# 核电子学与探测器技术发展与展望

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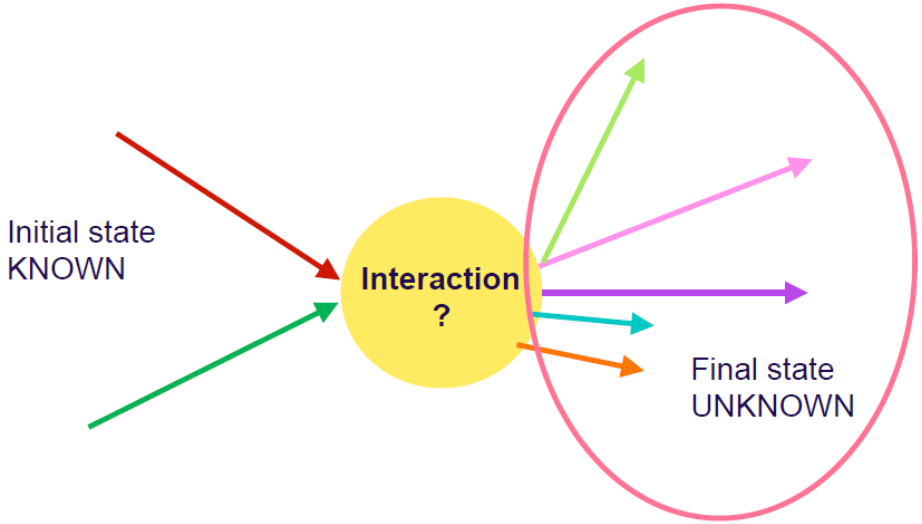
核探测与核电子学国家重点实验室

2017年7月4日

中国科学院

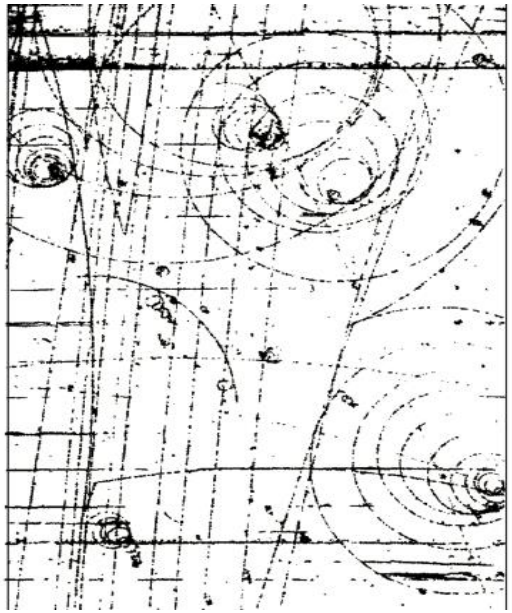
高能物理研究所、中国科学技术大学

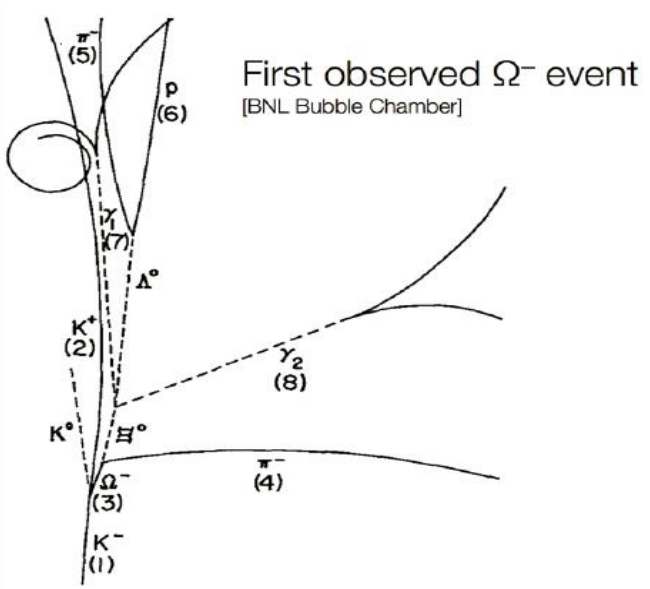
# 探测器



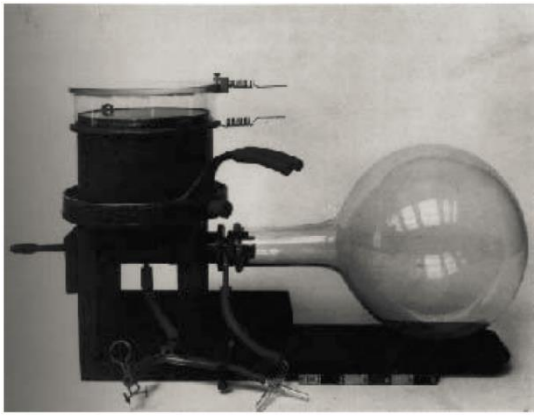

## 记录相互作用后的产物

- 测量位置信息/运动径迹
- 测量动量/能量
- 测量时间信息
- ……





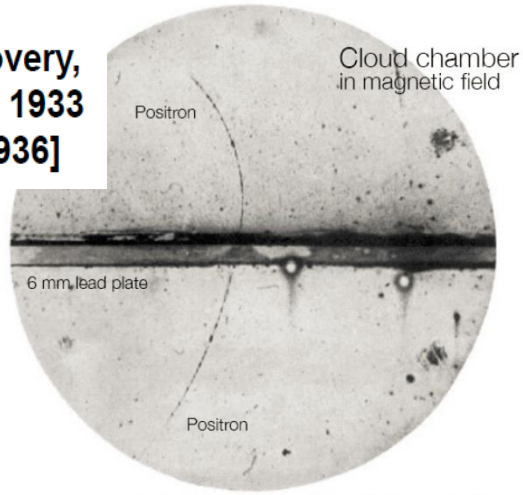
# 早期的探测器

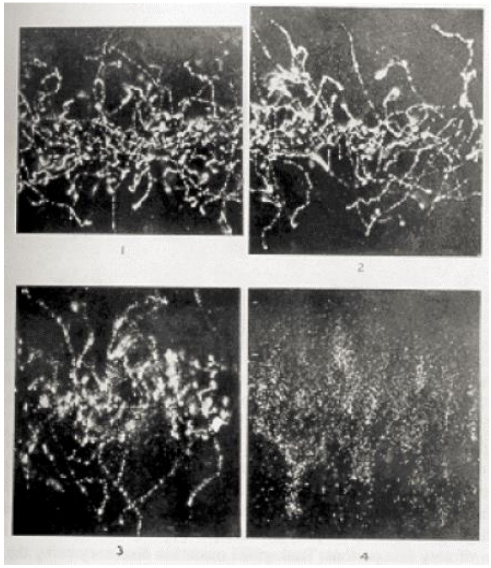


Wilson Cloud Chamber 1911

云室
乳胶
气泡室
……

**Positron discovery,**
**Carl Andersen 1933**
**[Nobel price 1936]**



X-rays, Wilson 1912

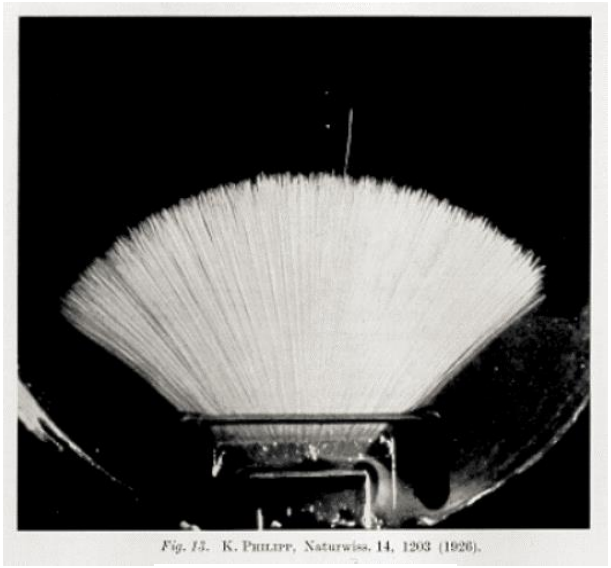
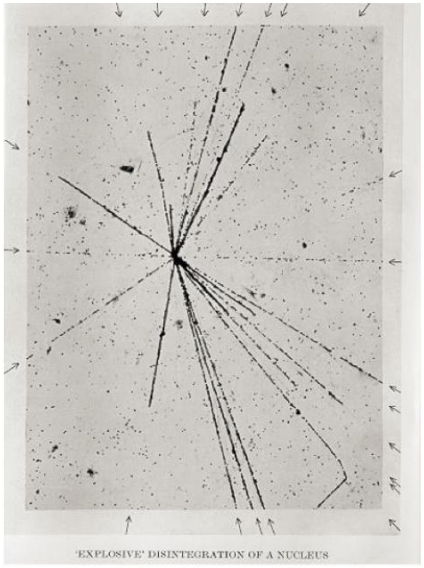


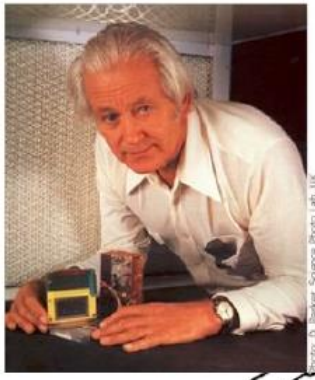
Fig. 13. K. Philipp, Naturwiss. 14, 1203 (1926).

Alphas, Philipp 1926




nuclear disintegrations in 1937

# 丝室



单丝计数率：1MHz

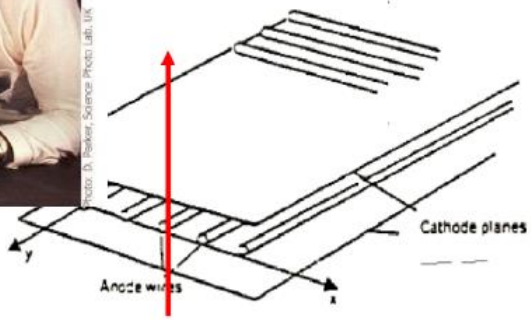
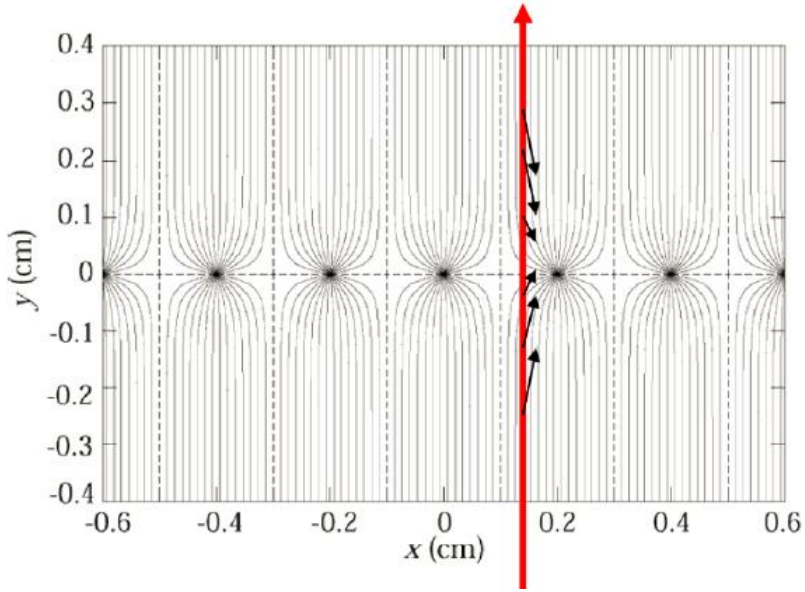
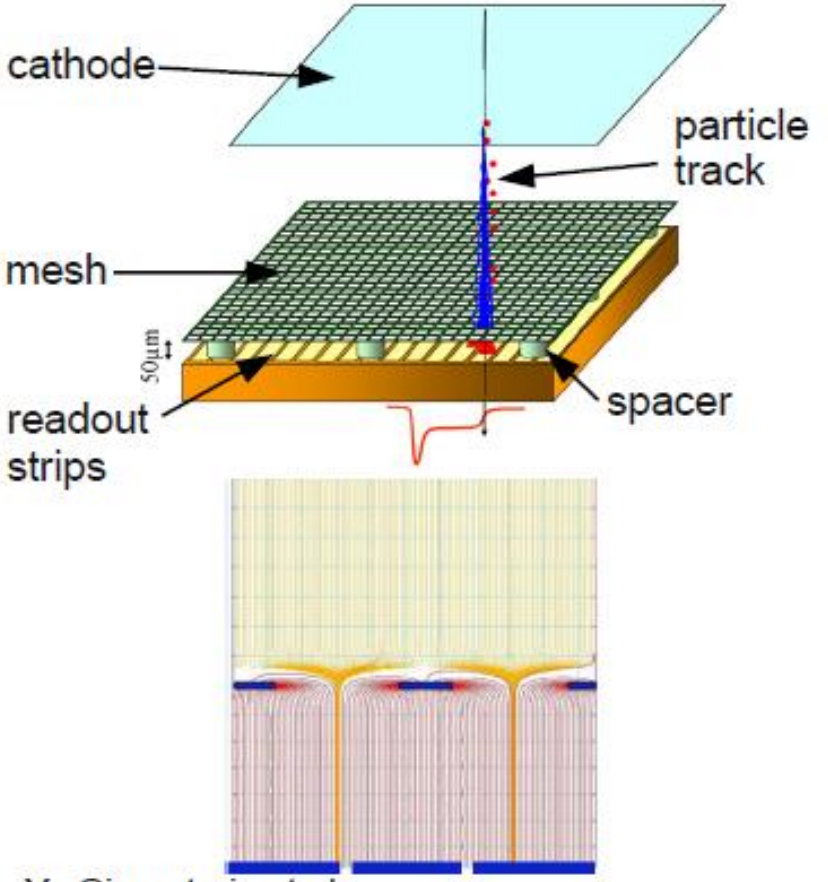



Abbildung 2.27: *Vieldrahtproportionalkammer.*



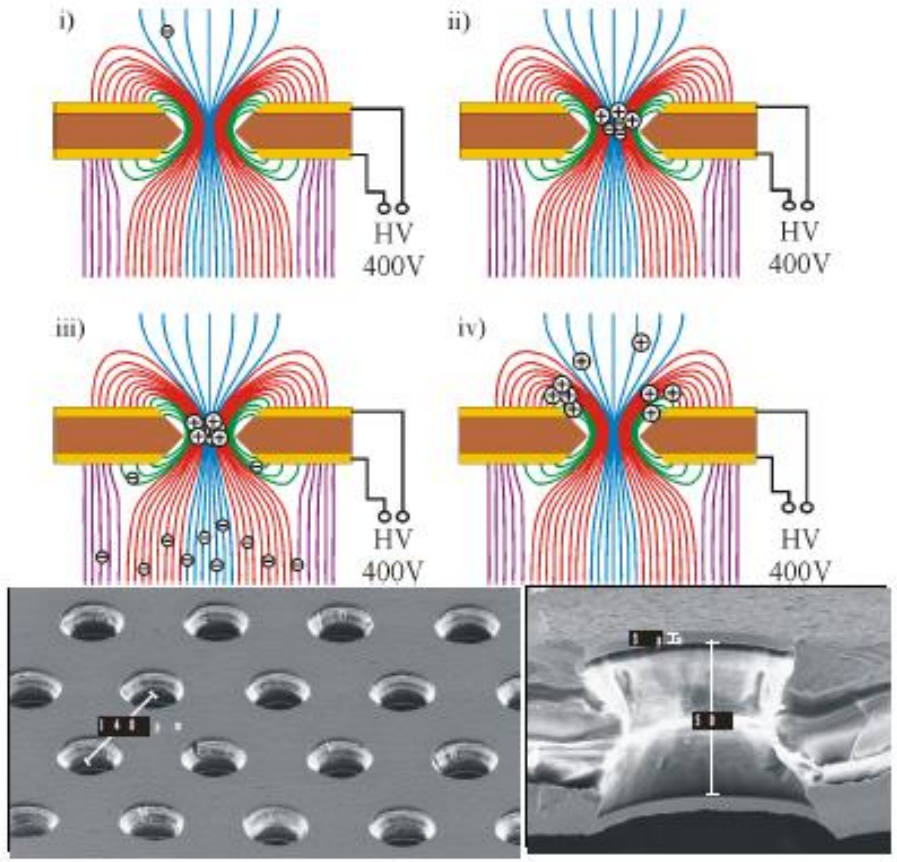

# 气体探测器（1D->2D）

## Micro-Mesh Gaseous Detectors



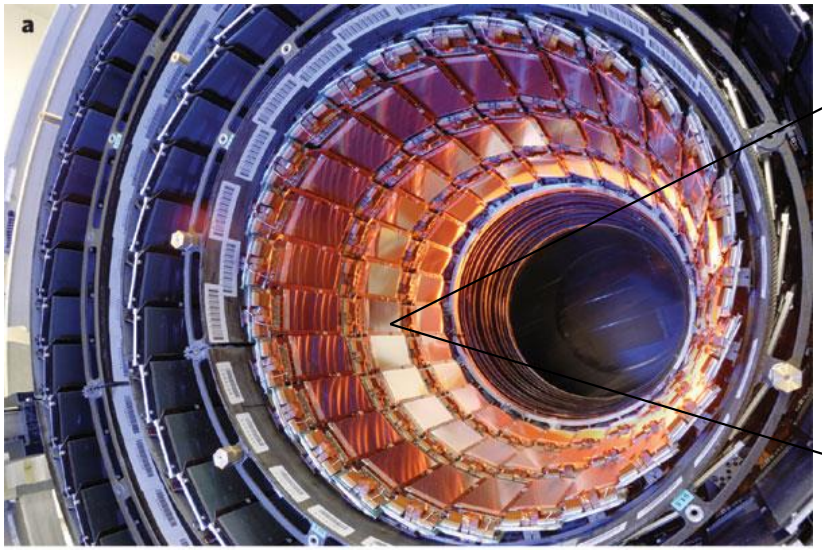

Y., Giomataris et al.,
Nucl. Instrum. Meth. A376:29-35,1996.

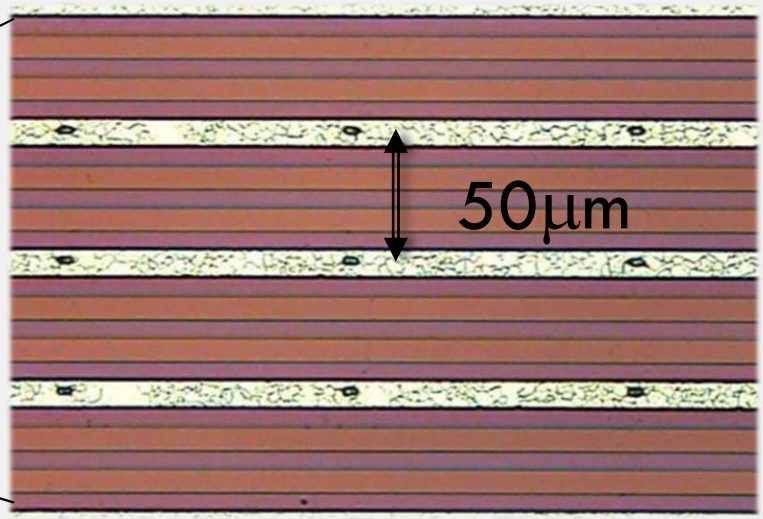
## Gas Electron Multipliers



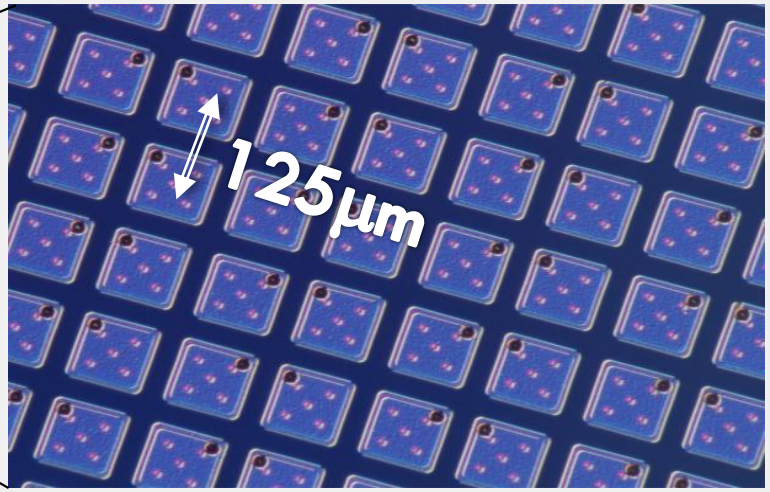

F. Sauli, Nucl. Instrum. Meth. A386:531-534,1997.

# 硅探测器（1D->2D）



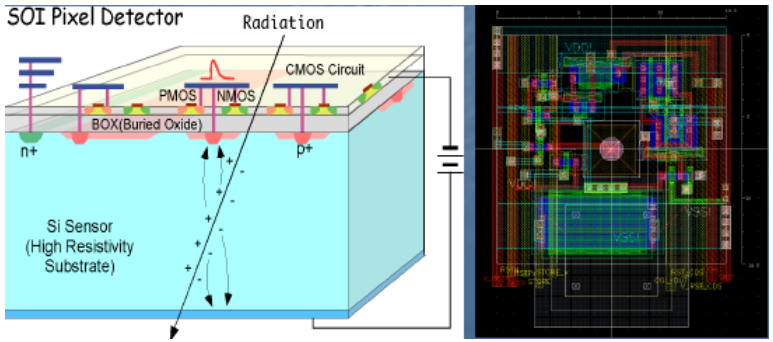




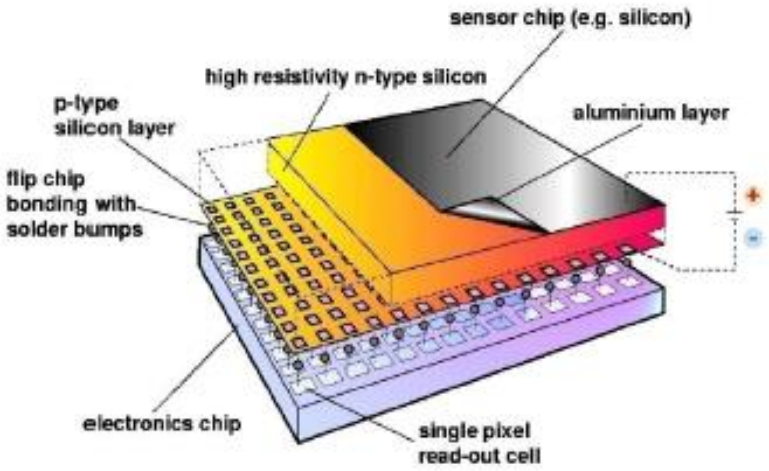
# Pixel detectors

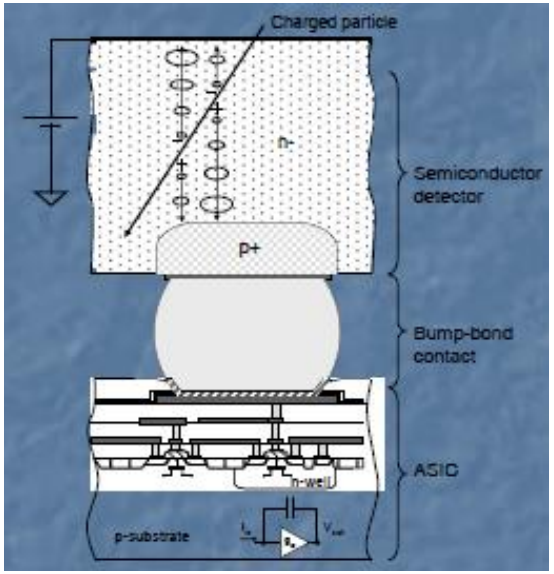
像素越小，位置分辨越好
电容越小，SNR越好
计数率更高

Monolithic pixels




Hybrid pixels: high cost of bump bonding

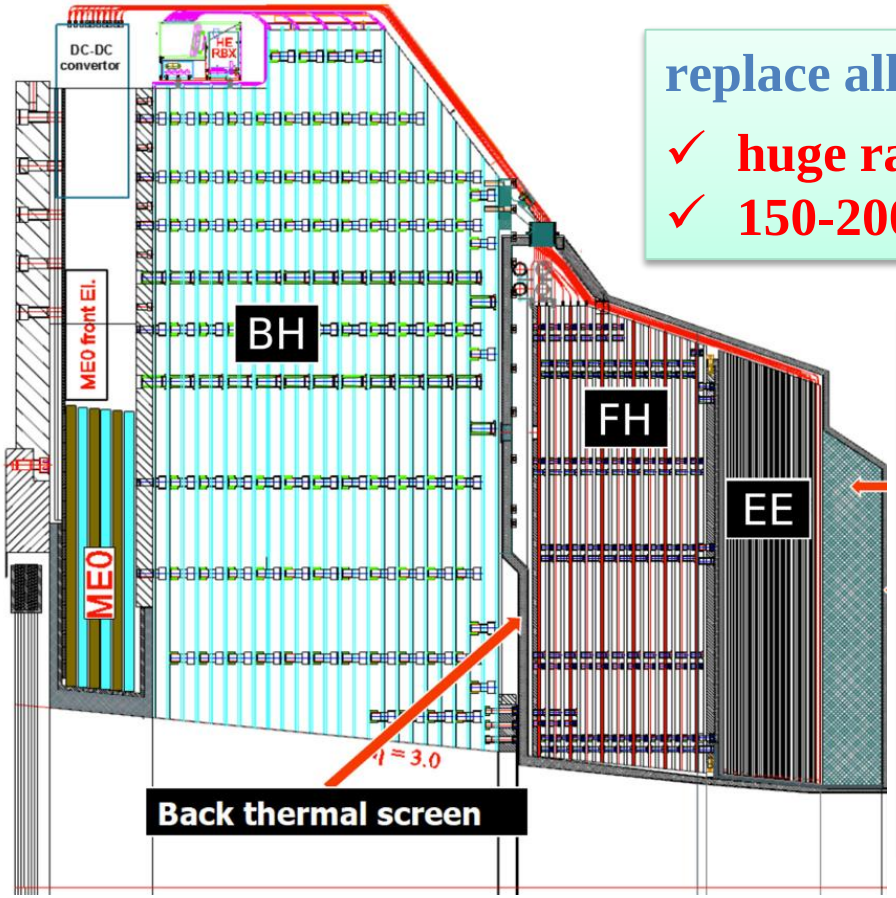


# 通道数增加

| | | ALICE | ATLAS | CMS | LHCB | ILD |
|---|---|---|---|---|---|---|
| Pixel | # channels | 9.8M | 80M | 66M | | 100M/ECAL<br>10M/HCAL |
| | # modules | 240 | 1788 | 1440 | | |
| Strips | # channels | 2.6M | 3.2m | 9.3M | 86k | |
| | # modules | 1698 | 4088 | 15148 | 43 | |

# CMS HGCAL: a sampling calorimeter




**replace all endcap calorimeters in ~2025**

- ✓ **huge radiation environment: ~$10^{16}$ n/cm$^2$**
- ✓ **150-200 pileup events per bunch-crossing**

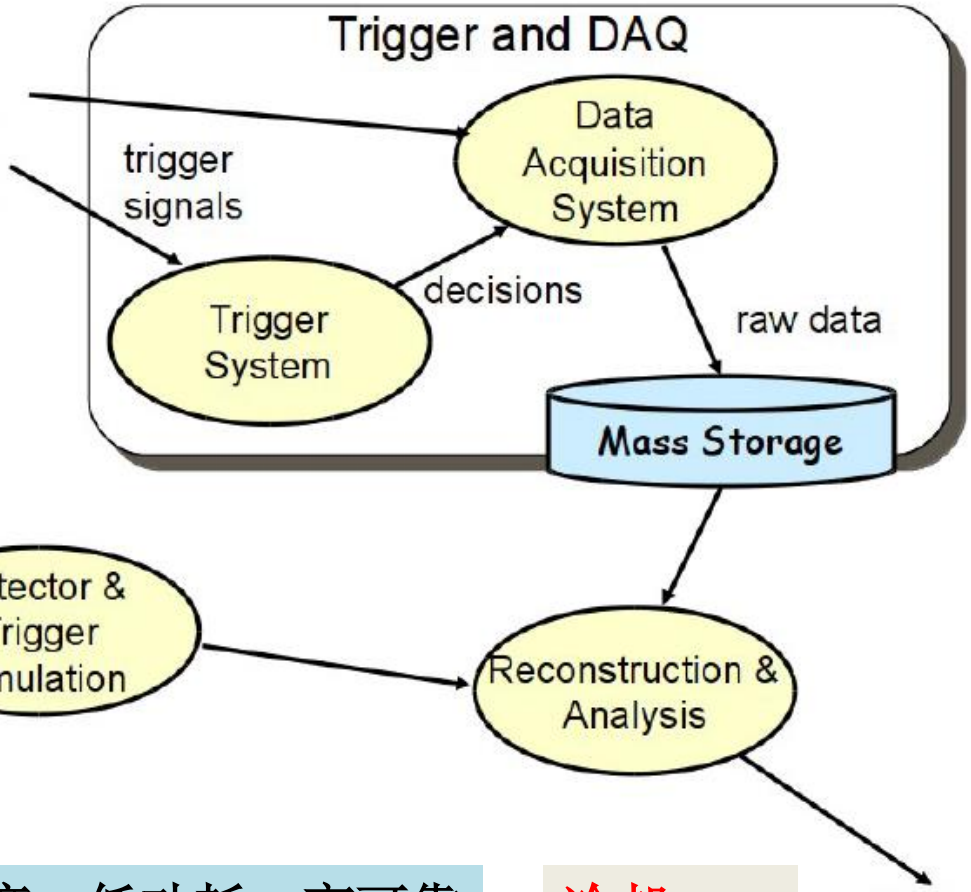
Key parameters:

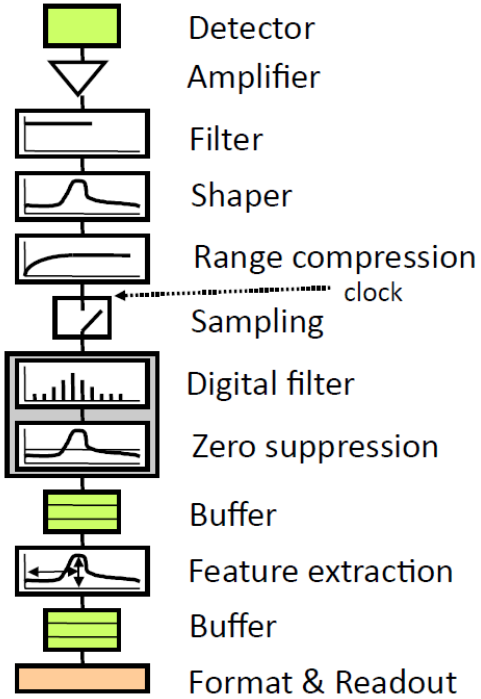
- **593 m$^2$ of silicon (3x CMS TK!)**
- 6M ch, 0.5 or 1 cm$^2$ cell-size
- 21,660 modules (8" or 2x6" sensors)
- 92,000 front-end ASICS.
- Power at end of life 115 kW
- ~230 tonnes per endcap

System Divided into three separate parts:

EE – **Silicon** with **tungsten** absorber – 28 sampling layers – 25 $X_o$ + ~1.3 λ
FH – **Silicon** with **steel** absorber – 12 sampling layers – 3.5 λ
BH – **Scintillator** with **steel** absorber – 11 layers – 5.5 λ

# 电子学、触发和数据获取

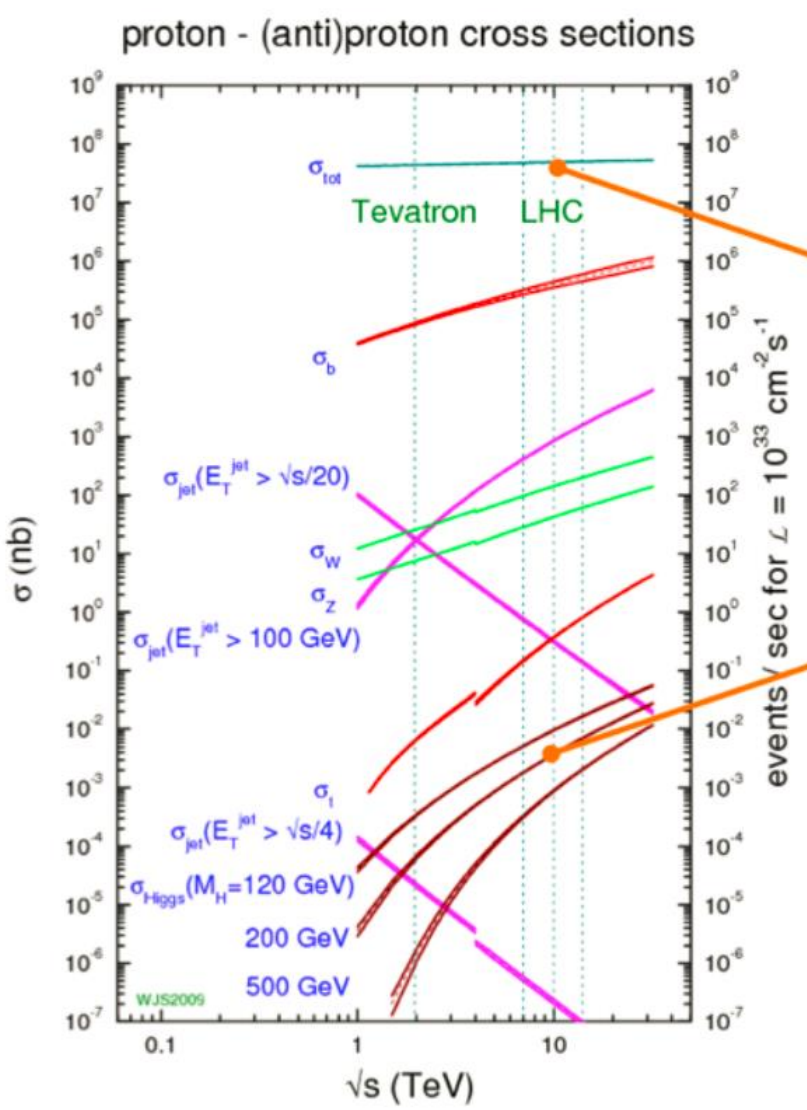



高密度、低功耗、高可靠
高速数据传输
**FPGA/DSP/CPU数据处理**

冷却
抗辐照
低物质量

# DETECTOR at LHC - Challenge




40 millions beam crossing/s
1 billion collisions/s

$10^8$ events/s

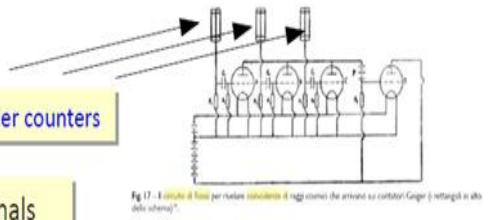
$\sim 10^{10}$

$10^{-2}$ events/s ~
10 events/min

[$m_H$ ~ 120 GeV]

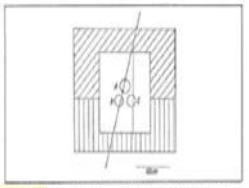
0.2% H → γγ
1.5% H → ZZ

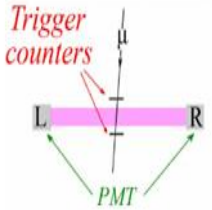
# 触发



Geiger-Muller counters

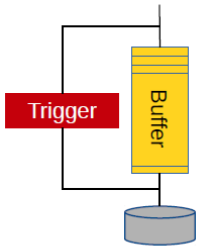
Rossi's circuit: coincidence of signals of 3 Geiger-Muller counters

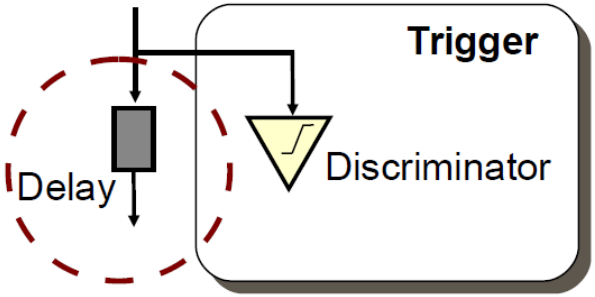


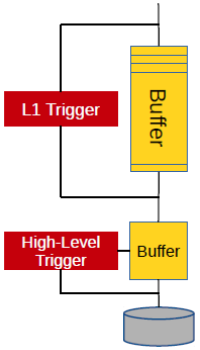


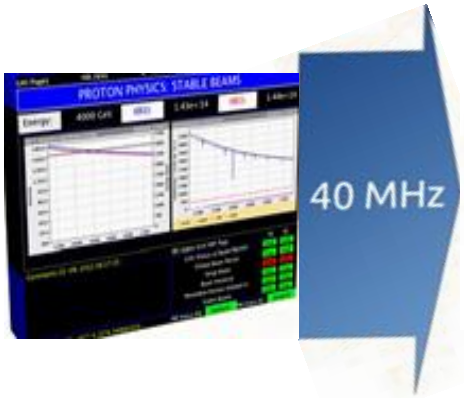

simplest case: 2-signal coincidence

高本底排除能力
高触发效率



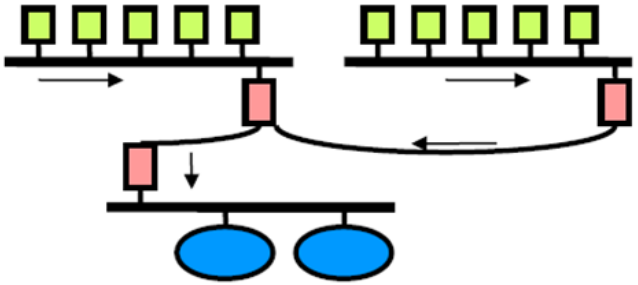



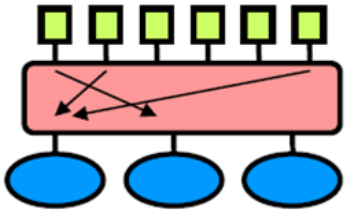



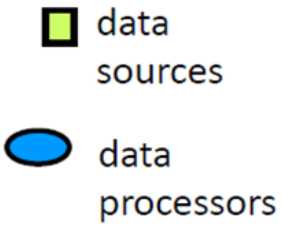



LHC　　L1 Trigger　　HightLevelTrigger　　离线分析

# 读出方式








总线式：

VME、PCI、SCSI、。。。

通过共享总线互联，需要仲裁

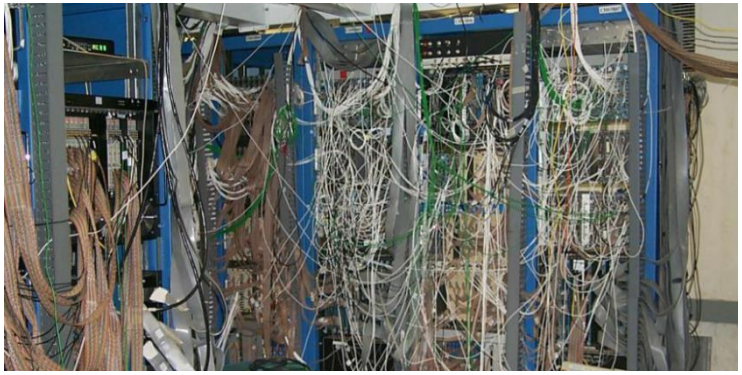
同一时刻只能访问一个设备

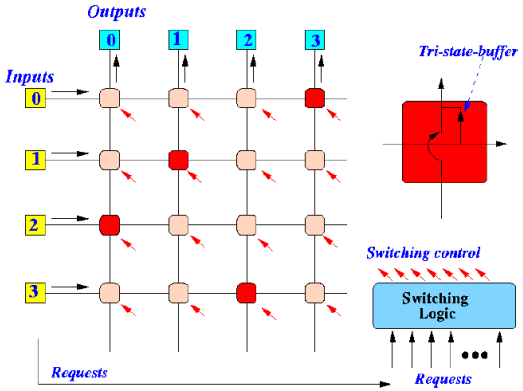
网络式：

Ethernet、Infiniband、。。。

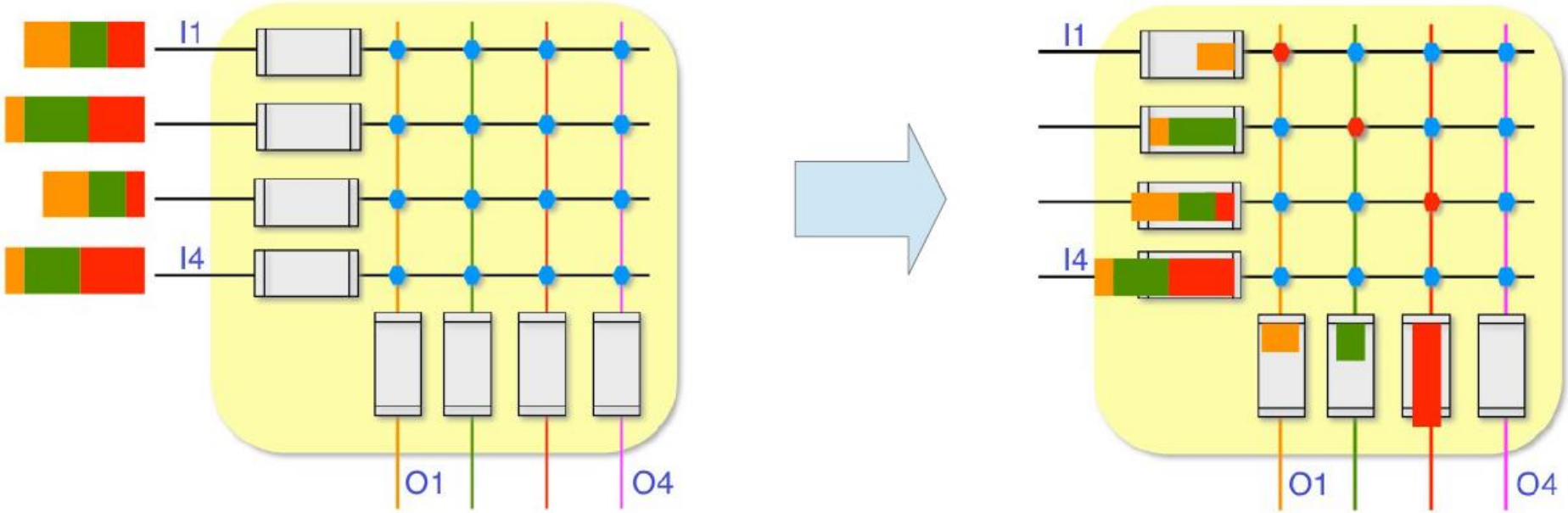
所有设备都有同等的权利，无需仲裁

同一时刻多个设备可以点对点访问






# 事例组装

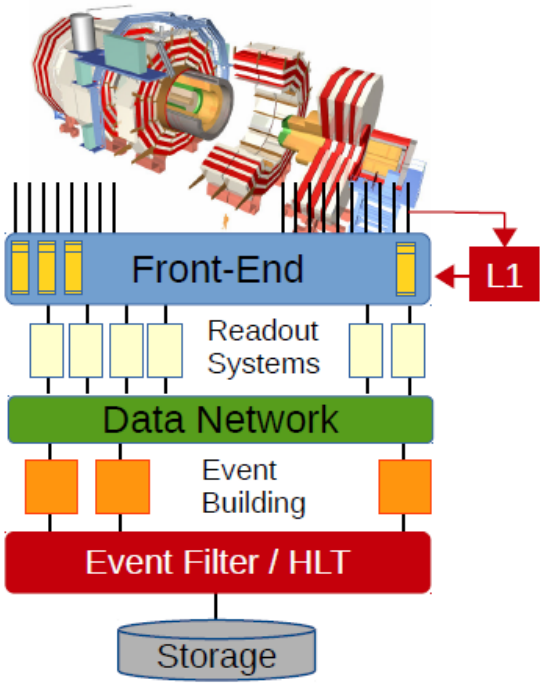



内存管理

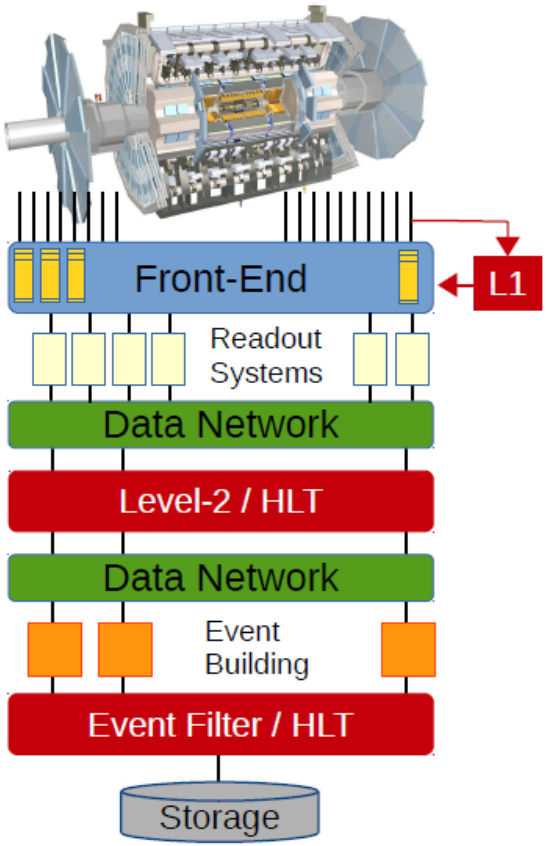
数据流管理

# ATLAS/CMS trigger and DAQ

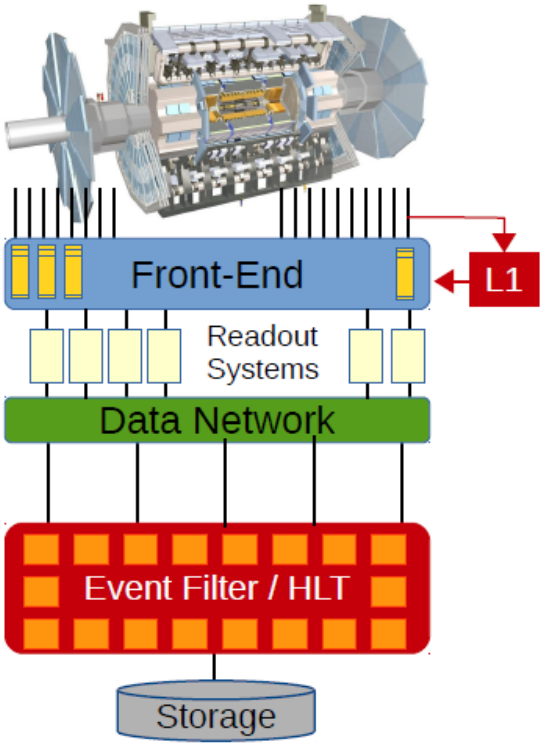
**CMS Run-1&2**
- 100 kHz EB
- Dedicated EB farm




**ATLAS Run-1**
- 5 kHz EB after L2
- Dedicated EB farm



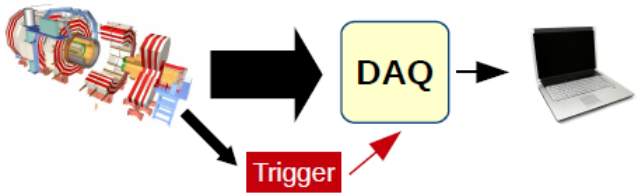

**ATLAS Run-2**
- incremental EB
- EB on HLT nodes

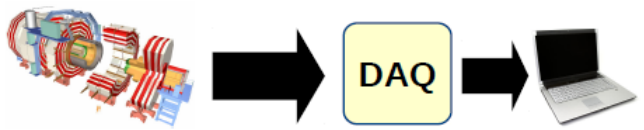


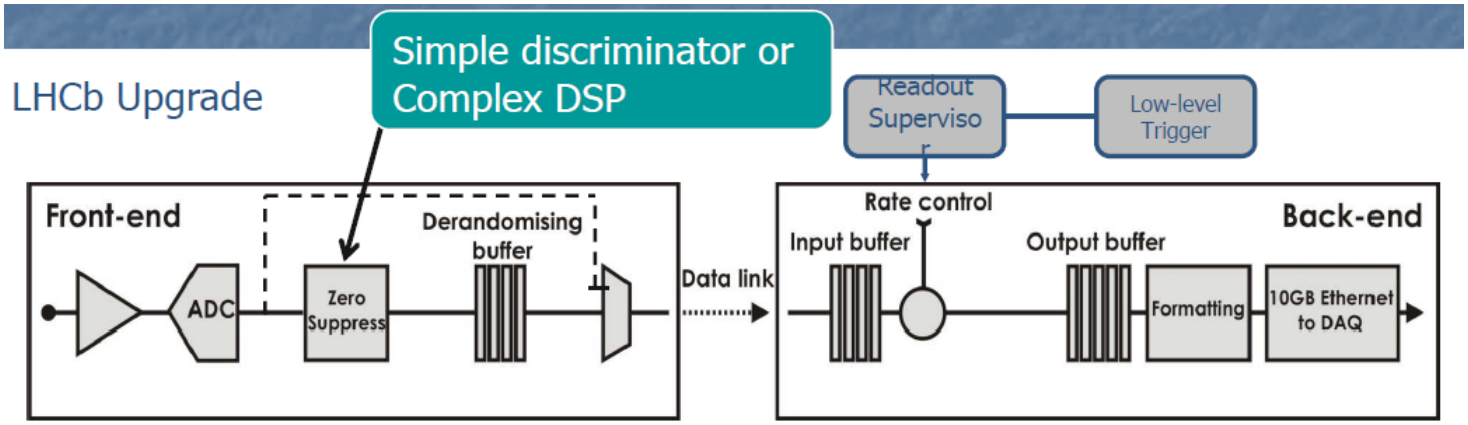
# Trigger-less DAQ

简化前端电子学
高速数据传输
零压缩，带时间戳，同步

LSST ~3GB/s
mu2E ~30GB/s
DUNE ~1TB/s (in 2020+)
……

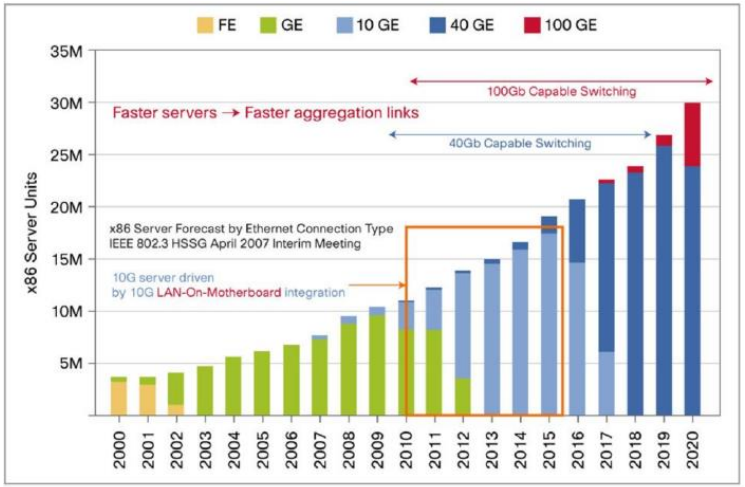


# The upgraded LHC experiments (LS2 & LS3)

- ALICE
  - Continuous readout at TPC limit (~50 kHz)
  - Merge of online and offline computing farm
- LHCb
  - No HW trigger → 40(30) MHz to HLT
- ATLAS/CMS
  - Increase HW trigger output rate to ~ 1 MHz
  - Replacement of the majority of FE electronics
  - New inner trackers incl. HW-based track triggers
  - Details of TDAQ systems still very much under discussion




*The Market Need for 40 Gigabit Ethernet, Cisco (2014)*

| | | # Trigger Levels HW | SW | Accept rate | | Event size | Event building | Permanent Storage |
|---|---|---|---|---|---|---|---|---|
| ALICE (Pb-Pb) | Run-3 | 0 | 1 | 50 kHz | | 60 MB | †0.5 TB/s | †90 GB/s |
| LHCb | Run-3 | 0 | 1 | 30 MHz | 20 kHz | 0.1 MB | 4 TB/s | 2 GB/s |
| ATLAS | Run-4 | 1 (or 2)‡ | 1 | 0.4(1) MHz | 10 kHz | 5 MB | 2(5) TB/s | 50 GB/s |
| CMS | Run-4 | 1 | 1 | 0.75 MHz | 7.5 kHz | 5 MB | 4 TB/s | 40 GB/s |

† Alice: event compression (factor~6) and only storing reconstructed objects
‡ Atlas: One or two-level HW trigger under discussion

# Summary

- 探测器的颗粒度越来越小，通道数巨大
- 尽量采用商用器件、设备
  - 计算机、网络、存储等技术的发展 → trigger-less DAQ
  - 多核CPU、GPU、FPGA、。。。
- 在线和离线、触发和电子学、探测器和电子学的结合越来越密切