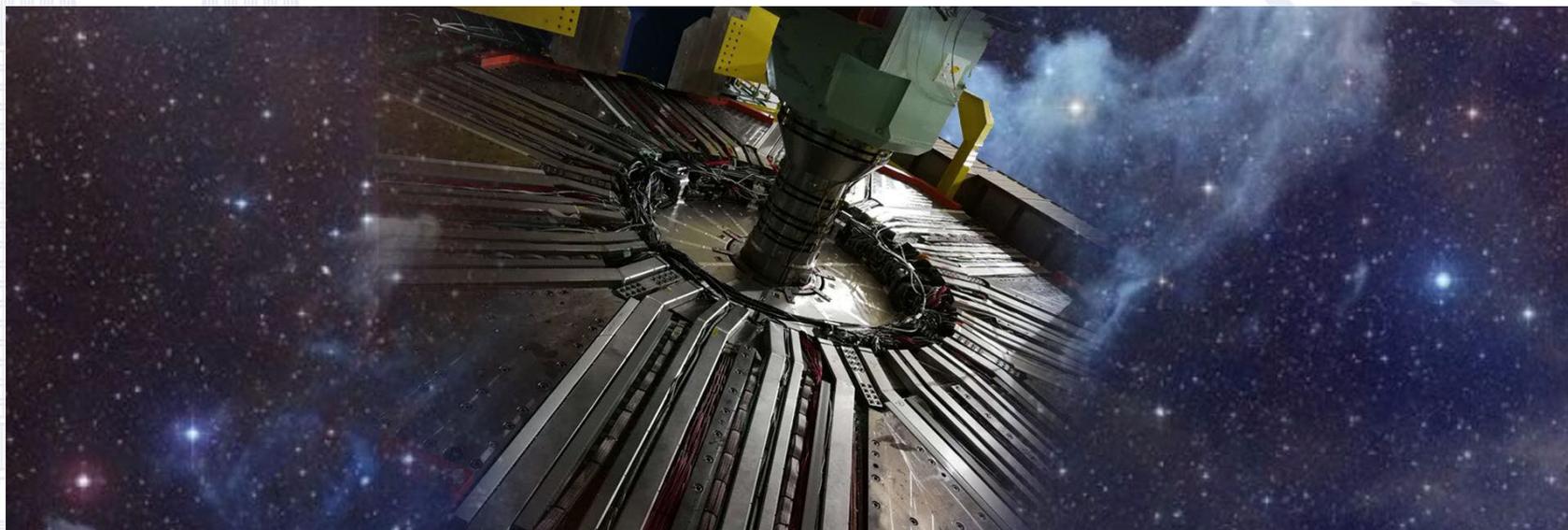
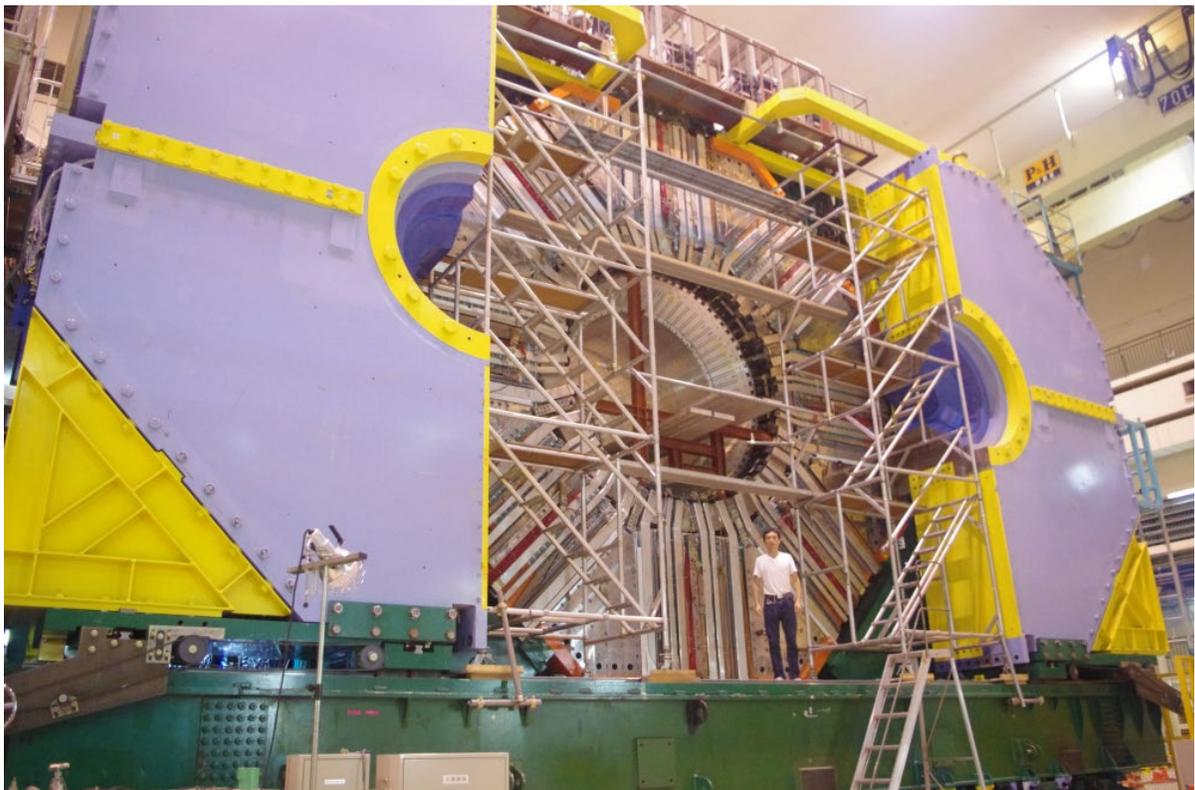


Belle II探测器与升级

王小龙 复旦大学

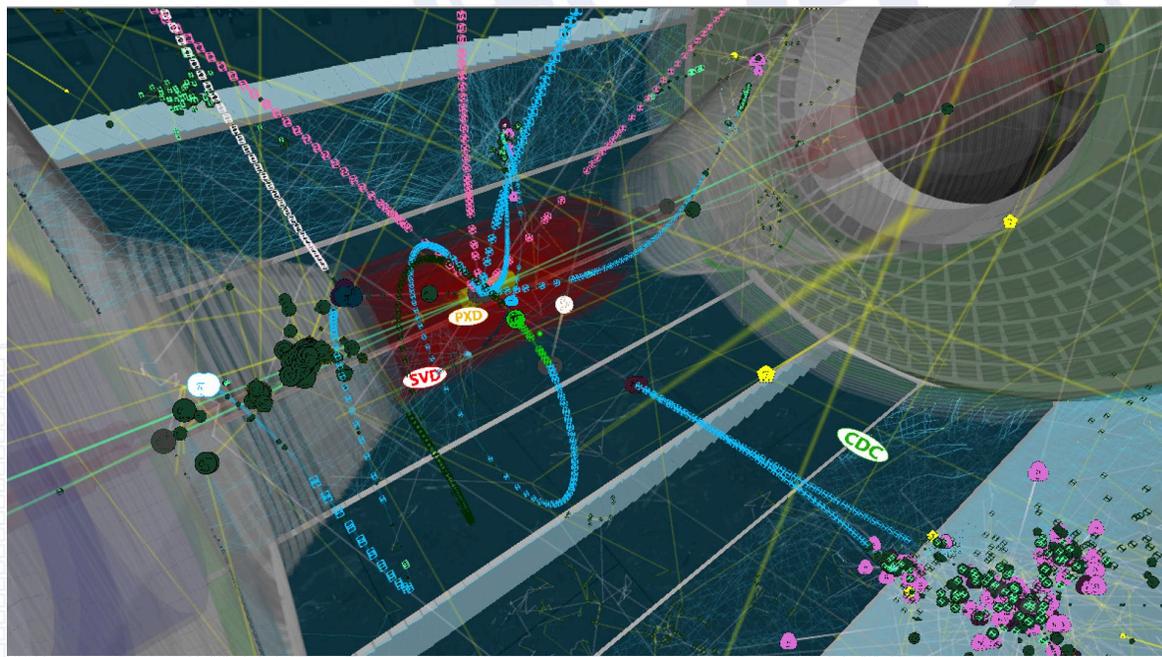
味物理前沿研讨会，2026年2月2日





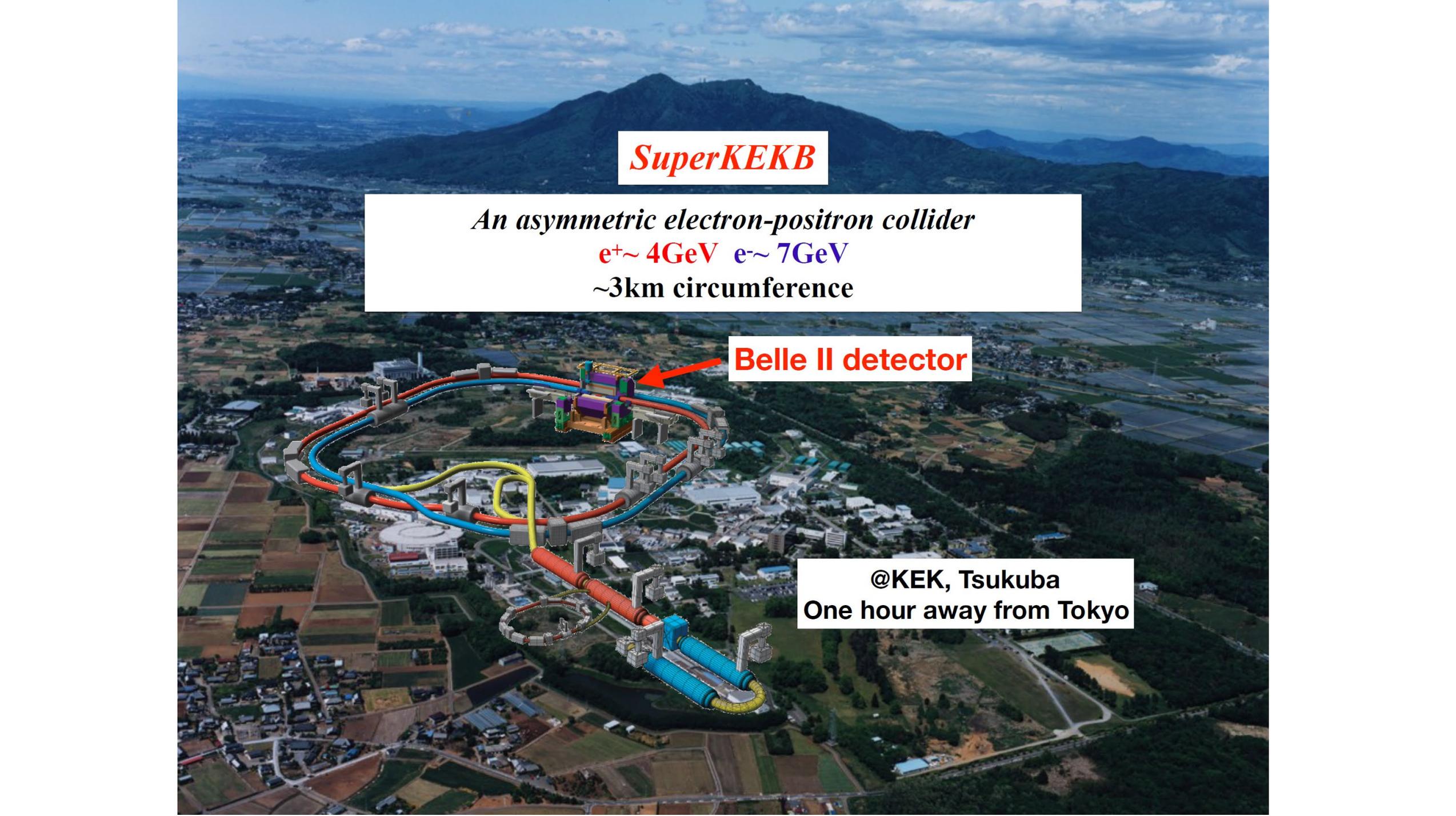
2014年，最早安装 Belle II 探测器

- 2016-2012: Belle 物理分析, 奇特强子
- 2012-2017: 建造 Belle II 探测器, KLM, iTOP
- 2017-: 提出 KLM 升级, 开展研发
- 2022-: 开展味物理与 CPV 研究
- 2026.1-: 提出双光子标记探测器新方案



- Belle II探测器
- Belle II探测器升级
- 复旦的探测器和电子学研发
 - 新的双光子标记探测器



An aerial photograph of the SuperKEKB facility in Tsukuba, Japan. The image shows a large circular accelerator ring with a 3D model overlaid. The model features two main rings, one red and one blue, representing the electron and positron beams. A yellow ring is also visible, likely representing the injection system. The Belle II detector is highlighted with a red arrow. The background shows a rural landscape with fields and a large mountain range under a blue sky with scattered clouds.

SuperKEKB

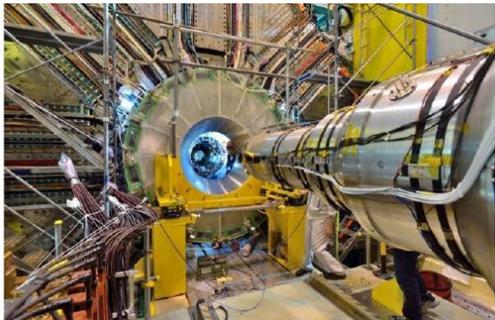
An asymmetric electron-positron collider

$e^+ \sim 4\text{GeV}$ $e^- \sim 7\text{GeV}$

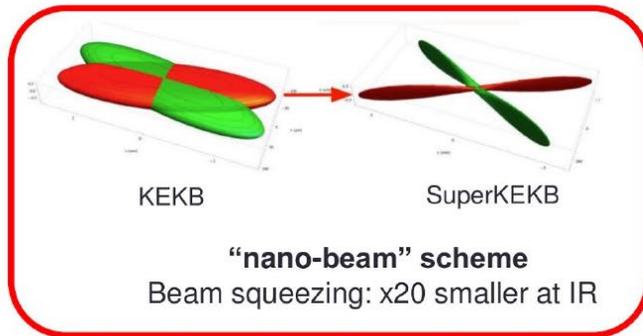
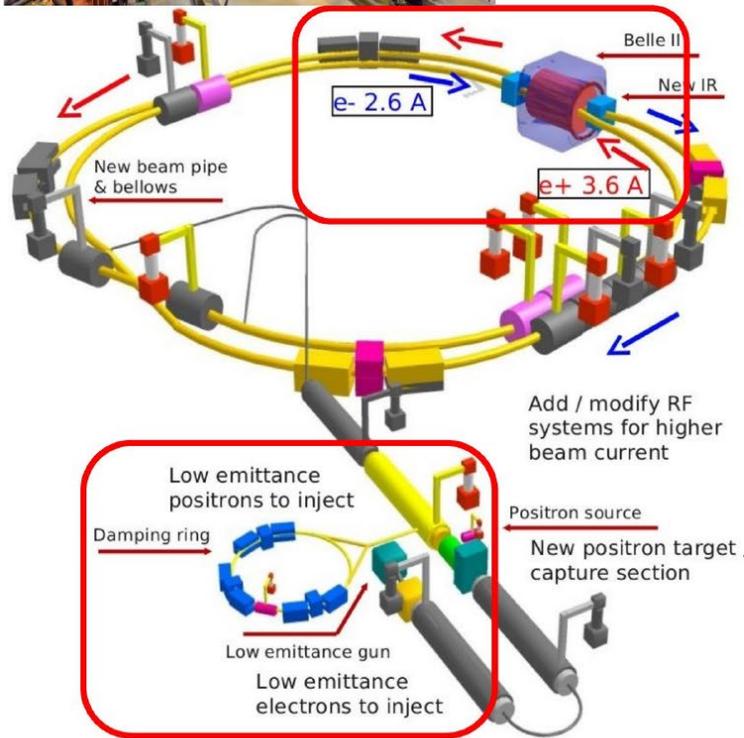
$\sim 3\text{km}$ circumference

Belle II detector

@KEK, Tsukuba
One hour away from Tokyo



SuperKEKB accelerator



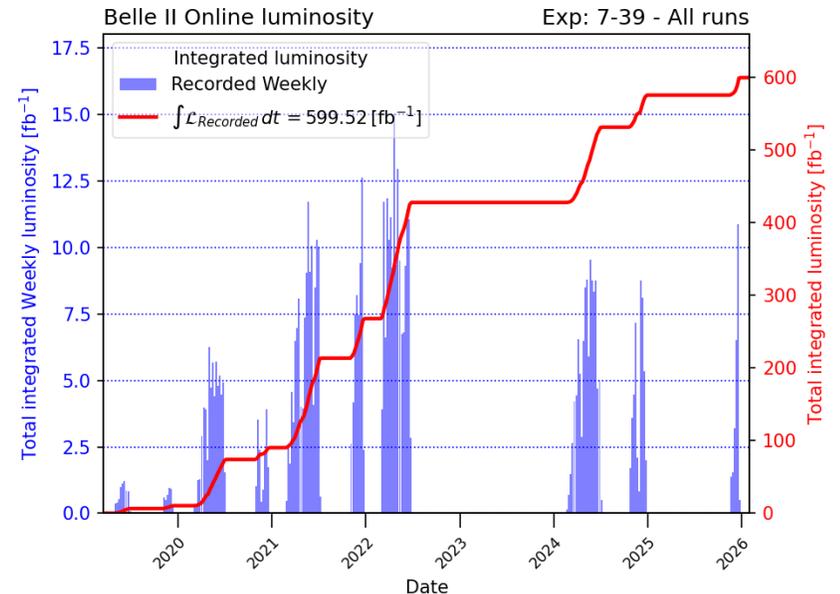
$$\text{Luminosity} = \frac{Y_{\pm}}{2er_e} \left(1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \frac{I_{\pm} \zeta_{\pm y} R_L}{\beta_y^* R_y}$$

x2

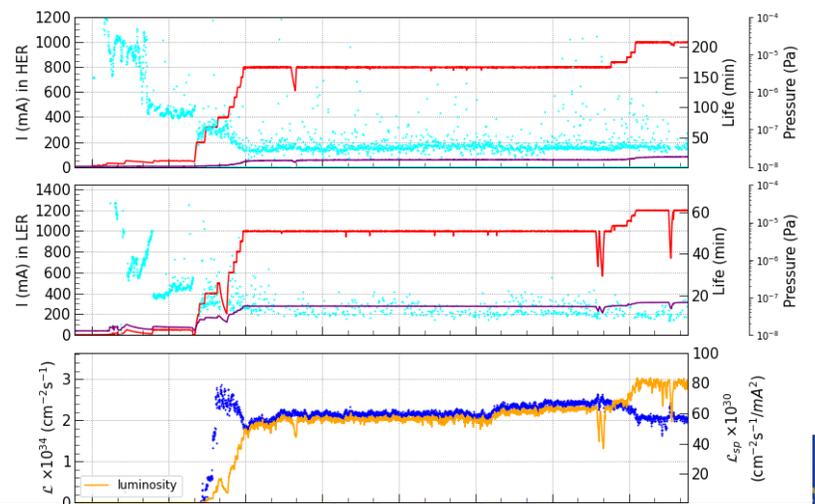
X1/20

Target luminosity: $8 \times 10^{35} \text{cm}^{-2} \text{s}^{-1}$
KEKB x 40!

$$6 \times 10^{35} \text{cm}^{-2} \text{s}^{-1}$$



02/01 14:19:06 - 02/02 14:19:06, 2026 JST
 $L_{\text{peak}} = 3.049 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ @ 12:17:56 02/02
 int. L/day 1031 / 1146 pb^{-1}
 HER I_{peak} 1000 mA n_b 2346 β_x^*/β_y^* 60 / 1 mm
 LER I_{peak} 1201 mA n_b 2346 β_x^*/β_y^* 60 / 1 mm



➤ Belle II 探測器



Belle II 探测器

$H = 7.1m, L = 7.4m, W = 1400t$

ECL

EM Calorimeter:

CsI(Tl), waveform sampling
Pure CsI for end-caps

K_L and muon detector:

Resistive Plate Counter (barrel outer layers) **KLM**
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

Particle Identification:

Time-of-Propagation counter (barrel) **iTOP**
Prox. focusing Aerogel RICH (fwd) **ARICH**

electron (7GeV)

Beryllium beam pipe

2cm diameter

Vertex Detector:

2 layers DEPFET + 4 layers DSSD **SVD**

PXD

CDC

Central Drift Chamber

He(50%):C₂H₆(50%), Small cells, long lever arm, fast electronics

positron (4GeV)

Readout (TRG, DAQ):

Max. 30kHz L1 trigger ~100% efficient for hadronic events.
1MB(PXD)+100kB(others) per event
→ over 30GB/sec to record

Offline computing:

Distributed over the world via GRID



➤ 半导体探测器:

硅像素: PXD

硅微条: SVD

➤ 闪烁体:

有机: KLM

无机: ECL

➤ 切伦科夫探测器:

内反射式: iTOP

环形成像: ARICH

➤ 气体探测器:

多丝正比: CDC

盖革/流光: KLM

➤ 光探测传感器:

ECL: 2 PIN diodes S2744_08

iTOP: MCP_PMT

ARICH: Hamamatsu HAPD

KLM: SiPM

➤ 电子学: 波形采样+时间精度

KLM: TARGETX ASIC

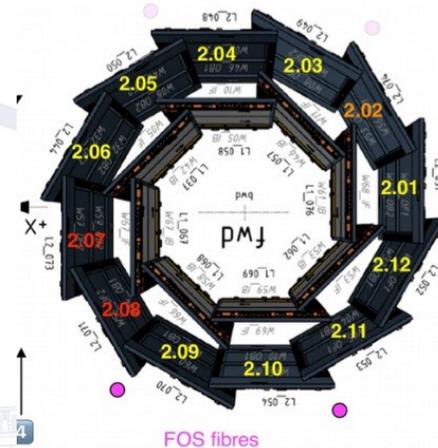
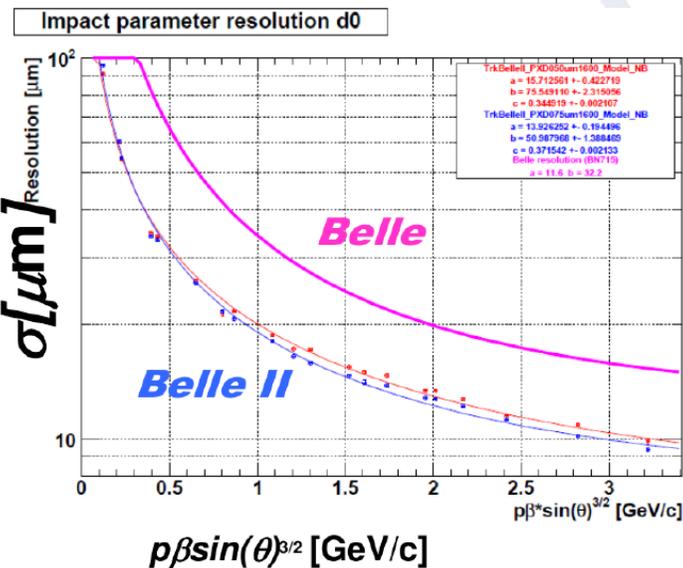
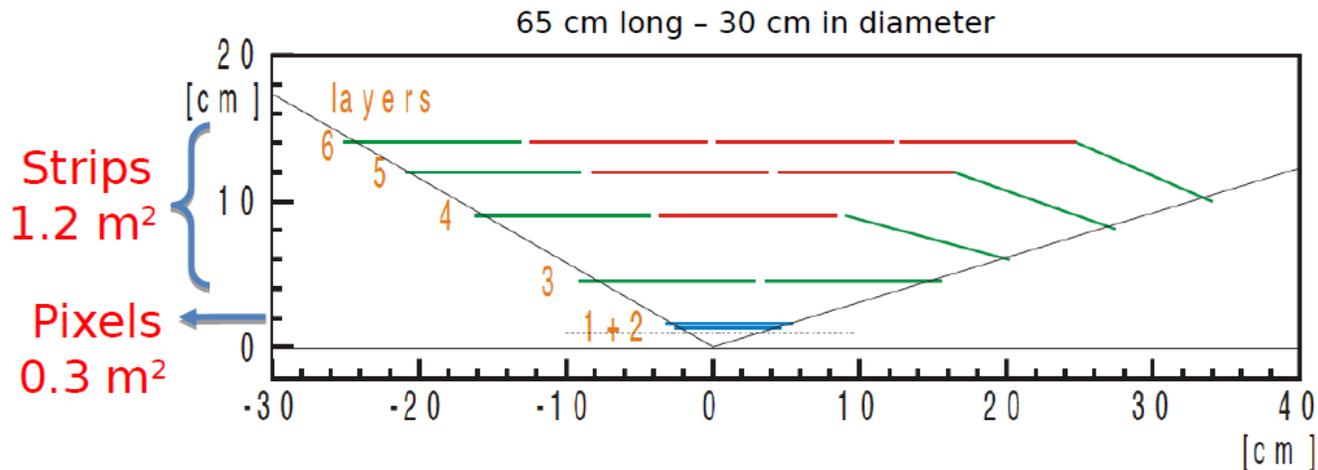
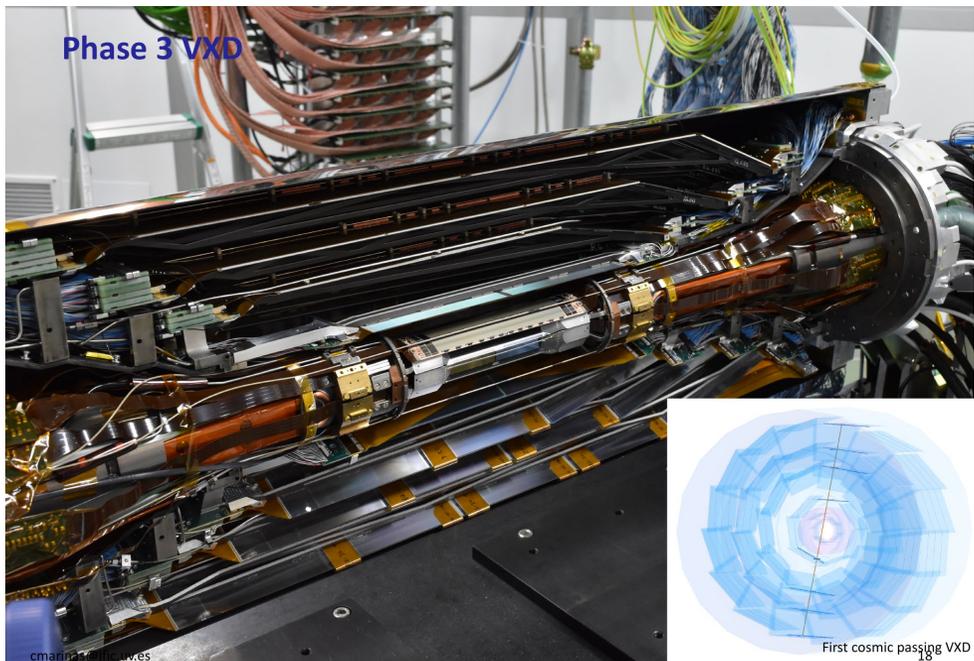
ECL: New waveform sampling with good timing

TOP: IRSX ASIC

ARICH: KEK custom ASIC

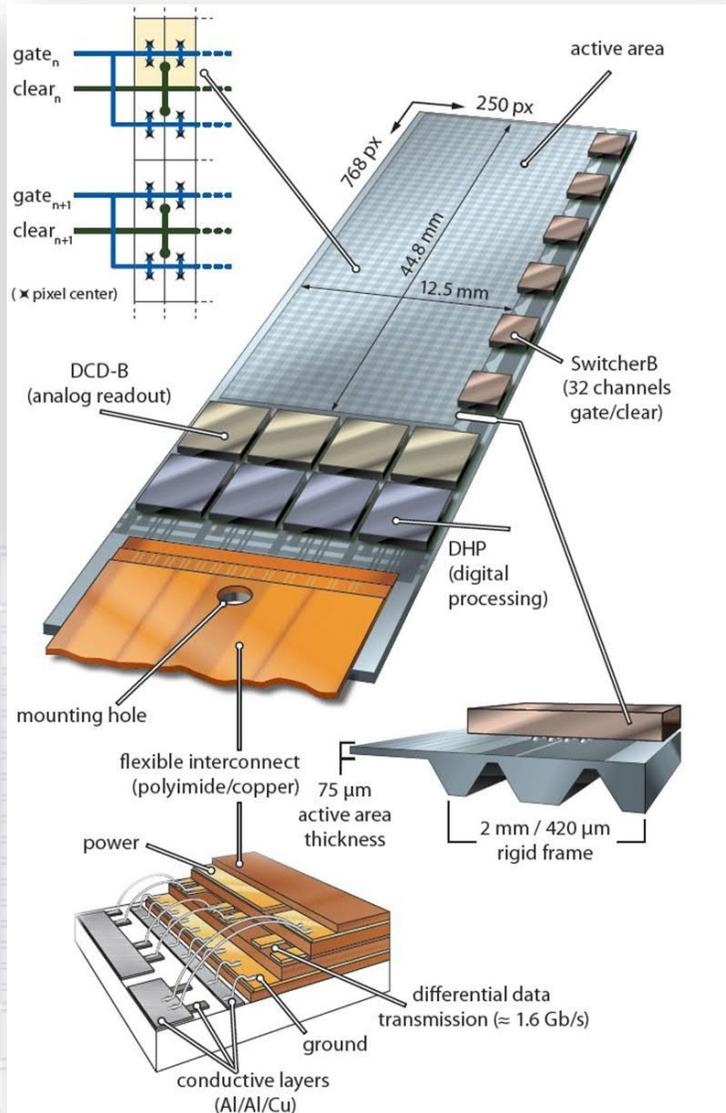
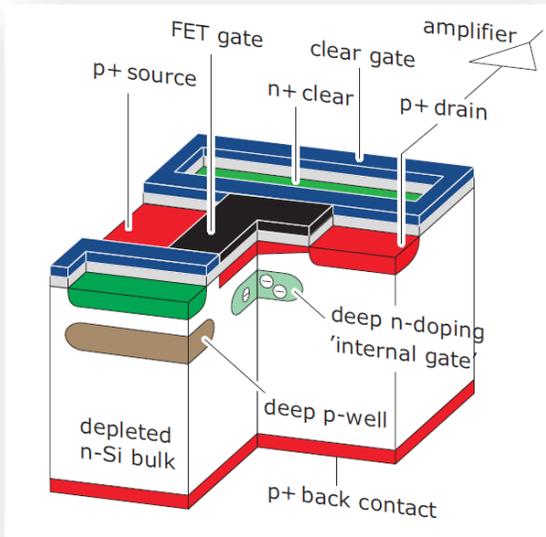
CDC: KEK custom ASIC

AVD: APV2.5 readout chip adapted from CMS

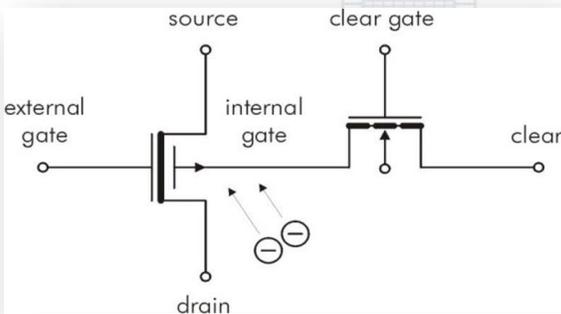


	Belle II	Belle
Beam Piper =	10mm	15mm
DEPFET		
Layer 1	$r = 14\text{mm}$	
Layer 2	$r = 22\text{mm}$	
DSSD		
Layer 3	$r = 38\text{mm}$	20mm
Layer 4	$r = 80\text{mm}$	43.5mm
Layer 5	$r = 104\text{mm}$	70mm
Layer 6	$r = 135\text{mm}$	88mm

硅像素探测器(PXD)



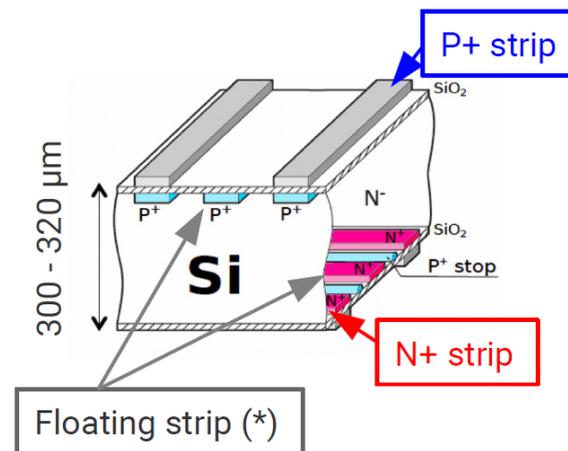
- **Fully depleted sensitive volume**
 - fast signal rise time (\sim ns), small cluster size
- In-house fabrication at MPS Semiconductor Lab
 - **Wafer scale devices possible**
 - **Thinning to (almost) any desired thickness**
 - no stitching, 100% fill factor
- no charge transfer needed
 - faster read out
 - better radiation tolerance
- **Charge collection in "off" state, read out on demand**
 - potentially low power device
- **Internal amplification**
 - charge-to-current conversion
 - r/o cap. independent of sensor thickness
 - **Good S/N for thin devices**



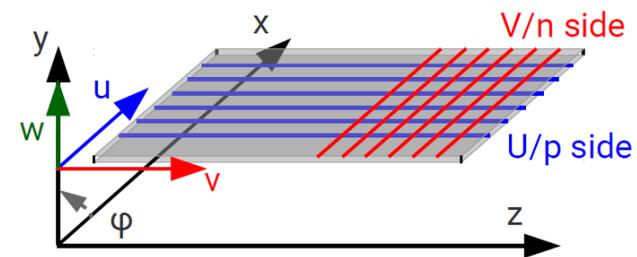
8M pixels in total

- 4层的双面硅微条探测器
- 覆盖立体角: **90%**
- 工作高压: **100V**
- 空间分辨: $\sim 15\mu m$
- 时间精度: **2-3ns RMS**
- 与**PXD**结合, 消除假径迹

○ Double-Sided Strip Detector (DSSD)



○ 2D information about position

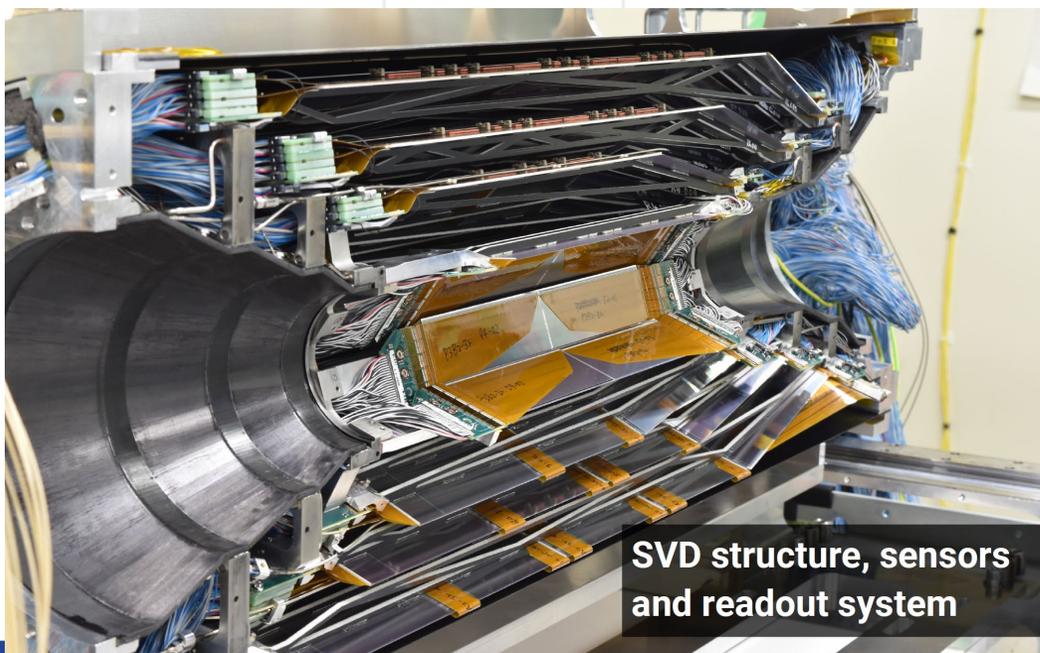
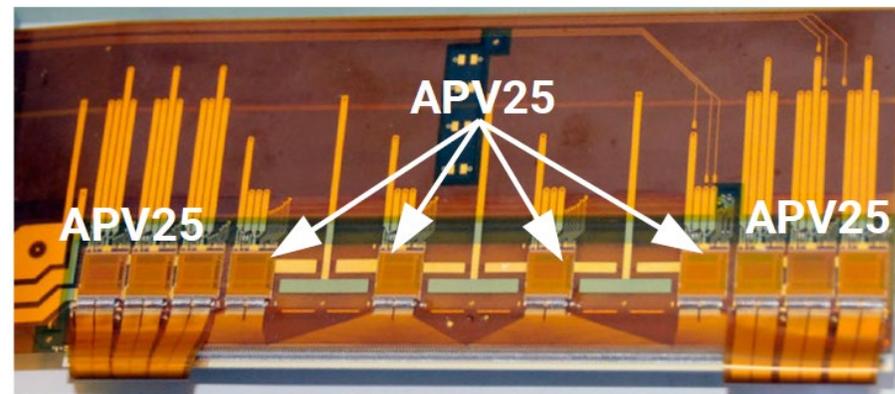


○ u-v coordinates are used on each sensor

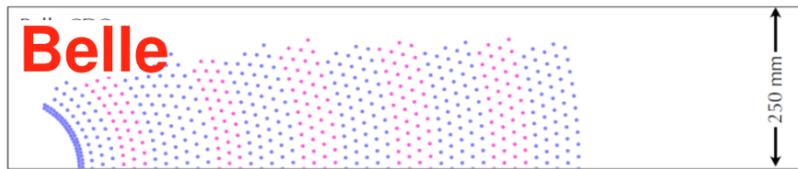
▷ p-strips: u (r-φ) information

▷ n-strips: v (z) information

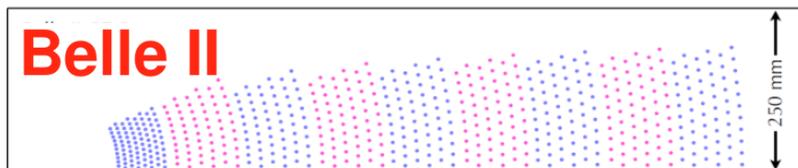
Readout front-end on a sensor



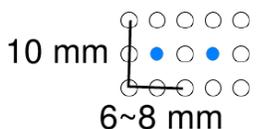
SVD structure, sensors and readout system



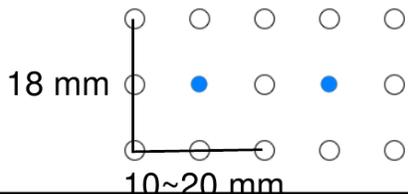
1200 mm



small cell



normal cell



	Belle	Belle II
inner most sense wire	r=88mm	r=168mm
outer most sense wire	r=863mm	r=1111.4mm
Number of layers	50	56
Total sense wires	8400	14336
Gas	He:C ₂ H ₆	He:C ₂ H ₆
sense wire	W(Φ30μm)	W(Φ30μm)
field wire	Al(Φ120μm)	Al(Φ120μm)

- Longer lever arm

- Improved momentum resolution and $\frac{dE}{dx}$

$$\sigma_{P_t}/P_t = 0.19P_t \oplus 0.30/\beta$$

$$\rightarrow 0.11P_t \oplus 0.30/\beta$$

- New readout system

- dead time: 1 ~ 2 μs → 200ns

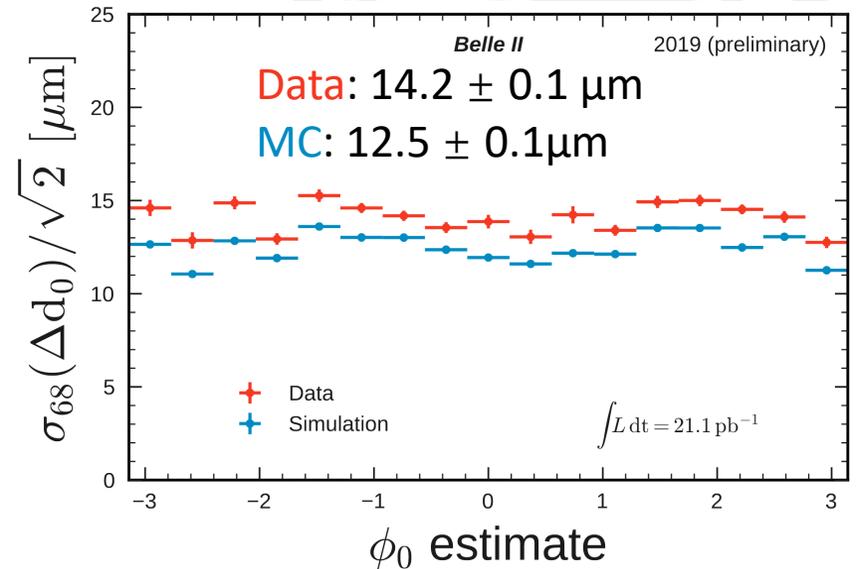
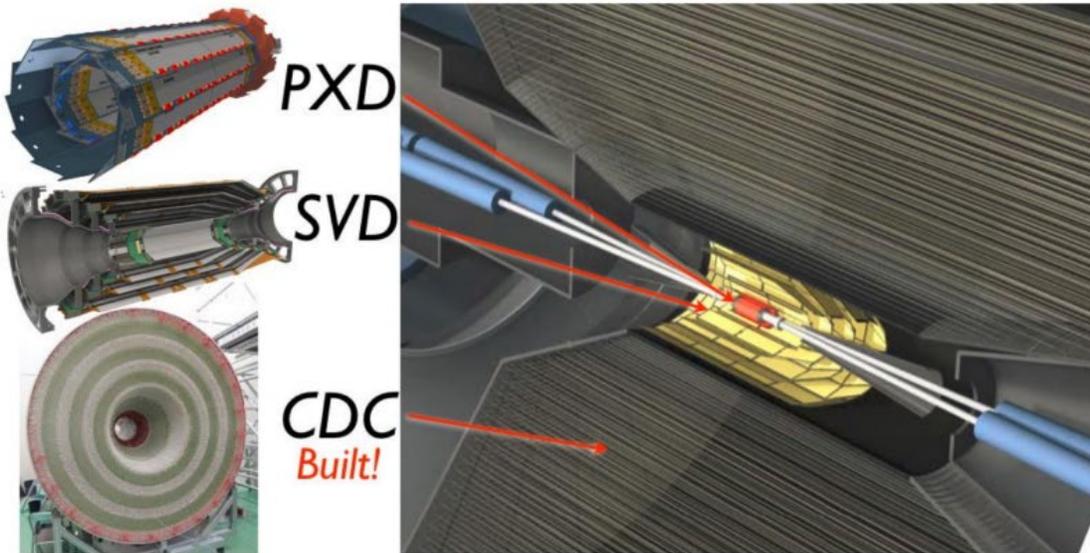
- Small cell

- smaller hit rate for each wire
- shorter maximum drift time



寻迹系统: PXD+SVD+CDC

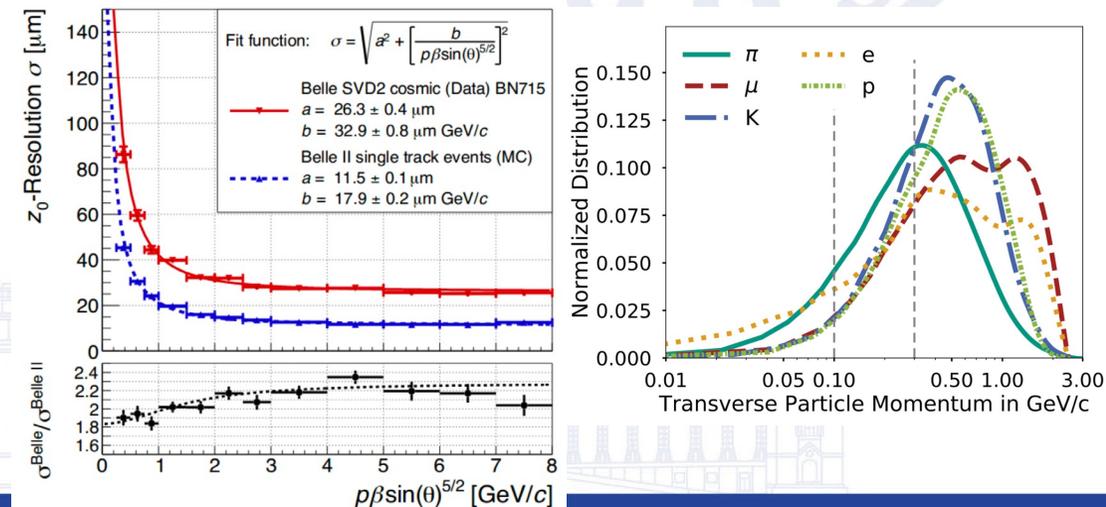
PXD provides ~2x better single vertex resolution wrt Belle.



Component	Type	Configuration	Readout	Performance
Beam pipe	Beryllium double-wall	Cylindrical, inner radius 10 mm, 10 μm Au, 0.6 mm Be, 1 mm coolant (paraffin), 0.4 mm Be		
PXD	Silicon pixel (DEPFET)	Sensor size: 15×100 (120) mm^2 pixel size: 50×50 (75) μm^2 2 layers: 8 (12) sensors	10 M	impact parameter resolution $\sigma_{z_0} \sim 20 \mu\text{m}$ (PXD and SVD)
SVD	Double sided Silicon strip	Sensors: rectangular and trapezoidal Strip pitch: 50(p)/160(n) - 75(p)/240(n) μm 4 layers: 16/30/56/85 sensors	245 k	
CDC	Small cell drift chamber	56 layers, 32 axial, 24 stereo $r = 16 - 112 \text{ cm}$ $-83 \leq z \leq 159 \text{ cm}$	14 k	

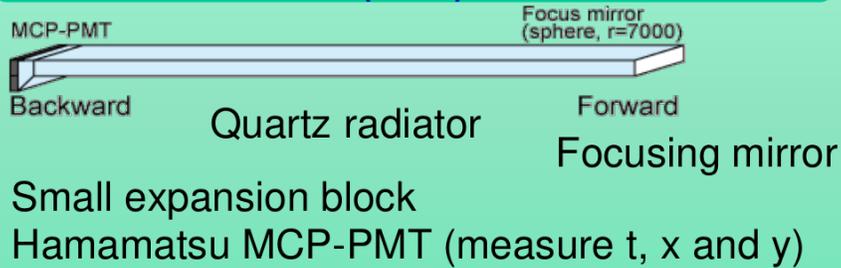
$\sigma_{r\phi} = 100 \mu\text{m}, \sigma_z = 2 \text{ mm}$
 $\sigma_{p_t}/p_t = \sqrt{(0.2\%/p_t)^2 + (0.3\%/\beta)^2}$
 $\sigma_{p_t}/p_t = \sqrt{(0.1\%/p_t)^2 + (0.3\%/\beta)^2}$ (with SVD)

位置分辨: $30 \mu\text{m} \rightarrow 15 \mu\text{m}$



桶部PID: 时间传播探测器(iTOP)

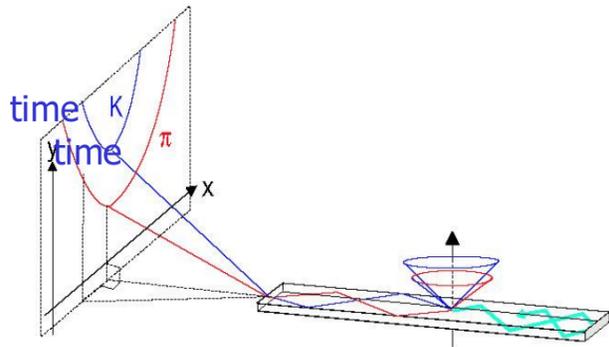
Barrel PID: Time of Propagation Counter (iTOP)



Cherenkov ring imaging with precise time measurement.

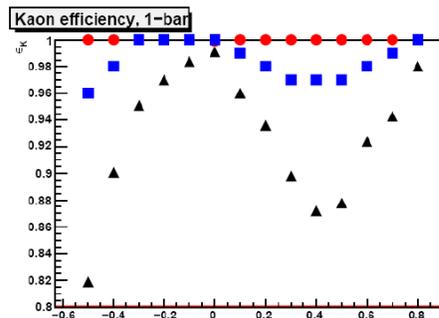
Device uses internal reflection of Cherenkov ring images from quartz like the BaBar DIRC

Cherenkov angle reconstruction from two hit coordinates and the time of propagation of the photo

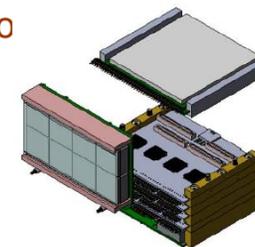
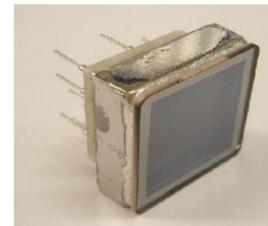
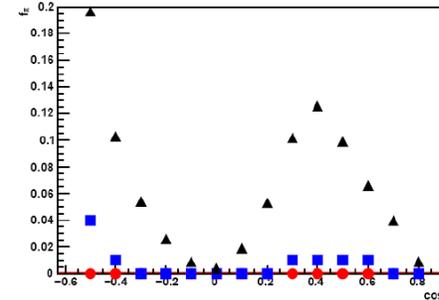


- 16 Quartz radiators
- 2.6m^L x 45cm^W x 2cm^T
- Excellent surface accuracy
- MCP-PMT
- Hamamatsu 16ch MCP-PMT Good TTS (<35ps) & enough lifetime
- Multialkali photo-cathode → SBA

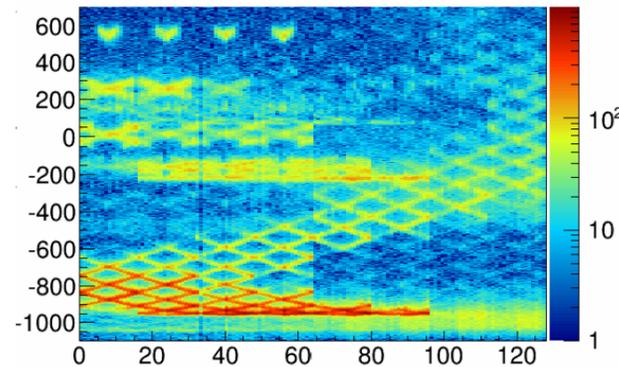
● 1.5, ■ 2.5, ▲ 3.5 GeV/c



■ Pion fake rate, 1-bar

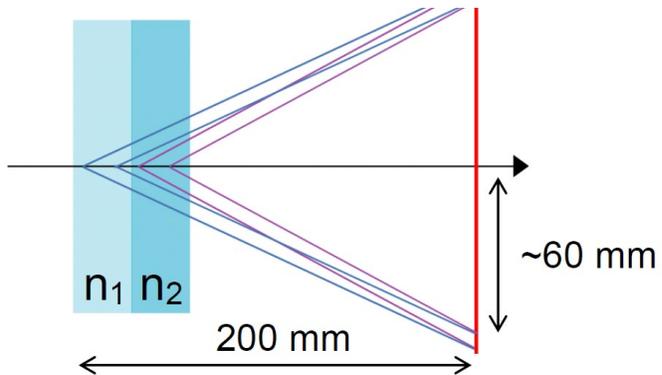


x-t diagram from beam-test time



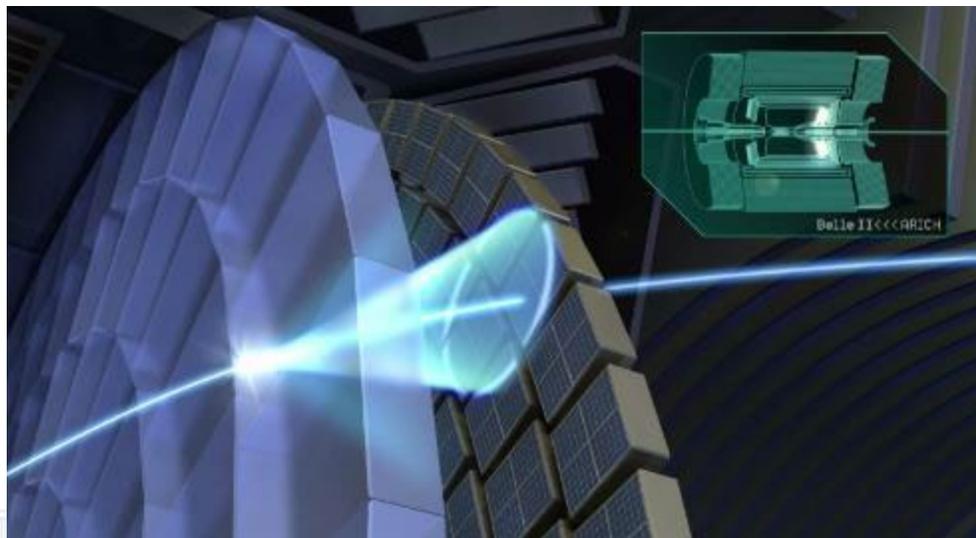
coordinate

端盖PID：气凝胶环形成像探测器(ARICH)



双层气凝胶起聚焦作用；
折射率：

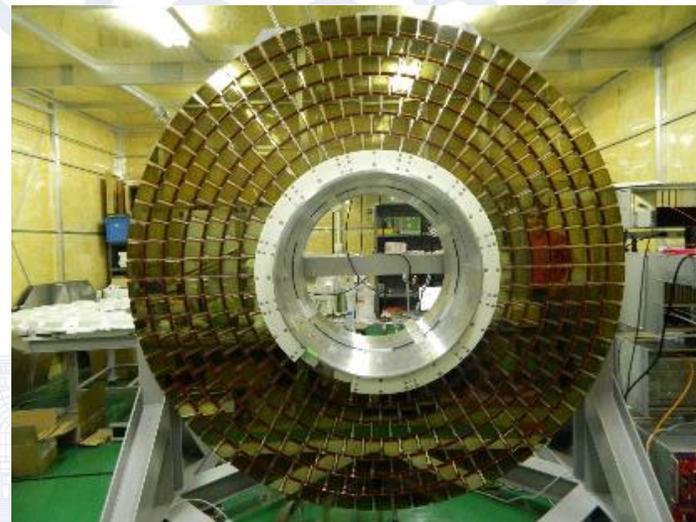
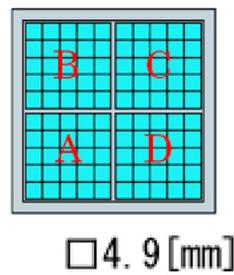
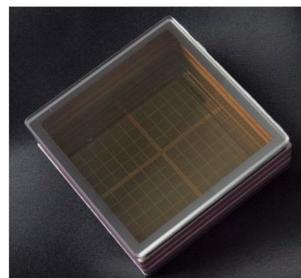
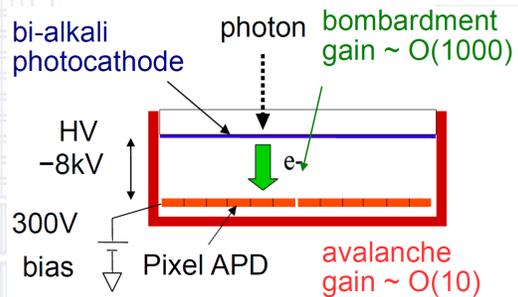
$$n_1 = 1.045, n_2 = 1.055$$



混合雪崩光电探测器：420 HAPDs
像素大小：4.9 mm

Hybrid: Vacuum tube + semi-conductor

- Developed with Hamamatsu Photonics.
- 144 channels (36-ch APD chip \times 4).
- Gain \sim 70000.
- Peak QE \sim 28%
- Size 73mm \times 73mm.
- Effective area 63mm \times 63mm (65%).

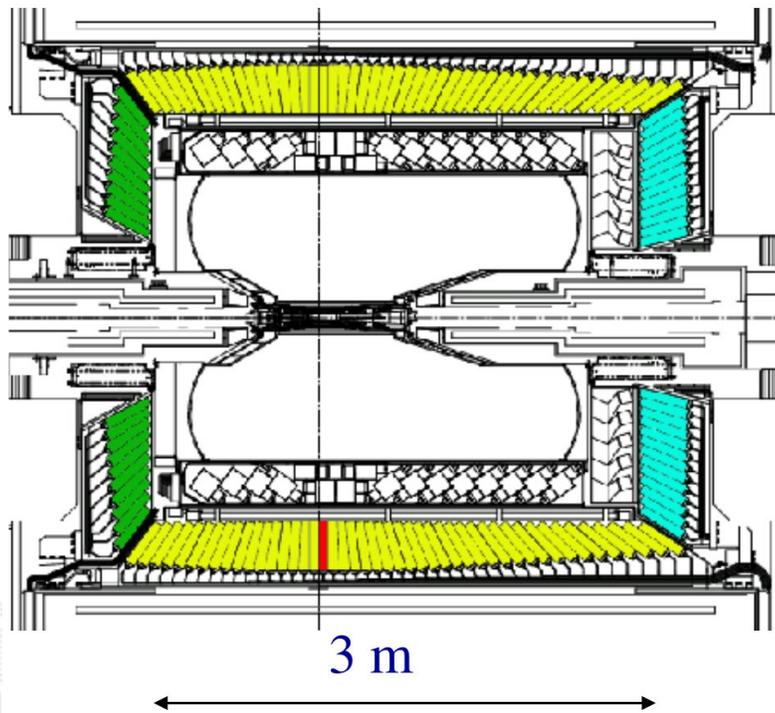


电磁量能器(ECL)

➤ 探测器任务

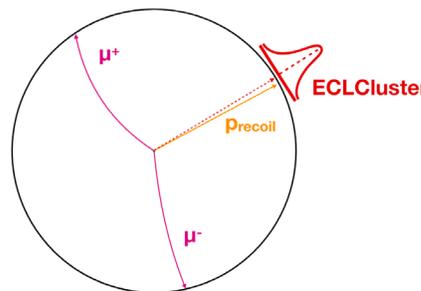
- ✓ 光子能量/角度, 20MeV-8GeV
- ✓ 电子鉴别
- ✓ K_L 探测(+KLM)
- ✓ 提供触发

➤ 亮度测量



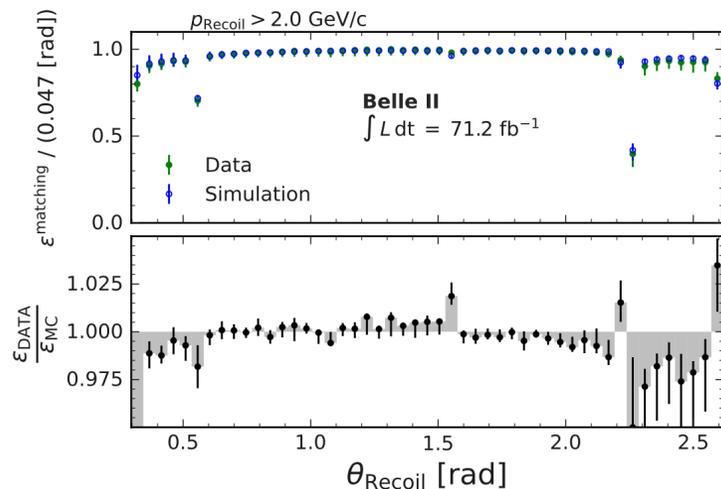
Number of crystal: **8736**
Total weight is **~43ton**

High efficiency with systematics at **0.3%** in barrel.
(similar to BABAR, was 2% at Belle)

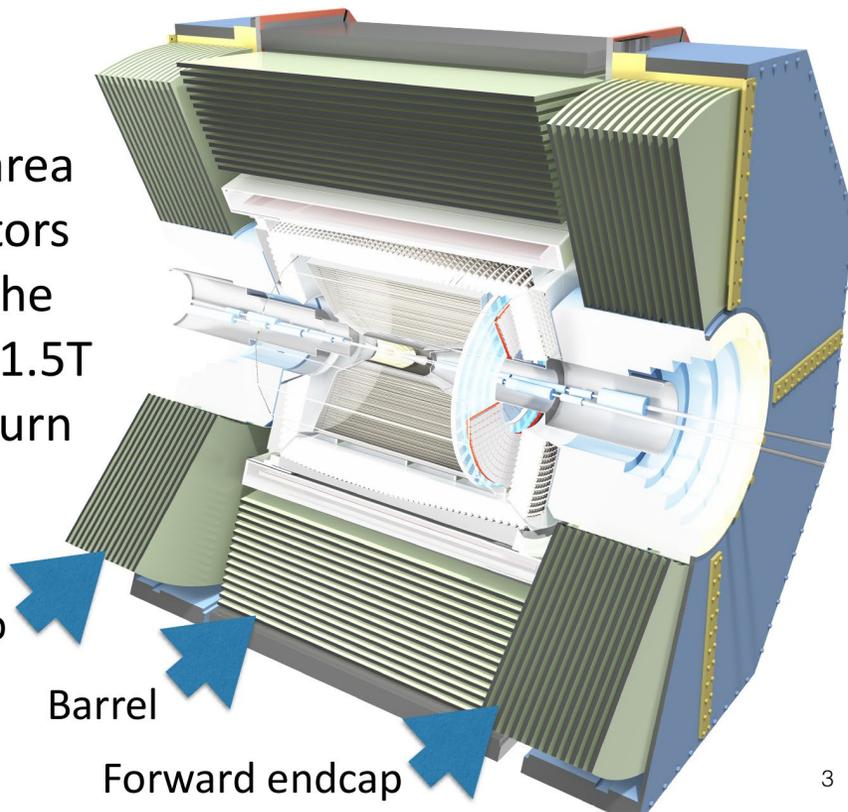


CsI(Tl) crystals: $L_{cr} = 30\text{cm} = 16.2X_0$

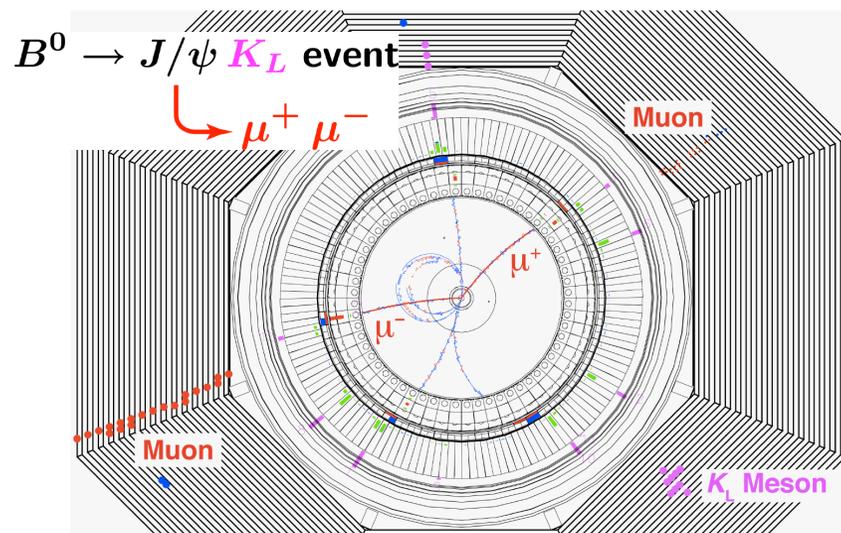
- 2/3 —— 俄罗斯Kharkov&BINP,
- 1/3 —— 上海硅酸盐所!



consists of large-area thin planar detectors interleaved with the iron plates of the 1.5T solenoid's flux return yoke.

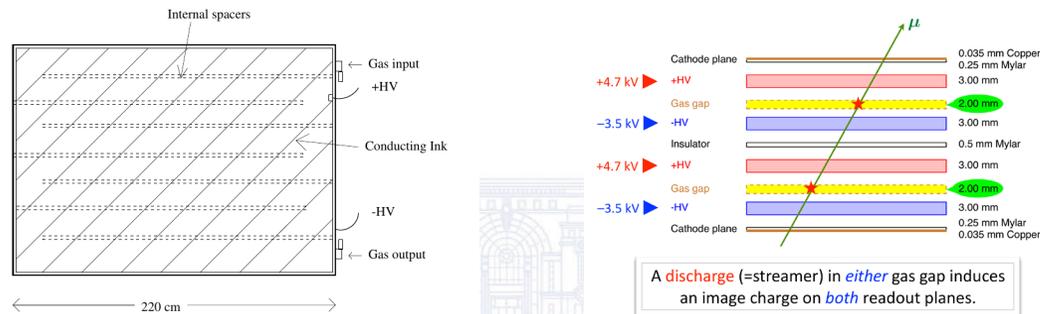


- Detect K_L mesons and muons (≈ 1 per event) with high efficiency and purity



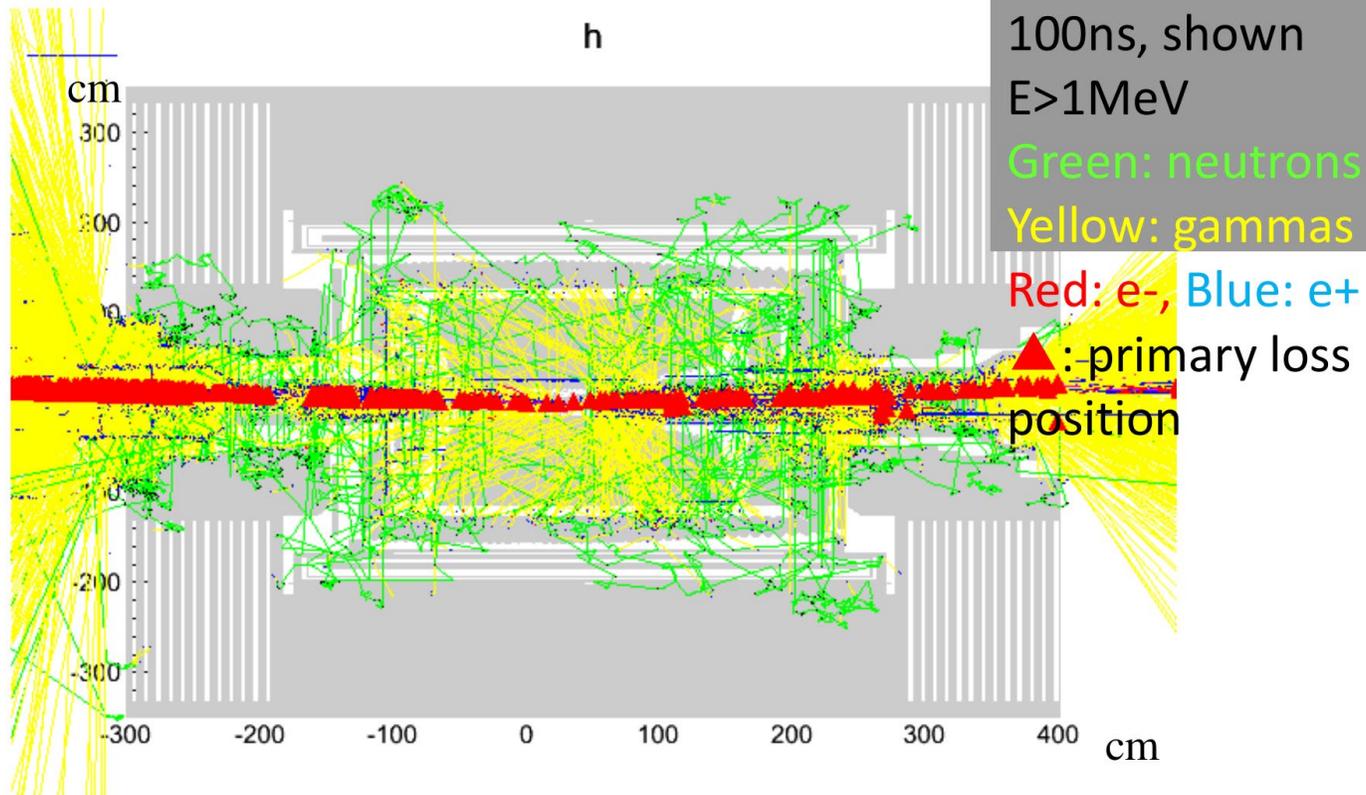
RPC in KLM

3



Q: What can we do with this largest subdetector??

实验运行中的本底分析



BKLM Layer	Neutron-induced RPC Rate (Hz/cm ²)	Resulting RPC Efficiency
0	14.2	0.13
1	10.2	0.39
2	6.4	0.62
3	3.6	0.78
4	2.2	0.86
5	1.3	0.91
6	0.8	0.94



all RPCs

scintillators and polystyrene filler

BKLM Layer	Neutron-induced RPC Rate (Hz/cm ²)	Resulting RPC Efficiency
0	-	-
1	-	-
2	1.9	0.9
3	1	0.94
4	0.6	0.96
5	0.2	0.98
6	0.2	0.98

n flux ÷ 3.5
⇒ recovered ε



... but projected ambient neutron rate in Belle II means that endcap RPCs would **never see muons**

Efficiency in Belle

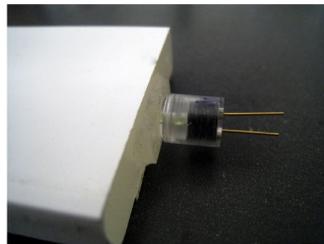
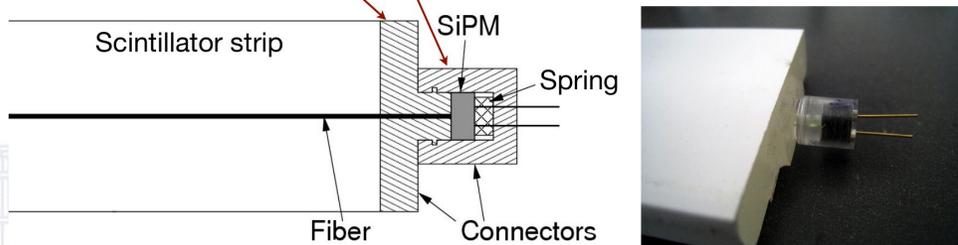
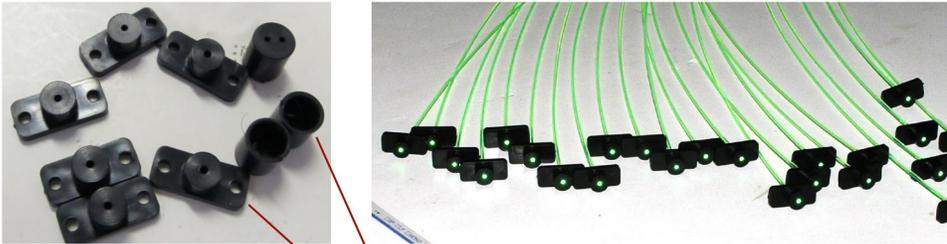
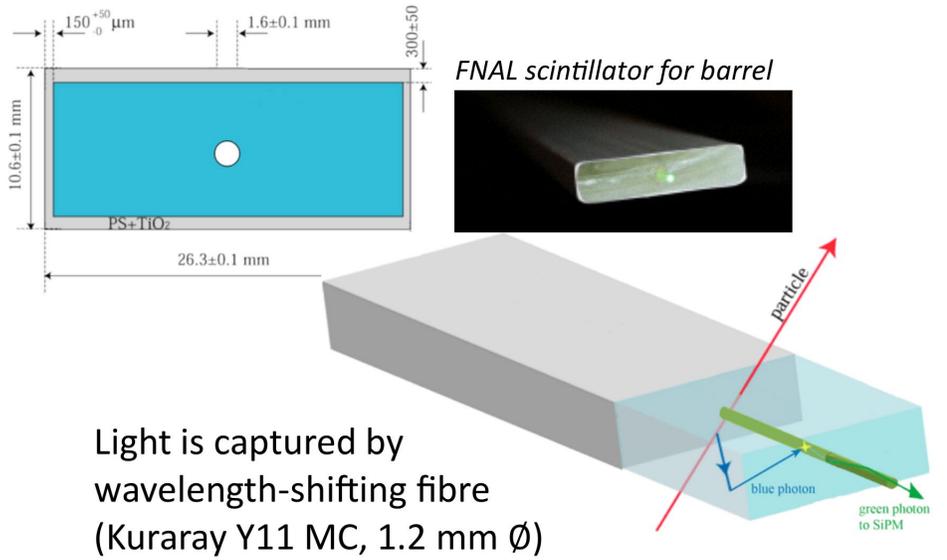
Layer	Barrel	Forward Endcap	Backward Endcap
0	0.97	0.91	0.9
1	0.98	0.93	0.9
2	0.99	0.94	0.9
3	0.99	0.94	0.9
4	0.99	0.94	0.89
5	0.99	0.92	0.88
6	0.99	0.93	0.89
7	0.99	0.92	0.87
8	0.99	0.92	0.86
9	0.99	0.9	0.85
10	0.99	0.87	0.82
11	0.99	0.82	0.8
12	0.99	0.78	0.81
13	0.99	0.77	0.76
14	0.99	-	-

Efficiency in Belle II

Layer	Barrel	Forward Endcap	Backward Endcap
0	0.9	0	0
1	0.94	0	0
2	0.96	0	0
3	0.97	0	0
4	0.98	0	0
5	0.98	0	0
6	0.98	0	0
7	0.99	0	0
8	0.98	0	0
9	0.99	0	0
10	0.99	0	0
11	0.99	0	0
12	0.99	0	0
13	0.99	0	0
14	0.99	-	-

- 高电阻率玻璃电极，使得RPC的信号恢复时间达到微秒量级。
- Belle II的事例率和束流本底显著增高，大量中子导致RPC“反应不过来”！
- 新的探测技术：塑闪+波移光纤+SiPM

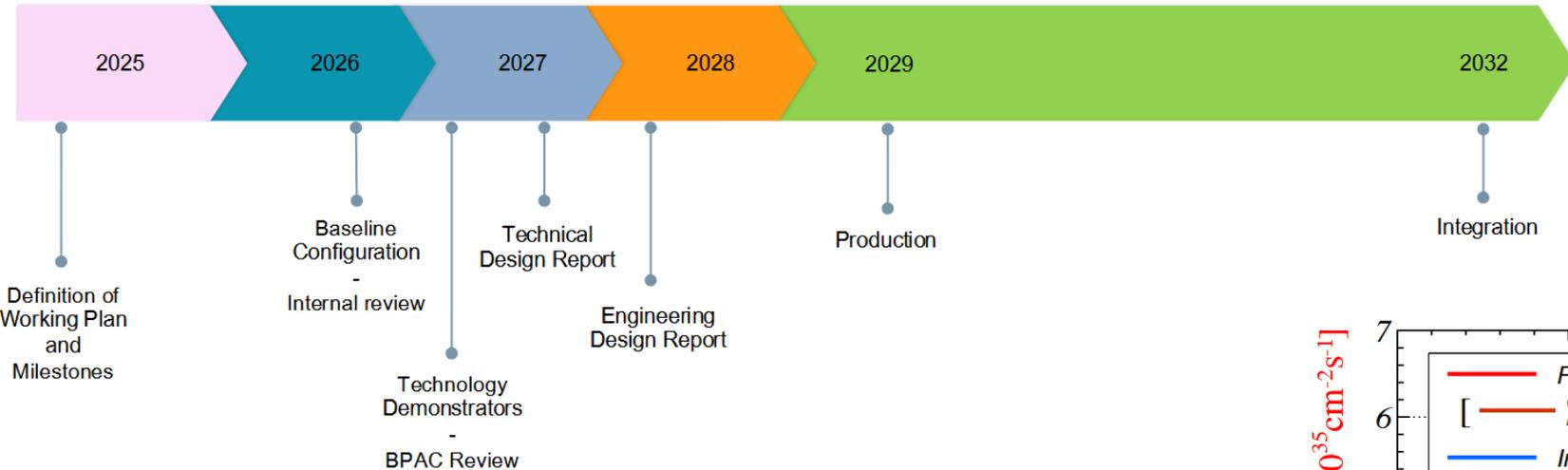
Barrel KLM in Belle II



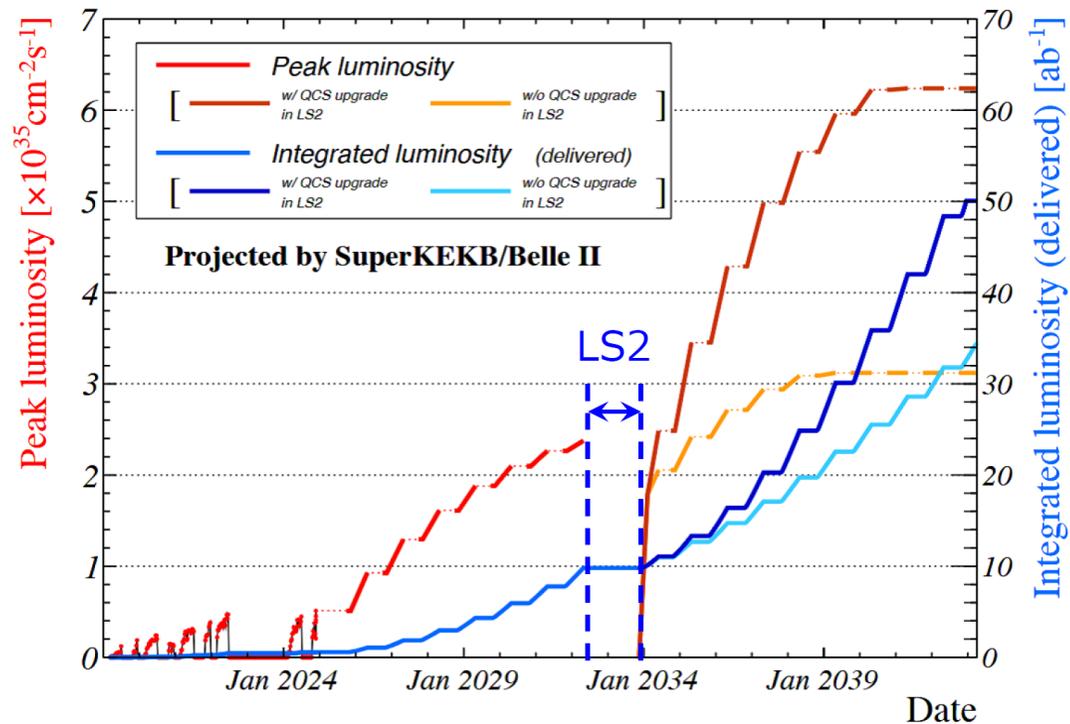
➤ Belle II实验升级



Belle II 实验升级升级



CDR: 2024, done.
TDR: 2027.
Upgrade: 2032 (LS2).





BELLE2-REPORT-2024-042
KEK-REPORT-2024-1
4 July 2024

The Belle II Detector Upgrades Framework Conceptual Design Report

Abstract

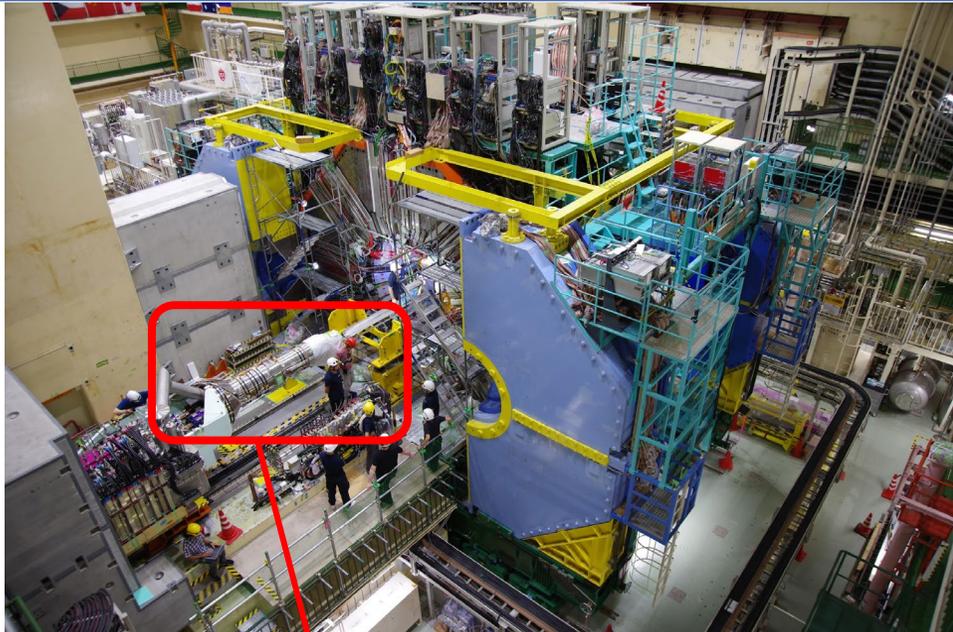
We describe the planned near-term and potential longer-term upgrades of the Belle II detector at the SuperKEKB electron-positron collider operating at the KEK laboratory in Tsukuba, Japan. These upgrades will allow increasingly sensitive searches for possible new physics beyond the Standard Model in flavor, tau, electroweak and dark sector physics that are both complementary to and competitive with the LHC and other experiments.

Subdetector	Function	upgrade activity	time scale
MDI	RMBA	Faster and more performant electronics	medium-term
VXD	Vertex Detector	all-pixels DMAPS CMOS sensors (VTX)	medium-term
CDC	Tracking	upgrade front end electronics	short/medium-term
TOP	PID, barrel	Replace not-life-extended ALD MCP-PMTs Front end electronics upgrade	medium-term medium-term
KLM	K_L, μ ID	replace 13 barrel layers of legacy RPCs with scintillators upgrade of electronics readout and proportional mode RPC readout <u>timing upgrade for K-long momentum measurement</u>	medium/long-term medium/long-term medium/long-term
Trigger		hardware and firmware improvements	continuous
DAQ		add 1300-1900 cores to HLT	short/medium-term
ARICH	PID, forward	replace HAPD with Silicon PhotoMultipliers replace HAPD with Large Area Picosecond Photodetectors	long-term long-term
ECL	γ, e ID	Add pre-shower detector in front of ECL Complement ECL PiN diodes with APDs or SiPM Replace CsI(Tl) with pure CsI crystals	long-term long-term long-term

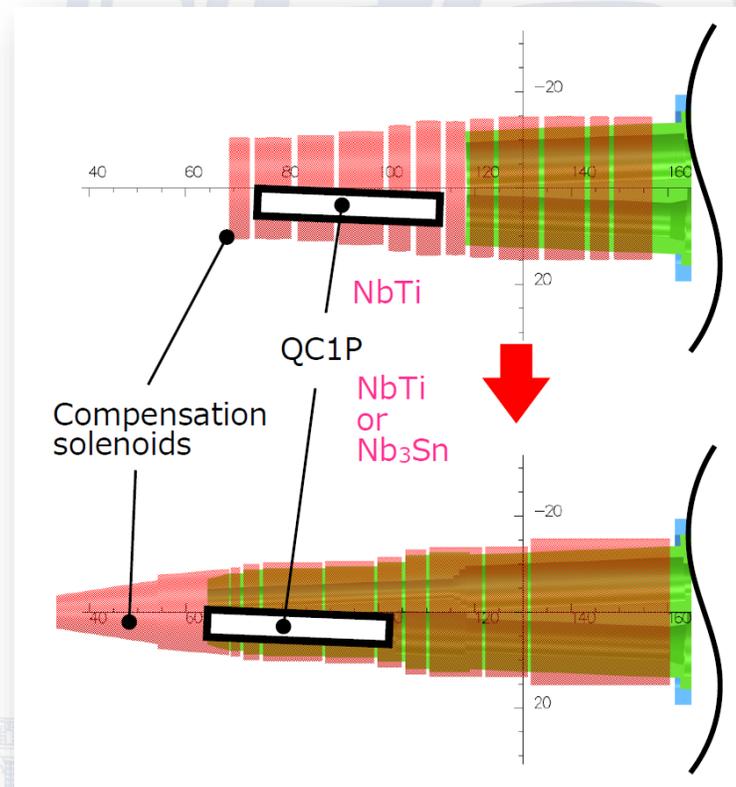
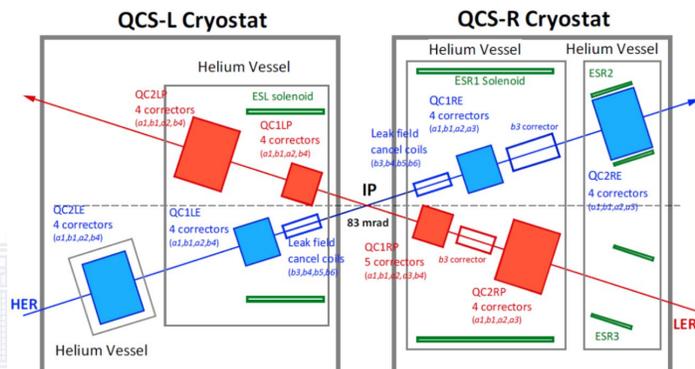
arXiv:2406.19421v2

最早提出 KLM 探测器升级方案

IR升级：QCS系统



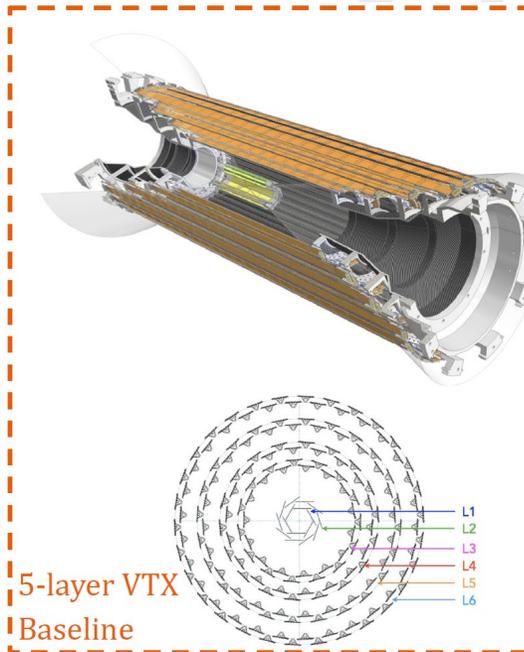
- 改造 QCS，使其更加靠近 IP，QCS1P 前移 10 cm。
- 增加补偿螺旋线圈，增加动力学孔径。
- 考虑采用新的超导材料： $NbTi \rightarrow Nb_3Sn$ 。



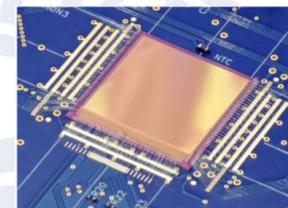
- PXD + SVD ⇒ **new VTX**
- Key **performance requirements for the upgrade:**
 - Higher spatial and time granularity to cope with the harsh background condition
 - Spatial resolution: $< 15 \mu\text{m}$
 - Low Material budget: 0.2% - 0.8% X/X_0 per layer for the inner and outer layers
 - Hit rates capability: up to 120 MHz/ cm^2 Fast timestamping: capabilities in 50-100 ns
 - Power dissipation: $< 200 \text{ mW}/\text{cm}^2$
 - Radiation tolerance (inner layer over 10 years operation): TID up to 1 MGy and NIEL of $5 \times 10^{14} \text{ neq}/\text{cm}^2$

A **5-layer depleted monolithic active pixel sensors** (DMAPS)

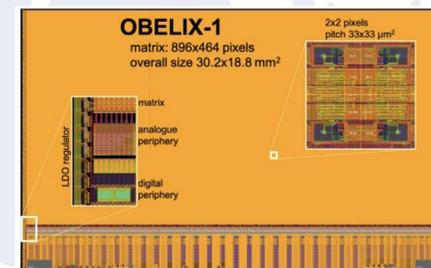
- Radius: 14 mm ~ 140 mm
- Improve low-momentum tracking and impact parameter resolution
- **TJ-Monopix2** is a good starting point



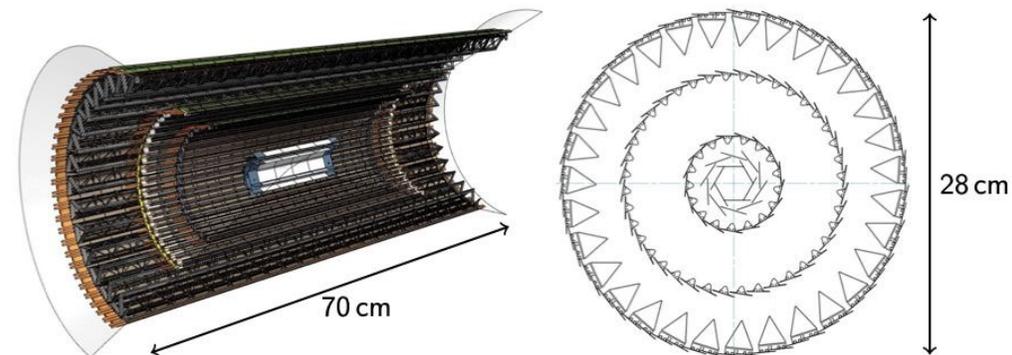
5-layer VTX
Baseline



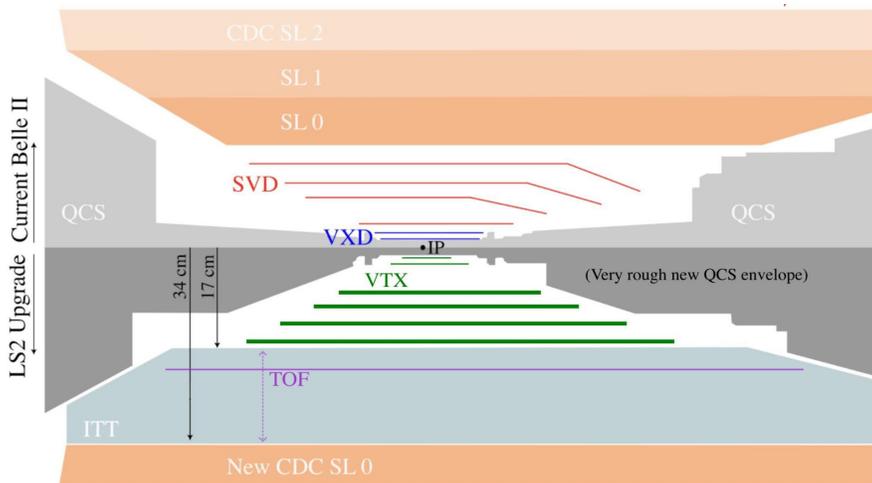
TJM2 sensor bonded on a test board



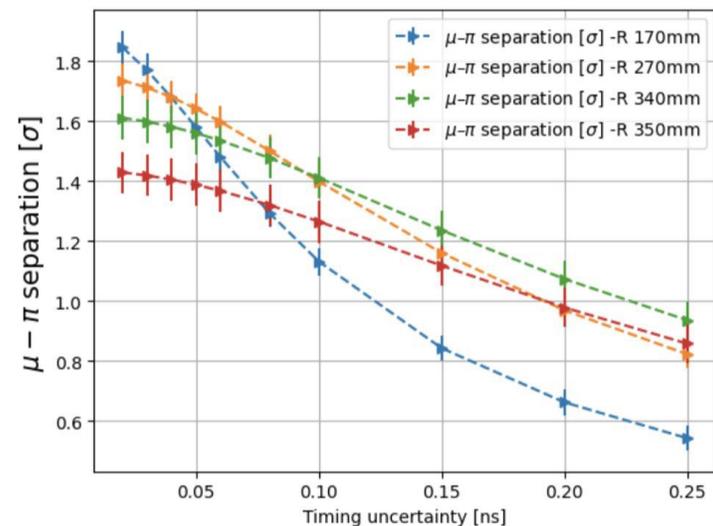
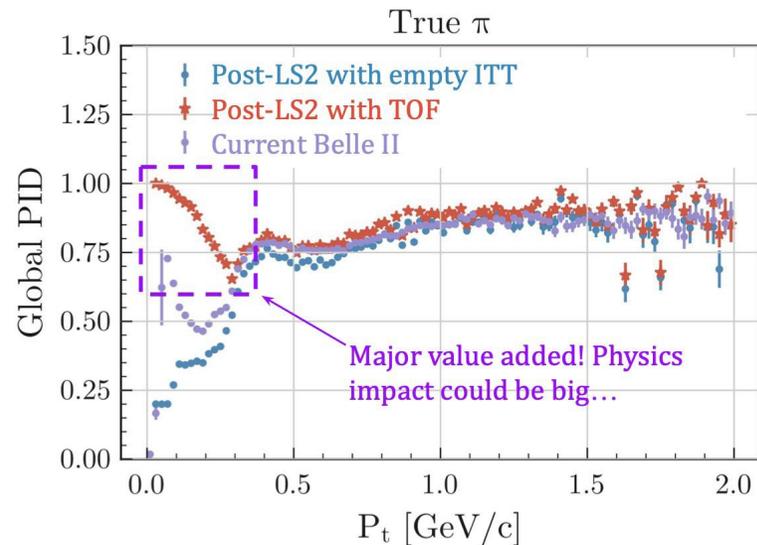
OBELIX sensor: Optimized BELLE II monolithic active pixel sensors



ITT: Inner Timing Tracker



- VTX的升级和CDC可能的改造，在二者之间造成空隙。
- 新的ITT探测器将弥补和提高低横动量粒子的探测和鉴别。
- 首选方案：AC-LGAD，时间分辨优于50 ps。

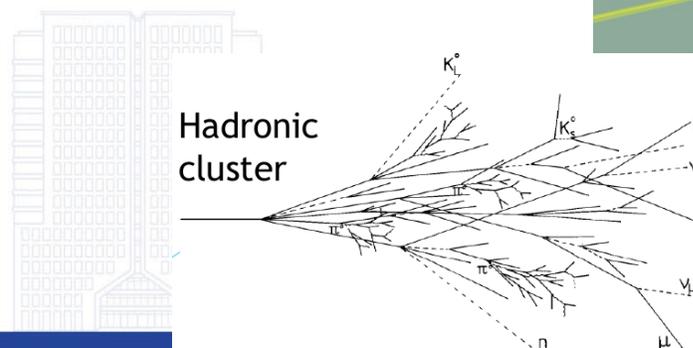
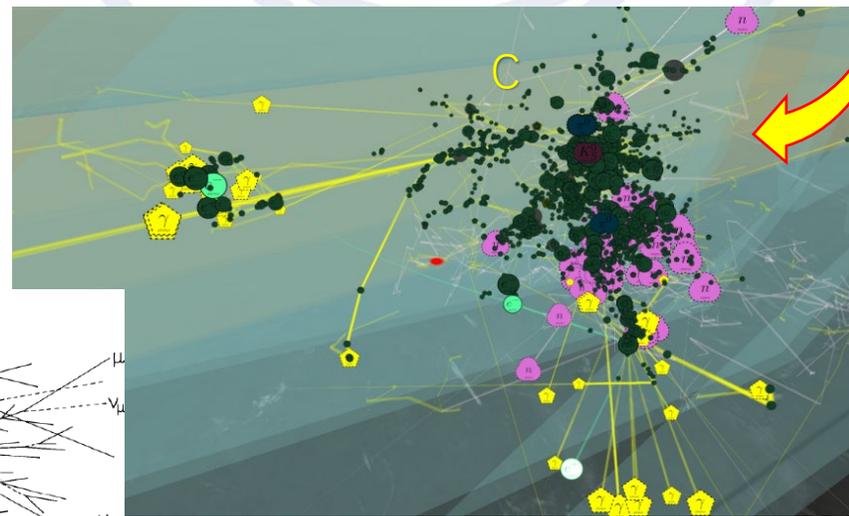
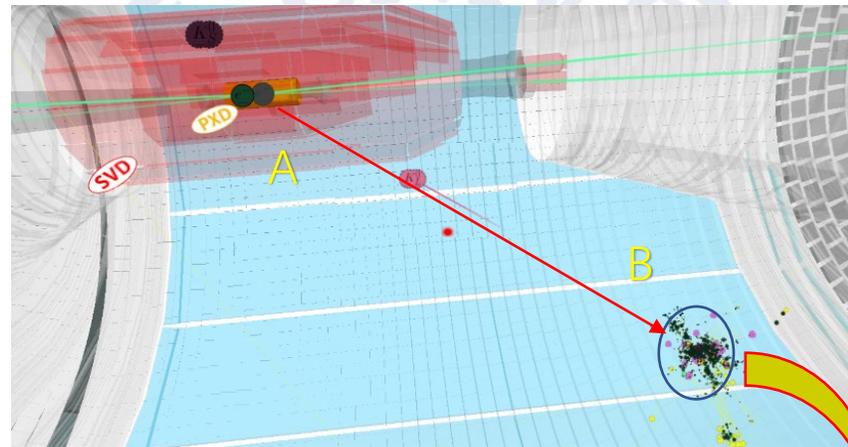


➤ 飞行时间的KLM探测器升级方案



如何直接测量中性强子的动量?

- 对撞机实验探测谱仪重建的稳定粒子: γ 、 e^\pm 、 μ^\pm 、 π 、Kaon、 p/\bar{p} ，以及**中子**。
- 中性强子的动量测量一直是一个难点: **K_L 和中子!**
 - 不带电，因此不在寻迹系统留下信号。
 - 强子量能器 (HCAL) 的困难: π^0 、 μ^\pm 、中微子等带走太多能量，已经原子核的激发，导致能量分辨率差。
 - HCAL的另一个典型问题: 造价高。
- **如果能直接测量中性强子的飞行时间?**



- There are many hits in a hadronic cluster, which is mainly produced in strong interaction with nuclear in the KLM. Fast time information is expected. If we can measure the stop time precisely, the time of flight can be determined, since the start time from Interaction Point (IP) has a precision of less than 30 ps.

- The relationship between the mass m , the momentum p , the distance L and the time of flight T :

$$T^2 c^2 - L^2 = m^2 L^2 c^2 p^{-2},$$

- The relationship between the precisions:

$$\delta p = \frac{T p^3}{m^2 L^2} \delta T$$

- For example: in Belle II detector, a $1.5 \text{ GeV}/c$ K_L with flies $L = 2 \text{ m}$ before creating a cluster in KLM, if the KLM has a performance of $\delta T = 100 \text{ ps}$, then, $T = 7.07 \text{ ns}$ and $\delta p = 0.19 \text{ GeV}/c$. Therefore, $\frac{\delta p}{p} = 13\%$!

- Neutron has a large mass than K_L .

Introduced this idea at the 34th Belle II General Meeting (B2GM).

Time of K_L in KLM

X.L. Wang
Fudan University

October 25, 2019

With scintillator+WLSFibre+MPPC technology, high resolution of time determination in an upgraded KLM is possible. A good time resolution δT of K_L flying in Belle II detector, determination of the velocity and hereafter the momentum of K_L is possible. Here the relationship between δT and the uncertainty of momentum of K_L (δp) will be discussed.

The momentum of K_L with a determined velocity β is

$$p = \gamma m v \tag{1}$$

where γ is the factor of special relativity, $m = 0.53 \text{ GeV}/c^2$ is the mass of K_L and $v = \beta c$ is the velocity of K_L .

$$\beta = v/c = L/tc \tag{2}$$

where L is the length of K_L flying between IP or a secondary vertex of decay and the hit point in KLM. So

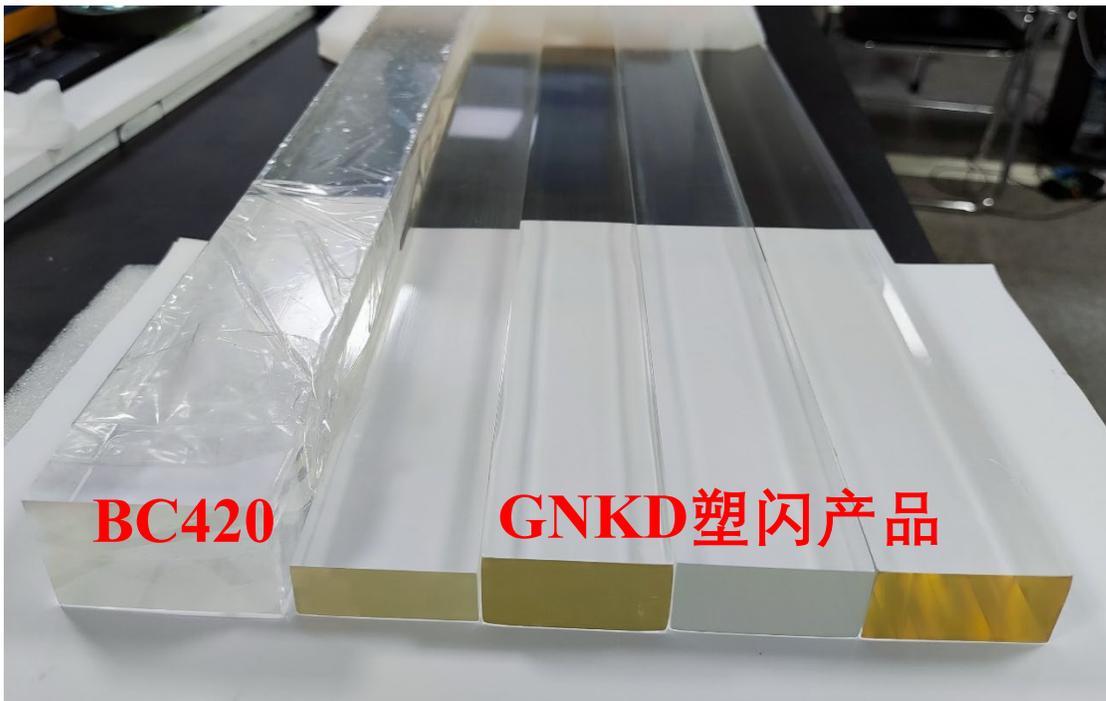
$$p = \gamma m v = \frac{m \beta c}{\sqrt{1 - \beta^2}} = \frac{m c L}{\sqrt{T^2 c^2 - L^2}} \tag{3}$$

$$T^2 c^2 - L^2 = m^2 L^2 c^2 p^{-2} \tag{4}$$

$$\frac{\delta T}{\delta p} = -\frac{m^2 L^2}{T \cdot p^3} \tag{5}$$

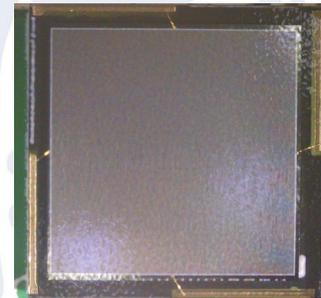
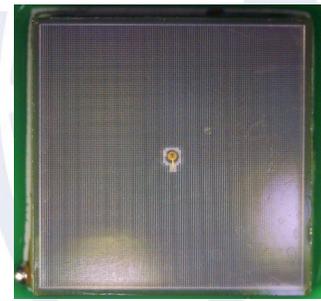
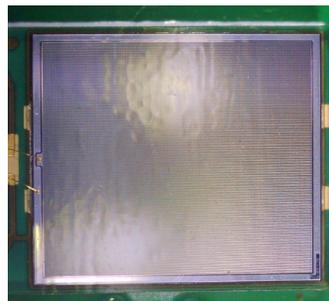
1

Arrays of large-size SiPMs



HAMAMATSU
PHOTON IS OUR BUSINESS

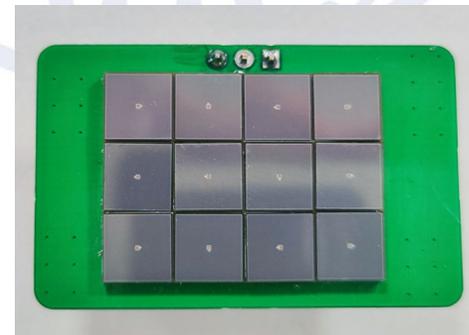
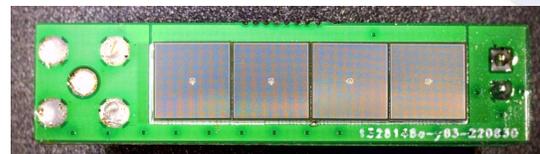
NDL



S13360-6025PE

S14160-6050HS

EQR1511-6060D-S



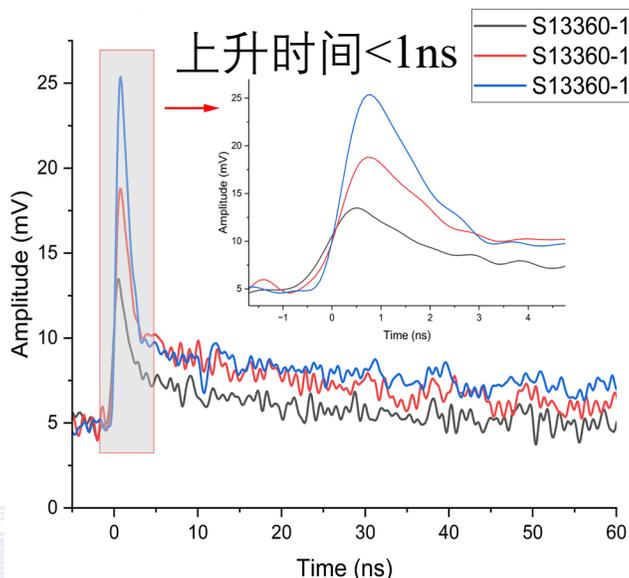
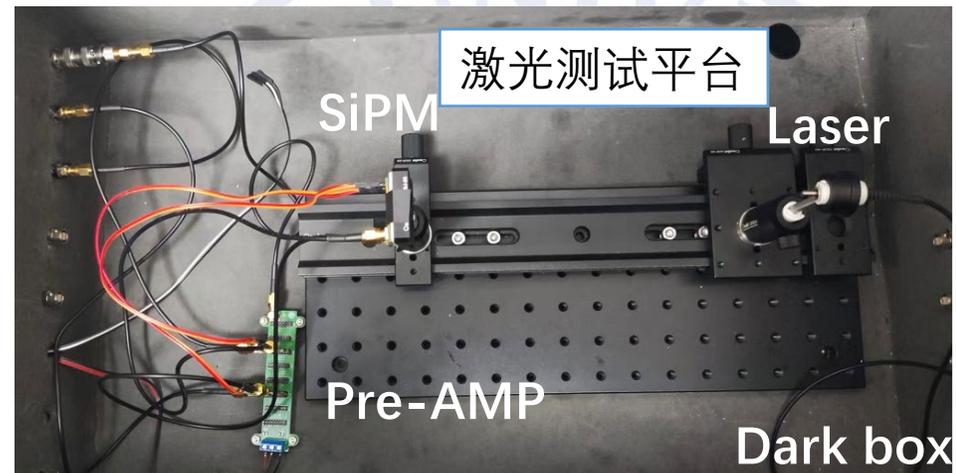
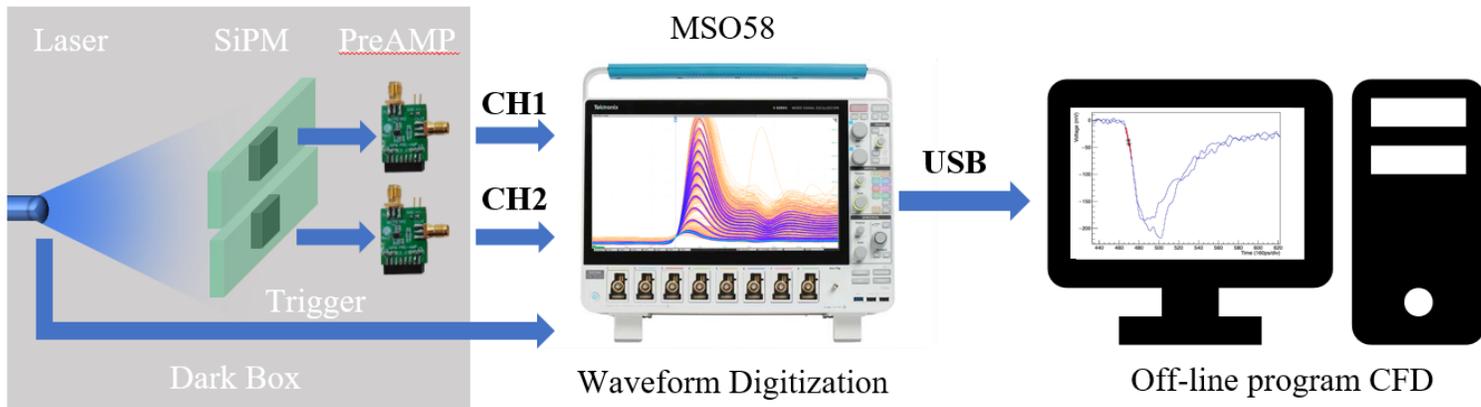
4×SiPM

12×SiPM

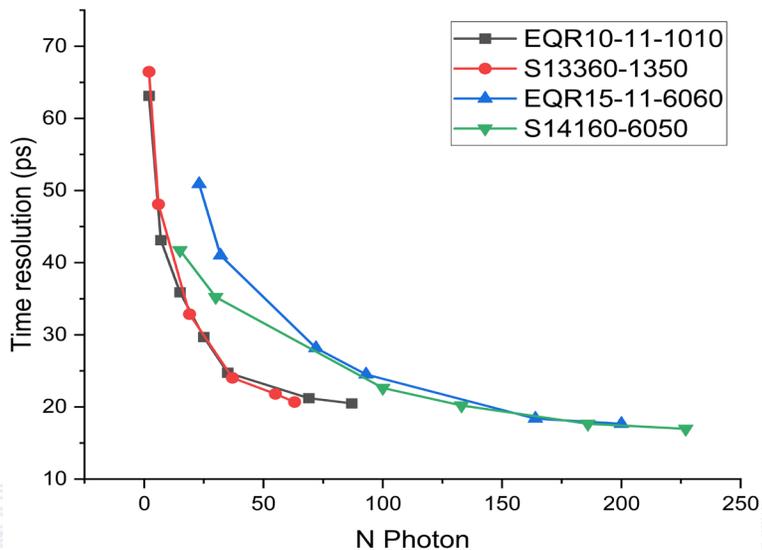


➤ 采用更厚衰减长度更长的闪烁体以及大尺寸的SiPM阵列提高光收集效率。

SiPM与前端电子学时间分辨测试



SiPM单光子信号



时间分辨随光子数收集的变化

Small area: ($1 \times 1 \text{ mm}^2$ / $1.3 \times 1.3 \text{ mm}^2$)
Photons > 5 , Time resolution < 50ps
Photons > 40 , Time resolution < 25ps

Large area: ($6 \times 6 \text{ mm}^2$)
Photons > 20 , Time resolution < 50ps
Photons > 70 , Time resolution < 25ps

王曦阳 et al. Nucl. Sci. Tech, 34, 169(2023)

Development of a high resolution Time-of-Flight with SiPM-readout Scintillator in Belle II for measurement of Neutral Hadron momentum

Xiyang Wang^{a, b, c}, Hongyu Zhang^{a, b}, Shiming Zou^{a, b}, Mingkuan Yuan^{a, b}, Zibing Bai^c, Deqing Fang^{a, b, c}, Kairui Huang^{a, b}, Ziyu Liu^{a, b}, Yugang Ma^{a, b, c}, Weiqi Meng^{a, b}, Ting Wang^a, Xiaolong Wang^{a, b, c}, Shiqing Xie^{a, b}, Mingjie Yang^a, Junhao Yin^{a, b}, Wanyi Zhuang^a

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ARTICLE INFO

Keywords:
Time-of-Flight
Time resolution
Muon detector
Scintillator
SiPM

ABSTRACT

Accurate momentum determination of a neutral hadron, such as a K_L meson or a neutron, remains a significant challenge in particle physics and nuclear physics experiments. The Belle II experiment presents an opportunity to address this challenge through an upgrade incorporating Time-of-Flight (TOF) capability for its large K_L and Muon Detector (KLM). We investigated the feasibility of momentum determination via TOF measurement. To achieve high time resolution for the KLM upgrade, we conducted research and development of cost-effective plastic scintillators and silicon photomultiplier arrays. A bulk attenuation length of 120 ± 7 cm has been achieved with a 135 cm-long bar, along with a time resolution of 70 ± 7 ps at its midpoint. A 50 cm-long scintillator demonstrates an exceptional time resolution of 47 ± 2 ps. These results highlight the potential of the proposed technology for improving neutral hadron momentum measurements in an upgraded Belle II KLM detector.

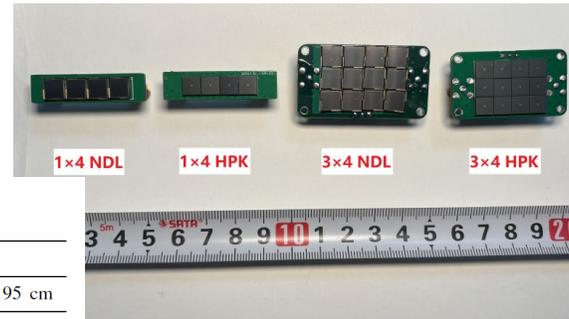
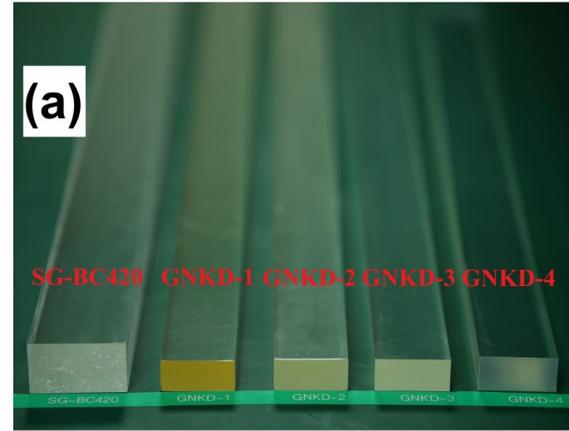
NIMA 1084, 171194(2026)

Table 1
Comparison of photon collection and time resolution at the near-end and far-end of scintillators with different L_{Att} .

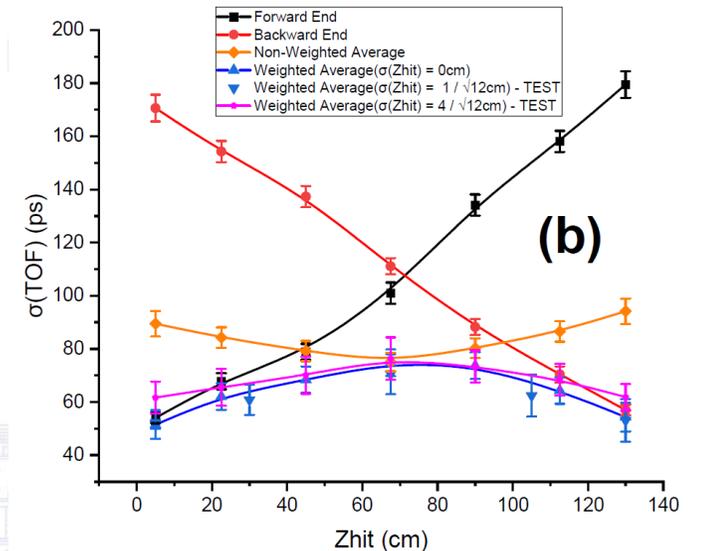
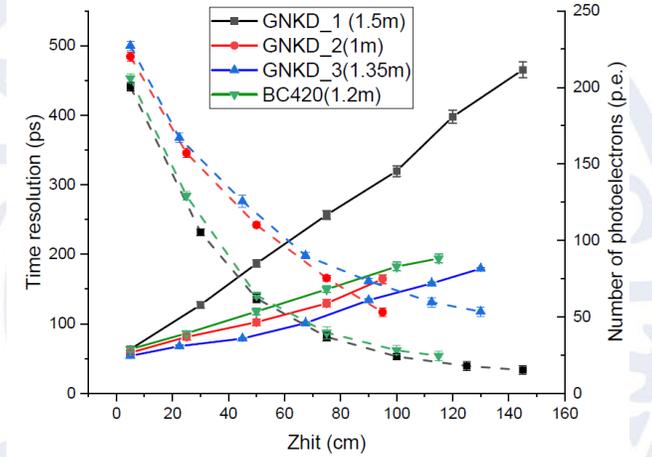
Type	Dimensions (cm ³)	L_{Att} (cm)	Time Resolution (ps)		nPE	
			$Z_{hit} = 5$ cm	$Z_{hit} = 95$ cm	$Z_{hit} = 5$ cm	$Z_{hit} = 95$ cm
BC420	5 × 3 × 120	80 ± 7	63 ± 4	175 ± 6	206	30
GNKD_1	4 × 2 × 150	73 ± 7	63 ± 4	307 ± 8	200	26
GNKD_2	4 × 2 × 100	63 ± 2	59 ± 4	164 ± 6	220	53
GNKD_3	4 × 2 × 135	115 ± 5	53 ± 2	138 ± 6	227	70
GNKD_4	4 × 2 × 50	/	44 ± 3	81 ± 5 ^a	341	154 ^a

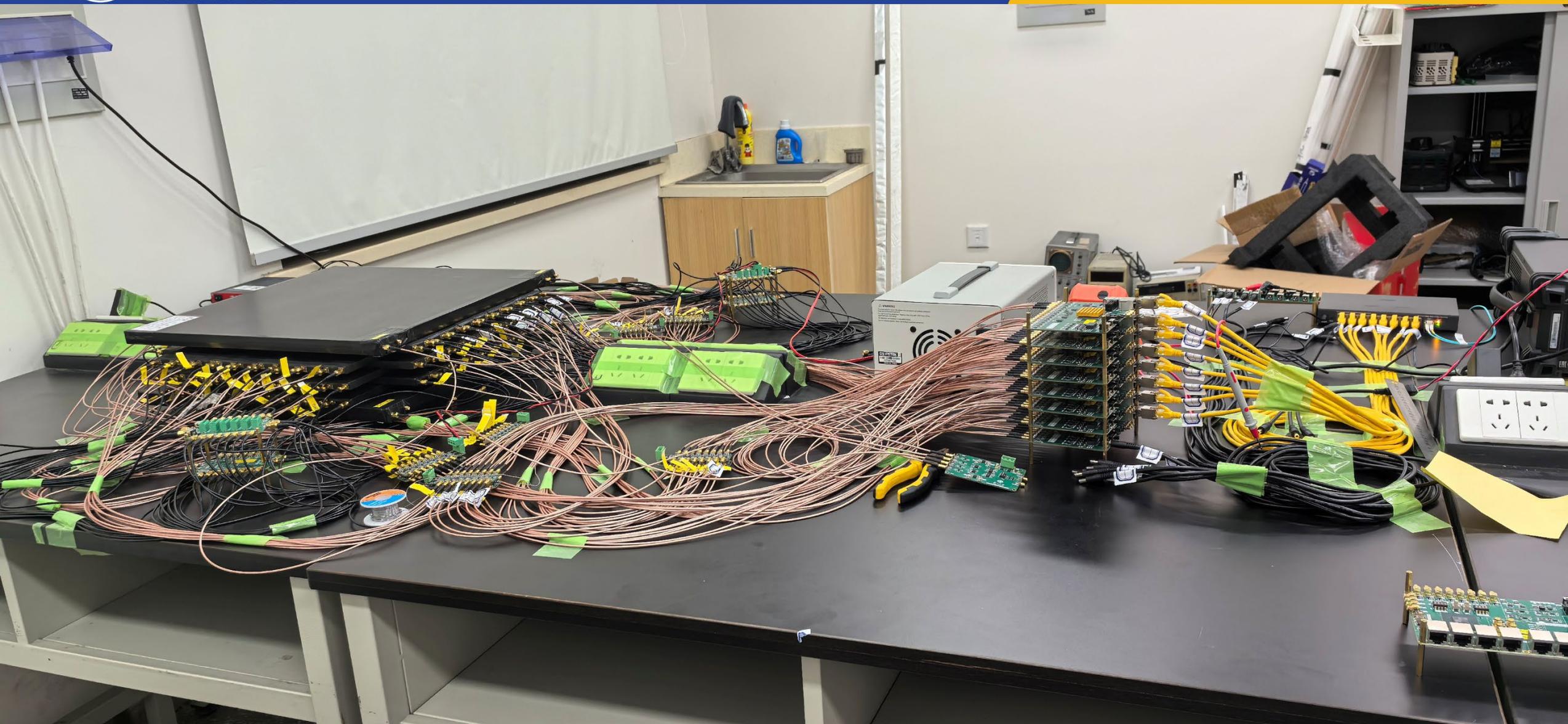
^a Measured at $Z_{hit} = 45$ cm.

GNKD3: $\sigma_T = 70 \pm 7$ ps
GNKD4: $\sigma_T = 47 \pm 2$ ps



HTR: High Time Resolution





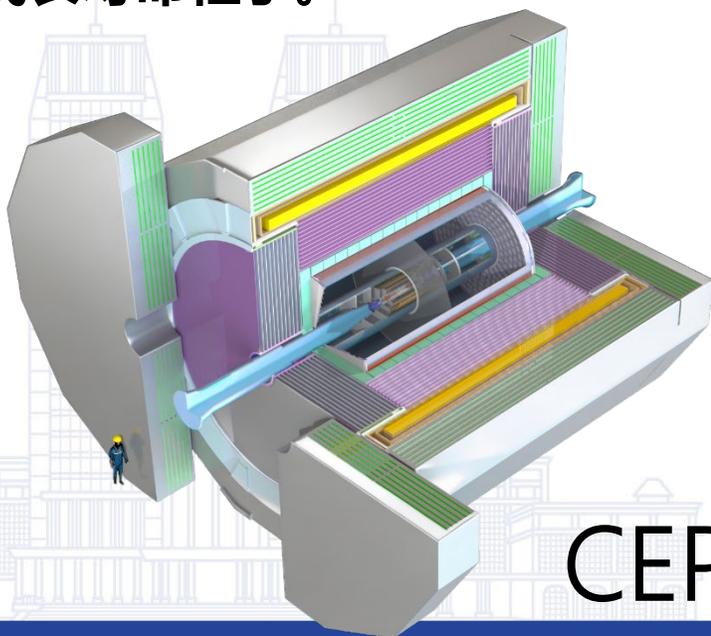
➤ KLM常规塑闪探测器升级方案



缪子探测器：最外层，体积最大的探测器，并且本底最低。对末态粒子进行探测器的最后机会。

■ **缪子探测器的主要任务是缪子鉴别，但不限于此：**

- 探测器强子量能器的能量泄露。
- 提供触发信息。
- 寻找长寿命粒子。

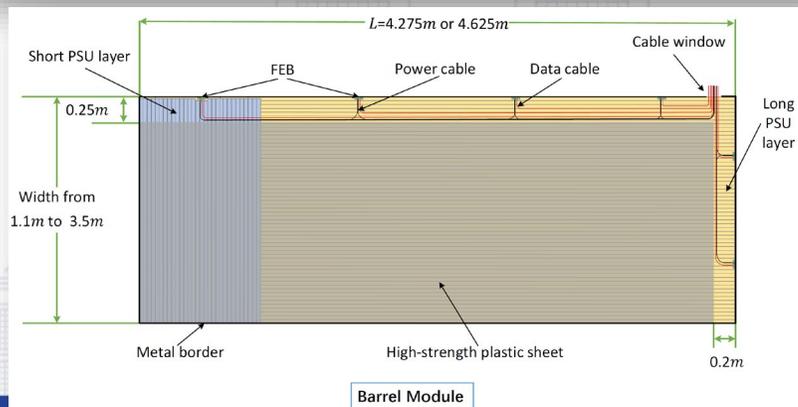
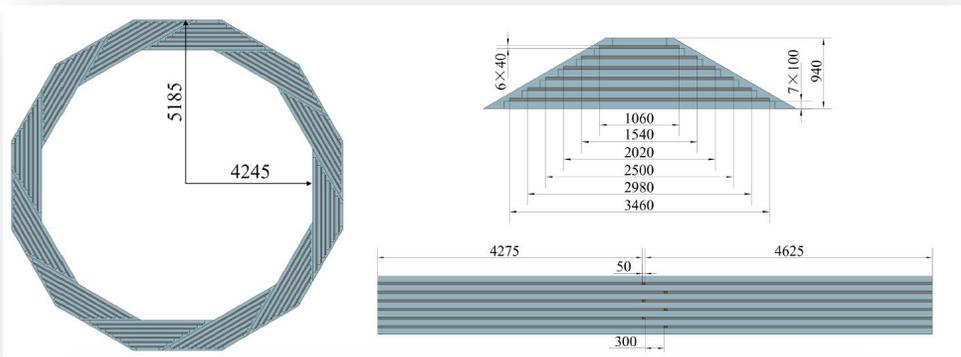


性能要求：

- 覆盖立体角: $0.98 \times 4\pi$
- 探测效率: $> 95\%$
- 位置分辨: $\sim 1\text{ cm}$
- 时间分辨: $\sim 1\text{ ns}$
- $\pi \rightarrow \mu$ 误判率: $< 1\%$
- 事例率承受能力: $50\text{ Hz}/\text{cm}^2$

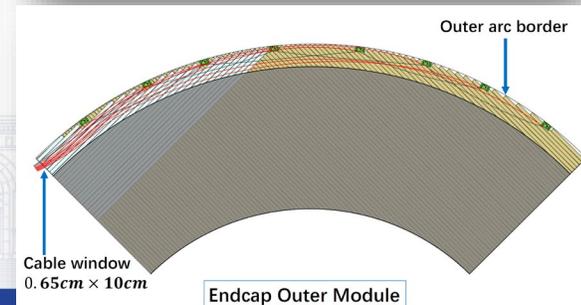
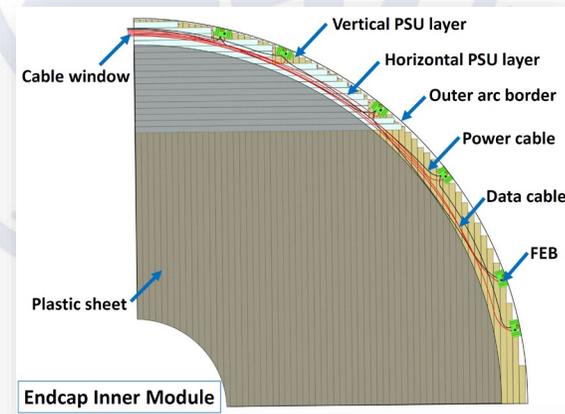
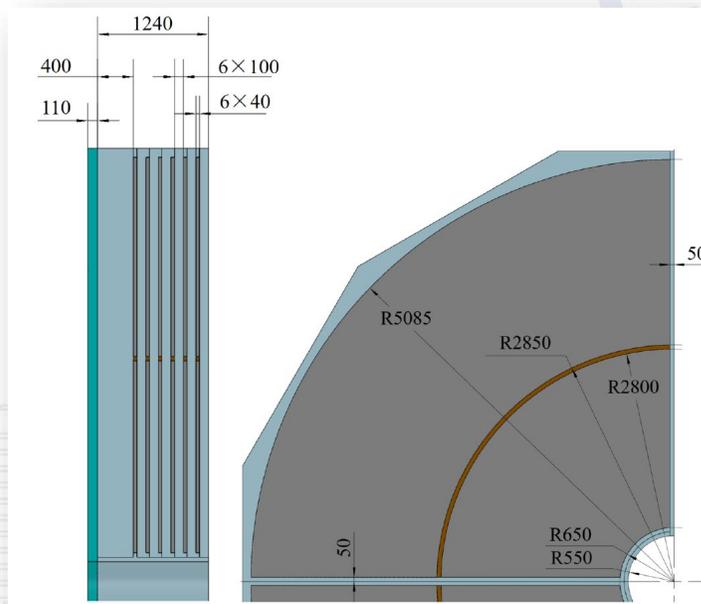
CEPC探测器

- 桶部几何结构: **6 superlayers**, 尽量覆盖探测立体角
 - 桶部: 螺旋式结构, 提升结构强度。
 - 长方形的探测模板。
 - 中间为间隔排列的5cm宽加强筋, 分割探测层。
 - 探测板长度: 4.275m 或者 4.625m.



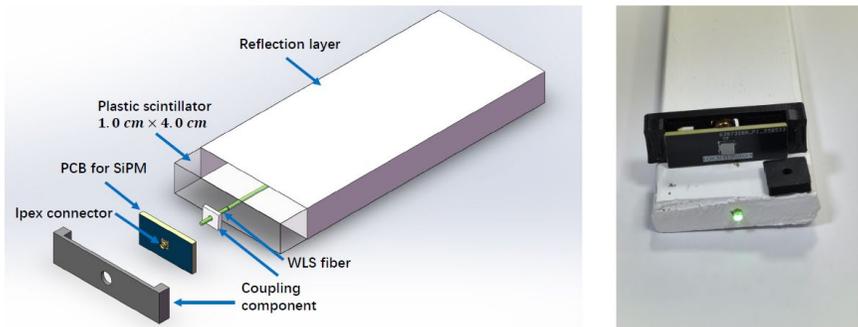
- 端盖几何: **6层探测器**

- 中部加强筋分为内外两个扇区:
 - Inner module: $R = 0.75 - 2.95m$
 - Outer module: $R = 3.00 - 5.20m$
- 靠近束流管区域的本地较高。
- 最长探测道: 4.2m

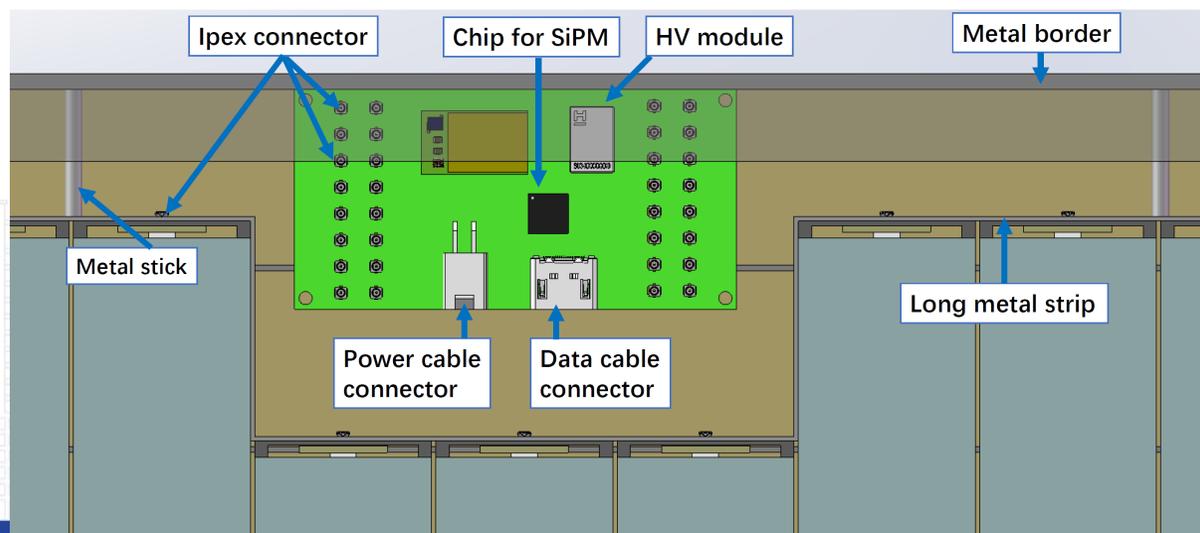
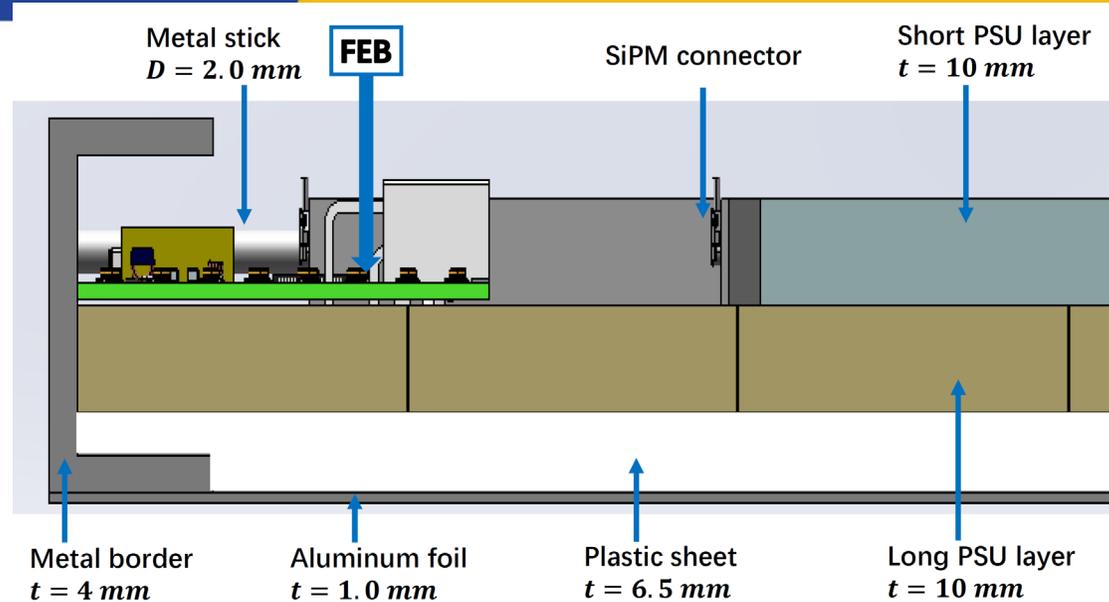
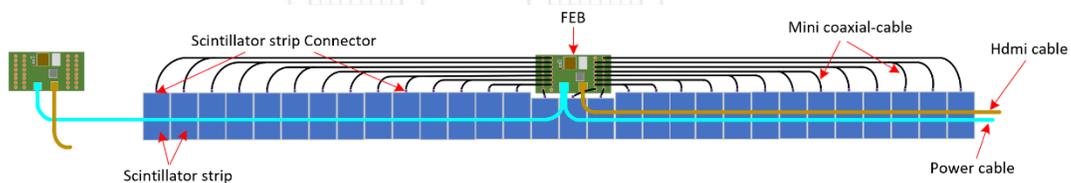


探测道和探测模板结构

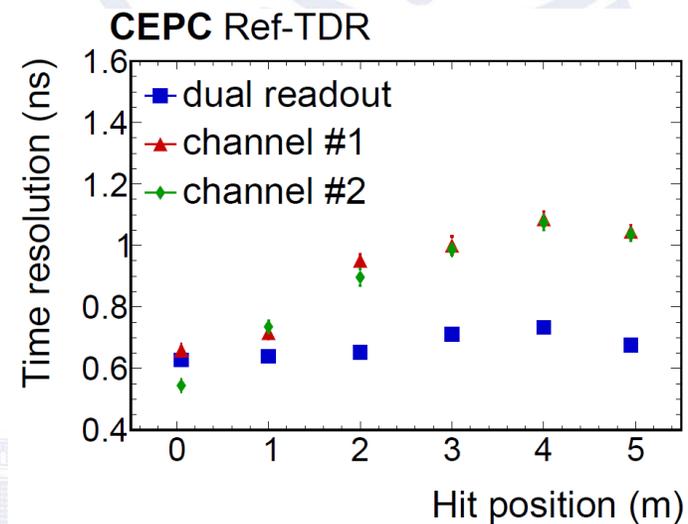
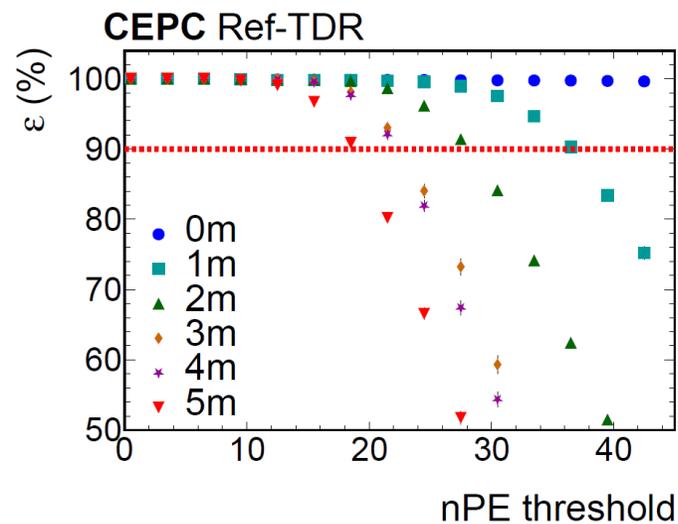
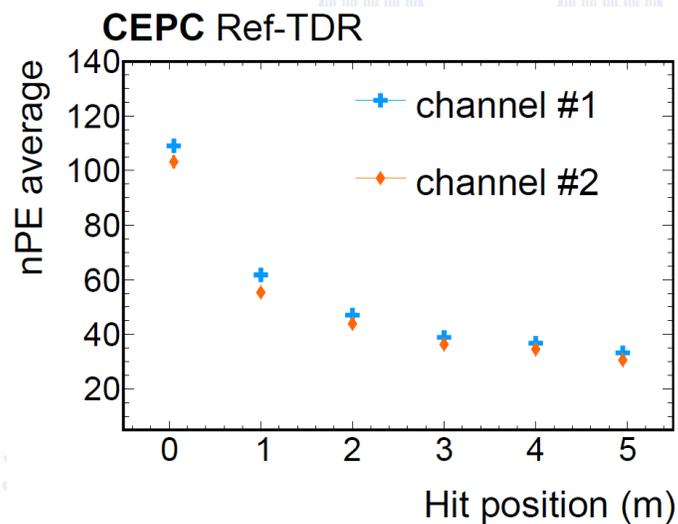
探测道单元 (PSU)



前端连接



- 改进5m最新国产塑闪。
- TiO₂反射层。
- 不使用光学胶。
- 探测光子数，效率和时间分辨均达到设计要求！



➤ 双光子标记探测器的构想

Fudan group is encouraged to focus on **forward tagger** as technology demonstrator. Before July:

- c. Simulation showing background robustness and placement
- d. Physics sensitivity for key channel(s)

UPO baseline configuration proposal

28 Jan 2026

双光子 vs 初态辐射

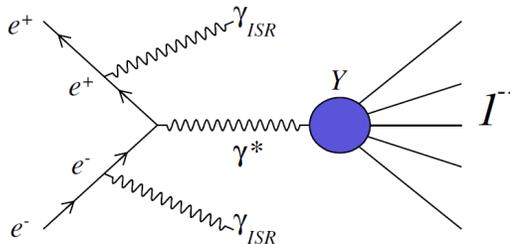
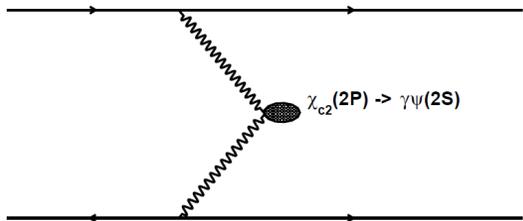


FIG. 9. The feyman diagrams of $\gamma\gamma \rightarrow \gamma\psi(2S)$ (left) and $e^+e^- \rightarrow \psi(2S)$ via ISR (right).

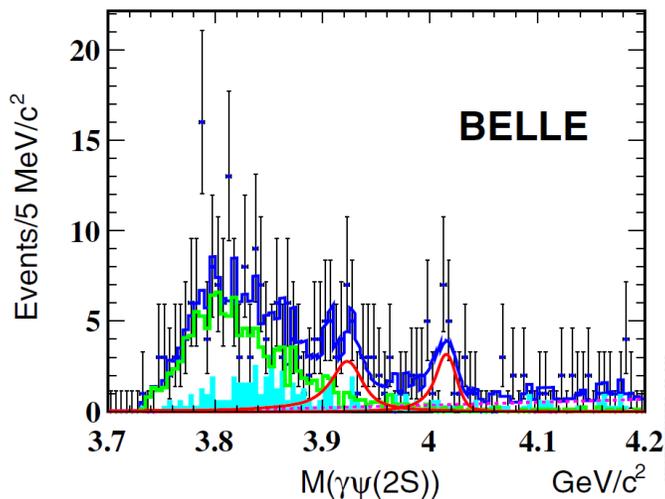


FIG. 6. The $\gamma\psi(2S)$ invariant mass distribution and the fit result. The points with error bars show the data while the shaded histogram is the normalized background from the $\psi(2S)$ mass sidebands. The solid blue curve shows the best fit results. The red signal curves from the convolutions of BW and CB functions show the contributions from the two structures. The green blank histogram shows the component of ISR events of $e^+e^- \rightarrow \psi(2S) \rightarrow \pi^+\pi^-J/\psi$. The pink dashed line shows the possible additional background, modeled by a second-order polynomial.

Belle: PRD 105, 112011 (2022)

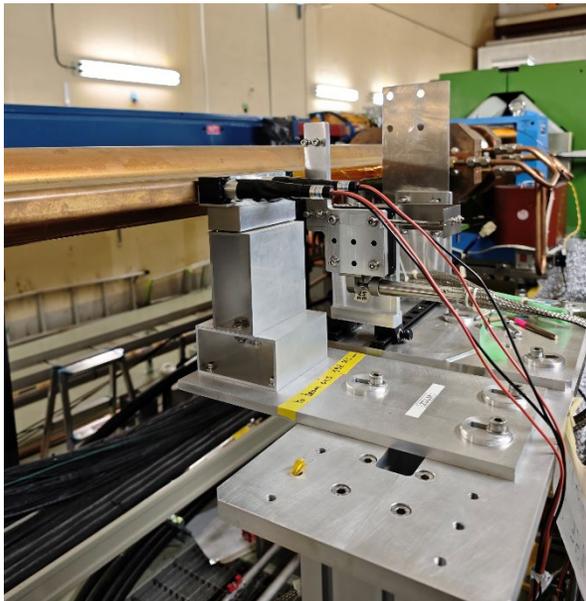
都具有 low Pt 的特点；
初态辐射过程经常造成双光子过程的本底。

双光子的特点：末态具有能量降低的 e^+e^- ，但是它们经常跟随束流离开 Belle II 探测器。
问题：如何探测这两个能量下降的粒子？

双光子标记探测器



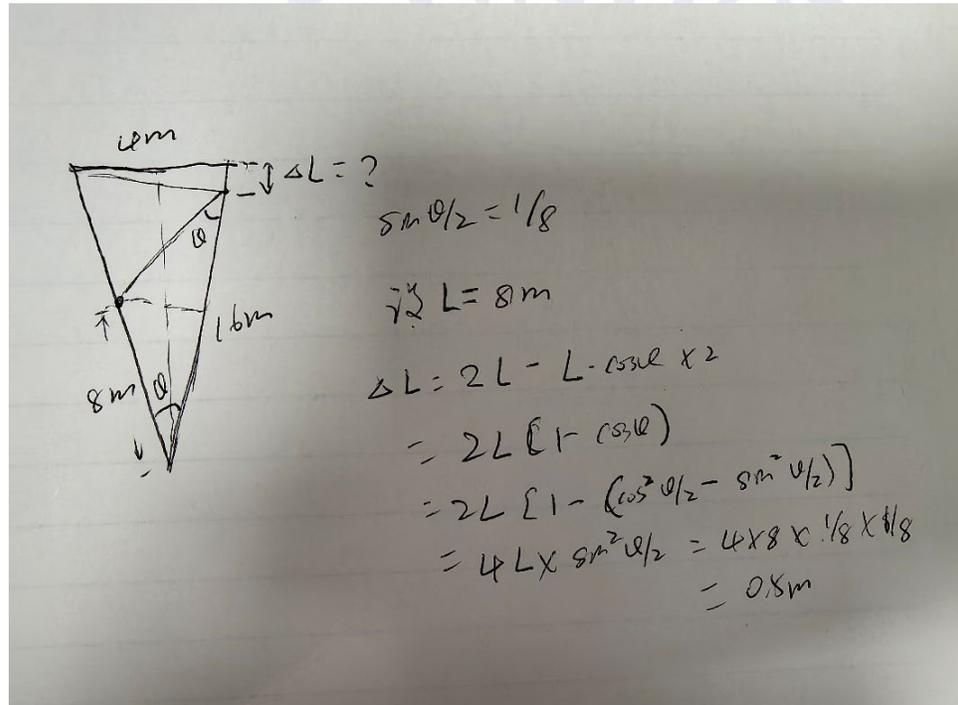
Dipole magnet near the Belle II detector



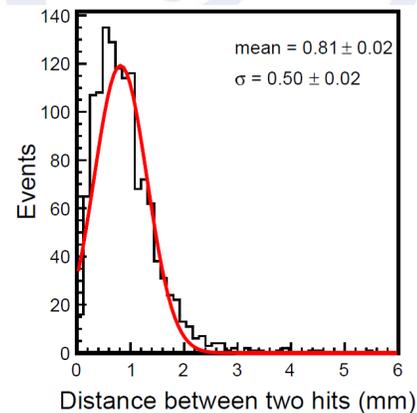
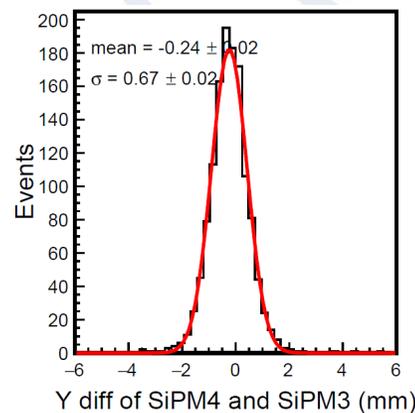
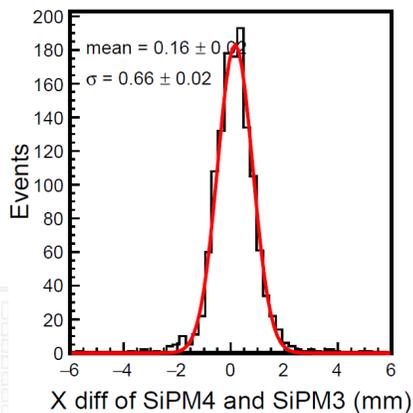
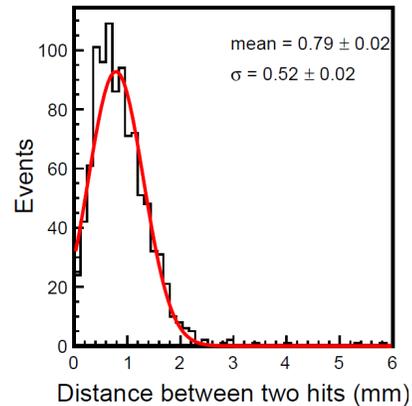
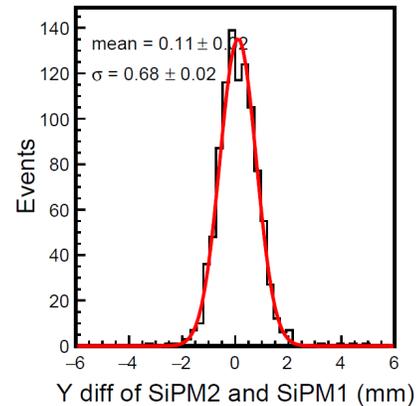
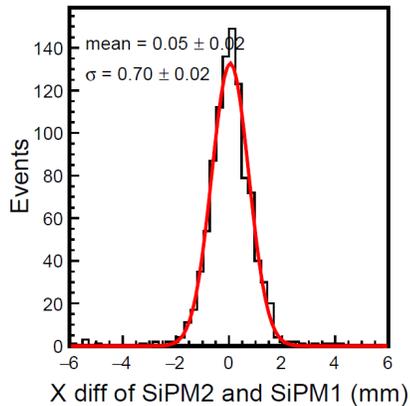
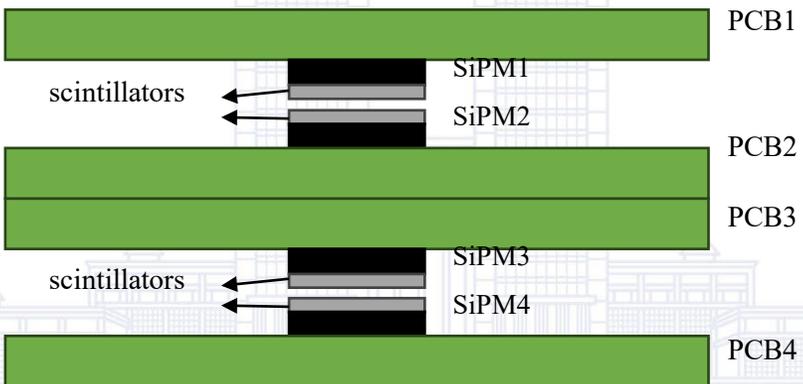
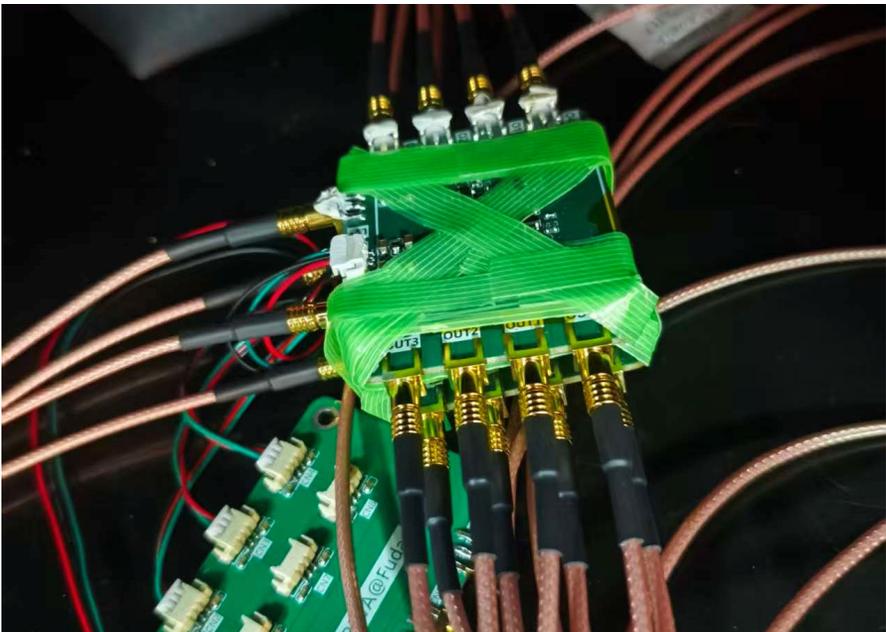
高能所的LGAD探测器:

Ch1: 6mm*3mm

Ch2: 6mm*6mm



e^\pm offset from HER may be about 0.5m. If we can detect the e^\pm near the beam pipe in the dipole magnet with high accuracy.



SiPM: 6mm*6mm, 4ch readout

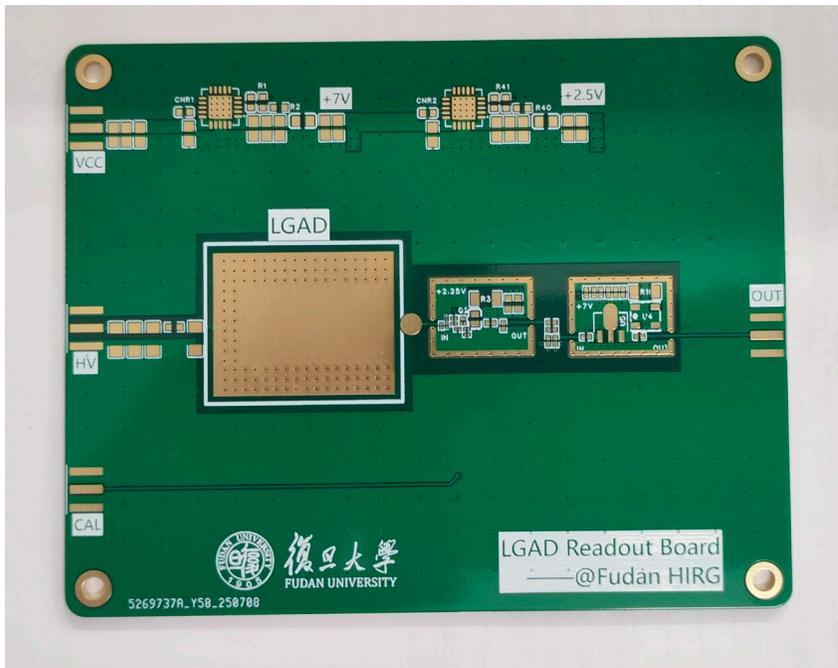
Resolution of 0.35mm!

Time resolution of 0.6ns!

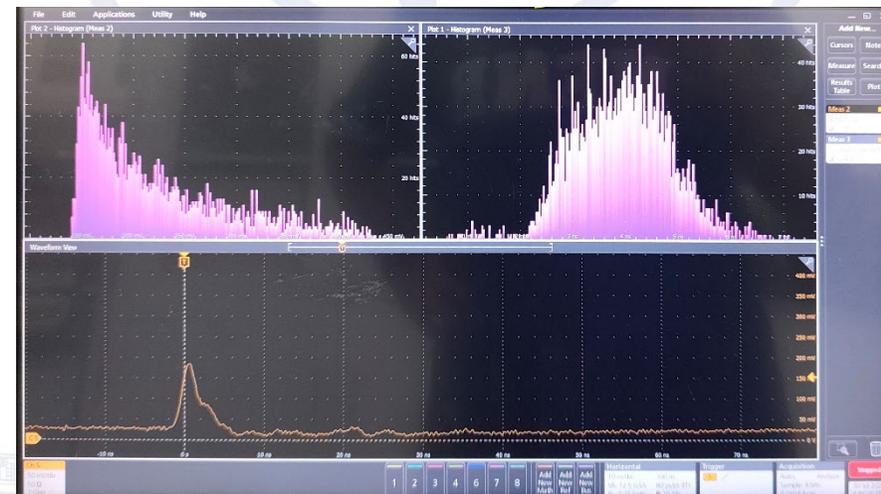
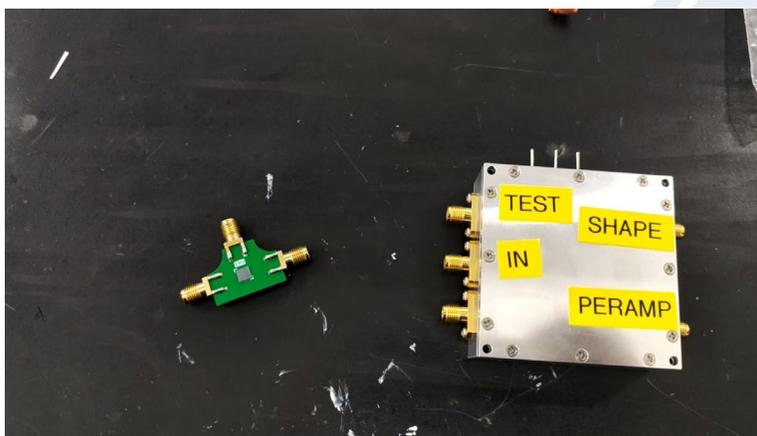
➤ 电子学研发



快响应前放用于塑闪窄脉宽测试

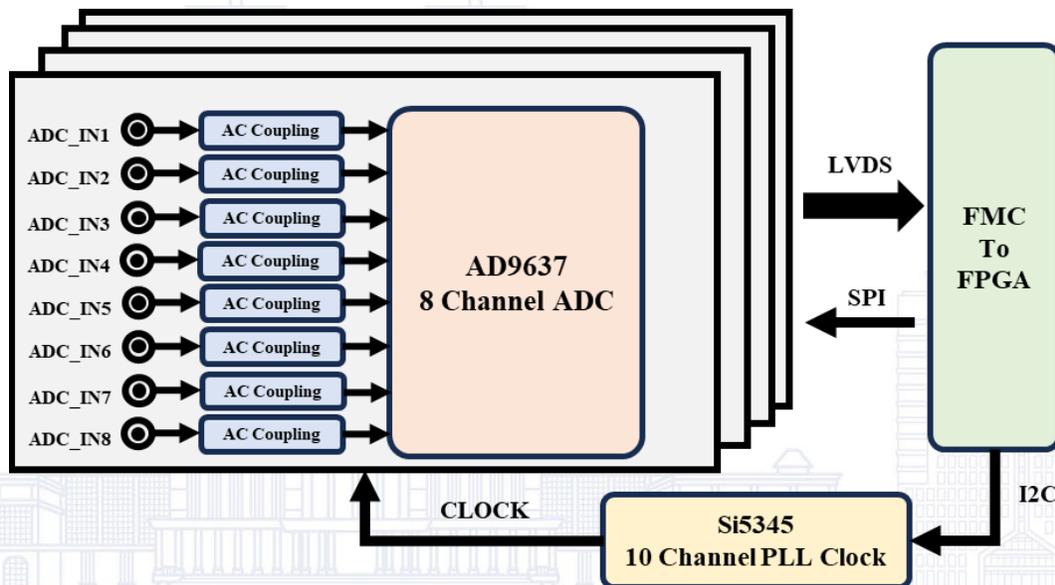


快响应前放用于LGAD测试



SiPM+激光测试：脉宽 $<2\text{ns}$!

SiPM+塑闪测试：脉宽 $3\text{-}5\text{ns}$!



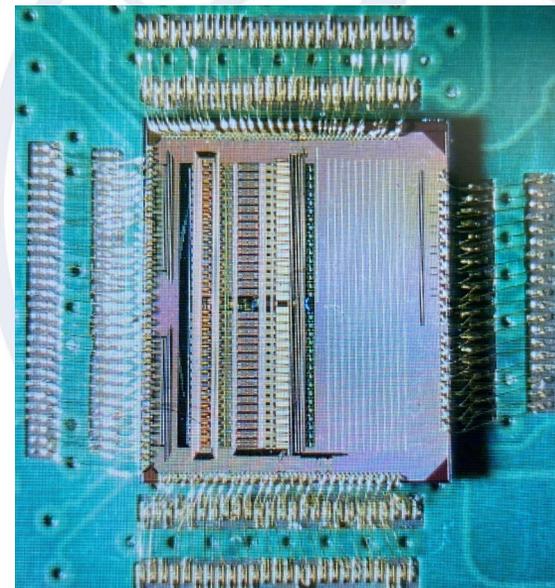
ADC Chip: AD9637 × 4
 Channel: 32通道
 Rate: 80 MSPS
 Bit Depth : 12bit
 Serial LVDS

拓展到千级通道

The MPT2321 chip is a SiPM signal processing SoC chip designed for high-precision time-of-flight signal processing.

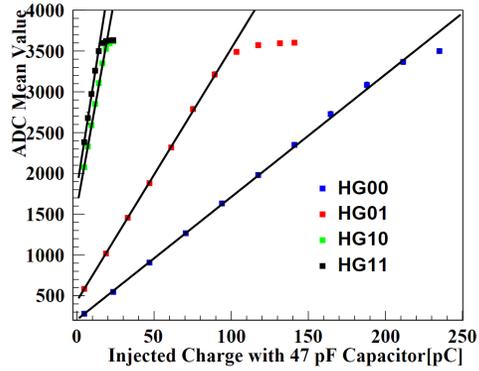
Features

- **32 input channels**
- Automatically select the range of measurement signals
- **50ps precision 20-bit TDC**
- **12bit ADC**
- Complete on-chip signal processing
- Standard IIC Bus Control
- 8b10b encoding transmission
- Multichannel LVDS data transmission
- 12 Mcps transmission event rate
- High integration, low power consumption
- 200M data transmission rate
- The maximum charge measurement dynamic range is 2.4 nC
- Minimum detectable signal range 4fC

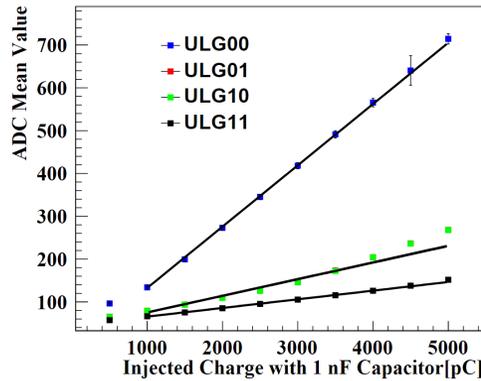


MPT2321 chip

Charge injection linearity test

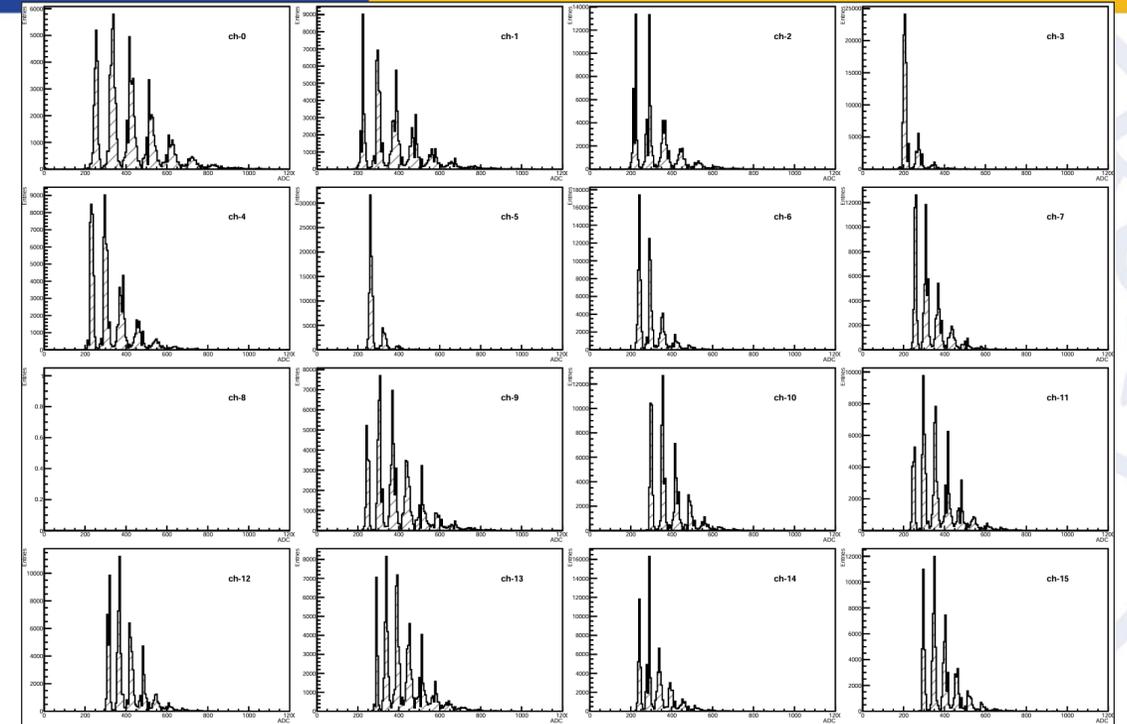


High-Gain mode

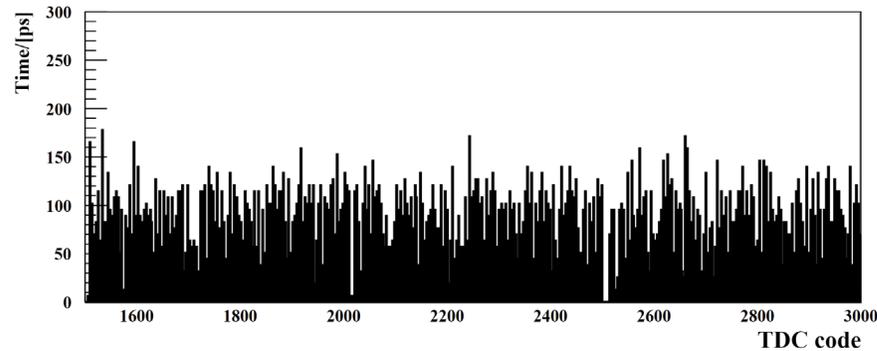


Low-Gain mode

Gain mode	Fitted slope(ADC/pC)	Fitting chi2
ULG00	0.1432 ± 0.0018	3.22
ULG01	0.0390 ± 0.0006	151.26
ULG10	0.0388 ± 0.0006	155.20
ULG11	0.0202 ± 0.0003	8.46
HG00	15.03 ± 0.07	14.17
HG01	30.92 ± 0.20	1.43
HG10	104.9 ± 1.01	17.56
HG11	120.2 ± 1.8	5.10



Charge spectrum combined with SiPM for each channel

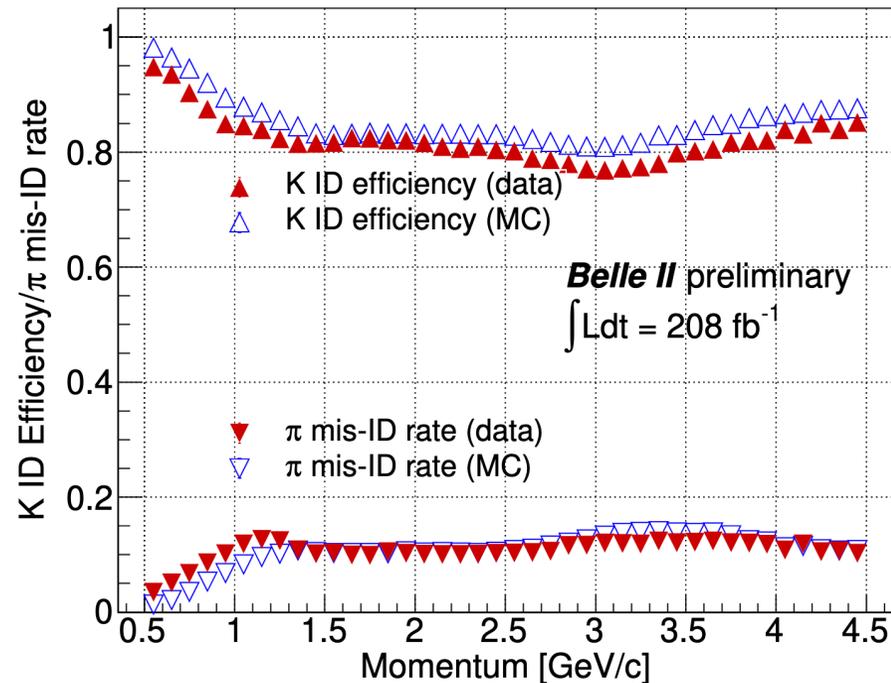
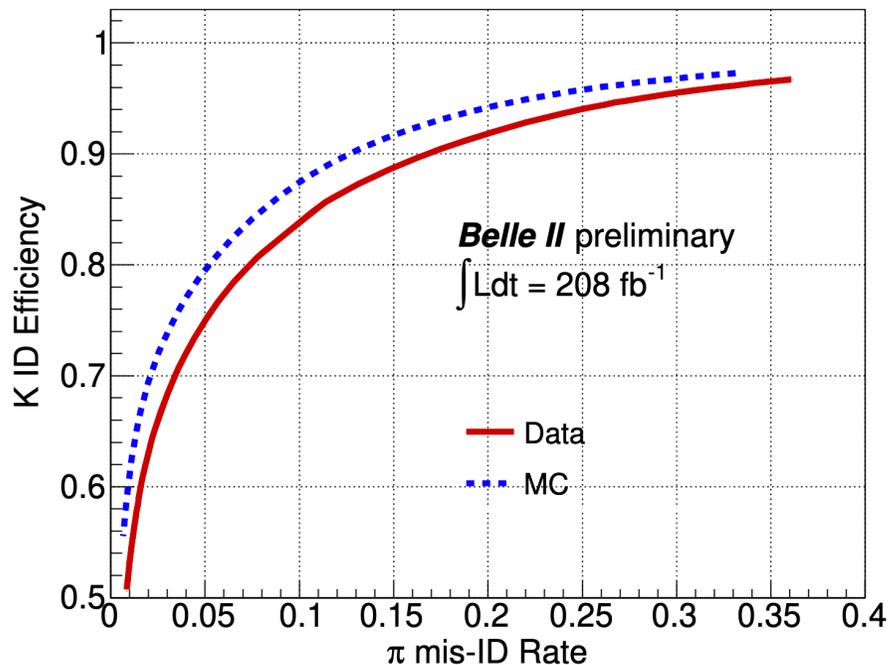


Bin width test of TDC

- Belle II实验是新一代超级B介子工厂。
- SuperKEKB加速器首次采用纳米束流方案，已实现 $0.5 \times 10^{35} \text{cm}^{-2} \text{s}^{-1}$ 的对撞亮度。近期运行稳定。
- Belle II探测器采用先进的探测技术。
- Belle II正在开展实验升级研究，预期于2032年升级。
- 复旦实验室提出KLM探测器的升级方案并开展大量研究。
- 复旦实验室提出新的双光子标记探测器方案。

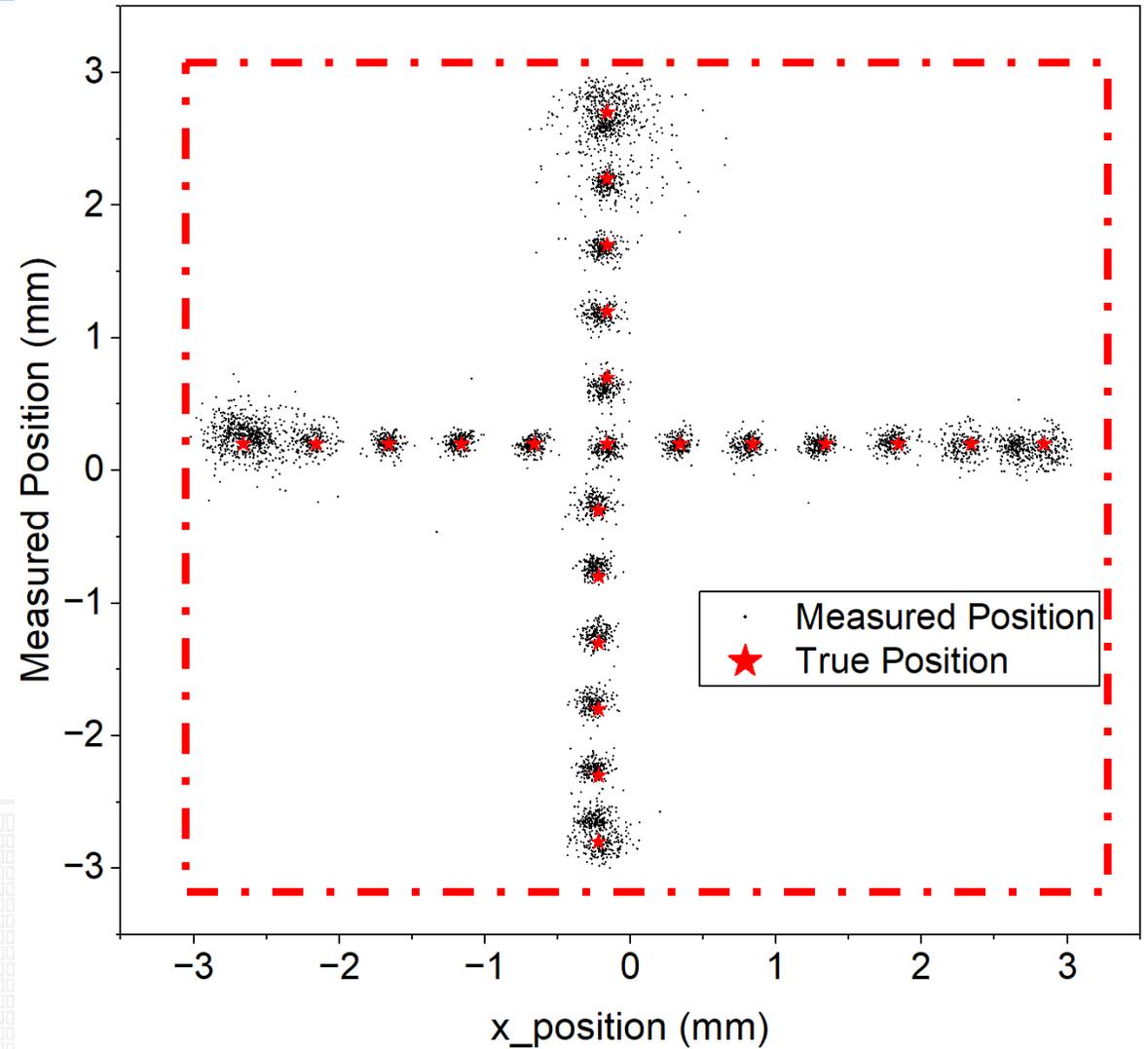
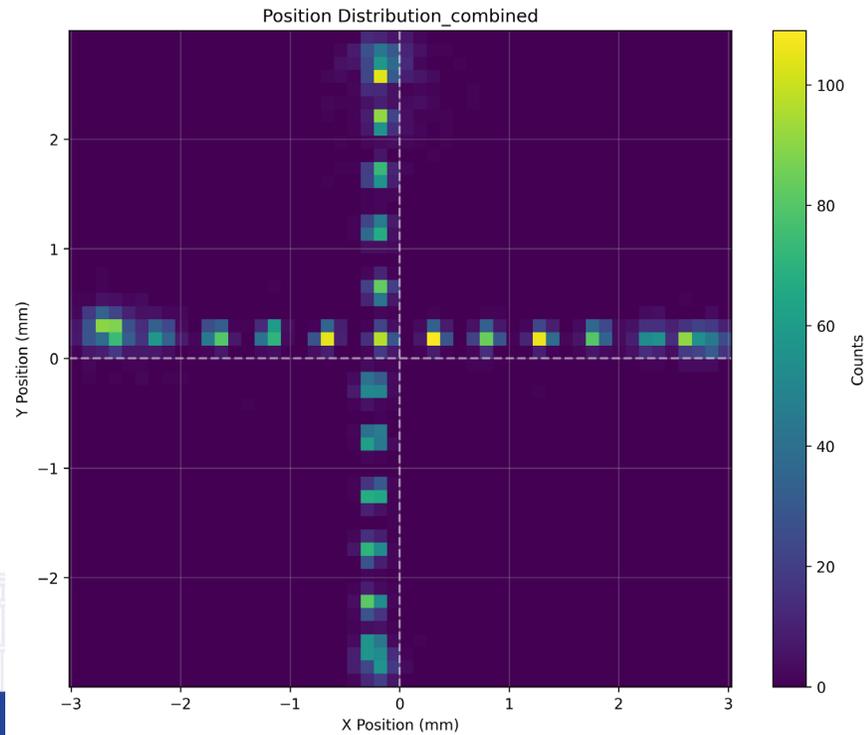
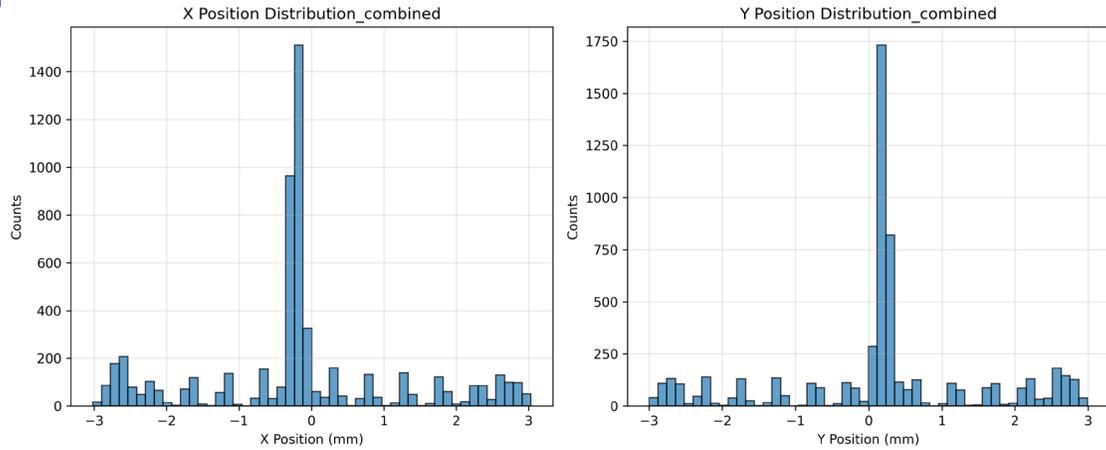
谢谢!





- Good kaon identification, currently slightly underperforming wrt Belle.
- Big efforts underway that will improve this (e.g. TOP software, Neural Network based ID).
- Systematics associated to Data/MC correction factors currently at 0.8-1% level (0.8% at Belle).

Reconstructions of multiple positions



Spatial resolution reduces near the borders.