



中国科学技术大学

University of Science and Technology of China

BESIII

基于DIRC方法对于高定时精度的PID探测器设计与BESIII上对于 $\Sigma^0 \rightarrow \Lambda e^+ e^-$ 超子辐射衰变的研究

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Midterm Progress Report

October 12, 2026

I

DIRC-like探测器的研究

◆ 选题依据

◆ LHCb Upgrade II中TORCH探测器的研究内容与进展

◆ STCF桶部BTOf探测器的研究内容与进展

II

BESIII上超子辐射衰变 $\Sigma^0 \rightarrow \Lambda e^+ e^-$ 的研究

◆ 选题依据

◆ 研究进展

III

研究计划与安排

研究背景



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粒子物理标准模型 — 被实验证实的最成功模型，但仍然存在一些“缺陷”

- 引力、暗物质和暗能量解释困难
- 宇宙正反物质不对称现象
- μ 子反常磁矩疑难
- 中微子质量问题……

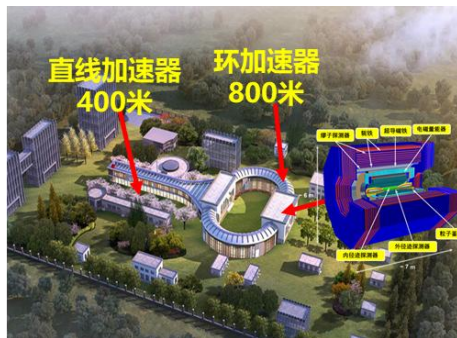
- **高能前沿**，通过在高能区产生新粒子和新现象直接发现新物理



大型强子对撞机 (LHC)

- 13 TeV p-p 对撞
- 直接寻找尚未发现的新粒子
- 成果：**发现希格斯粒子**……

- **高亮度前沿**，通过对重味夸克与轻子和玻色子的精确测量发现新物理迹象



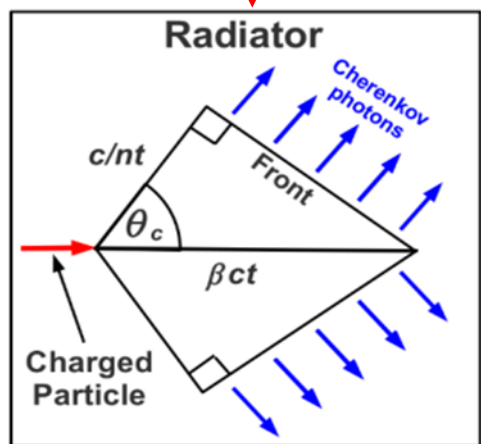
超级陶粲装置 (STCF)

- 峰值亮度 $0.5-1 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
- 能量区间 $E_{\text{cm}} = 2-7 \text{ GeV}$
- **极化束流** (Phase II)

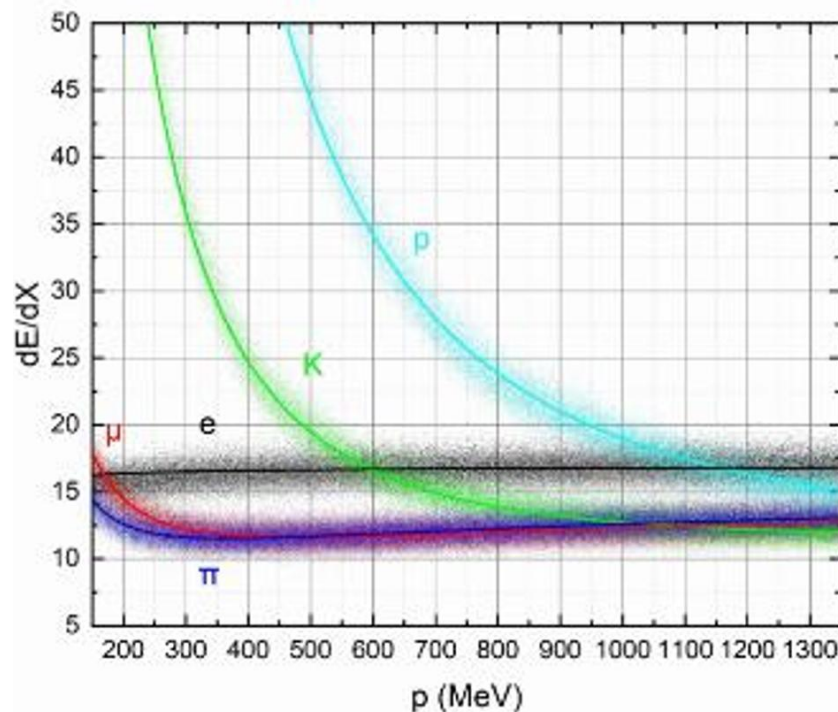
基于质量鉴别粒子

- 电离能损 dE/dx (低动量)
- 飞行时间 TOF
- 切伦科夫辐射和穿越辐射

PID探测器
两个备选
方案



$$\cos(\theta_c) = \frac{1}{n\beta}$$



飞行时间探测器 (TOF)

- 相同动量下, 使用不同质量粒子在相同距离内的飞行时间差实现粒子鉴别
- 闪烁体探测器, 多气隙阻性板 (MRPC) 等
- 本征时间分辨较差, 难以压制高亮度下的本底
- 难以鉴别高动量下的粒子

BESIII	Plastic scintillator	~100ps
	MRPC	~60ps
BELLE	Scintillator	~100ps

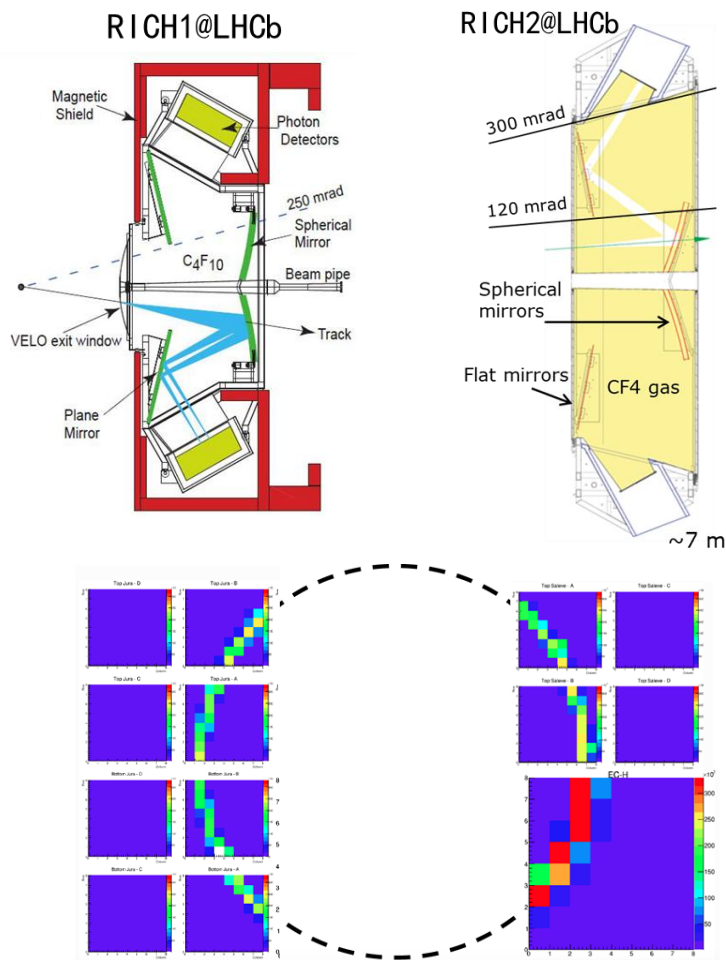
成像型切伦科夫探测器

- 通过探测高能带电粒子在介质中产生的切伦科夫辐射光子实现粒子鉴别
- 粒子鉴别能力强, 动量覆盖范围宽
- 环形成像切伦科夫探测器 (**RICH**)
- 内全反射型切伦科夫探测器 (**DIRC**)

RICH探测器



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RICH@LHCb

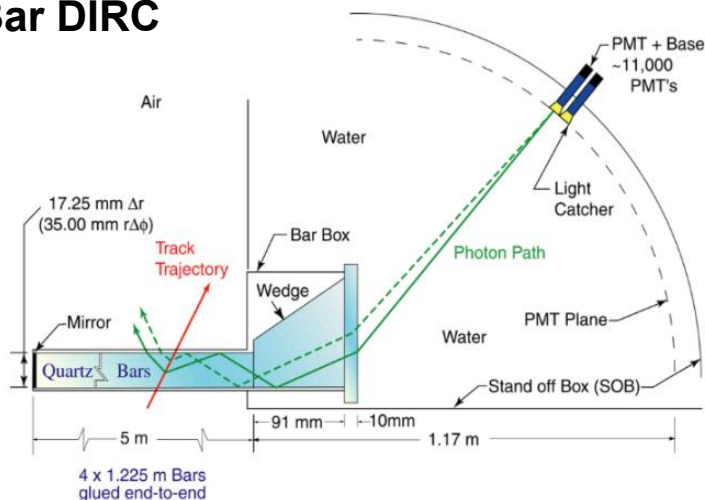
- 气凝胶辐射体, CF_4 (RICH1) 与 C_4F_{10} (RICH2)
- 使用球面镜加平面镜聚焦与传递光路
- 角分辨:
 - ✓ $\sim 1.66 \text{ mrad}$ @ RICH1
 - ✓ $\sim 0.66 \text{ mrad}$ @ RICH2
- 动量覆盖范围:
 - ✓ $2 \sim 60 \text{ GeV}/c$ @ RICH1
 - ✓ $15 \sim 100 \text{ GeV}/c$ @ RICH2
- ✓ 粒子鉴别方法: 基于图像识别的极大似然法

2016年LHCb Upgrade束流测试期间RICH切伦科夫环成像图

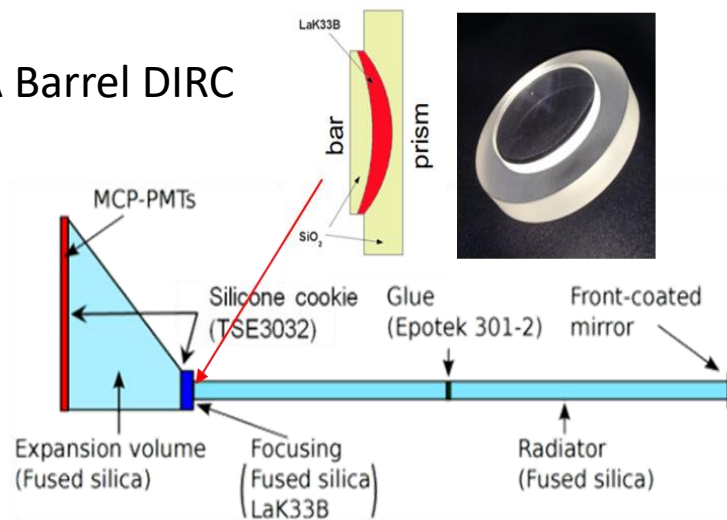
DIRC (Detection of Internally Reflected Cherenkov light) 探测器特征

- 内全反射型切伦科夫辐射体，同时作为光导
- 辐射体使用熔融石英板，光子传播角度固定，重建原理简单
- 表面粗糙度与平整度低 ($\sim 1\text{nm}$)，保证传播方向一致并减少光子损失
- 基于图像识别的极大似然法鉴别粒子

BaBar DIRC



PANDA Barrel DIRC

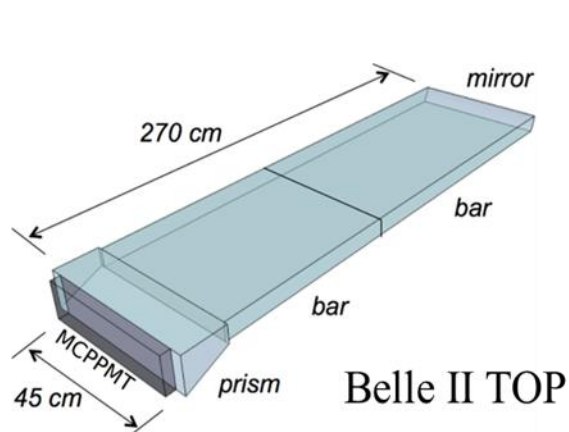


DIRC-like探测器

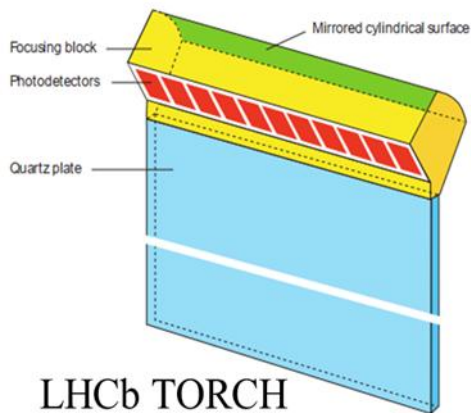


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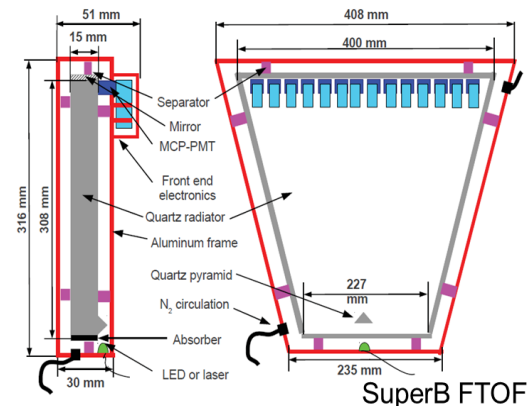
- 偏重于时间探测，通过时间信息实现鉴别
- 选用先进光子探测器件MCP-PMT实现超高定时精度



Belle II TOP



LHCb TORCH



SuperB FTOF

- Belle II iTOP通过测量光子传输时间，LHCb TORCH与SuperB FTOF通过测量粒子的飞行时间来实现粒子鉴别
- 时间性能优异，结构紧凑，运行维护简单，抗辐照能力强，耐高计数率
- 超高定时精度可有效压低本底带来的影响

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LHCb Upgrade II



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LHCb Upgrade II是欧洲大型强子对撞机LHC上底夸克探测系统LHCb的基于第一次升级改进后的第二次重大升级项目

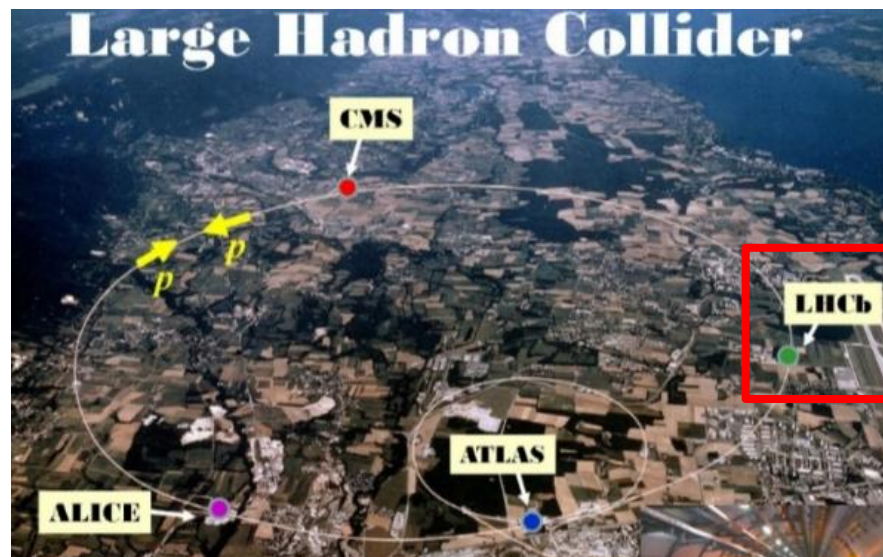
- 具备**高瞬时亮度运行能力**，**快速时间响应能力**并采用抗辐照技术，从而获得更强大的数据采集能力
- 是**重味物理领域**研究的重要平台，还支持味物理领域外的许多研究，如暗物质粒子直接搜寻、强子谱学与重离子碰撞中的QCD研究等

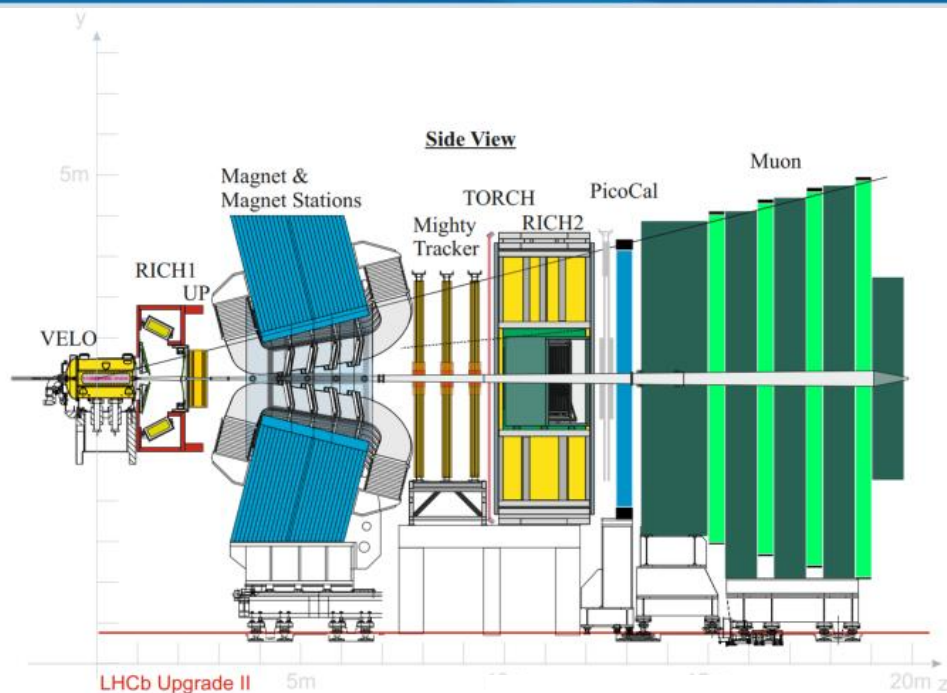
LHCb Upgrade I

- 瞬时亮度 $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- 目标数据 50 fb^{-1}

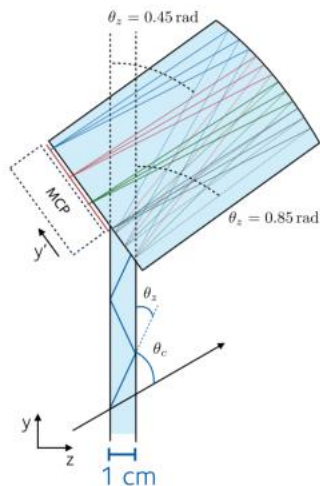
LHCb Upgrade II

- 瞬时亮度 $\sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- 目标数据 300 fb^{-1}
- 快速时间响应能力与抗辐照技术



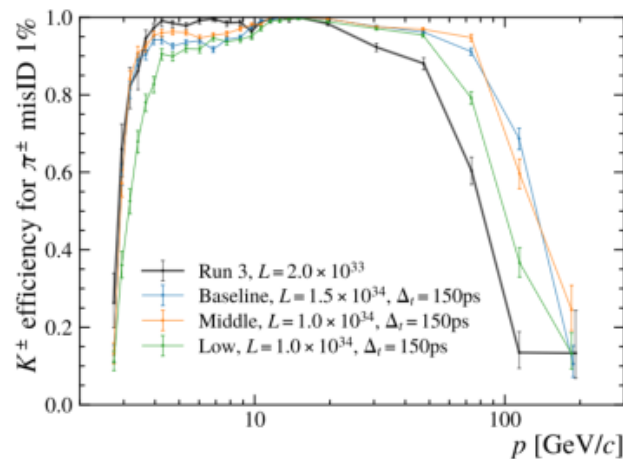


TORCH示意图:



LHCb Upgrade II 粒子鉴别系统

- 在大范围动量内实现 $\pi/K/p$ 的精确鉴别 (3σ)
- 由RICH1, RICH2以及新型的DIRC-like切伦科夫探测器**TORCH**组成
- RICH无法提供 $<10\text{GeV}/c$ 的 K/p 鉴别能力, 需要TORCH弥补
- 要求具备高精度定时能力以抑制本底



TORCH要求快速时间响应，在单光子本征时间分辨~70ps的情况下要求预期的探测器本征时间分辨为~15ps，光子数25~30

$$\sigma_{SPE}^2 \sim \left(\frac{\sigma_{elec}}{\sqrt{N_{p.e.}}} \right)^2 + \left(\frac{\sigma_{TTS}}{\sqrt{N_{p.e.}}} \right)^2 + \left(\frac{\sigma_{prop} \cdot t_{prop}}{\sqrt{N_{p.e.}}} \right)^2$$

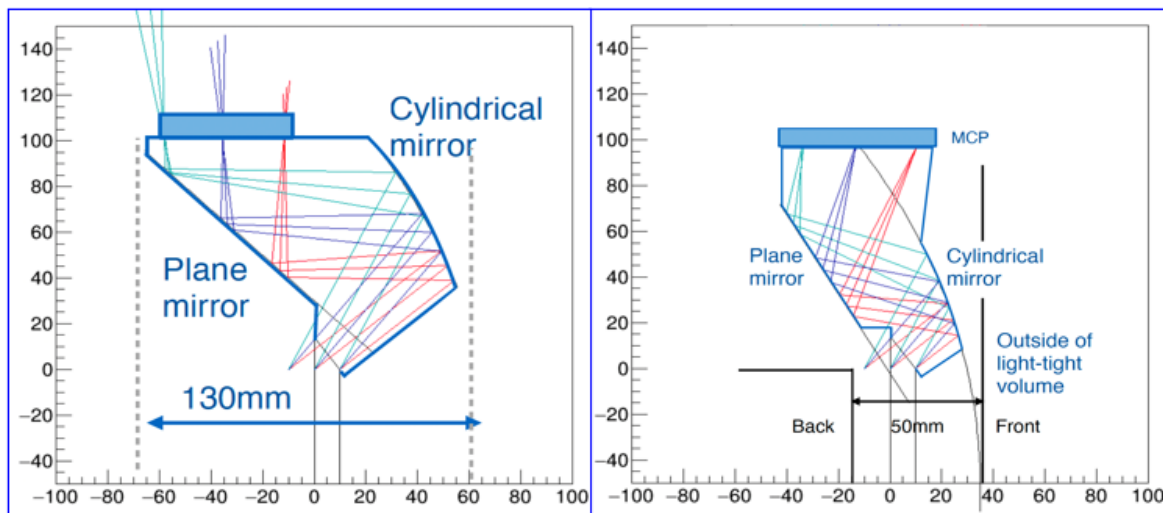
- σ_{elec} 电子学定时精度
- σ_{TTS} 光电器件渡越时间涨落
- $\sigma_{prop} \cdot t_{prop}$ 表征色散效应随光子传播时间增大的贡献

当前TORCH所面临的挑战：

- 光子数目难以达标
- 与TORCH预留空间不适配

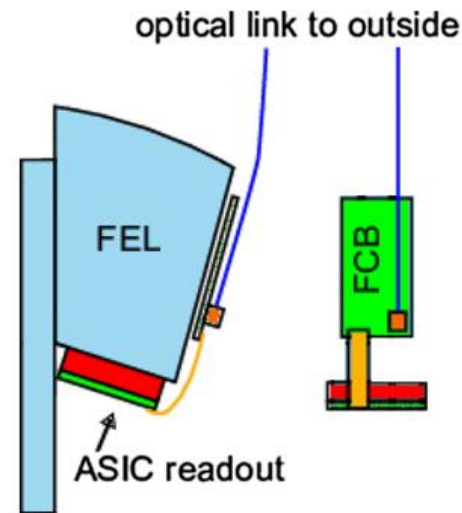
基于PANDA端盖DIRC探测器的技术对于TORCH的几何改进

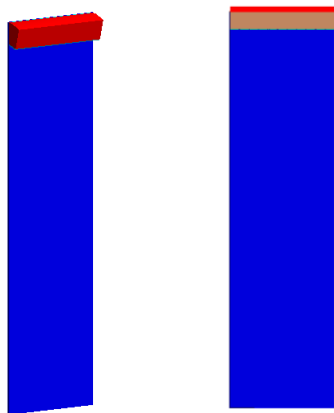
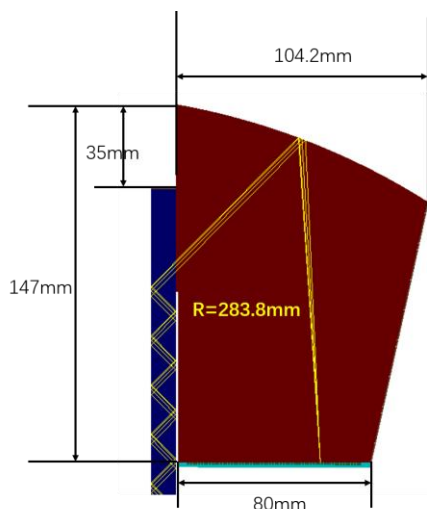
- 解决原有TORCH方案的几何难以与预留的尺寸与机械结构适配的问题
- 避免光子数因二次镜面反射导致的额外损失
- 采用电介质材料键合来连接聚焦体与石英板以减少光子数损失
- 需要配套的独立Geant4模拟与重建算法



TORCH改进型 (球面镜+平面镜)

TORCH-PANDADIRC



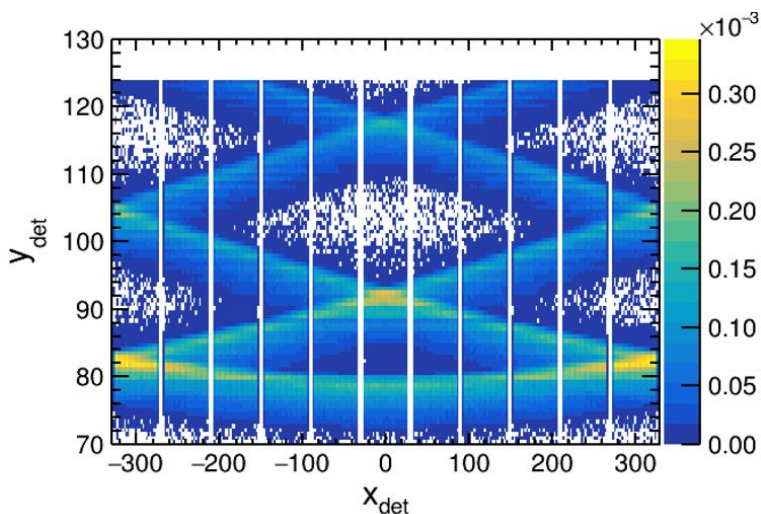


- 基于实际全尺寸的建模
- 尚未考虑前端探测器的影响
- 单块石英板尺寸2500mm * 660mm * 10mm
- 在石英板与聚焦模块间添加一狭窄空隙以增加大角度光子击中
- 光探测阵列由11个8*64的微通道光电倍增管组成

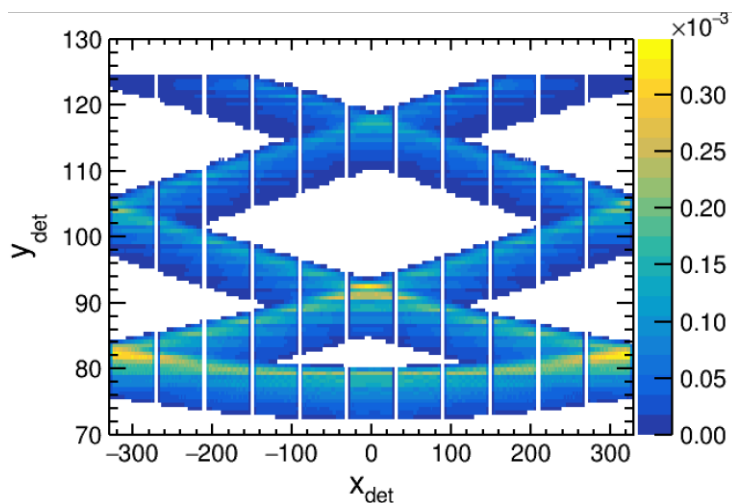
模拟结果与光子数



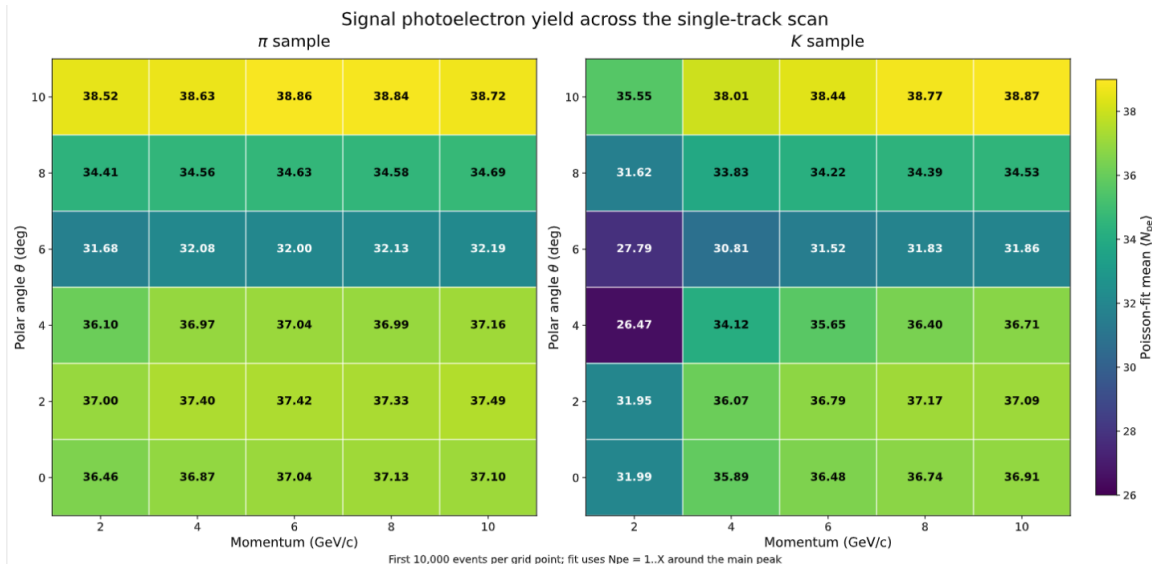
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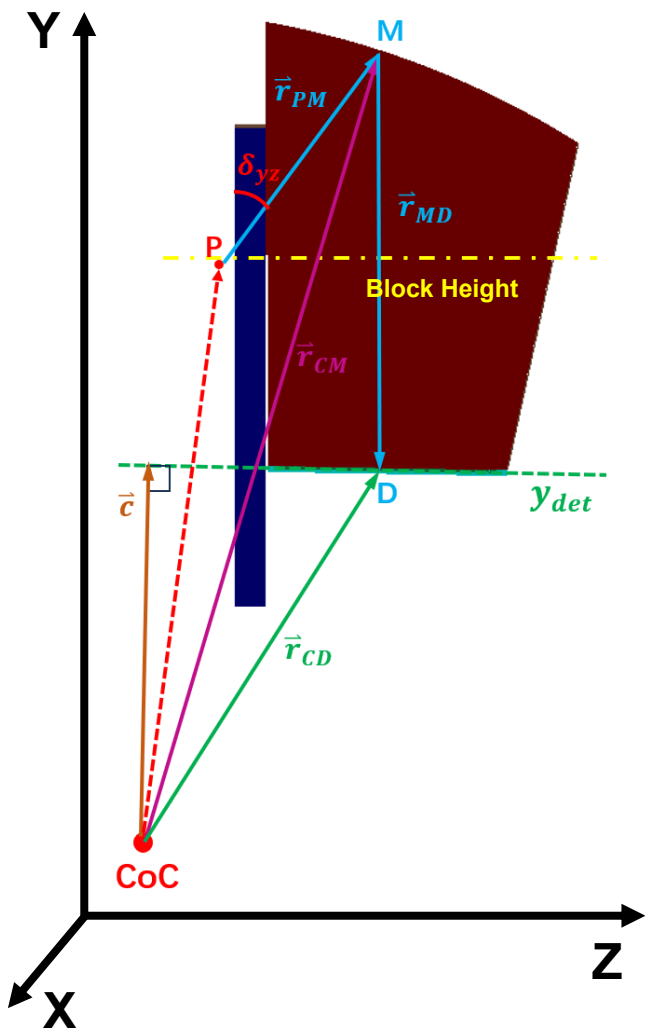
Simulation



Calculation

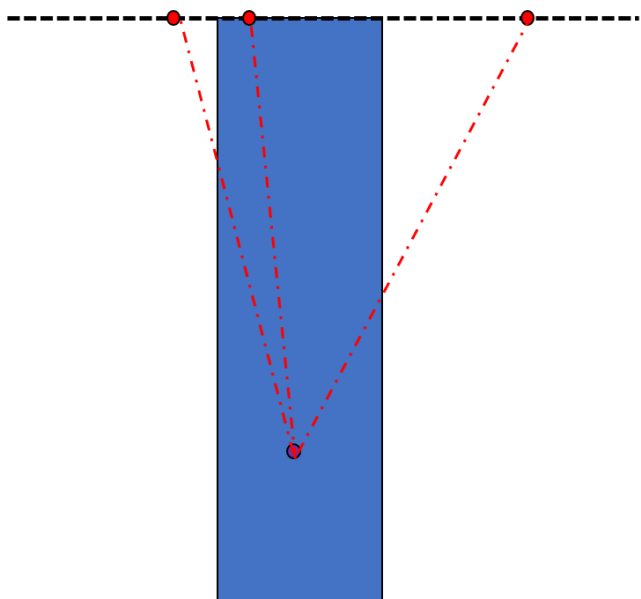


- 蒙卡抽样计算得到的分布与模拟一致（几何推导逻辑正确）
- 理想模拟下预期光子数>30



- 左图P点为YOZ平面内在Block Height上光子的等效出射点， δ_{yz} 为YOZ平面内光子与Y轴夹角
- 基于柱面镜的聚焦特性，通过预设一个P点位置，可以计算得到 δ_{yz}
- 从辐射体中径迹发光点（默认为中央）通过 δ_{yz} 可以重新计算出P点位置，经过多次上述迭代后，P点位置与 δ_{yz} 将达到收敛

XOY平面内光路示意图



➤ 在重建得到YOZ平面内的光路信息后，考虑在X方向可能的不同反射次数，对每一条光路内的光传输长度、光传输时间 (TOP)与粒子飞行时间 (TOF)进行精确重建，并挑选重建TOF与假设下预期的TOF最接近的路径作为信号路径

➤ $\text{TOF}_{\text{rec}} = \text{TOA} - \text{TOP}_{\text{rec}}$, TOA为光子到达时间，加入70ps的单高斯晃动

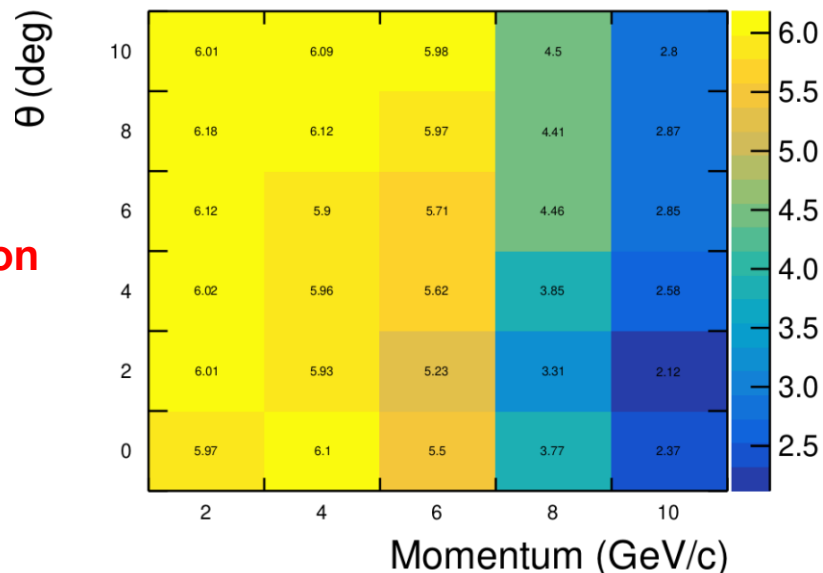
$$\text{➤ } \mathcal{L}_h = e^{-\bar{N}_h} \prod_{i=1}^N \bar{N}_h \frac{1}{\sqrt{2\pi}\sigma_t} \exp\left[-\frac{1}{2}\left(\frac{\text{TOF}_{\text{rec}}^i - \text{TOF}_{\text{hypo}}}{\sigma_t}\right)^2\right]$$

性能展示 (π/K)

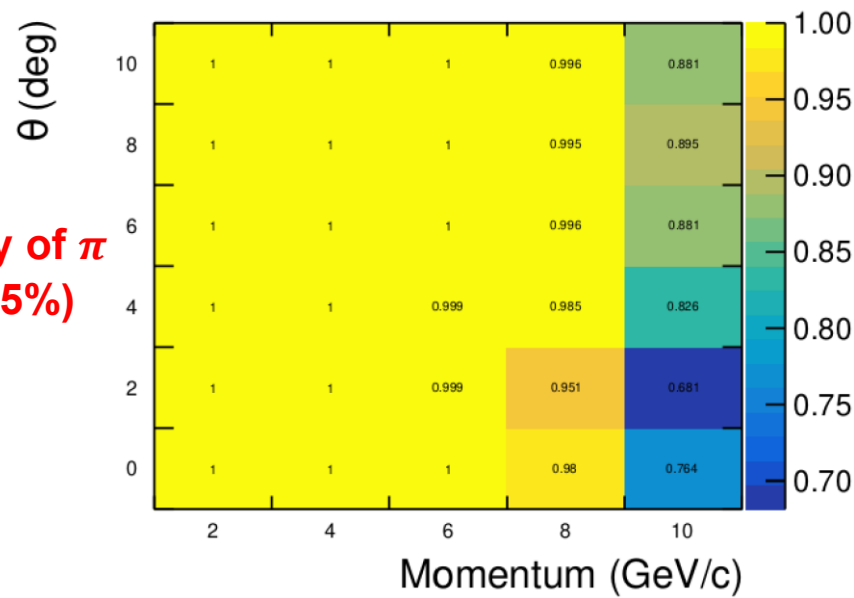


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Separation



Efficiency of π
(misID=5%)



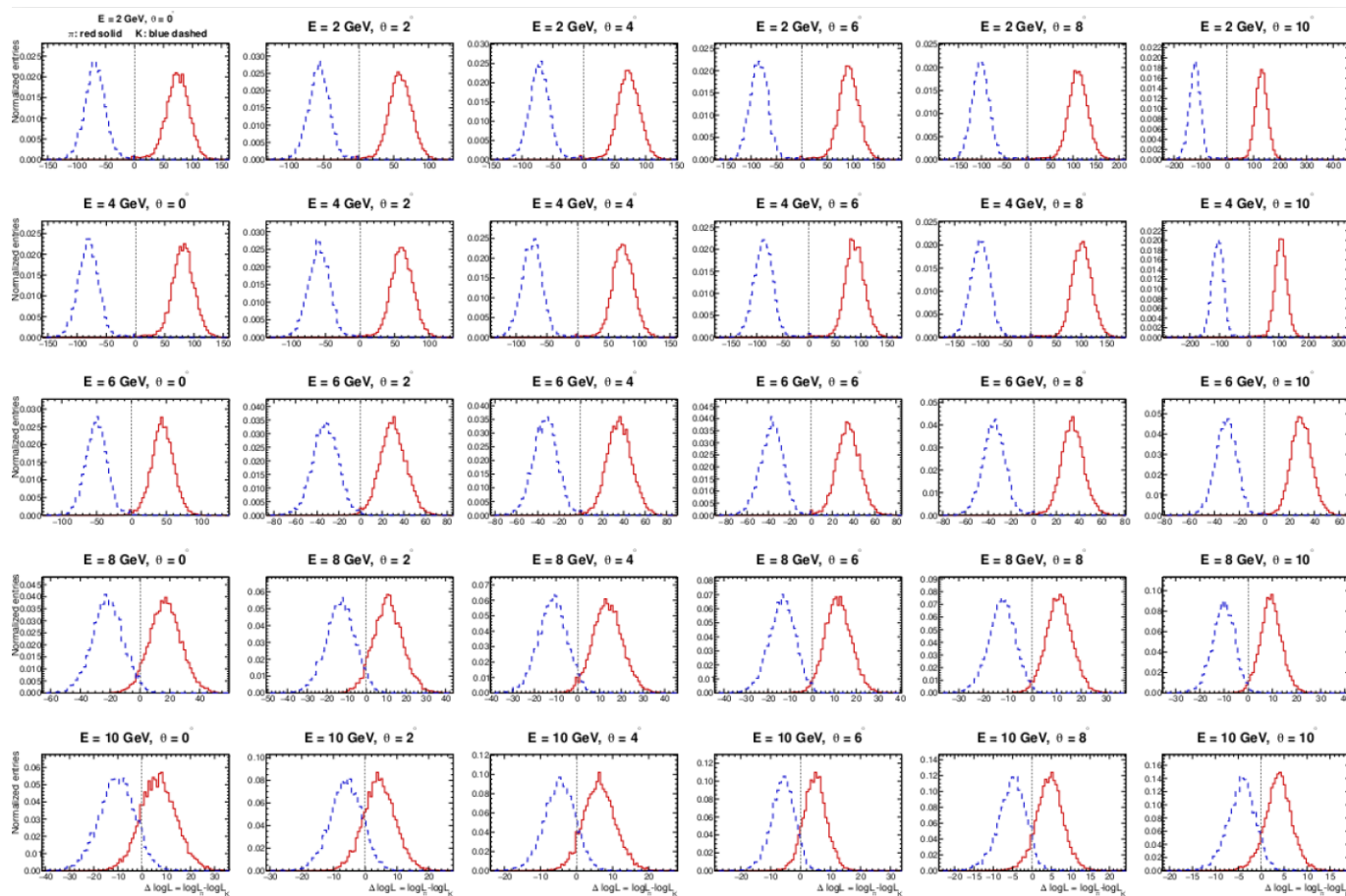
- 阳极分割导致的位置误差因素已被考虑在内
- 尚未考虑前端探测器质量的影响
- 当前IP点与石英板垂直距离为9.5m (与实际情况对应)
- 当前参数尚未与LHCb的模拟参数设置对齐。未来将予考虑

性能展示 (π/K)



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$\log L_\pi - \log L_K$ 分布



➤ 石英板@北玻所

- 加工粗糙度要求 $<1\text{nm}$ ，平整度要求 $<3\mu\text{m}$
- 需要考虑粗糙度与平整度测量（STCF BTOF样机已有测量经验）

➤ MCP-PMT@西光所

- 预期寿命 $>5\text{C}/\text{cm}^2$
- 预期MCP-PMT的本征分辨率约 30 ps

➤ 石英板与聚焦体键合技术@北玻所

- 熔融石英材料表面间通过分子力键合
- 目前北玻所键合材料尺寸 $<150\text{mm}$ (直径)
- 需要提升工艺+材料分割键合（如果分割材料，需要设计调整和G4模拟）

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超级陶粲装置 (STCF)



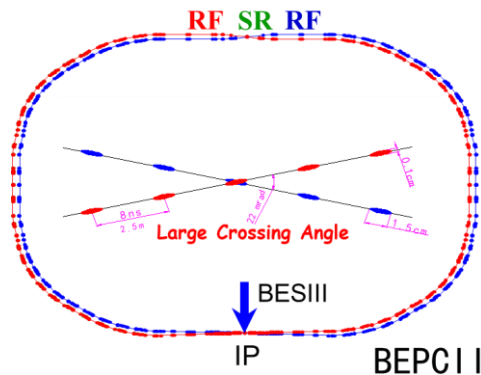
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超级陶粲装置是中国未来的高亮度正负电子对撞机项目

- 更高的亮度与更广泛的能量区间
- 是研究陶-粲物理、QCD、新型强子以及寻找新物理的重要平台

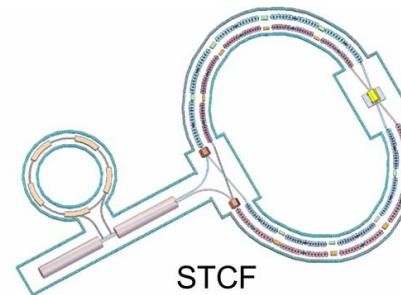
北京正负电子对撞机 (BEPCII)

- ❑ 峰值亮度 $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- ❑ 能量区间 $E_{\text{cm}} = 2\text{-}4.6 \text{ GeV}$
- ❑ 无极化



超级陶粲装置 (STCF)

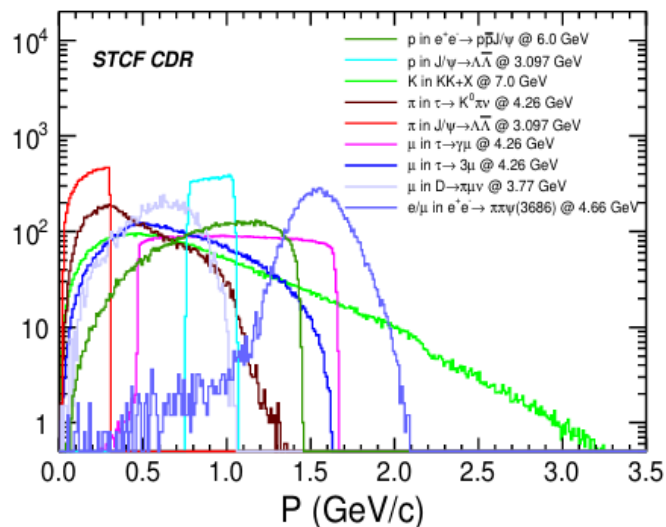
- ❑ 峰值亮度 $0.5\text{-}1 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
- ❑ 能量区间 $E_{\text{cm}} = 2\text{-}7 \text{ GeV}$
- ❑ 极化束流 (Phase II)



探测器布局



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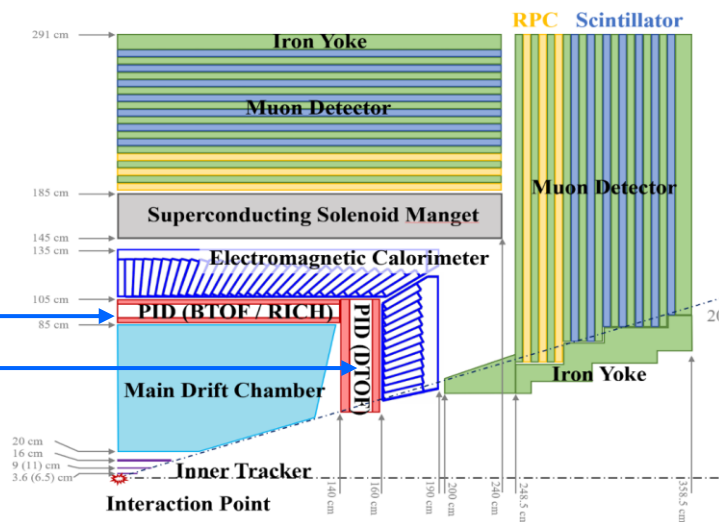


超级陶粲对粒子鉴别探测器需求

- 2GeV/c $\pi/K/p \sim 4\sigma$ (即2%误鉴别率下, 97%鉴别效率)
- 结构紧密: <20cm (为量能器预留空间)
- 物质质量: < 0.3 X_0 (减少能量畸变)
- 本底计数率: ~ 13 kHz/通道 (1倍本底)
- 桶部当前默认方案为**BTOF**方案, 通过DIRC-like技术实现 4σ 粒子鉴别

PID

- π/K (and K/p) 4σ separation power up to 2 GeV/c



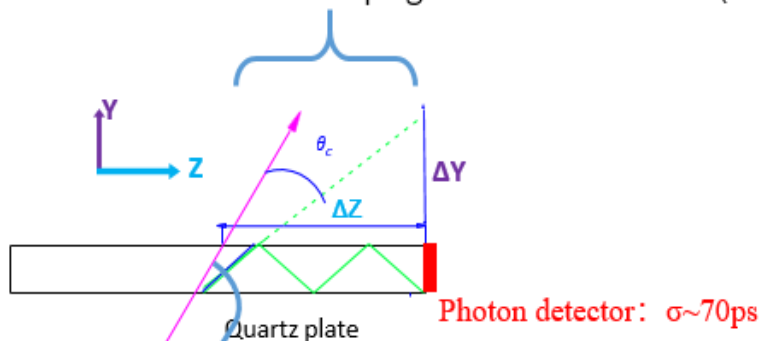
BTOF方案简介



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- 与IP点距离约为880mm，TOF与TOP呈互补关系
(需进行模拟研究分析)

TOP: Time of Propagation $\sim 3\text{ns}-15\text{ns}$ ($\theta=70^\circ$)



Note: Typically reflection times ~ 100

TOF: Time of Flight $\sim 3\text{ns}$ ($R \sim 880\text{mm}$)

- 使用新型MCP-PMT实现高定时精度 (70ps)
- 色散效应明显，在TOP较大时不可忽略，可通过滤波实现较好的单光子时间分辨，但同时会减少光子数
- 不需要聚焦系统，探测器结构更为紧凑
- STCF端盖的DTOF探测器也采用成熟的DIRC技术，且两者电子读出系统高度相似，维护也较为方便

$$\sigma_{tot}^2 \sim \sigma_{trk}^2 + \sigma_{T_0}^2 + \left(\frac{\sigma_{elec}}{\sqrt{N_{p.e.}}} \right)^2 + \left(\frac{\sigma_{TTS}}{\sqrt{N_{p.e.}}} \right)^2 + \left(\frac{\sigma_{det}}{\sqrt{N_{p.e.}}} \right)^2$$

- $N_{p.e.}$ 光电子数目
- σ_{trk} 径迹重建误差 ($\sim 10ps$)
- σ_{T_0} 参考时间误差 ($\sim 40ps$)
 - 即束团对撞时间
- BTOF本征时间分辨
 - σ_{elec} 电子学定时精度 ($\sim 10ps$)
 - σ_{TTS} 光电器件渡越时间涨落 ($\sim 70ps$)
 - σ_{det} BTOF重建误差

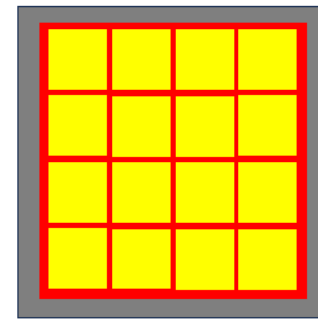
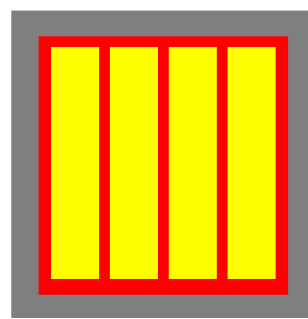
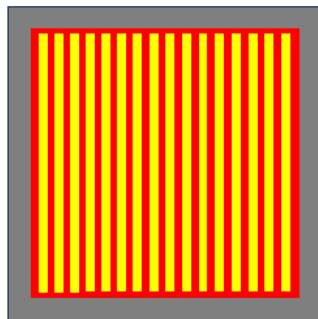
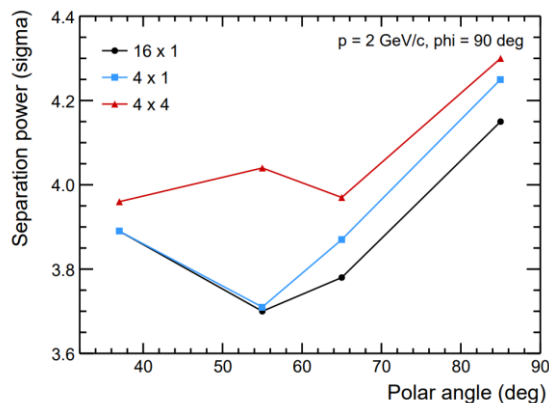
若采用传统TOF方法进行粒子鉴别, 若取 $L=1.1m$, $2GeV/c$ 下, 实现 $4\sigma \pi/K$ 区分度的时间分辨需 $\sigma \sim 26ps < \sigma_{T_0}$

提升时间分辨途径

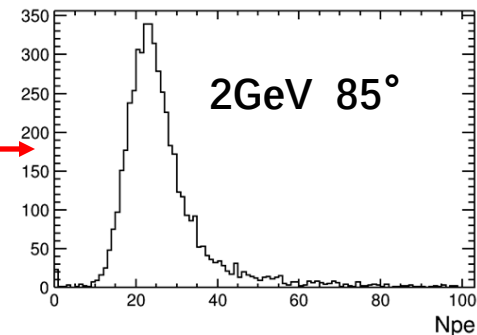
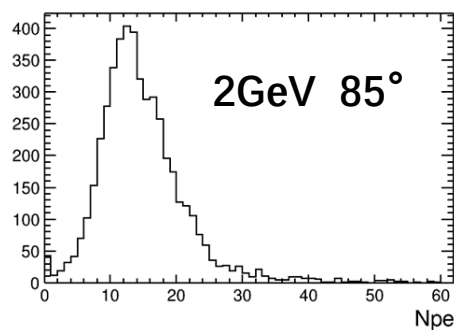
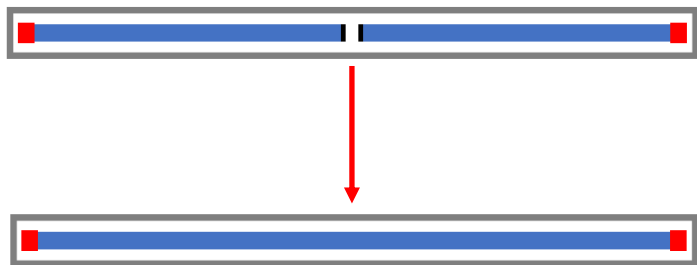
- 对单光子精确重建
- 提高单光子本征时间分辨
- 提高光电子数目

需要引入TOP信息弥补!

➤ PMT阳极分割方案优化



➤ Z方向相邻两块石英板相互拼接以提高大角度径迹的光电子数

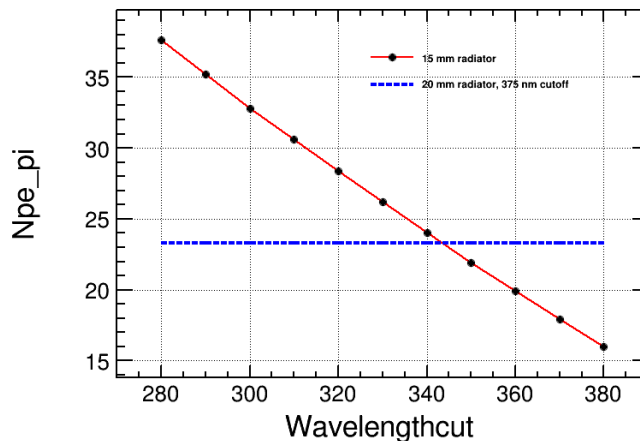
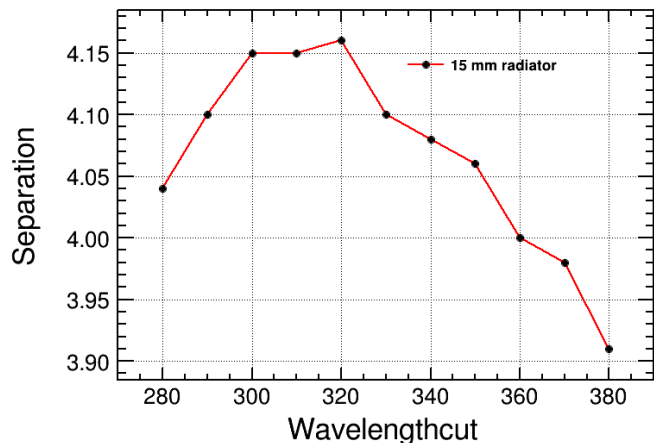


BTOF优化路线

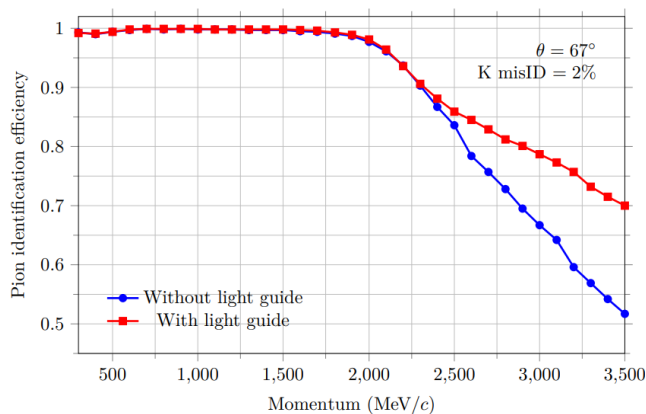


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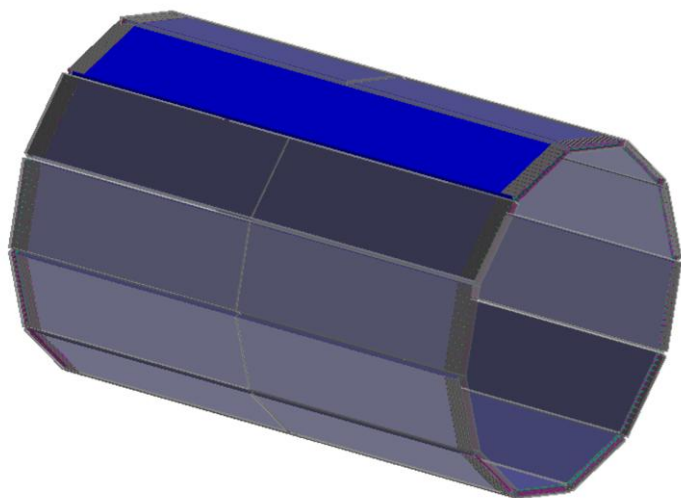
- 石英板厚度20mm→15mm && 滤波截断375nm→320nm



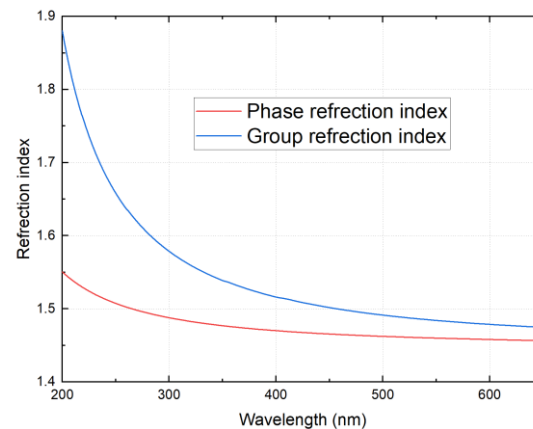
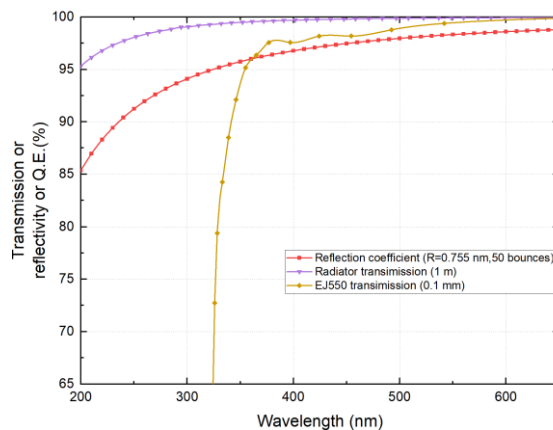
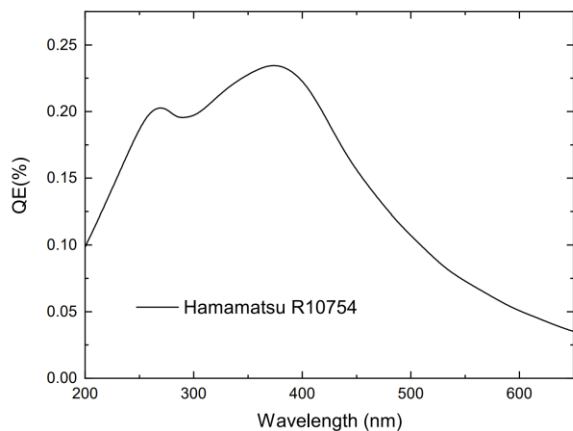
- 额外光学拓展区



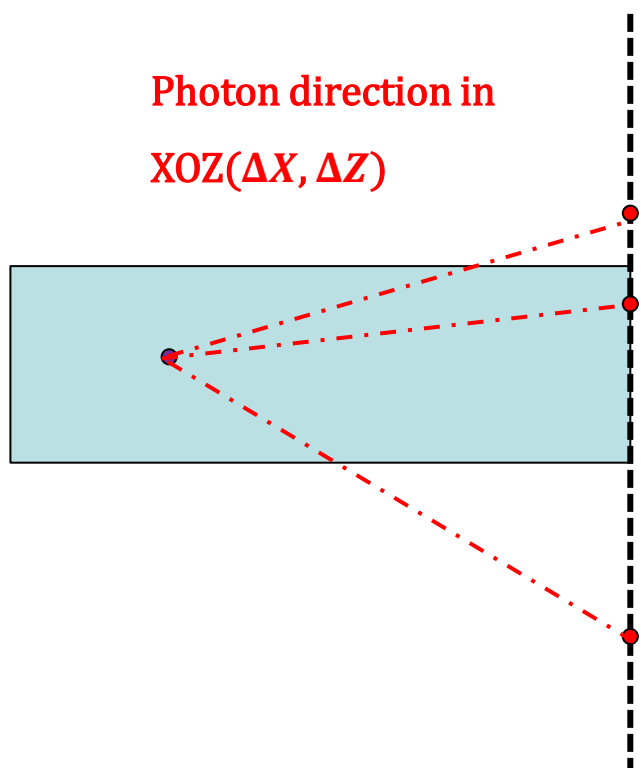
基于高性能离线软件系统OSCAR下的BTOF模拟程序来研究验证其预期性能



- 石英板尺寸1495mm * 450mm * 15mm
- 铝蜂窝板光学屏蔽盒~5mm
- 光电器件4*4，像素尺寸4.8mm * 4.8mm
- 径迹使用外推算法考虑前端探测器与外壳的物质质量影响



Timing Method

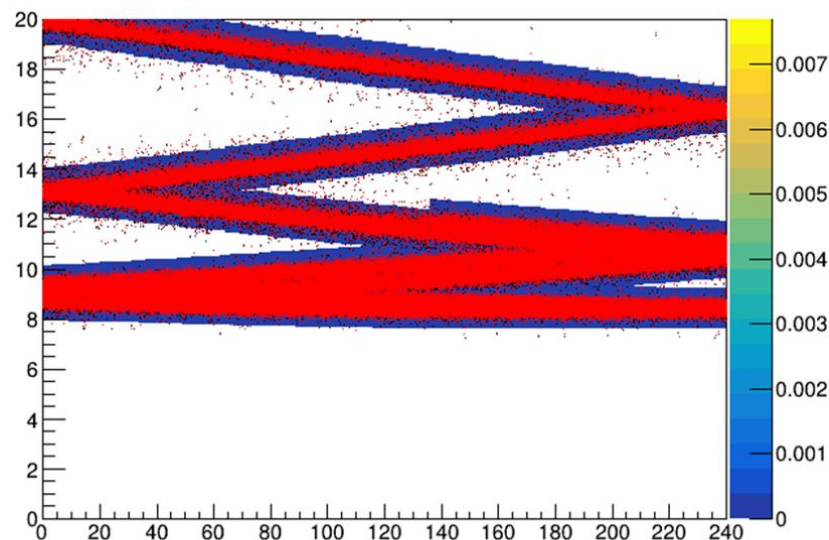


$$TOF = T - TOP - T_0 = T - \frac{L\bar{n}_g}{c} - T_0$$

- 加入数字化 (σ_{T_0} , σ_{TTS} 等) 的影响
- 存在多种可能路径
- 对于每种可能路径计算其TOP, 从而重建出TOF
- 挑选与预期假设(通过外推径迹得到)最接近的可能作为重建路径
- 加入全反射判选条件
- $\mathcal{L}_h = e^{-\bar{N}_h} \prod_{i=1}^{N_{pe}} \bar{N}_h S_h(TOF_{rec} | TOF_{hypo}) + B$

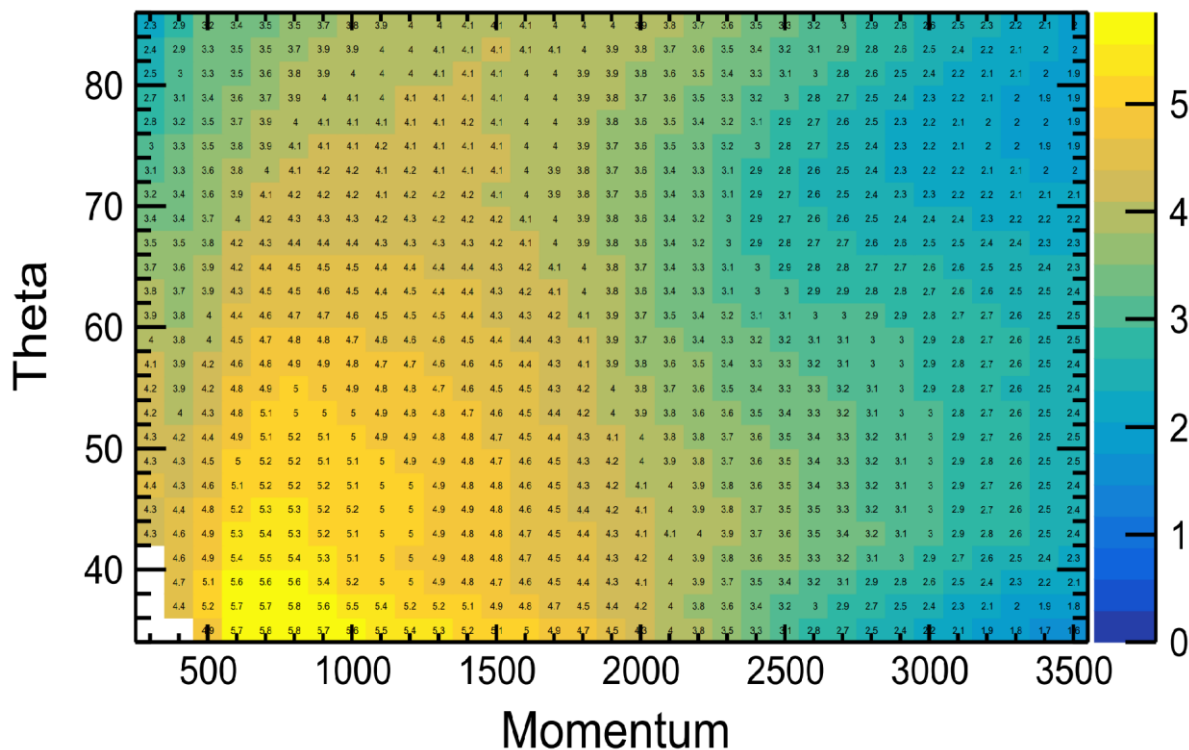
Imaging Method

- 加入数字化 (σ_{T_0} , σ_{TTS} 等) 的影响
- 对于每个事例根据径迹方向与切伦科夫角计算出切伦科夫光的T-Ch二维分布概率图 (T=TOF+TOP)
- 相比于一维算法引入空间坐标维度
- 加入通道死时间修正
- $\mathcal{L}_h = e^{-\bar{N}_h} \prod_{i=1}^{N_{pe}} \bar{N}_h S_h(ch_i, t_i) + B$



Comparison of calculated PDF and simulation

π/K 二维算法鉴别性能图 (混本底)



➤ 在2GeV以下基本可以满足STCF对于PID性能要求 ($\varphi \sim (0, 2\pi)$)

I

DIRC-like探测器的研究

- ◆ 选题依据
- ◆ LHCb Upgrade II中新型TORCH探测器的研究内容与进展
- ◆ STCF桶部BTOf探测器的研究内容与进展

II

BESIII上超子辐射衰变 $\Sigma^0 \rightarrow \Lambda e^+ e^-$ 的研究

- ◆ 选题依据
- ◆ 研究进展

III

研究计划与安排

I

DIRC-like探测器的研究

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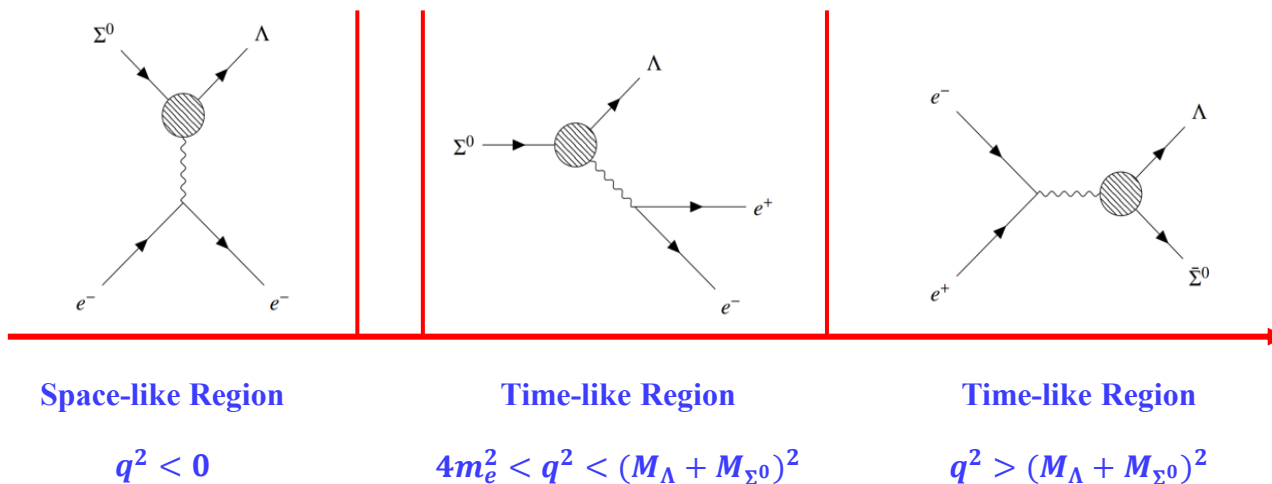
II

BESIII上超子辐射衰变 $\Sigma^0 \rightarrow \Lambda e^+ e^-$ 的研究

- ◆ 选题依据
- ◆ 研究进展

III

研究计划与安排



形状因子

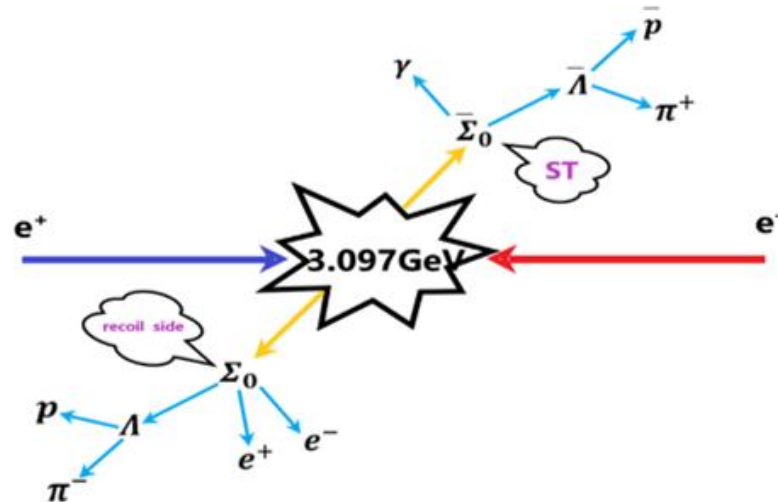
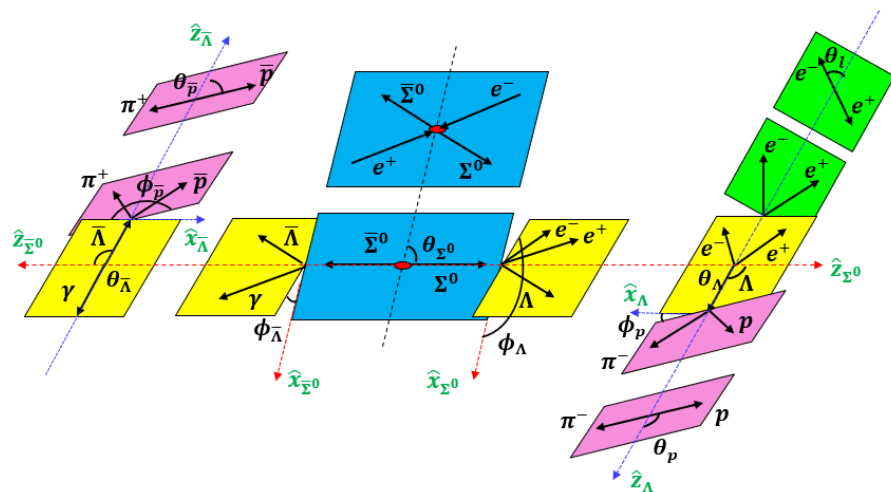
- 探究强子内部结构的重要物理量
- 揭示强子内部电荷与磁矩分布
- 描述相互作用随能量尺度（动量转移）的变化

研究依据

- 该过程分支比仅有理论计算，缺少实验测量结果
- BESIII拥有最大的具备高重子对分支比的J/ψ数据集

预期目标

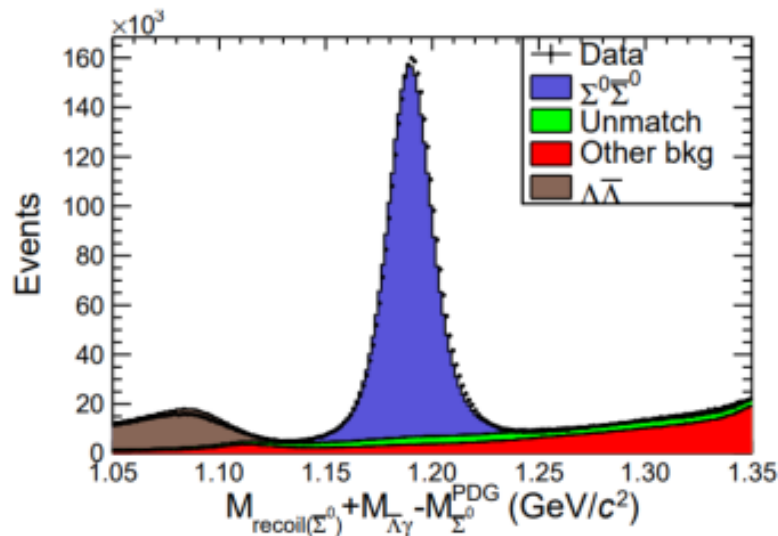
- $\Sigma^0 \rightarrow \Lambda e^+ e^-$ 过程分支比
- $\Sigma^0 \Lambda$ 跃迁磁矩



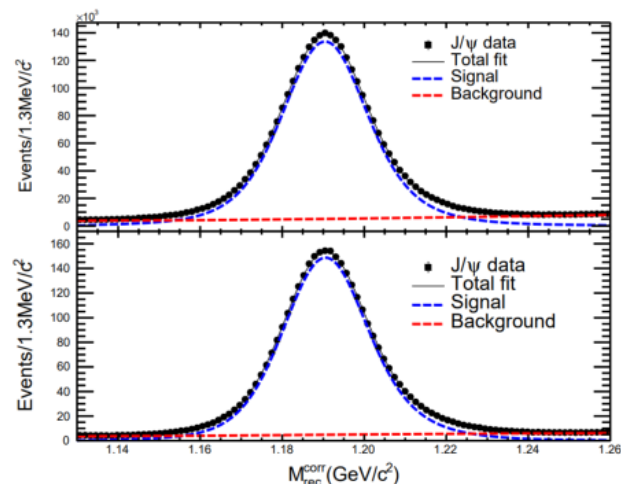
单双标分析策略

- 衰变链 $J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^0 \rightarrow \Lambda \bar{\Lambda} \gamma e^+ e^- \rightarrow p \bar{p} \pi^+ \pi^- \gamma e^+ e^-$, 包含电荷共轭道 .
- 单标端(ST), $\bar{\Sigma}^0 \rightarrow \bar{p} \pi^+ \gamma$, $\Sigma^0 \rightarrow anything$
- 双标端(DT), $\Sigma^0 \rightarrow p \pi^- e^+ e^-$
- N_{ST} 与 N_{DT} 为单双标信号事例数, ϵ_{ST} 和 ϵ_{DT} 为单双标信号效率.

单标结果



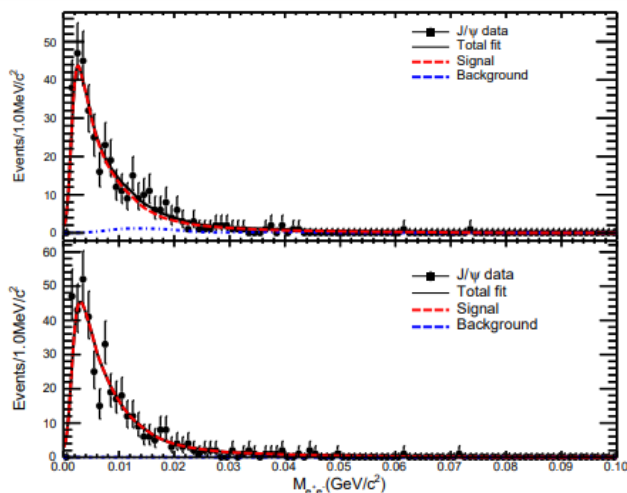
- 10B J/ψ inclusive MC 用于估计本底
- 信号区间内没有峰本底分布
- 本底包含非信号过程与光子truth信息不匹配的信号过程



- 利用单标端 Σ^0 反冲质量谱提取信号
- 信号PDF: 信号蒙卡形状卷积高斯函数
- 本底PDF: 二阶切比雪夫多项式

Modes	$J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^0, \bar{\Sigma}^0 \rightarrow \bar{\Lambda} \gamma, \Sigma^0 \rightarrow anything$	$J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^0, \Sigma^0 \rightarrow \Lambda \gamma, \bar{\Sigma}^0 \rightarrow anything$
ST Yields	2916940 ± 2655	3225220 ± 2645
ST efficiency(%)	36.46	38.13
$\mathcal{B}_{J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^0} (\times 10^{-3})$	1.242 ± 0.001	1.311 ± 0.001

双标结果



$$\Gamma_{\Sigma^0 \rightarrow \Lambda e^+ e^-} = \int d\Gamma_{\Sigma^0 \rightarrow \Lambda e^+ e^-} / dq^2 dq^2 = \int |G_M(0)|^2 W(q^2) dq^2$$

$$= \Gamma_{total} \mathcal{B}_{\Sigma^0 \rightarrow \Lambda e^+ e^-},$$

$$\mathcal{B}_{\Sigma^0 \rightarrow \Lambda e^+ e^-} = \frac{N_{DT}}{N_{ST}} \times \frac{\epsilon_{ST}}{\epsilon_{DT}} \times \frac{1}{\mathcal{B}_{\Lambda \rightarrow p \pi^-}}$$

- 利用 e^+e^- 不变质量谱提取信号
- 本底过程来源于 $\Sigma^0 \rightarrow \Lambda \gamma$ 过程
- 信号与本底过程均使用蒙卡形状描述

Modes	$\Sigma^0 \rightarrow \Lambda e^+ e^-$	$\bar{\Sigma}^0 \rightarrow \bar{\Lambda} e^+ e^-$
ST Yields	2916940 ± 2655	3225220 ± 2645
ST efficiency(%)	36.46	38.13
DT Yields	347.93 ± 23.19	405.05 ± 20.11
DT efficiency(%)	1.04	1.12
Individual $\mathcal{B}_{\Sigma^0 \rightarrow \Lambda e^+ e^-} (\times 10^{-3})$	$6.34 \pm 0.44_{\text{stat.}} \pm 0.21_{\text{sys.}}$	$6.29 \pm 0.33_{\text{stat.}} \pm 0.14_{\text{sys.}}$
Simultaneous $\mathcal{B}_{\Sigma^0 \rightarrow \Lambda e^+ e^-} (\times 10^{-3})$	$6.32 \pm 0.25_{\text{stat.}} \pm 0.18_{\text{sys.}}$	
Individual $G_M(0)$	$2.13 \pm 0.09_{\text{stat.}} \pm 0.05_{\text{sys.}}$	$2.12 \pm 0.06_{\text{stat.}} \pm 0.04_{\text{sys.}}$
Simultaneous $G_M(0)$	$2.13 \pm 0.04_{\text{stat.}} \pm 0.05_{\text{sys.}}$	
Individual $\mu / (\frac{e}{2m_p})$	$1.74 \pm 0.07_{\text{stat.}} \pm 0.03_{\text{sys.}}$	$1.73 \pm 0.05_{\text{stat.}} \pm 0.02_{\text{sys.}}$
Simultaneous $\mu / (\frac{e}{2m_p})$	$1.74 \pm 0.03_{\text{stat.}} \pm 0.03_{\text{sys.}}$	

Γ_1 $\Lambda \gamma$
 Γ_2 $\Lambda \gamma \gamma$
 Γ_3 $\Lambda e^+ e^-$

100 %
 $< 3 \%$
 $[a] \quad 5 \times 10^{-3}$

90%

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II

BESIII上超子辐射衰变 $\Sigma^0 \rightarrow \Lambda e^+ e^-$ 的研究

- ◆ 选题依据
- ◆ 研究进展

III

研究计划与安排

- 目前已经完成
 - TORCH新方案几何建模，重建算法与初步性能分析
 - BTOF设计及初步模拟
 - BTOF重建算法、粒子鉴别算法开发与性能分析
 - BESIII物理分析已完成组内review并投稿
- 2026~2027年完成
 - TORCH新方案多径迹性能分析
 - TORCH新方案样机关键技术实验与测试
 - BTOF文章撰写
- 2027~2028年完成
 - 撰写毕业论文，准备毕业答辩

Thanks!



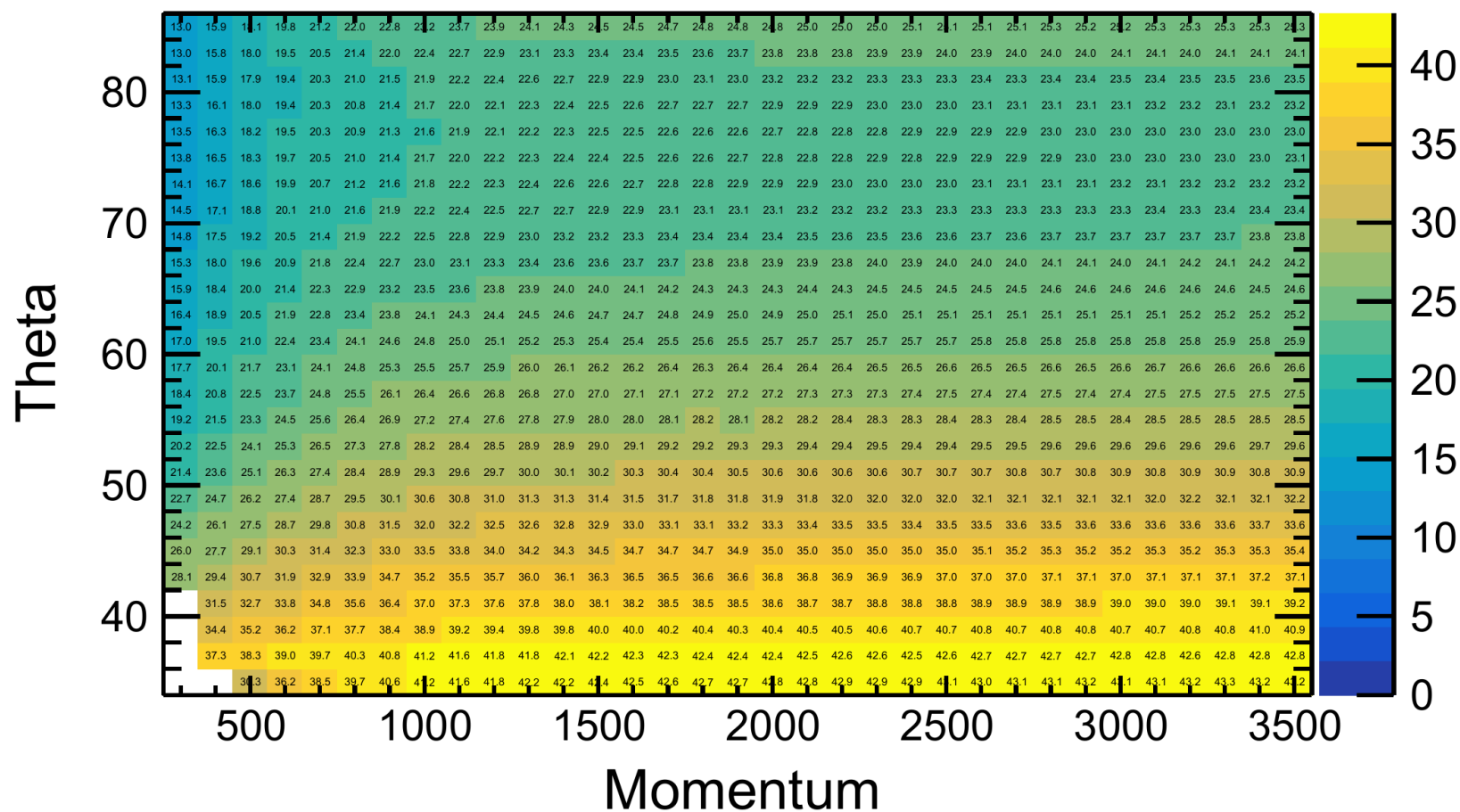
Back UP

BTOF光子数分布



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π 样本



BTOF重建(一维算法)



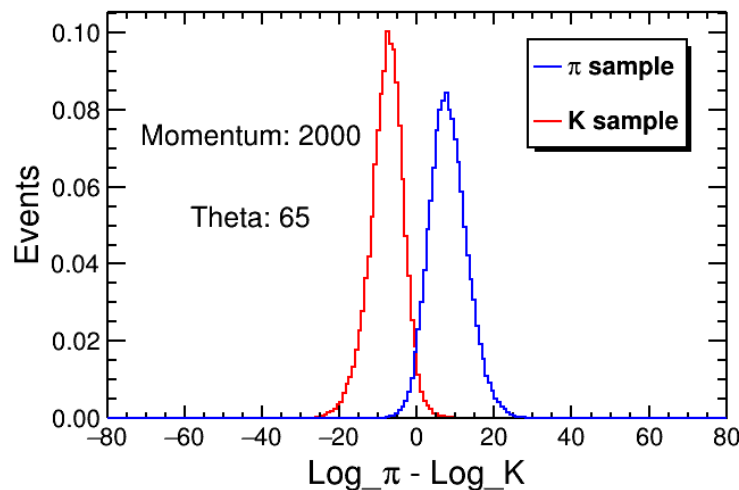
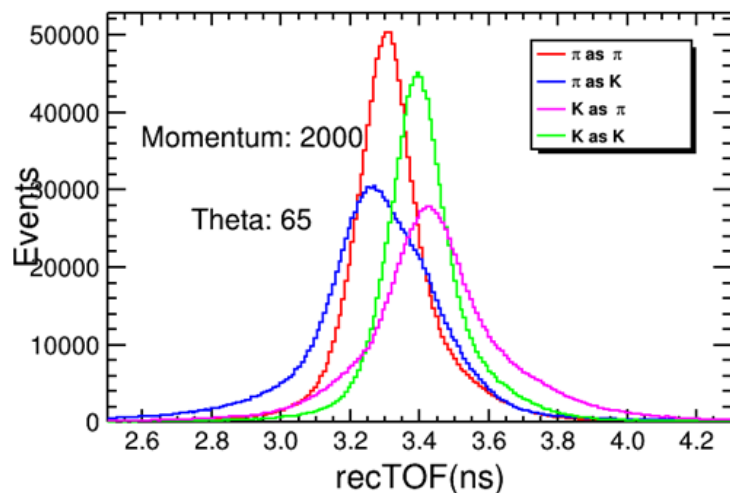
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ΔrecTOF ($\text{TOF}_{\text{rec}} - \text{TOF}_{\text{hypo}}$) 的分布使用三高斯模型描述:

ΔrecTOF

$$= \text{ratio1} * \text{Gaus1}(0, \text{resTOF}) + \frac{\text{ratio1}}{2} * \text{Gaus2}(0.135, \text{sigma1}) + (1 - 1.5 * \text{ratio1}) * \text{Gaus3}(0.05, \text{sigma2})$$

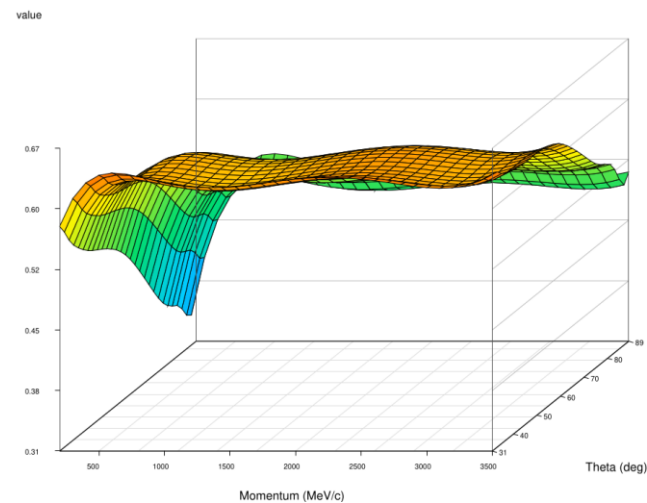
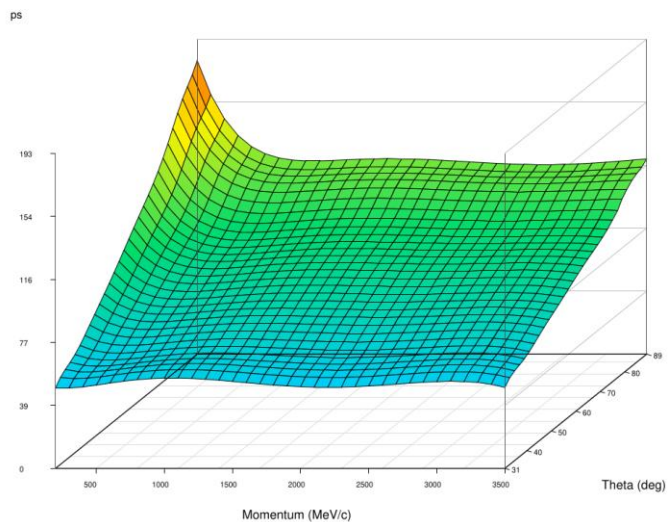
- **Gaus1**是主峰, **Gaus2**用来描述渡越时间涨落(TTS)的影响, **Gaus3**用于描述多次散射效应
- 以上参数通过拟合不同动量角度下的 ΔrecTOF 分布得到, 再通过一个关于动量和角度的函数统一描述



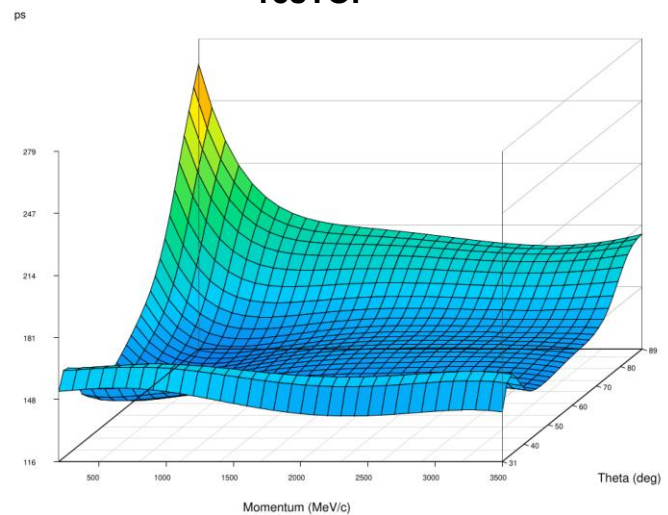
ΔrecTOF 参数分布



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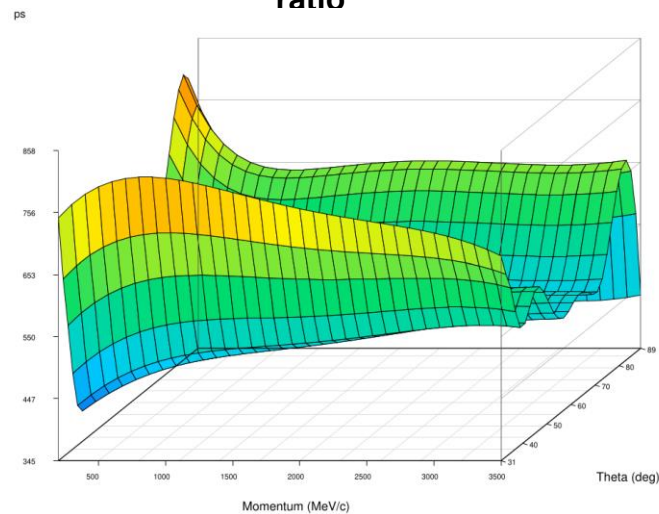


resTOF



sigma1

ratio



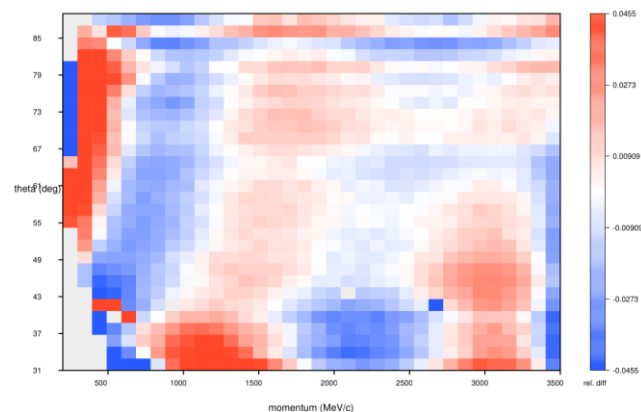
sigma2

Δ recTOF参数拟合结果

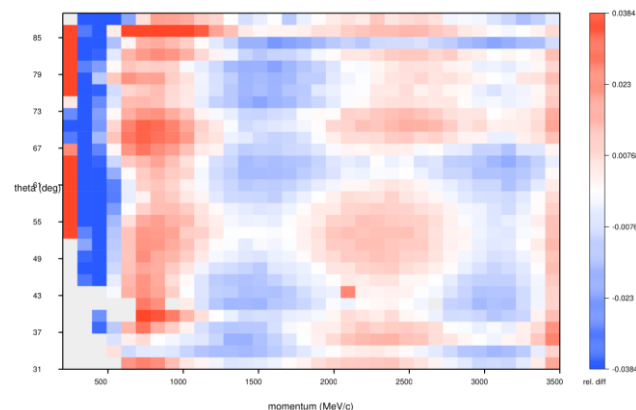


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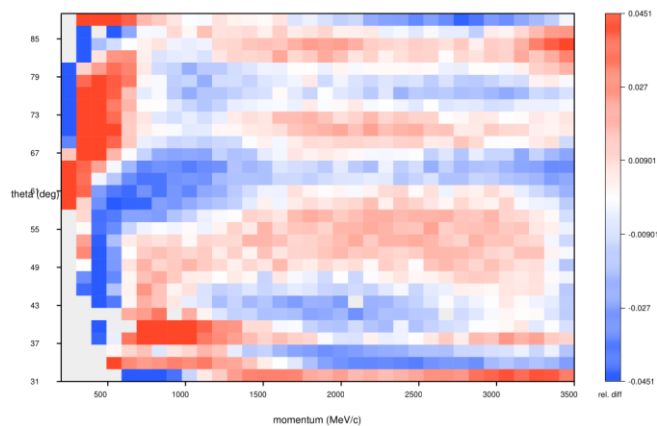
相对差别



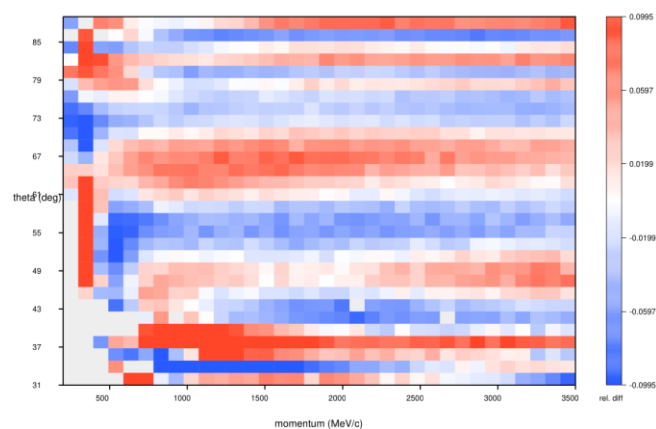
resTOF



ratio



sigma1



sigma2

- We integrated the $p(\bar{p})$ and $\Lambda(\bar{\Lambda})$ if we tag $\bar{\Sigma}^0(\Sigma^0)$. Then the amplitude for $J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^0$, $\bar{\Sigma}^0 \rightarrow \bar{\Lambda} \gamma$, $\bar{\Lambda} \rightarrow \bar{p} \pi^+$, $\Sigma^0 \rightarrow \text{anything}$ and its conjugate channel is written as:

$$\mathcal{W}_{\Sigma^0} = 2 \left(\alpha_- \sqrt{1 - \alpha_{\Sigma^0}^2} \sin \Delta\Phi_{\Sigma^0} \sin \theta_{\Sigma^0} \cos \theta_{\Sigma^0} \sin \theta_{\Lambda} \cos \theta_p \sin \phi_{\Lambda} + \alpha_{\Sigma^0} \cos^2 \theta_{\Sigma^0} + 1 \right)$$

$$\mathcal{W}_{\bar{\Sigma}^0} = 2 \left(\alpha_+ \sqrt{1 - \alpha_{\Sigma^0}^2} \sin \Delta\Phi_{\Sigma^0} \sin \theta_{\Sigma^0} \cos \theta_{\Sigma^0} \sin \theta_{\bar{\Lambda}} \cos \theta_p \sin \phi_{\bar{\Lambda}} + \alpha_{\Sigma^0} \cos^2 \theta_{\Sigma^0} + 1 \right)$$

- α_{Σ^0} and $\Delta\Phi_{\Sigma^0}$ are the decay parameters to describe $J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^0$
- α_- and α_+ are the decay parameters for $\Lambda(\bar{\Lambda}) \rightarrow p\pi^-(\bar{p}\pi^+)$
- $\theta_{\Sigma^0/\bar{\Sigma}^0}$, $\theta_{\Lambda/\bar{\Lambda}}$, $\phi_{\Lambda/\bar{\Lambda}}$, $\theta_{p/\bar{p}}$ are the helicity angles defined in the rest frame of their mother particles.

- The decay width can be computed as:

$$d\Gamma = \frac{1}{(2\pi)^5} \frac{1}{16M_{\Sigma^0}^2} \mathcal{W} |\vec{p}_l| |\vec{p}_\Lambda| dq d\Omega_l d\Omega_\Lambda$$

- The complete amplitude is written as[\[3\]](#):

$$\mathcal{W} = \frac{\alpha_{em}^2}{q^4} (q^2 - 4m_l^2) \sum_{\mu, \bar{\nu}=0}^3 \sum_{\mu'=0}^3 \sum_{\bar{\nu}'=0}^3 C_{\mu\bar{\nu}} a_{\mu\mu'}^{\Sigma^0} a_{\mu'0}^{\Lambda} a_{\bar{\nu}}^{\bar{\Sigma}^0} a_{\bar{\nu},0}^{\bar{\Lambda}}$$

- $\alpha_{em} = 4\pi/137$, q is the four-momentum transfer and m_l is the invariant mass of electron. $C_{\mu\bar{\nu}}$ represents for the polarization and spin correlation of $\Sigma^0 \bar{\Sigma}^0$. $a_{\mu\mu'}$ is the decay matrix of hyperons depending on the decay products, which is shown on backup.

[\[3\]](#): Phys. Rev. D108:016011, 2023.

$$C_{\mu\bar{\nu}} \propto \begin{pmatrix} 1 + \alpha_\psi \cos^2 \theta_1 & 0 & \beta_\psi \sin \theta_1 \cos \theta_1 & 0 \\ 0 & \sin^2 \theta_1 & 0 & \gamma_\psi \sin \theta_1 \cos \theta_1 \\ -\beta_\psi^2 \sin \theta_1 \cos \theta_1 & 0 & \alpha_\psi \sin^2 \theta_1 & 0 \\ 0 & -\gamma_\psi \sin \theta_1 \cos \theta_1 & 0 & -\alpha_\psi - \cos^2 \theta_1 \end{pmatrix}$$

- $C_{\mu\bar{\nu}}$ is a 4×4 real matrix representing polarizations and spin correlations of the baryons.

- Where the parameters β_ψ and α_ψ are expressed via α_ψ and $\Delta\Phi$ as $\beta_\psi =$

$$\sqrt{1 - \alpha_\psi^2 \sin(\Delta\Phi)} \text{ and } \gamma_\psi = \sqrt{1 - \alpha_\psi^2 \cos(\Delta\Phi)}$$

- $\alpha_\psi = \alpha_{\Sigma^0} = -0.449$ [5] $\Delta\Phi = -0.08$ [6]

- θ_1 in the electron-positron center-of-momentum (cm) system.

[5]: Phys. Rev. D95, 052003, 2017

[6]: Phys. Rev. Lett. 133, 101902, 2024

Decay matrix



$$A_{\mu\nu}^{\bar{\Sigma}^0} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\sin\theta_{\bar{\Lambda}}\cos\phi_{\bar{\Lambda}} \\ 0 & 0 & 0 & -\sin\theta_{\bar{\Lambda}}\sin\phi_{\bar{\Lambda}} \\ 0 & 0 & 0 & -\cos\theta_{\bar{\Lambda}} \end{pmatrix}$$

$$B_{\mu\nu}^{\Sigma^0} = \sum_{\kappa=0}^3 R_{\mu\kappa}^{(4)}(\Omega_l) b_{\kappa\nu}^{em}$$

$$a_{\mu\nu}^{\Lambda} = \begin{pmatrix} 1 & 0 & 0 & \alpha_{\Lambda} \\ \alpha_{\Lambda}\sin\theta_p\cos\phi_p & \gamma_{\Lambda}\cos\theta_p\cos\phi_p - \beta_{\Lambda}\sin\phi_p & -\beta_{\Lambda}\cos\theta_p\cos\phi_p - \gamma_{\Lambda}\sin\phi_p & \sin\theta_p\cos\phi_p \\ \alpha_{\Lambda}\sin\theta_p\sin\phi_p & \gamma_{\Lambda}\cos\theta_p\sin\phi_p + \beta_{\Lambda}\cos\phi_p & -\beta_{\Lambda}\cos\theta_p\sin\phi_p + \gamma_{\Lambda}\cos\phi_p & \sin\theta_p\sin\phi_p \\ \alpha_{\Lambda}\cos\theta_p & -\gamma_{\Lambda}\sin\theta_p & \beta_{\Lambda}\sin\theta_p & \cos\theta_p \end{pmatrix}$$

$$a_{\mu\nu}^{\bar{\Lambda}} = \begin{pmatrix} 1 & 0 & 0 & \alpha_{\bar{\Lambda}} \\ \alpha_{\bar{\Lambda}}\sin\theta_{\bar{p}}\cos\phi_{\bar{p}} & \gamma_{\bar{\Lambda}}\cos\theta_{\bar{p}}\cos\phi_{\bar{p}} - \beta_{\bar{\Lambda}}\sin\phi_{\bar{p}} & -\beta_{\bar{\Lambda}}\cos\theta_{\bar{p}}\cos\phi_{\bar{p}} - \gamma_{\bar{\Lambda}}\sin\phi_{\bar{p}} & \sin\theta_{\bar{p}}\cos\phi_{\bar{p}} \\ \alpha_{\bar{\Lambda}}\sin\theta_{\bar{p}}\sin\phi_{\bar{p}} & \gamma_{\bar{\Lambda}}\cos\theta_{\bar{p}}\sin\phi_{\bar{p}} + \beta_{\bar{\Lambda}}\cos\phi_{\bar{p}} & -\beta_{\bar{\Lambda}}\cos\theta_{\bar{p}}\sin\phi_{\bar{p}} + \gamma_{\bar{\Lambda}}\cos\phi_{\bar{p}} & \sin\theta_{\bar{p}}\sin\phi_{\bar{p}} \\ \alpha_{\bar{\Lambda}}\cos\theta_{\bar{p}} & -\gamma_{\bar{\Lambda}}\sin\theta_{\bar{p}} & \beta_{\bar{\Lambda}}\sin\theta_{\bar{p}} & \cos\theta_{\bar{p}} \end{pmatrix}$$

- The form factors are included in the decay matrix of $\Sigma^0 \rightarrow \Lambda e^+ e^-$, which is described with helicity amplitudes:

$$H_{\frac{1}{2}1}^V = \sqrt{2Q_-} \left[-F_1^V + \frac{M_{\Sigma^0} + M_{\Lambda}}{M_1} F_2^V \right] = -\sqrt{2Q_-} G_M$$
$$H_{\frac{1}{2}0}^V = \frac{\sqrt{Q_-}}{\sqrt{q^2}} \left[(M_{\Sigma^0} + M_{\Lambda}) F_1^V + \frac{q^2}{M_{\Sigma^0}} F_2^V \right] = \frac{\sqrt{Q_-}}{\sqrt{q^2}} (M_{\Sigma^0} + M_{\Lambda}) G_E$$

- F_1 and F_2 are the transition form factors, and $G_{E/M}$ are electromagnetic form factors. $Q_{\pm} = (M_{\Sigma^0} - M_{\Lambda})^2 \pm q^2$
- G_E can be safely neglected because the electric radius is estimated to be much smaller than the magnetic one[\[2\]](#) [\[4\]](#), so as we do in MC generation.

[\[2\]](#): Eur. Phys. J. C (2020) 80:218, 2020

[\[4\]](#): Eur. Phys. J. A53:117, 2017

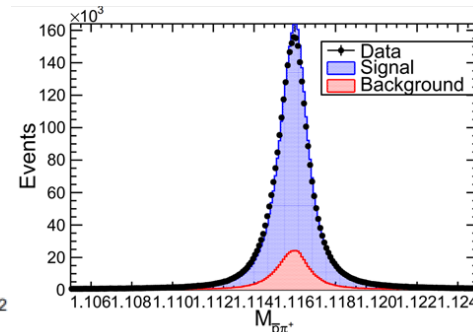
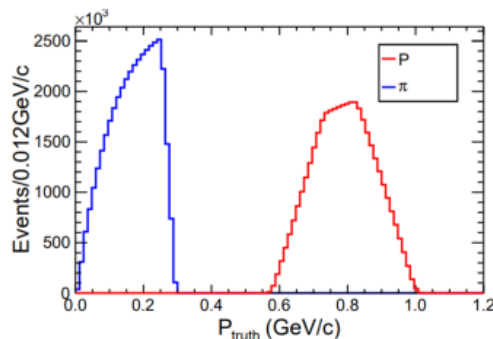
Event Selection

□ Good Tracks

- $|\cos\theta| < 0.93$
- $|V_z| < 30\text{cm}$
- $N_{good} \geq 2$

□ PID (dE/dx + TOF)

- p : $\text{Prob}(p) > \text{Prob}(\pi/K/e) \ \&\& \ P_{\bar{p}} > 0.55 \text{ GeV}/c$
- π : $\text{Prob}(\pi) > \text{Prob}(p/K/e) \ \&\& \ P_{\pi} < 0.35 \text{ GeV}/c$
- $N_{\bar{p}} \geq 1 \ \&\& \ N_{\pi^+} \geq 1$



□ Photon Selection

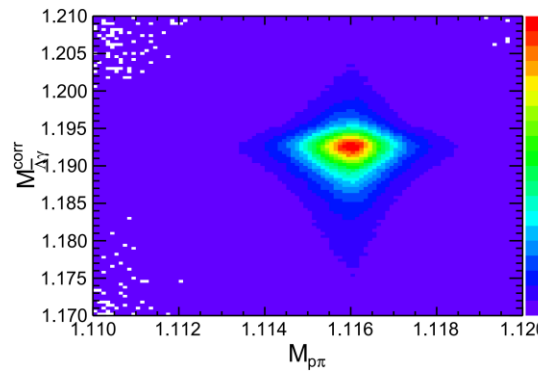
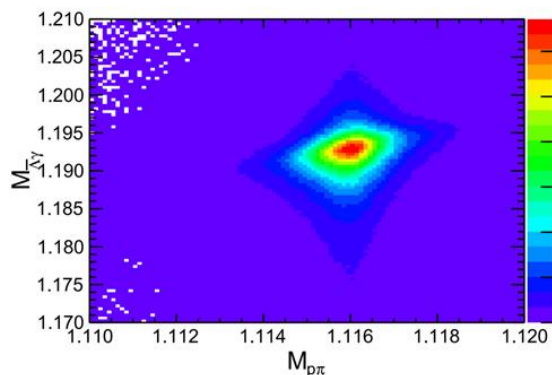
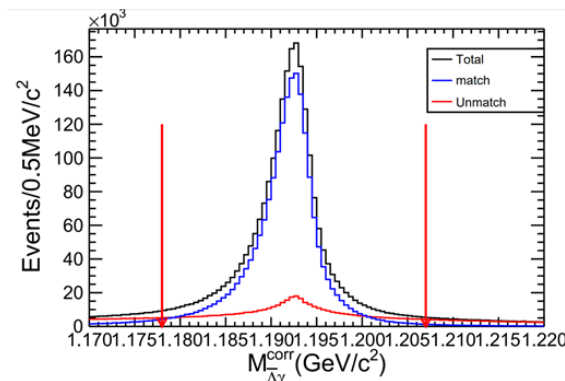
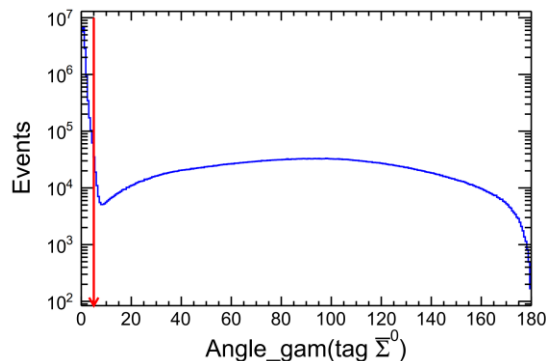
- Opening angle between shower and the nearest charged track $> 10^\circ$ ($> 20^\circ$ for $\bar{p}$)
- Barrel(Endcap): $E > 25(50)\text{MeV}$, $|\cos\theta| < 0.8(0.92)$
- $0 < T < 14$
- $N_\gamma \geq 1$

□ $\bar{\Lambda}$ Reconstruction

- Do vertex fit and secondary vertex fit of all $\bar{p}\pi^+$ combinations and choose the one with the minimum χ_{sec}^2
- $|M_{\bar{p}\pi^+} - M_\Lambda| < 8\text{MeV}/c^2$
- $L_{decay} > 0$
- $\chi_{sec}^2 < 200$

□ $\bar{\Sigma}^0$ Reconstruction

- Looping all γ candidates, and keep the ones with the minimum value of $|M_{\bar{\Lambda}\gamma}^{corr}(M_{\bar{\Lambda}\gamma} - M_{\bar{p}\pi^+} + M_{\Lambda})|$
- Match angle between selected photon and truth information: $\theta_{match} < 5^\circ$
- $|M_{\bar{\Lambda}\gamma}^{corr} - M_{\Sigma^0}| < 0.15 \text{ GeV}/c^2$



Event Selection

□ Good Tracks

- $|\cos\theta| < 0.93$
- $|V_z| < 30cm$
- $N_{good} \geq 6$

□ PID (dE/dx + TOF)

- $e: \frac{Prob(e)}{Prob(e)+Prob(\pi)+Prob(K)} > 0.8$
- $N_p \geq 1 \ \&\& \ N_{\pi^-} \geq 1$
- $N_{e^+} \geq 1 \ \&\& \ N_{e^-} \geq 1$
- For $e^\pm$: $|V_r| < 1cm \ |V_z| < 10cm$

□ Λ Reconstruction

- Reconstruction of Λ is the same as that of $\bar{\Lambda}$ on ST side

□ Kinematic Fit

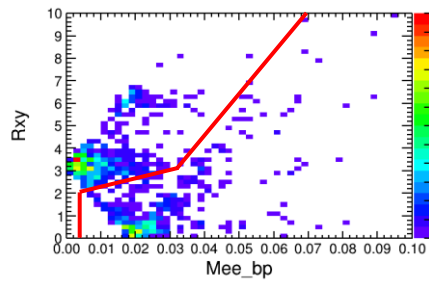
- Firstly a vertex fit of e^+e^- is performed to improve e^+e^- kinematic uncertainties
- Loop all e^+e^- with $\gamma, \Lambda, \bar{\Lambda}$ to do 4C kinematic Fit, find the successfully fit ones with the minimum value of χ_{kmf}^2 .

Table 1: Decay trees and their respective initial-final states.

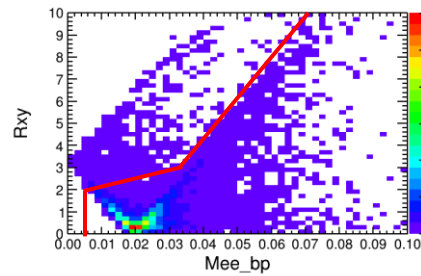
rowNo	decay tree (decay initial-final states)	iDcyTr	iDcyIFSts	nEtr	nCEtr
1	$J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^0, \Sigma^0 \rightarrow \Lambda \gamma, \bar{\Sigma}^0 \rightarrow \bar{\Lambda} \gamma, \Lambda \rightarrow \pi^- p, \bar{\Lambda} \rightarrow \pi^+ \bar{p}$ ($J/\psi \rightarrow \pi^+ \pi^- p \bar{p} \gamma \gamma$)	0	0	427	427
2	$J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^{*0}, \Sigma^0 \rightarrow \Lambda \gamma, \bar{\Sigma}^{*0} \rightarrow \pi^0 \bar{\Lambda}, \Lambda \rightarrow \pi^- p, \bar{\Lambda} \rightarrow \pi^+ \bar{p}$ ($J/\psi \rightarrow \pi^0 \pi^+ \pi^- p \bar{p} \gamma$)	1	1	3	430
3	$J/\psi \rightarrow \eta_c \gamma, \eta_c \rightarrow \Sigma^0 \bar{\Sigma}^0, \Sigma^0 \rightarrow \Lambda \gamma, \bar{\Sigma}^0 \rightarrow \bar{\Lambda} \gamma, \Lambda \rightarrow \pi^- p, \bar{\Lambda} \rightarrow \pi^+ \bar{p}$ ($J/\psi \rightarrow \pi^+ \pi^- p \bar{p} \gamma \gamma \gamma$)	2	2	2	432
4	$J/\psi \rightarrow \Lambda \Sigma^{*0}, \Lambda \rightarrow \pi^- p, \bar{\Sigma}^{*0} \rightarrow \pi^0 \bar{\Lambda}, \pi^0 \rightarrow e^+ e^- \gamma^F, \bar{\Lambda} \rightarrow \pi^+ \bar{p}$ ($J/\psi \rightarrow e^+ e^- \pi^+ \pi^- p \bar{p} \gamma^F$)	3	3	1	433
5	$J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^0 \gamma, \Sigma^0 \rightarrow \Lambda \gamma, \bar{\Sigma}^0 \rightarrow \bar{\Lambda} \gamma, \Lambda \rightarrow \pi^- p, \bar{\Lambda} \rightarrow \pi^+ \bar{p}$ ($J/\psi \rightarrow \pi^+ \pi^- p \bar{p} \gamma \gamma \gamma$)	4	2	1	434
6	$J/\psi \rightarrow \bar{\Lambda} \Sigma^0, \bar{\Lambda} \rightarrow \pi^+ \bar{p}, \Sigma^0 \rightarrow \Lambda \gamma, \Lambda \rightarrow \pi^- p$ ($J/\psi \rightarrow \pi^+ \pi^- p \bar{p} \gamma$)	5	4	1	435
7	$J/\psi \rightarrow \Lambda \Sigma^{*0}, \Lambda \rightarrow \pi^- p, \bar{\Sigma}^{*0} \rightarrow \pi^0 \bar{\Lambda}, \bar{\Lambda} \rightarrow \pi^+ \bar{p}$ ($J/\psi \rightarrow \pi^0 \pi^+ \pi^- p \bar{p}$)	6	5	1	436
8	$J/\psi \rightarrow \Lambda \Sigma^0 \gamma, \Lambda \rightarrow \pi^- p, \bar{\Sigma}^0 \rightarrow \bar{\Lambda} \gamma, \bar{\Lambda} \rightarrow \pi^+ \bar{p}$ ($J/\psi \rightarrow \pi^+ \pi^- p \bar{p} \gamma \gamma$)	7	0	1	437
9	$J/\psi \rightarrow \Lambda \Sigma^{*0}, \Lambda \rightarrow \pi^- p, \bar{\Sigma}^{*0} \rightarrow \pi^0 \bar{\Lambda}, \pi^0 \rightarrow e^+ e^- \gamma^F \gamma^f, \bar{\Lambda} \rightarrow \pi^+ \bar{p}$ ($J/\psi \rightarrow e^+ e^- \pi^+ \pi^- p \bar{p} \gamma^F \gamma^f$)	8	6	1	438

- From the analysis of DT inclusive topology, we can find that the most dominant background is $\Sigma^0 \rightarrow \Lambda \gamma$ from gamma conversion.

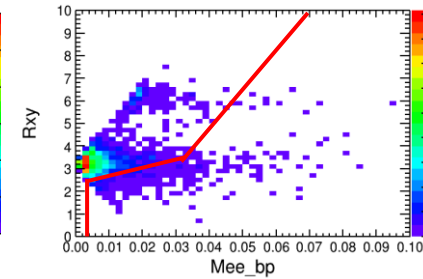
Gamma Conversion Veto



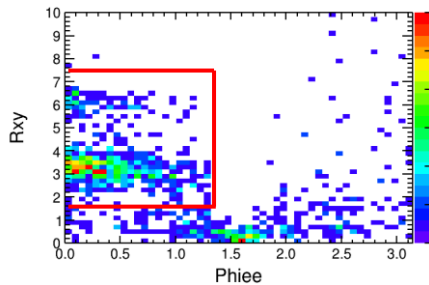
data



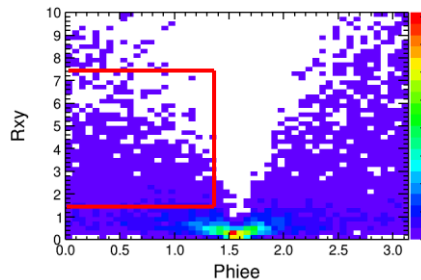
Signal mc



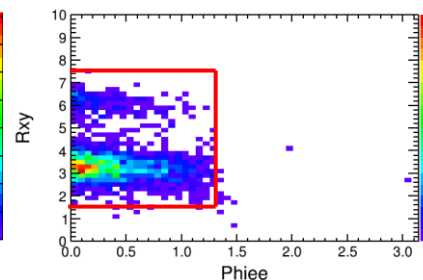
Bkg mc



data



Signal mc



Bkg mc

- $\Phi_{ee} < 75^\circ$ when $2\text{cm} < R_{xy} < 7.5\text{cm}$ is rejected.
- Events on high mass side of the curve are selected. The curve is defined between $(0.004\text{GeV}/c^2, 0\text{cm}), (0.004\text{GeV}/c^2, 2\text{cm}), (0.03\text{GeV}/c^2, 3\text{cm}), (0.07\text{GeV}/c^2, 10\text{cm})$

DT Analysis



Table 1: Decay trees and their respective initial-final states.

rowNo	decay tree (decay initial-final states)	iDeyTr	iDeyIFSts	nEtr	nCEtr
1	$J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^0, \Sigma^0 \rightarrow \Lambda \gamma, \bar{\Sigma}^0 \rightarrow \bar{\Lambda} \gamma, \Lambda \rightarrow \pi^- p, \bar{\Lambda} \rightarrow \pi^+ \bar{p}$ ($J/\psi \rightarrow \pi^+ \pi^- p \bar{p} \gamma \gamma$)	0	0	427	427
2	$J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^0, \Sigma^0 \rightarrow \Lambda \gamma, \bar{\Sigma}^0 \rightarrow \pi^0 \bar{\Lambda}, \Lambda \rightarrow \pi^- p, \bar{\Lambda} \rightarrow \pi^+ \bar{p}$ ($J/\psi \rightarrow \pi^+ \pi^- \pi^+ \pi^- p \bar{p} \gamma$)	1	1	3	430
3	$J/\psi \rightarrow \eta_c \gamma, \eta_c \rightarrow \Sigma^0 \bar{\Sigma}^0, \Sigma^0 \rightarrow \Lambda \gamma, \bar{\Sigma}^0 \rightarrow \bar{\Lambda} \gamma, \Lambda \rightarrow \pi^- p, \bar{\Lambda} \rightarrow \pi^+ \bar{p}$ ($J/\psi \rightarrow \pi^+ \pi^- p \bar{p} \gamma \gamma \gamma$)	2	2	2	432
4	$J/\psi \rightarrow \Lambda \bar{\Sigma}^0, \Lambda \rightarrow \pi^- p, \bar{\Sigma}^0 \rightarrow \pi^0 \bar{\Lambda}, \pi^0 \rightarrow e^+ e^- \gamma^F, \bar{\Lambda} \rightarrow \pi^+ \bar{p}$ ($J/\psi \rightarrow e^+ e^- \pi^+ \pi^- p \bar{p} \gamma^F$)	3	3	1	433
5	$J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^0 \gamma, \Sigma^0 \rightarrow \Lambda \gamma, \bar{\Sigma}^0 \rightarrow \bar{\Lambda} \gamma, \Lambda \rightarrow \pi^- p, \bar{\Lambda} \rightarrow \pi^+ \bar{p}$ ($J/\psi \rightarrow \pi^+ \pi^- p \bar{p} \gamma \gamma \gamma$)	4	2	1	434
6	$J/\psi \rightarrow \Lambda \bar{\Sigma}^0, \bar{\Lambda} \rightarrow \pi^+ \bar{p}, \Sigma^0 \rightarrow \Lambda \gamma, \Lambda \rightarrow \pi^- p$ ($J/\psi \rightarrow \pi^+ \pi^- \pi^+ \pi^- p \bar{p} \gamma$)	5	4	1	435
7	$J/\psi \rightarrow \Lambda \bar{\Sigma}^0, \Lambda \rightarrow \pi^- p, \bar{\Sigma}^0 \rightarrow \pi^0 \bar{\Lambda}, \bar{\Lambda} \rightarrow \pi^+ \bar{p}$ ($J/\psi \rightarrow \pi^+ \pi^- \pi^+ \pi^- p \bar{p}$)	6	5	1	436
8	$J/\psi \rightarrow \Lambda \bar{\Sigma}^0 \gamma, \Lambda \rightarrow \pi^- p, \bar{\Sigma}^0 \rightarrow \bar{\Lambda} \gamma, \bar{\Lambda} \rightarrow \pi^+ \bar{p}$ ($J/\psi \rightarrow \pi^+ \pi^- p \bar{p} \gamma \gamma$)	7	0	1	437
9	$J/\psi \rightarrow \Lambda \bar{\Sigma}^0, \Lambda \rightarrow \pi^- p, \bar{\Sigma}^0 \rightarrow \pi^0 \bar{\Lambda}, \pi^0 \rightarrow e^+ e^- \gamma^F \gamma^f, \bar{\Lambda} \rightarrow \pi^+ \bar{p}$ ($J/\psi \rightarrow e^+ e^- \pi^+ \pi^- p \bar{p} \gamma^F \gamma^f$)	8	6	1	438

rowNo	decay tree (decay initial-final states)	iDeyTr	iDeyIFSts	nEtr	nCEtr
1	$J/\psi \rightarrow \Sigma^0 \bar{\Sigma}^0, \Sigma^0 \rightarrow \Lambda \gamma, \bar{\Sigma}^0 \rightarrow \bar{\Lambda} \gamma, \Lambda \rightarrow \pi^- p, \bar{\Lambda} \rightarrow \pi^+ \bar{p}$ ($J/\psi \rightarrow \pi^+ \pi^- p \bar{p} \gamma \gamma$)	0	0	5	5
2	$J/\psi \rightarrow \Lambda \bar{\Sigma}^0, \Lambda \rightarrow \pi^- p, \bar{\Sigma}^0 \rightarrow \pi^0 \bar{\Lambda}, \pi^0 \rightarrow e^+ e^- \gamma^F, \bar{\Lambda} \rightarrow \pi^+ \bar{p}$ ($J/\psi \rightarrow e^+ e^- \pi^+ \pi^- p \bar{p} \gamma^F$)	1	1	1	6

Very Low Background Level after Conversion Cut !

Systematic Uncertainty



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University of Science and Technology of China

Source	$\Sigma^0 \rightarrow \Lambda e^+ e^-$ (%)	$\bar{\Sigma}^0 \rightarrow \bar{\Lambda} e^+ e^-$ (%)	Combined (%)
$\Lambda(\bar{\Lambda})$ reconstruction	1.0	1.0	1.0
e^+ tracking	0.3	0.3	0.3
e^- tracking	0.4	0.4	0.4
e^+ PID	0.3	0.3	0.3
e^- PID	0.3	0.3	0.3
Gamma conversion veto	1.1	1.1	1.1
$e^+ e^-$ vertex fit and 4C kinematic fit	1.3	1.3	1.3
Single tag fit	1.5	0.6	1.1
Double tag fit	2.8	2.4	2.6
Total Uncertainty of $\Sigma^0(\bar{\Sigma}^0) \rightarrow \Lambda(\bar{\Lambda}) e^+ e^-$	3.8	3.3	3.5