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粒子物理实验 数据处理

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STANDARD MODEL OF ELEMENTARY PARTICLES

QUARKS	UP mass 2,3 MeV/c ² charge 2/3 spin 1/2 u	CHARM 1,275 GeV/c ² 2/3 1/2 c	TOP 173,07 GeV/c ² 2/3 1/2 t	GAUGE BOSONS
	DOWN 4,8 MeV/c ² -1/3 1/2 d	STRANGE 95 MeV/c ² -1/3 1/2 s	BOTTOM 4,18 GeV/c ² -1/3 1/2 b	
	ELECTRON 0,511 MeV/c ² -1 1/2 e	MUON 105,7 MeV/c ² -1 1/2 μ	TAU 1,777 GeV/c ² -1 1/2 τ	
	ELECTRON NEUTRINO <2,2 eV/c ² 0 1/2 ν_e	MUON NEUTRINO <0,17 MeV/c ² 0 1/2 ν_μ	TAU NEUTRINO <15,5 MeV/c ² 0 1/2 ν_τ	
	GLUON 0 0 1 g	PHOTON 0 0 1 γ	Z BOSON 91,2 GeV/c ² 0 1 Z	
	HIGGS BOSON 126 GeV/c ² 0 0 H	W BOSON 80,4 GeV/c ² ±1 1 W		



BES III



标准模型

✓电弱统一理论

实验对电弱理论有很多精确的测量和检验；2012年 Higgs粒子的发现标志着电弱理论的巨大成功

✓量子色动力学

高能下的QCD得到实验的大量检验，QCD的渐进自由

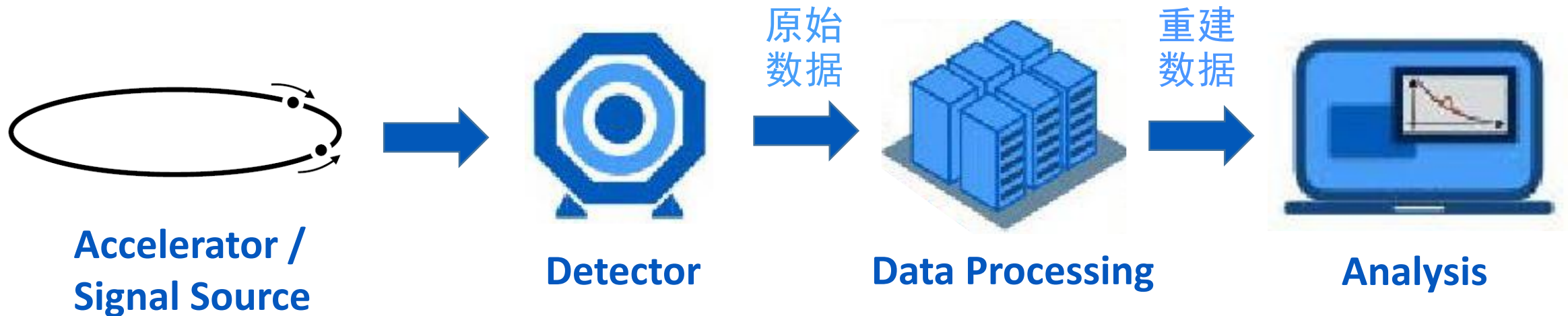
标准模型不能回答的问题

- 电弱对称性破坏和电弱相变
- 味对称和味结构
- 质量等级
- 暗物质
- 暗能量
- 反物质不对称
- 宇宙膨胀
- 引力的量子化和量子属性

标准模型不是终极理论

粒子物理实验

- 非常简单粗暴地划分：**理论** — 动力学；**实验** — 运动学
- 粒子物理实验的研究内容：
 - 粒子的产生：截面、产生机制
 - 粒子的性质：质量、寿命、共振宽度、自旋、宇称，……
 - 相互作用的物理规律：衰减常数、衰变分支比、能谱、形状因子、物理量的守恒与破坏，……
 - 寻找新粒子，新物理现象
- 测量/物理对象：带电粒子 e, μ, π, K, p 中性粒子 γ, K_L, ν, n 的四动量 (p_x, p_y, p_z, E)



粒子探测

• 微观粒子的探测是通过**粒子与宏观物质的相互作用**实现的

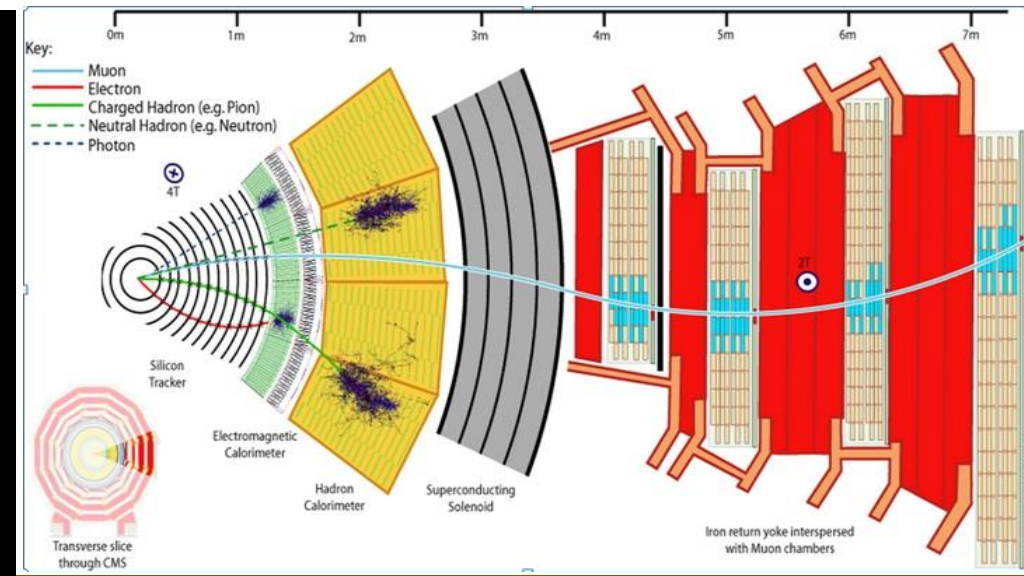
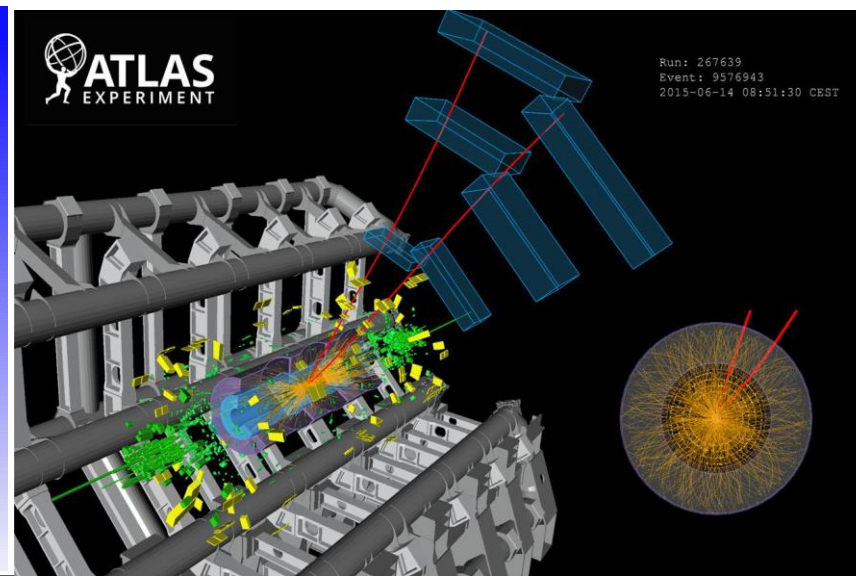
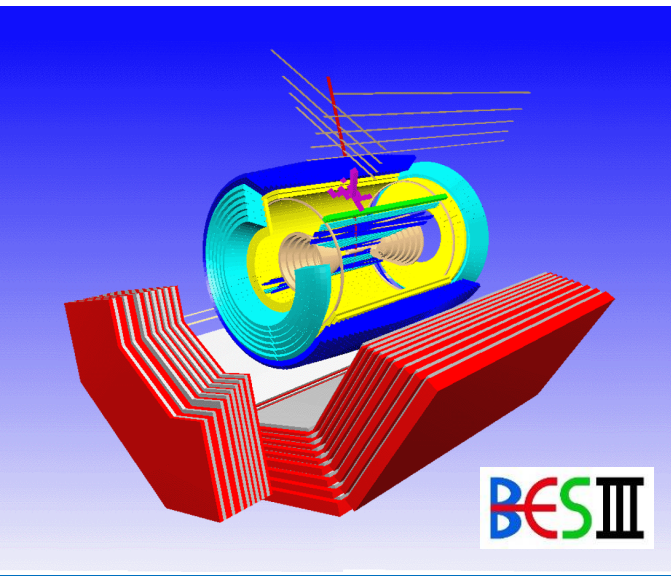
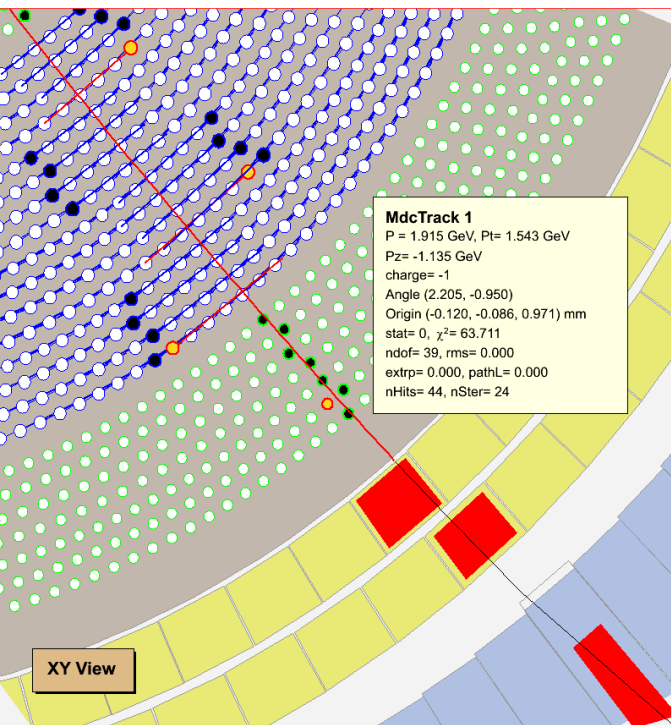
➤ 带电粒子与介子的分子，原子及核的碰撞

- ✓ 电离能损
- ✓ 多次散射
- ✓ 切伦科夫辐射
- ✓ 穿越辐射
- ✓ 韧致辐射
- ✓ 正负电子湮灭

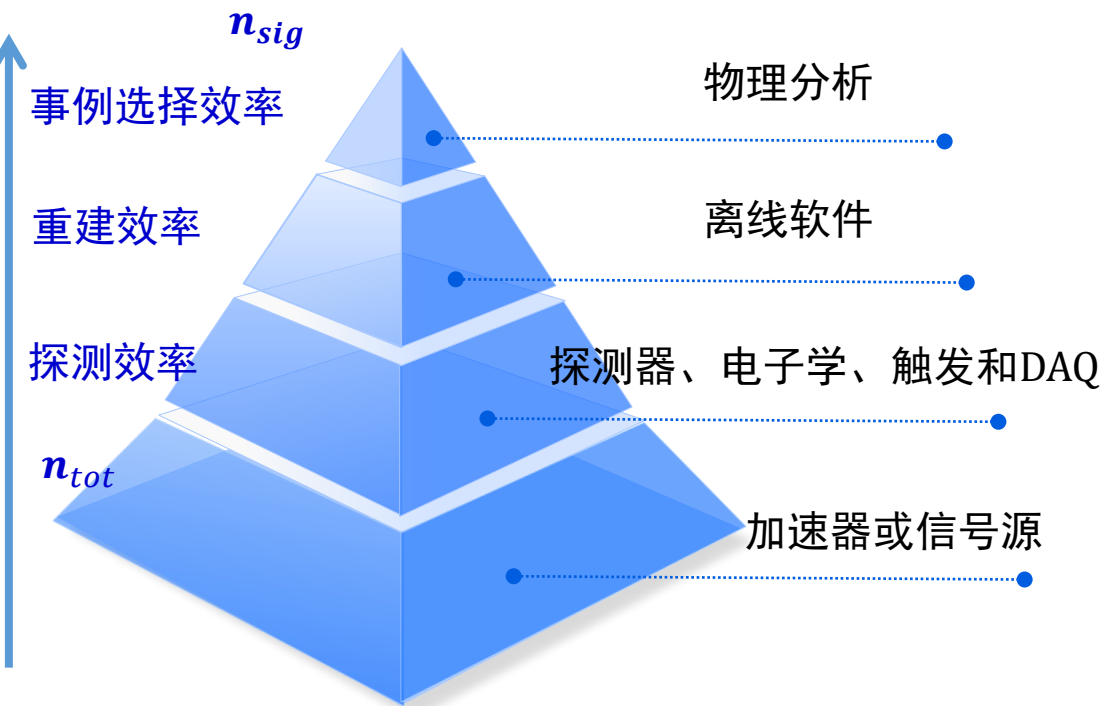
➤ 光子与探测器介质的作用

- ✓ 光电效应
- ✓ 康普顿散射
- ✓ 电子对产生

• 粒子与探测器相互作用输出的信号，经过电子学提取电荷，时间等信息，形成**原始数据**



数据产生、获取、处理和分析



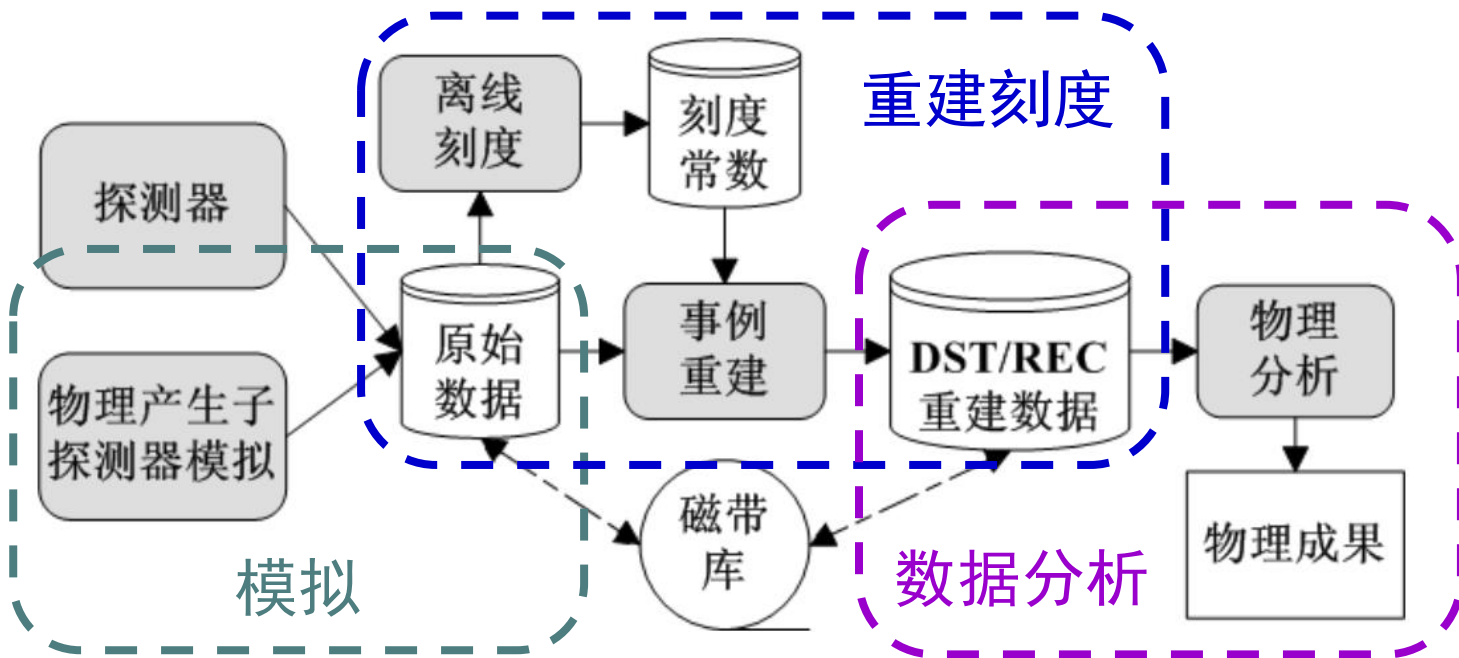
物理事例的产生、获取、处理和分析

- 高亮度的加速器或信号源 → 高统计量的实验数据 n_{tot}
- 高精度的探测器
 - 探测效率 / 探测器分辨
 - 物理过程：电离能损、电磁簇射，强子簇射等等
 - 束流/环境本底与电子学噪声
- 数据处理
 - 模拟 / 重建 / 刻度
- 物理分析
 - 事例选择效率： n_{sig} 统计误差
 - (质量) 分辨：信号显著性

$$BR = \frac{n_{sig}}{n_{tot} \cdot BR_{inter} \cdot \epsilon}$$

原始数据记录的电子学信号不能直接用于物理分析，需要在计算平台通过数据处理形成重建数据
计算与软件是粒子物理实验的重要环节！

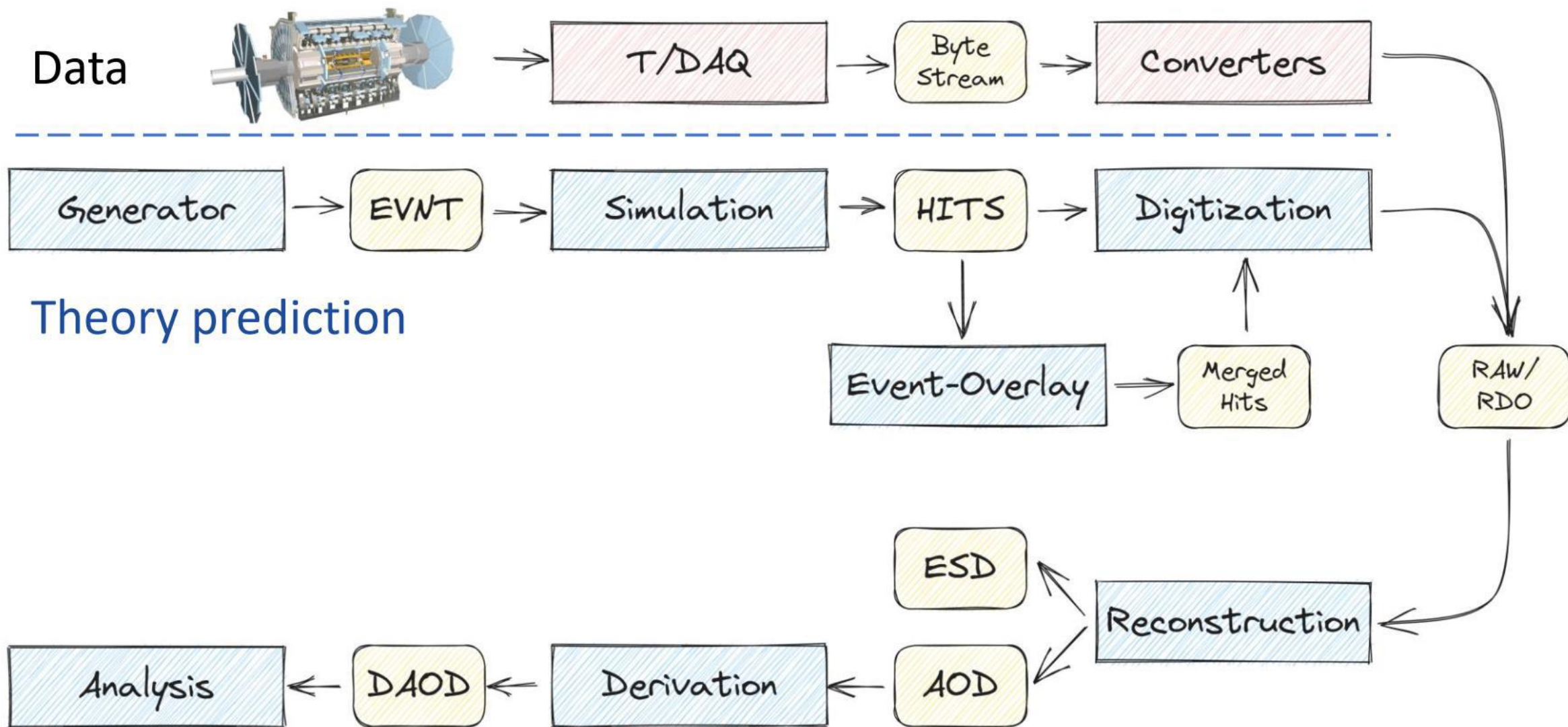
数据处理流程 (BESIII)



BESIII 数据处理和物理分析流程

- 模拟: signal MC / Inclusive MC
探测器设计 / 事例选择效率 / 本底分析
- 重建: 电子学信号 → 物理量
- 刻度
- 数据分析: Real Data / MC
研究物理过程与规律

数据处理流程 (ATLAS)



BESIII触发判选

触发 trigger 系统是快速实时事例选择和控制系统

- 利用BESIII各个子探测器电子学提供的原始信号和系统时钟，设计建造的快速高效的事例选择与数据读出控制系统

- **本底事例**

- **宇宙线**

- 排除比例 > 10:1

- 根据北京地区宇宙线通量 $170 \cdot m^{-2} \cdot s^{-1} \times 3m \times 3m \approx 1500Hz$

- **束流本底**

- 排除比例 > 10000:1

- ✓ 同步辐射光子

- ✓ 束流-气体非弹性韧致辐射 (Bremsstrahlung)、弹性库伦散射 (Coulomb Scattering) 和束团内部带电粒子之间的弹性散射-托歇克 (Touschek) 效应造成丢失粒子 (储存环挡板)

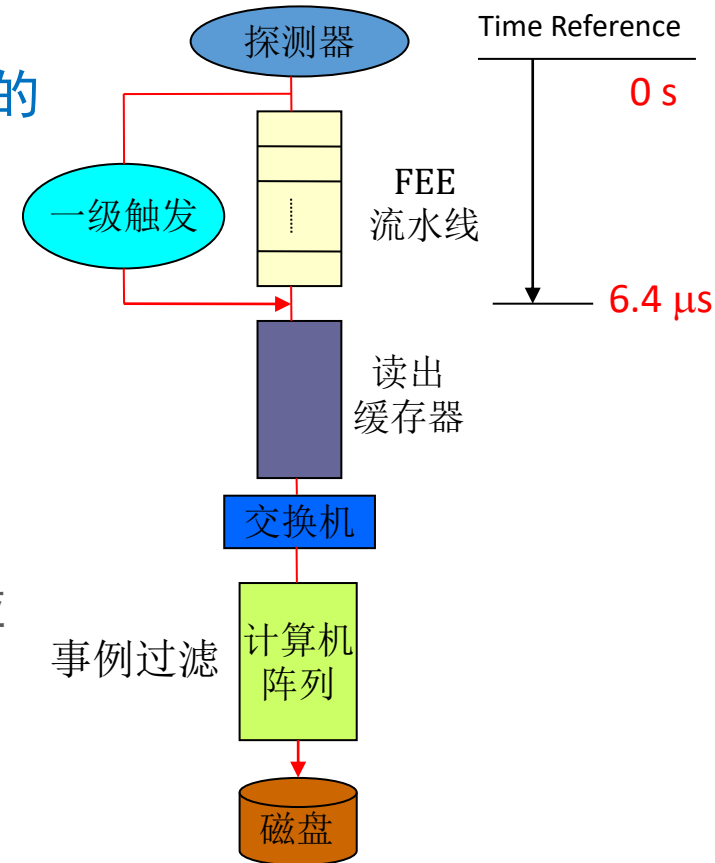
- ✓ 注入引起的丢失粒子 (注入期间降低探测器高压)

- **Bhabha 和 辐射Bhabha事例** 作为本底压低，保留作为刻度和亮度测量，通过预定标器进行比例减低

- **触发判选系统采用流水线方式**

- 探测器信号成形输出、电缆和触发电子学处理电路的延迟，不可能在两次对撞之间完成第一级触发，前端电子学数据采用流水线式进行存储处理

- **一级触发信号 L1 仅用于数据获取，不能作为时间参考**

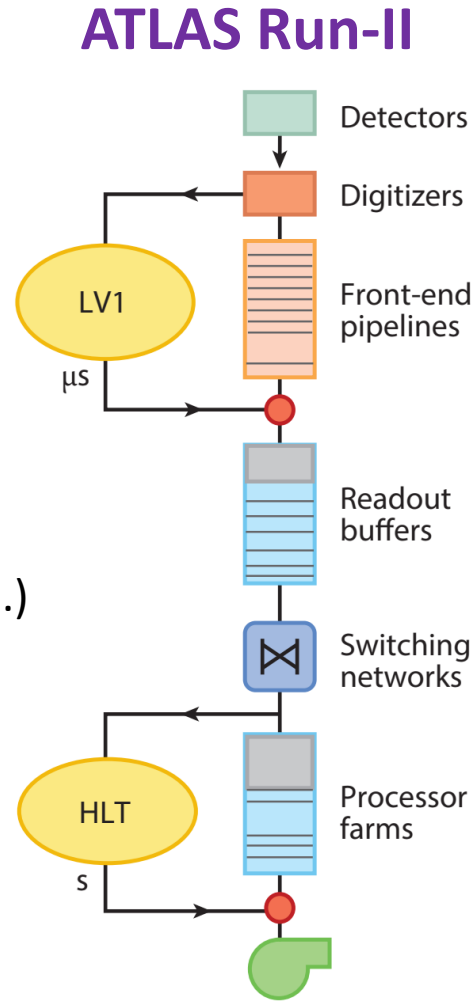


BESIII FEE 流水线和数据流程

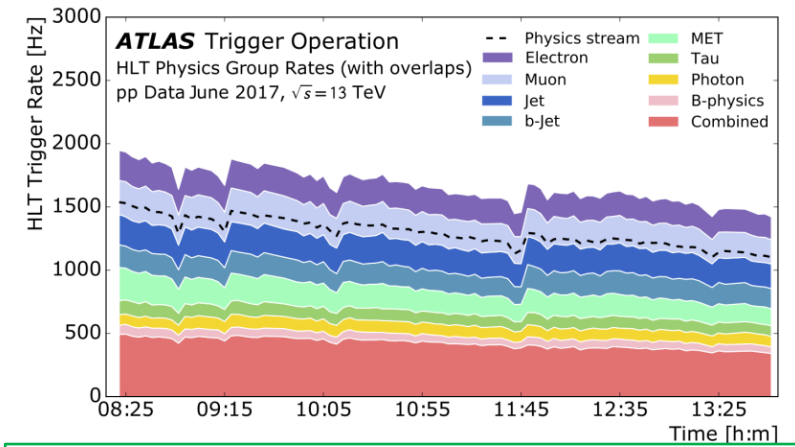
《北京谱仪 (BESIII) 的设计与研制》
第13章 触发判选系统

ATLAS触发判选

- ✓ 1G Hz interaction rate (pp)
- ✓ ~ 100 M readout channels
- ✓ **25ns bunch crossing rate**, total Event rate of 40M Hz
 - 1PB / sec
 - >> affordable storage
- ✓ **μ s first-level trigger decision**, rate reduces to <100k Hz
 - Limited by detector signal speed (e.g., Calo.)
 - Reduction rate 10^{-4}
- ✓ **ms-s higher-level trigger decision**, rate down to 1000Hz
 - Limited by HLT processing and DAQ downtime
 - Reduction rate 10^{-6}



- ◆ > 40K CPU cores dedicated to process HLT, with input decision from level-1
- ◆ **Close-to-offline software reconstruction**
 - ✓ Flexibility to look for complex topology for physics purpose (delayed muon trigger, VBF/VBS trigger, ...)



For data taking:
 Trigger Menu -collection of all HLT triggers,
 driven by physics ~3000 triggers

触发效率

Group	Channel	Conditions
Endcap Charged	CH01	NEClus.GE.1 && NETOF.GE.1 && STRk_BB
Barrel Charged	CH02	NBClus .GE. 1 && NBTOF .GE. 2 && NLtrk .GE. 2
	CH04	BTOF_BB && LTrk_BB
	CH05	Etot_L && NBTOF .GE. 1 && NLtrk .GE. 1
	CH06	NBClus .GE. 1 && NBTOF .GE. 1 && NLtrk .GE. 2
Neutral	CH09	NClus .GE. 1 && BEtot_H
	CH12	NClus. .GE. 2 && Etot_M

2018年 J/ψ 数据触发表

CPV, LFV, Dark Matter,
Faster-than-Light
Perpetual Motion Machine



NOT Trigger

- 触发的目标是高效选出有用的物理事例，并把极高的本底压缩到数据获取系统可以接受的程度
- 没有触发的事例永远地丢失了…… 触发效率研究对触发条件设置和物理研究十分重要
- 利用 2018年获取的 J/ψ 数据样本，挑选 **Bhabha事例**、**Dimu事例**和**带电强子事例**作为控制样本

$$\epsilon = \frac{N(sel, trig. conditions / channel)}{N_{sel}}$$

触发条件效率 $\epsilon_i: i = 0, 1, \dots, 47$

触发道效率 $c_j: j = 1, 2, 4, 5, 6, 9, 12$

物理事例触发效率 $g_k: k = 1, 2, 3$

CHj 成立时 Chi 成立的几率 $P(i|j)$

M. Ablikim et al. (BESIII Collaboration), Chin. Phys. C45(2021)023002

N. Berger et al Chin. Phys. C 34 (2010)1779-1784

BESIII数据获取系统 DAQ

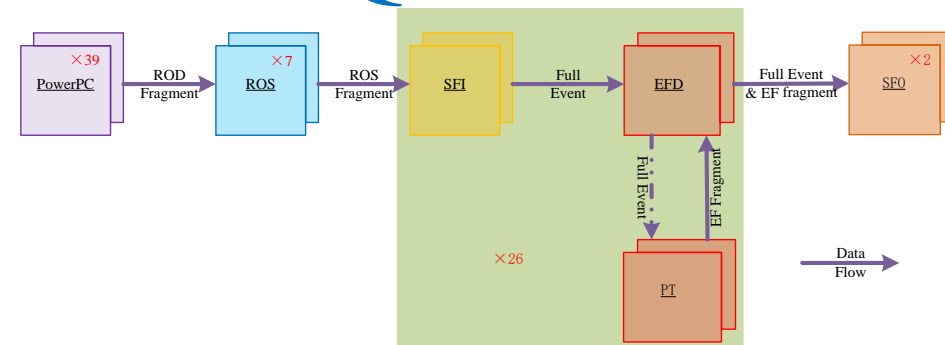
数据获取系统的主要任务：

完成包括漂移室、飞行时间计数器、电磁量能器、 μ 子计数器和触发判选等系统的数据读出和处理任务，保证同一次触发来自不同系统的数据同步组装成一个完整的事例。另外还需要与其他系统，如慢控制系统，进行信息交换。

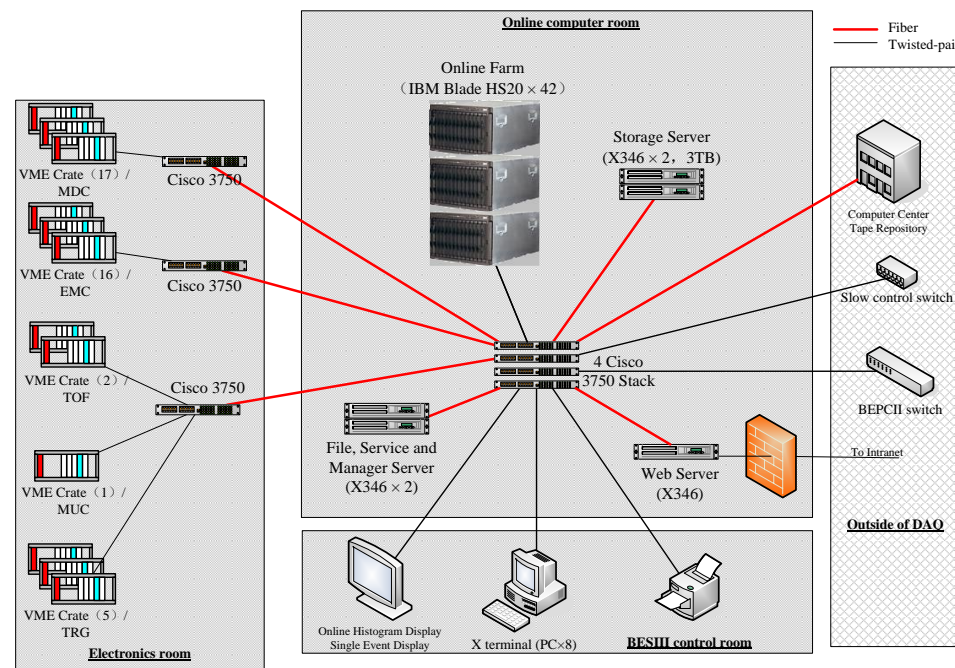
Sub-Detector	Channels
MDC (T+Q)	6796+6796
EMC	6240
TOF (T+Q)	448+448 / 2080+2080
MUC	9088
Total	~ 30K

- 触发率： 4KHz
- 事例长度： 12KB
- 数据带宽： 48MB/s

- DAQ数据流：三级事例组装、事例筛选和事例存储五个数据处理级别
 - ✓ 第一级是电子学读出机箱级的数据击中
 - ✓ 第二级是读出分支级的数据装配
 - ✓ 第三级是事例级的数据组装
- BESIII数据获取系统是分布式并行处理系统，由上百个处理器构成



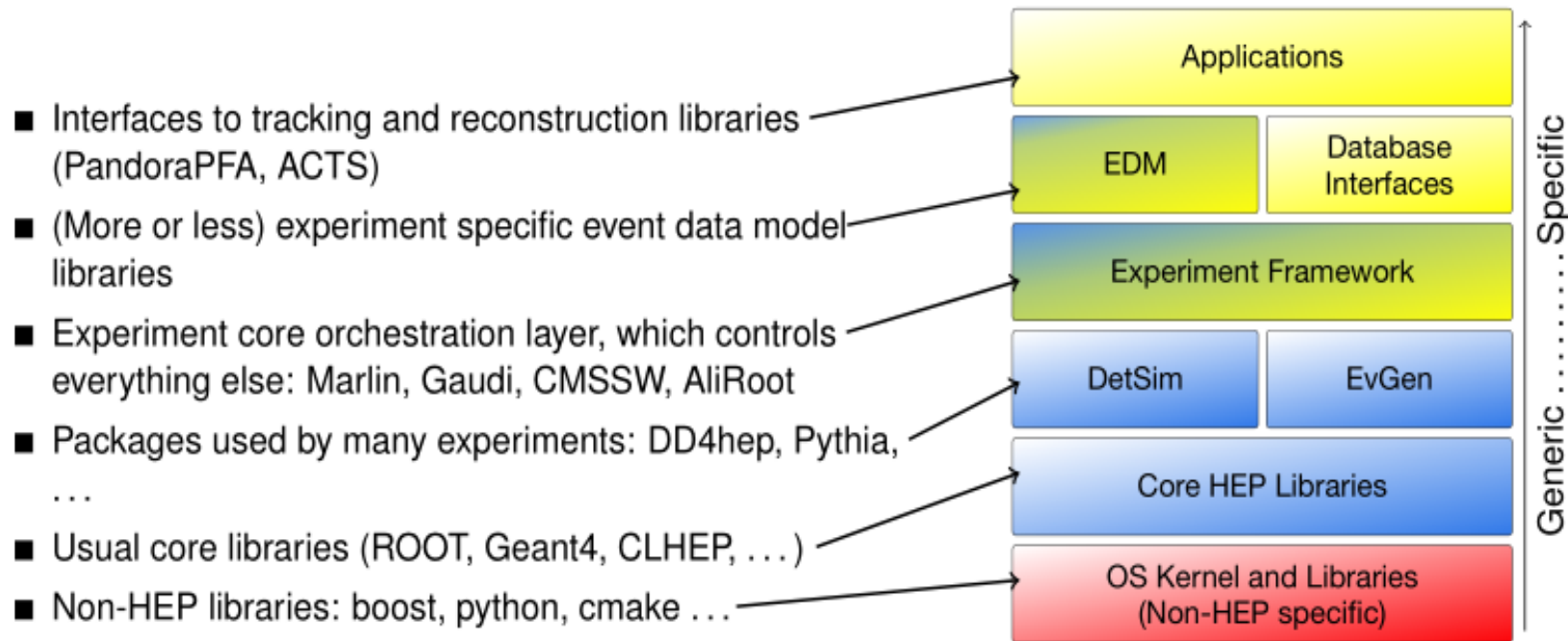
BESIII数据获取系统数据流图



BESIII数据获取系统硬件结构

粒子物理实验软件

Applications usually rely on large number of libraries, where some depend on others



- 软件框架提供有效的数据管理工具，不同软件模块的组合和动态库的链接机制
- 通过刻度与重建，压低各种条件的影响和排除噪声本底，最大限度挖掘加速器和探测器性能
- 实现精确的探测器模拟，为事例选择效率计算、选择条件优化和本底估计等提供可靠依据
- 利用优秀数理方法联合各种实验信息开发物理分析工具软件，进一步提高实验精度

BESIII实验离线软件系统

- BESIII离线数据处理和分析软件平台（BOSS）包括软件框架、模拟、刻度、重建和物理分析工具等部分
- 主要任务是对探测器获取和模拟产生的原始数据进行处理，生成用于物理分析使用的重建数据，同时提供物理研究的软件工具
- BOSS采用通用框架软件GAUDI和C++语言
- 软件平台：

✓有效的数据管理工具

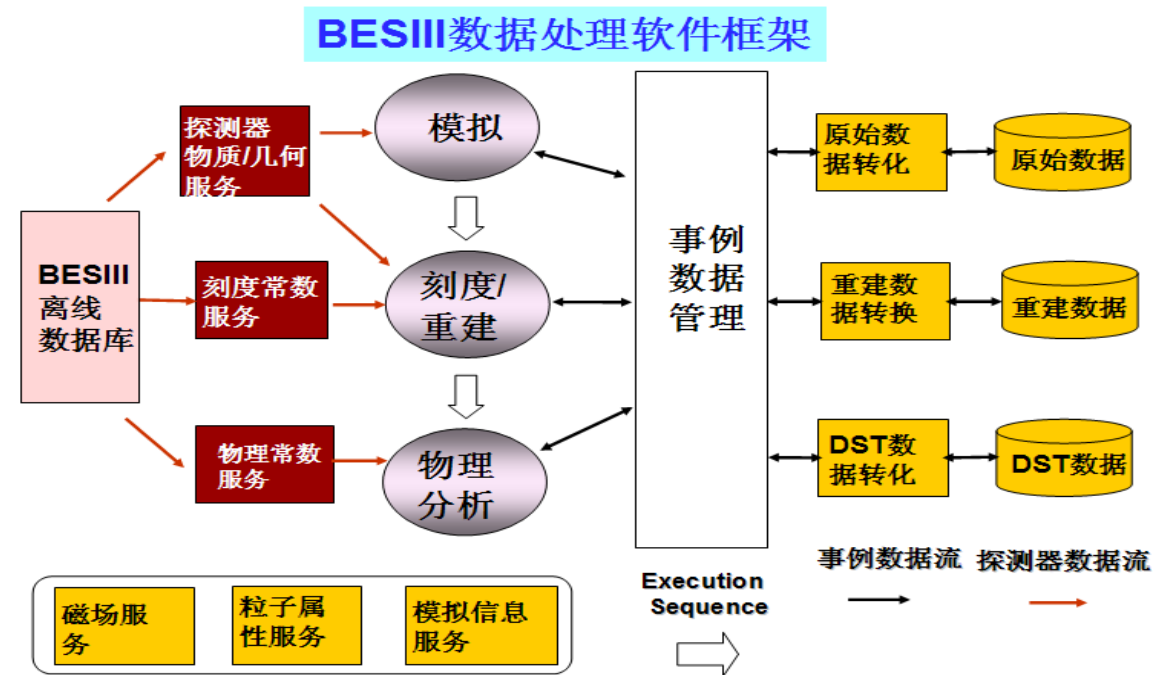
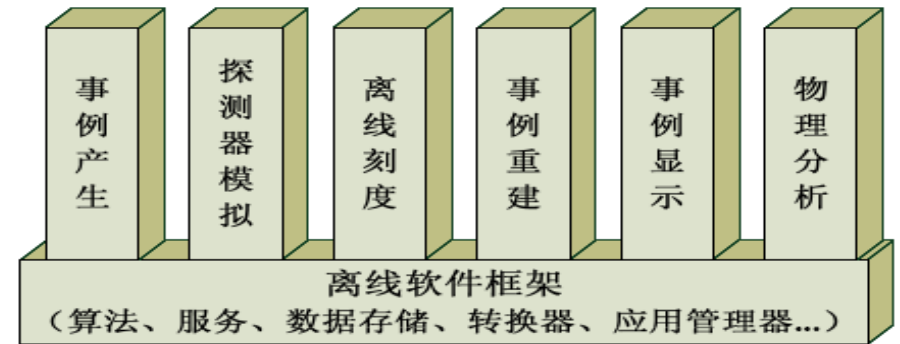
–事例数据

–常数数据

✓定义软件模块间的相互关系和接口标准

✓实现动态库的链接机制

✓通用软件库和工具软件的支持



软件框架

- 基础软件库和工具

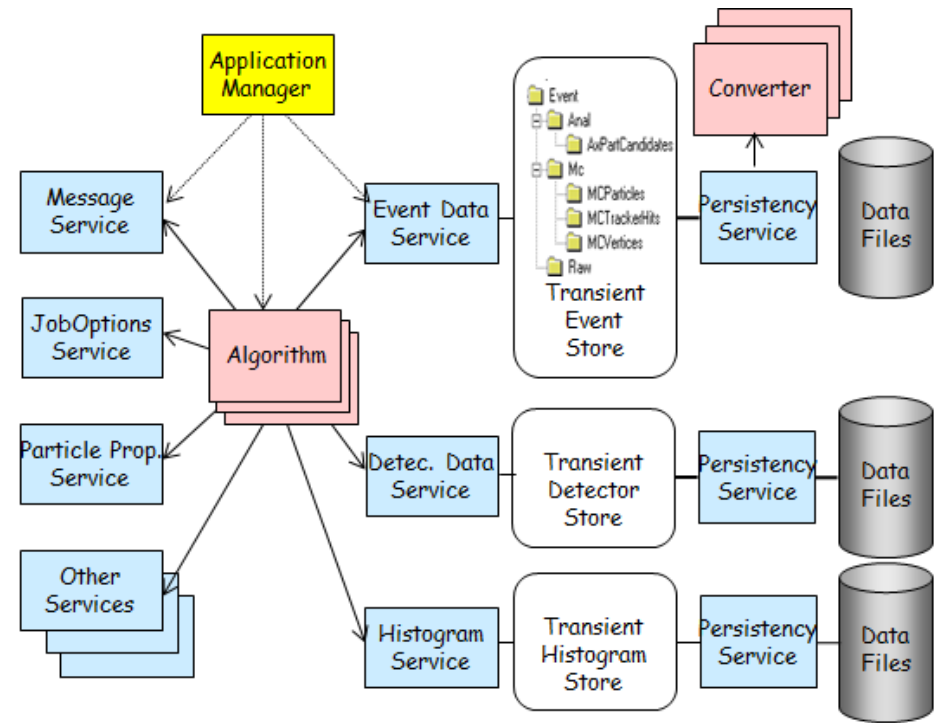
- 软件开发通用库和工具
- 高能物理领域通用的流行软件：Geant4, ROOT等

- 软件框架

- 狭义上指通用的离线软件框架，与实验无关，如Gaudi、SNiPER等
- 通常也包括与实验相关的通用功能模块，如数据模型及其I/O、数据库接口等

- 数据处理和分析软件

- 与实验紧密相关，需要有物理背景人员开发
- 专注于对数据的计算（算法），不用关心底层软件技术细节



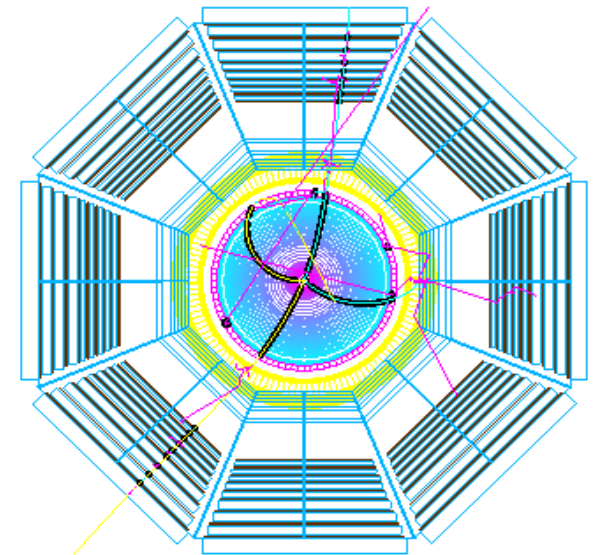
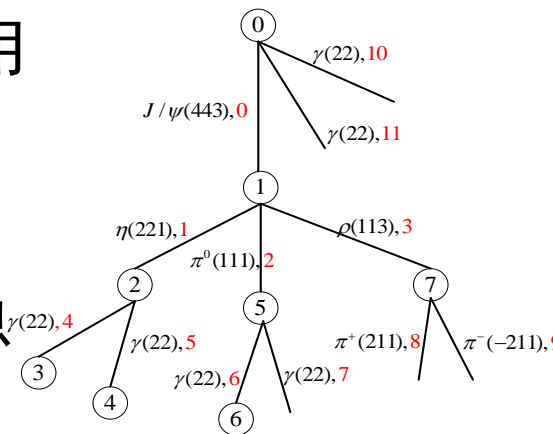
- GAUDI为应用程序提供了软件框架，开发人员将代码植入框架中，同时提供通用功能
- 算法（多变）和数据（稳定）分离，算法以插件形式动态嵌入框架执行
- 瞬态数据（内存）与持久数据（磁盘）分离

探测器模拟

- 物理研究中事例选择效率的计算，事例选择条件的优化、本底污染水平估计和物理结果的系统误差分析与模拟紧密相关
- 模拟与数据的不一致被认为是系统误差的主要来源，探测器模拟的精度是影响物理结果精度的来源之一
- BESIII探测器模拟软件

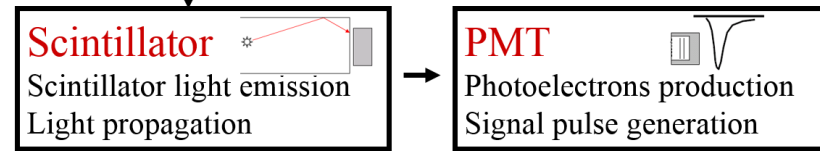
- ✓ 精细的探测器几何与物质描述
- ✓ 粒子在探测器中的传输和相互作用
- ✓ 探测器响应（数字化）
- ✓ 探测器运行的真实化模拟
- ✓ 完成的模拟真实（MCTruth）信息

Circle: vertex (vertexIndex)
Line: track (name, PDGcode, trackIndex)



$$\psi' \rightarrow \pi^+ \pi^- \quad J/\psi \rightarrow \pi^+ \pi^- \mu^+ \mu^-$$

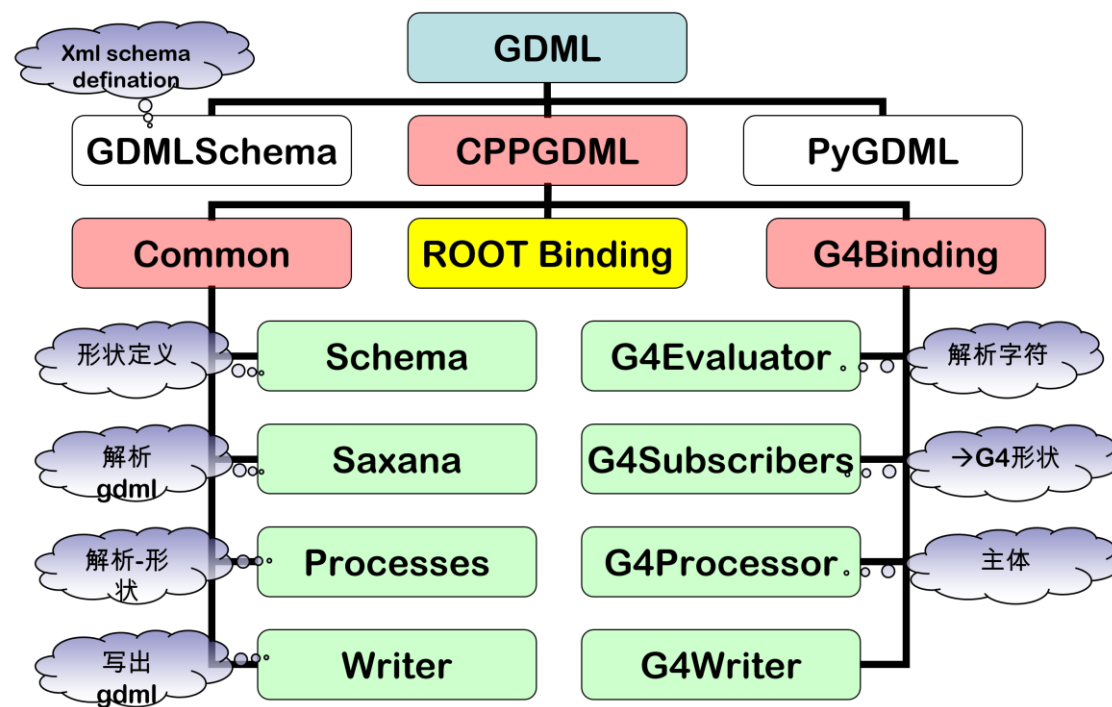
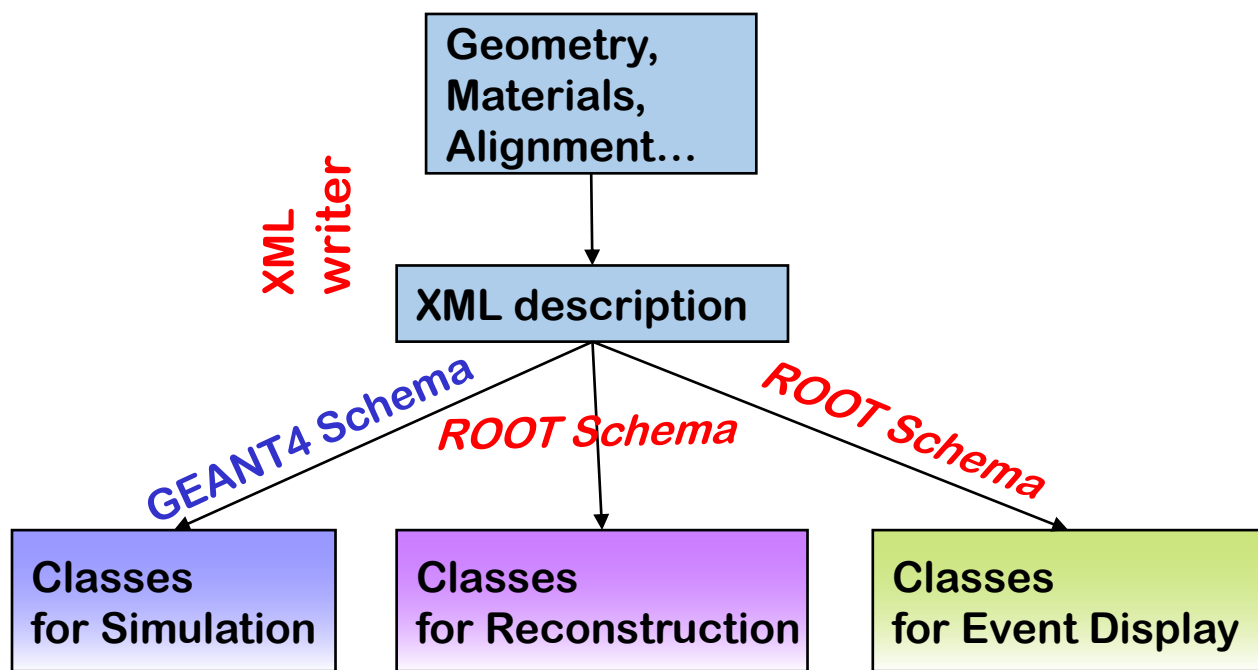
Geant4
Get hit information: energy loss, time, position



Digitization

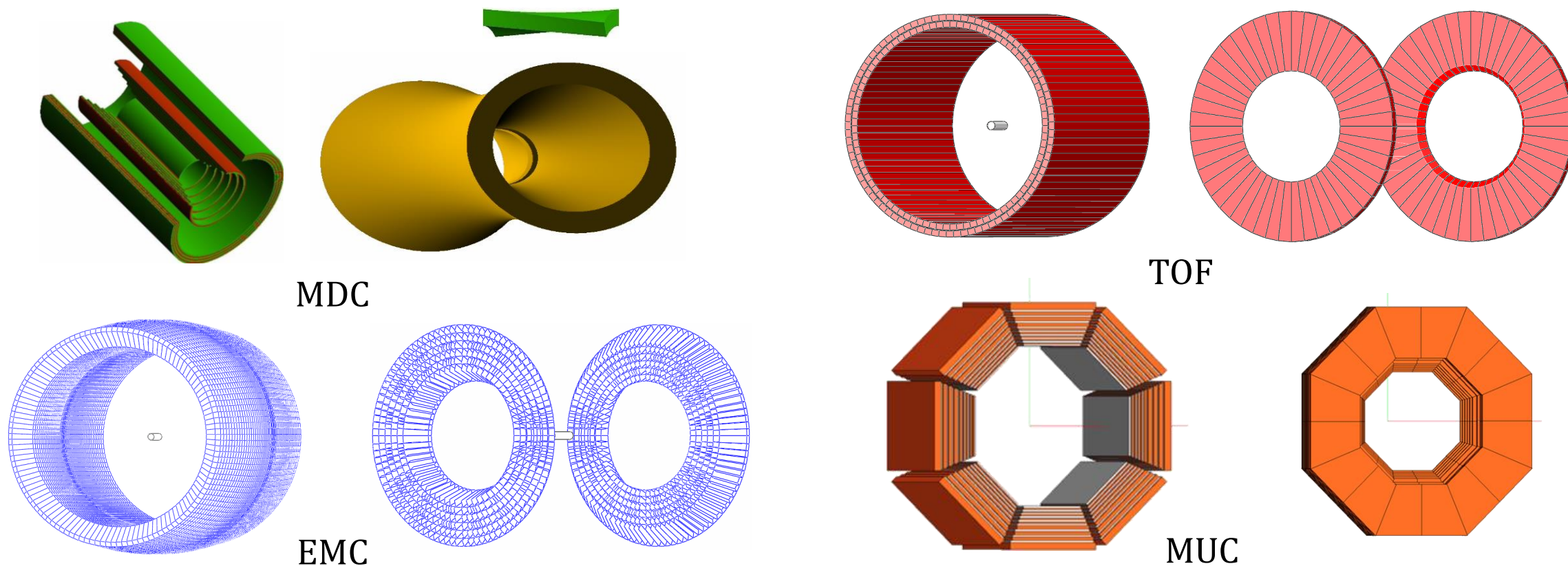
探测器几何与物质描述

- 基于GDML (Geometry Description Markup Language), 由GEANT4组开发
- 针对BESIII探测器拓展了GEANT4 Schema, 并开发了ROOT Schema
- 保证软件系统中的一致性, GDML文件用于探测器模拟、事例重建和事例显示



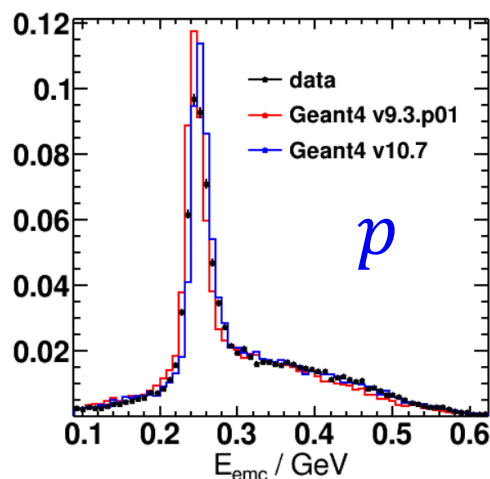
探测器几何与物理描述

- 漂移室 (MDC) 的位置校准 (Alignment) 和结构扭摆
- 特殊的几何形状无法用GEANT4描述: 如MDC斜丝单元和端盖EMC晶体的不规则形状等



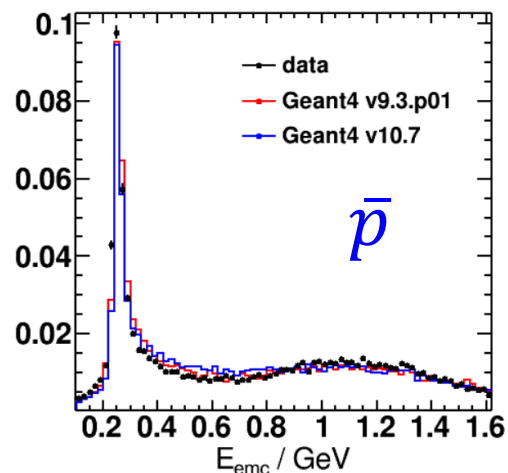
粒子在探测器中的传输与作用

- 电磁相互作用模型已经成熟
- 强相互作用没有统一的理论来描述
- 在GEANT4中提供了大量的强子模拟软件包
- 用户需要根据实验和模拟的对比来选择、测试或调试这些软件包



$$\chi_{9.3.p01}^2/ndf = 7.20833$$

$$\chi_{10.7}^2/ndf = 5.69283$$

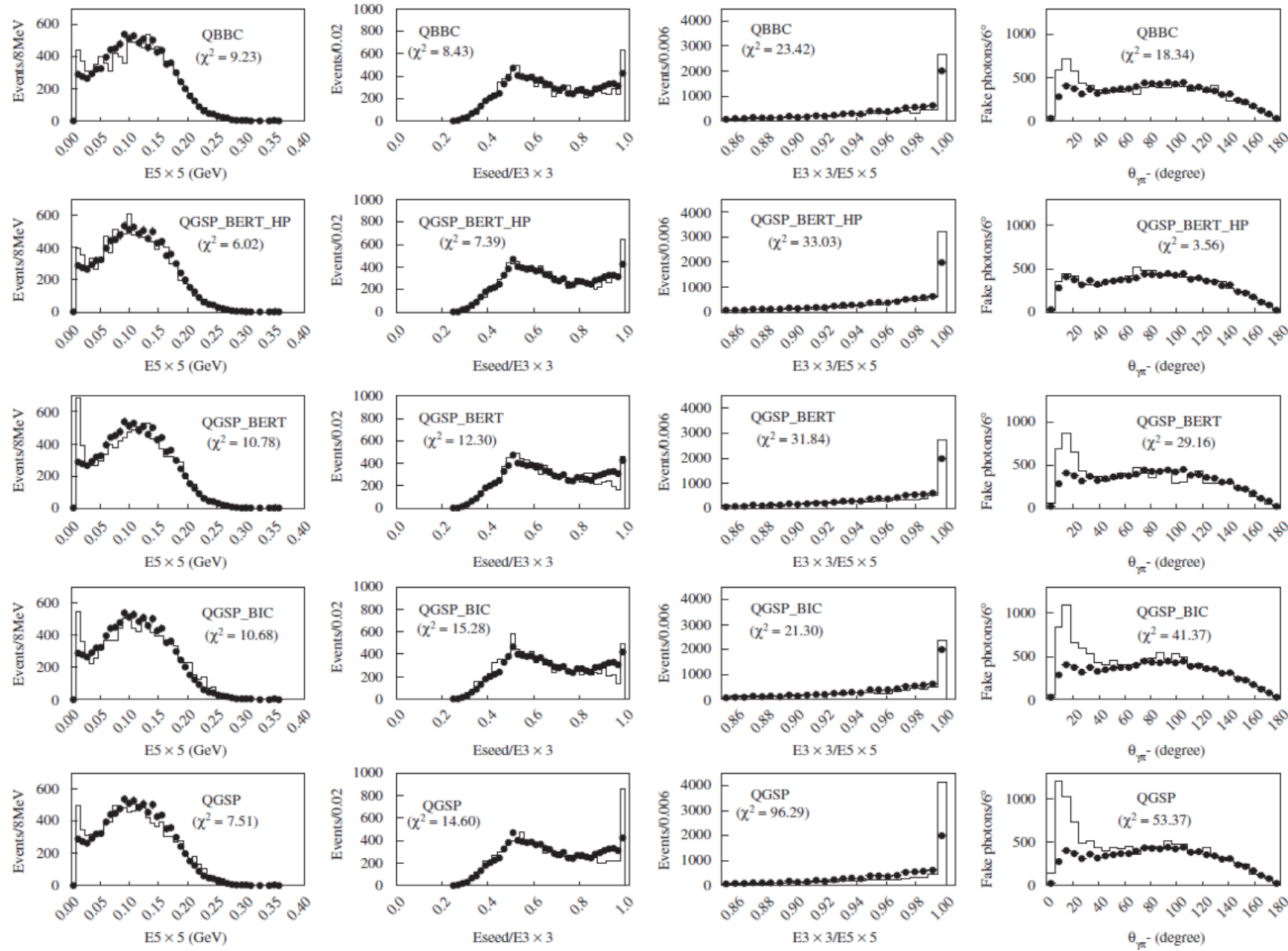


$$\chi_{9.3.p01}^2/ndf = 6.12524$$

$$\chi_{10.7}^2/ndf = 6.25258$$

package	description
LHEP	GHEISHA ported from Geant3
LHEP_BERT	E<3GeV Bertini cascade
LHEP_BIC	E>3GeV GHEISHA
	E<3GeV Binary cascade
	E>3GeV GHEISHA
LHEP_GN	GHEISHA + gamma nuclear processes
LHEP_HP	as LHEP, for neutrons with E<20MeV use evaluated cross section data
QGSP	E<25GeV GHEISHA
	E>25GeV quark-gluon string model
QGSP_BERT	E<3GeV Bertini cascade
	3<E<25GeV GHEISHA
	E>25GeV quark-gluon string model
QGSP_BIC	E<3GeV Bertini cascade
	3<E<25GeV GHEISHA
	E>25GeV quark-gluon string model
QGSC	same as QGSP ,but use chiral invariant phase space decay for fragmentation
FTFP	E<25GeV GHEISHA
	E>25GeV quark-gluon string model with fragmentation ala FRITJOF

强相互作用对比



IBM PC(2.33GHz/2GB), s/event

Physics lists	$\psi(2S) \rightarrow \pi^+ \pi^- J/\psi (J/\psi \rightarrow e^+ e^-)$	$\psi(2S) \rightarrow \pi^+ \pi^- J/\psi (J/\psi \rightarrow p\bar{p})$
QBBC	0.67	0.84
QGSP_BERT_HP	1.06	2.89
QGSP_BERT	0.69	0.85
QGSP_BIC	0.69	0.82
QGSP	0.67	0.57

更高精度往往意味着需要更多的计算资源 (CPU时间和内存)

Fig. 6. Comparison between data (dots with error bars) and models (histograms) for π^- from $\psi(2S) \rightarrow \pi^+ \pi^- J/\psi (J/\psi \rightarrow e^+ e^-)$, Monte Carlo samples are normalized to the number of events in data.

带电径迹重建效率的系统误差

- 利用“丢失”粒子的方法

带电径迹效率： $\varepsilon = \frac{n}{N}$

N : 预期粒子的数目

n : 重建得到粒子的数目

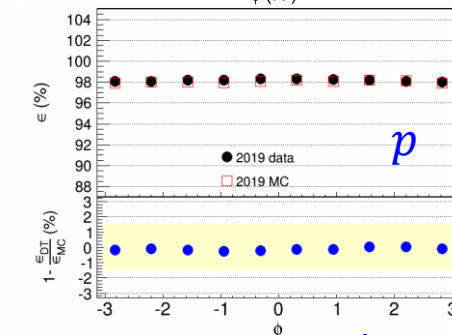
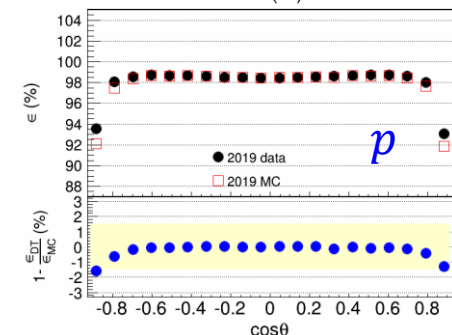
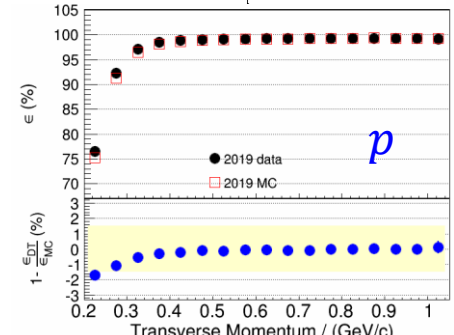
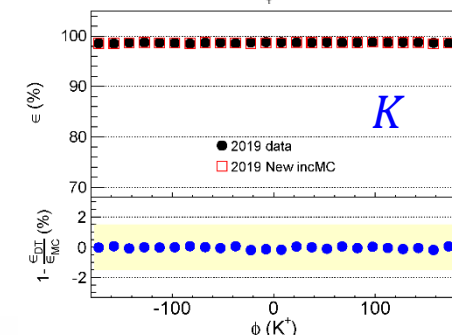
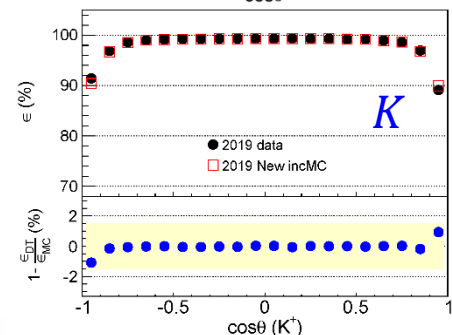
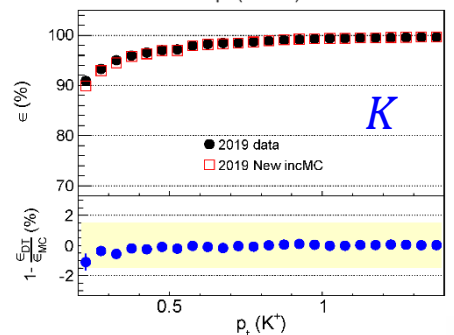
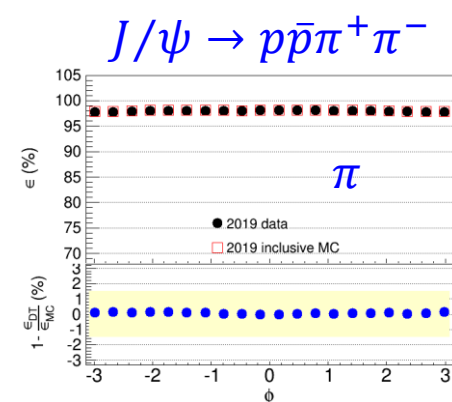
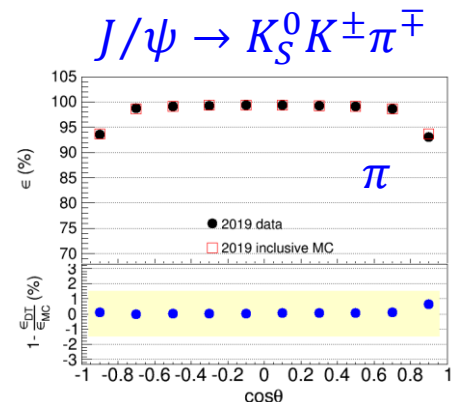
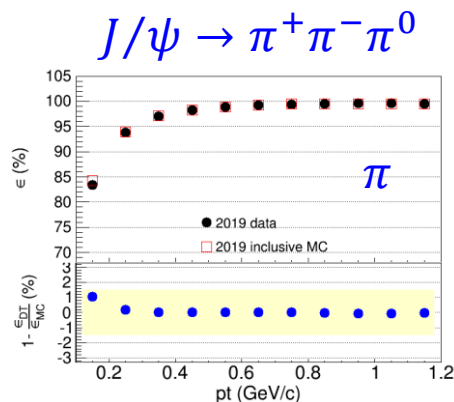
误差： $\delta = \sqrt{\varepsilon \cdot (1 - \varepsilon) / N}$

- 带电径迹效率的系统误差：

$$1 - \varepsilon_{Data} / \varepsilon_{MC}$$

- 优化事例选择条件，压低本底水平，改进拟合方法

- 粒子与探测器相互作用，特别是低动量粒子复杂的相互作用过程



动量

$\cos\theta$

ϕ

粒子鉴别效率的系统误差

- 联合电离能损 (dE/dx) 和飞行时间 (TOF) 进行粒子鉴别

粒子鉴别效率: $\epsilon = \frac{n}{N}$

N : 待鉴别粒子的数目

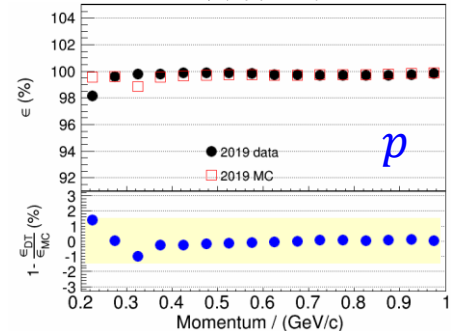
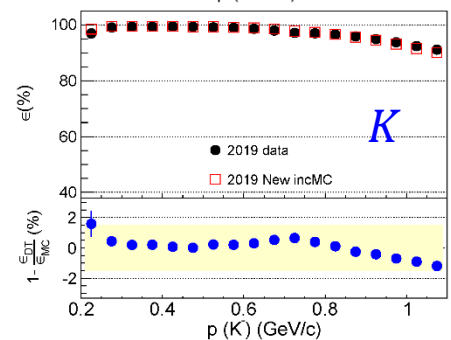
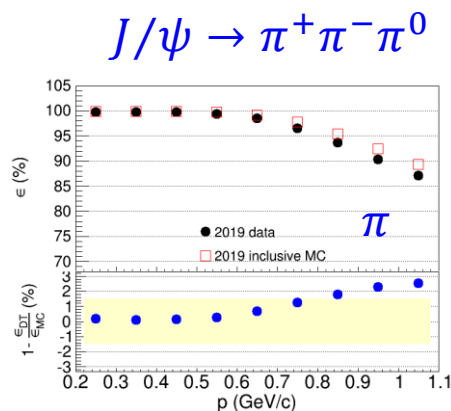
n : 正确鉴别粒子的数目

误差: $\delta = \sqrt{\epsilon \cdot (1 - \epsilon) / N}$

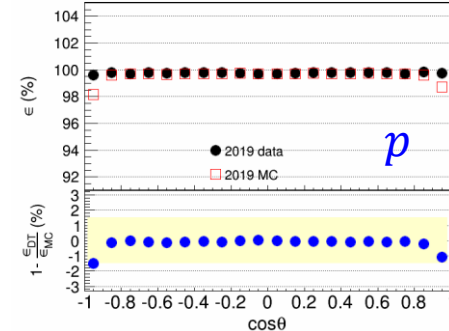
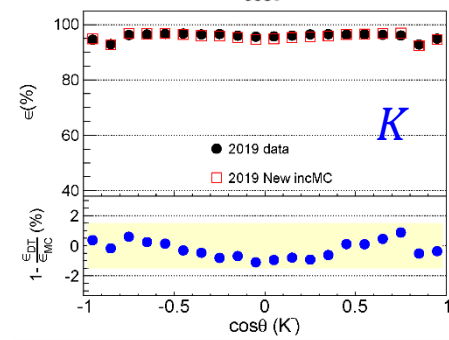
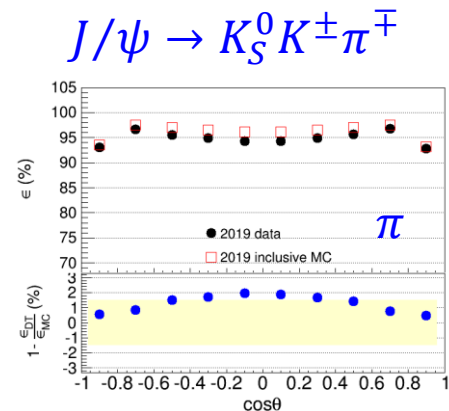
- 带电径迹效率的系统误差:

$$1 - \epsilon_{Data} / \epsilon_{MC}$$

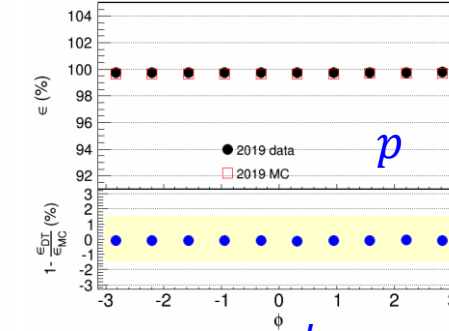
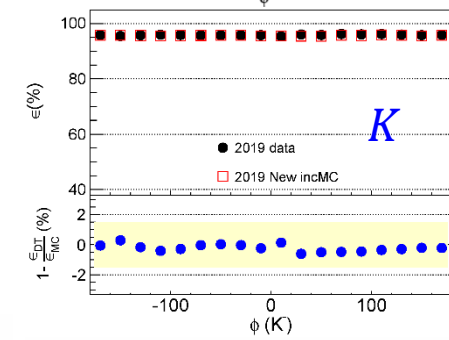
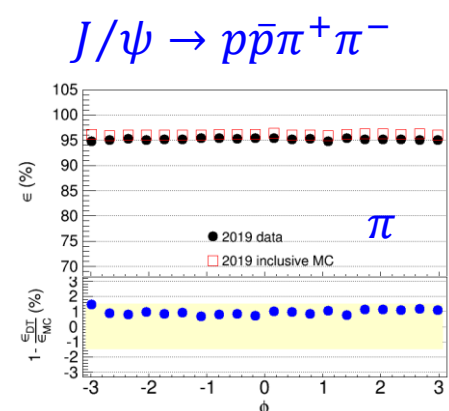
- 刻度和修正



动量



cos theta



phi

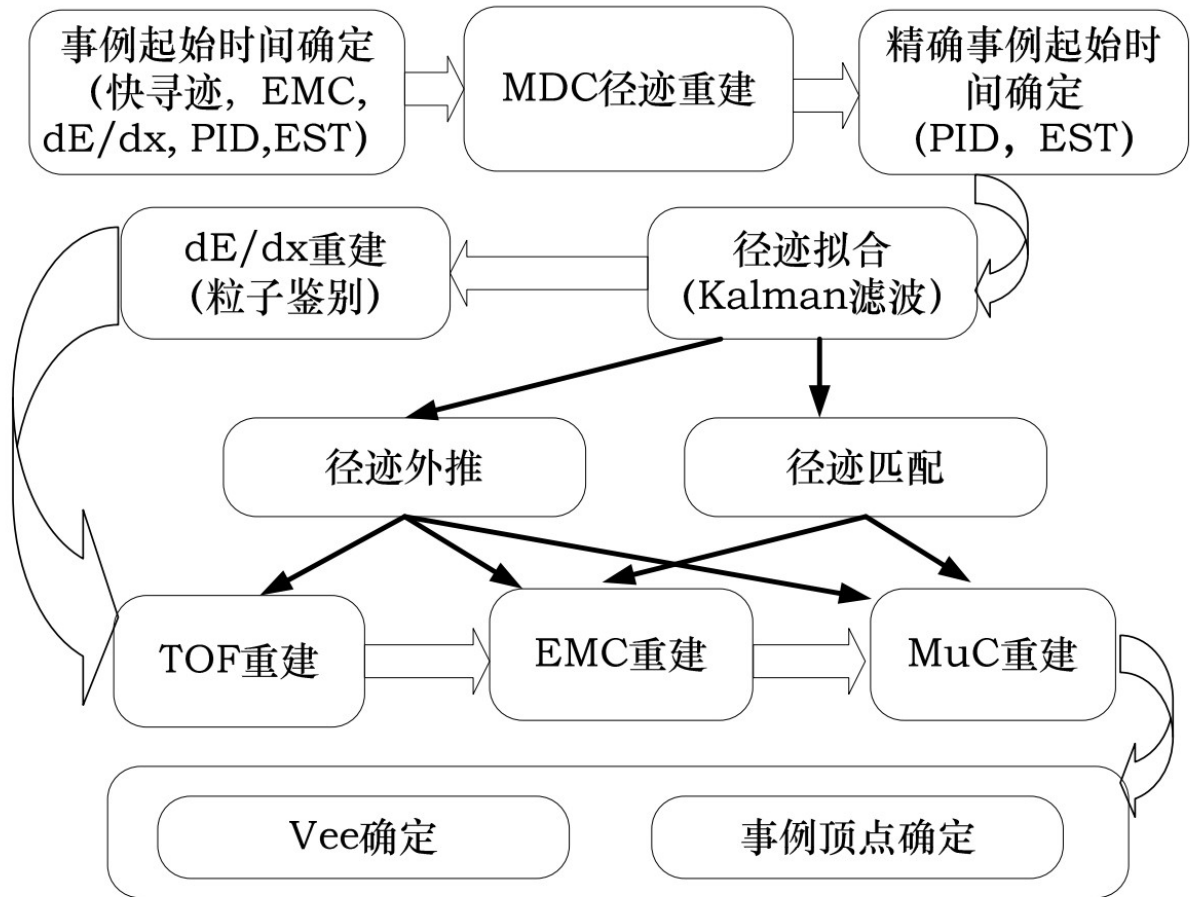
事例重建

- 原始数据记录的电子学信号在软件系统经过数据处理生成重建数据，用于物理分析

- 优良的探测器性能转化为动/能量分辨、信号显著性等
- 积分亮度，探测器效率和重建效率影响物理测量结果统计误差

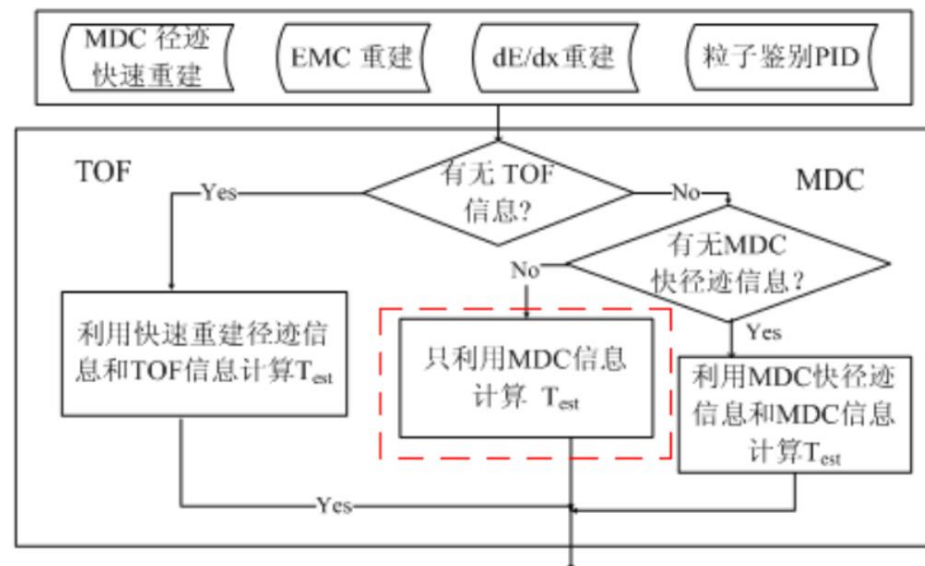
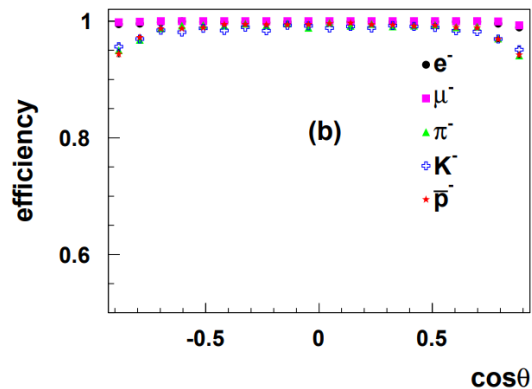
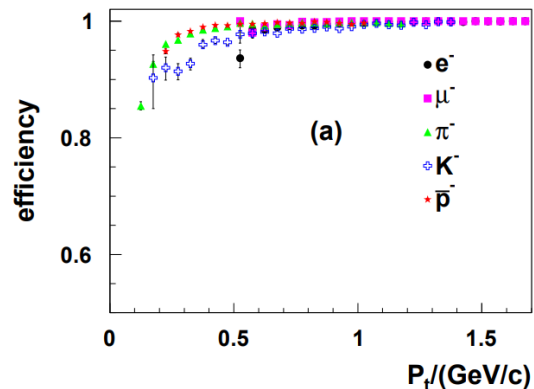
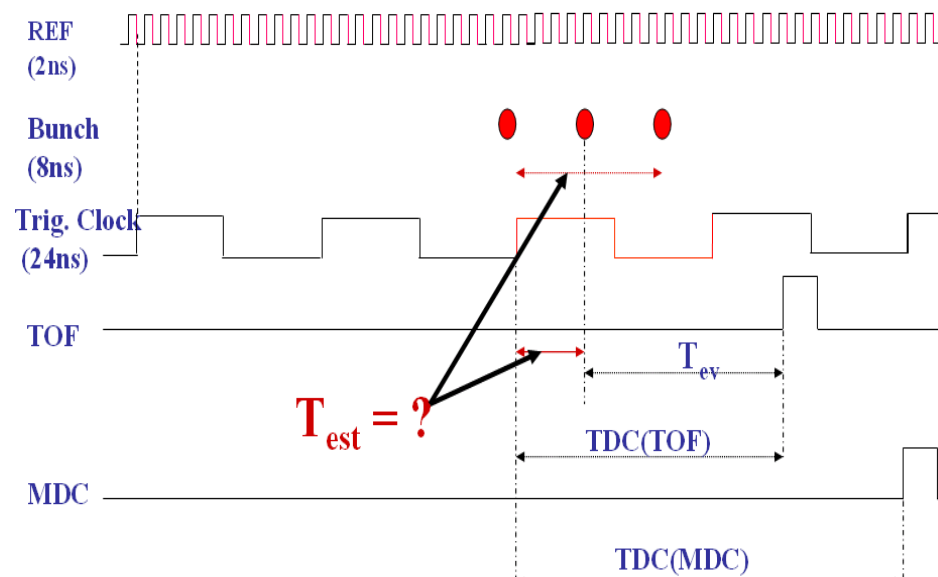
- 事例重建流程：**

- 快寻迹和事例起始时间重建
- MDC重建和Kalman滤波径迹拟合
- dE/dx、TOF、EMC和MUC重建
- 径迹外推和匹配



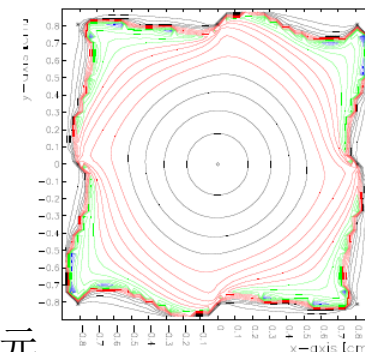
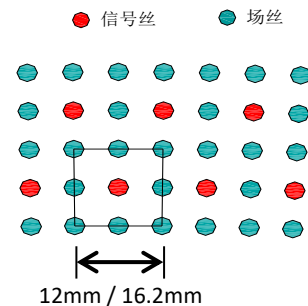
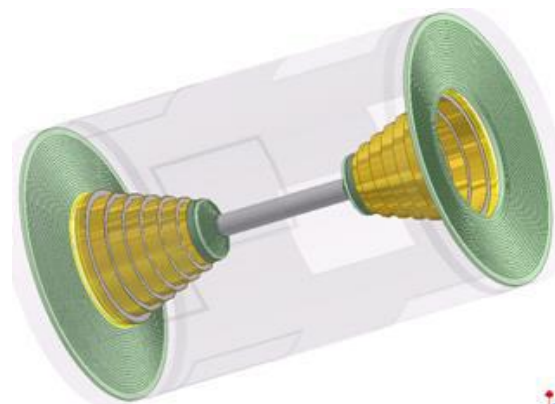
事例起始时间 Event Start Time

- BEPCII是一台双环，多束团的高亮度加速器。每6ns发生一次束团对撞
- 触发信号只能用于数据获取，不能用于时间参考
- 事例起始时间的重建是BESIII各个子探测器重建和刻度的起点
- 在离线环境下确定物理事例起始时间
 - MDC快重建和TOF信息
 - MDC快重建结果
 - EMC击中信息

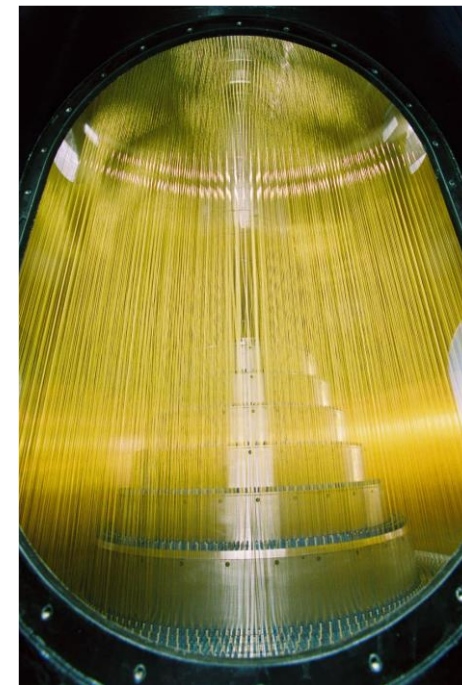
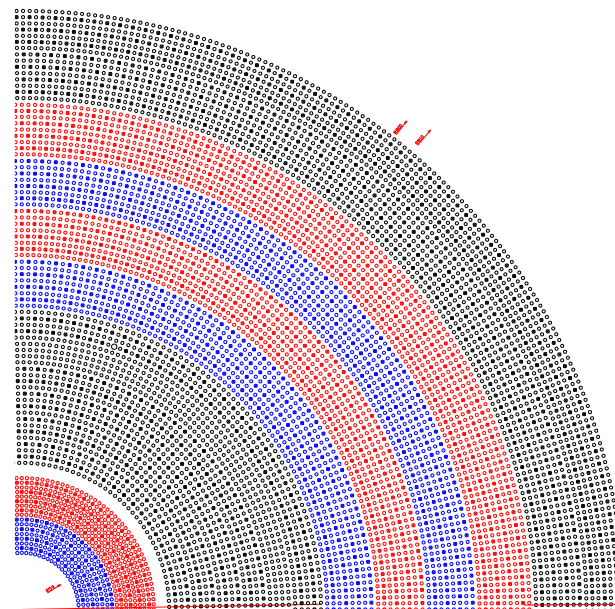
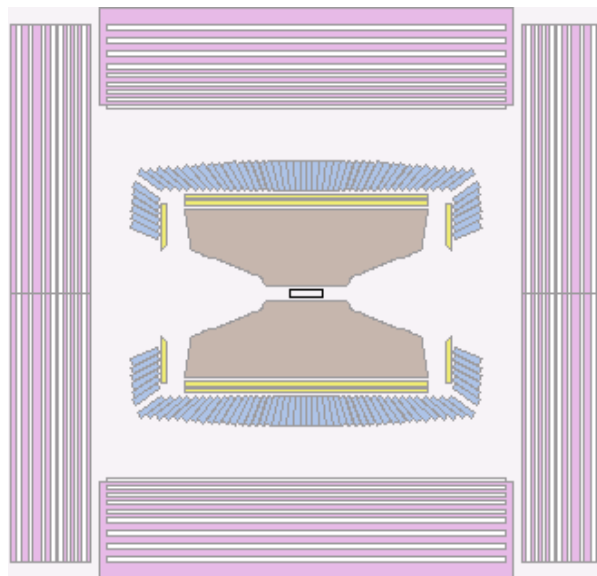
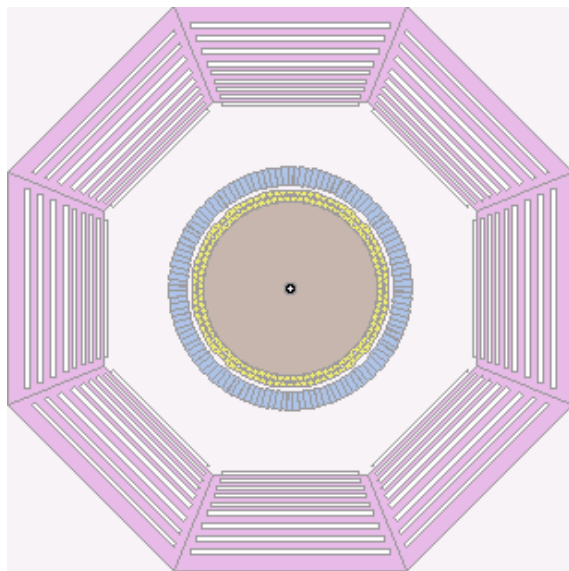


漂移室 (MDC)

- BESIII最内层探测器
- 立体角 $|\cos\theta| < 0.93$
- 氦基混合气体 $H_e - C_3H_8$ (60/40)
- 43个灵敏丝层 (24直丝+19斜丝)
- 6794个漂移单元

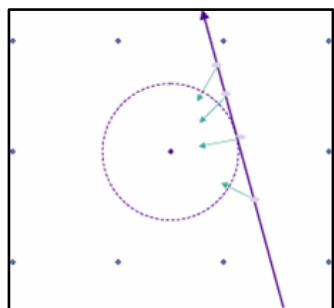


- 近似正方形小单元结构
- 相邻丝层相互错开半个单元
- 信号丝: $\varnothing 25\mu m$ 镀金钨丝 6796根
- 场丝: $\varnothing 110\mu m$ 镀金铝丝 21884根

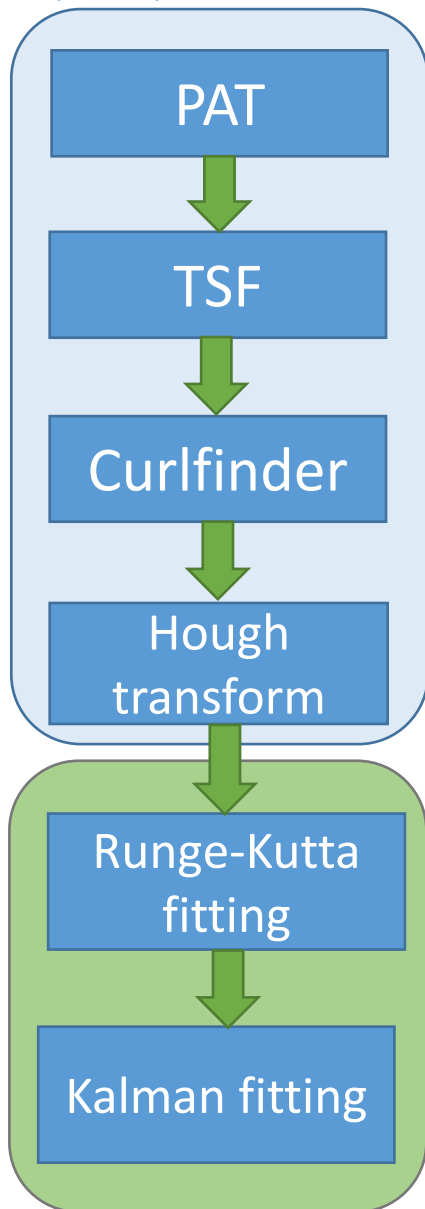
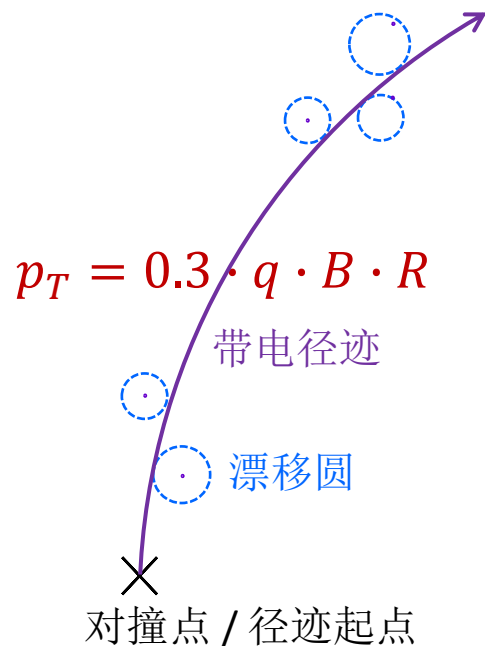


漂移室重建

- 径迹寻找（模式识别）
 - 每条径迹用到的击中
- 径迹拟合（参数估计）
 - 径迹参数+误差矩阵
- 径迹的统计检验
 - 研究 χ^2 残差，去除“坏”点

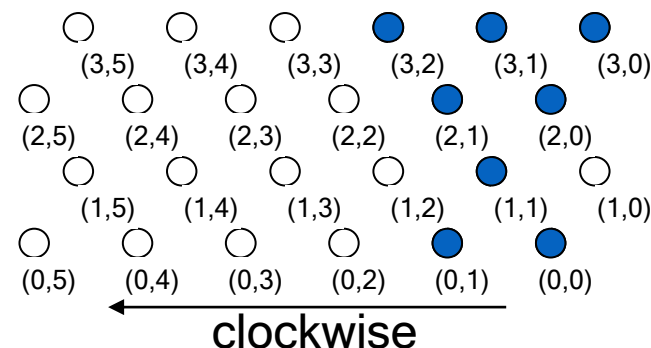


原始数据 重建数据
丝号, T, Q \rightarrow \vec{p}



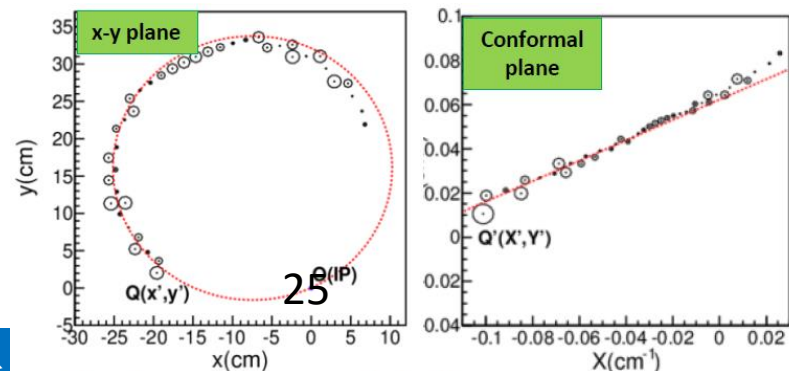
• 径迹寻找PAT

- 超层内模式匹配寻找径迹段
- 径迹段连接得到径迹

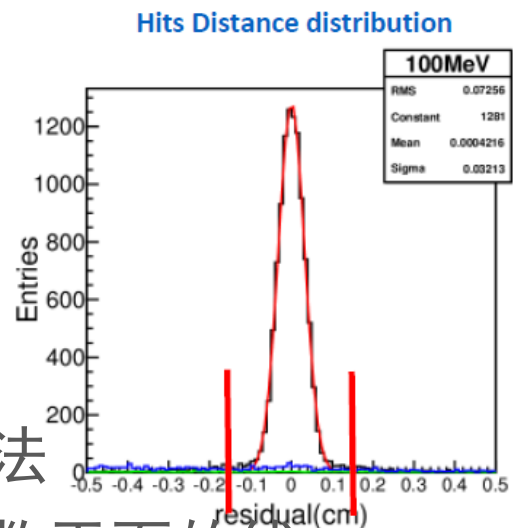
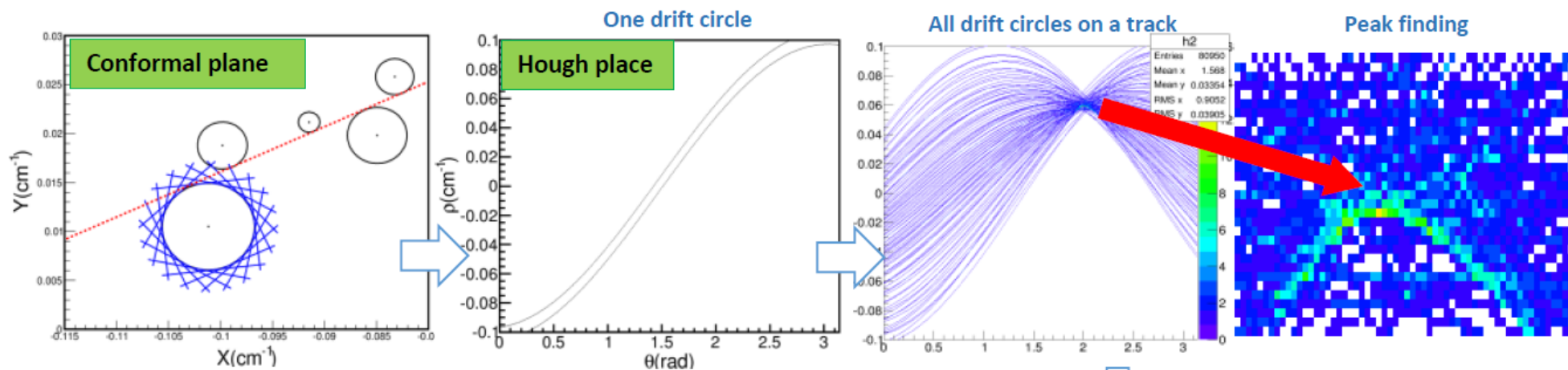


• 径迹寻找TSF

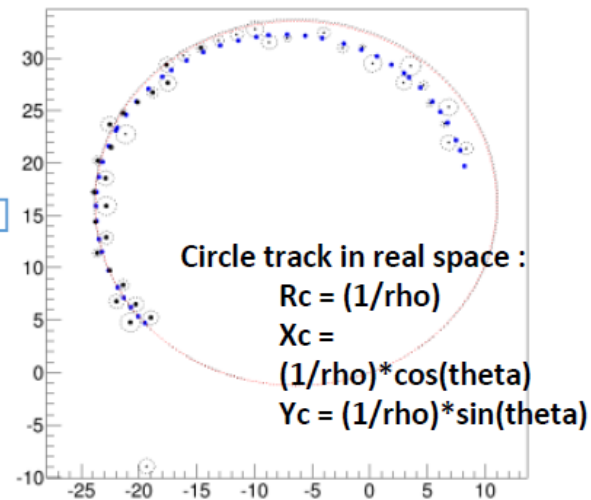
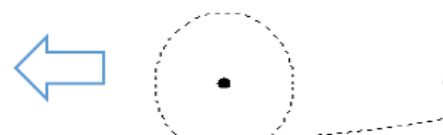
- 共性变换方法
- 在 $r-\phi$ ($x-y$) 平面 \rightarrow 共形面上的直线
- 在 $s-z$ 平面利用斜丝重建



漂移室重建



Pick axial hits:
Calc. distance between
candidate track and drift circles



Hough Transform

- 低横动量径迹寻找算法
- 真实空间的点 \leftrightarrow 参数平面的线

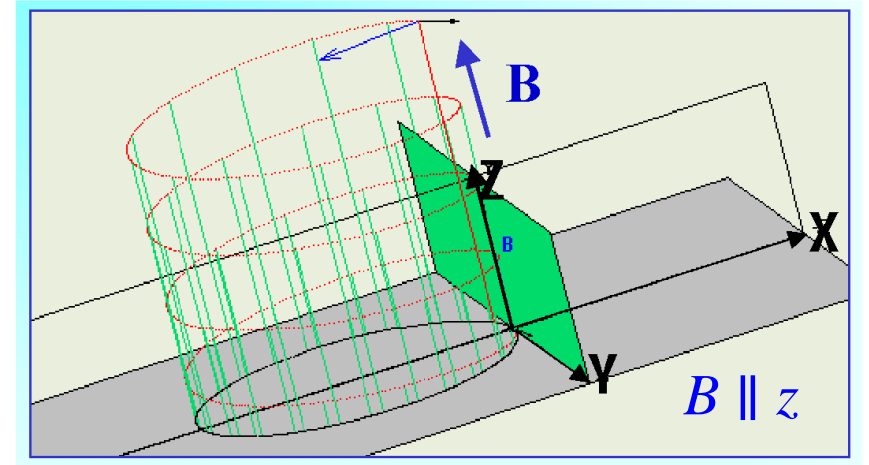
全局最小二乘径迹拟合：理想螺旋线

$$\chi^2 = \sum_{i=1}^{n_{hit}} \frac{(d_{mea}^i - d_{track}^i)^2}{\sigma_i^2}$$

$$x = x_0 + d_\rho \cos\phi_0 + \frac{\alpha}{\kappa} (\cos\phi_0 - \cos(\phi_0 + \phi))$$

$$y = y_0 + d_\rho \sin\phi_0 + \frac{\alpha}{\kappa} (\sin\phi_0 - \sin(\phi_0 + \phi))$$

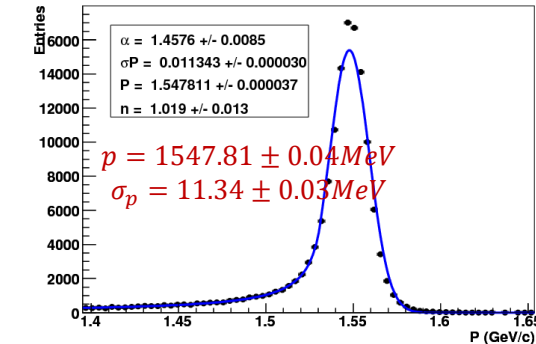
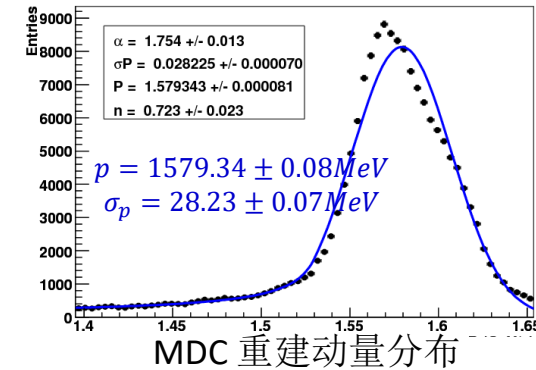
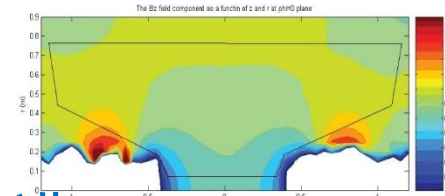
$$z = z_0 + d_z - \frac{\alpha}{\kappa} \lambda \cdot \phi$$



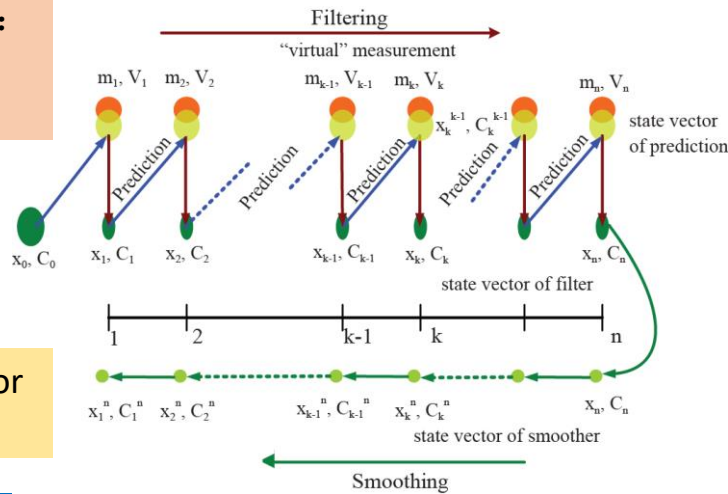
Kalman filter径迹拟合

- 多次散射
- 能量损失（束流管，漂移室内壁等物质效应）
- 磁场的非均匀性
- 其他：如丝下垂等

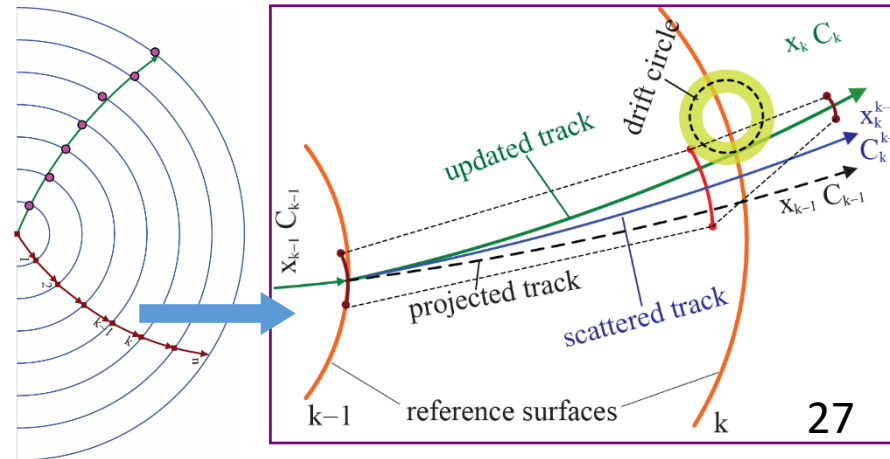
Kalman filter方法包括径迹参数和误差矩阵的改进



被估计的信号：
State Vector
状态矢量



Measured Vector
测量矢量



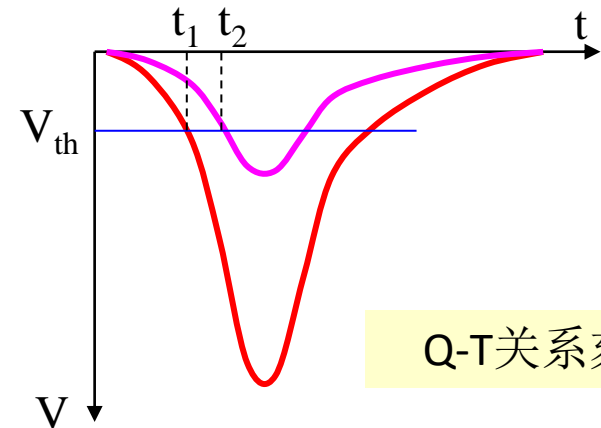
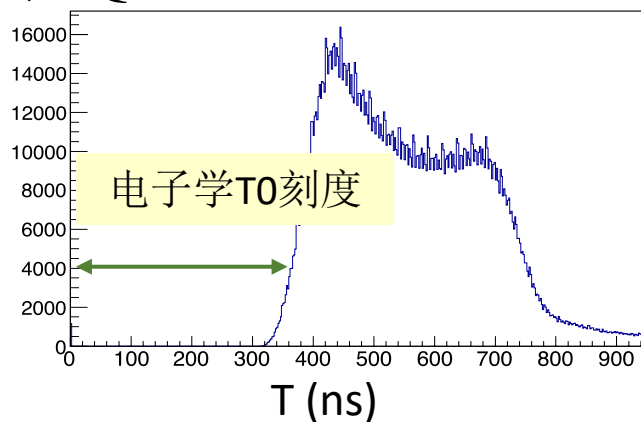
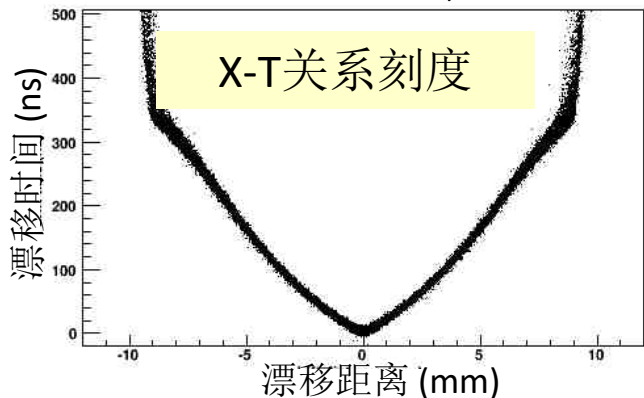
漂移室刻度和校准

- 径迹残差 $r = d_{mea} - d_{track}$

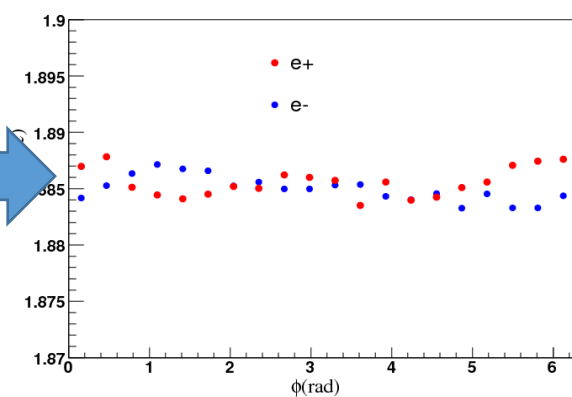
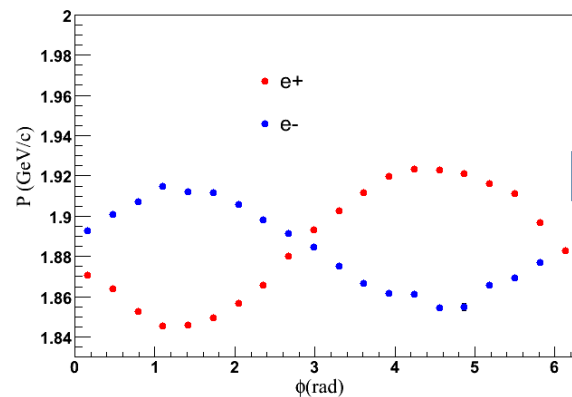
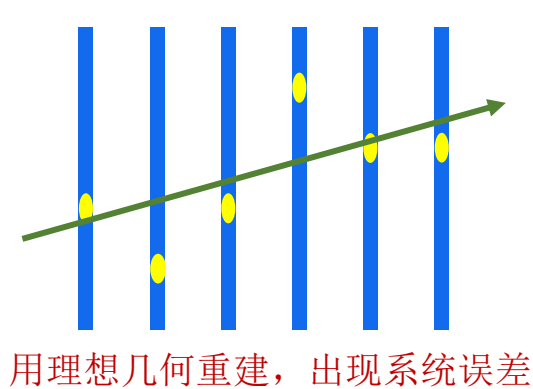
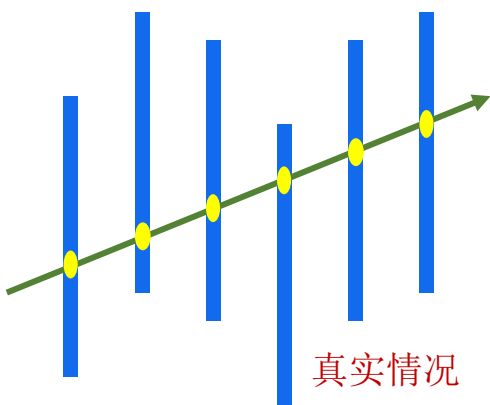
$$T_{TDC} = T_{Es} + T_{flight} + T_{drift} + T_{prop} + T_{elec} + T_{tw}$$

– 通常用残差分布的标准差来表征漂移室的空间分辨

- 刻度：X-T关系，电子学刻度，Q-T关系



- 几何位置校准

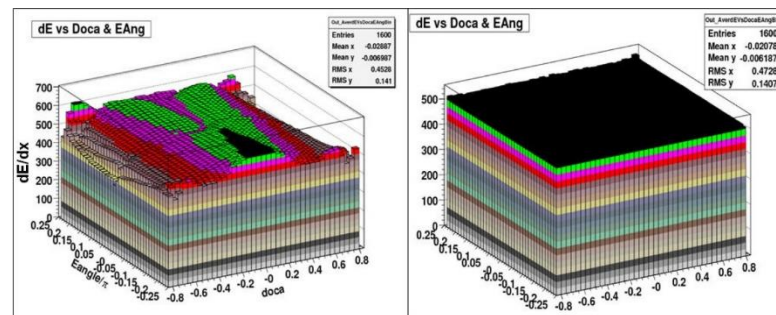
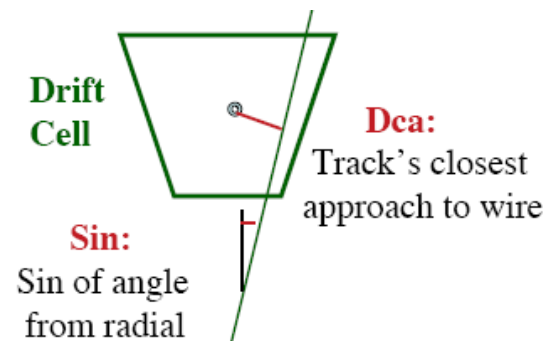
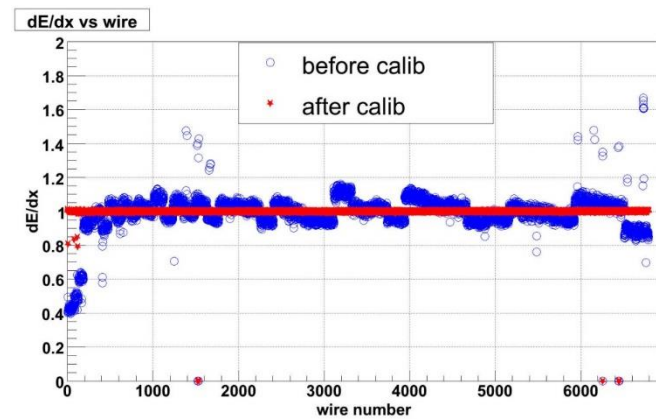
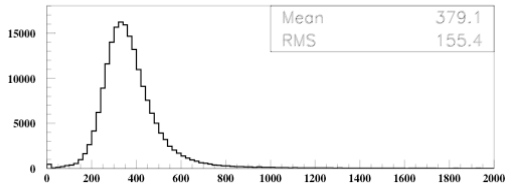
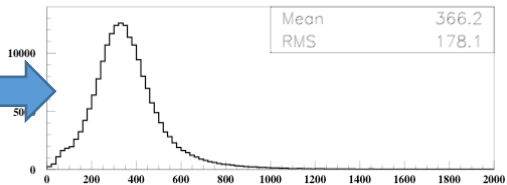
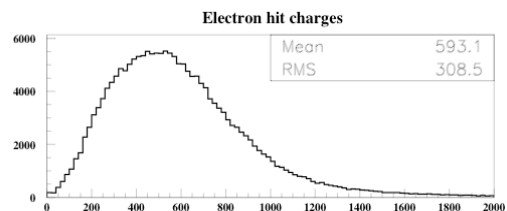
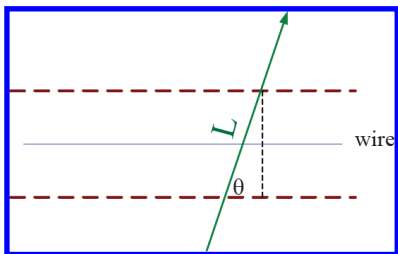
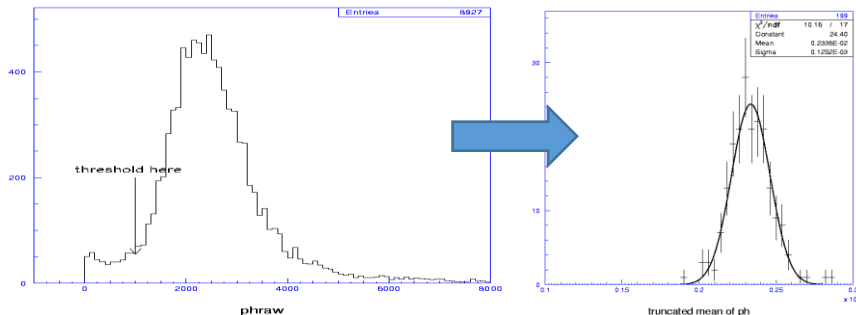
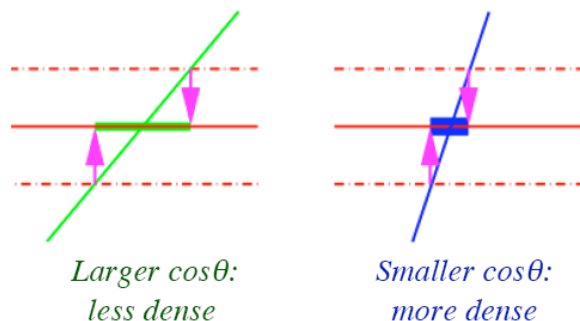


dE/dx重建刻度

• 电荷修正

- 击中电荷量的径迹长度修正
- 丝增益和run增益
- 漂移距离和入射角度联合修正
- 空间电荷效应

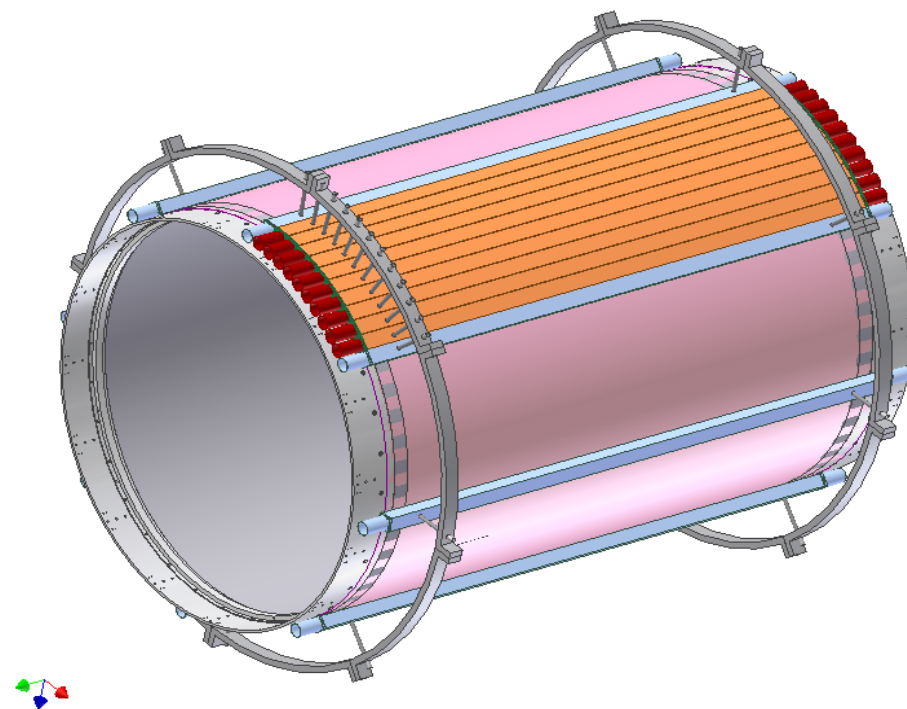
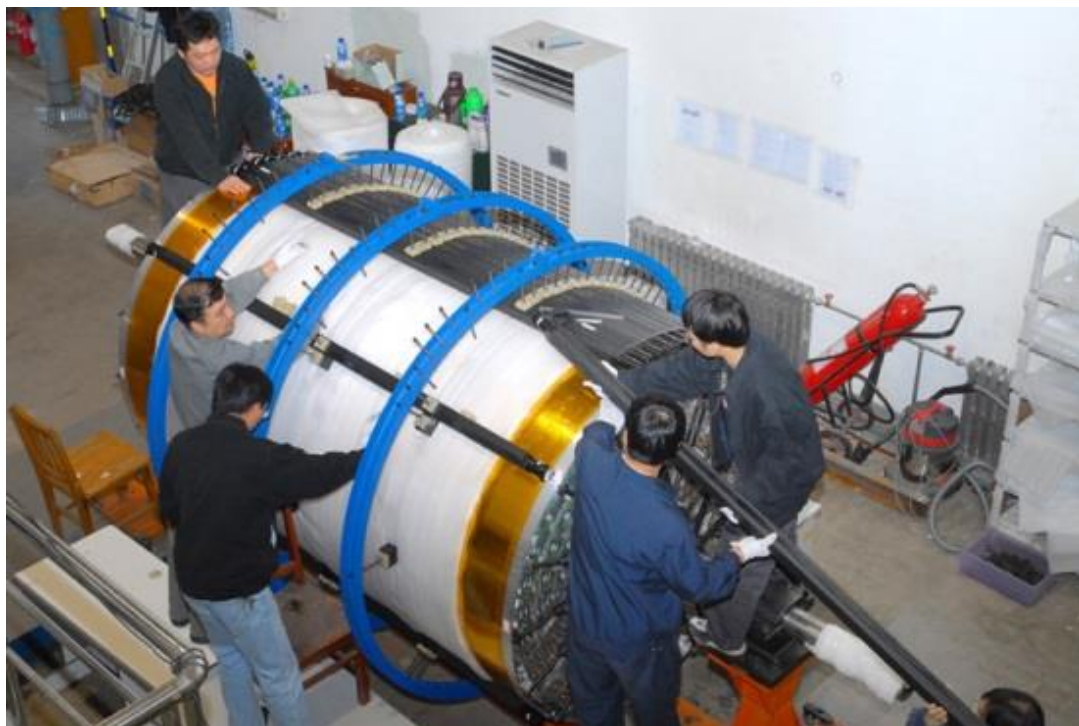
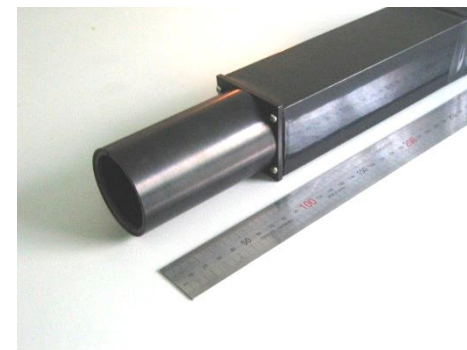
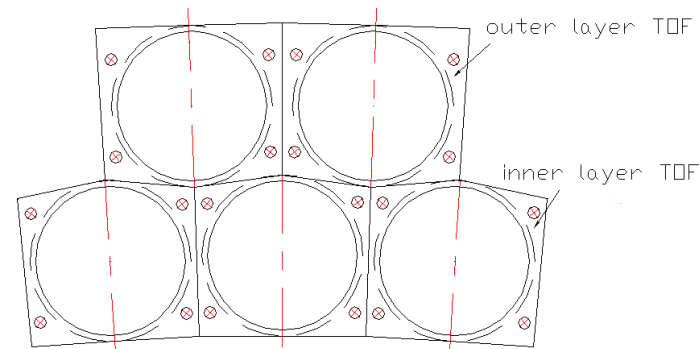
• 截断平均



桶部飞行时间探测器

- 桶部飞行时间探测器

- 双层、双端读出
- 每层88块BC408塑料闪烁体
- 闪烁体直接耦合精细网型抗磁光电倍增管



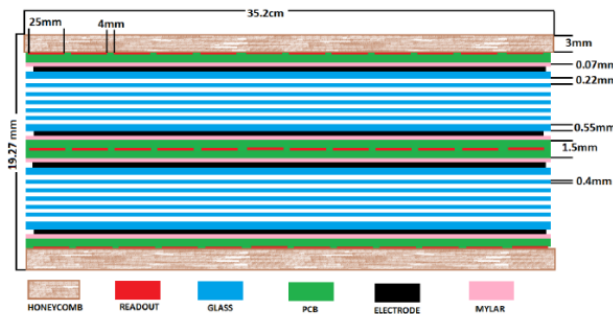
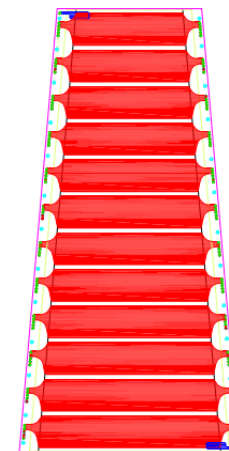
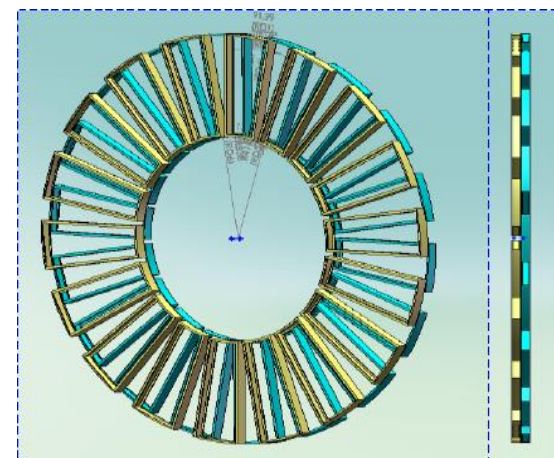
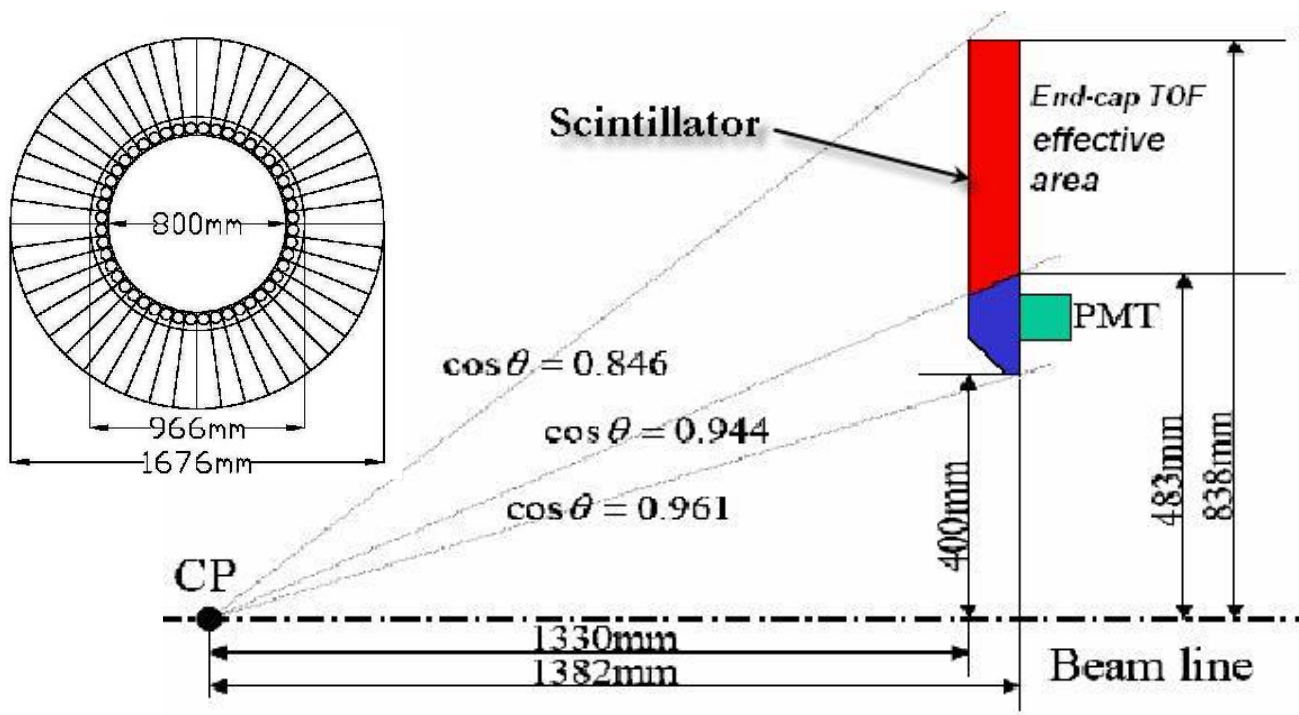
端盖飞行时间探测器

- 闪烁体端盖飞行时间探测器

- 两个端盖
- 每个端盖48块BC404塑料闪烁体
- 小端垂直耦合光电倍增管

- MRPC端盖飞行时间探测器

- 每个端盖36个模块
- 每个模块12个读出条，双端读出
- 内外层模块交错排列



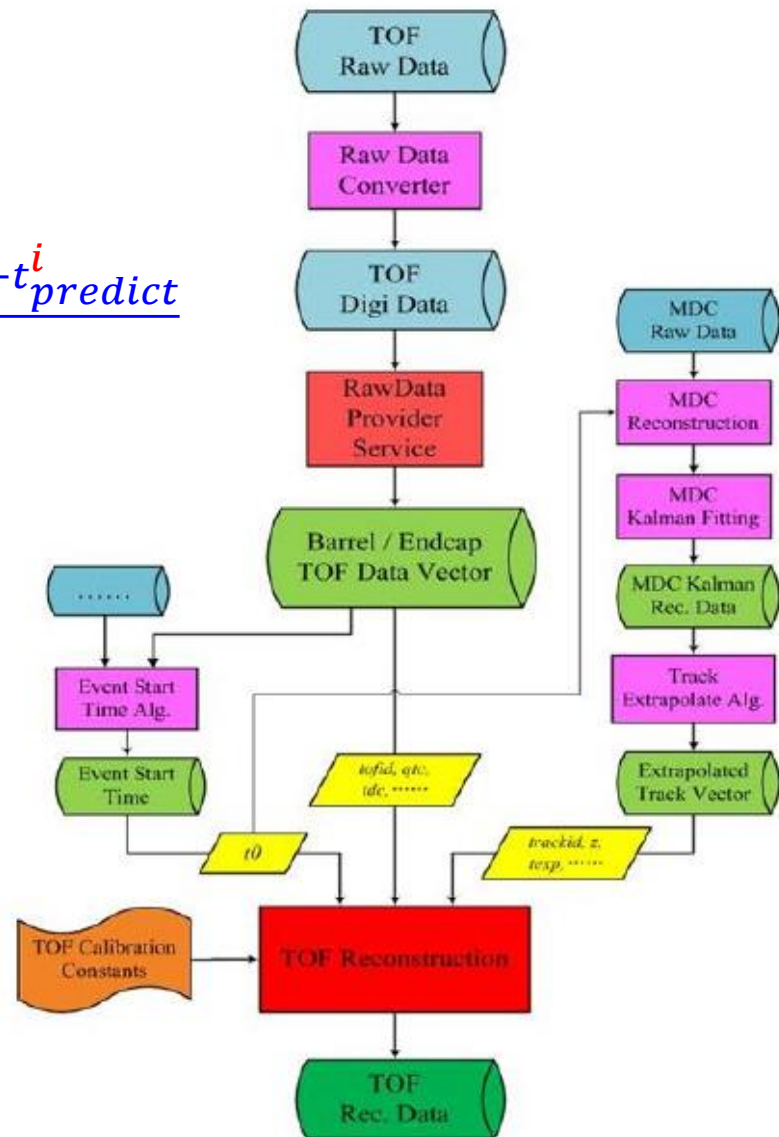
飞行时间探测器重建

- 飞行时间 (time-of-flight, TOF) — 动量- β 方法
- 粒子鉴别通过比较测量时间与预期时间差

$$t_{predict}^i = \frac{L}{c \cdot \beta_i}, \quad \beta_i = \frac{|\vec{p}|c}{E_i}, \quad E_i = \sqrt{m_i^2 + p^2} \quad \rightarrow \quad \chi = \frac{\Delta t}{\sigma} = \frac{t_{measure} - t_{predict}^i}{\sigma}$$

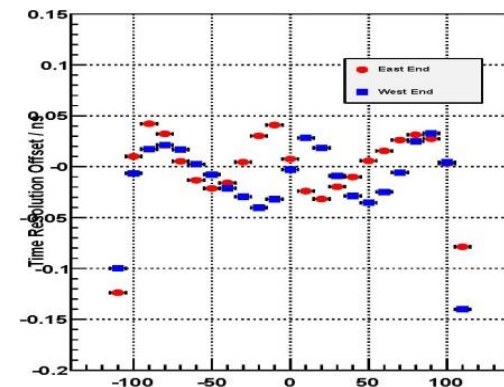
- 飞行时间探测器重建
 - 事例起始时间
 - ✓ 动量、径迹长度 \rightarrow 预期时间
 - ✓ 击中位置
 - 漂移室MDC重建 \rightarrow 径迹外推
 - TOF原始数据
 - 联合多次测量提高精度

$$\bar{t} = w_1 \cdot t_1 + w_2 \cdot t_2, \quad w_1 = \frac{\sigma_2^2 - \sigma_c^2}{\sigma_1^2 + \sigma_2^2 - 2\sigma_c^2}, \quad w_2 = \frac{\sigma_1^2 - \sigma_c^2}{\sigma_1^2 + \sigma_2^2 - 2\sigma_c^2}$$

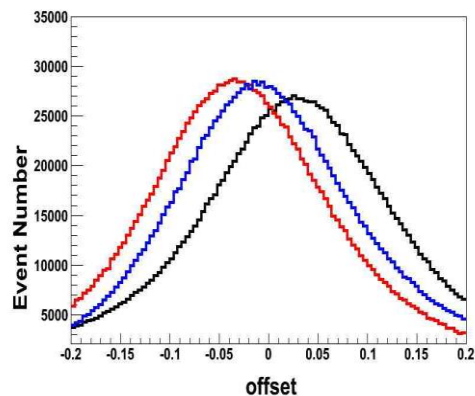
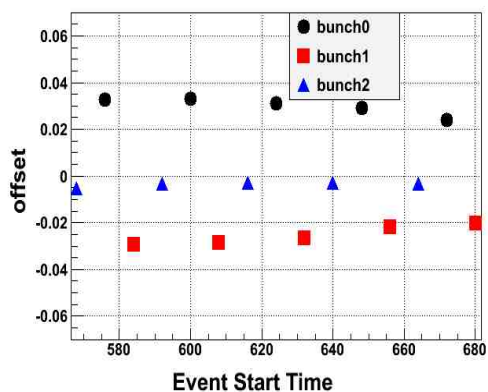


桶部飞行时间探测器重建

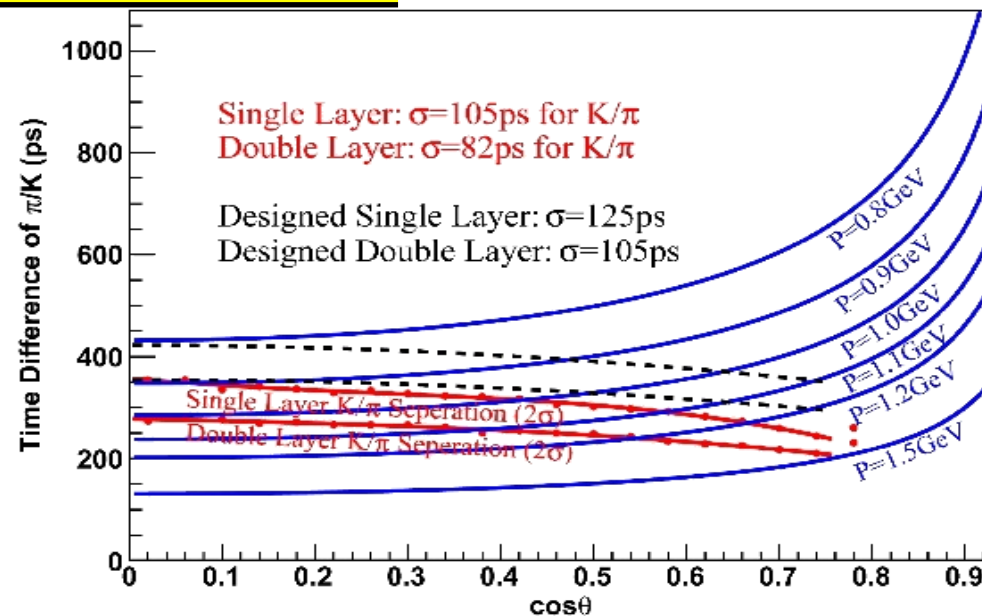
时间		项目	单层TOF	双层TOF
		设计指标	100~110	80~90
2009年	4月	验收指标	109	88
	7月	电子学曲线 / 高压 / 束团长度	100	80
	11月	卡曼滤波方法计算预期时间	98	78
2010年	10月	时间随击中位置偏移	93	74
2012年	6月	24ns内三次对撞的差别	内外层 80/90ps	65ps



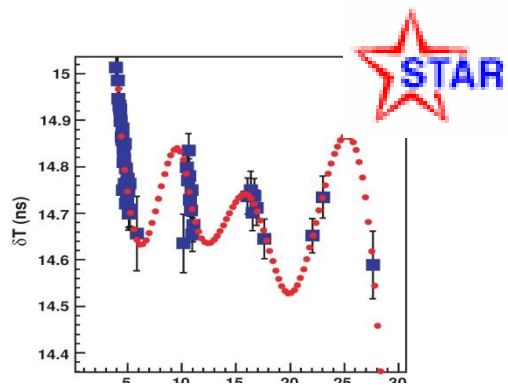
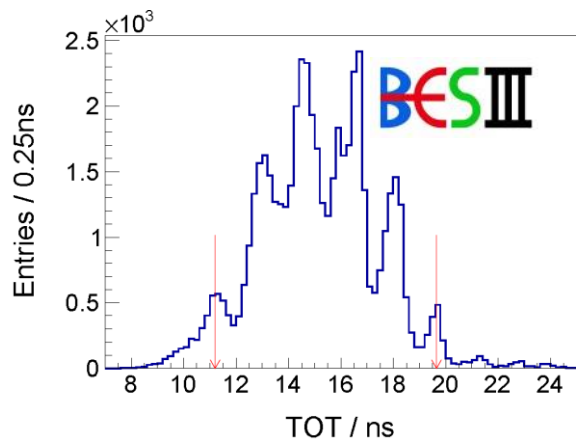
时间随击中位置: $\sim 4ps$



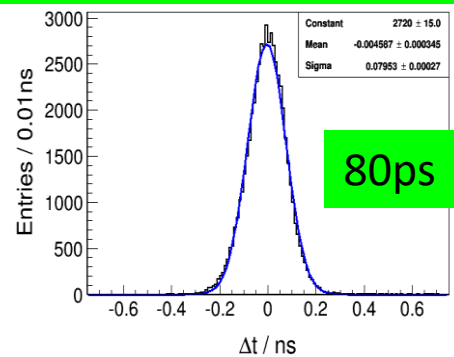
24ns内三次对撞 Δt 中心值的差别: $\sim 9ps$



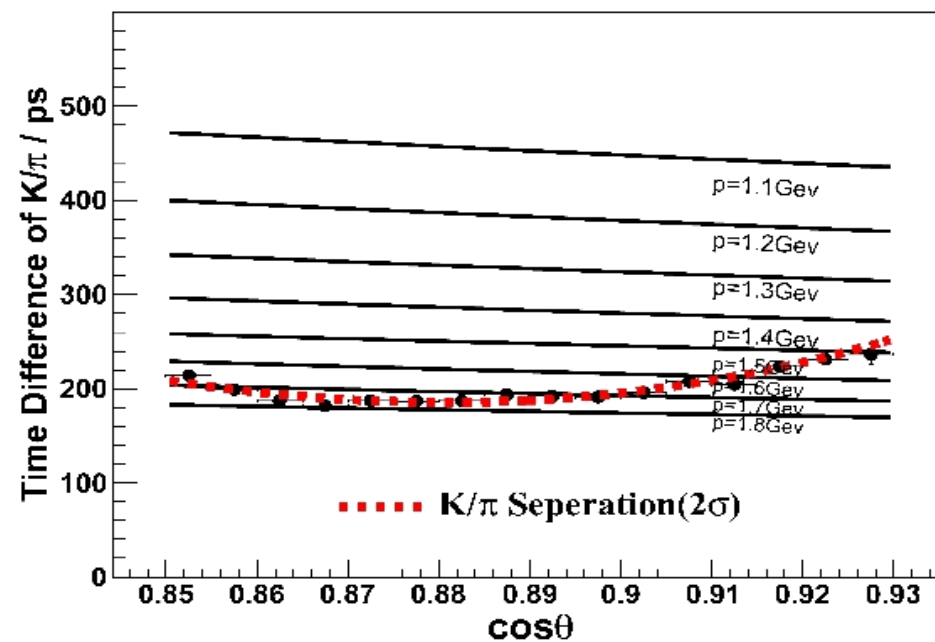
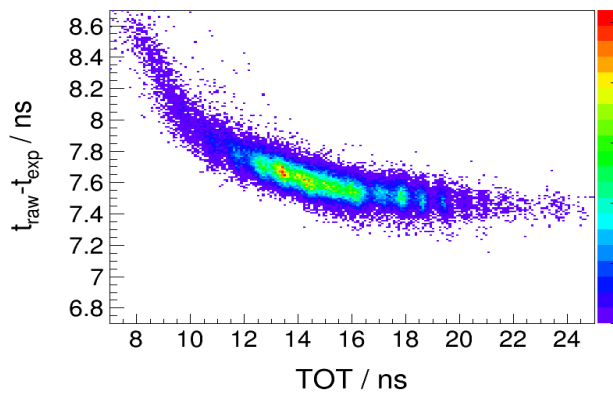
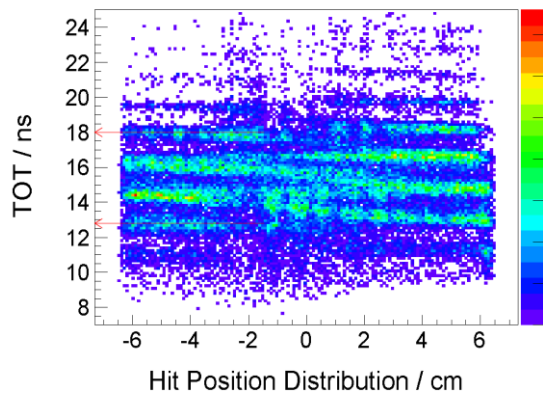
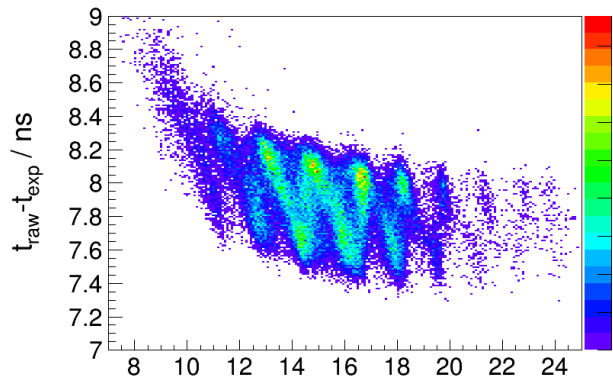
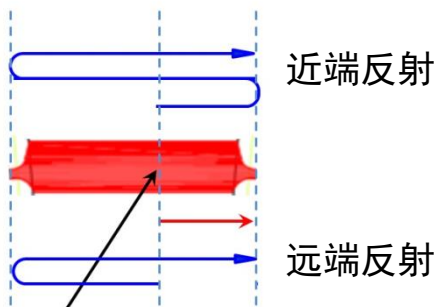
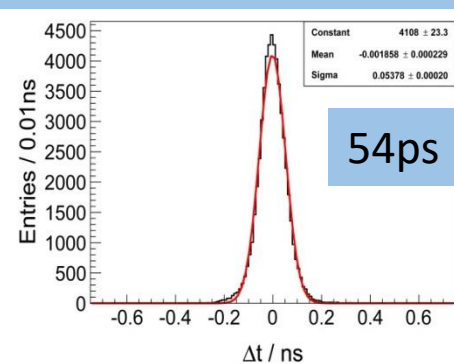
端盖飞行时间探测器重建



STAR实验的样条插值法

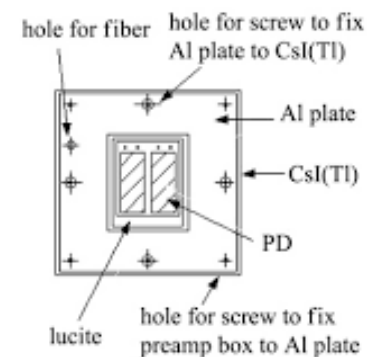
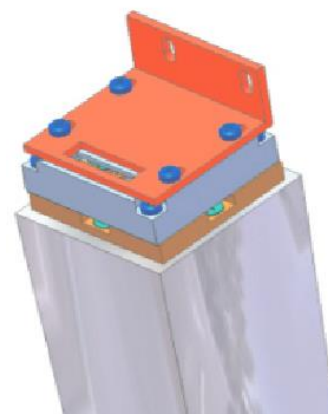
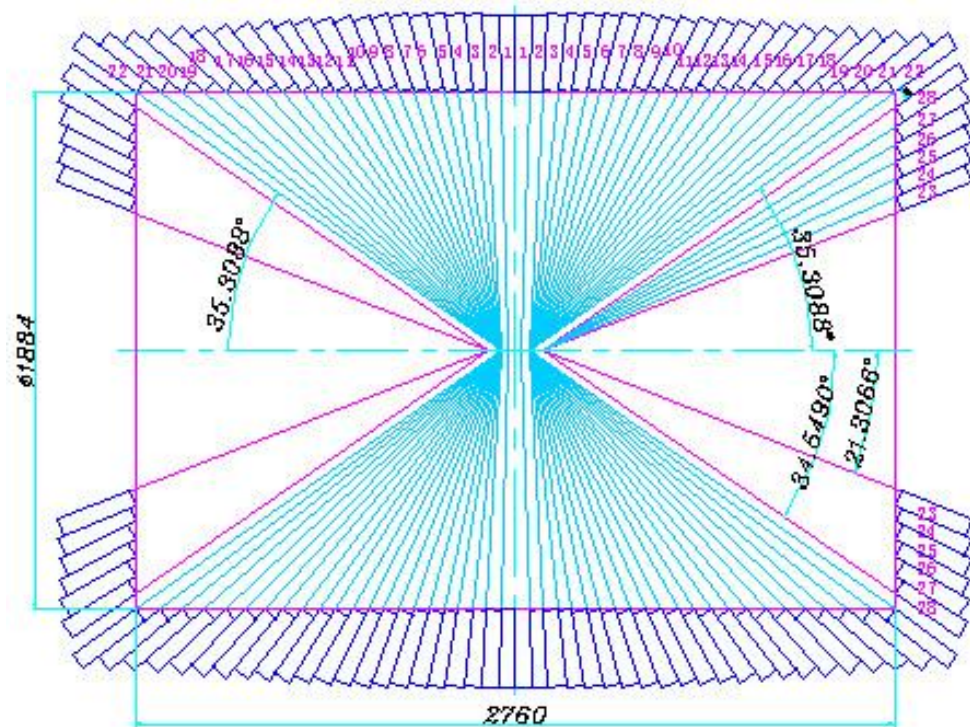


BESIII实验的刻度公式法

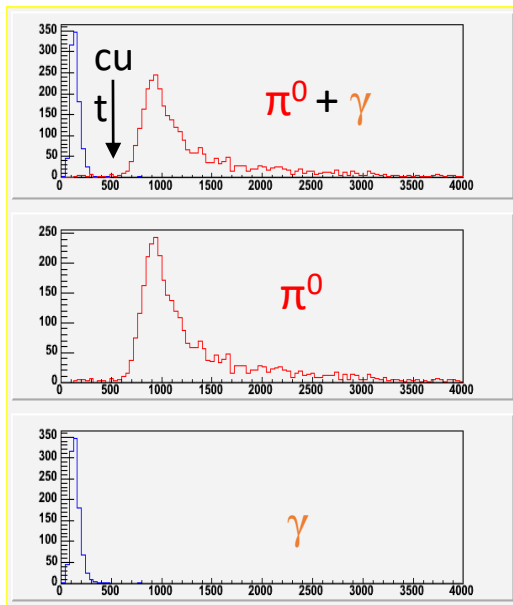
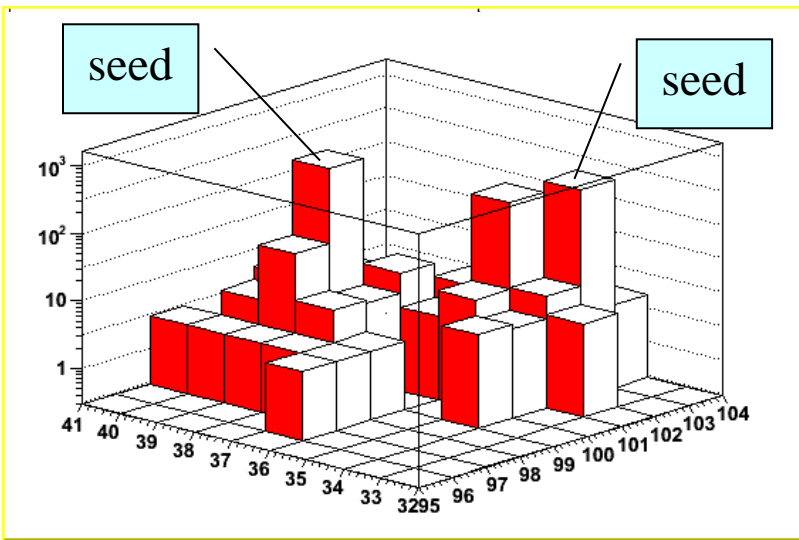
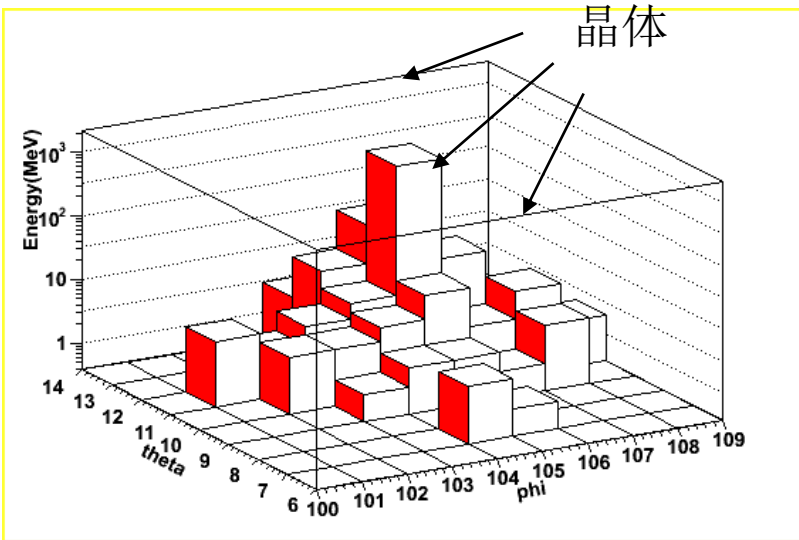
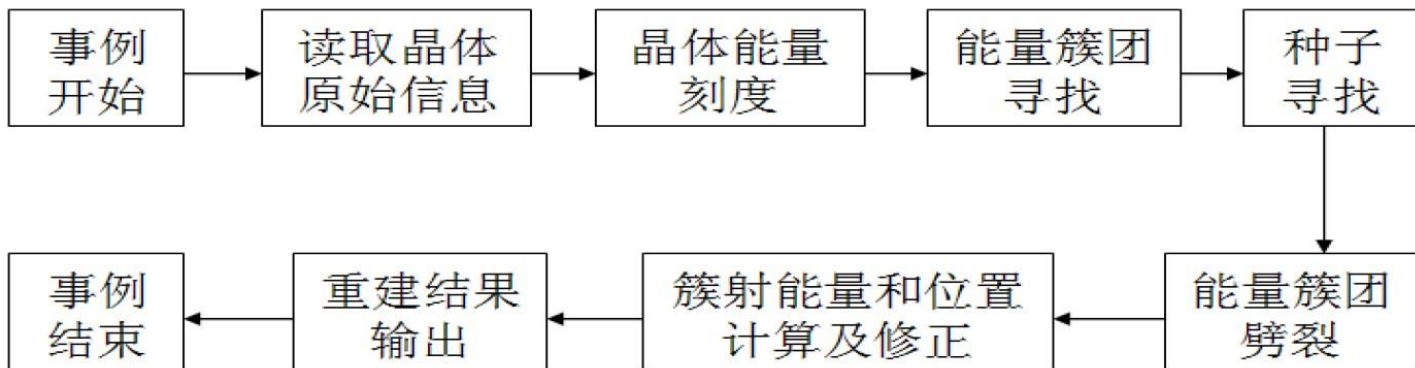


电磁量能器 (EMC)

- 全吸收型电磁量能器
- $6240C_sI(Tl)$ 晶体
- 颗粒度: $5 \times 5cm^2$ 和 $6.5 \times 6.5cm^2$, 长度 $28cm(15X_0)$
- 读出装置: 光二极管
- 能量分辨: $\sim 2.5\%$
- 位置分辨: $\sim 6mm$

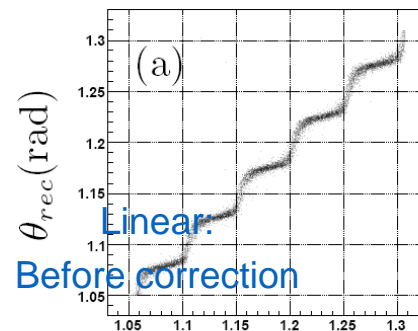


电磁量能器重建

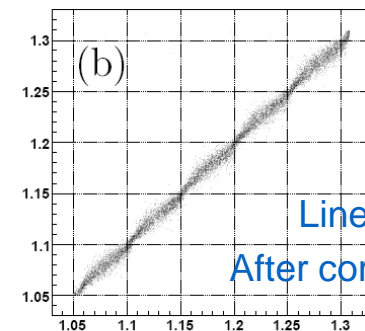


second moment

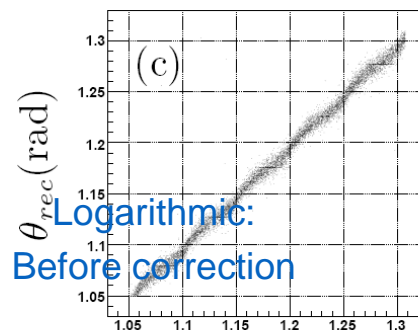
$$S = \frac{\sum_i E_i r_i^2}{\sum_i E_i}, r_i = r_{hit} - r_{center}$$



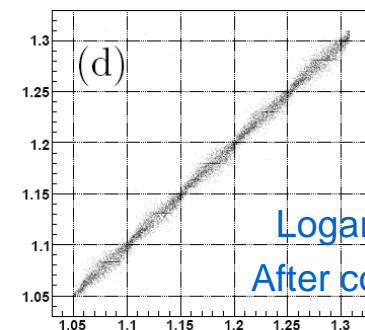
Linear: Before correction



Linear: After correction



Logarithmic: Before correction



Logarithmic: After correction

$\theta_{init}(\text{rad})$

电磁量能器刻度

• 均匀性刻度—探测单元的能量刻度

$$\begin{aligned} E_i^{dep} &= ADC_i \times C_i \\ &= ADC_i \times C_i^{Elec} \times g_i \\ &= E_i^{elec} \times g_i \end{aligned}$$

ADC_i : 探测单元*i*的脉冲幅度

C_i : 能量刻度系数

C_i^{Elec} : 通过放射源和宇宙线
测试得到的系数

g_i : 需要求解的刻度常数 ~ 1

Monte caro中
簇射团的沉积能量
预期沉积能量

$$\chi^2 = \sum_{k=1}^N \frac{E_{exp}^k - \sum_i^{5 \times 5} g_i \cdot E_i^{elec}}{\sigma(\theta, \phi)}$$

数据中簇射团
的沉积能量

$$E_{exp}^k = E_e(\theta, \phi) \times f(E_e, \theta, \phi)$$

$E_e(\theta, \phi)$ 入射电子的动能（真实能量）
 $f(E_e, \theta, \phi)$ 是能量泄露因子，由MC获得

电磁量能器刻度

能量响应刻度—簇射绝对能量刻度

簇射团能量 $E_{shower} = \sum_i E_i^{dep}$ \rightarrow 粒子能量 E_{true} 的关系

定义刻度因子: $E_{shower}/E_{true} = \exp(\alpha_i)$

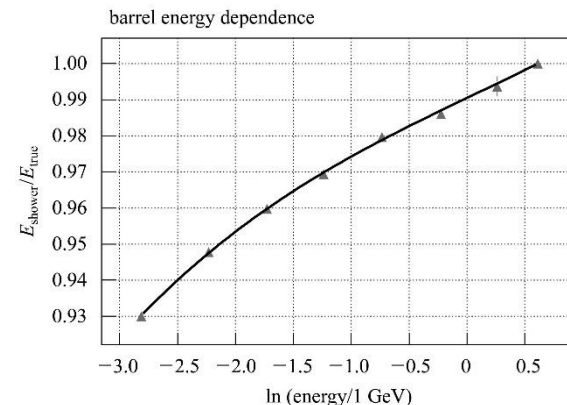
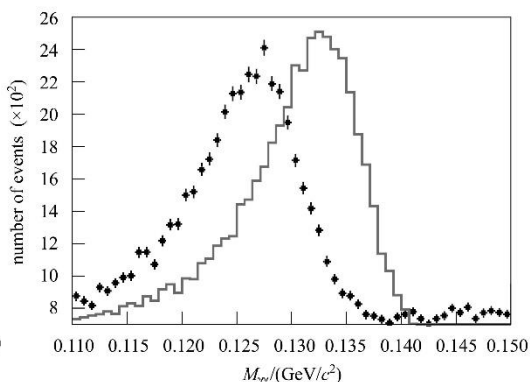
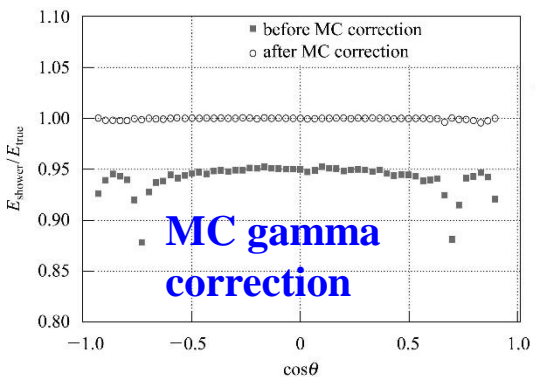
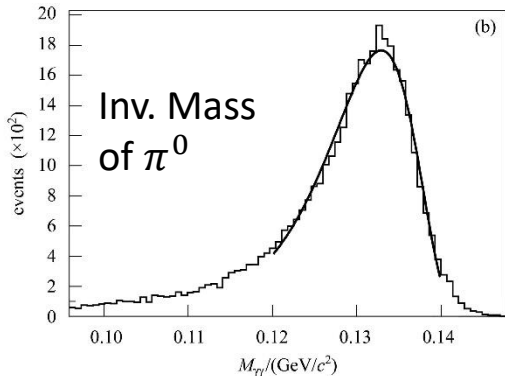
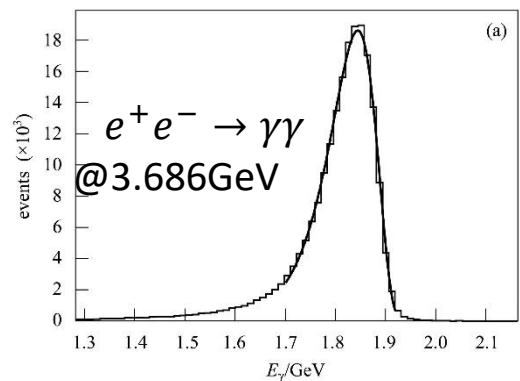
$$m_{\gamma\gamma}^{cor} = \sqrt{2 \cdot E_{low} \cdot \exp(-\alpha_{low}) \cdot E_{high} \cdot \exp(-\alpha_{high}) \cdot (1 - \cos\theta_{\gamma\gamma})}$$

$$= m_{\gamma\gamma}^{raw} \cdot \exp\left(-\frac{\alpha_{low}}{2} - \frac{\alpha_{high}}{2}\right)$$

$$C_{ij} = \frac{\alpha_i}{2} + \frac{\alpha_j}{2} \pm \sigma_{ij}, \text{ with } C_{ij} = \ln m_{\gamma\gamma}^{data} - \ln m_{\gamma\gamma}^{exp}$$

定义 $\chi^2 = \sum_i \sum_j \frac{\left(\frac{\alpha_i}{2} + \frac{\alpha_j}{2} - C_{ij}\right)^2}{\sigma_{ij}^2}$, 求极小得到

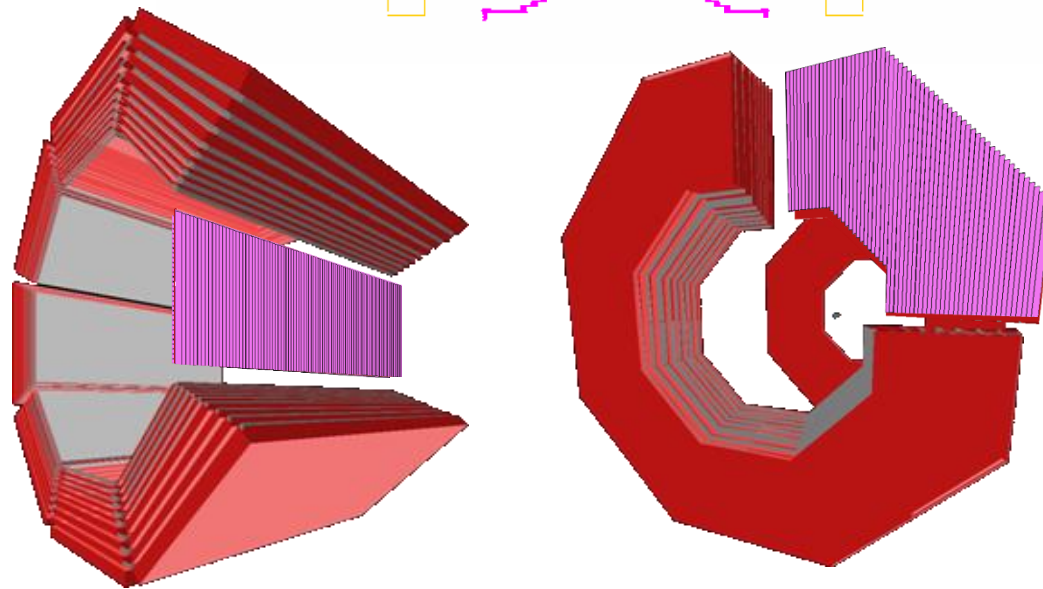
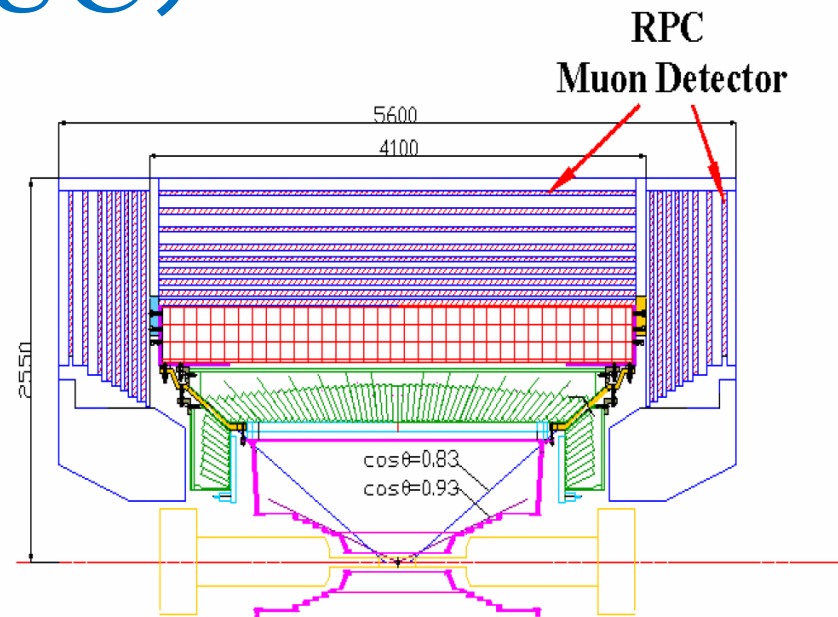
簇射团能量依赖的能量响应 $E_{shower}/E_{true} = a_0 + a_1 \cdot \ln E_{shower} + a_2 \cdot \ln^2 E_{shower}$



μ 子探测器 (MUC)

- 流光模式的阻性板室是灵敏探测器，吸收体是钨铁
- 桶部+端盖
- 阻性板室
 - 桶部：9层
 - 端盖：8层
- 一维读出条

4096 (EC) + 5056 (BR) = 9152strips

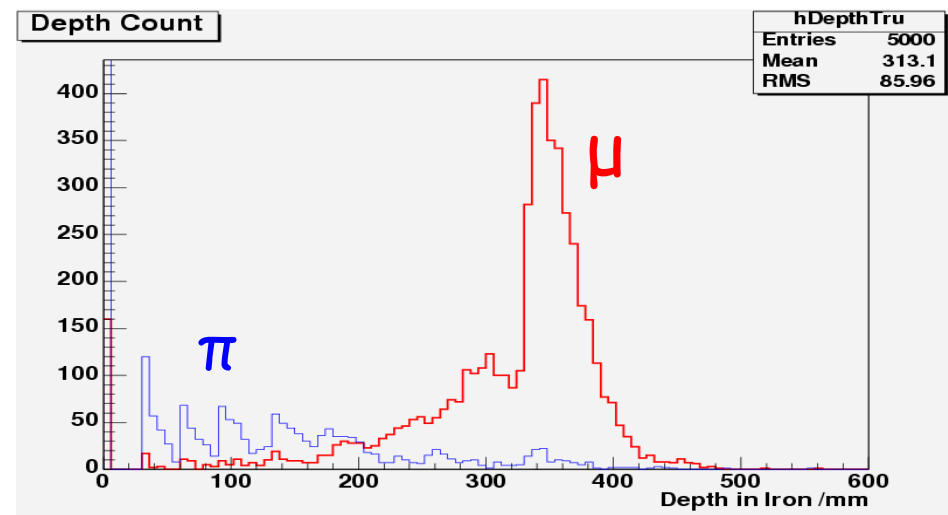
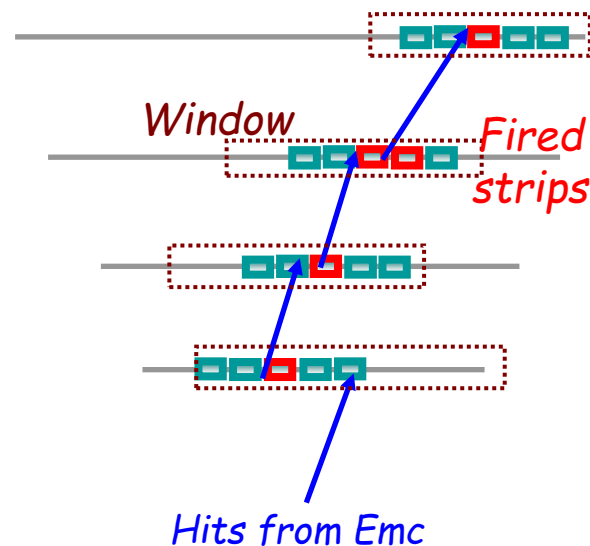


μ 子探测器重建

- 击中信息 \rightarrow 径迹：方向，位置，穿透深度等
- 重建步骤：几何构建，径迹寻找，径迹拟合，径迹参量计算
- 重建算法包括三种：
 - 外推重建：漂移室径迹做种子
 - 自重建：MUC击中做种子
 - 极点重建：EMC 或MUC击中联合对撞点外推，中性粒子

• μ/π 鉴别

1. 动量
2. 极角 θ
3. ϕ
4. 径迹的入射深度
5. 一层包括的最大击中数
6. 径迹外推与第一层着火读出条的匹配
7. 径迹外推与MUC重建径迹的匹配
8. MUC径迹的 χ^2
9. $\Delta\phi$ (径迹的弯曲角)



粒子鉴别

- 电离能损 dE/dx — 动量- $\beta\gamma$ (dE/dx)

$$\chi = \frac{(dE/dx)_{mea} - (dE/dx)_{exp}}{\sigma(dE/dx)}$$

– 电离能损 dE/dx 用 Bethe-Bloch公式来描述：
 $dE/dx \propto \log(\beta^2\gamma^2)/\beta^2$

– 适用的动量区间

✓ 低动量区间 ($\beta\gamma < 2$)

✓ 高动量区间 ($5 < \beta\gamma < 50$)

- 飞行时间 (TOF) — 动量- β 方法

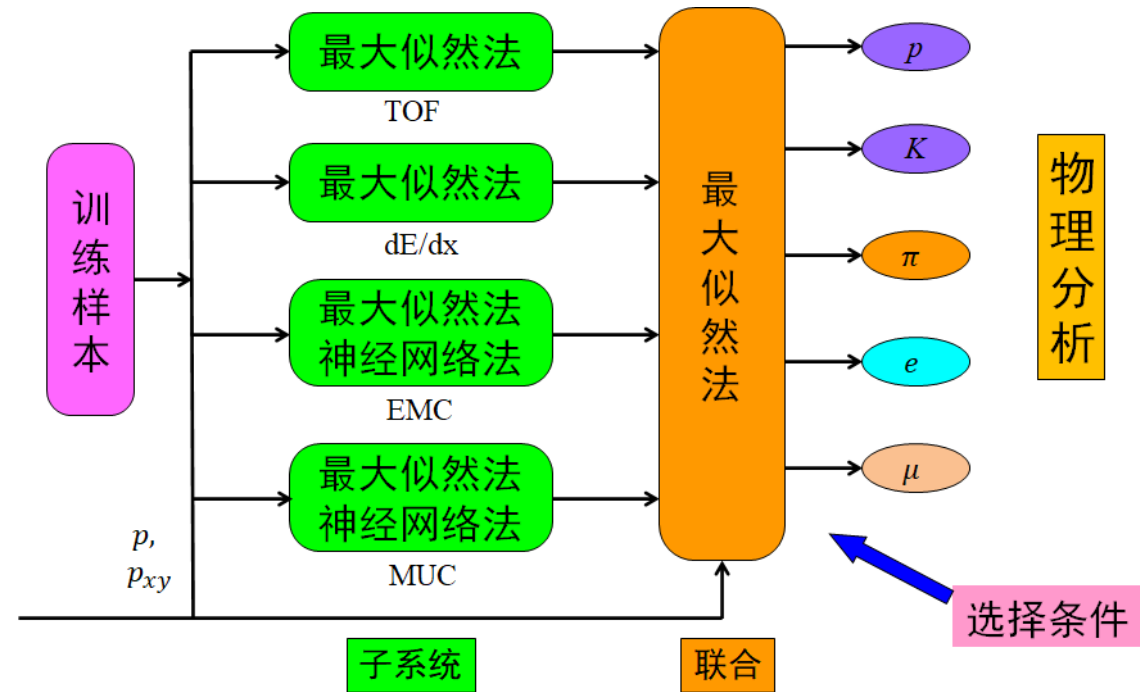
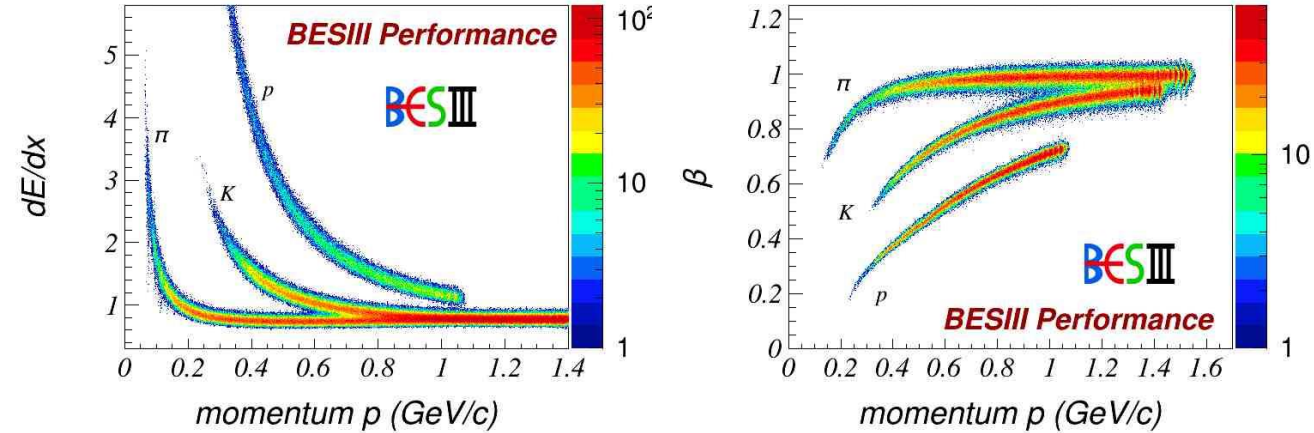
$$\chi = \frac{t_{measure} - t_{predict}^i}{\sigma}$$

– 适用的动量区间：低动量到高动量之间

- 联合 dE/dx 和 TOF进行**粒子鉴别**

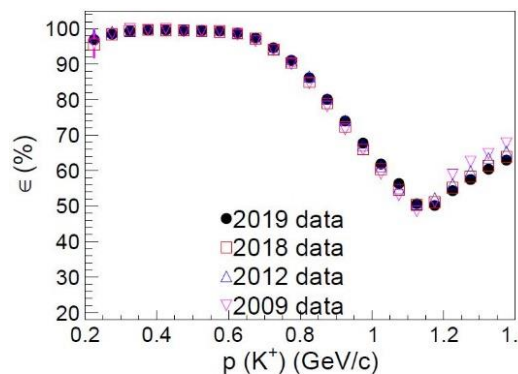
$$\chi_{comb} = \chi_{dE/dx} + \chi_{TOF}$$

- 利用机器学习联合各个子探测器用于粒子鉴别的信息，进一步提高粒子鉴别效率

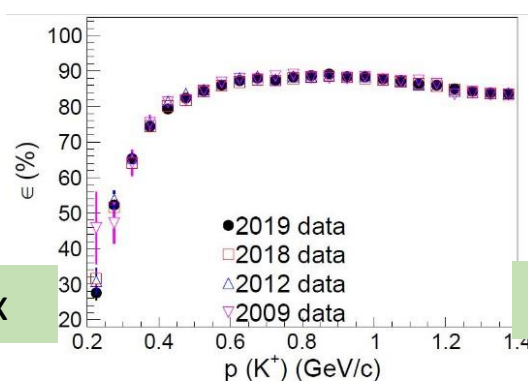


粒子鉴别

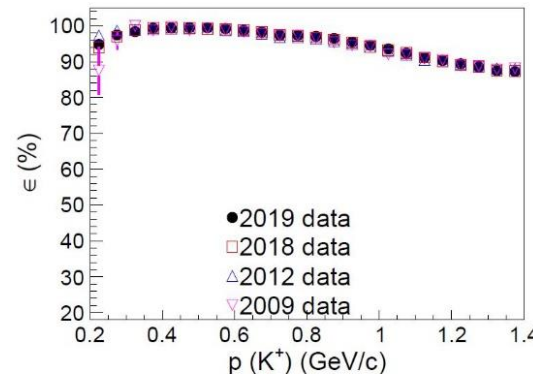
- 粒子鉴别是粒子物理实验的基本要求之一，特别对于改善 hadronic decay 物理过程的信噪比十分重要
- BESIII实验质心系能量从2~5.6GeV，多数对撞事例末态产物的动量在1GeV以下
- 出于工艺和造价的考虑，BESIII没有采用性能更好的切伦科夫探测器，利用优秀的数理方法弥补粒子鉴别能力的不足是十分必要的



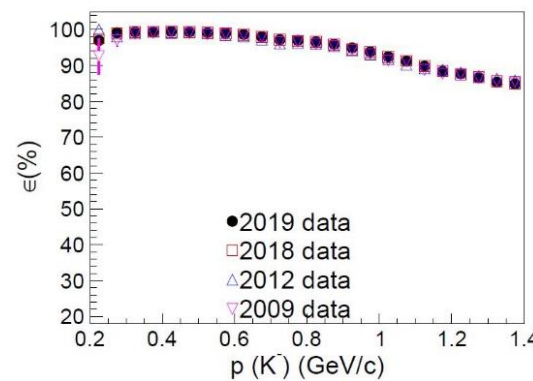
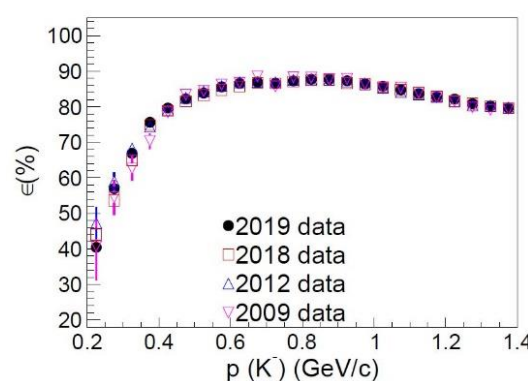
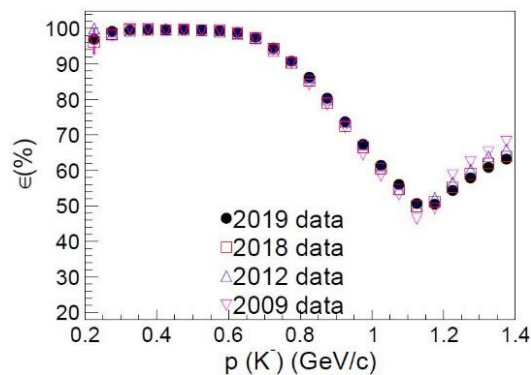
dE/dx



TOF



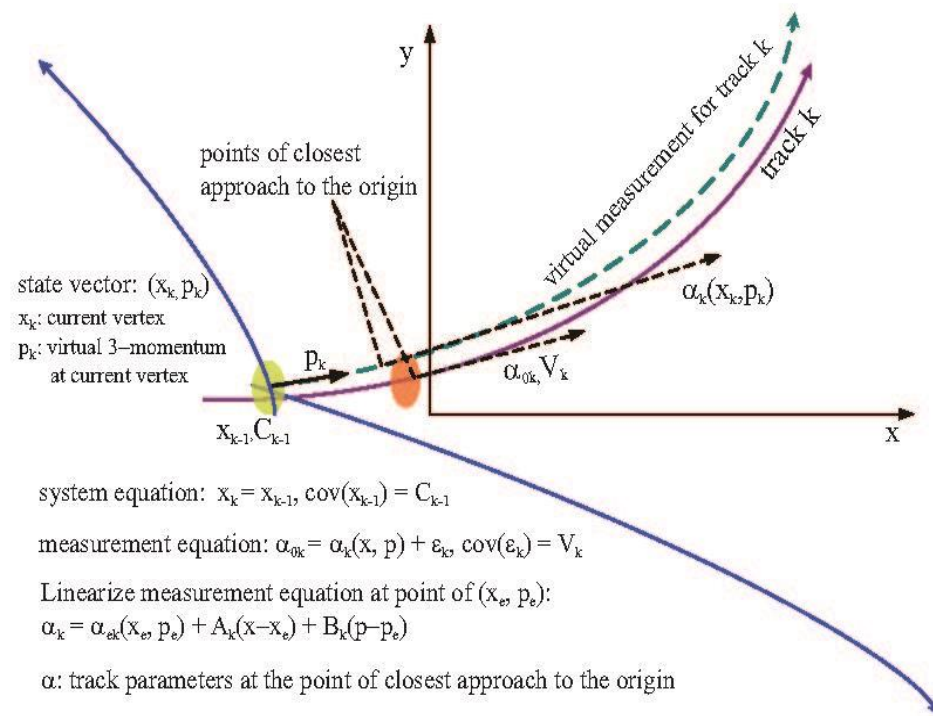
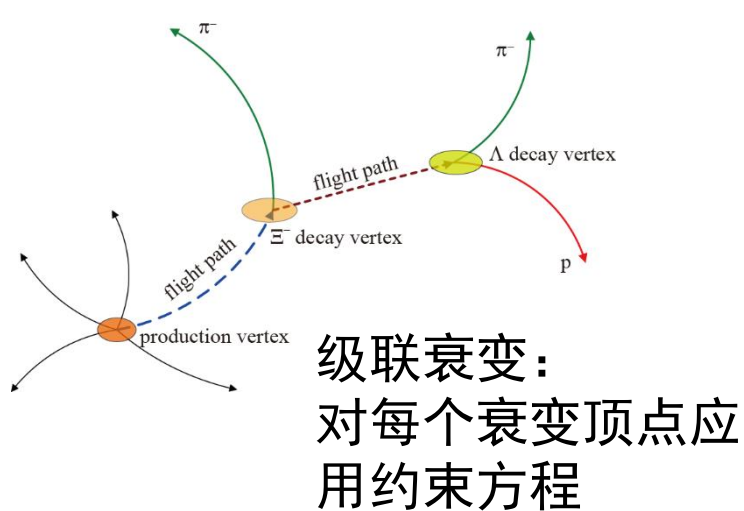
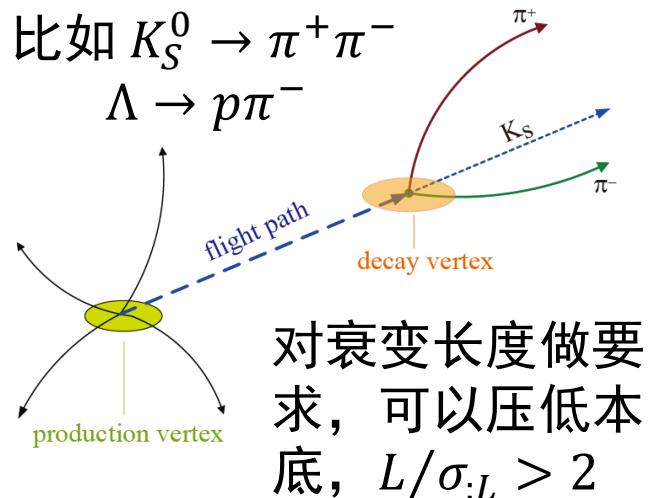
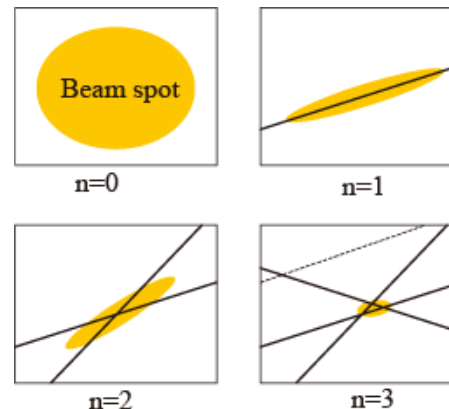
Combination



顶点拟合与次级顶点拟合

精确的顶点拟合/次级顶点拟合有效提高径迹质量，压低本底，提高信噪比

- 顶点拟合与探测器几何无关，只与径迹参数相关
- 多条径迹来自于空间中的同一个点，是“径迹团”的识别问题
- 次级顶点拟合
 - 中性粒子 — 直线: $K_S^0 \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p\pi^-$
 - 带电粒子 — 螺旋线: $\Xi^- \rightarrow \Lambda\pi^-$
- 基于Kalman Filter的顶点拟合算法



运动学拟合

- 运动学拟合的原理是一个数学计算过程，利用运动学上的守恒定律：

– 不变质量约束 $E^2 - p_x^2 - p_y^2 - p_z^2 - m_c^2 = 0$
 $\pi^0/\eta \rightarrow \gamma\gamma$

– 四动量守恒约束 $p^\mu - p_c^\mu = 0$
 $J/\psi, \psi' \rightarrow \text{anything}$

– 顶点约束
 $\vec{x}_p = \vec{x}_d - \gamma\vec{\beta}c\tau = \vec{x}_d - \frac{\vec{p}}{m}c\tau$

- 运动学拟合的作用
 - 提高粒子的能量、动量和质量分辨
 - 排除本底，提高信噪比
- 约束条件下的最小二乘拟合

$$\chi^2 = (\eta - \eta_0)^T V_{\eta_0}^{-1} (\eta - \eta_0) + 2\lambda^T (D\eta + d)$$

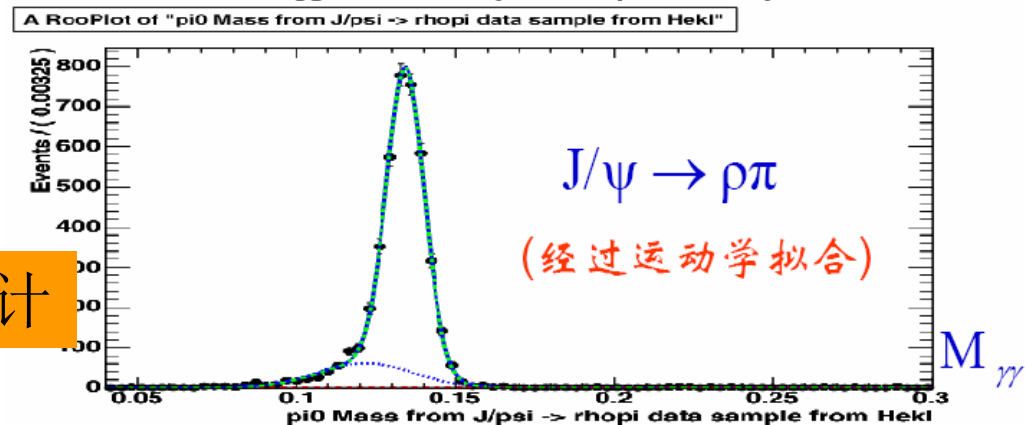
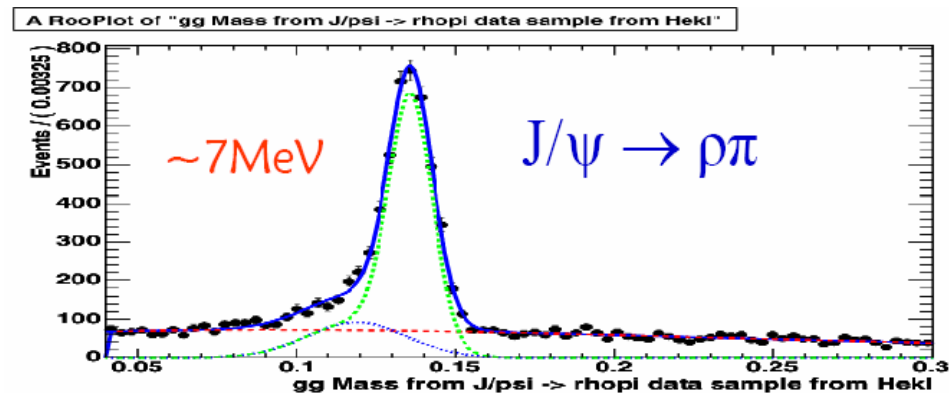
← 无约束的参数估计

← 约束方程

以 $J/\psi \rightarrow \rho\pi$ 为例

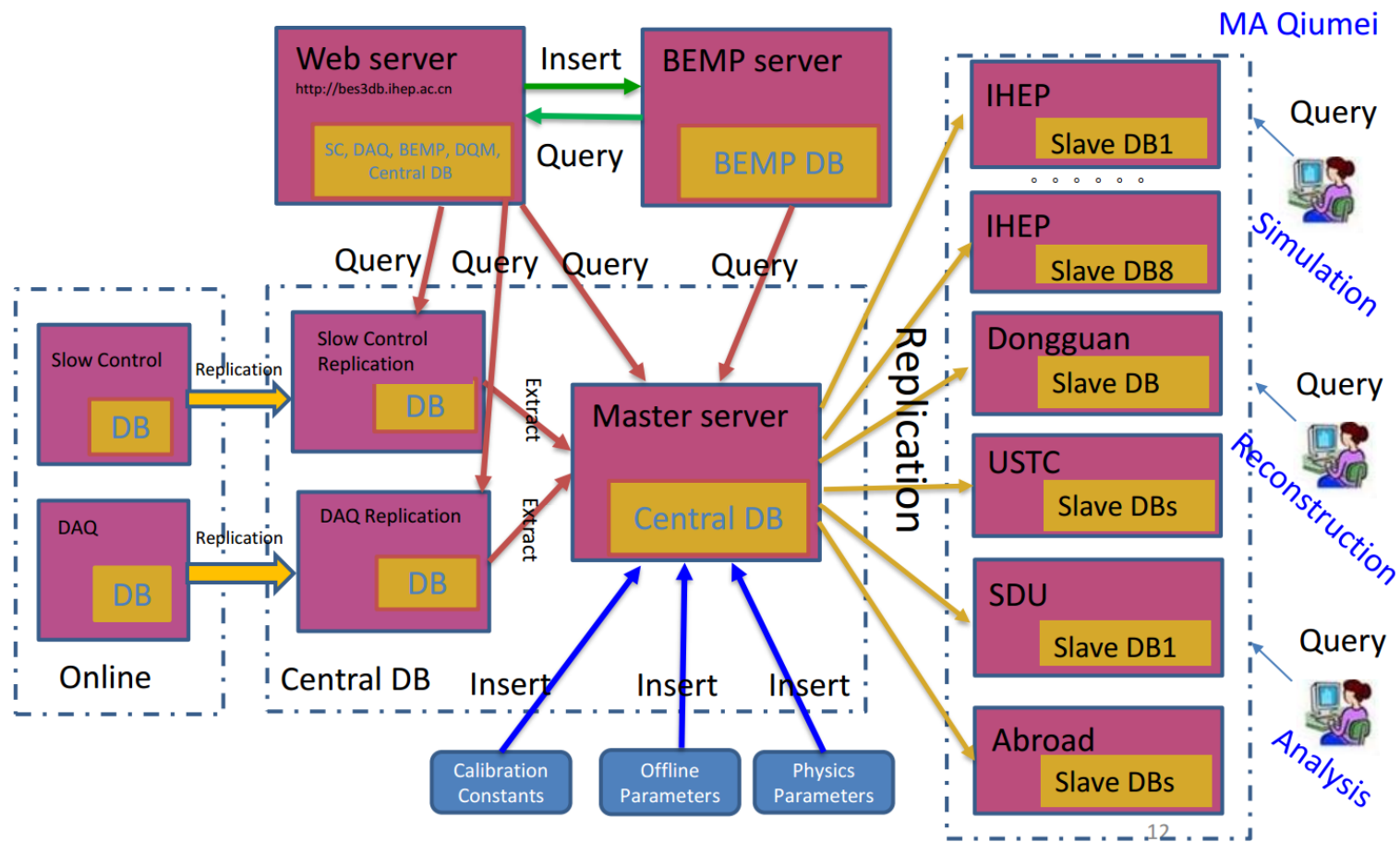
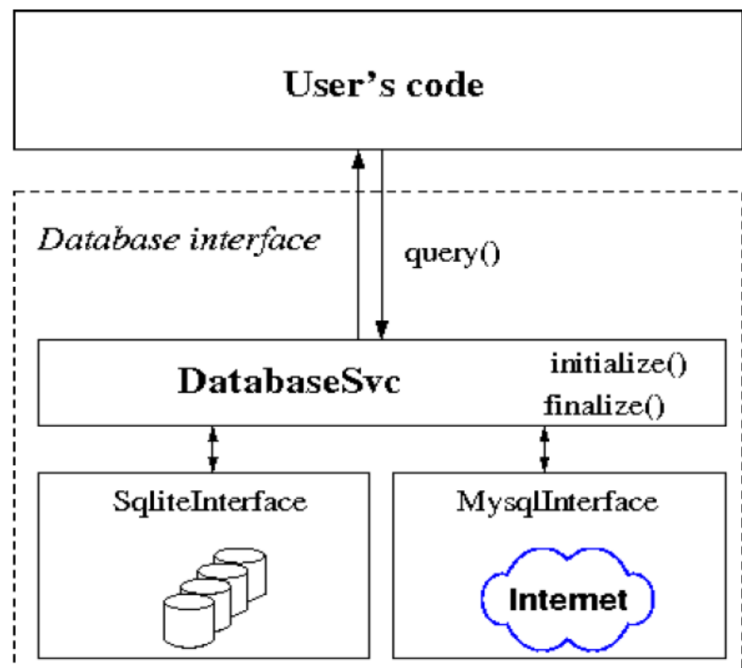
在大多数的 J/ψ 和 ψ' 分析中，末态粒子全部重建，要求满足能动量守恒：

$$\sum p_x^i = p_{cx}, \quad \sum p_y^i = p_{cy}, \quad \sum p_z^i = p_{cz}, \quad \sum E_i = E_c$$

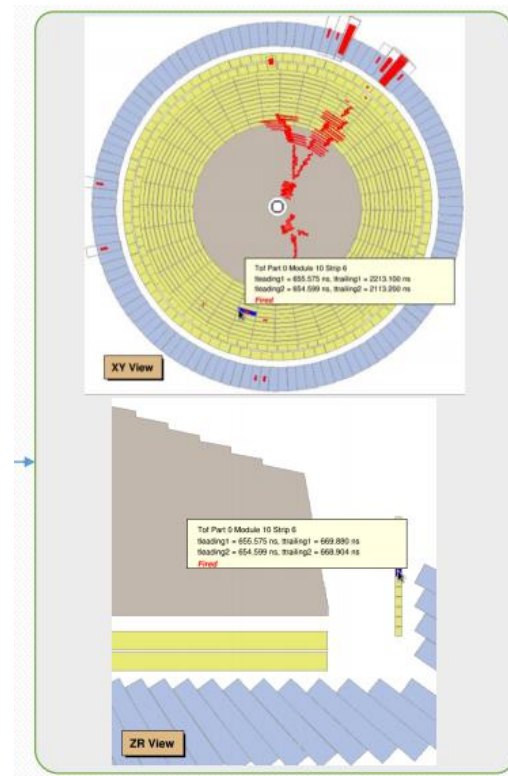
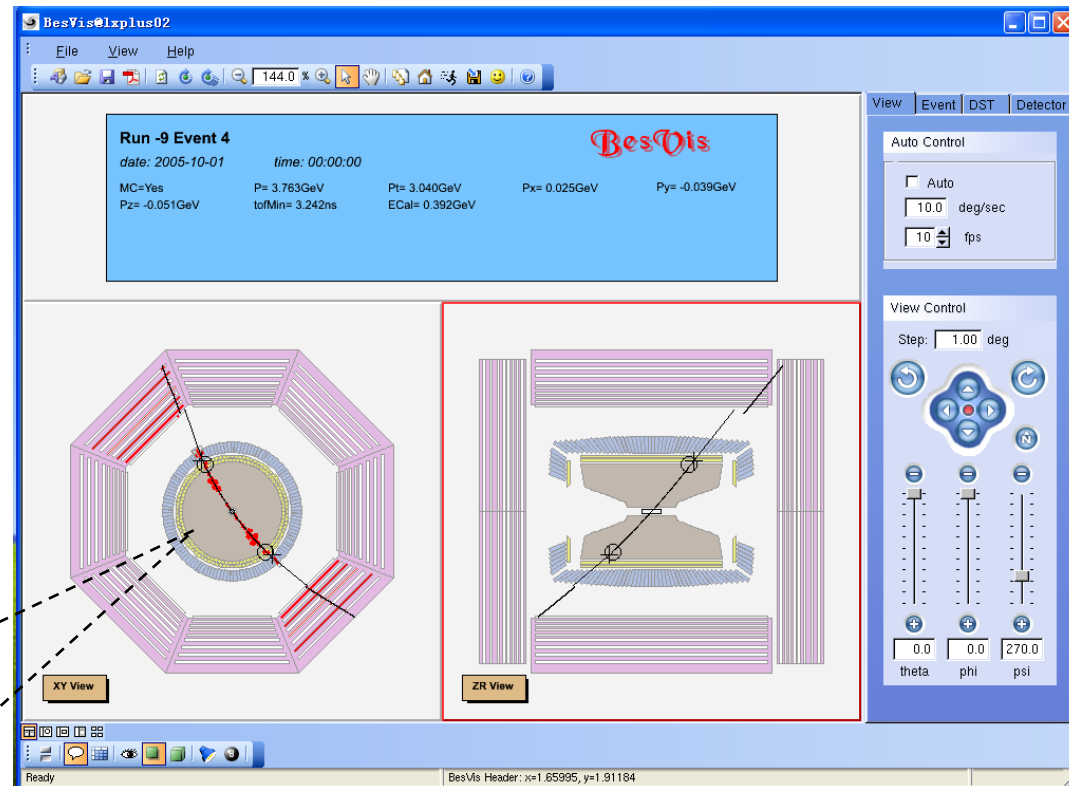
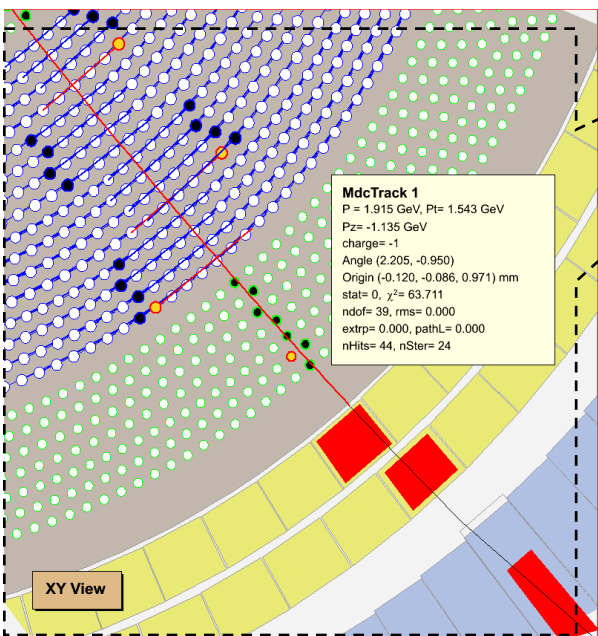
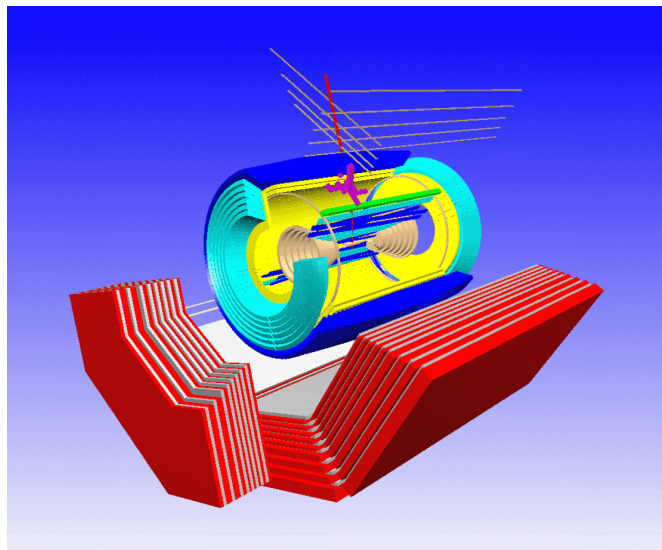


数据库

- 整个离线软件系统内通过统一的接口访问数据库
- DatabaseSvc支持Sqlite和Mysql两种后端
- 支持两种访问模式
 - ✓ One connection per job
 - ✓ One connection per query

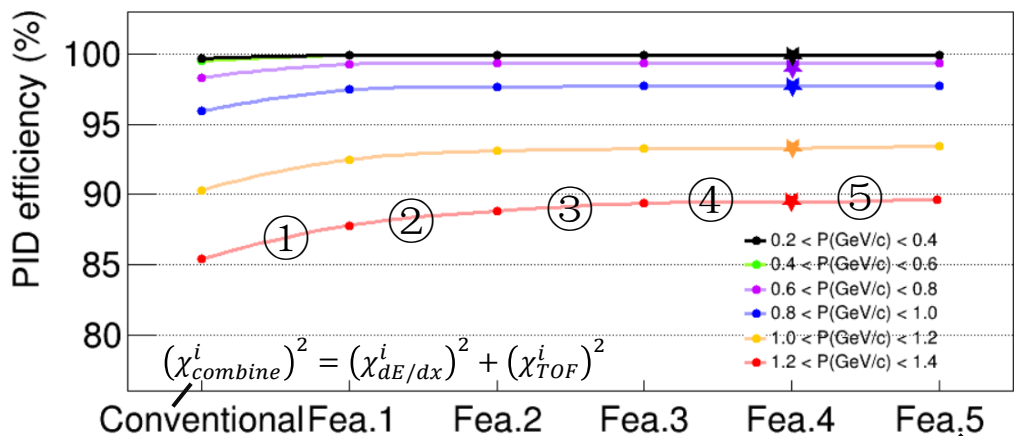


事例显示（可视化）



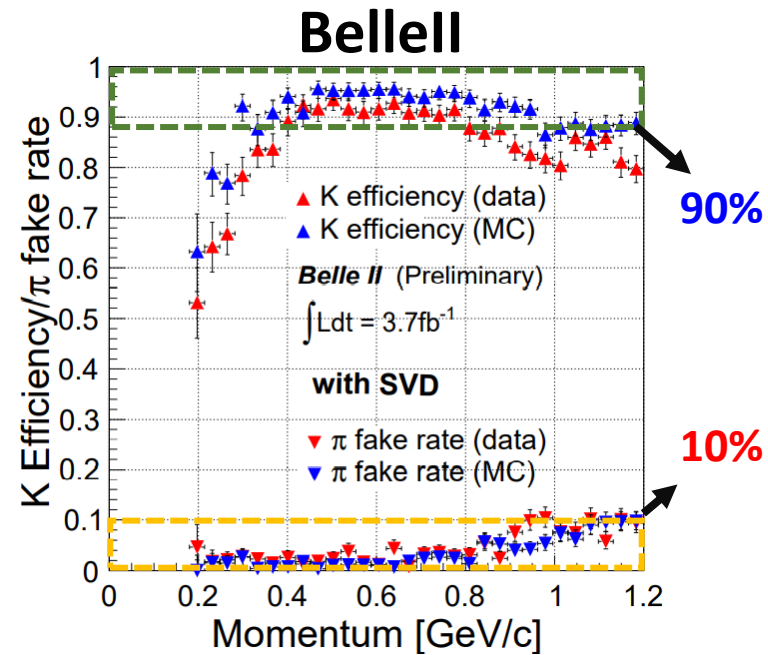
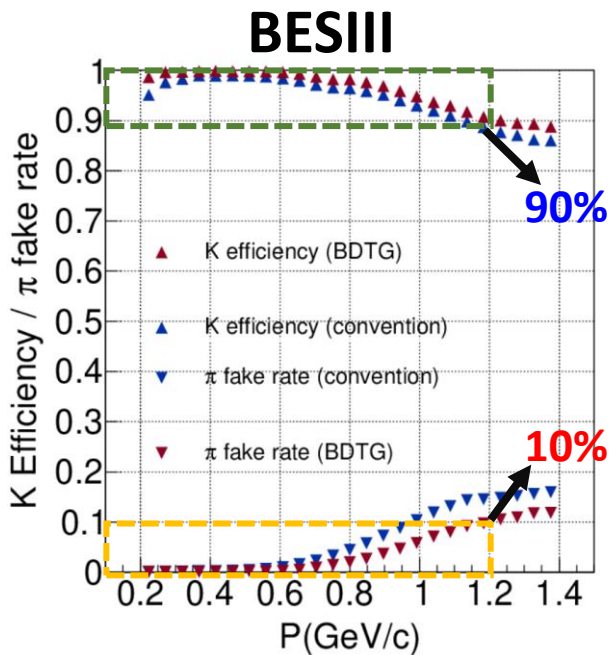
- 事例显示软件是在事例级别对实验数据的可视化分析
- 基于ROOT, OpenGL, XML
- 支持2D和3D显示
- 通过menu和toolbar进行控制操作
- 广泛应用于探测器设计、监控、事例产生、重建、探测器模拟、数据分析等

机器学习方法提高粒子鉴别效率



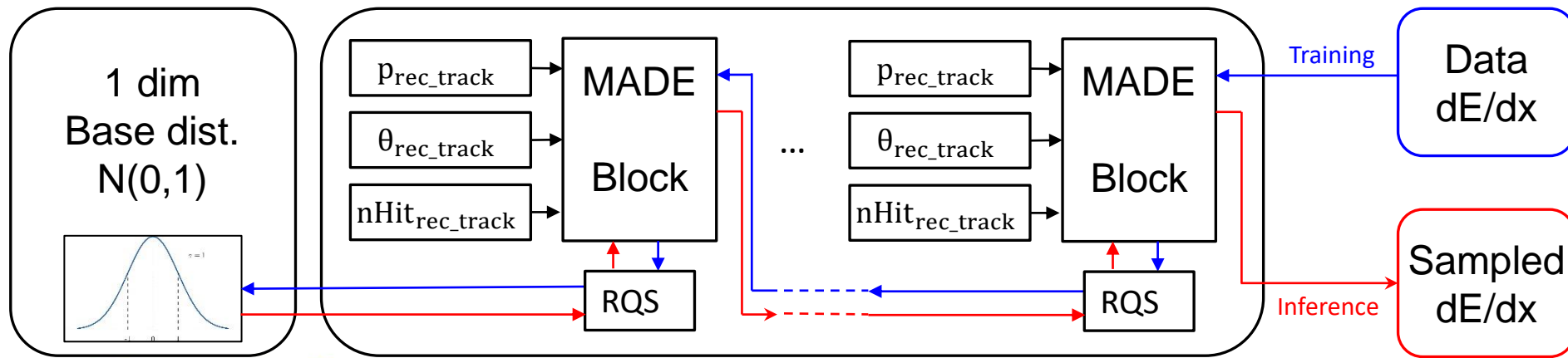
Conventional	Fea.1	Fea.2	Fea.3	Fea.4	Fea.5
P	P	P	P	P	Fea.4
$\cos\theta$	$\cos\theta$	$\cos\theta$	$\cos\theta$	$\cos\theta$	<i>nghits</i>
charge	charge	charge	charge	charge	path
$\chi_{dE/dx}$	$\chi_{dE/dx}$	$\chi_{dE/dx}$	$\chi_{dE/dx}$	$\chi_{dE/dx}$	e3/e5
$t_{11,12,21,22}$	$t_{11,12,21,22}$	$t_{11,12,21,22}$	$t_{11,12,21,22}$	$t_{11,12,21,22}$	a42Mom
	Q_{TOF}	Q_{TOF}	Q_{TOF}	Q_{TOF}	a20Mom
		E/P	E/P	E/P	$\Delta\phi$
		eS/e3x3	eS/e3x3	eS/e3x3	Time
		secMom	secMom	secMom	dE
		latMom	latMom	latMom	energy
		$Nhits_{Emc}$	$Nhits_{Emc}$	$Nhits_{Emc}$	Δx_{MUC}
		$\Delta\theta$	$\Delta\theta$	$\Delta\theta$	$\Delta\phi_{MUC}$
			depth	depth	maxHit
					χ_{MUC}^2
					$Nhits_{MUC}$
					$N Lay_{MUC}$

特征挑选
提升决策树

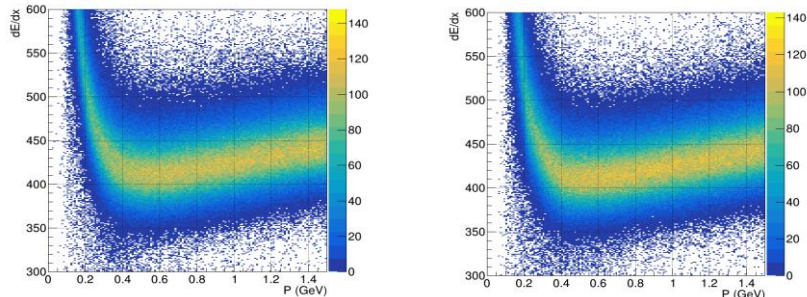


- 与传统方法相比
 - π 介子提升了~8% @ 1.4 GeV/c
 - K介子提升了~3% @ 1.4 GeV/c
- 验证了机器学习方法对强子样本没有依赖
- 新的方法对 π 介子和K介子鉴别的系统误差~1%水平
- 完成相关软件部署

机器学习方法提高模拟精度

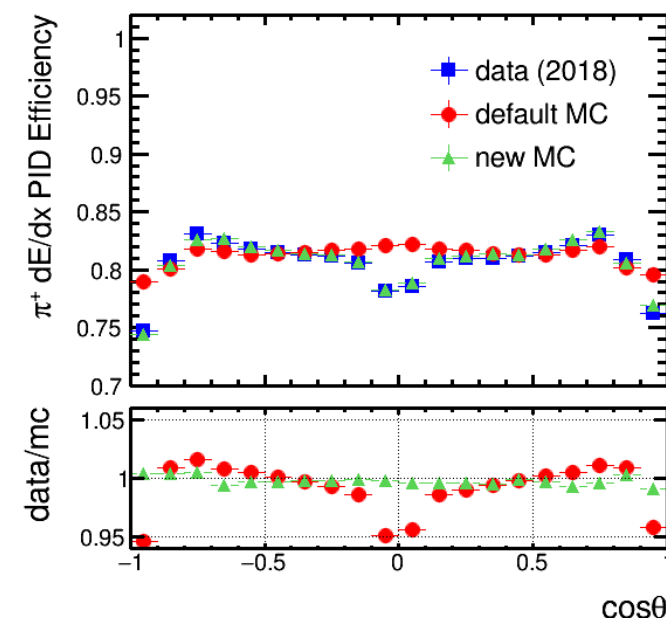
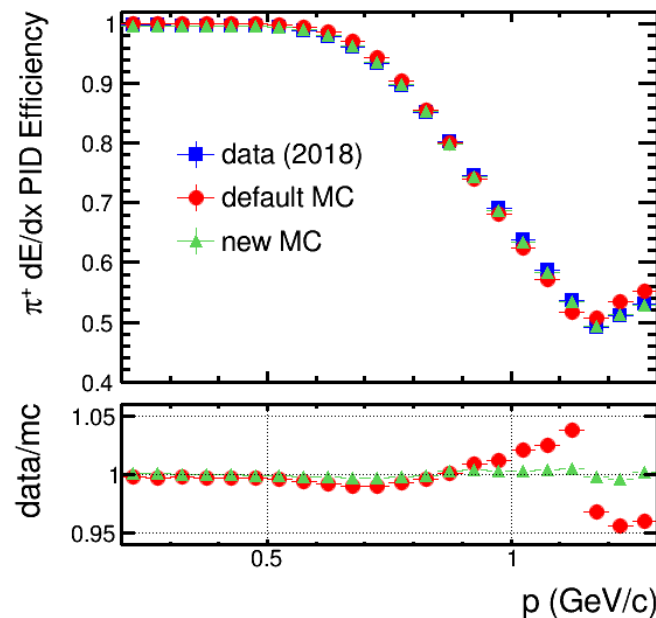
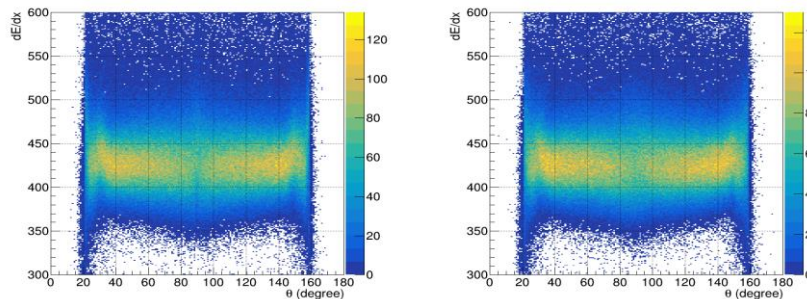


- 利用 Normalizing flow 方法实现 dE/dx 的精确模拟
- 粒子鉴别效率在较大动量区间内达到~1%的水平



Data

NN





European Strategy for Particle Physics 2018-2020

The European Strategy for Particle Physics is the cornerstone of Europe's decision-making process for the long-term future of the field.

Mandated by the CERN Council, it is formed through a broad consultation of the grass-roots particle physics community, it actively solicits the opinions of physicists from around the world, and it is developed in close coordination with similar processes in the US and Japan in order to ensure coordination between regions and optimal use of resources globally

The latest input is a newly published 250-page [physics briefing book](#), the result of an intense year-long effort to capture the status and prospects for experiment, theory, accelerators and computing for high-energy physics.

Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

Electroweak Physics: Richard Keith Ellis¹, Beate Heinemann^{2,3} (*Conveners*)
Jorge de Blas^{4,5}, Maria Cepeda⁶, Christophe Grojean^{2,7}, Fabio Maltoni^{8,9}, Alejandro Nisati¹⁰,
Elisabeth Petit¹¹, Riccardo Rattazzi¹², Wouter Verkerke¹³ (*Contributors*)

Strong Interactions: Jorgen D'Hondt¹⁴, Krzysztof Redlich¹⁵ (*Conveners*)
Anton Andronic¹⁶, Ferenc Siklér¹⁷ (*Scientific Secretaries*)
Nestor Armesto¹⁸, Daniël Boer¹⁹, David d'Enterria²⁰, Tetyana Galatyuk²¹, Thomas Gehrmann²²,
Klaus Kirch²³, Uta Klein²⁴, Jean-Philippe Lansberg²⁵, Gavin P. Salam²⁶, Gunar Schnell²⁷,
Johanna Stachel²⁸, Tanguy Pierog²⁹, Hartmut Wittig³⁰, Urs Wiedemann²⁰ (*Contributors*)

Flavour Physics: Belen Gavela³¹, Antonio Zoccoli³² (*Conveners*)
Sandra Malvezzi³³, Ana M. Teixeira³⁴, Jure Zupan³⁵ (*Scientific Secretaries*)
Daniel Aloni³⁶, Augusto Ceccucci²⁰, Avital Dery³⁶, Michael Dine³⁷, Svetlana Fajfer³⁸, Stefania Gori³⁷,
Gudrun Hiller³⁹, Gino Isidori²², Yoshikata Kuno⁴⁰, Alberto Lusiani⁴¹, Yosef Nir³⁶,
Marie-Helene Schune⁴², Marco Sozzi⁴³, Stephan Paul⁴⁴, Carlos Pena³¹ (*Contributors*)

Neutrino Physics & Cosmic Messengers: Stan Bentvelsen⁴⁵, Marco Zito^{46,47} (*Conveners*)
Albert De Roeck²⁰, Thomas Schwetz²⁹ (*Scientific Secretaries*)
Bonnie Fleming⁴⁸, Francis Halzen⁴⁹, Andreas Haungs²⁹, Marek Kowalski², Susanne Mertens⁴⁴,
Mauro Mezzetto⁵, Silvia Pascoli⁵⁰, Bangalore Sathyaprakash⁵¹, Nicola Serra²² (*Contributors*)

Beyond the Standard Model: Gian F. Giudice²⁰, Paris Sphicas^{20,52} (*Conveners*)
Juan Alcaraz Maestre⁶, Caterina Doglioni⁵³, Gaia Lanfranchi^{20,54}, Monica D'Onofrio²⁴,
Matthew McCullough²⁰, Gilad Perez³⁶, Philipp Roloff²⁰, Veronica Sanz⁵⁵, Andreas Weiler⁴⁴,
Andrea Wolzter^{4,12,20} (*Contributors*)

Dark Matter and Dark Sector: Shoji Asai⁵⁶, Marcela Carena⁵⁷ (*Conveners*)
Babette Döbrich²⁰, Caterina Doglioni⁵³, Joerg Jaeckel²⁸, Gordan Krnjaic⁵⁷, Jocelyn Monroe⁵⁸,
Konstantinos Petrakis⁵⁹, Christoph Weniger⁶⁰ (*Scientific Secretaries/Contributors*)

Accelerator Science and Technology: Caterina Biscari⁶¹, Leonid Rivkin⁶² (*Conveners*)
Philip Burrows²⁶, Frank Zimmermann²⁰ (*Scientific Secretaries*)
Michael Benedikt²⁰, Pierluigi Campana⁵⁴, Edda Gschwendtner²⁰, Erk Jensen²⁰, Mike Lamont²⁰,
Wim Leemans², Lucio Rossi²⁰, Daniel Schulte²⁰, Mike Seidel⁶², Vladimir Shiltsev⁶³,
Steinar Stapnes²⁰, Akira Yamamoto^{20,64} (*Contributors*)

Instrumentation and Computing: Xinchou Lou⁶⁵, Brigitte Vachon⁶⁶ (*Conveners*)
Roger Jones⁶⁷, Emilia Leogrande²⁰ (*Scientific Secretaries*)
Ian Bird²⁰, Simone Campana²⁰, Ariella Cattai²⁰, Didier Contardo⁶⁸, Cinzia Da Via⁶⁹, Francesco Forti⁷⁰,
Maria Gironi²⁰, Matthias Kasemann², Lucie Linssen²⁰, Felix Sefkow², Graeme Stewart²⁰ (*Contributors*)

Editors: Halina Abramowicz⁷¹, Roger Forty²⁰, and the Conveners



European Strategy for Particle Physics 2018-2020

Physics Briefing Book

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It is of utmost importance that both instrumentation and computing development activities be recognized correctly as fundamental research areas bearing a large impact on the final physics results.

“Physics Briefing Book Input for the European Strategy for Particle Physics Update 2020”,
 CERN-ESU-004, Chapter 11 Instrumentation and Computing, p205

regions and optimal use of resources globally

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2023 P5

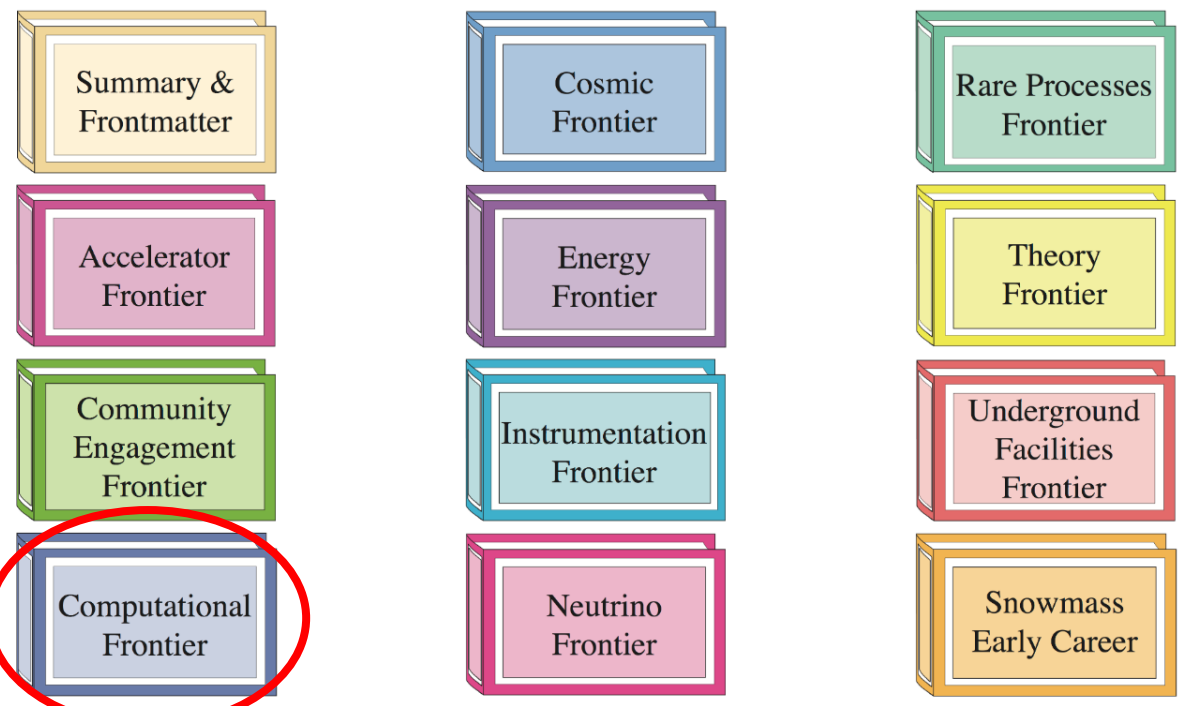
P5 (Particle Physics Projects Prioritization Panel) reports to HEPAP (High-Energy Physics Advisory Panel) that advises High-Energy Physics of DOE Office of Science and Division of Physics of NSF. We will build on the "Snowmass" community study to hash out priorities for the next 10 years within 20-year context.

<https://www.usparticlephysics.org/p5/>



The Future of HEP Software and Computing – the Snowmass report

V. Daniel Elvira (Fermilab) – CHEP 2023
 Representing my co-conveners, Ben Nachman (LBNL) and Steven Gottlieb (Indiana University), and all participants



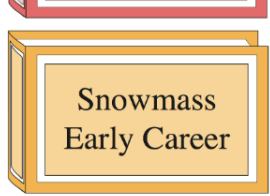
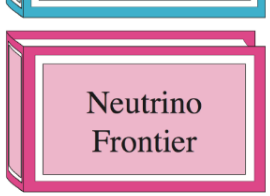
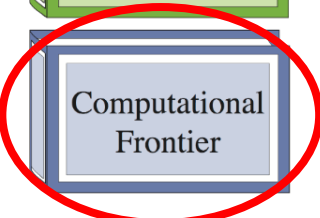
Final thoughts

- The Snowmass CompF process was a successful participative experience
 - The conveners hope the report represents the community faithfully
- Computing plays a fundamental role in the execution of current and future HEP theoretical, experimental, observational programs
 - Not a "service" but an "element" of the "scientific apparatus" in HEP experiments/surveys
- Modern computing architectures, newly established and emerging technologies are changing the way we do particle physics but also bringing transitional challenges
 - Balanced and timely support for software, from prototype all the way to deployment
 - Education, training, career paths in an inclusive, diverse and welcoming environment
- Strike a balance between R&D and improvement/maintenance of existing tools
 - Simulation common tools are underfunded
- Coordinating panel (CPSC) would play a critical role in achieving coordinated, timely, balanced, effective, sustainable investments in S&C for HEP
 - The DPF leadership plans to establish a task force with broad community representation to write a report on a proposed CPSC creation process



2023 P5 P5 (Particle Physics Projects Prioritization Panel) reports to HEPAP (High-Energy Physics Advisory Panel) that advises High-Energy P V f

Computing plays a fundamental role in the execution of current and future HEP theoretical, experimental, observational programs. — Not a “service” but an “element” of the “scientific apparatus” in HEP experiments/surveys “The Future of HEP Software and Computing — the Snowmass report”, V.Daniel Elvira (Fermilab), Ben Nachman (LBNL), and Steven Gottlieb (Indiana University) and all participants, 26th International Conference on Computing in High Energy & Nuclear Physics, May 8-12, 2023, Norfolk, USA



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总结

- 数据处理不仅仅是粒子物理实验的“工具”，是实验的重要环节
- 原始数据主要包括电子学测量的时间幅度等信息，同时包括噪声和本底，不能直接用于物理研究；需要经过数据处理，得到各个粒子的测量的物理量
- 刻度和重建算法的性能直接影响物理事例的探测性能，如探测效率和能量分辨率等
- 模拟与数据的不一致是系统误差的主要来源，利用各种方法提高模拟精度是改善物理测量精度的重要手段
- 新技术新思维将为物理研究提供更加强有力地支撑和推动

谢谢大家！