



环形正负电子对撞机  
Circular Electron Positron Collider

# CEPC探测器概念设计和预研究

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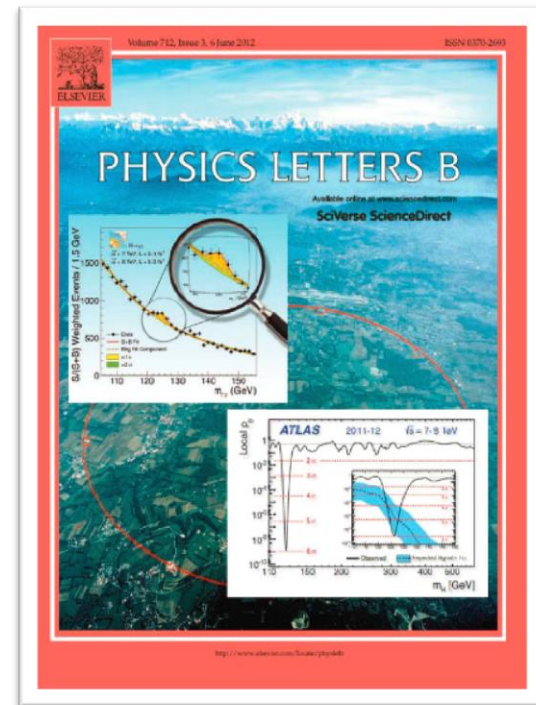
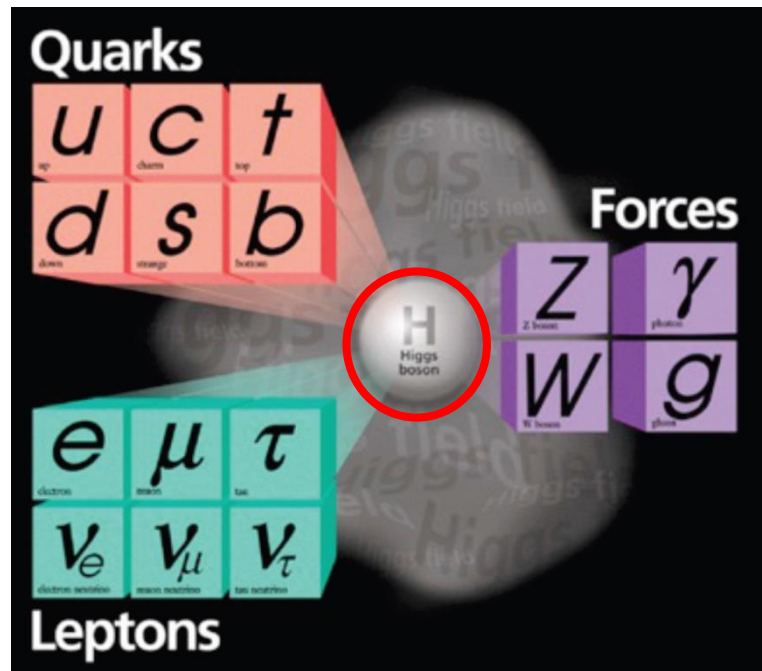
香山科学会议，北京  
2016年11月18-19日

# 报告提纲

- CEPC 物理目标
  - CEPC 探测器概念设计
    - 对撞机-探测器接口 (MDI)
    - 顶点探测器 (Vertex)
    - 径迹探测器 (Tracker)
    - 时间投影室 (TPC)
    - 电磁量能器 (ECAL)
    - 强子量能器 (HCAL)
    - 缪子探测器 (Muon)
    - 磁铁 (Magnet)
  - 科技部大科学装置CEPC探测器预研究
  - 结束语
- 详见欧阳群报告
- 详见李玉兰报告

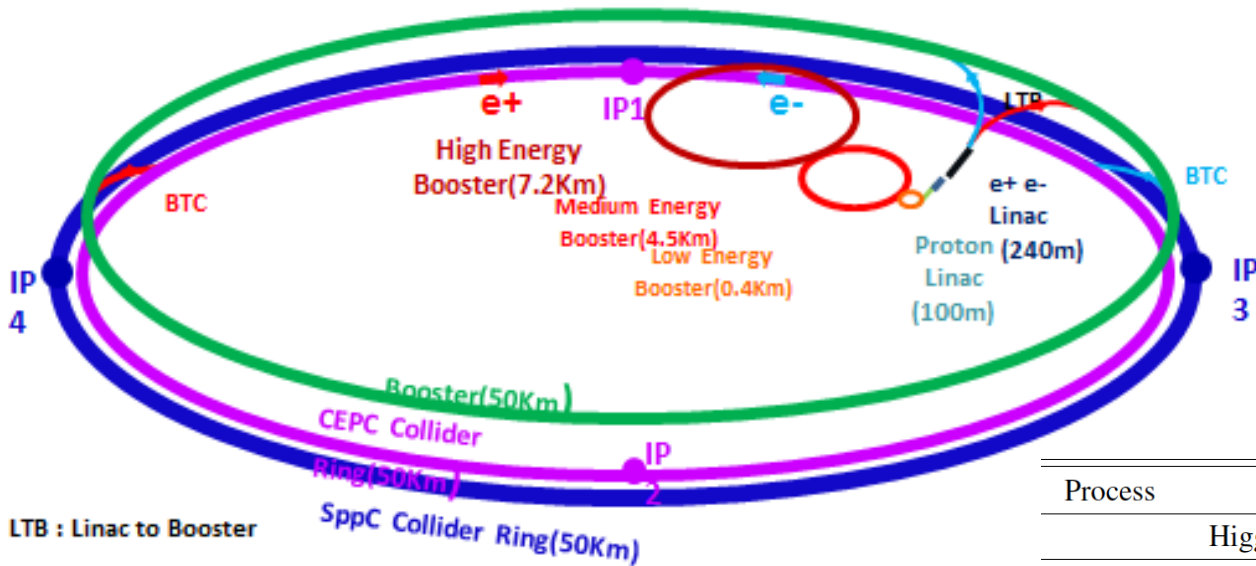
# CEPC – 环形正负电子对撞机

2012年，欧洲核子研究中心的大型强子对撞机实验发现了希格斯玻色子，揭示了基本粒子质量起源问题。为了在“干净”的对撞实验环境下对希格斯粒子的各种属性作非常精确测量，需要建造大型的正负电子对撞机作为“希格斯和Z玻色子工厂”。



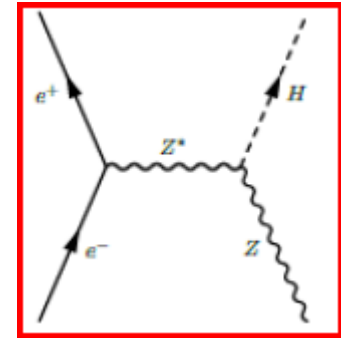
# CEPC 对撞机

**$e^+e^-$  Higgs (Z) 工厂**, 质心系能量:  $E_{\text{cm}} \approx 240\text{GeV}$ ,  
 对撞机亮度:  $\sim 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ , 运行10年,  $5\text{ab}^{-1}$   
 两个探测器,  $\sim 100$ 万 ZH 事例



LTP : Linac to Booster

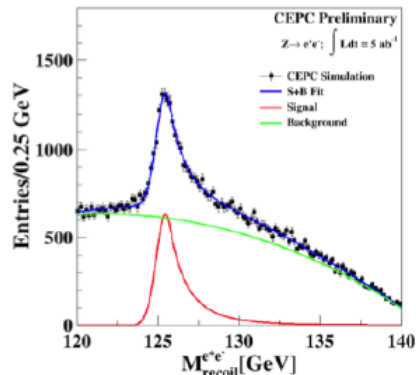
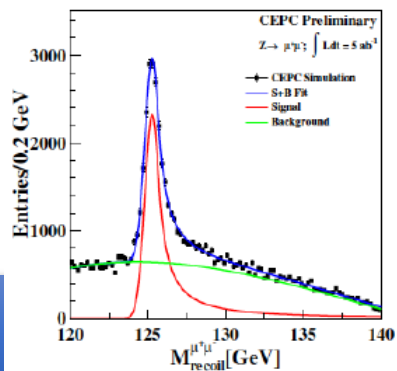
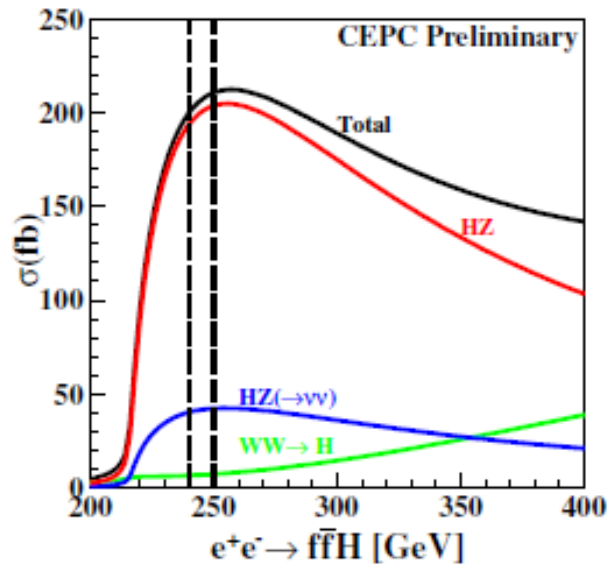
BTC : Booster to Collider Ring



Process	Cross section	Events in $5 \text{ ab}^{-1}$
Higgs boson production, cross section in fb		
$e^+e^- \rightarrow ZH$	212	$1.06 \times 10^6$
$e^+e^- \rightarrow \nu\bar{\nu}H$	6.72	$3.36 \times 10^4$
$e^+e^- \rightarrow e^+e^-H$	0.63	$3.15 \times 10^3$
Total	219	$1.10 \times 10^6$

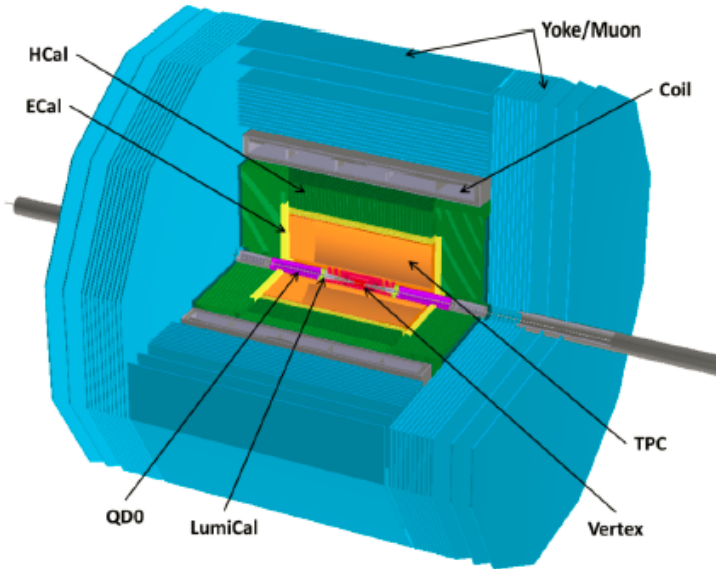
- 精确测量希格斯玻色子的各种属性：  
质量、宽度、分支比、产生截面、自旋宇称、耦合强度等。

→ 基于CEPC全探测器模拟



	PreCDR (Jan 2015)	Now (Aug 2016)
$\sigma(\text{ZH})$	0.51%	0.50%
$\sigma(\text{ZH})^* \text{Br}(\text{H} \rightarrow \text{bb})$	0.28%	0.21%
$\sigma(\text{ZH})^* \text{Br}(\text{H} \rightarrow \text{cc})$	2.1%	2.5%
$\sigma(\text{ZH})^* \text{Br}(\text{H} \rightarrow \text{gg})$	1.6%	1.3%
$\sigma(\text{ZH})^* \text{Br}(\text{H} \rightarrow \text{WW})$	1.5%	1.0%
$\sigma(\text{ZH})^* \text{Br}(\text{H} \rightarrow \text{ZZ})$	4.3%	4.3%
$\sigma(\text{ZH})^* \text{Br}(\text{H} \rightarrow \tau\tau)$	1.2%	1.0%
$\sigma(\text{ZH})^* \text{Br}(\text{H} \rightarrow \gamma\gamma)$	9.0%	9.0%
$\sigma(\text{ZH})^* \text{Br}(\text{H} \rightarrow \text{Z}\gamma)$	-	$\sim 4 \sigma$
$\sigma(\text{ZH})^* \text{Br}(\text{H} \rightarrow \mu\mu)$	17%	17%
$\sigma(\nu\nu\text{H})^* \text{Br}(\text{H} \rightarrow \text{bb})$	2.8%	2.8%
Higgs Mass/MeV	5.9	5.0
$\sigma(\text{ZH})^* \text{Br}(\text{H} \rightarrow \text{inv})$	95%. CL = 1.4e-3	1.4e-3
$\text{Br}(\text{H} \rightarrow \text{ee}/\text{emu})$	-	1.7e-4/1.2e-4
$\text{Br}(\text{H} \rightarrow \text{bb}\chi\chi)$	$< 10^{-3}$	3.0e-4

# CEPC 探测器设计



## ILD-like detector with additional considerations (*incomplete list*):

- Shorter  $L^*$  (**1.5/2.5m**) → constraints on space for the Si/TPC tracker
- No power-pulsing → lower granularity of vertex detector and calorimeter
- Limited CM (up to 250 GeV) → calorimeters of reduced size
- Lower radiation background → vertex detector closer to IP
- ...

与ILD探测器类似，但是需要根据物理目标和CEPC特点，通过关键物理过程的模拟重建和重要物理量所能达到的测量精度来优化探测器的设计。

Physics Process	Measured Quantity	Critical Detector	Required Performance
$ZH \rightarrow \ell^+ \ell^- X$	Higgs mass, cross section	Tracker	$\Delta(1/p_T) \sim 2 \times 10^{-5}$
$H \rightarrow \mu^+ \mu^-$	$BR(H \rightarrow \mu^+ \mu^-)$		$\oplus 1 \times 10^{-3} / (p_T \sin \theta)$
$H \rightarrow b\bar{b}, c\bar{c}, gg$	$BR(H \rightarrow b\bar{b}, c\bar{c}, gg)$	Vertex	$\sigma_{r\phi} \sim 5 \oplus 10 / (p \sin^{3/2} \theta) \mu\text{m}$
$H \rightarrow q\bar{q}, V^+ V^-$	$BR(H \rightarrow q\bar{q}, V^+ V^-)$	ECAL, HCal	$\sigma_E^{\text{jet}} / E \sim 3 - 4\%$
$H \rightarrow \gamma\gamma$	$BR(H \rightarrow \gamma\gamma)$	ECAL	$\sigma_E \sim 16\% / \sqrt{E} \oplus 1\% (\text{GeV})$

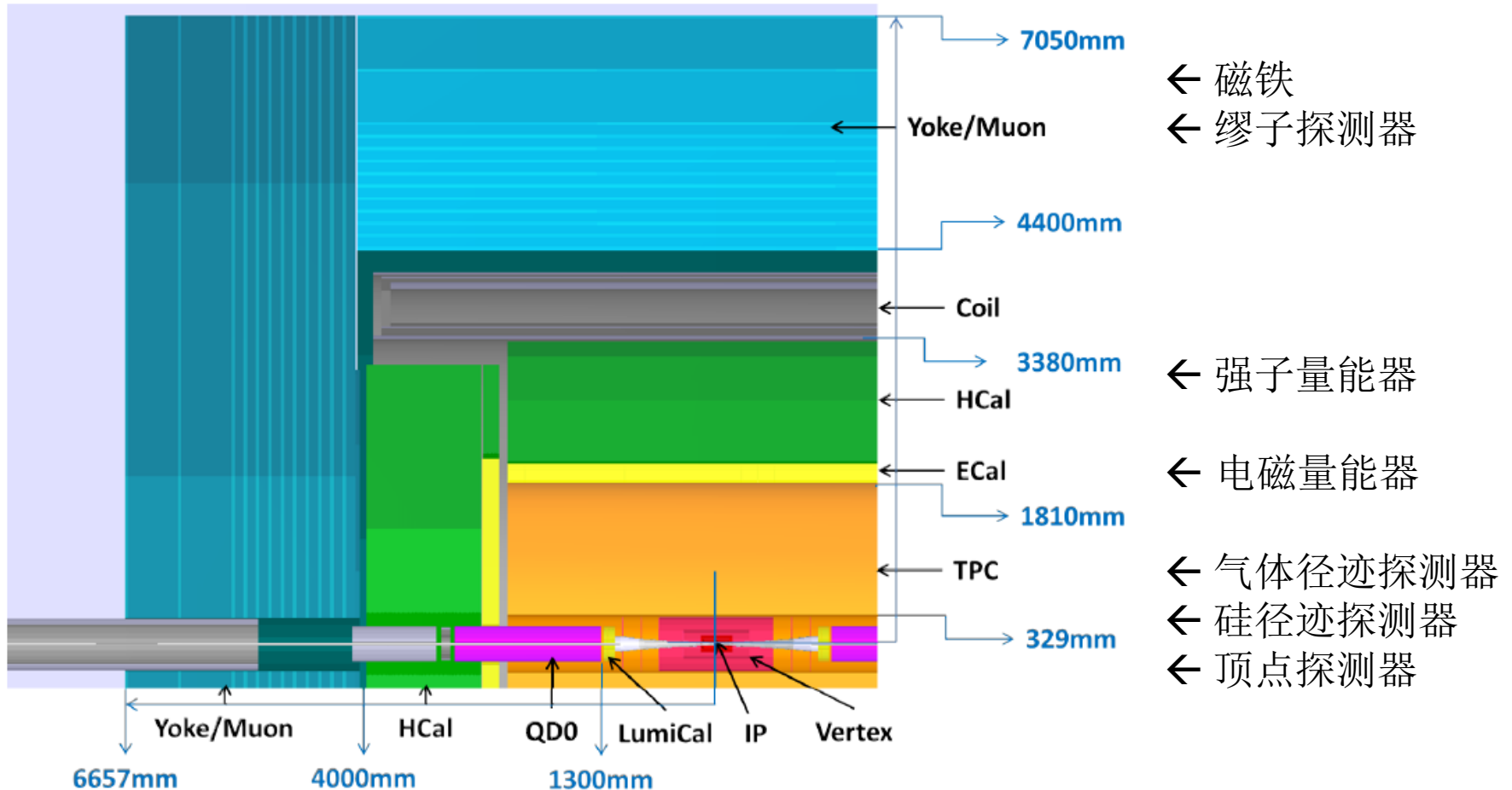
← Higgs mass

← Flavor tagging, BR

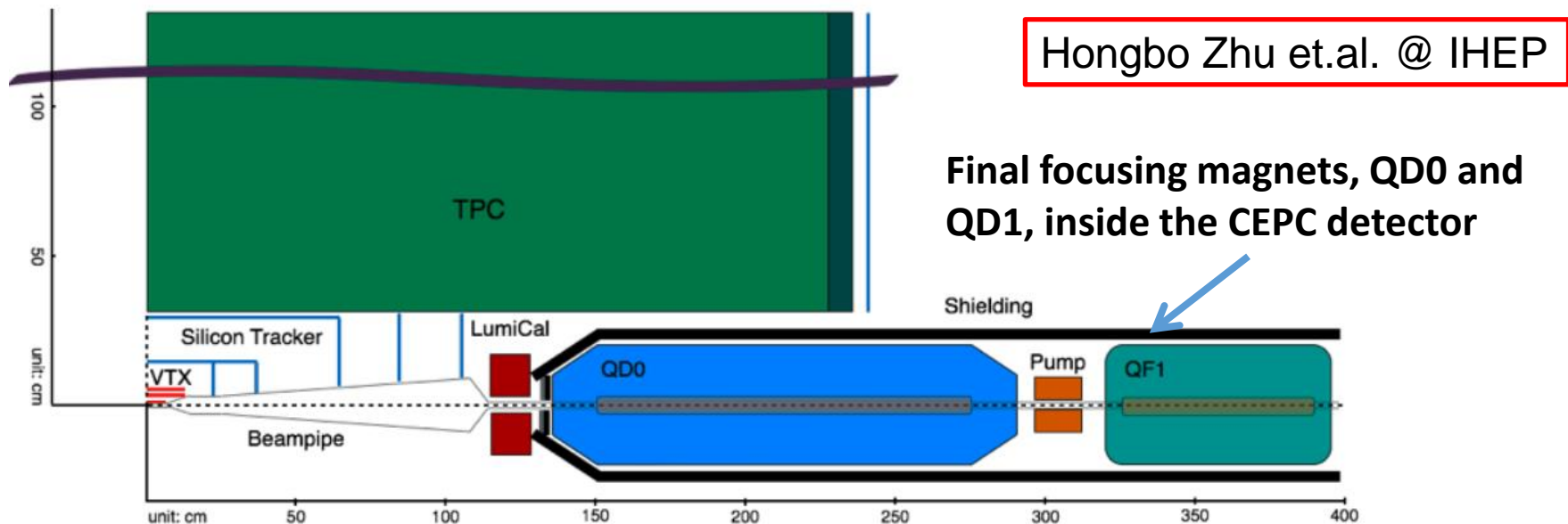
← W/Z dijet separation

# CEPC 探测器概念设计

CEPC preCDR, <http://cepc.ihep.ac.cn/preCDR/volume.html>



# CEPC 对撞机-探测器接口



- **缩短磁铁聚焦长度来提高亮度：** ( $L^*=1.5$ 米, ILC  $\sim 3.5$ 米)
- 聚焦磁铁塞入探测器内部  $\rightarrow$  对磁铁、探测器和亮度监测器的设计有重要影响和约束
- 需要细致研究对撞机和探测器的接口，理解束流引起的辐射背景和防护等



# CEPC 顶点和径迹探测器

**B = 3.5T**

详见欧阳群报告

- momentum resolution
- impact parameter resolution

## Performance requirements

$$\sigma_{1/p_T} = 2 \times 10^{-5} \oplus 1 \times 10^{-3} / (p_T \sin \theta)$$

$$\sigma_{r\phi} = 5 \mu\text{m} \oplus \frac{10}{p(\text{GeV}) \sin^{3/2} \theta} \mu\text{m}$$

## Vertex detector specifications:

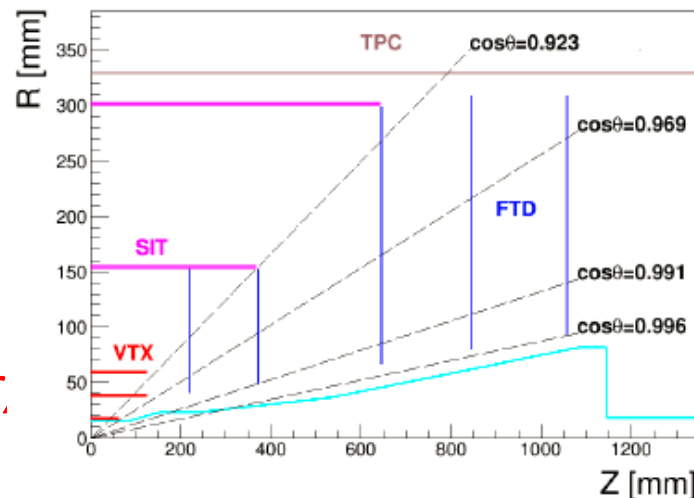
- spatial resolution near the IP:  $\leq 3 \mu\text{m}$
- material budget:  $\leq 0.15\% X_0 / \text{layer}$
- pixel occupancy:  $\leq 1 \%$
- Total ionising dose:  $\leq 1 \text{Mrad} / \text{year}$

Non-ionising fluences :  $\leq 3 \times 10^{12} n_{eq} / (\text{cm}^2 \text{yr})$

- first layer located at a radius:  $\sim 1.6 \text{cm}$

## Silicon tracker specifications:

- $\sigma_{\text{SP}} : \leq 7 \mu\text{m} \rightarrow$  small pitch (50  $\mu\text{m}$ )
- material budget:  $\leq 0.65\% X_0 / \text{layer}$



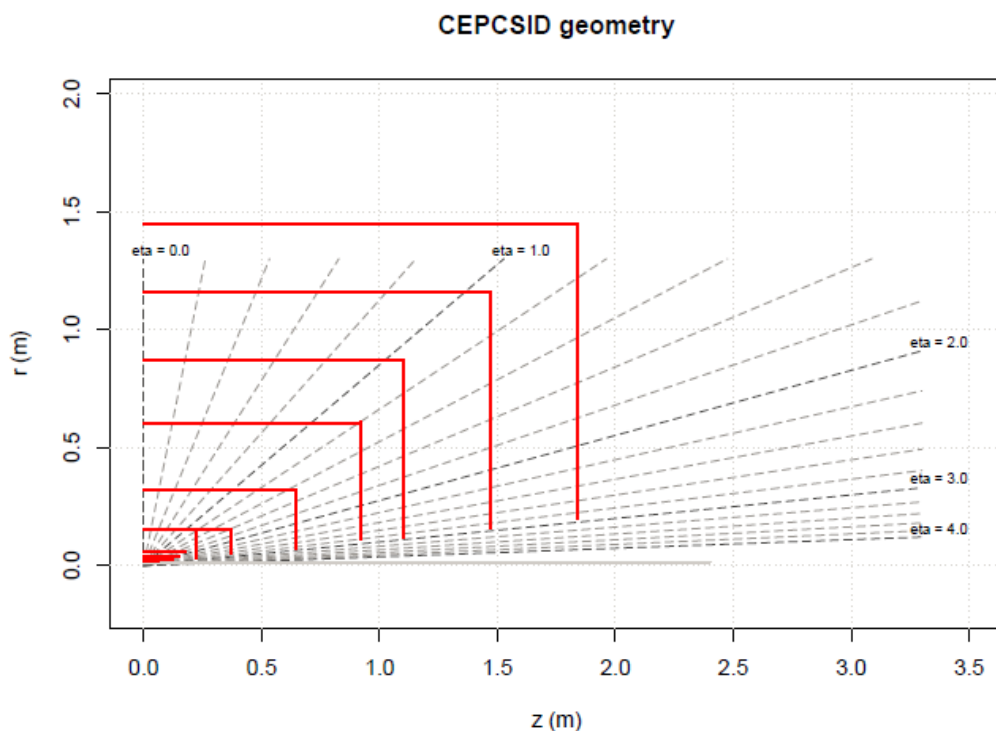
预研目标：设计高空间分辨、快读出、低功耗、抗辐照的硅像素探测器芯片

# CEPC 全硅径迹探测器：新设计

\* [http://cepc.ihep.ac.cn/cepc/cepc\\_twiki/index.php/Pure\\_Silicon\\_Detector](http://cepc.ihep.ac.cn/cepc/cepc_twiki/index.php/Pure_Silicon_Detector)

Weiming Yao (IHEP/LBNL)  
for Silicon Tracking Study Group\*

→ 根据CEPC\_V1的探测器几何设计，  
把整个TPC换成5层硅探测器结构



- 通过muon粒子模拟全硅探测器的响应，改进径迹重建模块。
- 初步研究表明单粒子性能与原有的CEPC\_V1性能相比拟，能达到预期物理目标。
- 将进一步优化硅探测器设计和径迹重建算法，有较大的性能提升空间。
- 需要综合考虑性能和造价

# CEPC 时间投影室 (TPC)

## Performance/Design Goals

Momentum resolution <sup>a</sup> at B=3.5T	$\delta(1/p_t) \simeq 10^{-4}/\text{GeV}/c$ TPC only
Solid angle coverage	Up to $\cos\theta \simeq 0.98$ (10 pad rows)
TPC material budget	$\simeq 0.05 X_0$ including the outer field cage in $r$ $< 0.25 X_0$ for readout endcaps in $z$
Number of pads/timebuckets	$\simeq 1-2 \times 10^6/1000$ per endcap
Pad pitch/no.padrows	$\simeq 1 \text{ mm} \times 4-10 \text{ mm}/\simeq 200$
$\sigma_{\text{point}}$ in $r\phi$	$< 100 \mu\text{m}$ (avg for straight-radial tracks)
$\sigma_{\text{point}}$ in $rz$	$\simeq 0.4 - 1.4 \text{ mm}$ (for zero – full drift)
2-hit resolution in $r\phi$	$\simeq 2 \text{ mm}$ (for straight-radial tracks)
2-hit resolution in $rz$	$\simeq 6 \text{ mm}$ (for straight-radial tracks)
dE/dx resolution	$\simeq 5 \%$
Performance	$> 97\%$ efficiency for TPC only ( $p_t > 1\text{GeV}/c$ ) $> 99\%$ all tracking ( $p_t > 1\text{GeV}/c$ )
Background robustness	Full efficiency with 1% occupancy,
Background safety factor	Chamber prepared for 10–20% occupancy (at the linear collider start-up, for example)

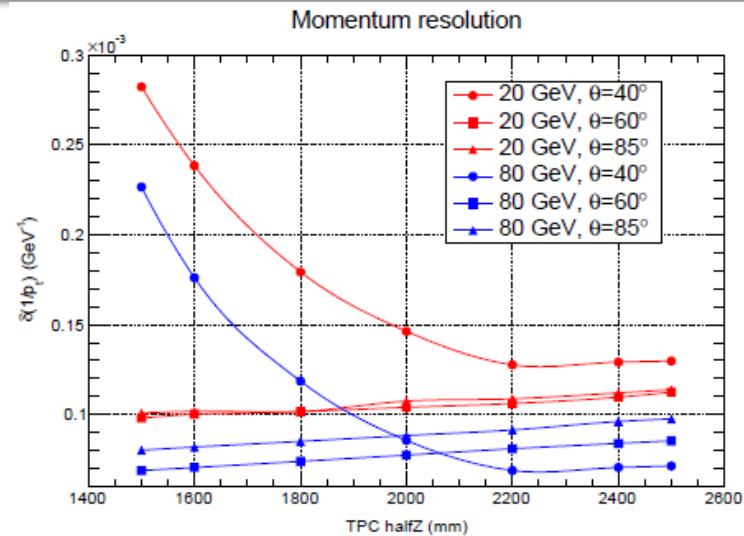
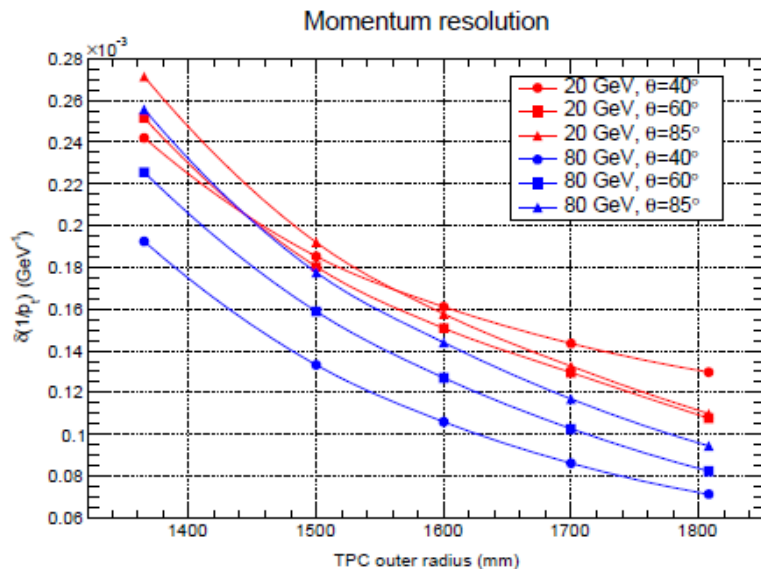
## Same as Main performance/ Design goals of ILD-TPC

<sup>a</sup>The momentum resolution for the combined central tracker is  $\delta(1/p_t) \simeq 2 \times 10^{-5}/\text{GeV}/c$

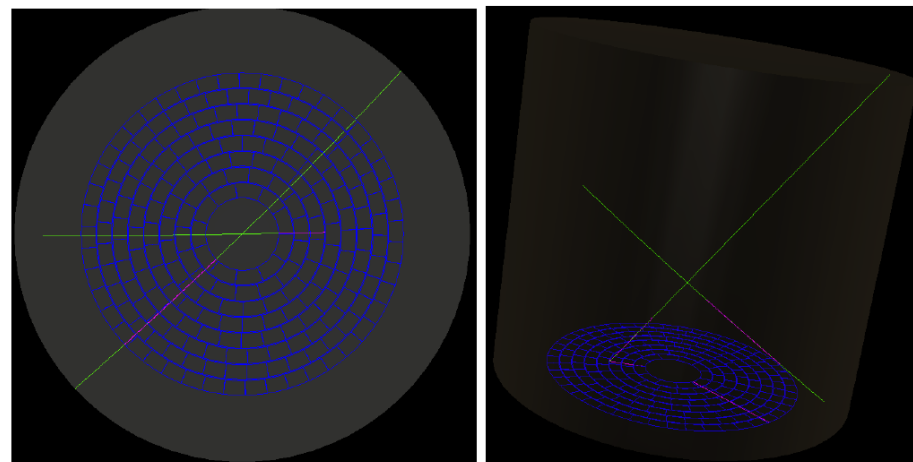
# TPC 概念设计

## Parameter of Simulation

- TPC, Half Z=2.0m
- $r_{in} = 329 \text{ mm}; r_{out} = 1808 \text{ mm}$
- $\text{Cos}(\theta) = \sim 0.95$
- pad size:  $1\text{mm} \times 6\text{mm}$
- Number of hits per track:  $\sim 200$
- $B = 3.5 \text{ Tesla, with } L^* = 1.5\text{m}$



$$e^+ e^- \rightarrow \mu^+ \mu^- \nu_e \bar{\nu}_e$$



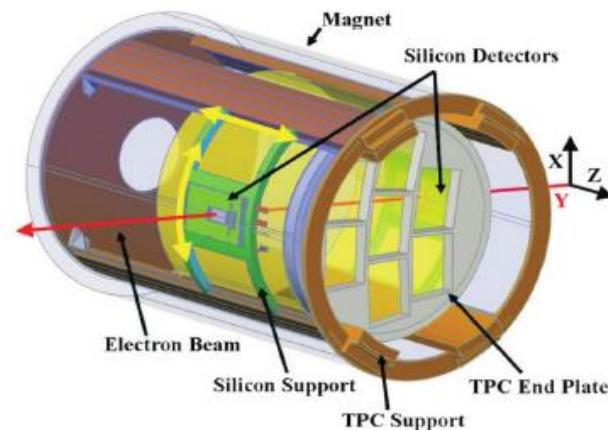
# 国际TPC探测器研究

## 国际上主要研制的探测器模块

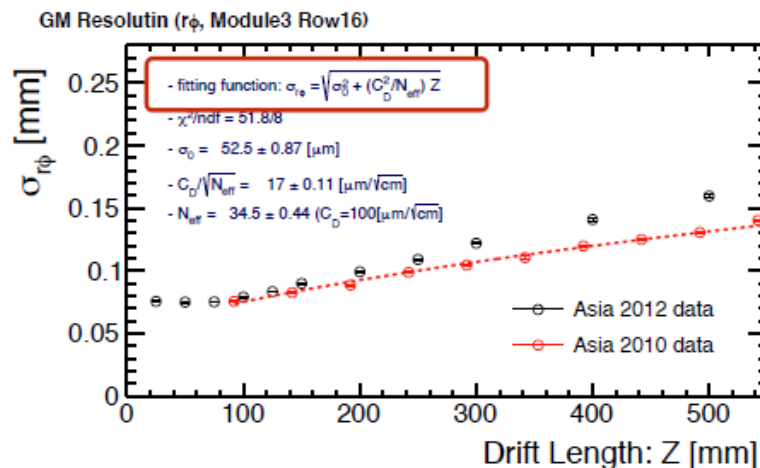
- GEM探测器模块
- 阻性/Micromegas探测器模块
- GridPix像素Micromegas模块
- 正离子门控探测器模块
- 采用AFTER/Timpeix等读出芯片

## 探测器主要指标和现在状态

- 多模块1T磁场下初步测试，单模块有效面积20cm×17cm，**状态：研制中**
- 采用门控通断电实现脉冲式直线对撞机的正离子反馈，依然在解决有效正离子“清除”同时提高电子通过率(有效电子数>30)的问题
- 采用已有芯片，功耗高，需优化及下一代读出
- 连续正离子抑制反馈研究，ALICE TPC升级选项



TPC测试模块安装示意图



KEK模块1.0T下测试结果

# 国内TPC研制（清华）

Yulan Li et.al.

- TPC cylinder length: 50 cm
- TPC Diameter = 32 cm
- Readout GEM: 100x100mm<sup>2</sup>
- 10x32 pads, staggered
  - ▣ Pad size: 9.5x1.5mm<sup>2</sup>
  - ▣ Pitch: 10 x 1.6 mm<sup>2</sup>
- Spatial resolution as a function of drift distance (B=1T)
- Best performance:  
 $\sigma_x = 100\mu\text{m} @ Z \sim 100\text{mm}$

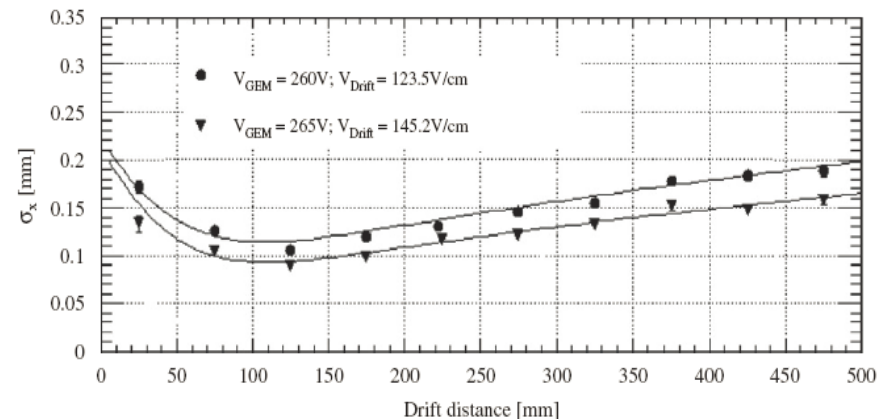


Fig. 6. x-Resolution for Ar-Iso-CF<sub>4</sub> = 96.3-3.1-0.6 gas with B = 1 T under two different test conditions ( $\varphi < 2^\circ$ ,  $\theta < 10^\circ$ ).

# TPC 关键技术难点

Huirong Qi et.al.

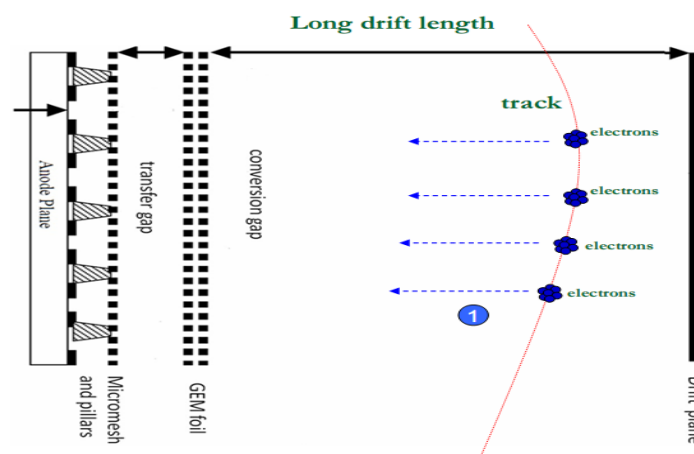
和ILC不同，CEPC 对撞频率高，探测器需要在连续状态下运行。

如何有效抑制连续正离子反馈(IBF) 是关键技术难点，解决方案有：

- GEM探测器在工作同时优化电场来实现正离子抑制
- Micromegas探测器在工作同时优化电场来实现正离子抑制
- 复合结构可叠加正离子反馈抑制能力，提高性能
- 同等增益下，降低工作高压，提高探测器性能
- 增加探测器长时间工作稳定性



Photo of the GEM+Micromegas Module with X-ray



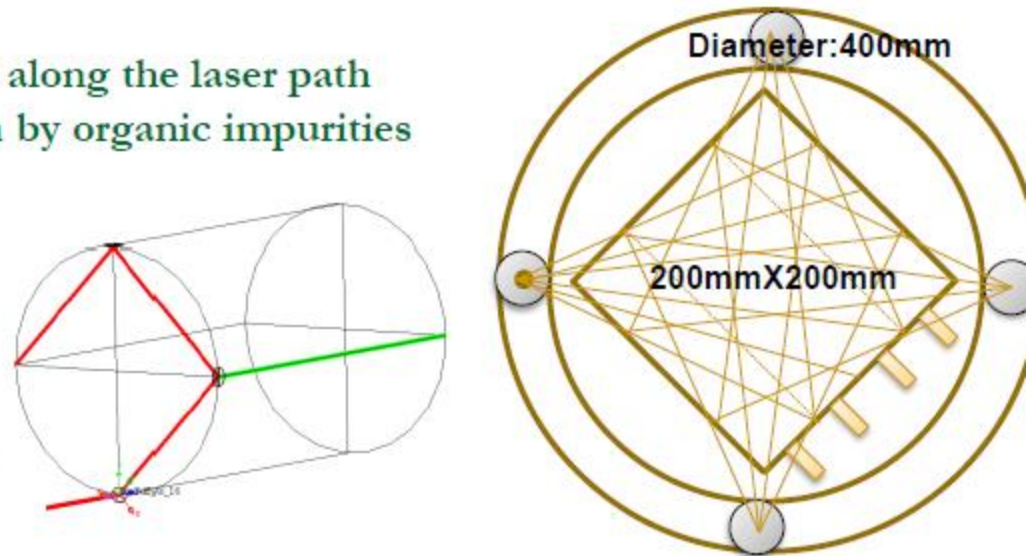
连续正离子抑制型  
探测器示意图

# Laser calibration for TPC prototype

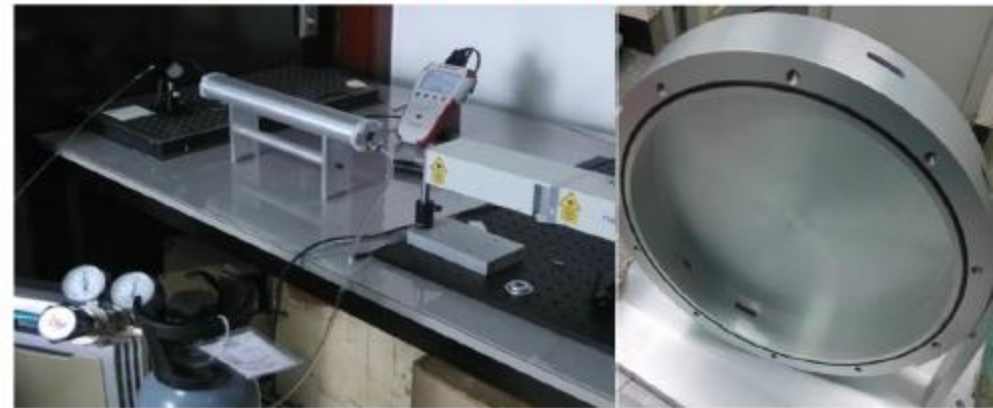
详见李玉兰报告

Supported by 国家自然科学基金重点基金

- Goals of laser for TPC detector
  - The ionization in the gas volume along the laser path occurs via two photon absorption by organic impurities
  - Drift velocity, gain uniformity
- To reduce the distortion effect
  - E×B effect study
  - Drift Velocity measurement
  - Good resolution in space and time
    - No production of  $\sigma$ -rays
    - No multiple scattering
- Baseline design (**DONE**)
  - Nd:YAG laser device
  - $\lambda = 266 \text{ nm}$  or  $E = h\nu = 4.66 \text{ eV}$
  - Energy:  $\sim 100 \text{ uJ/pulse}$
  - Duration of pulse: 5 ns
  - Active area:  $200\text{mm} \times 200\text{mm}$
  - Drift length: 500mm
  - Outer diameter:  $\sim 400\text{mm}$
  - GEM readout



Laser calibration baseline design



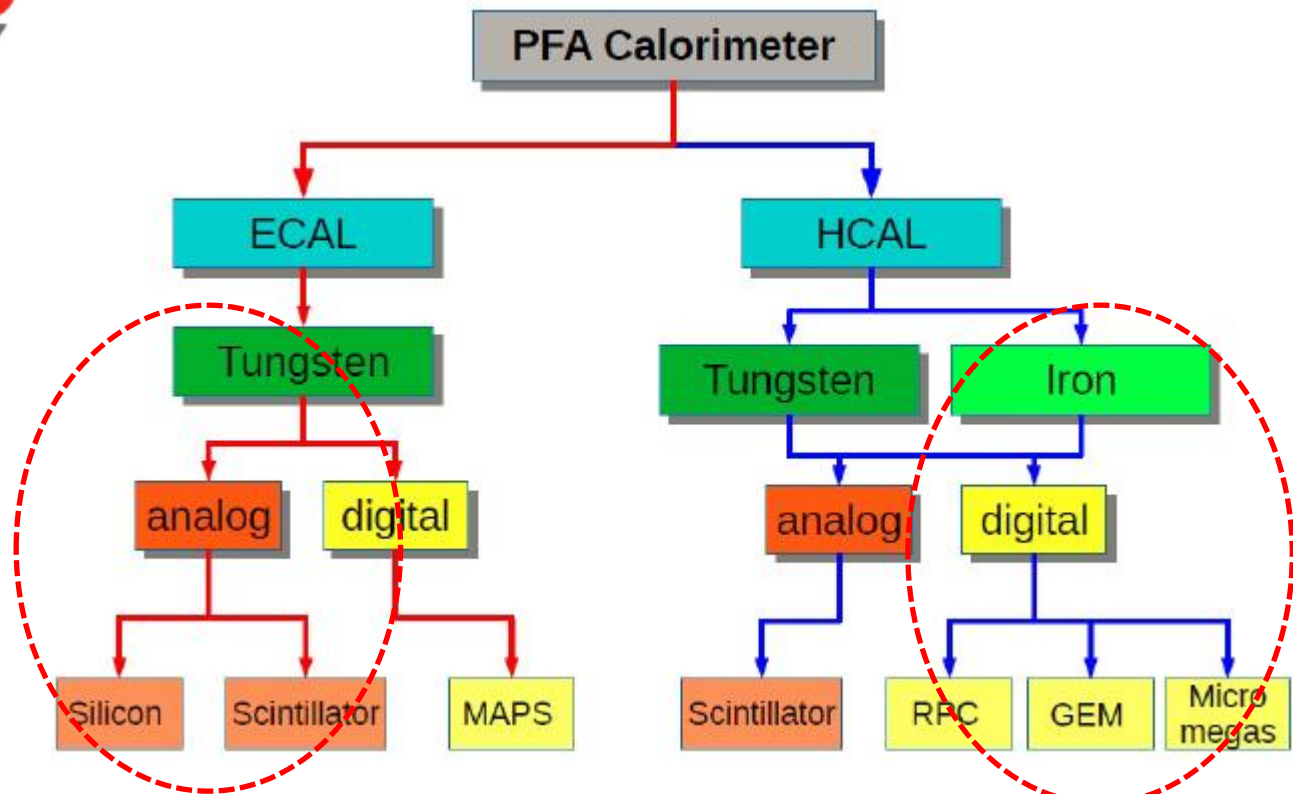
The assembled module test with 266nm laser



# CALICE: 成像型量能器



<https://twiki.cern.ch/twiki/bin/view/CALICE/CalicePapers>



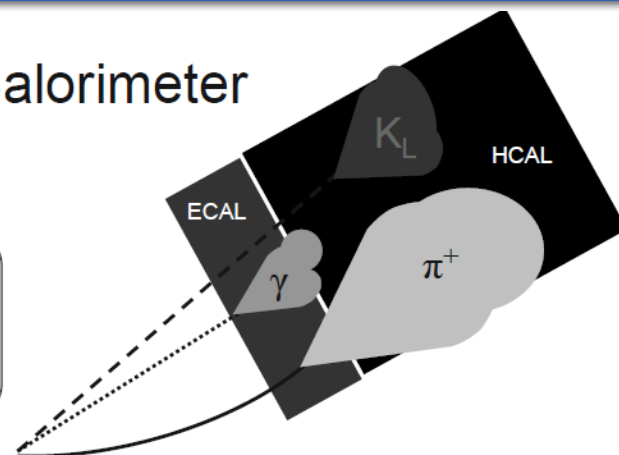
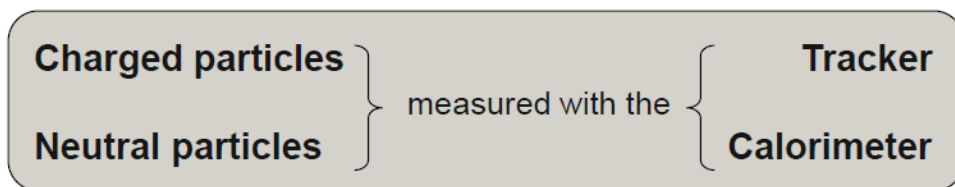
**Readout cell size:**  $144 - 9 \text{ cm}^2 \rightarrow 4.5 \text{ cm}^2 \rightarrow 1 \text{ cm}^2 \rightarrow 0.25 \text{ cm}^2 \rightarrow 0.13 \text{ cm}^2 \rightarrow 2.5 \times 10^{-5} \text{ cm}^2$

**Technology:** Scintillator + SiPM/MPPC    Scintillator + SiPM/MPPC    Gas detectors Silicon    Silicon    Silicon    Silicon (MAPS)

# 基于粒子流算法的成像量能器原理

## Particle Flow Algorithms and Imaging Calorimeter

The idea...

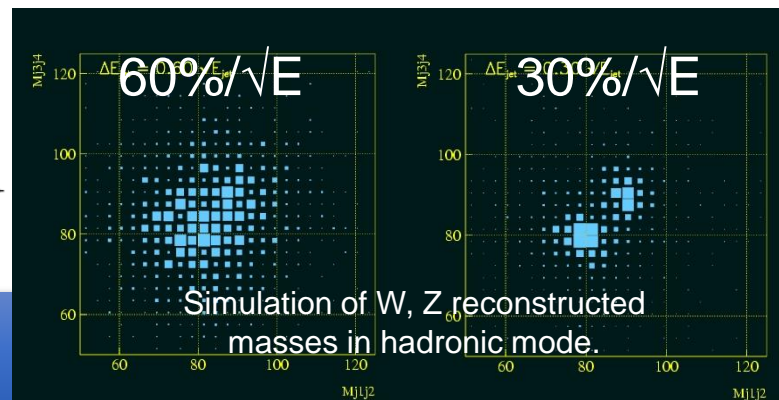


Particles in jets	Fraction of energy	Measured with	Resolution [ $\sigma^2$ ]
Charged	65 %	Tracker	Negligible
Photons	25 %	ECAL with $15\%/\sqrt{E}$	$0.07^2 E_{\text{jet}}$
Neutral Hadrons	10 %	ECAL + HCAL with $50\%/\sqrt{E}$	$0.16^2 E_{\text{jet}}$
Confusion		Required for $30\%/\sqrt{E}$	$\leq 0.24^2 E_{\text{jet}}$

}  $18\%/\sqrt{E}$

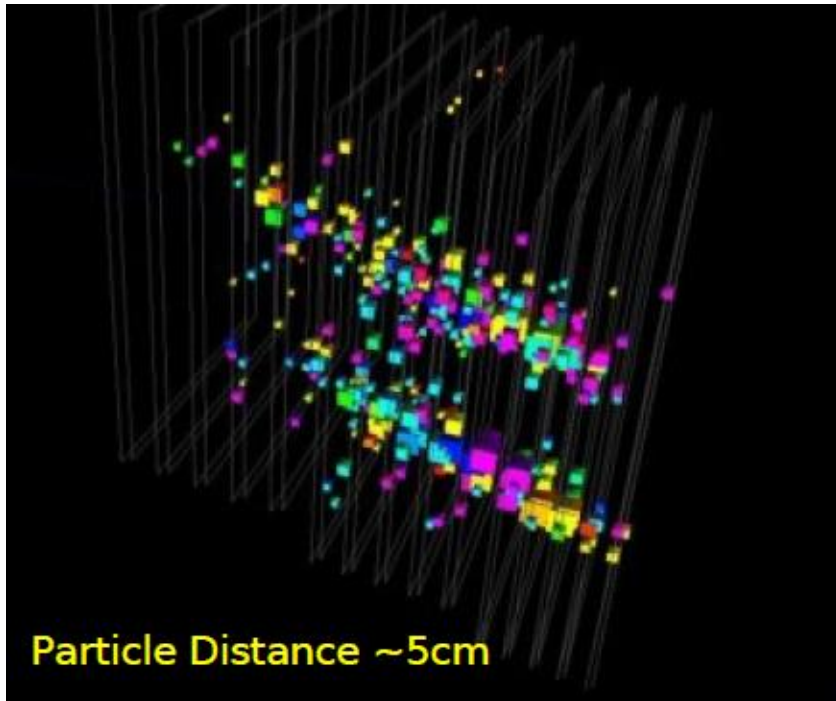
### Requirements for detector system

- Need excellent tracker and high B – field
- Large  $R_1$  of calorimeter
- Calorimeter inside coil
- Calorimeter as dense as possible (short  $X_0$ ,  $\lambda_I$ )
- Calorimeter with **extremely fine segmentation**

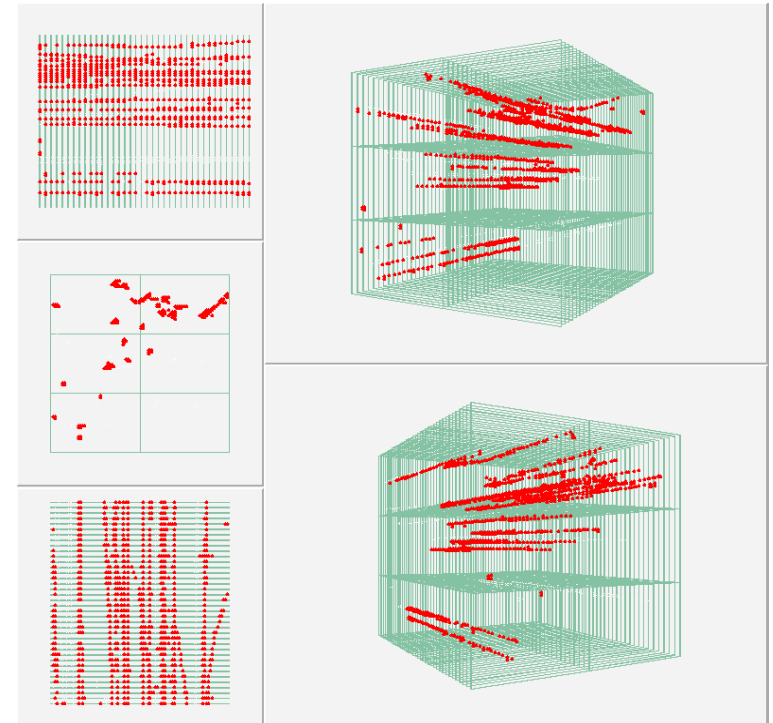


# 成像型量能器

L. Xia @ ANL



Two electrons ~5cm apart  
**SiW ECAL (电磁量能器)**



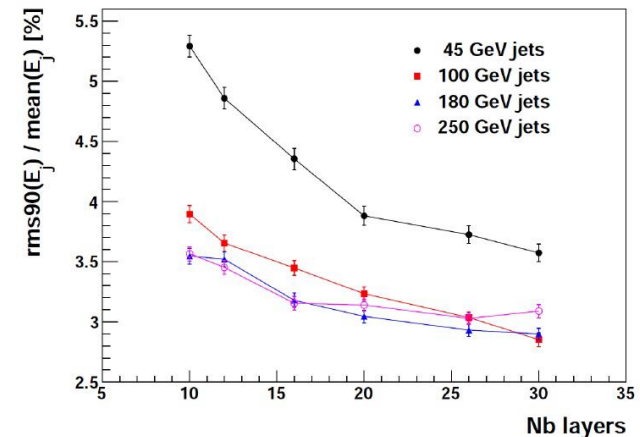
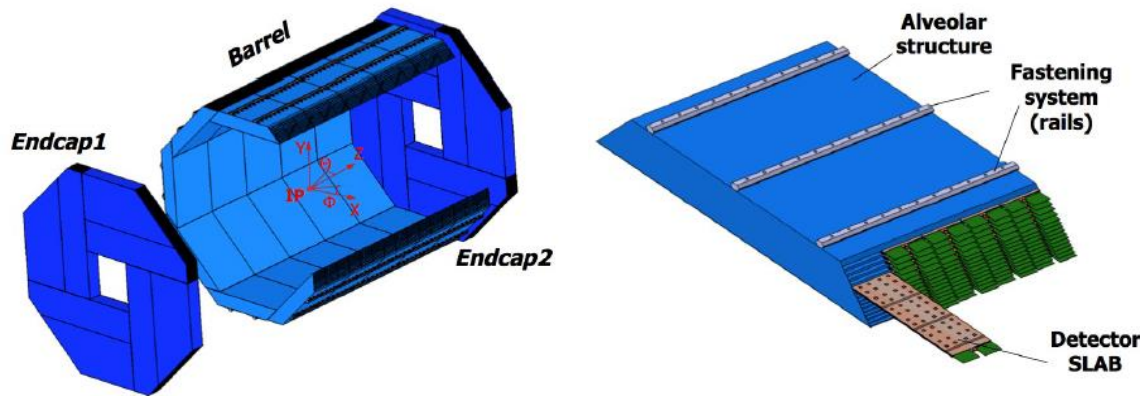
~20 muons in 1m<sup>2</sup> area  
**RPC DHCAL (强子量能器)**

➔ 为了提升喷注的能量和位置分辨，粒子流算法需要量能器有能力把喷注内部各簇射单元很好的区分开来。

# 电磁量能器 ECAL: Silicon-W

V. Boudry @ IN2P3

- The ECAL consists of a cylindrical barrel system and two large endcaps
  - Barrel: 5 octant wheels
  - Endcap: 4 quarters
- Two detector active sensors interleaved with tungsten absorber
  - silicon pixel  $5 \times 5 \text{ mm}^2$  with  $725 \mu\text{m}$  in thickness
  - PCB with VFE ASIC



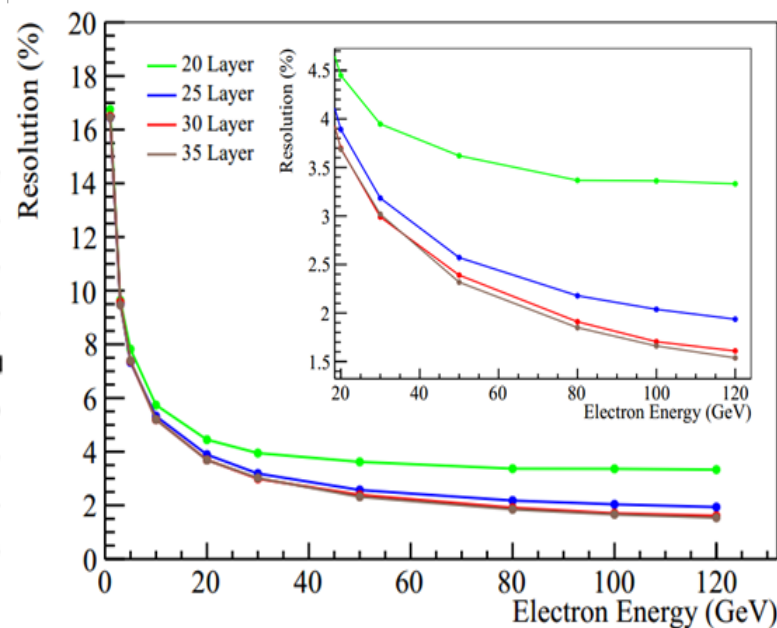
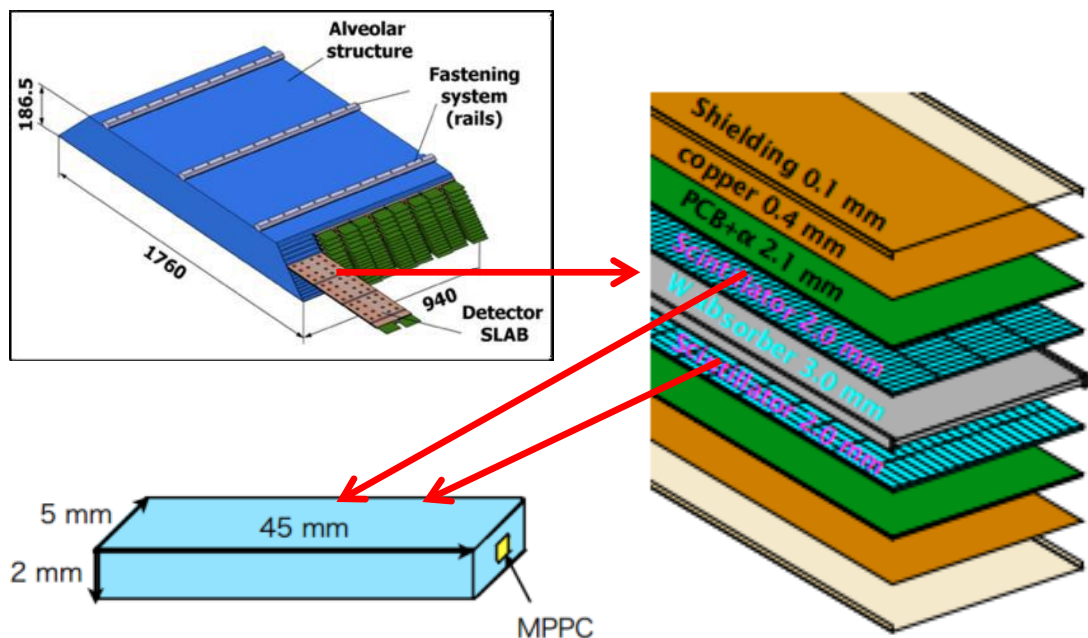
自支撑三明治结构: Silicon + W + Silicon

# 电磁量能器 ECAL: Scintillator-W

Zhigang Wang et.al.

A super-layer (7mm) is made of:

- Plastic scintillator (2mm) + Tungsten plate as absorber (3mm thick)
- A readout/service layer (2mm thick)



Scintillator + W + Scintillator

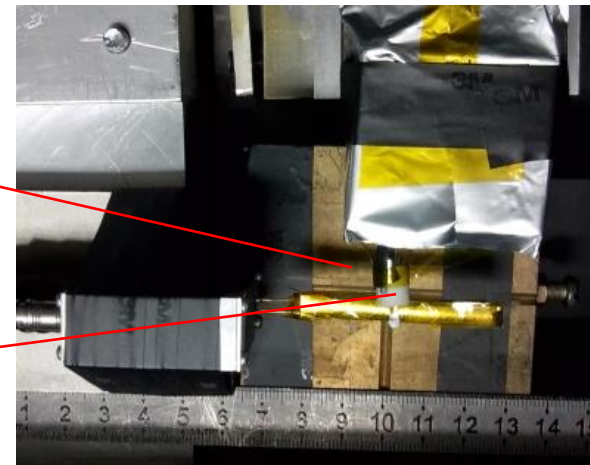
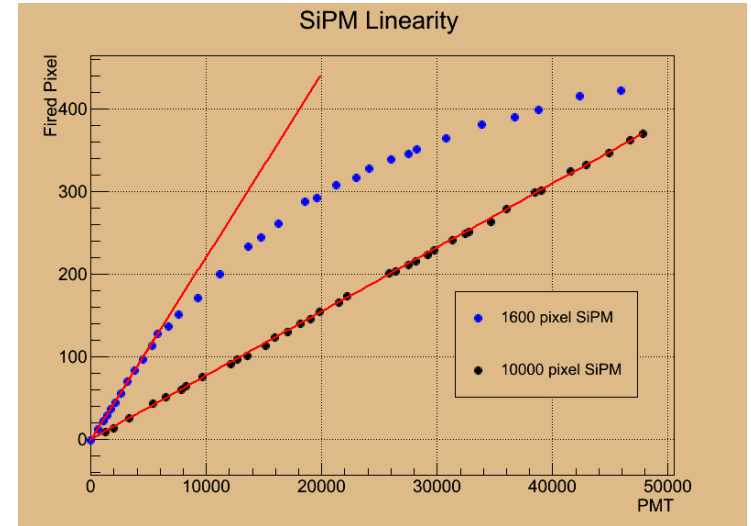
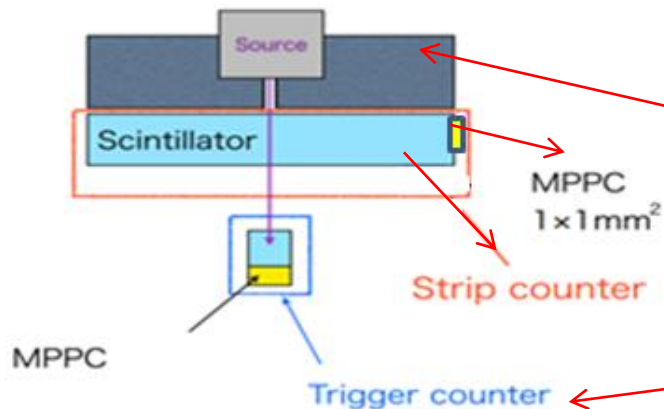
- The energy resolution of 25GeV electron is about 3.3% (cf. CALICE TB results)
- To achieve required energy resolution, the number of layers should be ~ 25.

# SiPM 性能测试 (IHEP, USTC)

→ SiPM 动态范围依赖于像素点数目，  
像素点越多，线性范围越大！

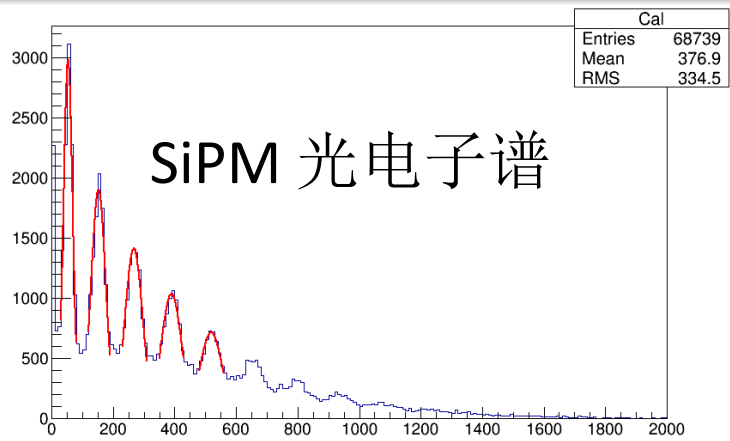
→ 光子探测效率：SiPM (10微米)探测效率  
只有SiPM (25微米)的三分之一！

Scintillator strip irradiated with  $\beta$   
collimated (1mm) from 铯Sr-90

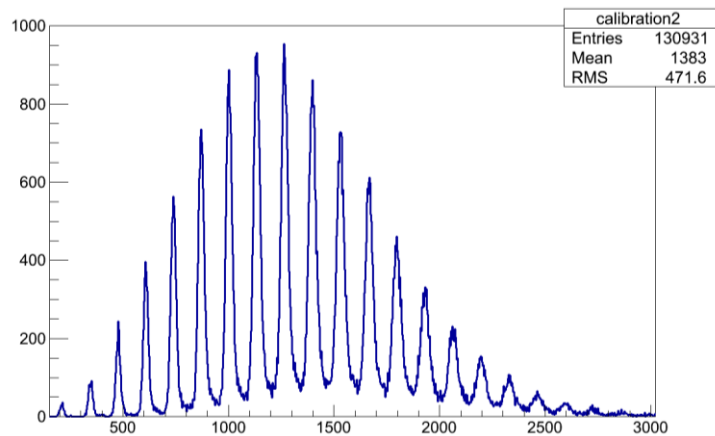


# SiPM 性能测试 (IHEP, USTC)

Z.G. Wang, Y.L. Zhang et.al.

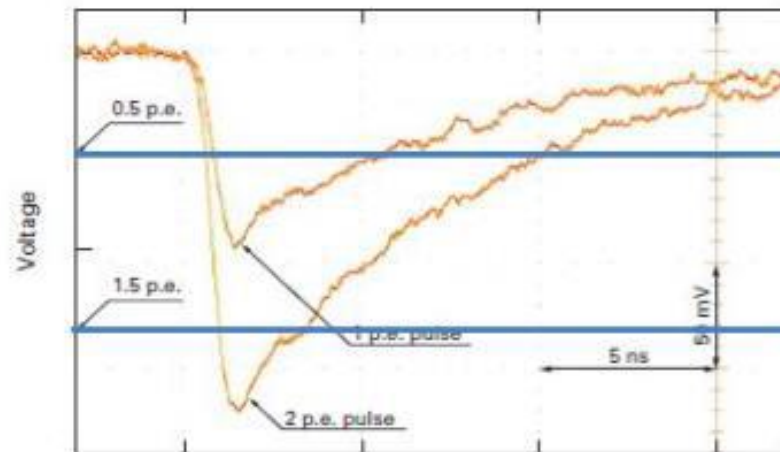


SiPM 光电子谱

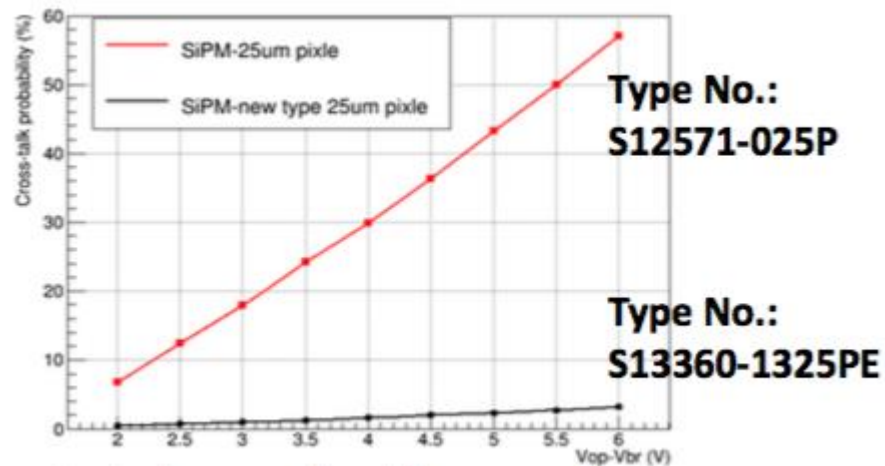


脉冲谱

光子计数效果良好!



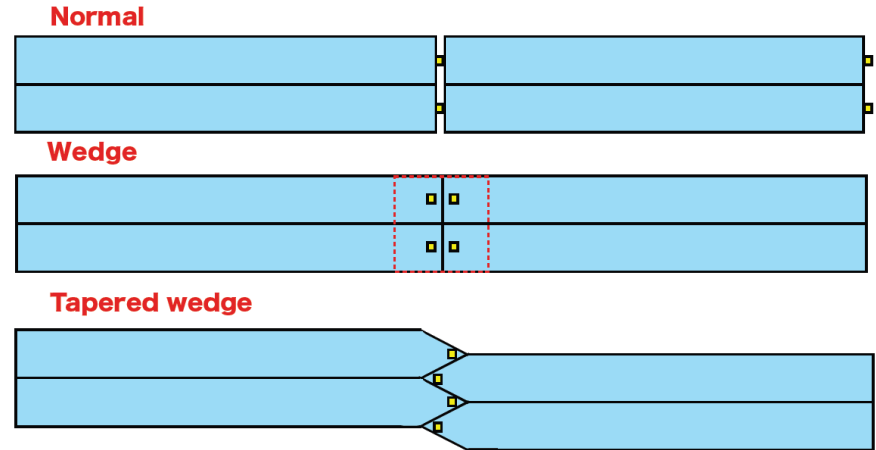
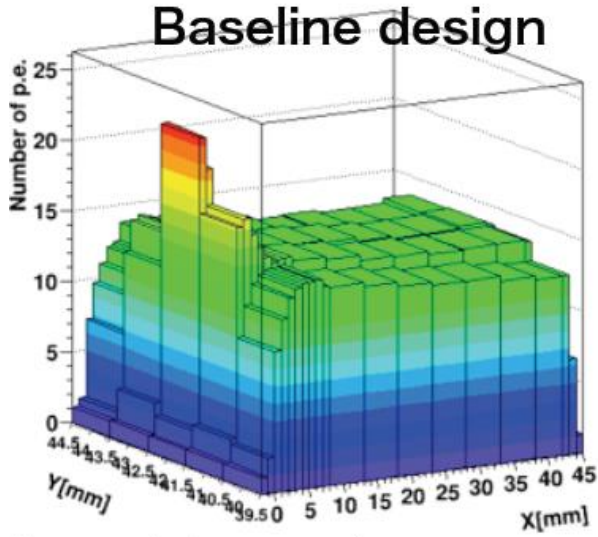
Cross talk rate = Events (> 1.5p.e)/Events (>0.5p.e)



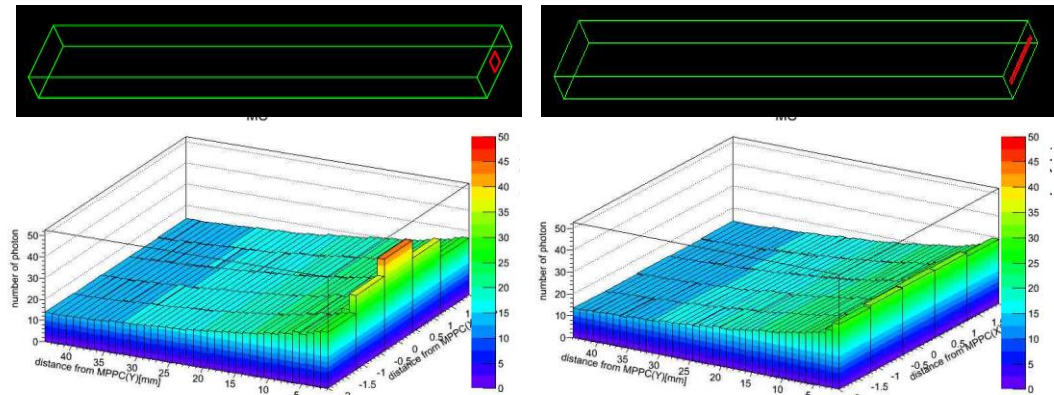
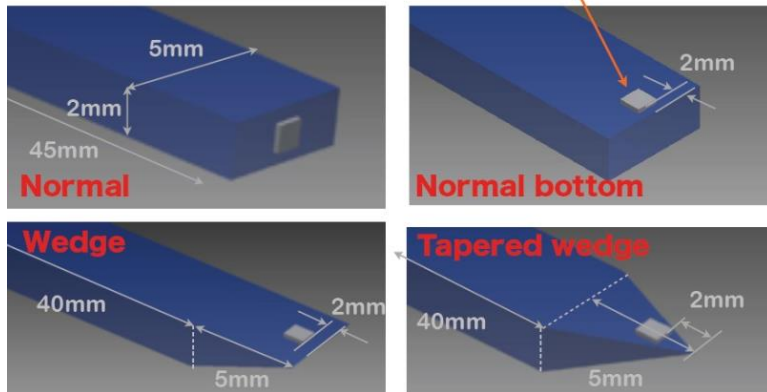
# 塑料闪烁体结构优化

Z.G. Wang et.al.

正在通过模拟和测试优化塑料闪烁体的几何结构和连接方式，提高信号读出的均匀性！



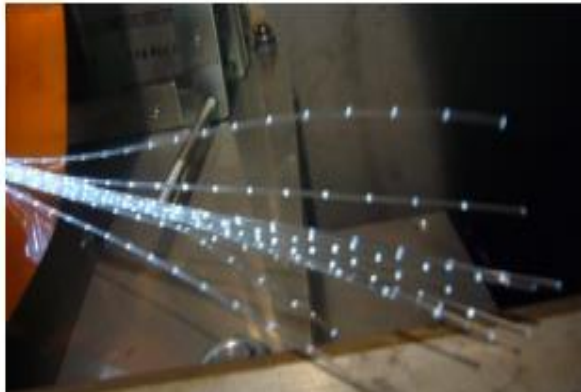
SiPM area:  $1 \times 1 \text{ mm}^2 \rightarrow 0.25 \times 4 \text{ mm}^2$ :





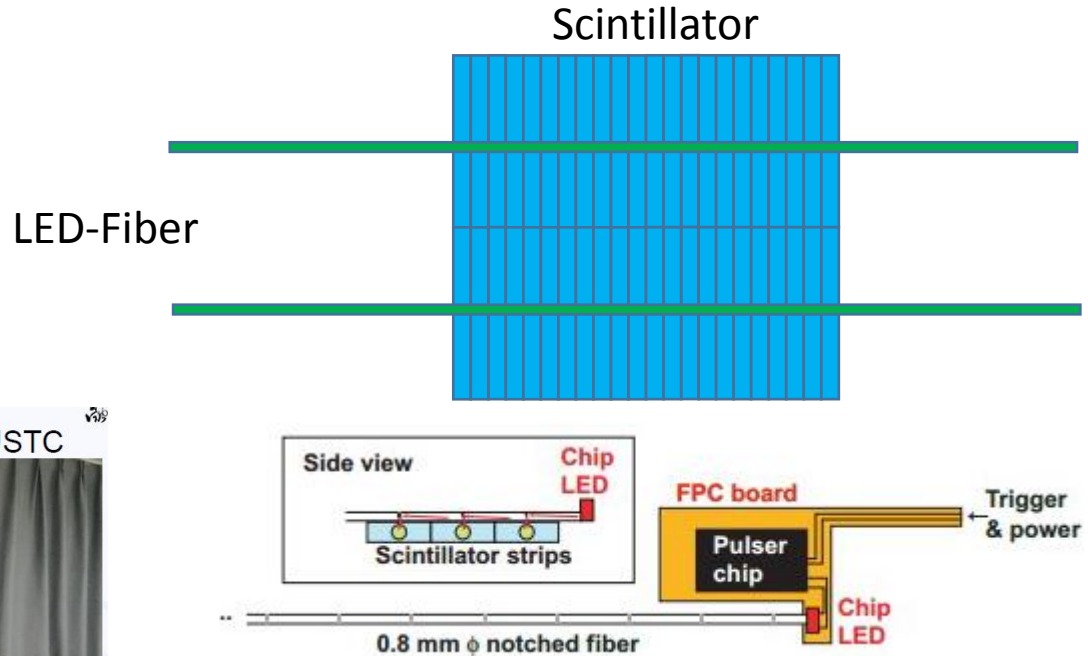
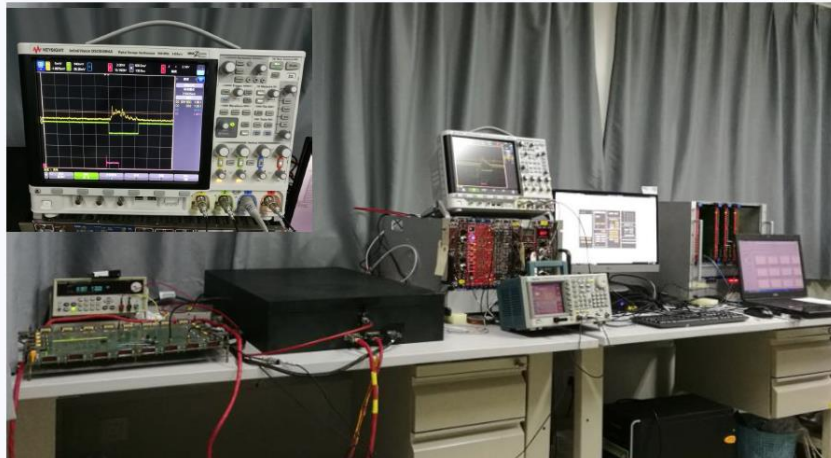
# 塑料闪烁体刻度系统

ECAL塑料闪烁体大约由800万闪烁条组成，需要对其光输出进行监测。  
正在研究光路分配系统，通过监测光电子谱的峰研究SiPM增益的变化！



LED calibration system

USTC



## LED – 光纤刻度系统:

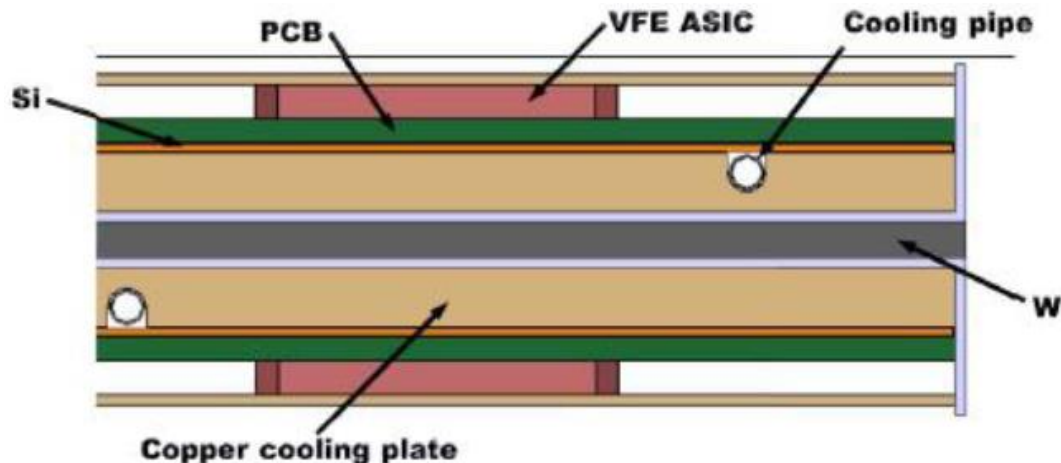
- 脉冲产生器，芯片LED 光导入带孔的光纤
- 带孔光纤把光传递到一组塑料闪烁条

# 主动制冷系统

- CEPC 束流对撞频率:  $2.8 \times 10^5$  Hz (3.6微秒), 探测器处于连续工作模式, 无法像ILC(约152微秒)探测器采取脉冲供电(Power pulsing)。
- 与ILC相比, CEPC探测器的前端电子学功耗大约高两个数量级, 因此需要考虑主动制冷系统(active cooling)。
  - Evaporative CO<sub>2</sub> cooling in thin pipes embedded in Copper exchange plate.
  - For CMS-HGCAL design: heat extraction of 33 mW/cm<sup>2</sup>, allows operation with  $6 \times 6$  mm<sup>2</sup> pixels with a safety margin of 2

➔ Transverse view of the slab with one absorber and two active layers.

➔ The silicon sensors are glued to PCB with VFE chips, cooled by the copper plates with CO<sub>2</sub> cooling pipes.



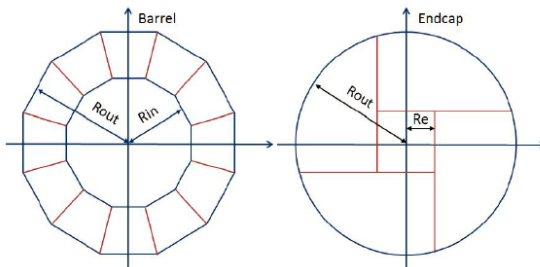
# CEPC 强子量能器

- The HCAL consists of
  - a cylindrical barrel system: 12 modules
  - two endcaps: 4 quarters
- Absorber: Stainless steel

- ❑ Active sensor
  - Glass RPC
  - Thick GEM or GEM
- ❑ Readout (  $1 \times 1 \text{ cm}^2$  )
  - Digital ( 1 threshold)
  - Semi-digital ( 3 thresholds)

## CEPC DHCAL OPTIMIZATION

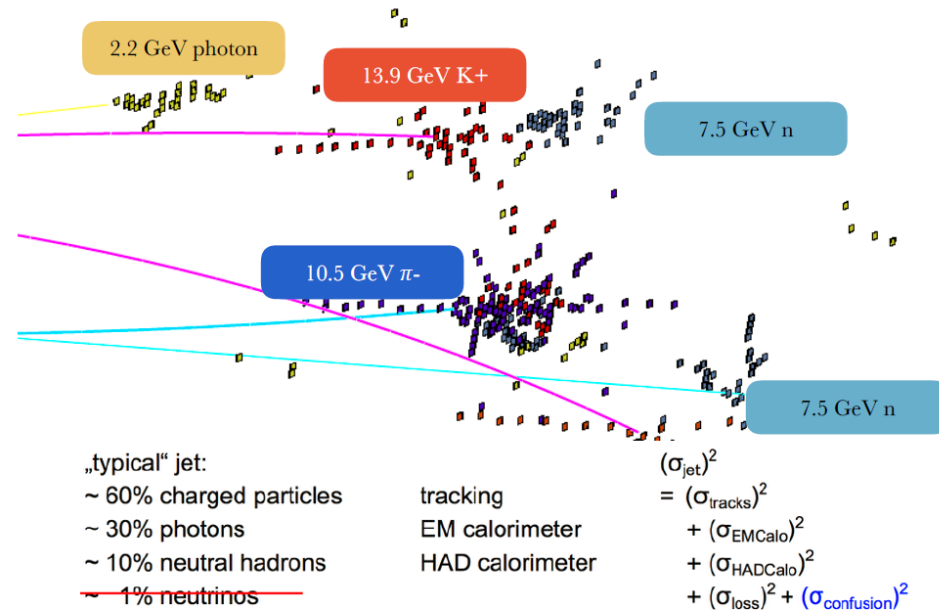
- To full fill the requirements of CEPC PFA, the DHCAL is optimized by the following:
  - layers of DHCAL, scanned from 20 layers to 48 layers.
  - size of each cell, scanned from 10 mm to 80 mm.
  - digitization (Q spectrum, spatial resolution, semi-Digi, etc..)



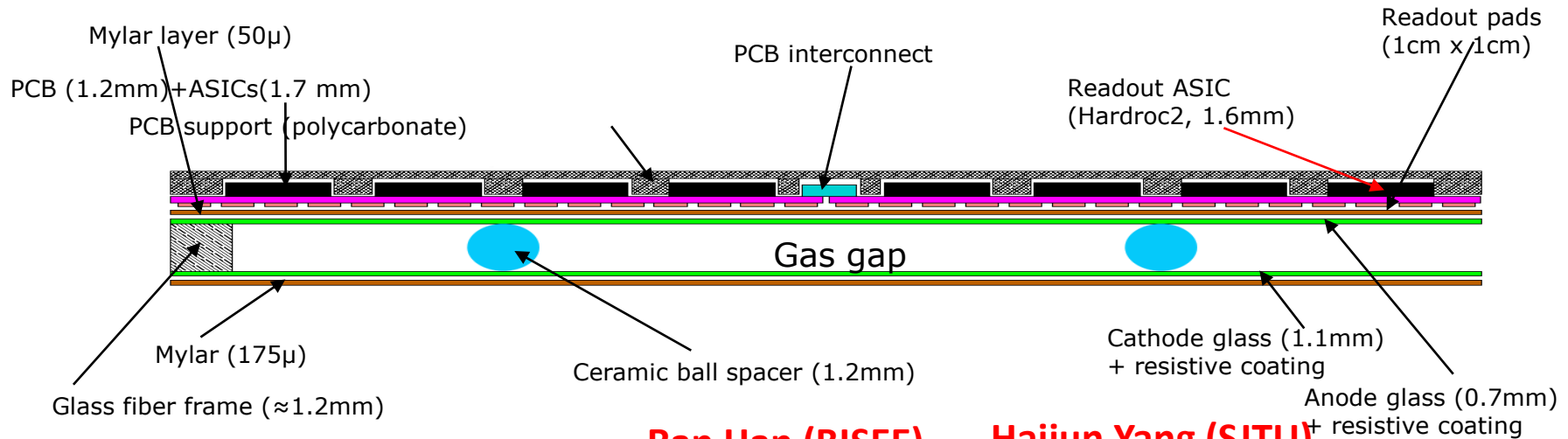
- The HCAL consists of
  - a cylindrical barrel system: 12 modules
  - two endcaps: 4 quarters
- Absorber: Stainless steel

## SIMULATION - PRELIMINARY

By Shi CHEN (UCAS)



# RPC 制作和性能

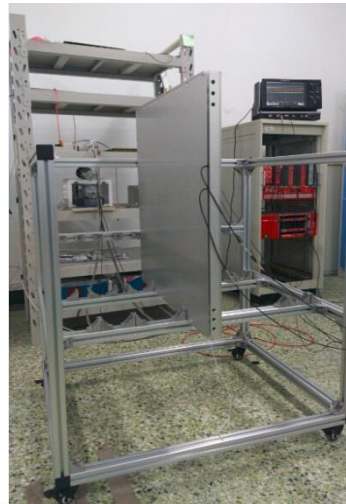


Ran Han (BISEE)

Haijun Yang (SJTU)

## 大面积玻璃RPC特点:

- ✓ Negligible dead zone (tiny ceramic spacers)
- ✓ Large size: 1 × 1 m<sup>2</sup>
- ✓ Cost effective
- ✓ Efficient gas distribution system
- ✓ Homogenous resistive coating



# RPC电子学读出系统

Imad Laktineh (IPNL)

## ASICs : HARDROC2

64 channels

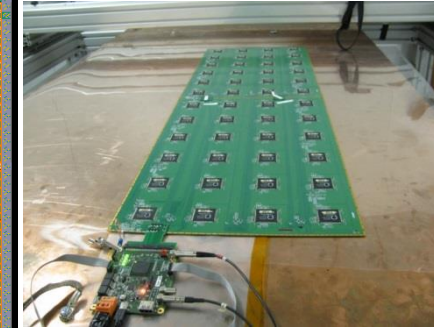
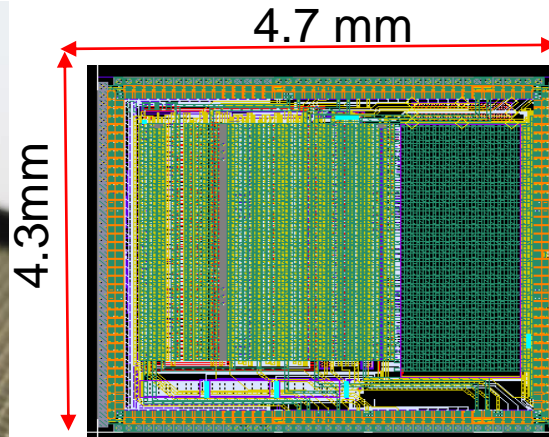
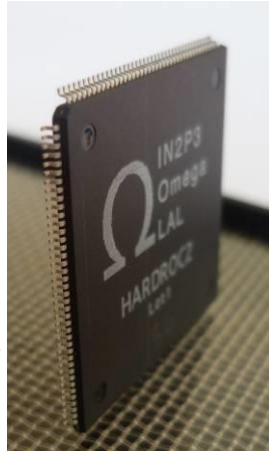
Trigger less mode

Memory depth : 127 events

### 3 thresholds

Range: 10 fC-15 pC

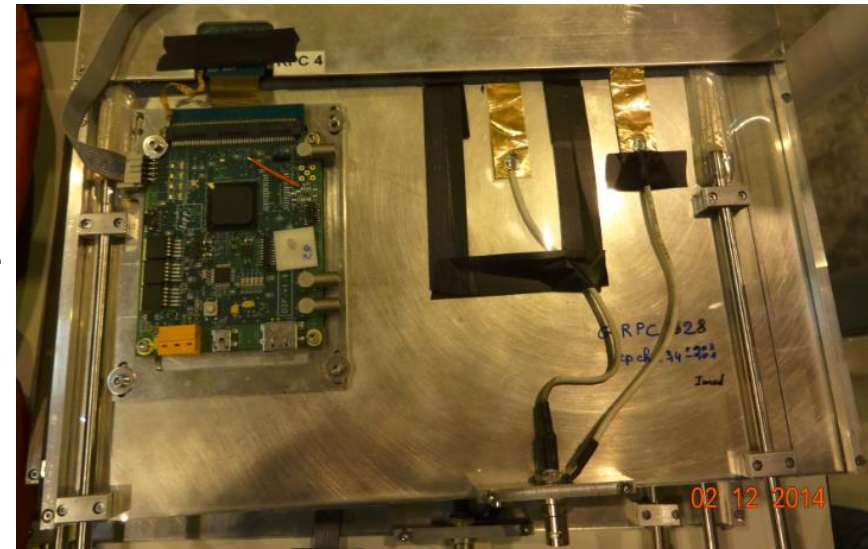
Gain correction → uniformity



**Printed Circuit Boards (PCB)** were designed to reduce the cross-talk with 8-layer structure and buried vias.

Tiny connectors were used to connect the PCB two by two so the 24X2 ASICs are daisy-chained. 1×1m<sup>2</sup> has 6 PCBs and 9216 pads.

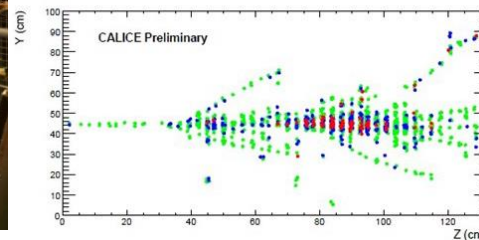
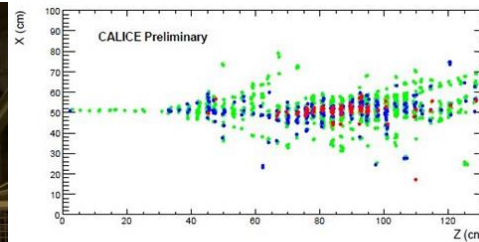
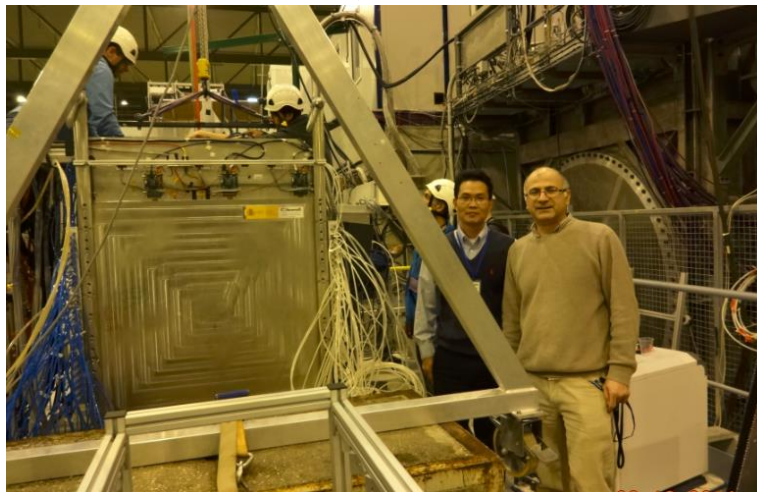
DAQ board (DIF) was developed to transmit fast commands and data to/from ASICs.



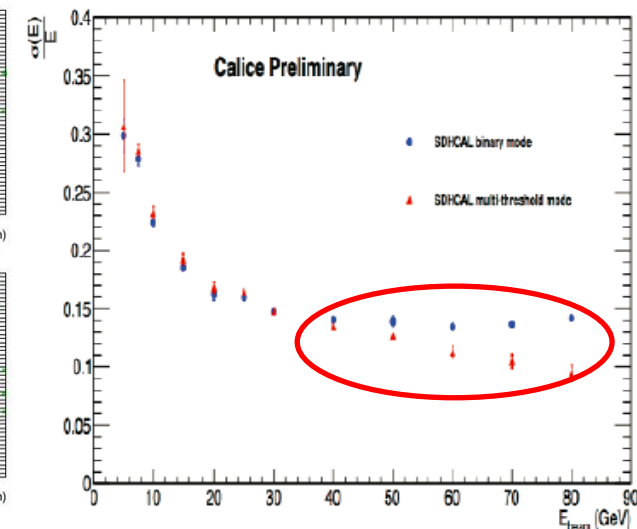
# DHCAL with RPC 原理样机

## Prototypes of DHCAL based on RPC

- ANL (J. Repond, L. Xia et.al.)  
1m<sup>3</sup>, 1 threshold, TB at CERN/Fermilab
- IPNL (I. Laktineh, R. Han, B. Liu et.al.)  
1m<sup>3</sup>, 3 thresholds, TB at CERN since 2012



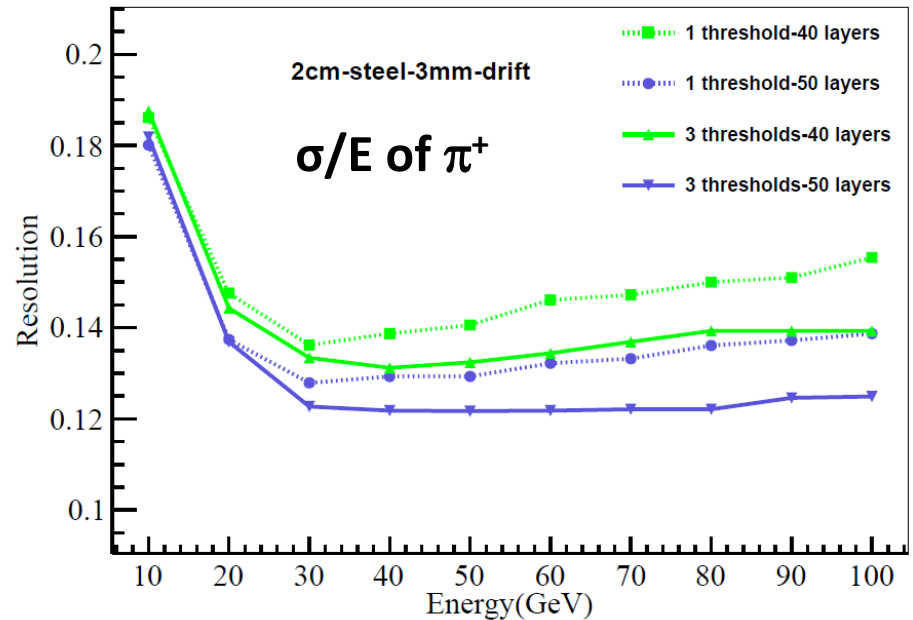
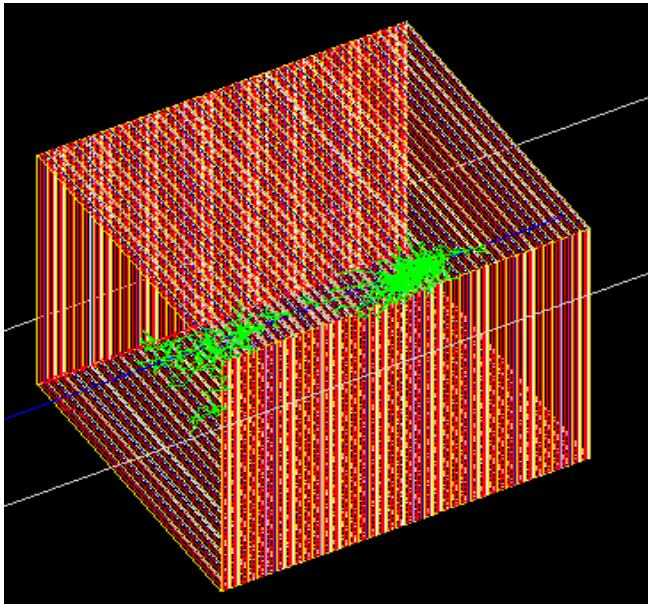
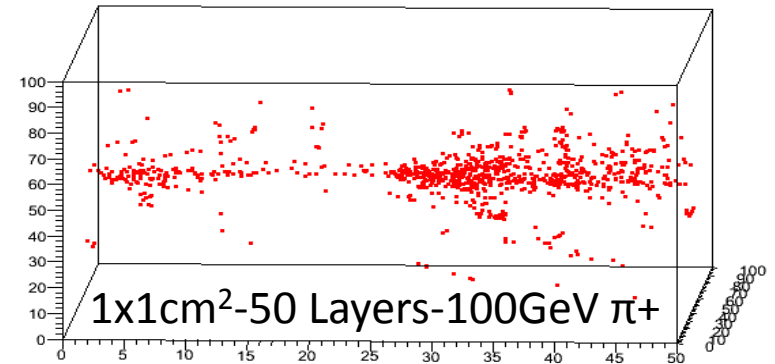
80 GeV Pion



# DHCAL Simulation

Boxiang Yu (IHEP)

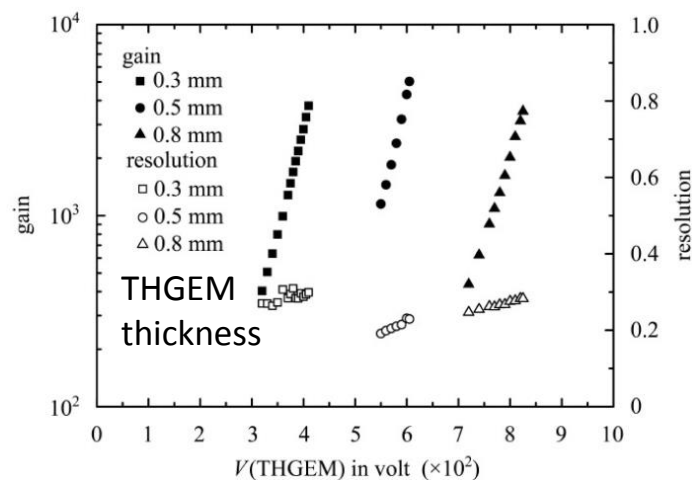
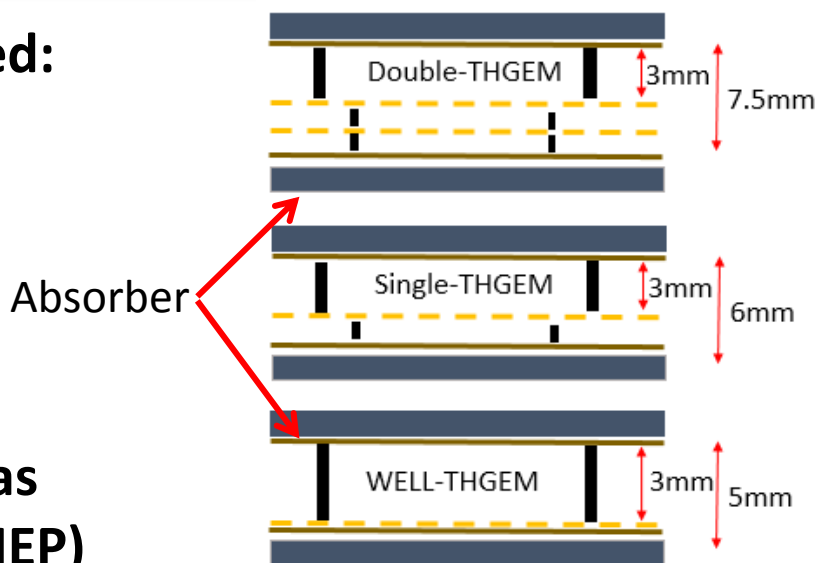
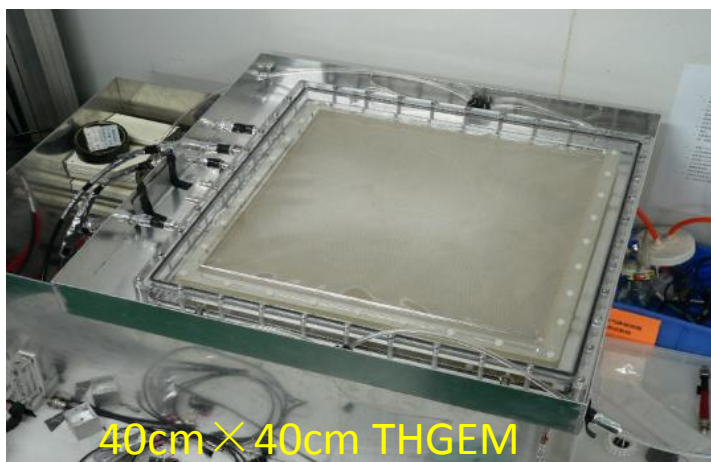
- Absorber: 2cm stainless steel
- Drift gap: 3mm
- No. of layers: 40, 50
- Ecell = 1, 5 and 10MIP if the charge is above the thresholds typically placed at 0.1, 1.5 and 2.5 MIPs



# DHCAL based on THGEM

Boxiang Yu (IHEP)

- Three THGEM options are explored:
  - Double - THGEM
  - Single - THGEM
  - WELL - THGEM
- WELL-THGEM is optimal choice  
Thinner, lower discharge
- $40 \times 40 \text{ cm}^2$  of THGEM (below) was produced in China (UCAS, GXU, IHEP)

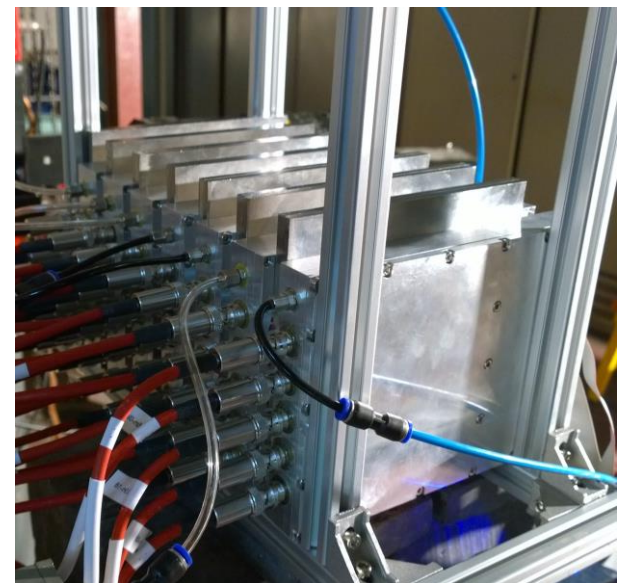
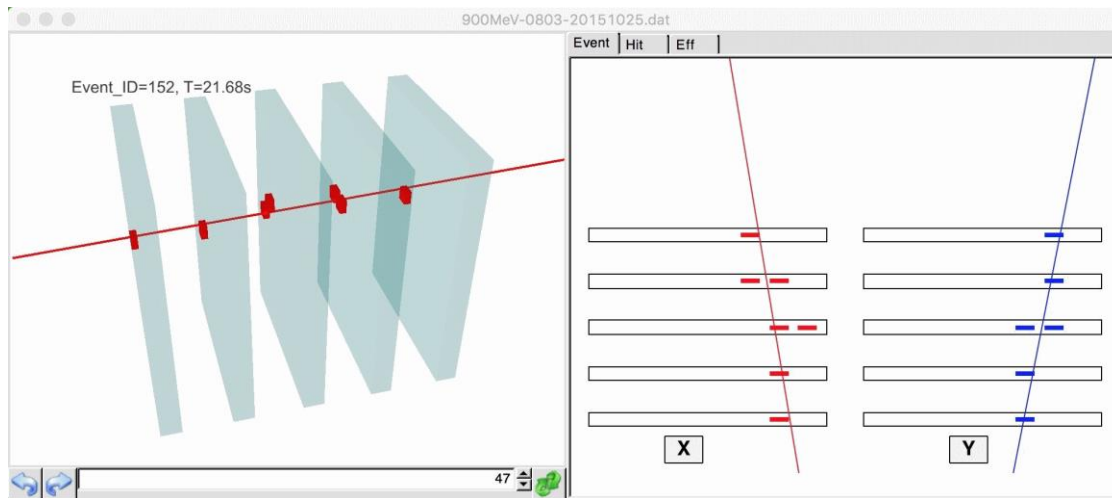
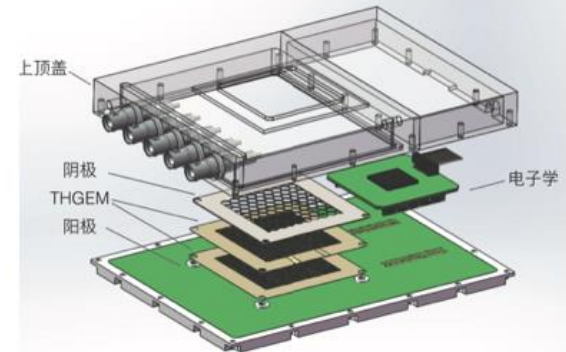




# WELL-THGEM Beam Test @ IHEP

- 7 THGEMs were installed, and 5 of them were used, and flushed with Ar/iso-butane = 97:3.
- 1 threshold, binary readout
- 900 MeV proton beam was used
- 5cm x 5cm sensitive region

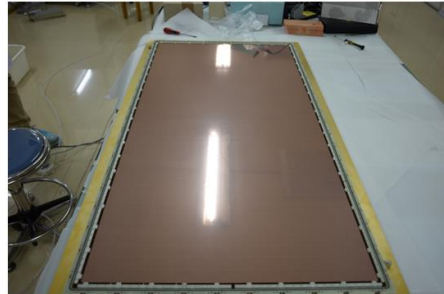
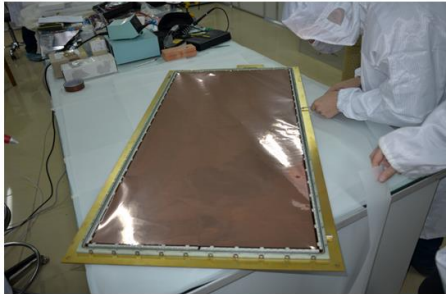
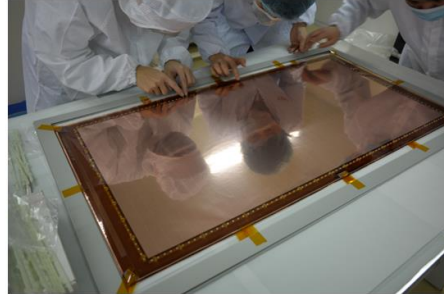
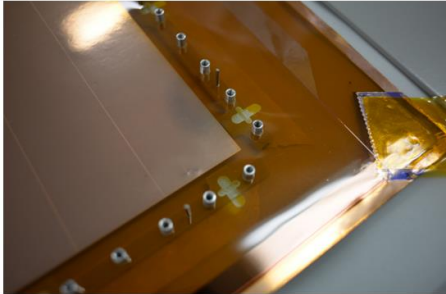
Hongbang Liu, Qian Liu (UCAS)



# Large-area GEM @ USTC

Jianbei Liu (USTC)

## GEM assembly using a novel self-stretching technique



- Large-area GEM ( $0.5 \times 1 \text{m}^2$ ) is one of main detector R&D focuses at USTC recently.
- Technology has been developed and matured to produce high-quality GEM detectors as large as  $\sim 1 \text{m}^2$  that are also applicable to CEPC DHCAL.

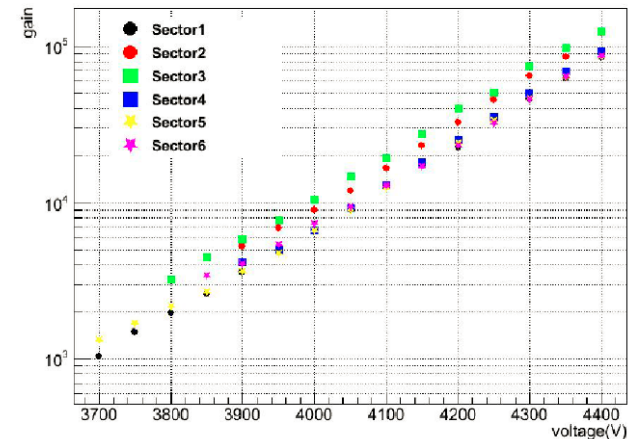
## APV25 GEM readout



## INFN APV25 chip



## Sector1~6



- ➔ Resolution uniformity  $\sim 11\%$
- ➔ Gain uniformity  $\sim 16\%$
- ➔ Can reach gain of  $10^4$  at 4000V

# Muon System (MPGD-微结构气体探测器)

Paolo Giacomelli (INFN, Bologna)



## Detectors for CEPC and SppC

- Detectors for CEPC could be built right now. They can be thought as developments of the LEP detectors, like the ILD and SID detectors for ILC
- Detectors for SppC are much more challenging and will require extensive R&D before being realised.
  - R&D for HL-LHC is a good starting point, but technologies will have to be pushed even further for SppC (and FCC-hh)
- In both cases muon detectors will be extremely large and will cover  $\sim 10000 \text{ m}^2$  in the barrel and  $3\text{-}5000 \text{ m}^2$  in the forward region
- Micro Pattern Gas Detectors (MPGD) could be used now to build a muon system for CEPC, and, with a significant R&D, should be able to cope with the harsher conditions of SppC.

Muon systems for CEPC-SppC will be very large:

Considering a large solenoid (similar order of magnitudes in other cases as well)

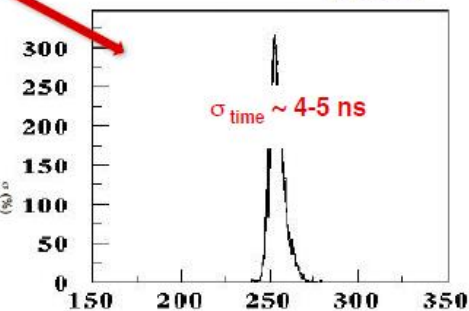
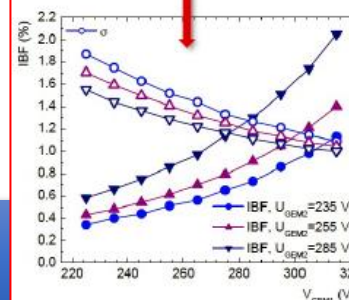
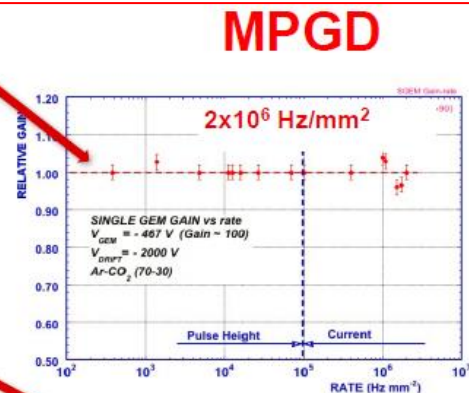
- ✓  $\sim 10000 \text{ m}^2$  in the barrel
- ✓  $\sim 3000 \text{ m}^2$  in the endcap
- ✓  $\sim 300 \text{ m}^2$  in the very forward



➤ Many technologies

- GEMs
- THGEMs
- MicroMegas
- $\mu$ Rwell

- ✓ High rate capability
- ✓ Excellent radiation hardness
- ✓ Large active areas / industrial production
- ✓ Good timing resolution
- ✓ Ion backflow/photon feedback reduction



# CEPC Muon System (RPC or Sct.)

Y.G. Xie(IHEP), L. Li(SJTU)

## Functions of muon system

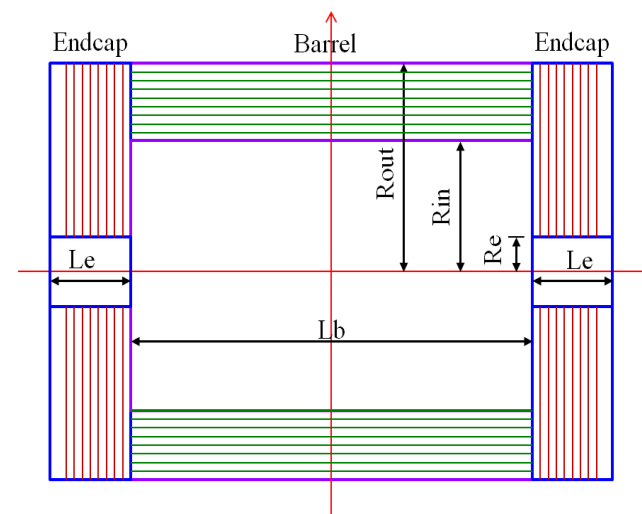
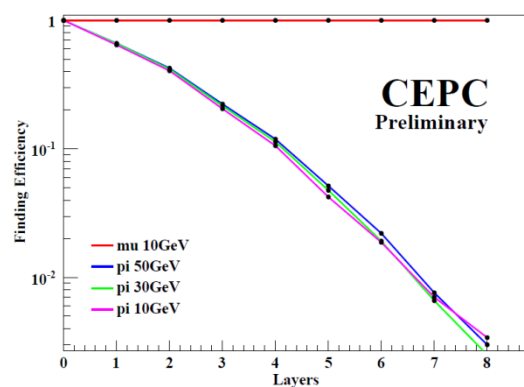
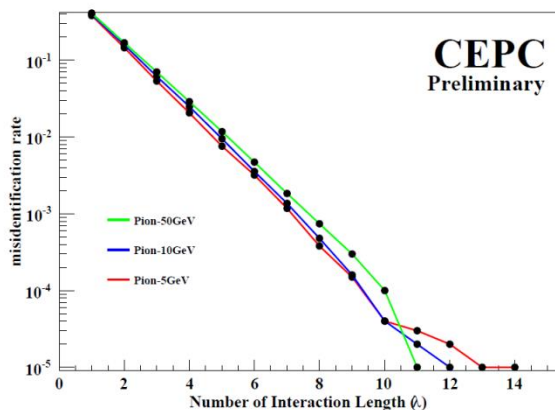
- To separate muons from hadrons
- A tail catcher of HCAL
- Solenoid return yoke & support structure

## Performance requirements

- $n_{\text{Layer}} \geq 8$ , iron thickness  $\geq 6\lambda$
- $\text{Eff} \geq 95\%$ , resolution  $\leq 2\text{cm}$
- Misidentification rate ( $\pi \rightarrow \mu$ )@40GeV  $< 1\%$

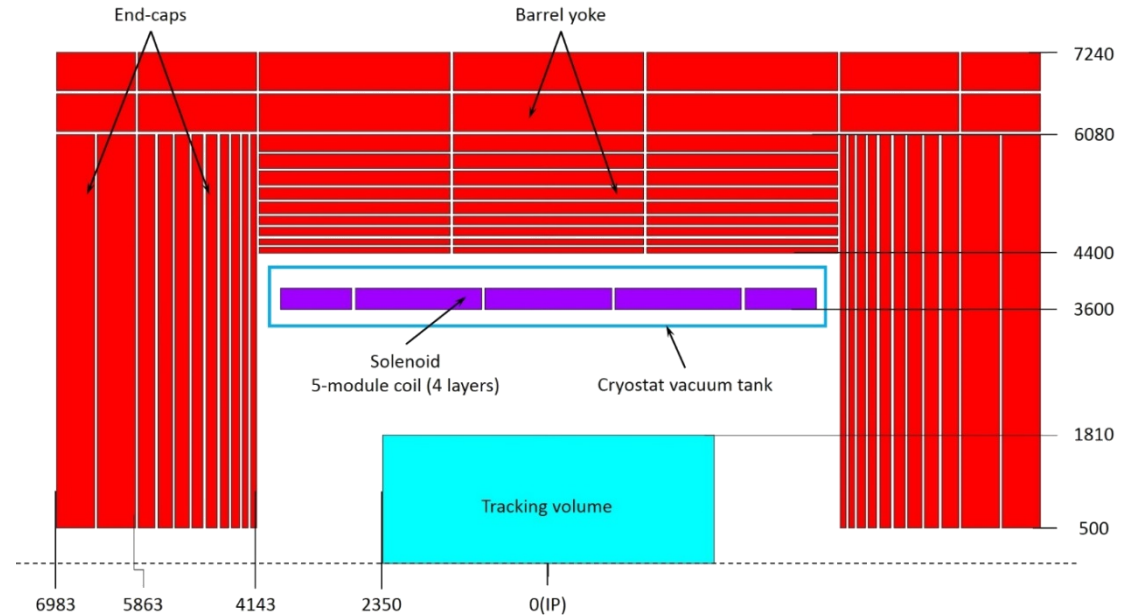
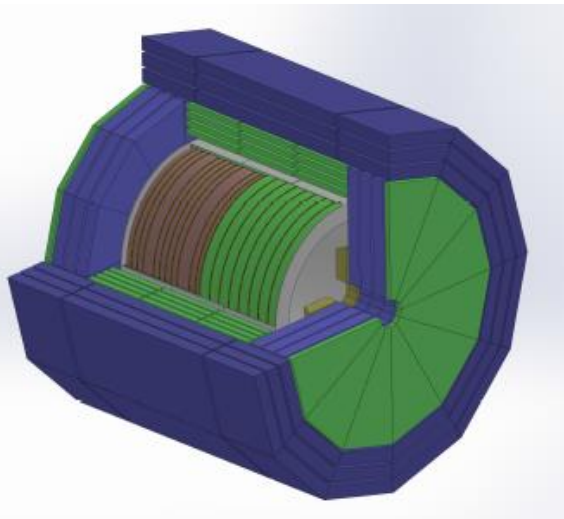
Item	Option	Baseline
Lb	3.6~5.6m	~4.6
Rin	2.5~3.5m	~3.0
Rout	4.5~5.5m	~5.0
Le	1.6~2.4m	~2.0
Re	0.6~1.0m	~0.8
Segmentation	8/10/12	10
Number of layers	6~10	8(~3cm per layer)
Total thickness of iron	6~10 $\lambda$ ( $\lambda=16.77\text{cm}$ )	8 (8/8/12/12/16/16/20/20/24cm, Sum=136cm)
Solid angle coverage	0.92~0.96 $\times 4$	0.94
Position resolution	1.5~2.5cm	2
	: 1~2cm	1.5
Average strip width	Wstrip: 2~4cm	3
Detection efficiency	92%~98%	95%
Reconstruction efficiency	92%~96%	94%

The standalone simulation results show the number of layers and the thickness of iron are reasonable.



# CEPC Magnet Design

Based on CEPC detector, a **3.5T** central field of superconducting solenoid is required (Inner R=6.8m, Length=8.05m) . (similar to CMS design)

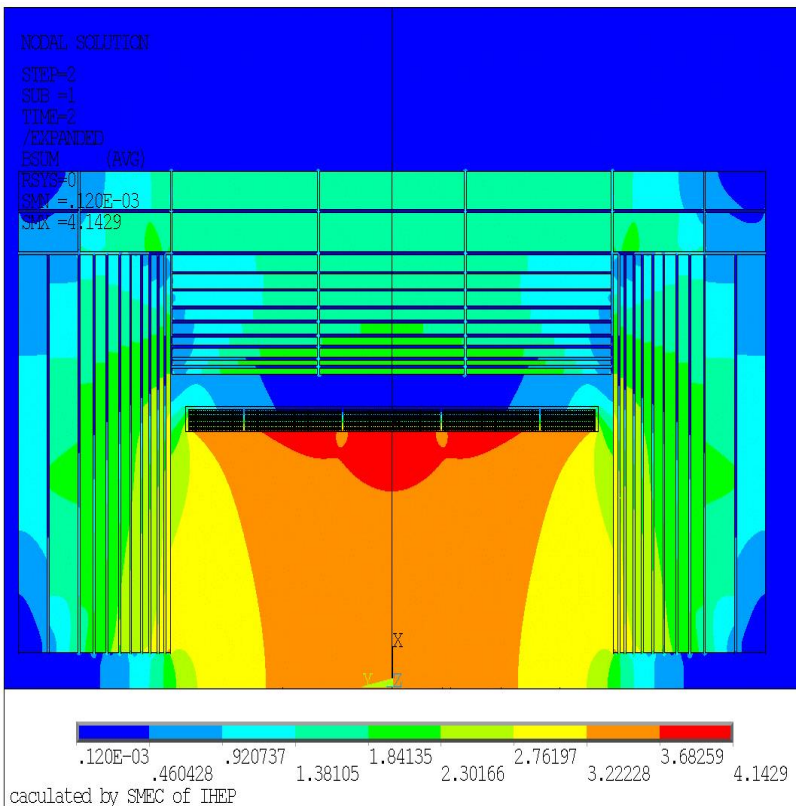


<b>Cryostat inner radius(mm)</b>	<b>3400</b>	<b>Barrel yoke outer radius(mm)</b>	<b>7240</b>
<b>Cryostat outer radius(mm)</b>	4250	<b>Yoke overall length(mm)</b>	13966
<b>Cryostat length(mm)</b>	8050	<b>Barrel weight(t)</b>	5775
<b>Cold mass weight(t)</b>	165	<b>End cap weight(t)</b>	6425
<b>Barrel yoke inner radius(mm)</b>	4400	<b>Total yoke weight(t)</b>	12200
<b>The solenoid central field(T)</b>	<b>3.5</b>	<b>Nominal current(KA)</b>	<b>18.575</b>
<b>Maximum field on conductor(T)</b>	3.85	<b>Total ampere-turns of solenoid(MAt)</b>	23.925
<b>Coil inner radius(mm)</b>	3600	<b>Inductance(H)</b>	10.4
<b>Coil outer radius(mm)</b>	3900	<b>Stored energy(GJ)</b>	1.8
<b>Coil length(mm)</b>	7600	<b>Stored energy per unit of cold mass(KJ/kg)</b>	10.91

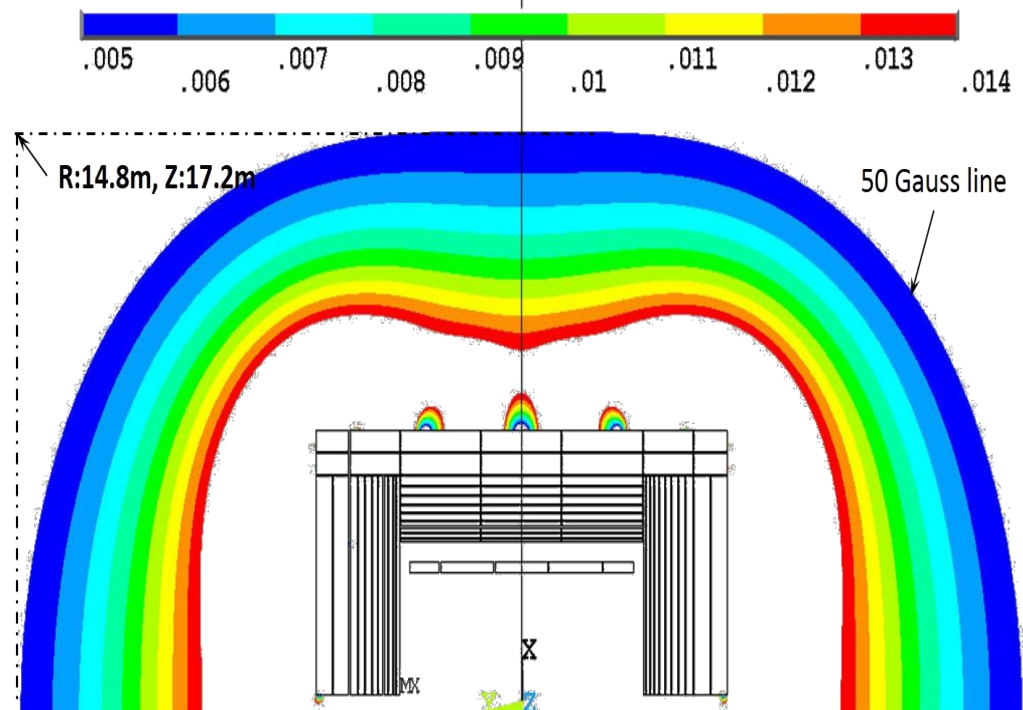
# Progress of field design

Feipeng Ning eg. (IHEP)

Magnetic field distribution: central field 3.5T, peak-peak field percent deviation of TV is 10.1%.



The 50 G line is at 14.8 m radial distance and 17.2 m axial distance with a total thickness of iron of 2.44 m both in the barrel and the two end-caps with the 3.5 T central field.



**Stray field distribution outside the magnet  
(the field is given in T)**

# Progress of the Rutherford cable

Ling Zhao et.al. (IHEP)



No. of strands: 20  
Strand R.: 1.0mm  
Materiel: Copper  
Complete:2015.5

No of strands : 17  
Strand R: 0.727mm  
Materiel :Nb/Ti  
Complete:2015.7

No of strands : 24  
Strand R : 0.727mm  
Materiel :Nb/Ti  
Complete:2015.8

Number of strands : 18  
Strand diameter : 1.2mm  
Materiel :Nb/Ti  
Complete time:2016.2

No of strands : 32  
Strand R : 1.2mm  
Materiel :Nb/Ti  
Tangle: 17.32  
Length:  $\gg$  100m  
RRR:  $\gg$  100  
Complete time:2016.5

Ling Zhao

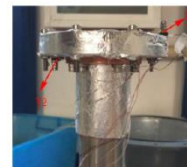
Development of testing device



IC test by induction method



Testing device is based on a small refrigerator.



RRR value test

Testing device based on small refrigerator for Ic and RRR value have put into use.

卢瑟福线缆研究  
取得了重要进展!

2016/09/18-19

Director - H. Yang @ SJTU

# CEPC 物理和探测器工作组

## ■ Physics and Detector Group Co-conveners

**Joao Guimaraes da Costa (IHEP)**

**Yuanning Gao (THU), Shan Jin (IHEP)**

## ■ Sub-groups and co-conveners

- Physics simulation and analysis:  
Gang Li, Manqi Ruan, Yaquan Fang (IHEP), Qiang Li (PKU)
- MDI: Hongbo Zhu (IHEP), Yiwei Wang (IHEP)
- Vertex: Qun Ouyang (IHEP), Xiangming Sun (CCNU), Meng Wang (SDU)
- TPC tracker: Yulan Li (THU), Huirong Qi (IHEP)
- ECAL and HCAL: Tao Hu (IHEP), Jianbei Liu (USTC), Haijun Yang (SJTU)
- Muon: Boxiang Yu (IHEP), Liang Li (SJTU)
- Magnet: Ling Zhao, Zian Zhu (IHEP)



# 科技部国家重点研发计划

## “高能环形正负电子对撞机相关的物理和关键技术预研究”

### 课题四：探测器关键技术预研

课题编号：2016YFA0400404

本课题分为四个探测技术研究方向：

- (1) 硅探测器ASIC芯片设计
- (2) 时间投影室关键问题研究
- (3) 电磁和强子量能器关键技术研究
- (4) 大动量范围粒子鉴别技术研究

项目负责人：高原宁（清华大学）

课题负责人：杨海军（上海交通大学）

参加单位：高能所、科大、清华、华师、交大

参加骨干13人：4正高、8副高、1中级

团队成员：4 职工、5 博士后、15 研究生



# 探测器课题任务分解

各子课题有多个单位参与研制，分工合作，密切配合。

	高能所	科大	清华	华师	交大
硅探测器	芯片设计			流片测试	
时间投影室	样机研制、 测试		读出芯片 设计测试		
电磁量能器	样机研制、 散热研究、 测试	读出电子 学设计			
强子量能器	ThGEM单元 研制测试	GEM单元 研制测试			RPC单元 研制测试
环像契伦科 夫探测器		样机研制、 测试			

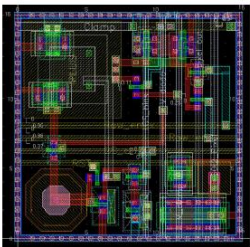
# 硅探测器芯片设计

- 研究内容：设计高分辨、快读出、低功耗CMOS像素探测器芯片
- 芯片指标：空间分辨 $3\text{-}5\mu\text{m}$ ；积分时间 $10\text{-}100\mu\text{s}$ ；功耗  $<100\text{mW}/\text{cm}^2$ ；抗辐照能力（TID） $\sim 1\text{MRad}$
- 指标先进：实现小像素单元 $< 16\mu\text{m}$ 电路架构的设计。

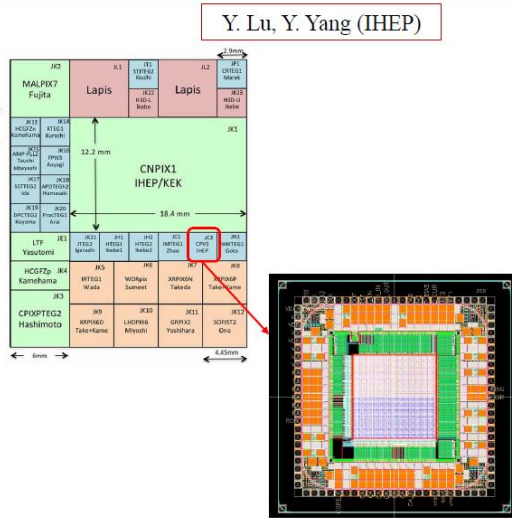
## Second SOI pixel prototype design

CPV2

- In-pixel CDS stage inserted
- To improve RTC and FPN noise
- To replace the charge injection threshold
- Submitted June, 2016



Pixel Layout:  $16 \times 16 \mu\text{m}^2$

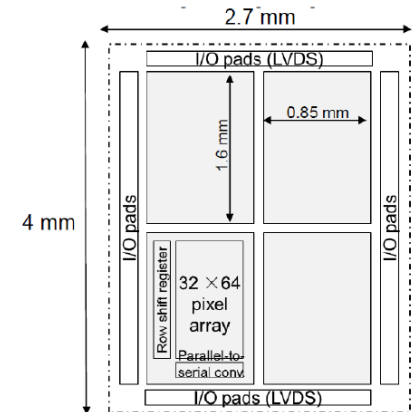


Y. Lu, Y. Yang (IHEP)

## Second CPS prototype - pixel design

Y. Zhang, Y. Yang (IHEP)

- Purpose: small-size digital pixel design verification
- Proposed floor plan:
  - 4 sub-matrices with different pixel structures, each matrix with 32 columns by 64 rows pixels
  - Pixel size: less than  $22 \times 22 \mu\text{m}^2$
  - Each pixel contains a sensing diode, a pre-amplifier and a discriminator



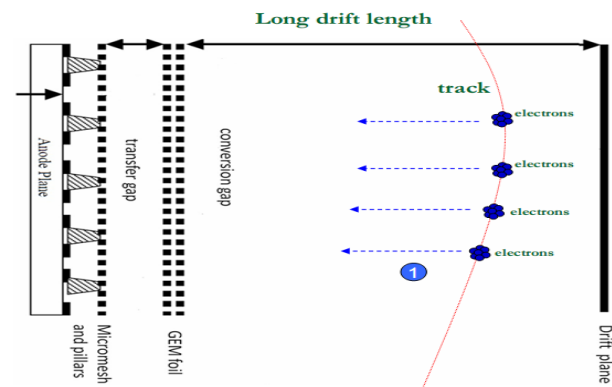
# 时间投影室

## 研究目标:

针对物理要求，研发低功耗读出电子学、连续正离子抑制型读出模块，及高分辨TPC原型机并进行磁场测试。

## 考核指标:

- 研制连续正离子反馈抑制的TPC原型机
- 位置分辨率:  $100\mu\text{m}$
- 连续正离子抑制:  $\sim 0.1\%$
- 单颗芯片集成16通道，功耗:  $5\text{mW}/\text{通道}$



连续正离子抑制型  
探测器示意图

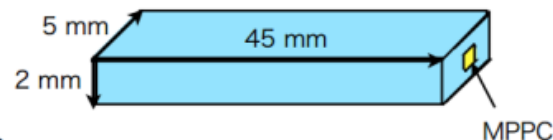
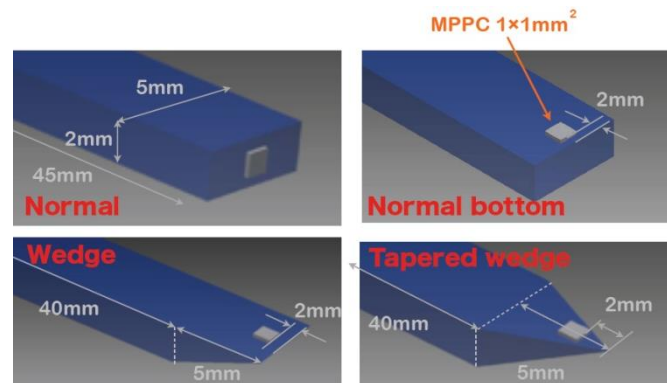
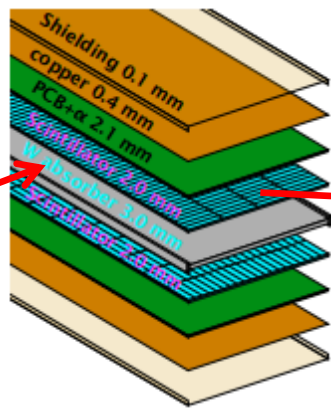
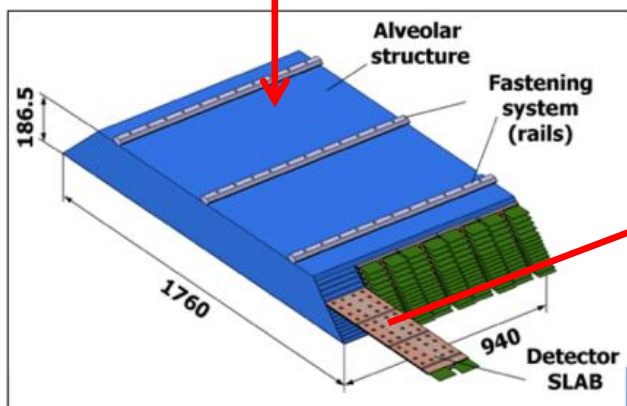
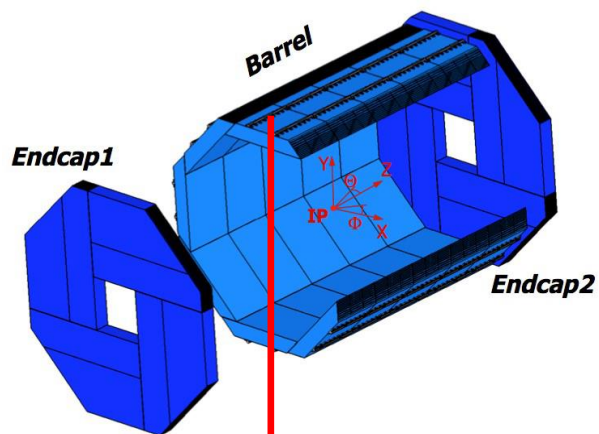
## 研究内容、方法和技术路线:

研制GEM-Micromegas复合探测器；采用先进65nm的集成电路工艺研发波形采样的低功耗和高集成度的ASIC读出电子学芯片；面向环形对撞束特有的连续束流时间结构特点，研制连续正离子抑制型读出模块。重点是采用该模块在1.0T磁场中实现位置分辨率 $100\mu\text{m}$ 的设计指标。

# 电磁量能器研究目标

## 研究目标和考核指标:

- (1) 解决基于SiPM读出电磁量能器的技术选型问题;
- (2) 实现电磁量能器读出单元颗粒度达到  $5 \times 5 \text{ mm}^2$ ;
- (3) 研制小型电磁量能器原理样机;
- (4) 针对CEPC的特点, 研制一套基于两相二氧化碳制冷的主动散热系统, 在 $-20^\circ\text{C}$ 下, 导热量大于 $30\text{mW}/\text{cm}^2$ ;
- (5) 发表2-3篇论文。



基于塑料闪烁体和  
硅光电探测器

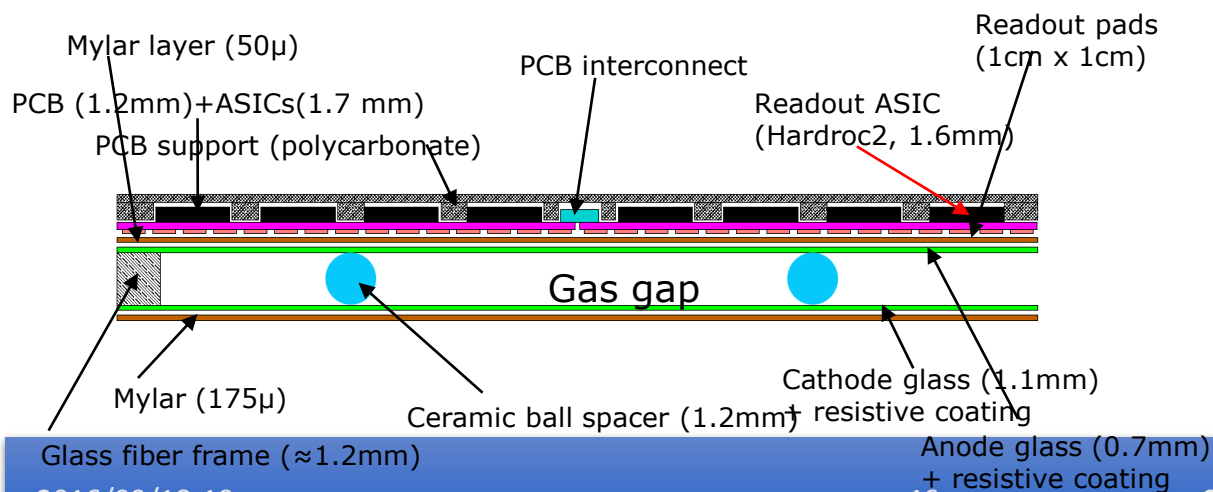
CEPC Detector - H. Yang @ SJTU

# 强子量能器研究目标

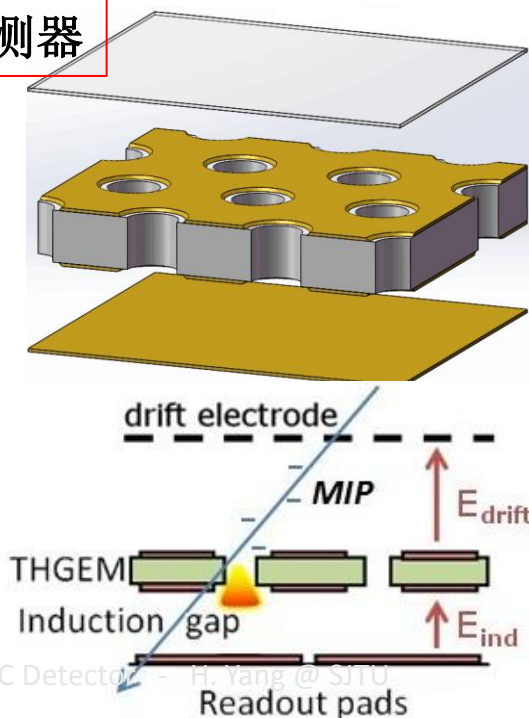
## 研究目标和考核指标:

1. 得到数字强子量能器的技术选型;
2. 在颗粒度达到 $1 \times 1 \text{cm}^2$ 条件下, 掌握厚度小于6mm的气体探测器制作工艺;
3. 制作面积达到 $1 \text{m} \times 0.5 \text{m}$ 的微孔型探测器单元模型, 探测器的整体增益均匀性好于20%, 计数率达到 $1 \text{MHz/s}$ , MIP粒子探测效率好于95%;
4. 制作面积达 $1 \text{m} \times 1 \text{m}$ 的平板型探测器单元模型, MIP粒子探测效率好于95%;
5. 发表2-3篇论文。

RPC平板型探测器



微孔型探测器



# 大动量范围粒子鉴别技术研究

## 研究内容

- 环像契伦科夫探测器的设计与优化;
- 基于ThGEM+MicroMegas组合;
- 环像契伦科夫探测器原型的研制和测试。

## 研究目标

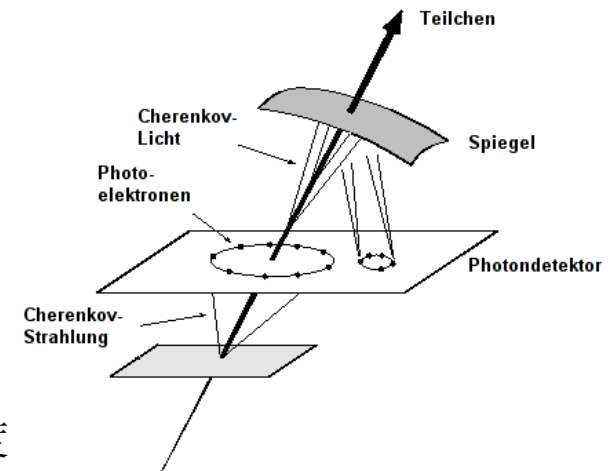
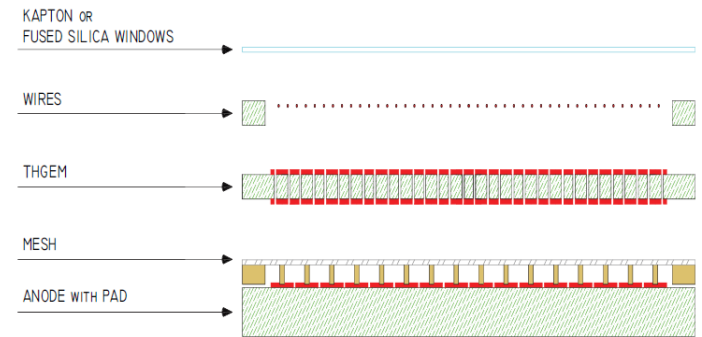
- 将微结构气体探测器应用于环像契伦科夫探测器，并验证其大动量范围（20-40GeV）的粒子鉴别能力。

**技术路线：**通过组合微结构气体探测器解决这一问题

- ThGEM: 光电转换（CsI镀层）、预放大，阻挡光子反馈。
- MicroMegas: 主放大，离子反馈小。

**考核指标：**单光子角分辨好于2mrad。

**创新点：**采用两种微结构气体探测器的组合，实现高灵敏度反馈的契伦科夫光探测。



# 科技部项目探测器课题参与人员

## ■ 课题负责人：杨海军

参加单位5家：高能所、科大、清华、华师、上海交大

参加骨干13人：4 正高、8 副高、1 中级

团队成员：4 职工、5 博士后、15 研究生

## ■ 高能所：欧阳群，魏微，卢云鹏，祁辉荣，王志刚，俞伯祥

职工：董明义、董静、张杰、赵梅；

博士后：周扬，鞠旭东，牛顺利，

学生：吴志岗、宋龙龙，张余炼，王海云，赵航，夏莉

## ■ 科大：刘建北，张云龙，李昕，

博士后：张志永，学生：牛亚洲

## ■ 清华：邓智，学生：刘丰，赵馨远

## ■ 华师：孙向明，杨苹，职工：肖乐、高超嵩

学生：周威、黄兴、任伟平、刘建超、李雅淑

## ■ 上海交大：杨海军，博士后：胡继峰，学生：刘冰

## ■ 拟招聘：1-2名职工，2-3名博士后，8-10名研究生

科技部CEPC预研究项目启动会





# 结束语

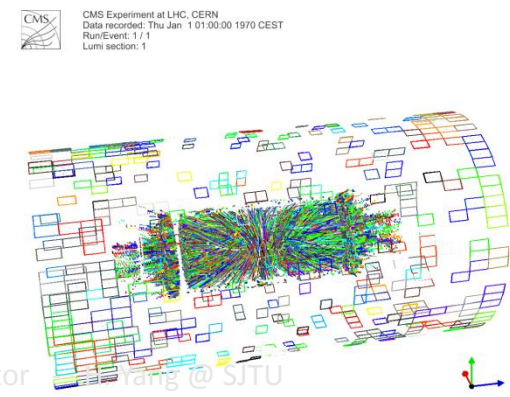
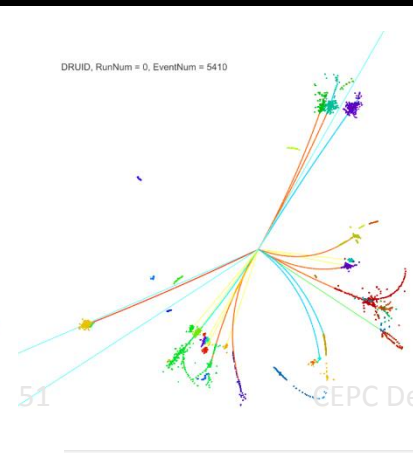
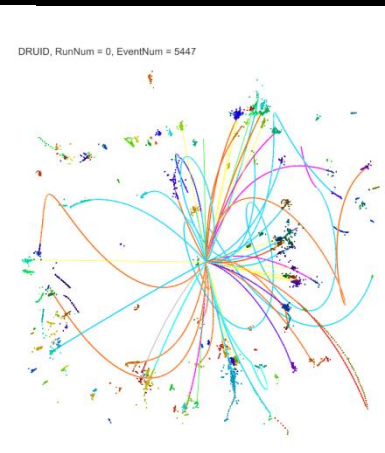
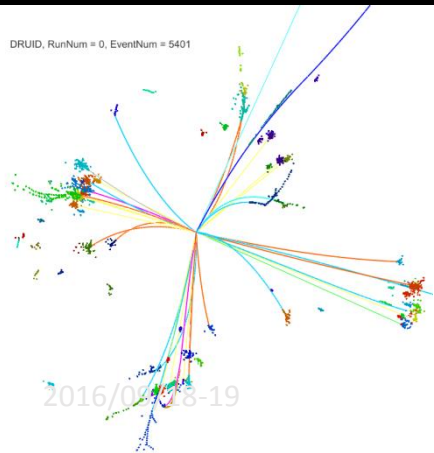
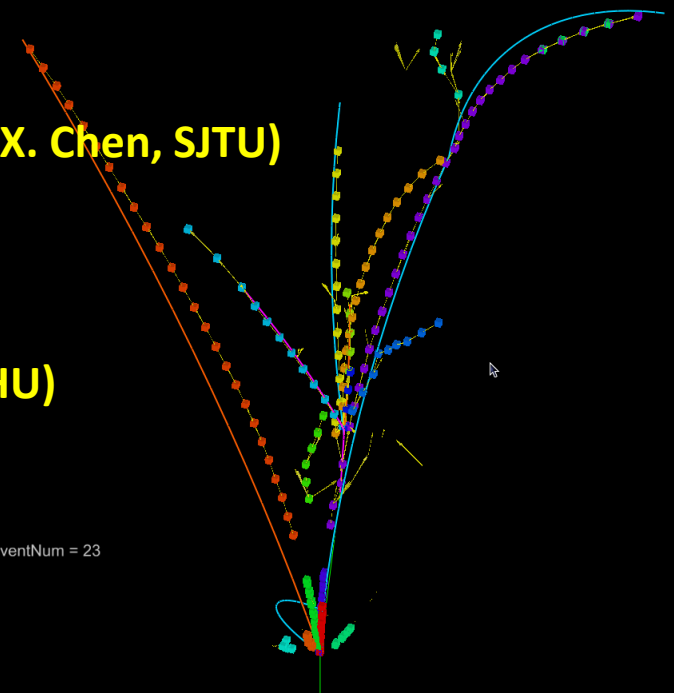
- 2013年起，CEPC物理和探测器工作组作了大量的调研工作，撰写了**CEPC初步概念设计报告**。
- 2015年，高能所通过所创新基金支持CEPC探测器预研究。
- 2016年，获得科技部国家重点研究计划经费资助，9月份正式启动了CEPC探测器关键技术的预研究。
- 目前积极推进硅探测器芯片设计、时间投影室、电磁和强子量能器、契伦科夫探测器等关键技术、探测器模拟和优化等研究。
- 同时通过国际合作，学习和掌握最新探测器技术。
- 预计2017年底前后提供**CEPC概念设计报告**。

**感谢CEPC工作组成员提供大量研究成果！  
谢谢各位专家的聆听，请提出宝贵意见！**

# Backup Slides

# Simulation & Reconstruction Software

- **Geant 4 Full Detector Simulation:**
  - Geometry can be edited freely (Y. Xu, NKU & X. Chen, SJTU)
  - A set of geometries has been generated
- **Reconstruction Chain**
  - Tracking: Clupatra & ILD tracking (B. Li, etc THU)
  - PFA: Arbor (M. Ruan, etc, IHEP)
  - Flavor Tagging: LFCIPlus (G. Li, etc, IHEP)



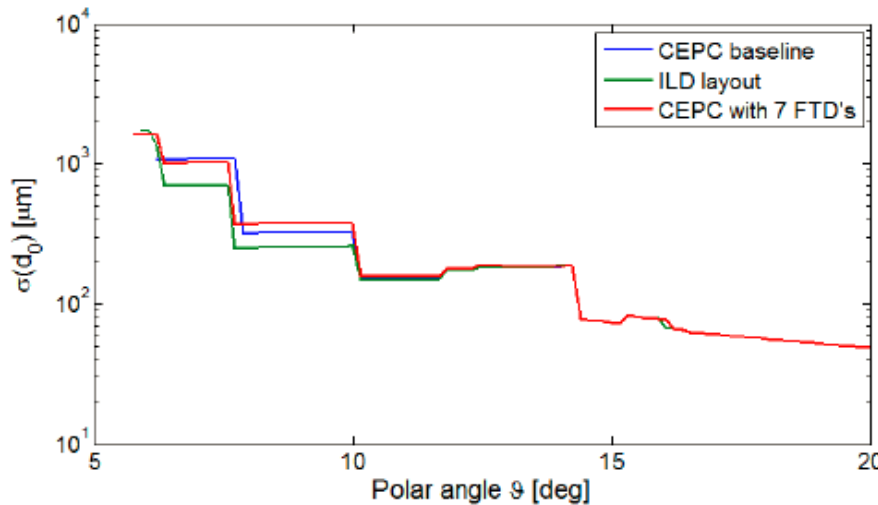
CMS  
CMS Experiment at LHC, CERN  
Data recorded: Thu Jan 1 01:00:00 1970 CEST  
Run/Event: 1 / 1  
Lumi section: 1

# CEPC MDI: Luminosity Measurement

- Luminosity measurement with the dedicated device, LumiCal, with a target uncertainty of  $10^{-3}$ , as required by precision measurements of the Higgs and Z physics.
  - Electromagnetic calorimeter with silicon-tungsten sandwich structure, to measure radiative Bhabha events
  - $\Delta L/L \sim 2\Delta\theta/\theta_{\min} \rightarrow$  necessary to achieve precise polar angle measurement better than  $\Delta\theta < 0.015$  mrad
- Online beam luminosity monitor allowing fast beam tuning
  - radiation hard sensor technologies (e.g. CVD diamond), to measure radiative Bhabha events at zero photon scattering angle  $\leftarrow$  similar design as for the SuperKEKB design

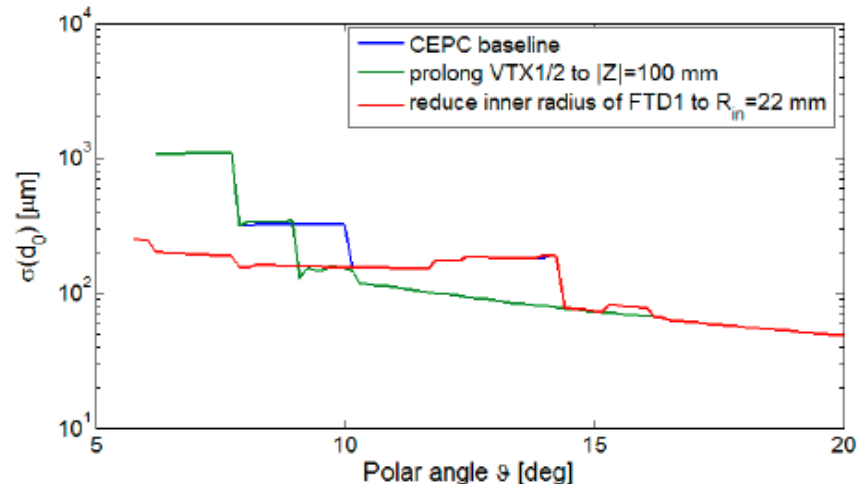
# Forward region with $L^* = 1.5\text{m}$

- Impact parameter resolution studied with LDT - fast simulation using Kalman filter



Performance loss in the low polar angle region ( $< 10^\circ$ ) with reduced number of FTD disks

The performance loss can be recovered with extended coverage of the pixel detector layers, either by prolonging first two VTX barrel layers or extending the first FTD disk down to  $r=22\text{mm}$



# CEPC Vertex and Silicon Tracker

Many technologies from ILC/CLIC R&D could be referred.

**BUT, unlike the ILD, the CEPC detector will operate in continuous mode.**

**Pixel sensor:** power consumption < 50mW/cm<sup>2</sup> with air cooling, readout < 20μs

- **HR-CMOS** sensor with a novel readout structure — **ALPIDE for ALICE ITS Upgrade**
  - In-pixel discriminator and digital memory based on a current comparator
  - In-column address encoder
  - <50mW/cm<sup>2</sup> expected
  - Capable of readout every ~4μs
- **SOI** sensor with similar readout structure
  - Fully depleted HR substrate, potential of 15μm pixel size design
  - Full CMOS circuit
- **DEPFET:** possible application for inner most vertex layer
  - small material budget, low power consumption in sensitive area

**Silicon microstrip sensor:** p<sup>+</sup>-on-n technology

pixelated strip sensors based on CMOS technologies

# CEPC Vertex and Si Tracker: Critical R&D plan

- Pixel sensors with low power consumption and high readout speed

- In-pixel discriminator
- In-matrix sparsification

*Similar to ALPIDE sensor for ALICE ITS Upgrade*



Starting design with HR-CMOS process

Exploring possibility with SOI process, especially for smaller pixel size

- Light weight mechanical design and cooling

- 0.05%(0.1%) material budget without(with) cabling
- Air cooling technology with acceptable vibration due to air flow

- Pixel sensor thinning to 50 $\mu$ m

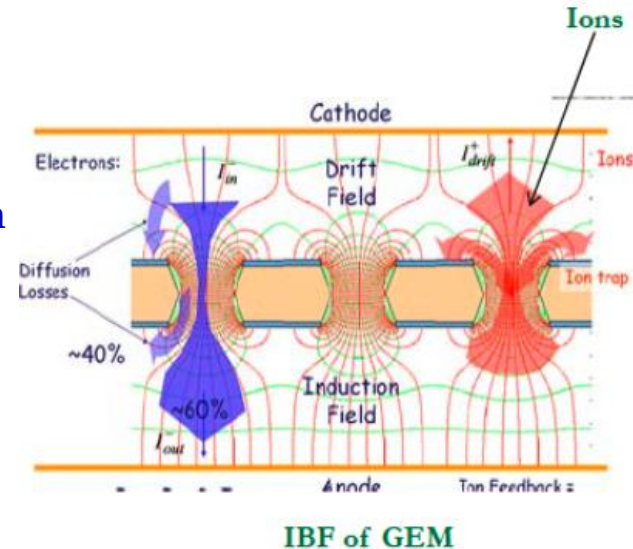
- Slim edge silicon microstrip sensor

- Low noise, low power consumption FEE for silicon microstrip

# CEPC TPC: Critical R&D plan

## ■ Physical design and optimization of the TPC

- Length, inner/outer radius, pad size
- E/B fields and uniformity requirements
- Working gas, counting rate, ion backflow suppression
- The time structure of the beam
- Sensors: GEM and Micromegas detectors ?



## ■ Critical R&D

- Large prototype design, construction and assembly
- Laser calibration and alignment device design, assembly
- Detector readout options (GEM+Pad, Micromegas+Resistive Pad, ThickGEM+Pad ?)
- Front-end readout electronics and DAQ
- Cooling system (eg. two-phase  $CO_2$  cooling, micro-channel  $CO_2$ )



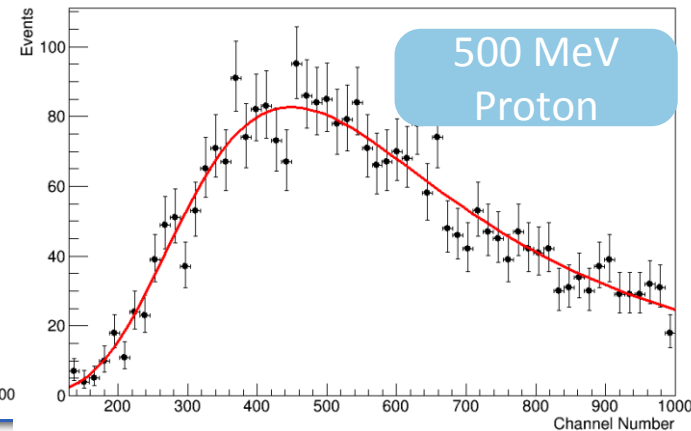
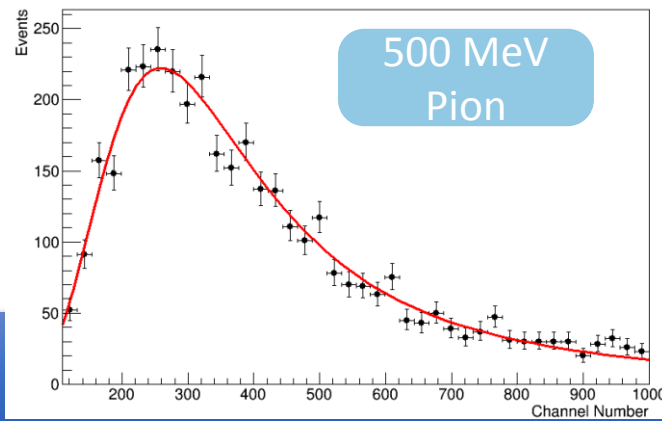
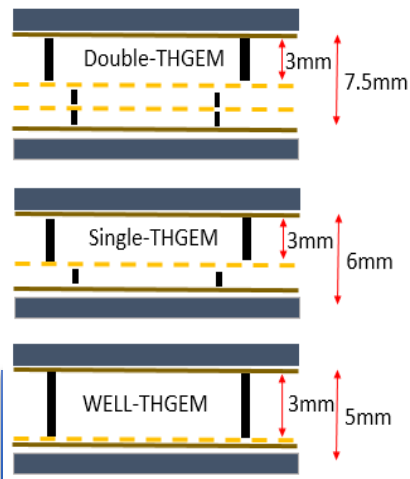
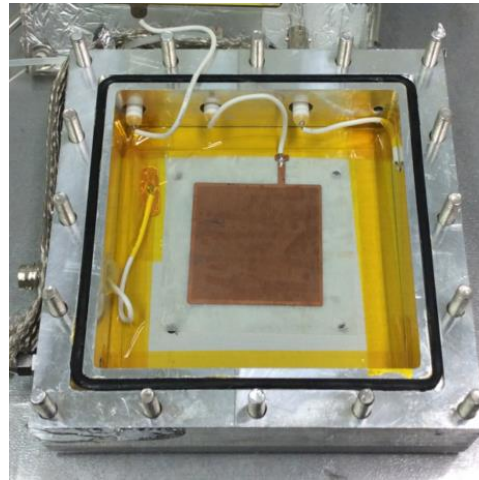
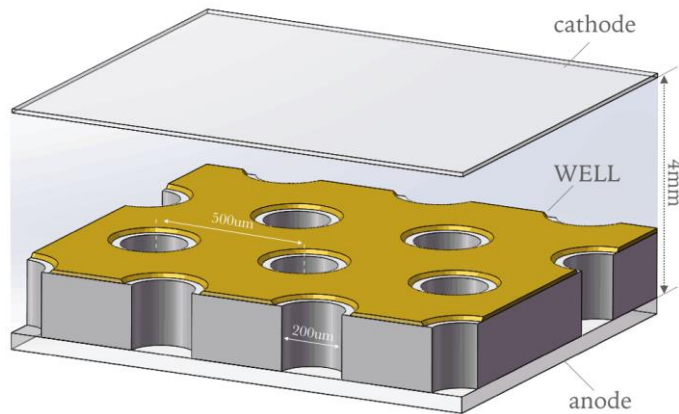
# WELL-THGEM Beam Test at IHEP

■ Detection efficiency of well-THGEM was measured with BEPC pion / proton beams.

■ Efficiency:

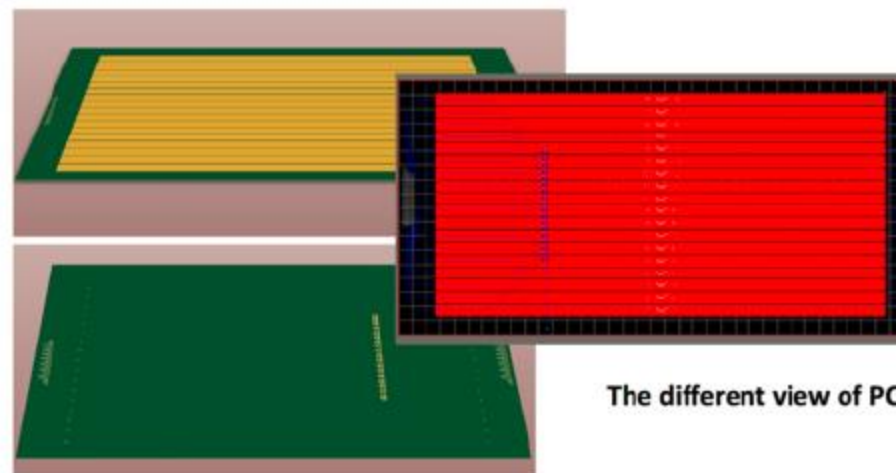
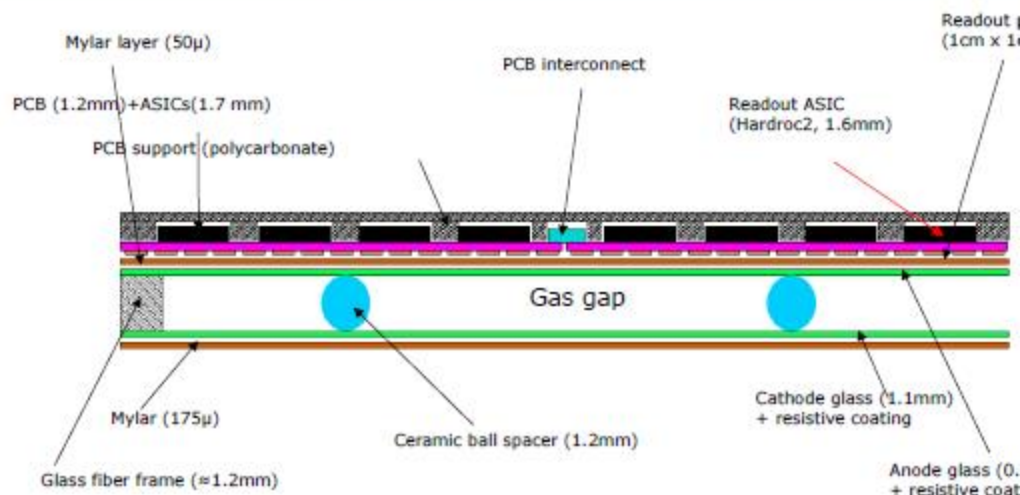
□ Ar/iso (97/3) ,Gain ~ 2000; Eff (proton) > 93%; Eff(Pion) > 82%

□ Ne/CH4 (95/5) ,Gain ~ 9000; Eff (proton) > 99%; Eff(Pion) > 94%



## ► Large Glass RPC R&D

- Negligible dead zone
- Large size:  $1 \times 1 \text{ m}^2$
- Cost effective
- Efficient gas distribution system
- Homogenous resistive coating



# Imaging calorimeter: Critical R&D

## ■ Detector optimization

- Optimize of the pad size of calorimeter
- Optimize the number of layers of calorimeters, help to reduce the size of magnets and cost
- Gas recirculation system, HV distribution system

## ■ Readout Electronics (PCB, low power ASIC FEE)

## ■ Cooling

- Power pulsing will NOT work at the CEPC, **effective cooling and power saving strategy need to be developed and tested**

## ■ Calibration

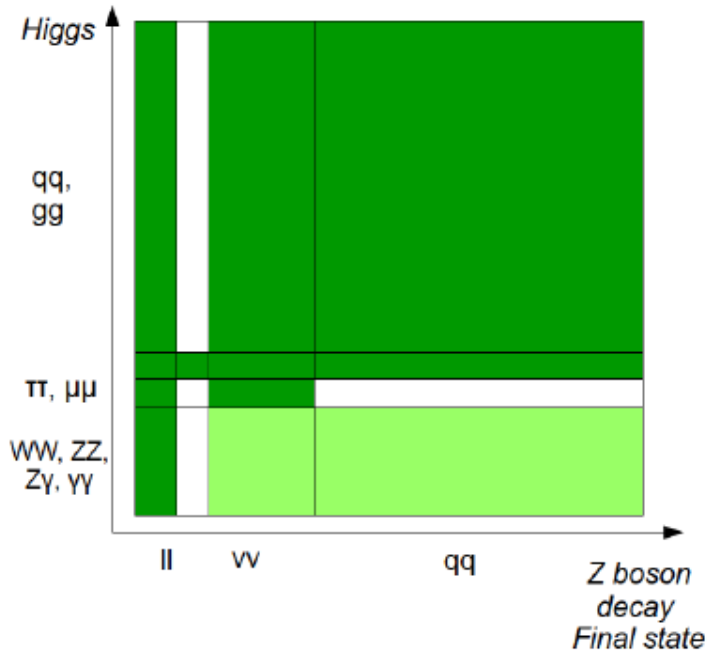
- Energy, position and density calibration etc.
- Detailed shower measurement gives possibility to use track segments (from data itself) to calibrate calorimeter

## ■ Mechanical: self-support and compact module

# Status of Higgs Analysis

M.Q. Ruan, G. Li, Y.Q. Fang et al.

## ■ Precision measurements at full simulation level.



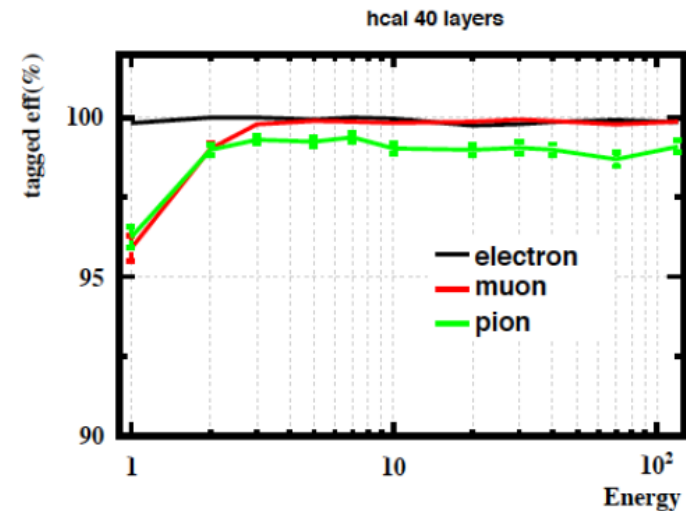
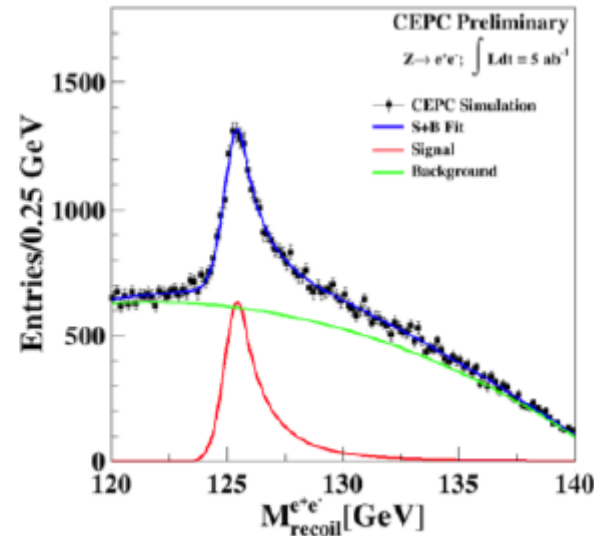
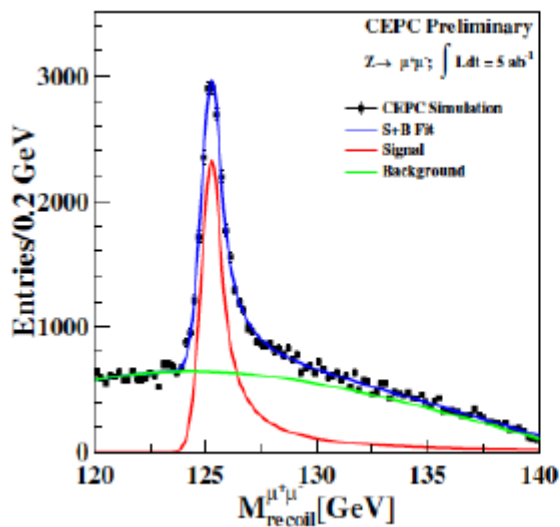
~o(50) independent analyses, mostly studied  
Full Simulation level

	PreCDR (Jan 2015)	Now (Aug 2016)
$\sigma(\text{ZH})$	0.51%	0.50%
$\sigma(\text{ZH}) \cdot \text{Br}(\text{H} \rightarrow \text{bb})$	0.28%	0.21%
$\sigma(\text{ZH}) \cdot \text{Br}(\text{H} \rightarrow \text{cc})$	2.1%	2.5%
$\sigma(\text{ZH}) \cdot \text{Br}(\text{H} \rightarrow \text{gg})$	1.6%	1.3%
$\sigma(\text{ZH}) \cdot \text{Br}(\text{H} \rightarrow \text{WW})$	1.5%	1.0%
$\sigma(\text{ZH}) \cdot \text{Br}(\text{H} \rightarrow \text{ZZ})$	4.3%	4.3%
$\sigma(\text{ZH}) \cdot \text{Br}(\text{H} \rightarrow \tau\tau)$	1.2%	1.0%
$\sigma(\text{ZH}) \cdot \text{Br}(\text{H} \rightarrow \gamma\gamma)$	9.0%	9.0%
$\sigma(\text{ZH}) \cdot \text{Br}(\text{H} \rightarrow \text{Z}\gamma)$	-	$\sim 4 \sigma$
$\sigma(\text{ZH}) \cdot \text{Br}(\text{H} \rightarrow \mu\mu)$	17%	17%
$\sigma(\text{vvh}) \cdot \text{Br}(\text{H} \rightarrow \text{bb})$	2.8%	2.8%
Higgs Mass/MeV	5.9	5.0
$\sigma(\text{ZH}) \cdot \text{Br}(\text{H} \rightarrow \text{inv})$	95%. CL = $1.4 \times 10^{-3}$	$1.4 \times 10^{-3}$
$\text{Br}(\text{H} \rightarrow \text{ee}/\text{emu})$	-	$1.7 \times 10^{-4}/1.2 \times 10^{-4}$
$\text{Br}(\text{H} \rightarrow \text{bb}\chi\chi)$	$< 10^{-3}$	$3.0 \times 10^{-4}$

# Detector Simulation & Optimization

		CEPC_v1, ILD	Test Geo 1	<b>TG 2</b>	<b>TG 3</b>
ECAL	Cell Size/mm	5	10	20	20
	# Layers	30	30	30	20
HCAL	Cell Size/mm	10	10	20	20
	# Layers	48	48	48	20
Ratio of Channels (X/ILD)	ECAL	1	1/4	1/16	1/24
	HCAL	1	1	1/4	1/10
Event Recon. Efficiency	$\mu\mu$ H	95.7%*	98.0%	96.5%	95.2%
	eeH	91.1%*	89.6%	89.1%	74.5%(???)

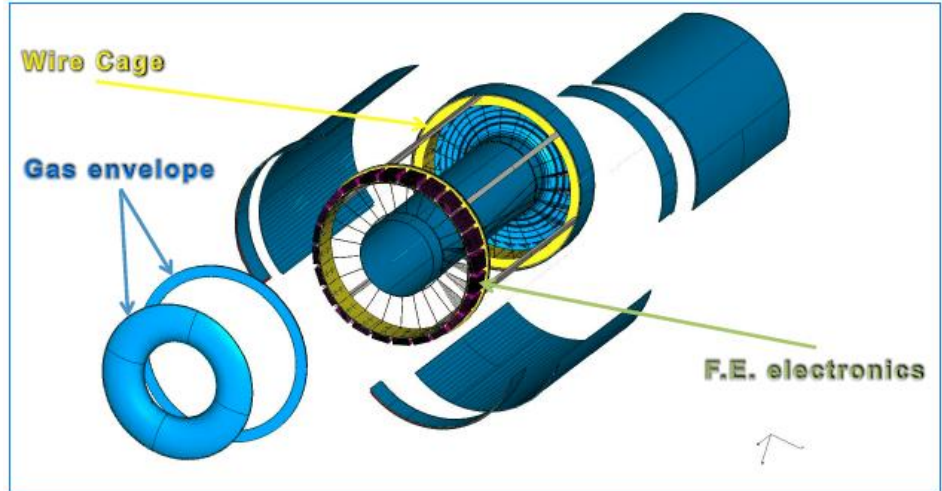
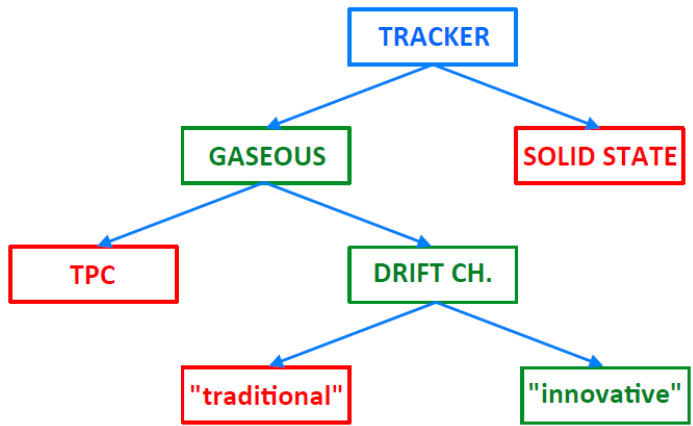
- To develop general lepton ID for calorimeter with high granularity (LICH) – Dan Yu et.al



# Drift Chamber with PID capability

F. Grancagnolo  
INFN – Lecce, ITALY

## Tracker alternatives



## A proposal for CepC (1)

- 24 super-layers, each one made of 8 para-axial layers (192 total) at stereo angles, arranged in 16 equal azimuthal sectors;
  - 18 square, single sense wire, drift cells per sector on each successive super-layer. Cell size is a function of super-layer radius;
  - Cell sizes ranging from 700 to 1000  $\mu\text{m}$ ;
  - Alternating sense and field wires (conventional geometry);
- Expected spatial resolutions:  $\sigma_{r\phi} < 100 \mu\text{m}$ ,  $\sigma_z < 1 \text{ mm}$
- Expected momentum resolution:  $\Delta p_t/p_t = 2.2 \times 10^{-4}$ ,  $\Delta p/p = 4.0 \times 10^{-4}$  for  $p_0$  at Radius = 320 mm;  $\Delta p/p = 2.5 \times 10^{-4}$  for  $p_0$  at Radius = 250  $\mu\text{m}$  - 2.5 mm Rohacell30 - must support 15 Tons - check for buckling
- Expected p. id.:  $\pi/\kappa$  separation  $> 3\sigma$  for  $p < 820 \text{ MeV}/c$  and  $p > 1100 \text{ MeV}/c$  (analogy to Mu2e I-Tracker):
- Gas envelope made of 6 ply (quasi-isotropic,  $6 \times 38 \mu\text{m} = 228 \mu\text{m}$ ) C-fiber plus  $0.3 \mu\text{m}$  Au, for a total of  $0.060 \text{ g}/\text{cm}^2 - 2.1 \times 10^{-3} X_0$ ;
  - Gas: 90% He - 10% iC4H10 ( $\delta = 4 \times 10^{-4} \text{ g}/\text{cm}^3$ ,  $X_0 = 1410 \text{ m}$ ), - 12.5 p.i./cm, gas gain:  $4 \times 10^5$  at  $V \approx 1400 \text{ V}$  on  $20 \mu\text{m}$  wire,  $v_{\text{drift}} \sim 2.5 \text{ cm}/\mu\text{s} - 4.7 \times 10^{-4} X_0/1\text{m track}$
  - Wires: - 161,280 sense (20 $\mu\text{m}$  Sn coated Ti); 648,480 field (40 $\mu\text{m}$  Sn coated C); 164,640 guard (50 $\mu\text{m}$  Sn coated Al) for a total equivalent thickness of  $9.8 \times 10^{-4} X_0/1\text{m track}$

## Drift Chamber "Innovations"

1. Separating gas containment from wire support functions
2. Using a larger number of thinner (and lighter wires)
3. No feed-through wiring
4. Using cluster timing for improved resolution
5. Using cluster counting for particle identification

## High-Rate GRPC

High-Rate GRPC may be needed in the very forward region

✓ Low resistive glass ( $10^{10}\Omega\cdot\text{cm}$ ) developed by Tsinghua was used to build few chambers.

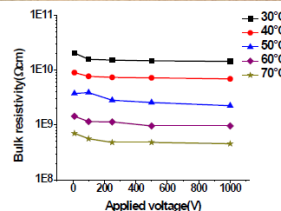
✓ 4 chambers were tested at DESY as well as standard GRPC(float glass)



## Low resistive glass



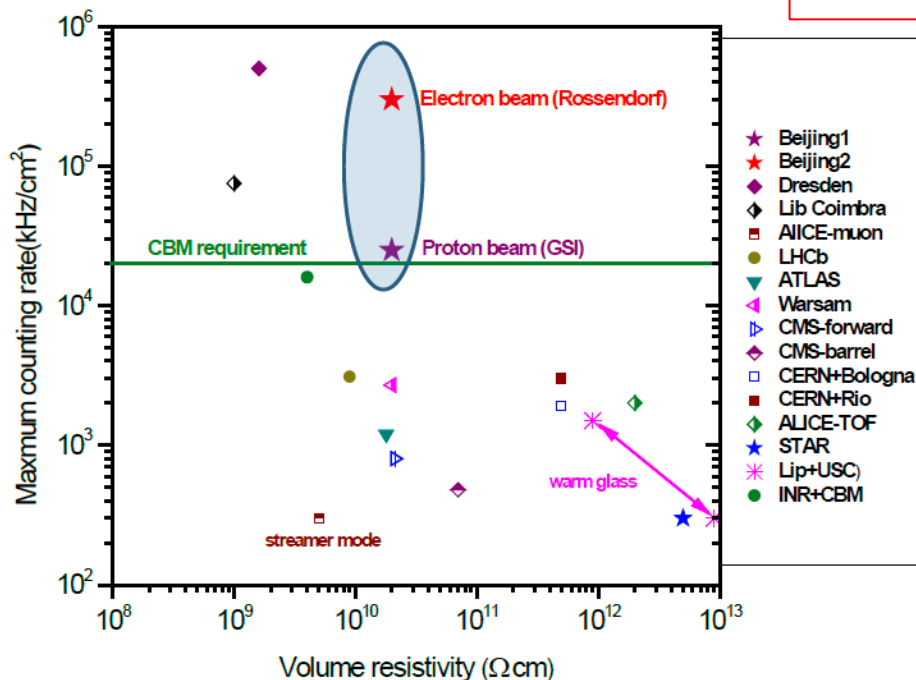
Dimension	33 x 27.6cm <sup>2</sup>
Bulk resistivity	$\sim 10^{10}\Omega\cdot\text{cm}$
Standard thickness	0.7, 1.1mm
Thickness uniformity	20 $\mu\text{m}$
Surface roughness	<10nm
Dielectric constant	7.5 - 9.5
DC measurement	Ohmic behavior stable up to 1C/cm <sup>2</sup>



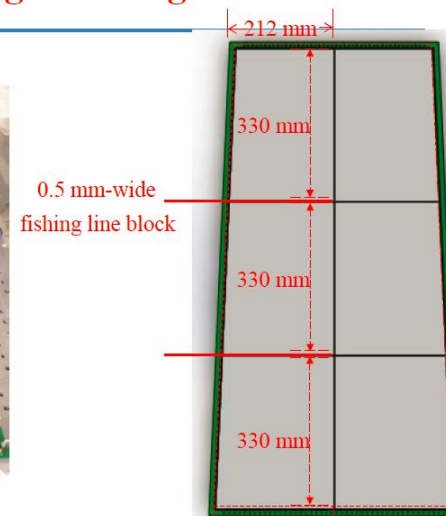
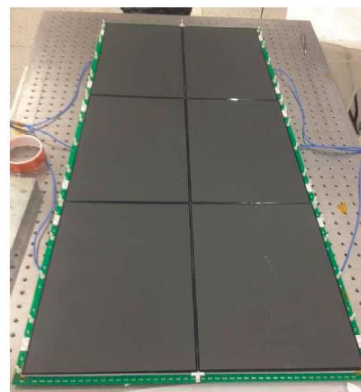
Wang Yi, Tsinghua University CEPC-SppC Study Group Meeting, Sept. 2-3 2016, Beihang Univ

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Yi Wang (THU)  
Imad Laktineh (IPNL)



## Development of high rate big module



Wang Yi, Tsinghua University CEPC-SppC Study Group Meeting, Sept. 2-3 2016, Beihang Univ

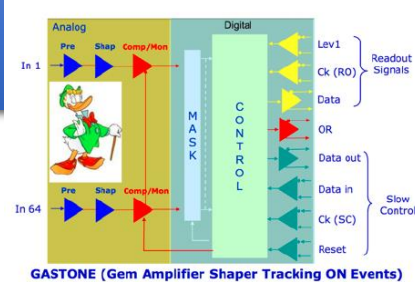
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# CONCLUSION

- Detector simulation:
  - Granularity of calorimeters optimization
  - Number of layers of calorimeters optimization
  - Digitization (RPC/GEM/THGEM)
- Detector R&D
  - RPC (Glass RPC, Polyamide RPC)
  - GEM (double GEM structure, self-stretching)
  - THGEM (Well-THGEM, double THGEM structure)

# DAQ SYSTEM: GASTONE

From Qian LIU/Hongbang LIU (UCAS / GXU)



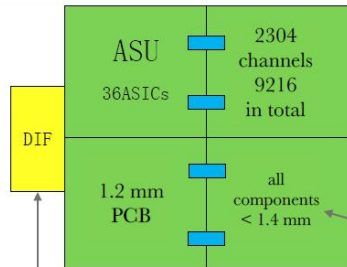
GASTONE (Gem Amplifier Shaper Tracking ON Events)

N channels	64
Chip dimensions	4.5 × 4.5 mm <sup>2</sup>
Input impedance	120 Ω
Charge sensitivity	16 mV/fC (C <sub>det</sub> =100 pF)
Peaking time	90 ns (C <sub>det</sub> =100 pF)
Crosstalk	< 3%
ENC	800 e <sup>-</sup> +40 e <sup>-</sup> /pF
Power consumption	~6 mW/ch
Readout	Serial LVDS (100 Mbps)



# HARDROC/MICROROC

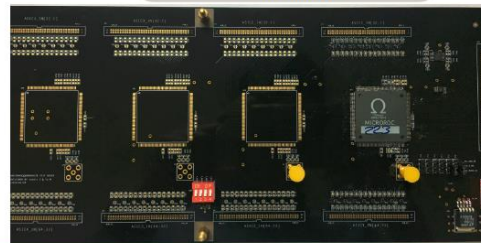
From Jianbei LIU (USTC)



Multi-thresholds	channels	Dynamic range
Hardroc2	64	10fC~10pC
Hardroc3	64	10fC~50pC
Microroc	64	1fC~500fC

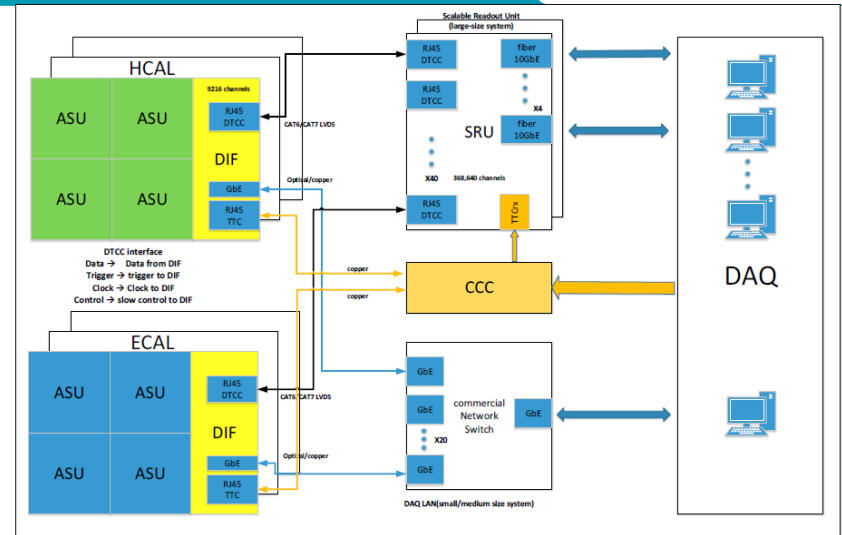
MICROROC is dedicated chip for GEM/MICROMEAS. MICROROC (pin pin compatible with HR2b) is based on HR2b same back-end, same readout format, same pinout, only the preamplifier is changing.

Active Sensor Unit (ASU) Test boards



# DAQ SYSTEM DESIGN

From Jianbei LIU (USTC)





# Consideration of RICH Det. for CEPC

Zhiyong Zhang, Jianbei Liu

## Motivation

**Z pole measurement is one of the goals of CEPC !**  
**The CEPC is expected to collect  $10^{10-12}$  Zs (in CEPC's pre-CDR).**

### Benefits from high-stat z pole data:

- Precision test of SM & new physics searches
- Fragmentation functions & QCD
- Heavy flavor physics, spectroscopy & new hadrons
- $\tau$ -lepton physics
- others



Hadron identification is crucial!

And a dynamic range of **GeV to 40 GeV** for  $\kappa, \pi$  is required.

Comparison of RICHs using C4F10 gas radiator.

	Forward RICH of DELPHI	RICH-1 of LHCb	CEPC RICH prototype
Goals	2.5 to 25 GeV/c	10 to 65 GeV/c	20-40GeV $\kappa, \pi$
Active area:	Two end caps	Two end caps	15cm * 15 cm
Granularity	Depend on the time resolution ( $\sim 8$ ns) and ( $\sim 5$ cm/ $\mu$ s) etc.	2.5*2.5 mm <sup>2</sup>	If 2.5*2.5mm <sup>2</sup>
Angle resolution	2.8 mrad	1.6mrad	2 mrad
Channels	26880	$\sim 200$ k	3600
Sensitive detector	MWPC (fast electrons signal rise time $\sim$ ns)	Silicon detector (rise time $\sim 5$ ns)	Hybrid (THGEM+Mmegas, rise time: $\sim 100$ ns)
Charge	3fC(or 30) (single photoelectron) to 1000fC (ionization)	5000e <sup>-</sup> = 8fC	$2 \times 10^5$ e <sup>-</sup> = 30fC to $\sim 900$ fC (ionization)
Event rate:	<25 KHz ?	40MHz	?
measurements	Digital time	Charge	Digital(Analog)

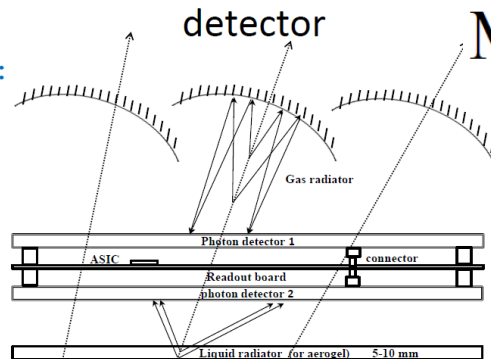
2016-9-2

CEPC-SppC Study Group workshop

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## Design considerations for the RICH detector

Structure:



- Gas radiator (C4F10 or C5F12): several GeV to 40 GeV
- Liquid Radiator (C6F14) or **Silica aerogel**: sub-GeV to 10 GeV

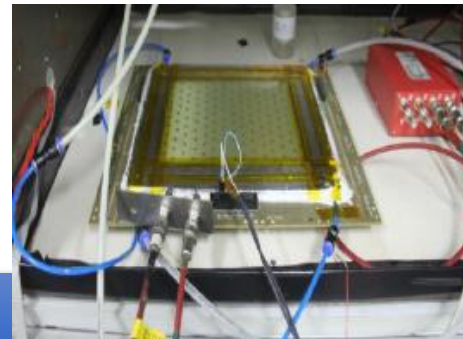
2016-9-2

CEPC-SppC Study Group workshop

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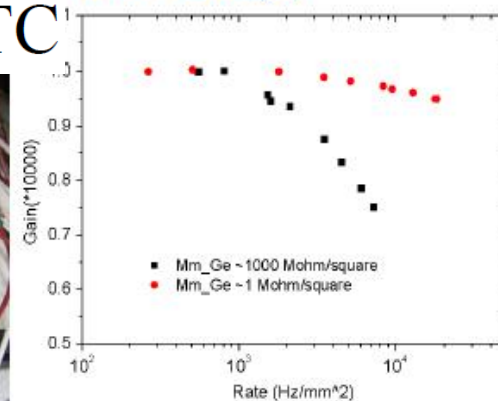
A 200 × 200 mm<sup>2</sup> prototype under testing

## Micromegas R&D at USTC



A typical <sup>55</sup>Fe x-ray spectrum

Gain vs the particle rate (8 keV Cu x-rays)



Gas gain versus mesh

# TPC Performance Comparison

	<b>GEM+MMG 420LPI ( IHEP )</b>	<b>2GEMs + MMG 450 LPI ( Yale University )</b>	<b>Micromegas only 450 LPI ( Yale University )</b>
Ion Back Flow	<b>~0.1%</b> <b>Edrift = 0.25 kV/cm</b>	(0.3 –0.4)% Edrift = 0.4 kV/cm	(0.4 –1.5)% Edrift= (0.1-0.4) kV/cm
<GA>	<b>4000~5000</b>	2000	2000
$\epsilon$ -parameter(=IBF*GA)	<b>4~5</b>	6~8	8~30
E –resolution	<b>~16%</b>	<12%	<= 8%
Gas Mixture ( 2-3 components)	<b>Ar + iC4H10</b>	Ne+CO2+N2, Ne+CO2,Ne+CF4, Ne+CO2+CH4	X + iC4H10 (Ar+CF4+iC4H10)
Sparking ( <sup>241</sup> Am)	<b>&lt;10<sup>-8</sup></b>	< 3.*10 <sup>-7</sup> (Ne+CO2) (N.Smirnov report)	~ 10 <sup>-7</sup> (S. Procureur report)
Possible main problem	<b>Thin frame</b>	More FEE channel	#
Goals	<b>CEPC TPC</b>	ALICE upgrade	#

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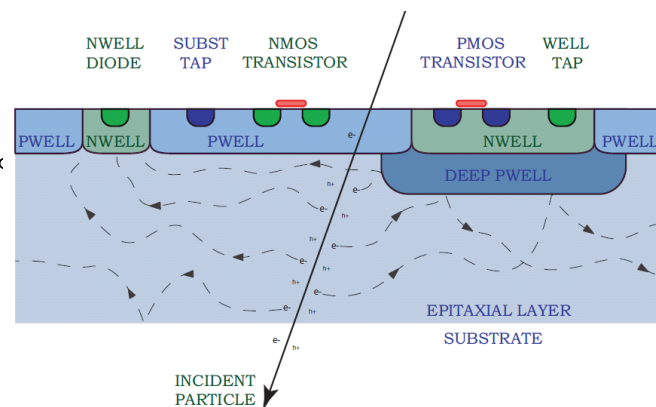
# 子课题一：硅探测器研究目标和内容

研究内容：设计高分辨、快读出、低功耗CMOS像素探测器芯片

芯片指标：空间分辨 $3\text{-}5\mu\text{m}$ ；积分时间 $10\text{-}100\mu\text{s}$ ；功耗  $<100\text{mW}/\text{cm}^2$ ；

抗辐照能力（TID） $\sim 1\text{MRad}$

指标先进：实现小像素单元 $< 16\mu\text{m}$ 电路架构的设计。



## 任务分解

1. 首先设计低噪声，抗辐射的MAPS像素前端。
2. 通过一次MPW流片测试像素参数一致性，研究并提高像素的一致性，通过束流测试空间分辨率和抗辐射能力。

## 关键技术

低噪声，抗辐射的MAPS像素前端；像素参数一致性控制；低噪声模拟输出和高速数字输出；空间分辨测试和抗辐射测试。

# 子课题一： 研究方案和技术路线

- 采用高阻、厚外延层CMOS工艺（比如TowerJazz CIS 0.18 $\mu\text{m}$ ）→提高信噪比；
- 像素内甄别，实现小像素耗尽型CPS设计→降低功耗；
- 新的读出电路架构（编码）设计和零压缩方法，降低功耗，提高读出速度；
- 优点：兼顾空间分辨和功耗。

## 进度安排

第一年：通过调研和比较，确定设计芯片工艺、电荷收集二极管设计方案、前置放大器参数和结构，探索像素阵列新读出结构。

第二年：在所选的工艺上进行MPW流片，测试所选用的工艺，主要测试电荷收集二极管的性能。**中期考核时完成第一次芯片设计及流片，提供初步测试报告。**

第三年：设计整体芯片并进行评审、工程批流片。准备测试系统硬件和测试文档。

第四年：芯片电学性能测试，外围电路工作状态测试，测量芯片的特性参数。

第五年：对芯片进行束流测试，实现芯片的空间分辨率达到5微米,积分时间小于100微秒，功耗小于100微瓦每平方厘米的要求。

发表论文2-3篇论文。

# 子课题一：CPS 第一版设计目标

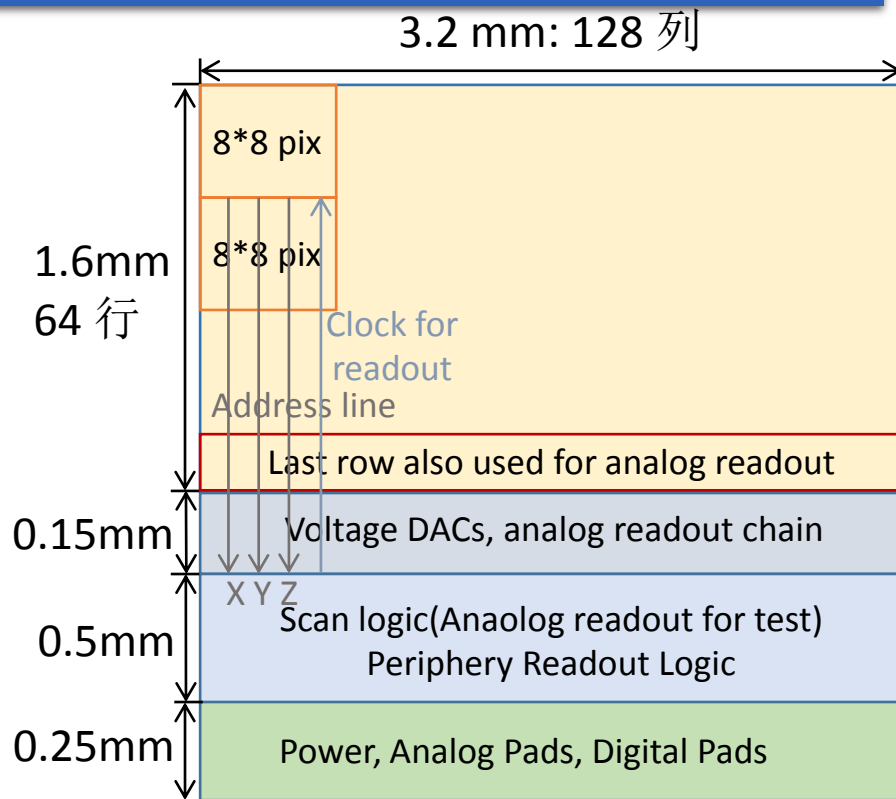
## 设计目标:

- 单像素尺寸:  $25 \times 25 \text{ } \mu\text{m}^2$
- 信号积分时间:  $< 3 \text{ } \mu\text{s}$
- 阵列读出速率:  $25 \text{ ns/hit}$
- 功耗密度:  $< 80 \text{ mW/cm}^2$

**方案:** 快速响应的前端电路  
+ 非零数据压缩读出

## 最新进展:

- 前端甄别器: 峰化时间  $800 \text{ ns}$ , 积分时间  $3 \text{ } \mu\text{s}$
- 非零数据压缩读出: 采用SuperPixel, 各SuperPixel子模块共用地址线以减少走线面积, 但电路实现面积需优化



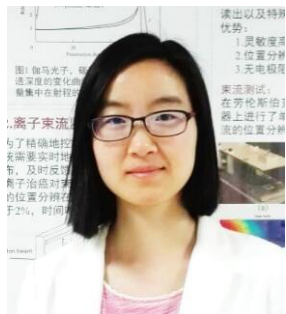
# 子课题一：硅探测器研究团队及基础

华中师范大学：

高能物理研究所： 专用实验室（软硬件条件）



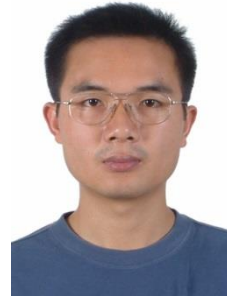
孙向明（教授）



杨莘（讲师）



欧阳群（研究员）



卢云鹏（副研究员）

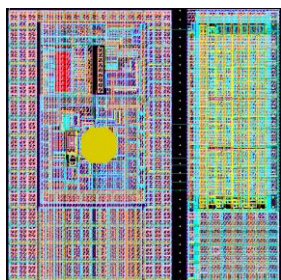


魏微（副研究员）

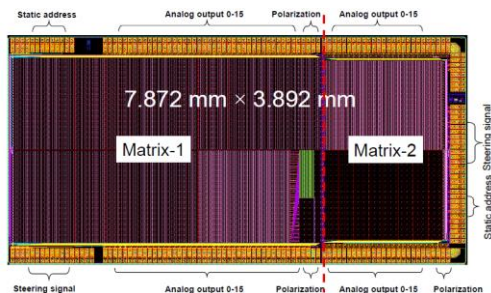
其他人员： 职工 4人 博士后2人 博士研究生 2人 硕士研究生 5人

已承担的硅像素探测器研究工作包括：

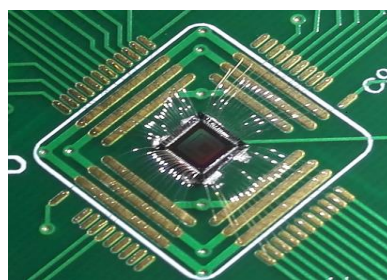
- 用于X射线成像的ASIC读出芯片，像素尺寸 $150\mu\text{m} \times 150\mu\text{m}$ 像素阵列  $72 \times 104$ ；
- CMOS和SOI工艺的单片型像素探测器。



读出ASIC芯片像素单元



CMOS像素探测器



计数型SOI芯片



Topmetal CMOS芯片

# 子课题二：时间投影室研究目标和内容

## 研究目标：

针对物理要求，研发低功耗读出电子学、连续正离子抑制型读出模块，及高分辨时间投影室TPC原型机并进行磁场测试。

## 考核指标：

- 研制一套连续正离子反馈抑制读出模块的TPC原型机
- 位置分辨率:  $100\mu\text{m}$
- 连续正离子抑制:  $\sim 0.1\%$
- 单颗芯片集成16通道，功耗:  $5\text{mW}/\text{通道}$

## 研究内容：

采用先进工艺研发波形采样的低功耗读出电子学芯片，面向环形对撞束特有的连续束流时间结构特点，研制连续正离子抑制型读出模块。重点是采用该模块在1.0T磁场中实现位置分辨率 $100\mu\text{m}$ 的设计指标。

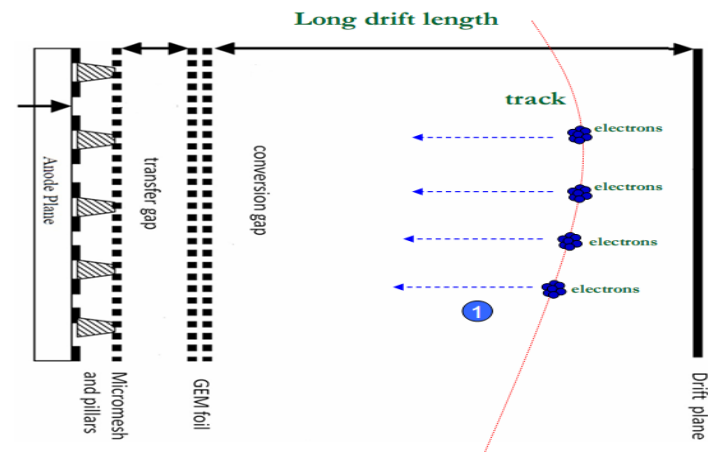
# 子课题二：研究方法及技术路线

## 研究方法及技术路线：

- 研制GEM-Micromegas复合探测器，保证探测器在同等增益下有效降低了打火率，从整体上提高了探测器的性能
- 实现连续工作同时的正离子反馈抑制
- 采用先进65nm的集成电路工艺，简化设计模拟成形电路和逐次比较型ADC，实现低功耗和高集成度的ASIC芯片研制(5mW/通道)

## 主要创新点：

结合环形对撞机特有的设计需求，针对国际上尚未实现的性能指标，采用新的工艺和复合型设计思想，预期实现高分辨率、兼顾稳定工作和低功耗要求读出芯片和探测器研发；在单项指标上达到领先，奠定可实用的技术路线。



连续正离子抑制型  
探测器示意图

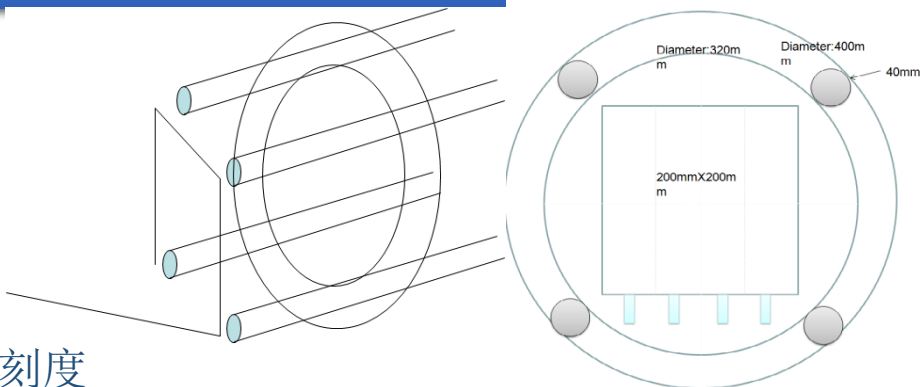


# 具体技术方案设计

第一年确定设计参量，探测器和电子学整体设计完成，开始制作

## 开始探测器方案的设计

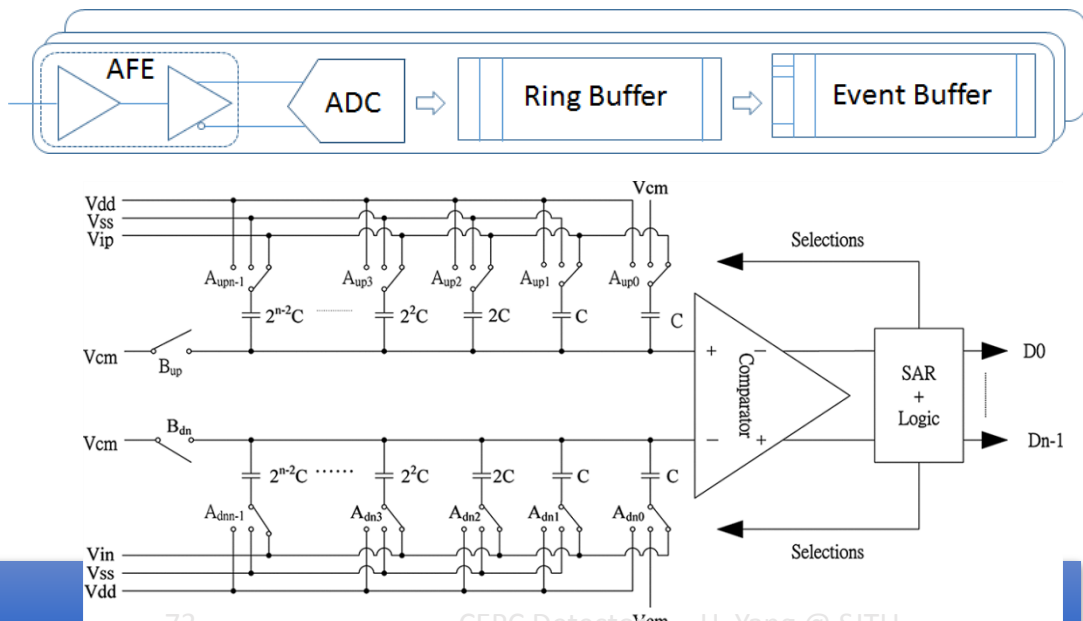
- 光路部分, 笼架结构四个分束Rods
- 内部场笼, 阴极电极板, 外部固定腔体部分
- 定位部分与前读出体基准
- $1\text{mm} \times 6\text{mm}$ 错位Pads排布读出
- 反射、透射、分束,  $1\text{mm}$ 激光束高斯中心位刻度
- 漂移长度 $500\text{mm}$ , 漂移速度及场均匀标定
- 位置分辨率1000路测量



室体设计示意图及端面板

## 开始电子学方案的设计

- 工艺选择: TSMC-65nm
- 单通道芯片的基本结构
- 关键电路单元的结构
  - 模拟前端: CSA+CR-RC
  - ADC: SAR-ADC, 两级缓存
- 尚需确定设计参数:
  - 输入信号动态范围和噪声
  - 波形采样频率和精度



SAR-ADC结构框图

# 子课题二： TPC研究团队和进度安排



高能所祁辉荣（副研）：高分辨正离子抑制型TPC研制  
清华大学邓智（副教授）： TPC低功耗读出电子学研究  
研究队伍（五年）：博士后1人+博士生3人+硕士生2人  
**已落实人员：**

**探测器博士生2人：张余炼，王海云**

**电子学博士生2人：刘丰，赵馨远**

## 进度安排

第一年：模拟研究主要涉设计参量，探测器整体设计，低功耗电子学模拟、设计，完成主要设备器件采购。

第二年：电子学芯片设计定型，开始制作和流片。

**中期目标：确定芯片电路设计方案，测试读出模块，完成项目方案评估及中期评估。**

## 预期成果

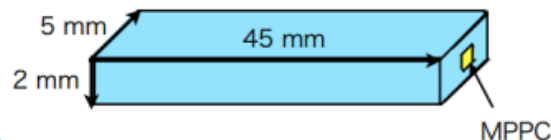
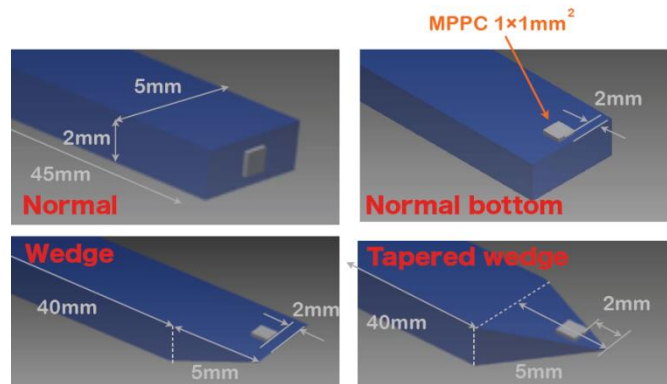
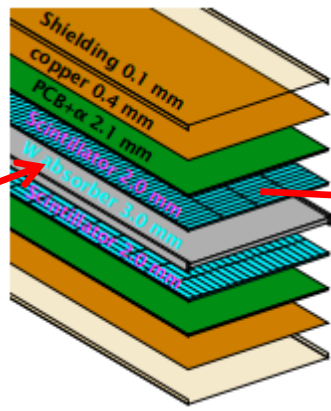
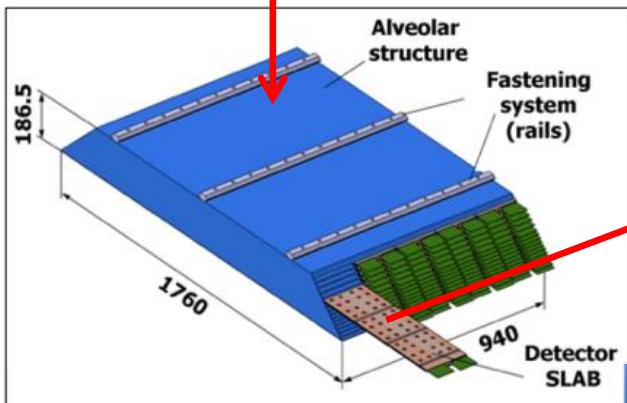
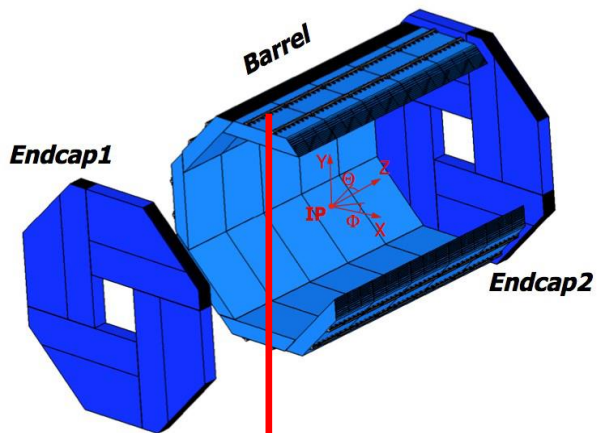
- 实现波形采样低功耗电子学读出芯片的设计，部分指标达到国际先进，完成项目方案评估。
- 模拟及实验研制连续正离子抑制型读出模块，完成原型机方案评估。
- 培养气体径迹探测器研究队伍，~4名研究生；

2016/09/18-19  
发表2篇SCI文章。

# 子课题三：电磁量能器研究目标

## 研究目标和考核指标：

- (1) 解决基于SiPM读出电磁量能器的技术选型问题；
- (2) 实现电磁量能器读出单元颗粒度达到  $5 \times 5 \text{ mm}^2$ ；
- (3) 研制小型电磁量能器原理样机；
- (4) 针对CEPC的特点，研制一套基于两相二氧化碳制冷的主动散热系统，在 $-20^\circ\text{C}$ 下，导热量大于 $30\text{mW}/\text{cm}^2$ ；
- (5) 发表2-3篇论文。



基于塑料闪烁体和  
硅光电探测器

CEPC Detector - H. Yang @ SJTU

## 课题三：研究方法和技术路线

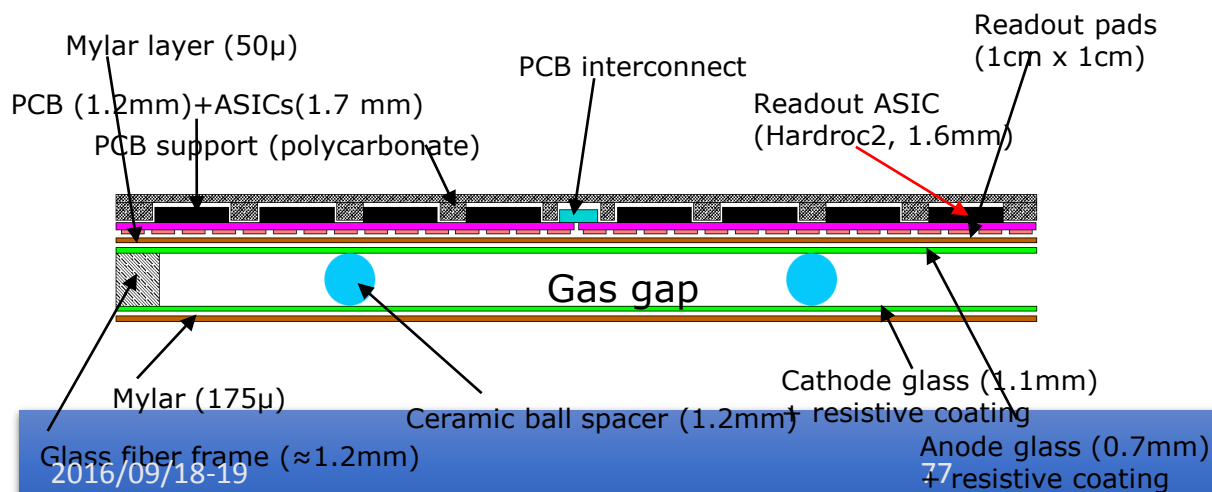
- **设计优化：**通过电磁量能器的设计与模拟优化，读出单元结构优化测试，不同灵敏材料性能测试和对比等，开展电磁量能器的技术选型。
- **读出单元结构研究：**针对目前存在的塑闪条光输出不均匀性进行研究。
- **新灵敏材料的研究：**相比于塑料闪烁体，无机闪烁体具有密度大、光输出高的优点，研究无机闪烁体在电磁量能器中的应用。
- **原理样机建造与测试：**研制一台基于闪烁体和SiPM读出的小型电磁量能器原理样机，该样机横截面 $18\text{cm} \times 18\text{cm}$ ，厚度25层。利用高能粒子束流研究电磁量能器能量分辨、位置重建等性能。通过分析样机束流实验结果研制方案可行性。
- **主动散热系统研究：**根据CEPC连续运行的特点以及量能器高颗粒度和高密度电子学通道对于散热的需求，研制基于两相二氧化碳的主动散热系统来保证电子学正常工作。

# 子课题三：强子量能器研究目标

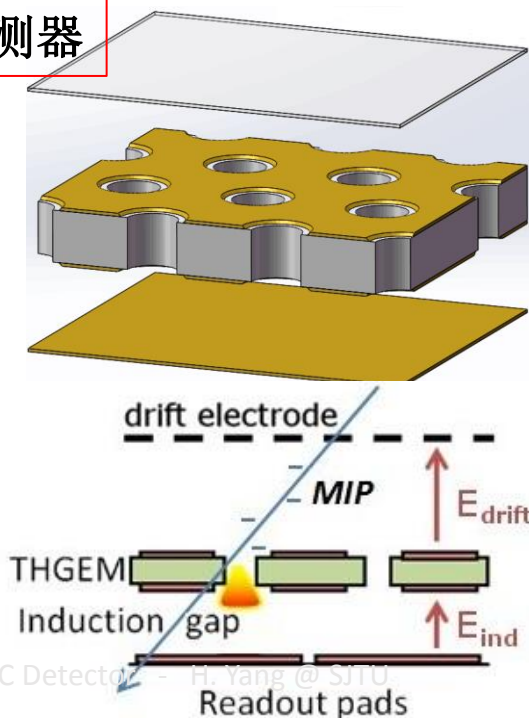
## 研究目标和考核指标：

1. 得到数字强子量能器的技术选型；
2. 在颗粒度达到 $1 \times 1 \text{cm}^2$ 条件下，掌握厚度小于6mm的气体探测器制作工艺；
3. 制作面积达到 $1 \text{m} \times 0.5 \text{m}$ 的微孔型探测器单元模型，探测器的整体增益均匀性好于20%，计数率达到 $1 \text{MHz/s}$ ，探测效率好于95%；
4. 制作面积达 $1 \text{m} \times 1 \text{m}$ 的平板型探测器单元模型，探测效率好于95%；
5. 发表2-3篇论文。

RPC平板型探测器



微孔型探测器



## 子课题三：研究方法和技术路线

- ❑ 通过强子量能器的设计与模拟优化，读出单元结构优化测试，不同灵敏材料性能测试和对比等，开展强子量能器的技术选型。
- ❑ 气体探测器具有容易大面积制作、造价低廉、在适当设计下可以有较高计数率和好的时间与空间分辨等优点，非常适合用作数字强子量能器的灵敏探测器。
- ❑ 针对平板型（RPC）和微孔型（THGEM、GEM）两种气体探测器进行性能研究和比较。探测器的设计优化要求量能器的灵敏层尽可能的紧凑，降低量能器的尺寸和造价。本课题通过探测器单元原型的研制掌握大面积紧凑型气体探测器的设计与制作的方法和工艺。大面积探测器有助于减少死区。
- ❑ 研制强子量能器单元样机，对量能器的关键技术进行原理验证。通过宇宙射线实验测试单元样机的各项性能指标包括增益、能量分辨、探测效率、多重度、计数率、时间分辨率、空间分辨以及稳定性等。

# 子课题三：年度计划

## 进度安排

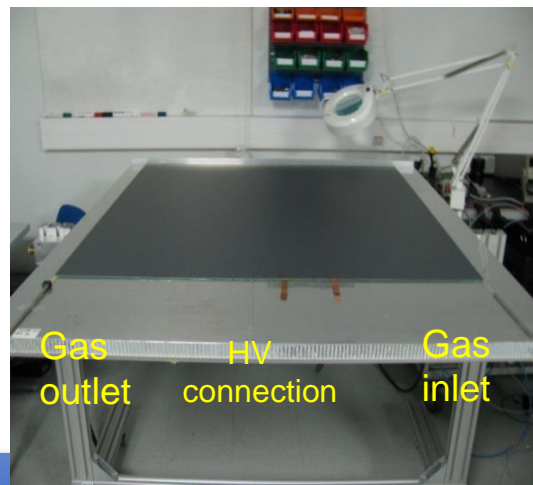
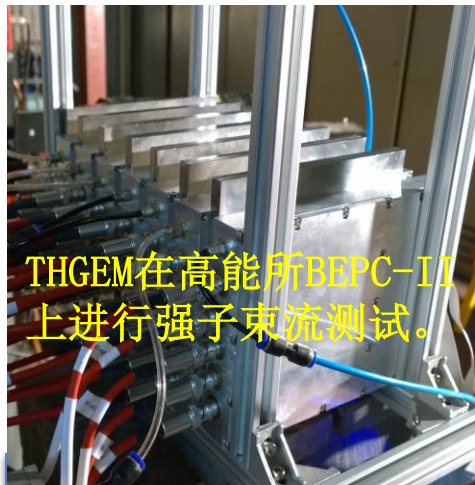
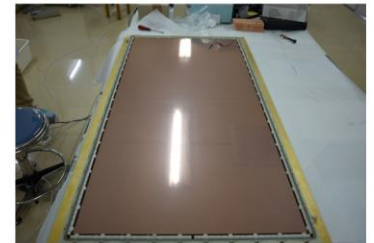
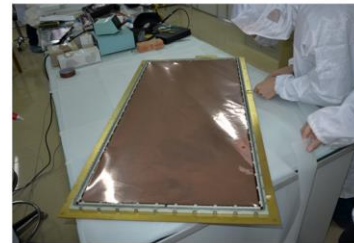
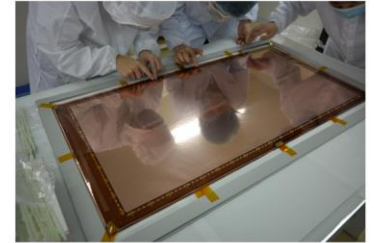
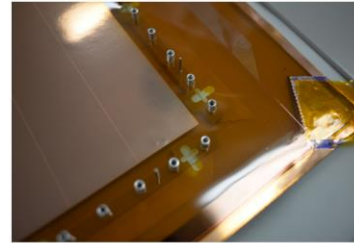
- 第一年：量能器的设计与优化模拟研究，读出单元结构优化测试，不同灵敏体性能测试和对比研究。
- 第二年：确定灵敏单元结构，完成SiPM选型，电子量能器读出板设计和制作；散热系统的模拟和研制。
- 第三年：完成量能器技术选型；进行电磁量能器原理样机试制；强子量能器单元探测器试制。
- 第四年：完成原理样机试制，进行宇宙线实验及束流测试实验；测试散热系统。
- 第五年：实验数据分析及总结，并发表研究论文。

## 预期成果

- 得到量能器技术选型；研制出高颗粒度电磁量能器原理样机和大尺寸紧凑型强子量能器单元模型；性能达到考核指标；培养一支量能器研究队伍；发表4-5篇论文。

# 子课题三：量能器研究基础

- 项目组成员负责完成了北京谱仪BESIII量能器的研制以及暗物质卫星DAMPE中BGO量能器的研制，拥有研制量能器的丰富经验。
- 依托高能所和中国科大联合负责的“核探测与核电子学国家重点实验室”，配置了进行量能器单元性能测试的相关硬件条件及数据分析基础。
- 在 高能所创新经费和中科大重要方向项目 培育基金支持下，开展了课题的初步研究。





# 子课题三：量能器研究团队

电磁量能器研究：2名骨干，1名博后(牛顺利)，2名博士，2名硕士

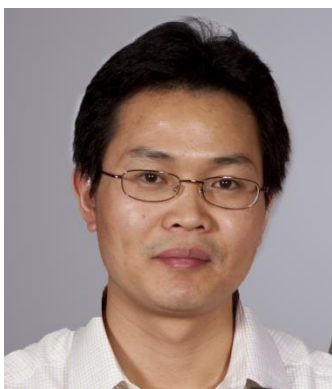


王志刚（副研，高能所）



张云龙（副研，科大）

强子量能器研究：3名骨干，1职工，1博后(胡继峰)，3博士，2硕士



杨海军（教授，交大）



俞伯祥（副研，高能所）



李昕（副研，科大）

# 子课题四：大动量范围粒子鉴别技术研究

## 研究内容

- 环像契伦科夫探测器的设计与优化；
- 基于ThGEM+MicroMegas组合的契伦科夫光探测器的研究；
- 环像契伦科夫探测器原型的研制和测试。

## 研究目标

- 将微结构气体探测器应用于环像契伦科夫探测器，并验证其大动量范围（20-40GeV）的粒子鉴别能力。

## 考核指标

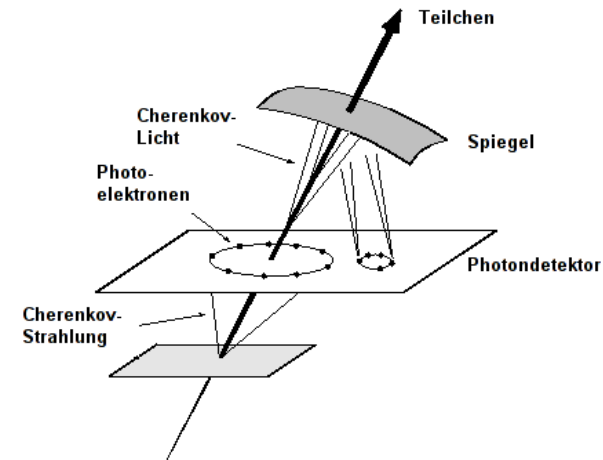
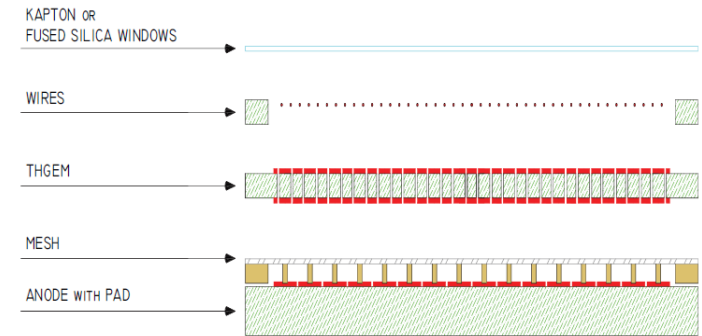
- 单光子角分辨好于2mrad。

## 创新点

- 采用两种微结构气体探测器的组合，实现高灵敏度、低光子和离子反馈的契伦科夫光探测。

# 子课题四： 研究方案和技术路线

- 拟解决的关键问题是如何实现高灵敏度、低本底、高计数率和抗辐照的单光子探测。
- 通过组合微结构气体探测器解决这一问题
  - **ThGEM**: 光电转换 (CsI镀层)、预放大, 阻挡光子反馈。
  - **MicroMegas**: 主放大, 离子反馈小。
- 研制环像契伦科夫探测器原型
  - 采用气体辐射体覆盖大动量范围
  - 采用球面镜将契伦科夫光汇聚到光探测器平面
  - 采用ThGEM+MicroMegas作为光探测器
- 利用高能粒子束测试原理样机的单光子角分辨, 验证其粒子鉴别能力。



环像契伦科夫探测器的工作原理

# 子课题四：年度计划

## ➤ 2016.7 – 2017.6

- 进行探测器原理和结构设计、模拟研究，对探测器关键参数进行优化，基本确定契伦科夫探测器总体设计。

## ➤ 2017.7 – 2018.6

- 试制不同结构的THGEM+Micromegas 混合型微结构气体探测器，并测试探测器主要性能，得到能够独立工作的单光子灵敏探测器。

## ➤ 2018.7 – 2019.6

- 设计球面聚焦反射镜，研究球面反射镜的相关基本参数，优化和完善RICH 探测器原理样机的整体设计。制作灵敏面积达 $10\text{cm} \times 10\text{cm}$  的RICH 样机。

## ➤ 2019.7 – 2020.6

- 完成原理样机的整机调试，对各读出单元进行刻度，利用宇宙射线完成样机初步测试和标定，完成切伦科夫光环形成像重建。

## ➤ 2020.7 – 2021.6

- 利用高能粒子束测试样机，获取、分析数据，通过样机束流测试完成RICH探测器设计方案的原理验证，实现预定指标：单光子角分辨 $2\text{mrad}$ 。

# 子课题四：研究团队及基础



刘建北，教授，中国科学技术大学

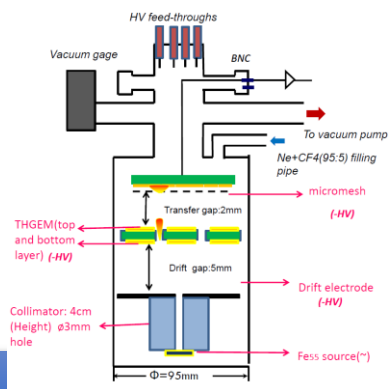
团队成员： 博士后张志永，博士生1人，硕士生1人

**研究基础：** 长期开展大面积GEM和MicroMegas等微结构气体探测器的研发，成功制作出各种探测器原型，具有扎实的研制微结构气体探测器的硬件条件和基础。此外，还具有高灵敏度光电测试平台。

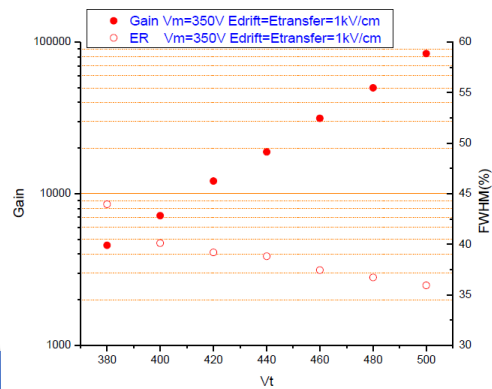


采用热压膜工艺制作的MicroMegas

## ThGEM+MicroMegas组合的初步尝试



探测器原型



增益及能量分辨