K^+ + \pi^- + \pi^- + K^-)$
- Y baryons: Yield = $Y_c \times 10^5$
  - $\pi^- + p \rightarrow Y^0 + K_S^0$: $(\pi^+ + \pi^-)$
  - $\pi^- + p \rightarrow Y^0 + K^{*0}$: $(K^+ + \pi^-)$
  - $\pi^+ + p \rightarrow Y^+ + K^{*+}$: $(K_S^0 + \pi^+) \rightarrow (\pi^+ + \pi^- + \pi^+)$
  - $\pi^- + p \rightarrow \Theta^+ + K^{*-}$: $(K_S^0 + \pi^-) \rightarrow (\pi^+ + \pi^- + \pi^-)$
- Ξ baryons: Yield = $Y_c \times 10^3$–10^4
  - $K^- + p \rightarrow \Xi^0 + K^{*0}$: $(K^+ + \pi^-)$
  - $K^- + p \rightarrow \Xi^- + K^{*+}$: $(K_S^0 + \pi^+) \rightarrow (\pi^+ + \pi^- + \pi^+)$
  - $\pi^- + p \rightarrow \Xi^- + K_S^0 + K^+$: $(\pi^+ + \pi^- + K^+)$
  - $\pi^- + p \rightarrow \Xi^- + K^{*0} + K^+$: $(K^+ + \pi^- + K^+)$
- Ω baryons: Yield = $Y_c \times 10^2$
  - $K^- + p \rightarrow \Omega^- + K_S^0 + K^+$: $(\pi^+ + \pi^- + K^+)$
  - $K^- + p \rightarrow \Omega^- + K^{*0} + K^+$: $(K^+ + \pi^- + K^+)$
- Drell-Yan channels
  - $\pi^- + p \rightarrow n + \mu^+ + \mu^-$: $(\mu^+ + \mu^-)$
  - $K^- + p \rightarrow Y^0 + \mu^+ + \mu^-$: $(\mu^+ + \mu^-)$

Byproducts

Event selection as you like !

✱Single scattered channels are difficult to be taken.
c.f. $\pi^- + p \rightarrow \Sigma^- + K^+$
- K^+ production rate: ~200 kHz

✱Kaon reaction is acceptable due to 1/200 beam rate.
c.f. $K^- + p \rightarrow \Xi^- + K^+$

DAQ: Module R&D

Common features: TDC base data taking

- Pulse height correction by TOT
- Pipelined data transfer with a high-speed data link.

- **MPPC readout**
  - Module with CITIROC/PETIROC chips

  ⇒ Open-It project with KEK electronics group

- **Wire chamber readout**
  - ASD + TDC readout modules
  - TDC LSB: ~1 ns

  ⇒ Collaboration with LEPS group

- **High resolution TDC module**
  - TDC (+ discrete amp)
  - TDC LSB: ~25 ps

✱Module R&D needs resources. However, those modules can be standard modules for the hadron hall experiments and so on.

Summary

- Charmed baryon spectroscopy
  - To understand essential degree of freedom of hadron

- Experiment at the J-PARC high-p beam line
  - Inclusive measurements by missing mass spectroscopy
  - Design of Spectrometer

- Status of essential parts for the E50 experiment
  - RICH
    - Designed RICH has good performances.
    - R&D are in progress: MPPC detector plane, spherical mirror
    - Test experiment at ELPH: Analysis on-going
  - High-rate detector
    - Narrow time gate is essential due to bad time structure.
    - Scintillating fiber tracker was chosen.
    - R&D: Fiber shape and configuration, readout module
  - DAQ
    - Grand design of DAQ system
    - On-line event reconstruction
    - Module R&D: MPPC readout, ASD+TDC for DC, HR TDC for counters

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Next Generation Hadron Experiment at the J-PARC High-p beam line

Let's do it together !

Thank you for your attention