Experimental study of in-medium spectral change of vector mesons at J-PARC.

K. Aoki

IPNS, KEK

J-PARC Hadron Section.

Reimei Workshop: Polarization phenomena and Lorentz symmetry violation in dense matter.

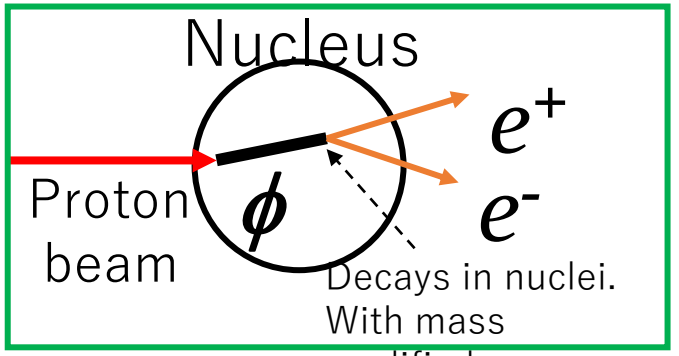
(Oct 6, 2022. Yonsei Univ. Korea)

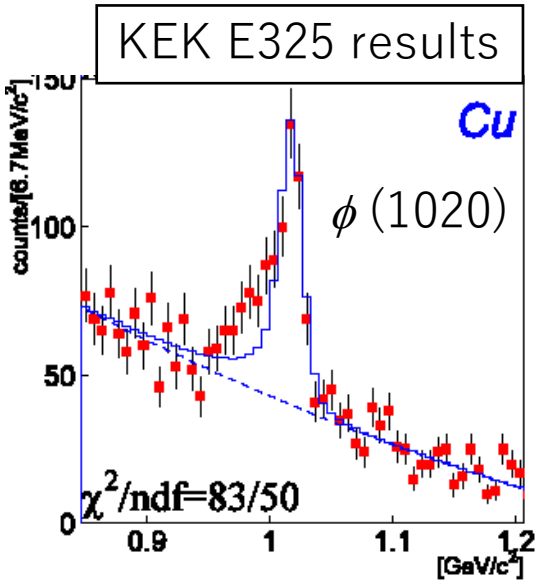
CONTENTS

- Physics motivation
- Related experiments (ϕ in cold nuclear matter)
- J-PARC E16 experiment
  - Basic idea
  - Experimental apparatus
  - Commissioning run.
  - Prospects
  - Polarization dependence of spectral change.
- Summary

Physics

- The origin of Hadron mass. A hadron, an excitation of QCD vacuum, reflects the nature of the vacuum.
  - **Spontaneous breaking of the chiral symmetry.**
    - An order parameter: $\langle \bar{q}q \rangle \neq 0$
    - depends on environment (temperature, ***density***)
    - Partially restored even at normal nuclear density.
    - Could result in measurable change in mass.
    - $\langle \bar{q}q \rangle$ ~35% reduction at ρ_0 for ***u*** and ***d***. what about ***s***?
  - $\langle \bar{q}q \rangle$ ← QCD sum rule→ mass
- J-PARC E16 experiment:
  - Use **p + A → ρ/ω/ϕ → e+e-**
  - Dielectron mass spectra are obtained.
    - mixture of decay inside and outside the nuclear target.
    - Sensitive to spectral change of vector mesons in nuclear medium.
  - Similar as KEK-E325, but collecting more data and do more systematic study.

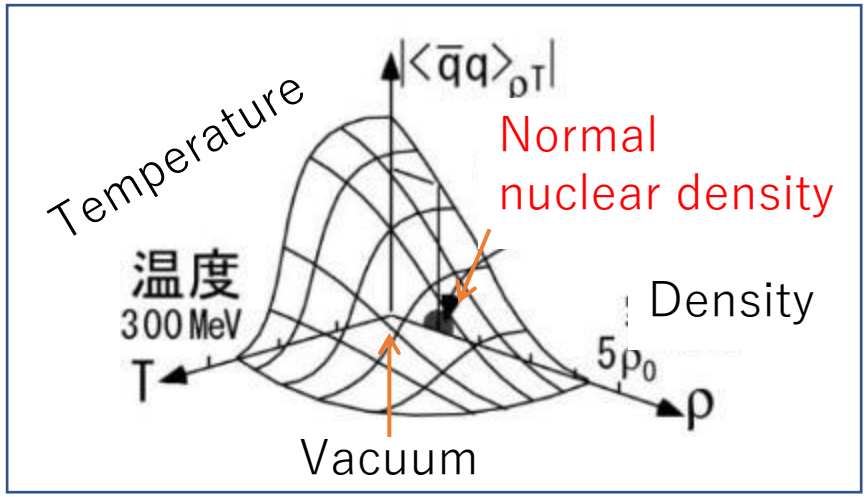




High stat.
Better res.

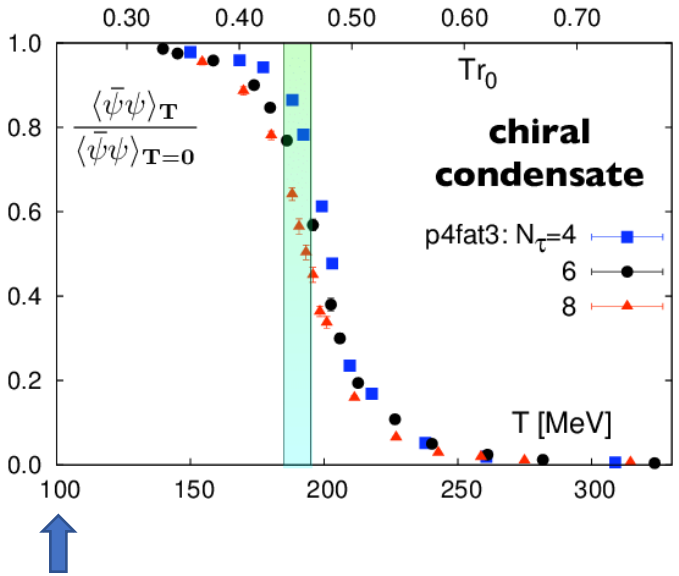
J-PARC E16

Chiral condensate in dense/hot medium



NJL model
M. Lutz et al.
Nucl.Phys. A542,52(1992)

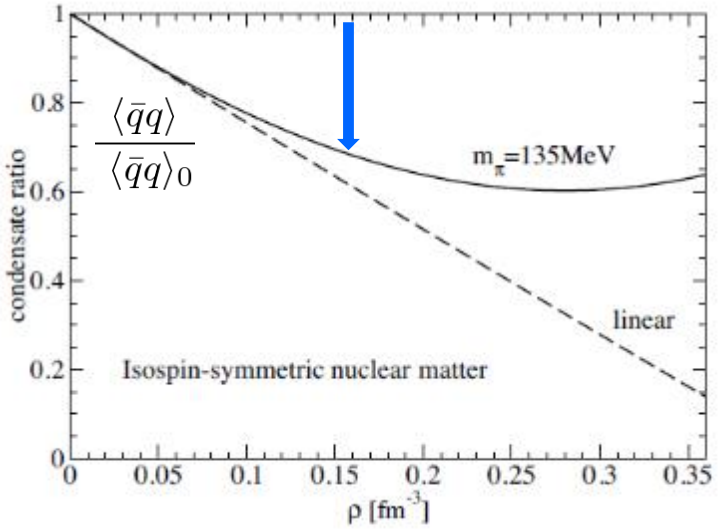
Temperature dependence



T=100 MeV

LQCD
W. Weise arXiv:1009.6201
M. Cheng et al.
PRD77, 014511(2008)

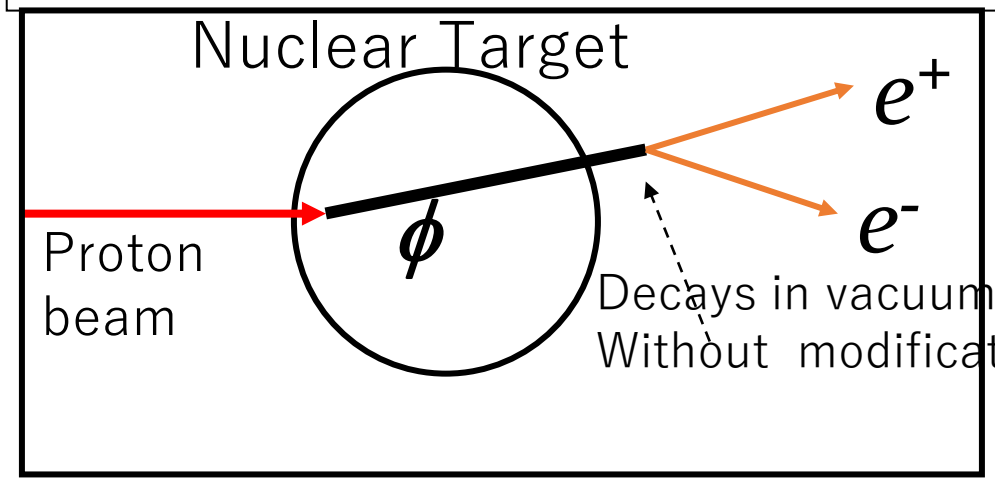
Density dependence

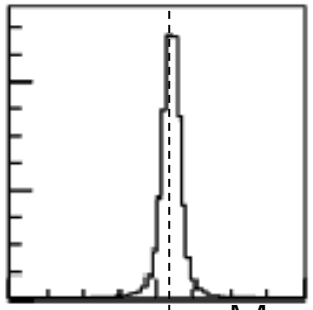


Nuclear chiral perturbation
Kaiser et al., PRC 77 (2008)

Probe: Vector meson→e^+e^- invariant mass

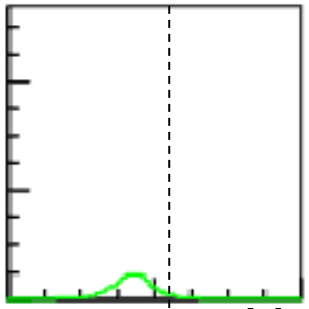
Example: p + A → ϕ + X





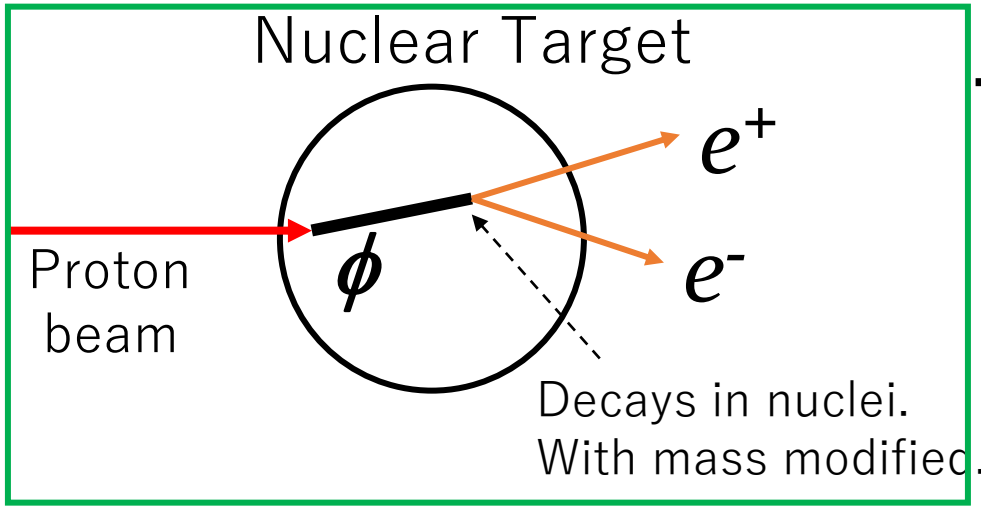
Well-known
Inv. mass
In vacuum

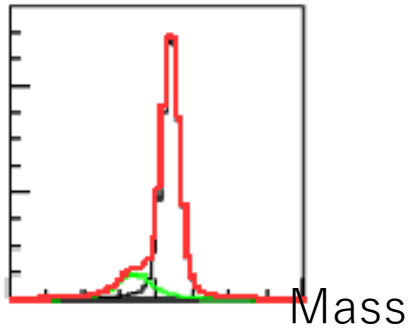
+



Modified mass
In nuclei.

||



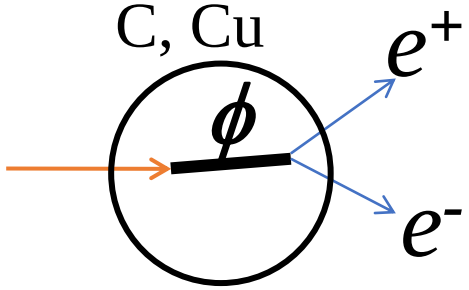


Observed
invariant
mass.

Lepton pair in the final state.
→ small final state interaction.

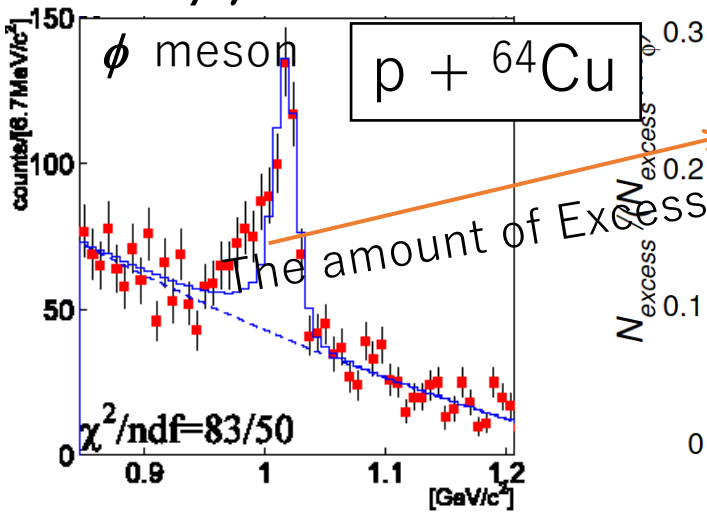
KEK-E325 results of ϕ meson

- The world's first results of ϕ modification.

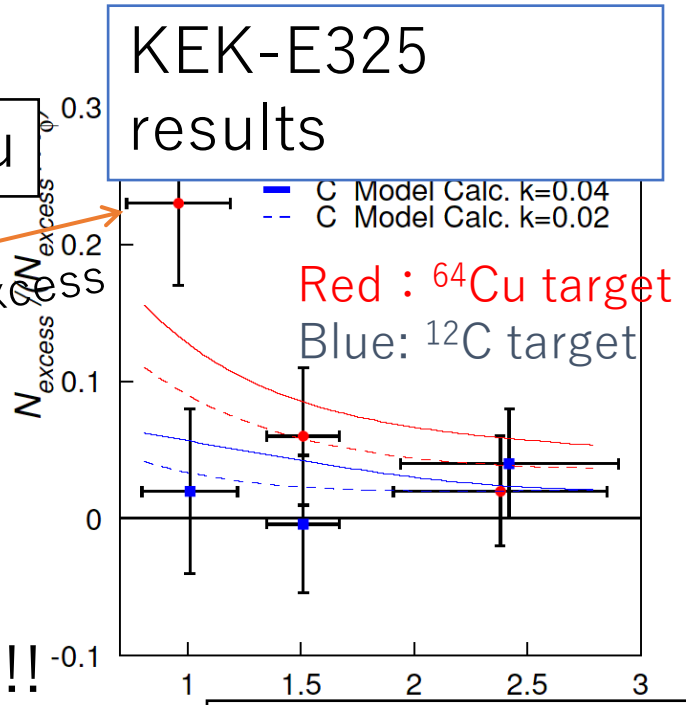


12GeV (10^9/spill)
Proton beam

$\beta\gamma < 1.25$



The amount of Excess



$\beta\gamma$ = p/M of ϕ

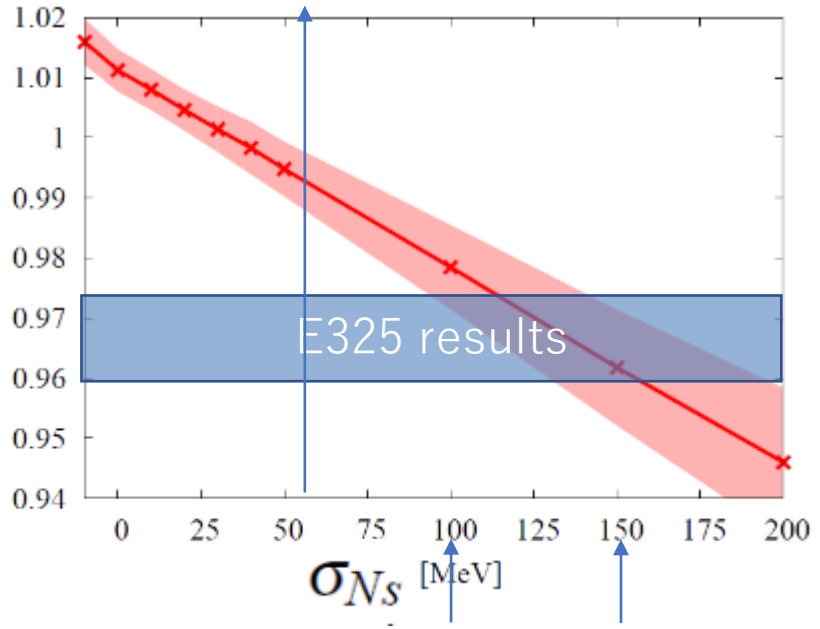
- Conclusion: Mass decreases in nuclei!!
  - Under the assumption of linear dependence of mass and width on density.
    - Mass: $-3.4\ ^{+0.6}_{-0.7}\%$ ↓ At normal nuclear density
    - Width: $\times 3.6^{+1.8}_{-1.2}$

QCD sum rule results

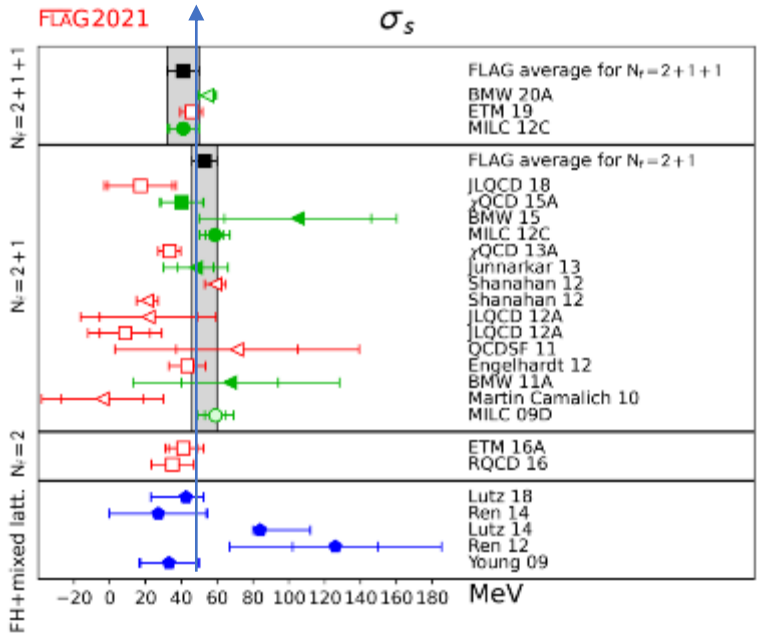
Gubler and Ohtani [Phys. Rev. D90, 094002(2014)]

They provide σ_s vs mass.
The σ_s is how much $\langle \bar{s}s \rangle$ reduced in nuclear matter.

$$\frac{m_\phi(\rho_0)}{m_\phi(0)}$$



14% 21% reduction in $\langle \bar{s}s \rangle$

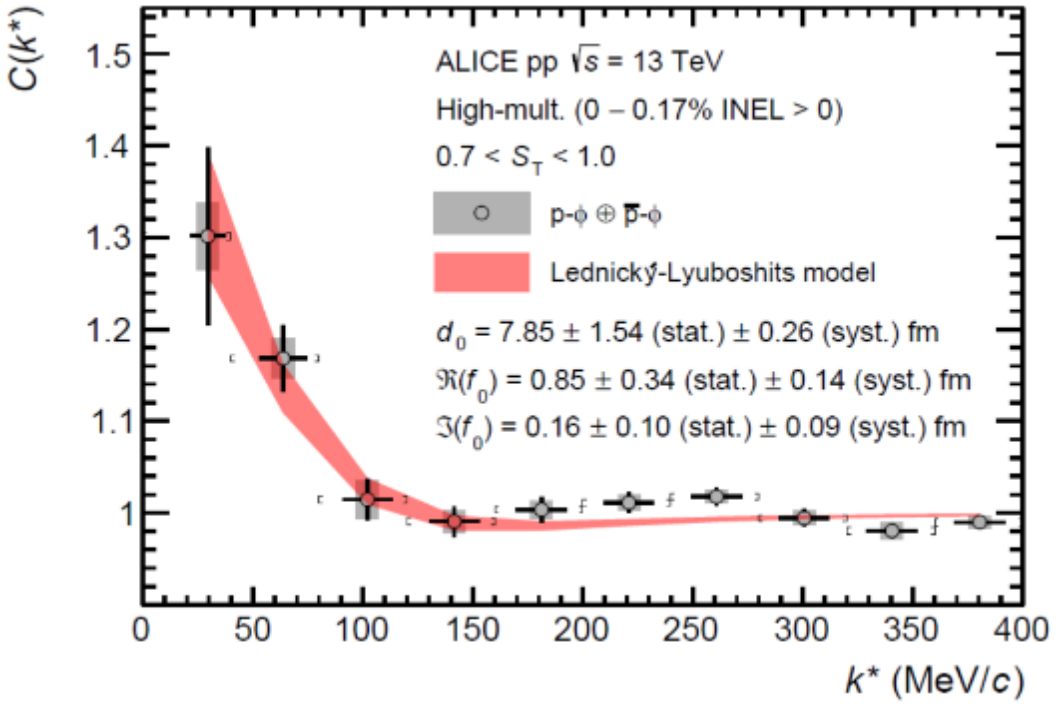


$$\langle \bar{s}s \rangle_\rho = \langle \bar{s}s \rangle_0 + \langle N|\bar{s}s|N \rangle \rho$$

$$\sigma_s = m_s \langle N|\bar{s}s|N \rangle \quad \left(= m_s \frac{\partial M_N}{\partial m_s}\right)$$

Information from p-ϕ interaction

ALICE two particle correlation



ALICE: Phys. Rev. Lett. 127, 172301(2021)
f_0 : scattering length.
d_0 : effective range.

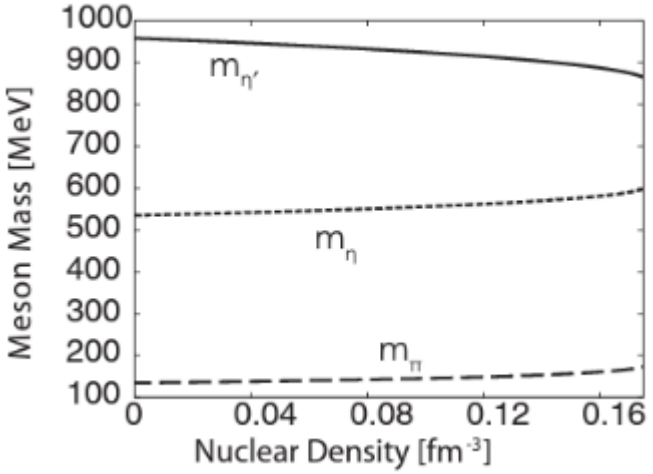
HAL QCD arXiv:2205.10544 (2022)
Scattering length and effective ranges are deduced for spin 3/2 combination.

$$a_0^{(3/2)} = -1.43(23)\ \text{fm}$$
$$r_0^{(3/2)} = 2.36(10)\ \text{fm}$$

- Mass reduction
  - ALICE: 5.8% ±
  - HAL QCD: 5.3% ±
  - E325 : 3.6% $^{+0.6}_{-0.7}$

-80MeV

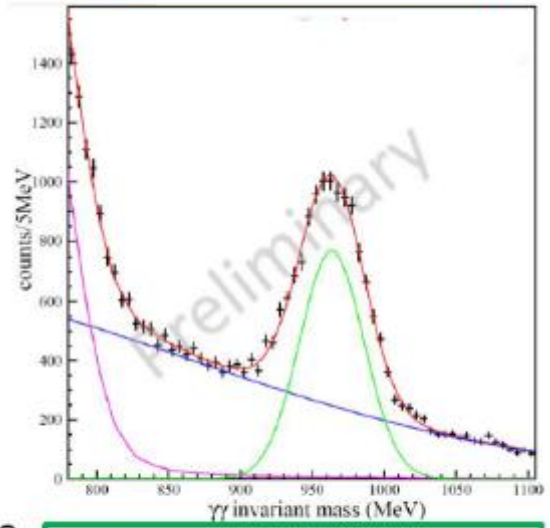
Eta' ~ U(1)A anomaly X $\langle\bar{q}q\rangle$



Linear sigma model
S. Sakai, D. Jido
PRC88, 064906 (2013)

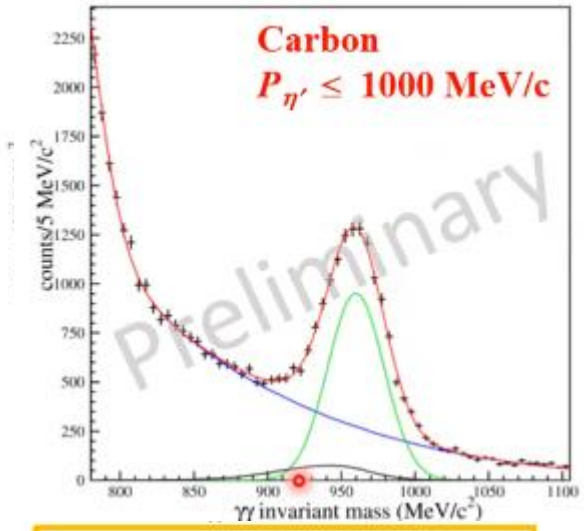
Fitting results

$p_{\eta'}$ >1000 MeV/c



signal significance 0.9σ

$p_{\eta'}$ <1000 MeV/c



signal significance 3.7σ

χ^2 difference test

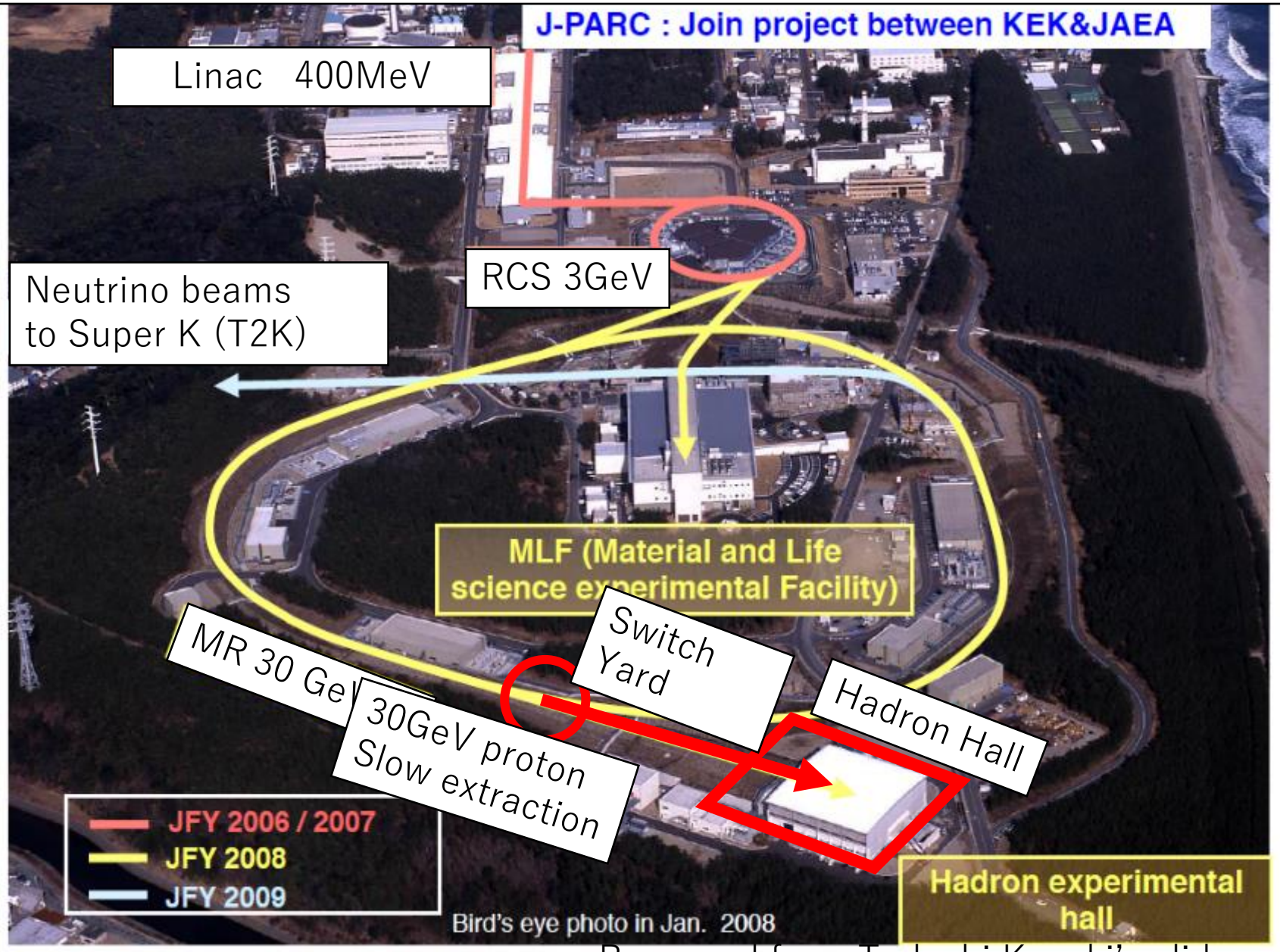
k1=0.06
k2 = 125

Mass modification

- γ +12C → eta' X , eta' → 2 γ
- Direct measurement of eta' mass modification.
- 6% mass reduction at normal nucl. Density.

Taken from slides of
Muramatsu at HEF EX WS
Tomida at REIMEI WS 2021.

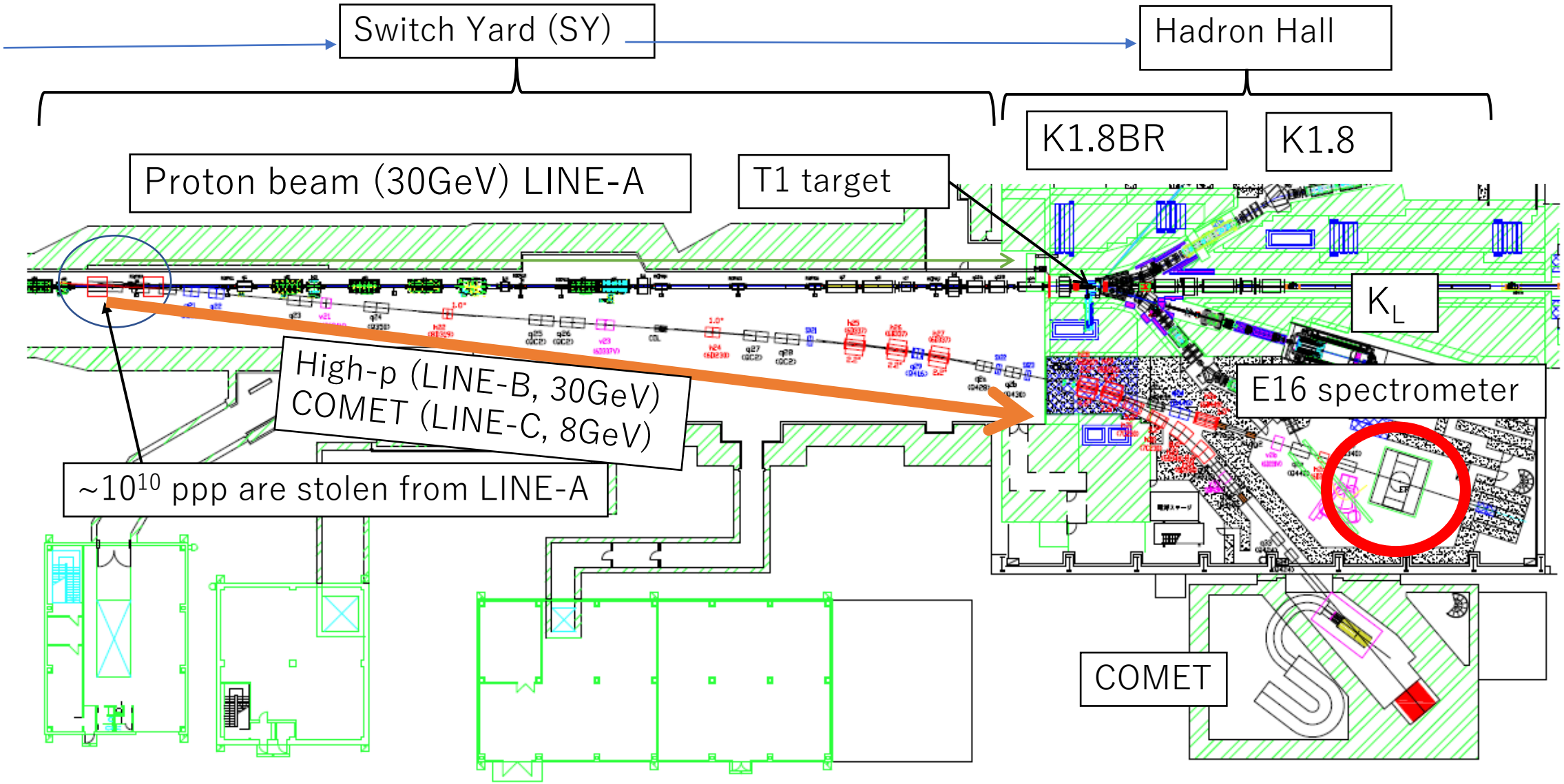
J-PARC (Proton Accelerator Research Complex)



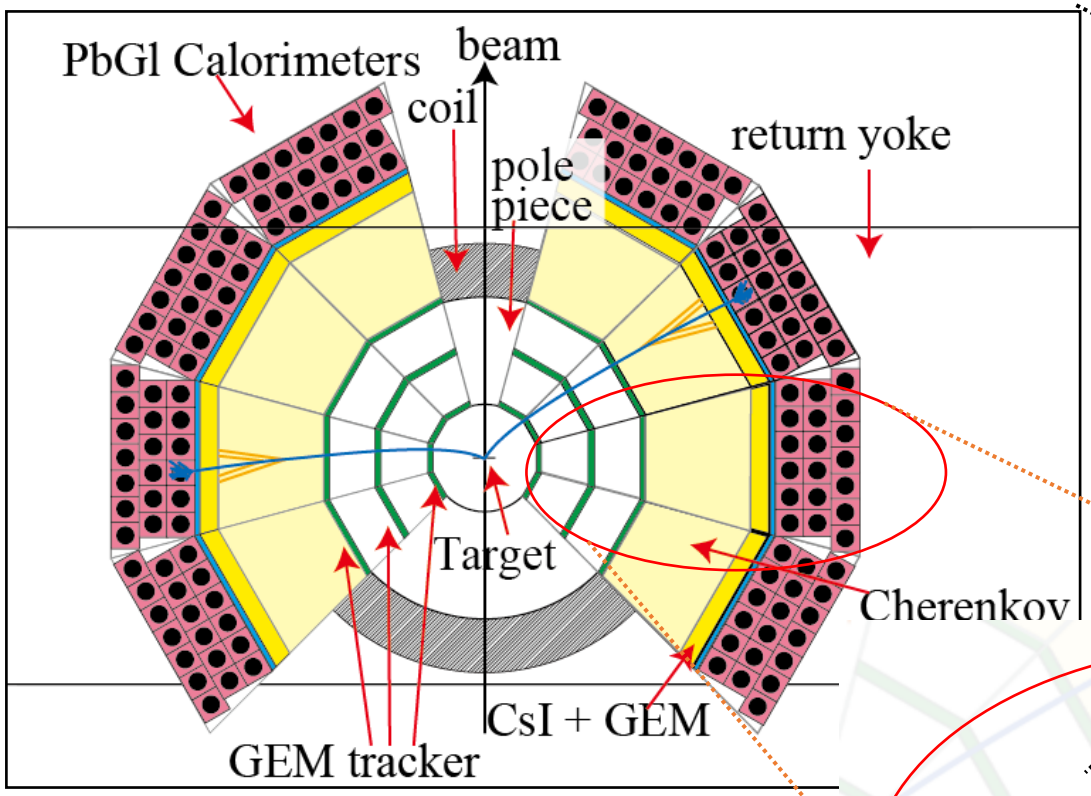
Borrowed from Tadashi Koseki's slide

Beam Line at J-PARC Hadron Hall

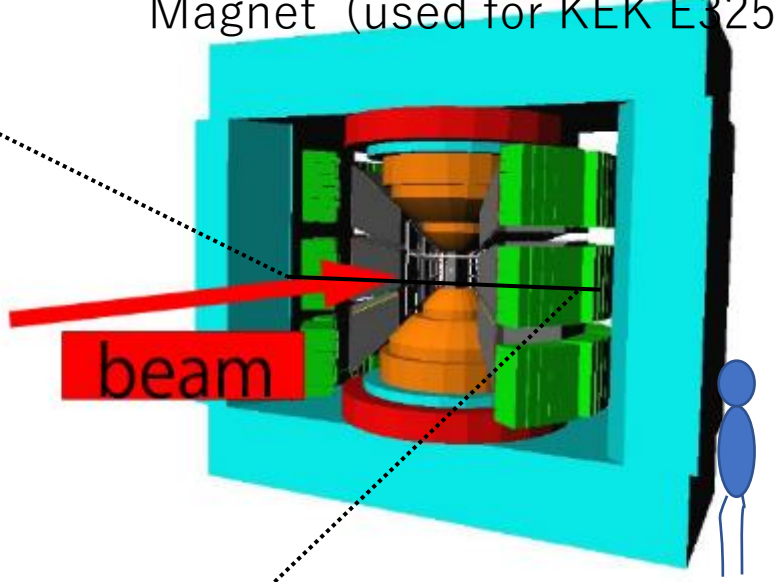
- 30GeV proton --- 65 kW (7×10^{13}ppp) as of 2021.

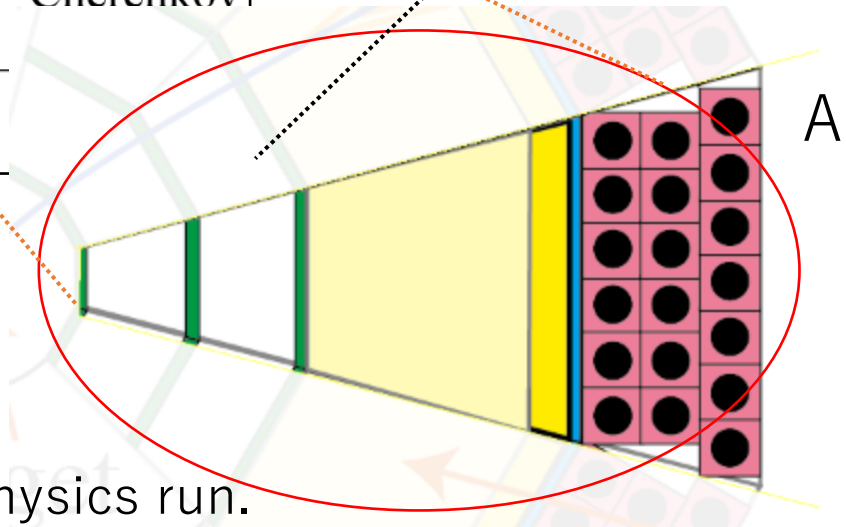


The J-PARC E16 spectrometer



Magnet (used for KEK E325)





A module

X 26

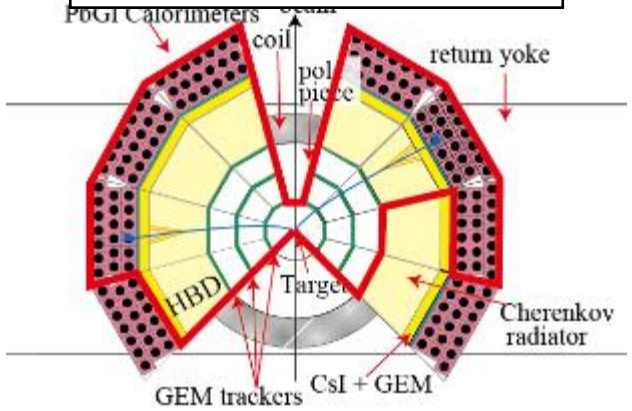
SSD : Tracking (not visible.)
GTR : Tracking
HBD : eID (Cherenkov)
LG : eID (Calorimeter)
26 modules in total. 8 for the 1st physics run.

Staging approach

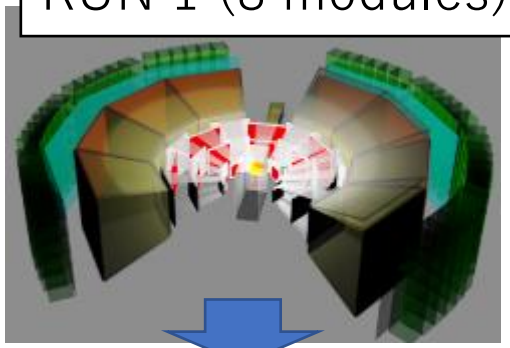
PAC approved

- **RUN 0abc - 2020,2021**– 403hrs.
  - **6 (SSD) + 8 (GTR) + 6 (HBD) + 6 (LG)** at last
  - C+Cu targets
  - Beam / Detector commissioning
- **RUN 0d - 2023 -- 200 hours.**
  - **10(SSD) + 10 (GTR) + 8 (HBD) + 8 (LG)**
  - Beam / Detector comm. + yield.
  - Upgraded Accelerator / DAQ. / Detectors.
- **RUN 1 2024(?)** -- 1280hrs (~53days)
  - **10 (SSD) + 10 (GTR) + 8 (HBD) + 8(LG)**
  - Physics data taking. ϕ : 15k for Cu.
- **RUN 2** -- 2560 hrs (~107 days)
  - **26 (SSD) + 26 (GTR) + 26 (HBD) + 26 (LG)**
  - + Pb/CH2 target
  - Needs additional budget.

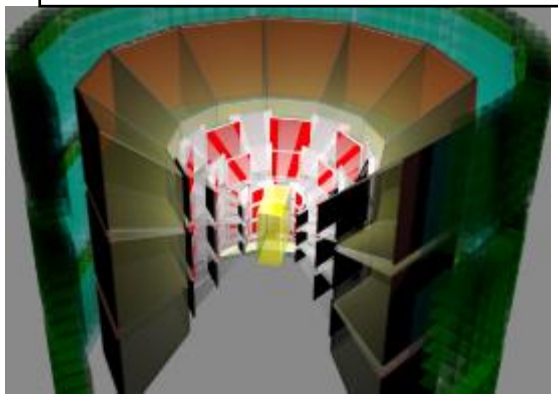
RUN 0 configuration



RUN 1 (8 modules)

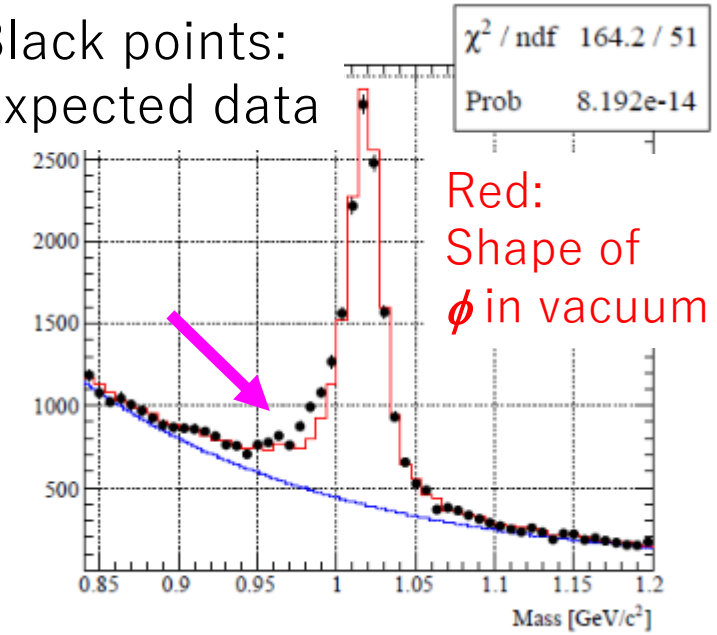


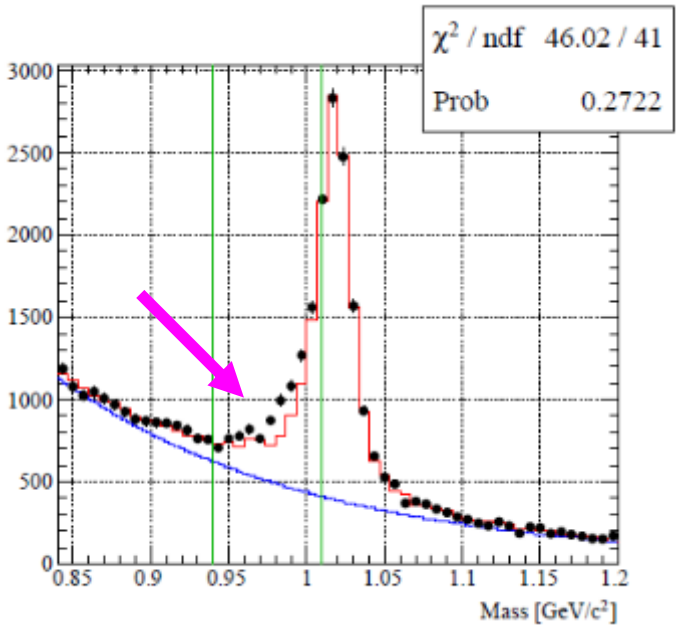
RUN 2 (26 modules)



RUN1, Cu target (INPUT:E325-BW)
Fit with BW in vacuum

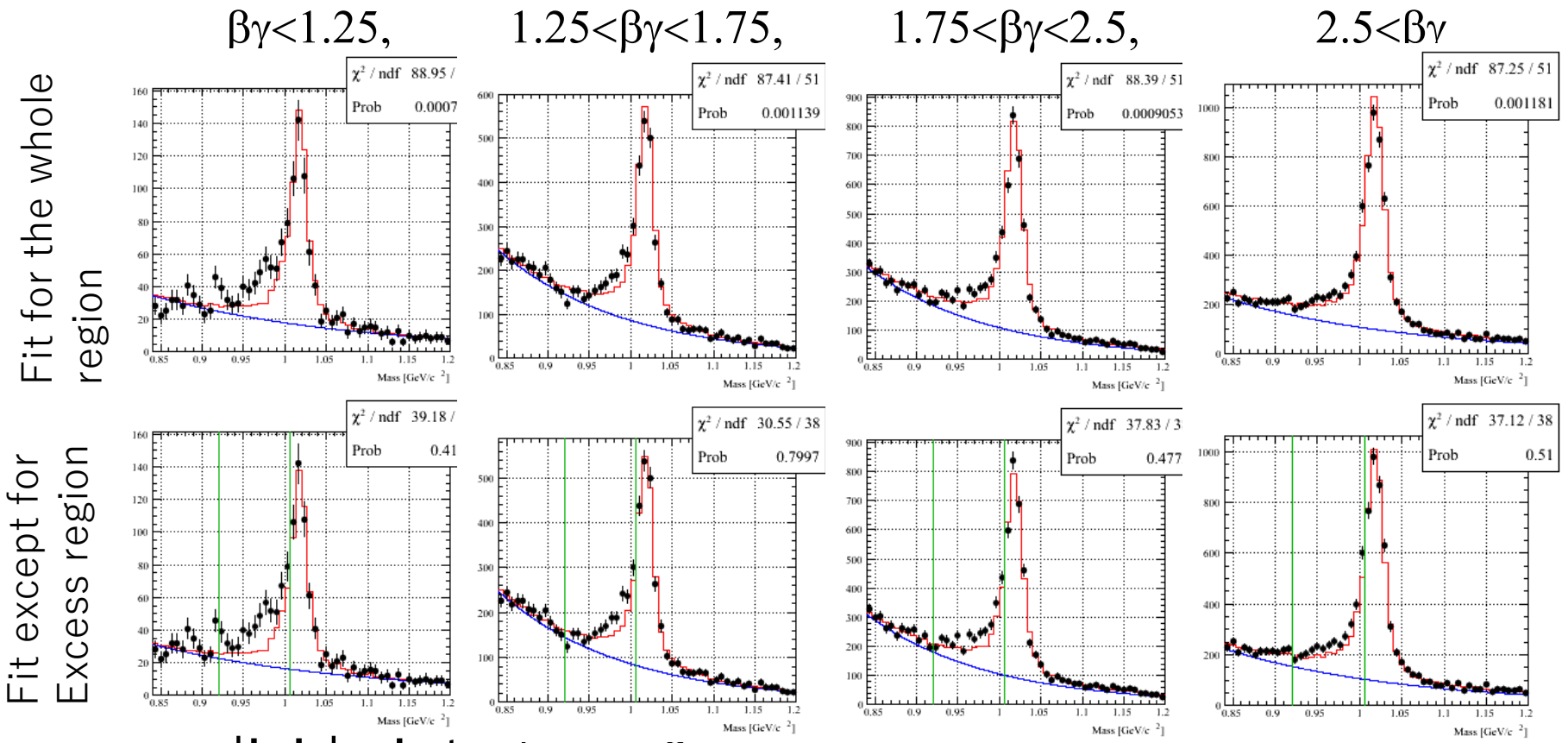
Black points:
Expected data





- ~15k ϕ for Cu target expected in RUN1
- Left plot: significant change seen (w/o $\beta\gamma$ selection)
  - fit with [vacuum shape + exponential bkg] fails due to the excess left side of the peak
- Right plot:
  - Excluding the excess region(0.94-1.01GeV/c^2), fit succeeds

RUN1, Cu target (INPUT:E325-BW)
Fit with BW (in vacuum)



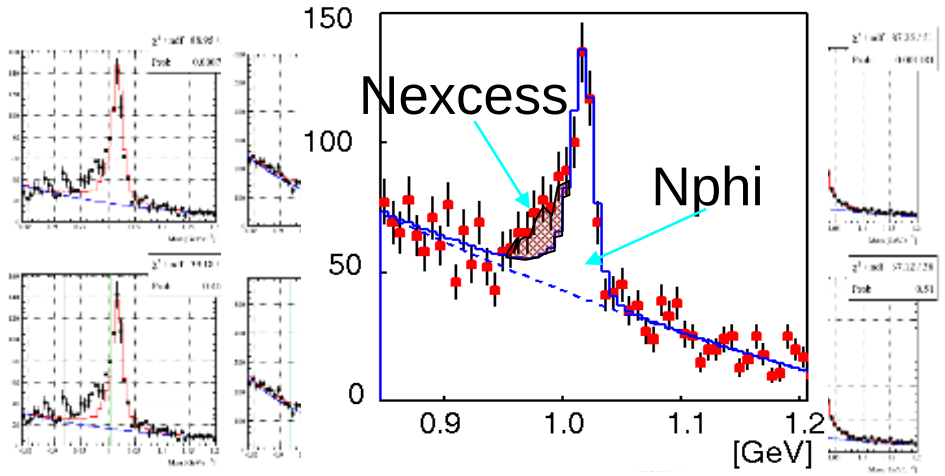
- divide into four βγ regions
- βγ dependence is examined → next

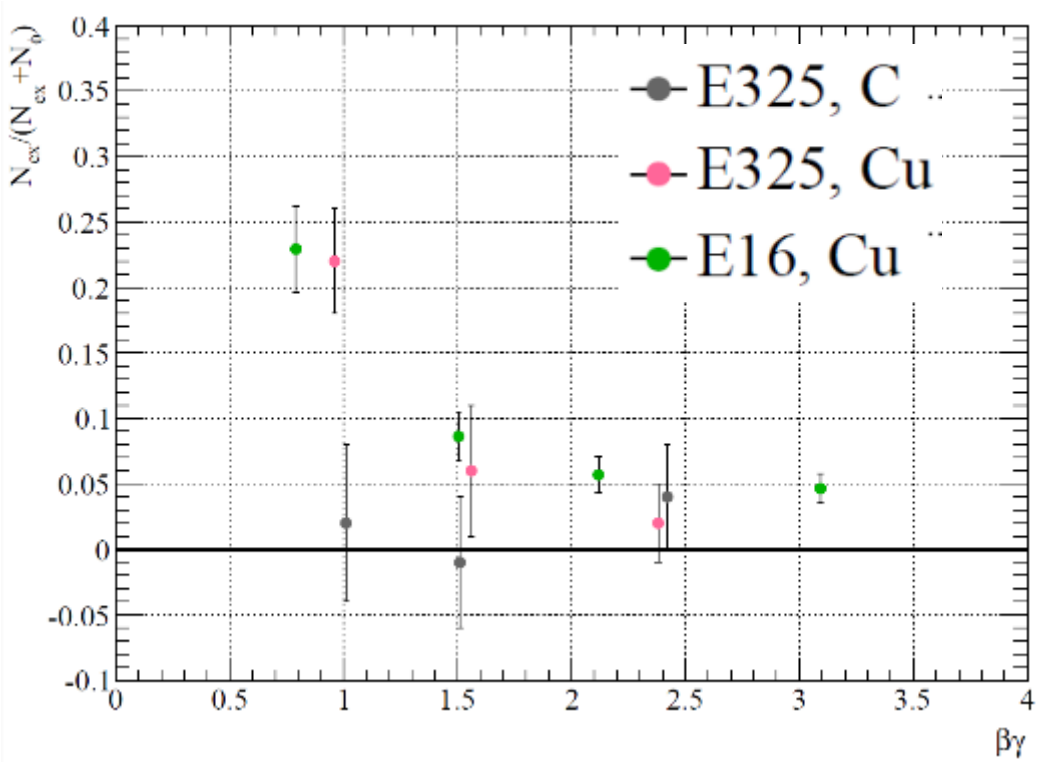
RUN1, Cu (INPUT:E325-BW)

Excess ratio vs $\beta\gamma$

$$\frac{N_{excess}}{N_{excess} + N_{\phi}}$$

- All $\beta\gamma$ bins for Cu are significant in E16
- (cf) E325 only fastest bg bin is significant.





- larger excess in lower βγ (slower) bin :

the tendency become more clear and significant

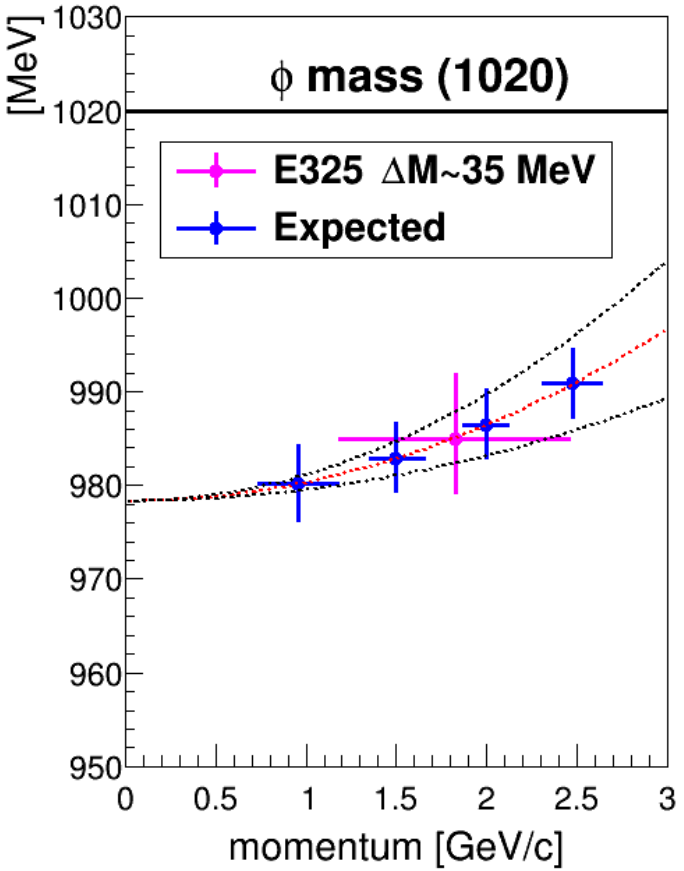
than that of E325.

Momentum dependence (Dispersion relation)

H.Kim P. Gubler PLB805, 10 (2020)extends the validity of momentum range.
Show you on later slides.

- Momentum dependence of mass can be obtained for the first time.
- Expectation of RUN1 x 2.5 is shown.

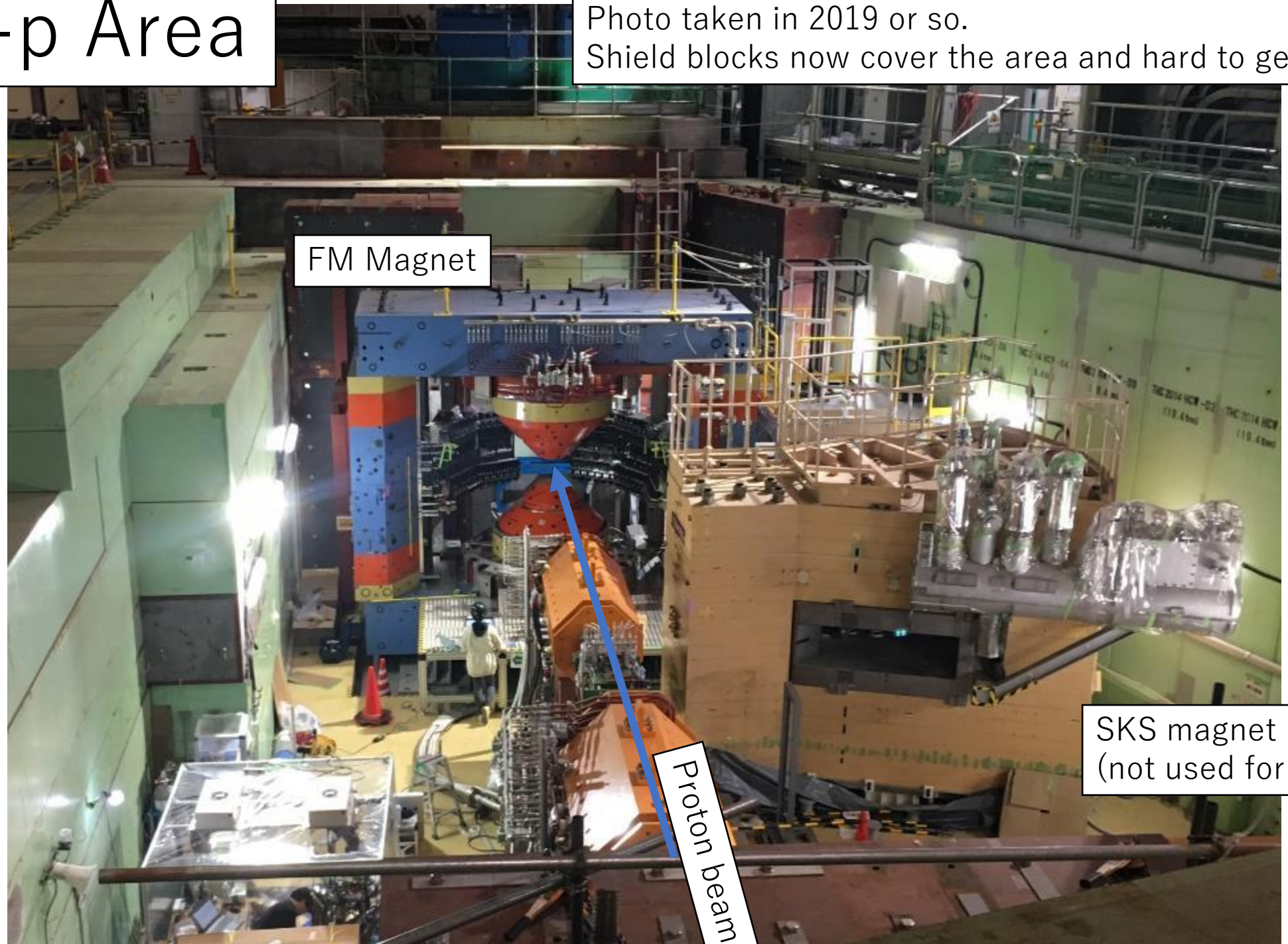
- Dispersion relation itself is an important property of pseudo particle.
- We can extrapolate mass into 0 momentum, where most of QCDSR calculation results applies.

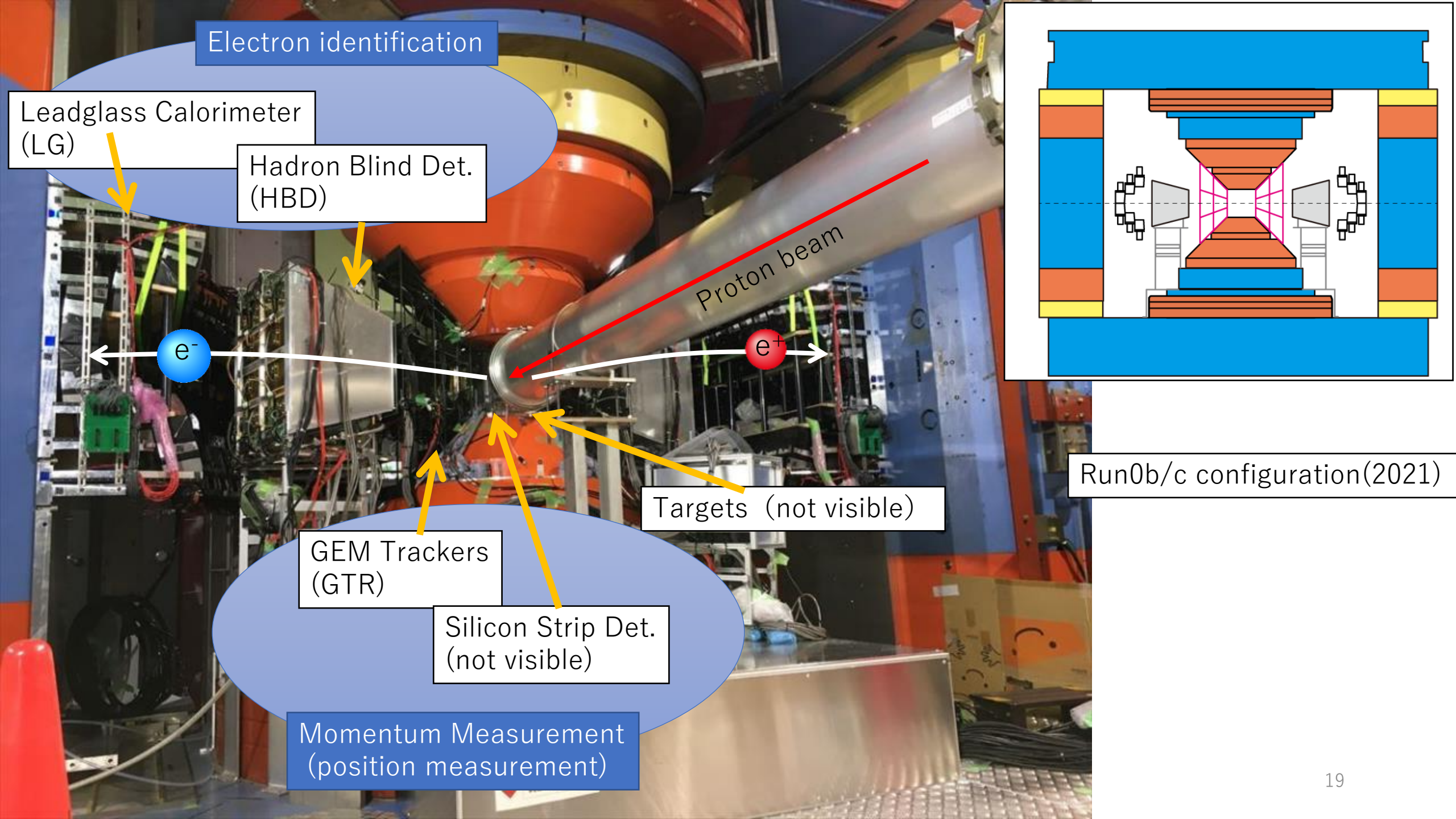


S.H. Lee PRC57, 927(1998)

High-p Area

Photo taken in 2019 or so.
Shield blocks now cover the area and hard to get this view.

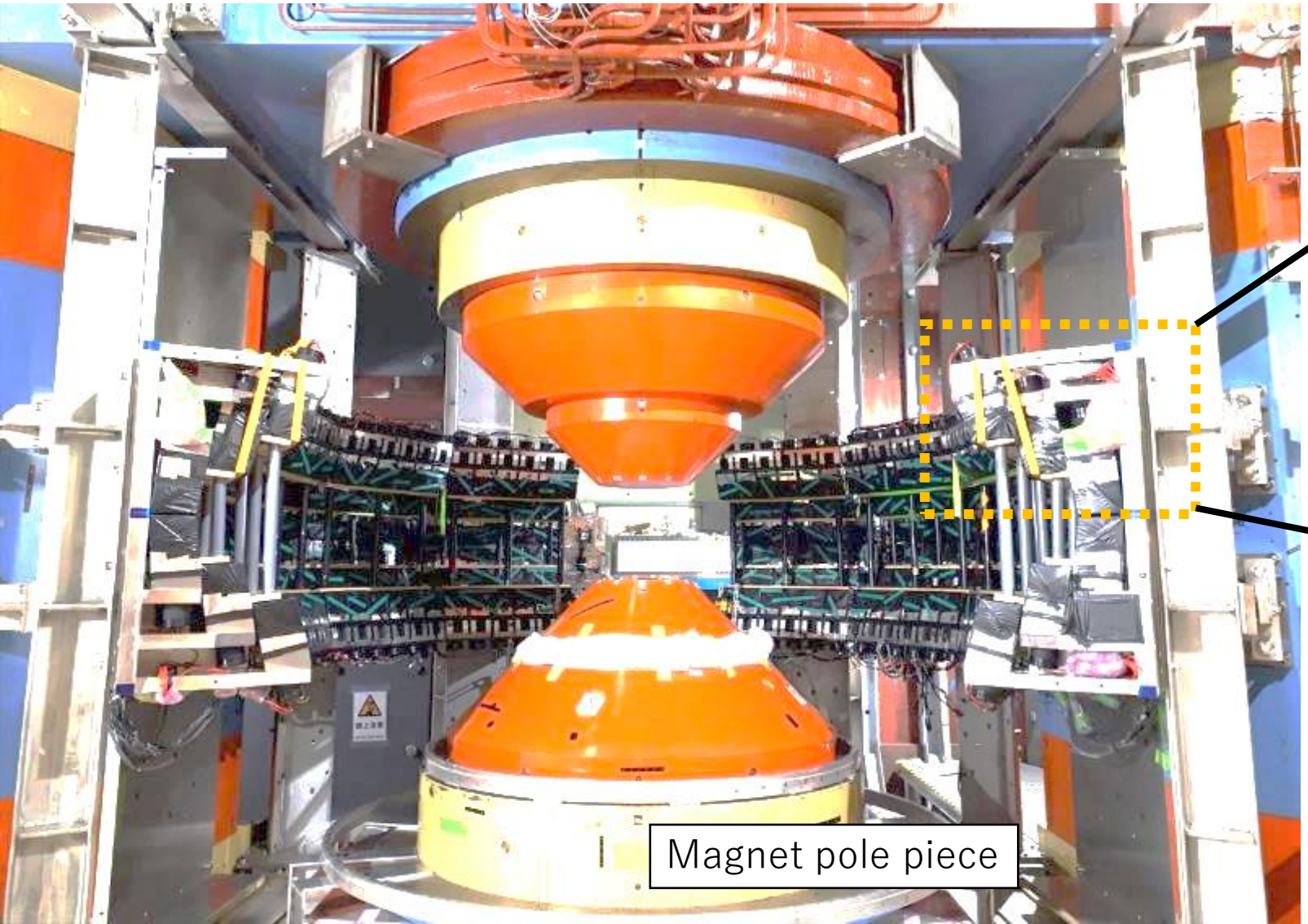


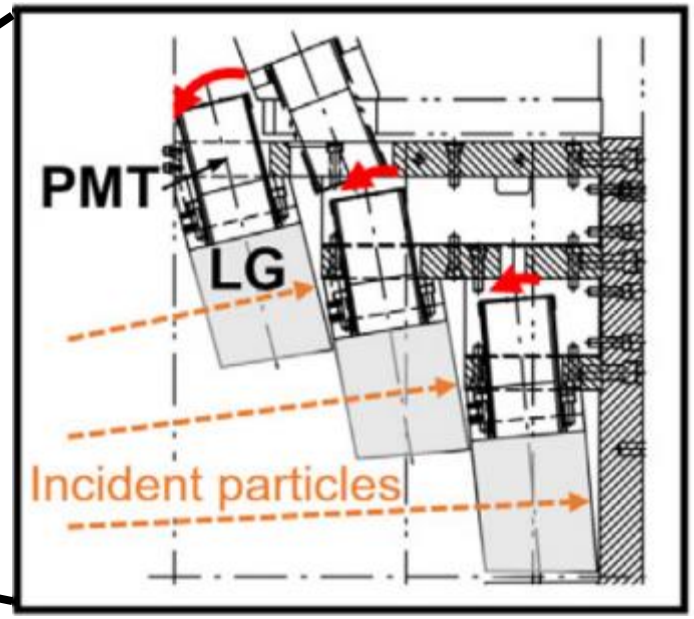


Run0b/c configuration(2021)

LG (Lead glass calorimeter)

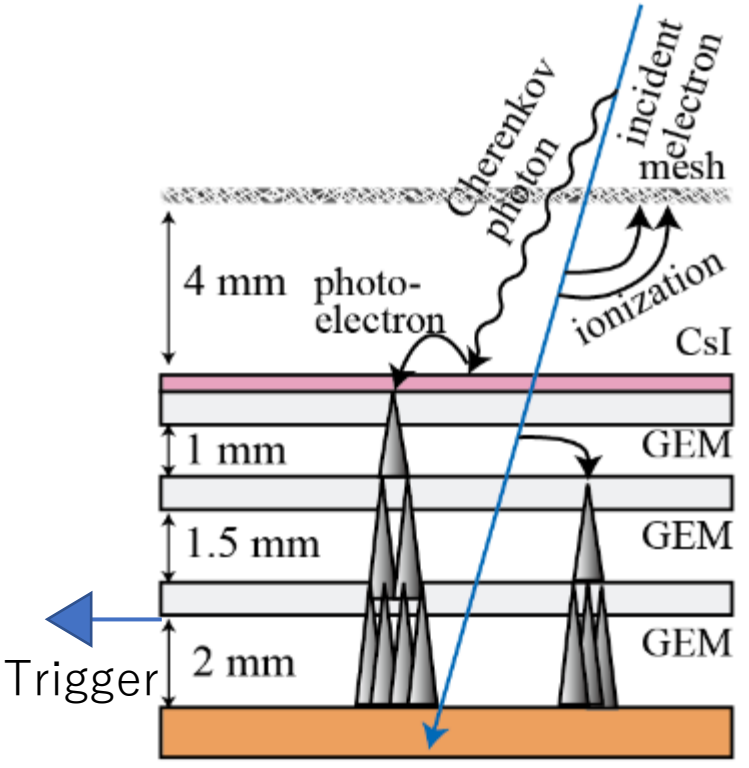
- Lead glass (TOPAZ) + PMT (Belle)
- Pion efficiency 10% (Reject 90%) while maintaining 90% efficiency for e- at 0.4GeV

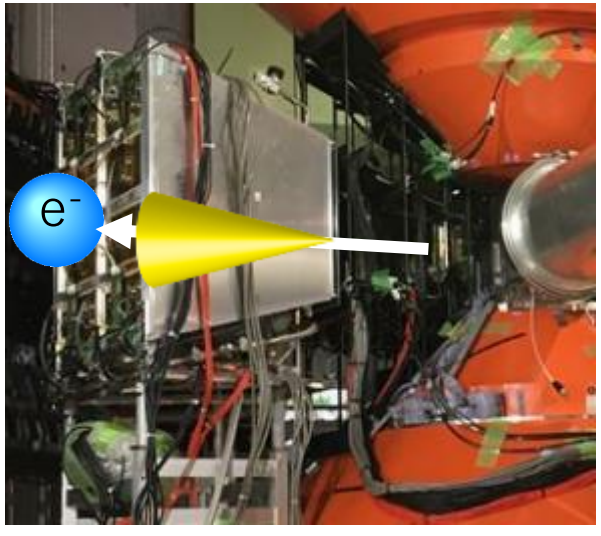


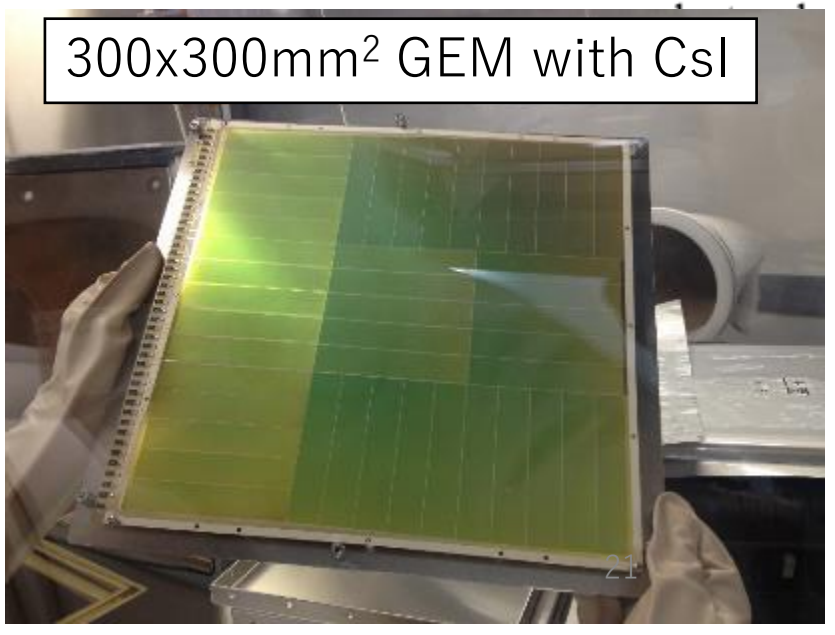


Hadron Blind Detector (Cherenkov Detector)

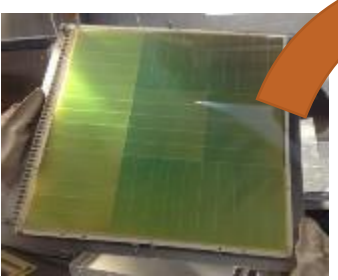
- Based on PHENIX HBD.
- CF4 serves as radiator and amplification gas
  - Radiator 50 cm. / p.e. ~ 11
- Gas Electron Multiplier (**GEM**) for amplification
- **CsI** is evaporated on top GEM
  - Photocathode (> ~6eV)
- Pion efficiency 2% (rejection 92%) while maintaining electron efficiency of 68%

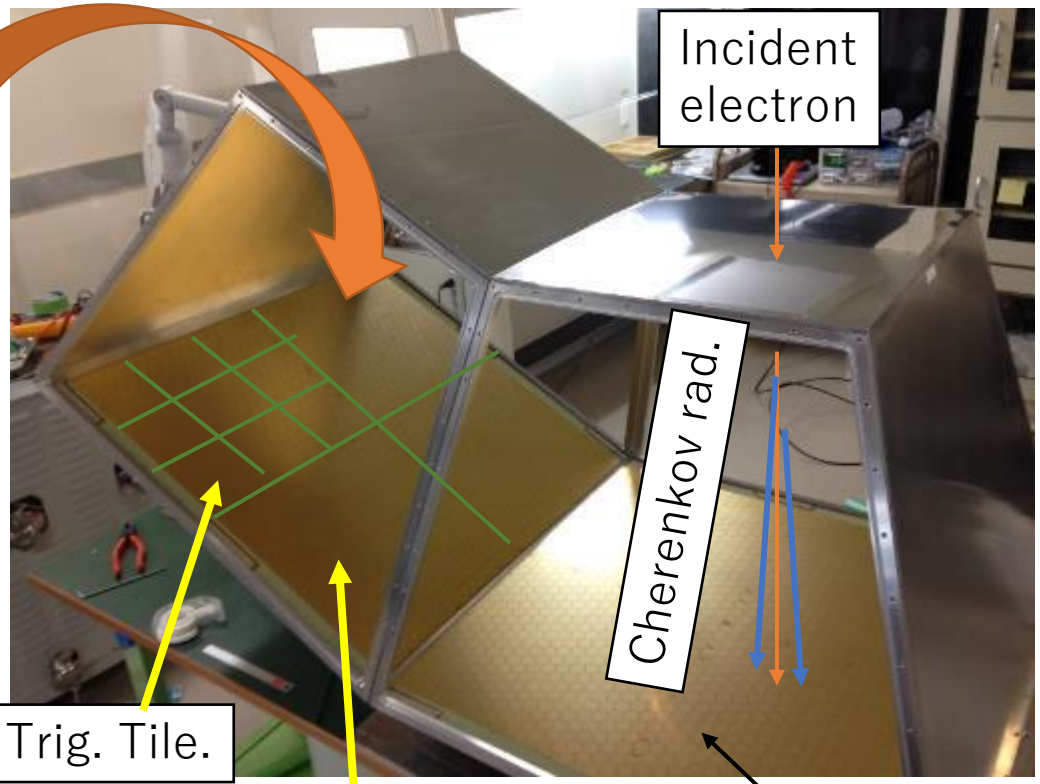


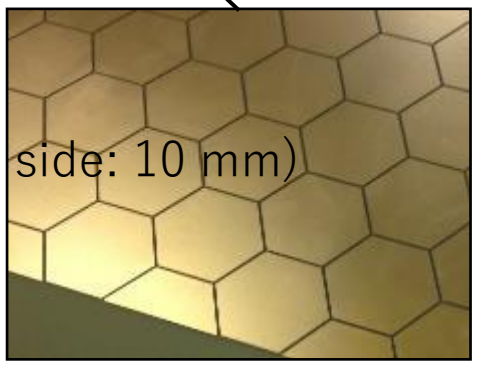




HBD







Hexagonal pads (a side: 10 mm)

HBD is under maintenance. Will be installed in this FY.

Nuclear Instruments and Methods in Physics Research A 819 (2016) 20–24

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journal homepage: www.elsevier.com/locate/nima

Development of a hadron blind detector using a finely segmented pad readout

Koki Kanno [a,b,*], Kazuya Aoki [c], Yoki Aramaki [b], Hideto En'yo [b], Daisuke Kawama [b], Yusuke Komatsu [a], Shinichi Masumoto [a], Wataru Nakai [a,b], Yuki Ohara [a], Kyoichiro Ozawa [c], Michiko Sekimoto [c], Takuya Shibukawa [a], Tomonori Takahashi [d], Yosuke Watanabe [a], Satoshi Yokkaichi [b]

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Hadron blind Cherenkov counters

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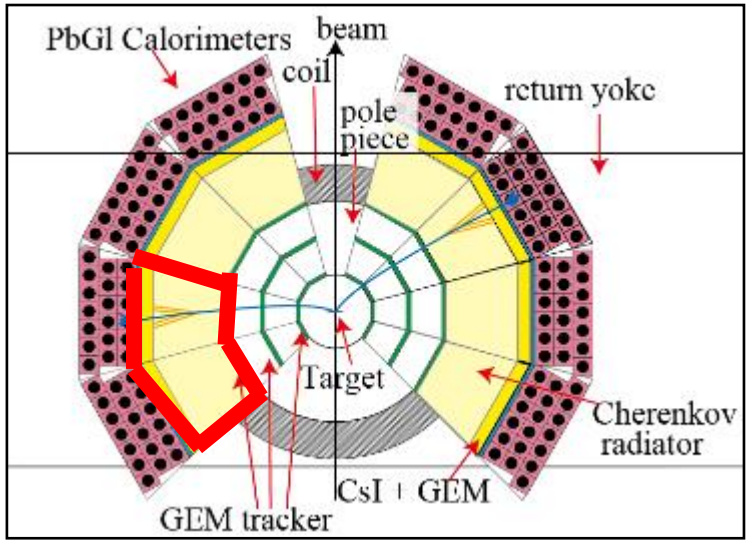
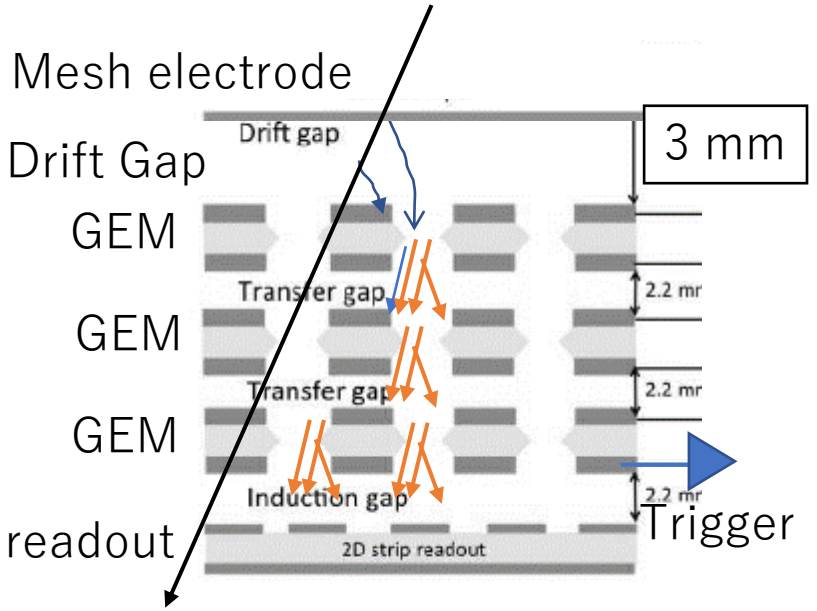
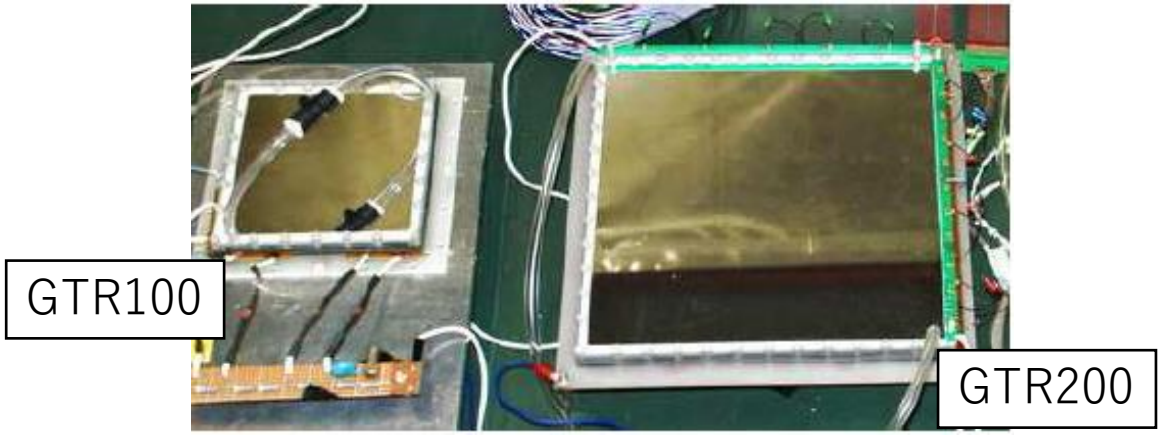
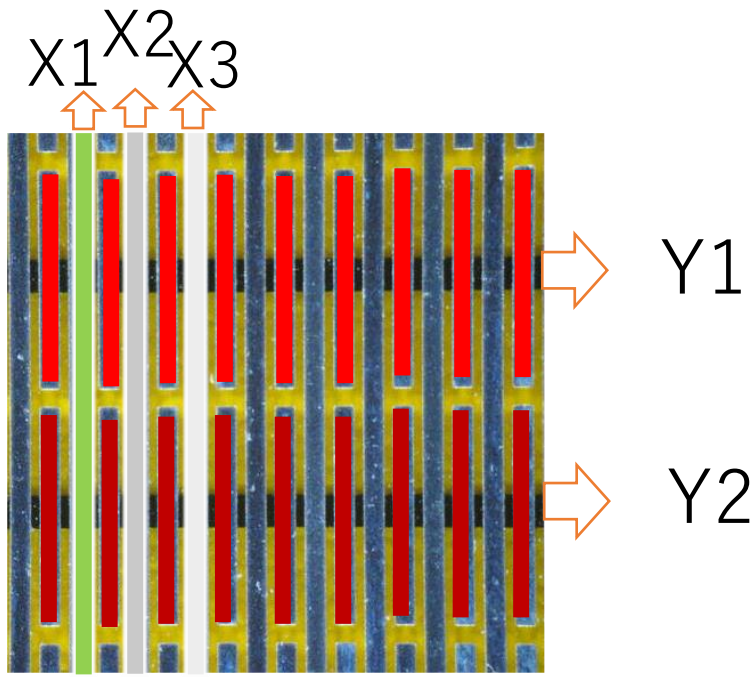


GTR (GEM Tracker)

- Ionization electrons in the drift gap are collected and amplified by GEMs.
- Charge collected on to 2D strip readout.
  - X: 350um pitch -- σ ~100um
    - Sensitive to bending direction.
    - 100 um resolution required.
  - Y: 1400um pitch -- σ ~300um

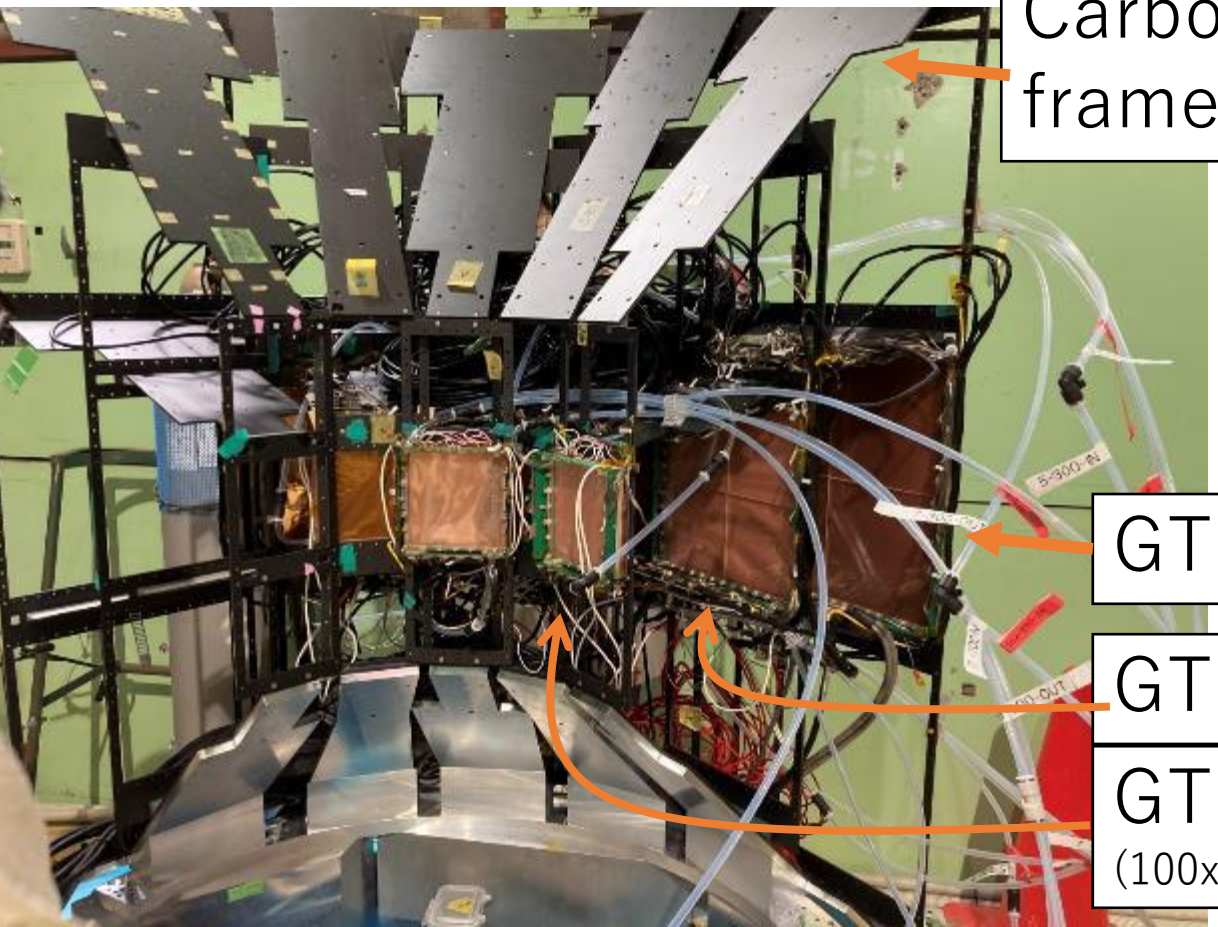


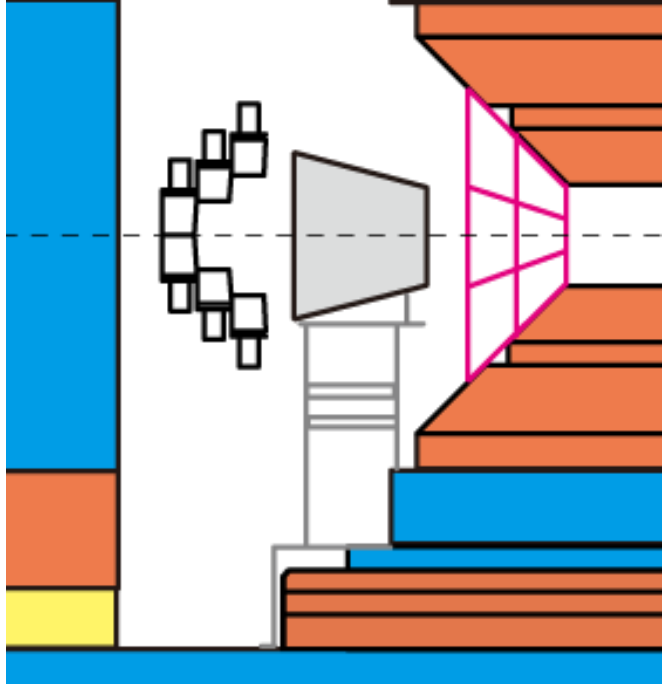


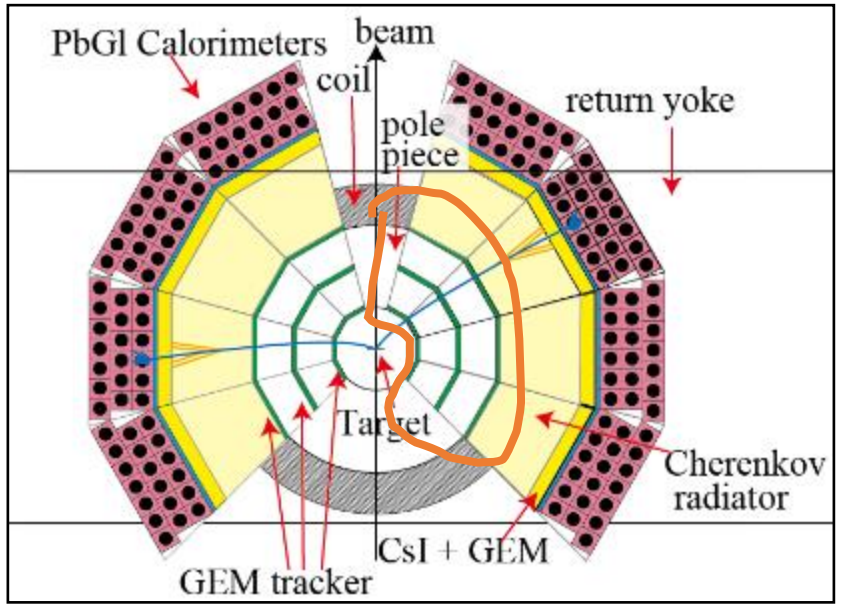


GTR (GEM Tracker)

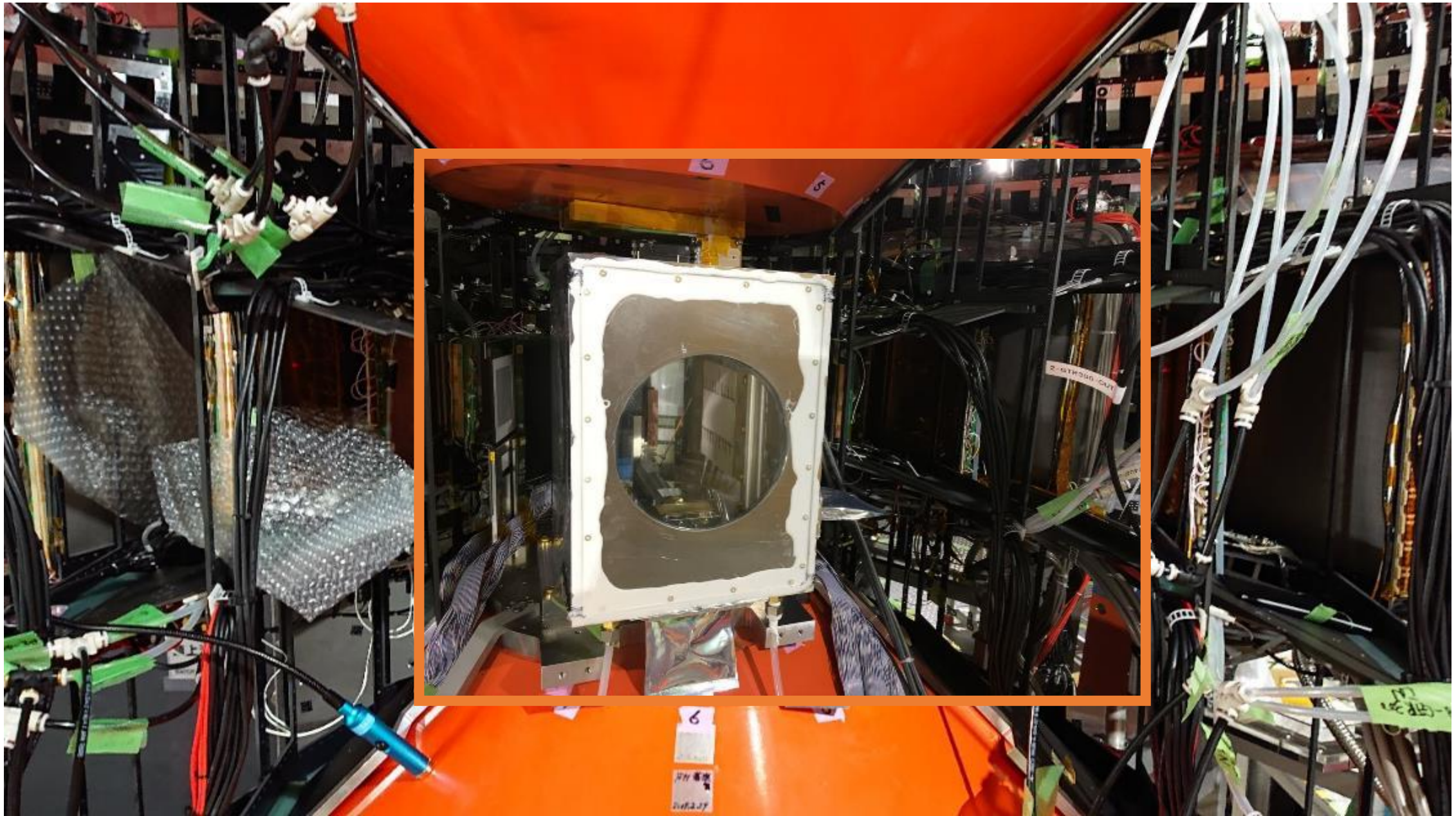
- A module consists of
  - GTR100, GTR200, GTR300
- Half of the setup installed Aug. 2022







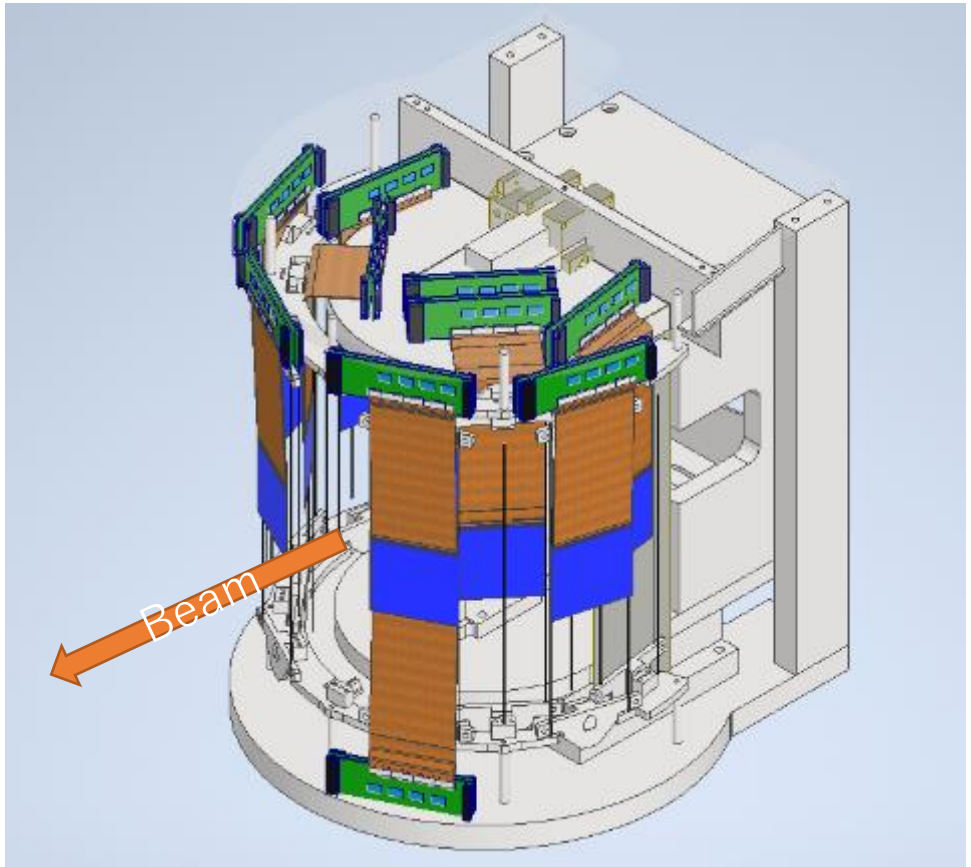
OLD SSD and target chamber



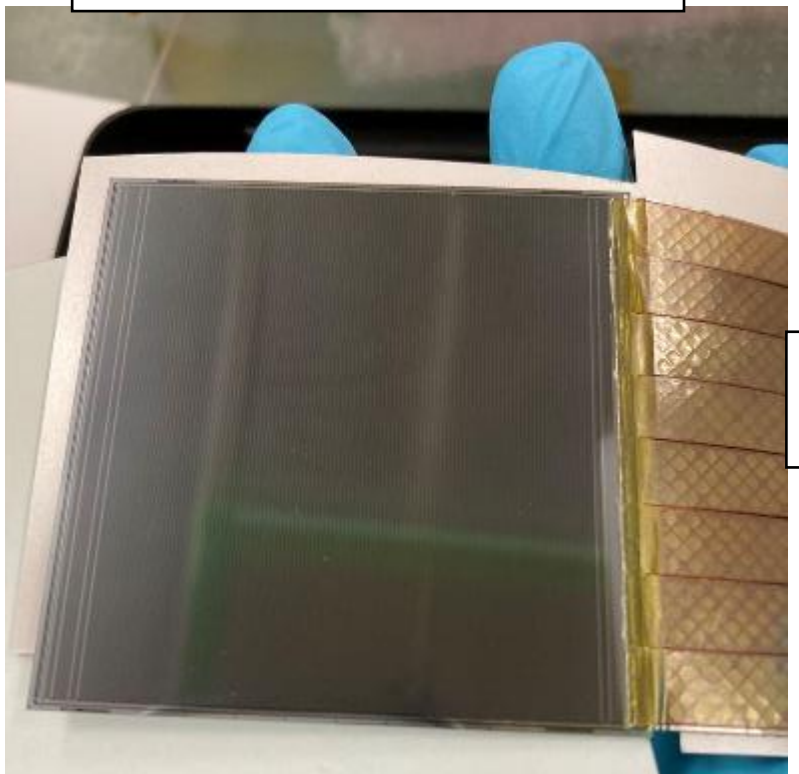
NEW SSD (STS)

- Under construction in collaboration with CBM-STS group at GSI (Germany)
- DAQ migration is ongoing by E16 Group.
- 10 sensors are prepared for Run0d and 1.

Sensitive area	60 x 60mm2
Thickness	300um
Strip pitch	58um
Strip direction	X, U(7.5deg)

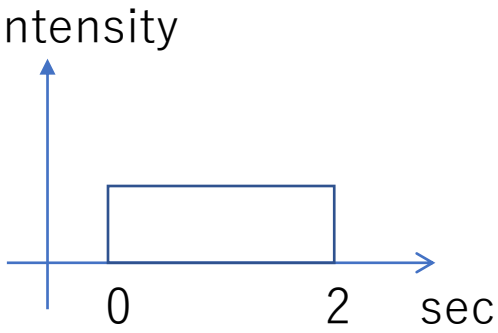


Si sensor (HAMAMATSU)



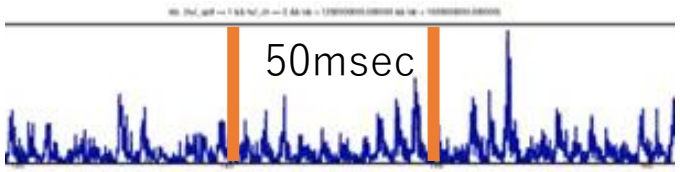
Micro-cables
Made in Kharkiv

Run0 a/b/c
beam line and detector commissioning.

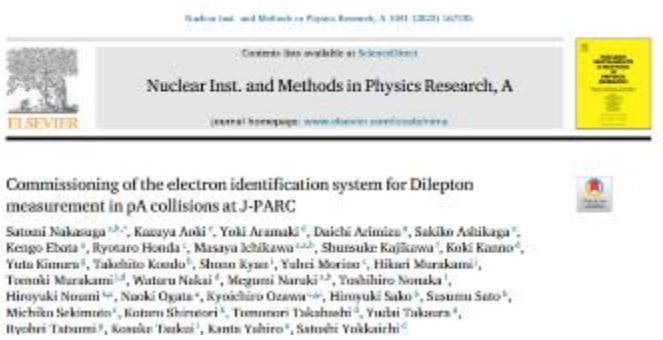


- Beam tuning / improvement.
  - Intensity / position adjustment
  - Reduction of radiation / background by adjusting optics, collimators.
  - Beam profile measured.
  - Bulk Time structure improvement.
  - Anomalous beam suppressed. (10 times intense beam etc..)

- Beam micro-structure remains.
  - Highly time-concentrated beam comes every ~5msec, and 5.2usec.
    - Resulted in very low live rate ~15%　(75% expected)
    - Enhance fake trigger due to overlapping events.
  - Improvement in the next run (Run0d) is expected by
    - Improvement of power supply of accelerator magnets. (5msec)
    - New optics with no dispersion at Lambertson magnet(5.2usec)
    - DAQ upgrade. (less dead time)
- Performance of detectors

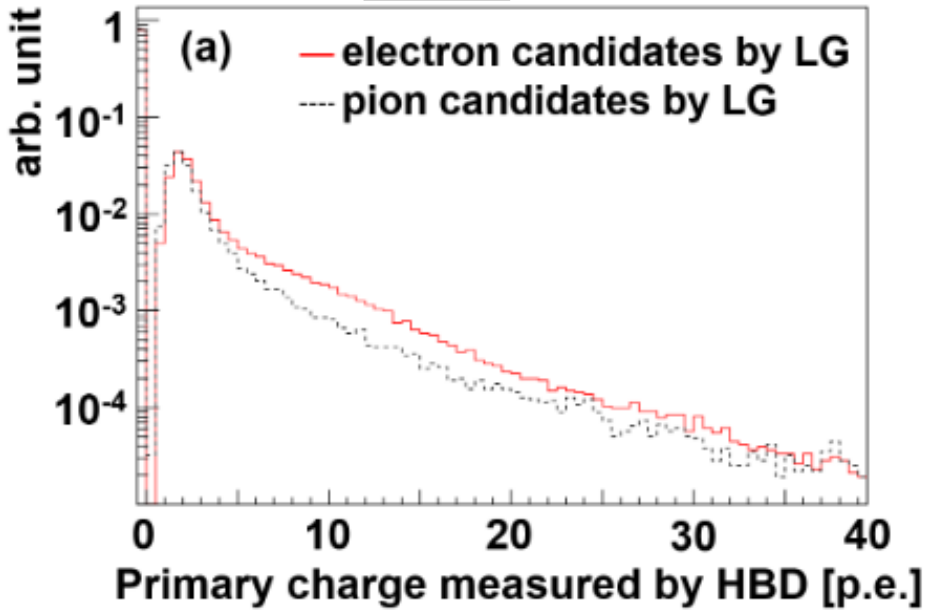


Electron ID performance



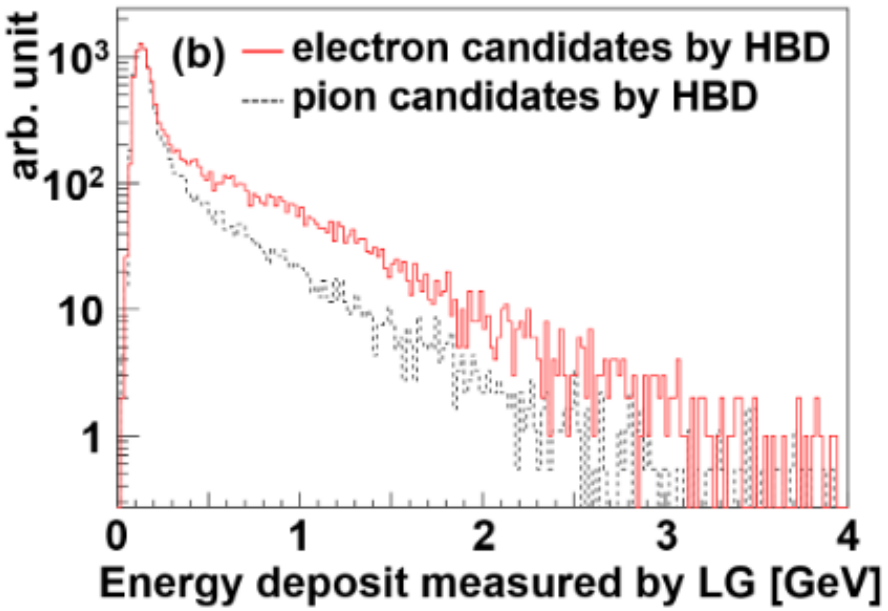
- Semi-online analysis
  - Left: HBD response for e and pi candidate determined by LG.
  - Right: Vice versa.

HBD



LG>100mV (0.5GeV)
LG<50mV

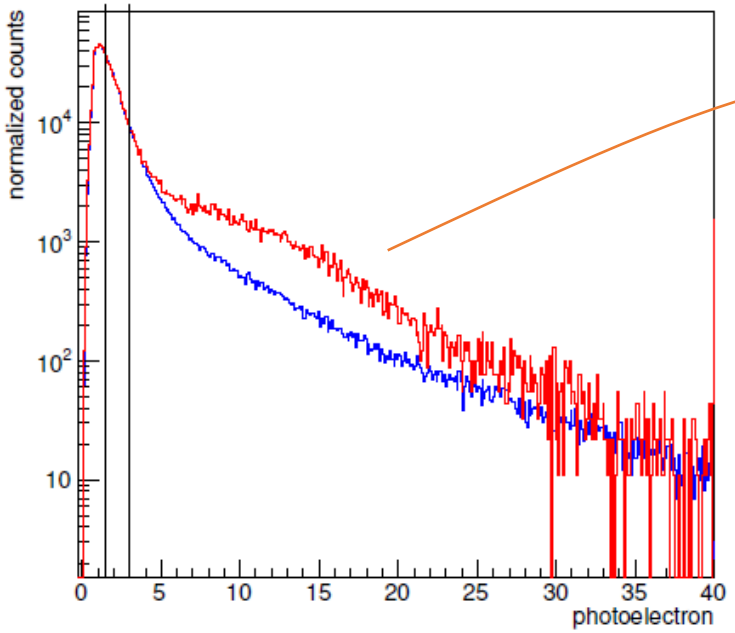
LG



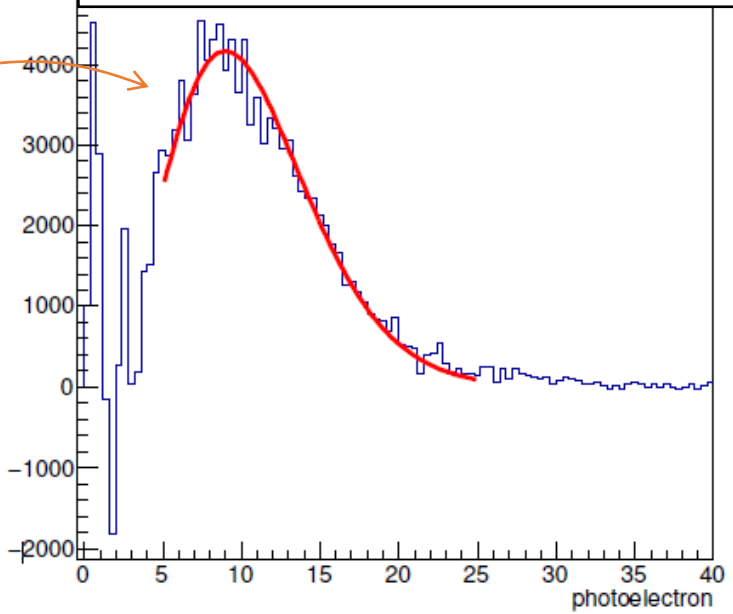
e:HBD>7 p.e.
pi: HBD f-bias.

NIMA1041, 167335(2022)

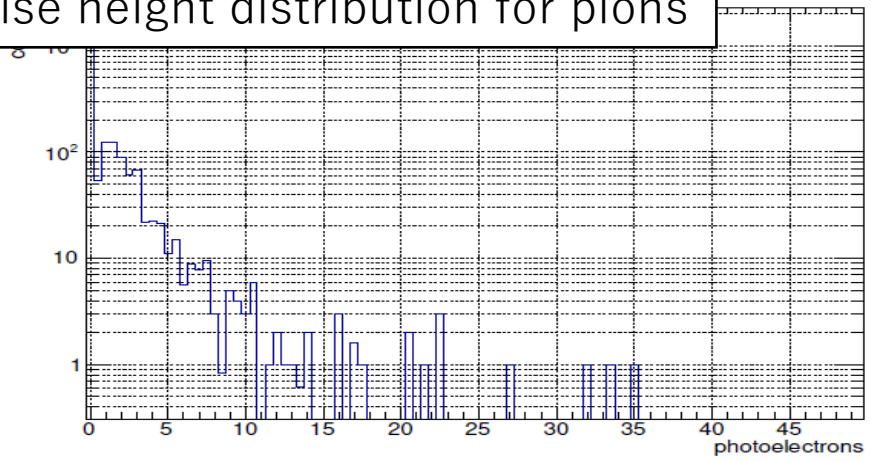
HBD performance



Pulse height distribution for electrons



Pulse height distribution for pions

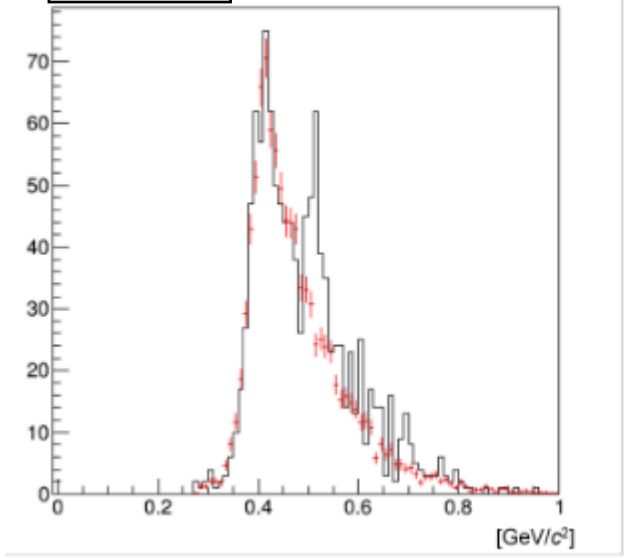


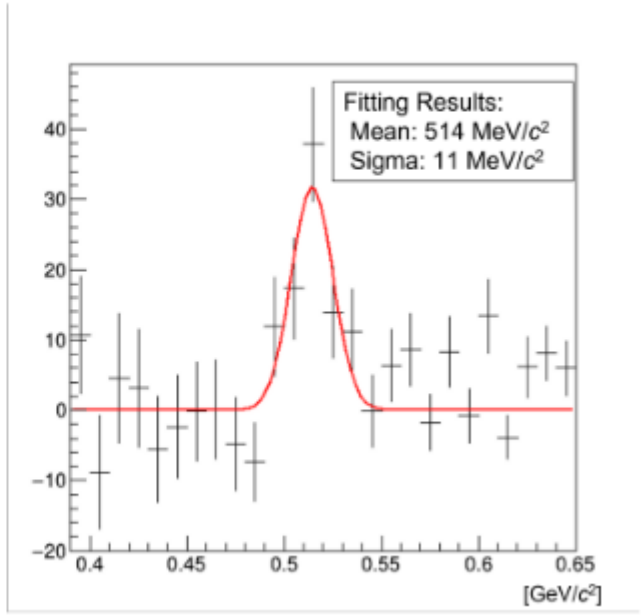
- 11 photoelectrons are observed.
- Consistent with expectation.

Tracking performance

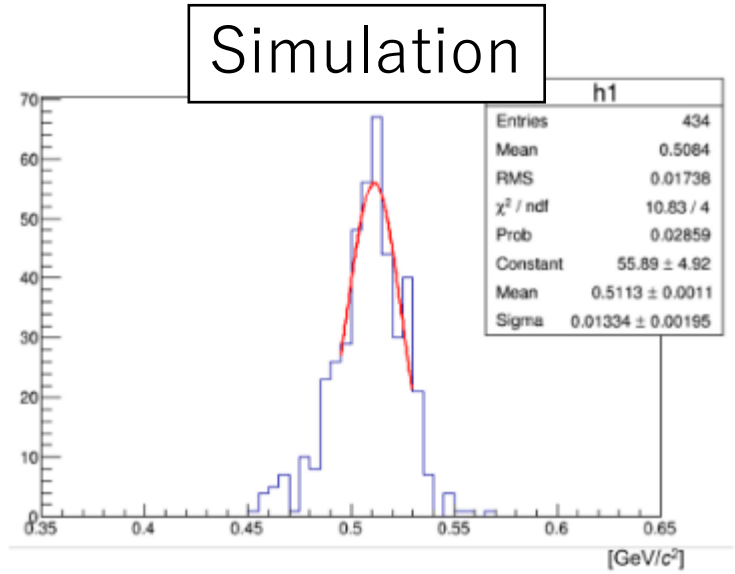
- Track reconstructed using 4-layers: SSD, GTR100/200/300
  - Currently position resolutions are ~2 times worse than expectation.
  - Ks ($K_s \to \pi^+\pi^-$) is seen and consistent with simulation.

Data





Simulation



Invariant mass in single arm
(event-mixing)

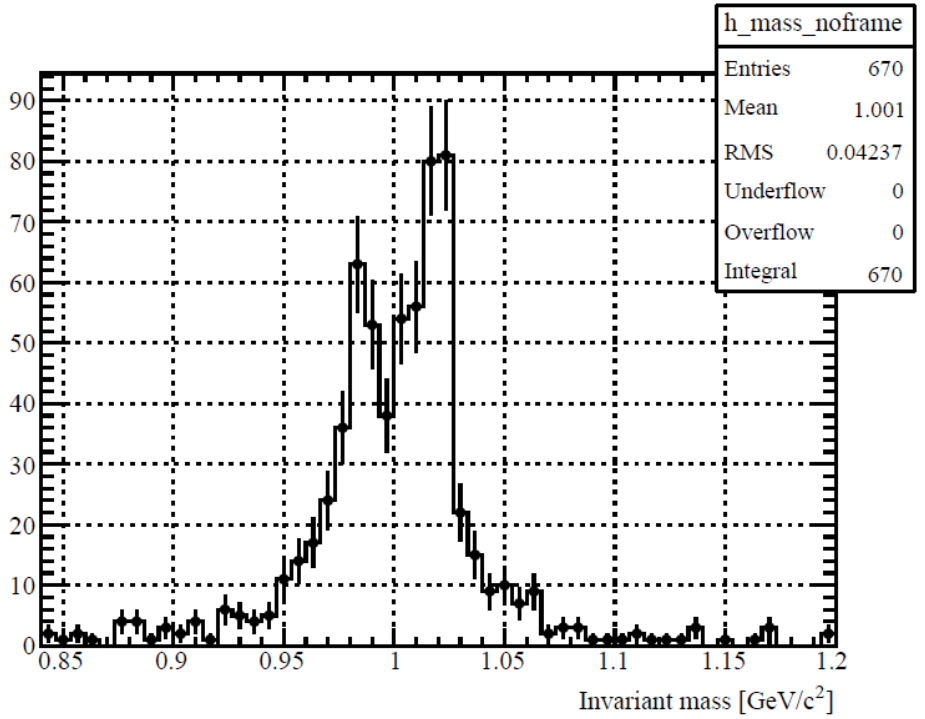
BG subtracted

Current status

- After Run0c (2021), all detectors (except for LG) are uninstalled for maintenance.
- Preparing for Run0d in 2023
  - Nov. 2021, two additional LG modules installation completed.
  - Aug. 2022, half of GTR installed. Half in preparation.
  - HBD/SSD preparation for install by Mar. 2023.
  - DAQ improvement on-going.
- Based on the outcome of run0d, we request for RUN1.

Expected in RUN2

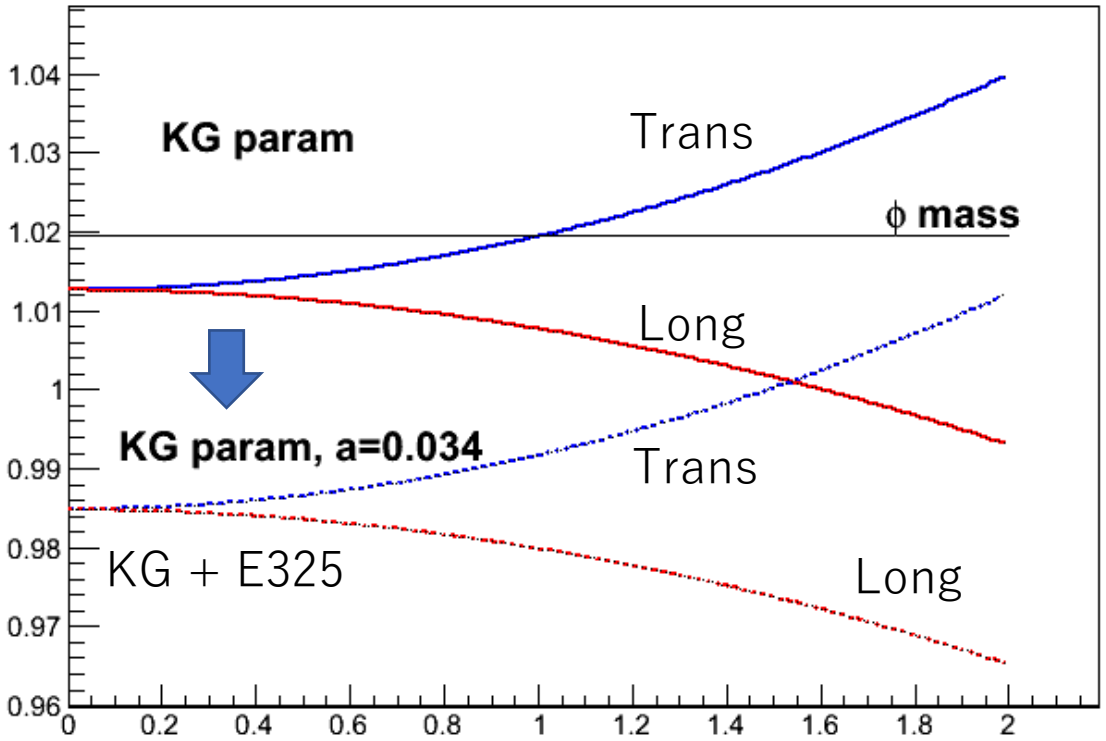
- RUN2 stat (320shifts)
- Pb target
- INPUT: E325-BW
- $\beta\gamma < 0.5$



Play with Kim-Gubler model

I.W. Park, P.Gubler, S.H.Lee, H.Sako, KA

- PLB 805, 10 (2020)
  - Trans: Transverse / Long: Longitudinal
  - Trans: Long = 2:1
- I replaced the shift by E325 value

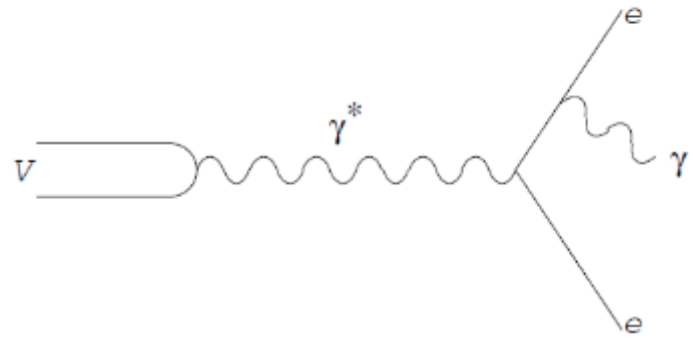


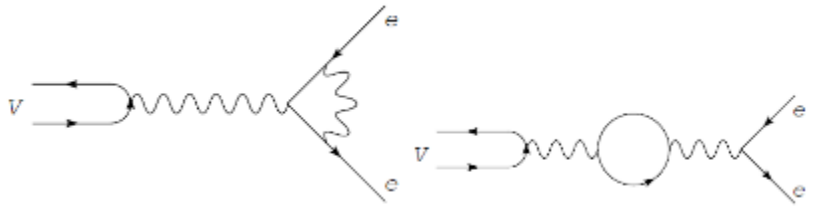
$$\frac{m_\phi^{\mathrm{L/T}}(\rho_N,\vec{q})}{m_\phi^{\mathrm{vac}}} = 1 + \left(a + b^{\mathrm{L/T}}|\vec{q}|^2\right)\frac{\rho_N}{\rho_0}.$$

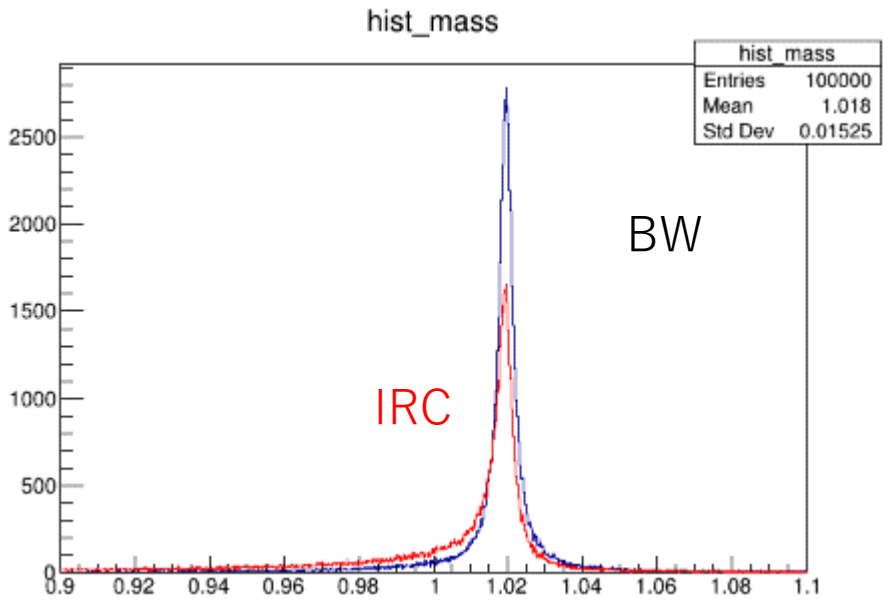
- KG param
  - b(T) = 0.067 pm 0.0034
  - b(L) = -0.0048 pm 0.0008/GeV
  - a = -0.0067
- KG + E325 param
  - a=0.034
  - b : same as KG param.

Internal Radiative Correction (IRC)

- Momentum distribution took from JAM.
- Mass : Breit-Wigner distribution.
- IRC done using software package PHOTOS
- IRC makes tail on lower side.

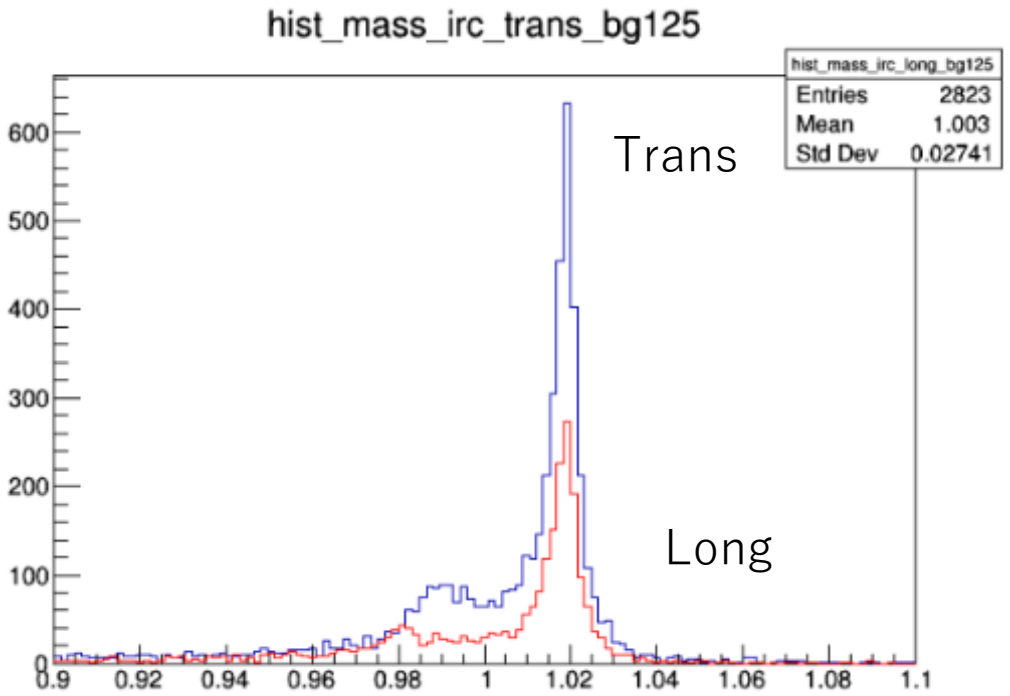


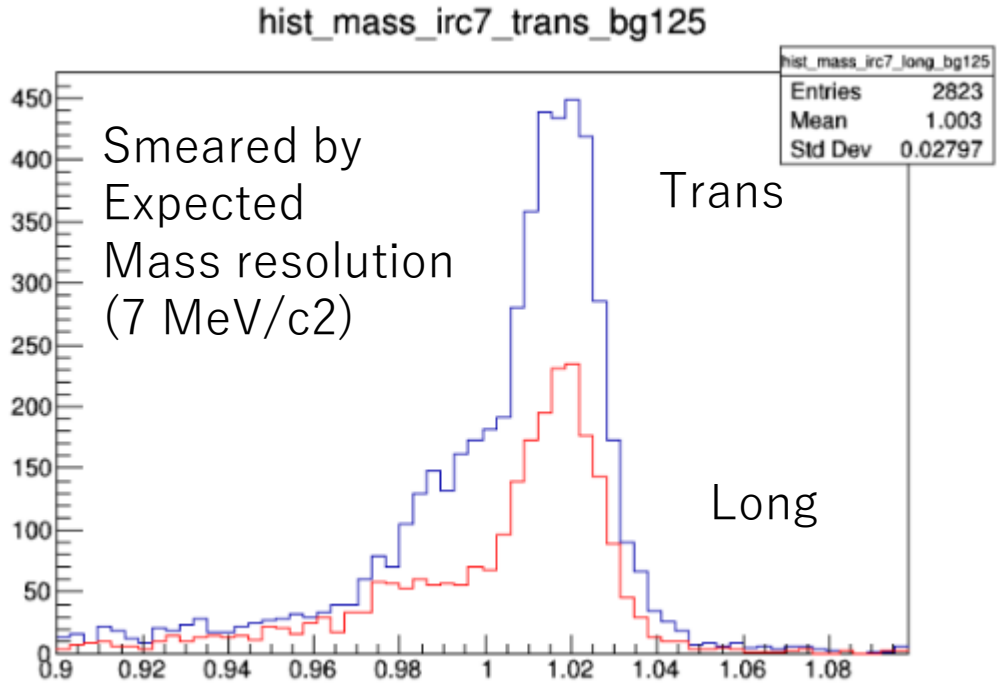




E325 MODEL mass distribution

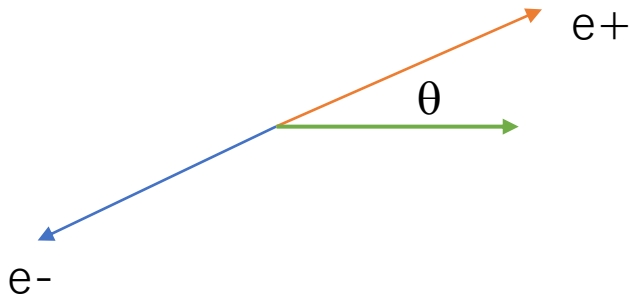
- E325 model assumption
  - Density assumed to be WS potential shape.
  - Phi production probability proportional to density.
    - According to mass-number dependence of X-sec (sigma(pA) ~ A)
  - # of entry is arbitrary. Run1 exp: ~1.7k Run2 exp: 12k for bg<1.25

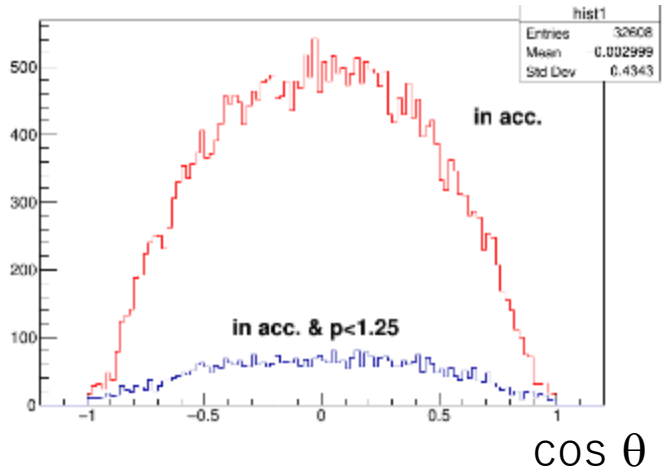




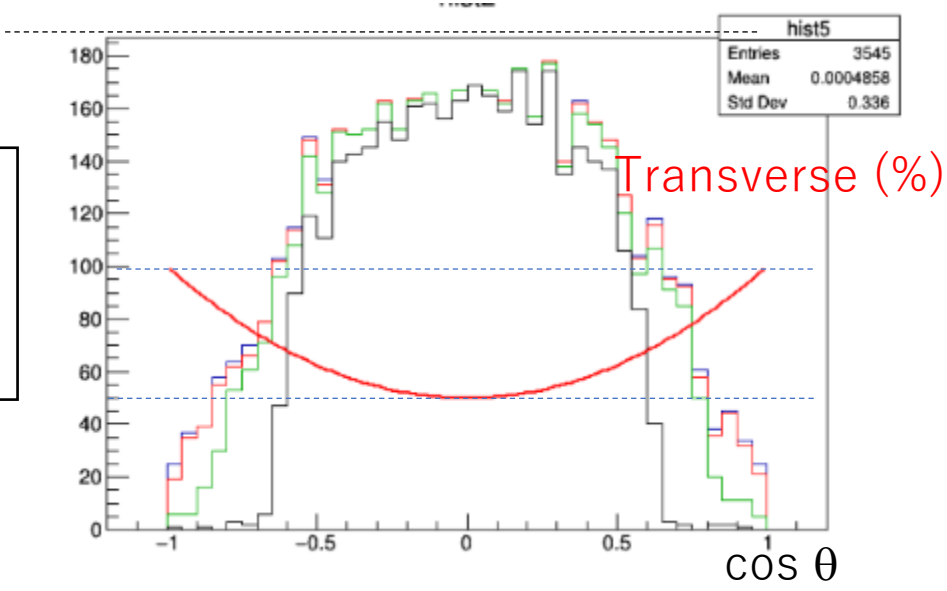
Experimentally distinguishing polarization

- GEANT4 as an acceptance filter.





In the acceptance & phi mom<1.25 & e+- momentum cut



none
>0.2
>0.3
>0.4

- Notes on the plot
  - # of entry is arbitrary.
  - Transverse pol fraction is overlayed.
- Results
  - Smaller acceptance for $\cos\theta = \pm 1$
  - Minimum energy requirement (0.4GeV at the trigger level) further cut those region.

Summary

- J-PARC E16 will measure dielectron in pA collisions at 30GeV to study the origin of hadron mass through spectral change of vector mesons in nuclear medium.
- Many related experiment and theory outcome. Getting interesting.
- We gradually increased our acceptance and reached an intermediate goal (RUN1), which is 1/3 of the design configuration(RUN2).
- Commissioning runs (Run0abc)
  - Beam condition improved but microstructure that caused low live rate remains. Expected to be improved in the next run.
  - Detectors work.
- We are preparing for Run0d planned in 2023.
  - Get PAC approval for RUN1 (1^{st} physics runs).
- Briefly discussed the possibility of measuring polarization dependent mass modification.