

高性能离线数据处理技术与软件以及物理模拟研究 中期检查汇报

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1: 山东大学 , 2: 郑州大学 ; 3: 中山大学

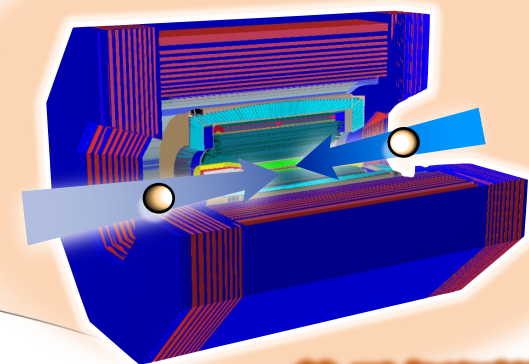
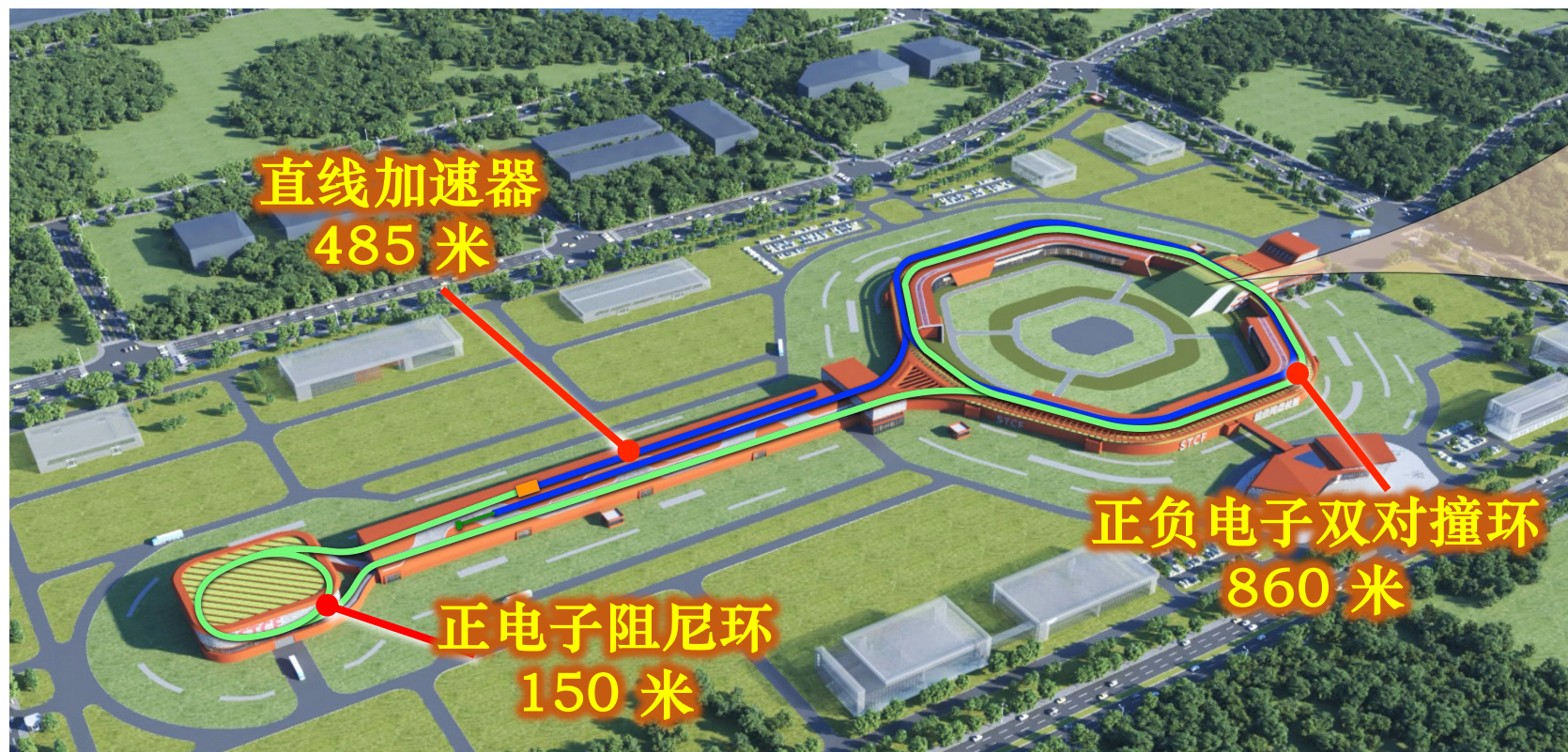
2026年9月20-21日

- 研究工作取得的突出进展或成果;
- 人才培养情况;
- 国际合作与交流情况;
- 经费使用情况;
- 总结

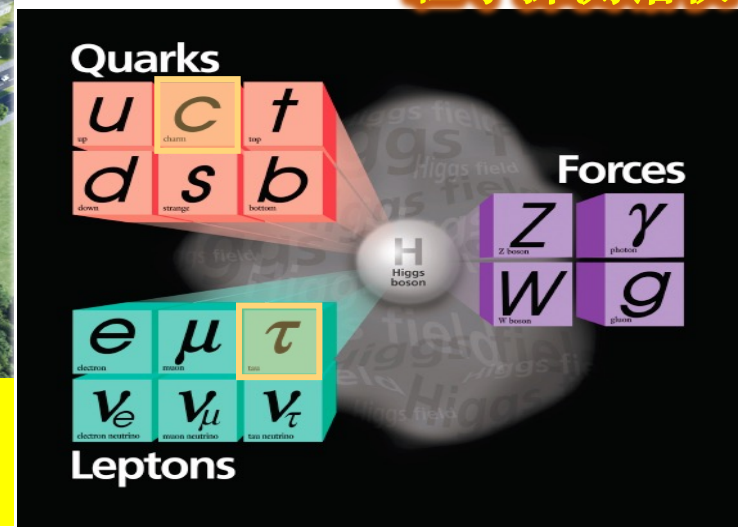
超级陶粲装置(STCF)



新一代GeV能区正负电子对撞机，国际粒子物理领域高亮度前沿核心装置，探索夸克如何构成物质和研究基本对称性的独特平台

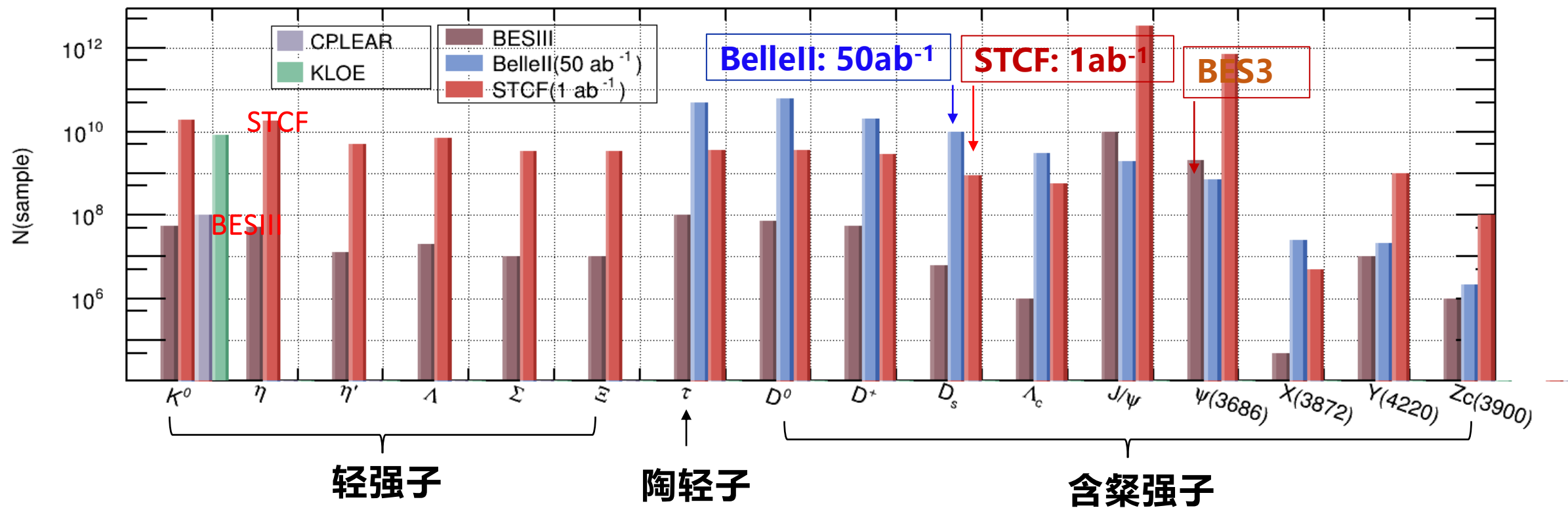


粒子探测谱仪



- 质心能量**2-7 GeV**，亮度 **$0.5 \sim 1 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$** (提升100倍)
- 两天实验 **$\approx$** 当前装置一年，对物质深层次结构解析能力提高1-2量级

STCF每年获取 1 ab^{-1} 数据，是**陶粲工厂**，同时也是**XYZ粒子**、**超子**、**轻介子工厂**

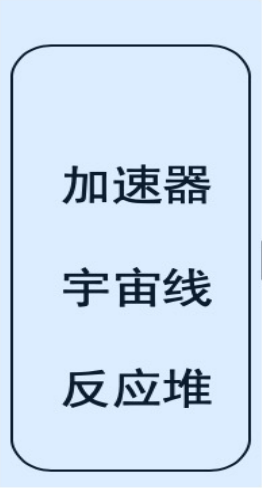


世界独特的超大数据样本 + 高分辨 + 低本底 → 高精度测量 → 重大发现

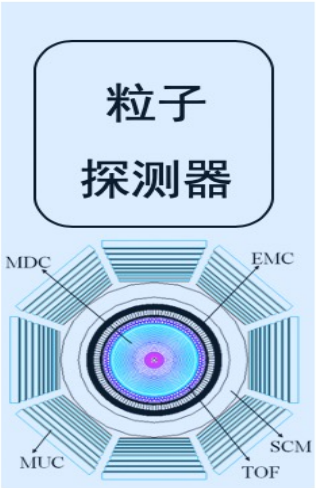
STCF超大数据对离线数据处理提出超强挑战



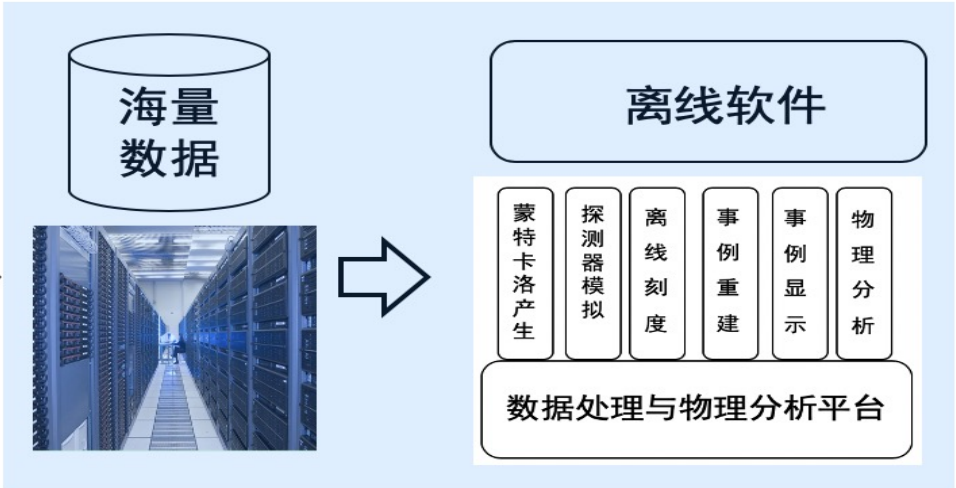
粒子源



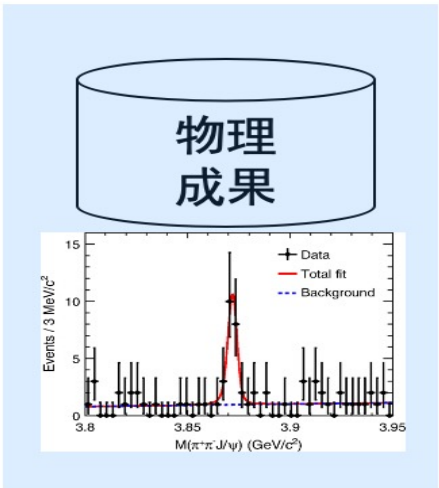
先进探测器



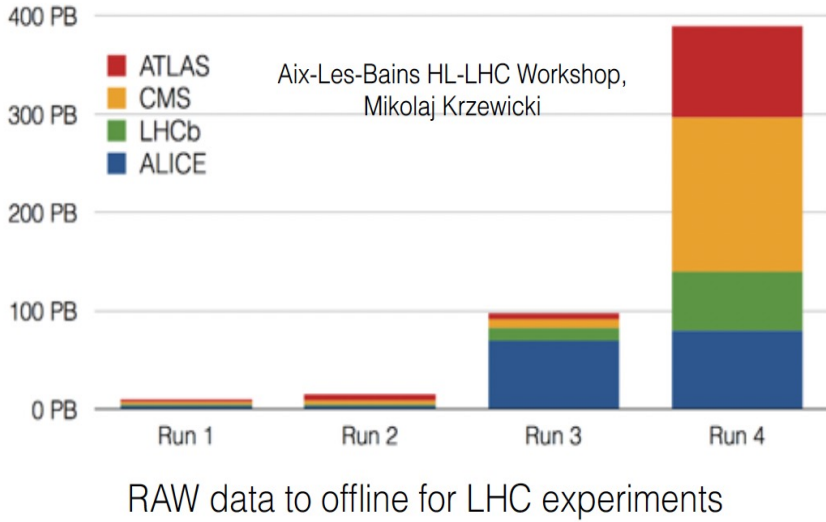
高性能计算与软件



物理分析



Experiments	Running time	Raw Data Volume (PB/Year)	Total Data Volume (PB)
BESIII	2008-2030	0.5	11
LHAASO	2019-2030	1.2	12
JUNO	2025-2035	2.0	20
STCF	-	200~300	-



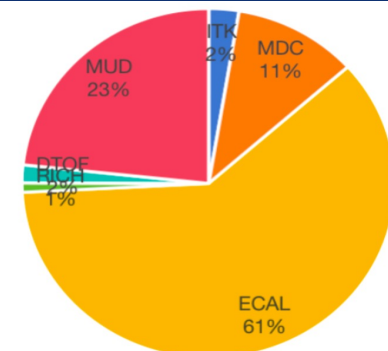
STCF超大数据对离线数据处理提出超强挑战



针对STCF具有**更高亮度、更宽能量范围、更强辐射本底、更高事例率等**,

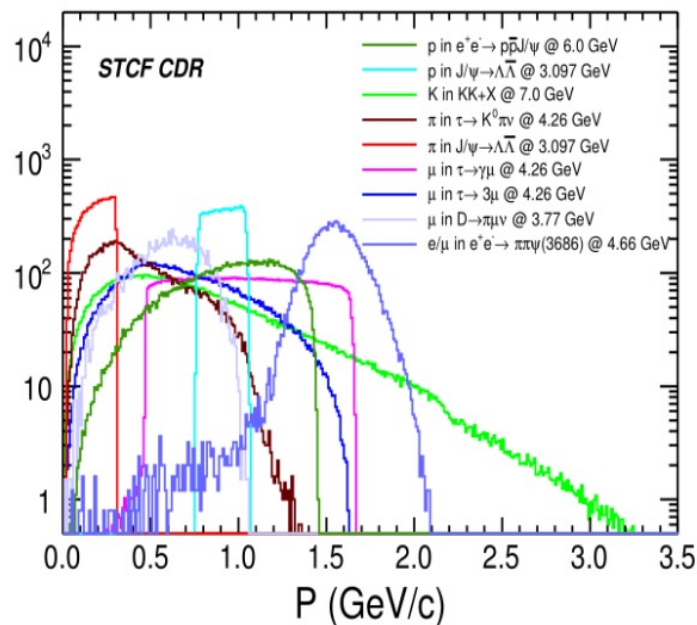
- **海量实验数据:** 每年200~300 PB
- **量能器模拟:** EMC模拟占> 50%
- **径迹重建:** 大量低动量径迹
- **粒子鉴别:** 末态粒子动量分布广

- > 先进计算技术
- > 快速模拟技术
- > 高本底重建技术
- > 强大粒子鉴别技术

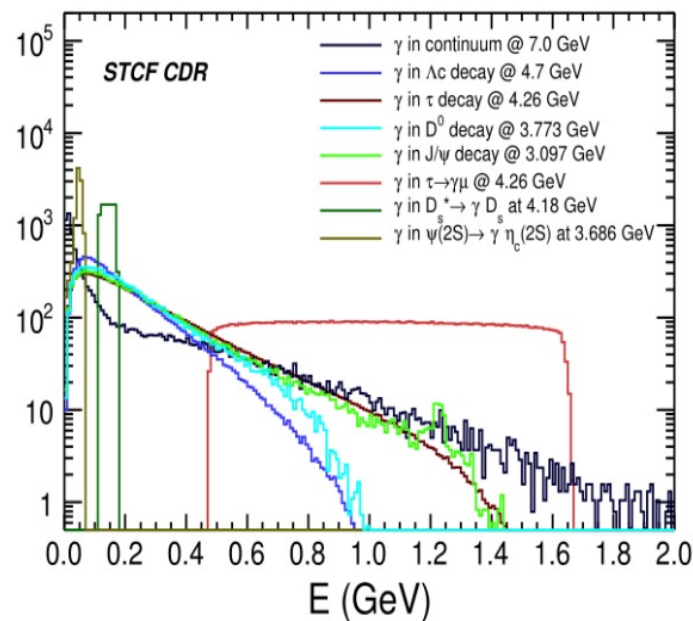


Geant4模拟耗时占比 (OSCAR 2.4.0)

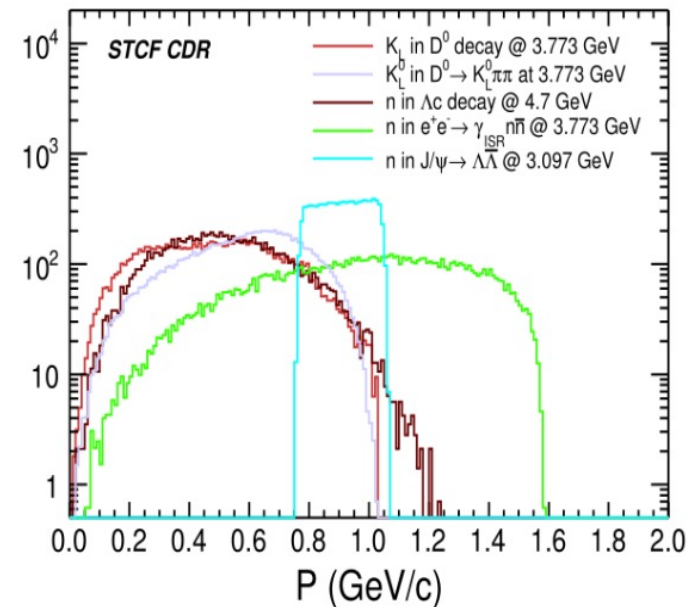
Charged particle momentum



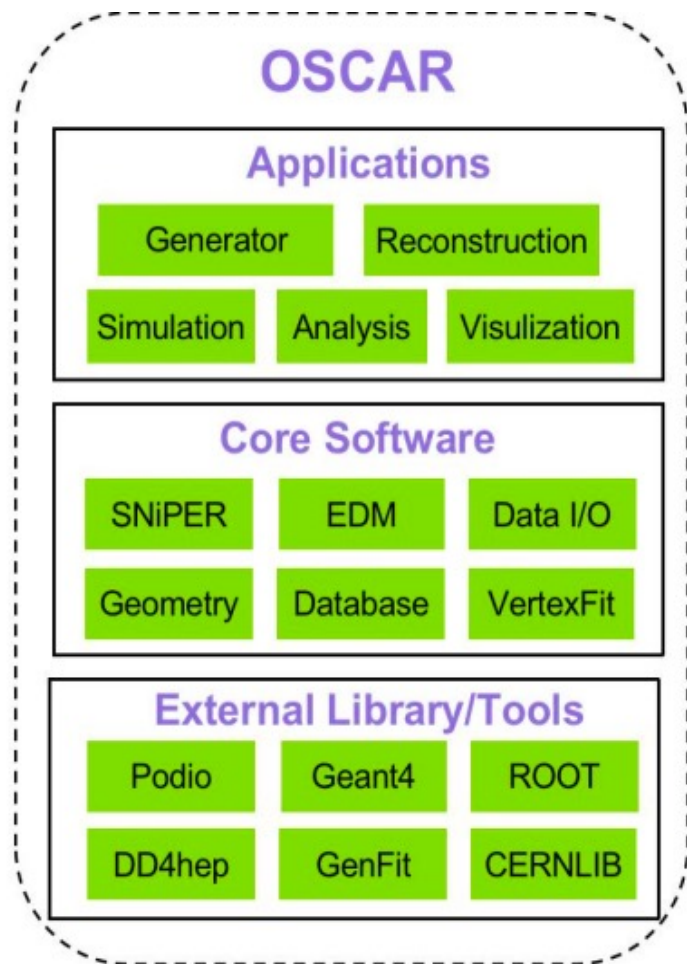
Photon energy



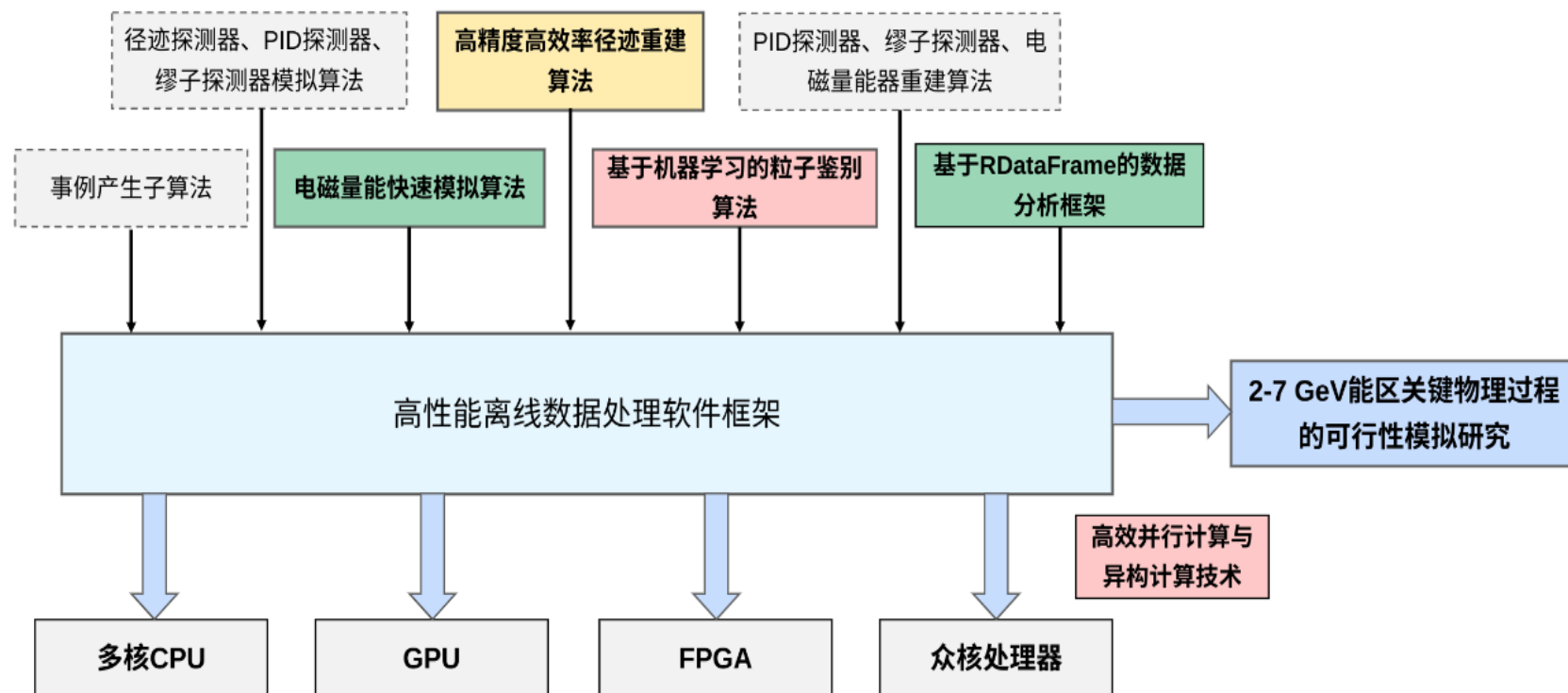
K_L, n momentum



采用我国的SNIper软件框架、以及国际先进软件与技术等**自主研发**



[W.H. Huang et al 2023 JINST 18 P03004](#)



Comput.Softw.Big Sci. 9 (2025) 1, 3
Mod.Phys.Lett.A 39 (2024) 40, 2440006
JINST 18 (2023) 03, P03004
J.Phys.Conf.Ser. 2438 (2023) 1, 012054

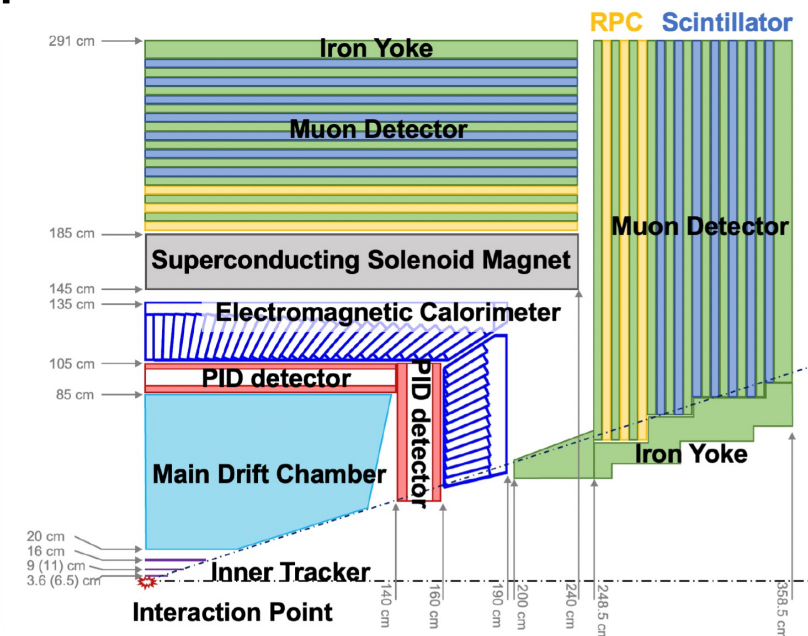
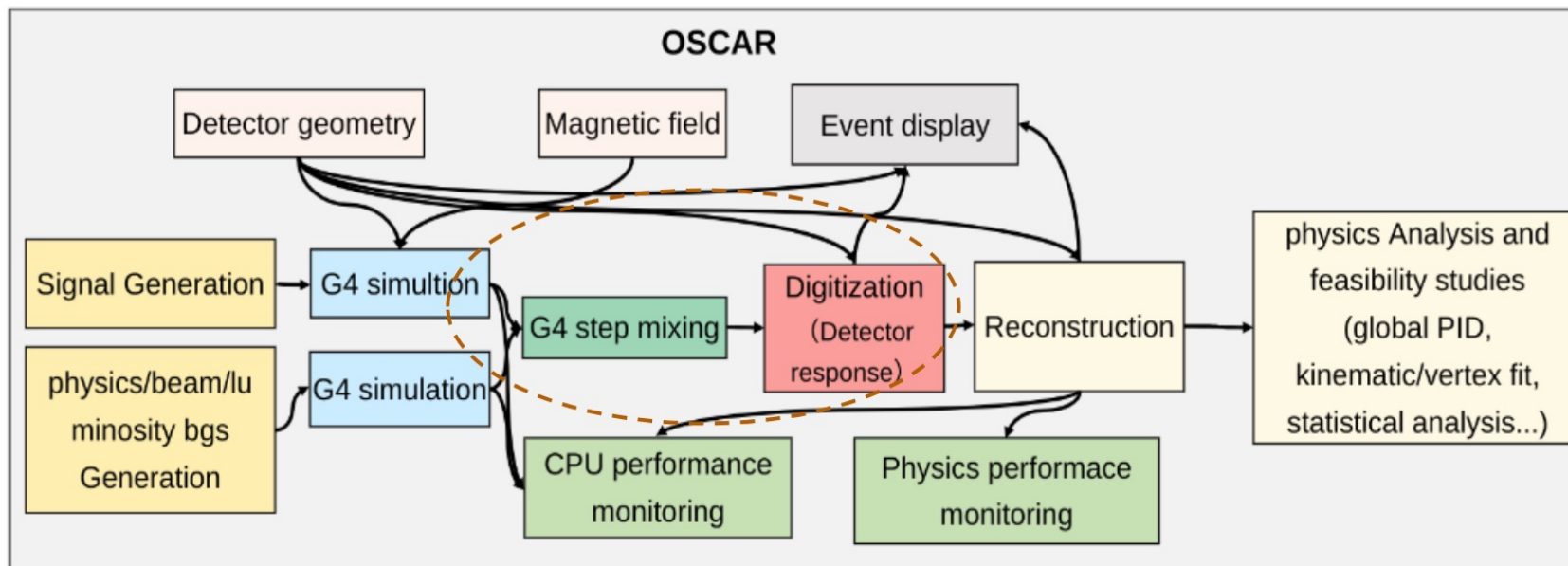
重要进展一：高性能探测器全模拟与快速模拟技术

采用国际上新兴的podio、DD4hep等先进软件与技术，研发和建立起STCF的探测器全模拟软件系统

- 实现常用事例产生子：Babayaga, KKMCM, Phokhara, DIAG36, BBBrem ...
- 支持多种探测器方案：ITK/ITM, MDC, RICH/TOF, DTOF/RICH, MUD
- 实现真实化模拟（数字化）
- 性能达到同类探测器相当水平

运行速度：~1200 ms/事例；

存储空间：J/ψ四径迹末态事例 ~110 kb/事例（分析专用数据格式可压缩至 ~4kb/事例）



基于全模拟响应性能开发出快速模拟算法

■ 采用抽样和参数化方法

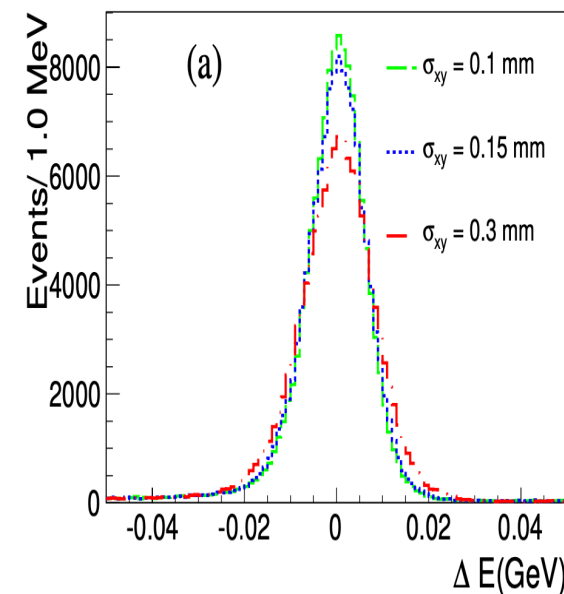
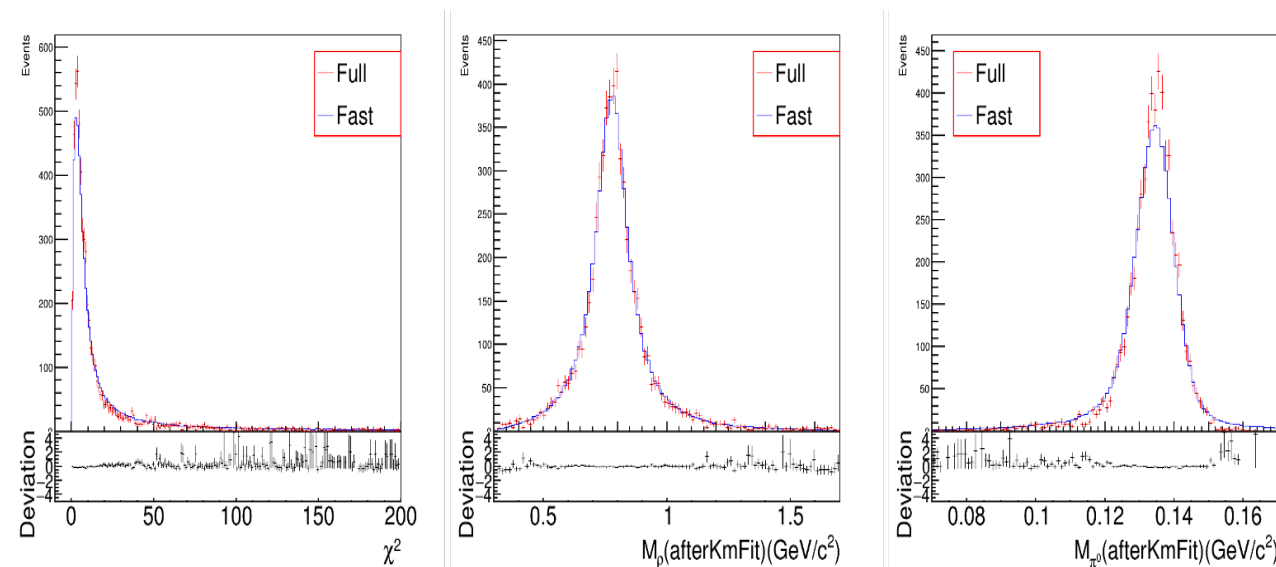
■ 速度提升 (~500倍) 和存储空间压缩 (~50倍)

- 运行速度: ~2 ms/事例
- 存储空间: J/ψ四径迹末态事例 ~2 kb

■ 通过多种性能配置优化探测器设计方案

■ 通过多个衰变道进行性能测试

- Feasibility study of $D_s^+ \rightarrow \tau^+ \nu_\tau$ decay and test of LFU with leptonic D_s^+ decays at STCF
- Sensitivity of CP violation of Λ decay in $J/\psi \rightarrow \Lambda \bar{\Lambda}$ at STCF,
- Sensitivity study of the charged lepton flavor violating process $\tau \rightarrow \gamma \mu$ at STCF
- Feasibility study of measuring $b \rightarrow s \gamma$ photon polarisation in $D^0 \rightarrow K_1(1270)^- e^+ \nu_e$ at STCF
- Feasibility study of CP violation in $\tau \rightarrow K_S \pi \nu_\tau$ decays at the Super Tau Charm Facility



基于全模拟响应性能开发出快速模拟算法

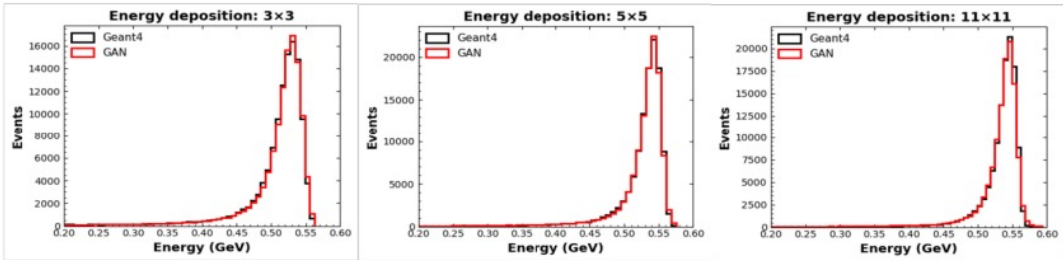
■ 基于生成对抗神经网络（GAN）开发电磁量能器快速模拟算法

■ 模拟速度相较于Geant4实现超两个数量级的提升

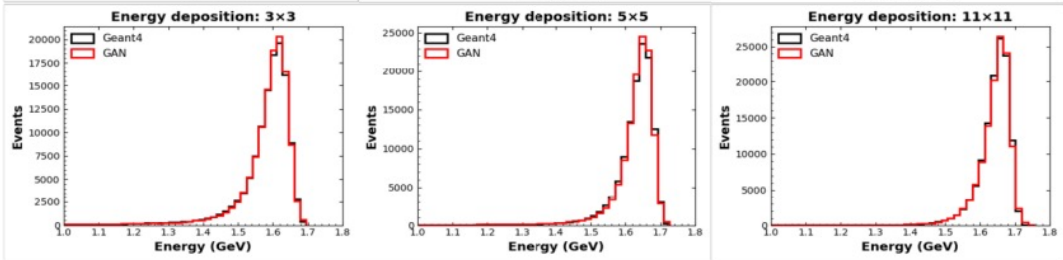
粒子类型	动量范围 (GeV/c)	Geant4速度 (ms/evt)	GAN速度 (ms/evt)	相对加速
电子	0-0.5	32.4	0.19	170.5
	0.5-1	78.3		412.1
	1-1.5	122.1		642.6
	1.5-2	178.3		938.4
光子	0-0.5	42.2	0.19	222.1
	0.5-1	45.2		237.9
	1-1.5	89.1		468.9
	1.5-2	90.3		475.3

电子模型性能

0.6GeV

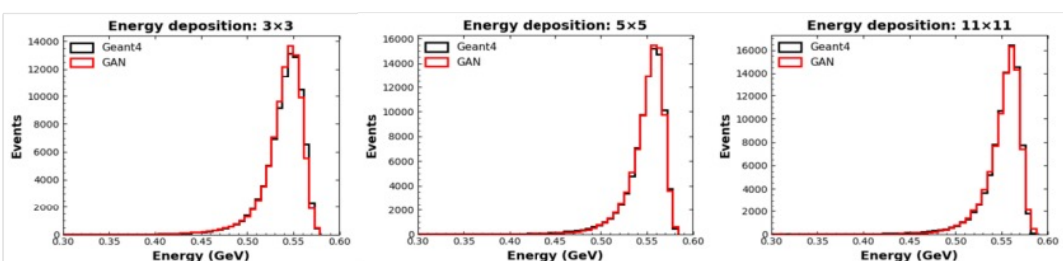


1.8GeV

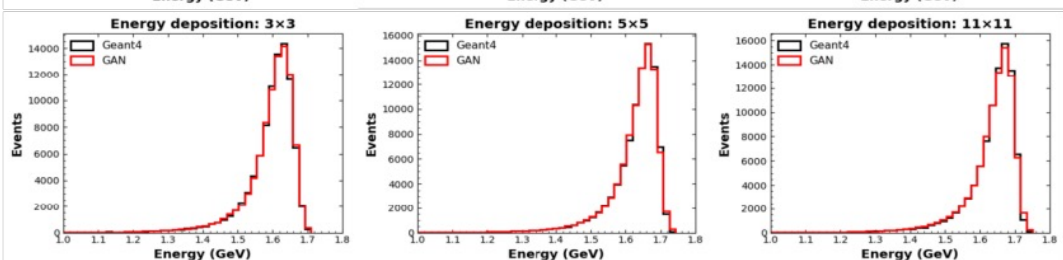


光子模型性能

0.6GeV



1.8GeV



STCF径迹重建面临的挑战

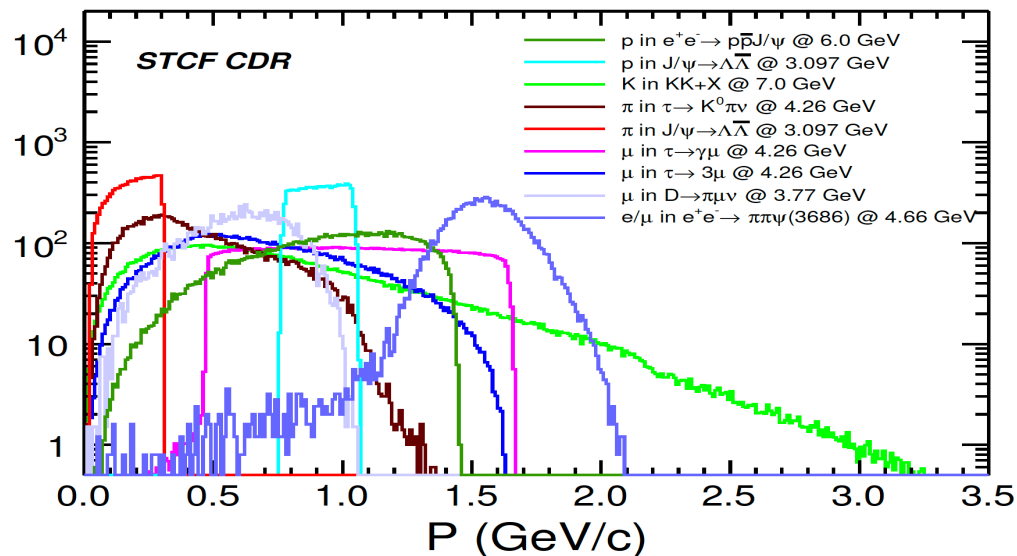
■ 丰富的物理研究对径迹重建性能的特殊需求

0.1 GeV/c以上效率高于90%，0.3 GeV/c以上效率高于99%；

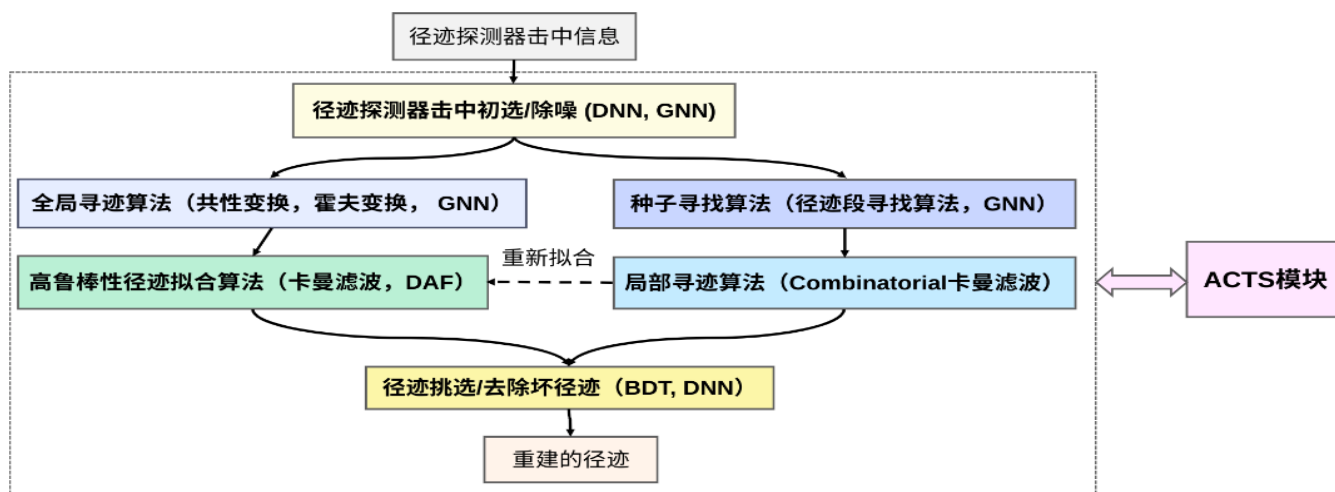
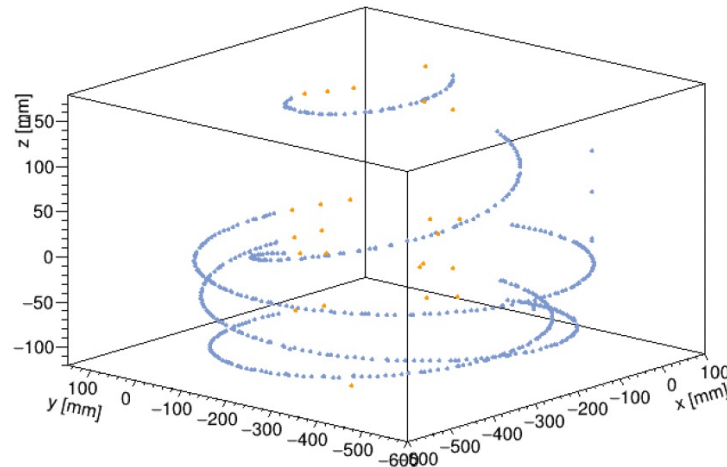
■ 高本底加大了径迹重建的难度

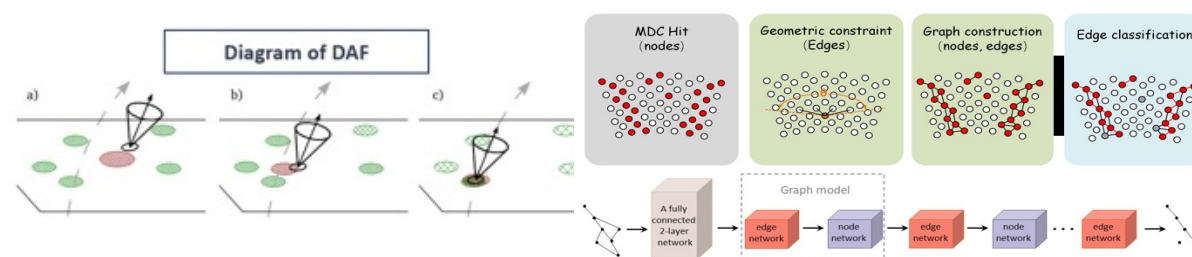
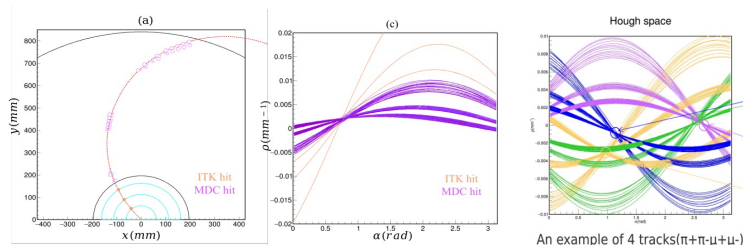
亮度相关本底、束流相关本底以及物理本底等

■ 研发多种径迹重建方法



An example of muon trajectory
($p_T = 100$ MeV, $\theta = 90^\circ$)





基于霍夫变换的全局寻迹(Hough) + 自适应的卡曼滤波(DAF in Genfit2) + 图神经网络去噪(GNN)

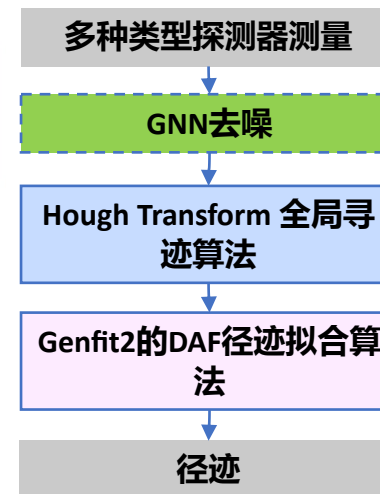
特点

覆盖全动量区间, 多径迹事例

长寿命粒子: 突破传统霍夫变换的局限

优化低动量径迹的重建效率

排除噪声击中、提升径迹分辨



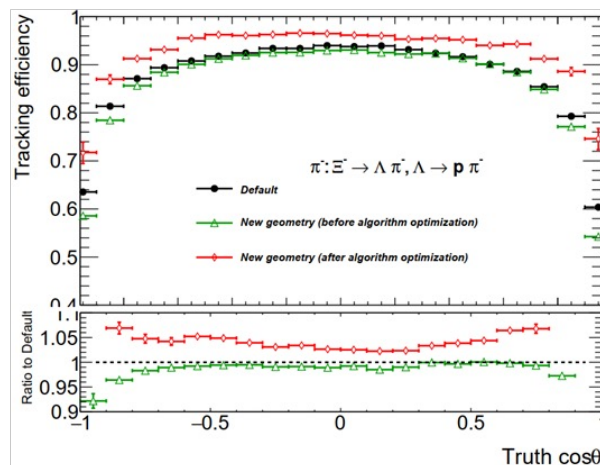
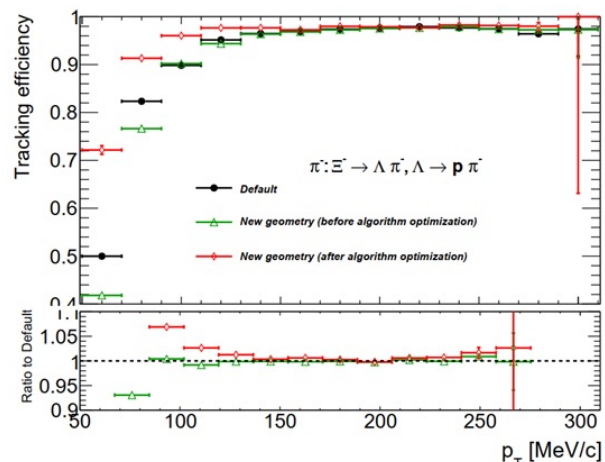
前期的重要进展:

- 与探测器设计和算法优化的深度结合: 低动量、长寿命粒子重建性能显著提升
- 更高本底情况下的方法研究: 高倍本底下重建效率稳定

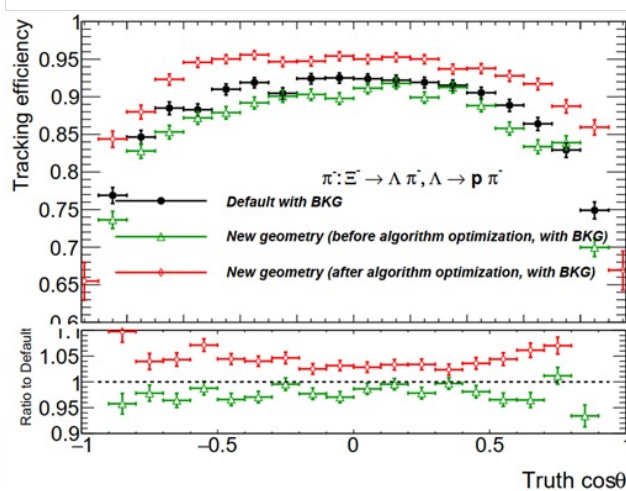
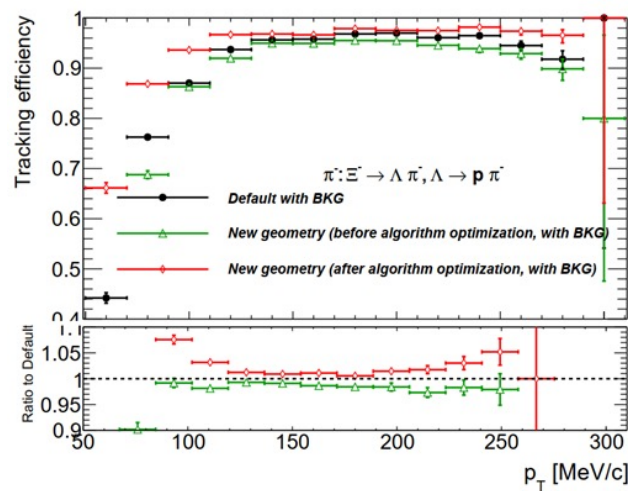
Hough变换+Genfit拟合的重建算法性能

结合探测器方案更新与算法优化，重建效率明显提升

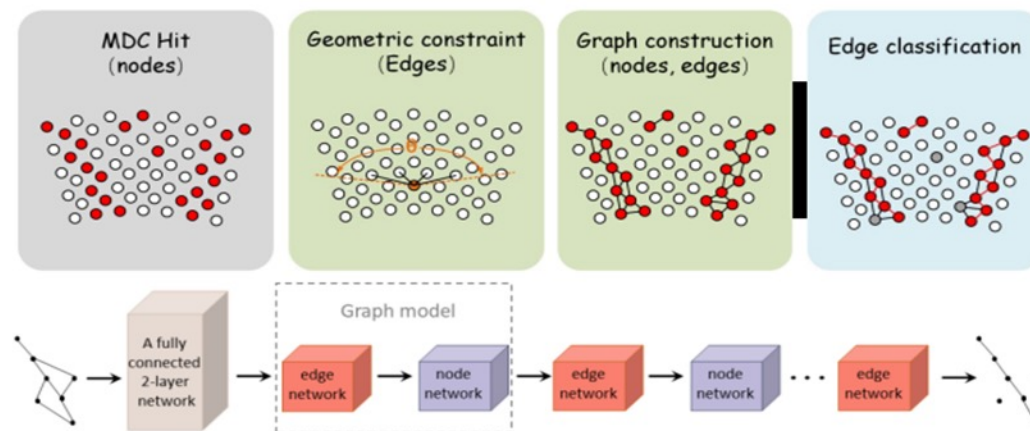
Pion from $J/\psi \rightarrow \Xi^- \bar{\Xi}^+ \rightarrow \Lambda \pi^- \bar{\Lambda} \pi^+ \rightarrow p \pi^- \pi^- \bar{p} \pi^+ \pi^+$



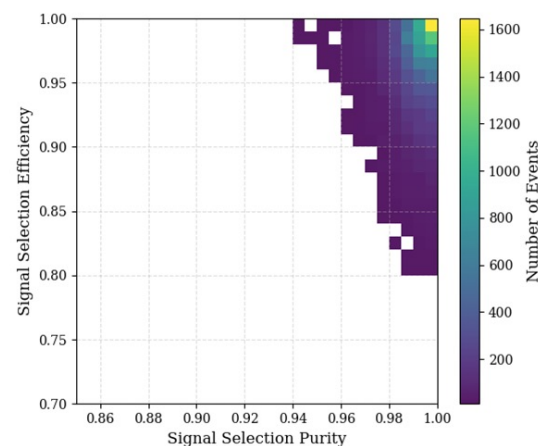
在高噪声水平下，径迹重建保持性能高水平：**displaced pion >90% @100MeV**



基于图神经网络的除噪方法在高噪声水平下展现了突出去噪能力
有望进一步提升高本底下的重建性能



测试集 $J/\psi \rightarrow \Xi^- \bar{\Xi}^+ \rightarrow \Lambda \pi^- \bar{\Lambda} \pi^+ \rightarrow p \pi^- \pi^- \bar{p} \pi^+ \pi^+$



信号挑选纯度和效率分布图

- 击中分类准确率 **98.1%**
- 信号挑选效率 **95.6%**
- 噪声移除率 **99.4%**

STCF高本底环境、大量低动量和长寿命粒子对径迹重建带来的挑战

- ACTS是国际上**新兴的通用径迹重建软件**
- 被**用于十多个**现有或未来国际实验、**良好的性能**在TeV实验和硅径迹探测器上得到**广泛验证**

开展系列基于ACTS的径迹重建方法的研究:

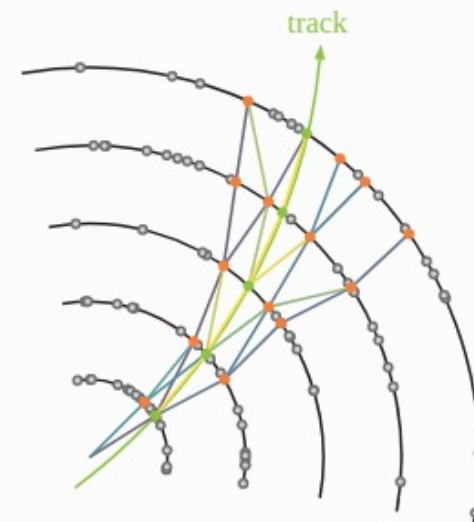
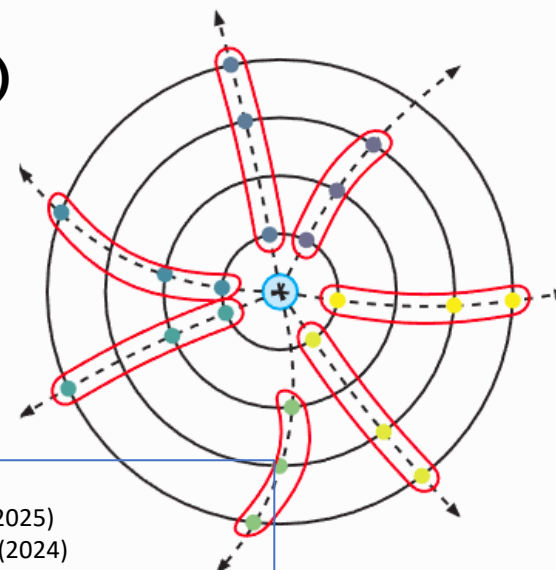
- **首次应用于**e+e-对撞机实验气体探测器 (uRWell+MDC)
- **首次验证**对于 $p_T < 200$ MeV粒子的寻迹性能
- **首次实现**全局霍夫变换和局部卡曼滤波算法的结合

Seeding

(find seeds using hits on ITk layers)

Combinatorial Kalman Filter (CKF)

(simultaneous track fitting + finding)

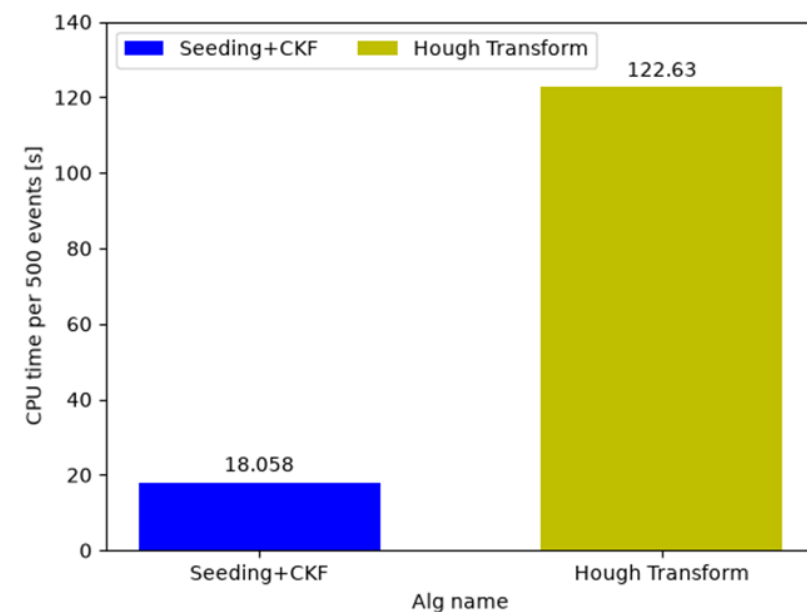
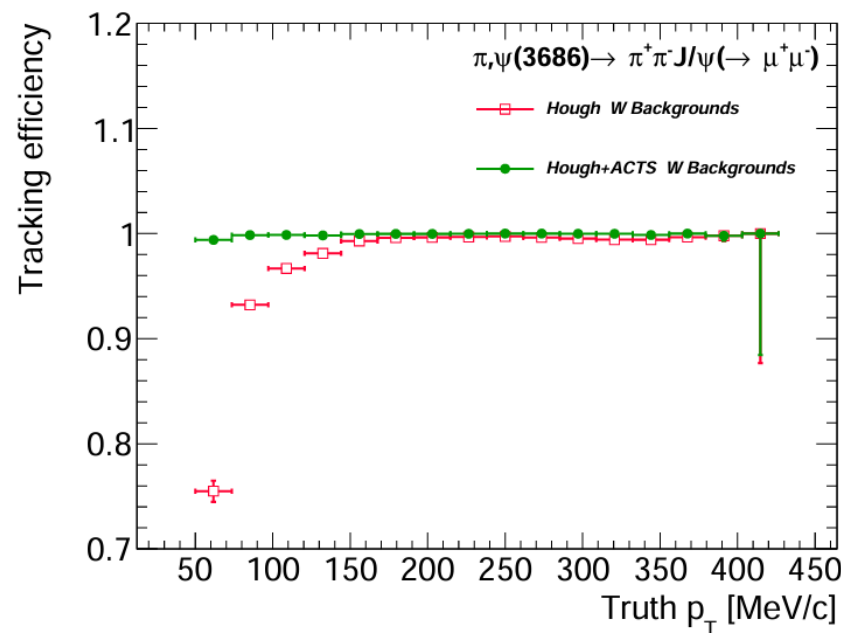
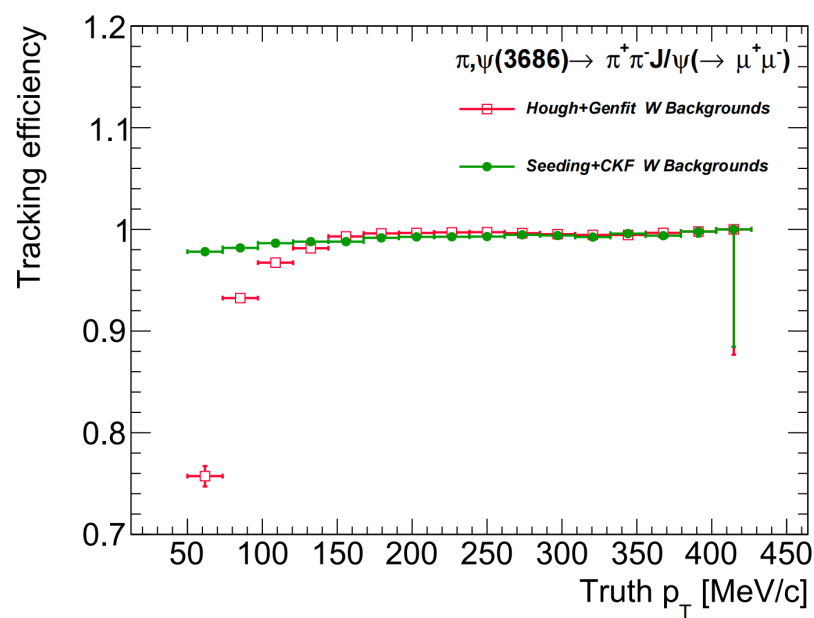


Figures from ACTS [readthedocs](#)

发表文章4篇, 并在CHEP, ACAT, CTD等国际高能物理软件和计算会议上报告多次

- H.Li et al, Studies of track finding for long-lived particles at the STCF, Nuclear Science and Techniques 36, 171 (2025)
- X. Ai, X. Huang, H. Li et al., Application of ACTS for gaseous tracking detectors. Mod. Phys. Lett. A 39, 2440009 (2024)
- Performance of Track Reconstruction at STCF Using ACTS, EPJ Web of Conferences 295, 03029 (2024)
- X. Ai, X. Huang, Y. Liu, Implementation of ACTS for STCF track reconstruction. J. Instrum. 18, P07026 (2023)

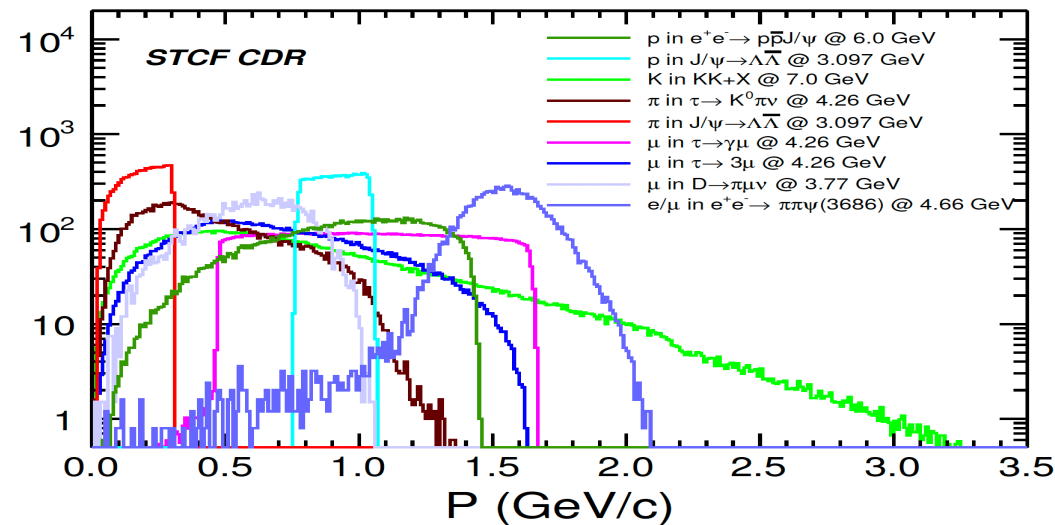
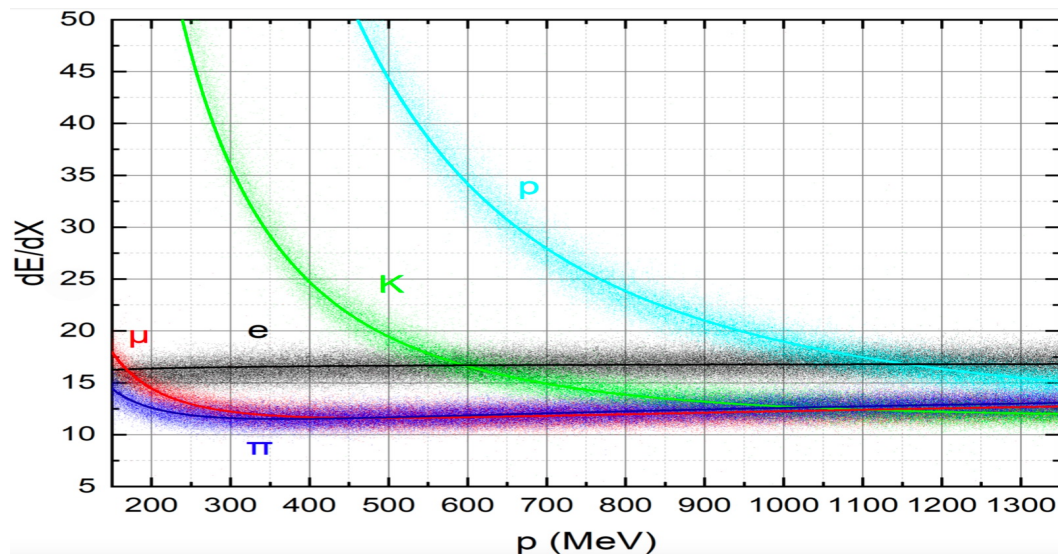
- 将ACTS中种子(triplet)寻找算法和组合卡曼滤波(CKF)算法用于STCF寻迹，实现优异的寻迹效率和速度：
 - 即便在有本底情况下，100 MeV以下的低动量粒子的tracking效率可达94%以上；速度提升6倍
- 用CKF打捞Hough无法重建的径迹，提升寻迹效率至98%以上



重要进展三：高效粒子鉴别技术的研究

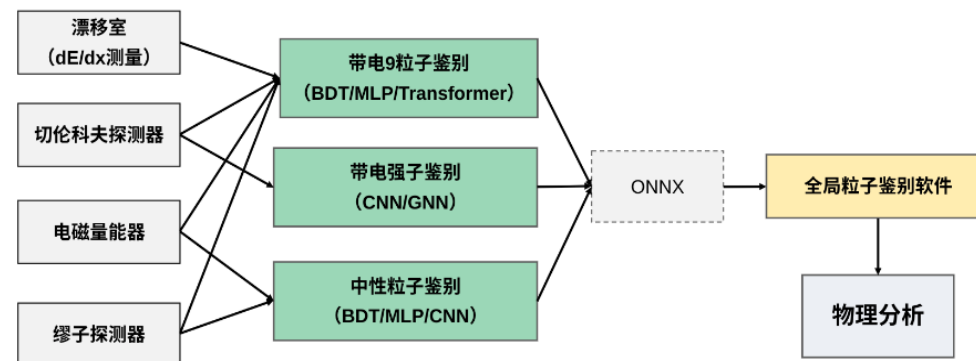
STCF对粒子鉴别提出更高要求：

- 对2 GeV/c以下 π/K 和 K/p 鉴别能力达到 3σ ,
- 对2 GeV/c以下 μ/π 误鉴别率低于3%，对 $\gamma/n/K_L$ 提供良好的鉴别能力。



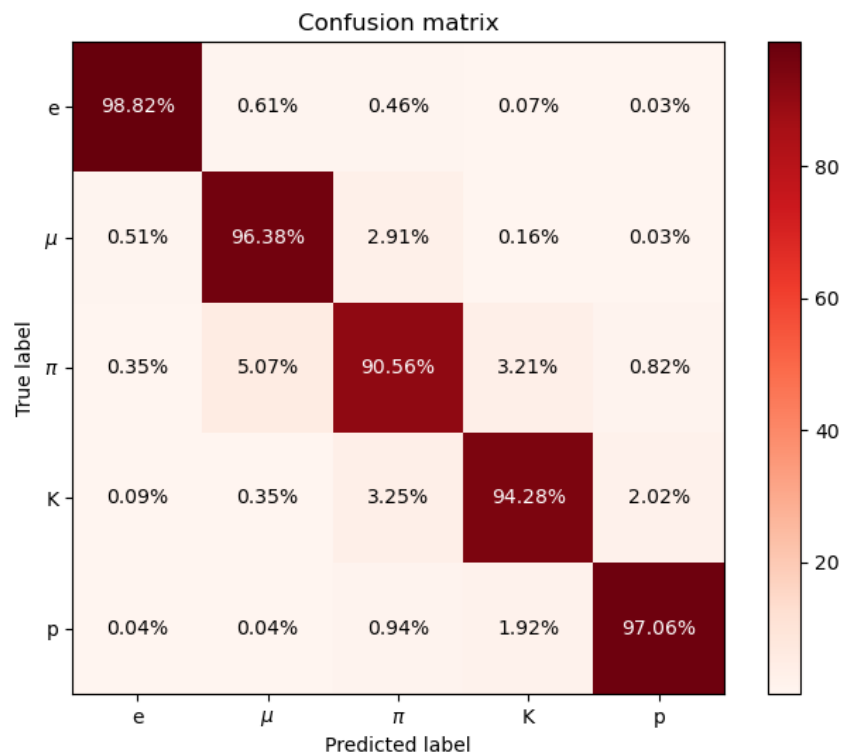
联合多个子探测器信息提高粒子鉴别能力

- 基于机器学习技术的全局鉴别算法
- 基于联合似然函数的粒子鉴别算法

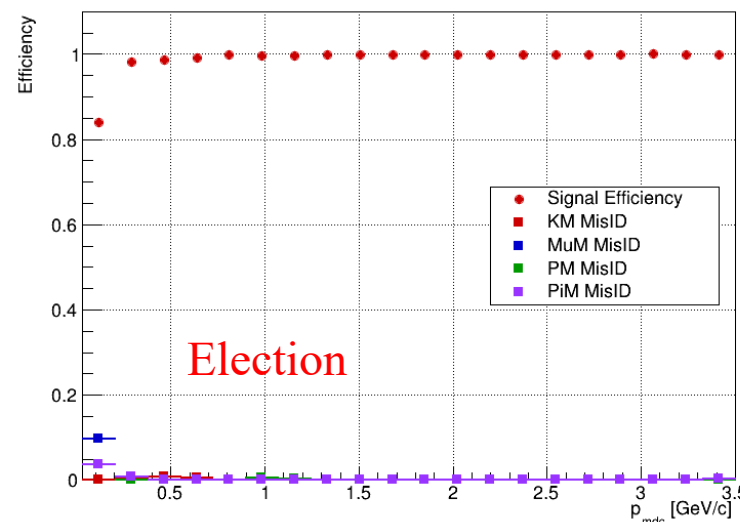
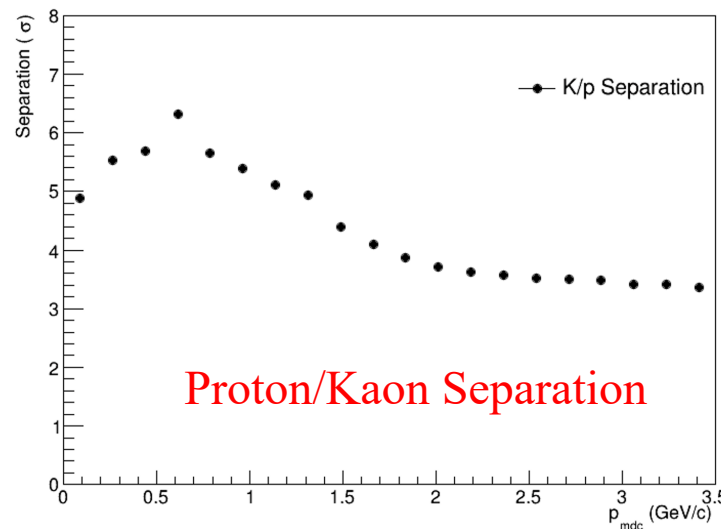
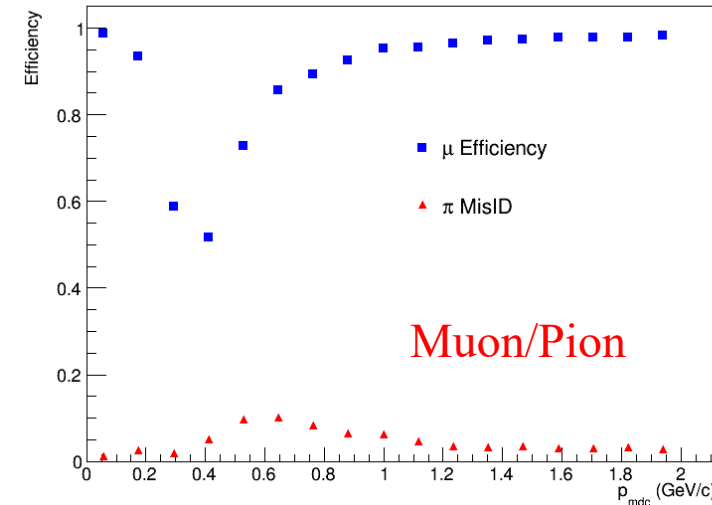
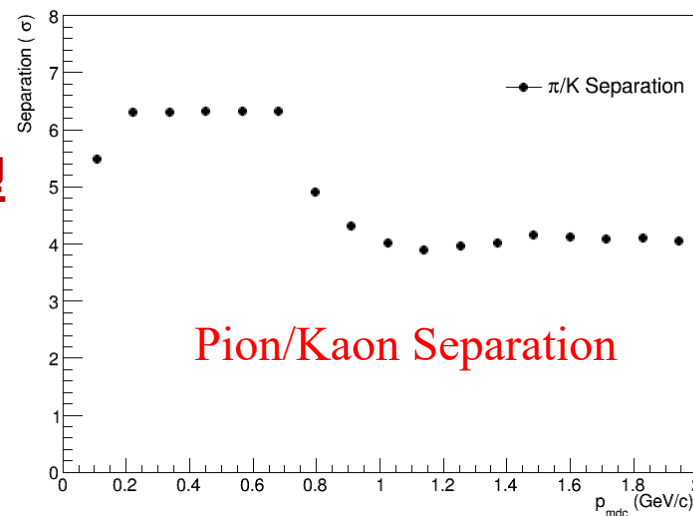


全局粒子鉴别算法研究 (GlobalPID)

- 从全部子探测器中提取特征量，训练BDT模型实现优于任意单个探测器的粒子鉴别性能



带电粒子鉴别混淆矩阵



Zhai Yuncong, et al. "Particle Identification Algorithms Based on Machine Learning for STCF." (2024) (ICHEP 2024)

Zhai, Yuncong, et al. "Particle identification algorithms based on machine learning for STCF." *Modern Physics Letters A* 39.40 (2024): 2440011.

- **联合所有探测器重建输出likelihood**，实现e/mu/pi/K/p五种带电粒子有效鉴别
- **根据不同探测器对不同粒子的鉴别能力，分别对不同likelihood设置不同权重**，实现性能提升

- **dE/dx测量**

- 五种粒子假设下的卡方值: $\chi_h^2 = \frac{\left(\frac{dE}{dx} - \left(\frac{dE}{dx}\right)_h\right)^2}{\sigma_h^2}$
- Likelihood: $\mathcal{L}_{dEdx} = e^{-\frac{\chi^2}{2}}$

- **PID探测器**

- 五种粒子假设下的likelihood: $\mathcal{L}_{PID}$

- **ECAL鉴别电子**

- BDT模型，鉴别为电子概率: P_e
- Likelihood: $\mathcal{L}_{ECAL} = \begin{cases} P_e, & \text{for electron} \\ 1 - P_e, & \text{for others} \end{cases}$

- **MUD鉴别缪子**

- BDT模型，鉴别为缪子概率: $P_{mu} = \frac{BDTExp+1}{2}$
- Likelihood: $\mathcal{L}_{MUD} = \begin{cases} P_{mu}, & \text{for muon} \\ 1 - P_{mu}, & \text{for others} \end{cases}$

- **Combined likelihood**

$$\mathcal{L}_h = \prod_{\text{det}} \mathcal{L}_{\text{det},h}^{w_1}$$

权重

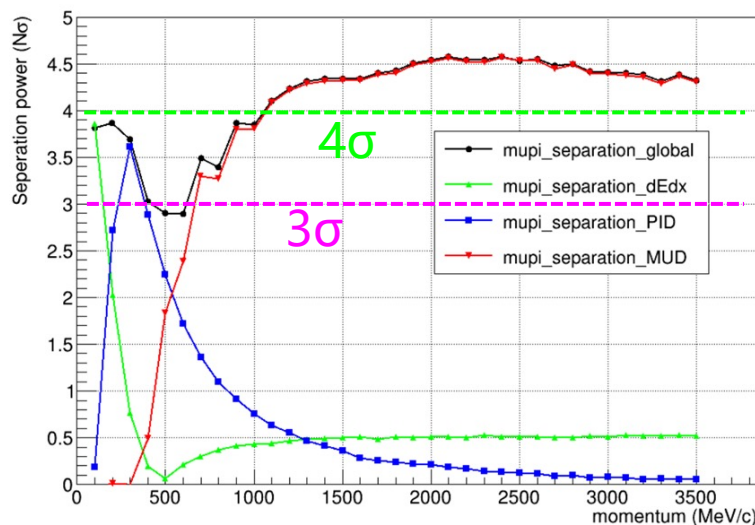
- **Likelihood ratio**

$$p(h) = \frac{P_{\text{prior},h} \mathcal{L}_h}{\sum_h P_{\text{prior},h} \mathcal{L}_h}$$

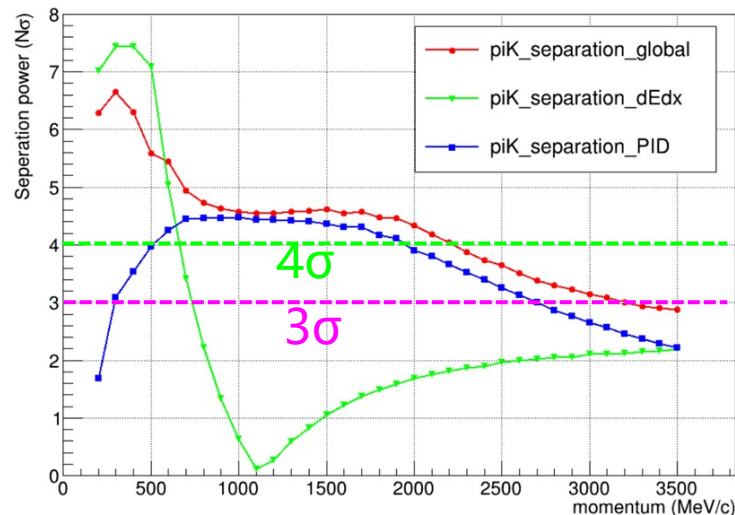
先验概率，即待测样本
不同粒子比例

当 $p(a) = \max\{p(h)\}$ 时，粒子鉴别为a

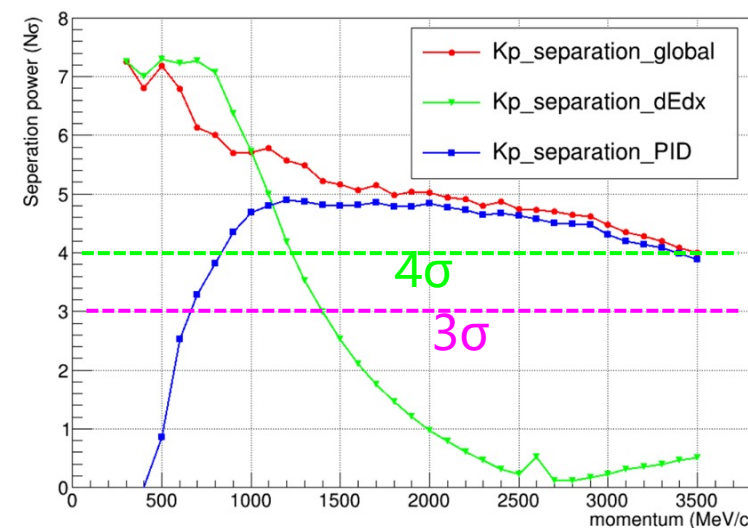
μ/π 鉴别



π/K 鉴别



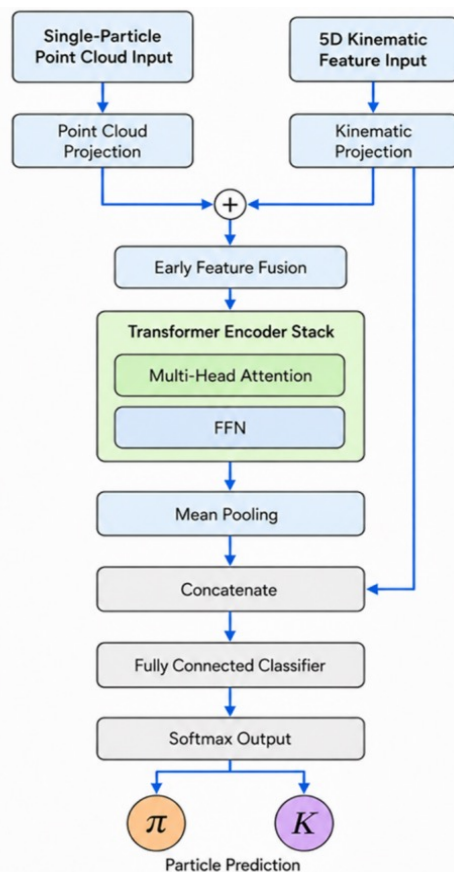
K/p鉴别



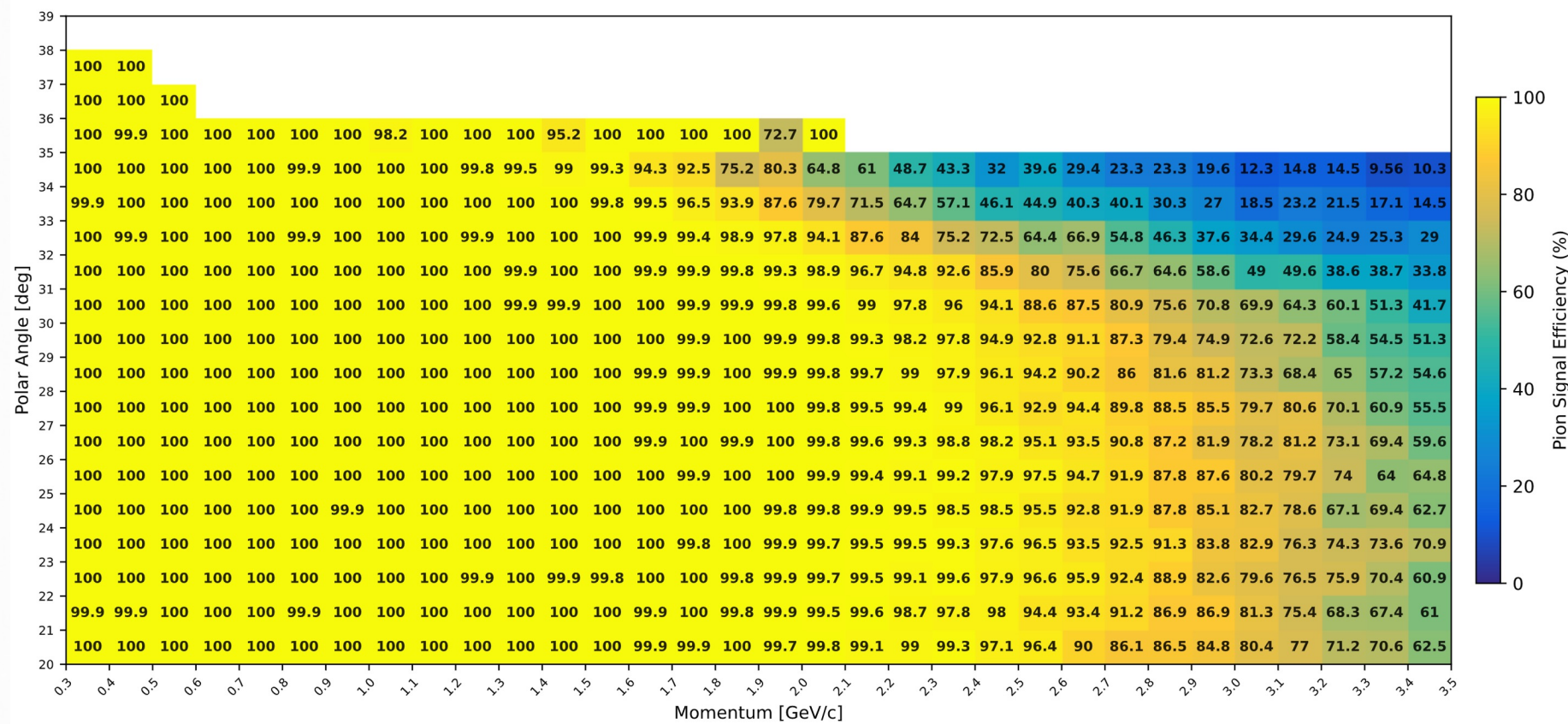
- μ/π separation: $N\sigma > 3$ across nearly almost all momenta
- π/K separation: $N\sigma \approx 4$ @ $p = 2.2$ GeV/c; $N\sigma \approx 3$ @ $p = 3.5$ GeV/c
- K/p separation: $N\sigma \approx 4$ @ $p = 3.5$ GeV/c

基于深度学习的强子鉴别技术研究

- 基于**CNN/Transformer**等深度学习模型，直接分析PID探测器切伦科夫光子分布，充分挖掘探测器性能，实现**高性能强子鉴别**



PID-B上的Transformer鉴别模型



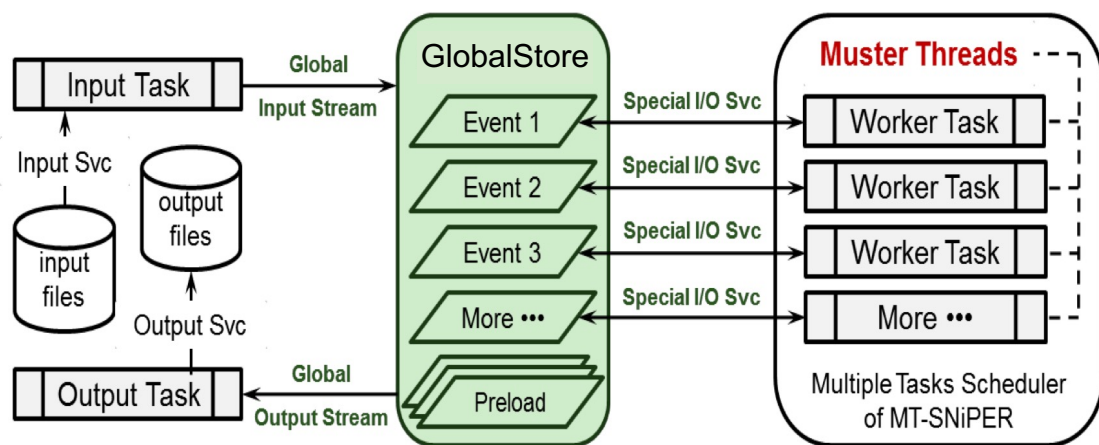
PID-B上的pion/kaon鉴别性能

重要进展四：基于高效并行计算离线数据处理技术

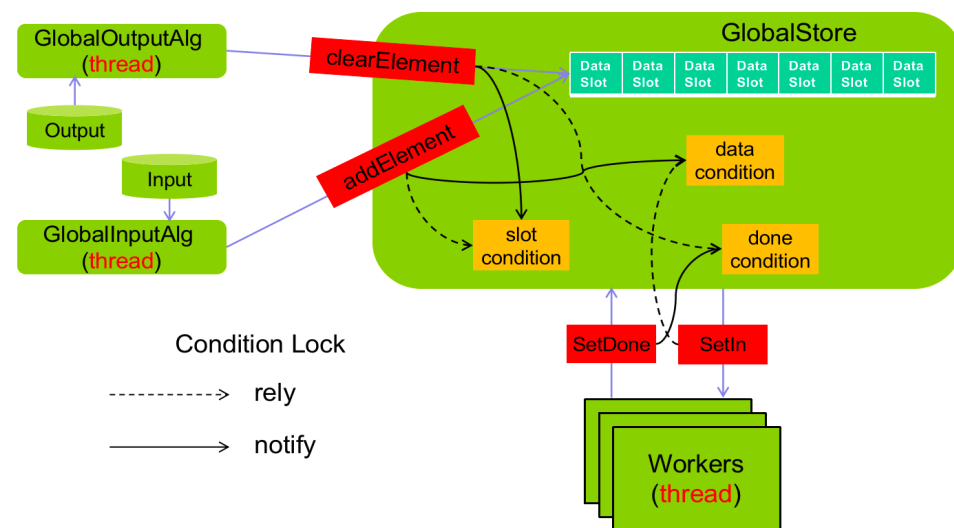
新型计算机硬件架构（多CPU、GPU）的快速发展为助力计算速度实现数量级的提升

传统的高能物理软件架构亟需发展和改进，特别是框架软件

- 扩展SNIper框架以及数据模型（EDM），实现高效并行的数据处理，显著提升STCF数据处理效率
 - 基于TBB扩展SNIper框架，实现数据处理流程并行管理和控制（MT-SNIper）
 - 重新实现podio::EventStore，实现并行化的事例数据管理
 - 使用户仅需通过更改作业配置切换串行/并行运行模式，实现高度透明的设计



基于TBB的MT-SNIper设计



扩展podio开发GlobalStore实现并行数据管理

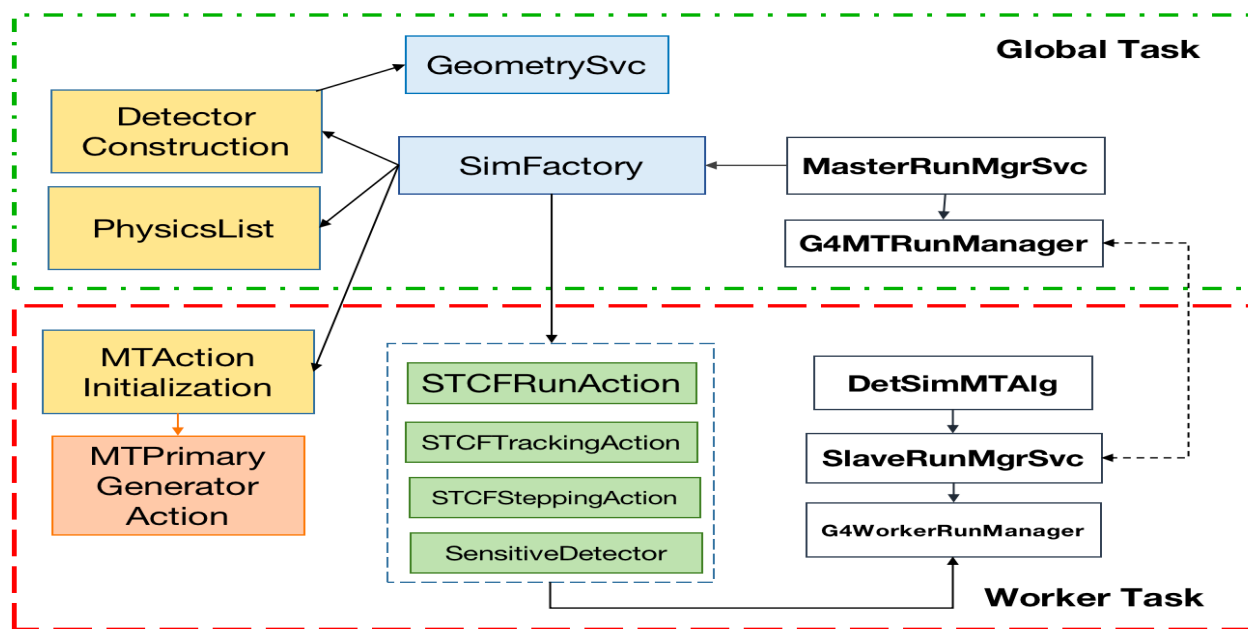
重要进展四：基于高效并行计算离线数据处理技术

将MT-SNiPER以及GlobalStore应用于OSCAR系统，实现并行化的探测器模拟和重建软件

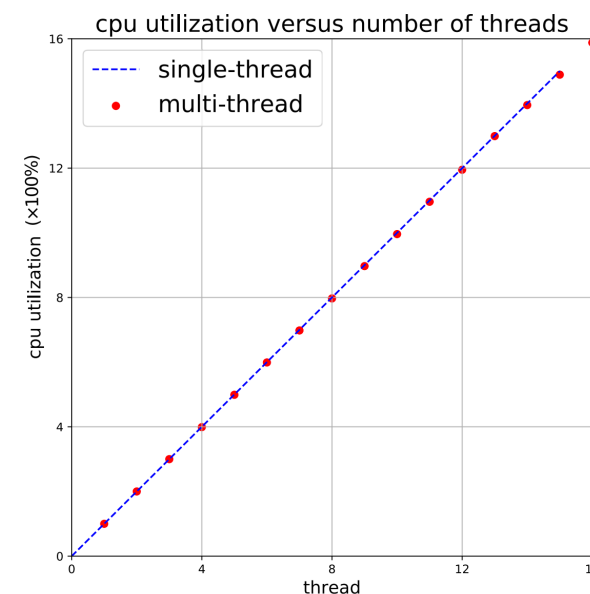
■ 开发事例间并行探测器模拟软件（事例内并行模拟软件正在开发中）

- 通过多线程共享探测器几何、物理列表、I/O缓存节省整体内存消耗

■ 初步性能测试显示出良好的性能以及可扩展性



并行化的探测器模拟软件



并行运行加速效果

Q. Q. Shi et al., *Parallelized Event Data Management System Based on MT-SNiPER Framework and PODIO* Comput.Softw.Big Sci. 9 (2025) 1, 3

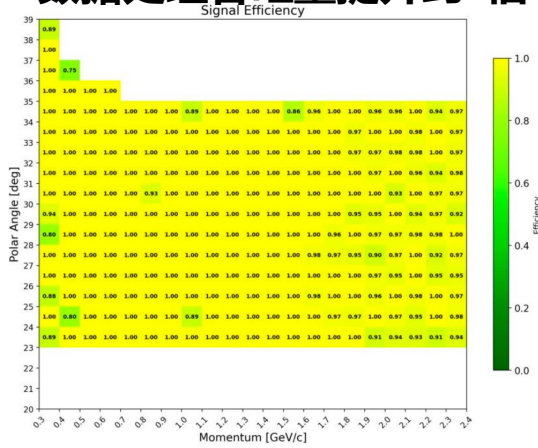
Teng Li et al., *Core software for the super tau-charm facility*, Mod. Phys. Lett. A 39 (2024) 40, 2440012

重要进展四：基于异构计算离线数据处理技术

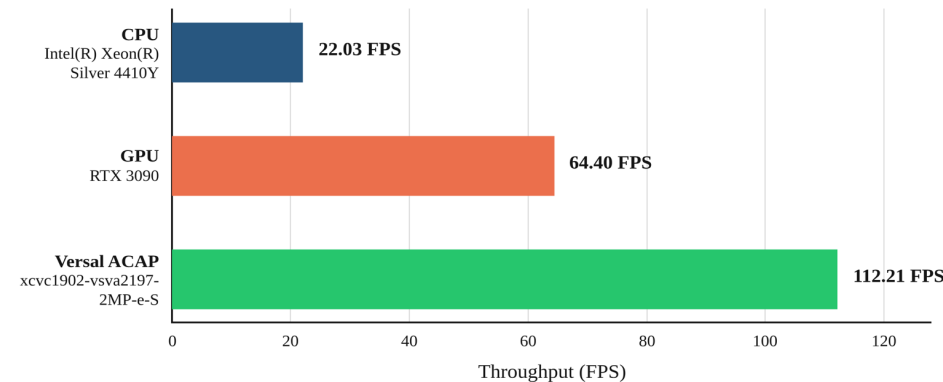


新型**异构计算架构**（CPU、FPGA、GPU、DPU）的快速发展助力提升数据处理速度，推动数据处理范式更新，**高能物理软件算法在异构计算平台的部署亟需发展和改进**

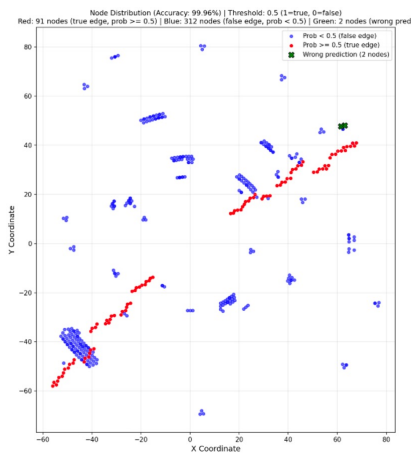
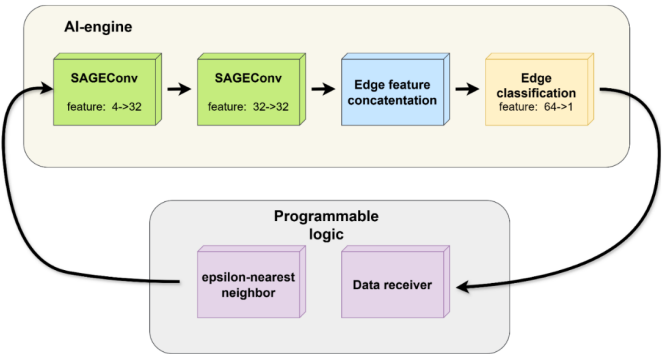
基于CNN的 π/K 鉴别算法在DPU上部署，较GPU数据处理吞吐量提升约2倍



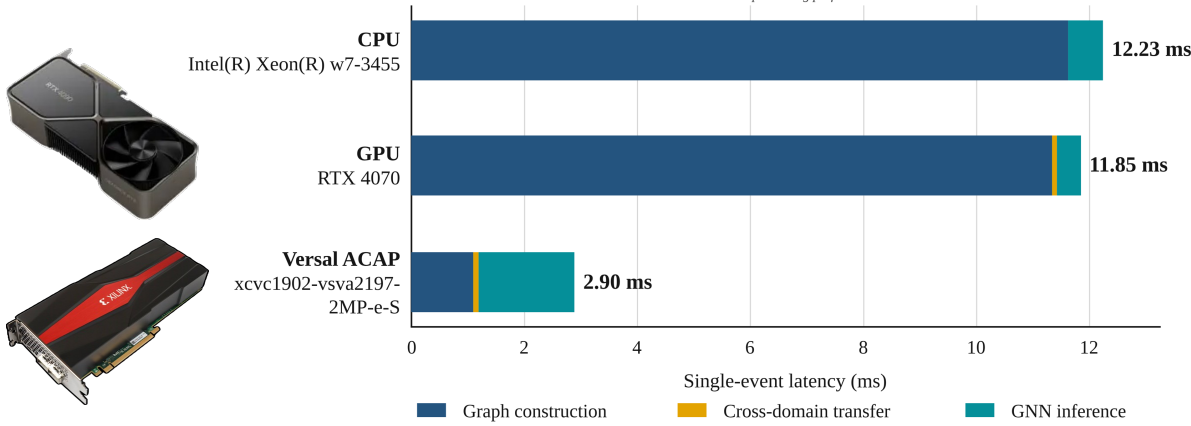
CNN inference throughput
CNN inference performance



实现基于GNN除噪算法在Versal ACAP上的部署，较GPU推理时延提升约4倍



Equivalent event-processing latency: CPU, GPU, and Versal ACAP
GNN event-processing performance

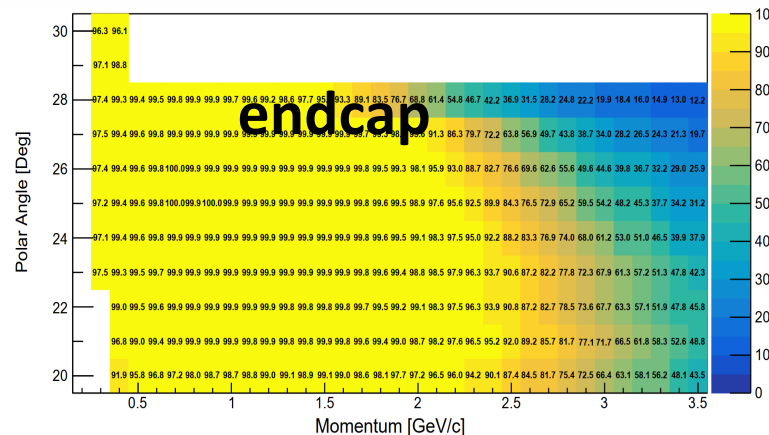
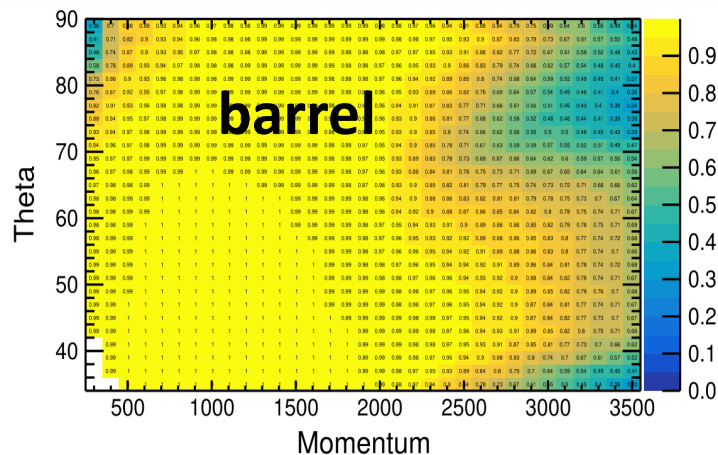


重要进展五：基于全模拟探测器方案的性能研究

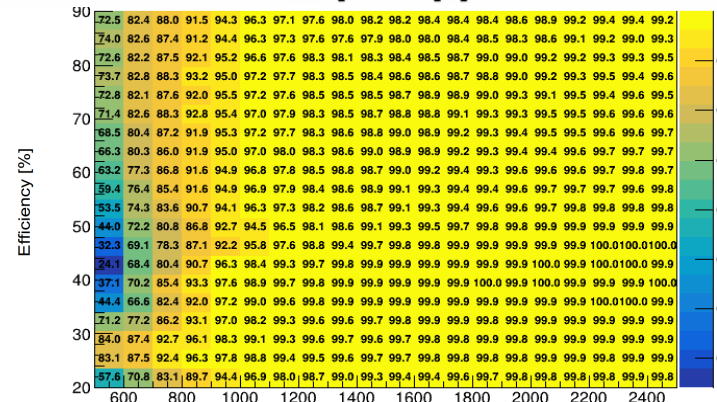


在OSCAR全模拟软件框架下，对STCF各探测器的预期性能进行了全面的研究和分析，改进了探测器的设计方案

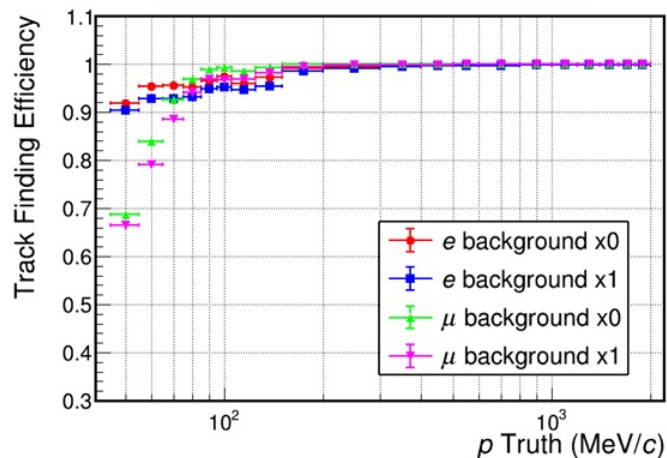
PID: $\pi/K \sim 4\sigma$ @ 2 GeV



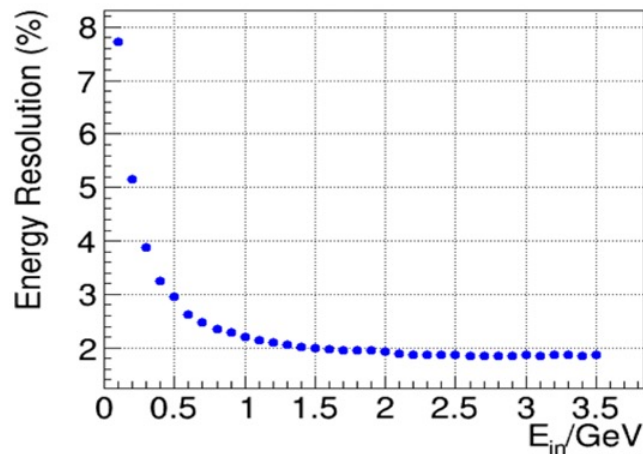
Muon ID eff. @ pi suppression=30



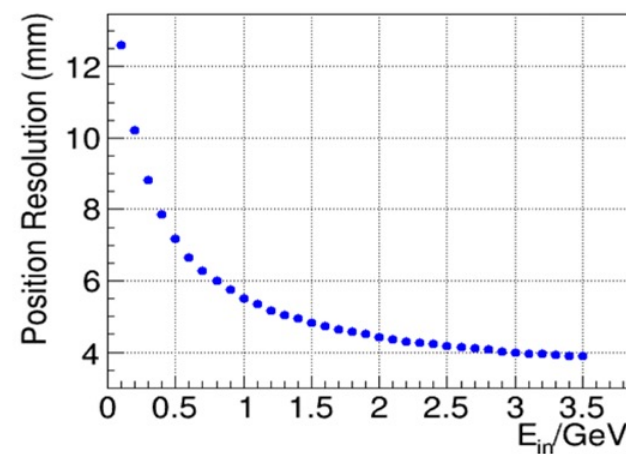
Tracking efficiency



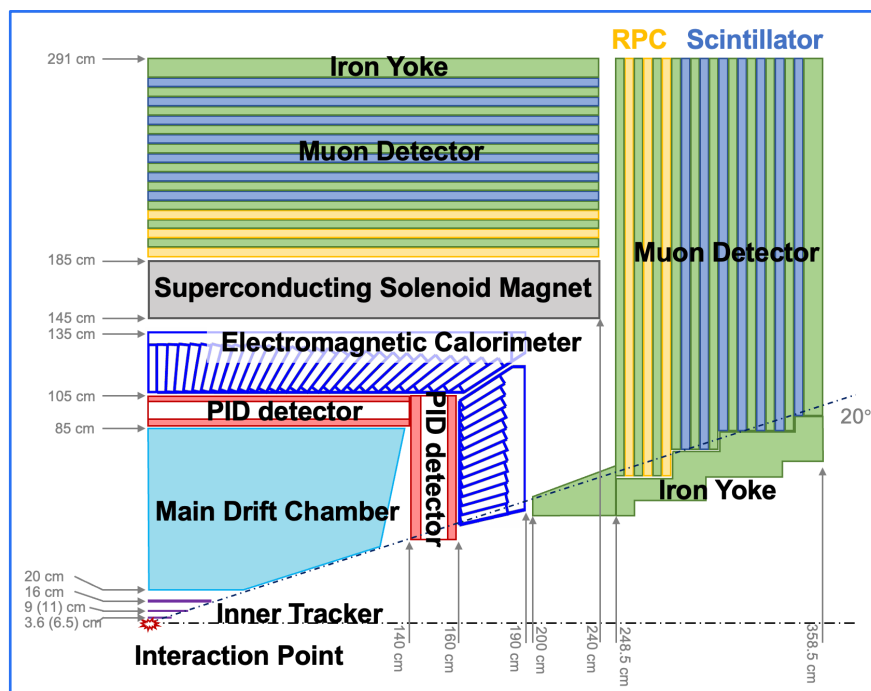
EMC energy resolution



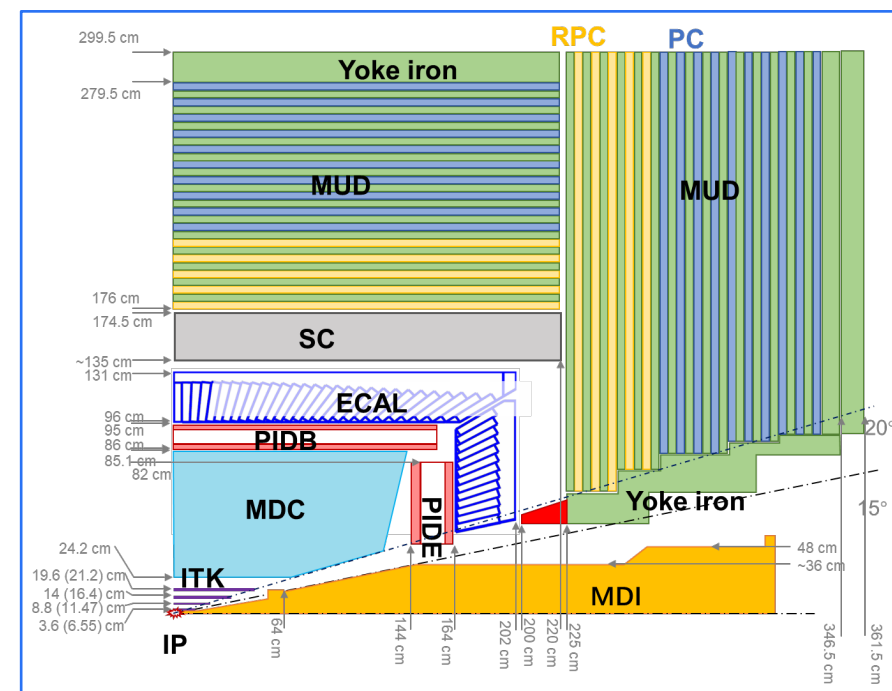
EMC position resolution



在OSCAR全模拟框架下，通过优化探测器几何设计，显著提升了STCF各子探测器在高本底环境下的预期性能。



CDR版本



当前版本

- **Tracker:** ITK 3 $\rightarrow$ 4 layers; MDC 48 $\rightarrow$ 42 layers (remove innermost & rearrange rest) .
- **PID & ECAL:** barrel longer & narrower (PID: RICH $\rightarrow$ BTOF; ECAL: +2 crystal rings)
endcaps narrower & outward (PID: RICH/DTOF/ASHIPH; ECAL: rearranged)
- **MUD:** 3 RPC + 7 PS $\rightarrow$ 5 RPC + 10 PS.

重要进展五：基于全模拟和快模拟软件已开展的全模拟物理过程

STCF

基于开发的**OSCAR全模拟软件平台**，对关键物理过程开展全模拟研究，优化探测器软件性能，保证物理目标的可行性。

基本对称性检验

物理目标	物理过程	性能检验
超子CP破坏和EDM研究	$J/\psi \rightarrow \Lambda \Lambda^-, \Xi^+ \Xi^-$	径迹重建和分辨, 顶点拟合
陶轻子物理 (EDM, 量子关联, 稀有衰变)	$\tau \rightarrow \pi(\pi\pi^0)\nu$	粒子鉴别, π^0 重建
	$\tau \rightarrow 3\mu$	π/μ 鉴别
	Radiative decay	光子重建
中性粲介子混合、衰变强相位	C-even correlated DD^-	D介子标记, 光子/ π^0 重建
Λ_c^+ 衰变中的CP破坏研究	$\Lambda_c^+ \rightarrow \Lambda K^+, \Sigma^0 K^+, \Sigma^+ K_S^0$	π/K 鉴别, 光子重建
K^0 - $\bar{K}^0$ 系统CPT对称性检验	$J/\psi \rightarrow K_S^0 K\pi$	顶点拟合
轻子味破坏	$J/\psi \rightarrow \gamma ll'$	轻子鉴别

强相互作用非微扰本质探索

物理目标	物理过程	性能检验
(类) 粲偶素态、多夸克态	X(3872)扫描	能量刻度和分辨
	$e^+e^- \rightarrow \pi Z_c(3900)$	径迹重建
	$e^+e^- \rightarrow P_c p^- \rightarrow J/\psi pp^-$	径迹重建, 低能质子重建
	$e^+e^- \rightarrow J/\psi \eta_c$	径迹分辨
极化碎裂函数	$e^+e^- \rightarrow KK, \pi\pi, K\pi$	π/K 鉴别
电磁形状因子	$e^+e^- \rightarrow pp^-$	质子鉴别
跃迁形状因子、超子衰变	$J/\psi \rightarrow l^+ l^- \pi^0/\eta$	π/μ 鉴别
	$\Sigma^+ \rightarrow \pi^0 p, \Sigma^+ \rightarrow \gamma p$	光子/ π^0 重建
	$\Lambda \rightarrow p e \nu, \Xi^- \rightarrow \Lambda e \nu$	顶点拟合, 电子鉴别

基本物理量精确测量

物理目标	物理过程	性能检验
R值测量	$e^+e^- \rightarrow \text{hadrons}$	亮度测量
双光子物理	$\gamma\gamma \rightarrow \text{hadrons}$	前向区
	$\eta c \rightarrow \gamma\gamma$	光子鉴别
陶轻子质量	$e^+e^- \rightarrow \tau^+ \tau^-$ near threshold	能量刻度和分辨
CKM矩阵元 $ V_{us} , V_{cs} , V_{cd} $	$D \rightarrow \pi \mu \nu, D \rightarrow \mu \nu$	D介子标记, π/μ 鉴别
	$D \rightarrow \text{inclusive}$	D介子标记
	$\tau \rightarrow K \nu$	π/K 鉴别
强相互作用跑动常数 α_s	$e^+e^- \rightarrow \tau^+ \tau^-, \tau \rightarrow l \nu \nu, \tau \rightarrow \pi \pi^0 \nu_\tau \rightarrow K \pi^0 \nu_\tau$	π/K 鉴别



发表物理模拟文章3篇：PRD 1篇、CPC 1篇、EPJC 1 篇；

PHYSICAL REVIEW D 112, 112002 (2025)

Prospects for P and CP violation in Λ_c^+ decays with a polarized beam at the Super Tau-Charm Facility

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☞ (Received 16 August 2025; accepted 12 November 2025; published 1 December 2025)

Weak decays of the charmed baryons offer an ideal platform to study parity (P) and charge conjugation-parity (CP) violation in the quark sector, to stringently test the Standard Model and search for new physics. It is a key goal in the next-generation positron-electron collider, such as the Super Tau-Charm Facility (STCF), Thanks to the quantum-entangled pair production with superhigh luminosity and the possibility of beam polarization, STCF provides a unique environment to probe such symmetry violations with unprecedented sensitivity. In this paper, we evaluate the precisions of the P -violating parameters and subsequently obtain the expected sensitivity of the CP -violating parameters in charmed baryon decays of $\Lambda_c^+ \rightarrow p\pi^0$, $p\pi$, AK^+ , $\Sigma^0 K^+$, and $\Sigma^+ K^0$, regarding to different polarization setups in STCF. The study suggests that the implementation of longitudinal beam polarization in STCF would greatly enhance the experimental capability in studying P and CP violation.

DOI: 10.1103/epd-w-trsj

I. INTRODUCTION

The Standard Model (SM) of particle physics is a remarkably successful theoretical framework that describes the properties of elementary particles and their interactions. However, it falls short of explaining several fundamental questions, such as the origin of the matter-antimatter asymmetry, the source of neutrino masses, and the nature of dark matter and dark energy. Charge conjugation-parity (CP) violation in baryons is considered one of the critical factors in addressing the matter-antimatter asymmetry problem [1]. To date, experimental observations of CP violation have been confirmed in charm and bottom meson systems, notably in B [2] and D mesons [3]. Recently, LHCb recently reported the first observation of CP violation in the bottom baryon sector [4], marking a significant milestone in the field. However, it is well known that the magnitude of CP violation predicted in the SM is insufficient to account for the observed dominance of

matter over antimatter in the Universe. Thus, probing CP violation in baryons and searching for potential new physics effects have become crucial to understanding the evolution of the Universe.

Parity (P) refers to the transformation properties of particles under spatial inversion. In 1956, Lee and Yang proposed the concept of parity-violation observables, specifically the parameter α , representing longitudinal polarization of daughter baryons in baryon weak decays [5]. Later that same year, a groundbreaking experiment conducted by Wu *et al.* demonstrated that parity is not conserved in weak decays [6], a finding that was subsequently confirmed by numerous experiments. Nowadays, parity violation has also been widely observed in the decays of charmed baryons [7–11]. For the decay process $\Lambda_c^+ \rightarrow BM$, where B and M represent a baryon with $J^P = \frac{1}{2}^+$ and a pseudoscalar meson with $J^P = 0^-$, respectively, parity-violating observables, α_{BM} , β_{BM} , and γ_{BM} , are defined in terms of the s - and p -wave decay amplitudes,

$$\begin{aligned}\alpha_{BM} &= 2\text{Re}(s^*p)/(|s|^2 + |p|^2), \\ \beta_{BM} &= 2\text{Im}(s^*p)/(|s|^2 + |p|^2), \\ \gamma_{BM} &= (|s|^2 - |p|^2)/(|s|^2 + |p|^2).\end{aligned}\quad (1)$$

Here, s and p represent the P -even and P -odd decay amplitudes, respectively. In a nonrelativistic framework, these correspond to the $L = 0$ (s -wave) and $L = 1$

Chinese Physics C Vol. 49, No. 11 (2025) 113001

Sensitivity study of the tau lepton electric dipole moment at the Super Tau-Charm Facility^{*}

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Abstract: This study investigates the intrinsic electric dipole moment (EDM) of the τ lepton, which is an important quantity in the search for physics beyond the Standard Model (BSM). In preparation for future measurements at the Super Tau-Charm Facility (STCF), we employ Monte Carlo simulations of the $e^+e^- \rightarrow \tau^+\tau^-$ process and optimize the analysis methodology for EDM extraction. Machine learning techniques are implemented to efficiently identify signal events ($\tau^\pm \rightarrow \pi^\pm \pi^0 \nu_\tau$), which result in a significant improvement in signal-to-noise ratio. Our optimized event selection algorithm achieves 80.0% signal purity with 6.3% efficiency. We develop an analytical approach for τ lepton momentum reconstruction and derive the squared spin density matrix along with optimal observables, which maximize the sensitivity to d_τ . The relationship between these observables and the EDM is established with the estimated sensitivity of $|d_\tau| < 3.89 \times 10^{-18} e\cdot\text{cm}$ at a 68% confidence level. These results provide a foundation for future experimental measurements of the τ lepton EDM in STCF experiments.

Keywords: beyond Standard Model, e^-e^- experiments, tau physics, electric dipole moment

DOI: 10.1088/1674-1137/adf6e0 CSTR: 32044.14.ChinesePhysicsC.49113001

I. INTRODUCTION

The electric dipole moment (EDM) is a physical quantity that characterizes the distribution of electric charge within a system. Theoretically, the EDM of a point-like particle is expected to be zero. Within the Standard Model (SM), due to charge-parity-conjugation (CP) violation, the intrinsic EDM of the τ lepton is predicted to be approximately $10^{-37} e\text{cm}$ [1–3], far below the experimental sensitivity. From the perspective of symmetry, a non-zero EDM signifies CP violation, which is a crucial prerequisite for the observed matter-antimatter asymmetry in the current observable universe. The CP violation predicted by the SM is minute and insufficient to account for the observed asymmetry [4]. However, some beyond the Standard Model (BSM) theories predict a significantly larger value, around $10^{-19} e\text{cm}$ [5, 6], making it feasible to measure the τ EDM experimentally and potentially reveal new physics.

tially reveal new physics.

For stable particles such as neutrons and electrons, EDM measurements typically employ precise experimental methods based on the spin precession phenomenon in strong electric or magnetic fields [7, 8]. When a particle with a non-zero EDM interacts with an electric field, its spin direction will undergo a slight deflection, which can be detected by highly sensitive experimental apparatuses. To date, numerous experiments have set extremely stringent upper limits on the EDMs of neutrons and electrons, further corroborating the predictions of the SM while providing crucial experimental constraints for new physics searches beyond the SM.

For short-lived particles such as heavy quarks and leptons, direct EDM measurements face significant challenges because of their extremely short lifetimes, which generally preclude traditional spin precession experiments [9]. Consequently, indirect approaches are adopted,

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https://doi.org/10.1140/epjc/s10052-025-15131-8

THE EUROPEAN
PHYSICAL JOURNAL C



Regular Article - Experimental Physics

Prospects of $|V_{us}|$ and axial vector form factors in $\Lambda \rightarrow pe^-\bar{\nu}_e$ decay at STCF

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Abstract We report a feasibility study of the hyperon semileptonic decay $\Lambda \rightarrow pe^-\bar{\nu}_e$ by using a fast simulation software package at STCF. With an anticipated integrated luminosity of 3.4 trillion J/ψ per year at a center-of-mass energy of 3.097 GeV, the statistical sensitivity of the branching fraction is determined to be 0.15%. The statistical sensitivities of form factors $g_{8\pi}$ and $g_{\pi\pi}$ are determined to be 0.4% and 2.15%, respectively. The projected sensitivity of $|V_{us}|$ is obtained by combining this result with $g_1(0)$ from Lattice QCD, to be 0.9%, including the systematic uncertainty from the LQCD input and the statistical uncertainties of input branching fraction and form factors. The precise measurement to be obtained at STCF will provide a rigorous test of the Standard Model.

researchers to study semileptonic and hadronic decays of Λ with unprecedented precision.

Currently, the $|V_{us}| = 0.2243 \pm 0.0008$ adopted by the Particle Data Group (PDG) is extracted from the kaon decay [2]. Combining this $|V_{us}|$ result and the independently measured $|V_{ud}|$ and $|V_{ub}|$, the equation can be obtained $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99848 \pm 0.00070$. There is a 2.3σ tension with unitarity, leading to poor consistency of the Standard Model global fit. Moreover, with the result extracted from the τ decay [3], the equation can be obtained $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99687 \pm 0.00087$, indicating a 3.6σ tension with KKM matrix unitarity. Besides, the hyperon semileptonic decay $\Lambda \rightarrow pe^-\bar{\nu}_e$ also provides a window to determine the value of $|V_{us}|$. If the most precise measurement of $|V_{us}| = 0.2250 \pm 0.0027$ from the hyperon decay is used [4], the equation $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99879 \pm 0.00136$ is obtained, thus in good agreement with unitarity. Although a considerable amount of relevant theoretical work has been recently updated [5, 6], the result of the hyperon semileptonic decay experiment is very outdated and scarce and shows a high statistical uncertainty compared to the results of the kaon decay and τ decay [3, 4, 7]. Therefore, precise measurements of $|V_{us}|$ through hyperon semileptonic decays are imperative for rigorously testing the unitarity of the CKM matrix.

For the hyperon semileptonic decays $B_1 \rightarrow B_2 + \ell + \bar{\nu}_\ell$, using M_1 and M_2 to denote the masses of B_1 and B_2 , the total decay rate for the electronic mode without radiative correction in the Standard Model, neglecting electron mass and setting $g_2(0) = 0$ [4, 8], is given by

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Springer

• 完成STCF上的CP破坏专题文章 《Physics Reports》杂志接收

CP violation studies at Super Tau-Charm Facility

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Abstract

Charge-parity (CP) violation in the tau-charm energy region is a promising area for sensitive tests of Standard Model (SM) predictions and searches for new, beyond the SM physics. A future Tau-Charm Facility that operates at center-of-mass energies between 2.0 and 7.0 GeV, with a peak luminosity of $0.5 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$, would provide huge numbers of hadrons and tau (τ) leptons that are produced in low-background environments and with well understood kinematic properties. In this report, prospects for unique studies of CP violation in the decay of charmed hadrons, and in the production and decay of hyperons and τ leptons at a next-generation tau-charm facility are discussed. In addition,

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• 完成多个全模拟分析并已撰写draft



note version 0.0

STCF Analysis Note

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January 6, 2026

Study of Λ CPV and EDM at STCF

Mingyu Yu^a, Jianyu Zhang^b, Xingtao Huang^c, and Jinlin Fu^d

Feasibility Study of Probing Quantum Entanglement with Pair-Produced $\tau^+\tau^-$ at STCF

Chentao Bao¹, Mingyi Liu^{2,3}, Lailin Xu^{2,3}, Xiaorong Zhou^{2,3}, and Hai Chen¹

²Dep

Study of $e^+e^- \rightarrow \eta_c J/\psi$ production at STCF

Zhuojuan Dong¹, Cong Geng², Jin Zhang³, and Xiaorong Zhou⁴

1,2,3Sun Yat-Sen University, Guangzhou

³State

Study of axial vector form factors through hyperon semileptonic decay $\Lambda \rightarrow pe^-\bar{\nu}_e$

Junxian Zhou^a, Shun Wang^b, Tao Luo^a, Xiaorong Zhou^c, and Cong Gen^d

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Study of CP violation in $\tau^- \rightarrow K_S \pi^- \nu_\tau$

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^cHenan Normal University

已培养研究生11名：博士毕业生5名、硕士毕业生6名；

■ 博士毕业生：

刘梦瑶（山大）

姚志鹏（山大）

翟云聪（山大）

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- 目组成员参加**CHEP2024, ACAT2024、FTCF2024、FTCF2025等国际会议并累计做报告30余次**，显著提升了我国在高性能离线数据处理技术与软件研发方面的国际影响力

谢谢各位专家，欢迎批评指正！