下一代高能物理实验中的大型气体径迹探测器与气体探测器发展前沿

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主要内容

- 气体探测器简介
- 下一代高能物理实验中的大型气体径迹探测器
- 气体探测器发展前沿
- 小结

气体探测器简介

- 气体探测器是核与粒子物理实验中非常重要的探测器
- 气体探测器的特点：

1) 物质密度小，时间响应快，空间分辨率高

2) 探测器的灵敏体积大小和形状几乎不受限制；

3) 辐射损伤不灵敏或易恢复；

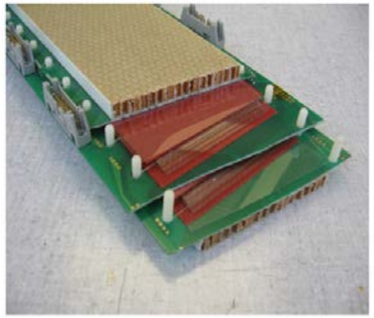
4) 造价低，经济可靠。

气体探测器种类及应用

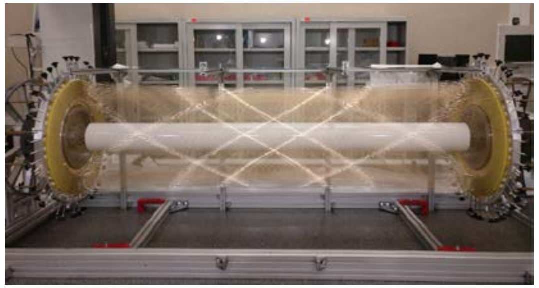
- G-M计数管，电离室，正比计数管，云室，气泡室，火花室等
- 多丝正比室，漂移室，时间投影室， RPC，MRPC等
- 微结构气体探测器：MSGC，GEM， MicroMEGAS，ThickGEM， μRWell等

物理实验中使用最早的探测器，对核和粒子物理的发展起巨大作用（核裂变，正电子和μ子，Ω^-粒子等）

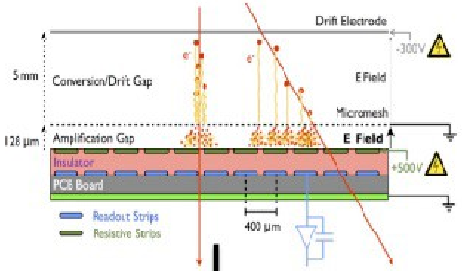
ALICE MRPC



MEGII drift chamber

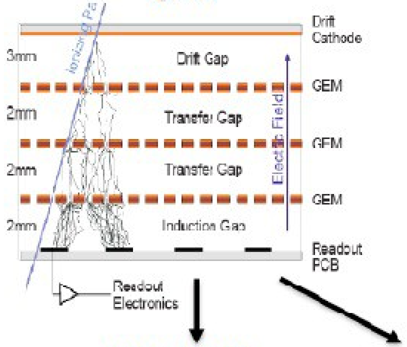


MicroMegas (MM)



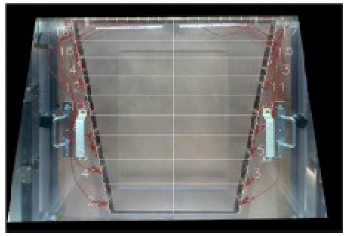
ATLAS new small wheels

GEM

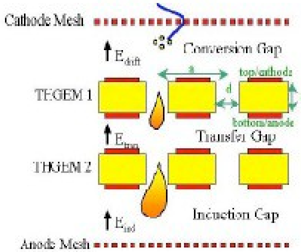


CMS GEM

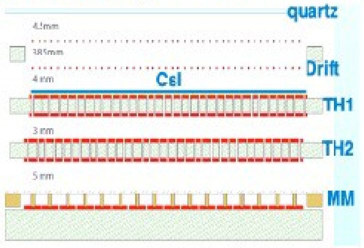
ALICE TPC upgrade



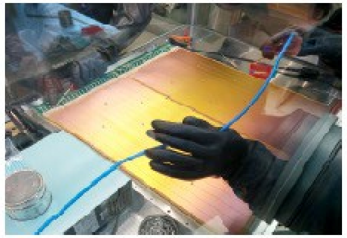
THGEM



Hybrid design THGEM + MM



COMPASS RICH



径迹探测器设计/选择的基本考虑

高能物理实验中，大型气体径迹探测器具有举足轻重的地位，被广泛使用。为下一代高能物理实验中径迹探测器至关重要的选项

- 满足物理要求
  - 立体角覆盖
  - 探测效率（双径迹分辨能力、计数能力、老化性能、前端电子响应）
  - 对角度、动量、顶点外推（包括多次散射）的最终分辨率贡献和粒子鉴别能力
- 系统复杂性
  - 单元通道总数
  - 相对的和整体的校准参数的稳定性
  - 各通道刻度的稳定性
- 系统接口
  - 加速器和探测器接口
  - 与顶点探测器（径迹外推）和外部电磁量能器间的接口
- 总成本

Gaseous Tracking (TPC, Drift Chambers, MPGD) @ Future Colliders

不完全列举

Experiment / Timescale	Application Domain	Gas Detector Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements/ Remarks
ALICE TPC UPGRADE CERN LS2	Heavy-Ion Physics (Tracking + dE/dx)	4-GEM / TPC	Total area: ~ 32 m^2 Single unit detect: up to 0.3m^2	**Max.rate**:100 kHz/cm^2 **Spatial res.:** ~300µm **Time res.:** ~ 100 ns **dE/dx:** 11 % **Rad. Hard.:** 50 mC/cm^2	- 50 kHz Pb-Pb rate; - Continues TPC readout - Low IBF and good energy resolution
ILC TPC DETECTOR: STARTt: > 2035	e+e- Collider Tracking + dE/dx	MM, GEM (pads) InGrid (pixels)	Total area: ~ 20 m^2 Single unit detect: ~ 400 cm^2 (pads) ~ 130 cm^2 (pixels)	**Max. rate**: < 1 kHz **Spatial res.:** <150µm **Time res.:** ~ 15 ns **dE/dx:** 5 %	Si + TPC Momentum resolution : dp/p < $9*10^{-5}$ 1/GeV Power-pulsing
CEPC TPC DETECTOR	e+e- Collider Tracking + dE/dx or dN/dx	MM, GEM (pads) InGrid (pixels)	Total area: ~ 2x10 m^2 Single unit detect: up to 0.04 m^2	**Max.rate**:>100 kHz/cm^2 **Spatial res.:** ~100µm **Time res.:** ~ 100 ns **dE/dx:** <5%	- Higgs run - Z pole run - Continues readout - Low IBF and dE/dx
FCC-ee and/or CEPC IDEA CENTRAL TRACKER START: >2030	e+e- Collider Tracking/ Triggering	He based Drift Chamber	Total volume: 50 m^3 Single unit detect: (12 m^2 X 4 m)	**Max. rate:** <1 MHz/cm^2 **Spatial res.:** <100 µm **Time res.:** 1 ns **Rad. Hard.:** NA	Particle sepration with cluster counting at 2% level
SUPER-CHARM TAU FACTORY START: > 2025	e+e- Collider Main Tracker	Drift Chamber	Total volume: ~ 3.6 m^3	**Max. rate**: 1 kHz/cm^2 **Spatial res.:** ~100 µm **Time res.:** ~ 100 ns **Rad. Hard.:** ~ 1 C/cm	
SUPER-CHARM TAU FACTORY START: > 2025	e+e- Collider Inner Tracker	Inner Tracker / (cylindrical µRWELL, or TPC / MPDG read.	Total area: ~ 2 - 4 m^2 Single unit detect: 0.5 m^2	**Max. rate**: 50-100 kHz/cm^2 **Spatial res.:** ~<100 µm **Time res.:** ~ 5 -10 ns **Rad. Hard.:** ~ 0.1-1 C/cm^2	Challenging mechanics & mat. budget < 1% X0

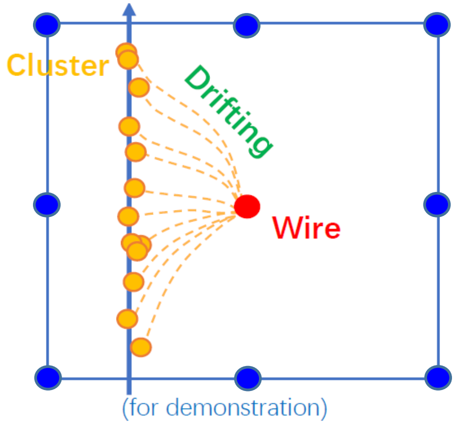
正负电子对撞机上的径迹探测器

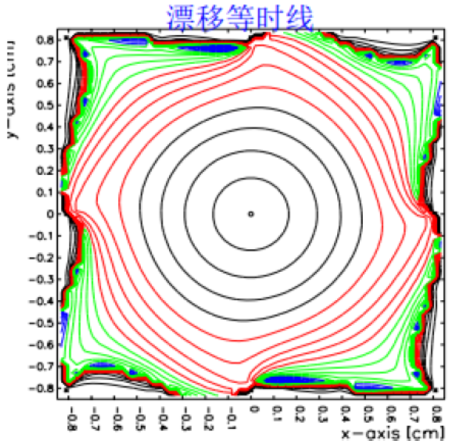
不完全列举

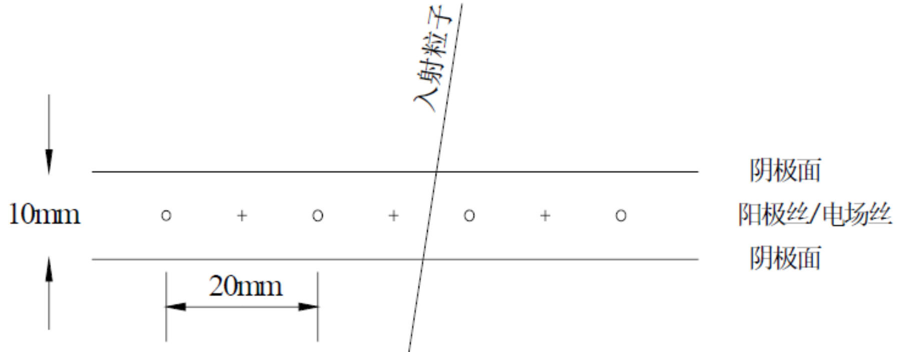
LEP	ALEPH	TPC
	DELPHI	TPC
	L3	Si + TEC
	OPAL	Drift Chamber
SLC	MARK2	Drift Chamber
	SLD	Drift Chamber
DAPHNE	KLOE	Drift Chamber
VEPP2000	CMD-2	Drift Chamber
PEP2	BaBar	Drift Chamber
KEKB	Belle	Drift Chamber
CESR	CLEO3	Drift Chamber
BEPCII	BESIII	Drift Chamber

ILC	ILD	TPC
	SiD	Si
CLIC	CLIC	Si
FCC-ee	CLD	Si
	IDEA	Drift Chamber
CEPC	Baseline	Si + TPC
	Backup	Si + Drift Chamber
	IDEA	Drift Chamber
KEKB	Belle2	Drift Chamber
SCTF	BINP	Drift Chamber
SCTF	HiEPA	Drift Chamber
SCTF (China)		Drift Chamber

漂移室







第一个漂移室 （Walenta等）

带电粒子与漂移室气体原子作用，产生激发或电离，粒子损失部分能量，在径迹上产生一系列电离电子

- 电离电子在电场作用下向阳极丝漂移，到达阳极丝表面附近产生雪崩放大，并输出信号
- 测量出电离电子的漂移时间并结合X-T关系得到入射粒子的位置信息；
- 信号电荷量还包含了入射粒子能量损失信息。

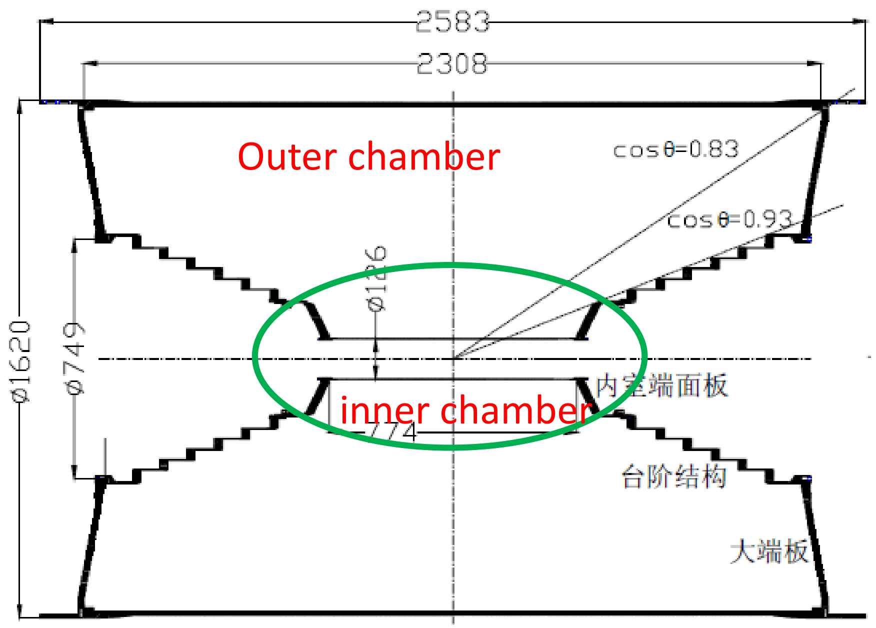
$$\sigma_x = \frac{1}{\sqrt{n}}\sqrt{2Dt} = \frac{1}{\sqrt{n}}\sqrt{\frac{2DL}{W}} = \frac{1}{\sqrt{n}}\sqrt{\frac{2DL}{\mu E}}$$

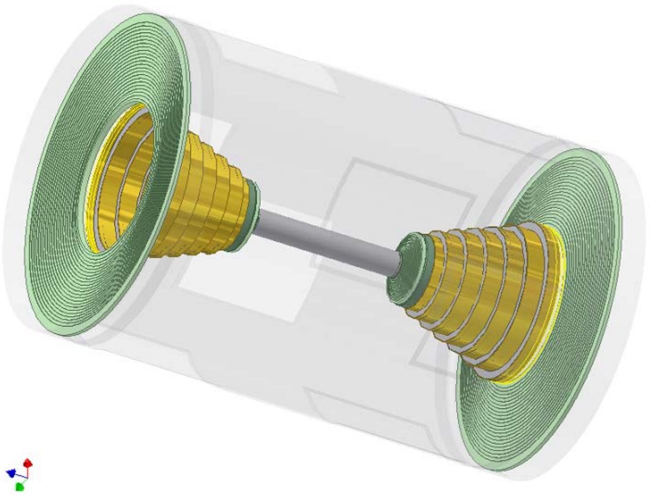
$$\sigma^2 = \sigma^2_{\text{扩散}} + \sigma^2_{\text{电离}} + \sigma^2_{\text{电子学}}$$

- 主要特点
  - 漂移室属于成熟的探测技术
  - 可以制作成大体积探测器
  - 空间分辨率高
  - 物质量低
  - 高计数率下工作的问题，老化问题

BESIII 漂移室(MDC)

丝层数	43 （内室: 8 +外室: 35）19直丝层，24斜丝层
单元数	6796
单元尺寸	内室: 12mm×12mm，外室: 16.2mm×16.2mm
半径	63 mm → 810 mm
长度	2308 mm
内筒	1.2mm （CF）
外筒	11.5mm （CF）
端面板	18mm Al （6层台阶，内室端面板:25mm Al）



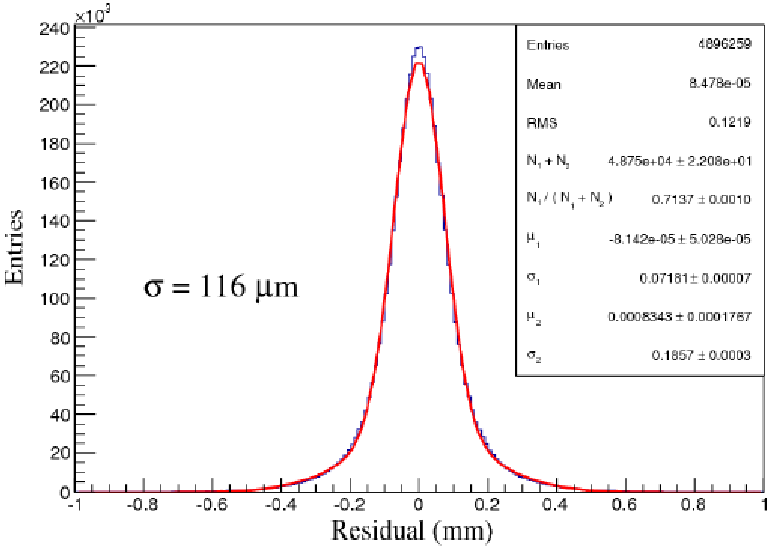


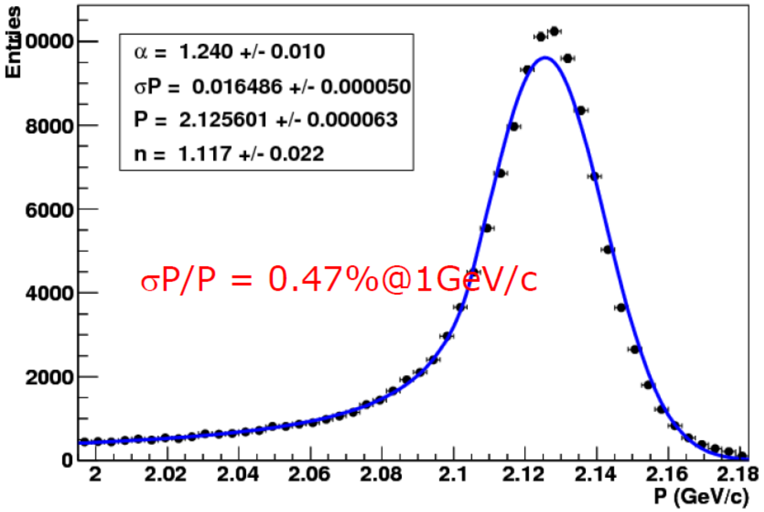
- 2006年低完成建造
- 2007年宇宙线测试及谱仪安装
- 2008年运行调试及取数
- 2009年开始物理取数，稳定运行超过15年

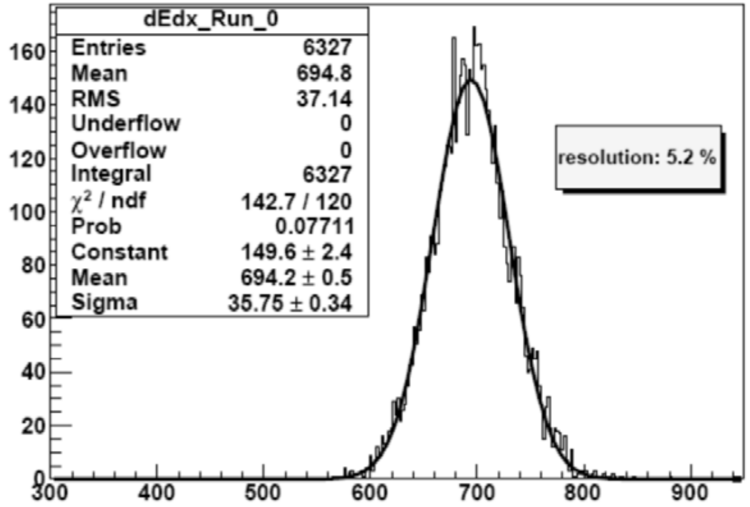
BESIII 漂移室(MDC)

Parameters	Design Performance	Achieved Performance
$\sigma_{r\phi}$	$130\ \mu m$	$\sigma_{r\phi} = 115\ \mu m$
$\Delta p/p$	$0.5\%@1GeV$ (B=1T)	$0.47\%@1GeV$ (B=1T)
$\sigma_{dE/dx}$	6%	5.2%

Residual distribution







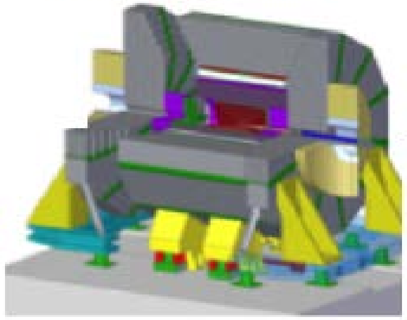
Bhabha from Run 50500

下一代高能物理实验中的漂移室

3.5(4) T solenoid, 8.8 x 8 m
Si Pixel + TPC R=1.8(1.5) m

ILD/ILC

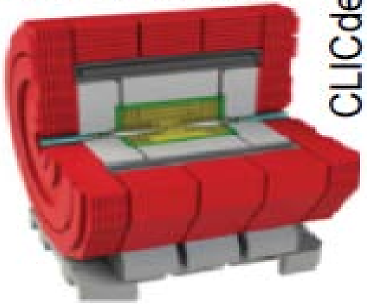
5T solenoid, 6.8 x 8 m
Full Si-Tracker R=1.2 m



SiD/ILC

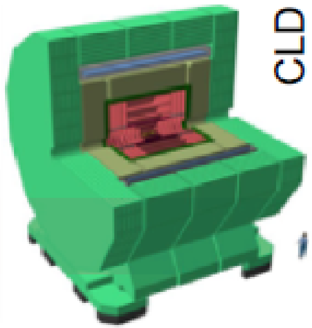
Power Pulsing options

5T solenoid, 6.8 x 6 m
Full Si-Tracker R=1.5 m



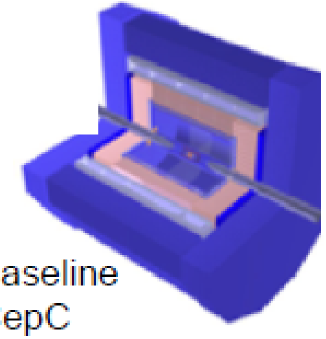
CLICdet

2T solenoid, 7.4 x 7.4 m
Full Si-Tracker R = 2m



CLD

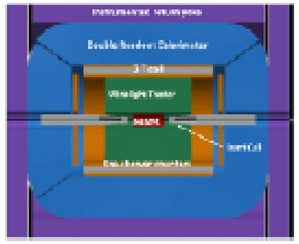
3T solenoid, 6.4 x 7.8 m
Si Pixel + TPC R=1.8m



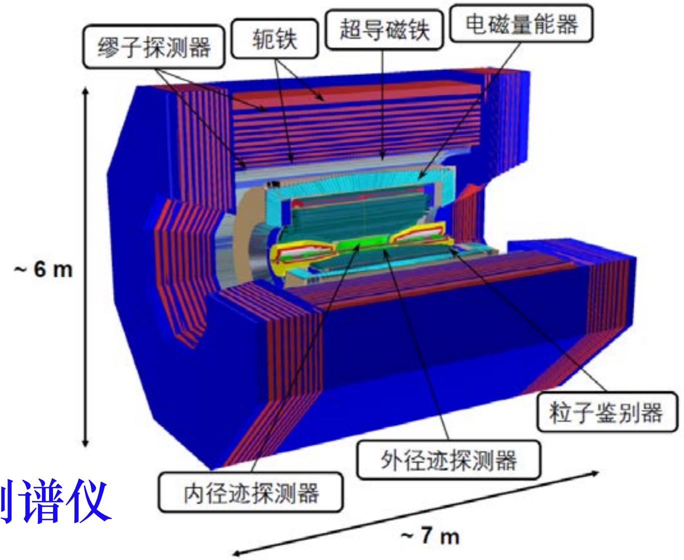
Baseline
CepC

2T solenoid, 4.2 x 6 m
Si Pixel + Drift Chamber R=2m

Pre-shower/MPGD
+ Dual Calorimetry



IDEA
FCC-ee / CepC

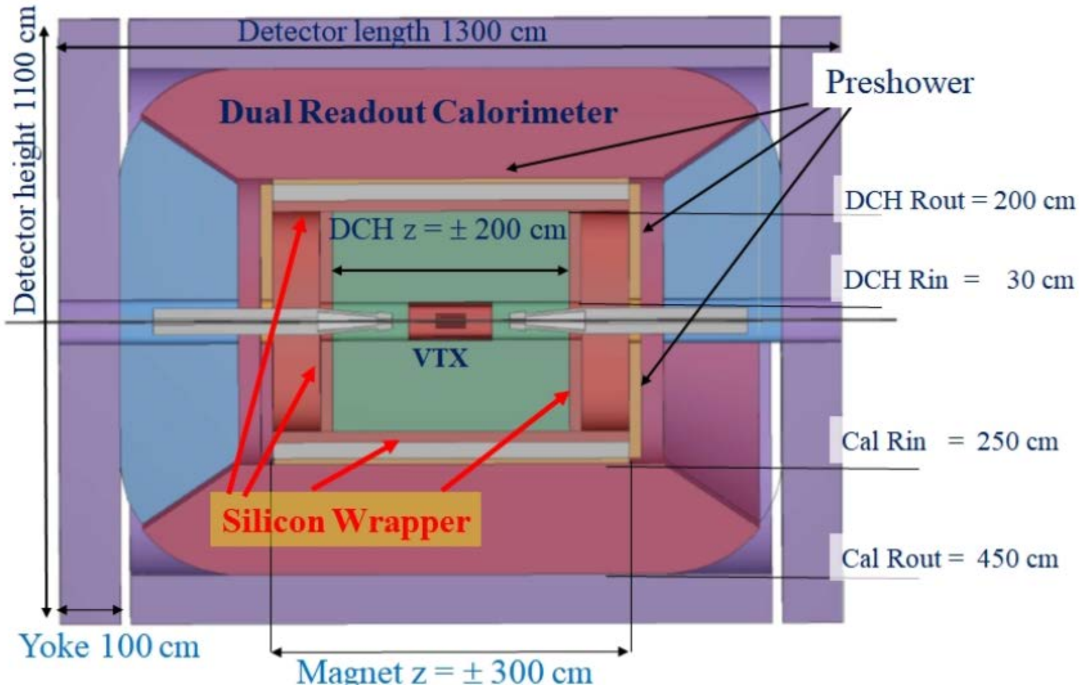


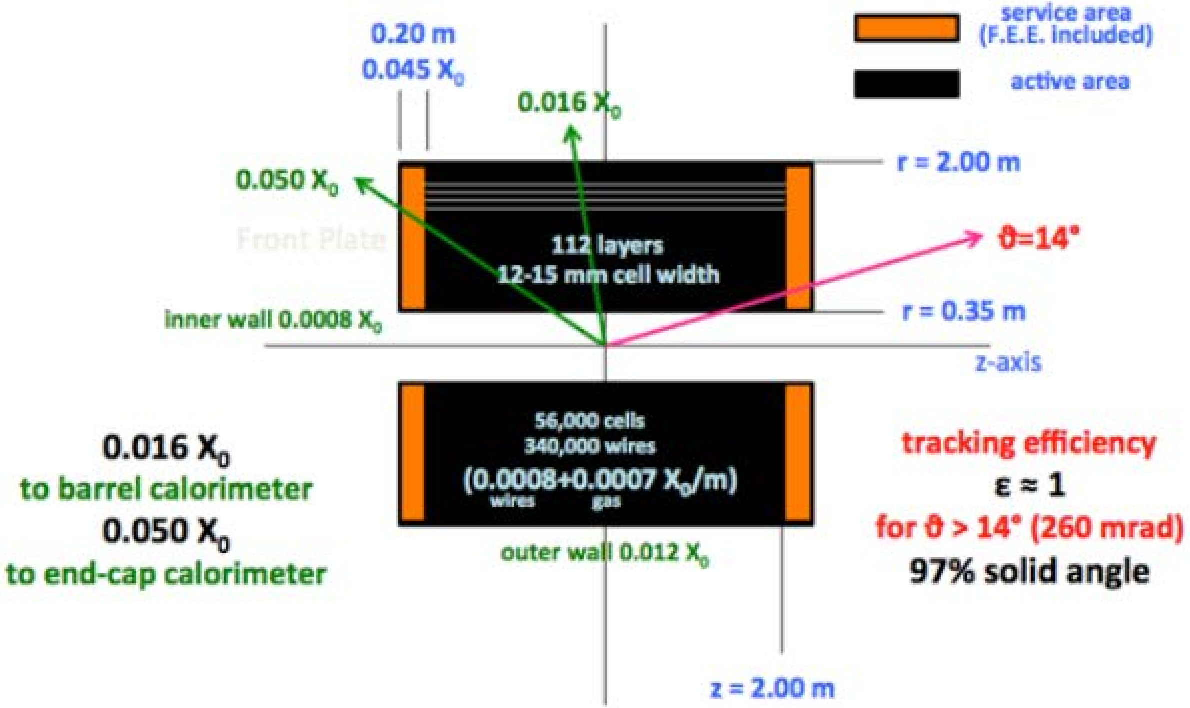
STCF探测谱仪

- 应用于ILC，CLIC，Fcc-ee，CEPC，STCF等

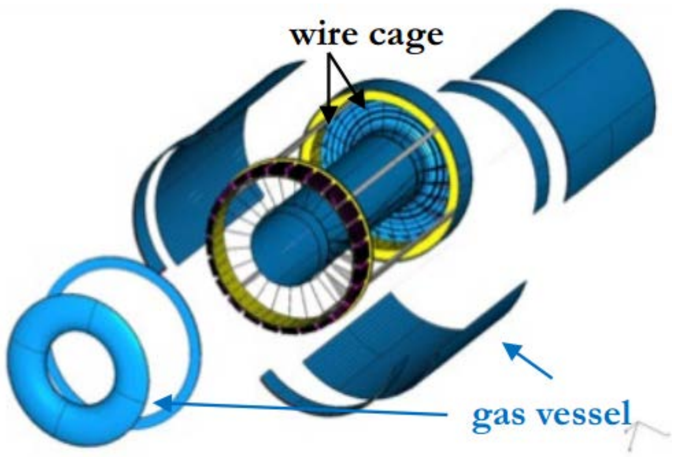
IDEA drift chamber

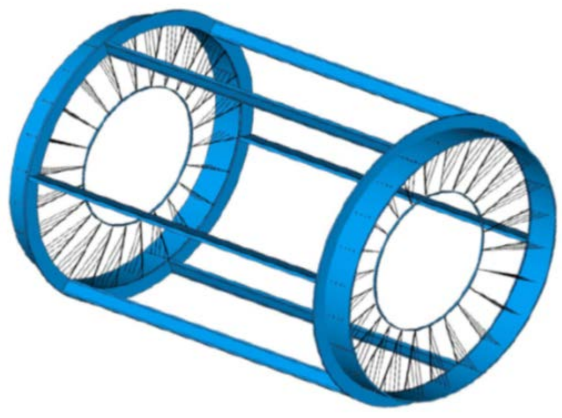
- 针对FCC-ee和CEPC的大体积超轻漂移室（IDEA漂移室）
  - 较小的多次散射影响
  - 高精度动量测量
  - 出色的粒子鉴别能力识别（通过原初电离计数方法Cluster counting）
- 设计来源于DAFNE KLOE漂移室及其用于**MEG II**实验的最新版本

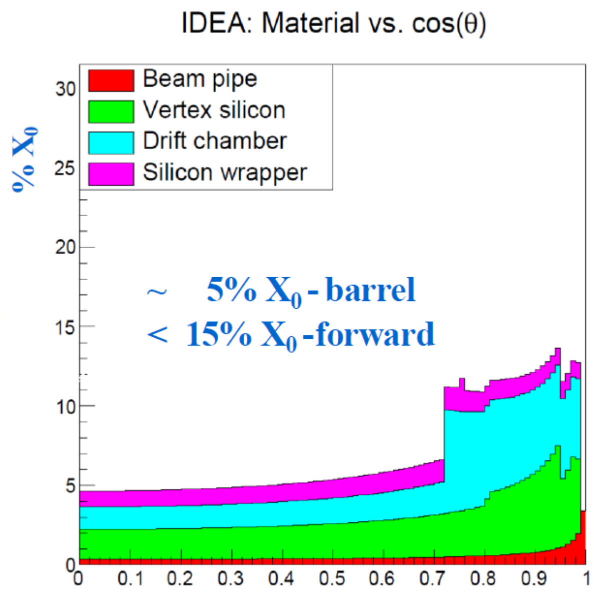


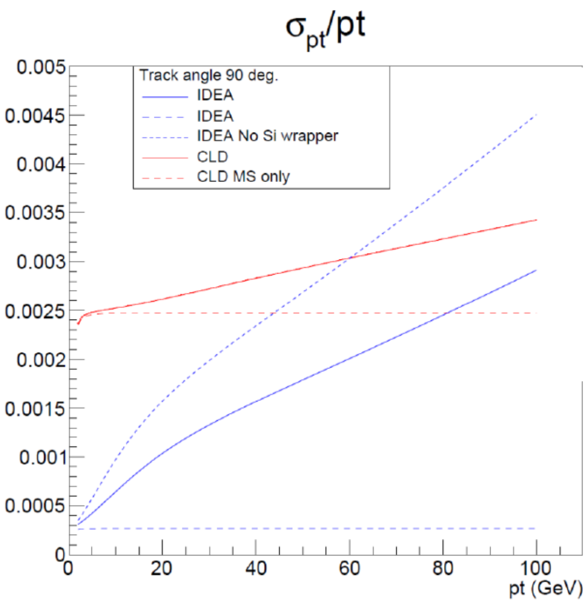


IDEA drift chamber

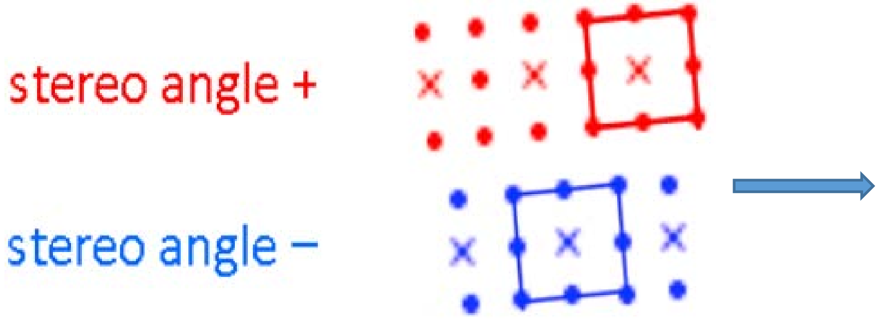




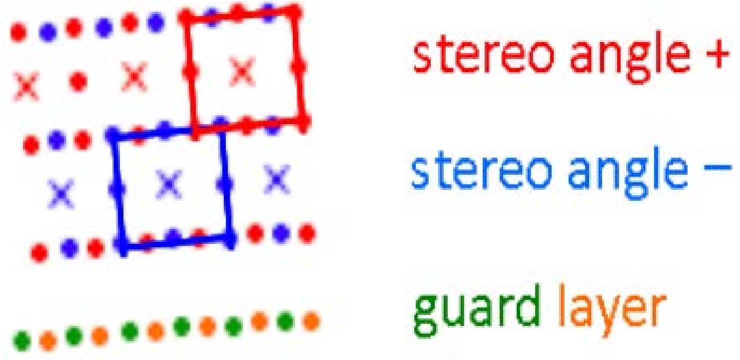




- 低物质量设计



场丝信号丝数量比: 3:1

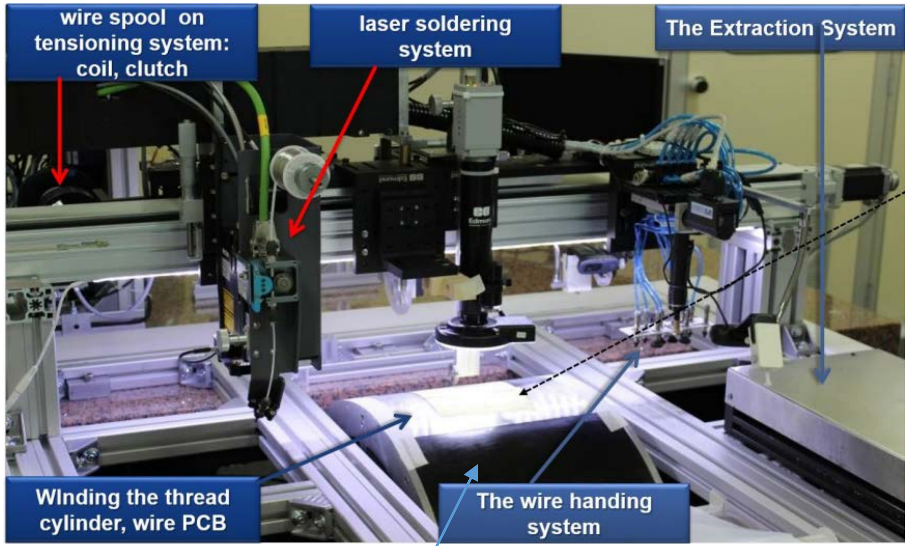


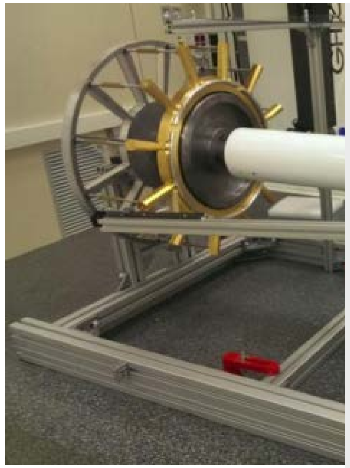
场丝信号丝数量比: 5:1

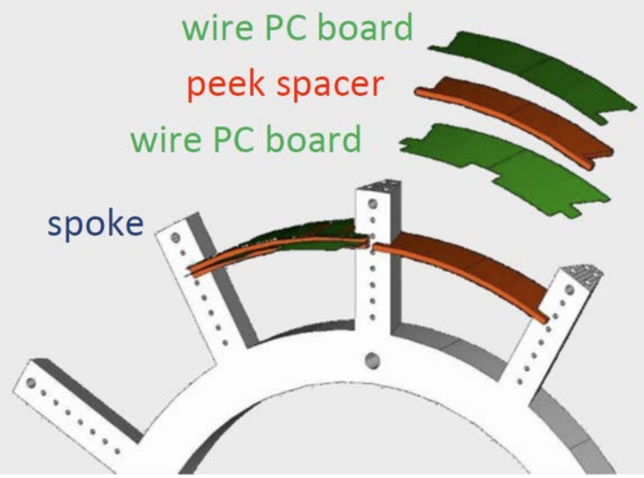
- 小单元, 布丝密度高
- 每个单元的场丝更多，可以使用更细的场丝
- 高密度布丝需要非常规布线丝流程，无定位子布线系统

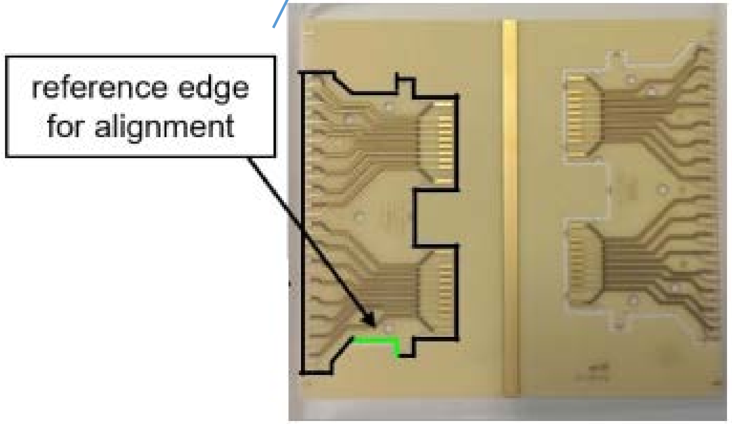
MEG II 漂移室

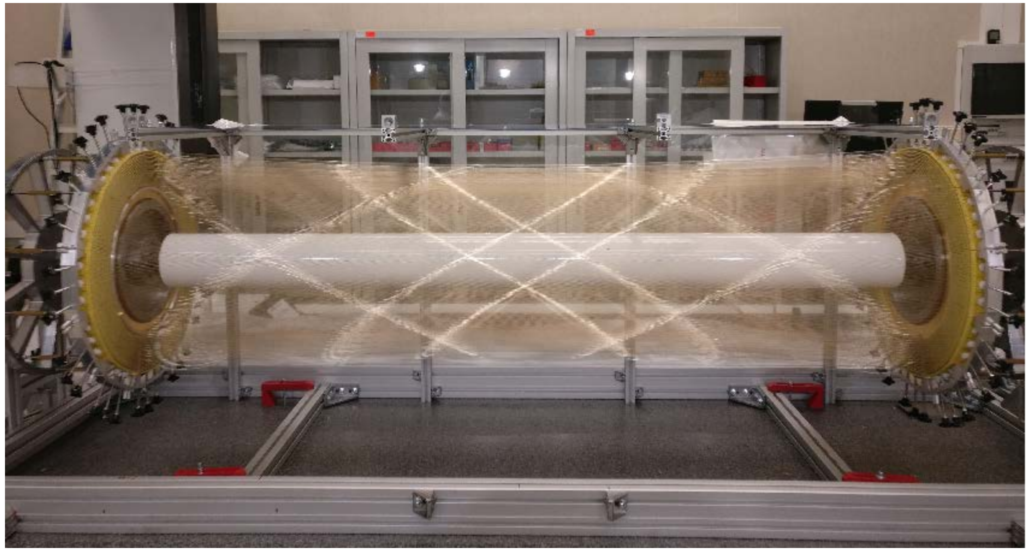
- 不使用定位子，丝焊接固定在PCB板上
- 复杂的装配工具
- 组装过程也较复杂
- 在MEGII漂移室上得到了验证







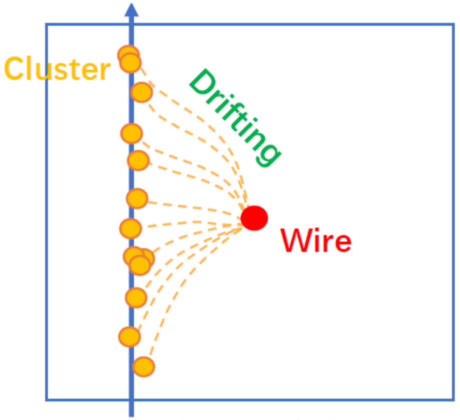




- length: 1.91 m
- radius: 17 cm- 29 cm
- 10 concentric layers
- Cell size : 6.6 mm -9.0 mm
- Total number of cells: 1920
- Total number of wires 13056

原初电离计数 (dN/dx) 方法

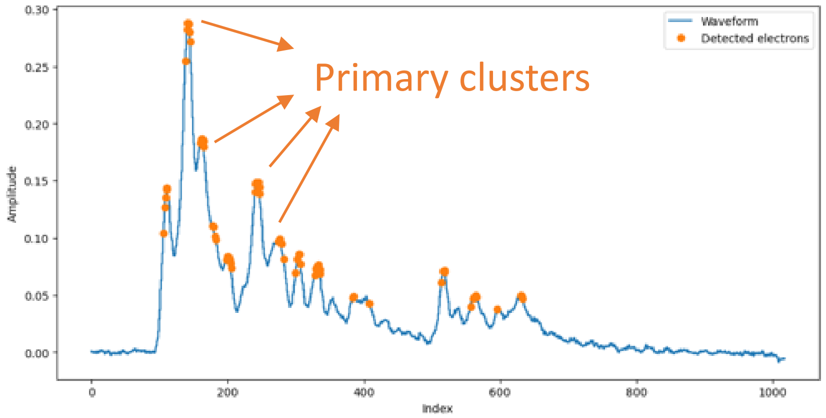
DC cell



(for demonstration)

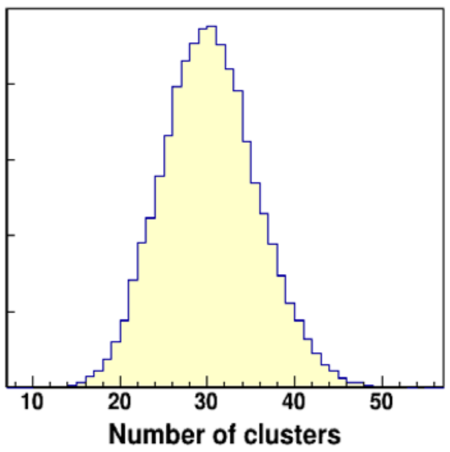
- 测量通过漂移室单元的簇团数量，簇团数量对应于原初电离的数量
- 原初电离的产额为泊松分布，波动小，分辨率可能比dE/dx高2倍

Waveform

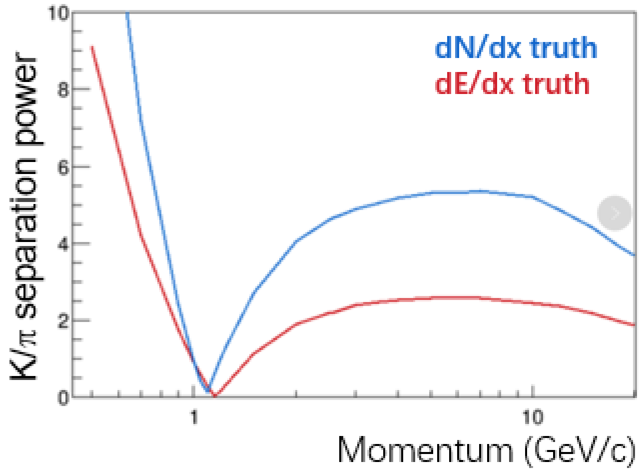


Require fast electronics and sophisticated counting algorithm

Counting clusters



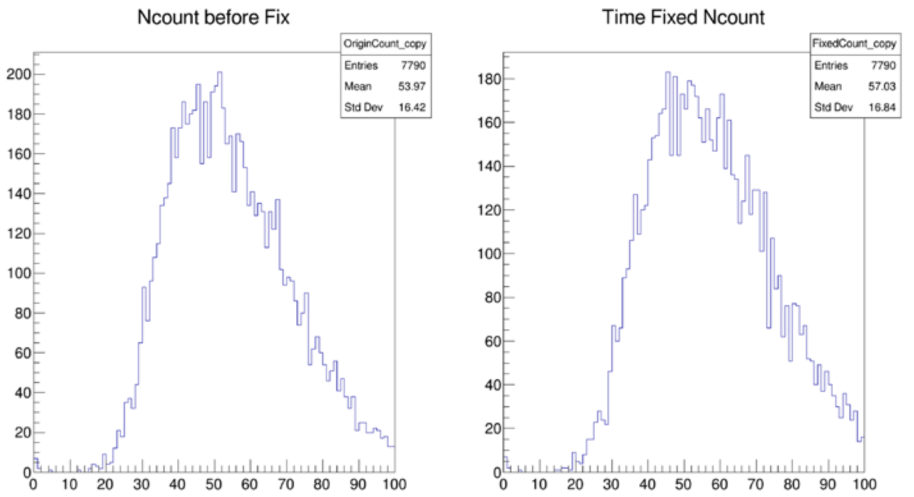
K/π separation power
dN/dx vs dE/dx

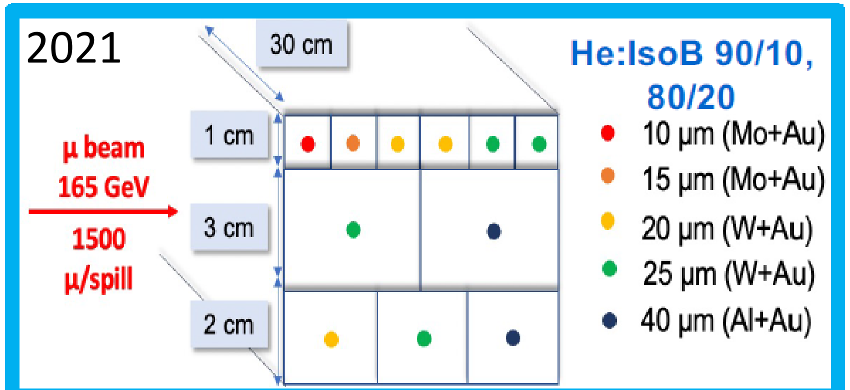


dN/dx is proposed in ILC, FCC-ee, CEPC

dN/dx束流实验

- 2021年11月和2022年7月两次在CERN-H8（βγ>400）进行了μ介子束流实验（pT=165/180 GeV）
- 2023年在CERN进行μ介子束流实验（动量为4-12 GeV）
- 2024年7月10日开始新的束流实验（与2023年配置相同）

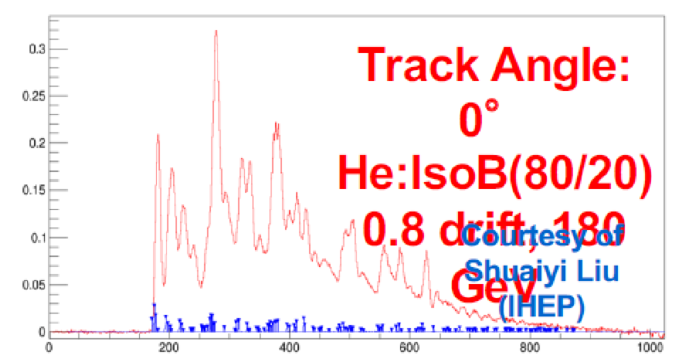




μ beam
165 GeV
1500
μ/spill

He:IsoB 90/10, 80/20

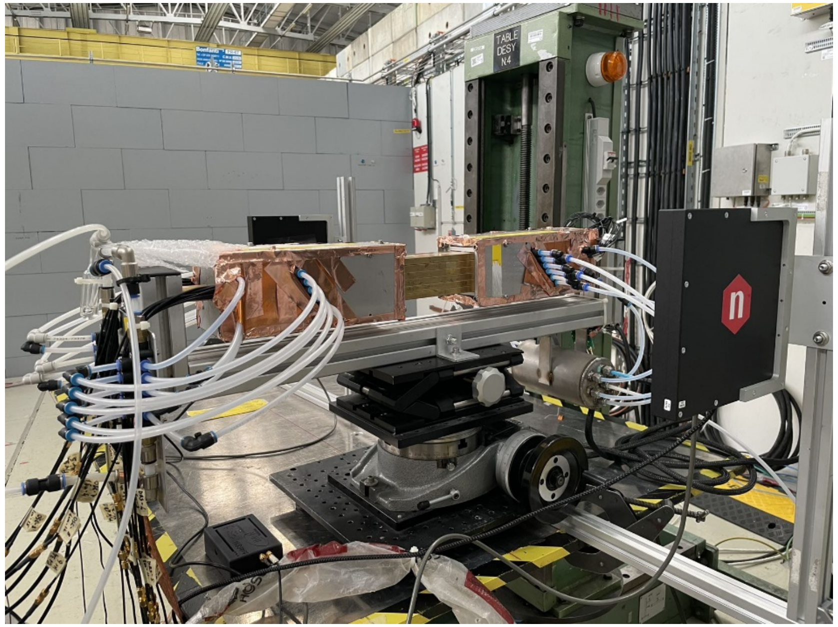
- ● 10 μm (Mo+Au)
- ● 15 μm (Mo+Au)
- ● 20 μm (W+Au)
- ● 25 μm (W+Au)
- ● 40 μm (Al+Au)

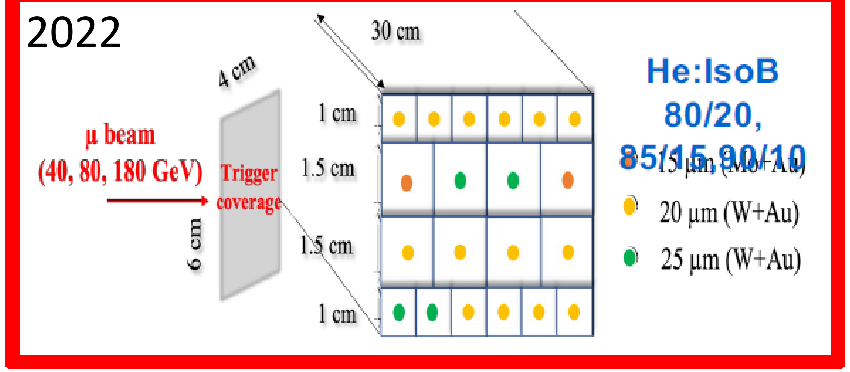


Track Angle: 0°
He:IsoB(80/20)
0.8 drift, 180 GeV

Courtesy of Shuaiyi Liu (IHEP)

2024.7

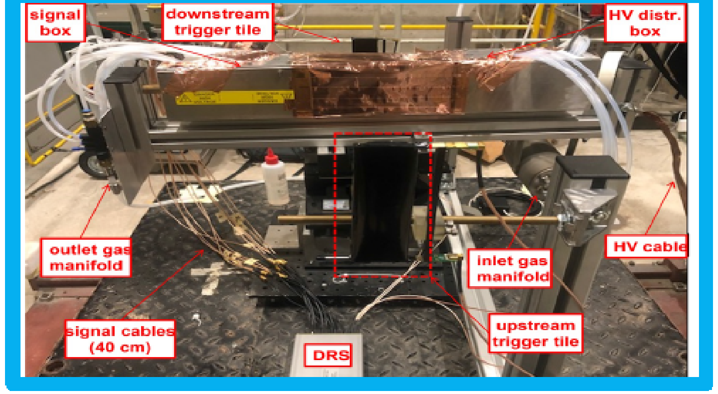




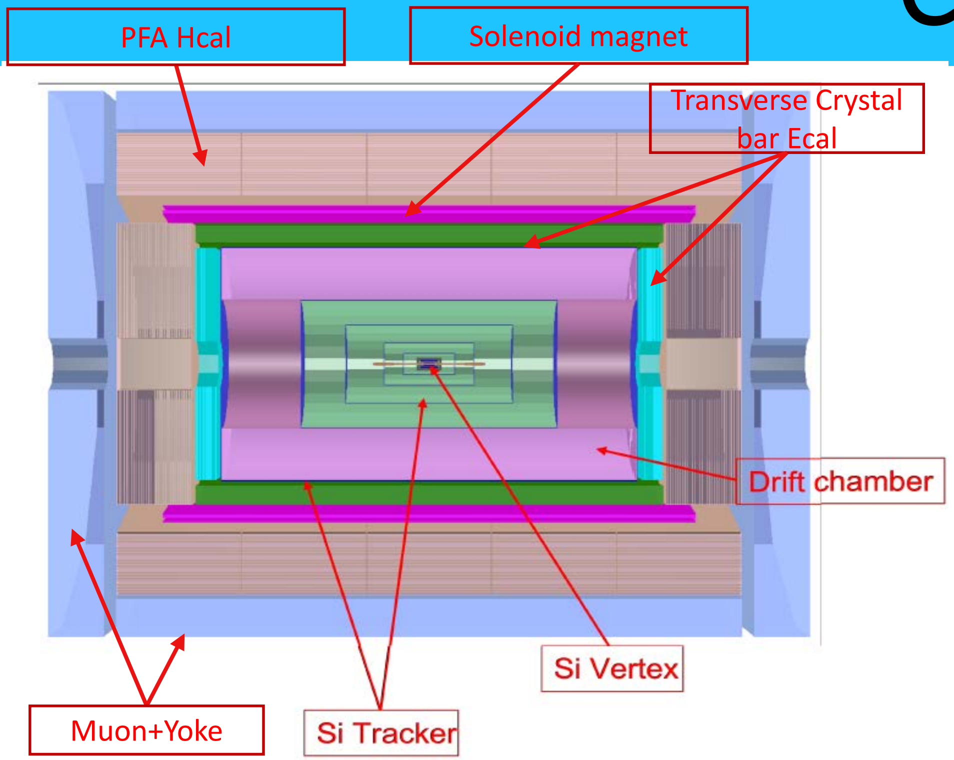
μ beam
(40, 80, 180 GeV)

He:IsoB 80/20, 85/15, 90/10

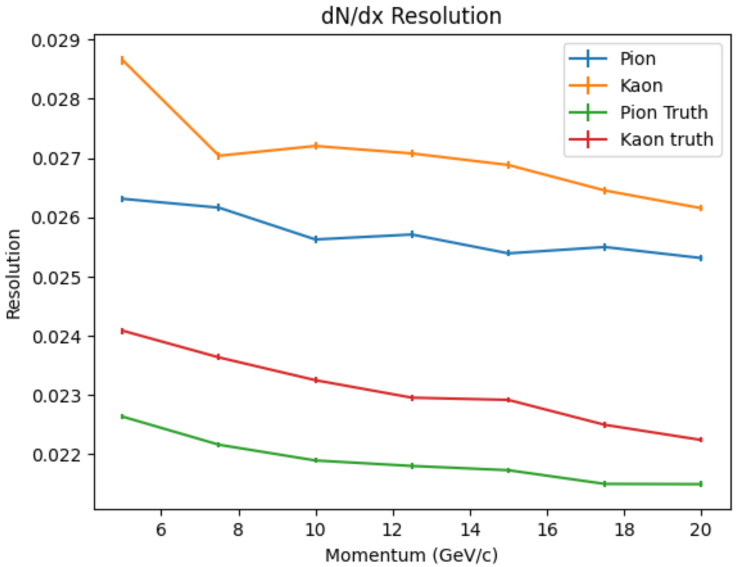
- ● 15 μm (Mo+Au)
- ● 20 μm (W+Au)
- ● 25 μm (W+Au)

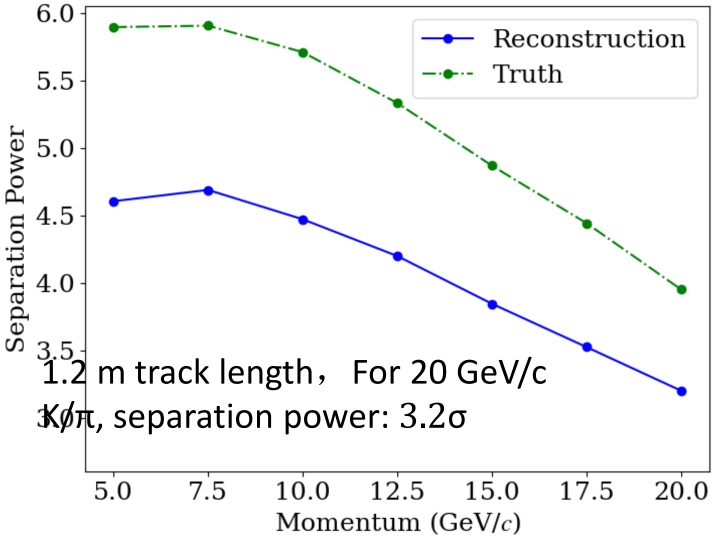


CEPC 漂移室

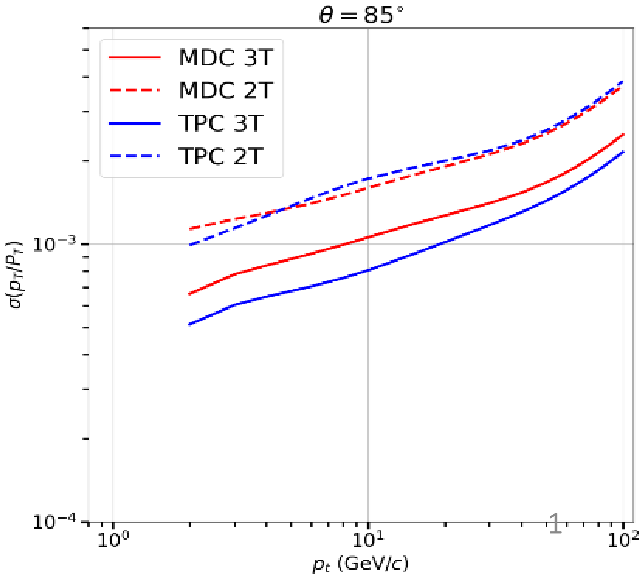


R extension	600-1800mm
Length of outermost wires（cosθ=0.85）	5800mm
Thickness of inner CF cylinder: (for gas tightness, without load)	200µm
Thickness of outer CF cylinder: (for gas tightness, without load)	300µm
Outer CF frame structure：	Equivalent CF thickness: 1.8 mm
Thickness of end Al plate:	20mm / 25mm
Cell size:	~ 18 mm × 18 mm
Cell number	27623
Ratio of field wires to sense wires	3:1
Gas mixture	He/iC$_4$H$_{10}$=90:10

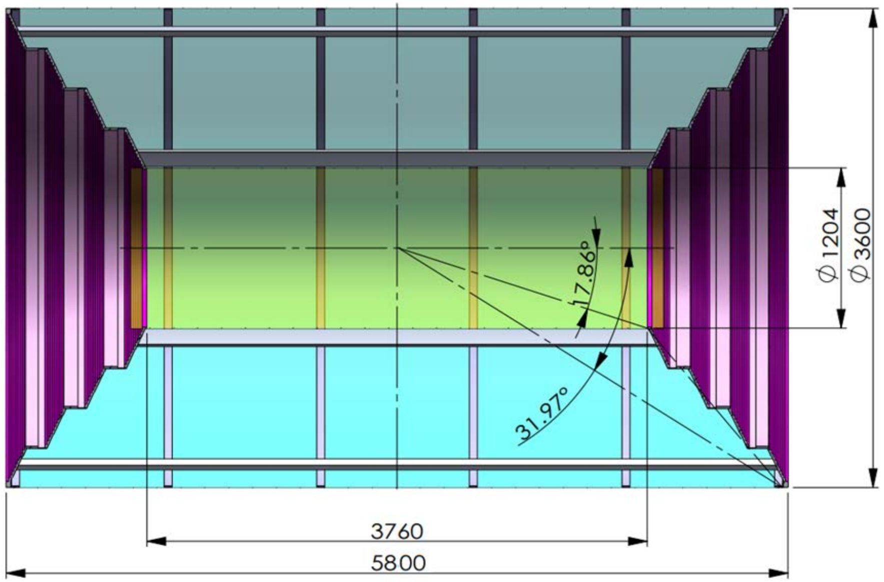


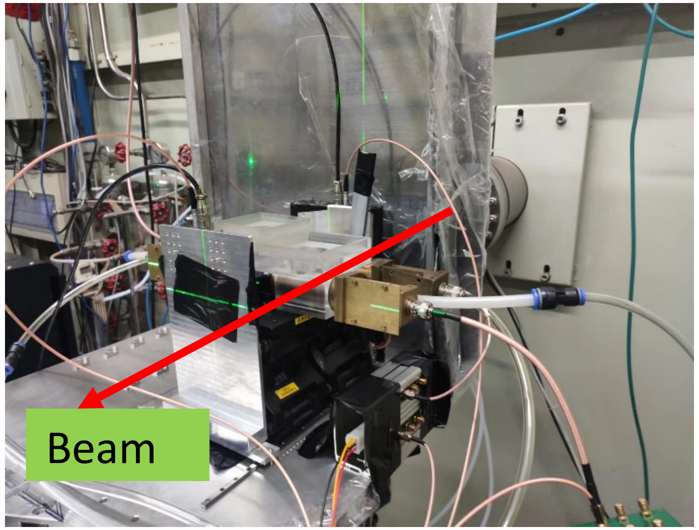


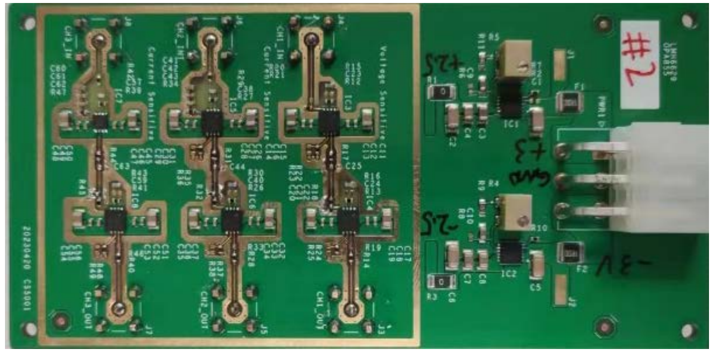
- 1.2 m track length， For 20 GeV/c K/π, separation power: 3.2σ



CEPC 漂移室

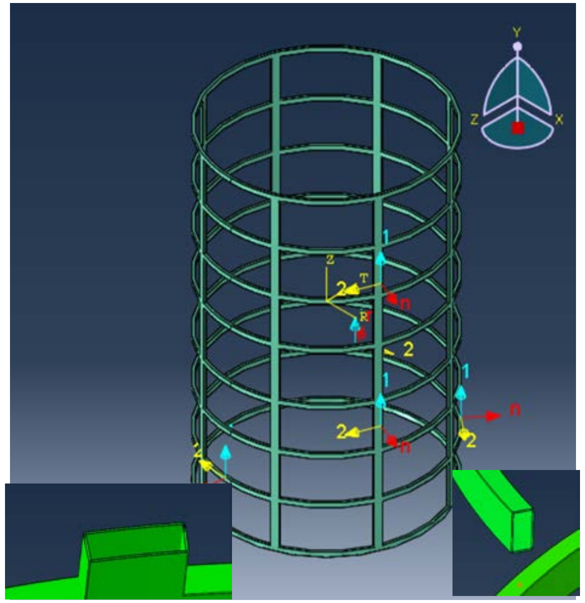


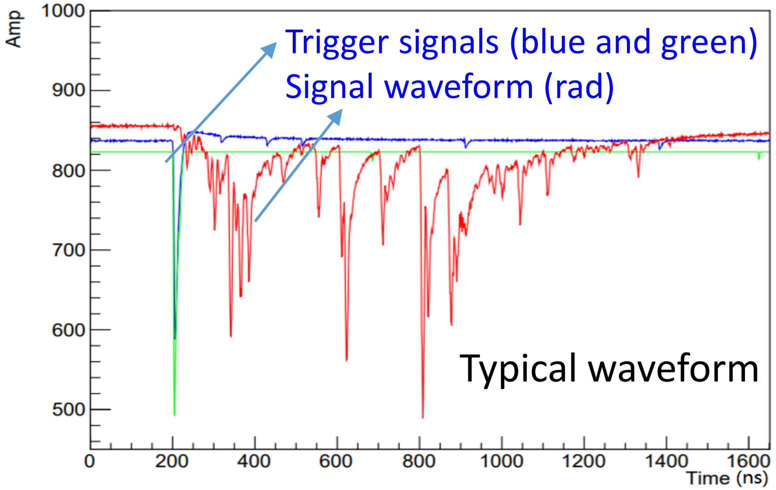


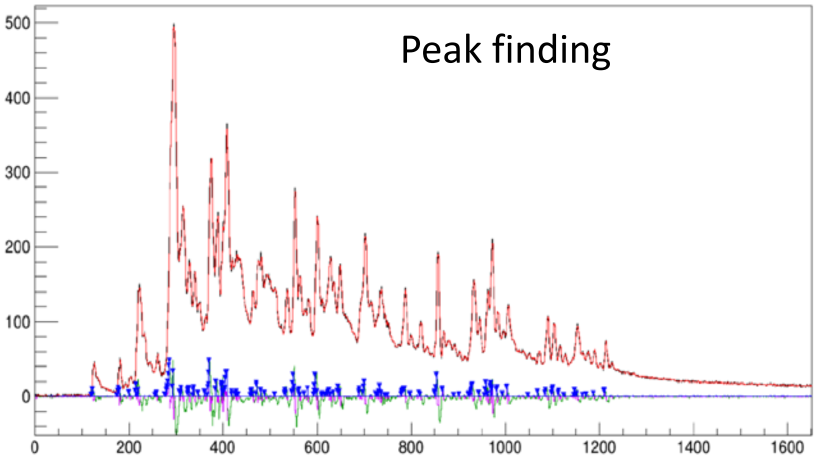


模型测试

低物质量碳纤维框架设计

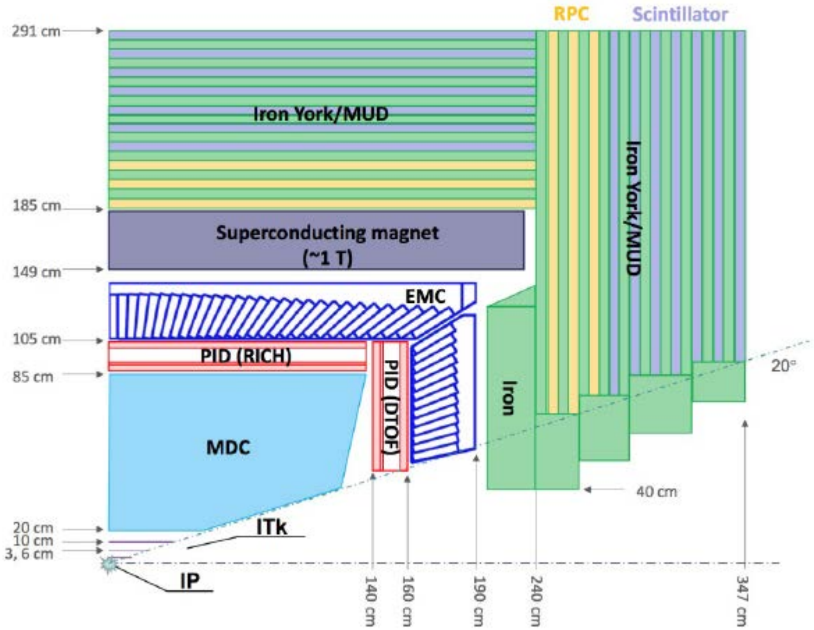


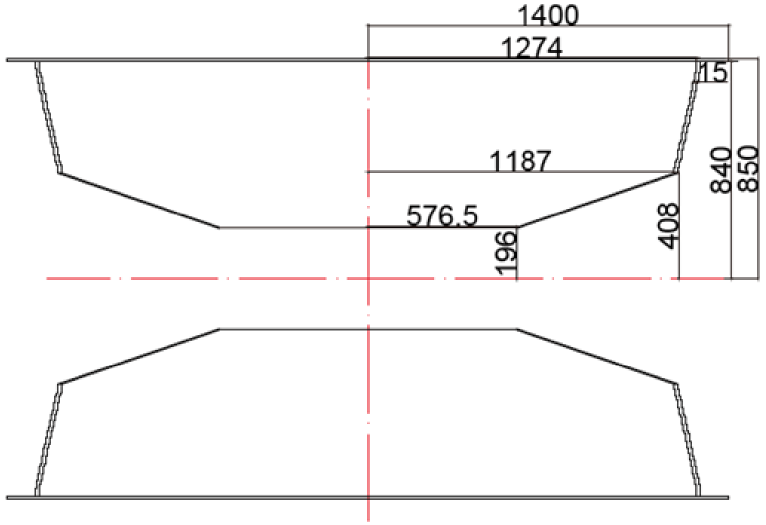


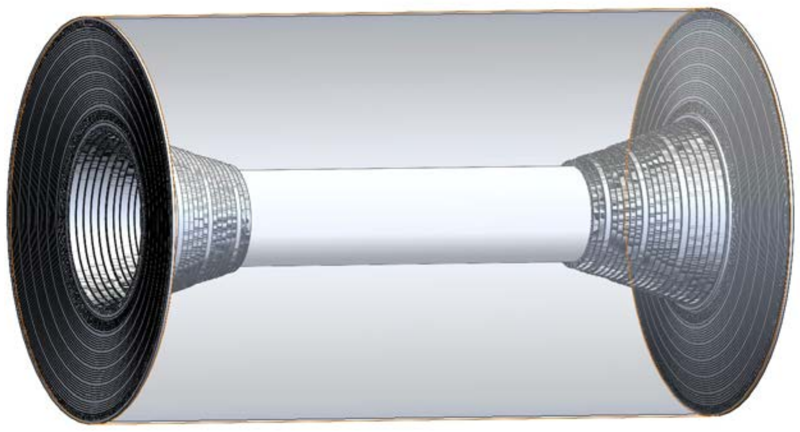


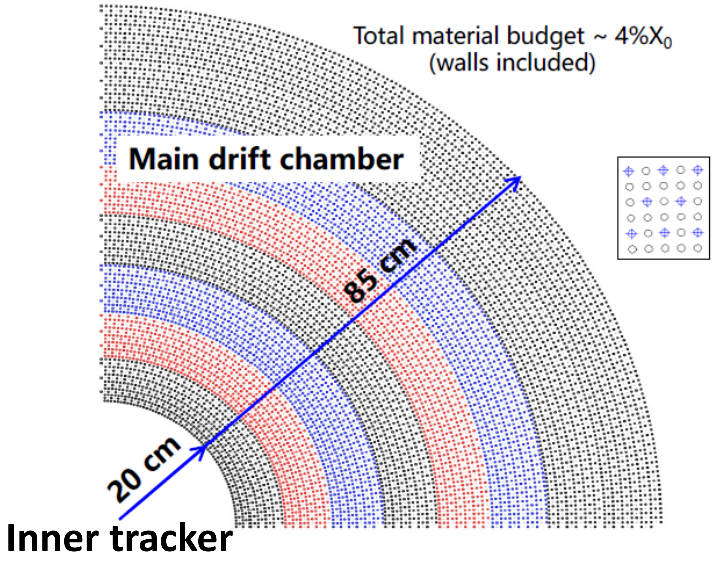
STCF-主漂移室（MDCH）

https://indico.pnp.ustc.edu.cn/event/1527/sessions/1137/#20240708 刘建北

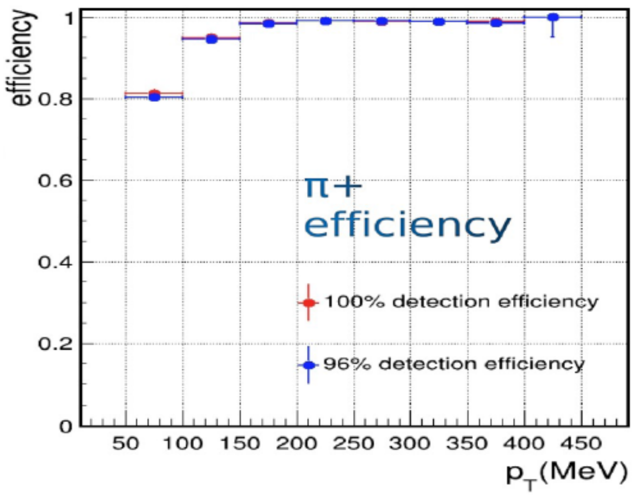




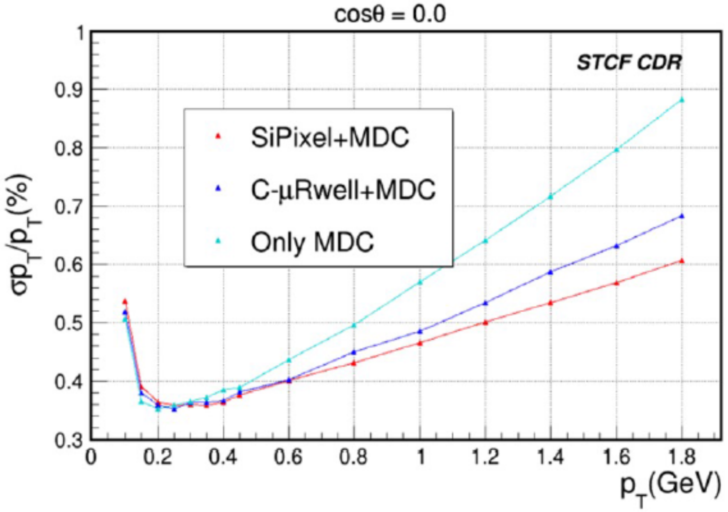




Tracking efficiency



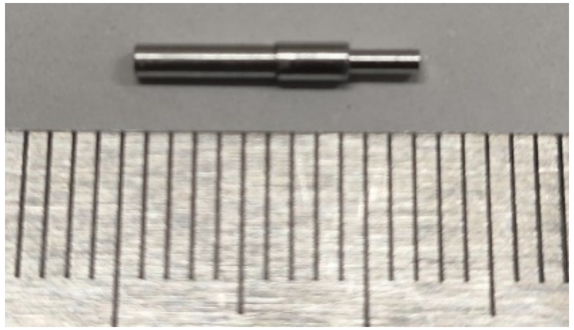
Momentum resolution



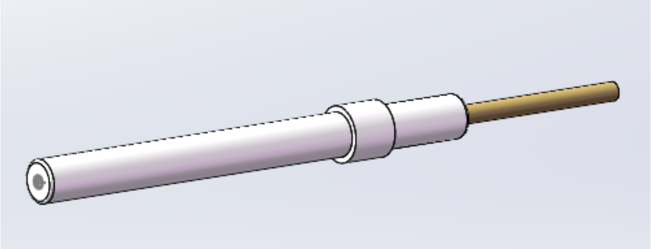
STCF-主漂移室（MDCH）

https://indico.pnp.ustc.edu.cn/event/1527/sessions/1123/#20240709 马朋

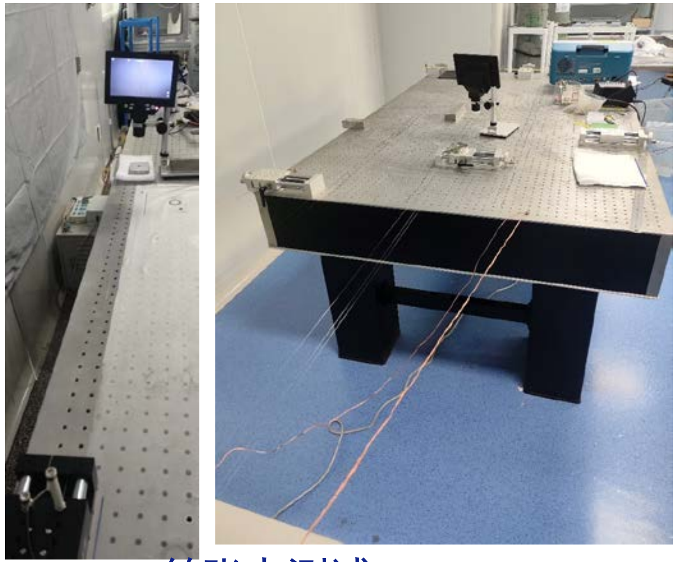
- 漂移单元的最大漂移时间约为 250 ns 主漂移室信号宽度约为500 ns，在 500 ns的时间窗内，MDC最内层信号堆积的概率约为18%，单通道的信号重叠概率很高。
  - （1）超小单元设计(~5 mm)
  - （2）高计数率电子学设计



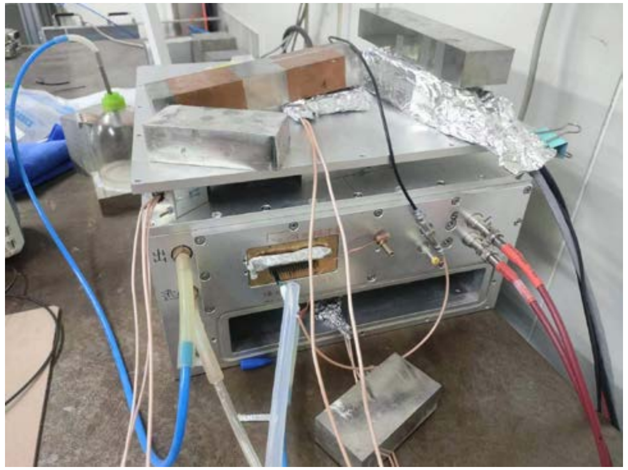
STCF 定位子V3减小尺寸



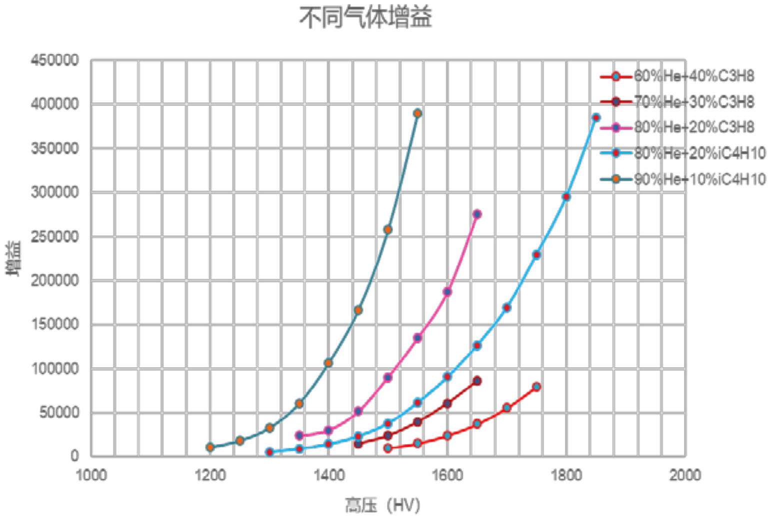
STCF 定位子V4绝缘定位子设计，电极连接



丝张力测试



10mm单元小样机测试



增益测试

计数率测试

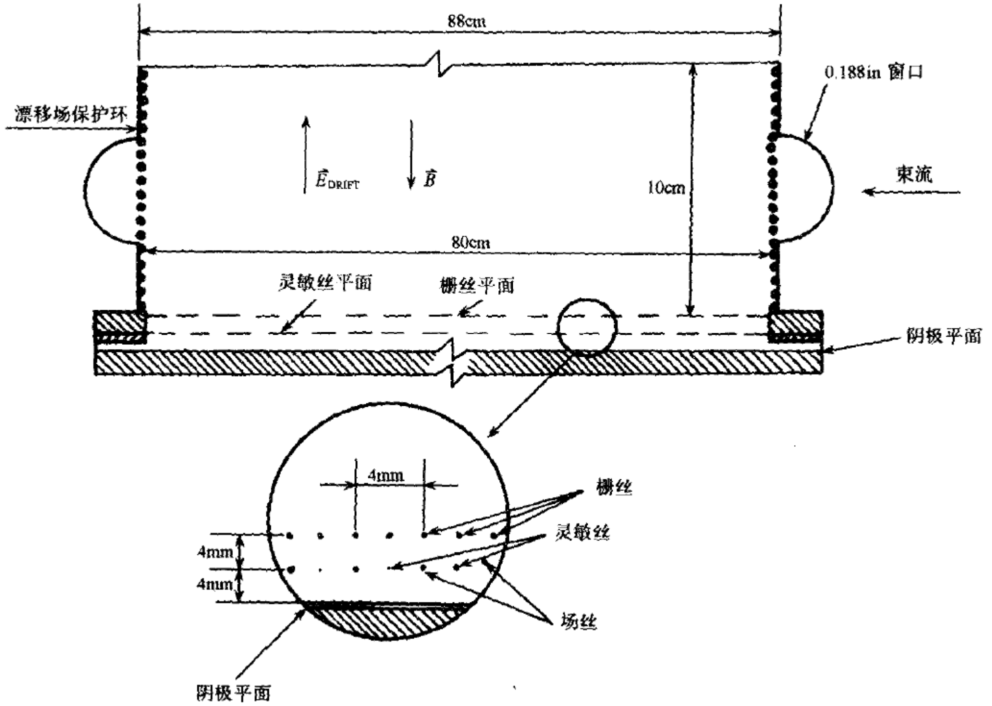
Future R&D Challenges of DC

- 新型漂移室的老化研究
  - 应对高计数率，更小尺寸的漂移单元
  - 更高电场
  - 原初电离计数所需的高增益
- 大体积下低物质量设计；新型结构设计，新型丝材料-新型合金金属化碳丝
  - 具体问题：丝腐蚀、涂层质量、…
- 工作气体使用无烃气体混合物
- 在提供高精度空间分辨（100μm量级）的同时，提高粒子鉴别能力；dN/dx性能验证
  - 高速电子学
  - 输入电容（丝长）的影响
  - 重建算法
- 大体积（长度）漂移室建造的具体技术（拉丝及精确定位，密封等）

时间投影室（TPC）

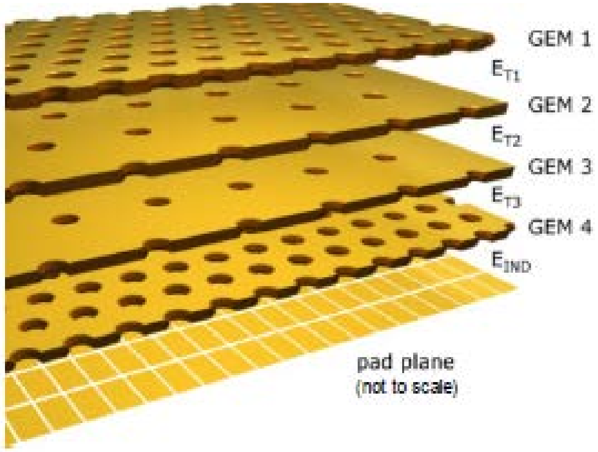
- 时间投影室(TPC)是在漂移室和多丝正比室的基础上发展起来粒子径迹探测器

- E和B方向平行且与阳极丝垂直
  - 电离的径迹会因电子横向扩散而变宽，强磁场减小这种影响
- 栅丝、阳极丝、场丝 ，阴极感应条平面
  - 栅丝使漂移场的电力线形成一个漏斗形，将电离电子聚集到灵敏丝上
  - 阳极丝测dE/dX
  - 空间丝上带电粒子的径迹坐标由丝上雪崩在感应片上感应信号的重心所决定
  - 漂移时间给出z向的位置，两者结合，给出带电粒子的三维坐标



- 主要特点
  - 高精度：空间分辨高
  - 可以制作成大体积探测器
  - 电子对撞机上的实验中，TPC 有好的动量分辨及粒子鉴别，而双径迹分辨则较差，这与电子对撞中多重性及径迹密度较低相对应
  - 重离子实验中，TPC 则有好的双径迹分辨，这在高径迹密度情况下是必要的。此外它们也有相当好的动量分辨率，但粒子鉴别能力则较差
  - 需解决正粒子反馈及高计数率下空间电荷效应问题

ALICE TPC 读出升级（ MPGD Readout ）

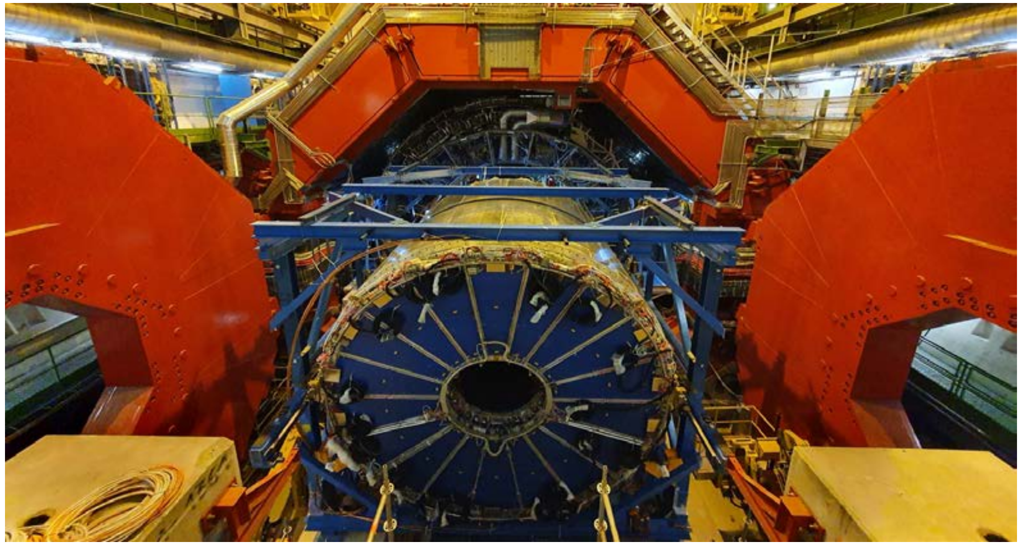


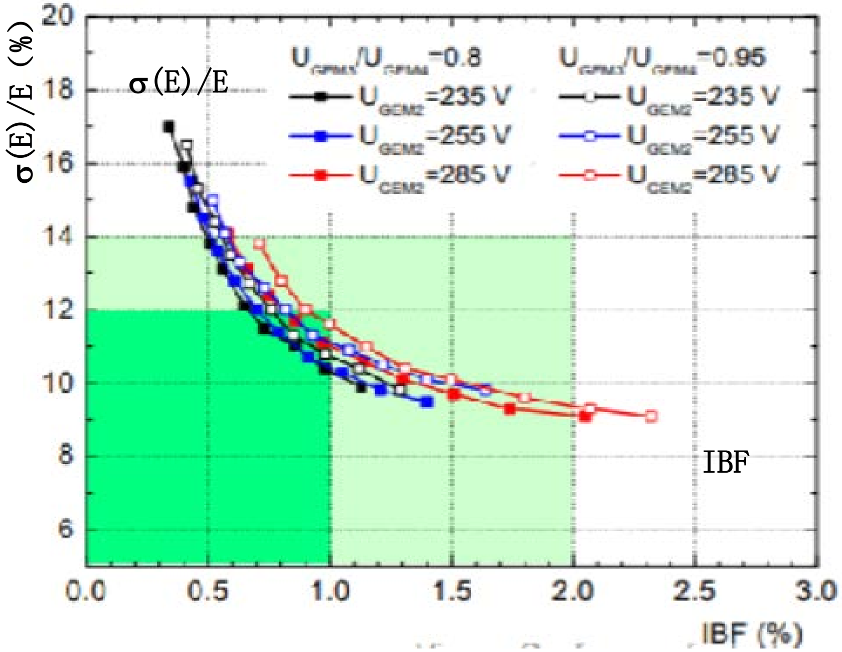
ALICE TPC升级 → 读出用 4-GEM替换 MWPC
GEM膜孔交错（以限制空间电荷效应）

-升级以实现TPC连续读出@ 50 kHz Pb-Pb collisions

- 物理需求:
  正离子反馈 (IBF) < 1%,
  能量分辨率： σ(E)/E < 12%

2020年8月 ALICE探测器重新安装TPC



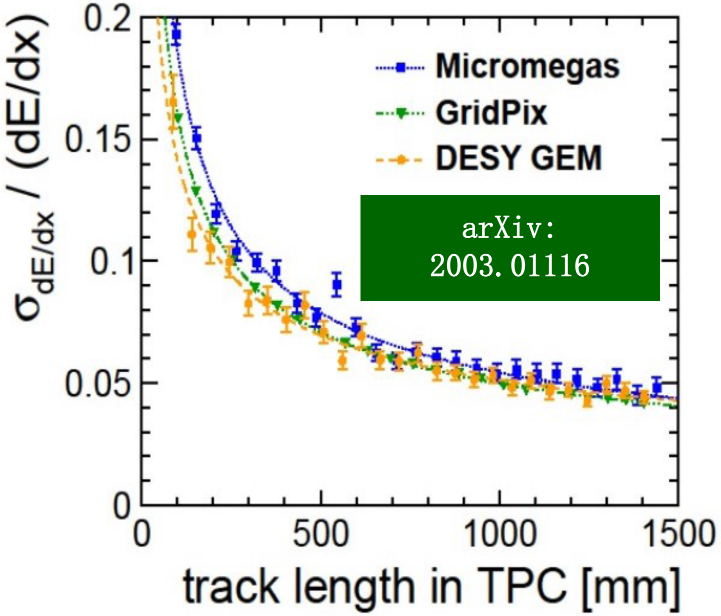


ILC TPC 采用MPGD 读出

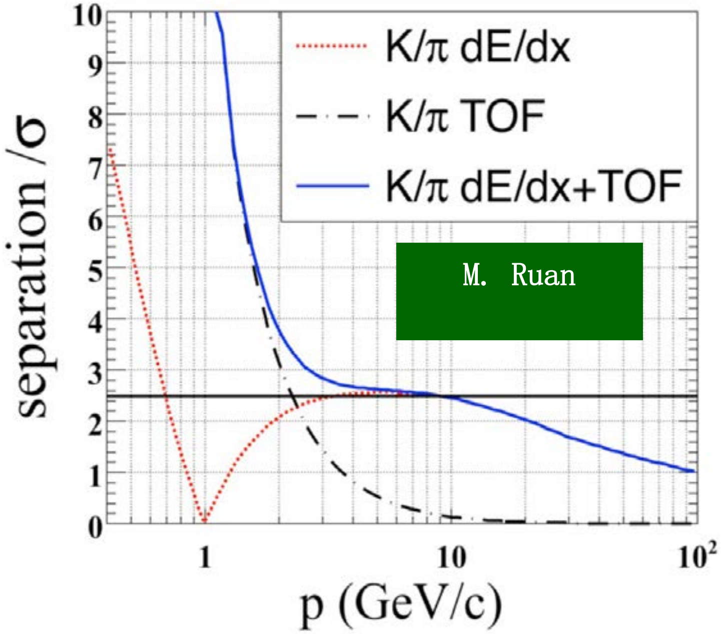
- **ILC-TPC 基于MPGD的读出方案**

- 物理要求
  - 横向平面空间分辨率:100um
  - dE/dx分辨率<5%
- GEM、MM和GridPix读出均可实现

- 若使用SiECAL，将dE/dx与ToF结合，可以覆盖P<10GeV的π-K鉴别



arXiv:
2003.01116

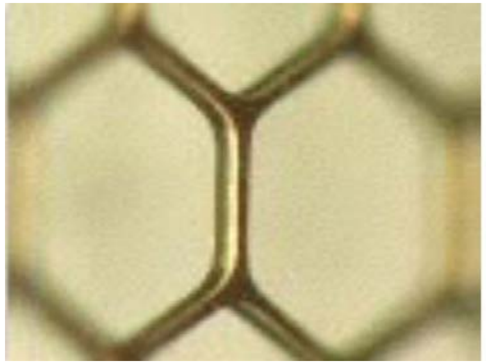


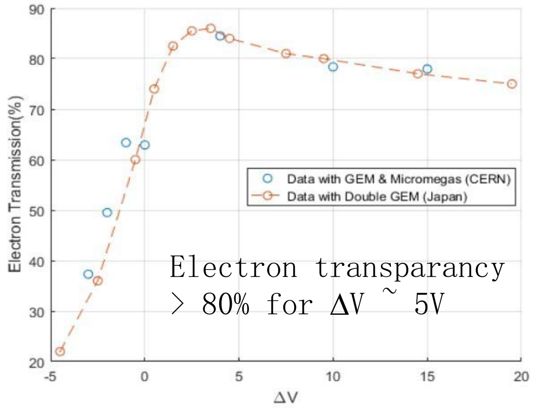
M. Ruan

- **ILC-TPC：基于大孔径GEM的门控方案**

→ 束流本底和雪崩过程中产生的离子

→ 基于ILC的束团结构(在第一个束团之前50us打开，在最后一个束团之后50us关闭)





Electron transparency
> 80% for ΔV ~ 5V

面向大规模像素的“GridPix” TPC

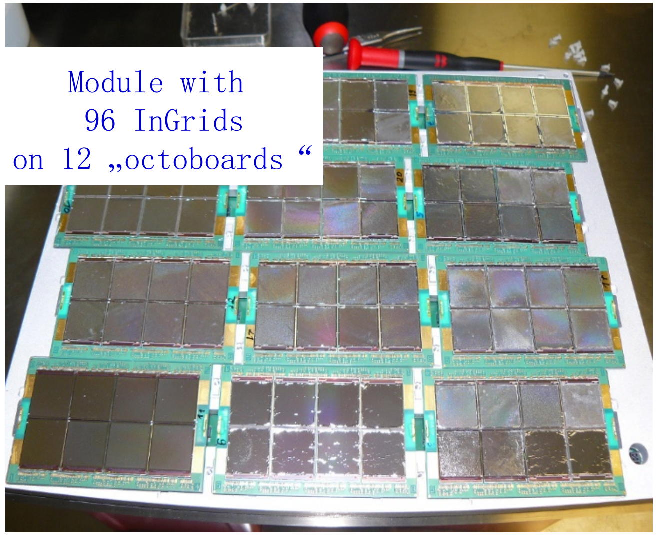
- FCC-ee / CEPC @ Z pole 运行下对TPC的主要考虑:
  - 气体的原初电离
  - 来自气体放大产生的离子
  - 功耗（无功率脉冲）
  - 在Z峰值运行期间以2T运行

→提出并研究 pixel - TPC 替代 pad - TPC （Z运行下）

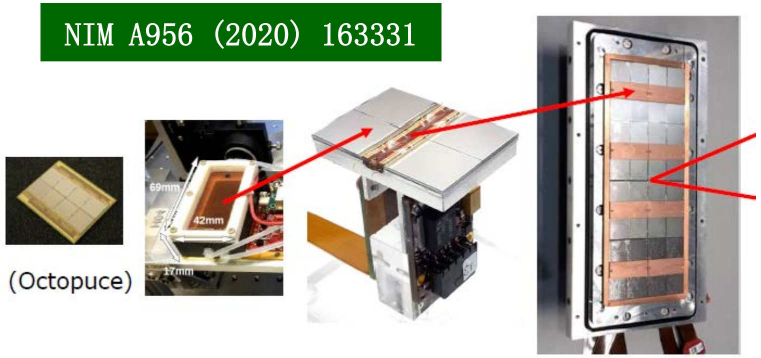
3 modules for LP TPC @ DESY: 160 (1 x 96 & 2 x 32) GridPixs

320 cm² active area, 10,5 M. channels,

new SRS Readout system

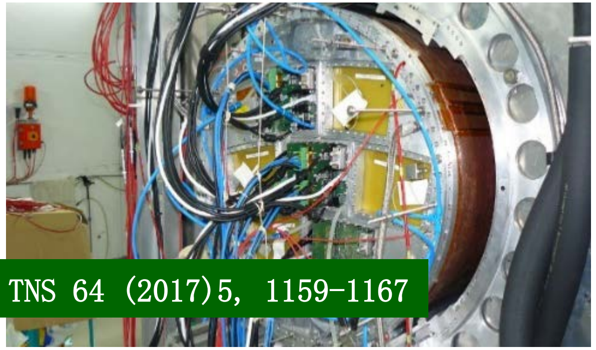

Module with
96 InGrids
on 12 „octoboards“

NIM A956 (2020) 163331



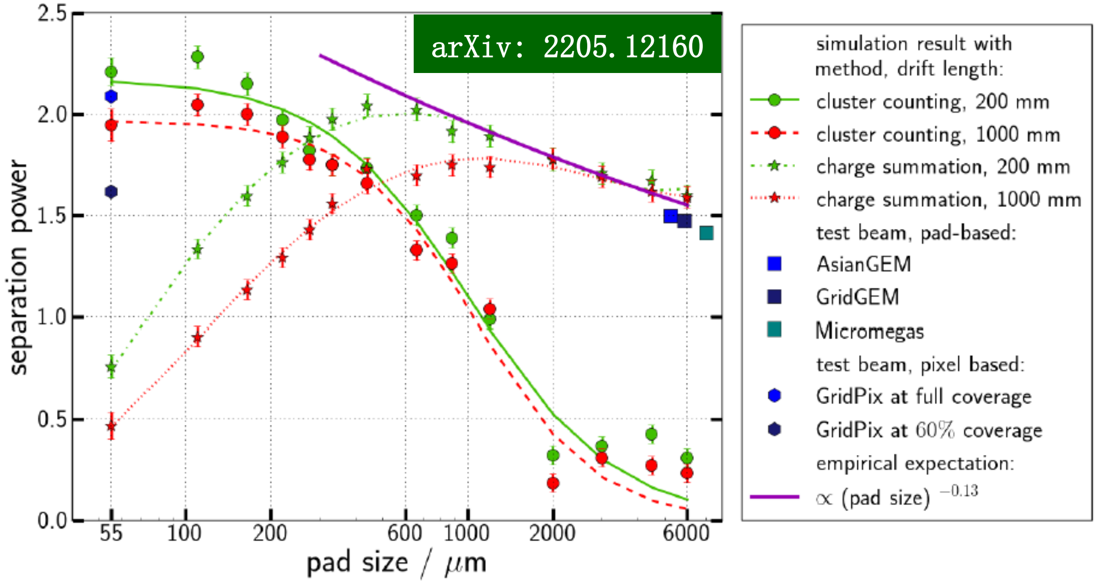
(Octopuce)			
(TimePix1)	TPX3 chip	Quad	Module
(2007-14)	2017	2018	2019

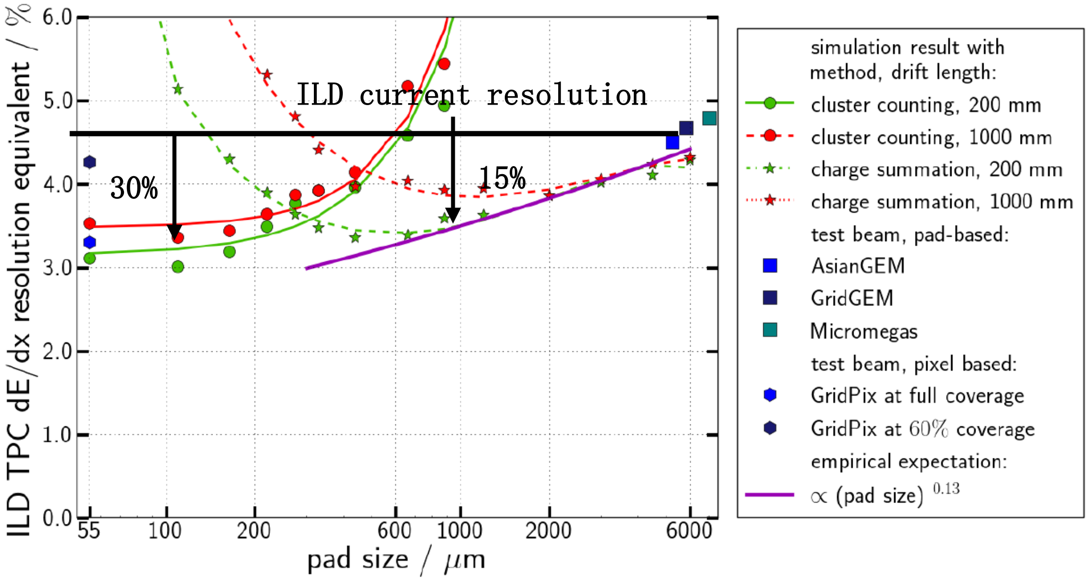
Testbeams with GridPixes:
160 GridPixes (Timepix) &
32 GridPixes (Timepix3)


IEEE TNS 64 (2017)5, 1159-1167

LP Endplate with 3 modules

原初电离计数（Cluster Counting）





- Simulation of PID with gaseous tracking and timing in ILD Prototype

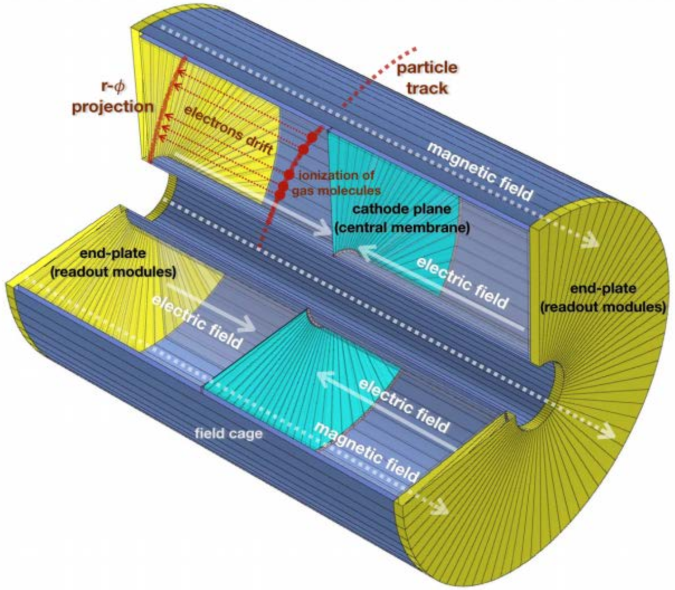
- <u>Current full ILD reconstruction:</u>

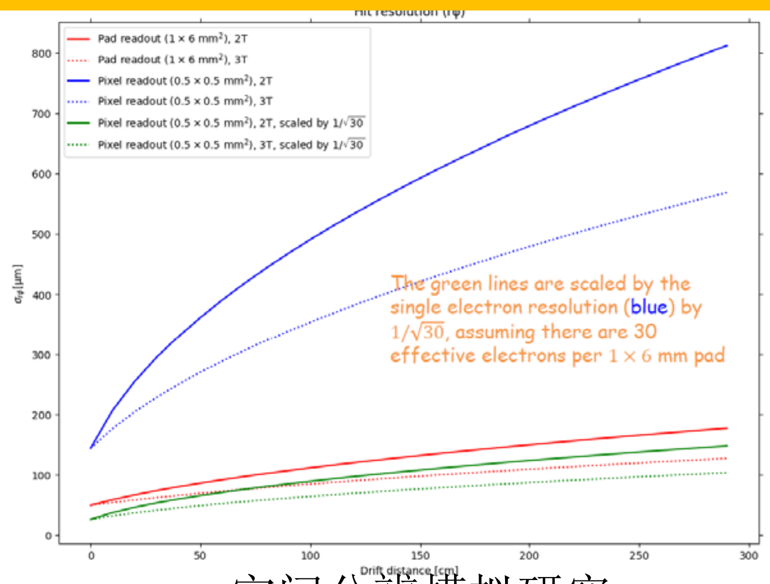
  - 6 mm pads： 4.6 % dE/dx resolution
  - 6 mm → 1 mm: 15% improved resolution via charge summing (dE/dx)
  - 6 mm → 0.1 mm: 30% improved res. via cluster counting (dN/dx)

CEPC时间投影室（TPC）

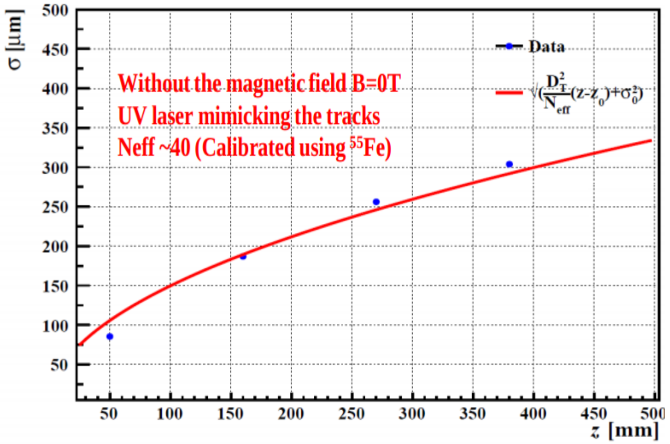
https://agenda.linearcollider.org/event/10134/sessions/5593/#20240710 Huirong Qi

- CEPC baseline探测器设计中，TPC作为径迹探测器
- 开展研究
  - 正离子反馈：复合读出结构
  - 激光标定：226nm UV laser
  - 粒子鉴别能力：dE/dx
  - 模型研究，读出pad：1mm×6mm

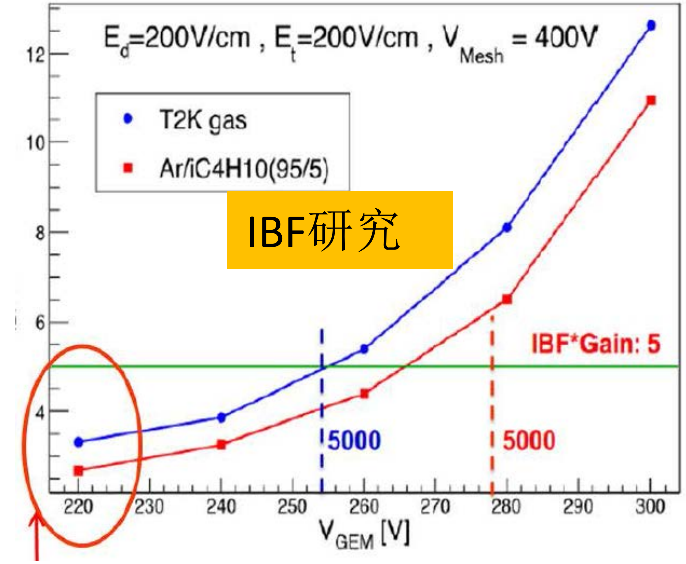




空间分辨模拟研究



读出pad：1mm×6mm

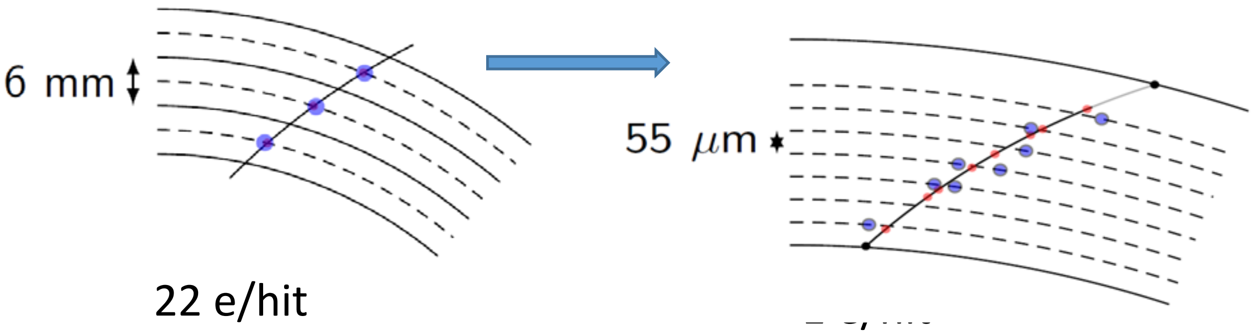


IBF研究

TPC像素读出

https://agenda.linearcollider.org/event/10134/sessions/5593/#20240710 Huirong Qi

- 像素读出：pad(1mm×6mm) → pixel
- 径迹长度上增加更多的测量点，有利于提高空间分辨率，利用空间dN/dx提升粒子鉴别能力，提供优异的双径迹分辨率，可以处理更高的计数率

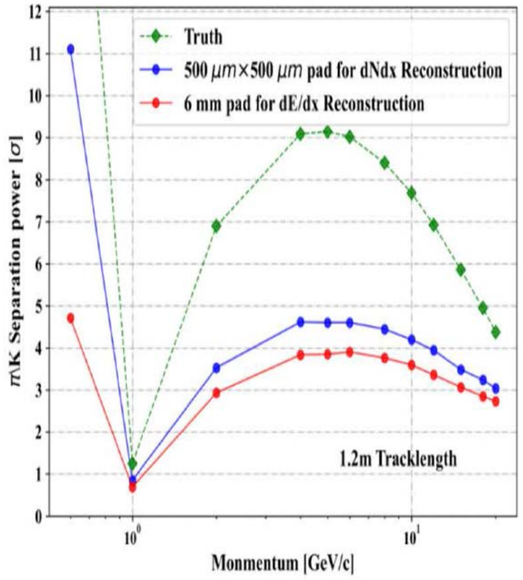


22 e/hit
~200hits/track

~10000hits/track

与清华大学合作研发的像素芯片

- 像素尺寸：500µm×500µm
- 高计数率： MHz/cm²
- 放大器增益: >40mV/fC
- 通道数: 128
- 时间分辨: 14bit (5ns bin)
- Time discriminator: TOA (Time of Arrival)
- 功耗: <1mW/pixel，相当于400mW/cm²，100mW/cm² (目标功耗)
- 工艺：180nm，未来 60nm CMOS



粒子鉴别性能模拟研究

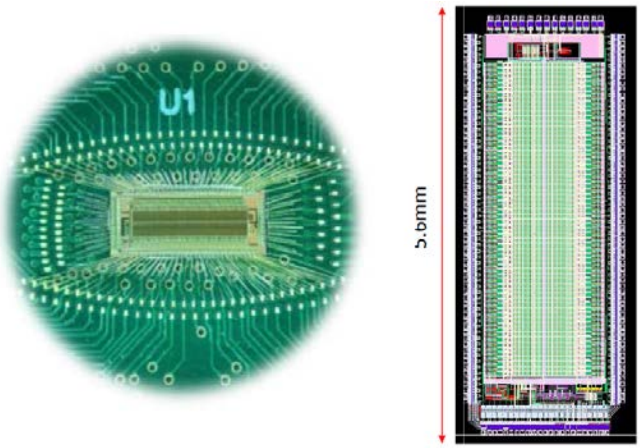


Photo and layout of ASIC Chip R&D for TPC

Future R&D Challenges of “GridPix” TPC

- 优化焊盘尺寸以提高位置分辨率
  - 像素尺寸>200 μm以降低成本
  - 大像素下的信噪比
- dN/dx重建算法
- 正离子反馈抑制研究（双栅极，石墨烯涂层等）
- 工作气体Ar/CF$_4$/iC$_4$H$_{10}$的进一步验证
- 老化研究：保护层抗蚀性降低， Gridpix脆性结构打火及抗辐射性能方面的研究
- 低物质量设计（端面板结构及读出探测器，功耗、冷却）
- 大体积TPC建造的具体技术（场笼、高压、冷却、密封等）

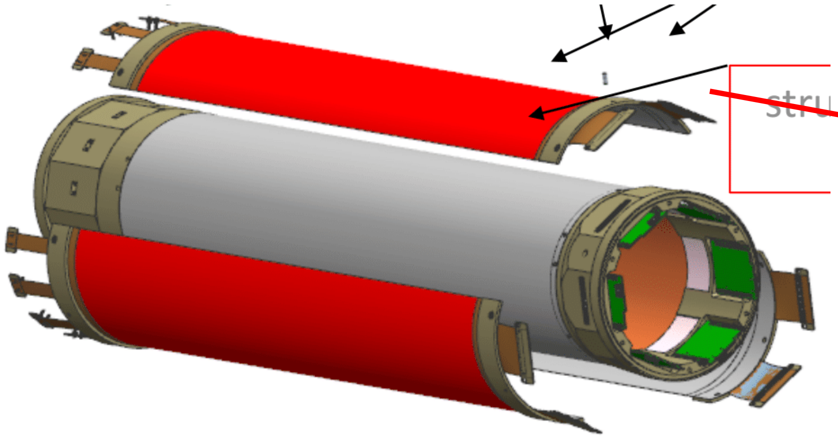
圆筒形微结构内径迹探测器

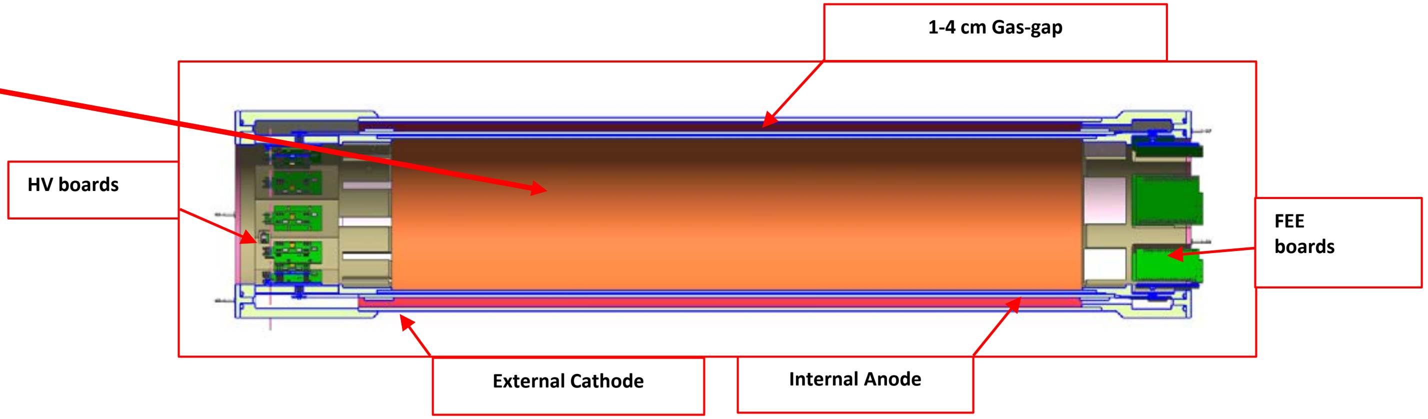
- 将微结构探测器的柔性电极卷曲成圆筒型，为内径迹探测器的一种选择方案
- 主要特点：
  - 可以在下相对高计数率环境下工作
  - 空间分辨率较高，抗老化能力强
  - 工艺相对复杂，物质量相对较大
  - 重建算法相对复杂

Flexible RWELL + readout PCB

Cylindrical μRWELL:

- Modular roof-tile detector
- 4 layers
- Length 60 cm
- Diameter 10-40 cm





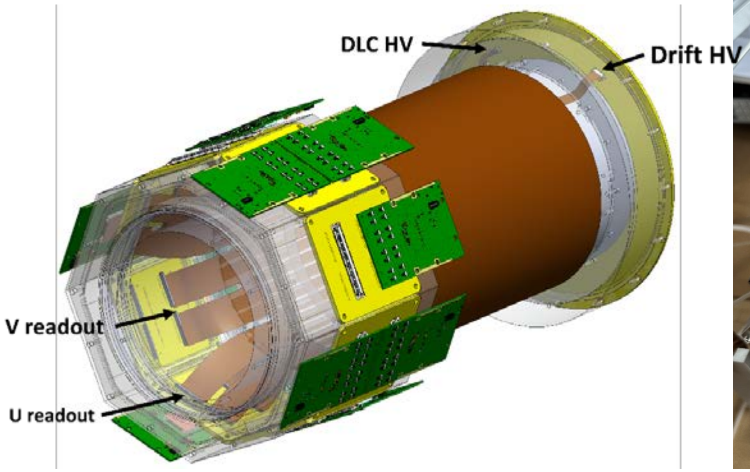
L. Shektmann
G. Bencivenni

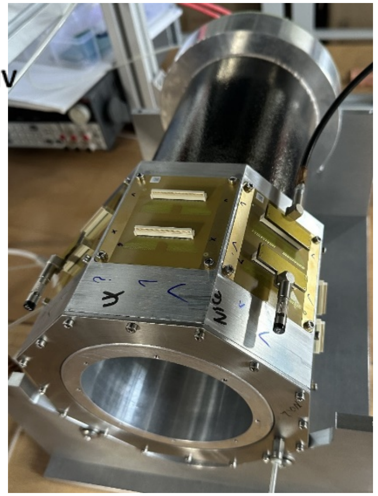
Cylindrical MPGDs has been also developed & used: GEMs (KLOE, BESIII，STCF), Micromegas (CLAS12)

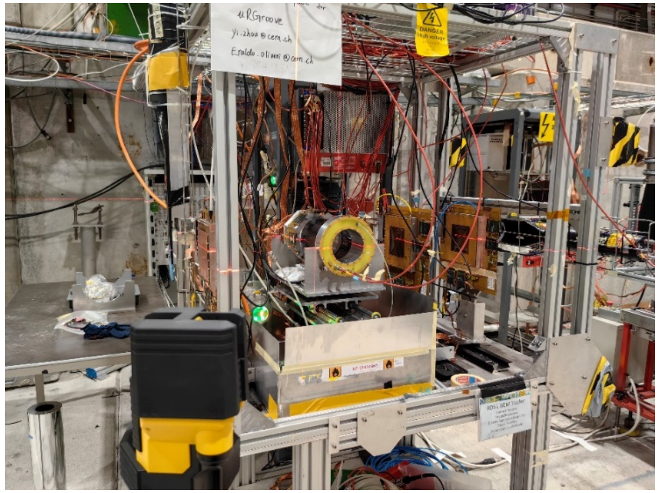
STCF-ITKW探测器

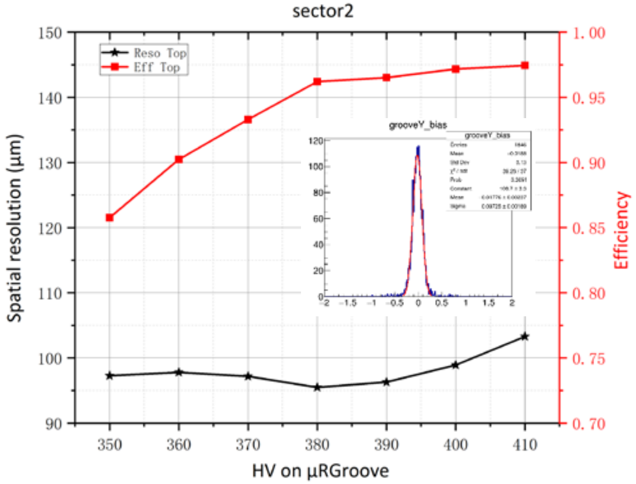
圆柱形阻性微槽型探测器（C-μRGroove）

https://indico.pnp.ustc.edu.cn/event/1527/sessions/1123/#20240709 何思齐







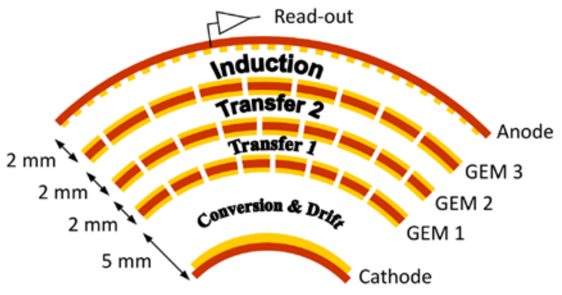


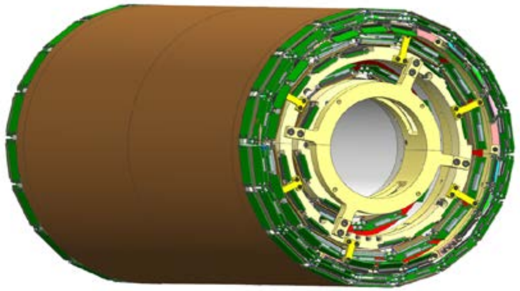
- 内外筒模具中部为分瓣圆柱，电极粘接完成后可拆卸
- 读出条软板向上曲折以接入**FEE**转接板，转接板位于外筒侧面
- 高压**PCB**板构成另一侧端盖，高低压分离设计。

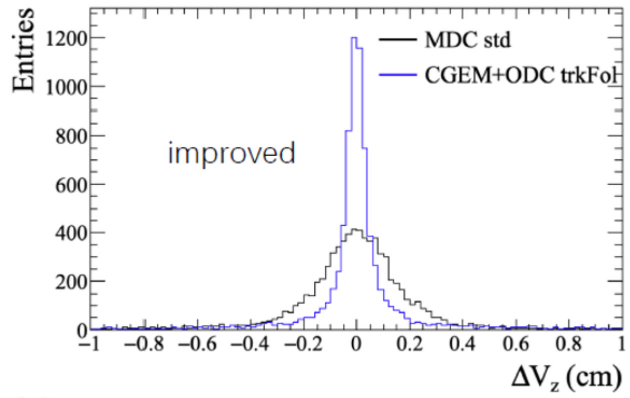
✓ 位置分辨初步结果：**90~100μm**
✓ 探测效率**>95%;**
✓ **μTPC**初步结果：整个**sector ~150μm**
X 褶皱可能影响位置分辨
X 不同**sector**具有一定程度的不均匀性
➢ 后续测试正在进行
➢ 精细的修正算法

BESIII CGEM内径迹室

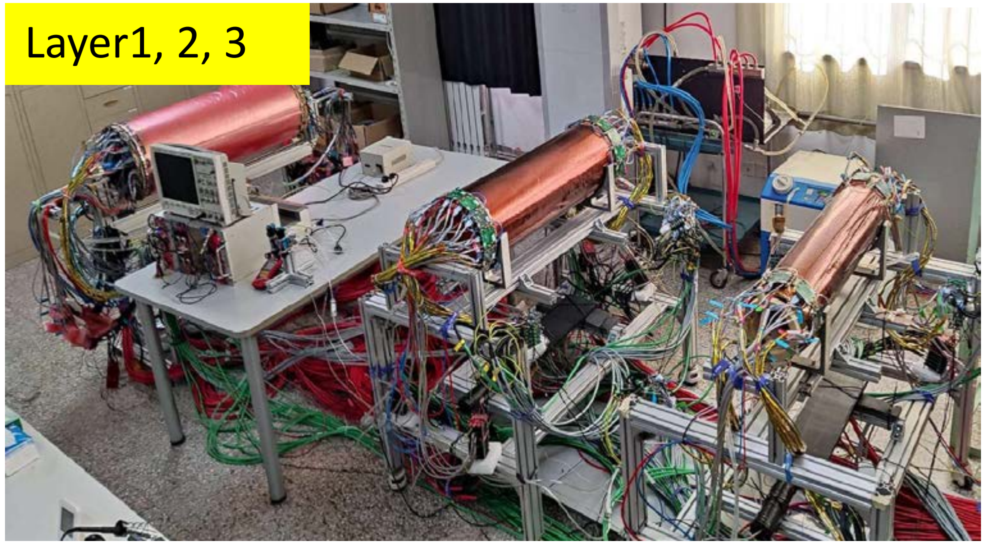
- 3层圆筒GEM内径迹室替换漂移室内室（与意大利INFN合作，其中第三层在高能所完成建造）
  - z向分辨率显著提高：~1.5 mm → ~0.5 mm
  - 计数率高：$>10^4$ Hz/cm^2
  - 抗老化能力强：比漂移室具有更强的抗老化能力
- 将于今年夏季进行安装，为先进微结构气体探测器在BESIII实验上的首次使用

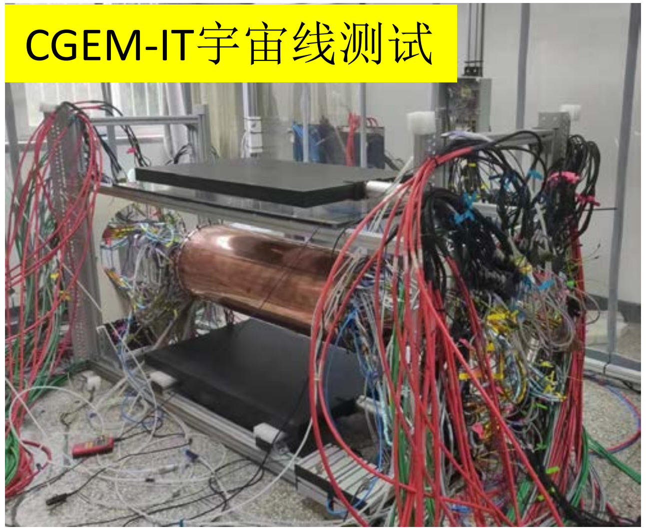







Layer3建造


Layer1, 2, 3


CGEM-IT宇宙线测试

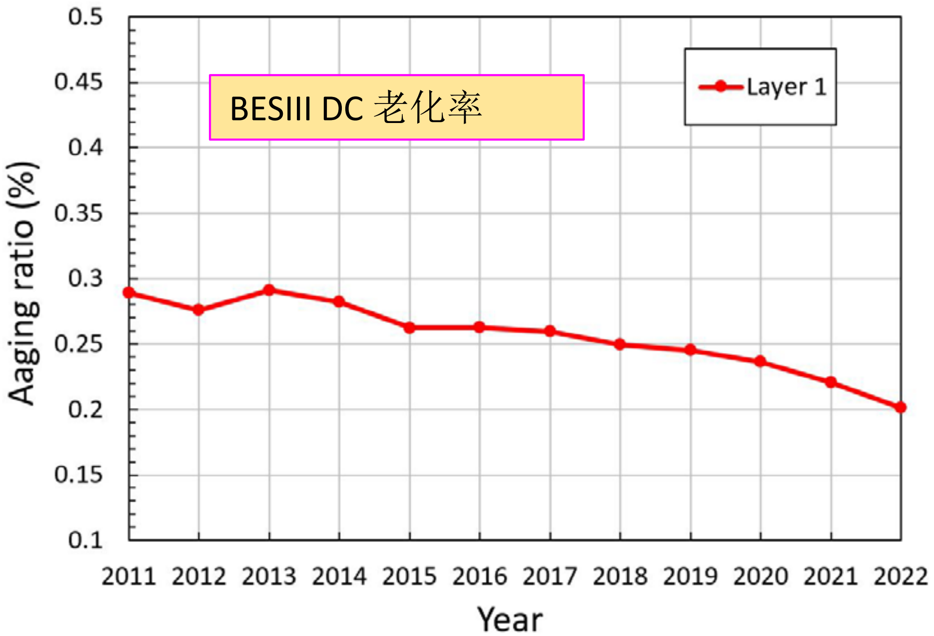
气体径迹探测器老化考虑

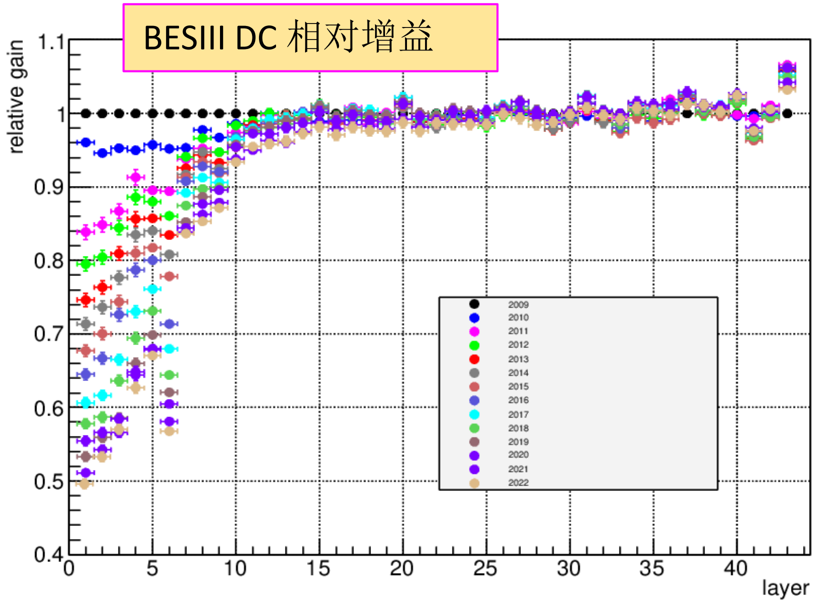
- 一个高能物理实验的长取数周期

  ⟹ 径迹探测器长期稳定工作，老化问题

- 老化与多个高度相关的参数相关，由综合因素决定
- 仅凭累积电荷无法准确描述

$$R = -(1/G)(dG/dQ) \quad (\%\ \text{per C/cm})$$





宏观因素：
- ✓ 气体混合物（气体性质、微量污染物）
- ✓ 气体流量和压力
- ✓ 电极的几何形状/材料和电场配置

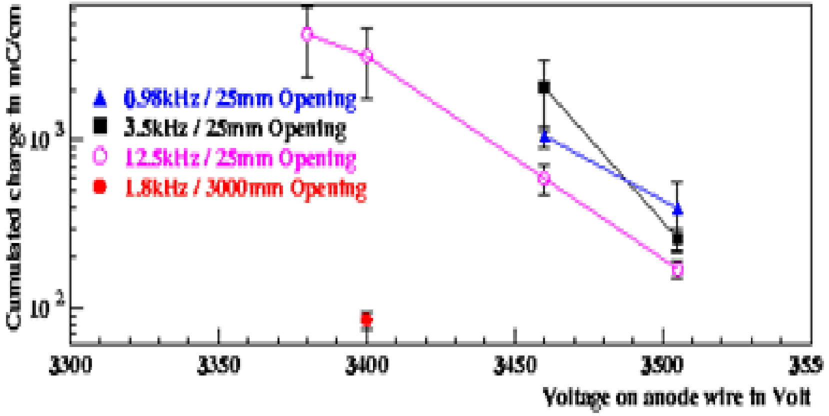
- ✓ 建造材料
- ✓ 辐射强度
- ✓ 气体增益
- ✓ 辐照区域大小

微观因素：

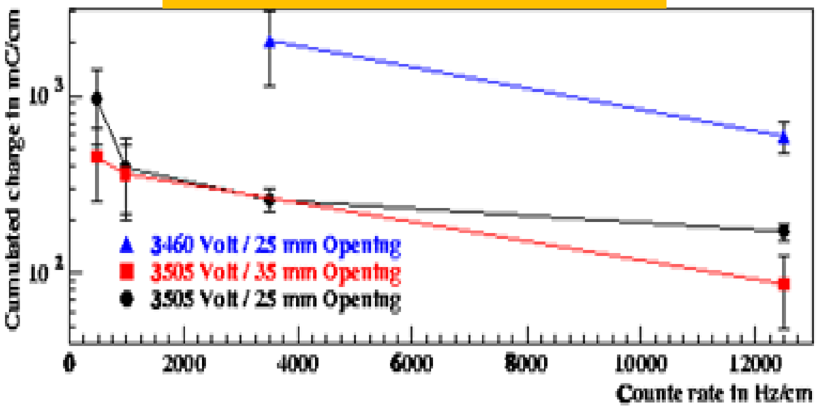
- ✓ 作用截面
- ✓ 电离密度
- ✓ 电子或光子能量
- ✓ 电子、离子、自由基密度
- ✓ …

老化效应的影响因素

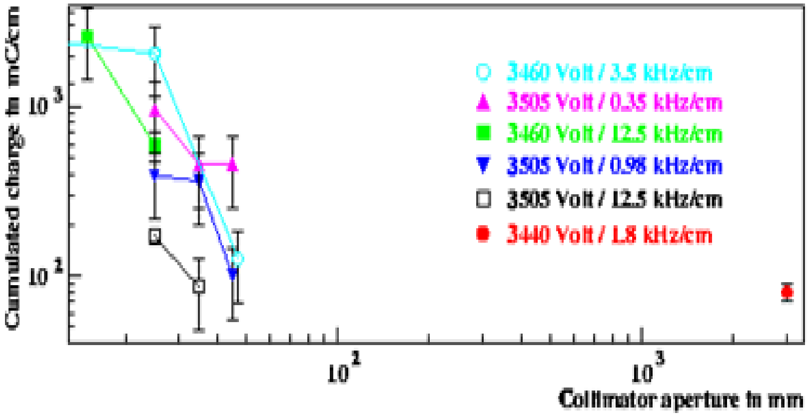
HV



Irradiation rate



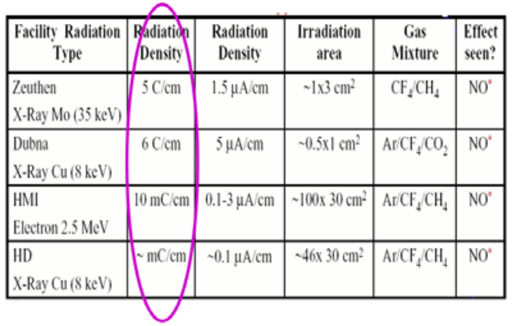
Irradiation area



实验验证决定老化的主要因素：

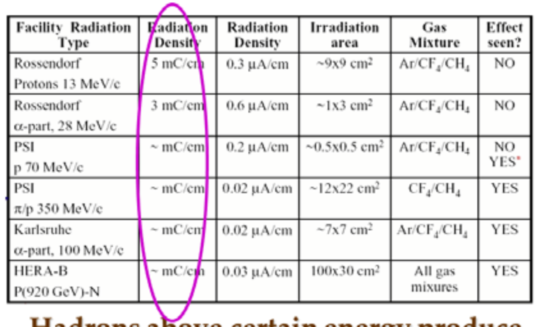
- 辐照剂量率
- 电离密度
- 高压（气体增益）
- 粒子类型和能量
- 气体置换率

Particle type & energy; Irradiation area



Facility Radiation Type	Radiation Density	Radiation Density	Irradiation area	Gas Mixture	Effect seen?
Zeuthen X-Ray Mo (35 keV)	5 C/cm	1.5 µA/cm	~1x3 cm^2	CF_4/CH_4	NO*
Dubna X-Ray Cu (8 keV)	6 C/cm	5 µA/cm	~0.5x1 cm^2	$Ar/CF_4/CO_2$	NO*
HMI Electron 2.5 MeV	10 mC/cm	0.1-3 µA/cm	~100x 30 cm^2	$Ar/CF_4/CH_4$	NO*
HD X-Ray Cu (8 keV)	~ mC/cm	~0.1 µA/cm	~46x 30 cm^2	$Ar/CF_4/CH_4$	NO*

X-rays or e$^-$ can not trigger Malter effect independently of their energy or radiation intensity



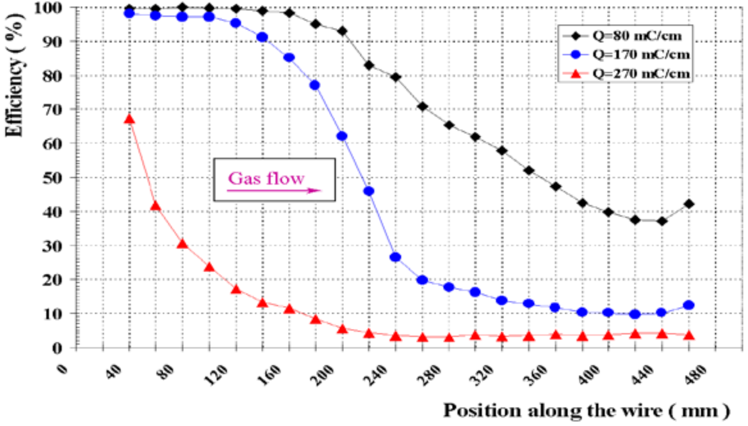
Facility Radiation Type	Radiation Density	Radiation Density	Irradiation area	Gas Mixture	Effect seen?
Rossendorf Protons 13 MeV/c	5 mC/cm	0.3 µA/cm	~9x9 cm^2	$Ar/CF_4/CH_4$	NO
Rossendorf α-part, 28 MeV/c	3 mC/cm	0.6 µA/cm	~1x3 cm^2	$Ar/CF_4/CH_4$	NO
PSI p 70 MeV/c	~ mC/cm	0.2 µA/cm	~0.5x0.5 cm^2	$Ar/CF_4/CH_4$	NO YES*
PSI π/p 350 MeV/c	~ mC/cm	0.02 µA/cm	~12x22 cm^2	CF_4/CH_4	YES
Karlsruhe α-part, 100 MeV/c	~ mC/cm	0.02 µA/cm	~7x7 cm^2	$Ar/CF_4/CH_4$	YES
HERA-B P(920 GeV)-N	~ mC/cm	0.03 µA/cm	100x30 cm^2	All gas mixures	YES

Hadrons above certain energy produce Malter effect at ~mC/cm as in HERA-B

(Irradiation area above certain limit is necessary for ignition of Malter effect)

HERA-B Tracker: NIMA515, p. 155 (2003)

Gas flow & Irradiation area



HERA-B Muon: NIMA515, p. 202 (2003)

建造抗辐射性能好的气体探测器—经验法则

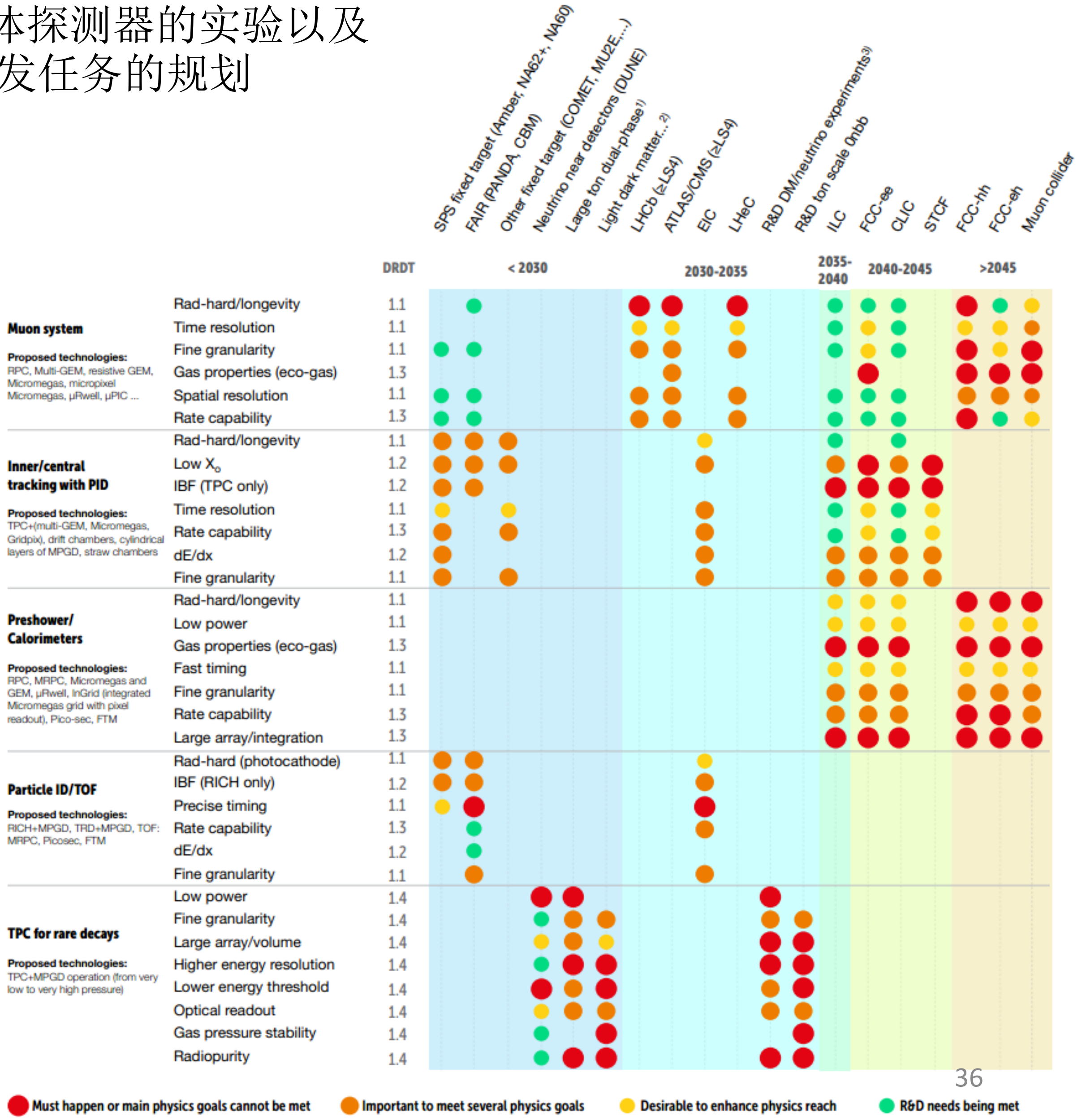
- 材料的选择：明确的“不可用”和“可用”的材料
- 气体的选择，尤其高计数率环境中
- 合适的装配程序、所有工艺的最大清洁度和所有系统零件的质量检查
- 模型实验验证
  - 构建一个“全尺寸原型”（探测器中最小的独立单元）
  - 仔细选择探测器材料（胶、室体内部材料）、工作气体等
  - 将探测器的整个区域暴露在真实的辐射分布中（粒子类型、气体增益、电离密度）
  - 对几个相同的原型进行老化研究：系统地改变所有参数（气体增益、辐照强度、气体流量等），分别验证
  - 不要将任何给定参数的老化结果外推超过一个数量级

- 与传统丝室等气体探测器相比，MPGD似乎对辐射引起的老化不太敏感？这可能是由于倍增和读出电极分离、较小的表面电场等原因

ECAF Gaseous Detector R&D Roadmap

- Muon system
  - RPC, Multi-GEM, resistive GEM, Micromegas, micropixel Micromegas, µRwell, µPIC ...
- Inner/central tracking with PID
  - TPC+(multi-GEM, Micromegas, Gridpix), drift chambers, cylindrical layers of MPGD, straw chambers
- Preshower/ Calorimeters
  - RPC, MRPC, Micromegas and GEM, µRwell, InGrid (integrated Micromegas grid with pixel readout), Pico-sec, FTM
- Particle ID/TOF
  - RICH+MPGD, TRD+MPGD, TOF: MRPC, Picosec, FTM
- TPC for rare decays
  - TPC+MPGD operation (from very low to very high pressure)

使用气体探测器的实验以及
DRDT研发任务的规划



		DRDT	SPS fixed target (Amber, NA62+, NA60)	FAIR (PANDA, CBM)	Other fixed target (COMET, MU2E,...)	Neutrino near detectors (DUNE)	Large ton dual-phase[1]	Light dark matter...[2]	LHCb (≥LS4)	ATLAS/CMS (≥LS4)	EIC	LHeC	R&D DM/neutrino experiments[3]	R&D ton scale 0nbb	ILC	FCC-ee	CLIC	STCF	FCC-hh	FCC-eh	Muon collider
			< 2030						2030-2035						2035-2040	2040-2045			>2045		
Muon system **Proposed technologies:** RPC, Multi-GEM, resistive GEM, Micromegas, micropixel Micromegas, µRwell, µPIC ...	Rad-hard/longevity	1.1		🟢					🔴	🔴		🔴			🟢	🟢	🟢		🔴	🟢	🟡
	Time resolution	1.1							🟡	🟡		🟡			🟢	🟡	🟢		🟡	🟡	🟠
	Fine granularity	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟡	🟢		🔴	🟡	🔴
	Gas properties (eco-gas)	1.3								🟠						🔴			🔴	🔴	🔴
	Spatial resolution	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🟠	🟠	🟠
	Rate capability	1.3	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🔴	🟢	🟡
Inner/central tracking with PID **Proposed technologies:** TPC+(multi-GEM, Micromegas, Gridpix), drift chambers, cylindrical layers of MPGD, straw chambers	Rad-hard/longevity	1.1	🟠	🟠	🟠						🟡				🟢		🟢				
	Low X_0	1.2	🟠	🟠	🟠						🟠				🟠	🔴	🟠	🔴			
	IBF (TPC only)	1.2	🟠	🟠											🔴	🔴	🔴	🔴			
	Time resolution	1.1	🟡		🟡						🟠				🟢	🟡	🟢	🟡			
	Rate capability	1.3	🟠		🟠						🟠				🟢	🟡	🟢	🟡			
	dE/dx	1.2	🟠								🟠				🟠	🟠	🟠	🟠			
	Fine granularity	1.1	🟠		🟠						🟠				🟠	🟠	🟠	🟠			
Preshower/ Calorimeters **Proposed technologies:** RPC, MRPC, Micromegas and GEM, µRwell, InGrid (integrated Micromegas grid with pixel readout), Pico-sec, FTM	Rad-hard/longevity	1.1													🟡	🟡	🟡		🔴	🔴	🔴
	Low power	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Gas properties (eco-gas)	1.3													🔴	🔴	🔴		🔴	🔴	🔴
	Fast timing	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Fine granularity	1.1													🟠	🟠	🟠		🟠	🟠	🟠
	Rate capability	1.3													🟠	🟠	🟠		🔴	🔴	🟠
	Large array/integration	1.3													🔴	🔴	🔴		🔴	🔴	🔴
Particle ID/TOF **Proposed technologies:** RICH+MPGD, TRD+MPGD, TOF: MRPC, Picosec, FTM	Rad-hard (photocathode)	1.1	🟠	🟠							🟡										
	IBF (RICH only)	1.2	🟠	🟠							🟠										
	Precise timing	1.1	🟡	🔴							🔴										
	Rate capability	1.3		🟢							🟠										
	dE/dx	1.2		🟢																	
	Fine granularity	1.1		🟠							🟠										
TPC for rare decays **Proposed technologies:** TPC+MPGD operation (from very low to very high pressure)	Low power	1.4				🔴	🔴						🔴								
	Fine granularity	1.4				🟢	🟠	🟠					🟠	🟠							
	Large array/volume	1.4				🟡	🟠	🟡					🔴	🔴							
	Higher energy resolution	1.4				🟢	🔴	🔴					🔴	🔴							
	Lower energy threshold	1.4				🔴	🟠	🔴					🟠	🔴							
	Optical readout	1.4				🟡	🟠	🟠					🟠	🟠							
	Gas pressure stability	1.4				🟢		🔴						🔴							
	Radiopurity	1.4				🟢	🔴	🔴					🔴	🔴							

🔴 Must happen or main physics goals cannot be met
🟠 Important to meet several physics goals
🟡 Desirable to enhance physics reach
🟢 R&D needs being met

ECAF Gaseous Detector R&D Roadmap

- Muon探测
- 径迹探测
- 粒子鉴别
- Preshower 量能器
- TPC用于稀有衰变

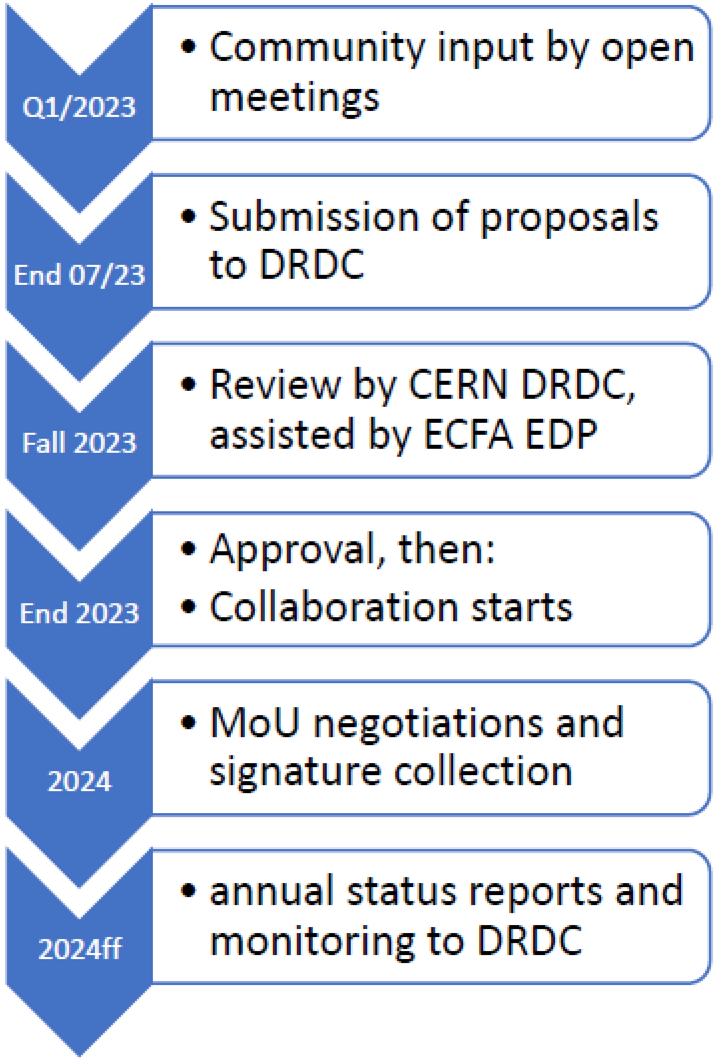
- 提高气体探测器的时间、空间分辨、以及长期稳定性
- 提高大型气体径迹室的径迹测量能力和粒子鉴别能力（不同读出方案dE/dx和dN/dx ）
- 低物质量、高计数率、气体对环境友好
- 提高高、低气压TPC的灵敏度

The main activity areas corresponding to the major drivers from future facilities. Detector R&D Themes：

- DRDT 1.1 - Improve time and spatial resolution for gaseous detectors with long-term stability.
- DRDT 1.2 - Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes.
- DRDT 1.3 - Develop environmentally friendly gaseous detectors for very large areas with high-rate capability.
- DRDT 1.4 - Achieve high sensitivity in both low and high-pressure TPCs.

From ECFA Task forces to DRD collaborations

- Collected input from the communities in open meetings happening in the beginning of 2023
- Summer 2023: **Submission deadline of DRD proposals**
- **Approval of first DRD collaborations in December 2023 RB**
- Once approved, DRD collaborations started in 2024



Q1/2023
- Community input by open meetings

End 07/23
- Submission of proposals to DRDC

Fall 2023
- Review by CERN DRDC, assisted by ECFA EDP

End 2023
- Approval, then:
- Collaboration starts

2024
- MoU negotiations and signature collection

2024ff
- annual status reports and monitoring to DRDC

DRD1: Gaseous Detectors

- A collaboration website exists: https://drd1.web.cern.ch

DRDTs				
1.1	1.2	1.3	1.4	Work Packages
●	●	●		Trackers/hodoscopes
●	●	●		Drift chambers
●	●	●		Straw chambers
●	●	●	●	Tracking TPCs
●		●		Calorimetry
●	●	●		Photon detection (PID)
●		●		Timing detectors
●	●	●	●	Reaction/decay TPCs
●		●		Beyond HEP

Forum for discussion on common topics

- WG1: Technologies
- WG2: Applications
- WG3: Gas and material studies
- WG4: Detector physics, simulations and software tools
- WG5: Electronics for gaseous detectors
- WG6: Detector production
- WG7: Common test facilities
- WG8: Training and dissemination

Working Groups

- WG1: Technological Aspects and Developments of New Detector Structures, Common Characterization and Physics Issues
  - Study technologies such as wire, RPC, MPGD, and Large Volume Detectors (DC and TPC). Increase size, operate at higher rates, improve stability, and exploration of new technologies and innovations
- WG2: Applications
  - Focus on applications that use gaseous detectors technologies as sensing and amplification mediums
- WG3: Gas and Material Studies, and link to Novel Technologies
  - High-performance and environmentally friendly gas mixtures, gas systems, and material studies, including wires, resistive materials and solid converters, long-term operation
- WG4: Detector Physics, Modelling and Simulation frameworks
  - understand and model the basic physical processes taking place in gaseous detectors, develop suitable simulation and software tools
- WG5: Electronics for Gaseous Detectors
  - develop, apply electronics for Gaseous Detectors, includes analog front ends for specific needs and new front-end ASICs
- WG6: Production and Technology Transfer
  - focuses on the manufacturing and production of gaseous detectors, enabling the realization of innovative solutions and the efficient implementation of industrial technology
- WG7: Common Test Facilities and Infrastructures
  - aims to facilitate access to analysis and testing facilities for prototypes and the final detector system
- WG8: Knowledge Transfer, Training and Career
  - concentrates on knowledge exchange, training opportunities, outreach and education, promotion of positive environment and better recognition for early career researchers

未来发展

- 特点：
  - 任务驱动：粒子物理实验或其他实验上的应用（tracker, inner tracker, PID, Muon detector, 宇宙线测试 ）
  - 大面积、大体积应用，小面积的应用优势较难体现，新技术发展

- 未来发展方向：
  - 提高粒子物理实验中的径迹探测、粒子鉴别等性能
  - 新技术、新方法 （dN/dx）
  - 低物质量：发展新材料（碳丝）；布丝方法；超轻结构设计，减少多次散射
  - 复合探测器及新读出结构（气体+像素读出， pixelated TPC）
  - 探索高气压TPC在中微子探测中的应用
  - 圆筒MPGD内径迹室研制及应用

小结

- 大型气体探测器在过去和目前高能物理实验中被广泛使用，发挥了不可替代的作用
- 随着新技术、新方法和新材料的发展，大型气体探测器如漂移室和时间投影室等仍为下一代高能物理实验中径迹探测器至关重要的选项
- 以未来高能物理实验为目标，主要发展方向/技术：
  - 提高粒子物理实验中的径迹探测、粒子鉴别等性能
  - 新技术、新方法（dN/dx）
  - 低物质量：发展新材料（碳丝）；布丝方法；超轻结构设计，减少多次散射
  - 复合探测器及新读出结构（气体+像素读出， pixelated TPC）
  - ……

非常感 谢！